From CryptoVerif Specifications to Computationally Secure Implementations of Protocols

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Protocol verification

	Symbolic	Computational
Specifications	FDR, AVISPA, ProVerif, . . .	CryptoVerif, CertiCrypt, . . .
Implementations	FS2PV, F7, Spi2Java, Andy's talk, . . .	FS2CV, Computational F7, Andy's talk, , . . .

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Implementations	FS2PV, F7, Spi2Java, Andy's talk, . . .	FS2CV, Computational F7, Andy's talk, our work, . . .

Our approach

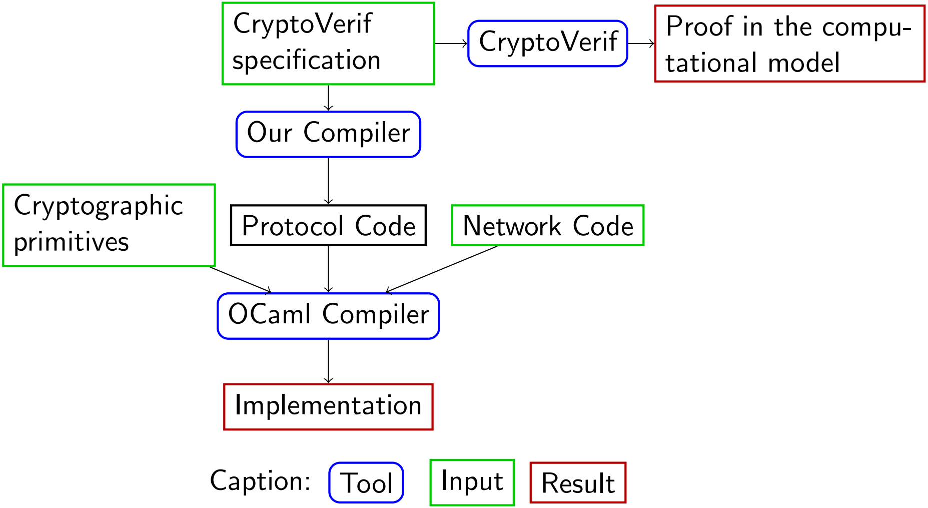
Generate protocol implementations from specifications.

- Specification proved secure in the computational model by CryptoVerif.
- Specification translated into an OCaml implementation by our compiler.

Goal: proved implementations of cryptographic protocols.

Remark: FS2CV does the translation in the other direction!

Overview of our approach



Choice of the target language

- Why OCaml?
  - Memory safe. Easier to show that the network code does not access the protocol memory.
  - Clean semantics.
  - Crypto library available.
- Writing a compiler into another language would not be difficult.

  Proving the security of the generated protocol may be more difficult.

CryptoVerif

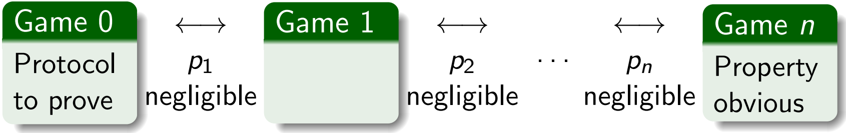
CryptoVerif is an automatic prover:

- in the computational model.
- proves secrecy and correspondence (authentication) properties.
- provides a generic method for specifying properties of cryptographic primitives.
- works for *N* sessions (polynomial in the security parameter), with an active adversary.
- gives a bound on the probability of an attack (exact security).
- possibility to guide the prover (manual mode).

Proofs by sequences of games

CryptoVerif produces proofs by sequences of games, like those of cryptographers [Shoup, Bellare&Rogaway]:

- The first game is the real protocol.
- One goes from one game to the next by syntactic transformations or by applying the definition of security of a cryptographic primitive. The difference of probability between consecutive games is negligible.
- The last game is "ideal": the security property is obvious from the form of the game.
  (The advantage of the adversary is 0 for this game.)



Game 0

Protocol to prove

$\longleftrightarrow$ p_1 negligible

Game 1

$\longleftrightarrow$ p_2 negligible

$\cdots$

$\longleftrightarrow$ p_n negligible

Game n

Property obvious

The CryptoVerif specification language: terms

CryptoVerif represents protocols and games in a process calculus.

$M, N ::=$	terms
x	variable
$f(M_1, \ldots, M_m)$	function application

Function symbols f correspond to functions computable by polynomial-time deterministic Turing machines.

The CryptoVerif specification language: processes

$Q ::=$	oracle definitions
0	nil
$Q \mid Q'$	parallel composition
$\text{foreach } i \leq n \text{ do } Q$	replication n times
$O[\widetilde{i}](x_1 : T_1, \dots, x_k : T_k) := P$	oracle definition
$P ::=$	oracle body
$\text{return}(M_1, \dots, M_k); Q$	return
end	end
$x \overset{R}{\leftarrow} T; P$	random number
$x : T \leftarrow M; P$	assignment
$\text{if } M \text{ then } P \text{ else } P'$	conditional
$\text{insert } Tbl(M_1, \dots, M_k); P$	insert in table
$\text{get } Tbl(x_1 : T_1, \dots, x_k : T_k) \text{ suchthat } M \text{ in } P \text{ else } P'$	get from table

Example

$$\mathsf{A} \longrightarrow \mathsf{B} : \mathrm{enc}(r, Kab)$$

$$\begin{aligned}&\textsf{process}\ Ostart() := rKab \overset{R}{\leftarrow} keyseed; Kab \leftarrow \mathrm{kgen}(rKab); \textsf{return}();\\ &\qquad (\textsf{foreach}\ i1 \leq N\ \textsf{do}\ processA \mid\\ &\qquad\ \ \textsf{foreach}\ i2 \leq N\ \textsf{do}\ processB)\end{aligned}$$

- The oracle *Ostart* generates Kab.
- This symmetric key will not be known by the opponent.
- Only after *Ostart* has been called, we can call at most N times *processA* and at most N times *processB*.

Example

$$\mathrm{A} \longrightarrow \mathrm{B} : \mathrm{enc}(r, Kab)$$

$$\text{let } processA = OA() := r \overset{R}{\leftarrow} nonce; s \overset{R}{\leftarrow} seed;$$
$$\text{return}(\mathrm{enc}(\mathrm{nonceToBitstring}(r), Kab, s)).$$

$$\text{let } processB = OB(m : bitstring) :=$$
$$\text{let } \mathrm{injbot}(\mathrm{nonceToBitstring}(r' : nonce)) = \mathrm{dec}(m, Kab) \text{ in}$$
$$\text{return}().$$

- *OA* sends the encryption of r under *Kab* (probabilistic encryption)
- *OB* decrypts the received message

Example — summary

$$\text{let } \mathit{processA} = \mathit{OA}() := r \overset{R}{\leftarrow} \mathit{nonce}; s \overset{R}{\leftarrow} \mathit{seed};$$
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$$\text{let } \mathit{processB} = \mathit{OB}(m : \mathit{bitstring}) :=$$
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$$\text{process } \mathit{Ostart}() := \mathit{rKab} \overset{R}{\leftarrow} \mathit{keyseed}; \mathit{Kab} \leftarrow \text{kgen}(\mathit{rKab}); \text{return}();$$
$$(\text{foreach } i1 \leq N \text{ do } \mathit{processA} \mid$$
$$\text{foreach } i2 \leq N \text{ do } \mathit{processB})$$

Annotations: Separation in multiple programs

$$\begin{array}{l} \text{let } \mathit{processA} = \mathit{pA}\{\mathit{OA}() := r \xleftarrow{R} \mathit{nonce}; s \xleftarrow{R} \mathit{seed}; \\ \qquad \text{return}(\text{enc}(\text{nonceToBitstring}(r), \mathit{Kab}, s))\}. \end{array}$$

$$\begin{array}{l} \text{let } \mathit{processB} = \mathit{pB}\{\mathit{OB}(m : \mathit{bitstring}) := \\ \qquad \text{let } \text{injbot}(\text{nonceToBitstring}(r' : \mathit{nonce})) = \text{dec}(m, \mathit{Kab}) \text{ in} \\ \qquad \text{return}()\}. \end{array}$$

$$\begin{array}{l} \text{process } \mathit{keygen}\ [\mathit{Kab} > \mathit{fileKab}]\ \{\mathit{Ostart}() := \\ \qquad \mathit{rKab} \xleftarrow{R} \mathit{keyseed}; \mathit{Kab} : \mathit{key} \leftarrow \text{kgen}(\mathit{rKab}); \text{return}()\}; \\ \quad (\text{foreach } i1 \leq N \text{ do } \mathit{processA} \mid \\ \quad\ \text{foreach } i2 \leq N \text{ do } \mathit{processB}) \end{array}$$

Annotations: External data files

$$\begin{aligned}
&\mathsf{let}\ \mathit{processA} = \mathit{pA}\{\mathit{OA}() := r \overset{R}{\leftarrow} \mathit{nonce};\ s \overset{R}{\leftarrow} \mathit{seed};\\
&\qquad \mathsf{return}(\mathsf{enc}(\mathsf{nonceToBitstring}(r), \mathit{Kab}, s))\}.
\end{aligned}$$

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\end{aligned}$$

Annotations: types and functions

- OCaml type representing a CryptoVerif type:
  implementation type *keyseed* = 128. (bitstring of 128 bits)
  implementation type *host* = "*string*" [serial = "*id*","*id*"].
- OCaml function representing a function in the protocol specification :
  implementation fun kgen = "*sym_kgen*".
  implementation fun injbot = "*injbot*" [inverse = "*injbot_inv*"].
  - In the CryptoVerif specification, there are assumptions about these functions.
    - Functional assumptions: $\mathrm{dec}(\mathrm{enc}(m, k, s), k) = \mathrm{injbot}(m)$.
    - Security assumptions: encryption is IND-CPA and INT-CTXT.
  - These assumptions must be manually verified.

Annotations: tables

- get/insert handle tables of keys:
  - insert $keytbl(h, k)$
    inserts element h, k in the table $keytbl$.
  - get $keytbl(h', k')$ suchthat $h' = h$ in P else P'
    stores in h', k' an element of table $keytbl$ such that $h' = h$,
    i.e., stores in k' the key of h, and runs P.
    Runs P' when no such element exists.
- Tables are stored in files:
  implementation table $keytbl = "filekeytbl"$.

Treatment of tables in CryptoVerif

For proving the protocol, CryptoVerif encodes tables as arrays:

- The variables are considered as arrays with one cell for each copy of the definition.
  - Useful for remembering all values taken by the variable.
- foreach $i \leq n$ do $\ldots$ insert $keytbl(h, k)$

  becomes

  foreach $i \leq n$ do $\ldots keytbl_1[i] \leftarrow h; keytbl_2[i] \leftarrow k$
- get $keytbl(h', k')$ suchthat $h' = h$ in P else P'

  becomes

  find $u \leq n$ suchthat defined$(keytbl_1[u], keytbl_2[u]) \wedge keytbl_1[u] = h$
  then $h' \leftarrow keytbl_1[u]; k' \leftarrow keytbl_2[u]; P$ else P'

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- Generalized to several insertions by looking up in the variables defined at each insertion.

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Avoiding arrays is more intuitive and simplifies the compilation.

Compilation to OCaml

For each program, the compiler generates an OCaml module where it defines a function for each oracle.

- A function $\texttt{init} : \texttt{unit} \to \tau$ returns the tuple of functions representing the oracles available at the beginning of the program.
  - `init` may also read variables from files when needed.
- Each oracle O is represented by a function that
  - takes as argument the arguments of O
  - and returns
    - the tuple of functions representing oracles that follow O,
    - the result of O.

Compilation to OCaml: example

$$\text{let } processA = pA\{OA() := r \xleftarrow{R} nonce; s \xleftarrow{R} seed; \\ \text{return}(\text{enc}(\text{nonceToBitstring}(r), Kab, s))\}.$$

The generated module PA has the following interface :

```
open Base
open Crypto

type type_oracle_OA = unit -> (unit * string)
val init :  unit -> type_oracle_OA
```

Compilation to OCaml: replication

- When an oracle is under replication, it is compiled into an ordinary function:

  `fun` $[\![args]\!]$ `->` $[\![body]\!]$

- When an oracle is not under replication, it is compiled into a function that can be called only once:

```
let token = ref true in
fun ⟦args⟧ ->
  if (!token) then
    begin
      token := false;
      ⟦body⟧
    end
  else raise Bad_call
```

Compilation to OCaml: terms and body (1)

CryptoVerif	OCaml
M	$\llbracket M \rrbracket$
x	$\llbracket x \rrbracket$
$f(M_1, \dots, M_n)$	$\llbracket f \rrbracket\ \llbracket M_1 \rrbracket\ \dots\ \llbracket M_n \rrbracket$
P	$\llbracket P \rrbracket$
$x \xleftarrow{R} T; P$	$\texttt{let}\ \llbracket x \rrbracket\ \texttt{=}\ \llbracket rand_T \rrbracket\texttt{()}\ \texttt{in}\ \llbracket P \rrbracket$
$x \leftarrow M; P$	$\texttt{let}\ \llbracket x \rrbracket\ \texttt{=}\ \llbracket M \rrbracket\ \texttt{in}\ \llbracket P \rrbracket$
if M then P else P'	$\texttt{if}\ \llbracket M \rrbracket\ \texttt{then}\ \llbracket P \rrbracket\ \texttt{else}\ \llbracket P' \rrbracket$
end	$\texttt{raise Match\_fail}$
return$(M_1, \dots, M_n); Q$	$\texttt{(}\llbracket Q \rrbracket\texttt{, (}\llbracket M_1 \rrbracket\texttt{, ..., }\llbracket M_n \rrbracket\texttt{))}$

When a variable needs to be written to a file, it is written just after its definition.

Compilation to OCaml: terms and body (2)

insert $Tbl(M_1, \dots, M_n); P$

compiled into

$\texttt{insert\_in\_table}\ [\![Tbl]\!]\ \texttt{[}[\![serial_{T_1}]\!]\ [\![M_1]\!]\texttt{;}\dots\texttt{;}[\![serial_{T_n}]\!]\ [\![M_n]\!]\texttt{]}\texttt{;}\ [\![P]\!]$

get $Tbl(x_1 : T_1, \dots, x_n : T_n)$ suchthat M in P else P'

compiled into

$$\begin{array}{l}
\texttt{let l = get\_from\_table}\ [\![Tbl]\!] \\
\quad \texttt{(function [}[\![x_1]\!]\texttt{'; ...; }[\![x_n]\!]\texttt{'] ->} \\
\qquad \texttt{let }[\![x_1]\!]\texttt{ = exc\_bad\_file }[\![Tbl]\!]\texttt{ (}[\![deserial_{T_1}]\!]\ [\![x_1]\!]\texttt{') in }\dots \\
\qquad \texttt{let }[\![x_n]\!]\texttt{ = exc\_bad\_file }[\![Tbl]\!]\texttt{ (}[\![deserial_{T_n}]\!]\ [\![x_n]\!]\texttt{') in} \\
\qquad \texttt{if }[\![M]\!]\texttt{ then (}[\![x_1]\!]\texttt{, ..., }[\![x_n]\!]\texttt{) else raise Match\_fail} \\
\quad \texttt{| \_ -> raise (Bad\_file }[\![Tbl]\!]\texttt{))} \\
\texttt{in} \\
\texttt{if l = [] then }[\![P']\!]\texttt{ else} \\
\texttt{let (}[\![x_1]\!]\texttt{, ..., }[\![x_n]\!]\texttt{) = rand\_list l in }[\![P]\!]
\end{array}$$

Assumptions

- Assumptions on the network code:
  - No unsafe OCaml functions (such as `Obj.magic`).
  - No mutation of values received from or passed to generated functions.
  - No fork after obtaining and before calling an oracle that can be called only once.

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  - Programs are executed in the order specified in the CryptoVerif process.
  - Several programs that insert data in the same table are not run concurrently.

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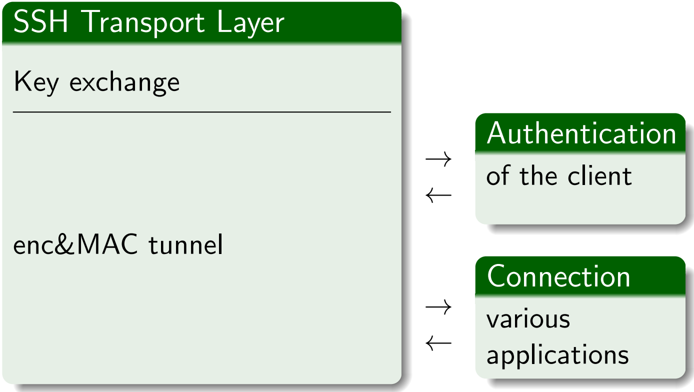
- Assumptions on program execution:
  - Programs are executed in the order specified in the CryptoVerif process.
  - Several programs that insert data in the same table are not run concurrently.
- Other:
  - Types that represent CryptoVerif data are not recursive.
  - The files used by generated code are not read/written by other code.

Application: SSH

- Secure SHell: an important protocol



SSH Transport Layer

Key exchange

---

enc&MAC tunnel

→
←

Authentication

of the client

→
←

Connection

various applications

SSH v. 2.0

SSH Transport Layer Protocol: key exchange

Client C Server S

$$\xrightarrow{id_C=\text{SSH-2.0-version}_C}$$

$$\xleftarrow{id_S=\text{SSH-2.0-version}_S}$$

$$\xrightarrow{\text{KEXINIT}, cookie_C, algos_C}$$

$$\xleftarrow{\text{KEXINIT}, cookie_S, algos_S}$$

$$x \overset{R}{\leftarrow} [2, q-1], e = g^x \quad \xrightarrow{\text{KEYDH\_INIT}, e} \quad y \overset{R}{\leftarrow} [1, q-1], f = g^y$$

$$K = f^x \quad \xleftarrow{\text{KEYDH\_REPLY}, pk_S, f, sign(H, sk_S)} \quad K = e^y$$

$$pk_S,\ sign(H, sk_S)\ \text{ok?} \quad \xrightarrow{\text{NEWKEYS}}$$

$$\xleftarrow{\text{NEWKEYS}}$$

$algos =$ diffie-hellman-group14-sha1, ssh-rsa, aes128-cbc, hmac-sha1

$H = \text{SHA1}(id_C, id_S, cookie_C, algos_C, cookie_S, algos_S, pk_S, e, f, K)$

SSH Transport Layer Protocol: packet protocol

$$\begin{aligned}
sessionid &= H\\
IV_C &= \mathrm{SHA1}(K, H, \text{“}A'', sessionid)\\
IV_S &= \mathrm{SHA1}(K, H, \text{“}B'', sessionid)\\
K_{enc,C} &= \mathrm{SHA1}(K, H, \text{“}C'', sessionid)\\
K_{enc,S} &= \mathrm{SHA1}(K, H, \text{“}D'', sessionid)\\
K_{MAC,C} &= \mathrm{SHA1}(K, H, \text{“}E'', sessionid)\\
K_{MAC,S} &= \mathrm{SHA1}(K, H, \text{“}F'', sessionid)
\end{aligned}$$

$$packet = packet\_length || padding\_length || payload || padding$$

$$\text{Client } C \quad \begin{array}{c} \xrightarrow{enc(K_{enc,C}, packet, IV_C), MAC(K_{MAC,C}, sequence\_number_C || packet)} \\ \xleftarrow{enc(K_{enc,S}, packet, IV_S), MAC(K_{MAC,S}, sequence\_number_S || packet)} \end{array} \quad \text{Server } S$$

CryptoVerif proof

- Modeled the SSH Transport Layer Protocol in CryptoVerif.
- Proved the authentication of the server to the client
  - Automatic by CryptoVerif
- The authentication of the client to the server requires the authentication protocol.
- Secrecy of the key requires extensions of CryptoVerif.
- Secrecy of messages sent over the tunnel cannot be proved:
  - Length of the packet leaked,
  - CBC mode with chained IVs.

Generated implementation

- Manually written cryptographic primitives.
    - based on CryptoKit.
- Manually written network code:
    - Key generators,
    - Client,
    - Server.

  They call the code generated from the CryptoVerif model.
- Format respected at the bit level.
    - Interact with other SSH implementations (OpenSSH).
- Some features omitted:
    - Key re-exchange
    - IGNORE, DISCONNECT messages

Demo

- ssh.ocv
- Prove by CryptoVerif
- Compile: key generation, client, server
- Run

Conclusion

- CryptoVerif specifications
  - proved secure in the computational model by CryptoVerif,
  - translated into OCaml implementations.
- Our approach favors the methodology:
  1. Write a formal specification;
  2. Prove it;
  3. Then, build an implementation.
- In progress: prove the soundness of the compiler.
  - specification secure ⇒ implementation secure
- Future work: extend the specification language, with loops, mutable variables, ...
  - extensions of CryptoVerif and of the compiler