Verified Models and Reference Implementations for the TLS 1.3 Standard Candidate

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  - After 20 drafts, on the verge of standardization

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  - Security: remove broken legacy crypto constructions

Attacks against TLS 1.2

RC4	Keystream biases	[Mar'13]
Lucky13	MAC-Encode-Encrypt CBC	[Mar'13]
POODLE	SSLv3 MAC-Encode-Encrypt	[Dec'14]
FREAK	Export-grade 512-bit RSA	[Mar'15]
LOGJAM	Export-grade 512-bit DH	[May'15]
SLOTH	RSA-MD5 signatures	[Jan'16]
DROWN	SSLv2 PSA-PKCS#1v1.5 Enc	[Mar'16]
SWEET32	3DES Encryption	[Oct'16]

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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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  - 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)
    [Dowling et al. CCS'15, Krawczyk et al. EuroS&P'16, Li et al. S&P'16]
  - 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?

TLS 1.2 and its proofs: a checkered history

Historically, published proofs of TLS missed many attacks

Large gaps between simplified models and the deployed protocol

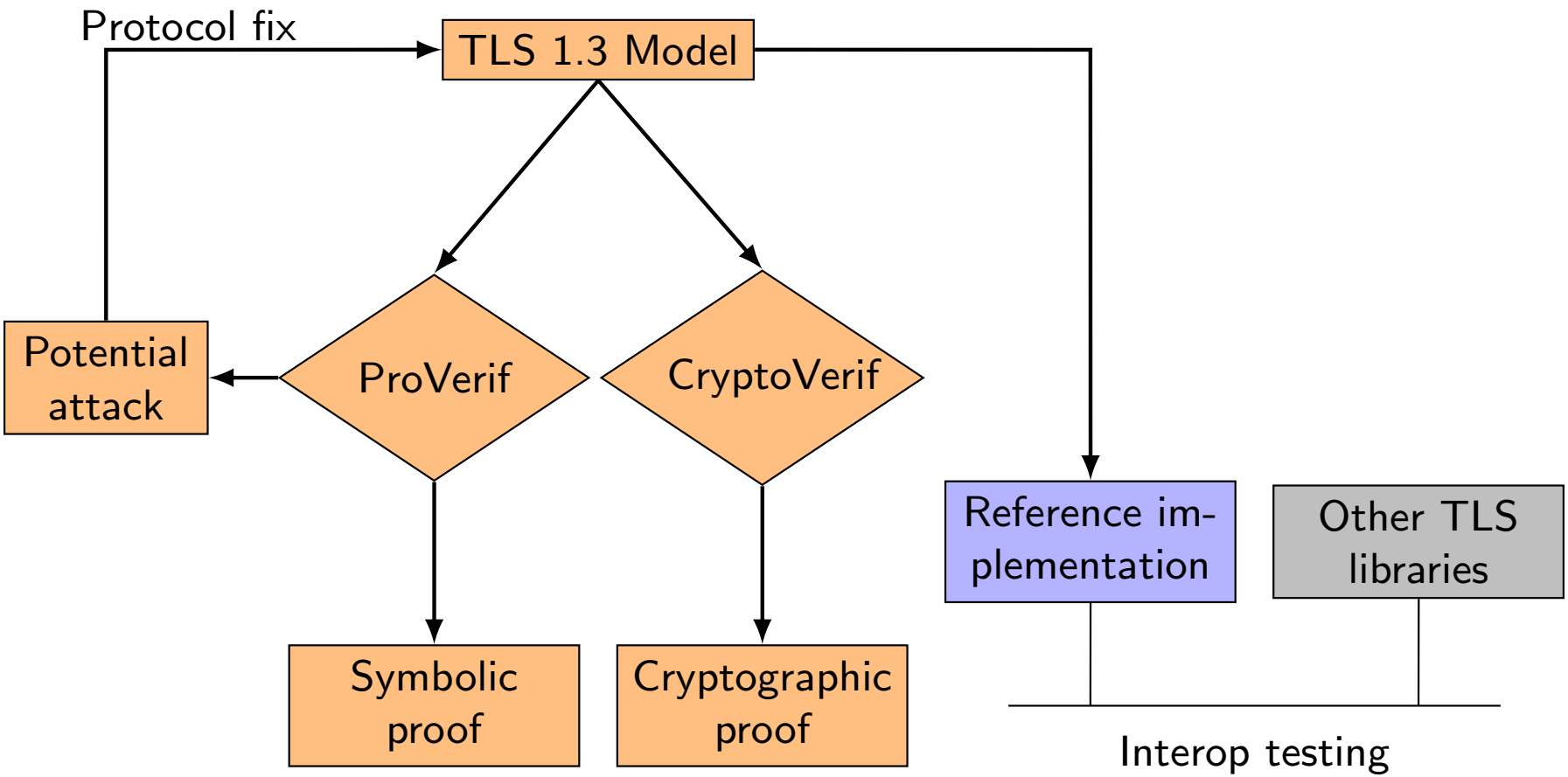
1. Proofs ignored "ugly" implementation details
   - e.g. AES-CBC padding, RSA-PKCS#1v1.5 padding
2. Proofs relied on strong crypto assumptions on primitives
   - e.g. collision resistant hash functions, strong Diffie-Hellman groups
3. Proofs ignored composition with obsolete/unpopular modes
   - e.g. SSLv2, EXPORT ciphers, renegotiation

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

Our approach

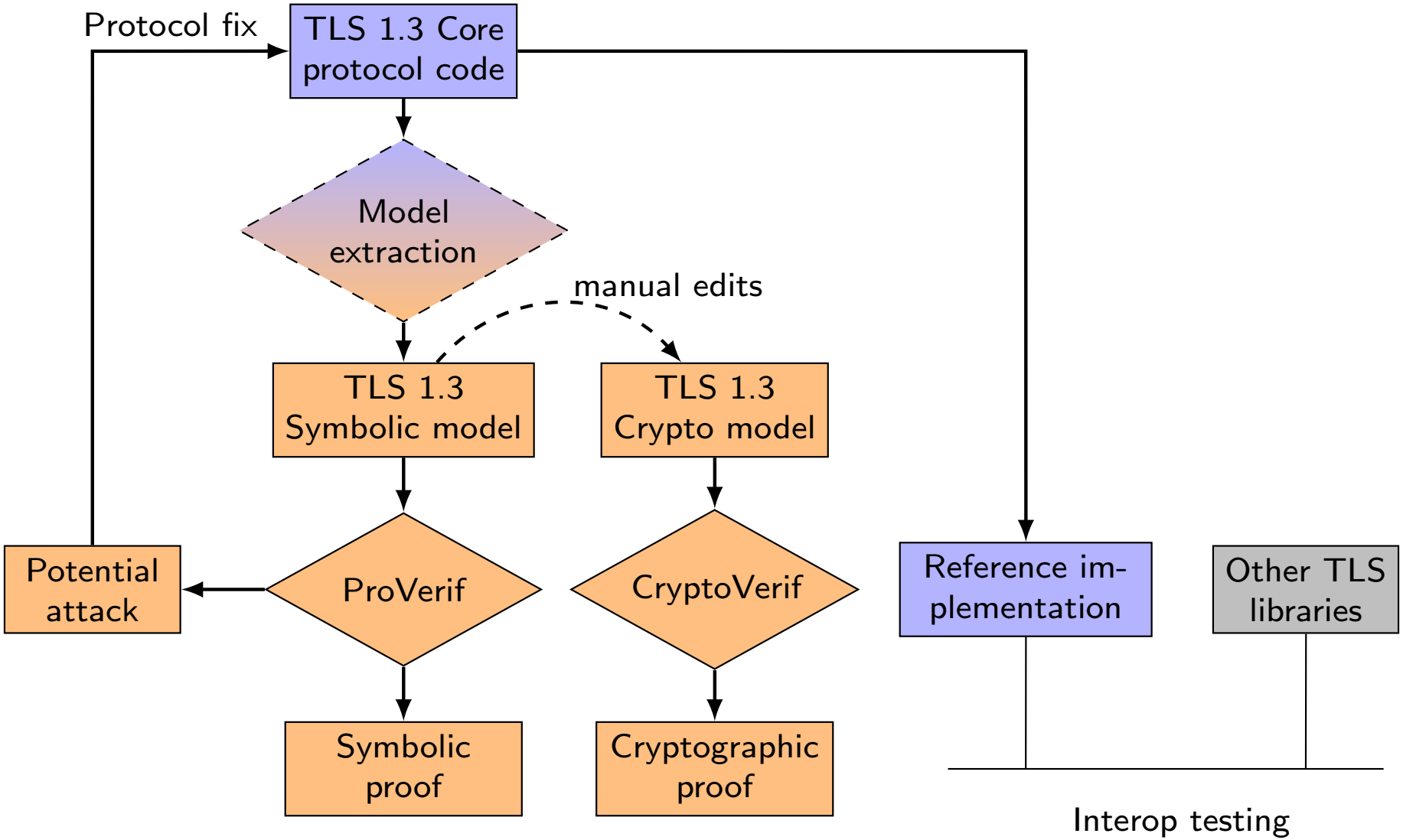
- Use automated verification tools to handle protocol complexity
  - Easy to extend as protocol evolves, or as we model new features
- Symbolically analyze protocol against known attack vectors
  - Find or prove the absence of downgrade attacks to TLS 1.2 (using ProVerif)
- Build a mechanically-checked 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



(Inspired by: Verified interoperable implementations of security protocols, TOPLAS 2008.)

Our current toolchain



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
reduc 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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  - 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

Modeling TLS 1.3 in ProVerif

TLS 1.3 1-RTT handshake

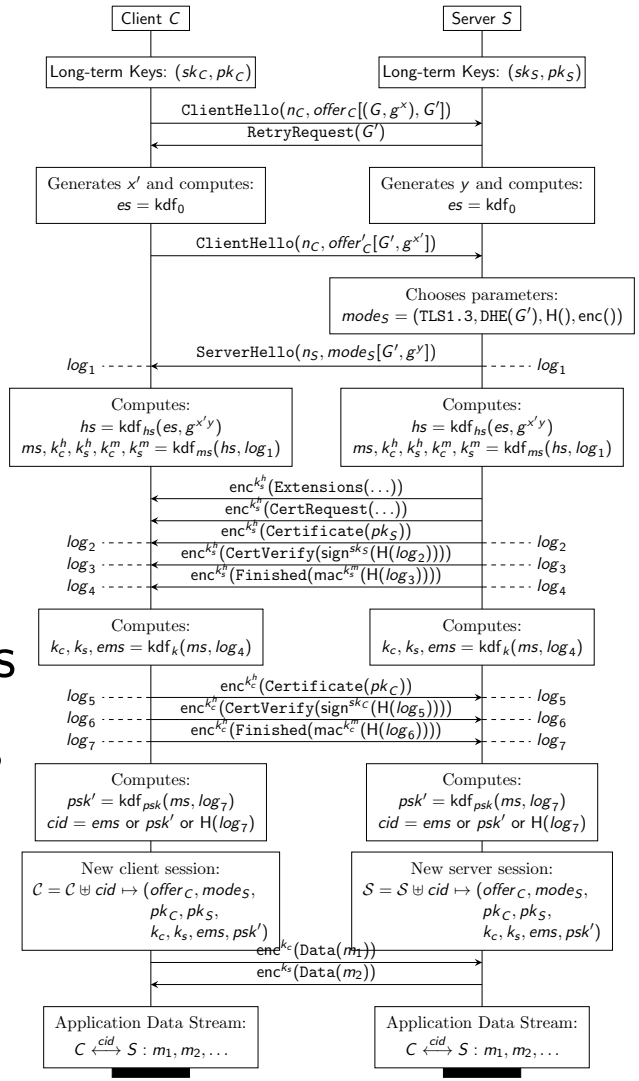
- 12 messages in 3 flights, 16 derived keys, then data exchange

+ PSK-based 0-RTT

+ TLS 1.2

- Agile Crypto: ∼400 lines
- TLS models: ∼500 lines

Modeling is easy, verification takes effort



Key Derivation Functions:

$\text{HKDF-Extract}(k, s) = \text{HMAC-H}^k(s)$

$\text{hkdf-expand-label}_1(s, l, h) =$
$\text{HMAC-H}^s(len_{\text{H}()} \| \text{“TLS 1.3,”} \| l \| h \| 0x01)$

$\text{Derive-Secret}(s, l, m) =$
$\text{hkdf-expand-label}_1(s, l, \text{H}(m))$

1-RTT Key Schedule:

$\text{kdf}_0 = \text{HKDF-Extract}(0^{len_{\text{H}()}}, 0^{len_{\text{H}()}})$

$\text{kdf}_{hs}(es, e) = \text{HKDF-Extract}(es, e)$

$\text{kdf}_{ms}(hs, log_1) = ms, k_c^h, k_s^h, k_c^m, k_s^m$ where
$ms = \text{HKDF-Extract}(hs, 0^{len_{\text{H}()}})$
$hts_c = \text{Derive-Secret}(hs, \text{hts}_c, log_1)$
$hts_s = \text{Derive-Secret}(hs, \text{hts}_s, log_1)$
$k_c^h = \text{hkdf-expand-label}(hts_c, \text{key}, \text{“”})$
$k_c^m = \text{hkdf-expand-label}(hts_c, \text{finished}, \text{“”})$
$k_s^h = \text{hkdf-expand-label}(hts_s, \text{key}, \text{“”})$
$k_s^m = \text{hkdf-expand-label}(hts_s, \text{finished}, \text{“”})$

$\text{kdf}_k(ms, log_4) = k_c, k_s, ems$ where
$atc_c = \text{Derive-Secret}(ms, \text{ats}_c, log_4)$
$ats_s = \text{Derive-Secret}(ms, \text{ats}_s, log_4)$
$ems = \text{Derive-Secret}(ms, \text{ems}, log_4)$
$k_c = \text{hkdf-expand-label}(ats_c, \text{key}, \text{“”})$
$k_s = \text{hkdf-expand-label}(ats_s, \text{key}, \text{“”})$

$\text{kdf}_{psk}(ms, log_7) = psk'$ where
$psk' = \text{Derive-Secret}(ms, \text{rms}, log_7)$

PSK-based Key Schedule:

$\text{kdf}_{es}(psk) = es, k^b$ where
$es = \text{HKDF-Extract}(0^{len_{\text{H}()}}, psk)$
$k^b = \text{Derive-Secret}(es, \text{pbk}, \text{“”})$

$\text{kdf}_{0RTT}(es, log_1) = k_c$ where
$ets_c = \text{Derive-Secret}(es, \text{ets}_c, log_1)$
$k_c = \text{hkdf-expand-label}(ets_c, \text{key}, \text{“”})$

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 msg($conn, S$) sent from anonymous C to server S

$$\textbf{query}\ \text{attacker}(\text{msg}(conn, S)) \Longrightarrow \text{false}$$

Refining security queries

- QUERY: is msg($conn, S$) secret?

$$\textbf{query}\ \text{attacker}(\text{msg}(conn, S)) \Longrightarrow \text{false}$$

- FALSE: ProVerif finds a counterexample if S's private key is compromised.

Refining security queries

- QUERY: is msg($conn, S$) secret
  as long as S is uncompromised?

$$\textbf{query}\ \text{attacker}(\text{msg}(conn, S)) \Longrightarrow \text{event}(\text{WeakOrCompromisedKey}(S))$$

- 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

$$\begin{aligned}\textbf{query}\ & \mathrm{attacker}(\mathrm{msg}(\mathit{conn}, S)) \Longrightarrow \\ & \mathrm{event}(\mathrm{WeakOrCompromisedKey}(S)) \vee \\ & \mathrm{event}(\mathrm{ServerChoosesAE}(\mathit{conn}, S, \mathit{WeakAE})) \vee \\ & \mathrm{event}(\mathrm{ServerChoosesKEX}(\mathit{conn}, S, \mathit{WeakDH})) \vee \\ & \mathrm{event}(\mathrm{ServerChoosesKEX}(\mathit{conn}', S, \mathit{WeakRSADecryption})) \vee \\ & \mathrm{event}(\mathrm{ServerChoosesHash}(\mathit{conn}', S, \mathit{WeakHash}))\end{aligned}$$

- 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, http://cryptoverif.inria.fr/

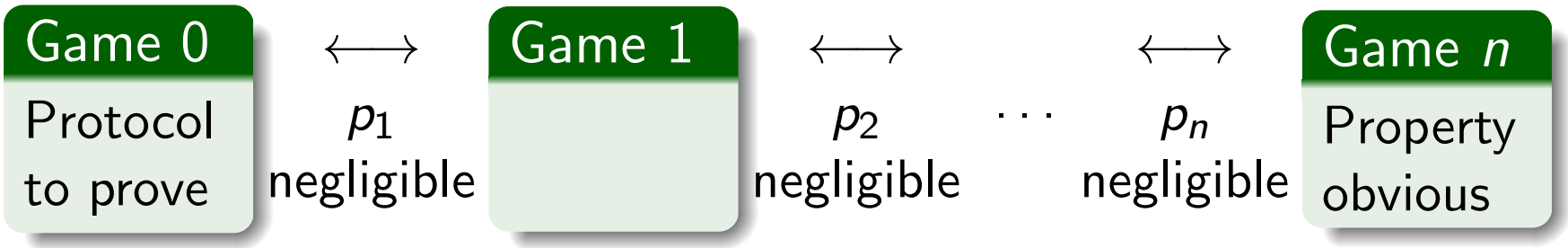
CryptoVerif is a semi-automatic prover that:

- 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.)



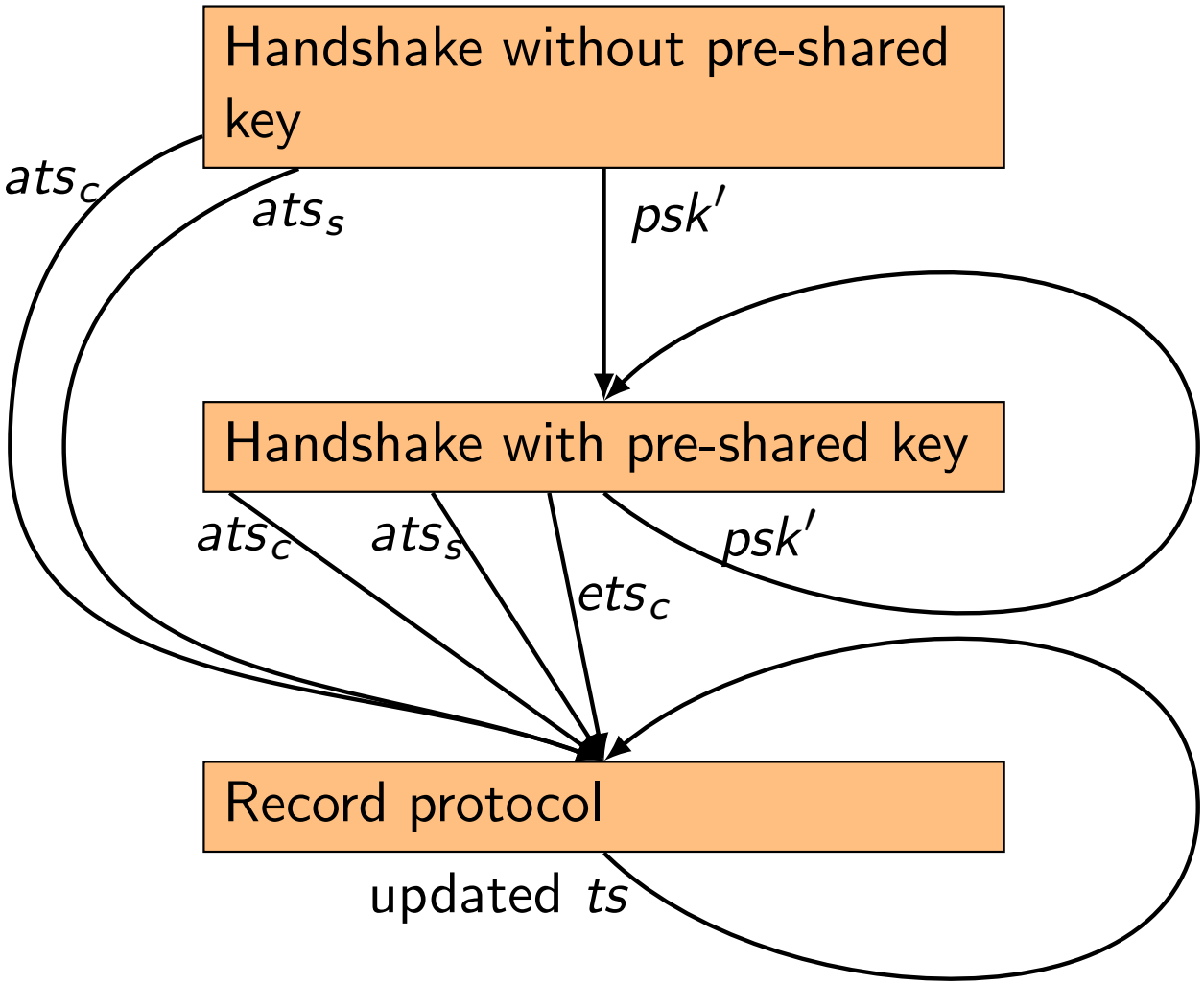
Input and output of the tool

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.

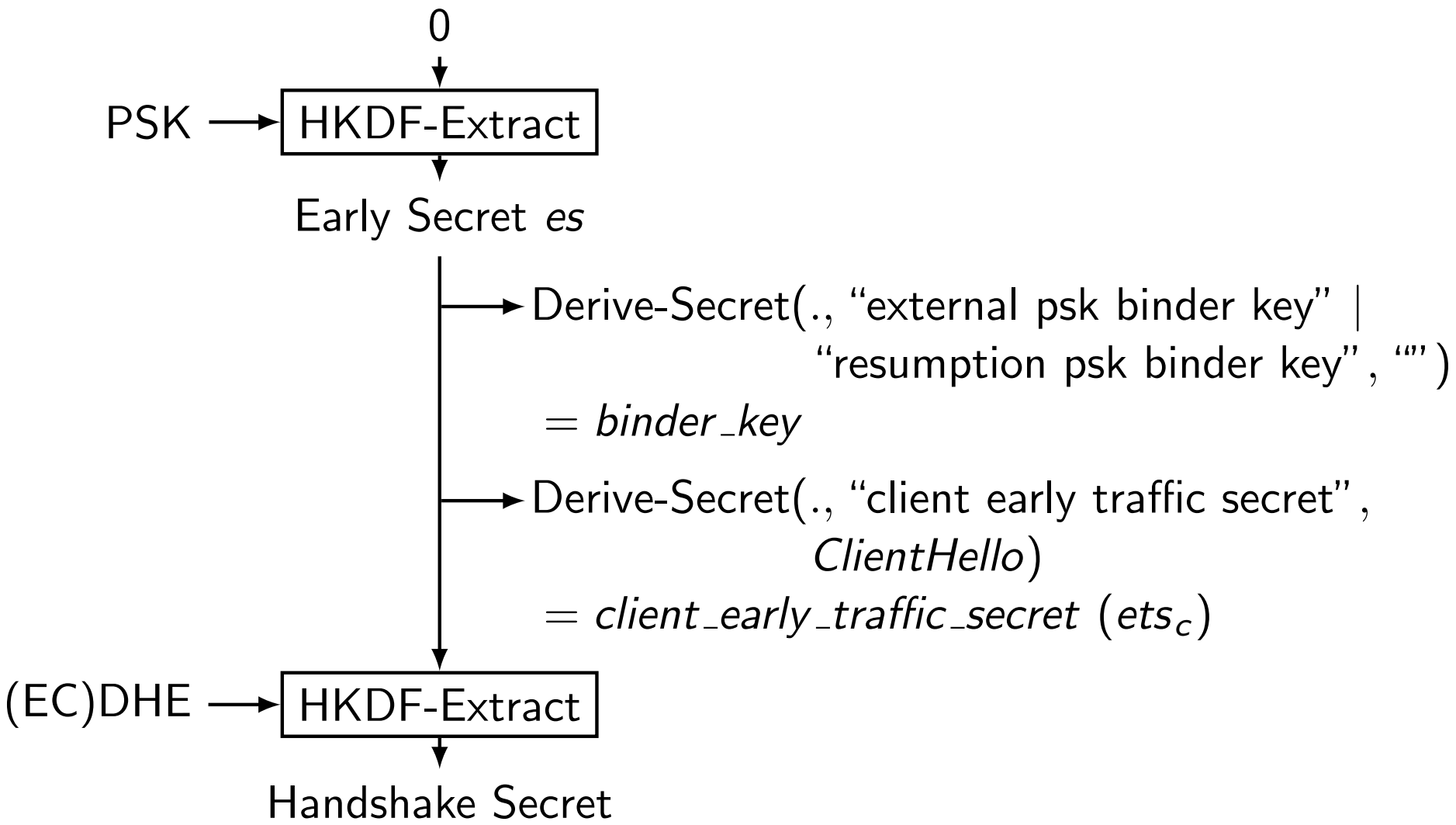
Structure of the proof

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



Key schedule (Draft-18, excerpt)



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 $0^{len_{\mathsf{H}()}}$
    - avoids confusion between handshakes with and without Diffie-Hellman exchange.
  - Diffie-Hellman group elements different from $len_{\mathsf{H}()} \| \text{“}\mathtt{TLS\ 1.3,}\text{”} \| l \| h \| \mathtt{0x01}$.
    - 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:
  - $x \mapsto \text{HMAC-H}^{0^{len_{\text{H}()}}}(x)$ and $x \mapsto \text{HMAC-H}^{\text{kdf}_0}(x)$ are independent random oracles.
  - HMAC-H is a PRF, for keys different from $0^{len_{\text{H}()}}$ and 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

- $\mathsf{mac}_{\mathsf{H}}^{k}(m) = \mathsf{mac}^{k}(\mathsf{H}(m))$ is an SUF-CMA MAC.
- $\mathsf{sign}_{\mathsf{H}}^{sk}(m) = \mathsf{sign}^{sk}(\mathsf{H}(m))$ is an UF-CMA signature.

Lemmas on primitives: key schedule

Lemma

When es is a fresh random value,

- $e \mapsto \text{HKDF-Extract}(es, e)$ *and*
- $log_1 \mapsto \text{Derive-Secret}(es, \text{ets}_c, log_1)$
  are indistinguishable from independent random functions, and
- $k^b = \text{Derive-Secret}(es, \text{pbk}, \text{“”})$ *and*
- $\text{HKDF-Extract}(es, 0^{len_{\text{H}()}})$
  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:
  - psk' or $\mathrm{H}(log_7)$:
    If a client session and a server session have the same psk' or $\mathrm{H}(log_7)$, then all their parameters are equal (collision-resistance).
  - *ems*:
    If a client session and a server session have the same *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 $x \mapsto \text{HMAC-H}^{\text{kdf}_0}(x)$.
- Replace variables that contain $g^{x'y}$ with their values to make equality tests $m = g^{x'y}$ appear.
- Gap Diffie-Hellman assumption.
- $\Rightarrow$ the handshake secret *hs* is a fresh random value.
- Lemmas on key schedule $\Rightarrow$ 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 $\mathrm{enc}^{k_t}(psk)$; 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.

Handshake with pre-shared key: security (2)

For 0-RTT, we show:

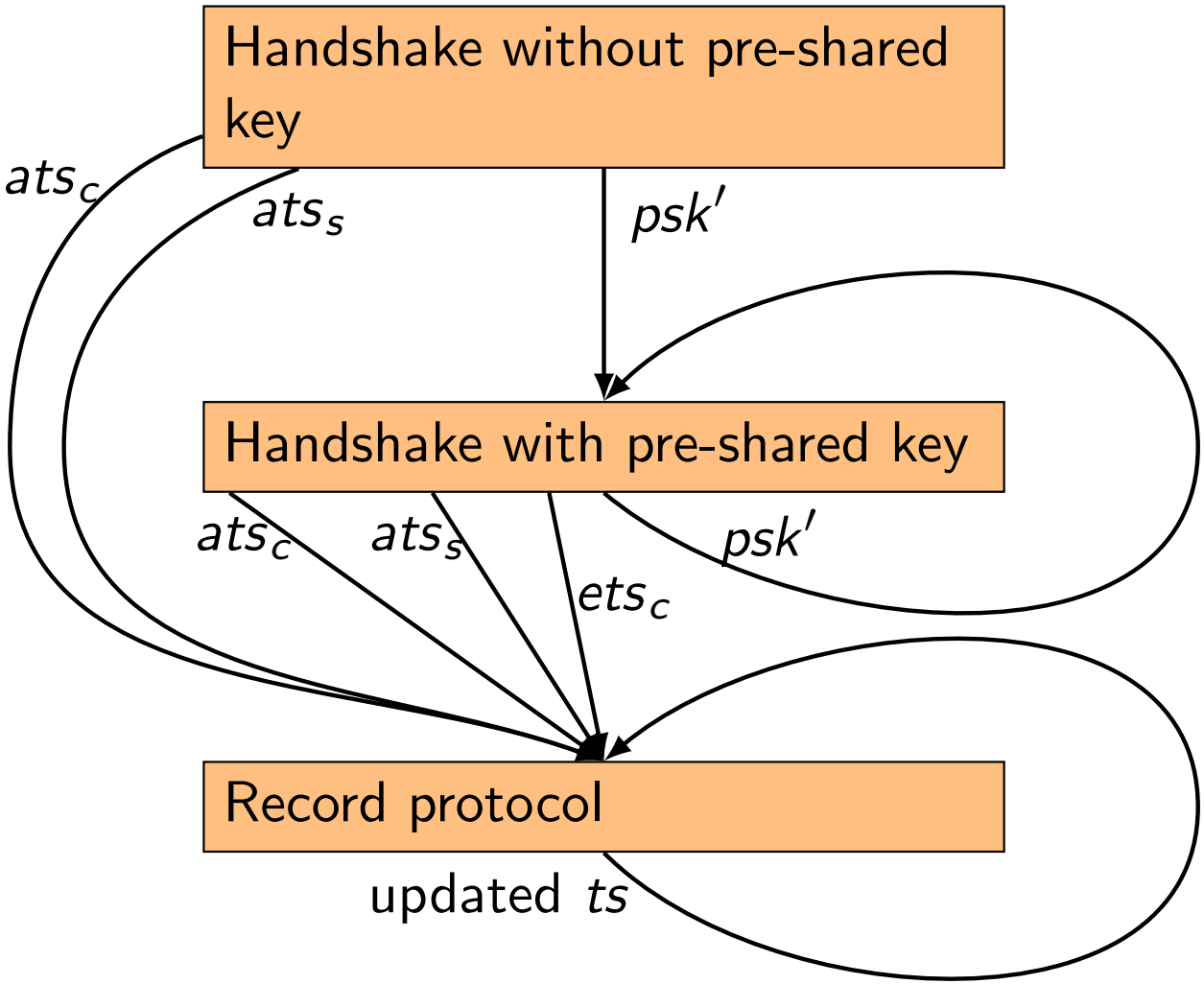
- Client-side: The keys ets_c are indistinguishable from independent random values.
- Server-side:
  - If the received ClientHello message has been sent by the client, then this session matches a session of the client with same key ets_c.
  - Otherwise,
    - If the ClientHello message has been received 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



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 $\widetilde{msg}$, there is a distinct session of A that obtains the key k after sending/receiving $\widetilde{msg}$.
  - Same key: If B obtains a key k after sending/receiving $\widetilde{msg}$ and A obtains a key k' after sending/receiving $\widetilde{msg}$, then $k = k'$.
- System S' assumes a fresh random key shared by A' and B'.
- The composed system $S_{composed}$ 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 $S_{composed}$.

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 detais
  - Other parts of the implementation are not verified (unlike miTLS)

RefTLS architecture

Mostly written in Flow

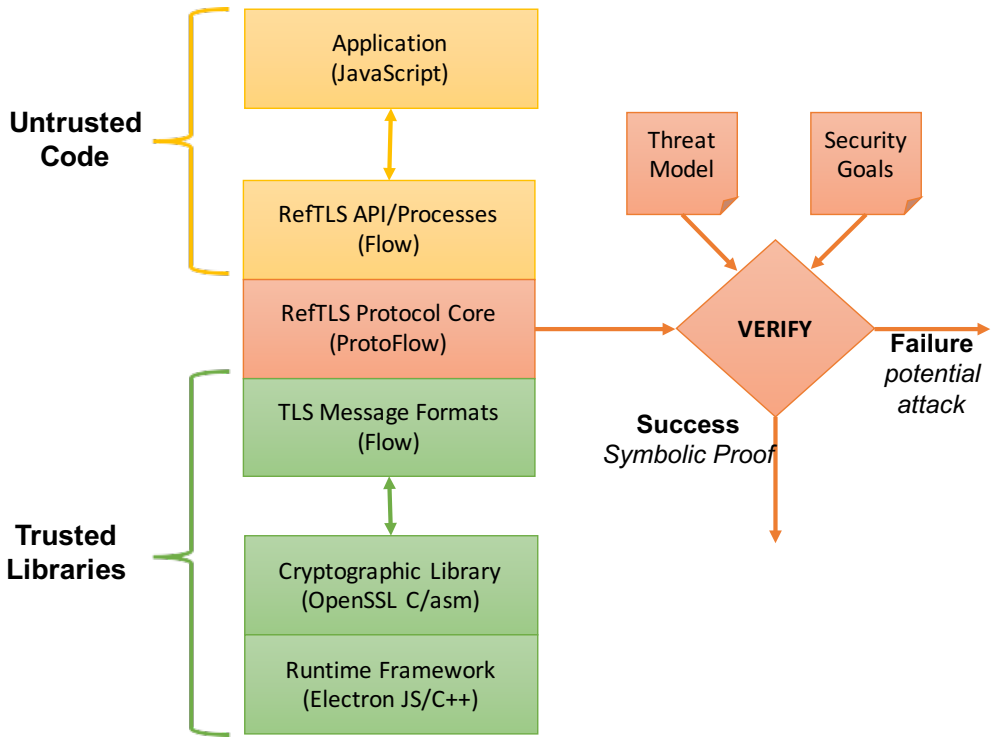
- Statically-typed JavaScript

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 comprehensize 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`