MetaCP: Cryptographic Protocol Design Tool for Formal Verification

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Abstract. We present MetaCP, a tool to aid the cryptographer throughout the process of designing and modelling a communication protocol suitable for formal verification. The crucial innovative aspect of the tool is its data-centric approach, where protocol specification is stored in a structured way rather than in natural languages to facilitate its interpretation to multiple target languages. Previous work shows a single exporting plugin (for Tamarin) which required aftermath modifications. By improving the expressiveness of the specification data structure we extend the tool to export to an additional formal language, i.e. ProVerif, as well as a C++ implementation. Starting with its modern graphical interface, MetaCP allows us to model the Diffie-Hellman key exchange, traditionally referred to as a case study, in just a few minutes. Ultimately, we use the formal tools to verify the executability and correctness of the automatically exported models. The design core of MetaCP is freely available in an online demo that provides two further sample protocols, Needham-Schroeder and Needham-Schroeder-Lowe, along with instructions to use the tool to begin modelling from scratch and to export the model to desired external languages.

Keywords: Cryptography · Protocol Design · Protocol Verification.

1 Introduction

Design and specification of cryptographic protocols are usually the first stage when creating a new protocol. Their implementation and verification is commonly deferred to a secondary stage, and often done by a separate set of people. At this second stage, the specification gets interpreted into a formal language able to run the protocols or verify security properties in the form of automated theorems. We can appreciate that such interpretations are affected by (at least) two problems: first, the language of specification may be ambiguous or contain gaps that become noticeable only at later stages\textsuperscript{4}, and second, proposed interpretations are difficult to reuse as they exist only on papers. More specifically,

\textdagger \textsuperscript{\textdaggerdbl} Equally collaborative work.
\textsuperscript{4} This is a common concern when one models from specification [8,12].
the interpretation is a manual refinement from the specification language, that is often a mix of maths and natural language, to a formal language of choice, with limited semantics, that consequently may only capture a subset of the initial specification. The model interpreting the design of a protocol is the first mathematical artefact in the process of formal verification, but the interpretation process itself is not mathematical and currently manually done by experts. Hence, papers need to be written to convince the readers that a particular interpretation indeed captures the aspects relevant to the analysis. As a consequence, different researchers may formalise the same specification differently, even more likely if they choose different formal languages. The natural outcome of this process is that their output may show different results, depending on what security details are being modelled. Indeed, protocols proven correct by one interpretation may be found to suffer from several vulnerabilities when formalised differently [10]. Nonetheless, both are valid interpretations of the same protocol. It is therefore important to analyse the same specification from multiple interpretations that can cover security aspects more exhaustively. However, the state of the art tools focus their automation on the last part of the verification process, i.e. after the model has been developed.

We found in the tool MetaCP [4] a promising first effort to tame the above mentioned difficulties. It focuses on the modelling part of the process of formal verification, completely delegating the security proofs to external tools. A mechanised refinement from structured specification to formal languages can offer consistency, reusability and repeatability: if some security aspect is specified in the same manner multiple times, it will always be formalised in the same manner. Not only does MetaCP improve a previously manual and bespoke process, but it also does so in record time and without the need of expert knowledge of multiple formal languages – experts are still required to check the final results or to adjust the exported code to cover further aspects unsupported by its plugins. We extend the core of the tool to support new plugins (ProVerif and C++) on top of previous work (Tamarin plugin); we also model executability and correctness as a first attempt to model security properties from specification\(^5\). In this paper, we discuss in more details the architecture of MetaCP in Section 3, its workflow in Section 4, and the interpretation process in Section 5. In the latter, we illustrate one possible interpretation from the structured specification of MetaCP to ProVerif; analogous reasoning applies when exporting to C++ or Tamarin that we do not discuss in detail. We emphasise that the tool supports for multiple interpretations across the same target language too\(^6\); so, the interpretations we propose can easily coexist with many others to both different or same languages.

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\(^5\) The tool is available at [http://metacp.eu](http://metacp.eu).

\(^6\) Not only across different languages. Same language plugins maybe useful to capture different aspects of the protocol ultimately analysed or run with the same tool.
2 Related Work

The tools that allow to mechanise security proofs and finally perform formal security evaluation, e.g. Tamarin [12], ProVerif [6], EasyCrypt [5] among others, have improved in the past decades and enjoy a wide spread use. However, these tools do not provide any means to relate to the whole design process, impacting the usability and effectiveness of the evaluations. As it stands, it is very difficult for the casual user, and highly time-consuming for the security professional unaware of those formal languages, to ascertain the truthfulness of a formal protocol analysis, and how it relates to the original protocol.

Witnessing the sensibility of the research community about this problem, projects such as CAPSL (Common Authentication Protocol Specification Language) [9], AVISPA (Automated Validation of Internet Security Protocols) [3] or AVANTSSAR (Automated Validation of Trust and Security of Service-Oriented Architectures) [2] have attempted to unify the verification process by presenting a single intermediate language of specification, and by automating the translation into various back-end tooling. These proposed approaches based themselves on the assumption that most people would be familiar with their intermediate language. Even with the integration of multiple verification options, research shows that protocols found to be secure by a tool (i.e. AVISPA) were later found flawed when modelled manually in a different languages (i.e. ProVerif) [10]; this is (also) due to the strict semantics of the intermediate language. Another approach ProScript [11], proposes a new high level language for the specification of security protocols based on Javascript. ProScript is able to export to applied PI calculus (without a sound translation and similar methodology to ours), whose result is automatically verifiable in ProVerif and manually in CryptoVerif. However, its closeness to the exported language limits its expressivity, and the task of supporting new languages is as difficult as it would be with ProVerif itself. These demonstrate the need for simplifying the integration to more tooling in the back-end verification as the field advances.

3 Architecture

The crucial innovative aspect of MetaCP is its data-centric approach, where the protocol specification is stored in a structured way, as shown in Figure 1. The benefits of this approach are manifold and enable for unprecedented little effort in going from the design to formal verification of security protocols.

The MetaCP architecture is composed of three kinds of components: design, specification, and export. At the design level, we provide an intuitive Graphical Design Editor (GDE) that allows for creating, dragging and dropping elements that will be later saved into the specification. The GDE is written in a modern web application framework, using ReactJs, Bootstrap, NodeJs, and Redux. At the specification level, we provide a data structure written in XML language meant to collect the information required to fully describe a security protocol. Such structure follows a minimal syntax described in Section 3.1, and
its code can later be interpreted by means of a plugin. The tool provides two plugins towards formal verification languages, one for Tamarin [4] and one for ProVerif (presented in Section 5), that automatically interpret the protocol described in their syntax. Furthermore, a third plugin exports into C++ code for which parties can truly exchange messages over the Internet and cryptographic operations are done with the Crypto++ library. As its discussion would be similar to the ProVerif plugin, we briefly illustrate it in Appendix A. We found it comfortable to write the new plugins in XSLT, but they can be written in any language of choice. All components, design, specification and export, can be developed independently, and their synergy provides a tool usable to kickstart projects from the design to formal verification languages. More details are explained in the following subsections.

3.1 Protocol Specification and Verification Data Structure

The ability for MetaCP to automatically translate into multiple verification languages resides in its description language, denoted as Protocol Specification and Verification data structure (PSV). A PSV file collects information about the protocol as a data structure in an XML language whose constraints are defined in a Document Type Definition (DTD) file. PSV is suitable to be easily extended and enjoys multiple interpretations. DTDs merely enforces the structure without adding strong constraints to the semantics, thus not breaking the flexibility required by our approach. Our approach is sensibly different from all previous approaches, where researchers struggled to find a single semantics capable of embracing the semantics of all desired target languages [9,3,2,11]. The single generic semantics approach could work well for a few languages whose

XML is unconventional for formal languages, but a popular language for presentation or data structures; its format is purposely easy to be manipulated by both humans and machines.
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semantics were not too far apart, but would either fail, or find it very difficult, to capture the requirements of other languages.

We illustrate how MetaCP is suitable for being a multi-language translation tool, through a traditional example of reference in cryptography, the Diffie-Hellman key exchange (DHKE). We export it to ProVerif (and C++), as compared to the previous sole Tamarin plugin [4]. The plugin also generates code for the automatic analysis of executability, in Tamarin, and correctness, in ProVerif.

**Basic structure of PSV.** MetaCP plugins rely on the following basic structure of the PSV. Generally speaking, a party in a protocol manipulates variables whose values match a type related to some mathematical set, prepares them to be sent to the other party (or parties) through a communication channel, and elaborates the input received from the channel. For a set $X$, we use the notation $X^*$ for the Kleene closure and $^\circ X$ for $X \cup \{\perp\}$ where $\perp$ is considered as none.

We start considering the set of non empty strings denoted as $\mathcal{L} = \Sigma^* \setminus \{\varepsilon\}$, a set of variable modifiers $T = \{\text{nonce}, \text{const}, \text{entity}, \text{var}\}$, channel modifiers $C_T = \{\text{insecure}, \text{auth}, \text{secure}\}$ and hints $H$. Hints are label providing suggestions on the semantic interpretation of various elements. For example, a variable may be labelled as private asymmetric key. We do not list all hints explicitly as it is unnecessary; it will be up to the exporting plugin to interpret the hints. A descriptive high-level top-down description of the model in PSV is provided in Sec. 3.2. Instead Table 1 shows syntactic elements in bottom-up description as sets. Support to security properties is still immature in MetaCP, and the tool

| Set symbol | Set description | XML/xPath description |
|------------|-----------------|------------------------|
| $V$        | $\mathcal{L}^\circ T$ | (variable/argument) |
| $P$        | $\mathcal{L}^\circ K$ | (entity) |
| $K$        | $V^* \times P$ | (knowledge) |
| $\tau$     | $\mathcal{L} \times \tau^* \times \circ H$ | (set) |
| $D_v$      | $V \times \tau \times P \times \circ H$ | (declaration[@variable]) |
| $D_f$      | $\mathcal{L} \times \circ H$ | (function) |
| $F$        | $D_f \times^\circ (V^* \cup F)$ | (application) |
| $E$        | $\mathcal{L} \times V^* \times (F, V \cup F)$ | (equation) |
| $C$        | $\mathcal{L} \times C_T$ | (channel) |
| $C$        | $V \times \{\text{det, prob}\} \times (V \cup F \cup \tau)$ | (assignment) |
| $R$        | $^\circ K \times P \times C^*$ | (finalise) |
| $M$        | $^\circ K^* \times C^* \times V^* \times C \times V^* \times C^*$ | (message) |
| $\Pi$      | $P^* \times M^* \times^\circ \tau^* \times^\circ S$ | (protocol) |
| $M$        | $^\circ \tau^* \times^\circ D_f \times^\circ D_v \times^\circ E \times \Pi$ | (model) |

defines only executability (Tamarin plugin) and correctness (ProVerif plugin).
Correctness is similar to executability in that it tests if the end of the protocol is reachable, but differently it also tests final conditions. In the PSV, this notion is provided in the finalisation element, $R$.

The syntactic structure introduced in Table 1 shows the XML tags corresponding to the syntactic elements they describe relevant to the discussion in this paper. The full syntactic description of PSV is accessible from the DTD\(^8\).

### 3.2 High-level description of the structure of PSV

The standard flow of a PSV file is shown in Figure 2 and includes the following sections: declarations and the protocol.

Declarations. To allow for a type system over all the structures used within a protocol specification, e.g. variables, constants and functions, the declarations of the corresponding membership sets are mandatory beforehand. Each subsequent declaration needs to refer to an existing set identifier.

Protocol. A protocol is composed of entities, messages, a final elaboration step after the messages, and finally the desired properties. The entities are the participants of the protocol that exchange messages whose directives affect their knowledge. The final elaboration step can include statements; for example, at the end of a key exchange protocol, the parties may reconstruct the key at that stage. Security properties that can be currently specified are correctness, authentication and secrecy. We do not discuss the security properties on this paper, and we reserve to comprehensively study them in future works.

The messages are structured in four parts: the knowledge, the sender, the receiver and a communication channel in the between. The knowledge part is

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\(^8\) The DTD for PSV is available here: [http://metacp.eu/meta-cp.dtd?v=0.1](http://metacp.eu/meta-cp.dtd?v=0.1).
per entity and lists all the known variables and constants by the entity before either sending or receiving the message. The knowledge is beneficial to detect or restrict the designer not to use unknown structures. The sender part shows two sub-parts: the first can include statements required to construct the message to send, and the second is the message as it is pushed to the channel. Similarly, the receiver part shows two sub-parts but, in this case, they are inverted: the first is the incoming message, while the second are statements manipulating variables in the knowledge of the receiver, which has been just augmented with the received message. We remark that the received message may not be the same as originally sent by the sender. Any manipulation to the message can be done in the channel part. This structure has the benefit of allowing the designer to model different scenarios of interest. In particular, (i) systematically biased channels can be implemented with a function in the channel, (ii) man in the middle may be embedded inside the message, without creating additional messages and simplifying the design of attacks, and (iii) faults can be implemented either as empty received messages or probabilistic functions in the channel. The above listed scenarios are merely examples, and other scenarios can benefit from this particular structure of the message. Using the DHKE running example, we cherry-picked the first message sent in the protocol in Figure 3. We replaced the details of its content with a brief summary.

Fig. 3: Example high level structure of a PSV message

```xml
<message [...] from="Alice" to="Bob">
  <knowledge entity="Alice"> [...] knows g </knowledge>
  <knowledge entity="Bob"> [...] </knowledge>
  <pre>[...] elaborates gx]</pre>
  <event type="send">[...] sends gx]</event>
  <channel></channel>
  <event type="receive">[...] receives gx]</event>
  <post></post>
</message>
```

3.3 Graphical Design Editor

Whilst we see the XML as intuitive and in line with how you would describe a protocol in a specification, in practice, MetaCP is equipped with a modern Graphical Design Editor (GDE) as illustrated in the left part of Figure 4, to aid the user with the design of the protocol rather than focusing on a formalisation i.e. the PSV. The GDE mimics the standard drawing process most familiar to any protocol designer, and it lets the user specify variables, functions and message flow. It does so through a smooth drag and drop design, making it easy to piece together the protocol. The GDE is intended to guide a user through the coherent
definition of the PSV, automatically providing the following relationships in the data structure: first, the knowledge is automatically augmented as the protocol is constructed, and second, the GDE will enforce correct typing across the protocol and functions. The ability to store further relations and information about the protocol is a significant aid that modern frameworks for programming languages usually incorporate as the basics. Once a desired protocol is drawn out, it can be saved as PSV. Figure 4 highlights how some parts of the design reflect to the structure in PSV format.

Fig. 4: The graphical design of MetaCP (left) is saved as the PSV format (right).

3.4 Exporting Plugins

A plugin provides a fully automated protocol-agnostic interpreter from PSV code to the desired semantics of the target language. We remark that our plugins are examples of interpretation of the target semantics: additional plugins targeting the same language are allowed.

The combination of the benefits of the GDE and the exporting plugins can sensibly improve the experience of protocol designers, even if they are expert in a specific language. To the best of our knowledge, the languages used in formal verification for protocols do not enjoy frameworks for design or editing. In addition, many tools work (or can work) with untyped variables and constants. So in comparison to other languages, their source code is more prone to subtle and hard-to-spot bugs that can decide a security property to verify or not. Imagine simply asking for the confidentiality of a never-used variable - due to a typo - it can verify correctly as unknown to any attacker.

Plugins can be called in the GDE directly, as well as natively, e.g. as scripts in a shell, once the PSV is available. The architecture of MetaCP is such that all the components, PSV (with DTD), GDE and exporting plugins, are independent. So when a plugin is called in the GDE, it automatically and transparently generates a PSV as input to the plugin.
4 Workflow

The aim of MetaCP is to facilitate the design and modelling process up to the formal verification of a cryptographic protocol. With this goal in mind, the ideal workflow of the user of MetaCP can be summarised by the following points:

1. Design the protocol with the aid of the graphical design editor of MetaCP.
2. Save the design to PSV format, that ideally specifies the protocol.
3. Export the PSV to any target language or format, e.g. pi-calculus.
4. Run the formal verification tool, e.g. ProVerif, to formally verify the protocol exported with MetaCP.

Only the first and the last step are interactive, as both saving and exporting are automated. Nevertheless, the user can intervene and manually modify the result of any step of the process. After saving to PSV, the user might enrich the PSV with additional information that are not supported by the GDE, e.g. with security properties. Similarly, after exporting to pi-calculus, the user might modify model if required to verify later in ProVerif. Modifying the PSV is as easy as modifying an XML file. Differently, modifying the exported protocol requires expertise in the target format or language. The application of our automatic exporting plugin (e.g. PSV-to-ProVerif) can be as good (or as wrong) as the manual modelling task (e.g. English-to-ProVerif); while both need to show convincing arguments, the former is mechanised and can be consistently reused.

4.1 Graphical design editor MetaCP-GDE

To show the design process, we provide some details of the MetaCP graphical design editor, introduced in Section 3.3. The MetaCP-GDE is composed by the following macro-blocks: a section with two parties, a (moveable) toolbox, the exchanged messages and the final operations.

Parties Currently, the GDE supports two parties, Alice and Bob, each with their knowledge, as shown by Figure 5. The user can drop variables to the knowledge of either party, determining their initial knowledge i.e. what they know before running the protocol.

Fig. 5: Party structure in the GDE.

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9 This step is outside of MetaCP and discussed for completeness.
Toolbox The toolbox is illustrated in Figure 6. The toolbox is split in sections for handing sets, functions, constants, variables and statements. They contain buttons to add new elements. Functions themselves cannot be directly dragged out of the toolbox, and they require the user to create an application of the functions, i.e. provide the arguments of the function. A type match helps the user to avoid incorrect function applications or statements. Once new objects are created, they can be dragged and dropped to target boxes external to the toolbox.

Fig. 6: Toolbox in the GDE.

Messages The structure of the messages exchanged by Alice and Bob is illustrated in Figure 7. An arrow shows the direction of the message from the sender to the receiver. The user can drop statements from the toolbox to the pre and post boxes that are computations made by the parties before and after the message has been exchanged. A box with knowledge is automatically populated according to the initial knowledge and the computations made by the parties in the message. Additionally, the user can drop variables and constants to the event box above the arrow, representing what is being sent by the sender.

Fig. 7: Message structure in the GDE.
Final operations Final operations are statements computed (offline) by either of the parties after every message has been exchanged. For example in the case of a key exchange protocol, they may contain the final elaboration of the exchanged key done by each party.

4.2 Diffie-Hellman key exchange

As a case study, we show some details of the workflow to successfully design and formally verify the Diffie-Hellman key exchange (DHKE) protocol, a traditional protocol of reference in cryptography. This case study saves to PSV and then exports to ProVerif as intended, i.e. no manual intervention is required. The workflow to design the DHKE protocol, illustrated in Figure 8a and 8b, can be summarised by the following steps:

– Declare the sets, constants and variables that will be used across the protocol.
– Create the function applications that will be assigned to variables.
– Add two messages, the first from Alice to Bob, the last from Bob to Alice.
– Drag statements to the target boxes of the messages, drag variables and constants to define the message exchanged.
– Finally, drag variables to the initial knowledge of the parties.

Formal verification To have a complete picture of MetaCP, we also briefly illustrate the formal verification step. In particular, our plugin automatically models correctness based on the equality of the final keys. The output from ProVerif running the automatically exported protocol, see Figure 9, shows the formal verification of correctness. We stress that this part is delegated to external tools that can parse the language exported through related MetaCP plugins, in our example ProVerif.

5 Exporting to ProVerif

As the PSV is a structured container of the specification of the protocol, interpreting plugins confer semantics to that specification from the point of view of their target language. Hence, a plugin can be seen as the effort of applying the semantics of the target language to the structure of the source PSV. To do that, the plugin translates the PSV into the target language grammar. If they were two languages with their own semantics, some sort of bisimulation certifying that semantics are preserved in the translation would be expected. Differently in this case, we illustrate how the methodology of our ProVerif plugin does not introduce errors in the target code upon certain conditions. The most convenient way to describe the validity of the interpretation of a plugin is by demonstrating how the PSV structure uniquely maps to the target syntax to model the protocol, similarly to a refinement. The interpretation methodology is illustrated in Fig. 10 and can be summarised in the following points: (i) in a first step
Fig. 8: Workflow for DHKE in the GDE

(a) Definitions.

(b) Build messages and drag elements.

Fig. 9: Final part of ProVerif’s output showing correctness, as compared to Tamarin’s executability; the model was exported automatically from the same design in MetaCP.
it handles declarations and descriptions of types, entities, functions (including constants) and channels, (ii) then it creates the processes by entity, extracting from the messages the relevant parts, and (iii) it creates a process describing the protocol run for infinite repetitions of the two entity-related processes.

Fig. 10: The interpretation process automatised in the ProVerif plugin of MetaCP.

The semantics that the DTD confers to the PSV is very intuitive and is meant to be interpreted directly. For an alternative notation of DTD semantics, the technique described in [14] can be used. We only describe the rules in charge of interpreting a by-entity process in pi-calculus, as they where the least obvious and probably the most interesting, in Fig. 11 and Fig. 12. The key to read those rule is as follows: at the conclusion (bottom or bottom-right) we have the grammar of the applied pi-calculus, which is inferred by the parts above its line or at the left of the corresponding inline symbol $\vdash$, while the lines above are the interpretation reading from the PSV whose notation uses xPath directives. For a comprehensive explanation of the applied pi-calculus grammar, syntax and semantics, we refer to Abadi et al. [1]; similarly for the xPath directives, we refer to Clark et al. [7]. Additionally, we use the notation explained as follows. We refer to the (ordered) sets of elements generated by an application of an xPath directive $d$ within angle brackets, i.e. $\langle d \rangle$. If the result set is a singleton, we also refer to the single element with the same notation. Some rules are parametric, the parameter passed to them is superscripted after their name, so the notation $[r]^p$ is for the rule named “$r$” with parameter $p$.

To read attributes from tags, we use square brackets notation, so we denote the attribute type from the tag in $e$ as $e[@type]$. Unlike other common rules, they have to be explicitly called. The notation we use to apply a rule to all elements of a set of elements is a vertical bar with the application domain as subscript, e.g. to apply the rule $[r]$ to all elements in $\langle d \rangle$, we write $[r]|_{e \in \langle d \rangle}$.

As a short notation, if the rule to apply has the same name as the xPath directive of the set, we omit it leaving only the $\forall$ symbol, e.g. $[r]|_{e \in \langle \rangle}$ is short for $[r]|_{e \in \langle r \rangle}$. Finally, we shorten the call of two rules applying to set of diverse
Fig. 11: Rules applied by the ProVerif plugin in MetaCP for variables, arguments and function applications.

\[
[v\text{variable}]^m[\text{variable}]^m:\quad v \in (\text{variable}|\text{argument}) \quad m = \bot \\
\quad x \leftarrow v[@\text{id}] \vdash x
\]

\[
[v\text{variable}]^m[\text{argument}]^m:\quad v \in (\text{variable}|\text{argument}) \quad m = "\text{typed}" \\
\quad \tau \leftarrow (\text{declaration}[\text{variable} = v[@\text{id}] | [\text{@id}]) \\
\quad x \leftarrow v[@\text{id}] \quad \vdash x : \tau
\]

\[
\text{[application]}:\quad a \in \langle \text{application} \rangle \\
\quad f \leftarrow a[\text{function}] \\
\quad l \leftarrow f[\text{arity}] \\
\quad M_1, M_2, \ldots, M_l \leftarrow \langle \text{application}|\text{argument} \rangle "\text{typed}"_v \\
\quad f (M_1, M_2, \ldots, M_l)
\]

Fig. 12: Rules applied by the ProVerif plugin in MetaCP for messages in the protocol along with depending rules. Generic insecure channel denoted as ε.

\[
\text{[entity]}:\quad e \in \langle \text{entity} \rangle \\
\quad P \leftarrow \langle \text{message} \rangle "\text{from}".0 \vdash P
\]

\[
\text{[message]}^e:\quad m \in \langle \text{message} \rangle \quad m[@\text{from}] = e \\
\quad P \leftarrow \langle \text{pre} \rangle , \langle \text{event} \rangle, \forall e \in \langle \text{event} \rangle \vdash P
\]

\[
\text{[message]}^p:\quad m \in \langle \text{message} \rangle \quad m[@\text{to}] = e \\
\quad P \leftarrow \langle \text{event} \rangle | e \in \langle \text{event} \rangle \vdash P
\]

\[
\text{[pre],[post]}:\quad P \leftarrow \langle \text{assignment} \rangle | v \vdash P
\]

\[
\text{[assignment]}:\quad a \in \langle \text{assignment} \rangle \\
\quad a[@\text{type}] = "\text{probabilistic}" \\
\quad n \leftarrow a[@\text{variable}] \\
\quad \tau \leftarrow (\text{declaration}[\text{variable} = n])
\]

\[
\text{[assignment]}:\quad a \in \langle \text{assignment} \rangle \\
\quad a[@\text{type}] = "\text{deterministic}" \\
\quad x \leftarrow a[@\text{variable}] \\
\quad M \leftarrow \langle \text{application} \rangle | v
\]

\[
\text{[event]}:\quad e \in \langle \text{event} \rangle \\
\quad e[@\text{type}] = "\text{send}" \\
\quad v \leftarrow \langle \text{variable} \rangle \quad \vdash v(v)
\]

\[
\text{[event]}:\quad e \in \langle \text{event} \rangle \\
\quad e[@\text{type}] = "\text{receive}" \\
\quad v \leftarrow \langle \text{variable} \rangle "\text{typed}" | v \vdash v(v)
\]

elements, e.g. el1 el2 with the vertical bar |, e.g. [el1|el2] will apply to elements whose tag is either el1 or el2 in the order they appear in the application domain.

As the reader may already have noticed, the rules in Fig. 11 and Fig. 12 rely on some assumed relationships between the elements in the PSV. These rela-
tionships cannot be enforced by the DTD: for example, the rule [variable] "typed" assumes that the type will be actually found in the declarations. The DTD can only guarantee that the variable specified appears as an identifier in the past, but it cannot guarantee that the identifier was actually defined for the desired element. By designing the protocol with the GDE, MetaCP is able to generate a PSV where these relationships are always valid. To enforce such relationships in the PSV itself, we reserve ourselves to upgrade the DTD to the more powerful XML Schema Definition [13]. As introduced before, the GDE currently confers a type system to the functions, variables and statements to respect across the whole protocol, and manages the knowledge automatically at each step of the protocol. In particular, the extra properties provided by using the GDE are that all messages are exchanged between intended parties, and all statements can refer only to corresponding pre-declared sets, variables and functions, according to the knowledge of the party at that specific point of the protocol.

5.1 Correctness

Our first attempt to model security properties models correctness, as opposed to the automated executability in the case of Tamarin [4]. They are similar properties: the former checks if a final condition is met after a honest execution of the protocol (e.g. for a key agreement protocol, all parties must share the same key), the latter simply checks whether all the rules describing the protocol can run in the desired order. Thus, correctness may fail even if executability holds. Also, correctness is a traditional security property, while executability is mostly used as a self-check that the code is not affected by (major) errors.

As we presented the ProVerif plugin in Section 5, we describe correctness. It is modelled in PSV by mean of the tag \langle correctness \rangle. Inside of it, one can specify a relation that ultimately evaluates to boolean. We discuss the details for our use case, DHKE, where correctness is the equality $k_A = k_B$, as the final result of running the protocol.

\[
\langle\text{correctness}\rangle
\langle\text{application function="eq"}\rangle
\langle\text{argument id="kA"}\rangle \langle\text{argument id="kB"}\rangle
\langle/\text{application}\rangle
\langle/\text{correctness}\rangle
\]

One way to model correctness in ProVerif is through events: in particular, the exporting plugin automates correctness by

- creating two tables $\text{finalA}(Zp)$ and $\text{finalB}(Zp)$;
- injecting into the parties’ processes a command to fill the tables with the shared key: $\text{insert finalA}(exp(gy, x))$ for Alice and analogously for Bob;
- appending a process agreement, that can generate the desired event, to the protocol process:

\[10\] Tamarin uses multiset rewriting and the protocol algorithms are split into labelled transitions called rules.
let agreement = get finalA(kA) in get finalB(kB) in
  event correctness(kA, kB).

– and finally, creating the event event correctness(Zp, Zp) and querying
  for it to be triggered by any execution where the keys are the same:

query k: Zp; event(correctness(k, k)) => true = true.

We’ve already shown the result of the verification for the DHKE in Figure 9.

6 Conclusion

MetaCP is a first-of-its-kind tool aiding the protocol expert through the process of design and formal specification. It is based on a data-centric approach where the protocol specification is described as a data structure. This approach allows for repeatable and reliable interpretations of the specification: in other words, it helps mechanising the reasoning behind the interpretation, that now is exclusively explained on papers. Furthermore, we showed how centralising the specification eases the modelling of cryptographic protocols to simultaneously export to multiple target languages.

The current specification focuses on having enough expressivity to allow interpretations towards multiple (very different) formal verification languages: we presented in this paper a new plugin for ProVerif, over the only plugin for Tamarin that existed before [4]. Additionally, we have been able to automatically generate C++ code that can run the protocol for real over the Internet. We do not present the details here as they would be similar to the ProVerif plugin (see Appendix A for details on how to run the code).

Documentation and a simplified demo of the tool have been released\textsuperscript{11} (the entire source code will be released later on). We also note that the demo does not support all the features provided by the PSV, e.g. it only allows to design two-party protocols and no security properties can be specified yet. Motivated from the current limitations in manual interpretations to single tools, we see the application of our approach to the verification of protocols simultaneously to two languages an exciting and now very possible prospect that increases repeatability, rigour and trust in the results. After its promising entrance, MetaCP is far from a mature solution. Future extensions envision the inclusions of security properties along with the protocol model to further accelerate the verification process. Finally, having showcased the flexibility of the approach through these first plugins, further plugins are an obvious next step to incorporate further verification and programming languages alike.

References

1. Abadi, M., Blanchet, B., Fournet, C.: The applied pi calculus: Mobile values, new names, and secure communication. Journal of the ACM (JACM) 65(1), 1–41 (2017)

\textsuperscript{11} The demo is available at http://metacp.eu.
A Generating C++ code from the design

To provide a broader evaluation of the expressivity of the PSV in its current development (see the DTD for details), we created a plugin that targets C++ and allows for two parties to truly run the protocol over the Internet. Even if the plugin is agnostic of the particular protocol under design, we tested it only for our use case, the Diffie-Hellman key exchange. The PSV does not contain as many implementation details as a programming language, i.e. C++, so it
is necessary for the plugin to make some assumptions: the protocol is a two-party protocol, and two sets \( \mathbb{N} \) and \( \mathbb{Z}_p \) are present. The plugin looks for group exponentiation operations, in particular:

- The group exponentiation constant of type \( \mathbb{Z}_p \) is the generator, and the constant of type \( \mathbb{N} \) is considered as the modulo \( p \). We remark that such values are globally declared, so that entity-scoped values will not be treated the same way.
- If a function with signature \( \text{exp} : \mathbb{Z}_p \rightarrow \mathbb{N} \rightarrow \mathbb{Z}_p \) is found, its implementation gets filled with modular exponentiation with modulo \( p \), where \( p \) references the global value \( p \).

The implementation of cryptographic functions is borrowed from the library Crypto++\textsuperscript{12}, the implementation of the network operations is borrowed from the library Asio\textsuperscript{13}. Those are examples of interpretation details that are allowed from the structured nature of the PSV; though in the future, such details may be very well part of its definition - to strictly specify that use of a particular routine is mandated by the specification.

We do not go in further details of the C++ plugin, as they are analogous to the process explained in Section 5 for the ProVerif plugin. Rather, we go into the details of how to compile and run the code, to appreciate the actual usability of the automatically generated implementation. Additionally to the above mentioned libraries, the plugin relies on an external open-source class\textsuperscript{14} to easily map send and receive operations. Once all dependencies are installed, assuming that the automatically generated C++ code is saved as \texttt{dh.cpp}, compilation is straightforward, see Figure 13. We notice that the generator \( g \) and the prime number \( p \) defining the modulus of the group set \( \mathbb{Z}_p \) are publicly known by the entities before they run the protocol. Hence, they are asked as arguments. In the

\textbf{Fig. 13: Compiling the source code automatically generated by the C++ plugin of MetaCP.} For simplicity, we assume we’re using a *nix machine.

\begin{verbatim}
Terminal - Compile and run DHKE
File Edit Help

user@metacp.eu$ c++ -c channel.cpp -o channel.o
user@metacp.eu$ c++ channel.o dh.cpp -o dh -pthread -lcryptopp
user@metacp.eu$ ./dh
Syntax: ./dh <g> <p> <A|B> [remote-host]

\end{verbatim}

\textsuperscript{12} https://cryptopp.com/.
\textsuperscript{13} https://think-async.com/Asio/.
\textsuperscript{14} Downloading the files C++/net/channel.cpp and C++/net/channel.h from https://github.com/nitrogl/snippets/ suffices.
example in Figure 14 we used the following:

\[ g = 3 \]
\[ p = 9692442802821327950508911771308328052666887550900435682895207347568406495843849224672416130967884554259211675299291454161197981395799145169370398324975923 \]

where \( p \) is a 512-bit prime number. The security parameter specified in the PSV is indeed 512.

To enact the algorithm as either Alice or Bob, an additional argument is required that matches the identifier of the entity used in the PSV. Finally, the remote host to send messages to can be specified as an optional argument - localhost is used if omitted. The execution runs between machines over the Internet, as shown in Figure 14.

Fig. 14: An actual run of the Diffie-Hellman key exchange protocol, directly from the design. As we see the two hosts are able to exchange a secret key correctly.

We remark that the Diffie-Hellman key exchange protocol is known to suffer from man-in-the-middle attacks; so it is not of particular interest in the real-world. Traditionally though, the DHKE is used as a reference protocol comparing with related work. Its attacks can be easily shown by ProVerif and Tamarin; a few manual tweaks are required with the MetaCP auto-generated scripts. The C++ plugin can be used to generate instances of the other two available examples, the Needham-Schroeder and the Needham-Schroeder-Lowe protocols.

\[ \text{As a network detail, server ports need to be are opened either manually (port forwarding or triggering) or automatically (UPnP, DMZ) if hosts are behind a router.} \]
B Protocol refinement using plugins for ProVerif and C++

In the following, we provided a quick comparison between the specification in PSV format and the output of plugins to appreciate structure similarities and dissimilarities. In particular, Figure 15 shows different PSV elements and roughly the corresponding code output by two plugins, ProVerif and C++. Some of the corresponding parts are highlighted with the same colour across multiple languages.

Fig. 15: The plugins refining the PSV to C++ and ProVerif.