Cryptographic protocols systematic analysis: the importance of tuple bracketing

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***Abstract*—Why having secure cryptographic primitives is not enough to have a secure conversation? What are the main protocols used today and how to check their safety? Our work consisted, on one hand, in adding a new step to the verification of security protocols and, on the other, in analysing these results.**

***Index Terms*—cryptography, protocol, safety, ProVerif, analysis**

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I. Introduction

A. Global context

The internet has drowned our world. And with it the networks have been developing at a very fast rate. They are everywhere. More and more information are exchanged throughout this global network, from the most trivial material between mere friends to the most crucial one between states. It is essential to keep those information away from the knowledge of what could be malicious persons or organisation. In others words, the networks need to be secured. The security of networks is a complete subject of study on its own as there as many ways to secure a network as there are ways to go around this security.

This problem goes beyond the simple technical and physical organisation of the networks. Indeed, the ways that one sends or receives the messages on the network is also of an extreme importance. Throughout the development of these exchanges we realised that in order to have a better understanding of how the messages were exchanged and how some were caught by malicious users, we needed to add norms and standards upon those exchanges. These set of rules are what we call protocols. Historically these protocols started very simple and are now complex algorithms that are being used to secure and insure that all the data stay hidden. As the threat grew bigger and bigger, it is in the end of the 1970's that protocols started to be created (some of the first ones being : Needham-Schroeder, Kerberos, Otway-Rees, Yahalom) and we are now using far more complex protocols (SSL, TLS, SET which are protocols that still being updated up to now), this complex protocols are used to secure most of the exchanges on the Internet, and can for instance be used for the e-voting.

To give a bit of insight, we shall study one of the oldest protocol there is. It was invented by Roger Needham, and Michael Schroeder, british and american computer scientists, and described in a paper published in December 1978 [3].

The simplest form of the Needham-Schroeder protocol can be resumed by those three exchanges only (Fig. 1).

Fig. 1. Description of the Yahalom Protocol

$$
\begin{array}{|lcc|}
\hline
A \rightarrow B & : & \{A, N_A\}_{pk(B)} \\
B \rightarrow A & : & \{N_A, N_B\}_{pk(A)} \\
A \rightarrow B & : & \{N_B\}_{pk(B)} \\
\hline
\end{array}
$$

With A and B two machines willing to exchange a message: N_B. For all the followings examples we are going to consider that this N_B value and all the others N values are simple numbers but in fact it could be any kind of data that needs to be transferred from A to B. We call them nonce: a randomly generated number created by a machine for a single usage. They are used as the session IDs.

In this simple example of the Needham-Schroeder protocol we only illustrate the actual communication between the two machines but in reality, there are other operations that need to be done in order to properly set up the communication. Indeed, each machine needs to know the public key of the other. The process of this key exchange is almost the same for all the protocols and it is why we are not giving as much details for this part as we will for the others.

Finally, one machine must reveal on the public channel its will to communicate with another. That is done by simply exchanging on the channel a message with A, B. This allows the two machines to be prepared for the communication to come.

On the protocol itself, you can see that it is fairly simple. Indeed, A wants to communicate with B to retrieve a particular nonce named N_B. To do so it sends a message with its name and another nonce N_A. This message is obviously encrypted with the public key of B that A got earlier on. B receives this message and generates another nonce N_B. He then sends its response with N_A as well as N_B. He hides this exchange by encrypting it all with the public key of A. At this point, A has received the data that it wanted, that is to say N_B. But only to confirm that the exchange went as expected it sends a last message to B with the N_B nonce only. B is now sure that A received the information safely. One could think that with this set of rules it would be hard to intercept the N_B value. As indeed, all the exchange is encrypted properly with the public key of the recipient and thus completely hidden from any machine apart from A and B.

However, as always, it cannot be that simple and we will see now, how a malicious machine can actually take hold of the message by a well known type of attack called man-in-the-middle.

The point of the intruder is to impersonate another machine. It will be able to impersonate the machine A from machine B's perspective and vice versa.

In the next illustration we will show you how an intruder named C can get access to the value N_B without any of the other two machines involved realising it. And thus showing how the simple protocol that is Needham-Schroeder can be attacked in order to get access to a specific value or to impersonate another machine.

This allows us to illustrates how protocols even though they exist to secure the exchanges on a network, there are ways to avoid those limitations and still get access to the data exchanged. Although, this protocol stays very simple it shows something that is common to all the security protocols created through history, even the most recent ones. It is the work of computer scientist like Roger Schroeder, to try and come up with protocols that are not possible to attack. It is a

Fig. 2. Description of the attack of the Needham-Schroeder Protocol

$$A \xrightarrow{\{A, N_A\}_{pk(C)}} C \rightarrow C(A) \xrightarrow{\{A, N_A\}_{pk(B)}} B$$

$$A \xleftarrow{\{N_A, N_B\}_{pk(A)}} B$$

$$A \xrightarrow{\{N_B\}_{pk(C)}} C \rightarrow C(A) \xrightarrow{\{N_B\}_{pk(B)}} B$$

***Attack** : B is speaking to C instead of A.*

very hard work on its own as there all a lot of protocols that were invented and all of those are potential targets of attacks. We will need tools to help us find those attacks and eventually prove that a protocol is safe or not.

It is worth noticing that the issue of a protocol's safety is undecidable (see [5]), that means that no existing algorithms is able to give a proper output for any given protocol. It sometimes means that with some versions of some protocols, the verification tools won't be able to give an answer as to whether or not a protocol is safe.

B. Existing tools

We will see now that there are a lot of tools available. Indeed, creating a software that is able to help us is a subject that interested a lot in the past decades. This software would need to simulate the execution of a protocol taking into account as much complexity of the physical networks as possible. It would also be able to find if a specified protocol is safe, and if not to show the entire process that lead to an attack.

As stated above, this topic is really wide and it is unthinkable to create a software that would be able to solve all the problems. Therefore, there are multiple software that currently exist. The most famous software are ProVerif, Tamarin Prover. Otherwise, software for more specific applications include : AVISPA, KISS, YAPA, CryptoVerif, ...

Throughout our work we used the ProVerif software.

C. Subject of study

Now that the general context is set, our aim, when working on this subject was to understand the effects of tuple bracketing inside the specifications of the security protocols. Indeed, as seen with the Needham-Schroeder protocol example, many protocols need to exchange multiple values to their counterpart. This data, when designed inside of a computer needs to be represented inside a data structure. For the most part, software use tuples for this representation. Basically, a tuple is a list of values one after the other. Obviously a tuple structure needs bracketing. And it has been noticed that this bracketing is really important in the specification of a protocol, as indeed, the original specification is modified when a different bracketing is used. This difference of specification is not proven to be safe, and as we will see throughout this whole report, it can have dramatic changes on a protocol and its potential attacks. Our subject of study was the creation of a program that would allow us to verify whether or not modification of bracketing inside the specification of protocols would have any impact on its safety, and if so, understand why and report it.

D. Contribution

During the period of our work, we had to first understand these notions of security protocols, specification, attacks, and ProVerif, the tool used to verify the security of protocols. We were at the same time introduced to the important matter of tuple bracketing. We then, following the terms of the subject of study, to design a lexical parser for the ProVerif language whose aim was to mark all the tuples inside of a given ProVerif program used to specify a security protocol. Doing so, we created and generated the complete list of possible bracketing of this particular file, and then looked through all of those, searching for any difference between the original one and the generated ones.

As a result, we discovered an attack to the Yahalom security protocol. It is a success in itself as it was not sure at all that the protocols we studied were impacted in any way by this change of bracketing, but we managed to prove that one was. And even more significant, this attack on the Yahalom protocol was not listed in any of the specific litterature about the subject. This find leaves hope to find more and more attacks on other protocols and in doing so, finding a way to prevent them and look towards safer exchanges of information.

II. The importance of bracketing

A. Some more case study with the Needham-Schroeder protocol

Going back to the Needham-Schroeder protocol, we saw that there is an attack on the standard protocol, and with discovery as with much others, researcher tryied to find a way to prevent this attack from ever existing again and thus increasing drastically the security of the protocol.

Gavin Lowe wrote about this and invented a modified version of Needham-Schroeder protocol (see [4]). This protocol was designed to prevent the man-in-the-middle attack. As indeed, we explained that this attack was possible because the intruder impersonating one of the machines. Thus, Lowe explains that by adding the identity of the machine inside the protocol itself, this kind of attack is not possible anymore. That gives us the modified version of the Needham-Schroeder protocol know as Needham-Schroeder-Lowe :

Fig. 3. Description of attack of the "fixed" for the Needham-Schroeder Protocol

$A \to B$	:	$\{A, N_A\}_{pk(B)}$
$B \to A$	:	$\{B, N_A, N_B\}_{pk(A)}$
$A \to B$	:	$\{N_B\}_{pk(B)}$

Here, with the B value added to the second message of the exchange, A is now sure that B is actually being the one talking to it.

What is going to interest us next is this second message. Here we see that there are three values that are being exchanged and we need to represent it with a tuple structure. Gavin Lowe, when he decided to add this identity value, chose to put this value on the left of the tuple. That leaves us with the tuple : $\{B, N_A, N_B\}$. But what would happen if this value was put in another place in the tuple. One further question is how to represent this tuple. We saw, that a machine needs to represent the tuple and according to the tool used, the tuple can be represented by a three-element tuple, or by a combination of doubles.

With those two questions at hand, we are left with the possibilities illustrated on the Figure 4

B. Consequences

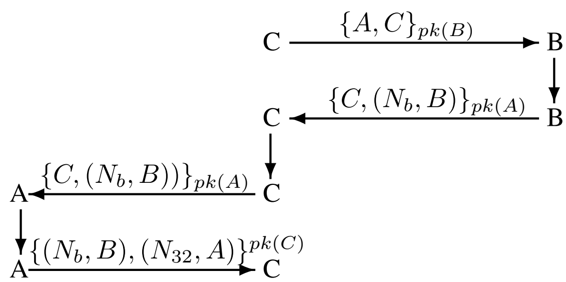
Now, that we explained that a tuple can actually be bracketed in different ways, it is important to know what are the consequences of it on the security of protocols. To do so, we can use a formal verification tool such as ProVerif, to check the results on the possibilities.

It has been found that an attack exists on some of the possibilites. This attack is described on Figure 5.

Fig. 4. Possibilities of bracketing from the second message of Needham-Schroeder-Lowe

$(N_A, (N_B, B))$	(1)
$((N_A, N_B), B)$	(2)
$(N_A, (B, N_B))$	(3)
$((N_A, B), N_B)$	(4)
$(B, (N_A, N_B))$	(5)
$((B, N_A), N_B)$	(6)

Fig. 5. Description of the attack of the Needham-Schroeder Protocol using a bad bracketing



***Attack :** A is speaking to C instead of B.*

As you can see from the description, C can still impersonate A but this time it is through the N_A value. Indeed, as we said before this value is not necessarily a number and we have the proof right here as N_A equals C. With this little trick the machine A now thinks that it has been talking with C ever since the beginning. Based on this belief, it sends him the useful information encrypted with the intruder's public key.

Here it is another case of a man-in-the-middle attack, but this time it is not based on a weakness of the protocol itself but only based on an implementation detail that is the bracketing choice.

Remark :

In order to bring a correction to this attack there is no other choice than to force the bracketing of the tuple. But this time, using a bracketing that will not link the identity value with the important information. In our examples, that is to say B and N_B. If we take a look at all the possible bracketing for the protocol, we can in fact choose from all the possibilities except for the number (1) and (3).

We, then, based on the example of the Needham-Schroeder protocol, understand the actual importance of the bracketing. Indeed, behind tuples can hide thing such as security attacks that can eventually lead to very high risk for those who use this protocol. That is why, the work the we undertook is of a great importance as it might allow us to find attacks on protocol that are yet to be found.

III. ProVerif tool presentation

In this chapter we are going to take a closer look at the tool that we used to work on this bracketing issue. It will allow us to understand in a better way what is a tuple in ProVerif and how it is defined. We will also look at the security properties that are verified by the tool and finally the outputs given by ProVerif to understand if a security breach exists.

A. Language syntax

It is now time to dive into the ProVerif tool. This tool uses a language to help describe security protocols. To do so, it needs proper expressions, with defined keywords and syntax. A formal tool used to describe such a language is called a grammar and as with all the computer language, ProVerif uses a grammar. As it is a language that is quite complexe, the grammar that is associated is as difficult. To help with the understanding of the language, we will use a simplification of the grammar in Figure 6

Fig. 6. Simplified version of the ProVerif grammar from [1]

$M, N ::=$	$terms$
x, y, z	$variable$
a, b, c, k, s	$name$
$f(M_1, ..., M_n)$	$constructor\,application$
$D ::=$	$expressions$
M	$termh(D_1, ..., D_n)$
$function\,application$	
$fail$	$failure$
P, Q	$processes$
$\mathbf{0}$	nil
$out(N, M); P$	$output$
$in(N, x : T); P$	$input$
$P \vert Q$	$parallel\,composition$
$!P$	$replication$
$new\,a : T; P$	$restriction$
$let\,x : T = DinPelseQ$	$expression\,evaluation$
$if\,M\,then\,P\,else\,Q$	$conditional$

There are a few points that are worth noticing in this grammar. Here is a list of those points with the explanations of what is their purpose inside the ProVerif language.

- **process :** Structure and keyword used to specify in general what are going to be the action executed for this procotol. Inside of it are usually created all the global data that needs to be created beforehand, for instance, the authentification keys of the machines. It also always to specify which functions are going to be called in thus initialising the protocol execution.

```
process
new Kas: key; new Kbs: key;
```

```
insert keys(A, Kas);
insert keys(B, Kbs);
(
 (!processInitiator(A, Kas)) |
 (!processResponder(B, Kbs)) |
 (!processS) |
 (!processK)
)
```

Here we see an example in an actual ProVerif file, of what a process statement can look like. With, as it can be seen, the keys creation and initialisation of the functions stating the execution of a protocol.

- **let :** This keyword is important as it has many uses. First, it allows to create an environment like a function. Often times, it is used to create function to state the exact and detailled execution of a process inside a security protocol. For instance, in Needham-Schroeder protocol, ProVerif will need (in a simple version of the protocol) a function with a let statement to describe the behaviour of the machine A and another to describe machine B's.

```
let clientA(A:host, B:host,pkA:pkey,
    skA:skey,pkB:pkey,n:bitstring) =

 out(c,aenc((A,n),pkB));
 in(c,x:bitstring);
 let (=n,nn: bitstring) = adec(x,skA) in
 out(c, aenc(nn,pkB)).
```

- **event :** Keyword used to specifies a special point in the execution of the protocol's specification. Indeed, when designed the protocol inside ProVerif we sometimes want to be able to trigger some events after they have happened. This event keyword aims at resolving this issue.

```
event beginBparam(host, host).
event endBparam(host, host).
event beginAparam(host, host).
event endAparam(host, host).



...

let processInitiator(pkS: spkey, ...) =
 in(c, (xA: host, hostX: host));
 if xA = A || xA = B then
 let skxA =
 if xA = A then skA else skB in
 let pkxA = pk(skxA) in
 (* Real start of the role *)
 event beginBparam(xA, hostX);
 out(c, (xA, hostX));
 ...
 event beginBfull(xA, hostX, pkX, ...);
 ...
 if hostX = B || hostX = A then
 event endAparam(xA, hostX);
 event endAfull(xA, hostX, pkX, ...);
 out(c, sencrypt(secretANa, Na));
 out(c, sencrypt(secretANb, NX2)).

...
```

- **new :** Keyword used to create a structure. This structure can be a variable of any type. In most of the examples, we can notice that nearly all the keywords : new, are used to define and create new nonces (see the definition of a nonce in the introduction).

```
new Nb: nonce;
```

- **query :** Keyword used to specify the security properties that ProVerif needs to verify during its execution. If the query is verified then no intruder can breach this property, if not then ProVerif found some way for an intruder to break this particular security property using the specification of the protocol.

```
query attacker(secretANa);
      attacker(secretANb);
      attacker(secretBNa);
      attacker(secretBNb).
```

- **out, in :** Keyword used to specify that a particular process needs, at this point in the protocol, to send (out) or receive (in) a message on the global channel, representing the network. It, most of the times, needs to be followed by a specific format of information, amongst those are single variable, tuples, functions calls, etc ...
  In the example used for the let expression we can clearly see an example of simple exchanges. This piece of ProVerif code is actually the specification for the machine A in the simple Needham-Schroeder protocol that we used as an example in the introduction. We can see that it matches exactly the output and the inputs stated by the protocol specification itself.

As stated in the chapters above, an expression that is extremely important in our work is the tuple structure. Now that we saw of the language can be formalised, we need to take a closer look at the language itself in order to understand how it is all organised.

As we can see from the simplified grammar described above, the ProVerif language, as any other programming language allows to write instructions and build a proper ProVerif program to specify a security protocol.

Therefore, there is at least a rule in the grammar to express the syntax of tuples. This needs a brief explanation of the notion of terms in ProVerif. A TERM is an expression used in all the ProVerif logical operations. And as any operation, this rule must be recursive and call itself on the right and left parts of the operator in question. Here, in ProVerif, there are three different type of terms. The first one is called TERM, the second PTERM and the last one GTERM. Each one of them allows the grammar to derivate towards specific operations and of course, have the same property of recursivity and priority of the operators.

Now, a tuple is simply a sequence of terms. So for each type of term stated above, there is a matching rule allowing to generate tuples. For example, the rule generating tuples for a TERM term is specified in Figure 7 extracted from the Proverif manual.

Fig. 7. Grammar rule for a tuple of terms extracted from the ProVerif manual [2]

$$\boxed{\begin{array}{c}\langle term\rangle ::= (seq\langle term\rangle)\\ with\, seq\langle X\rangle = \langle X\rangle, ..., \langle X\rangle\end{array}}$$

Now that we know exactly what a ProVerif tuple is we can take a closer look at the security properties that the language can verifying and especially the ones that are going to interest us during our working process.

B. Security properties

The description of the protocol is written in ProVerif (Example files are available in Annex A). The software then tries to execute a set of derivations leading to an attack. The attacker has to breach a security feature. In this part, we will explain what are those features and properties of security.
In practice, the user must specify which data ProVerif must check (for instance "The channel must not know that information", considering the channel as the attacker). To be clear, you can estimate that a protocol is safe is neither the channel nor the protagonists are fooled. The channel cannot know the id of the sessions and the protagonists must only speak to other machines that are actually the one they think they are.

Properties checked: We would like to know if a protocol is safe, but how to ask to the software "*Is this protocol safe?*". It depends on which property we want to check. Let's present briefly three main properties often checked : secret, authentication, and interference. These properties are declared inside a ProVerif program using the query keyword, explained earlier on.

- **Secret** : In a conversation, the secret must be preserved. For instance, when Bob and Alice are talking, it must not be possible that Eve can understand the messages. As we have said, we can consider that the attacker (Eve) is the channel, *i.e.* an attacker know all these public information which are the information exchanged that anyone can read. So for instance it is possible to implement in the protocol an encrypted exchange from Alice to Bob, called `secret`, and a specification of the secret query could be "The channel must not be able to know `secret`".
- **Authentication** : The authentication security query states that all users must be right about the identity of the machine they are addressing when sending and receiving a message. In other words, the intruder must not be able to impersonate any other machine.
- **Non-interference** : The non-interference is a property that guaranty that it is not possible to know where they are from. The content of the message could be public, but other properties are not distinguishable among several messages. Let's study an example where the property of non-interference is important. That is the case of anonymity. For instance, for e-voting, it would have no purpose to verify the secret of the data, as it is known by everyone. (yes or no or name of a candidate in a vote for example), but what is important is to ensure the anonymity of the person that voted. That is of course a strong simplification of what actually is the interference, but enough to help understand it generally. In this study, the aim of our works is not to give a formal definition of non-interference, but the properties checked on some files (only a little part is about non-interference) are similar to this kind of verification.

C. Outputs

Once the ProVerif program is executed, it gives an output that the user has to check in order to see whether the protocol specified in the program is actually safe or not. Listed underneath, are all the possible outputs given by ProVerif with the interpretation that one can make of it.

- Either the protocol is analysed as **"safe"** : "ProVerif" has not found any derivation that allows the attacker to break one of the specified query. The queries are marked as "true" and even if that doesn't necessarily means that the protocol is safe, that implies that the algorithm of formal verification cannot find a way to break the conditions specified in any of the queries.
- Or "not safe" when **"a trace has been found"**. A trace is the sequence of events which leads to a security breach inside the protocol. That means that the software manages to build this sequence of events, and the protocol is necessarily not safe.
  In this kind of output, there is the detail of messages passing through the channel leading to the attack, and a link on each message to the corresponding operation of the protocol (there are not all the messages but with the protocol it is possible to find whose the message is from, who is the recipient, and why this message was sent and what will be the answer). So that is possible to reconstruct the attack with the sequence of event, the dialogue between the protagonist.
- Or **"cannot be proved"**. It is importance to note that, as we have said, formal verification is undecidable. That is why to resolve these issues ProVerif make approximations, and when something looks like an attack, the tool tries to find the trace leading to the actual attack. But sometimes it cannot find this trace, and that is a possible reason why the safety of the protocol "cannot be proved". Or sometimes, there is

nothing looking like an attack, but ProVerif is not able to demonstrate that the protocol is safe. That is the other possible reason for the "cannot be proved" output.

- **"TimeOut"** is not really an output of ProVerif, but it is possible that a protocol verification takes up to an infinite time to end as the problem is undecidable. For instance, big protocols like TLS can be running for weeks, but for "little protocols" (with very simple processes and a little number of rules used), if the material resources are continually increasing, it is possible thanks to heuristic rules to conjecture that the program will not stop. For our work purposes we took a time out of five minutes, considering that the original files took few milliseconds at most to be executed, we can say that if the execution did not end in five minutes, then it will never end. Although, of course, we cannot affirm this for certain. We firstly have made our tests with `TimeOut=30` seconds, because running on all our files spent between 4 and 6 hours (on a personal computer, with 8Go RAM, core i7-7th, SSD). Indeed, most of the files do not take more than 1 minute to be executed, and for this kind of protocols, if the execution takes more than five minutes it is possible to suppose, considering the complexity of the execution of the original protocol, that this execution is infinite. After running once, and having the first results, we saw that some files stopped after 2 minutes. So we made another test with TimeOut equals to `300` seconds.

IV. Our work

The main aim of your work consists in finding a way to take all the possibilities into account when verifying the security of a protocol.
As it is not sure that the multiplicity of possibilities will have any effect on the security checks of the protocol, the second phase of our work heavily depends on the results given by ProVerif. Indeed, we will have to check if the new outcomes given match the original one and if not, we will need to analyse them in order to better understand what exactly changed.

A. Overview

Let's explain the process that we followed in order to check all the possibilities for a given protocol.
In the rest of this document, a "file" is a file in '.pv' format, describing a protocol, written in ProVerif.

1) Goals: One goal which could be interesting would be, for a given protocol file, to generate all the combinations of bracketing for a tuple. So, all the combinations to "understand" the protocol will be checked.
For instance, sending `((a,b),c)` while the recipient is waiting for `(e,f)` could be a mean to send information not checked by a protagonist. This issue is not found if each n-tuple is considered as a unique structure for a given integer n.
To allow all the possibilities, for a tuple, it would be necessary to generate all the 2-tuples.
Example: *A file containing the following tuples :* (a_1, a_2, a_3, a_4) *and* (b_1, b_2, b_3) *should generate the following files :*

1) $(a_1,(a_2,(a_3,a_4)))$, $(b_1,(b_2,b_3))$
2) $(a_1,((a_2,a_3),a_4))$, $(b_1,(b_2,b_3))$
3) $((a_1,a_2),(a_3,a_4))$, $(b_1,(b_2,b_3))$
4) $((a_1,(a_2,a_3),a_4))$, $(b_1,(b_2,b_3))$
5) $(((a_1,a_2),a_3),a_4)$, $(b_1,(b_2,b_3))$
6) $(a_1,(a_2,(a_3,a_4)))$, $((b_1,b_2),b_3)$
7) $(a_1,((a_2,a_3),a_4))$, $((b_1,b_2),b_3)$
8) $((a_1,a_2),(a_3,a_4))$, $((b_1,b_2),b_3)$
9) $((a_1,(a_2,a_3),a_4))$, $((b_1,b_2),b_3)$
10) $(((a_1,a_2),a_3),a_4)$, $((b_1,b_2),b_3)$

How many tuples are there?
How many files should be generated?

2) Choices and Strategy:
a) About the Catalan number: The number of generated tuples for a n-tuple is given by the Catalan number.
For an integer n, the $n-th$ Catalan number is defined by :

$$n \in N, C_n = \frac{1}{n+1}\binom{2n}{n} = \frac{(2n)!}{(n+1)!\,n!} = \prod_{k=2}^{n} \frac{n+k}{k}$$

So, for a given n-tuple, the number of existing combinations is growing exponentially (if the factorial function is approximated like exponential, where the exponent is a polynomial function).

b) Tuples generated: Let's study a given n-tuple t.
$t = \{a_i\}_{i \in [\![0,n-1]\!]}$.
For $k \in [\![0, n-1]\!]$, let's call $left_k$ (respectively $right_k$) the set of all the existing combinations for $\{a_i\}_{i \in [\![0,k-1]\!]}$ (respectively $\{a_i\}_{i \in [\![k,n-1]\!]}$).
So, all the combinations for this cut are given by the product set $left_k \times right_k$.

So, for this tuple t, all the combinations (set called F_t) are given by :

$$\left\{ \bigcup_{k=1}^{n-1} left_k \times right_k \right\}$$

Now, $left_k$ and $right_k$ are in fact the same functions, which we can called $cut(E)$, where E is either the left side or the right side of t. So, the combinations are given by $cut(\{a_i\}_{i \in [\![0,k-1]\!]}) \times cut(\{a_i\}_{i \in ,n-1]\!]})$.

In fact, this function cut is a recursive-function, using this cutting with k from 0 to $n-1$.
The length of the tuple defines a base case.

$$cut(t) = \begin{cases} \emptyset & if\ card(t) = 0 \\ A = a_0 & if\ card(t) = 1 \\ (A) = (a_0, a_1) & if\ card(t) = 2 \\ (cut(left), cut(right)) & else \end{cases}$$

Once the combinations for a given tuple are found, we have to generate the new files for this given protocol specification.

c) Files generated: Which files (and how many) are we going to generate?

Choice about bracketing
With the explanation given so far it is that given a `out(a,b,c)` message, our algorithm generates an output similar to `out((a,b),c)`. Now, on the other part of the protocol there must be a line matching this output. This line corresponds to the receiving part of it. This line of code starts with the `let/in` key words. It is clear that those two lines must be generated using the same format. Indeed, there is no reason to bracket a message in one way and the same message later on in the program in another. In fact, as the person cannot know the content of the message, we can suppose that for one given format, the generation for all the tuples of this format will be generated in the same way. But actually, this is more consistent because not only there is no reason for a person to decide to proceed with another choice of bracketing but the algorithm is implemented for all the protagonists. That is why for a given format the generation is deterministic and cannot propose several possibilities. Moreover the matching process of ProVerif will simply not work if the output format does not match the receiving format. Thus it is completely mandatory to generate those lines using the exact same format.

Besides, it is possible for a person to send `out(a,b,c)` like `out((a,b),c)`. But in another exchange send a longer or shorter message with a different format. For instance the protagonists can decide to send something like `(d,((e,f),g))` for this original tuple : `(d,e,f,g)`.

Number of files
That is why we made the choice to regroup the tuples by size and to bracket all group of tuple in the same way. For instance, all the 3-tuples could be generated like `(a,(b,c))` and all the 4-tuples like `((d,e),(f,g))`.
The number of combinations for a kind of tuple (identified by its size) is given by the Catalan number. So, to check all the possibilities, if F_n is the set of the combinations for the n-tuples (so $card(F_n) = C_n$), if n_i is the set of the existing tuples sizes, the combinations of format is given by the product set $F = F_0 \times (F_1 \times (F_2 ...))$.
So the number of files is :

$$N_f = card(F) = \prod_i card(F_i) = \prod_i C_i$$

In the rest of the document, $N_f = card(F)$ is the number of files generated for a given file.

B. Implementation

1) Vocabulary:

- Let's pay a more detailed attention to the definition of what really is a **tuple** inside the description of a protocol. Of course, we are only studying here the tuples which are exchanged between two protagonists (for instance `(session_id, size, (message, host_B), host_A)` is a real tuple because it defines information which is sent to anther person). However, `sign(message, private_key_A)` or `out(host_A,message)` are functions and not "packages of information" and that is why we don't have to take this kind of tuples into consideration. So let's only call "tuple" the "information-tuple".
- A **combination** is a possible combination for all the tuples of a given size. For instance, `(a,(b,c),d)` is a combination for all the 4-tuples.
- **Combinations** are a "combination of combinations", that is a "set of combination/format for a given size".
  For instance, "*Let's bracket all the* 3*-tuples like* `(a,(b,c))` *and all the* 4*-tuples like* `((a,b),(c,d))`" is a possible combination for a file which would contain (and only contain) 3-tuples and 4-tuples (and possibly 2-tuples and/or 1-tuples because in our definition of the function cut, the number of possibilities for such tuples is 1). It is important to notice that the number of all the possible combinations for a given file is N_f (The 0-tuples will not be taken into consideration).

2) Tools: We have used several tools and programming languages to process.

- First of all, **ProVerif** is the software designed to check the safety of a given protocol. It has its own language.
- **Antlr** is the software used to write the grammar and then to generate the parser/lexer [6].
- We used **Java** to set up Antlr and implement a "Visitor", actions done on each syntactic rules after the parsing of a file. We used this language to handle the combinations and create all the files.
- We used **C** programming language (and **gcc** compiler) to execute ProVerif on each file and to compare the result with the one of the original file.

3) Description of the algorithm: Now, let's suppose that we have the program parsing a given file in the ProVerif language.
Strategy: We have, for a given file, to generate all the combinations and for each combination, generate a new file. In order to know the combinations, we need to know all the tuples which exist in this file, then generate , for each tuple, its possible bracketing, which allows us to generate all the "combinations of bracketing" grouped by size. Finally, for each of these combinations we can generate the right file.

Parsing: Before creating the files, we need to parse the original file. While parsing it, we keep in memory each tuple that we come across.
Firstly we wanted to insert in the grammar the operations to execute, like keep in memory the tuple once the rule is matched, but the parser creation tool we used (Antlr) did not allow this kind of operations. So we have implemented a "visitor" which execute for each rule some operations. Once the corresponding rules of the grammar are matched, a structure of `Tuple` is created.
Remark : At first, we thought that the problem of tuple matching would be easy to implement and we thought about managing those operations by creating a simple parser that would parse the files character by character and match the tuples. But, obviously, this was not as simple as that, as for instance, function calls and function definitions are also matching the format of a tuple and so it was mandatory for us to use a syntactic parser such as Antlr, in Java.

Coming back to the creation of a tuple, in this structure `Tuple tuple` we generate all the existing combinations for this tuple as a field of the structure. The combinations for a given tuple are generated as we have explained in the formal definition (for each possible cut of the n-tuple in left-member and right-member, we do the product set of the possibilities for the two members).

Now, we have stored in a structure `Tuples tuples` all the `tuple` (which have in its fields its size and its combinations). Thanks to the formula written above, we can compute the number of files to generate.

Creating a file: As we have said, all the tuples of a given size will be bracketed in the same way. So, we have to list all the sizes of tuples existing in the file, and then generate each combinations, *i.e.* for each combination for a given size, generate all the combinations for the other sizes.
Example: *If there are (only) 2-tuples 3-tuples and 4-tuples in a given file, the combinations are (i, j, k) format, where i is the i-th bracketing for the 2-tuples, j the j-th bracketing for the 3-tuples, k the k-th bracketing for the 4-tuples. So the combinations are $(0, 0, 0)$, $(0, 0, 1)$, $(0, 0, 2)$, $(0, 0, 3)$, $(0, 0, 4)$, $(0, 1, 0)$, $(0, 1, 1)$, $(0, 1, 2)$, $(0, 1, 3)$, $(0, 1, 4)$.*

Then, with the number of the file, we can have the right combinations (in the example above $(0, 1, 2)$ for instance).
We then have to write, for each file, its new version with the matching combinations. In order to do that, we copy the original file and, when the parser comes across a tuple, it is replaced by the corresponding combination. In fact, knowing the number of file that are being written (that is the combinations number) we can have the number of each combination (In the example above, we know that the file's 7-th file, number 6, will be generated using the combinations $(0, 1, 1)$.). Finally, we write the k-th combination of the tuple instead of the original text.

How to find the number of combinations with only the number of the file being created ? To find the right combination for each tuple knowing only the file number `i`, we use counter-like structure, where the base is different for each digit. Each digit represents a size, and contains the k-th combination for all the tuples of this size. Indeed, here, each cell is a number, *a priori* on a different base. However, only `i`, the number of the file, is known. The maximum of the cell is the number of possible bracketing for the tuples of the size corresponding to this range. For instance, if the 3-rd cell of our structure corresponds to the tuples of size 4, the number in this cell could be between 0 and 5. And so we have to find the combination (set of) combinations/bracketting corresponding.
Example : *To illustrate this issue, it is possible to draw a parallel with a time-counter. Let's consider 19200s, and we have to find from this number (which corresponds to the number of the file in our case) the amount of days, hours, minutes, and seconds. There are 60 seconds in a minute, 60 minutes in an hour, but 24 hour in a day. How would you do to find these numbers from the original number only?*
Implementation : So there are two ways to proceed.
Either by several euclidean divisions and using the integer part and the rest, recursively, the base changing (which is the divisor) to each function call (which the value is the number of possible combinations for a tuple of the current size).
Or, the other way, *a priori* easier to implement, is to increment the counter for each loop step.

Writing: Now, for each step of the loop on the number of files, we know for each size which bracketing we have to choose. We have implemented a structure that contains the lines where there is a tuple (and containing this tuple). During the creation of a tuple, the line is noticed to this structure. So that when writing the file, we can copy all the lines and when a line should be modified, we replace the tuple by its current combination given by the number of the file being created.

Details: For further details about the practical implementation, please refer to the Annex B, where implementation choices, details of the strategy, and possible optimisations are detailed.

Running ProVerif: Now, we have all the possibilities of tuple-bracketing. We have automated the execution of ProVerif on these files and the comparison with the output of the original file.
We did that in C language. The single parameter is a directory. All the sub-directories will be parsed, and a sub-directory containing files should be a protocol, where the original is the number 0 and the other files are other possibilities. That is the output of our program written in Java which creates all the files. Now, for each protocol, ProVerif is ran on the original file, and then for each generated file, the output is compared with that of the original, and a summary of the results is given in a `txt` file in this directory.

V. Results

A. An interesting result on the Yahalom protocol

Now let us study all the files marked as "different", *i.e.* the output of the file is not the same as the one of the original file. As we have said, the output is one of the four possible result which is not necessarily a ProVerif output (like TimeOut).

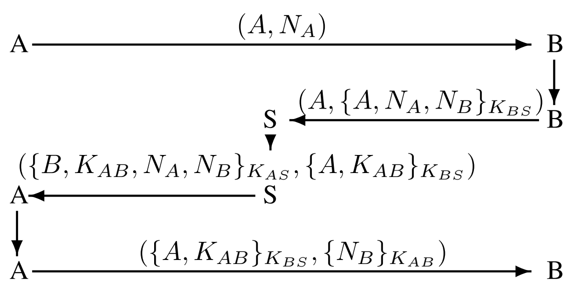
B. Yahalom Protocol

The original file (SimplerYahalom-unid.pv, available in Annex A) is marked as "safe", but traces are found in the 2^{nd} file generated (SimplerYahalom-unid_2.pv, also available in Annex A).
Let's describe the original protocol and then its attack on the bracketing.

1) Description of the protocol:

- Here is the description of the Yahalom Protocol (Fig. 8).
- S is here a trusted sever, "arbitror".
- N_X is a nonce generated by X.
- K_{XY} is a symmetric key shared between and (only known by) X and Y.
- Here, K_{AB} is generated by S. It will be the session key between A and B.

Fig. 8. Description of the Yahalom Protocol



2) Attack: One of the file created ("SimplerYahalom-unid_2.pv" in the Annex A) is shown as having an attack. Let's study the trace.
First, we have these messages (Fig. 9). With the help of the protocol, we have to find whose message it is.

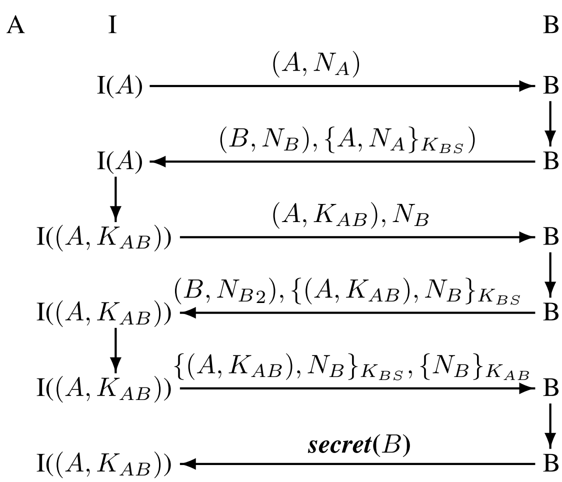
Now, we can suppose that the conversations are as described below (Fig. 10).

In the first part of the conversation ((1) and (2)), I is impersonating A. Then, I is impersonating a fictive protagonist (A, K_{AB}) (messages (3), (4), (5) and (6)). So, at the end of the conversation, I knows information that B sends to I, that I knows thanks to K_{AB}.
You can note that here the host A does not intervene in the process, which is quite amazing.

Fig. 9. Messages of attack of the Yahalom Protocol (Trace)

in	(A, N_A)	(1)
out	$((B, N_B), \{A, N_A\}_{K_{BS}})$	(2)
in	$((A, K_{AB}), N_B)$	(3)
out	$((B, N_{B2}), \{(A, K_{AB}), N_B\}_{K_{BS}})$	(4)
in	$(\{(A, K_{AB}), N_B\}_{K_{BS}}, \{N_B\}_{K_{AB}})$	(5)
out	***secret*(B)**	(6)

Fig. 10. Description of attack of the Yahalom Protocol



Nota Bene: *After the analyse of the file (for instance with the online tool available here), there are several traces. However, the other traces are similar to the one presented above.*

C. Listing of all the results

(Faire le tableau complet des resultats sur tous les fichiers/dossier)

Throughout the execution of our scripts on the multiple examples that we were given, most of them ended up giving no result at all, the complete list of the protocol tested is available in the annex of this document. It is worth noticing that are included inside the files that we tested few variations of the original protocols. As explained earlier, it is possible for a protocol to be tested on multiple security properties, and sometimes it is needed to build a slightly different version of the protocol to test them. Moreover, we might also want to try and check if few modification such as the correction of a previous attack or a different kind of encryption would make any difference in the output given by ProVerif.

(Tableau des protocoles tests)
(Ajouter une reference bibliographique pour chaque protocole test)

Protocol
Denning-Sacco
Diffie-Hellman
Needham-Schroeder
Otway-Rees
Woo-Lam
Yahalom
ssh-transport
basic
dh-fs
epassportUK
handshake
macs
private_authentication
proba-pk
vote
wmf

Now, on some protocols the results given by ProVerif were different from the original from and some bracketing combination based on this original form. For some, it is due to a time out of ProVerif : as explained before, the execution was too long for us to keep going and is a sign of a problem on the ProVerif end. For some others the result is different, whether they are safe, or not, and even not proven for some.
(Tableau des protocols differents (time out, safe, not safe, not proven))

Protocol		Resul	
		Not proven	Timed
Needham-Schroeder	Needham-SchroederPK-corr	0	2
	Needham-SchroederSK-comp	0	4
	Needham-SchroederSK-corr	0	10
	Needham-SchroederSK-corr-comp	0	10
	Needham-SchroederSK-corr-compapprox	0	10

Name of the protocol			*Original Output*
Needam-Schroeder		*	-
Yahalom	SimplerYahalom-unid	*	-
		SimplerYahalom-unid_2.p	Safe
	Yahalom	*	-
		Yahalom_4.pv_5.pv	?
OtwayRees	OtwayRees	Most of the files	?
		*	-
	OtwayRees-key	Most of the files	?
		*	-
	OtwayRees-prob	Most of the files	?
		*	-

References

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[5] Durgin Lincoln Mitchell, N. A. Durgin, P. D. Lincoln, J. C. Mitchell, and A. Scedrov. Undecidability of bounded security protocols. 1999.

[6] Terence Parr. *The Definitive ANTLR Reference, Building Domain-Specific Languages*. Pragmatic Bookshelf, 2nd edition, 2013. https://doc.lagout.org/programmation/Pragmatic%20Programmers/The%20Definitive%20ANTLR%20Reference.pdf.

VI. Annexes

A. Annex A : SimplerYahalom-unid pv files

Here above are two files describing by the same way the Yahalom protocol.

The file marked as _0 is the original file (without changes). The file marked as _2 is one of the generated file where there is the attack we have talked about. We can notice that indeed the tuples are bracketted as described. Here (in the _2 file), the 2-tuples are obviously bracketted like $(a_1, a_2$, the 3-tuples are bracketted like $((a_1, a_2), a_3)$.

Maybe that is clearer to see the differences above between these files in Fig. 11.

files/SimplerYahalom–unid_0.pv

```
free c: channel.

type key.
type host.
type nonce.

fun nonce_to_bitstring(nonce): bitstring
    [data,typeConverter].

(* Shared key encryption *)

fun encrypt(bitstring,key): bitstring.
reduc forall x: bitstring, y: key;
    decrypt(encrypt(x,y),y) = x.

(* Secrecy assumptions *)

not attacker(new Kas).
not attacker(new Kbs).

(* 2 honest host names A and B *)

free A, B: host.

(* the table host names/keys
   The key table consists of pairs
   (host, key shared between the host and
        the server) *)
table keys(host, key).

(* Queries *)

free secretA, secretB: bitstring [private
    ].
query attacker(secretA);
      attacker(secretB).

event endAparam(host, host).
event endBparam(host, host).
event beginAparam(host, host).
event beginBparam(host, host).
event endBkey(host, host, nonce, key).
event beginBkey(host, host, nonce, key).

query x: host, y: host; inj-event(
    endAparam(x, y)) ==> inj-event(
    beginAparam(x, y)).
query x: host, y: host; inj-event(
    endBparam(x, y)) ==> inj-event(
    beginBparam(x, y)).
query x: host, y: host, z: nonce, t: key;
     inj-event(endBkey(x,y,z,t)) ==> inj-
    event(beginBkey(x,y,z,t)).

(* Role of the initiator with identity xA
     and key kas shared with S *)

let processInitiator(xA: host, kas: key)
    =
  new Na: nonce;
  out(c, (xA, Na));
  in(c, (nb: nonce, m1: bitstring, m2:
      bitstring));
        let (b: host, kab: key, na2:
            nonce) = decrypt(m1, kas) in
  event beginBparam(b, xA);
  event beginBkey(b, xA, nb, kab);
        if na2 = Na then
        out(c, (m2, encrypt(
            nonce_to_bitstring(nb), kab)))
            ;
  (* OK protocol finished
     If the interlocutor is honest,
        execute the events endAparam
           and send a test message to
              check that the key kab is
              secret *)
  if b = A || b = B then
  event endAparam(xA, b);
  out(c, encrypt(secretA, kab)).

(* Role of the responder with identity xB
     and key kbs shared with S *)

let processResponder(xB: host, kbs: key)
    =
  in(c, (a: host, na: nonce));
  event beginAparam(a, xB);
        new Nb: nonce;
  out(c, (xB, Nb, encrypt((a, na), kbs)))
      ;
  in(c, (m3: bitstring, m4: bitstring));
        let (=a, kab: key, =Nb) = decrypt
            (m3, kbs) in
        if nonce_to_bitstring(Nb) =
```

```
           decrypt(m4, kab) then
  (* OK protocol finished
           If the interlocutor is honest,
               execute the events
               endBparam
           and endBkey, and send a test
               message to check that the
               key kab
     is secret *)
  if a = A || a = B then
  event endBparam(xB, a);
  event endBkey(xB, a, Nb, kab);
  out(c, encrypt(secretB , kab)).

(* Server *)

let processS =
  in(c, (b: host, nb: nonce, m5:
      bitstring));
  get keys(=b, kbs2) in (* get the key of
       b from the key table *)
         let (a: host, na: nonce) =
            decrypt(m5,kbs2) in
  get keys(=a, kas2) in (* get the key of
       a from the key table *)
         new kab: key;
  out(c, (nb, encrypt((b, kab, na), kas2)
      , encrypt((a, kab, nb), kbs2))).

(* Key registration *)

let processK =
        in(c, (h: host, k: key));
        if h <> A && h <> B then insert
            keys(h,k).

(* Start process *)

process
  new Kas: key; new Kbs: key;
  insert keys(A, Kas);
  insert keys(B, Kbs);
  (
          (* Launch an unbounded number
             of sessions of the initiator
              *)
          (!processInitiator(A, Kas)) |
          (* Launch an unbounded number
             of sessions of the responder
              *)
          (!processResponder(B, Kbs)) |
          (* Launch an unbounded number
             of sessions of the server *)
          (!processS) |
          (* Key registration process *)
     (!processK)
          )
```

Here is one of the file generated.

files/SimplerYahalom–unid_2.pv

```
free c: channel.

type key.
type host.
type nonce.

fun nonce_to_bitstring(nonce): bitstring
    [data,typeConverter].

(* Shared key encryption *)

fun encrypt(bitstring,key): bitstring.
reduc forall x: bitstring, y: key;
    decrypt(encrypt(x,y),y) = x.

(* Secrecy assumptions *)

not attacker(new Kas).
not attacker(new Kbs).

(* 2 honest host names A and B *)

free A, B: host.

(* the table host names/keys
   The key table consists of pairs
   (host, key shared between the host and
       the server) *)
table keys(host, key).

(* Queries *)

free secretA, secretB: bitstring [private
    ].
query attacker(secretA);
      attacker(secretB).

event endAparam(host, host).
event endBparam(host, host).
event beginAparam(host, host).
event beginBparam(host, host).
event endBkey(host, host, nonce, key).
event beginBkey(host, host, nonce, key).

query x: host, y: host; inj-event(
    endAparam(x, y)) ==> inj-event(
    beginAparam(x, y)).
query x: host, y: host; inj-event(
    endBparam(x, y)) ==> inj-event(
    beginBparam(x, y)).
```

```
query x: host, y: host, z: nonce, t: key;
     inj-event(endBkey(x,y,z,t)) ==> inj-
    event(beginBkey(x,y,z,t)).

(* Role of the initiator with identity xA
     and key kas shared with S *)

let processInitiator(xA: host, kas: key)
    =
  new Na: nonce;
  out(c, (xA, Na));
  in(c, ((nb: nonce, m1: bitstring), m2:
      bitstring));
        let ((b: host, kab: key), na2:
            nonce) = decrypt(m1, kas) in
  event beginBparam(b, xA);
  event beginBkey(b, xA, nb, kab);
        if na2 = Na then
        out(c, (m2, encrypt(
            nonce_to_bitstring(nb), kab)))
            ;
  (* OK protocol finished
     If the interlocutor is honest,
         execute the events endAparam
            and send a test message to
                check that the key kab is
                secret *)
  if b = A || b = B then
  event endAparam(xA, b);
  out(c, encrypt(secretA, kab)).

(* Role of the responder with identity xB
     and key kbs shared with S *)

let processResponder(xB: host, kbs: key)
    =
  in(c, (a: host, na: nonce));
  event beginAparam(a, xB);
        new Nb: nonce;
  out(c, ((xB, Nb), (encrypt((a, na), kbs
      ))));
  in(c, (m3: bitstring, m4: bitstring));
        let ((=a, kab: key), =Nb) =
            decrypt(m3, kbs) in
        if nonce_to_bitstring(Nb) =
            decrypt(m4, kab) then
  (* OK protocol finished
            If the interlocutor is honest,
                 execute the events
                endBparam
            and endBkey, and send a test
                message to check that the
                key kab
     is secret *)
  if a = A || a = B then
  event endBparam(xB, a);
  event endBkey(xB, a, Nb, kab);
  out(c, encrypt(secretB, kab)).

(* Server *)

let processS =
  in(c, ((b: host, nb: nonce), m5:
      bitstring));
  get keys(=b, kbs2) in (* get the key of
       b from the key table *)
         let (a: host, na: nonce) =
             decrypt(m5,kbs2) in
  get keys(=a, kas2) in (* get the key of
       a from the key table *)
        new kab: key;
  out(c, ((nb, encrypt(((b, kab), na),
      kas2)), (encrypt(((a, kab), nb),
      kbs2)))).

(* Key registration *)

let processK =
         in(c, (h: host, k: key));
         if h <> A && h <> B then insert
             keys(h,k).

(* Start process *)

process
  new Kas: key; new Kbs: key;
  insert keys(A, Kas);
  insert keys(B, Kbs);
  (
          (* Launch an unbounded number
              of sessions of the initiator
               *)
          (!processInitiator(A, Kas)) |
          (* Launch an unbounded number
              of sessions of the responder
               *)
          (!processResponder(B, Kbs)) |
          (* Launch an unbounded number
              of sessions of the server *)
          (!processS) |
          (* Key registration process *)
    (!processK)
         )
```

Fig. 11. Differences between the two following files

```
 ------------------------- : ---------------------------------------------------------------------------------------------------------------------------------
$ ls
SimplerYahalom-unid_0.pv  SimplerYahalom-unid_1.pv  SimplerYahalom-unid_2.pv
 ------------------------- : ---------------------------------------------------------------------------------------------------------------------------------
$ diff SimplerYahalom-unid_0.pv SimplerYahalom-unid_2.pv
94,95c94,95
<       in(c, (nb: nonce, m1: bitstring, m2: bitstring));
<         let (b: host, kab: key, na2: nonce) = decrypt(m1, kas) in
---
>       in(c, ((nb: nonce, m1: bitstring), m2: bitstring));
>         let ((b: host, kab: key), na2: nonce) = decrypt(m1, kas) in
113c113
<       out(c, (xB, Nb, encrypt((a, na), kbs)));
---
>       out(c, ((xB, Nb), (encrypt((a, na), kbs))));
115c115
<         let (=a, kab: key, =Nb) = decrypt(m3, kbs) in
---
>         let ((=a, kab: key), =Nb) = decrypt(m3, kbs) in
129c129
<       in(c, (b: host, nb: nonce, m5: bitstring));
---
>       in(c, ((b: host, nb: nonce), m5: bitstring));
134c134
<       out(c, (nb, encrypt((b, kab, na), kas2), encrypt((a, kab, nb), kbs2))).
---
>       out(c, ((nb, encrypt(((b, kab), na), kas2)), (encrypt(((a, kab), nb), kbs2)))).
 ------------------------- : ---------------------------------------------------------------------------------------------------------------------------------
$
```

B. Annex B : Practical implementation

Implementation of the parsing: Let's detail how we proceed in order to implement the parsing of an original file and the creation of the files which should be generated.
As we have said, we implement this part in `Java` ; so the following commands and the specific vocabulary are relative to the `Java` language.

Aim of the classes: Let's present the classes we have created.

- A **`Tuple`** is an `ArrayList` in which the elements are the elements of the Tuple. Built with its context, it contains its original form and will contain all its combinations.
- **`Tuples`** is an `ArrayList`, global list of the tuples present in a given file. For a given file (original file, not a generated file), there is only one instance of this class.
- **`Combinations`** is a final class, is built once the file is parsed and contains the list of the tuples. It is not designed to be changed once built. It generates all the combinations for each tuple, and then indicates how many files will need to be generated.
- **`CombinationsHandler`** knows the instance (because unique) of combinations. It aims to handle the creation of each child-file.

Sequence of events:

- Parsing of the original file
  - If a `Tuple tuple` is checked :
    - An object `Tuple tuple` containing this one is created
      - All combinations are generated as an attribute-field of this object.

        Implementation : The new file is not generated here because Antlr does not handle perfectly the insertion. And would not allow us to have a good amount of control over the creation of the files.

    - `tuple` is added to the list `Tuples tuples`, the list of all the tuples of the given file.
    - The modification of a line is indicated in a `HashMap`, it notifies for each line which tuple is linked to it. As there may be several tuples for a given line, the key of the `HashMap` is the line number, but the value is an `ArrayList` of Tuple. So the `HashMap` is defined like this : `HashMap<int,ArrayList<Tuple>>`.

      Implementation : Indeed, when the file is being created, it allows usto go directly to the lines which should be modified. Thus it prevents us from doing more replace operations than there are tuples in the file.
      What's more, there may be several tuples in a line and a `HashMap` helps to optimise this management.

- The number of file which need to be created is calculated.

  Implementation : `sizes` is the list of sizes of tuples present in the original file.

  Example : *`sizes=3,6,7` means that the file contains and contains only tuples of size 3, 6, and 7.*

- Let us loop through this number of files.
  For a file number `i` :
  - The file number `i` is created.
  - The right set of combinations. To find the right combination for each tuple knowing only the file number `i`, we use counter-like structure, where the base is different for each digit. Each digit represents a size, and contains the k-th combination pour all the tuples of this size. It is also noteworthy that is consistent with the formula (i) which corresponds to the maximum of the counter.

    Implementation : `indexOfCombinations` provides information for each size of which combination (combination number) must be used. Thus the size of `indexOfCombinations` is `sizes.size()`. Furthermore, `therefore.get(k)` provides information about the combination of tuples of k-element, corresponding to a size equals to `sizes.get(k)`.
    In practice, we need to move up the information string the other way around. From a tuple, we would like to know its combination. So we have to know its index in `indexOfCombinations`, which we can obtain, for a given tuple, by looking into `sizes.indexOf(tuple.size())`.
    Finally, it is also worthy of note that for a tuple of size k, its cell in `indexOfCombinations` ranges from 0 to the number of possible combinations for a tuple of size k.

    Example : *Continuing the previous example, if `indexOfCombinations=1,3,0`, all tuples of size 3 will be bracketted depending on the 2nd bracketting (number 1), those of size 6 with the 4th, and those of size 7 with the 1st.*

    - Each tuple is parsed and its combinations for the file number i is stocked.
  - The file number i is written by reading the original file line by line.
    - If the line number i must undergo a change :
      - For each tuple linked to the line, this one is replaced by the combination corresponding to the file number i.

        · The new line is printed.
    * Else, the line read is printed in the new file
  - The numbers of combination are updated for each category of tuple (distributed by size).

    Implementation : All combinations of number of combination for each category of tuple must be parsed. As we have said above in the section "Our Work" of the report, we use the counter-like structure. The counter is incremented for each loop step.

Design choices: In addition to the explanations above, maybe the reasons about a few choices should be detailed :

- **Why do we not create the file at the same time we analyse the original file?** There are several reasons why we create the files after the parsing of the original file. Some of these reasons are explained above (need to know the number of files, management of the operations by Antlr analysing a file, ...). But the creation of the data structures, the knowledge of the other objects, the management of the Java imports, are some reasons why we do not replace the tuples 'on the fly'.
- **What about the complexity / optimisation?** Maybe some functions could be a little bit more optimised (for instance, the replacement of several tuples in one line, currently there is one 'replace' by tuple), but this kind of optimisation is not something that will drastically change the complexity of the program that we have today.

- **Are all files able to be parsed?** Currently, our version of the ProVerif grammar contains the main rules (all rules needed to parse the files of the folder "secr-auth", "weak-secr", "choice", "non-interf" from the folder 'examples' in the software ProVerif). The remaining rules will be added, in order to parse all the files.