Verified Models and Reference Implementations for the TLS 1.3 Standard Candidate

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Transport Layer Security (TLS) 1.3

- Next version of the most popular secure channel protocol.
  - Completely redesigned from TLS 1.2
  - After 20 drafts, on the verge of standardization
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  - Security: remove broken legacy crypto constructions
## Attacks against TLS 1.2

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<th>Attack</th>
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  - Efficiency: reduce handshake roundtrip latency
    - 0-RTT when the client and server have a pre-shared key
    - 0.5-RTT
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  - Security: remove broken legacy crypto constructions
  - Efficiency: reduce handshake roundtrip latency
    - 0-RTT when the client and server have a pre-shared key
    - 0.5-RTT
  - These are potentially contradictory goals

- Needs extensive security analysis before deployment!
  - The IETF called for academics to formally analyze the protocol drafts.
Analyzing TLS 1.3

- Many published analyses for intermediate TLS 1.3 drafts
  - Cryptography proofs (of drafts 5, 9, 10)
  - Symbolic protocol analysis (of draft 10)
    [Cremers et al. S&P’16]
  - Verified implementation (of draft 18 record protocol)
    [Bhargavan et al. S&P’17]
  - Symbolic and computational proofs (of draft 18)
    [Bhargavan et al. S&P’17; this talk]

- Are we done? Is it secure?
  - If we deploy TLS 1.3, will it expose new attacks?
Historically, published proofs of TLS missed many attacks
Large gaps between simplified models and the deployed protocol

1. Proofs ignored “ugly” implementation details
   - e.g. AES-CBC padding, RSA-PKCS#1v1.5 padding

2. Proofs relied on strong crypto assumptions on primitives
   - e.g. collision resistant hash functions, strong Diffie-Hellman groups

3. Proofs ignored composition with obsolete/unpopular modes
   - e.g. SSLv2, EXPORT ciphers, renegotiation

How do we ensure that TLS 1.3 proofs do not fall into these traps?
Our approach

- Use automated verification tools to handle protocol complexity
  - Easy to extend as protocol evolves, or as we model new features
- Symbolically analyze protocol against known attack vectors
  - Find or prove the absence of downgrade attacks to TLS 1.2 (using ProVerif)
- Build a mechanically-checked cryptographic proof of TLS 1.3
  - Explore the crypto assumptions needed by TLS 1.3 (using CryptoVerif)
- Synchronize verified models with RFC and its implementations
  - Extract ProVerif model from an interoperable implementation (RefTLS)
Our vision: one model, three tasks

(Typed by: Verified interoperable implementations of security protocols, TOPLAS 2008.)
Our current toolchain

- Protocol fix
- TLS 1.3 Core protocol code
- Model extraction
- TLS 1.3 Symbolic model
- TLS 1.3 Crypto model
- Potential attack
- ProVerif
  - Symbolic proof
- CryptoVerif
  - Cryptographic proof
- Reference implementation
- Other TLS libraries
- Interop testing
Symbolic analysis to find downgrade (and other) attacks

Recent attacks on legacy crypto in TLS:

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Legacy crypto remains in TLS libraries for backwards compatibility.

Is TLS 1.3 secure, if it is deployed alongside older versions of TLS?

- Can a man-in-the-middle **downgrade** TLS 1.3 peers to use legacy crypto?
Modeling weak crypto in ProVerif

- Classic symbolic (Dolev-Yao) protocol models idealize crypto
  - Perfect black-boxes that cannot be opened without relevant key
- We model agile crypto primitives parameterized by algorithm
  - Given a **strong** algorithm, the primitive behaves ideally
  - Given a **weak** algorithm, the primitive completely breaks
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  - e.g. a weak Diffie-Hellman group behaves like a trivial 1-element group

```
fun dh_ideal(element, bitstring): element.
equation forall x: bitstring, y: bitstring;
    dh_ideal(dh_ideal(G, x), y) = dh_ideal(dh_ideal(G, y), x).

fun dh_exp(group, element, bitstring): element
reduce forall g: group, e: element, x: bitstring;
    dh_exp(WeakDH, e, x) = BadElement
otherwise forall g: group, e: element, x: bitstring;
    dh_exp(StrongDH, BadElement, x) = BadElement
otherwise forall g: group, e: element, x: bitstring;
    dh_exp(StrongDH, e, x) = dh_ideal(e, x).
```
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  - Given a **weak** algorithm, the primitive completely breaks
  - e.g. a weak Diffie-Hellman group behaves like a trivial 1-element group
  - Similarly, we model strong and weak authenticated encryption, hash functions, MACs, RSA encryption and signatures.
- Our model is overly conservative, it may not indicate real exploits
  - Our goal is to verify TLS 1.3 against future attacks on legacy crypto
TLS 1.3 1-RTT handshake

- 12 messages in 3 flights, 16 derived keys, then data exchange
- + PSK-based 0-RTT
- + TLS 1.2
- Agile Crypto: ~400 lines
- TLS models: ~500 lines

Modeling is easy, verification takes effort

Key Derivation Functions:

\[ \text{HKDF-Extract}(k, s) = \text{HMAC-H}^k(s) \]
\[ \text{hkdf-expand-label}_1(s, l, h) = \text{HMAC-H}^h([l || h || 0x01]) \]
\[ \text{Derive-Secret}(s, l, m) = \text{hkdf-expand-label}_1(s, l, H(m)) \]

1-RTT Key Schedule:

\[ kdf_0 = \text{HKDF-Extract}(0^{len_H}, 0^{len_H}) \]
\[ kdf_{ms}(es, e) = \text{HKDF-Extract}(es, e) \]
\[ kdf_{ms}(hs, log_1) = ms, k^h, k^s, k^m, k^m \text{ where} \]
\[ ms = \text{HKDF-Extract}(hs, 0^{len_H}) \]
\[ k^h = \text{hkdf-expand-label}(hs, key, "") \]
\[ k^s = \text{hkdf-expand-label}(hs, key, "") \]
\[ k^m = \text{hkdf-expand-label}(hs, finished, "") \]
\[ k^m = \text{hkdf-expand-label}(hs, finished, "") \]
\[ kdf_{sk}(ms, log_4) = k^c, k^s, ems \text{ where} \]
\[ ats_c = \text{Derive-Secret}(ms, ats_c, log_4) \]
\[ ats_s = \text{Derive-Secret}(ms, ats_s, log_4) \]
\[ ems = \text{Derive-Secret}(ms, ems, log_4) \]
\[ k^c = \text{hkdf-expand-label}(ats_c, key, "") \]
\[ k^s = \text{hkdf-expand-label}(ats_s, key, "") \]
\[ kdf_{psk}(ms, log_7) = psk' \text{ where} \]
\[ psk' = \text{Derive-Secret}(ms, rms, log_7) \]

PSK-based Key Schedule:

\[ kdf_{es}(psk) = es, k^b \text{ where} \]
\[ es = \text{HKDF-Extract}(0^{len_H}, psk) \]
\[ k^b = \text{Derive-Secret}(es, pbk, "") \]
\[ kdf_{0RTT}(es, log_1) = k^c \text{ where} \]
\[ ects_c = \text{Derive-Secret}(es, ects_c, log_1) \]
\[ k^c = \text{hkdf-expand-label}(ets_c, key, "") \]
Writing and verifying security goals

- We state security queries for data sent between honest users
  - **Secrecy**: messages between honest peers are unknown to an adversary
  - **Authenticity**: messages between honest peers cannot be tampered
  - **Replay prevention**: messages between honest peers cannot be replayed
  - **Forward secrecy**: secrecy holds even if the peers’ long-term keys are leaked after the session is complete

- Secrecy query for \(\text{msg}(\text{conn}, S)\) sent from anonymous \(C\) to server \(S\)

\[
\text{query} \ \text{attacker}(\text{msg}(\text{conn}, S)) \Rightarrow \text{false}
\]
Refining security queries

 QUERY: is msg(conn, S) secret?

query attacker(msg(conn, S)) \implies false

 FALSE: ProVerif finds a counterexample if S’s private key is compromised.
Refining security queries

- **QUERY**: is $\text{msg}(\text{conn}, S)$ secret as long as $S$ is uncompromised?

  *query* attacker($\text{msg}(\text{conn}, S)$) $\implies$ event($\text{WeakOrCompromisedKey}(S)$)

- **FALSE**: ProVerif finds a counterexample if the AE algorithm is weak.
Refining security queries

- **QUERY**: Strongest secrecy query that can be proved in our model

```
query attacker(msg(conn, S)) \implies 
  event(WeakOrCompromisedKey(S)) \lor 
  event(ServerChoosesAE(conn, S, WeakAE)) \lor 
  event(ServerChoosesKEX(conn, S, WeakDH)) \lor 
  event(ServerChoosesKEX(conn', S, WeakRSAEncryption)) \lor 
  event(ServerChoosesHash(conn', S, WeakHash))
```

- **TRUE**: ProVerif finds no counterexample
Conclusion: Downgrade security for TLS 1.2 + TLS 1.3

- Messages on a TLS 1.3 connection between honest peers are secret:
  1. if the connection does not use a weak AE algorithm,
  2. the connection does not use a weak DH group,
  3. the server never uses a weak hash algorithm for signing, and
  4. the server never participates in a TLS 1.2 RSA key exchange.

- Analysis confirms preconditions for downgrade resilience in TLS 1.3
  - identifies weak algorithms in TLS 1.2 that can harm TLS 1.3 security
Mechanized computational proof

- **Mechanized** verification of **TLS 1.3 Draft-18 in the computational model.**
  - + Handshake with PSK and/or DHE.
  - + Handshake with and without client authentication.
  - + 0-RTT and 0.5-RTT data, key updates.
  - - No post-handshake authentication.
  - - No version or ciphersuite negotiation: only strong algorithms.
  - - For PSK-DHE, we do not prove forward secrecy wrt. the compromise of PSK.

- We prove security properties of the initial handshake, the handshake with pre-shared key, and the record protocol using CryptoVerif.

- We compose these pieces manually.
CryptoVerif is a semi-automatic prover that:

- works in the computational model.
- generates proofs by sequences of games.
- proves secrecy and correspondence 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), with an active adversary.
- gives a bound on the probability of an attack (exact security).
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.)
Input and output of the tool

1. Prepare the input file containing
   - the specification of the **protocol** to study (initial game),
   - the **security assumptions** on the cryptographic primitives,
   - the **security properties** to prove.

2. Run CryptoVerif
   - Automatic proof strategy or manual guidance.

3. CryptoVerif outputs
   - the **sequence of games** that leads to the proof,
   - a **succinct explanation** of the transformations performed between games,
   - an upper bound of the **probability** of success of an attack.
Structure of the proof

1. Computational assumptions
2. Lemmas on primitives
3. Protocol pieces
   - Handshake without pre-shared key
   - Handshake with pre-shared key (PSK and PSK-DHE)
   - Record protocol
4. Compose the pieces together
Structure of the proof: final composition

Handshake without pre-shared key

Handshake with pre-shared key

Record protocol

updated $ts$

$ats_c$, $ats_s$, $psk'$, $ets_c$
Key schedule (Draft-18, excerpt)

PSK → HKDF-Extract

Early Secrets

- Derive-Secret(., “external psk binder key” | “resumption psk binder key”, “” )
  = binder_key

- Derive-Secret(., “client early traffic secret”, ClientHello)
  = client_early_traffic_secret (ets_c)
Assumptions (1)

- **Diffie-Hellman:**
  - gap Diffie-Hellman (GDH)
    - needed in particular for 0.5-RTT
  - Diffie-Hellman group of prime order
  - Diffie-Hellman group elements different from $0^{len_H()}$
    - avoids confusion between handshakes with and without Diffie-Hellman exchange.
  - Diffie-Hellman group elements different from $len_H(\| “TLS 1.3,” \| l \| h \| 0x01)$.  
    - avoids collision between HKDF-Extract$(es, e)$ and Derive-Secret$(es, pbk, “”) \) or Derive-Secret$(es, ets_c, log_1)$.  
    - independently discovered and discussed on the TLS mailing list.
    - change in Draft-19 makes this assumption unnecessary: add a Derive-Secret stage before HKDF-Extract.
Assumptions (2)

- **Signatures**: sign is UF-CMA.
- **Hash functions**: H is collision-resistant.
- **HMAC**:
  - $x \mapsto \text{HMAC-}H^{0_{\text{len}H}}(x)$ and $x \mapsto \text{HMAC-}H^{k_{\text{kdf}}_0}(x)$ are independent random oracles.
  - HMAC-H is a PRF, for keys different from $0^{\text{len}H}$ and $k_{\text{kdf}}_0$.
- **Authenticated Encryption**: IND-CPA and INT-CTXT provided the same nonce is never used twice with the same key.
Lemmas on primitives: MAC and signatures

- \( \text{mac}_H^k(m) = \text{mac}^k(H(m)) \) is an SUF-CMA MAC.
- \( \text{sign}_H^{sk}(m) = \text{sign}^{sk}(H(m)) \) is an UF-CMA signature.
Lemma

When $es$ is a fresh random value,

- $e \mapsto \text{HKDF-Extract}(es, e)$ and
- $log_1 \mapsto \text{Derive-Secret}(es, ets_c, log_1)$
  are indistinguishable from independent random functions, and
- $k^b = \text{Derive-Secret}(es, pbk, "")$ and
- $\text{HKDF-Extract}(es, 0^{\text{len}_H()})$
  are indistinguishable from independent fresh random values
  independent from these random functions.

- Proved using CryptoVerif.
- Similar lemmas for other parts of the key schedule.
- Used as assumption in the proof of the protocol.
Handshake without pre-shared key: model

- Model a honest client and a honest server.
- May interact with dishonest clients and servers included in the adversary.
- Ignore negotiation (RetryRequest).
- Give the handshake keys to adversary:
  - The adversary can encrypt and decrypt messages.
  - The security proof does not rely on that.
- Server always authenticated.
- With and without client authentication.
- The honest client and server may be dynamically compromised.
Handshake without pre-shared key: honest sessions

- The **client** is in a **honest session** if
  - the server public key is the one of the honest server, and
  - the honest server is not compromised, or it is compromised and the messages received by the client have been sent by the honest server.

- The **server** is in a **honest session** if
  - client authenticated:
    - the client public key is the one of honest client, and
    - the honest client is not compromised, or it is compromised and the messages received by the server have been sent by the honest client.
  - client not authenticated: the Diffie-Hellman share received by the server has been sent by the honest client.
Handshake without pre-shared key: security (1)

- **Key authentication:**
  - If the honest client terminates a honest session, then the honest server has accepted a session with that client, and they agree on:
    - keys $ats_c$, $ats_s$, and $ems$,
    - all messages until the server Finished message.
  - If the honest server terminates a honest session, then the honest client has accepted a session with that server, and they agree on the keys and on all messages.

- **Replay prevention:** the previous properties are injective.

- **Key secrecy:** the keys
  - $ats_c$, $ems$, $psk'$ client side, when the client terminates a honest session;
  - $ats_s$ server side, when the server sends its Finished message and the received Diffie-Hellman share comes from the client (for 0.5-RTT) are indistinguishable from independent fresh random values.
Handshake without pre-shared key: security (2)

- **Same key:**
  - If the honest client terminates a honest session and the honest server has accepted a session with the same messages, then they have the same key.
  - If the honest server terminates a honest session and the honest client has accepted a session with the same messages, then they have the same key.

- **Unique channel identifier:**
  - $\text{psk}'$ or $\text{H}(\log_7)$:
    - If a client session and a server session have the same $\text{psk}'$ or $\text{H}(\log_7)$, then all their parameters are equal (collision-resistance).
  - $\text{ems}$:
    - If a client session and a server session have the same $\text{ems}$, then they have the same $\log_4$ (collision-resistance), so all their parameters are equal (CryptoVerif).
Handshake without pre-shared key: guidance

- Signature under $sk_S$.
- Introduce tests to distinguish cases, depending on
  - whether the Diffie-Hellman share received by the server is a share $g^{x'}$ from the client,
  - and whether the Diffie-Hellman share received by the client is the share $g^y$ generated by the server upon receipt of $g^{x'}$.
- Random oracle assumption on $x \mapsto \text{HMAC-H}^{kdf_0}(x)$.
- Replace variables that contain $g^{x'y}$ with their values to make equality tests $m = g^{x'y}$ appear.
- Gap Diffie-Hellman assumption.
- ⇒ the handshake secret $hs$ is a fresh random value.
- Lemmas on key schedule ⇒ other keys are fresh random values.
- MAC.
- Signature under $sk_C$. 
Handshake with pre-shared key: model

- Includes handshakes with and without Diffie-Hellman exchange.
- Includes 0-RTT.
- Ignore the ticket $\text{enc}^{k_t}(\text{psk})$; consider a honest client and a honest server that share the PSK.
- Give the handshake keys to adversary (as before).
- Certificates optional, since the client and server are already authenticated by the PSK.
Handshake with pre-shared key: security (1)

Same properties as for the initial handshake, but

- **No compromise of PSK.**
  - Limitation of CryptoVerif: cannot prove forward secrecy wrt. to the compromise of PSK for PSK-DHE.

- **Weaker properties for 0-RTT:**
  - **Key authentication:** No authentication for $ets_c$:
    - several binders, and only one of them is checked;
    - the adversary can alter the others, yielding a different $ets_c$ server-side.
  - **Replay prevention:** No replay protection for $ets_c$.
  - **Secrecy of keys:** The keys $ets_c$ server-side are not independent of each other, due to the replay.
For 0-RTT, we show:

- **Client-side**: The keys $ets_c$ are indistinguishable from independent random values.

- **Server-side**:
  - If the received ClientHello message has been sent by the client, then this session matches a session of the client with same key $ets_c$.
  - Otherwise,
    - If the ClientHello message has been received before, then the key $ets_c$ computed by the server is the same as in the previous session with the same ClientHello message.
    - Otherwise, the key $ets_c$ computed by the server is indistinguishable from a fresh random value, independent from other keys.
Record protocol

The client and the server share a fresh random traffic secret.

- **Key secrecy**: The updated traffic secret is indistinguishable from a fresh random value.
- **Message secrecy**: When the adversary provides two sets of plaintexts \( m_i \) and \( m'_i \) of the same padded length, it is unable to determine which set is encrypted, even when the updated traffic secret is leaked.
- **Message Authentication**: If a message \( m \) is decrypted by the receiver with a counter \( c \), then the message \( m \) has been encrypted and sent by an honest sender with the same counter \( c \).
- **Replay Prevention**: The authentication property above is injective.
Composition

Handshake without pre-shared key

Handshake with pre-shared key

Record protocol

updated \( ts \)

\( ats_c \)  \( ats_s \)  \( psk' \)  \( ets_c \)
Composition: main theorem (informal)

- **System S**: key exchange; $A$ and $B$ obtain a key such that:
  - **Key secrecy**: The keys obtained by $A$ are indistinguishable from independent random values.
  - **One-way injective authentication**: For each session of $B$ that obtains a key $k$ after sending/receiving $\overline{\text{msg}}$, there is a distinct session of $A$ that obtains the key $k$ after sending/receiving $\overline{\text{msg}}$.
  - **Same key**: If $B$ obtains a key $k$ after sending/receiving $\overline{\text{msg}}$ and $A$ obtains a key $k'$ after sending/receiving $\overline{\text{msg}}$, then $k = k'$.

- **System S'** assumes a fresh random key shared by $A'$ and $B'$.

- The composed system $S_{\text{composed}}$ runs the key exchange followed by $A'$ with the key obtained by $A$ and $B'$ with the key obtained by $B$.

- The security properties of $S$ and $S'$ carry over to $S_{\text{composed}}$. 
Composition (in progress)

- The previous theorem allows to perform most compositions.
- More tricky composition theorems for 0-RTT, because the properties are weaker.
- A simpler composition theorem for key update.
Mechanized computational proof: conclusion

- **Mechanized verification of TLS 1.3 Draft-18 in the computational model.**
  - + Handshake with PSK and/or DHE.
  - + Handshake with and without client authentication.
  - + 0-RTT and 0.5-RTT data, key updates.
  - — No post-handshake authentication.
  - — No version or ciphersuite negotiation: only strong algorithms.
  - — For PSK-DHE, we do not prove forward secrecy wrt. the compromise of PSK.

- **CryptoVerif** proves properties of the handshake with (resp. without) pre-shared-key and of the record protocol.

- We infer properties of the whole system by **manual composition**.

- **Modular** approach essential to be able to handle such a complex protocol.

- **TLS 1.3 Draft-18 is well-designed** to allow such a proof.
RefRLS: a reference implementation

- **Supports TLS 1.0-1.3 and interoperates with other libraries**
  - Supports Draft 20 1-RTT with (EC)DHE and/or PSK (No 0-RTT)
  - Supports common TLS 1.2 modes (RSA, DHE with AES-CBC, AES-GCM)

- **Distributed as a JavaScript library for ease of deployment**
  - Can be used within Node.js and Electron apps
  - Meant for early adopters and interop testing, **not for production code!**

- **We extract core protocol functions from the implementation**
  - Ensures that we did not miss some RFC/implementation details
  - **Other parts of the implementation are not verified (unlike miTLS)**
RefTLS architecture

Mostly written in Flow

- Statically-typed JavaScript
- Identify, isolate protocol core
- Protocol state machine
- Includes all crypto processing: encryption, signing, DHE, ...

Core written in ProScript

- Typed JavaScript subset that can be compiled to ProVerif
  [Kobeissi et al. EuroS&P’17]
Results and limitations

- We present a comprehensive analysis of TLS 1.3 draft 18
  - Symbolic analysis, cryptographic proofs, a reference implementation
- Many limitations, missing features, unverified components
  - Symbolic model ignores resumption, post-handshake authentication
  - Crypto proof ignores negotiation, legacy versions, post-handshake authentication
  - Unverified protocol code: message parsing, crypto library, Node

http://github.com/inria-prosecco/reftls