End-To-End Cryptographic Verification: From Assembly to Security Theorems

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MPRI 2-30

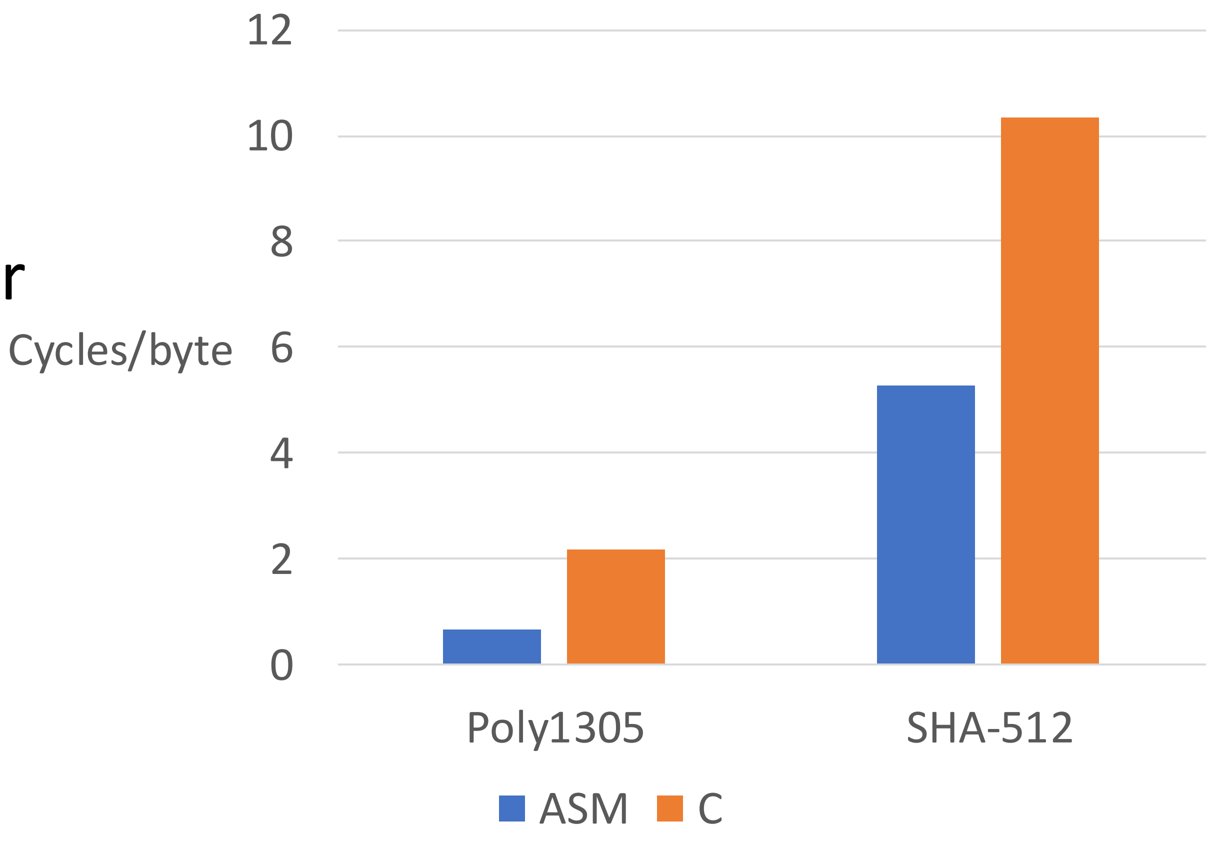
Outline

- Last week:
  - Verification of stateful code
  - Application to HACL*: A verified C cryptographic library

- Today:
  - Verifying cryptographic code in assembly
  - Symbolic Analysis with Dolev-Yao*
  - End-to-End Verification: the Noise* example

Cryptographic Implementations in Assembly

- SIMD instructions
- More optimizations (instruction ordering, register allocation, clever loop unrolling, …)
- Avoid compiler-induced vulnerabilities



Performance comparison in OpenSSL. Smaller is better.

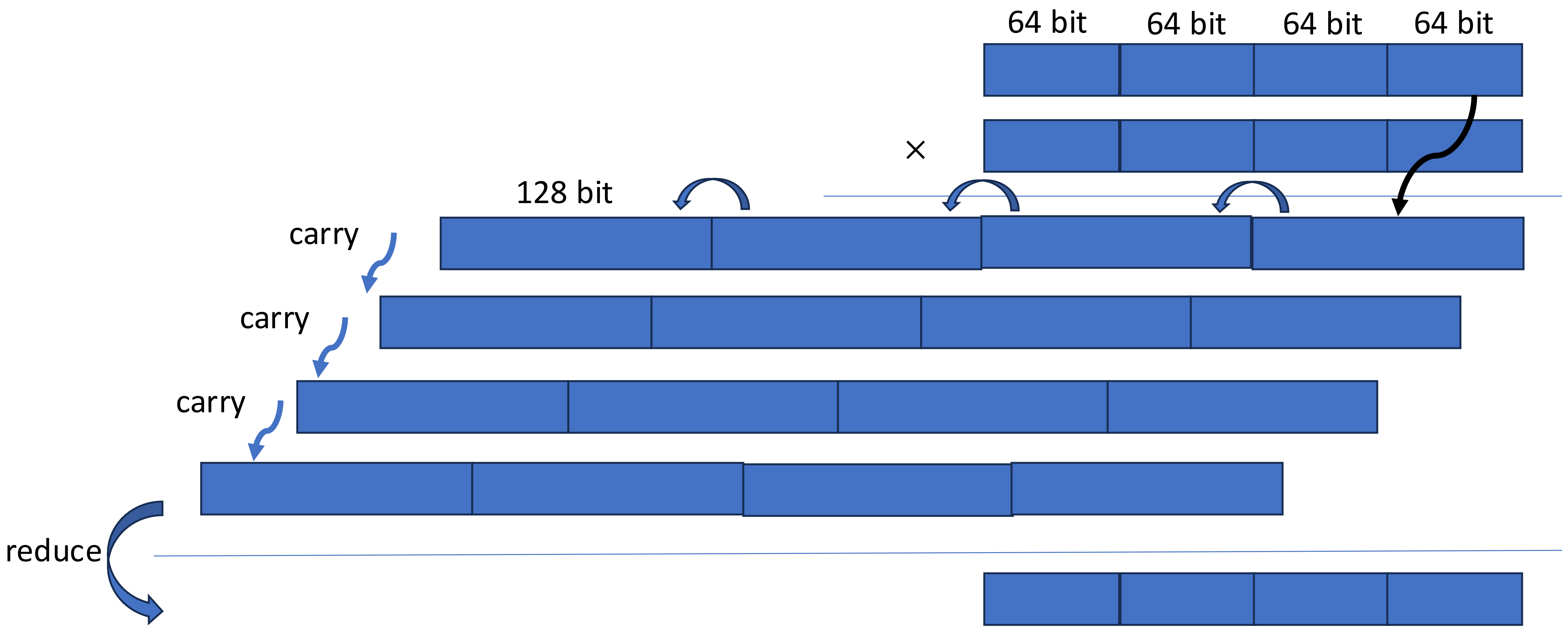
Data from Zinzindohoué et al, CCS 17

The AES Instruction Set (AES-NI)

- Introduced in 2008, present on most Intel processors nowadays
- 6 instructions that speed up (and simplify) AES implementations:
  - AESENC: Perform one AES encryption round
  - AESENCLAST: Perform the last AES encryption round
  - AESDEC: Perform one AES decryption round
  - AESDECLAST: Perform the last AES decryption round
  - Also, AESKEYGENASSIST and AESIMC for parts of round key generation

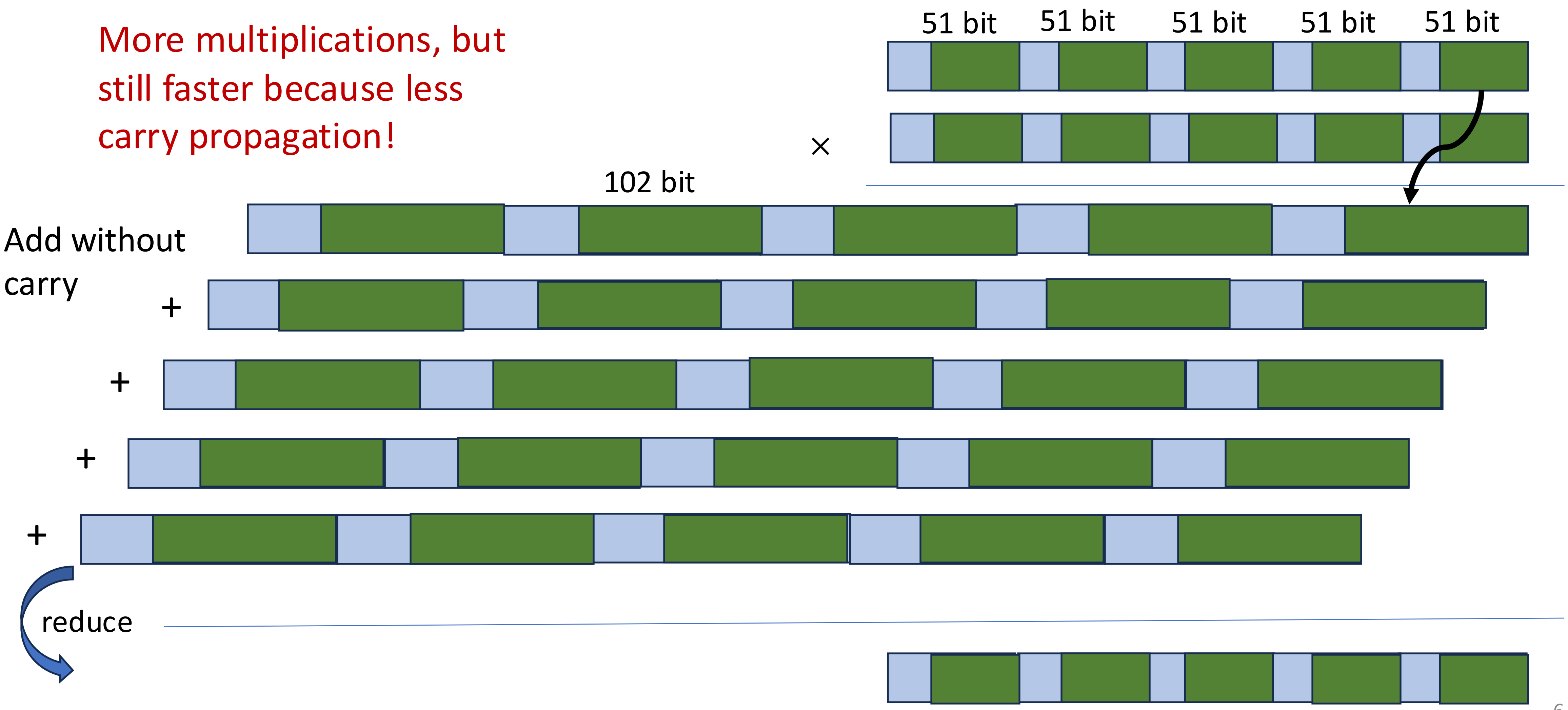
- Some similar instructions for SHA (SHA-EXT since 2013)

Reminder: 256-bit Modular Multiplication



Unsaturated 256-bit Modular Multiplication

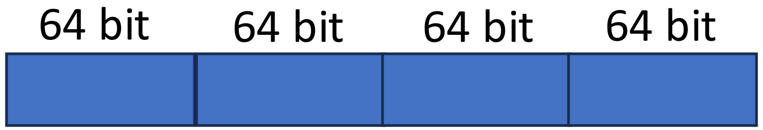
More multiplications, but still faster because less carry propagation!



Saturated Arithmetic with Intel ADX

How to (pre-)compute a ladder: Improving the Performance of X25519 and X448, Oliveira et al., SAC' 2017

- Intel ADX extension offers two new instructions for addition (ADCX and ADOX) with two distinct carry flags.
- Significantly reduces carry propagation, it can be delayed
- Saturated implementations can now outperform optimized unsaturated ones!



Efficient and Trustworthy?

Moderncrypto mailing list, Feb 2018

```
Quoting "Jason A. Donenfeld" <Jason at zx2c4.com>:
> Hi Armando,
>
> I've started importing your precomputation implementation into kernel
> space for use in kbench9000 (and in WireGuard and the kernel crypto
> library too, of course).
>
> - The first problem remains the license. The kernel requires
> GPLv2-compatible code. GPLv3 isn't compatible with GPLv2. This isn't
> up to me at all, unfortunately, so this stuff will have to be licensed
> differently in order to be useful.
>

The rfc7748_precomputed library is now released under LGPLv2.1.
We are happy to see our code integrated in more projects.

Quoting "Jason A. Donenfeld" <Jason at zx2c4.com>:
> - It looks like the precomputation implementation is failing some unit
> tests! Perhaps it's not properly reducing incoming public points?
>
> There's the vector if you'd like to play with it. The other test
> vectors I have do pass, though, which is good I suppose.

Thanks, for this observation. The code was missing to handle some carry bits,
producing incorrect outputs for numbers between 2p and 2^256. Now, I have
rewritten some operations for GF(2^255-19) considering all of these cases.
More tests were added and fuzz test against HACL implementation.
```

Efficient, but very tricky code. We would like to establish its correctness formally

How to Reason about Assembly

- Low* was a *shallow embedding* of C in F*: We reuse F* syntax, write F* programs and extract them to C
- Assembly differs heavily from F*:
  - No variables, only registers
  - Unstructured control-flow based on jumps
  - No types/abstraction, flat memory model mapping physical addresses to bytes
- The languages are too far, we need a deeper model of assembly in F*

Assembly Verification Plan

- Model the syntax of assembly programs as an F* datatype *(deep embedding)*
- Define semantics for assembly programs
- Write a program to verify using our embedding
- Based on the semantics, establish its correctness in F*

Vale: Verifying High-Performance Cryptographic Assembly Code, Bond et al., USENIX Security 17

A Verified, Efficient Embedding of a Verifiable Assembly Language, Fromherz et al., POPL' 19

Modeling Intel x64 Assembly Syntax

```
type reg = Rax | Rbx | Rcx | Rdx …

type operand =
  | OConst: int -> operand
  | OReg: r: reg -> operand
  | OMem: m:mem_addr -> operand

type ins =
  | Mov64: dst:operand -> src:operand -> ins
  | Add64: dst:operand -> src:operand -> ins
  …
```

Structured Assembly Control-Flow

- Even in assembly, cryptographic code usually follows some structured control-flow (branching, loops)
- We do not model unstructured control-flow (gotos/arbitrary jumps)

```
type cond =
  | Lt: o1: operand -> o2: operand -> cond
  | Eq: o1: operand -> o2: operand -> cond
  …
type code =
  | Ins: ins:ins -> code
  | Block: block:list code -> code
  | IfElse: ifCond:cond -> ifTrue:code -> ifFalse:code -> code
  | While: whileCond:cond -> whileBody:code -> code
```

Generating Executable Assembly Code

- A trusted printer transforms a value of type code into an ASM file

```
Block([
  Ins(Mov64 (OReg rax) (OReg rbx));
  Ins(Add64  (OReg rax) (OConst 1))])
```

```
    mov %rax %rbx
    add  $1, %rax
```

```
IfElse (Eq (OReg rcx) (OReg rdx))
    (… //then branch)
    (… //else branch)
```

```
    cmp %rcx %rdx
    jne L1
    … // then branch
    jmp L2
L1:
    … // else branch
L2:
```

Defining Assembly Semantics

- We want to define an interpreter for assembly code:

```
val eval (s:state) (c: code) : a * state
```

```
type state = {
   regs:reg → nat64;
   flags:nat64;
   mem:map int nat8;
   xmms:xmm → (nat32 ∗ nat32 ∗ nat32 ∗ nat32);
   ok:bool;
}
```

Defining Assembly Semantics

```
let eval_operand (o:operand) (s:state) : nat64 = match o with
  | OReg r -> s.regs r
  | OConst n -> n
  …

let valid_src_operand (o:operand) (s:state) = match o with
  | OMem addr -> forall p. p >= addr && p < addr + 8 => Map.contains s.mem p
  | _ -> true

let valid_dst_operand (o:operand) (s:state) = match o with
  | OConst  _-> false
  | OReg r -> r <> rsp
  …
```

Defining Assembly Semantics

- Semantics in a monadic style to simplify notations
- Underspecify when possible to simplify model (e.g., flags)

```
let eval_ins (ins:ins) =
  s <- get;
  match ins with
  | Mov64 dst src -> . . .
  | Add64 dst src ->
    check (valid_src_operand src);; check (valid_dst_operand dst);;
    havoc flags;;
    let sum = eval_operand dst s + eval_operand src s in
    let new_carry = sum ≥ pow2_64 in
    set_operand dst ins (sum % pow2_64);;
    set_flags (update_cf s.flags new_carry)
```

The Vale Language

- Writing a full program as an AST is tedious (e.g., Block([Ins(Mov64 (OReg rax) (OReg rbx)); Ins(Add64 (OReg rax) (OConst 1))]))
- Vale exposes a user-friendly language to simplify writing code

Example Vale Code

```
procedure Triple()
  modifies rax; rbx; flags;
  requires rax < 100;
  ensures rbx == 3 * old(rax);
{
  Move(rbx, rax);
  Add(rax, rbx);
  Add(rbx, rax);
}
```

→

Vale AST

```
Block([
   Ins (Mov64(rbx, rax));
   Ins (Add64(rax, rbx));
   Ins (Add64(rbx, rax));
]
```

The Vale Language: Inlining

- Vale supports *inline if* statements, which are evaluated during **code generation**
- Useful for selecting instructions and for unrolling loops

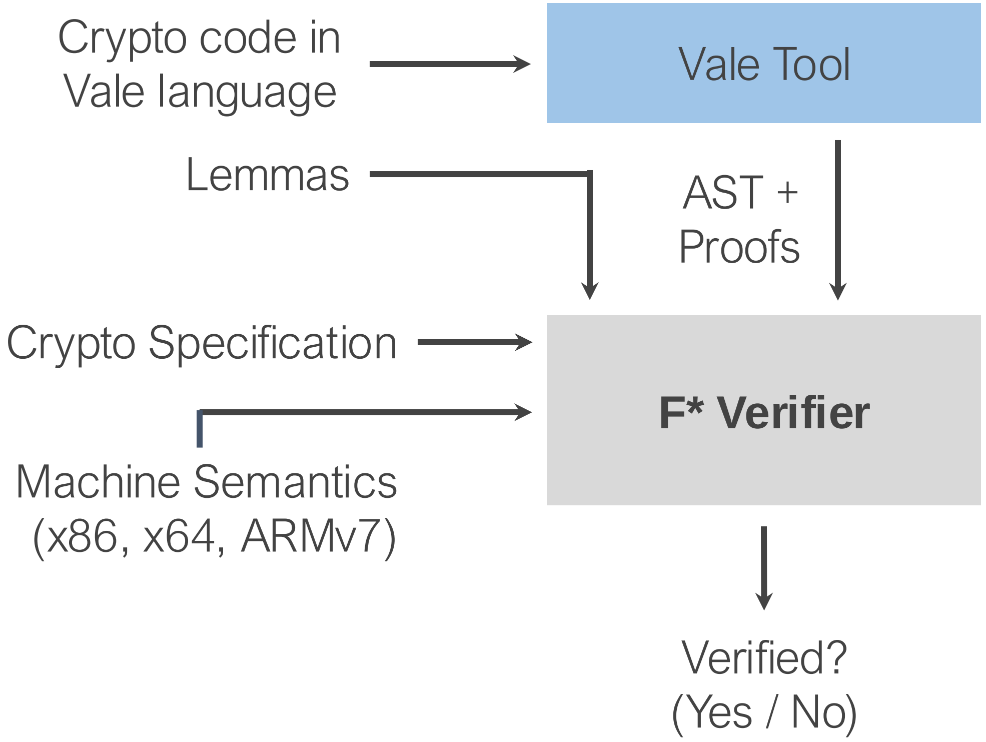
Target Instruction Selection
(**Platform-dependent** optimization)

```
inline if(platform == x86_AESNI) {
  ...
}
```

Loop Unrolling
(**Platform-independent** optimization)

```
inline if (n > 0) {
  ...
  recurse(n - 1);
}
```

Vale: A Summary



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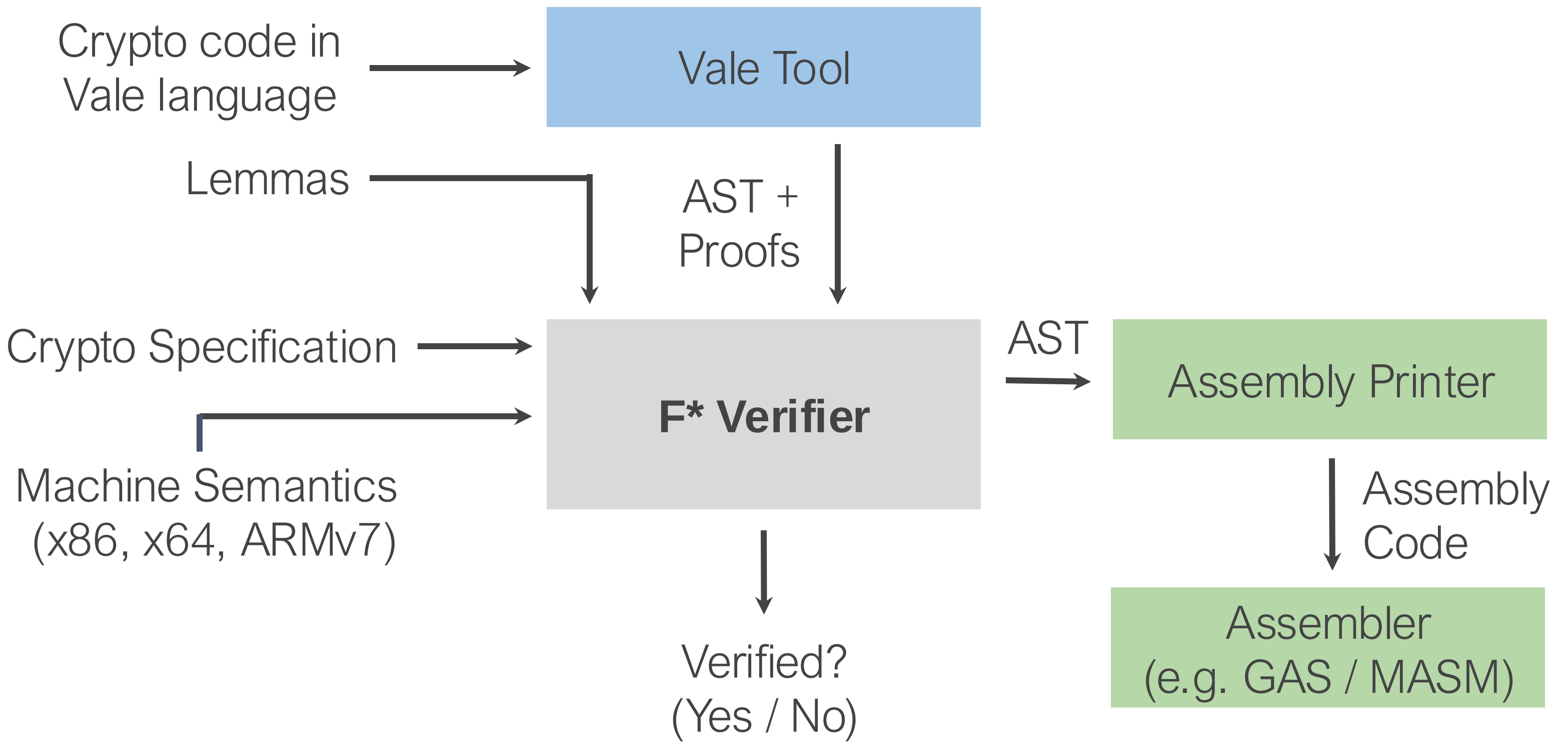
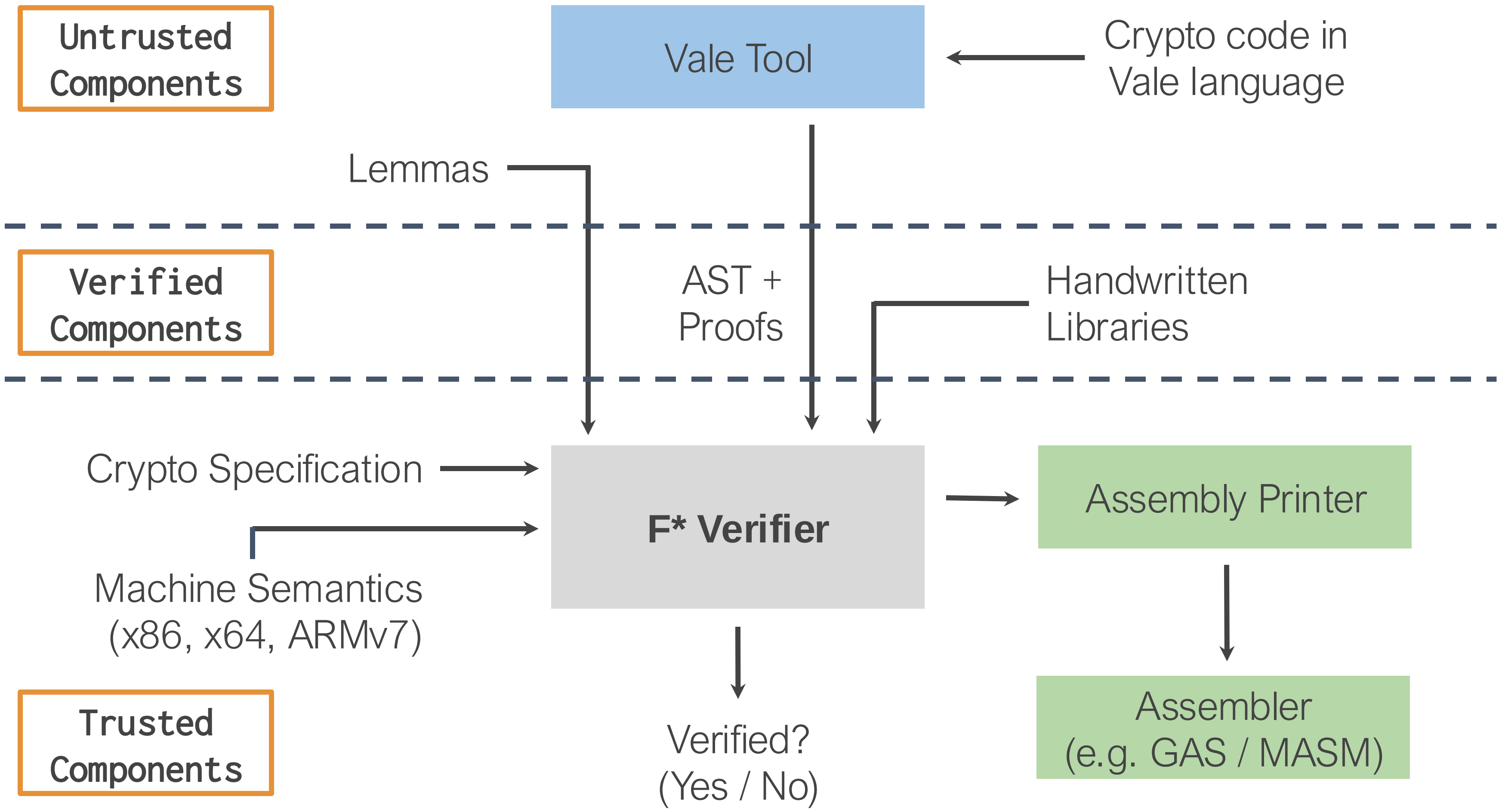


Vale: A Summary



Information Leakage

Secrets should not leak through:

- **Digital side channels:** Observations of program behavior through cache usage, timing, memory accesses, …
- **Residual Program State:** Secrets left in registers or memory after termination of program

Non-Interference by Taint Analysis

- **Core idea:** Mark some inputs as secret (“taint” them)
- Static analysis *propagates* the taint throughout the program
- If taint is propagated to attacker-observable components, raise error

- We can prove the correctness of the analysis based on the semantics
  - Possible because we can directly reason on the deeply embedded semantics

```
val taint_analysis: c:code -> isPub:(loc -> bool) -> b:bool{b ==⇒ isLeakageFree c isPub}
```

Taint Analysis Example

```
let f (x : int) =
    y := x;
    z := 0;
    w := z + y;
```

```
let f (x : int) =
    y := x;
    z := 0;
    w := z + y;
```

- Mark input x as secret
- Propagate taint through program

Taint Analysis: Join Operator

```
let f (x : int, p: int) =
  z := p;
  if z > 0
    y := x;
  else
    y := 0;
  w := z + y;
```

```
let f (x : int, p: int) =
  z := p;
  if z > 0
    y := x;
  else
    y := 0;
  w := z + y;
```

- When joining two execution paths, we take the ”highest” value for each variable

Taint Analysis: Raising Errors

```
let f (x : int) =
  c := x + 2;
  if c > 0
    y := 1;
  else
    y := 2;
```

```
let f (x : int) =
  c := x + 2;
  if c > 0
    y := 1;
  else
    y := 2;
```

✖

```
let g (x : int, a: int[]) =
  y := a[x];
```

```
let g (x : int, a: int[]) =
  y := a[x];
```

✖

Taint Analysis: Erasing Taint

```
let f (x : int) =
  i := x + 2;
  c := xor(x, x);
  if c > 0
    y := 1;
  else
    y := 2;
```

```
let f (x : int) =
  i := x + 2;
  c := xor(x, x);
  if c > 0
    y := 1;
  else
    y := 2;
```

- While tainted in theory, the output of some operations does not depend on its inputs
- We can soundly erase the taint in these cases

Taint Analysis: Memory Accesses

```
let f (x : int, y: int, a: int[]) =
  a[0] := x;
  c := a[y];
  if c > 0
    y := 1;
  else
    y := 2;
```

- Is this program constant-time?
- Depends on the values of y

Taint Analysis: Memory Accesses

```
let f (x : int, y: int, a: int[]) =
  a[0] := x;
  if y > 0
    c := a[y];
  else
    c := 2;
   if c > 0 …
```

- Is this program constant-time?
- Yes, however tracking this requires tracking information about possible values of y
- We need a precise analysis to avoid false positives

Taint Analysis: Memory Accesses

```
let f (x : int, p1: *int, p2: *int) =
  *p1 := x;
  y := *p2;
  if y > 0 …
```

- Is this program constant-time?
- Depends on whether p1 and p2 alias
- We need aliasing information, either inferred (points-to analysis) or provided by programmer

Vale Taint Information

- We annotate all memory accesses with taint information

  OMem: m:mem_addr -> t:taint -> operand

- We instrument semantics to ensure well-formedness of tainted memory operations
  - A public-annotated read of secret values is a “failure”
  - This can be checked when proving functional correctness (already requires precise aliasing information)
- Taint analysis can directly leverage memory operation taint
- Taint is erased at runtime, only used for the analysis

Automatically Optimizing Assembly Code

- Handwritten assembly code is already manually optimized
- Some small changes can yield performance improvements on some architectures (depending on microarchitectural details)
- **Idea:** Try peephole optimizations to tweak code, while proving that the code transformations preserve semantics

Verified Transformations and Hoare Logic: Beautiful Proofs for Ugly Assembly Language, Bosamiya et al., VSTTE’ 20

Semantically Equivalent Transformations

```
let semantically_equivalent (c1 c2: code) =
  (forall (s1 s2:state). equiv_states s1 s2 ==>
          equiv_states (eval_code c1 s1) (eval_code c2 s2))

type transform = c1: code -> c2:code{semantically_equivalent c1 c2}
```

- **Goal:** Define transformations satisfying the *transform* type
- Can be proven correct as an F* theorem thanks to our deep embedding of semantics

Transformation Example: Xor Rewriting

- Replace all occurences of *mov {reg}, 0* by *xor {reg} {reg}*

- Semantically equivalent? Yes, *xor n n* is equal to 0, so this is equivalent to setting the value 0 in register *{reg}*

Instruction Reordering

- If we have two instructions A and B, we can swap them if there is no read-write or write-write conflict

- Formally, we can rewrite A; B into B; A if

$$\forall\, l \in writes(A).\ l \notin reads(B) \land l \notin writes(B)$$

add(r1, r2) is defined as r1 := r1 + r2

Can add(rax, rbx); add(rcx, rdx) be rewritten into add(rcx, rdx); add(rax, rbx)?

Can add(rbx, rax); add(rcx, rbx) be rewritten into add(rcx, rbx); add(rbx, rax)?

Can add(rax, rbx); add(rcx, rbx) be rewritten into add(rcx, rbx); add(rax, rbx)?

Block Instruction Reordering

- Instruction reordering can be extended to **groups** of instructions

  $\forall (X, Y) \in (A, B).$

  $\forall\ l \in \text{writes}(X).\ l \notin \text{reads}(Y) \land l \notin \text{writes}(Y)$

Ex: A = add rax, 1; adc rbx, 1, B = add rcx, 1; adc rdx, 1

- In each block, adc (add with carry) relies on the carry of the previous instruction
- We can swap blocks, but not individual instructions

Optimizing for Processor Generation

- So far, optimizations for an **architecture** (e.g., Intel x64 vs ARM)
- Transformations enable optimization for a processor generation (e.g., Intel’s i5-2500, i7-3770, i7-7600U, or i9-9900K)
- Workflow:
  - Start from verified assembly code
  - Try many verified transformations
  - Benchmark; if faster than previous fastest, keep this version
- Experimental results: Speedups of up to 27% compared to OpenSSL

Back to Curve25519

- We can implement efficient core modular arithmetic in assembly
  - Use ADX + BMI2 instructions
  - Prove correctness and side-channel resistance using Vale
- We would prefer to write the rest of the code in C
  - Add/Double formulae, Montgomery ladder
  - Implement and verify in Low*, retrieve executable C code
- How to interoperate between the two?

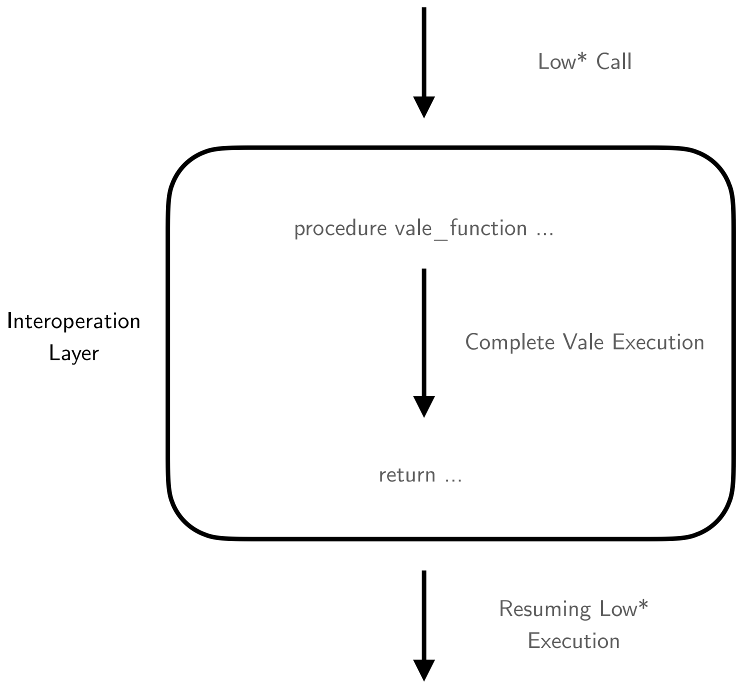
Interoperating between C and Assembly

Several questions

- How to relate memory models?
- How to enforce calling conventions across function calls?
- How to unify specifications?
- How to preserve security guarantees?

Interoperating between Vale and Low*

- We do not need a generic interoperation
  - For crypto, no callbacks from assembly to C, no allocation in assembly, …



We call a Vale function from Low*, entirely execute it, and finally resume Low* execution

Interoperation, Formally

```
let call_assembly (c:vale_code) arg1 … argn
  : Stack uint64
   (requires lift_pre P) (ensures lift_post Q)
= let h0 = get() in
   let s0 = initial_vale_state h0 arg1 … argn in
   let s1 = eval c s0 in
   let rax, h1 = final_lowstar_state h0 s1 in
   put h1; rax
```

- Small, trusted model of interoperation
- Parametric in calling conventions (Windows, Linux, inline assembly, …)
- Lifting of specifications is verified against the trusted model
- Lift_* is done generically

Interoperation: Calling Conventions

```
let initial_vale_state_linux_x64 h0 arg1 arg2 arg3 =
  let init_regs r =
     if r = rdi then arg1 else
     if r = rsi then arg2 else
     if r = rdx then arg3
  in let init_mem = lower h0 in …
  { ok = true; regs = init_regs; mem = init_mem; … }
```

- In practice: arity-generic to support an arbitrary number of arguments
- Stack spilling if too many arguments
- Calling conventions also require some registers to be preserved by callee (e.g., RBX, RSP, RBP, and R12–R15 on Linux x64)

Interoperation at Work: Optimizing Curve25519

Low*

```
let curve25519 (...) = ...
  fmul1 out f1 f2;
  ...
```

Interop

```
val fmul1 (dst:u256) (a:u256) (b:uint64{v f2 < pow2 17}) :
  Stack unit
    (requires fun h -> adx_enabled /\ bmi2_enabled /\ ...)
    (ensures ...)
```

Vale

```
procedure fmul1(...)...
    lets dst_ptr @= rdi; inA_ptr @= rsi; b @= rdx;
    requires adx_enabled && bmi2_enabled && ...
    ensures ...
{
    fast_mul1(0, inA_b); ... Mov64(b, 38);
    carry_pass(false, 0, dst_b);
}
```

Interoperation at Work: Optimizing Curve25519

Implementation	Radix	Language	CPU cycles
donna64	51	C	159634
fiat-crypto	51	C	145248
amd64-64	51	Assembly	143302
sandy2x	25.5	Assembly + AVX	135660
HACL* + Vale (portable)	51	C	135636
OpenSSL	64	Assembly + ADX	118604
Oliveira et al.	64	Assembly + ADX	115122
HACL* + Vale (targeted)	64	C + Assembly + ADX	113614

Unverified
Verified

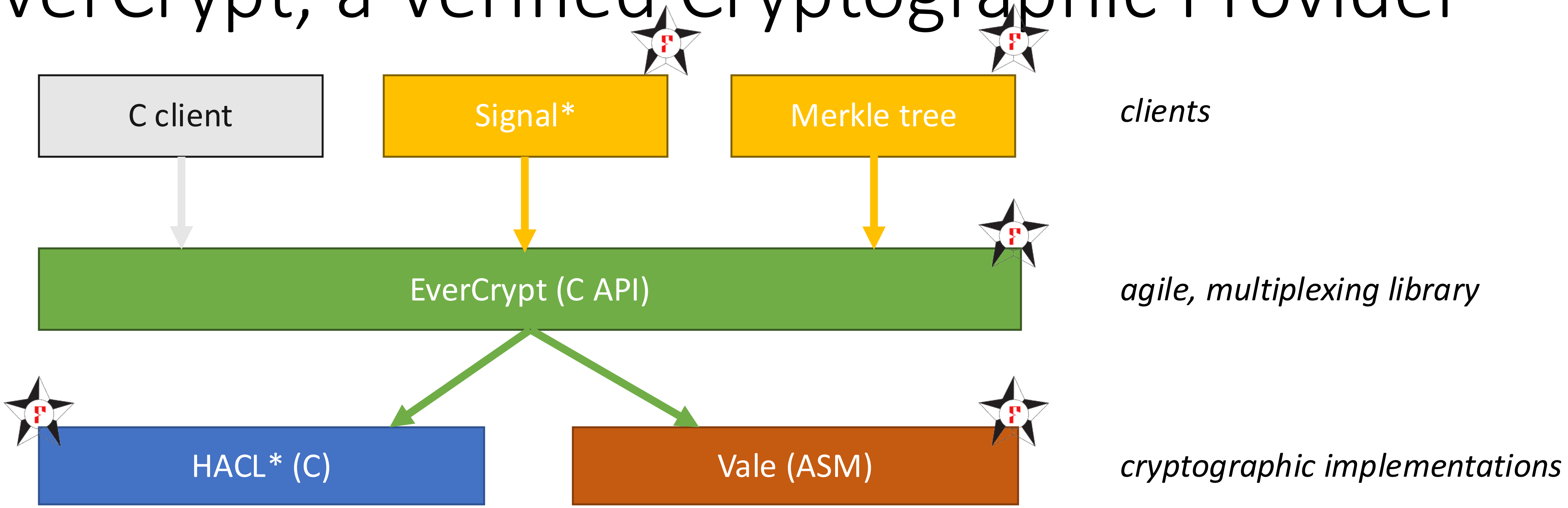
Verification code can reach state-of-the-art performance, sometimes outperforming the best existing unverified implementations

Towards a Cryptographic Provider

- We focused so far on verifying individual implementations

- Clients expect a **cryptographic library** with user-friendly APIs, not a collection of primitives
  - APIs must be grouped by family (Agility)
  - Must allow to switch between implementations (Multiplexing)
  - Must cover all cryptographic needs (comprehensive)

EverCrypt, a Verified Cryptographic Provider



- Layer on top of HACL* + Vale
- Provides generic APIs for hashes, AEAD, … with a single, unified specification
- Performs multiplexing between available implementations (depending on CPU features available, user preference, …)
- Usable by verified and unverified clients alike

EverCrypt: Agility

- Verifies that multiple algorithms satisfy the same family of specifications
- Provides a unified API
- Makes switching from one algorithm to the other straightforward

EverCrypt_Hash.c

```c
void EverCrypt_Hash_init(EverCrypt_Hash_state_s *s)
{
  EverCrypt_Hash_state_s scrut = *s;
  if (scrut.tag == EverCrypt_Hash_MD5_s)
  {
    uint32_t *p1 = scrut.case_MD5_s;
    Hacl_Hash_Core_MD5_init(p1);
  }
  else if (scrut.tag == EverCrypt_Hash_SHA1_s)
  {
    uint32_t *p1 = scrut.case_SHA1_s;
    Hacl_Hash_Core_SHA1_init(p1);
  }
  else if (scrut.tag == EverCrypt_Hash_SHA2_224_s)
  {
    uint32_t *p1 = scrut.case_SHA2_224_s;
    Hacl_Hash_Core_SHA2_init_224(p1);
  }
  else if (scrut.tag == EverCrypt_Hash_SHA2_256_s)
  {
    uint32_t *p1 = scrut.case_SHA2_256_s;
    Hacl_Hash_Core_SHA2_init_256(p1);
  }
  else if (scrut.tag == EverCrypt_Hash_SHA2_384_s)
  {
    uint64_t *p1 = scrut.case_SHA2_384_s;
    Hacl_Hash_Core_SHA2_init_384(p1);
  }
  else if (scrut.tag == EverCrypt_Hash_SHA2_512_s)
  {
    uint64_t *p1 = scrut.case_SHA2_512_s;
    Hacl_Hash_Core_SHA2_init_512(p1);
  }
  else
```

```
1  - 62k EverCrypt_Hash.c   C/*l   unix | 359: 0   39%
```

EverCrypt: Multiplexing

- Several implementations with different levels of optimization (e.g., portable C, C with SIMD, Intel ASM with ADX+BMI2)
- Several versions require assumptions on CPU architecture (e.g., Intel x64, presence of AESNI instruction set)
- We want to use the fastest implementation available, but to avoid illegal instruction errors

EverCrypt: Multiplexing

- Mix of architecture requirements (has_avx/is_x64) and user preferences (wants_vale)
- Functions require as a precondition to run with the right extension set
- CPU instructions (cpuid) can inform about available extensions
- Leverage Low*/Vale interop to lift this information to the Low* level, and guarantee to avoid illegal instruction errors

EverCrypt_Poly1305.c

```
*/
void EverCrypt_Poly1305_poly1305(uint8_t *dst, uint8_t *src, uint32_t len1, uint8_t *key)
{
  bool avx2 = EverCrypt_AutoConfig2_has_avx2();
  bool avx = EverCrypt_AutoConfig2_has_avx();
  bool vale1 = EverCrypt_AutoConfig2_wants_vale();
  #if EVERCRYPT_TARGETCONFIG_X64
  if (avx2)
  {
    Hacl_Poly1305_256_poly1305_mac(dst, len1, src, key);
    return;
  }
  #endif
  #if EVERCRYPT_TARGETCONFIG_X64
  if (avx)
  {
    Hacl_Poly1305_128_poly1305_mac(dst, len1, src, key);
    return;
  }
  #endif
  #if EVERCRYPT_TARGETCONFIG_X64
  if (vale1)
  {
    EverCrypt_Poly1305_poly1305_vale(dst, src, len1, key);
    return;
  }
  #endif
  Hacl_Poly1305_32_poly1305_mac(dst, len1, src, key);
}
```

- 19k EverCrypt_Poly1305.c   unix | ??: 0   Bottom

EverCrypt: Available Algorithms

Algorithm	C version	ASM version	Agile API
AEAD			
AES-GCM		✓ (AESNI)	✓
ChachaPoly	✓		✓
ECDH			
Curve25519	✓	✓ (BMI2 + ADX)	
P-256	✓		
Hashes			
MD5, SHA1	✓		✓
SHA2	✓	✓ (SHAEXT)	✓
SHA3	✓		
Blake2	✓		

Algorithm	C version	ASM version	Agile API
Key Derivation			
HKDF	✓	✓	✓
Ciphers			
Chacha20	✓		
AES-128,256		✓ (AESNI)	
MACS			
HMAC	✓	✓	✓
Poly1305	✓	✓	
Signatures			
Ed25519	✓		
P-256	✓		

Many functionalities, covering most of the standard cryptographic needs

End-to-End Verification

- So far, we saw different techniques for verifying the **safety and correctness** of low-level, efficient cryptographic implementations
- How to also preserve security guarantees at the protocol level?

- Case study: the Noise protocols

Noise: A Library of Verified High-Performance Secure Channel Protocol Implementations,* Ho et al., S&P' 22

(Noise* slides from Son Ho, DY* slides from Karthik Bhargavan)

What is Noise?

- **What does a handshake protocol do?**
  - Exchange data to have a **shared secret** to communicate
  - Various use cases (one-way encryption, authenticated servers, mutual authentication, etc.)
  - Varying security
- Various protocols, some of them **very advanced and complex** (ex.: TLS):
  - Backward compatibility
  - Cipher suites negotiation
  - Session resumption
  - …
- When advanced features not needed: **Noise** family of protocols

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

→ s, se

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

Noise Protocol Example: IKpsk2

IKpsk2:

← s

. . .

→ e, es, s, ss

← e, ee, se, psk

Noise Protocol Example: IKpsk2

Initiator **Responder**

IKpsk2:

← s

. . .

→ e, es, s, ss, [d0]

← e, ee, se, psk, [d1]

↔ [d2, d3, …]

The handshake describes how to:

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

Noise Protocol Example: IKpsk2

Initiator **Responder**

IKpsk2:

← s

. . . **Exchange key material**

→ e, es, s, ss, [d0]

← e, ee, se, psk, [d1]

↔ [d2, d3, …]

The handshake describes how to:

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

Noise Protocol Example: IKpsk2

Initiator **Responder**

IKpsk2:

← s

s: static

. . .

e: ephemeral

→ e, es, s, ss, [d0]

← e, ee, se, psk, [d1]

↔ [d2, d3, …]

The handshake describes how to:

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

Noise Protocol Example: IKpsk2

Initiator **Responder**

IKpsk2:

← s

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

→ e, es, s, ss, [d0]

← e, ee, se, psk, [d1]

↔ [d2, d3, …]

The handshake describes how to:

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

Noise Protocol Example: IKpsk2

Initiator **Responder**

IKpsk2:

← s

. . .

→ e, es, s, ss, [d0]

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

↔ [d2, d3, …]

The handshake describes how to:

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

Noise Protocol Example: IKpsk2

Initiator **Responder**

IKpsk2:

Premessages
- ← s
- . . .

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

Transport
- ↔ [d2, d3, …]

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

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

Noise Protocol Example: IKpsk2

Initiator **Responder**

IKpsk2:

Premessages
← s
. . .

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

Transport
↔ [d2, d3, …]

The handshake describes how to:

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

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

Noise Protocol Example: IKpsk2

Initiator | **Responder**

IKpsk2:

Premessages
- ← s
- . . .

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

Transport
- ↔ [d2, d3, …]

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

The handshake describes how to:

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

Secrets are **chained**:

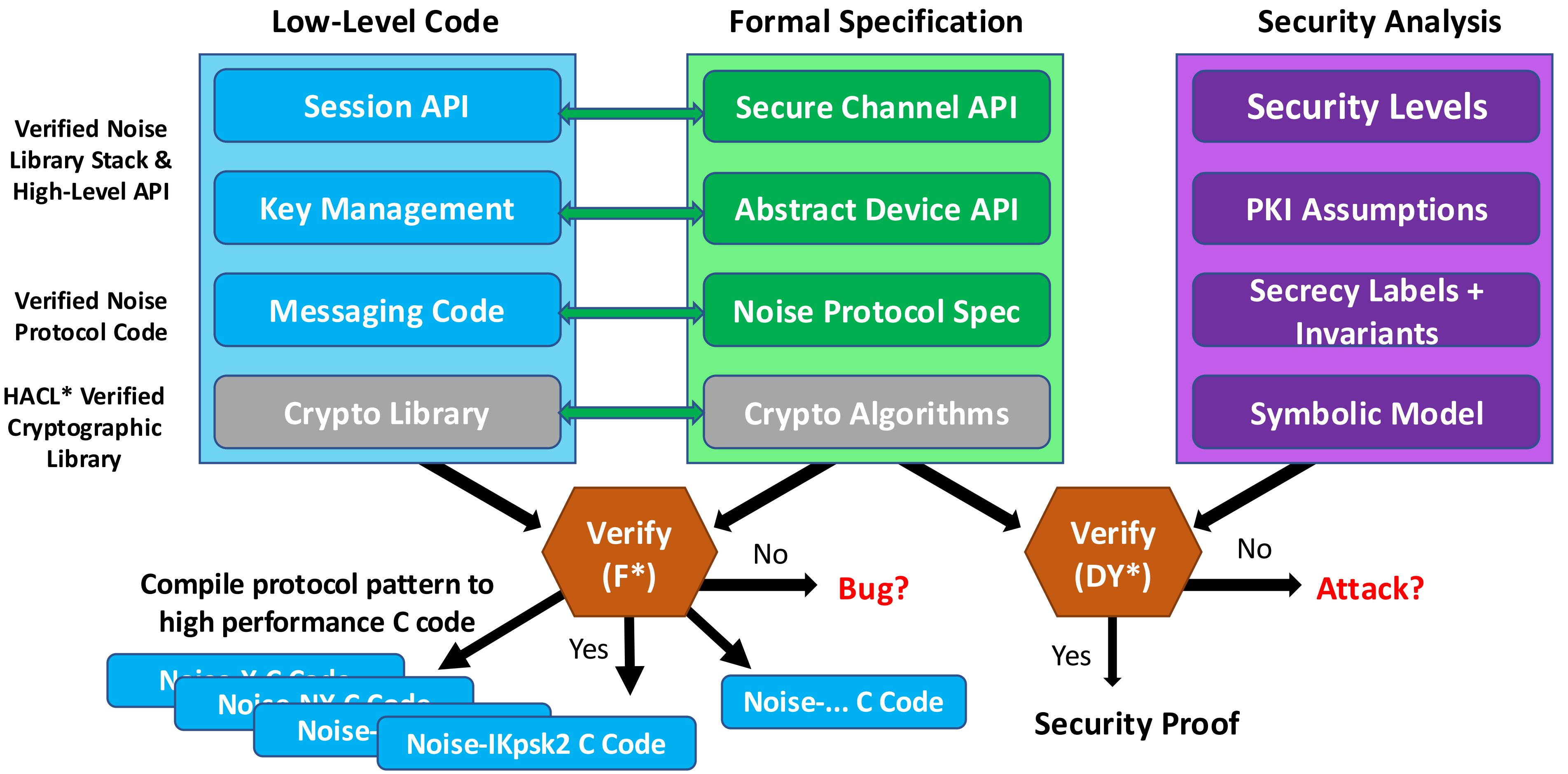
- d0 encrypted with a key derived from es, ss
- d1 encrypted with a key derived from es, ss, ee, se, psk

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

What is **Noise***?

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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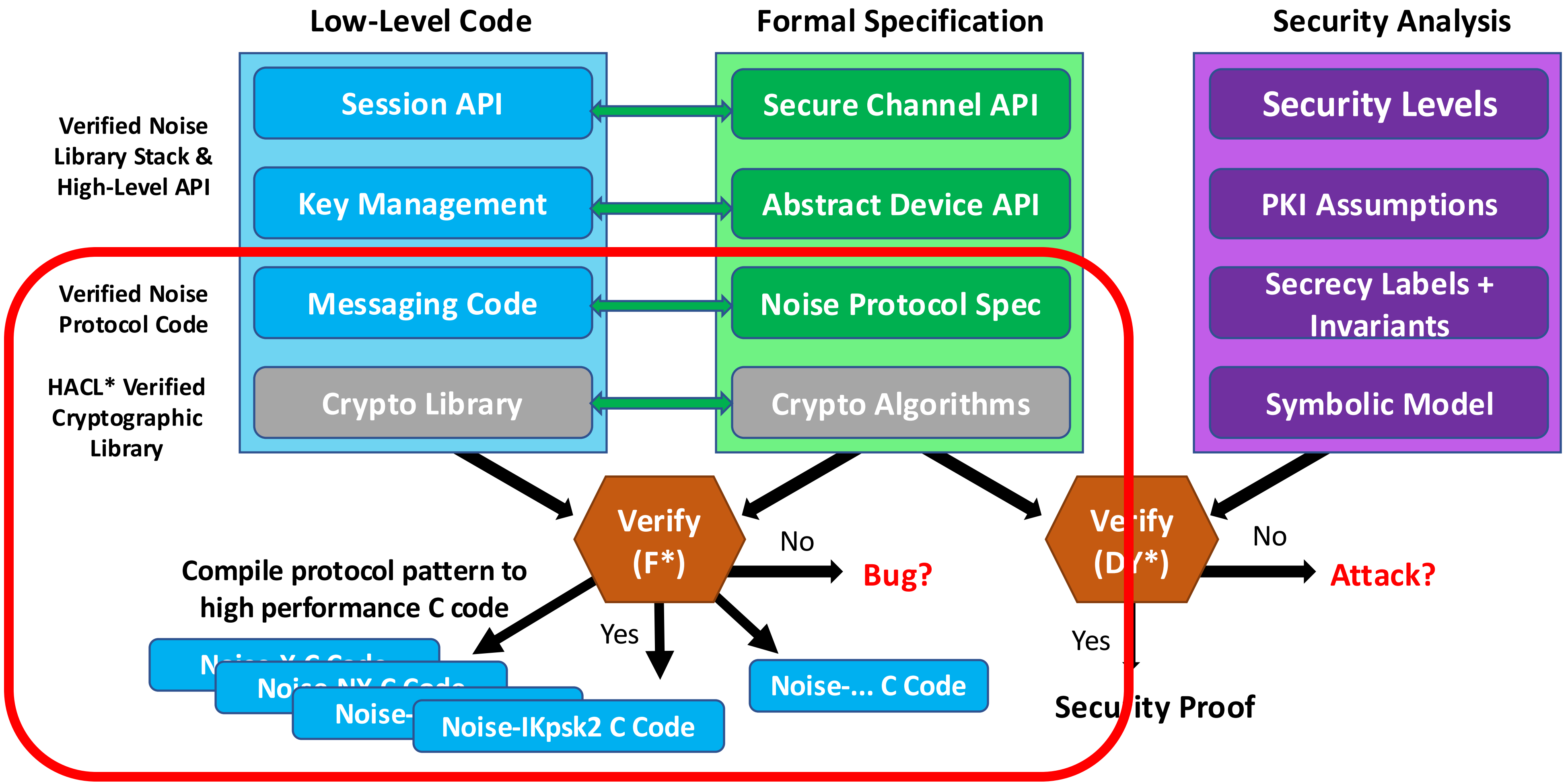

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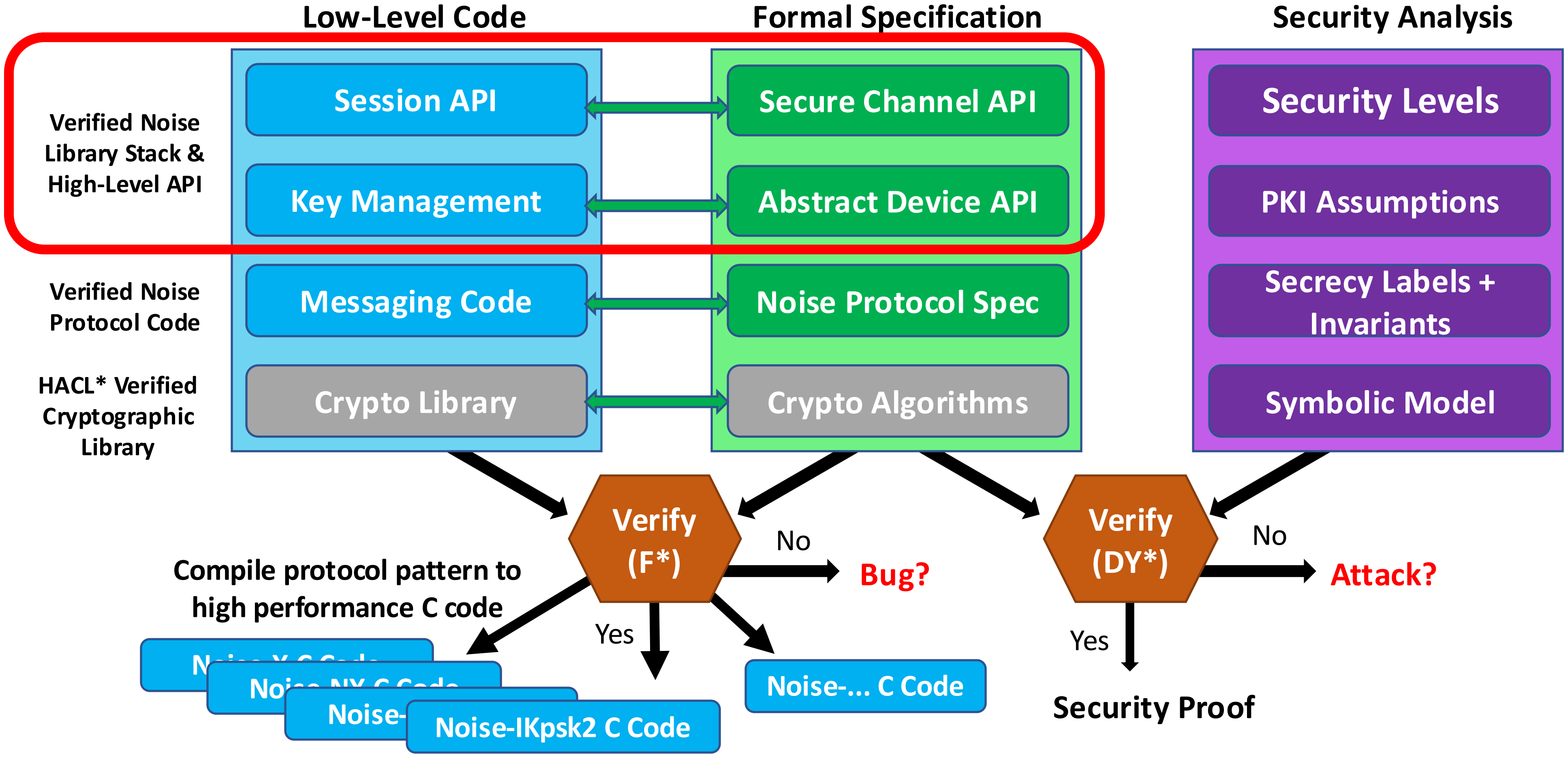

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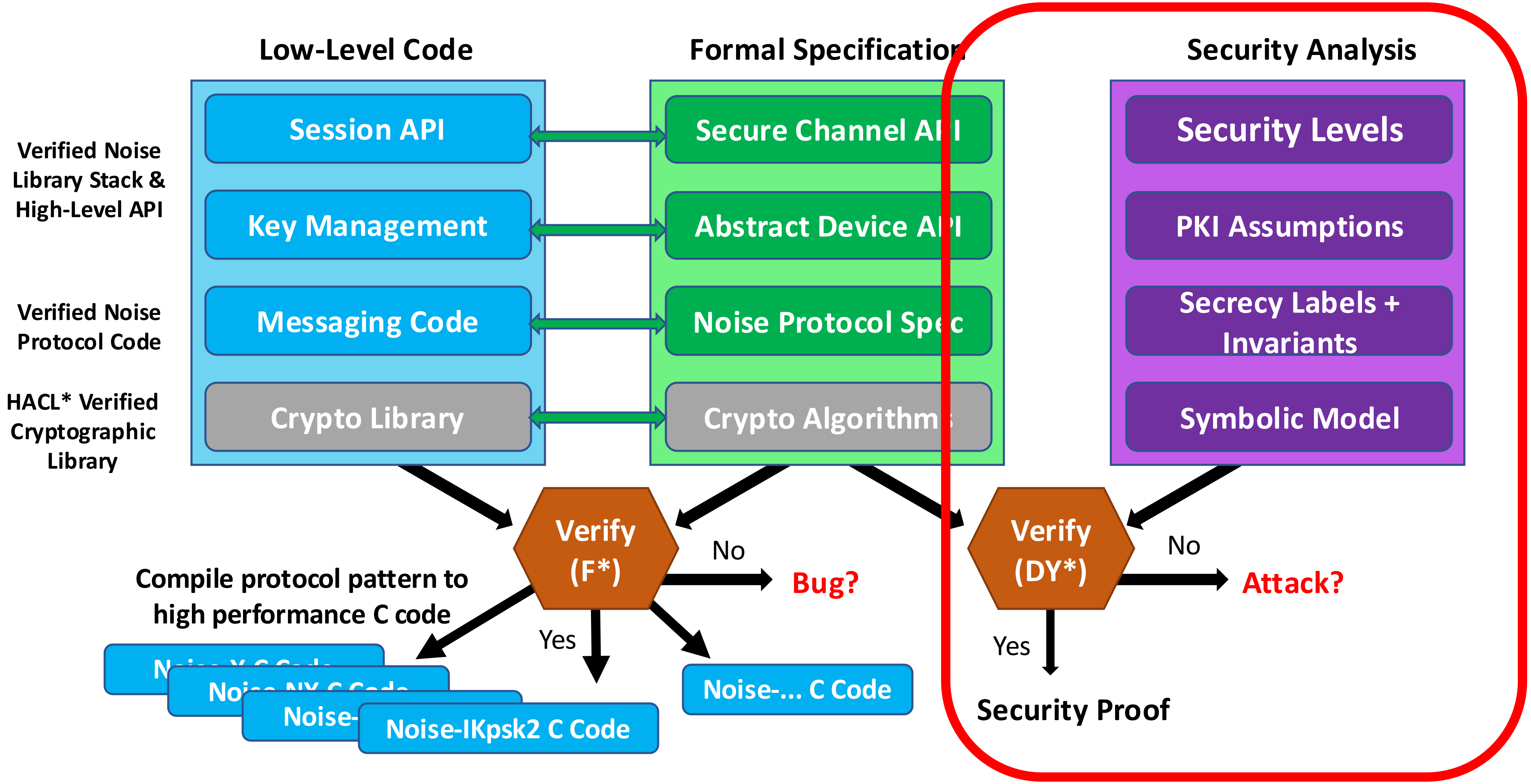
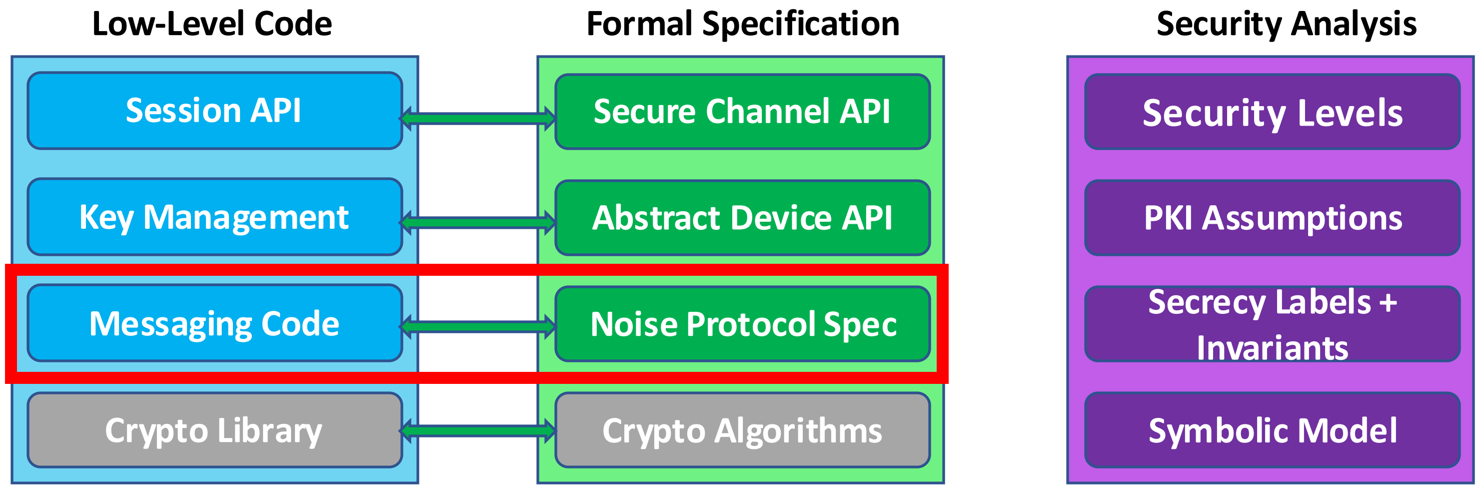


The Noise* protocol compiler



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:

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 tokens1 st1 with
      | Fail e -> Fail e
      | Res (msg2, st2) ->
        Res (msg1 @ msg2, st2)
```

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)
```

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)

- Large-scale, higher-level application of techniques seen on cryptographic primitives (Lecture 3)

➡ 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

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

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 k ->
      let sym_st1 = mix_hash k.pub st.sym_state in
      let sym_st2 =
      if true // This is `is_psk`
      then mix_key k.pub sym_st1
      else sym_st1
      in
      let st1 = { st with sym_state = sym_st2; } in
      let msg1 = k.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 k ->
      let sym_st1 = mix_hash k.pub st.sym_state in
      let sym_st2 = mix_key k.pub sym_st1 in
      let st1 = { st with sym_state = sym_st2; } in
      let msg1 = k.pub in
      Res (msg1, st1)
    end
  with
  | 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

```
let send_IKpsk2_message0 (st : handshake_state) =
  match // E
    begin match st.ephemeral with
    | None -> Fail No_key // Unreachable if proper precondition
    | Some k ->
      let sym_st1 = mix_hash k.pub st.sym_state in
      let sym_st2 = mix_key k.pub sym_st1 in
      let st1 = { st with sym_state = sym_st2; } in
      let msg1 = k.pub in
      Res (msg1, st1)
    end
  with
  | 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)
```

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

```
// Simplified
let rec send_message_tokens_m =
  fun initiator is_psk tokens st outlen out ->
  match tokens with
  | Nil -> success _
  | tk :: tokens' ->
    let tk_outlen = token_message_vs tk in
    let tk_out = sub out 0ul tk_outlen in
    let r1 = send_message_token_m 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 k ->
      let sym_st1 = mix_hash k.pub st.sym_state in
      let sym_st2 = mix_key k.pub sym_st1 in
      let st1 = { st with sym_state = sym_st2; } in
      let msg1 = k.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) ->
        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 =
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  match tokens with
  | Nil -> success _
  | tk :: tokens' ->
    let tk_outlen = token_message_vs tk in
    let tk_out = sub out 0ul tk_outlen in
    let r1 = send_message_token_m 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
if r = Success then
  ... // "if" branch
else
  ... // "else" branch
```

Always succeeds!

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
if r = Success then
  ... // "if" branch
else
  ... // "else" branch
```

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') -> ...
```

Unreachable!

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

Always succeeds!

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```
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
```

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 : 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!

```
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
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  ... // "else" branch
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  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
- Make **function signatures** more informative (**unit elimination**)

```
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):

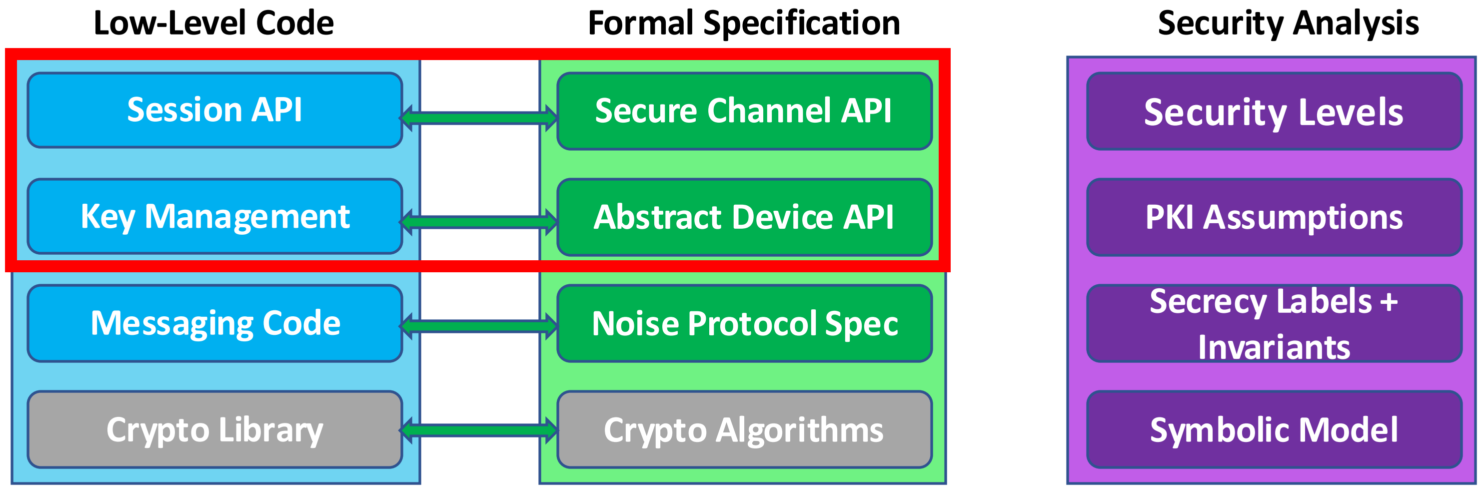
```
/* e */
curve25519_generate_secret(handshake->ephemeral_private);
if (!curve25519_generate_public(dst->unencrypted_ephemeral,
                                handshake->ephemeral_private))
        goto out;
message_ephemeral(dst->unencrypted_ephemeral,
                  dst->unencrypted_ephemeral,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

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- Initiator and responder must remember which key belongs to whom

Peer Management

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- 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

Peer Management

Key Validation

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Peer Management

Key Validation

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- Initiator and responder must remember which key belongs to whom — **Peer Management**
- Responder receives a static key during the handshake
  - Peer lookup (if key already registered)
  - Unknown key validation — **Key Validation**
- Long-term key storage — **Key Storage**
- Transitions are low-level
  - State Machine — **State Machine**
  - Message lengths
  - Invalid states (if failure)

High-Level API

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- Initiator and responder must remember which key belongs to whom — **Peer Management**
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  - Peer lookup (if key already registered)
  - Unknown key validation — **Key Validation**
- Long-term key storage — **Key Storage**
- Transitions are low-level
  - State Machine — **State Machine**
  - Message lengths
  - Invalid states (if failure)
- Early data
  - when is it safe to send secret data? — **Message Encapsulation**
  - when can we trust the data we received?

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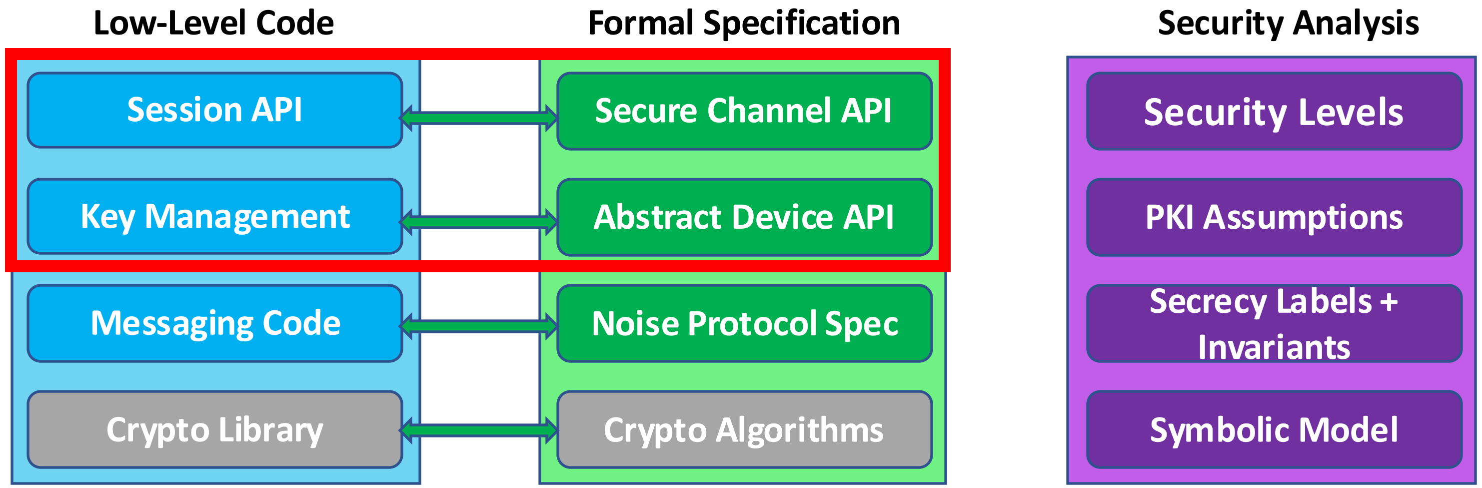

- State Machines
- Peer Management
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Meta-Programmed State Machine

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

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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

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// With precondition: step <= 2 /\ (step % 2) == 0
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  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(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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Meta parameter
(i ∈ {0, 1, …})

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}
```

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Meta parameter (i ∈ {0, 1, …})

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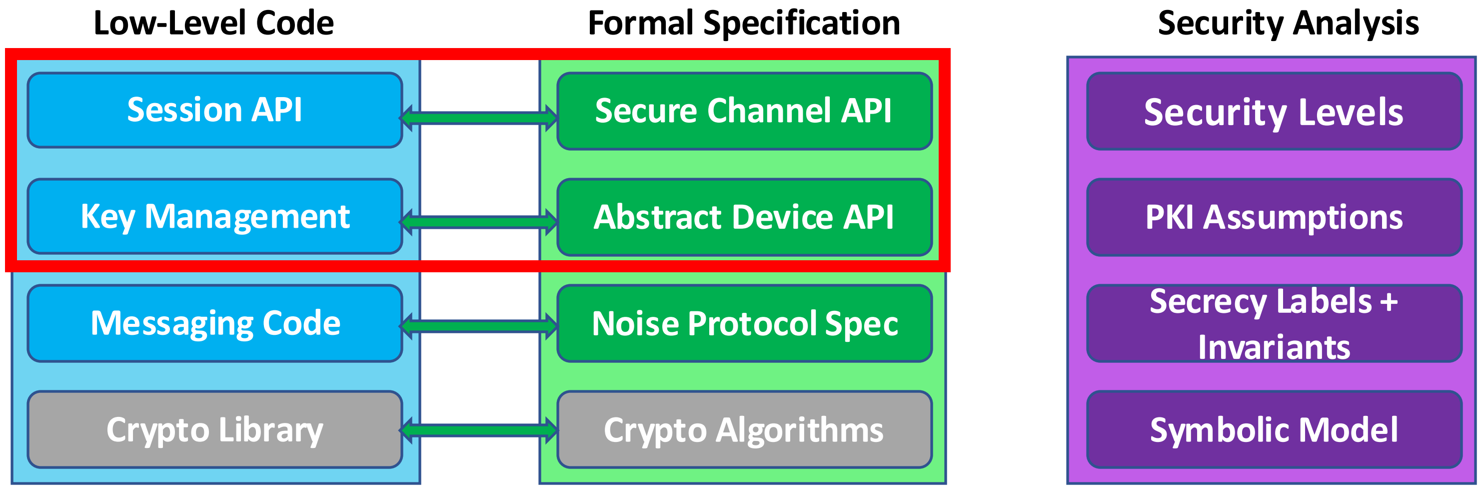
    ... // last possible send_message function
  else if step = size i then
    ... // instantiated send_message function
  else
    handshake_send ... (i+2) step // Increment i by 2
```

```
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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...
```

```
// 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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← s **initiator knows responder from beginning**

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→ e, es, s, ss

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Responder learns initiator's identity

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peer_id parameter: varies with pattern and role

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...
```

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...
```

psk parameter only if pattern uses it

IKpsk2:

← s — initiator knows responder from beginning

...

Responder learns initiator’s identity

→ e, es, s, ss

← e, ee, se, psk

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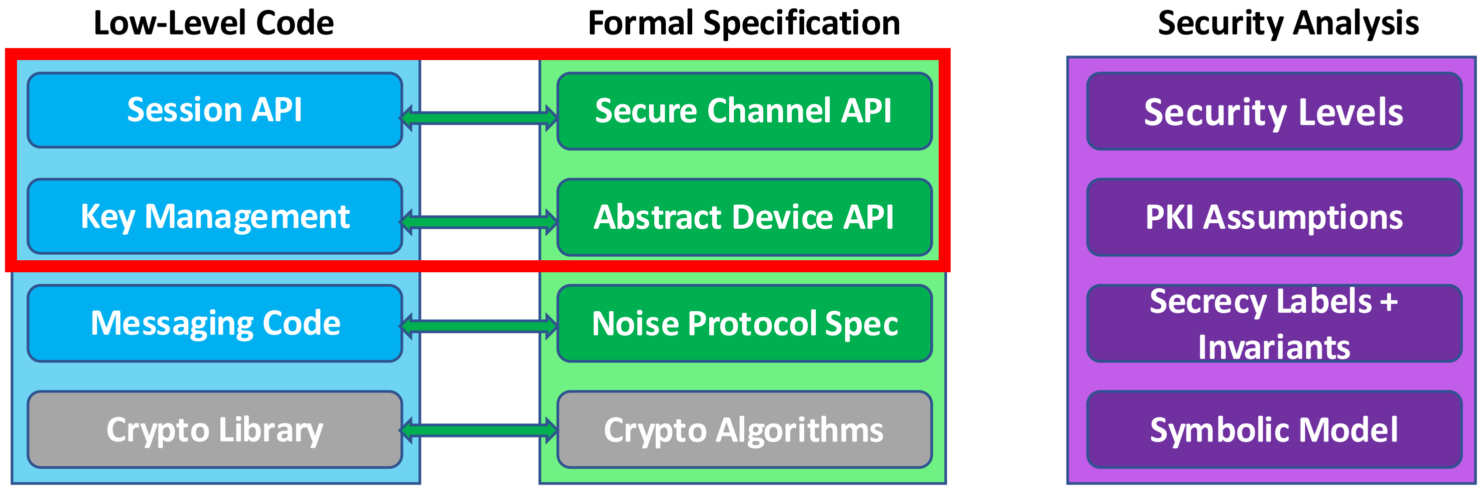

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Key Storage and Validation

IKpsk2:

← s

...

→ e, es, s, ss

← e, ee, se, psk

XX:

→ e

← e, ee, s, es

→ s, se

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

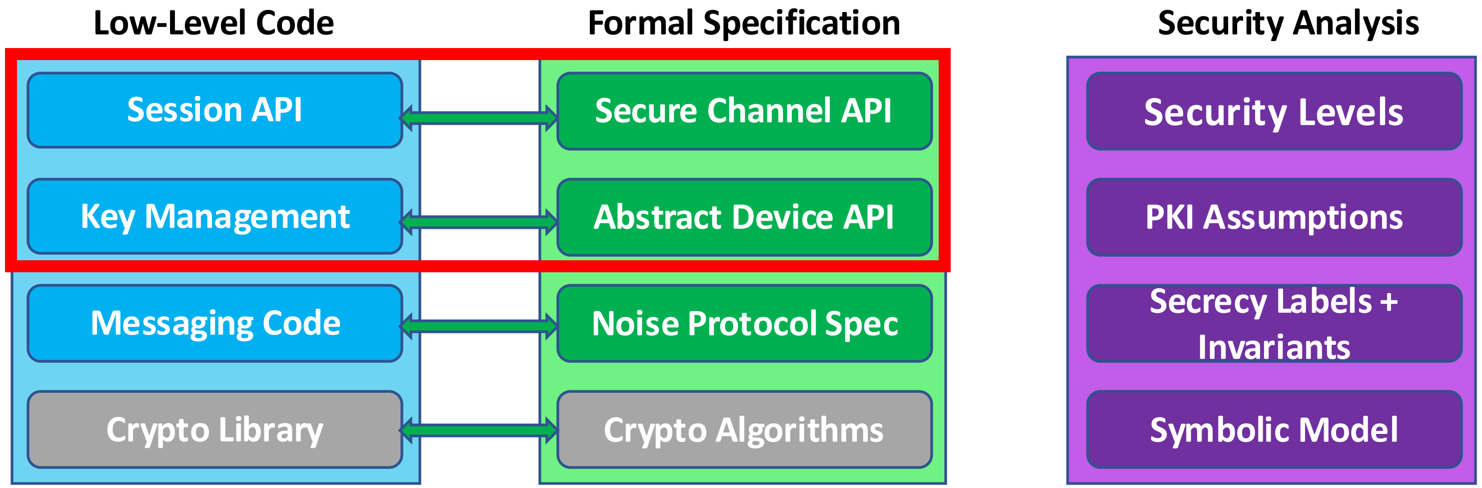
WhatsApp: we actually **transmit** keys, which must be validated by some external mean

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`

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

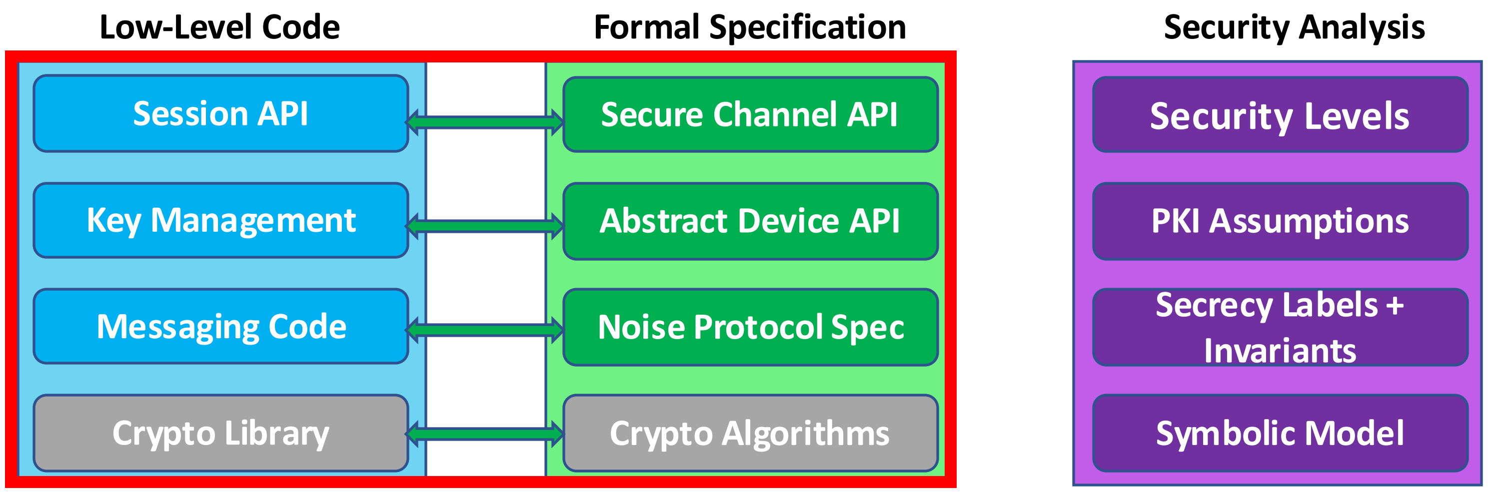
XX	Payload Conf. Level	
	→	←
→ e	0	-
← e, ee, s, es	-	1
→ s, se	5	-
←	-	5
→	5	-
…		

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…):

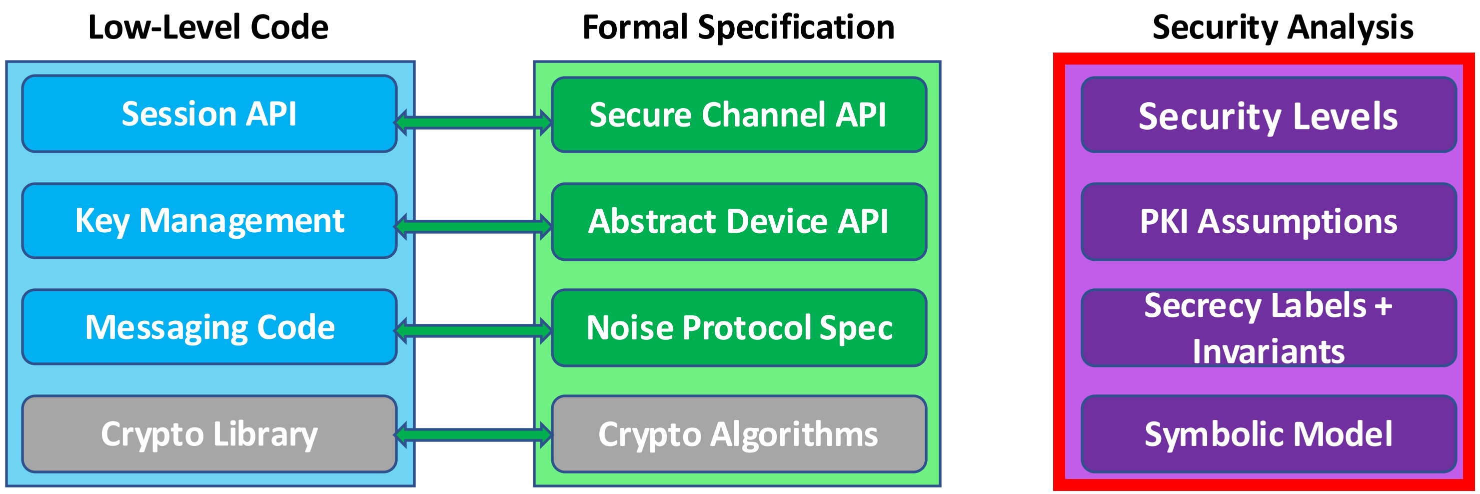
```
if (sn.tag == Noise_DS_Initiator)
{
  Noise_init_state_t sn_state = sn.val.case_DS_Initiator.state;
  if (sn_state.tag == Noise_IMS_Transport)
  {
    Noise_encap_message_t encap_payload = payload[0U];
    bool next_length_ok;
    if (encap_payload.em_message_len <= (uint32_t)4294967279U)
    {
      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*

- Dolev-Yao* (abbreviated into DY*) is a symbolic analysis framework in F*

- Successfully used for the symbolic analysis of several protocols (ACME standard, part of MLS, Signal, …)

DY : A Modular Symbolic Verification Framework for Executable Cryptographic Protocol Code,* Bhargavan et al., EuroS&P’ 21

DY*: Symbolic Bitstring Model

- DY* relies on a symbolic model of bitstrings

```
type bytes =
  | Constant: string -> bytes
  | Fresh: nat -> bytes
  | Concat: bytes -> bytes -> bytes
  | AEnc: bytes -> bytes -> bytes -> bytes
  | PK: bytes -> bytes
  | PEnc: bytes -> bytes -> bytes
  | VK: bytes -> bytes
  | Sig: bytes -> bytes -> bytes
```

DY*: Symbolic Model

- Bytes with different constructors are considered disjoint

```
let pke_enc pk m = PEnc pk m
let pke_dec sk c = match c with
    | PEnc p m -> if p = PK sk then Some m else None
    | _ -> None

let sign sk m = Sig sk m
let verify vk m sg = match sg with
    | Sig sk m’ -> if vk = VK sk && m = m’ then true else false
    | _ -> false
```

DY*: Global Protocol Trace

- The execution of a protocol is expressed as a trace of events

```
type principal = string

type entry =
    | FreshGen: p: principal -> entry
    | Send: from: principal -> to: principal -> msg: bytes -> entry
    | Store: at: principal -> state: bytes -> entry
    | Event: p: principal -> ev: bytes -> entry
    | Compromise:  p: principal -> entry

type trace = list entry
```

DY*: Executing Protocol Actions

- Each action extends the protocol trace (or uses it if it depends on past events)

```
let gen p : trace -> trace = fun tr -> FreshGen p :: tr

let recv p : trace -> option bytes =
  let rec recv_aux p tr : option bytes = match tr with
    | [] -> None
    | Send from to msg :: tr’ -> if to = p then Some msg else recv_aux p tr’
    | _ :: tr’ -> recv_aux p tr’
  in recv_aux p
```

DY*: Executing Attacker Actions

```
let compromise p : trace -> trace =  fun tr -> Compromise p :: tr
```

- Attacker can call compromise p to gain control of p
- Attacker can call gen p (for compromised p) to get fresh bytes
- Attacker can call recv p (to read any message)
- Attacker can call retrieve p (for compromised p) to read its state
- Attacker can call send p1 p2 m (for any message m it knows)
- Attacker **cannot** call event or store

DY*: Attacker Knowledge

```
val attacker_knows: trace -> bytes -> prop
```

- Attacker always knows Constant s
- Attacker learns msg from each Send from to msg in trace
- Attacker learns st from each Store p st (for compromised p)
- Attacker can call any crypto function with values it already knows (concat, split, pk_enc, pk_dec, sign, …)

DY*: Reachable Traces

- Defines “well-formed” execution traces according to attacker capabilities
- Assume some protocol:

```
val sendMsg1: principal -> principal -> trace -> trace
val recvMsg1: principal -> trace -> trace
```

```
let rec reachable (tr: trace) : prop =
  (exists p1 p2 tr’. tr == sendMsg1 p1 p2 tr’ ∧ reachable tr’) ∨
  (exists p tr’. tr == recvMsg1 p tr’ ∧ reachable tr’) ∨
  (match tr with
   | [] -> True
   | FreshGen p :: tr’ -> List.mem (Compromise p) tr’ ∧ reachable tr’
   | Send p1 p2 m :: tr’ -> attacker_knows tr’ m ∧ reachable tr’
   | Compromise p :: tr’ -> reachable tr’
   | _ -> False
```

DY*: Stating Confidentiality Goals

```
let protocol_sent p secret tr =
  List.mem (Event p (concat (literal "Send") secret)) tr

let compromised p tr = List.mem (Compromise p) tr

val confidentiality_lemma () : Lemma (forall tr p m.
  reachable tr ∧ protocol_sent p m tr ∧ attacker_knows tr m =>
    compromised p tr
  )
```

- Case analysis on all reachable traces (by induction on length of trace)
- Reason about all possible interleavings of attacker and protocol actions

DY*: Stating Authentication Goals

```
let protocol_sent p1 p2 secret tr = …
let protocol_received p1 p2 secret tr = …

val authentication_lemma () : Lemma (forall tr p1 p2 m.
   reachable tr ⋀ protocol_received p1 p2 m tr =>
      protocol_sent p1 p2 m tr ⋁ compromised p1 tr
   )
```

- **Correspondance Assertion:** Received p1 p2 m => Sent p1 p2 m
- Again, proved for all possible interleavings

DY* - Modular Labels

Instead of proving each property by induction on traces, DY* relies on security labels

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`

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, [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
```

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

```
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`

- 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 - Dolev-Yao*

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

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']))

Strong forward-secrecy

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 – Security Predicates

Confidentiality level 5 (**strong forward secrecy**), from the sender's perspective:

```
can_flow i (CanRead [S p sid] ⊔ CanRead [P peer]) l /\
can_flow i (CanRead [S p sid] ⊔ get_dh_label re) l /\
(compromised_before i (S p sid) \/ compromised_before i (P peer) \/
 (∃ sid'. get_dh_label re == CanRead [S peer sid']))
```

Handshake secrets are only readable by the peer and the current session sid at p

Handshake secrets are also bound to some peer ephemeral key re

Unless the peer's long-term keys and the specific session S p sid were compromised before the session is complete, the peer ephemeral key must have label S peer sid'

Security Analysis - Summary

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 (l1 : label) (priv : dh_private_key l1)
       (l2 : label) (pub : dh_public_key l2) :
  dh_result (join l1 l2) // label: l1 ⊔ l2
```

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

IKpsk2 (from the responder's point of view)

← s

. . .

→ 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 **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

5. We prove that those **security predicates are satisfied** by the target labels

Main Takeaways

- **Do not roll your own crypto**
  - Implementing cryptography is error-prone, and mistakes can have disastrous consequences
- But if you do, formally verify it
  - Successful verification tools exist for both C and Assembly
  - Verification can also help with code maintenance, and extending to new architectures/variants at a lower cost
- Many tools and techniques allow to reason about the security of protocol models
- End-to-end verification is still tricky, however several recent projects offer promising solutions