Noise*,
A Library of Verified High-Performance Secure Channel Protocol Implementations

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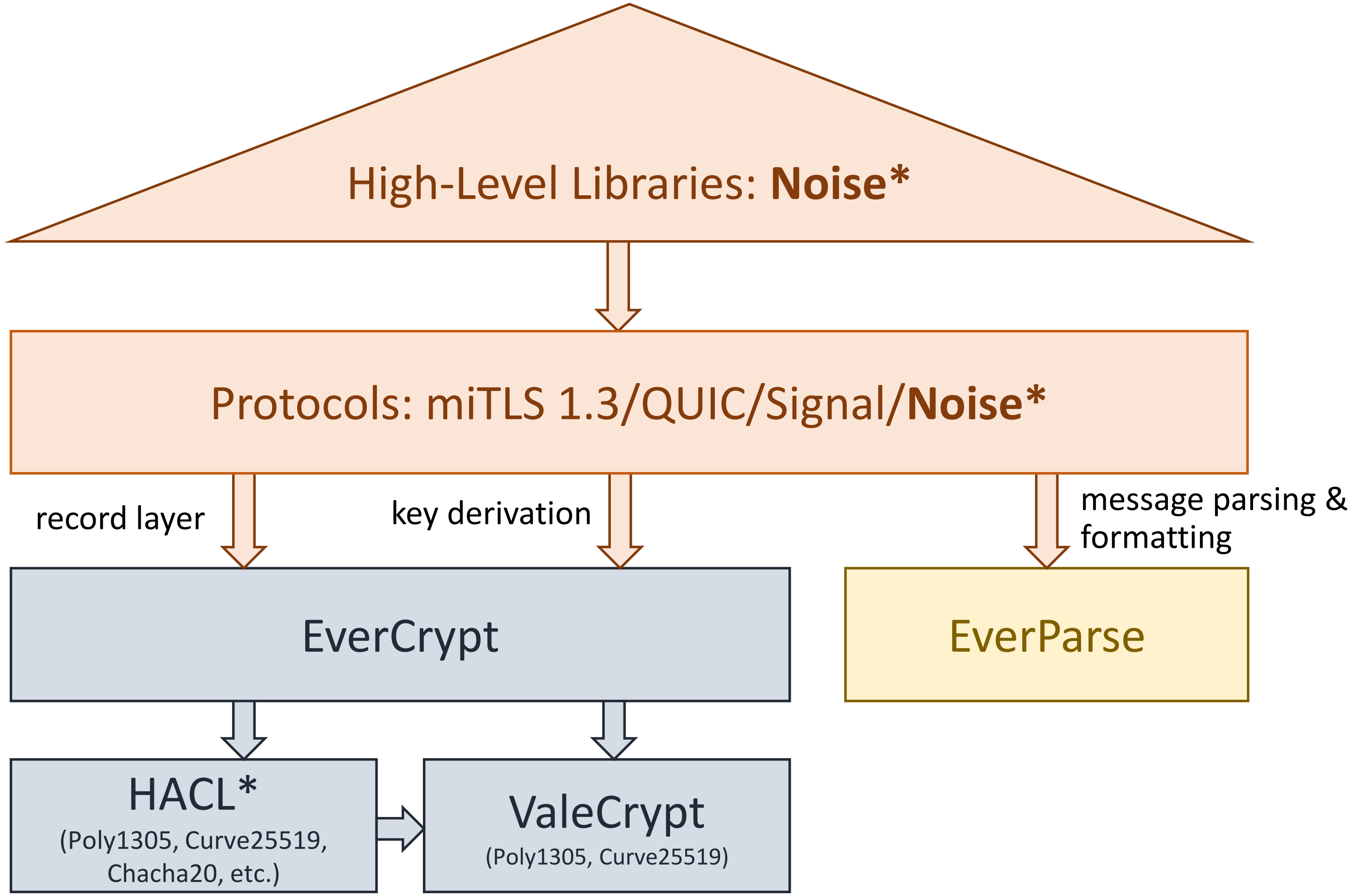
Everest: Verified Components for the HTTPS Ecosystem



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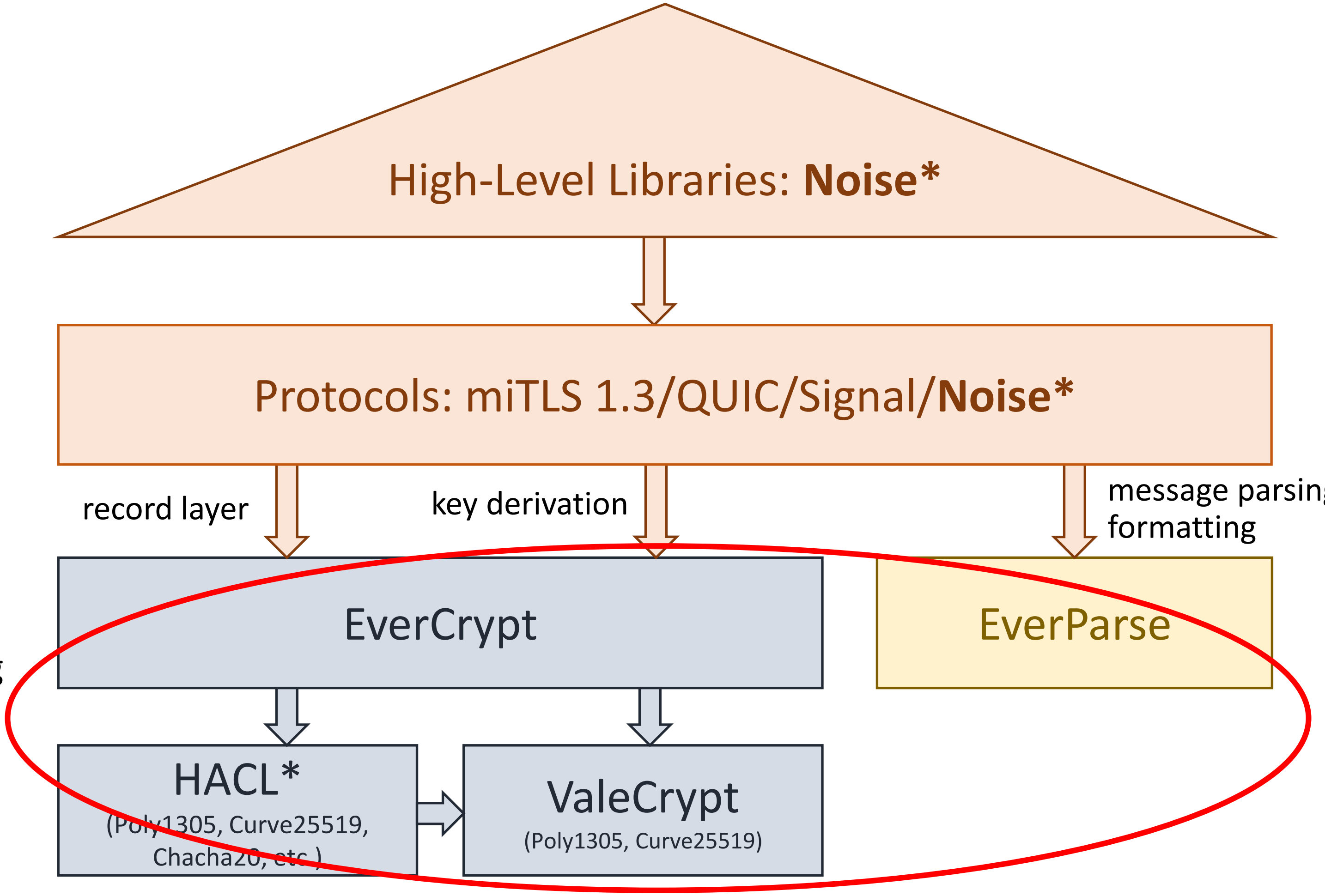

Memory and type safety (buffer overflows, dangling pointers...), functional correctness (optimized implementations are "correct"), side channels...

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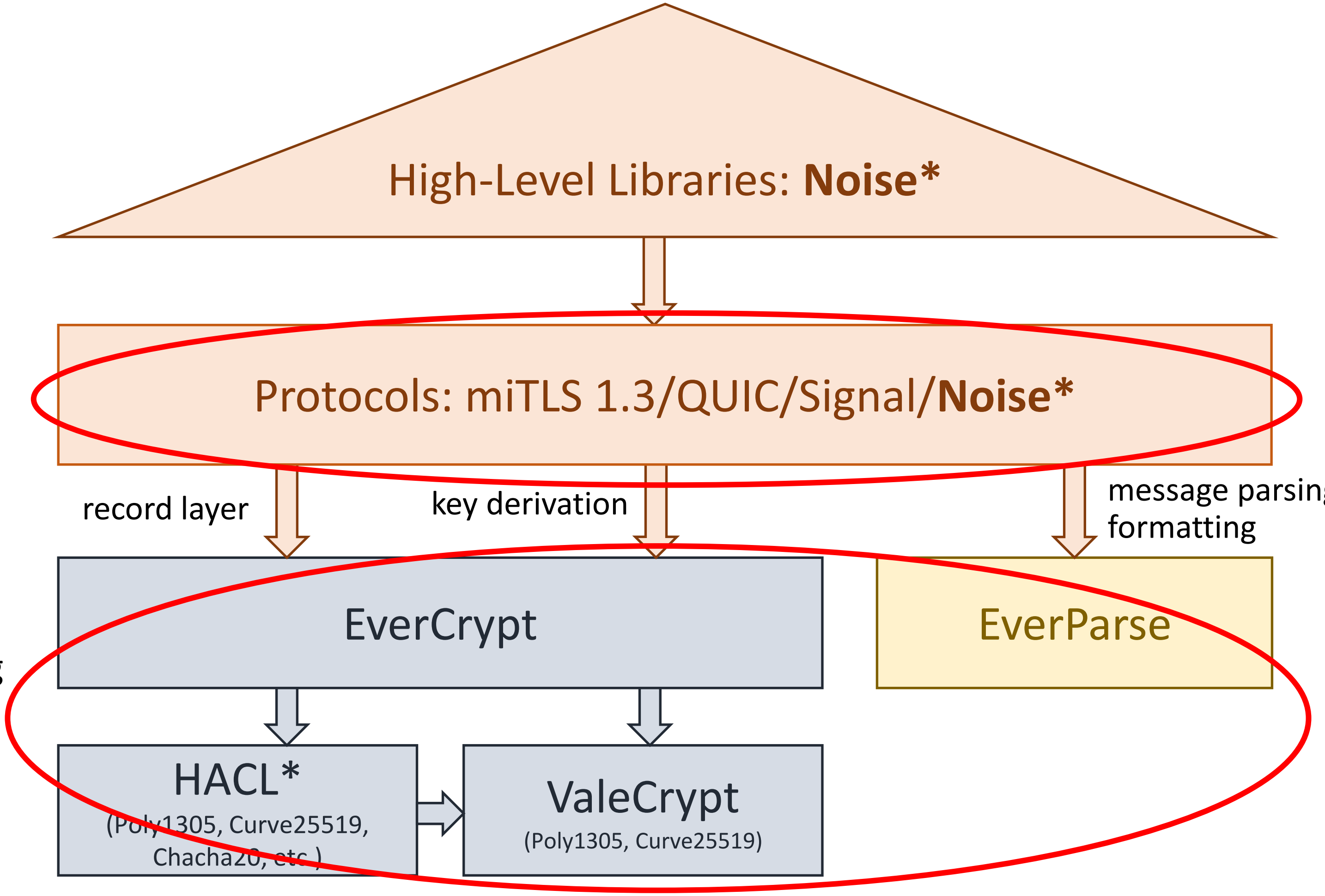

Security (secret data remains secret, message was sent by Alice...)...

Memory and type safety (buffer overflows, dangling pointers...), functional correctness (optimized implementations are "correct"), side channels...

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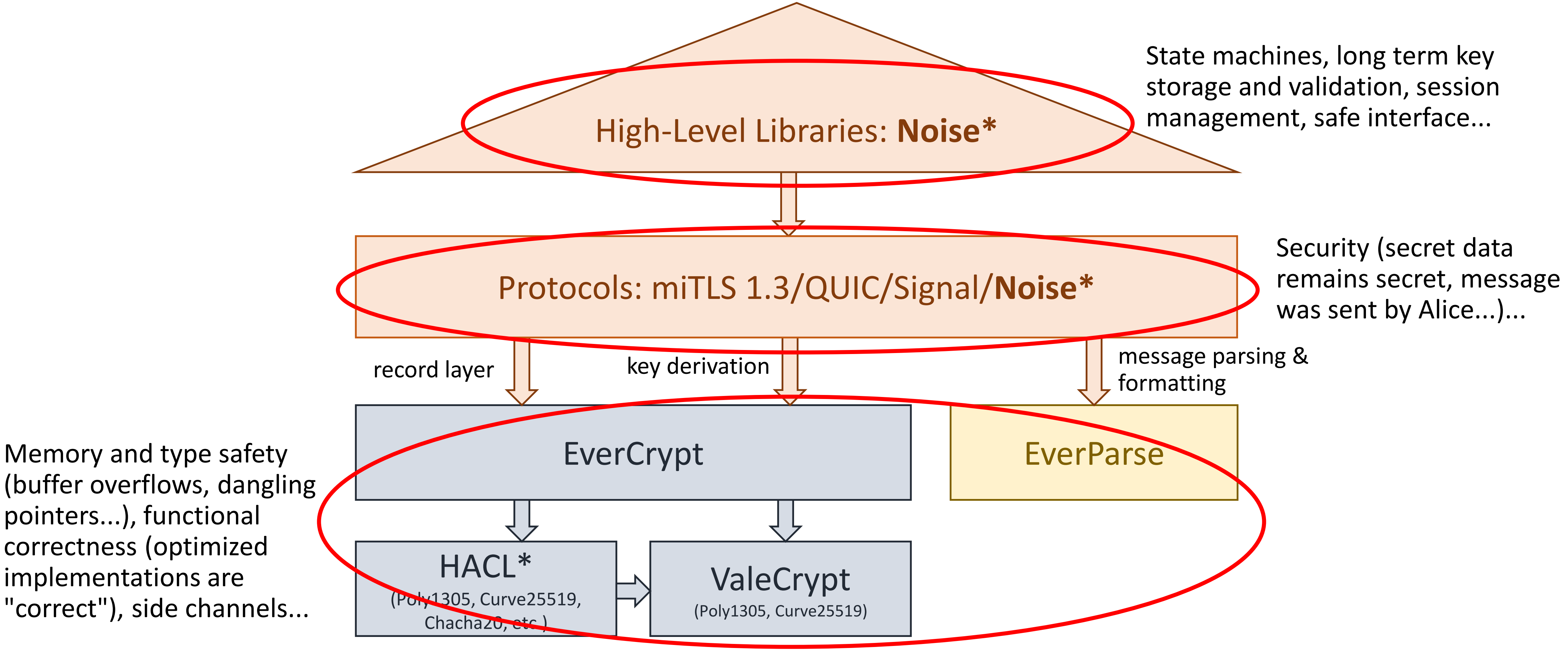

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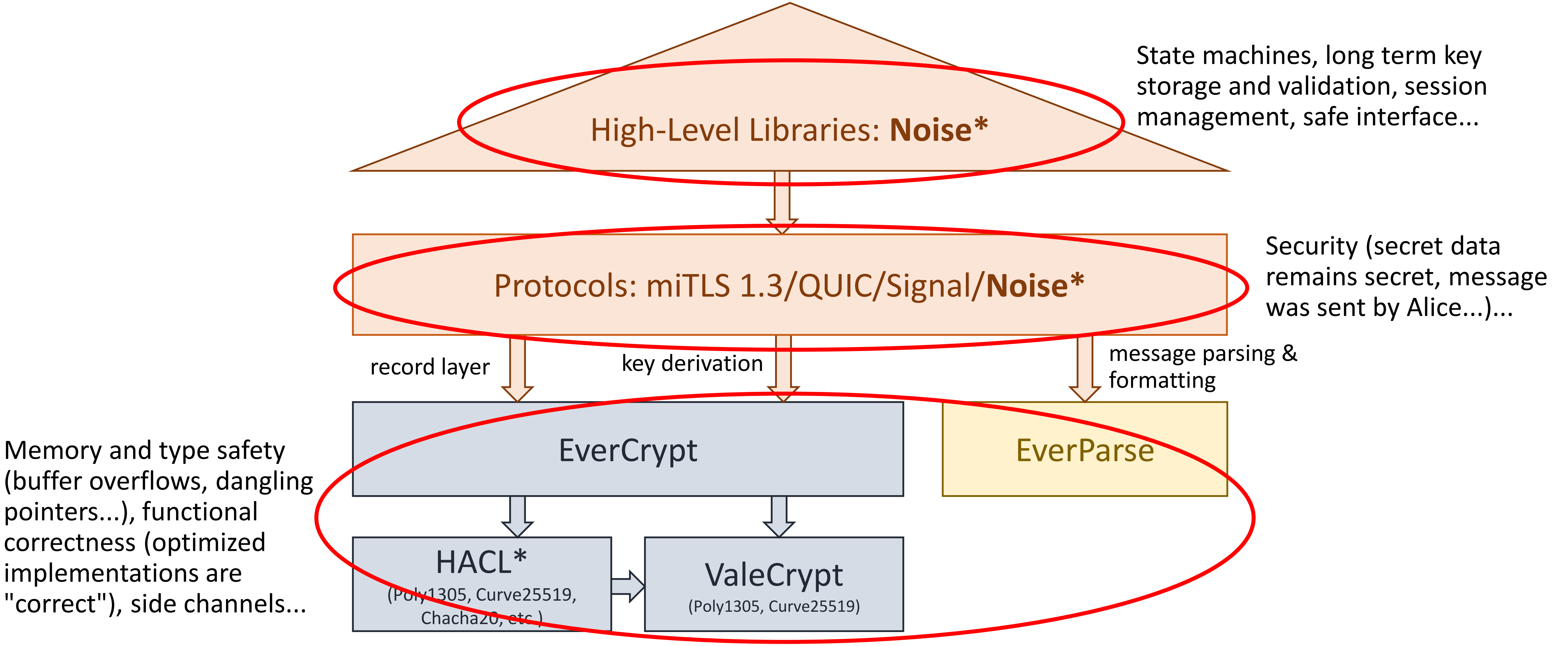

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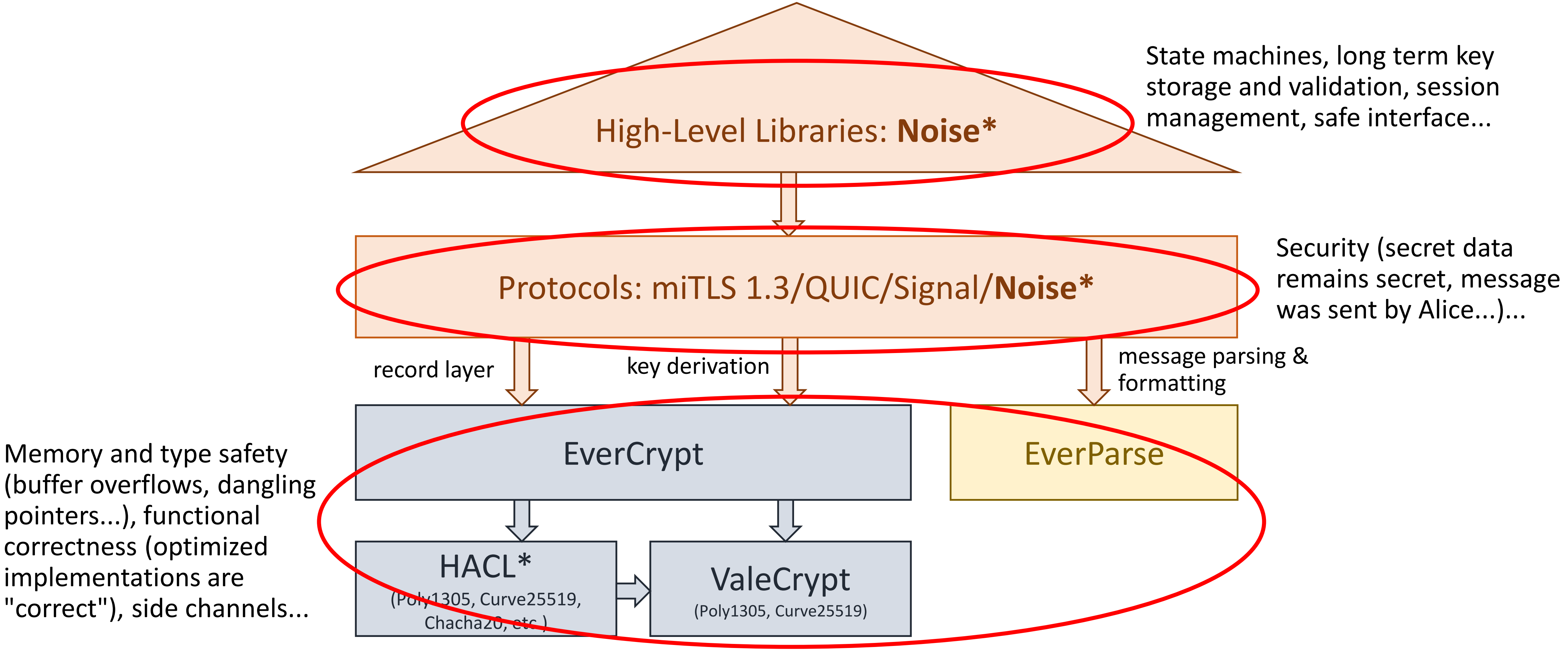

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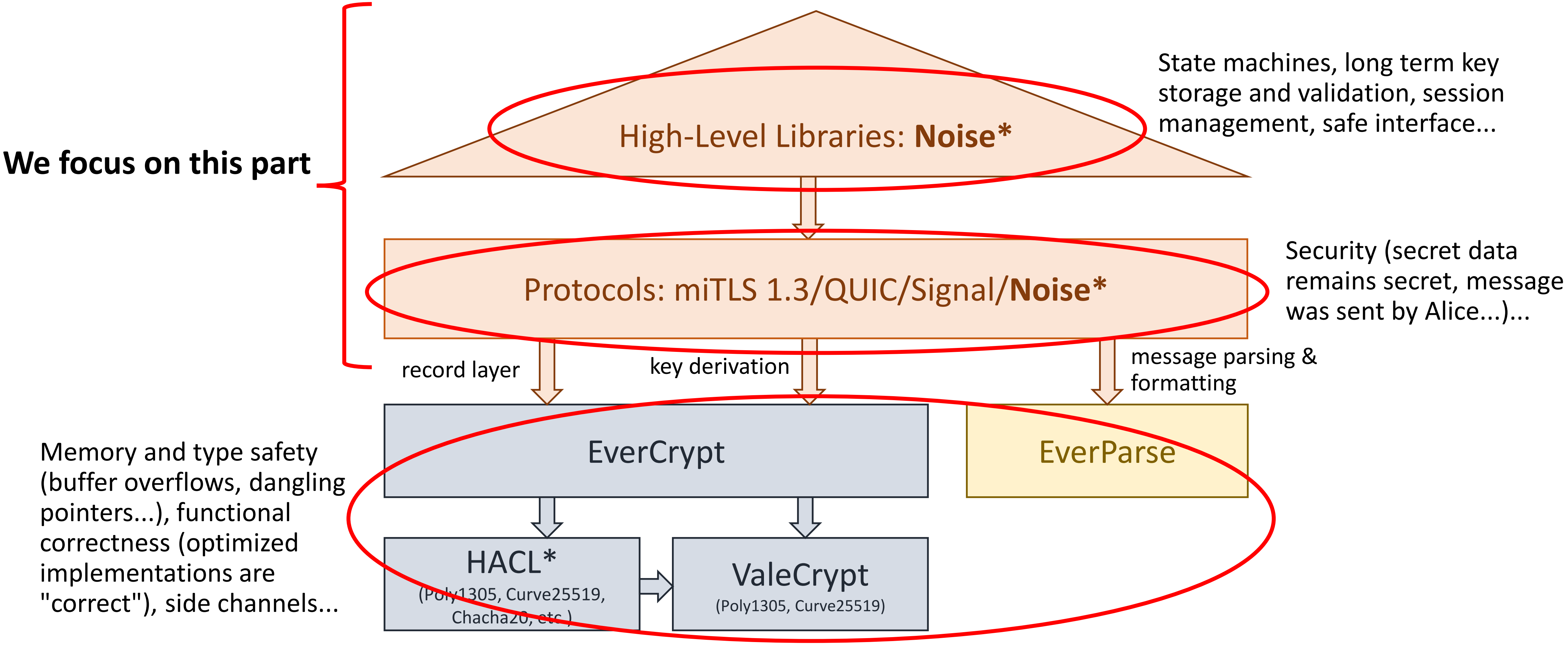

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  - Session resumption
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  - Session resumption
  - …
- When advanced features not needed: **Noise** family of protocols

Noise Protocol Framework : Examples

X:

← s

. . .

→ e, es, s, ss

IK:

← s

. . .

→ e, es, s, ss

← e, ee, se

IKpsk2:

← s

. . .

→ e, es, s, ss

← e, ee, se, psk

NX:

→ e

← e, ee, s, es

XX:

→ e

← e, ee, s, es

→ s, se

XK:

← s

. . .

→ e, es

← e, ee

→ s, se

Today: **59+ protocols** (but might increase)

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(one-way encryption: NaCl Box, HPKE...)

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(mutual authentication and 0-RTT)

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← e, ee, s, es

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XX:

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← e, ee, s, es

→ s, se

XK:

← s

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Today: **59+ protocols** (but might increase)

Noise Protocol Framework : Examples

X:

← s

. . .

→ e, es, s, ss

(one-way encryption: NaCl Box, HPKE...)

IK: **WhatsApp**

← s

. . .

→ e, es, s, ss

← e, ee, se

IKpsk2: **Wireguard VPN**

← s

. . .

→ e, es, s, ss

← e, ee, se, psk

(mutual authentication and 0-RTT)

NX:

→ e

← e, ee, s, es

(authenticated server)

XX:

→ e

← e, ee, s, es

→ s, se

XK: **Lightning, I2P**

← s

. . .

→ e, es

← e, ee

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Today: **59+ protocols** (but might increase)

Noise Protocol Example: IKpsk2

IKpsk2:

← s

. . .

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Noise Protocol Example: IKpsk2

IKpsk2:

← s

. . .

→ e, es, s, ss, [d0]

← e, ee, se, psk, [d1]

↔ [d2, d3, …]

Noise Protocol Example: IKpsk2

Initiator **Responder**

IKpsk2:

← s

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→ e, es, s, ss, [d0]

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The handshake describes how to:

- Exchange key material
- Use those to derive shared secrets (Diffie-Hellman operations…)
- Send/receive encrypted data

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s: static
e: ephemeral

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. . . **Derive shared secrets (Diffie-Hellman operations…)**

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← s

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→ e, es, s, ss, [d0]

← e, ee, se, psk, [d1] **Send/receive encrypted data**

↔ [d2, d3, …]

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Secrets are **chained**:
- d0 encrypted with a key derived from es, ss
- d1 encrypted with a key derived from es, ss, ee, se, psk

⇒ **The more the handshake progresses, the more secure the shared secrets are**

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Early data (TLS 0-RTT, 0.5-RTT)

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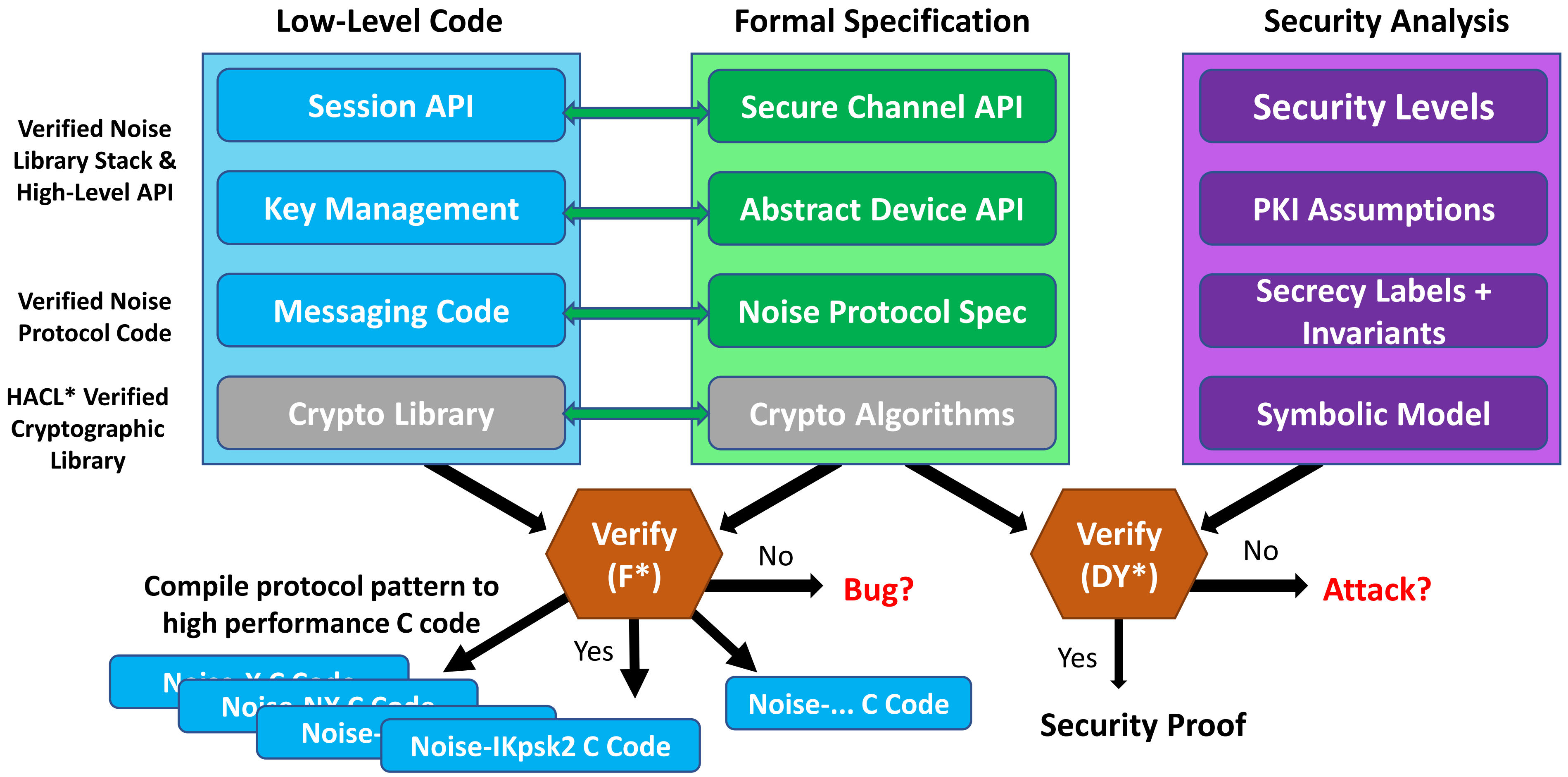
Correctly implemented protocols?

- **Noise* compiler**: Noise protocol "pattern" → verified, specialized C implementation
- On top: complete, verified **library stack** exposed through a **high-level, defensive API**
- Complemented with a formal **symbolic security analysis**



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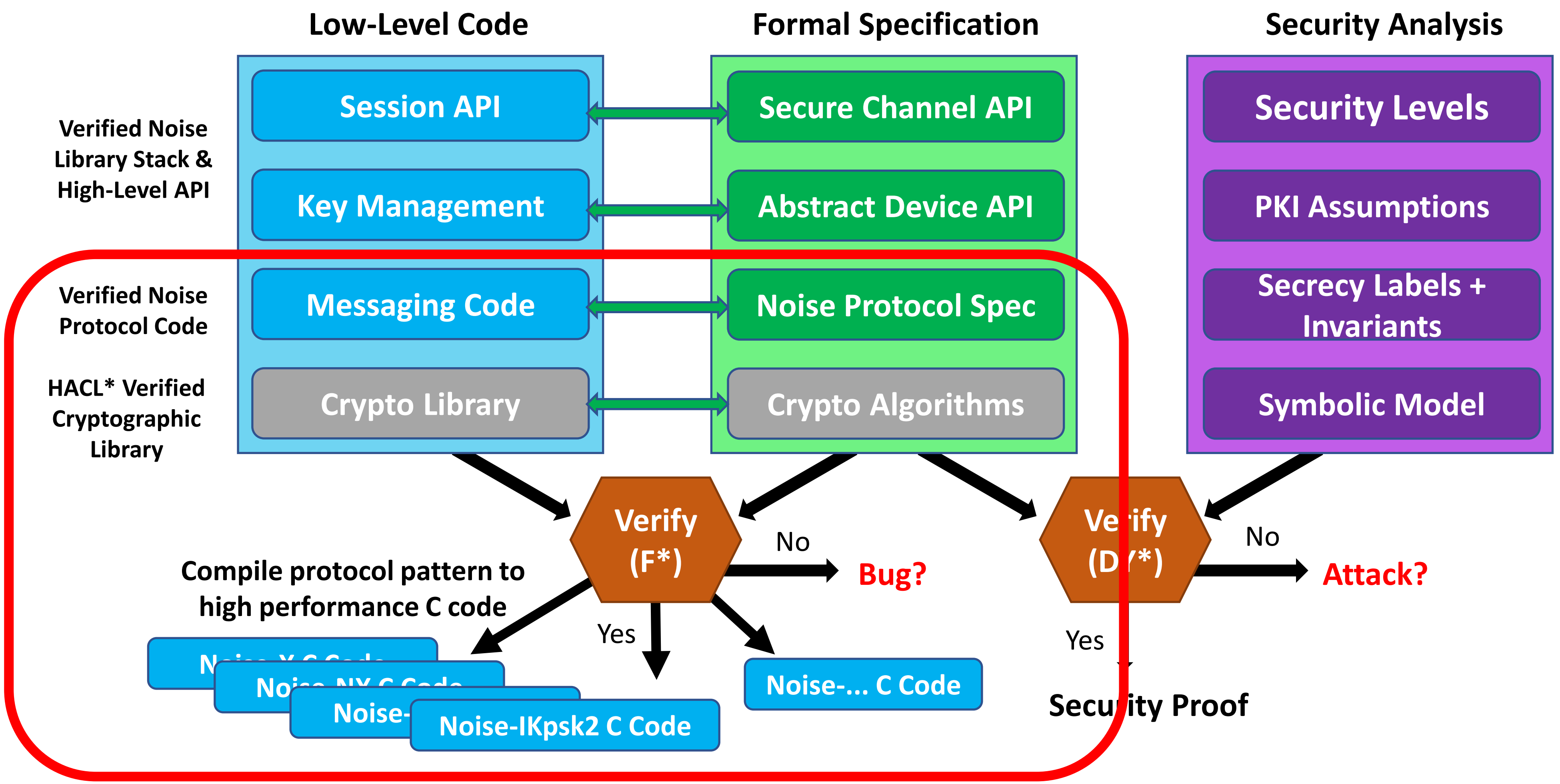

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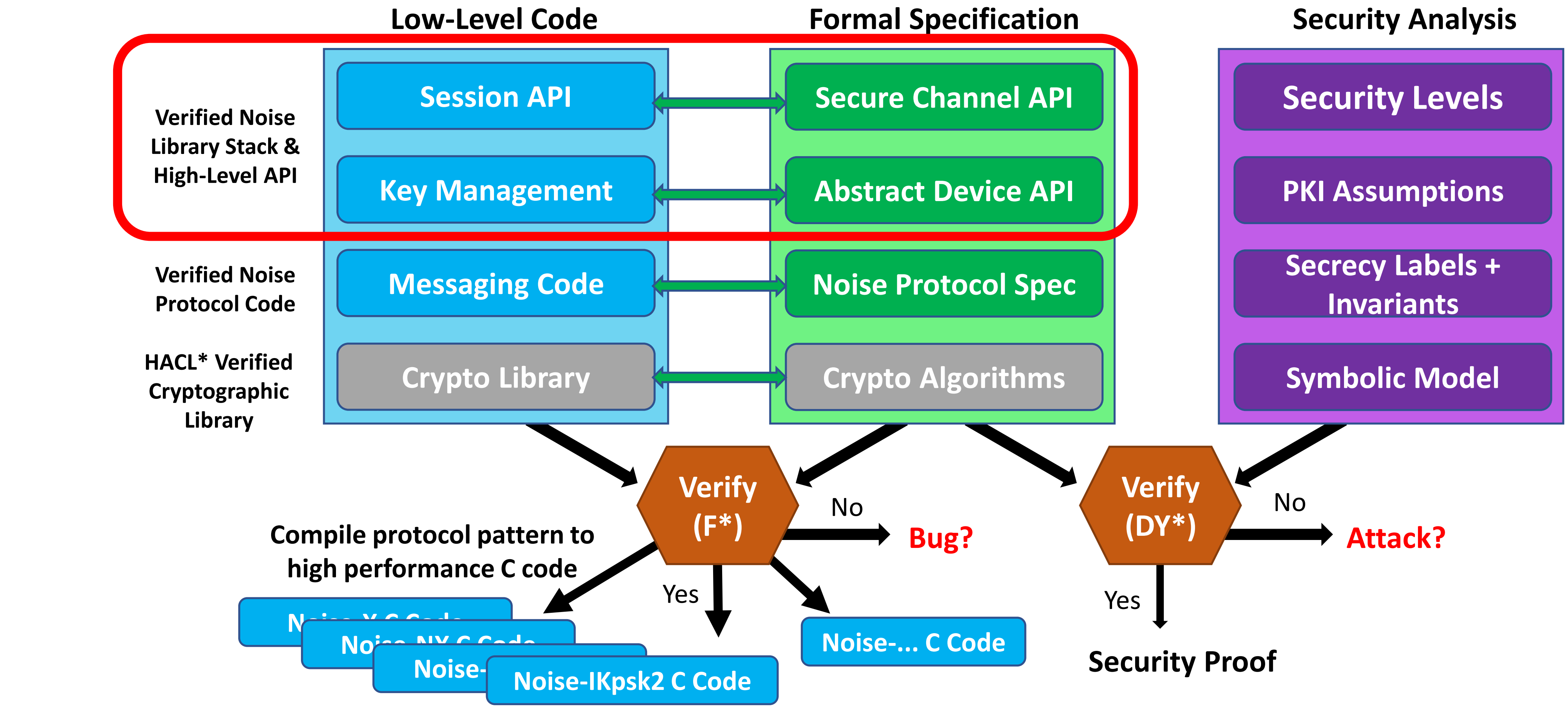

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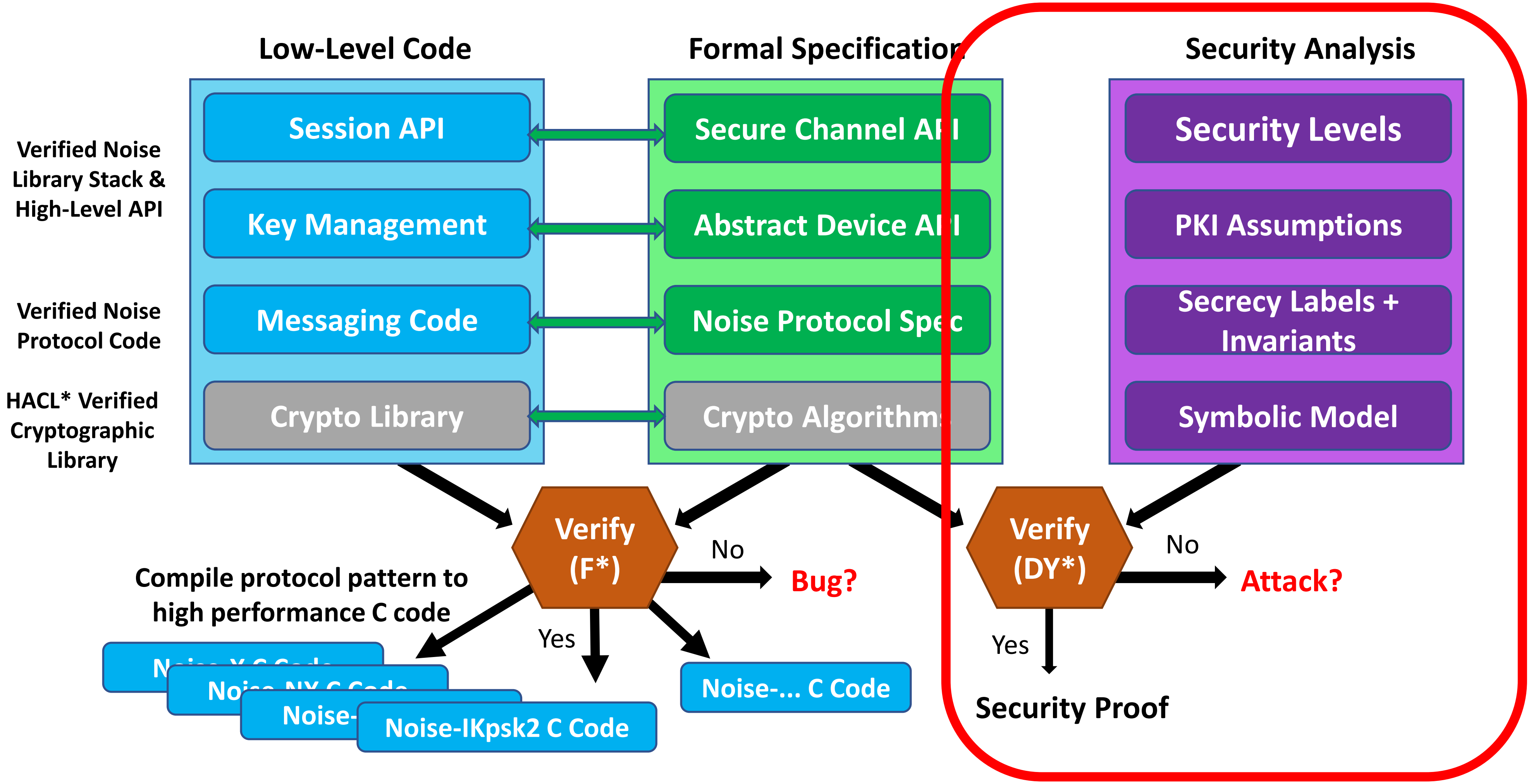

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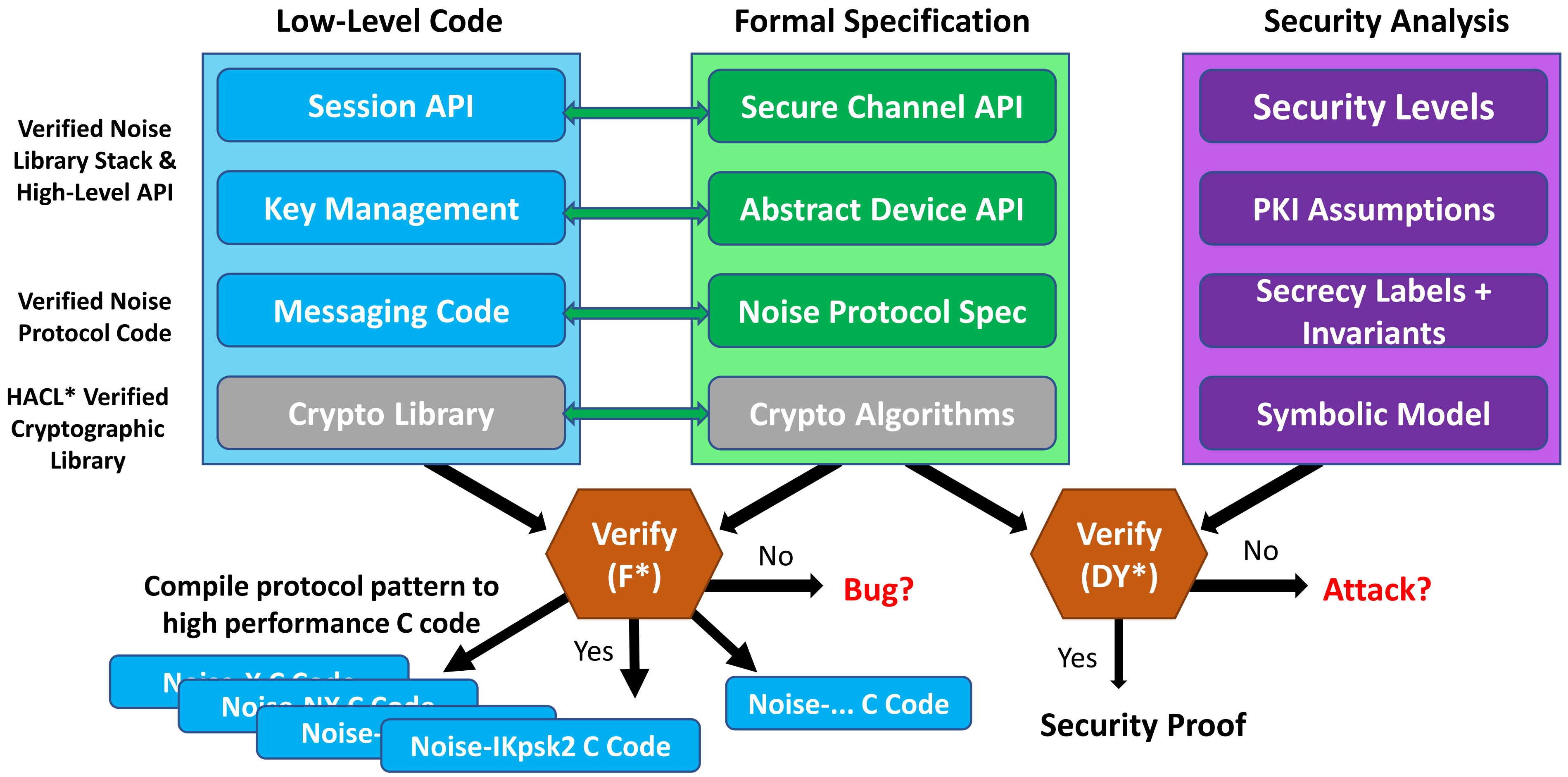
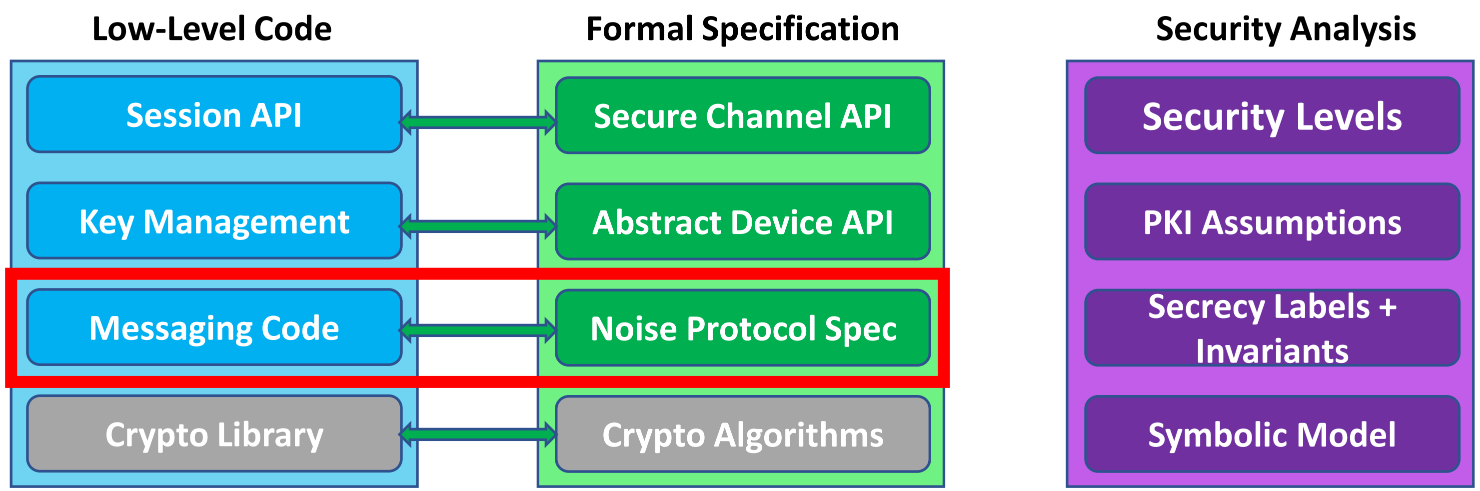


How did we implement the Noise* protocol compiler?



Formal Functional Specification of Noise

noiseprotocol.org:

- `message_patterns`: A sequence of message patterns. Each message pattern is a sequence of tokens from the set `("e", "s", "ee", "es", "se", "ss")`. (An additional `"psk"` token is introduced in Section 9, but we defer its explanation until then.)

A `HandshakeState` responds to the following functions:

- **`Initialize(handshake_pattern, initiator, prologue, s, e, rs, re)`**: Takes a valid `handshake_pattern` (see Section 7) and an `initiator` boolean specifying this party's role as either initiator or responder.

  Takes a `prologue` byte sequence which may be zero-length, or which may contain context information that both parties want to confirm is identical (see Section 6).

  Takes a set of DH key pairs `(s, e)` and public keys `(rs, re)` for initializing local variables, any of which may be empty. Public keys are only passed in if the `handshake_pattern` uses pre-messages (see Section 7). The ephemeral values `(e, re)` are typically left empty, since they are created and exchanged during the handshake; but there are exceptions (see Section 10).

  Performs the following steps:

  - Derives a `protocol_name` byte sequence by combining the names for the handshake pattern and crypto functions, as specified in Section 8. Calls `InitializeSymmetric(protocol_name)`.
  - Calls `MixHash(prologue)`.
  - Sets the `initiator`, `s`, `e`, `rs`, and `re` variables to the corresponding arguments.
  - Calls `MixHash()` once for each public key listed in the pre-messages from `handshake_pattern`, with the specified public key as input (see Section 7 for an explanation of pre-messages). If both initiator and responder have pre-messages, the initiator's public keys are hashed first. If multiple public keys are listed in either party's pre-message, the public keys are hashed in the order that they are listed.
  - Sets `message_patterns` to the message patterns from `handshake_pattern`.

- **`WriteMessage(payload, message_buffer)`**: Takes a `payload` byte sequence which may be zero-length, and a `message_buffer` to write the output into. Performs the following steps, aborting if any `EncryptAndHash()` call returns an error:

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F* theorem prover

F* **specification** written as an **interpreter**:

```
// Process a message (without its payload)
let rec send_message_tokens #nc initiator is_psk tokens
  (st : handshake_state) : result (bytes & handshake_state) =
  match tokens with
  | [] -> Res (lbytes_empty, st)
  | tk::tokens1 ->
    // First token
    match send_message_token initiator is_psk tk st with
    | Fail e -> Fail e
    | Res (msg1, st1) ->
      // Remaining tokens
      match send_message_tokens initiator is_psk tokens st1 with
      | Fail e -> Fail e
      | Res (msg2, st2) ->
        Res (msg1 @ msg2, st2)
```

Shallow embedding in Low*

Low*: effectful subset of F* modelling C

```
// Low* signature
val aead_encrypt :
     key:lbuffer uint8 32ul
  -> nonce:lbuffer uint8 12ul
  -> alen:size_t
  -> aad:lbuffer uint8 alen
  -> len:size_t
  -> input:lbuffer uint8 len
  -> output:lbuffer uint8 len
  -> tag:lbuffer uint8 16ul ->

  Stack unit

  (requires (fun h0 ->
    live h0 key /\ live h0 nonce /\ … /\
    disjoint key output /\ disjoint nonce output /\ … ))

  (ensures (fun h0 _ h1 ->
    modifies2 output tag h0 h1 /\
    Seq.append (as_seq h1 output) (as_seq h1 tag) ==
    Spec.aead_encrypt (as_seq h0 key) (as_seq h0 nonce)
                      (as_seq h0 input) (as_seq h0 aad)))


// Low* implementation
let aead_encrypt k n aadlen aad mlen m cipher mac =
  chacha20_encrypt mlen cipher m k n 1ul;
  derive_key_poly1305_do k n aadlen aad mlen cipher mac
```

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Formal pre/postconditions

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Proof obligations sent to Z3 SMT solver

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     key:lbuffer uint8 32ul
  -> nonce:lbuffer uint8 12ul
  -> alen:size_t
  -> aad:lbuffer uint8 alen
  -> len:size_t
  -> input:lbuffer uint8 len
  -> output:lbuffer uint8 len
  -> tag:lbuffer uint8 16ul ->

  Stack unit
```

Formal pre/postconditions

```
  (requires (fun h0 ->
    live h0 key /\ live h0 nonce /\ … /\
    disjoint key output /\ disjoint nonce output /\ … ))

  (ensures (fun h0 _ h1 ->
    modifies2 output tag h0 h1 /\
    Seq.append (as_seq h1 output) (as_seq h1 tag) ==
    Spec.aead_encrypt (as_seq h0 key) (as_seq h0 nonce)
                      (as_seq h0 input) (as_seq h0 aad)))
```

```
// Low* implementation
let aead_encrypt k n aadlen aad mlen m cipher mac =
  chacha20_encrypt mlen cipher m k n 1ul;
  derive_key_poly1305_do k n aadlen aad mlen cipher mac
```

Proof obligations sent to Z3 SMT solver

KreMLin: Low* → C (erasure, monomorphization…)

```
// Generated C code
void
Hacl_Chacha20Poly1305_32_aead_encrypt(
  uint8_t *k,
  uint8_t *n,
  uint32_t aadlen,
  uint8_t *aad,
  uint32_t mlen,
  uint8_t *m,
  uint8_t *cipher,
  uint8_t *mac
)
{
  Hacl_Chacha20_chacha20_encrypt(mlen, cipher, m, k, n, (uint32_t)1U);
  uint8_t tmp[64U] = { 0U };
  Hacl_Chacha20_chacha20_encrypt((uint32_t)64U, tmp, tmp, k, n, (uint32_t)0U);
  uint8_t *key = tmp;
  poly1305_do_32(key, aadlen, aad, mlen, cipher, mac);
}
```

Shallow embedding in Low*

Low*: effectful subset of F* modelling C

```
// Low* signature
val aead_encrypt :
     key:lbuffer uint8 32ul
  -> nonce:lbuffer uint8 12ul
  -> alen:size_t
  -> aad:lbuffer uint8 alen
  -> len:size_t
  -> input:lbuffer uint8 len
  -> output:lbuffer uint8 len
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```

Formal pre/postconditions

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  (requires (fun h0 ->
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                      (as_seq h0 input) (as_seq h0 aad)))
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let aead_encrypt k n aadlen aad mlen m cipher mac =
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{
  Hacl_Chacha20_chacha20_encrypt(mlen, cipher, m, k, n, (uint32_t)1U);
  uint8_t tmp[64U] = { 0U };
  Hacl_Chacha20_chacha20_encrypt((uint32_t)64U, tmp, tmp, k, n, (uint32_t)0U);
  uint8_t *key = tmp;
  poly1305_do_32(key, aadlen, aad, mlen, cipher, mac);
}
```

Low* has been successfully used for: cryptographic primitives, protocols (TLS, Signal…), …

⇒ **We can implement an interpreter for Noise in Low***

Target code

Wireguard VPN (IKpsk2):

```
/* First message: e, es, s, ss */
handshake_init(handshake->chaining_key, handshake->hash,
               handshake->remote_static);

/* e */
curve25519_generate_secret(handshake->ephemeral_private);
if (!curve25519_generate_public(dst->unencrypted_ephemeral,
                                handshake->ephemeral_private))
        goto out;
message_ephemeral(dst->unencrypted_ephemeral,
                  dst->unencrypted_ephemeral, handshake->chaining_key,
                  handshake->hash);

/* es */
if (!mix_dh(handshake->chaining_key, key, handshake->ephemeral_private,
            handshake->remote_static))
        goto out;

/* s */
message_encrypt(dst->encrypted_static,
                handshake->static_identity->static_public,
                NOISE_PUBLIC_KEY_LEN, key, handshake->hash);

/* ss */
if (!mix_precomputed_dh(handshake->chaining_key, key,
                        handshake->precomputed_static_static))
        goto out;
```

Our Low* code follows the structure of the below spec.:

```
let rec send_message_tokens #nc initiator is_psk tokens st =
  match tokens with
  | [] -> Res (lbytes_empty, st)
  | tk::tokens1 ->
    // First token
    match send_message_token initiator is_psk tk st with
    | Fail e -> Fail e
    | Res (msg1, st1) ->
      // Remaining tokens
      match send_message_tokens initiator is_psk tokens st1 with
      | Fail e -> Fail e
      | Success (msg2, st2) ->
        Res (msg1 @ msg2, st2)
```

Target code

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               handshake->remote_static);

/* e */
curve25519_generate_secret(handshake->ephemeral_private);
if (!curve25519_generate_public(dst->unencrypted_ephemeral,
                                 handshake->ephemeral_private))
        goto out;
message_ephemeral(dst->unencrypted_ephemeral,
                  dst->unencrypted_ephemeral, handshake->chaining_key,
                  handshake->hash);

/* es */
if (!mix_dh(handshake->chaining_key, key, handshake->ephemeral_private,
            handshake->remote_static))
        goto out;

/* s */
message_encrypt(dst->encrypted_static,
                handshake->static_identity->static_public,
                NOISE_PUBLIC_KEY_LEN, key, handshake->hash);

/* ss */
if (!mix_precomputed_dh(handshake->chaining_key, key,
                        handshake->precomputed_static_static))
        goto out;
```

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    | Res (msg1, st1) ->
      // Remaining tokens
      match send_message_tokens initiator is_psk tokens st1 with
      | Fail e -> Fail e
      | Success (msg2, st2) ->
        Res (msg1 @ msg2, st2)
```

Specialized, idiomatic C code: no recursion, no token lists, etc.

Target code

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/* e */
curve25519_generate_secret(handshake->ephemeral_private);
if (!curve25519_generate_public(dst->unencrypted_ephemeral,
                                handshake->ephemeral_private))
        goto out;
message_ephemeral(dst->unencrypted_ephemeral,
                  dst->unencrypted_ephemeral, handshake->chaining_key,
                  handshake->hash);

/* es */
if (!mix_dh(handshake->chaining_key, key, handshake->ephemeral_private,
            handshake->remote_static))
        goto out;

/* s */
message_encrypt(dst->encrypted_static,
                handshake->static_identity->static_public,
                NOISE_PUBLIC_KEY_LEN, key, handshake->hash);

/* ss */
if (!mix_precomputed_dh(handshake->chaining_key, key,
                        handshake->precomputed_static_static))
        goto out;
```

Our Low* code follows the structure of the below spec.:

```
let rec send_message_tokens #nc initiator is_psk tokens st =
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    match send_message_token initiator is_psk tk st with
    | Fail e -> Fail e
    | Res (msg1, st1) ->
      // Remaining tokens
      match send_message_tokens initiator is_psk tokens st1 with
      | Fail e -> Fail e
      | Success (msg2, st2) ->
        Res (msg1 @ msg2, st2)
```

Specialized, idiomatic C code: no recursion, no token lists, etc.

How to specialize an interpreter for a given input?
How to turn an interpreter into a compiler?

Hybrid Embeddings

Idea: use F* to meta-program as much as possible:

- Similar to super advanced **C++ templates**
- Write a meta-program once, specialize N times (⇒ 59 patterns)

Hybrid Embeddings

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- Write a meta-program once, specialize N times (⇒ 59 patterns)

Historically, long arc of meta-programming in F*:

- EverCrypt agility (2020)
- HACLxN vector types (2021)
- Streaming Functor (2021)
- EverParse (Ongoing)

Hybrid Embeddings

Idea: use F* to meta-program as much as possible:

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Historically, long arc of meta-programming in F*:

- EverCrypt agility (2020)
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- Streaming Functor (2021)
- EverParse (Ongoing)

➡ With **Noise***: complete, meta-programmed protocol stack

Hybrid Embeddings

```
let send_IKpsk2_message0 (st : handshake_state) =
  send_message_tokens true true [E; ES; S; SS] st
```

Hybrid Embeddings

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let send_IKpsk2_message0 (st : handshake_state) =
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```

Hybrid Embeddings

```
let send_IKpsk2_message0 (st : handshake_state) =
  match [E; ES; S; SS] with
  | [] -> Res (empty, st)
  | tk :: tokens1 ->
    match send_message_token true true tk st with
    | Fail e -> Fail e
    | Res (msg1, st1) ->
      match send_message_tokens true true tokens1 st1 with
      | Fail e -> Fail e
      | Res (msg2, st2) ->
        Res (msg1 @ msg2, st2)
```

Hybrid Embeddings

```
let send_IKpsk2_message0 (st : handshake_state) =
  match send_message_token true true E st with
  | Fail e -> Fail e
  | Res (msg1, st1) ->
    match send_message_tokens true true [ES; S; SS] st1 with
    | Fail e -> Fail e
    | Res (msg2, st2) ->
      Res (msg1 @ msg2, st2)
```

Hybrid Embeddings

```
let send_IKpsk2_message0 (st : handshake_state) =
  match send_message_token true true E st with
  | Fail e -> Fail e
  | Res (msg1, st1) ->
    match send_message_token true true ES st1 with
    | Fail e -> Fail e
    | Res (msg2, st2) ->
      match send_message_token true true S st2 with
      | Fail e -> Fail e
      | Res (msg3, st3) ->
        match send_message_token true true SS st3 with
        | Fail e -> Fail e
        | Res (msg4, st4) ->
          Res (msg1 @ msg2 @ msg3 @ msg4, st4)
```

Hybrid Embeddings

```
let send_IKpsk2_message0 (st : handshake_state) =
  match // E
    begin match st.ephemeral with
    | None -> Fail No_key
    | Some e ->
      let sym_st1 = mix_hash k.pub st.sym_state in
      let sym_st2 =
      if true // This is `is_psk`
      then mix_key e.pub sym_st1
      else sym_st1
      in
      let st1 = { st with sym_state = sym_st2; } in
      let msg1 = e.pub in
      Res (msg1, st1)
    end
  with
  | Fail e -> Fail e
  | Res (msg1, st1) -> // Other tokens:
    match send_message_token true true ES st1 with
    | Fail e -> Fail e
    | Res (msg2, st2) ->
      match send_message_token true true S st2 with
      | Fail e -> Fail e
      | Res (msg3, st3) ->
        …
```

Hybrid Embeddings

```
let send_IKpsk2_message0 (st : handshake_state) =
  match // E
    begin match st.ephemeral with
    | None -> Fail No_key // Unreachable if proper precondition
    | Some e ->
      let sym_st1 = mix_hash k.pub st.sym_state in
      let sym_st2 = mix_key e.pub sym_st1 in
      let st1 = { st with sym_state = sym_st2; } in
      let msg1 = e.pub in
      Res (msg1, st1)
    end
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  | Fail e -> Fail e // Unreachable if proper precondition
  | Res (msg1, st1) -> // Other tokens:
    match send_message_token true true ES st1 with
    | Fail e -> Fail e
    | Res (msg2, st2) ->
      match send_message_token true true S st2 with
      | Fail e -> Fail e
      | Res (msg3, st3) ->
        match send_message_token true true S st2 with
        | Fail e -> Fail e
        | Res (msg4, st4) ->
          Res (msg1 @ msg2 @ msg3 @ msg4, st3)
```

Hybrid Embeddings

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let send_IKpsk2_message0 (st : handshake_state) =
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      let sym_st2 = mix_key e.pub sym_st1 in
      let st1 = { st with sym_state = sym_st2; } in
      let msg1 = e.pub in
      Res (msg1, st1)
    end
  with
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      | Fail e -> Fail e
      | Res (msg3, st3) ->
        match send_message_token true true S st2 with
        | Fail e -> Fail e
        | Res (msg4, st4) ->
          Res (msg1 @ msg2 @ msg3 @ msg4, st3)
```

Embeddings in Low* are **shallow**: partial reduction applies!

```
// Simplified
let rec send_message_tokens_m =
  fun smi initiator is_psk tokens st outlen out ->
  match tokens with
  | Nil -> success _
  | tk :: tokens' ->
    let tk_outlen = token_message_vs nc smi tk in
    let tk_out = sub out 0ul tk_outlen in
    let r1 = send_message_token_m smi initiator ... In
    ...
```

⇒ Compilation through **staging**: first step with F* normalizer

Hybrid Embeddings

```
let send_IKpsk2_message0 (st : handshake_state) =
  match // E
    begin match st.ephemeral with
    | None -> Fail No_key // Unreachable if proper precondition
    | Some e ->
      let sym_st1 = mix_hash k.pub st.sym_state in
      let sym_st2 = mix_key e.pub sym_st1 in
      let st1 = { st with sym_state = sym_st2; } in
      let msg1 = e.pub in
      Res (msg1, st1)
    end
  with
  | Fail e -> Fail e // Unreachable if proper precondit
  | Res (msg1, st1) -> // Other tokens:
    match send_message_token true true ES st1 with
    | Fail e -> Fail e
    | Res (msg2, st2) ->
      match send_message_token true true S st2 with
      | Fail e -> Fail e
      | Res (msg3, st3) ->
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    let r1 = send_message_token_m smi initiator ... In
    ...
```

⇒ Compilation through **staging**: first step with F* normalizer

E disappeared!
⇒ "**meta**" parameters (and computations) vs "runtime" parameters (and computations)

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
```

```
// Low*
let r : error_code = send_message_token ... S ... in
if r = Success then
  ... // "if" branch
else
  ... // "else" branch
```

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
```

Unreachable!

```
// Low*
let r : error_code = send_message_token ... S ... in
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Always succeeds!

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```

Always succeeds!

F* has dependent types!

```
type error_code_or_unit (b : bool) =
  if b then error_code else unit

let is_success (b : bool) (r : error_code_or_unit b) :
  bool =
  if b then r = Success else true
```

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
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  bool =
  if b then r = Success else true
```

```
let can_fail (tk : token) : bool =
  match tk with
  | S -> false
  | ...
```

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st’) -> ...
```

Unreachable!

```
// Low*
let r : error_code_or_unit (can_fail S) = send_message_token ... S ... in
if is_success (can_fail S) r then
  ... // “if” branch
else
  ... // “else” branch
```

F* has dependent types!

```
type error_code_or_unit (b : bool) =
  if b then error_code else unit

let is_success (b : bool) (r : error_code_or_unit b) :
  bool =
  if b then r = Success else true
```

```
let can_fail (tk : token) : bool =
  match tk with
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  | ...
```

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
```

Unreachable!

```
// Low*
let r : error_code_or_unit (can_fail S) = send_message_token ... S ... in
if is_success (can_fail S) r then
  ... // "if" branch
else
  ... // "else" branch
```

After partial reduction

```
// Low*
let r : error_code_or_unit false = send_message_token ... S ... in
if is_success #false r then
  ... // "if" branch
else
  ... // "else" branch
```

F* has dependent types!

```
type error_code_or_unit (b : bool) =
  if b then error_code else unit

let is_success (b : bool) (r : error_code_or_unit b) :
  bool =
  if b then r = Success else true
```

```
let can_fail (tk : token) : bool =
  match tk with
  | S -> false
  | ...
```

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
```

Unreachable!

```
// Low*
let r : error_code_or_unit (can_fail S) = send_message_token ... S ... in
if is_success (can_fail S) r then
  ... // "if" branch
else
  ... // "else" branch
```

After partial reduction

```
// Low*
let r : unit = send_message_token ... S ... in
if is_success #false r then
  ... // "if" branch
else
  ... // "else" branch
```

F* has dependent types!

```
type error_code_or_unit (b : bool) =
  if b then error_code else unit

let is_success (b : bool) (r : error_code_or_unit b) :
  bool =
  if b then r = Success else true
```

```
let can_fail (tk : token) : bool =
  match tk with
  | S -> false
  | ...
```

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
```

Unreachable!

```
// Low*
let r : error_code_or_unit (can_fail S) = send_message_token ... S ... in
if is_success (can_fail S) r then
  ... // "if" branch
else
  ... // "else" branch
```

After partial reduction

```
// Low*
let r : unit = send_message_token ... S ... in
if true then
  ... // "if" branch
else
  ... // "else" branch
```

F* has dependent types!

```
type error_code_or_unit (b : bool) =
  if b then error_code else unit

let is_success (b : bool) (r : error_code_or_unit b) :
  bool =
  if b then r = Success else true
```

```
let can_fail (tk : token) : bool =
  match tk with
  | S -> false
  | ...
```

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
```

Unreachable!

```
// Low*
let r : error_code_or_unit (can_fail S) = send_message_token ... S ... in
if is_success (can_fail S) r then
  ... // "if" branch
else
  ... // "else" branch
```

After partial reduction

```
// Low*
let r : unit = send_message_token ... S ... in
... // "if" branch
```

F* has dependent types!

```
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  match tk with
  | S -> false
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```

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
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Unreachable!

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// Low*
let r : error_code_or_unit (can_fail S) = send_message_token ... S ... in
if is_success (can_fail S) r then
  ... // "if" branch
else
  ... // "else" branch
```

After partial reduction

```
// Low*
let r : unit = send_message_token ... S ... in
... // "if" branch
```

F* has dependent types!

```
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  if b then error_code else unit

let is_success (b : bool) (r : error_code_or_unit b) :
  bool =
  if b then r = Success else true
```

```
let can_fail (tk : token) : bool =
  match tk with
  | S -> false
  | ...
```

Write **general dependent types** which reduce to **precise non-dependent types**:

- Drastically improve code quality (make it smaller, more readable, more idiomatic)

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
```

Unreachable!

```
// Low*
let r : error_code_or_unit (can_fail S) = send_message_token ... S ... in
if is_success (can_fail S) r then
  ... // "if" branch
else
  ... // "else" branch
```

After partial reduction

```
// Low*
let r : unit = send_message_token ... S ... in
... // "if" branch
```

F* has dependent types!

```
type error_code_or_unit (b : bool) =
  if b then error_code else unit

let is_success (b : bool) (r : error_code_or_unit b) :
  bool =
  if b then r = Success else true
```

```
let can_fail (tk : token) : bool =
  match tk with
  | S -> false
  | ...
```

Write **general dependent types** which reduce to **precise non-dependent types**:

- Drastically improve code quality (make it smaller, more readable, more idiomatic)
- Make extracted types (structures, etc.) more precise

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
```

Unreachable!

```
// Low*
let r : error_code_or_unit (can_fail S) = send_message_token ... S ... in
if is_success (can_fail S) r then
  ... // "if" branch
else
  ... // "else" branch
```

After partial reduction

```
// Low*
let r : unit = send_message_token ... S ... in
... // "if" branch
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Write **general dependent types** which reduce to **precise non-dependent types**:

- Drastically improve code quality (make it smaller, more readable, more idiomatic)
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- Make **function signatures** more informative (**unit elimination**)

```
val f (x : uint32_t) (y : unit) : unit // Low*
void f (x : uint32_t); // Generated C
```

Tweaking Control-Flow and Types

```
// Spec
match send_message_token true true S st with
| Fail e -> Fail e
| Res (msg, st') -> ...
```

Unreachable!

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```
val f (x : uint32_t) (y : unit) : unit // Low*
void f (x : uint32_t); // Generated C
```

- **We don't have to choose between genericity and efficiency**

Generated Code (IKpsk2)

Noise*

```
/* e */
Impl_Noise_Instances_mix_hash(ms_h, (uint32_t)32U, mepub);
Impl_Noise_Instances_kdf(ms_ck, (uint32_t)32U, mepub, ms_ck, mc_state, NULL);
memcpy(tk_out, mepub, (uint32_t)32U * sizeof (uint8_t));
/* es */
uint8_t *out_ = pat_out + (uint32_t)32U;
Impl_Noise_Types_error_code
r11 = Impl_Noise_Instances_mix_dh(mepriv, mremote_static, mc_state, ms_ck, ms_h);
Impl_Noise_Types_error_code r2;
if (r11 == Impl_Noise_Types_CSuccess)
{
  /* s */
  uint8_t *out_1 = out_;
  uint8_t *tk_out2 = out_1;
  Impl_Noise_Instances_encrypt_and_hash((uint32_t)32U,
    mspub,
    tk_out2,
    mc_state,
    ms_h,
    (uint64_t)0U);
  /* ss */
  Impl_Noise_Types_error_code
  r = Impl_Noise_Instances_mix_dh(mspriv, mremote_static, mc_state, ms_ck, ms_h);
  Impl_Noise_Types_error_code r20 = r;
  Impl_Noise_Types_error_code r21 = r20;
  r2 = r21;
}
else
  r2 = r11;
```

Wireguard VPN (for reference):

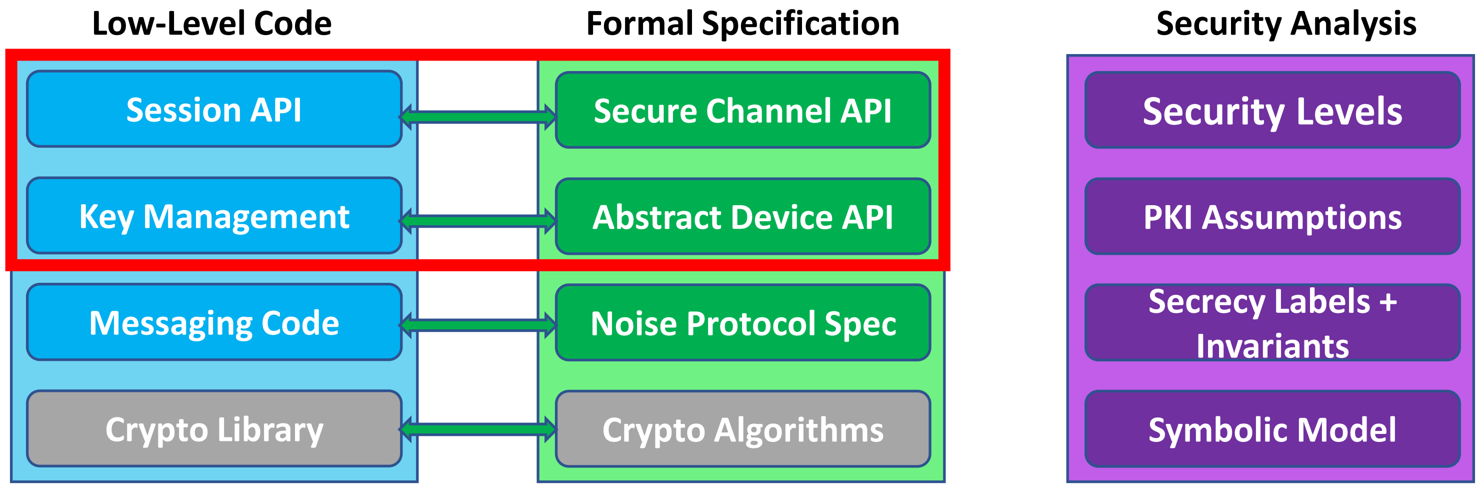
```
/* e */
curve25519_generate_secret(handshake->ephemeral_private);
if (!curve25519_generate_public(dst->unencrypted_ephemeral,
                                handshake->ephemeral_private))
        goto out;
message_ephemeral(dst->unencrypted_ephemeral,
                  dst->unencrypted_ephemeral, handshake->chaining_key,
                  handshake->hash);

/* es */
if (!mix_dh(handshake->chaining_key, key, handshake->ephemeral_private,
            handshake->remote_static))
        goto out;

/* s */
message_encrypt(dst->encrypted_static,
                handshake->static_identity->static_public,
                NOISE_PUBLIC_KEY_LEN, key, handshake->hash);

/* ss */
if (!mix_precomputed_dh(handshake->chaining_key, key,
                        handshake->precomputed_static_static))
        goto out;
```

What does the high-level API give us?



- State Machines
- Peer Management
- Key Storage & Validation
- Message Encapsulation

High-Level API

IKpsk2:

← s

. . .

→ e, es, s, ss, [d0]

← e, ee, se, psk, [d1]

↔ [d2, d3, …]

- Initiator and responder must remember which key belongs to whom
- Responder receives a static key during the handshake
  - Peer lookup (if key already registered)
  - Unknown key validation
- Long-term key storage
- Transitions are low-level
  - State Machine
  - Message lengths
  - Invalid states (if failure)
- Early data
  - when is it safe to send secret data?
  - when can we trust the data we received?

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Peer Management

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Peer Management

Key Validation

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Peer Management

Key Validation

Key Storage

High-Level API

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Peer Management

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Peer Management

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Message Encapsulation

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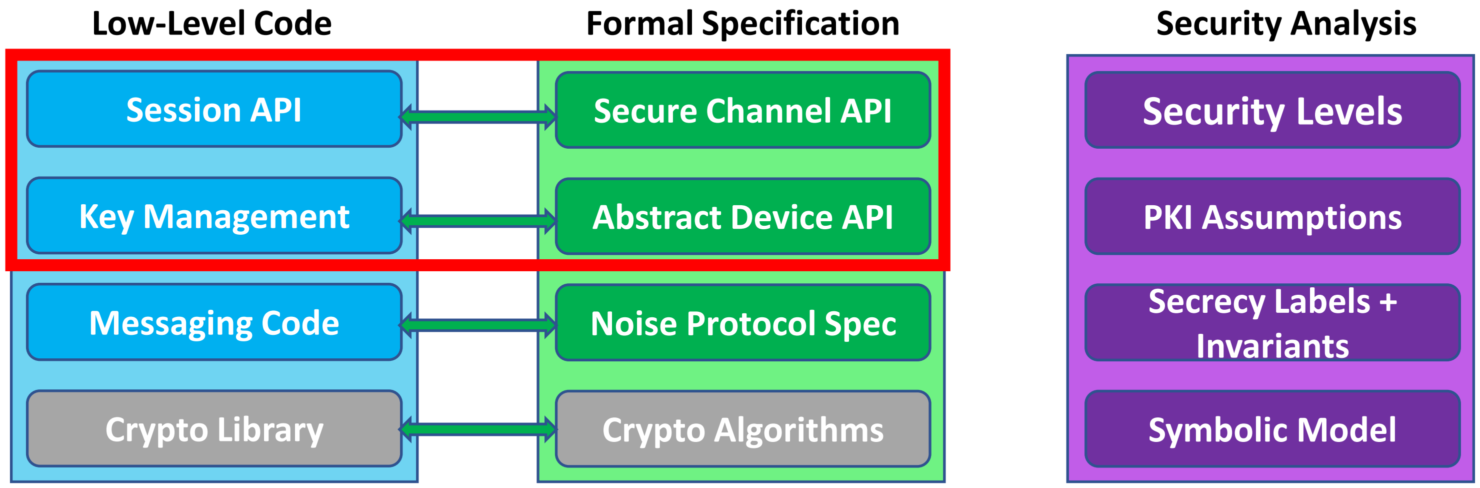

- State Machines
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Meta-Programmed State Machine

With 3 messages (ex.: XX):

```
//
error_code handshake_send(..., uint step, ...) {
  if (step == 0)
    return send_message0(...);
  else if (step == 1)
    return send_message1(...);
  else if (step == 2)
    return send_message2(...);
  ...
}
```

Meta-Programmed State Machine

With 3 messages (ex.: XX):

```
//
error_code handshake_send(..., uint step, ...) {
  if (step == 0)
    return send_message0(...);
  else if (step == 1)
    return send_message1(...);
  else if (step == 2)
    return send_message2(...);
  else
    ... // Unreachable!!
}
```

Meta-Programmed State Machine

With 3 messages (ex.: XX):

```
// With precondition: step <= 2
error_code handshake_send(..., uint step, ...) {
  if (step == 0)
    return send_message0(...);
  else if (step == 1)
    return send_message1(...);
  else // No check - step == 2
    return send_message2(...);
}
```

Meta-Programmed State Machine

With 3 messages (ex.: XX):

```
// With precondition: step <= 2
error_code handshake_send(..., uint step, ...) {
  if (step == 0)
    return send_message0(...); // initiator state
  else if (step == 1)
    return send_message1(...); // responder state!
  else // No check - step == 2
    return send_message2(...); // initiator state
}
```

`state` is a **dependent type**, reduced and monomorphized at extraction time!

Meta-Programmed State Machine

With 3 messages (ex.: XX):

```
// With precondition: step <= 2 /\ (step % 2) == 0
error_code initiator_handshake_send(..., uint step, ..., initiator_state st) {
  if (step == 0) {
    return send_message0(...);
  else // No check - step == 2
    return send_message2(...);
}
```

```
// With precondition: step <= 2 /\ (step % 2) == 1
error_code responder_handshake_send(..., uint step, ..., responder_state st) {
  return send_message1(...);
}
```

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Meta-Programmed State Machine

With 3 messages (ex.: XX):

```
// With precondition: step <= 2 /\ (step % 2) == 0
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    return send_message0(...);
  else // No check - step == 2
    return send_message2(...);
}
```

```
// With precondition: step <= 2 /\ (step % 2) == 1
error_code responder_handshake_send(..., uint step, ..., responder_state st) {
  return send_message1(...);
}
```

`state` is a **dependent type**, reduced and monomorphized at extraction time!

```
// Generated from an F* inductive
struct state {
  int tag;
  union {
    struct initiator_state;
    struct responder_state;
  } val;
}
```

```
// Top-level `handshake_send` function
error_code handshake_send(..., uint step, ..., state* st) =
   // Match and call the proper function
   ...
}
```

Meta-Programmed State Machine

With 3 messages (ex.: XX):

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// With precondition: step <= 2 /\ (step % 2) == 0
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```
// With precondition: step <= 2 /\ (step % 2) == 1
error_code responder_handshake_send(..., uint step, ..., responder_state st) {
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`state` is a **dependent type**, reduced and monomorphized at extraction time!

Actually inlined: structs passed by value

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```

Meta Programmed State Machine(s)

We program the 2 state machines (initiator/responder) at once:

Target C code:

```
error_code initiator_handshake_send(...) {
  if (step == 0) {
    return send_message0(...);
  else
    return send_message2(...);
}

error_code responder_handshake_send(...) {
  return send_message1(...);
}
```

F* code:

```
// Pre: initiator==((i%2)==0) /\ i < num_handshake_messages
let rec handshake_send_i (initiator:bool) ... (i:nat) (step:UInt32.t) =
  if i+2 >= num_handshake_messages then
    ... // last possible send_message function
  else if step = size i then
    ... // instantiated send_message function
  else
    handshake_send ... (i+2) step // Increment i by 2
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F* code:

Meta parameter
(i ∈ {0, 1, …})

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Meta parameter ($i \in \{0, 1, \ldots\}$)

Runtime parameter

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Meta parameter (i ∈ {0, 1, …})

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  else if step = size i then
    ... // instantiated send_message function
  else
    handshake_send ... (i+2) step // Increment i by 2
```
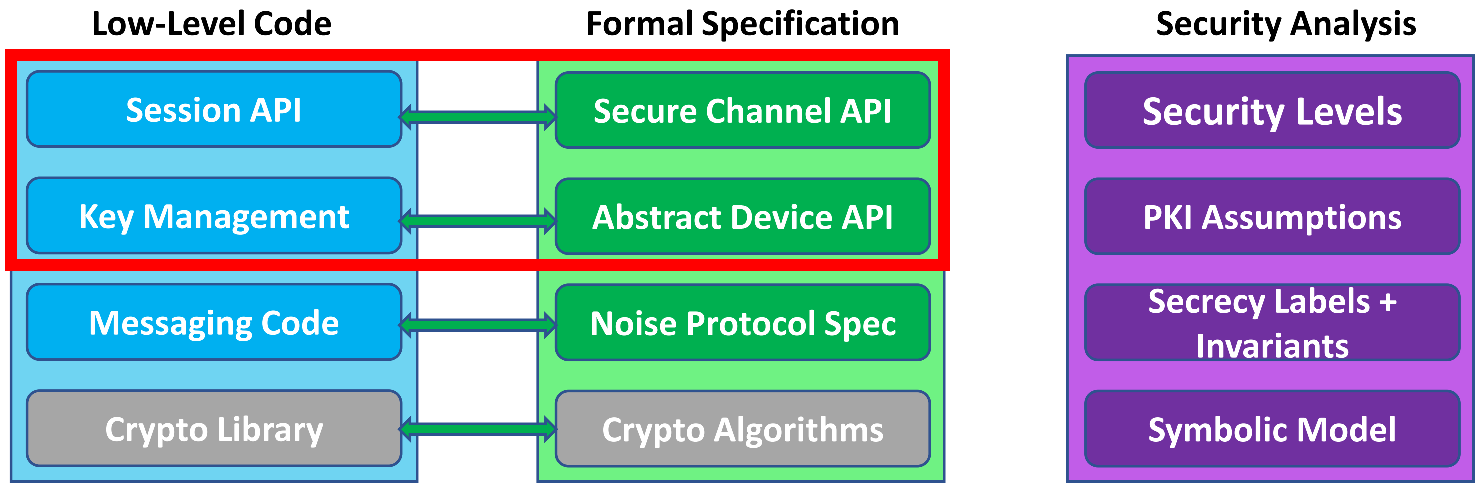

```
let initiator_handshake_send ... step = handshake_send true ... 0 step
let responder_handshake_send ... step = handshake_send false ... 1 step
```

What does the high-level API give us?



- State Machines
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Devices and Peers (IKpsk2)

Device contains our **static identity** and stores remote **peers information** (linked list, no recursive functions):

Initialization and **premessages** phase:

```
// Alice
device* dv;
dv = create_device("Alice", alice_private_key, alice_public_key);

bob = device_add_peer(dv, "Bob", bob_public_key, alice_bob_psk);
charlie = device_add_peer(dv, "Charlie",
                          charlie_public_key,
                          alice_charlie_psk);
...
```

```
// Bob
device* dv;
dv = create_device("Bob", bob_private_key, bob_public_key);

...
```

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charlie = device_add_peer(dv, "Charlie",
                          charlie_public_key,
                          alice_charlie_psk);
...
```

```
// Bob
device* dv;
dv = create_device("Bob", bob_private_key, bob_public_key);

...
```

Handshake phase:

```
// Alice: talk to Bob
session *sn;
sn = create_initiator(dv, bob_id);
uint8_t out[...];
send_message(sn, "Hello Bob!", out, outlen);
... // Send message over the network
```

```
// On Bob's side
session *sn;
sn = create_responder(dv); // We don't know who we talk to yet
uint8_t msg[...];
... // Receive message over the network
receive_message(sn, out, msg_len); // Discover it is Alice
```

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                          charlie_public_key,
                          alice_charlie_psk);
...
```

```
// Bob
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dv = create_device("Bob", bob_private_key, bob_public_key);

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IKpsk2:

← s **initiator knows responder from beginning**

...

→ e, es, s, ss

← e, ee, se, psk

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                          alice_charlie_psk);
...
```

```
// Bob
device* dv;
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...
```

IKpsk2:

← s **initiator knows responder from beginning**

...

Responder learns initiator's identity

→ e, es, s, ss

← e, ee, se, psk

Handshake phase:

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device* dv;
dv = create_device("Alice", alice_private_key, alice_public_key);

bob = device_add_peer(dv, "Bob", bob_public_key, alice_bob_psk);
charlie = device_add_peer(dv, "Charlie",
                          charlie_public_key,
                          alice_charlie_psk);
...
```

```
// Bob
device* dv;
dv = create_device("Bob", bob_private_key, bob_public_key);

...
```

IKpsk2:

← s **initiator knows responder from beginning**

... **Responder learns initiator's identity**

→ e, es, s, ss

← e, ee, se, psk

Handshake phase:

```
// Alice: talk to Bob
session *sn;
sn = create_initiator(dv, bob_id);
uint8_t out[...];
send_message(sn, "Hello Bob!", out, outlen);
... // Send message over the network
```

```
// On Bob's side
session *sn;
sn = create_responder(dv); // We don't know who we talk to yet
uint8_t msg[...];
... // Receive message over the network
receive_message(sn, out, msg_len); // Discover it is Alice
```

peer_id parameter: varies with pattern and role

Devices and Peers (IKpsk2)

Device contains our **static identity** and stores remote **peers information** (linked list, no recursive functions):

Initialization and **premessages** phase:

```
// Alice
device* dv;
dv = create_device("Alice", alice_private_key, alice_public_key);

bob = device_add_peer(dv, "Bob", bob_public_key, alice_bob_psk);
charlie = device_add_peer(dv, "Charlie",
                          charlie_public_key,
                          alice_charlie_psk);
...
```

```
// Bob
device* dv;
dv = create_device("Bob", bob_private_key, bob_public_key);

...
```

psk parameter only if pattern uses it

IKpsk2:

← s — initiator knows responder from beginning

...

Responder learns initiator’s identity

→ e, es, s, ss

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Handshake phase:

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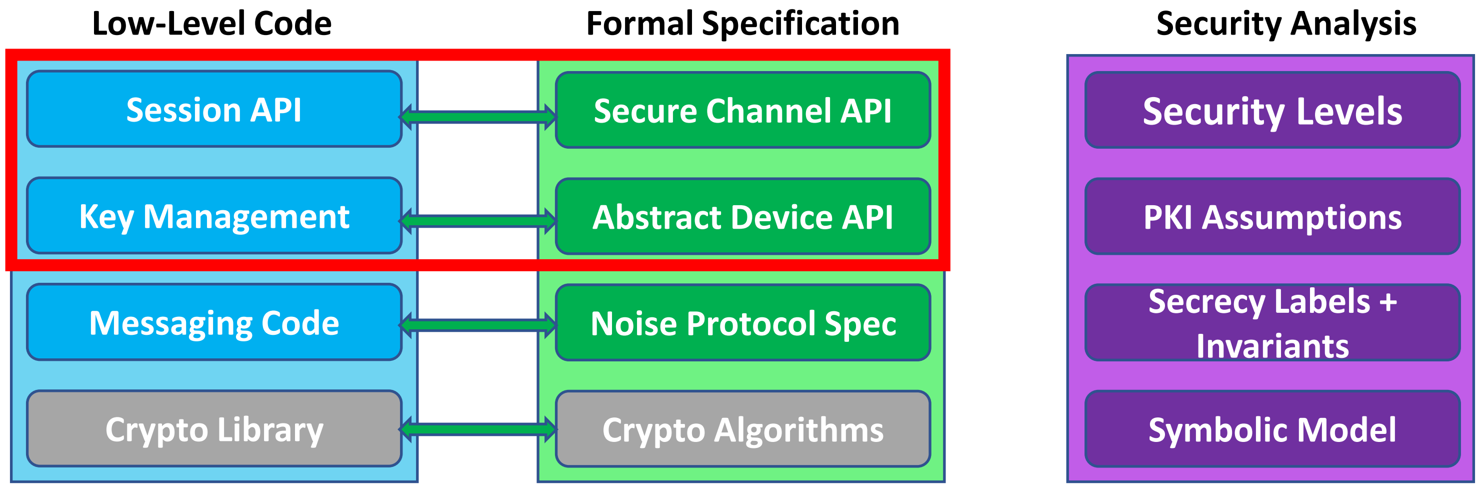
What does the high-level API give us?



- State Machines
- Peer Management
- Key Storage & Validation
- Message Encapsulation

Key Storage and Validation

IKpsk2:

← s

. . .

→ e, es, s, ss

← e, ee, se, psk

Wireguard VPN: all remote static keys **must have been registered** in the device before

XX:

→ e

← e, ee, s, es

→ s, se

WhatsApp: we actually **transmit** keys, which must be validated by some external mean

Key Storage and Validation

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Wireguard VPN: all remote static keys **must have been registered** in the device before

WhatsApp: we actually **transmit** keys, which must be validated by some external mean

We parameterize our implementation with:

- **Policy** (`bool`): can we accept unknown remote keys? (Wireguard: `false` / WhatsApp: `true`)
- **Certification** function: `certification_state → public_key → payload → option peer_name`

Key Storage and Validation

IKpsk2:

← s

. . .

→ e, es, s, ss

← e, ee, se, psk

Wireguard VPN: all remote static keys **must have been registered** in the device before

XX:

→ e

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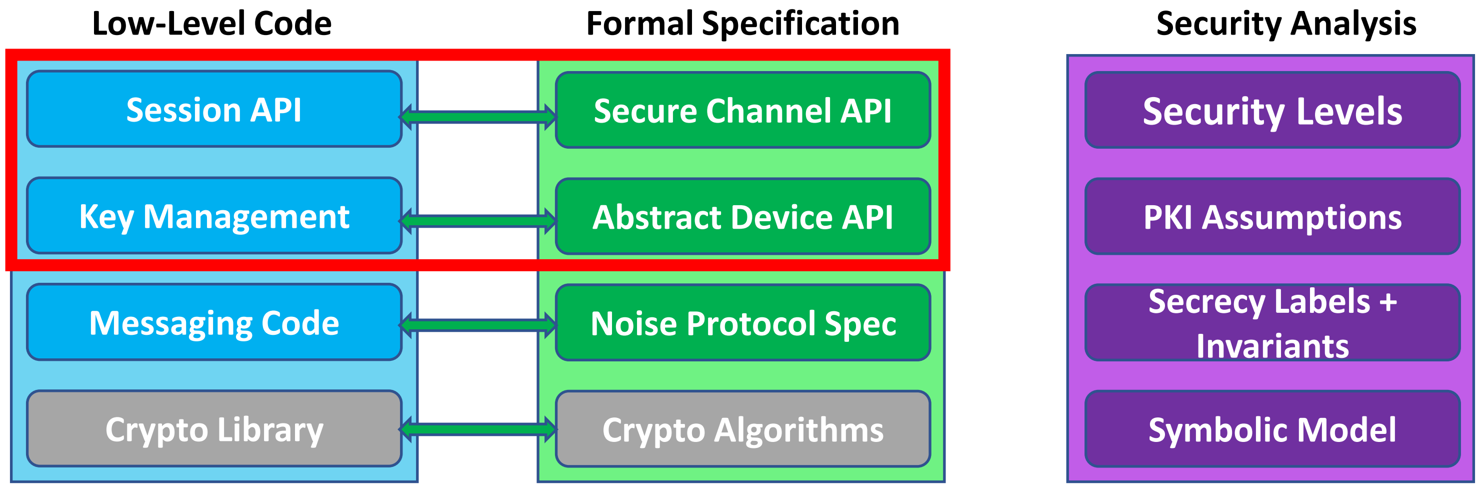
We parameterize our implementation with:

- **Policy** (`bool`): can we accept unknown remote keys? (Wireguard: `false` / WhatsApp: `true`)
- **Certification** function: `certification_state → public_key → payload → option peer_name`

Long-term keys storage (on disk): serialization/deserialization functions for device static identity and peers (random nonces + device/peer name as authentication data).

What does the high-level API give us?



- State Machines
- Peer Management
- Key Storage & Validation
- Message Encapsulation

Message Encapsulation – Security Levels

Every payload has an **authentication level** (≤ 2) and a **confidentiality level** (≤ 5):

IKpsk2	**Payload Conf. Level**	
	→	←
← s		
. . .		
→ e, es, s, ss	2	-
← e, ee, se, psk	-	4
→	5	-
←	-	5

Message Encapsulation – Security Levels

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IKpsk2	Payload Conf. Level	
	→	←
← s		
. . .		
→ e, es, s, ss	2	-
← e, ee, se, psk	-	4
→	5	-
←	-	5

XX	Payload Conf. Level	
	→	←
→ e	0	-
← e, ee, s, es	-	1
→ s, se	5	-
←	-	5
→	5	-
…		

Message Encapsulation – Security Levels

Every payload has an **authentication level** (≤ 2) and a **confidentiality level** (≤ 5):

IKpsk2	Payload Conf. Level	
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← s		
. . .		
→ e, es, s, ss	2	-
← e, ee, se, psk	-	4
→	5	-
←	-	5

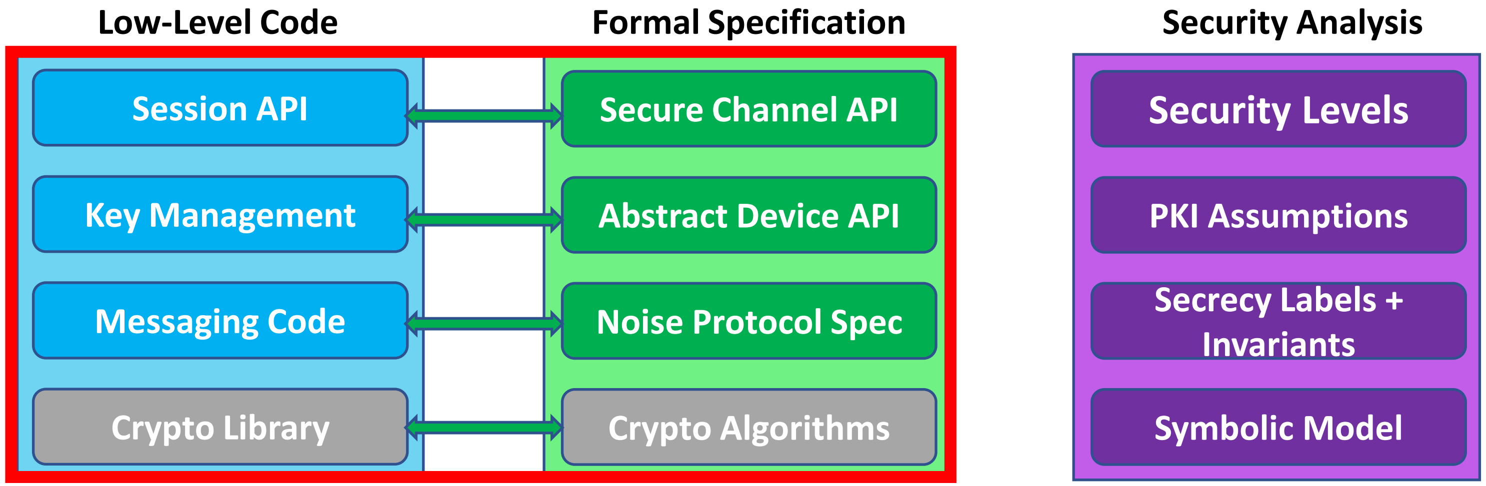
XX	Payload Conf. Level	
	→	←
→ e	0	-
← e, ee, s, es	-	1
→ s, se	5	-
←	-	5
→	5	-
…		

We protect the user from sending secret data/trusting received data **too early** (dynamic checks on **user-friendly auth./conf. levels**):

```
encap_message_t *pack_with_conf_level(
  uint8_t requested_conf_level, // <--- confidentiality
  const char *session_name, const char *peer_name, uint32_t msg_len, uint8_t *msg);

bool unpack_message_with_auth_level(
  uint32 t *out_msg_len, uint8 t **out_msg, char *session_name, char *peer_name,
  uint8_t requested_auth_level, // <--- authentication
  encap_message_t *msg);
```

Generated Code & Performance



Generated Code (IKpsk2)

Some signatures:

```
Noise_peer_t
*Noise_device_add_peer(Noise_device_t *dvp, uint8_t *pinfo, uint8_t *rs, uint8_t *psk);

void Noise_device_remove_peer(Noise_device_t *dvp, uint32_t pid);

Noise_peer_t *Noise_device_lookup_peer_by_id(Noise_device_t *dvp, uint32_t id);

Noise_peer_t *Noise_device_lookup_peer_by_static(Noise_device_t *dvp, uint8_t *s);

Noise_session_t *Noise_session_create_initiator(Noise_device_t *dvp, uint32_t pid);

Noise_session_t *Noise_session_create_responder(Noise_device_t *dvp);

void Noise_session_free(Noise_session_t *sn);

Noise_rcode
Noise_session_write(
  Noise_encap_message_t *payload,
  Noise_session_t *sn_p,
  uint32_t *out_len,
  uint8_t **out
);

Noise_rcode
Noise_session_read(
  Noise_encap_message_t **payload_out,
  Noise_session_t *sn_p,
  uint32_t inlen,
  uint8_t *input
);
```

`session_write` (length checks, security level checks…):

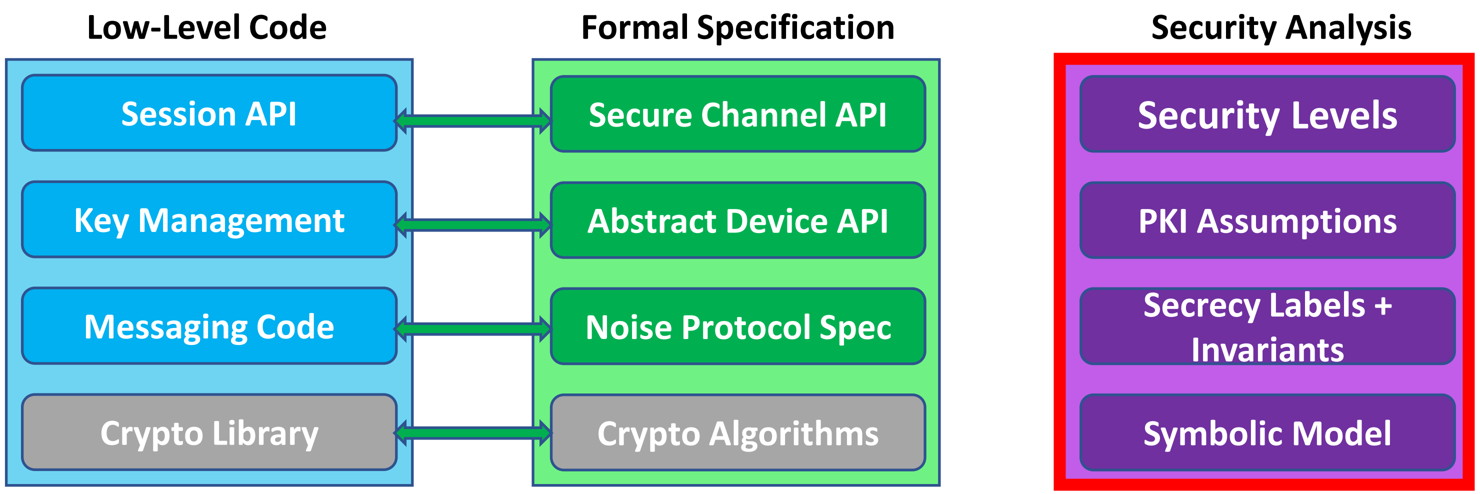
```
if (sn.tag == Noise_DS_Initiator)
{
  Noise_init_state_t sn_state = sn.val.case_DS_Initiator.state;
  if (sn_state.tag == Noise_IMS_Transport)
  {
    Noise_encap_message_t encap_payload = payload[0U];
    bool next_length_ok;
    if (encap_payload.em_message_len <= (uint32_t)4294967279U)
    {
      out_len[0U] = encap_payload.em_message_len + (uint32_t)16U;
      next_length_ok = true;
    }
    else
      next_length_ok = false;
    if (next_length_ok)
    {
      bool sec_ok;
      if (encap_payload.em_message_len == (uint32_t)0U)
        sec_ok = true;
      else
      {
        uint8_t clevel = (uint8_t)5U;
        if (encap_payload.em_ac_level.tag == Noise_Conf_level)
        {
          uint8_t req_level = encap_payload.em_ac_level.val.case_Conf_level;
          sec_ok =
            (req_level >= (uint8_t)2U && clevel >= req_level)
            || (req_level == (uint8_t)1U && (clevel == req_level || clevel >= (uint8_t)3U))
            || req_level == (uint8_t)0U;
        }
        else
          sec_ok = false;
      }
      if (sec_ok)
```

Performance

Pattern	Noise*	Custom	Cacophony	NoiseExpl.	Noise-C
X	6677	N/A	2272	4955	5603
NX	5385	N/A	2392	4046	5065
XX	3917	N/A	1593	3149	3577
IK	3143	N/A	1357	2459	2822
IKpsk2	3138	3756	1194	2431	N/A

Performance Comparison, in handshakes / second. Benchmark performed on a Dell XPS13 laptop (Intel Core i7-10510U) with Ubuntu 18.04

Security Analysis



Security Analysis - Dolev-Yao*

DY*: framework for symbolic analysis developed in F*.
We do the security analysis **once and for all**.

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We **formalize the Noise security levels with predicates**, and prove that those predicates are satisfied at the proper steps of the proper handshakes:

Level	Confidentiality Predicate (over i, idx, and l)
0	$\top$
1	can_flow i (CanRead [S idx.p idx.sid] ⊔ idx.peer_eph_label) l
2	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l
3	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l ∧ can_flow i (CanRead [S idx.p idx.sid] ⊔ idx.peer_eph_label) l
4	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l ∧ can_flow i (CanRead [S idx.p idx.sid] ⊔ idx.peer_eph_label) l ∧ (compromised_before i (P idx.p) ∨ compromised_before i (P idx.peer) ∨ (∃sid'. peer_eph_label == CanRead [S idx.peer sid']))
5	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l ∧ can_flow i (CanRead [S idx.p idx.sid] ⊔ idx.peer_eph_label) l ∧ (compromised_before i (S idx.p idx.sid) ∨ compromised_before i (P idx.peer) ∨ (∃sid'. peer_eph_label == CanRead [S idx.peer sid']))

Level	Authentication Predicate (over i, idx, and l)
0	$\top$
1	can_flow i (CanRead [P idx.p; P idx.peer]) l
2	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l

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3	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l ∧ can_flow i (CanRead [S idx.p idx.sid] ⊔ idx.peer_eph_label) l
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Strong forward-secrecy

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0	⊤
1	can_flow i (CanRead [P idx.p; P idx.peer]) l
2	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l

Security Analysis - Dolev-Yao*

Define labels for the data-types:

- `CanRead [P "Alice"]` : static data that can only be read by principal `"Alice"`
- `CanRead [S "Bob" sid]` : ephemeral data that can only be read by principal `"Bob"` at session `sid`

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Annotate the data types to give them usages and labels:

- `dh_private_key l` : private key of label `l`
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- `dh_private_key l` : private key of label `l`
- `dh_public_key l` : public key associated to a private key of label `l`

```
// DH signature (simplified)
val dh (l1 : label) (priv : dh_private_key l1)
       (l2 : label) (pub : dh_public_key l2) :
  dh_result (join l1 l2) // l1 ⊔ l2
```

Security Analysis - Dolev-Yao*

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  dh_result (join l1 l2) // l1 ⊔ l2
```

For now: those annotations are purely **syntactic**

Security Analysis - Example

Alice **Bob**

→ e, es, s, ss, [d]

```
let ck0 = hash "Noise_IKpsk2_..." in
// e
...
// es
let dh_es = dh e rs in
let ck1, sk1 = kdf2 ck0 dh_es in
// s
...
// ss
let dh_ss = dh s rs in
let ck2, sk2 = kdf2 ck1 dh_ss in
// d (plain text)
let cipher =
  aead_encrypt sk2 ... plain
in
...
// Output
concat ... cipher
```

Security Analysis - Example

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in
...
// Output
concat ... cipher
```

```
l_es := ((CanRead [S "Alice" sn]) ⊔ (CanRead [P "Bob"]))
dh_es : dh_result l_es
```

Security Analysis - Example

Alice **Bob**

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// e
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...
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dh_es : dh_result l_es
```

```
l_ss := ((CanRead [P "Alice"])    ⊔ (CanRead [P "Bob"]))
dh_ss : dh_result l_ss
```

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```
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dh_ss : dh_result l_ss
```

```
ck0 : chaining_key public
ck1 : chaining_key (public ⊓ l_es)
ck2 : chaining_key ((public ⊓ l_es) ⊓ l_ss)
```

Security Analysis - Example

Alice **Bob**

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```

```
val aead_encrypt
    (#l : label)
    (sk : aead_key l)   // encryption key
    (iv : msg public)   // nonce
    (plain : msg l)     // plaintext
    (ad : msg public) : // authentication data
    msg public
```

Security Analysis - Example

Alice **Bob**

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```
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l_es := ((CanRead [S "Alice" sn]) ⊔ (CanRead [P "Bob"]))
dh_es : dh_result l_es
```

```
l_ss := ((CanRead [P "Alice"])    ⊔ (CanRead [P "Bob"]))
dh_ss : dh_result l_ss
```

```
ck0 : chaining_key public
ck1 : chaining_key (public ⊓ l_es)
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```
val aead_encrypt
    (#l : label)
  → (sk : aead_key l)    // encryption key
    (iv : msg public)    // nonce
  → (plain : msg l)      // plaintext
    (ad : msg public) :  // authentication data
    msg public
```

We can then send the encrypted message: register a **Send** event in a global trace

Security Analysis: `can_flow`

- Labels are purely **syntactic**
- **Semantics** of DY* are given through a `can_flow` predicate which states properties about a global trace of events
- The content of a message sent over the network is **compromised** if its label flows to `public`

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- Labels can flow to more secret labels (i is a timestamp):

```
can_flow i (CanRead [P p1]) (CanRead [P p1] ⊓ CanRead [P p2])
```

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- Labels can flow to more secret labels (i is a timestamp):

```
can_flow i (CanRead [P p1]) (CanRead [P p1] ⊓ CanRead [P p2])
```

- The attacker can **dynamically compromise** a participant's current state: event `Compromise p ...`
- A label is compromised (and data with this label) if it flows to `public` :

```
compromised_before i (P p) ==> can_flow i (CanRead [P p]) public
compromised_before i (S p sid) ==> can_flow i (CanRead [S p sid]) public
...
```

Security Analysis: `can_flow`

- Labels are purely **syntactic**
- **Semantics** of DY* are given through a `can_flow` predicate which states properties about a global trace of events
- The content of a message sent over the network is **compromised** if its label flows to `public`

- Labels can flow to more secret labels (i is a timestamp):

```
can_flow i (CanRead [P p1]) (CanRead [P p1] ⊓ CanRead [P p2])
```

- The attacker can **dynamically compromise** a participant's current state: event `Compromise p ...`
- A label is compromised (and data with this label) if it flows to `public` :

```
compromised_before i (P p) ==> can_flow i (CanRead [P p]) public
compromised_before i (S p sid) ==> can_flow i (CanRead [S p sid]) public
...
```

- If a label flows to `public` we can deduce the existence of compromise events :

```
can_flow i (CanRead [P p]) public ==> compromised_before i (P p)
```

Security Analysis – Security Predicates

Confidentiality level 5 (**strong forward secrecy**):

```
can_flow i (CanRead [S p sid] ⊔ CanRead [P peer]) l /\
... /\
(... \/
 ...)
```

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Confidentiality level 5 (**strong forward secrecy**):

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can_flow i (CanRead [S p sid] ⊔ CanRead [P peer]) l /\
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Authentication invariant (an aead encrypt/decrypt):

```
... \/
begin match opt_rs, opt_re with
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```

Certification of remote static key gives:

```
get_dh_label rs = CanRead [P peer]
```

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We do the security analysis **once and for all**.

1. We **add annotations** to types to reflect security properties:

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Level	Confidentiality Predicate (over i, idx, and l)
0	⊤
1	can_flow i (CanRead [S idx.p idx.sid] ⊔ idx.peer_eph_label) l
2	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l
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Strong forward-secrecy

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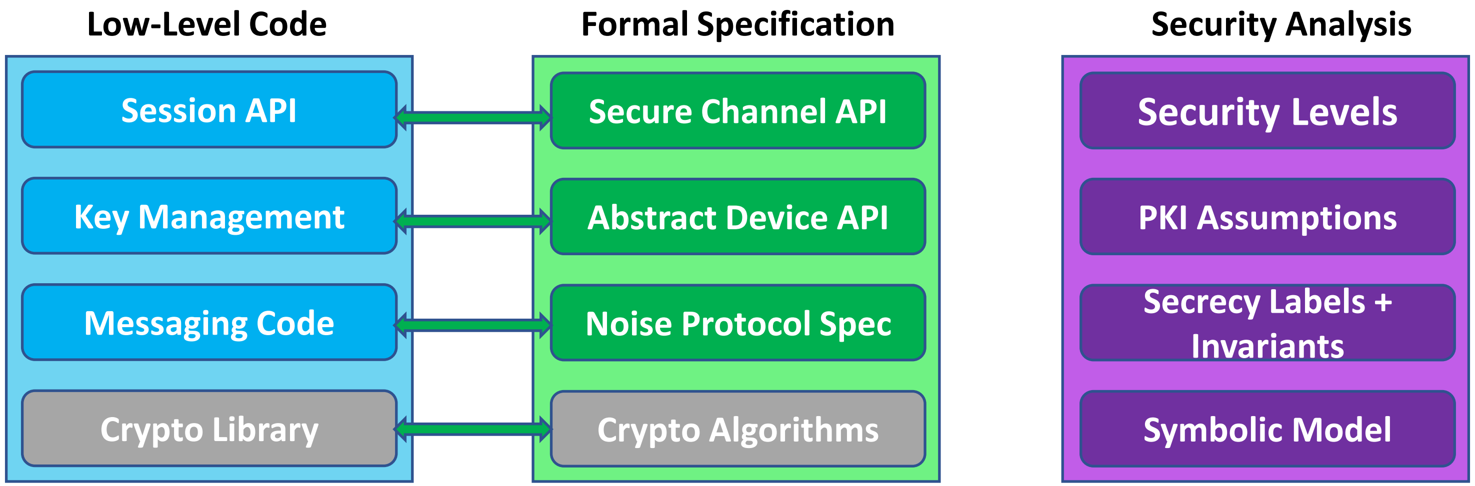
Conclusion

We introduced **Noise***, which is:

- A compiler from Noise protocol patterns to efficient, verified C code, executed in F* normalizer
- A complete, verified library stack exposed through a high-level, defensive API
- A symbolic security analysis generically performed on protocol and API



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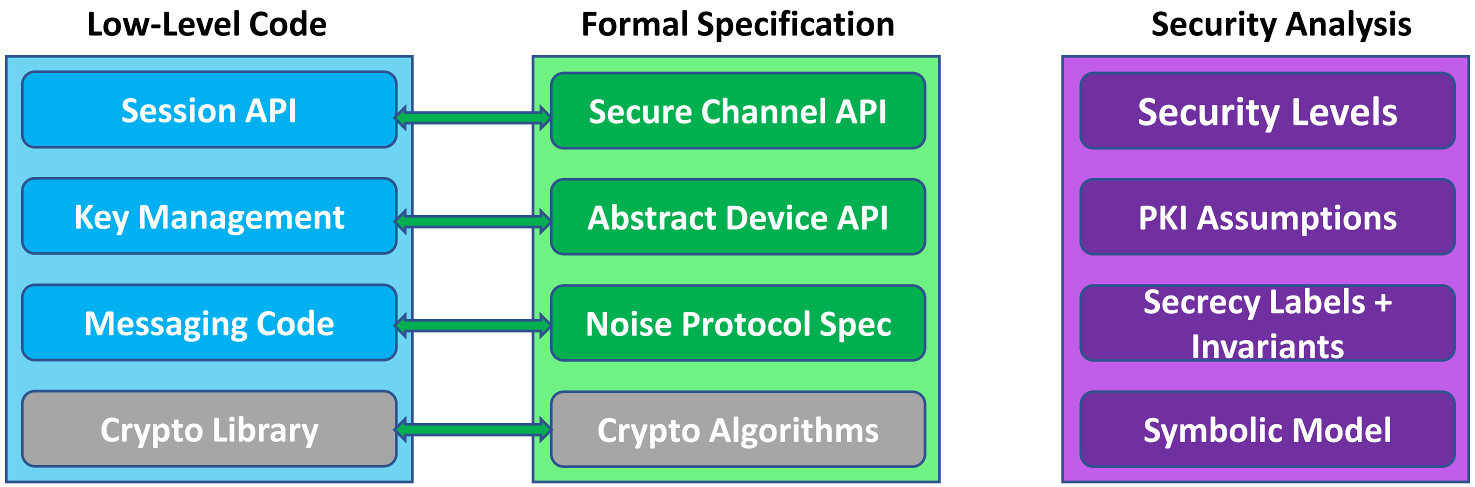
Noise* showcases techniques useful for:

- **Fully verified software stack**
- **Automated production** of code where we don't sacrifice **precision** or **performance**



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Security Analysis - Dolev-Yao*

DY*: framework for symbolic analysis developed in F*.
We do the security analysis **once and for all**.

1. We **add annotations** to types to reflect security properties:

```
// DH signature (simplified)
val dh' (priv : dh_private_key Alice)
        (pub : dh_public_key Bob) :
  dh_result (join Alice Bob) // Alice ⊔ Bob
```

2. We **generate target labels** for every step of the handshake:

IKpsk2 (from the responder's point of view)

← s

...

Strong forward-secrecy

→ e, es, s, ss, [d]   l1 = (peer_eph_label ⊔ CanRead [P p]) ⊓ (. . .)

← e, ee, se, psk, [d]   l2 = (peer_eph_label ⊔ CanRead [P p]) ⊓ (. . .) ⊓

(peer_eph_label ⊔ CanRead [S p sid]) ⊓ (. . .)

. . .

3. We prove that the **handshake state meets** at each stage of the protocol the **corresponding security label**

4. We prove an **ephemeral authentication invariant** to link the remote ephemeral to the remote static (while remote static is validated by certification function)

5. We **formalize the Noise security levels** with predicates over labels:

Level	Confidentiality Predicate (over i, idx, and l)
0	⊤
1	can_flow i (CanRead [S idx.p idx.sid] ⊔ idx.peer_eph_label) l
2	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l
3	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l ∧ can_flow i (CanRead [S idx.p idx.sid] ⊔ idx.peer_eph_label) l
4	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l ∧ can_flow i (CanRead [S idx.p idx.sid] ⊔ idx.peer_eph_label) l ∧ (compromised_before i (P idx.p) ∨ compromised_before i (P idx.peer) ∨ (∃sid'. peer_eph_label == CanRead [S idx.peer sid']))
5	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l ∧ can_flow i (CanRead [S idx.p idx.sid] ⊔ idx.peer_eph_label) l ∧ (compromised_before i (S idx.p idx.sid) ∨ compromised_before i (P idx.peer) ∨ (∃sid'. peer_eph_label == CanRead [S idx.peer sid']))

Level	Authentication Predicate (over i, idx, and l)
0	⊤
1	can_flow i (CanRead [P idx.p; P idx.peer]) l
2	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l

6. We prove that those **security predicates are satisfied** by the target labels by combining 3. and 4.

Security Analysis - Dolev-Yao*

DY*: framework for symbolic analysis developed in F*

Define labels for the data-types:

- `CanRead [P p]` : only principal p can read
- `CanRead [S p sid]` : only principal p at session `sid`

Annotate the data types to give them usages and labels:

- `dh_private_key l` : private key of label `l`
- `dh_public_key l` : public key associated to a private key of label `l`

```
// DH signature (simplified)
val dh (l1 : label) (priv : dh_private_key l1)
       (l2 : label) (pub : dh_public_key l2) :
  dh_result (join l1 l2) // l1 ⊔ l2
```

Security Analysis - Example

Alice **Bob**

→ e, es, s, ss

```
let ck0 = hash "Noise_IKpsk2_25519_..." in
// e
...
// es
let dh_es = dh e rs in
let ck1, sk1 = kdf2 ck1 dh_es in
// s
...
// ss
let dh_ss = dh s rs in
let ck2, sk2 = kdf2 ck2 dh_ss in
// d (plain text)
let cipher = aead_encrypt sk2 ... plain in
...
// Output
... @ cipher
```

Alice must have the following keys:

```
e: dh_private (CanRead [S "Alice" sn])
s: dh_private (CanRead [P "Alice"])
rs: dh_public (CanRead [P "Bob"])
```

```
// DH signature (simplified)
val dh (l1 : label) (priv : dh_private_key l1)
       (l2 : label) (pub : dh_public_key l2) :
  dh_result (join l1 l2) // label: l1 ⊔ l2
```

All annotations are syntactic (labels are syntactic)

```
dh_es: dh_result ((CanRead [S "Alice" sn]) ⊔ (CanRead [P "Bob"]))

dh_ss: dh_result ((CanRead [P "Alice"])    ⊔ (CanRead [P "Bob"]))
```

Security Analysis - Example

```
let ck0 = hash "Noise_IKpsk2_..." in
// e
...
// es
let dh_es = dh e rs in
let ck1, sk1 = kdf2 ck0 dh_es in
// s
...
// ss
let dh_ss = dh s rs in
let ck2, sk2 = kdf2 ck2 dh_ss in
// d (plain text)
let cipher =
  aead_encrypt sk2 ... plain
in
...
// Output
... @ cipher
```

```
l_es := ((CanRead [S "Alice" sn]) ⊔ (CanRead [P "Bob"]))
l_ss := ((CanRead [P "Alice"])    ⊔ (CanRead [P "Bob"]))
```

```
dh_es : dh_result l_es
dh_ss : dh_result l_ss
```

```
ck0 : chaining_key public
ck1 : chaining_key (public ⊓ l_es)
ck2 : chaining_key ((public ⊓ l_es) ⊓ l_ss)
```

```
val aead_encrypt
 ➡(sk : aead_key l)    // encryption key
   (iv : msg public)    // nonce
 ➡(plain : msg l)      // plaintext
   (ad : msg public) : // authentication data
   msg public
```

We can then send the encrypted message: insert a **Send** even in a global trace

Security Analysis – Target Labels

IKpsk2 (from the responder's point of view)

← s

…

→ e, es, s, ss, [d]   (peer_eph_label ⊔ CanRead [P p]) ⊓ (CanRead [P peer] ⊔ CanRead [P p])

← e, ee, se, psk, [d]   (peer_eph_label ⊔ CanRead [P p]) ⊓ (CanRead [P peer] ⊔ CanRead [P p]) ⊓ (peer_eph_label ⊔CanRead [S p sid]) ⊓ (CanRead [P peer] ⊔ CanRead [S p sid]) ⊓ (CanRead [P peer] ⊔ CanRead [P p])

← [d]

→ [d]

← [d]

Security Analysis – Target Labels

IKpsk2 (from the responder's point of view)

← s

…

→ e, es, s, ss, [d] (peer_eph_label ⊔ CanRead [P p]) ⊓ (CanRead [P peer] ⊔ CanRead [P p])

← e, ee, se, psk, [d] (peer_eph_label ⊔ CanRead [P p]) ⊓ (CanRead [P peer] ⊔ CanRead [P p]) ⊓
(peer_eph_label ⊔CanRead [S p sid]) ⊓ (CanRead [P peer] ⊔ CanRead [S p sid]) ⊓ (CanRead [P peer] ⊔ CanRead [P p])

← [d]

→ [d]

← [d]

Security Analysis – Target Labels

IKpsk2 (from the responder's point of view)

← s

Responder learns information about the initiator's ephemeral by linking it to the initiator's static key

…

→ e, es, s, ss, [d] (peer_eph_label ⊔ CanRead [P p]) ⊓ (CanRead [P peer] ⊔ CanRead [P p])

← e, ee, se, psk, [d] (peer_eph_label ⊔ CanRead [P p]) ⊓ (CanRead [P peer] ⊔ CanRead [P p]) ⊓ (peer_eph_label ⊔CanRead [S p sid]) ⊓ (CanRead [P peer] ⊔ CanRead [S p sid]) ⊓ (CanRead [P peer] ⊔ CanRead [P p])

← [d]

→ [d]

← [d]

Security Analysis – Target Labels

IKpsk2 (from the responder's point of view)

← s

…

→ e, es, s, ss, [d]

← e, ee, se, psk, [d]

← [d]

→ [d]

← [d]

Responder learns information about the initiator's ephemeral by linking it to the initiator's static key

(peer_eph_label ⊔ CanRead [P p]) ⊓ (CanRead [P peer] ⊔ CanRead [P p])

(peer_eph_label ⊔ CanRead [P p]) ⊓ (CanRead [P peer] ⊔ CanRead [P p]) ⊓
(peer_eph_label ⊔CanRead [S p sid]) ⊓ (CanRead [P peer] ⊔ CanRead [S p sid]) ⊓ (CanRead [P peer] ⊔ CanRead [P p])

Authentication invariant gives us information upon receiving messages

Upon receiving a message: we get information from the **current label** and previously used keys.
The authentication invariant is verified whenever encrypting data (and retrieved when decrypting).

Security Analysis: Annotating the Types

"Computational" Definitions

```
type cipher_state = {
  sk : option aead_key;
  n : nat;
}
```

```
type symmetric_state (nc : config) = {
  c_state : cipher_state;
  ck : chaining_key nc;
  h : hash nc;
}
```

```
type handshake_state (nc : config) = {
  sym_state : symmetric_state nc;
  static : option (keypair nc);
  ephemeral : option (keypair nc);
  remote_static : option (public_key nc);
  remote_ephemeral : option (public_key nc);
  preshared : option preshared_key;
}
```

Symbolic Definitions

```
type cipher_state (i:nat) (l:label) = {
  k : option (aead_key i l);
  n: nat;
}
```

```
type symmetric_state (nc:config) (i:nat) (l:label) = {
  c_state : cipher_state i l;
  ck : chaining_key nc i l;
  h : hash nc i;
  ...; // Omitted ghost fields
}
```

```
type handshake_state (nc:config) (i:nat) (l:label) (idx:index) = {
  sym_state : symmetric_state nc i l idx.p idx.si;
  static : option (static_keypair nc i (readers [P idx.p]));
  ephemeral : option (ephemeral_keypair nc i (readers [S p idx.si]));
  remote_static : option (not_validated_key nc i); // Externally validated
  remote_ephemeral : option (not_validated_key nc i); // Externally validated
  preshared : psk:option (preshared_key i idx.p idx.peer);
}
```

We then rewrite the protocol and the API specification functions by using those annotated types (and symbolic functions)

Security Analysis: `can_flow`

- Labels are purely syntactic
- Semantics of DY* are given through a `can_flow` predicate which states properties about a global trace of events

- Labels can flow to more secret labels (i is a timestamp):

```
can_flow i (CanRead [P p1]) (CanRead [P p1] ⊓ CanRead [P p2])
```

- The attacker can **dynamically compromise** a participant's current state: event `Compromise p sid`
- If a label is compromised, it flows to `public` (actually an equivalence):

```
compromised_before i (P p) ==> can_flow (CanRead [P p]) public
compromised_before i (S p sid) ==> can_flow (CanRead [S p sid]) public
...
```

Security Analysis : Noise Security Goals

"Strong Forward Secrecy" (level 5)

Level	Confidentiality Predicate (over i, idx, and l)
0	$\top$
1	can_flow i (CanRead [S idx.p idx.sid] $\sqcup$ idx.peer_eph_label) l
2	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l
3	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l $\wedge$ can_flow i (CanRead [S idx.p idx.sid] $\sqcup$ idx.peer_eph_label) l
4	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l $\wedge$ can_flow i (CanRead [S idx.p idx.sid] $\sqcup$ idx.peer_eph_label) l $\wedge$ (compromised_before i (P idx.p) $\vee$ compromised_before i (P idx.peer) $\vee$ ($\exists$sid'. peer_eph_label == CanRead [S idx.peer sid']))
5	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l $\wedge$ can_flow i (CanRead [S idx.p idx.sid] $\sqcup$ idx.peer_eph_label) l $\wedge$ (compromised_before i (S idx.p idx.sid) $\vee$ compromised_before i (P idx.peer) $\vee$ ($\exists$sid'. peer_eph_label == CanRead [S idx.peer sid']))

Level	Authentication Predicate (over i, idx, and l)
0	$\top$
1	can_flow i (CanRead [P idx.p; P idx.peer]) l
2	can_flow i (CanRead [S idx.p idx.sid; P idx.peer]) l

Security Analysis : API

- **Authentication** (slightly simplified):

```
// Slightly simplified:
val unpack_message_with_auth_level :
  #mi:mindex ->
  alevel:auth_level -> // ← Requested authentication level
  msg:encap_message mi ->
  Pure (option (lvl_bytes mi.i mi.l)) (requires True)
  (ensures (fun res ->
    match res with
    | Some b -> expected_auth_label alevel mi mi.l // ← Security guarantees
    | None -> True
   ))
```

- **Confidentiality:** slightly more subtle, but information can be exposed

Linked Lists and Automated Framing

- In C: high-level comments discouraging from looking up peers and performing peer removal at the same time
- In F*: possible to formally reason about peer disjointness

```
// Peer insertion (simplified)
val device_add_peer dv peer_name rs psk : ST (peer_p idc)
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->

    peer_invariant h1 p dv /\
    loc_includes (device_footprint dv) (peer_footprint p) /\

    peer_get_id h1 p = device_get_peers_counter h0 dv /\
    device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\

    device_no_removal dv h0 h1 /\
    ...))
```

```
// Peer deletion (simplified)
val device_remove_peer dv pid : ST unit
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    device_removed_peer dv pid h0 h1 /\
    ...)
```

Linked Lists and Automated Framing

- In C: high-level comments discouraging from looking up peers and performing peer removal at the same time
- In F*: possible to formally reason about peer disjointness

```
// Peer insertion (simplified)
val device_add_peer dv peer_name rs psk : ST (peer_p idc)
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
                                     Peer belongs to device
    peer_invariant h1 p dv /\
    loc_includes (device_footprint dv) (peer_footprint p) /\

    peer_get_id h1 p = device_get_peers_counter h0 dv /\
    device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\

    device_no_removal dv h0 h1 /\
    ...))
```

```
// Peer deletion (simplified)
val device_remove_peer dv pid : ST unit
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    device_removed_peer dv pid h0 h1 /\
    ...)
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    peer_get_id h1 p = device_get_peers_counter h0 dv /\
    device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\
    device_no_removal dv h0 h1 /\
    ...))
```

Peer belongs to device

Peer has unique id

```
// Peer deletion (simplified)
val device_remove_peer dv pid : ST unit
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    device_removed_peer dv pid h0 h1 /\
    ...)
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    loc_includes (device_footprint dv) (peer_footprint p) /\
    peer_get_id h1 p = device_get_peers_counter h0 dv /\
    device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\
    device_no_removal dv h0 h1 /\
    ...))
```

Peer belongs to device

Peer has unique id

No peer removed

```
// Peer deletion (simplified)
val device_remove_peer dv pid : ST unit
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    device_removed_peer dv pid h0 h1 /\
    ...)
```

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// Peer insertion (simplified)
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  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    peer_invariant h1 p dv /\
    loc_includes (device_footprint dv) (peer_footprint p) /\
    peer_get_id h1 p = device_get_peers_counter h0 dv /\
    device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\
    device_no_removal dv h0 h1 /\
    ...))
```

Peer belongs to device

Peer has unique id

No peer removed

```
// Peer deletion (simplified)
val device_remove_peer dv pid : ST unit
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    device_removed_peer dv pid h0 h1 /\
    ...)
```

Peer with id pid was removed

Linked Lists and Automated Framing

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```
// Peer insertion (simplified)
val device_add_peer dv peer_name rs psk : ST (peer_p idc)
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  (ensures (fun h0 p h1 ->
    peer_invariant h1 p dv /\
    loc_includes (device_footprint dv) (peer_footprint p) /\
    peer_get_id h1 p = device_get_peers_counter h0 dv /\
    device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\
    device_no_removal dv h0 h1 /\
    ...))
```

Peer belongs to device

Peer has unique id

No peer removed

```
// Peer deletion (simplified)
val device_remove_peer dv pid : ST unit
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    device_removed_peer dv pid h0 h1 /\
    ...)
```

Peer with id pid was removed

"Simple" framing lemma: if modified memory is disjoint from peer, peer is left unchanged

Linked Lists and Automated Framing

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  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    peer_invariant h1 p dv /\
    loc_includes (device_footprint dv) (peer_footprint p) /\
    peer_get_id h1 p = device_get_peers_counter h0 dv /\
    device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\
    device_no_removal dv h0 h1 /\
    ...))
```

Peer belongs to device

Peer has unique id

No peer removed

```
// Peer deletion (simplified)
val device_remove_peer dv pid : ST unit
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    device_removed_peer dv pid h0 h1 /\
    ...)
```

Peer with id pid was removed

"Simple" framing lemma: if modified memory is disjoint from peer, peer is left unchanged

Advanced framing lemmas:

```
// Frame lemma (insertion)
val peer_no_removal_frame_invariant p dv h0 h1 : Lemma
  (requires (
    peer_invariant h0 p dvp /\
    device_no_removal dvp h0 h1))
  (ensures (
    peer_invariant h1 p dvp /\
    peer_v h0 p == peer_v h1 p))
  [SMTPat (peer_invariant h0 p dvp);
   SMTPat (device_no_removal dvp h0 h1)]
```

```
// Frame lemma (removal)
  val peer_removed_peer_frame_invariant pid p dvp h0 h1 :
  Lemma
  (requires (
    peer_invariant h0 p dvp /\
    device_removed_peer dvp pid h0 h1 /\
    peer_get_pid h0 p <> Some pid))
  (ensures (
    peer_invariant h1 p dvp /\
    peer_v h0 p == peer_v h1 p))
  [SMTPat (peer_invariant h0 p dvp);
   SMTPat (device_removed_peer dvp pid h0 h1)]
```

Linked Lists and Automated Framing

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```
// Peer insertion (simplified)
val device_add_peer dv peer_name rs psk : ST (peer_p idc)
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
   peer_invariant h1 p dv /\
   loc_includes (device_footprint dv) (peer_footprint p) /\
   peer_get_id h1 p = device_get_peers_counter h0 dv /\
   device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\
   device_no_removal dv h0 h1 /\
   ...))
```

Peer belongs to device

Peer has unique id

No peer removed

```
// Peer deletion (simplified)
val device_remove_peer dv pid : ST unit
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
   device_removed_peer dv pid h0 h1 /\
   ...)
```

Peer with id pid was removed

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    peer_get_pid h0 p <> Some pid))
  (ensures (
    peer_invariant h1 p dvp /\
    peer_v h0 p == peer_v h1 p))
  [SMTPat (peer_invariant h0 p dvp);
   SMTPat (device_removed_peer dvp pid h0 h1)]
```

Linked Lists and Automated Framing

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- In F*: possible to formally reason about peer disjointness

```
// Peer insertion (simplified)
val device_add_peer dv peer_name rs psk : ST (peer_p idc)
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    peer_invariant h1 p dv /\
    loc_includes (device_footprint dv) (peer_footprint p) /\
    peer_get_id h1 p = device_get_peers_counter h0 dv /\
    device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\
    device_no_removal dv h0 h1 /\
    ...))
```

Peer belongs to device

Peer has unique id

No peer removed

```
// Peer deletion (simplified)
val device_remove_peer dv pid : ST unit
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    device_removed_peer dv pid h0 h1 /\
    ...)
```

Peer with id pid was removed

"Simple" framing lemma: if modified memory is disjoint from peer, peer is left unchanged

Advanced framing lemmas:

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  (ensures (
    peer_invariant h1 p dvp /\
    peer_v h0 p == peer_v h1 p))
  [SMTPat (peer_invariant h0 p dvp);
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    device_removed_peer dvp pid h0 h1 /\
    peer_get_pid h0 p <> Some pid))
  (ensures (
    peer_invariant h1 p dvp /\
    peer_v h0 p == peer_v h1 p))
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  (ensures (fun h0 p h1 ->
   peer_invariant h1 p dv /\
   loc_includes (device_footprint dv) (peer_footprint p) /\
   peer_get_id h1 p = device_get_peers_counter h0 dv /\
   device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\
   device_no_removal dv h0 h1 /\
   ...))
```

Peer belongs to device

Peer has unique id

No peer removed

```
// Peer deletion (simplified)
val device_remove_peer dv pid : ST unit
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
   device_removed_peer dv pid h0 h1 /\
   ...)
```

Peer with id pid was removed

"Simple" framing lemma: if modified memory is disjoint from peer, peer is left unchanged

Advanced framing lemmas:

```
// Frame lemma (insertion)
val peer_no_removal_frame_invariant p dv h0 h1 : Lemma
  (requires (
    peer_invariant h0 p dvp /\
    device_no_removal dvp h0 h1))
  (ensures (
    peer_invariant h1 p dvp /\
    peer_v h0 p == peer_v h1 p))
  [SMTPat (peer_invariant h0 p dvp);
   SMTPat (device_no_removal dvp h0 h1)]
```

SMT Pattern

```
// Frame lemma (removal)
  val peer_removed_peer_frame_invariant pid p dvp h0 h1 :
  Lemma
  (requires (
    peer_invariant h0 p dvp /\
    device_removed_peer dvp pid h0 h1 /\
    peer_get_pid h0 p <> Some pid))
  (ensures (
    peer_invariant h1 p dvp /\
    peer_v h0 p == peer_v h1 p))
  [SMTPat (peer_invariant h0 p dvp);
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```

Linked Lists and Automated Framing

- In C: high-level comments discouraging from looking up peers and performing peer removal at the same time
- In F*: possible to formally reason about peer disjointness

```
// Peer insertion (simplified)
val device_add_peer dv peer_name rs psk : ST (peer_p idc)
  (requires (fun h0 -> ...))
  (ensures (fun h0 p h1 ->
    peer_invariant h1 p dv /\
    loc_includes (device_footprint dv) (peer_footprint p) /\
    peer_get_id h1 p = device_get_peers_counter h0 dv /\
    device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\
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   device_get_peers_counter h1 dv = device_get_peers_counter h0 dv + 1 /\
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```

Noise Patterns: IKpsk2

IKpsk2:

← s

. . .

→ e, es, s, ss

← e, ee, se, psk

Noise Patterns: IKpsk2

IKpsk2:

← s

. . .

→ e, es, s, ss

← e, ee, se, psk

} Premessages

Noise Patterns: IKpsk2

IKpsk2:

← s

. . .

→ e, es, s, ss

← e, ee, se, psk

Premessages: ← s, . . .

Handshake Messages: → e, es, s, ss and ← e, ee, se, psk

Noise Patterns: IKpsk2

IKpsk2:

← s

. . .

→ e, es, s, ss, [d0]

← e, ee, se, psk, [d1]

Premessages: ← s, . . .

Handshake Messages: → e, es, s, ss, [d0]; ← e, ee, se, psk, [d1]

Noise Patterns: IKpsk2

IKpsk2:	
← s . . .	Premessages
→ e, es, s, ss, [d0] ← e, ee, se, psk, [d1]	Handshake Messages
↔ [d2, d3, …]	Transport

Noise Patterns: IKpsk2

Initiator **Responder**

IKpsk2:

← s . . .	Premessages
→ e, es, s, ss, [d0] ← e, ee, se, psk, [d1]	Handshake Messages
↔ [d2, d3, …]	Transport

Noise Patterns: IKpsk2

Initiator **Responder**

IKpsk2:

← s

. . .

→ e, es, s, ss, [d0]

← e, ee, se, psk, [d1]

↔ [d2, d3, …]

Premessages

Handshake Messages

Transport

Noise Patterns: IKpsk2

Initiator **Responder**

IKpsk2:

← s
...
→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
↔ [d2, d3, …]

Premessages

Handshake Messages

Transport

Noise Patterns: IKpsk2

Initiator **Responder**

IKpsk2:

← s
. . .
→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
↔ [d2, d3, …]

Premessages

Handshake Messages

Transport

Noise Patterns: IKpsk2

Initiator **Responder**

IKpsk2:

← s
. . .

→ e, es, s, ss, [d0]

← e, ee, se, psk, [d1]

↔ [d2, d3, …]

Premessages: ← s, . . .

Handshake Messages: → e, es, s, ss, [d0]; ← e, ee, se, psk, [d1]

Transport: ↔ [d2, d3, …]

Noise Patterns: IKpsk2

responder sends **S_r_pub** before handshake
(uses Public Key Infrastructure…)

Initiator **Responder**

IKpsk2:

← s
. . .
→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
↔ [d2, d3, …]

Premessages: ← s, . . .
Handshake Messages: → e, es, s, ss, [d0]; ← e, ee, se, psk, [d1]
Transport: ↔ [d2, d3, …]

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
message := []

(..., ck0) := initialize(protocol_name, ...);

Initiator **Responder**

IKpsk2:

← s
. . .
→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
↔ [d2, d3, ...]

Premessages

Handshake Messages

Transport

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
message := []

e:
(E_i_priv, E_i_pub) := generate_keypair ()
message := message ++ E_i_pub
... // omitted: hash, nonce

(..., ck0) := initialize(protocol_name, ...);

Initiator **Responder**

IKpsk2:

← s
. . .
→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
↔ [d2, d3, ...]

Premessages

Handshake Messages

Transport

Noise Patterns: IKpsk2

Initial chaining Key

```
(...,  ck0) := initialize(protocol_name, ...);
message := []

e:
  (E_i_priv, E_i_pub) := generate_keypair ()
  message := message ++ E_i_pub
  ... // omitted: hash, nonce
```

Initiator **Responder**

```
(..., ck0) := initialize(protocol_name, ...);

e:
  (E_i_pub, message) := read_e (message)
  ...
```

IKpsk2:

← s
. . .
→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
↔ [d2, d3, ...]

Premessages

Handshake Messages

Transport

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
message := []

e:
(E_i_priv, E_i_pub) := generate_keypair ()
message := message ++ E_i_pub
... // omitted: hash, nonce

es: DH(Ephemeral, Static)
dh0 := DH(E_i_priv, S_r_pub)

Initiator **Responder**

IKpsk2:

← s
. . .
} Premessages

→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
} Handshake Messages

↔ [d2, d3, …]
} Transport

(..., ck0) := initialize(protocol_name, ...);

e:
(E_i_pub, message) := read_e (message)
...

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
message := []

e:
(E_i_priv, **E_i_pub**) := generate_keypair ()
message := message ++ **E_i_pub**
... // omitted: hash, nonce

es: DH(Ephemeral, Static)
dh0 := DH(E_i_priv, **S_r_pub**)

Initiator **Responder**

IKpsk2:

← s
. . .
} Premessages

→ e, es, s, ss, [d0]
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} Handshake Messages

↔ [d2, d3, ...] } Transport

(..., ck0) := initialize(protocol_name, ...);

e:
(**E_i_pub**, message) := read_e (message)
...

es:
dh0 := DH(S_r_priv, **E_i_pub**)

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
message := []

e:
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message := message ++ E_i_pub
... // omitted: hash, nonce

es: DH(Ephemeral, Static)
dh0 := DH(E_i_priv, S_r_pub)

Initiator

Responder

IKpsk2:

← s
. . .
} Premessages

→ e, es, s, ss, [d0]
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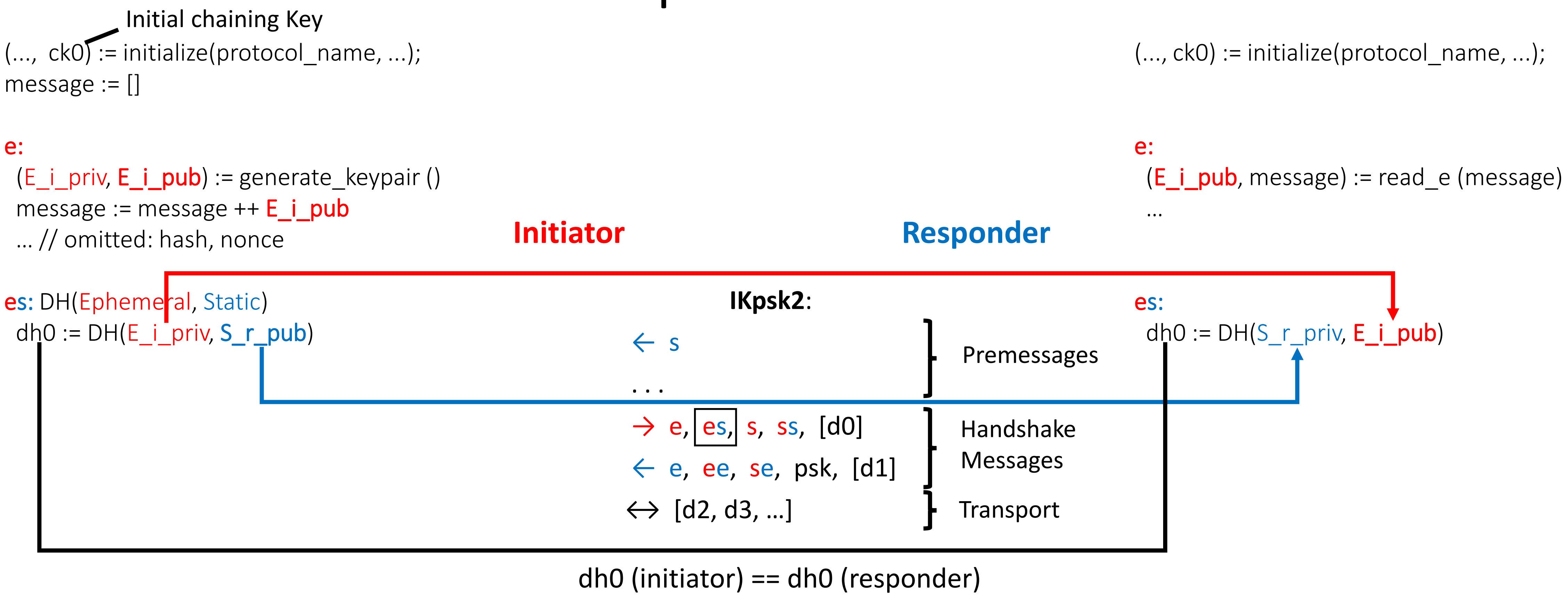
Noise Patterns: IKpsk2



Noise Patterns: IKpsk2

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(..., ck0) := initialize(protocol_name, ...);
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← s
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Noise Patterns: IKpsk2

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... // omitted: hash, nonce

es: DH(Ephemeral, Static)
dh0 := DH(E_i_priv, S_r_pub)
(ck1,sk1) := mix_key(ck0, dh0)
...

Initial chaining key

Diffie-Hellman result

Initiator **Responder**

IKpsk2:

← s
. . .
→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
↔ [d2, d3, ...]

Premessages

Handshake Messages

Transport

(..., ck0) := initialize(protocol_name, ...);

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(E_i_pub, message) := read_e (message)
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Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
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es: DH(Ephemeral, Static)
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...

Diffie-Hellman result
Initial chaining key
New chaining key
Symmetric encrypt/decrypt key

Initiator **Responder**

IKpsk2:

← s
...
→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
↔ [d2, d3, ...]

Premessages
Handshake Messages
Transport

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← s
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← e, ee, se, psk, [d1]
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Premessages

Handshake Messages

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 message := message ++ E_i_pub
 ... // omitted: hash, nonce

es: DH(Ephemeral, Static)
 dh0 := DH(E_i_priv, S_r_pub)
 (ck1,sk1) := mix_key(ck0, dh0)
 ...

s:
 enc_s := aead_encrypt(sk1, ..., S_i_pub)
 message := message ++ enc_s
 ...

Initiator **Responder**

IKpsk2:

← s . . .	Premessages
→ e, es, s, ss, [d0] ← e, ee, se, psk, [d1]	Handshake Messages
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Initiator **Responder**

IKpsk2:

← s
. . .
Premessages

→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
Handshake Messages

↔ [d2, d3, ...]
Transport

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dh0 := DH(S_r_priv, E_i_pub)
(ck1,sk1) := mix_key(ck0, dh0)
...

s:
(enc_s, message) := read_enc_s (message)
S_i_pub := aead_decrypt(sk1, ..., enc_s)
...

Uses authentication data: may fail (if message is corrupted or if not same symmetric key)

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
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(E_i_priv, E_i_pub) := generate_keypair ()
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} Premessages

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} Handshake Messages

↔ [d2, d3, ...]
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Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
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e:
(E_i_priv, E_i_pub) := generate_keypair ()
message := message ++ E_i_pub
... // omitted: hash, nonce

es: DH(Ephemeral, Static)
dh0 := DH(E_i_priv, S_r_pub)
(ck1,sk1) := mix_key(ck0, dh0)
...

s:
enc_s := aead_encrypt(sk1, ..., S_i_pub)
message := message ++ enc_s
...

ss: DH(Static, Static)
dh1 := DH(S_i_priv, S_r_pub)
(ck2,sk2) := mix_key(ck1, dh1)
...

Initiator **Responder**

IKpsk2:

← s
...
} Premessages

→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
} Handshake Messages

↔ [d2, d3, ...]
} Transport

(..., ck0) := initialize(protocol_name, ...);

e:
(E_i_pub, message) := read_e (message)
...

es:
dh0 := DH(S_r_priv, E_i_pub)
(ck1,sk1) := mix_key(ck0, dh0)
...

s:
(enc_s, message) := read_enc_s (message)
S_i_pub := aead_decrypt(sk1, ..., enc_s)
...

ss:
dh1 := DH(S_r_priv, S_i_pub)
(ck2,sk2) := mix_key(ck1, dh1)
..

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
message := []

e:
(E_i_priv, E_i_pub) := generate_keypair ()
message := message ++ E_i_pub
... // omitted: hash, nonce

es: DH(Ephemeral, Static)
dh0 := DH(E_i_priv, S_r_pub)
(ck1,sk1) := mix_key(ck0, dh0)
...

s:
enc_s := aead_encrypt(sk1, ..., S_i_pub)
message := message ++ enc_s
...

ss: DH(Static, Static)
dh1 := DH(S_i_priv, S_r_pub)
(ck2,sk2) := mix_key(ck1, dh1)
...

[d0]:
cipher := aead_encrypt(sk2, ..., d0)
message := message ++ cipher
...

Initiator **Responder**

IKpsk2:

← s
. . .
→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
↔ [d2, d3, ...]

Premessages
Handshake Messages
Transport

(..., ck0) := initialize(protocol_name, ...);

e:
(E_i_pub, message) := read_e (message)
...

es:
dh0 := DH(S_r_priv, E_i_pub)
(ck1,sk1) := mix_key(ck0, dh0)
...

s:
(enc_s, message) := read_enc_s (message)
S_i_pub := aead_decrypt(sk1, ..., enc_s)
...

ss:
dh1 := DH(S_r_priv, S_i_pub)
(ck2,sk2) := mix_key(ck1, dh1)
..

[d0]:
d0 := aead_decrypt(sk2, ..., message)
...
...

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
message := []

e:
(E_i_priv, E_i_pub) := generate_keypair ()
message := message ++ E_i_pub
... // omitted: hash, nonce

es: DH(Ephemeral, Static)
dh0 := DH(E_i_priv, S_r_pub)
(ck1,sk1) := mix_key(ck0, dh0)
...

s:
enc_s := aead_encrypt(sk1, ..., S_i_pub)
message := message ++ enc_s
...

ss: DH(Static, Static)
dh1 := DH(S_i_priv, S_r_pub)
(ck2,sk2) := mix_key(ck1, dh1)
...

[d0]:
cipher := aead_encrypt(sk2, ..., d0)
message := message ++ cipher
...

Initiator **Responder**

IKpsk2:

← s
. . .
} Premessages

→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
} Handshake Messages

↔ [d2, d3, ...] } Transport

- we exchange keys
- we derive same values for ck, sk at every step

(..., ck0) := initialize(protocol_name, ...);

e:
(E_i_pub, message) := read_e (message)
...

es:
dh0 := DH(S_r_priv, E_i_pub)
(ck1,sk1) := mix_key(ck0, dh0)
...

s:
(enc_s, message) := read_enc_s (message)
S_i_pub := aead_decrypt(sk1, ..., enc_s)
...

ss:
dh1 := DH(S_r_priv, S_i_pub)
(ck2,sk2) := mix_key(ck1, dh1)
..

[d0]:
d0 := aead_decrypt(sk2, ..., message)
...
...

Noise Patterns: IKpsk2

Initiator

(..., ck0) := initialize(protocol_name, ...); ← Initial chaining Key
message := []

e:
 (E_i_priv, E_i_pub) := generate_keypair ()
 message := message ++ E_i_pub
 ... // omitted: hash, nonce

es: DH(Ephemeral, Static)
 dh0 := DH(E_i_priv, S_r_pub)
 (ck1,sk1) := mix_key(ck0, dh0)
 ...

s:
 enc_s := aead_encrypt(sk1, ..., S_i_pub)
 message := message ++ enc_s
 ...

ss: DH(Static, Static)
 dh1 := DH(S_i_priv, S_r_pub)
 (ck2,sk2) := mix_key(ck1, dh1)
 ...

[d0]:
 cipher := aead_encrypt(sk2, ..., d0)
 message := message ++ cipher
 ...

IKpsk2:

← s
. . .
} Premessages

→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
} Handshake Messages

↔ [d2, d3, ...]
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Initiator **Responder**

IKpsk2:

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. . .
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Noise Patterns: IKpsk2

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IKpsk2:

← s
. . .
} Premessages

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Noise Patterns: IKpsk2

Initial chaining Key

Initiator | **Responder**

Initiator:

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es: DH(Ephemeral, Static)
  dh0 := DH(E_i_priv, S_r_pub)
  (ck1,sk1) := mix_key(ck0, dh0)
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s:
  enc_s := aead_encrypt(sk1, ..., S_i_pub)
  message := message ++ enc_s
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ss: DH(Static, Static)
  dh1 := DH(S_i_priv, S_r_pub)
  (ck2,sk2) := mix_key(ck1, dh1)
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[d0]:
  cipher := aead_encrypt(sk2, ..., d0)
  message := message ++ cipher
  ...
```

IKpsk2:

← s . . .	Premessages
→ e, es, s, ss, [d0] ← e, ee, se, psk, [d1]	Handshake Messages
↔ [d2, d3, …]	Transport

- we exchange keys
- we derive same values for ck, sk at every step

Responder:

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(..., ck0) := initialize(protocol_name, ...);

e:
  (E_i_pub, message) := read_e (message)
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es:
  dh0 := DH(S_r_priv, E_i_pub)
  (ck1,sk1) := mix_key(ck0, dh0)
  ...

s:
  (enc_s, message) := read_enc_s (message)
  S_i_pub := aead_decrypt(sk1, ..., enc_s)
  ...

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  dh1 := DH(S_r_priv, S_i_pub)
  (ck2,sk2) := mix_key(ck1, dh1)
  ..

[d0]:
  d0 := aead_decrypt(sk2, ..., message)
  ...
  ...
```

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
message := []

e:
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dh0 := DH(E_i_priv, S_r_pub)
(ck1,sk1) := mix_key(ck0, dh0)
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enc_s := aead_encrypt(sk1, ..., S_i_pub)
message := message ++ enc_s
...

ss: DH(Static, Static)
dh1 := DH(S_i_priv, S_r_pub)
(ck2,sk2) := mix_key(ck1, dh1)
...

[d0]:
cipher := aead_encrypt(sk2, ..., d0)
message := message ++ cipher
...

Initiator **Responder**

IKpsk2:

← s
. . .
} Premessages

→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
} Handshake Messages

↔ [d2, d3, ...]
} Transport

- we exchange keys
- we derive same values for ck, sk at every step

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e:
(E_i_pub, message) := read_e (message)
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es:
dh0 := DH(S_r_priv, E_i_pub)
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(enc_s, message) := read_enc_s (message)
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dh1 := DH(S_r_priv, S_i_pub)
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..

[d0]:
d0 := aead_decrypt(sk2, ..., message)
...
...

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
message := []

e:
 (E_i_priv, E_i_pub) := generate_keypair ()
 message := message ++ E_i_pub
 ... // omitted: hash, nonce

es: DH(Ephemeral, Static)
 dh0 := DH(E_i_priv, S_r_pub)
 (ck1,sk1) := mix_key(ck0, dh0)
 ...

s:
 enc_s := aead_encrypt(sk1, ..., S_i_pub)
 message := message ++ enc_s
 ...

ss: DH(Static, Static)
 dh1 := DH(S_i_priv, S_r_pub)
 (ck2,sk2) := mix_key(ck1, dh1)
 ...

[d0]:
 cipher := aead_encrypt(sk2, ..., d0)
 message := message ++ cipher
 ...

Initiator **Responder**

IKpsk2:

← s
. . .
} Premessages

→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
} Handshake Messages

↔ [d2, d3, ...]
} Transport

- we exchange keys
- we derive same values for ck, sk at every step

(..., ck0) := initialize(protocol_name, ...);

e:
 (E_i_pub, message) := read_e (message)
 ...

es:
 dh0 := DH(S_r_priv, E_i_pub)
 (ck1,sk1) := mix_key(ck0, dh0)
 ...

s:
 (enc_s, message) := read_enc_s (message)
 S_i_pub := aead_decrypt(sk1, ..., enc_s)
 ...

ss:
 dh1 := DH(S_r_priv, S_i_pub)
 (ck2,sk2) := mix_key(ck1, dh1)
 ..

[d0]:
 d0 := aead_decrypt(sk2, ..., message)
 ...
 ...

Noise Patterns: IKpsk2

Initial chaining Key

(..., ck0) := initialize(protocol_name, ...);
message := []

e:
(E_i_priv, E_i_pub) := generate_keypair ()
message := message ++ E_i_pub
... // omitted: hash, nonce

es: DH(Ephemeral, Static)
dh0 := DH(E_i_priv, S_r_pub)
(ck1 sk1) := mix_key(ck0, dh0)
...

ck1, sk1: DH(E_i, S_r)

s:
enc_s := aead_encrypt(sk1, ..., S_i_pub)
message := message ++ enc_s
...

ss: DH(Static, Static)
dh1 := DH(S_i_priv, S_r_pub)
(ck2 sk2) := mix_key(ck1, dh1)
...

ck2, sk2: DH(E_i, S_r), DH(S_i, S_r)

[d0]:
cipher := aead_encrypt(sk2, ..., d0)
message := message ++ cipher
...

Initiator **Responder**

IKpsk2:

← s
. . .
} Premessages

→ e, es, s, ss, [d0]
← e, ee, se, psk, [d1]
} Handshake Messages

↔ [d2, d3, ...]
} Transport

- we exchange keys
- we derive same values for ck, sk at every step
- ck, sk become “more secret” at every DH

(..., ck0) := initialize(protocol_name, ...);

e:
(E_i_pub, message) := read_e (message)
...

es:
dh0 := DH(S_r_priv, E_i_pub)
(ck1,sk1) := mix_key(ck0, dh0)
...

s:
(enc_s, message) := read_enc_s (message)
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