Automated Proof Techniques for Cryptographic Assurance

Bruno Blanchet

EPI Prosecco

INRIA Paris

September 2016

Models of protocols

Two models of security protocols:

- Symbolic model (Dolev-Yao):
  - Primitives are black boxes. encrypt
  - Messages are terms on these primitives. $\text{encrypt}(\mathit{Hello}, k)$
  - The adversary is restricted to apply only those primitives.

  This model facilitates the automation of proofs.
- Computational model:
  - Messages are bitstrings. 01100100
  - Primitives are functions on bitstrings. $\text{encrypt}(011, 100100) = 111$
  - The adversary is any (probabilistic polynomial-time) Turing machine.

  This model is more realistic: the adversary can apply any algorithm.

Models of protocols

Two models of security protocols:

- Symbolic model (Dolev-Yao): ProVerif
  - Primitives are black boxes. encrypt
  - Messages are terms on these primitives. encrypt($Hello$, k)
  - The adversary is restricted to apply only those primitives.

  This model facilitates the automation of proofs.
- Computational model: CryptoVerif
  - Messages are bitstrings. 01100100
  - Primitives are functions on bitstrings. $\text{encrypt}(011, 100100) = 111$
  - The adversary is any (probabilistic polynomial-time) Turing machine.

  This model is more realistic: the adversary can apply any algorithm.

Protocol verification in the symbolic model

Security protocols are infinite state:

- The attacker can create messages of unbounded size.
- Unbounded number of sessions of the protocol.

Solutions:

- Bound the state space arbitrarily:
  exhaustive exploration (model-checking, . . .);
  find attacks but not prove security.
- Bound the number of sessions:
  the insecurity is NP-complete (with reasonable assumptions).
- Unbounded case:
  the problem is undecidable.

Solutions to undecidability

To solve an undecidable problem, we can

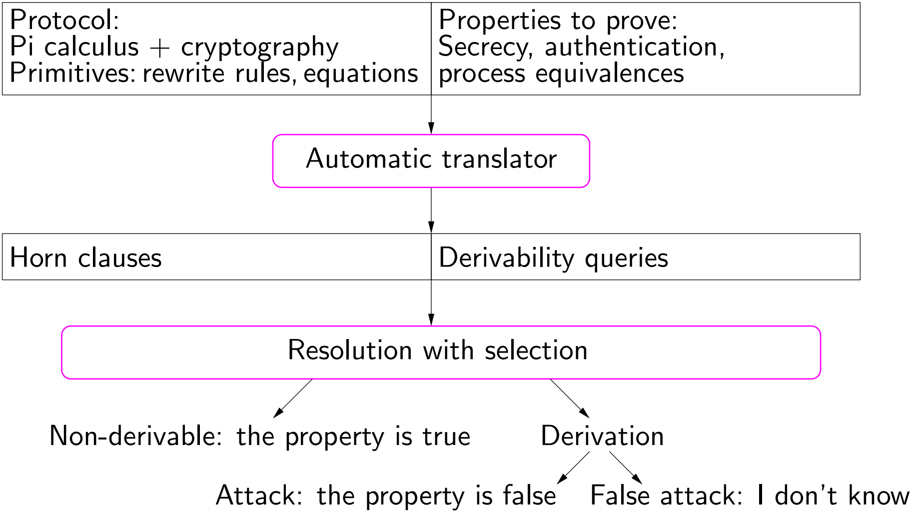
- Use approximations, abstraction.
- Terminate on a restricted class.
- Rely on user interaction or annotations.

In ProVerif, we do the first two, using a very precise abstraction by Horn clauses.

Features of ProVerif

- Fully automatic.
- Works for unbounded number of sessions and message space.
- Handles a wide range of cryptographic primitives, defined by rewrite rules or equations.
- Handles various security properties: secrecy, authentication, some equivalences.
- Limitations:
  - Does not always terminate. However, efficient in practice:
    small examples verified in less than 0.1 s; complex ones in minutes.
  - May answer "I don't know" (false attack). However, very precise in practice: no false attack in our tests for secrecy and authentication.

ProVerif


Protocol:
Pi calculus + cryptography
Primitives: rewrite rules, equations
Properties to prove:
Secrecy, authentication,
process equivalences
Automatic translator
Horn clauses
Derivability queries
Resolution with selection
Non-derivable: the property is true
Derivation
Attack: the property is false
False attack: I don't know

The Horn clause representation

The main predicate:

$\text{attacker}(M)$ *means* *"the attacker may have M"*.

Thanks to this predicate, we can model actions of the adversary:

Example: Shared-key encryption and decryption

$\text{attacker}(m) \wedge \text{attacker}(k) \rightarrow \text{attacker}(\text{encrypt}(m, k))$
$\text{attacker}(\text{encrypt}(m, k)) \wedge \text{attacker}(k) \rightarrow \text{attacker}(m)$

and of the protocol participants:

Example: A receives M and replies with M'

$\text{attacker}(M) \rightarrow \text{attacker}(M')$

CryptoVerif

The protocol verifier CryptoVerif:

- works directly in the computational model.
- proves secrecy and correspondence (authentication) properties.
- provides a generic method for specifying properties of cryptographic primitives which handles MACs (message authentication codes), symmetric encryption, public-key encryption, signatures, hash functions, Diffie-Hellman key agreements, ...
- works for N sessions (polynomial in the security parameter).
- gives a bound on the probability of an attack (exact security).
- has automatic and manual modes.

Produced proofs

As in Shoup's and Bellare&Rogaway's method, the proof is a sequence of games:

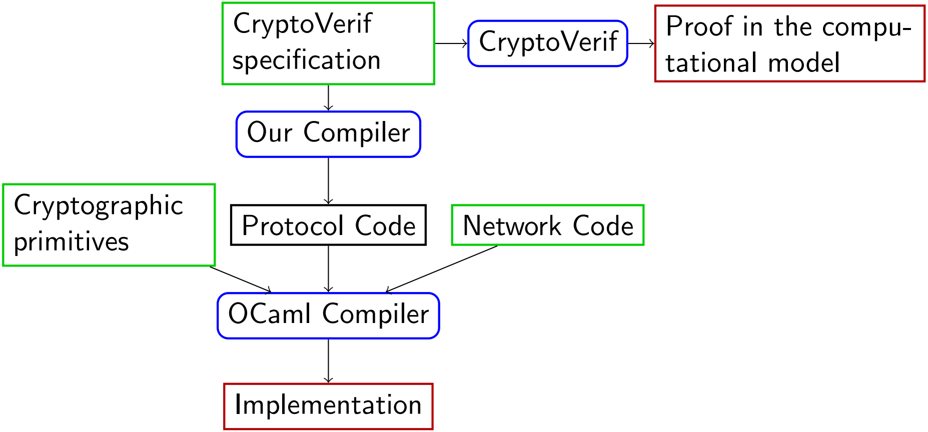
- The first game is the real protocol.
- One goes from one game to the next by syntactic transformations or by applying the definition of security of a cryptographic primitive. The difference of probability between consecutive games is negligible.
- The last game is "ideal": the security property is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

Game 0		Game 1				Game n
Protocol to prove	$\longleftrightarrow$ p_1 negligible		$\longleftrightarrow$ p_2 negligible	$\cdots$	$\longleftrightarrow$ p_n negligible	Property obvious

Models vs. implementations

- ProVerif and CryptoVerif automatically analyze protocol models.
- Just that models are very abstract:
  - Protocol models may miss implementation attacks.
- Verified models are good
  - . . . but verified implementations are much better!

Generation of implementations (David Cadé)



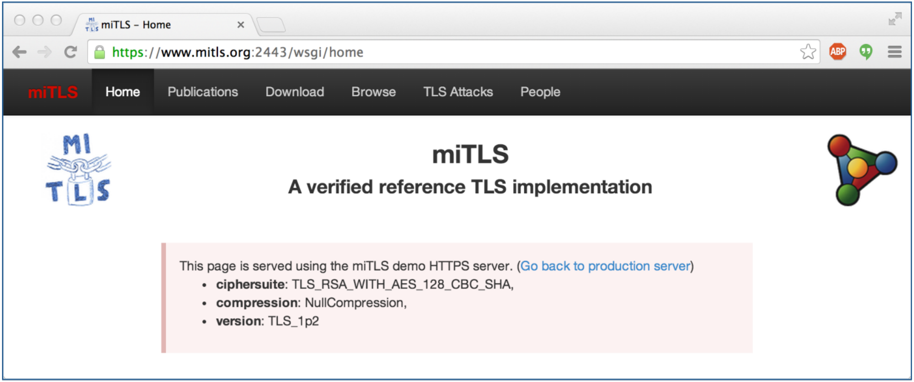
Caption: Tool Input Result

Verified implementations with F*, https://www.fstar-lang.org/

- F* is a new programming language
- ... putting together:
  - impure functional programming in ML
    - extracts to OCaml and F#, interoperates
  - the automation of SMT-based verification systems
    - like in Why3, Frama-C, Boogie, VCC, Dafny
  - the expressive power of interactive proof assistants based on dependent types
    - like in Coq, Agda, or Lean

miTLS, `http://www.mitls.org/`

- Formally verified reference implementation of TLS 1.2 in F7/F* (working towards TLS 1.3)
- Written from scratch focusing on verification



Lead to the discovery of many attacks in TLS implementations

Conclusion

Verified security protocols at several levels:

- Specifications:
  - In the symbolic model: ProVerif
    Available at `http://proverif.inria.fr/`
  - In the computational model: CryptoVerif
    Available at `http://cryptoverif.inria.fr/`
- Implementations:
  - Generation of implementations from specifications: CryptoVerif
  - Direct verification of implementations: F*.
    Available at `https://www.fstar-lang.org/`

See `http://prosecco.inria.fr/`