Mechanized Cryptographic Proofs of Protocols and their Link with Verified Implementations

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— adapted from iacr.org

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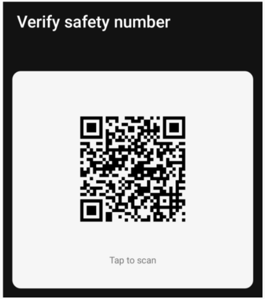
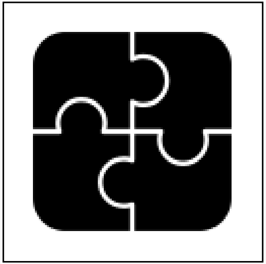


Cryptographic Security



Strongest assurance for specification level of cryptosystems:
Provable Security

In practice: reduction proofs in the computational model.

Game-Based Proofs

Like in a board game:

- Participants:
- Actions:
- Winning Condition

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Critique I: Relevance to Real-World Systems

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Practice-Oriented Provable Security

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Common critique [Hv17]: Assumptions and abstractions are **too far from reality**!

Practice-Oriented Provable Security tries to find useful answers to:

- Which key size is secure?
- How many users should be allowed?

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Call for “automated tools, that can help write and verify game-based proofs”.
— [Hal05; BR06]

Game-Based Proofs with the CryptoVerif Proof Assistant

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- CryptoVerif constructs a sequence of computationally indistinguishable games
- built-in proof strategy, and detailed guidance by user

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- CryptoVerif constructs a sequence of computationally indistinguishable games
- built-in proof strategy, and detailed guidance by user
- supports indistinguishability, secrecy, authentication properties
- computes exact security probability bound

Thesis Goals

Increase **applicability** and **visibility** of computer-aided proofs

Thesis Statement: Cryptographic proofs of practical usefulness are feasible using automated proof assistants.

Outline

Part I. Case studies on real-world protocols.

- The **Hybrid Public Key Encryption** standard
- The **WireGuard VPN** protocol

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Part II. Linking Cryptographic Proofs to Implementations.

- **cv2fstar**: translate CryptoVerif models to executable F* specifications

Part I: The Hybrid Public Key Encryption Standard

Joël Alwen, Bruno Blanchet, Eduard Hauck, Eike Kiltz, Benjamin Lipp, and Doreen Riepel. “Analysing the HPKE Standard”. EUROCRYPT 2021.

Richard L. Barnes, Karthik Bhargavan, Benjamin Lipp, and Christopher A. Wood. “Hybrid Public Key Encryption”. RFC 9180. February 2022.

Hybrid Public Key Encryption (HPKE)

- *Hybrid* in the spirit of the KEM/DEM paradigm:
  asymmetric building block as Key Encapsulation Mechanism,
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- Requirements: modern crypto, provable security, test vectors, freely implementable.

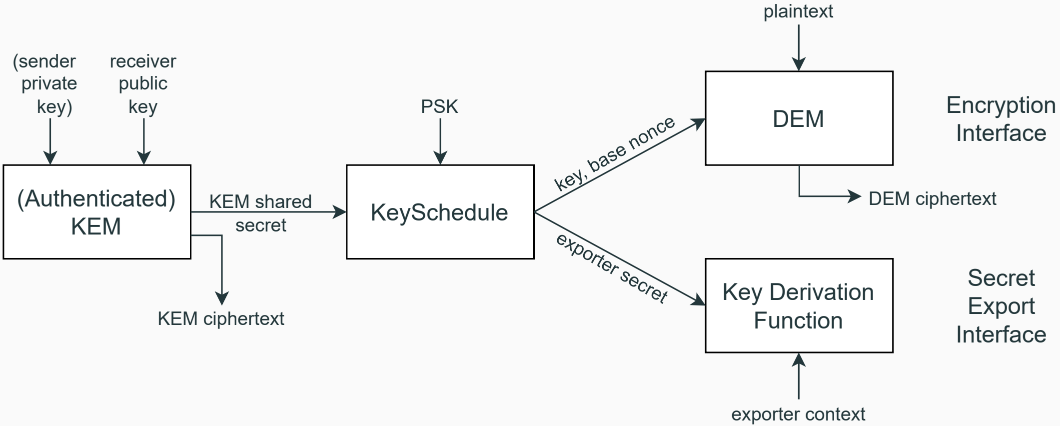
HPKE Specifies Different APIs

- Single-Shot Encryption: encrypt one message
- Single-Shot Secret Export: provide one secret of (almost) *arbitrary* length
- Multi-Shot: multiple messages, and multiple secrets

HPKE Specifies Four Different Modes

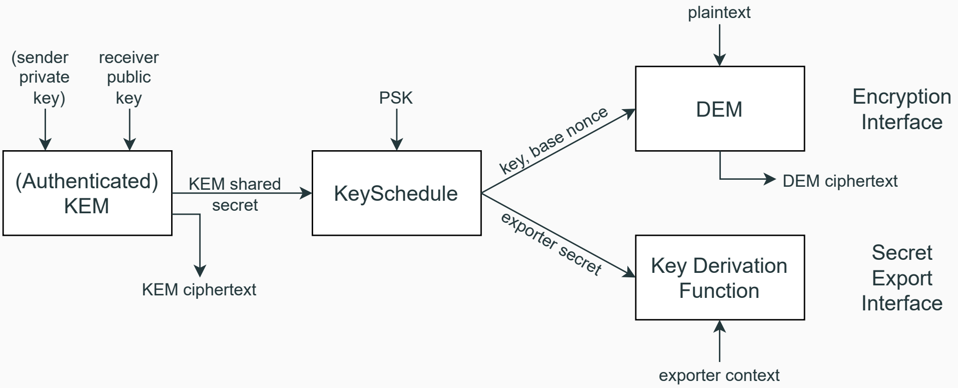
	receiver key pair	sender key pair	pre-shared key
Base	y	n	n
Auth	y	y	n
PSK	y	n	y
AuthPSK	y	y	y

Overview of the Construction



Contributions to the HPKE Standard

1. Preliminary cryptographic analysis **of all modes and interfaces** leading to
   - **redesign of DHKEM** and the key schedule such that DHKEM is CCA-secure on its own
   - introduce **proper oracle separation** using labels



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2. Updating HPKE specification in the HACL* library
    - has been upstreamed
    - used to compute input parameter length limits, indicated in the RFC

Contributions to the HPKE Standard

3. Detailed cryptographic analysis of the **Auth mode** leading to
    - composition theorems about Auth mode's security
    - with exact security bounds
    - development of the **nominal groups framework** for modeling elliptic curves

Security Notions for AKEM and APKE

Chosen-Ciphertext Indistinguishability (CCA)
confidentiality of AKEM and APKE ciphertexts

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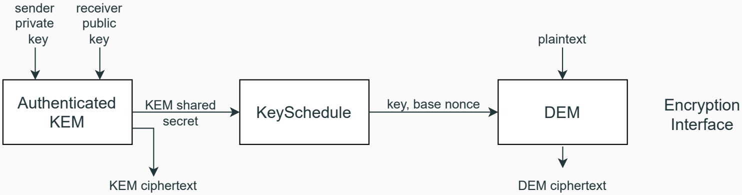
Insider adversary can *provide* sender or receiver *secret* key,
this is stronger than compromise of honestly generated key pairs

Proofs About HPKE's Auth Mode



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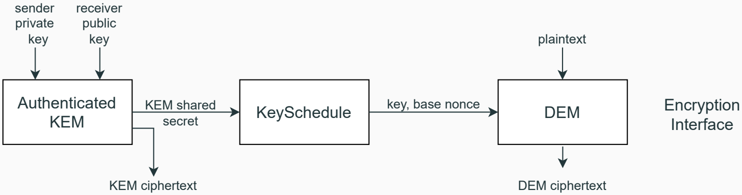

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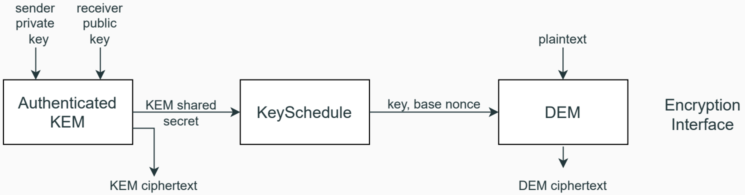

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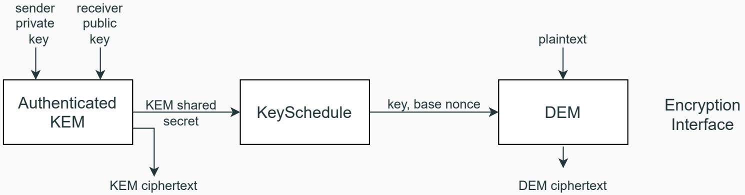

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- CryptoVerif: **composition theorems** for Outsider-CCA, Insider-CCA, and Outsider-Auth of the AKEM/DEM construction
- Hand-written non-tight proof of **single-user/two-user** $\Rightarrow$ **multi-user security notions** for AKEM, to close gap to proofs of, e.g., PQ KEMs

Elliptic Curves and Nominal Groups

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  For each honestly generated public key, there is a small number of equivalent public keys.

We define a framework of **(rerandomisable) nominal groups** to cover both prime-order and non-prime-order groups in one model.

In short: We do not assume a group structure, but only an exponentiation function with certain properties.

Exact Security of HPKE

Algorithm choices with their security level:

- Elliptic curves from 128 to 256 bits
- Hash functions from 256 to 512 bits
- AEAD with key length from 128 to 256 bits,
  the auth tag length is always 128 bits.

Proof result: the length of the auth tag limits the overall security level to 128 bits.

HPKE: Conclusion and Future Work

HPKE Auth mode satisfies its desired security properties with a **maximum security level of 128 bits**.

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Future Work:

- open question: multi-key security of current AEAD schemes
- detailed analysis of (Auth)PSK mode

Part I: The WireGuard VPN Protocol

Benjamin Lipp, Bruno Blanchet, and Karthikeyan Bhargavan. "A Mechanised Cryptographic Proof of the WireGuard Virtual Private Network Protocol". IEEE EuroS&P 2019.

The WireGuard Virtual Private Network (VPN)

Protocol and implementation in progress since 2015

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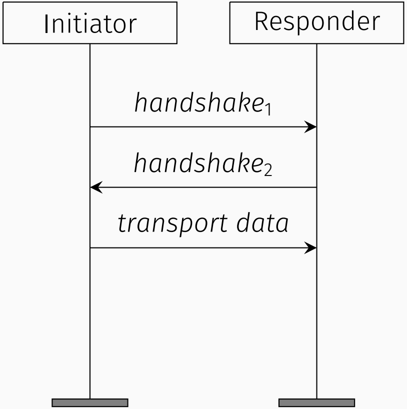
  - only a few thousand lines of code
- integration into the **Linux kernel** in 2020
- organizations and VPN providers started adopting it

WireGuard's Main Protocol



Based on protocol IKpsk2 from the Noise Protocol Framework

1st transport data msg must come from initiator

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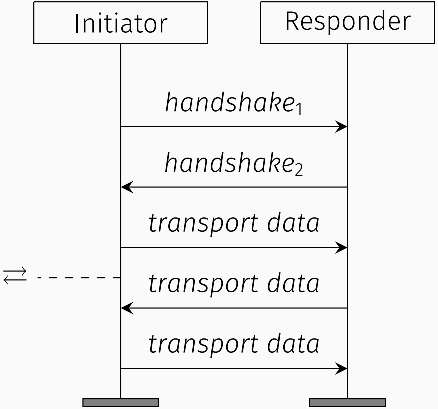

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Our Contributions

Mechanized cryptographic proof of WireGuard using CryptoVerif, analysing:

- the entire protocol, including transport data messages
- usual properties for secure channels
- identity hiding
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Related work:

- WireGuard: DowlingPaterson'18, DonenfeldMilner'18
- IKpsk2: KobeissiNicolasBhargavan'19, Suter-Dörig'18, Girol'19

Analyzed Properties

Usual secure channel properties:

Confidentiality
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Additional properties in WireGuard:

- Resistance against denial of service (no replay of 1st msg, cookie enforces round-trip)
- Identity hiding (weak)

Chain of Random Oracle Calls

8 chained calls to
one random oracle.

$$
\begin{aligned}
C &\leftarrow \text{const} \\
C &\leftarrow \text{hkdf}(C, v_0) \\
C \| k_1 &\leftarrow \text{hkdf}(C, v_1) \\
C \| k_2 &\leftarrow \text{hkdf}(C, v_2) \\
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C &\leftarrow \text{hkdf}(C, v_5) \\
C \| \pi \| k_3 &\leftarrow \text{hkdf}(C, v_6) \\
T^{\rightarrow} \| T^{\leftarrow} &\leftarrow \text{hkdf}(C, \epsilon)
\end{aligned}
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Game Size Explosion in CryptoVerif

Considering all collision cases leads to exponential growth of number of branches:

v_0

$== v_0[i]$
$== v_1[i]$
$== v_2[i]$
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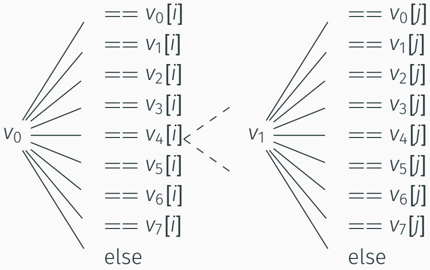

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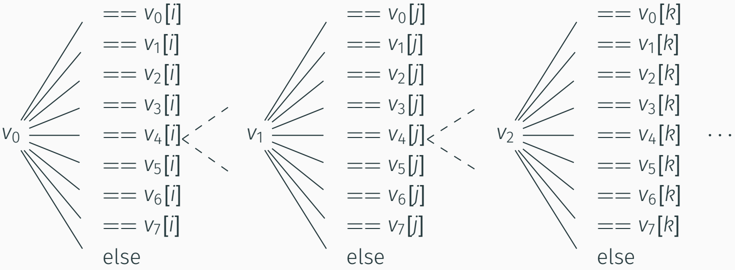

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3 independent calls to
3 *independent* random oracles.

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A Theoretical Attack leading to Identity Mis-Binding

Definition: Resistance against Identity Mis-Binding

Two honest parties deriving the same traffic keys in some sessions

- agree on each other's identities
- even if one or both of them have been interacting with a dishonest party or an honest party with compromised keys

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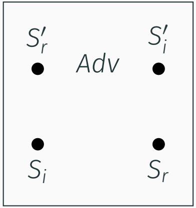

- Let S_i, S_r, E_i, E_r, and *psk* be compromised.
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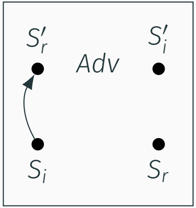

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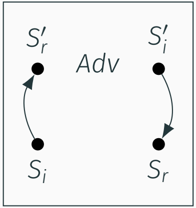

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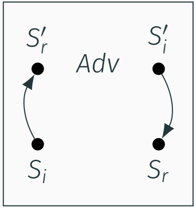

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$\rightarrow$ The two sessions derive the same traffic keys but are between different parties.

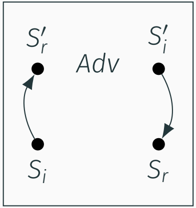
A Theoretical Attack leading to Identity Mis-Binding

Definition: Resistance against Identity Mis-Binding

Two honest parties deriving the same traffic keys in some sessions

- agree on each other's identities
- even if one or both of them have been interacting with a dishonest party or an honest party with compromised keys

Theoretical Attack:



- Let S_i, S_r, E_i, E_r, and *psk* be compromised.
- Adversary constructs $S'_i \neq S_i, S'_r \neq S_r$ as *different but equivalent* static keys

$\rightarrow$ The two sessions derive the same traffic keys but are between different parties.

Mitigation: include static public keys S_i^{pub} and S_r^{pub} into key derivation

WireGuard: Conclusion and Future Work

WireGuard protocol is cryptographically secure

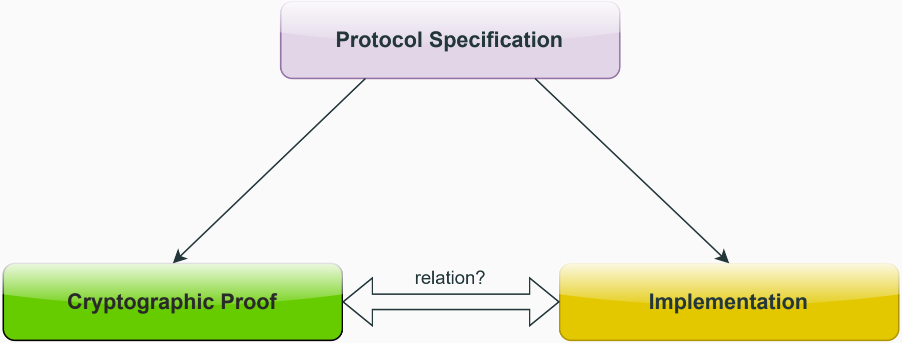
- theoretical identity mis-binding attack
- weak identity hiding

Possible future work

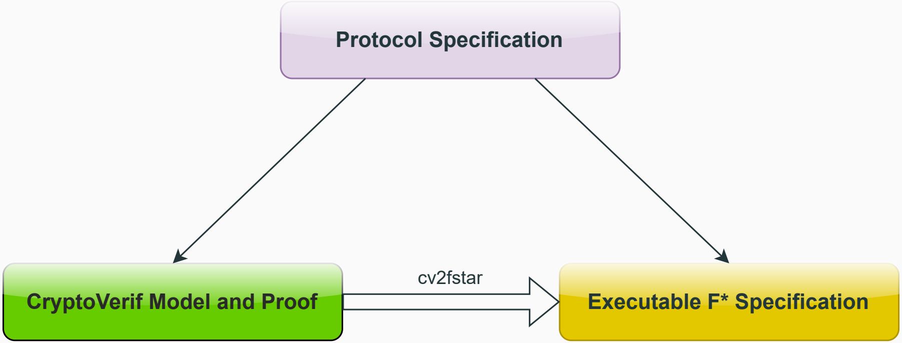
- more Noise protocols
- use PRF-ODH assumption

Part II: Translate CryptoVerif Models to Executable $F^\star$ Specifications

Problem Statement



Proposal: cv2fstar



Output Language: F⋆

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- rich type system
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- rich type system
- extracts to OCaml and F#;
  C, WebAssembly (KaRaMeL)
- interactive proofs and discharging to SMT
- HACL⋆ High-Assurance Cryptographic Library

  used in Mozilla’s NSS, Windows Kernel, Linux Kernel, WireGuard, Microsoft’s QUIC implementation, Tezos blockchain

Detailed Motivation

1. obtain implementation with cryptographic security guarantees
   $\rightarrow$ cv2fstar provides an automatic translation from CryptoVerif

2. provably instantiate non-cryptographic assumptions of the CryptoVerif model
   $\rightarrow$ cv2fstar generates lemmas as proof obligations

3. reuse CryptoVerif theorems for further proofs
   $\rightarrow$ future work: translate as assumed lemmas

Related Work

Large body of research, in three groups:

1. Model $\rightarrow$ Implementation
2. Implementation $\rightarrow$ Model
3. Proofs on Code

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cv2fstar uses approach (1). Builds upon cv2ocaml.

F⋆ Specifications in Pure State-Passing Style

state = entropy $*$ tables $*$ sessions $*$ events

entropy: explicitly track randomness used for random sampling

tables: each table has an append-only list of entries

sessions: map of session ID $\rightarrow$ list of session entries.
enforces oracle order, implements variable scope in oracle sequences

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```
val oracle: state -> nat -> t -> state * option (nat * T)
```

Translating Oracle Sequences Using Sessions

```
O1(...) :=
  a <- ...;
  ...
  return(...);

O2(...) :=
  b <- a;
  ...
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O3(...) :=
  c <- f(a, b);
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CryptoVerif semantics:

- Oracles can only be called in order
- Variables stay in scope for following oracles

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F* implementation:

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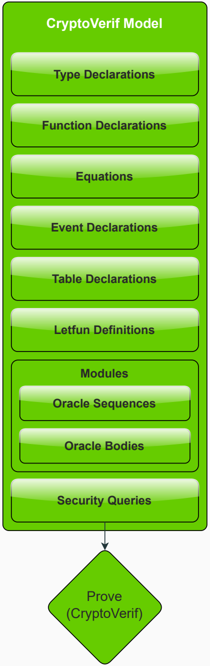
- return a session ID
- following oracle is called with session ID, retrieves values of free variables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Modules
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Oracle Bodies
Security Queries
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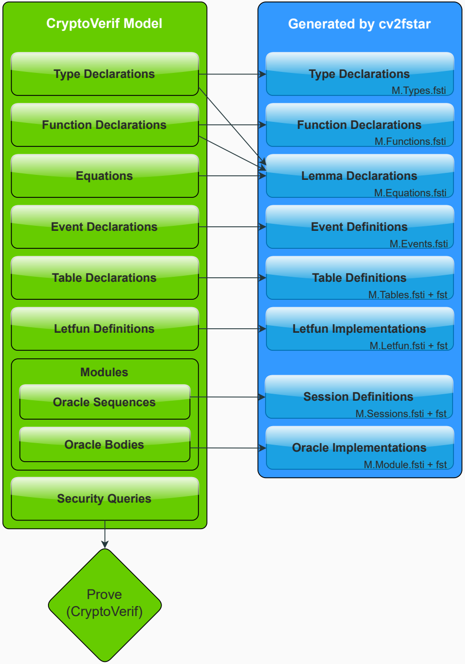
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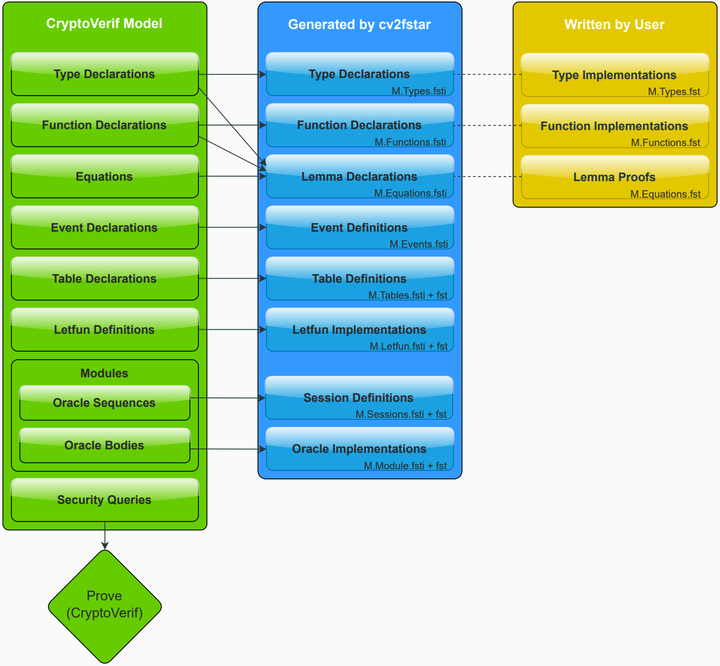
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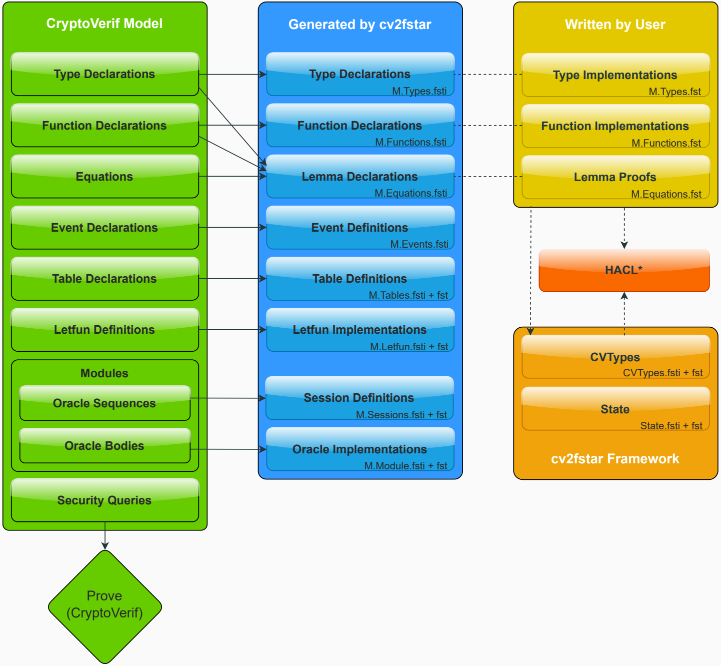
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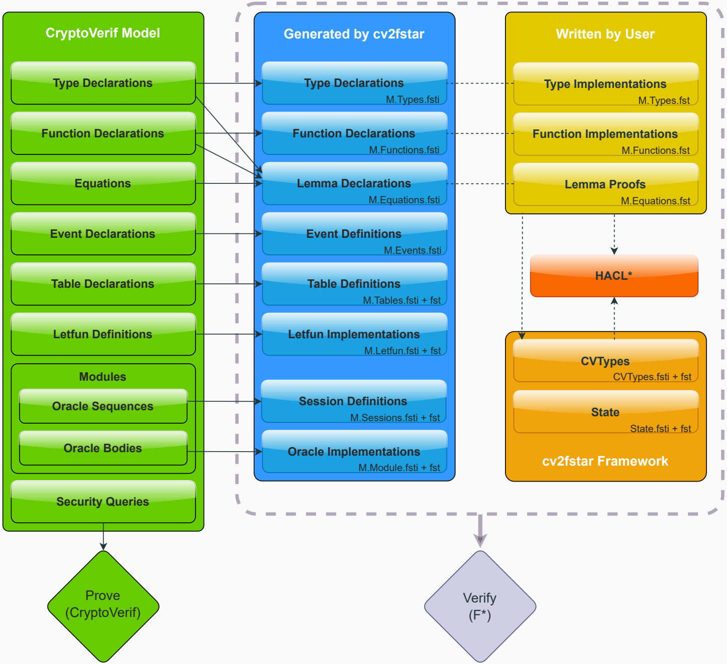
cv2fstar Framework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cv2fstar Framework
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Non-Cryptographic Assumptions to Lemmas

4 sources from which lemmas are generated as proof obligations:

1. explicit equations

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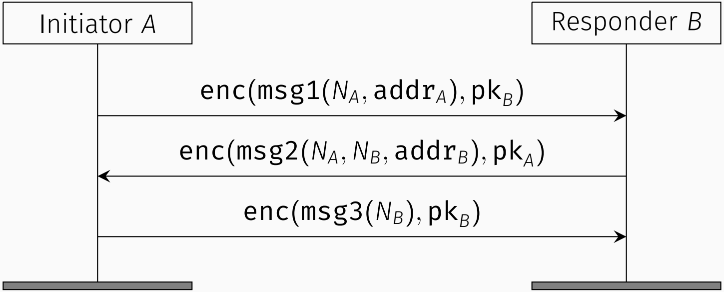
3. correctness of inverses for functions declared `[data]`
4. correctness of inverses for (de)serialization functions

Case Study: The Needham-Schroeder-Lowe Protocol (NSL)



NSL: Source Code Statistics

		# files	# SLOC	# PLOC
cv2fstar handwritten framework	F*	12	870	150
NSL handwritten	CryptoVerif	1	170	0
NSL generated by cv2fstar	F*	20	910	0
NSL handwritten	F*	3	370	100

51 lemmas generated for NSL
42 trivial for F*: proven by `()`
18 coming from CryptoVerif's standard library (all trivial for F*)

≈ 100 lines of proof code in NSL.Equations.fst, 150 in CVTypes.fst(i) combined.

cv2fstar: Conclusion

We have shown that cv2fstar

- allows to translate CryptoVerif models to executable code
- interoperable with HACL⋆
- allows to fill in implementation details in F⋆,
  and to prove that they fulfill the CryptoVerif model's assumptions

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Future Work (excerpt)

- Translate CryptoVerif theorems to F⋆:
  correspondance, secrecy, indistinguishability properties
- WireGuard case study, link with Noise* implementation

Thesis Conclusion

Thesis Conclusion: Part I

- Writing highly-detailed cryptographic proofs using CryptoVerif is feasible for real-world protocols.
- More detailed models of elliptic curves than any handwritten analysis before: use Curve25519 with confidence.
- WireGuard: carefully modeled very close to its implementation.
- HPKE: concrete security bounds; influence on standard.

Thesis Conclusion: Part II

cv2fstar compiles CryptoVerif models to executable F* specifications.

- cryptographic properties on executable code
- prove properties about implementation details

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Interest and demand is clearly there, from cryptographers and standardization bodies.

Challenges

Multitude of proof methodologies and security notions:
game-based, simulation-based, UC, state-separating proofs.

“does not have a very appealing ‘business case”’
— Halevi [Hal05]

Challenges:

- small user base
- incentives and funding for researchers and developers?

Specific Goals?

- Teaching material
- More accessible user interfaces
- Artifact evaluation at more publication venues. (CHES is leading by example since 2021!)

→ Build up trust in the tools within the community.

Future Work

Generally: continue using and developing cryptographic proof assistants in the area of practice-oriented provable security.

- Collaborate with cryptographers, support standardization efforts
- Usability of proof assistants
- Consider quantum adversaries

Computer-aided cryptographic proofs are an exciting and in-demand research effort, with many promising open problems!