The B2Scala Tool: Integrating Bach in Scala with Security in Mind

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Process algebras have been widely used to verify security protocols in a formal manner. However they mostly focus on synchronous communication based on the exchange of messages. We present an alternative approach relying on asynchronous communication obtained through information available on a shared space. More precisely this paper first proposes an embedding in Scala of a Linda-like language, called Bach. It consists of a Domain Specific Language, internal to Scala, that allows us to experiment programs developed in Bach while benefiting from the Scala eco-system, in particular from its type system as well as program fragments developed in Scala. Moreover, we introduce a logic that allows to restrict the executions of programs to those meeting logic formulae. Our work is illustrated on the Needham-Schroeder security protocol, for which we manage to automatically rediscover the man-in-the-middle attack first put in evidence by G. Lowe.

1 Introduction

Besides the use of theorem provers, process algebras have been widely used to verify security protocols in a formal manner. A seminal effort in this direction is reported in [19]. There the author illustrates how modeling in CSP [12] and utilizing the FDR tool [10] can be used to produce an attack on the Needham-Schroeder protocol. As another example, the article [2] demonstrates how state reduction techniques can be applied to analyze a model of the Bilateral Key Exchange protocol written in mCRL [6]. In these two cases the models rely on synchronous communication obtained by the exchange of messages. Although this type of communication has been fundamental in the theory of concurrency and has consequently benefited from extensive research support, it is not necessarily intuitive for analyzing security protocols. Indeed, the idea of exchanging messages in a synchronous manner between partners rests on the assumption that the communication takes place instantaneously on agreed actions and thus does not naturally leave room for an intruder to intercept messages. As an evidence at the programming level, in the above two pieces of work, this has lead the authors to duplicate the exchange of messages in their model.

Another path of research has been initiated by Gelernter and Carriero, who advocated in [9] that a clear separation between the interactional and the computational aspects of software components has to take place in order to build interactive distributed systems. Their claim has been supported by the design of a model, Linda [3], originally presented as a set of inter-agent communication primitives which may be added to almost any programming language. Besides process creation, this set includes primitives for adding, deleting, and testing the presence/absence of data in a shared dataspace. In doing so they proposed a new form of synchronization of processes, occurring asynchronously, through the availability or absence of pieces of information on a shared space. A number of other models, now referred to as

coordination models, have been proposed afterwards. These models seem highly attractive to us because, in practice, message exchanges do not occur atomically through the synchronous communication of actors. Instead, they must happen through a medium – such as a network – which can be easily modeled as a shared space.

The aim of this paper is to explore how coordination models can be used to analyze security protocols. More concretely, we will focus on a specific coordination model, named Bach, will derive a tool, named B2Scala, and will employ it to produce the attack on the Needham-Schroeder protocol [20] first put in evidence by G. Lowe (see [19]).

Implementing coordination models can be done in three different ways. First, as illustrated by Tucson [7], one may provide an implementation as a stand alone language. This has the advantage of offering support for a complete algebra-like incarnation of Linda but at the expense of having to re-implement classical programming constructs that are proposed in conventional languages (like variables, loops, lists, . . .). The second approach, illustrated by pSpaces [18] is to provide a set of APIs in a conventional language in order to access the shared space through dedicated functions or methods. This approach benefits from the converse characteristics of the first one: it is easy to access classical programming constructs but the abstract control flow that is offered at a process algebraic level, like non-deterministic choice and parallel composition, is to be coded in an ad hoc manner. Finally, a third approach consists in using a domain specific language embedded inside an existing language. We will turn to this approach since, in principle, it enjoys the benefits of the first two approaches. More specifically, this paper proposes to embody the Bach coordination language inside Scala. In doing so we will profit from the Scala eco-system while benefiting from all the abstractions offered by the Bach coordination language. A key feature is that we will interpret control flow structures, which we put in good use to restrict computations to those verifying logic formulae. As an interesting consequence, we shall be able to produce the man-in-the-middle attack of the Needham-Schroeder security protocol first put in evidence by G. Lowe.

The rest of the paper is structured as follows. Section 2 presents the Needham-Schroeder use-case as well as the Bach and Scala languages. Section 3 describes the B2Scala tool, both from the point of view of its usage by programmers and from the implementation point of view. A logic is proposed in Section 4 together with its effect on reducing executions. Section 5 illustrates how B2Scala coupled to constraint executions can be used to analyze the Needham-Schroeder protocol. Finally Section 6 draws our conclusions and compares our work with related work.

2 Background

2.1 Use-case: the Needham-Schroeder Protocol

The Needham-Schroeder protocol, developed by Roger Needham and Michael Schroeder in 1978 [20], is a pioneering cryptographic solution aimed at ensuring secure authentication and key distribution within network environments. Its primary objective is to establish a shared session key between two parties, typically referred to as the principal entities, facilitating encrypted communication to safeguard data confidentiality and integrity. The protocol unfolds in a series of steps: initialization, where a client (A) requests access to another client (B) from a trusted server (S), followed by the server's response, which involves authentication, session key generation, and ticket encryption. Subsequently, communication with party B ensues, facilitated by the transmission of the encrypted ticket, along with nonces to ensure freshness. Parties exchange messages encrypted with the session key and incorporate nonces to prevent replay attacks. Mutual authentication is achieved through encrypted messages exchanged between A and B, leveraging the established session key and nonces. Despite its early contributions, the original protocol

exhibited vulnerabilities, notably the reflection attack. In response, refined versions have emerged, such as the Needham-Schroeder-Lowe [19] and Otway-Rees protocols [17].

The description of the Needham-Schroeder public key protocol is often slimmed down to the three following actions:

$$Alice \longrightarrow Bob \quad : \quad message(na : a)_{pkb}$$
$$Bob \longrightarrow Alice \quad : \quad message(na : nb)_{pka}$$
$$Alice \longrightarrow Bob \quad : \quad message(nb)_{pkb}$$

where each transition of the form $X \rightarrow Y : m$ represents message m being sent from X to Y. Moreover, the notation m_k represents message m being encrypted with the public key k.

This version assumes that the public keys of Alice and Bob (resp. *pka* and *pkb*) are already known to each other. The full version also involves communication between the parties and a trusted server to obtain the public keys.

In this model, Alice initiates the protocol by sending to Bob her nonce *na* together with her identity *a*, the whole message being encrypted with Bob's public key *pkb*. Bob responds by sending to Alice her nonce *na* together with his nonce *nb*, the whole message being encrypted this time with Alice's public key *pka*. Finally Alice sends to Bob his nonce *nb*, as a proof that a session has been safely made between them. The message is this time encrypted with Bob's public key.

It is worth stressing that, although public keys are known publicly (as the noun suggests), it is only the owners of the corresponding private keys that can decrypt encrypted messages. For instance, the first message sent to Bob can only be decrypted by him.

It is also worth noting that, although sending messages appears as an atomic action in the above description, this is in fact not the case. Messages are transmitted through some medium, say the network, and thus are subject to be read or picked up by opponents. This will be illustrated in Section 5 where a more detailed model will be examined.

2.2 The Bach Coordination Language

Bach [8, 15] is a Linda dialect developed at the University of Namur by the authors. It borrows from Linda the idea of a shared space and reformulates data and the primitives according to the constraint logic programming setting [24]. The following presentation is based on the one of article [1].

2.2.1 Definition of data

According to the logic programming setting, we assume a non-empty set of function names, each one associated with an arity, which indicates the number of arguments the function takes. We assume a non-empty subset of function names associated with an arity 0, namely taking no argument. Such function names are subsequently referred to as *tokens*. Based on their existence, so-called structured pieces of information are introduced inductively as expressions of the form $f(a_1, \cdots, a_n)$ where f is a function name associated with arity n and where arguments $a_1, \ldots, a_n$ are structured pieces of information, understood either as tokens or in the structured form under description. Note that, as the special case where $n = 0$, tokens are considered as being structures information terms. The set of structured pieces of information is subsequently denoted by $\mathscr{I}$. For short, *si-term* is used later to denote a structured piece of information.

Example 1 *The nounces used by Alice and Bob in the Needham-Schroeder protocol are coded by the tokens* na *and* nb, *respectively. Similarly, their public keys are coded by the tokens* pka *and* pkb. *A*

(T) $\quad \langle\, tell(t) \mid \sigma \,\rangle \longrightarrow \langle\, E \mid \sigma \cup \{t\} \,\rangle$	**(G)** $\langle\, get(t) \mid \sigma \cup \{t\} \,\rangle \longrightarrow \langle\, E \mid \sigma \,\rangle$

$$\textbf{(A)} \ \langle\, ask(t) \mid \sigma \cup \{t\} \,\rangle \longrightarrow \langle\, E \mid \sigma \cup \{t\} \,\rangle \qquad \textbf{(N)} \quad \frac{t \notin \sigma}{\langle\, nask(t) \mid \sigma \,\rangle \longrightarrow \langle\, E \mid \sigma \,\rangle}$$

Figure 1: Transition rules for the primitives (taken from [1])

$$\textbf{(S)} \quad \frac{\langle A \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}{\langle A \,;\, B \mid \sigma \rangle \longrightarrow \langle A' \,;\, B \mid \sigma' \rangle} \qquad\qquad \textbf{(C)} \quad \frac{\langle A \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}{\substack{\langle A + B \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle \\ \langle B + A \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}}$$

$$\textbf{(P)} \quad \frac{\langle A \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}{\substack{\langle A \,\|\, B \mid \sigma \rangle \longrightarrow \langle A' \,\|\, B \mid \sigma' \rangle \\ \langle B \,\|\, A \mid \sigma \rangle \longrightarrow \langle B \,\|\, A' \mid \sigma' \rangle}} \qquad \textbf{(Pc)} \quad \frac{P(\bar{x}) = A, \langle A[\bar{x}/\bar{u} \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}{\langle P(\bar{u}) \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}$$

Figure 2: Transition rules for the operators (taken from [1])

message encrypted by Alice with Bob's public key and providing Alice's nounce with her identity 'a' is encoded as the following structured piece of information `encrypt(na, a, pkb)`.

2.2.2 Agents

Following the concurrent constraint setting, Linda primitives `out`, `rd` and `in` respectively used to output a tuple, check its presence and consume one occurrence are reformulated as `tell`, `ask`, `get`, acting on si-terms. We add to them a negative counterpart, `nask` checking the absence of a si-term. The execution of these primitives is described by the transition relation defined in Figure 1. The configurations to be considered are pairs of instructions, for the moment reduced to simple primitives, coupled to the contents of the shared space. Following the concurrent constraint setting, the shared space is referred to as the *store*. It is taken as a multiset of si-terms. Moreover, the E symbol is used to denote a terminated computation. Consequently, rule (T) expresses that the execution of the $tell(t)$ primitive always succeeds and add an occurrence of t to the store. Rule (A) requires $ask(t)$ to succeed that t is present on the store. As this primitive just makes a test, the contents of the store is unchanged. According to rule (G), the $get(t)$ primitive acts similarly but remove one occurrence of t. Finally, as specified by rule (N), the primitive $nask(t)$ succeeds in case t is absent from the store.

Primitives are combined to form more complex agents by means of traditional operators from concurrency theory: sequential composition, denoted by the ; symbol, parallel composition, denoted by the || symbol, and non-deterministic choice, denoted by the + symbol.

Procedures are defined by associating an agent with a procedure name possibly coupled to parameters. As usual, we shall assume that the associated agents are guarded, in the sense that the execution of a primitive preceeds any call or can be rewritten in such a form. Procedures are subsequently declared after the `proc` keyword.

The execution of complex agents is defined by the transition rules of Figure 2. Sequential, parallel and choice composition operators are given the convention semantics in rules (S), (P) and (C), respec-

tively. Rule (Pc) dictates that the procedure call $P(\overline{u})$ operates as the agent A that defines P with the formal arguments $\overline{x}$ replaced by the actual ones $\overline{u}$. It is important to note that, in these rules, agents of the form $(E;A)$, $(E \parallel A)$ and $(A \parallel E)$ are rewritten as A.

Example 2 *As an example, the behavior of Alice and Bob can be coded as follows:*

```
proc Alice = tell(encrypt(na,a,pkb)); get(encrypt(na,nb,pka));
             tell(encrypt(nb,pkb)).

      Bob = get(encrypt(na,a,pkb); tell(encrypt(na,nb,pka));
            get(encrypt(nb,pkb)).
```

Note that Alice and Bob only tell messages encrypted with the public key of the other and only get messages encrypted with their public key, which simulates their sole use of their private key.

It is also worth stressing that we will present a model of the Needham-Schroeder protocol and not a concrete implementation. Hence the above tokens (na, nb, . . .) are to be understood as globally defined and not as a form of local variables.

2.3   The Scala Programming Language

Scala is a statically typed language known for its concise syntax and seamless fusion of object-oriented and functional programming. Variables can be declared as immutable or mutable, as illustrated by the following code snippet.

```
val immutableVariable: Int = 42
var mutableVariable: String = "Hello, Scala!"
```

Methods are introduced with the *def* keyword, can be generic (with type parameters specified in square brackets), can be written in curried form (with multiple parameter lists) and have a return type which is specified at the end of the signature. Here is a simple example for adding two integers.

```
def add(x: Int, y: Int): Int = x + y
```

Methods are typically included in the definition of objects, classes and traits, which act as interfaces in Java. Of particular interest for the implementation of B2Scala is the definition of *case classes* which are classes that automatically define setter, getter, hash and equal methods.

Two main additional features of Scala are worth stressing.

2.3.1   Functions and objects

Functions may be coded by defining objects with an apply function. For instance, if we define

```
object tell {
    def apply(siterm: SI_Term) = TellAgent(siterm)
}

object Agent {
        def apply(agent: BSC_Agent) = CalledAgent(agent)
}
```

then the evaluation of

```
val P = Agent { tell(f(1,2)) }
```

consists first in evaluating *tell* on the si-term $f(1,2)$, which results in the structure *TellAgent*($f(1,2)$), and then in evaluating the function *Agent* on this value, which results in the structure *CalledAgent*(*TellAgent*($f(1,2)$)). It is that result which is assigned to *P*.

2.3.2 Strictness and lazyness

Scala is a strict language that eagerly evaluates expressions. However there are cases in which it is desirable to postpone the evaluation of expressions, for instance to handle recursive definitions of agents. To that end, Scala proposes two basic mechanisms: call-by-name of arguments of functions and so-called thunks. To understand these two concepts, let us modify the add function so that it returns the double of its first argument, regardless of the value of the second one:

```
def  doubleAdd ( x :   Int ,   y :   =>  Int )  =  x  +  x
```

The first argument is passed using the call-by-value strategy. It is evaluated whenever the function is called. In contrast, the second argument is passed using the call-by-name strategy. Accordingly, it is evaluated when needed and thus in our example not evaluated at all. However one step further needs to be made to handle recursive expressions that we want to evaluate step by step. In that case, so-called thunks are used. They amount to consider functions requiring no arguments, as in the following definition

```
def  myIf [A]( cond :   Boolean ,   onTrue :   ()  =>  A,
                          onFalse :   ()  =>  A ) :   A  =  {
      if  ( cond )  onTrue ()  else  onFalse ()
}
```

Note that the arguments *onTrue* and *onFalse* are functions taking no arguments and leading to expressions rather than simply expressions.

To conclude this point, it is possible to delay the evaluation of val-declared expression by using the *lazy* keyword, such as in

```
lazy  val  recursiveExpression  =   (1+ recursiveExpression )∗2
```

3   The B2Scala Tool

3.1   Programming interface

To embed Bach in Scala, two main issues must be tackled: on the one hand, how is data declared, and, on the other hand, how are agents declared.

3.1.1   Data

As regards data, the trait *SI_Term* is defined to capture si-terms. Concrete si-terms are then defined as case classes of this trait. For instance in order to manipulate $f(1,2)$ in one of the primitives (tell, ask, ...) the following declaration has to be made:

```
case  class  f ( x : Int ,   y :   Int )  extends  SI_Term
```

Similarly, tokens can be declared as in

```
case  class  a ()  extends  SI_Term
```

However that leads to duplicate parentheses everywhere as in *tell*(*a*()). To avoid that a *Token* class has been defined as a case class of *SI_Term*. It takes as argument a string so that token *a* can be declared as

```
val a = Token(''a'')
```

Accordingly, *a* may now be used without parentheses, as in *tell*(*a*).

Example 3 *As examples, the public keys and nonces used in the Needham-Schroeder protocol are declared as the following tokens:*

```
val pka = Token(''pka'')
val pkb = Token(''pkb'')
val na = Token(''na'')
val nb = Token(''nb'')
```

Encrypted messages are coded by the following si-terms:

```
case class encrypt2(n: SI_Term,k: SI_Term) extends SI_Term
case class encrypt3(n: SI_Term,x: SI_Term,k: SI_Term) extends SI_Term
```

Note that Scala does not allow the same name to be used for different case classes. We have thus renamed them according to the number of arguments.

3.1.2   Agents

The main idea for programming agents is to employ constructs of the form

```
val P = Agent { (tell(f(1,2))+tell(g(3))) || (tell(a)+tell(b)) }
```

which encapsulate a Bach agent inside Scala definitions. The *Agent* object is the main ingredient to do so. It is defined as an object with an apply method as follows

```
object Agent {
    def apply(agent: BSC_Agent) = CalledAgent(() => agent)
}
```

It thus consists of a function mapping a *BSC_Agent* into the Scala structure *CalledAgent* taking a thunk, which consists of a function taking no argument and returning an agent. As we saw above, this is needed to treat in a lazy way recursively defined agent.

The *BSC_Agent* type is in fact a trait equipped with the methods needed to parse Bach composed agents. Technically it is defined as follows:

```
trait BSC_Agent { this: BSC_Agent =>
  def *(other: => BSC_Agent) =
          ConcatenationAgent( () => this , other _)
  def ||(other: => BSC_Agent) =
          ParallelAgent( () => this , other _)
  def +(other: => BSC_Agent) =
          ChoiceAgent( () => this , other _)
}
```

As ; is a reserved symbol in Scala, sequential composition is rewritten with the ∗ symbol.

The definition of the composition symbol ∗, || and + employs Scala facility to postfix operations. Using the above definitions, a construct of the form *tell*(*t*)+*tell*(*u*) is interpreted as the call of method + to *tell*(*t*) with argument *tell*(*u*).

It is worth observing that the composition operators take agent arguments with call-by-name and deliver structures using thunks, namely functions without arguments to agents.

It will be useful later to generalize choices such that they offer more than two alternatives according to an index ranging over a set, such as in $\sum_{x \in L} ag(x)$ where $ag(x)$ is an agent parameterized by x. This is obtained in B2Scala by the following construct

```
GSum(L, x => ag(x))
```

where `L` is a list.

3.2 Implementation of the Domain Specific Language

The implementation of the domain specific language is based on the same ingredients as those employed in the Scan and Anemone workbenches [13, 14]. They address two main concerns: how is the store implemented and how are agents interpreted.

3.2.1 The store

The store is implemented as a mutable map in Scala. Initially empty, it is enriched for each told structured piece of information by an association of it to a number representing the number of its occurrences on the store. The implementation of the primitives follows directly from this intuition. For instance, the execution of a tell primitive, say `tell(t)`, consists in checking whether `t` is already in the map. If it is then the number of occurrences associated with it is simply incremented by one. Otherwise a new association `(t,1)` is added to the map. Dually, the execution of `get(t)` consists in checking whether `t` is in the map and, in this case, in decrementing by one the number of occurrences. In case one of these two conditions is not met then the get primitive cannot be executed.

3.2.2 Interpretation of agents

Agents are interpreted by repeatedly executing transition steps. This boils down to the definition of function `run_one`, which assumes given an agent in an internal form, namely as a subtype of *BSC_Agent*, and which returns a pair composed of a boolean and an agent in internal form. The boolean aims at specifying whether a transition step has taken place. In this case, the associated agent consists of the agent obtained by the transition step. Otherwise, failure is reported with the given agent as associated agent.

The function is defined inductively on the structure of its argument, say `ag`. If `ag` is a primitive, then the `run_one` function simply consists in executing the primitive on the store. If `ag` is a sequentially composed agent ag_i ; ag_{ii}, then the transition step proceeds by trying to execute the first subagent ag_i. Assume this succeeds and delivers ag' as resulting agent. Then the agent returned is ag' ; ag_{ii} in case ag' is not empty or more simply ag_{ii} in case ag' is empty. Of course, the whole computation fails in case ag_i cannot perform a transition step, namely in case `run_one` applied to ag_i fails.

The case of an agent composed by a parallel or choice operator is more subtle. Indeed for both cases one should not always favor the first or second subagent. To avoid that behavior, we use a boolean variable, randomly assigned to 0 or 1, and depending upon this value we start by evaluating the first or second subagent. In case of failure, we then evaluate the other one and if both fails we report a failure. In case of success for the parallel composition we determine the resulting agent in a similar way to what we did for the sequentially composed agent. For a composition by the choice operator the tried alternative is simply selected.

The computation of a procedure call is performed by computing the defining agent.

4   Constrained executions

The fact that Bach agents are interpreted in the B2Scala tool opens the door to select computations of interest. This is obtained by stating logic formulae to be met.

Two main approaches have been used in concurrency theory to describe properties by means of logic formulae. One approach, exemplified by Linear Temporal Logic (LTL) [22], is based on Kripke structures. In two words, LTL extends classical propositional logic by introducing temporal operators that allow to describe how properties evolve over time. For instance, $X\Phi$ means that Φ holds in the next state while $\Phi U \Psi$ specifies that Φ holds until Ψ holds. Central to this approach are, on the one hand, a transition relation between states, indicating which states can be reached from which states, and, on the other hand, a labelling function that assigns to each state a set of atomic propositions that are true in that state.

The other approach is based on labelled transition systems. It is exemplified by the Hennessy-Milner logic (HML) [11]. This logic provides a way to specify properties in terms of actions and capabilities. The two following modalities are the key concepts of HML:

- $<a>\Psi$ means that, by following the labelled transition system, it is possible to make a transition by a such that the resulting process satisfies Ψ

- $[a]\Psi$ means that, whenever a is performed the resulting process satisfies Ψ.

However, since they are finite HML formulae can only describe properties with a finite depth of reasoning. A way to circumvent this problem is to use a generalisation called the μ-calculus [16]. It extends HML with fixed-point operators, such as in $\mu X.(\Phi \vee <a>X)$ which states that there is a path where Φ holds directly or after having repeatedly taken a-transitions.

The logic we use is inspired by these three logics. It is subsequently presented in two steps by describing so-called basic formulae and the bsL-calculus. The effect on computations is then specified. This yields so-called constrainted computations.

4.1   Basic formulae

Similarly to LTL logic, we first specify formulae that are true on states. Obviously, a key concept in our coordination setting is whether a si-term is present on the store under consideration. This is specified by a construct of the form $bf(t)$ which requires that the si-term t is present on the current store. The formal definition is as follows.

Definition 1 *For any si-term t, the formula $bf(t)$ holds on store σ iff $t \in \sigma$. This is subsequently denoted as $\sigma \models bf(t)$. Such formulae are subsequently called bf-formulae.*

As expected, bf-formulae can be combined with the classical logic operators. Formulae built in this way are called *basic formulae*. The formal definition is as follows.

Definition 2 *Basic formulae are the formulae meeting the following grammar:*

$$b ::= bf(t) \mid !b \mid b_1 \vee b_2 \mid b_1 \wedge b_2$$

where $bf(t)$ denotes a bf-formula, b, b_1, b_2 denote basic formulae and the symbols !, $\vee$, $\wedge$ respectively express the negation, the disjunction and the conjuction of basic formulae.

The fact that a basic formula f holds on the store σ is defined from the relation $\models$ on bf-formulae according to the traditional truth tables of propositional logic. By extension, this will be subsequently denoted by $\sigma \models f$.

Example 4 *As an example, $bf(i\_running(Alice,Bob))$ is a bf-formula that states that the si-term $i\_running(Alice,Bob)$ is on the store, which can be used to specify that Alice and Bob have initiated a session.*

4.2 The bsL calculus

Similarly to Hennessy-Milner logic and the mu-calculus, we now turn to specify sequences of properties that have to hold on the sequences of stores produced by computations. Obviously, as we want to restrict computations, we have to discard the $[\ldots]$ modality. However we can use the $<\ldots>$ modality in the following manner. Remember that in HML the formula $<a><b>F$ expresses that it is possible to do an a step followed by a b step and reach a process in which F holds. In a similar way, we will express by $bf(a);bf(b)$ the property that it is possible to do a step which leads to $bf(a)$ being true followed by a step after which $bf(b)$ is true. This is for instance performed by the Bach agent $tell(a);tell(b)$. Note that as a reminder of the sequential composition of agents in Bach, we have used the ";" to compose sequentially bf-formulae. As noticed in the above mu-calculus formula, besides sequential composition, we shall also use disjunction to allow the choice between several paths. This leads us to the following grammar where, by analogy to Bach operators, the "+" symbol is used to indicate disjunction.

Definition 3 *BsL-formulae are the formula defined by the following grammar:*

$$f \quad ::= \quad b \mid P \mid f_1 + f_2 \mid f_1 \; ; \; f_2$$

where b denotes a basic formula, f_1 and f_2 are bsL-formulae and P a variable to be defined by an equation of the form $P = f'$ with f' being a bsL-formula. As usual in concurrency theory, we assume that f' is guarded in the sense that a bf-formula is requested before variable P is called recursively.

Example 5 *As an example, the attack on the Needham-Schroeder protocol may be discovered by finding a computation that obeys the bsL-formula X defined by*

$$X \quad = \quad (\, not(i\_running(Alice,Bob)) \; ; \; X \,) + r\_commit(Alice,Bob)$$

that is by a computation that does not produce the si-term $i\_running(Alice,Bob)$ and that ends when $r\_commit(Alice,Bob)$ appears on the store. Restated in other terms such a computation never includes the start of a session between Alice and Bob but terminates with Alice and Bob ending the session by committing together.

4.3 Constrained computations

We are now in a position to detail how computations may be constrained by bsL-formulae. Intuitively, if f is a bsL-formula composed of a sequence of basic formulae, a computation c is considered to be constrained by f if the sequence of stores involved in c successively obeys the successive basic formulae in f. This is defined by means of the auxiliary $\vdash$ relation, itself defined by the rules of Figure 3. Intuitively, the notation $\sigma \vdash f \; [f']$ states that a first basic formula of f is satisfied on the store σ and that the remaining formulae of f' need to be satisfied. Accordingly rule (BF) asserts that if the basic formula b

$$\text{(BF)} \qquad \frac{\sigma \models b}{\sigma \vdash b\, [\varepsilon]} \qquad\qquad \text{(PF)} \qquad \frac{P = f, \quad \sigma \vdash f\, [f']}{\sigma \vdash P\, [f']}$$

$$\text{(CF)} \qquad \frac{\sigma \vdash f_1\, [f_3]}{\begin{array}{c} \sigma \vdash (f_1 + f_2)\, [f_3] \\ \sigma \vdash (f_2 + f_1)\, [f_3] \end{array}} \qquad \text{(SF)} \qquad \frac{\sigma \vdash f_1\, [f_3]}{\sigma \vdash (f_1\, ;\, f_2)\, [(f_3\, ;\, f_2)]}$$

Figure 3: Transition rules for the $\vdash$ relation

$$\text{(ET)} \qquad \frac{\langle A \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle, \quad \sigma' \vdash f\, [f']}{\langle A @ f \mid \sigma \rangle \hookrightarrow \langle A' @ f' \mid \sigma' \rangle}$$

Figure 4: Extended transition rule

is satisfied by the store σ then it is also the first formula to be satisfied and nothing remains to be established. The symbol ε is used there to denote an empty sequence of basic formulae. Rule (PF) states that if formula P is defined as f and if a first bf-formula of f is satisfied by σ yielding f' to be satisfied next then so does P with f' to be satisfied next. Finally rules (CF) and (SF) specify the choice and sequential composition of bsL-formulae as one may expect.

Given the $\vdash$ relation, we can define constrained computations by extending the $\rightarrow$ transition relation as the $\hookrightarrow$ relation specified by rule (ET) of Figure 4. Informally this rule states that if, on the one hand, agent A can do a transition from the store σ yielding a new agent A' and a new store σ' and if, on the other hand, a first formula of f is met by σ' yielding f' as a remaining bsL-formula to be established, then agent A can make a constrained transition from store σ and bHM-formula f to agent A' to be computed on store σ' and with respect to bHM-formula f'.

It is worth noting that the encoding in B2Scala is quite easy. On the one hand, bf-formulae are defined similarly to Bach primitives through the `bf` function and are combined as primitives are. On the other hand, bsL formulae are defined by the `bsL` function and recursive definitions are handled in the same way as recursive agents.

The interpretation of agents is then made with respect to a bsL-formula. Basically, a step is allowed by the `run_one` function if one step can be made according to the bsL-formula, as specified by the $\hookrightarrow$ transition relation. This results in a new agent to be solved together with the continuation of the bsL-formula to be satisfied.

5   The Needham-Schroeder protocol in B2Scala

As an application of the B2Scala tool, let us now code the Needham-Schroeder protocol and exhibit a computation that reflects G. Lowe's attack. The interested reader will find the code, the tool and a video of its usage under the web pages of the authors at the addresses mentioned in [21].

Allowing for an attack requires us to introduce an intruder. It is subsequently named Mallory. This being said, the first point to address is to declare nonces and public keys for all the participants of the

protocol, namely Alice, Bob and Mallory. This is achieved by the following token declarations:

```
val na = Token("Alice_nonce")
val nb = Token("Bob_nonce")
val nm = Token("Mallory_nonce")

val pka = Token("Alice_public_key")
val pkb = Token("Bob_public_key")
val pkm = Token("Mallory_public_key")
```

It will also be useful later to refer to the three participants, which can be achieved by means of the following token declarations:

```
val alice   = Token("Alice_as_agent")
val bob     = Token("Bob_as_agent")
val mallory = Token("Mallory_as_intruder")
```

To better view who takes which message produced by whom, encrypted messages introduced in Section 3, are slightly extended as si-terms of the form *message*(*Sender*, *Receiver*, *Encryted_Message*). Moreover, to highlight which message is used in the protocol, we shall subsequently rename encrypted messages as *encrypt_n*, with *n* the number in the sequence of messages. This has the additional advantage of avoiding to overload case classes, which is forbidden in Scala. The following declarations follow.

```
case class encrypt_i(vNonce: SI_Term, vAg: SI_Term,
                        vKey: SI_Term) extends SI_Term
case class encrypt_ii(vNonce: SI_Term, wNonce: SI_Term,
                        vKey: SI_Term) extends SI_Term
case class encrypt_iii(vNonce: SI_Term,
                        vKey: SI_Term) extends SI_Term
case class message(agS: SI_Term, agR: SI_Term,
                        encM: SI_Term) extends SI_Term
```

Finally, si-terms are introduced to indicate with whom Alice and Bob start and close their sessions. They are declared as follows:

```
case class a_running(vAg: SI_Term) extends SI_Term
case class b_running(vAg: SI_Term) extends SI_Term
case class a_commit(vAg: SI_Term) extends SI_Term
case class b_commit(vAg: SI_Term) extends SI_Term
```

We are now in a position to code the behavior of Alice, Bob and Mallory. Coding Alice's behavior follows the description we gave in Example 2 in Section 2. The code is provided in Figure 5. Although Alice wants to send a first encrypted message to Bob, she can just put her message on the network, hoping that it will reach Bob. The network is simulated here by the store, which leaves room to Mallory to intercept it. As a result, the first action is for Alice to start of a session. Hopefully it is with Bob but, to test for a possible attack, we have to take into account the fact that Mallory can take Bob's place. This is coded by offering a choice between Bob and Mallory by the GSum([bob,mallory], ...) construct. Calling this actor *Y*, Alice's first action is to tell the initialization of the session with *Y*, thanks to the a_-running(Y) si-term being told and then to tell the first encrypted message with her nonce, her identity and the public key of Y. The sender and receiver of this message are respectively *Alice* and *Y*. Then Alice waits for a second encrypted message with her nonce and what she hopes to be Bob's nonce, this message being encrypted by her public key. As the second nonce is unknown a new choice is offered with the *WNonce* si-term. Finally, Alice sends the third encrypted message with this nonce, encoded with

```
val Alice = Agent {
  GSum( List(bob,mallory), Y => {
     tell(a_running(Y)) *
     tell( message(alice, Y, encrypt_i(na, alice, public_key(Y))) ) *
     GSum( List(na,nb,nm),   WNonce => {
        get( message(Y, alice, encrypt_ii(na,WNonce,pka)) ) *
        tell( message(alice,Y,encrypt_iii(WNonce,public_key(Y))) ) *
        tell( a_commit(Y) )
     })
  })
}
```

Figure 5: Coding of Alice in B2Scala

```
val Bob = Agent {
  GSum( List(alice,mallory),  Y => {
     tell(b_running(Y)) *
     GSum( List(alice,mallory), VAg => {
        get( message(Y,bob,encrypt_i(na,VAg,pkb)) ) *
        tell( message(bob,Y,encrypt_ii(na,nb,public_key(VAg))) ) *
        get( message(Y,bob,encrypt_iii(nb,pkb)) ) *
        tell( b_commit(VAg) )
     })
  })
}
```

Figure 6: Coding of Bob in B2Scala

the public key of *Y* and terminates the session by telling the a_commit(Y) si-term. It is worth noting that public_key(Y) consists of a call to a Scala function that returns the public key corresponding to the *Y* argument.

Coding Bob's behavior proceeds in a dual manner. This time the coding has to take into account that Mallory can have taken Alice's place. Hence the first choice GSum([alice,mallory], ...) with *Y* denoting the sender of the message. Moreover, the identity of the agent in the first message being got can be different from *Y*. A second choice GSum([alice,mallory], ...) results from that. The whole agent is given in Figure 6.

As an intruder, Mallory gets and tells messages from Alice and Bob, possibly modifying some parts in case the messages are encrypted with his public key. This applies for the three kinds of message sent/received by Alice and Bob. Figure 7 provides the code for the first message. It presents three GSum choices resulting from the three unknown arguments VNonce, VAg, VPK of the message. In all the cases, Bob's attitude is to get the message and to resend it, by modifying the public key if he can decrypt the message, namely if VPK is his public key.

To conclude the encoding of the protocol in B2Scala, a bsL-formula *F* is specified, on the one hand, by excluding a session starting between Bob and Alice and, on the other hand, by requiring the end of the session by Bob with Alice. These two requirements are obtained through the basic formulae inproper_init and end_session, as specified below:

```
val inproper_init = not( bf(a_running(bob)) or bf(b_running(alice)) )
```

```
lazy  val  Mallory : BSC_Agent  =  Agent  {

   ( GSum(  List ( na , nb ,nm) ,  VNonce  => {
      GSum(  List ( alice , bob ) ,  VAg  => {
       GSum(  List ( pka , pkb ,pkm) ,  VPK  => {
          get (  message ( alice , mallory , encrypt_i (VNonce ,VAg ,VPK) )  )  *
          (  if  (  VPK ==  pkm)  {
              tell (  message ( mallory , bob , encrypt_i (VNonce ,VAg , pkb ) )  )
            } else  {
              tell (  message ( mallory , bob , encrypt_i (VNonce ,VAg ,VPK) )  )
          } )  *  Mallory
        })
       })
      }) )         + . . .
```

Figure 7: Coding of Mallory in B2Scala

```
val  end_session  =  bf ( b_commit ( alice ) )
```

Formula *F* is then coded recursively by requiring *F* after a step meeting `inproper_init` and by stopping the computation once a step is done that makes `end_session` holds. This is specified as follows.

```
val  F  =  bsL  {  ( inproper_init  *  F)  +  end_session  }
```

Computations are started by invoking the following Scala instructions

```
val  Protocol  =  Agent  {  Alice  ||  Bob  ||  Mallory  }

val  bsc_executor  =  new  BSC_Runner
bsc_executor . execute ( Protocol ,F)
```

The result is given in Figure 8 in a verbose form in which all the primitives are displayed as Scala objects. As we shall see in a few lines, it produces G. Lowe's attack. To view that, let us reformulate the Scala objects *TellAgent*, *GetAgent* and *BSC_Token* in their corresponding Bach counterparts. The listing of Figure 8 then becomes as follows, where numbers are introduce to facilitate the explanation:

```
 ( 1 )    tell ( a_running ( mallory ) )
 ( 2 )    tell ( b_running ( mallory ) )
 ( 3 )    tell ( message ( alice , mallory , encrypt_i ( na , alice ,pkm) ) )
 ( 4 )    get ( message ( alice , mallory , encrypt_i ( na , alice ,pkm) ) )
 ( 5 )    tell ( message ( mallory , bob , encrypt_i ( na , alice , pkb ) ) )
 ( 6 )    get ( message ( mallory , bob , encrypt_i ( na , alice , pkb ) ) )
 ( 7 )    tell ( message ( bob , mallory , encrypt_ii ( na ,nb , pka ) ) )
 ( 8 )    get ( message ( bob , mallory , encrypt_ii ( na ,nb , pka ) ) )
 ( 9 )    tell ( message ( mallory , alice , encrypt_ii ( na ,nb , pka ) ) )
 (10)    get ( message ( mallory , alice , encrypt_ii ( na ,nb , pka ) ) )
 (11)    tell ( message ( alice , mallory , encrypt_iii ( nb ,pkm) ) )
 (12)    get ( message ( alice , mallory , encrypt_iii ( nb ,pkm) ) )
 (13)    tell ( a_commit ( mallory ) )
 (14)    tell ( message ( mallory , bob , encrypt_iii ( nb , pkb ) ) )
 (15)    get ( message ( mallory , bob , encrypt_iii ( nb , pkb ) ) )
 (16)    tell ( b_commit ( alice ) )
```

```
Welcome to the B2Scala excution engine.
We are going to process the following query.
| => root / Compile / packageBin / mappings 0s
CalledAgent(bscala.bsc_agent.Agent$$$Lambda$5534/0x0000000802821440@10669894)


Successfully evaluated        TellAgent(a_running(BSC_Token(Mallory_as_intruder)))
Successfully evaluated        TellAgent(b_running(BSC_Token(Mallory_as_intruder)))
Successfully evaluated        TellAgent(message(BSC_Token(Alice_as_agent),BSC_Token(Mallory_as_intruder),encrypt_i(BSC_Token(Alice_nounce),BSC_Token(Alice_as_agent),BSC_Token(Mallory_public_key))))
Successfully evaluated        GetAgent(message(BSC_Token(Alice_as_agent),BSC_Token(Mallory_as_intruder),encrypt_i(BSC_Token(Alice_nounce),BSC_Token(Alice_as_agent),BSC_Token(Mallory_public_key))))
Successfully evaluated        TellAgent(message(BSC_Token(Mallory_as_intruder),BSC_Token(Bob_as_agent),encrypt_i(BSC_Token(Alice_nounce),BSC_Token(Alice_as_agent),BSC_Token(Bob_public_key))))
Successfully evaluated        GetAgent(message(BSC_Token(Mallory_as_intruder),BSC_Token(Bob_as_agent),encrypt_i(BSC_Token(Alice_nounce),BSC_Token(Alice_as_agent),BSC_Token(Bob_public_key))))
Successfully evaluated        TellAgent(message(BSC_Token(Bob_as_agent),BSC_Token(Mallory_as_intruder),encrypt_ii(BSC_Token(Alice_nounce),BSC_Token(Bob_nounce),BSC_Token(Alice_public_key))))
Successfully evaluated        GetAgent(message(BSC_Token(Bob_as_agent),BSC_Token(Mallory_as_intruder),encrypt_ii(BSC_Token(Alice_nounce),BSC_Token(Bob_nounce),BSC_Token(Alice_public_key))))
Successfully evaluated        TellAgent(message(BSC_Token(Mallory_as_intruder),BSC_Token(Alice_as_agent),encrypt_ii(BSC_Token(Alice_nounce),BSC_Token(Bob_nounce),BSC_Token(Alice_public_key))))
Successfully evaluated        GetAgent(message(BSC_Token(Mallory_as_intruder),BSC_Token(Alice_as_agent),encrypt_ii(BSC_Token(Alice_nounce),BSC_Token(Bob_nounce),BSC_Token(Alice_public_key))))
Successfully evaluated        TellAgent(message(BSC_Token(Alice_as_agent),BSC_Token(Mallory_as_intruder),encrypt_iii(BSC_Token(Bob_nounce),BSC_Token(Mallory_public_key))))
Successfully evaluated        GetAgent(message(BSC_Token(Alice_as_agent),BSC_Token(Mallory_as_intruder),encrypt_iii(BSC_Token(Bob_nounce),BSC_Token(Mallory_public_key))))
Successfully evaluated        TellAgent(a_commit(BSC_Token(Mallory_as_intruder)))
Successfully evaluated        TellAgent(message(BSC_Token(Mallory_as_intruder),BSC_Token(Bob_as_agent),encrypt_iii(BSC_Token(Bob_nounce),BSC_Token(Bob_public_key))))
Successfully evaluated        GetAgent(message(BSC_Token(Mallory_as_intruder),BSC_Token(Bob_as_agent),encrypt_iii(BSC_Token(Bob_nounce),BSC_Token(Bob_public_key))))
Successfully evaluated        TellAgent(b_commit(BSC_Token(Alice_as_agent)))
```

Figure 8: Screenshot of the computation

Lines (1), (2), (13) and (16) evidence that Alice and Bob have actually exchanged messages with Mallory whereas they thought they would speak to each other. In fact Mallory manages to make himself appear as Bob to Alice and as Alice to Bob. Let us abstract from these lines. It is then worth observing that the above listing makes appear tell and get in pairs employing the same message. This corresponds to one actor sending the message to another actor, which is translated in our framework as the first actor telling the message and the second one getting it. By reusing the description of Section 2.1, the listing can then be summed up as follows:

$$
\begin{array}{rcll}
Alice \longrightarrow Mallory & : & message(na : alice)_{pkm} & \text{(lines 3 and 4)} \\
Mallory \longrightarrow Bob & : & message(na : alice)_{pkm} & \text{(lines 5 and 6)} \\
Bob \longrightarrow Mallory & : & message(na : nb)_{pka} & \text{(lines 7 and 8)} \\
Mallory \longrightarrow Alice & : & message(na : nb)_{pka} & \text{(lines 9 and 10)} \\
Alice \longrightarrow Mallory & : & message(nb)_{pkm} & \text{(lines 11 and 12)} \\
Mallory \longrightarrow Bob & : & message(nb)_{pkb} & \text{(lines 14 and 15)}
\end{array}
$$

This is in fact the attack identified by G. Lowe in [19]. It consists essentially in placing Mallory in between Alice and Bob, in having him forward Alice's first message, by changing the public key encrypting the message, in getting Bob's reply and transfer it as such, and finally in forwarding Alice's reply to Bob, again by changing the public key encrypting the message.

Note that a key ingredient for producing the above computation is that imposing `inproper_init` to hold forces the first choice in Alice's code and Bob's code to be made such that Y takes Mallory as value.

6   Conclusion

In the aim of formally verifying security protocols, this paper has proposed an embedding of the coordination language Bach in Scala, in the form of an internal Domain Specific Language, named B2Scala. It has also proposed a logic that allows for constraining executions. The Needham-Schroeder protocol has been modeled with our proposal to illustrate its interest in practice.

The choice for an internal Domain Specific Language has been motivated by the possibility of taking profit from the Scala eco-system, notably its type system, while benefiting from all the abstractions offered by the Bach coordination language. We hope to have convinced the reader of these two features through the coding of the Needham-Schroeder protocol. Indeed, on the one hand, the *BSC_Agents* coding Alice, Bob and Mallory mimick the procedures that would have been written directly in Bach. Moreover the sequential composition operator, the parallel composition operator and the non-deterministic choice

operator have been used as one would have used them in Bach. This feature allows to embed the Bach control flow operators in B2Scala. It is here also worth observing that a similar description could have been written in a pure process algebra setting like the one used in the workbenches Scan and Anemone. However type checking is not supported by these workbenches but is given for free in B2Scala. Moreover, auxiliary concepts like *public_key(Y)* would have been rewritten as mapping functions, with care for completeness of the code left to the programmer while it is provided for free in B2Scala (through completeness verification done by Scala for the match operation).

On the other hand, the code to be written is a real Scala code. Examples of that are the definitions of tokens or si-terms, which are Scala case classes. In that respect, it is worth stressing that arguments of si-terms need to be declared with a type, which is verified at compilation time. Moreover, they can be obtained as the result of a Scala function, as exemplified by the use of *public_key(Y)* in the coding of Alice and Bob (see Figures 5 and 6). It is also to be noted that the *GSum* construct offers a form of local variable, binding the Scala and Bach worlds. Take for instance the first GSum of Figure 5 :

```
GSum( List(bob,mallory), Y => {
    tell(a_running(Y)) * ...
```

There *Y* plays the role of a local variable which has to be bound to *bob* or *mallory*. Once the value has been decided (by the run_one function through the alternative selected for the choice, see Section 3.2.2), it can be used later in the code. Similarly, the second *GSum* construct allows to bind *WNonce* to the value selected by the *get* primitive:

```
GSum( List(na,nb,nm),   WNonce => {
    get( message(Y, alice , encrypt_ii(na,WNonce,pka)) ) * ...
```

This being said, our main goal in this paper is to offer a modelling language to describe and reason on systems, such as the Needham-Schroeder protocol, rather than a programming language to code the implementation of the protocol. In these lines, it is worth observing that a direct modelling for analysis purposes would not have been possible in (pure) Scala since we would lack the abstraction offered by process algebras like Bach.

As reported in [5], many coordination languages have been implemented, in some cases as stand alone languages, like Tucson [7], but mostly as API's of conventional languages, accessing tuple spaces through dedicated functions or methods, as in pSpaces [18]. To the best or our knowledge, B2Scala is the first implementation of a coordination language as a Domain Specific Language. We are also not aware of an implementation done in Scala. However, our work is linked to the work on Caos [23], which provides, by using Scala, a generic tool to implement structured operational semantics and to generate intuitive and interactive websites. In practice, one has however to define the semantics of the language under consideration by using Scala. In contrast, we take an opposite approach which already offers an implementation of the Bach constructs and in which programmers need to code Bach-like programs in a Scala manner. Moreover we propose a logic to constraint executions, which is not proposed in [23].

Scafi [4] is another research effort to integrate a coordination language in Scala. It targets a different line of research in the coordination community by being focussed on aggregate computing. Moreover, to the best of our knowledge, no support for constrained executions is proposed.

This work is a continuation of previous work on the Scan and Anemone workbenches [13, 14]. It differs by the fact that both Scan and Anemone interpret directly Bach programs. Moreover the PLTL logic they use is different from the logic proposed in this paper.

As regards the Needham-Schroeder protocol, to our best knowledge, it has been never been modeled in a coordination language, most probably because the Coordination community and the one on security are quite different. Nevertheless it has been modeled in more classical process algebras. In [19] the

author uses CSP and its associated FDR tool to produce an attack on the protocol. This analysis has been complemented in [2] by using the mCRL process algebra and its associated model checker. Our work differs by using a process algebra of a different nature. Indeed the Bach coordination language rests on asynchronous communication which happens by information being available or not on a shared space. This allows to naturally model messages being put on the network as si-terms told on the store. Similarly the action of an intruder is very intuitively modeled by getting si-terms. In contrast, [2] and [19] use synchronous communication which does not naturally introduce the network as a communication medium and which technically forces them to model the intruder by duplicating Alice and Bob's send and receive actions by intercept and fake messages.

Our work open several paths for future research. First the synergy with Scala given by B2Scala offers a natural way of making interfaces much more user friendly than the one of Figure 8. Second we have only investigated the use of B2Scala to analyze the Needham-Schroeder protocol. Our current research aims at exploring the security of other protocols, such as the Quic protocol. Finally, our logic is used to restrict computations at run-time without lookahead strategies, which could lead to select computations that fail later to meet the remaining logic formulae. As a solution to that problem, we are investigating how statistical model checking can be married with B2Scala.

7 Acknowledgment

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