High Assurance Post Quantum Cryptography

Karthikeyan Bhargavan

Joint work with many others at Cryspen, Inria, Signal, ...

OpenSSL Conference, 2025

CRYSPEN

Formal Methods for Crypto

- Computer-Aided Cryptography, a.k.a. High Assurance Cryptography

  "Applying formal, **machine-checkable** approaches to the design, analysis, and implementation of cryptography."

  SoK: Computer-Aided Cryptography, IEEE S&P 2021
  Barbosa, Barthe, Bhargavan, Blanchet, Cremers, Liao, Parno

- Analyze cryptographic **designs** early to find attacks or uncover assumptions
- Comprehensively analyze **specifications** and standards before publication
- Formally verify efficient **implementations** to prevent bugs and side-channels
- .... and **repeat** these steps over and over again as these artifacts evolve

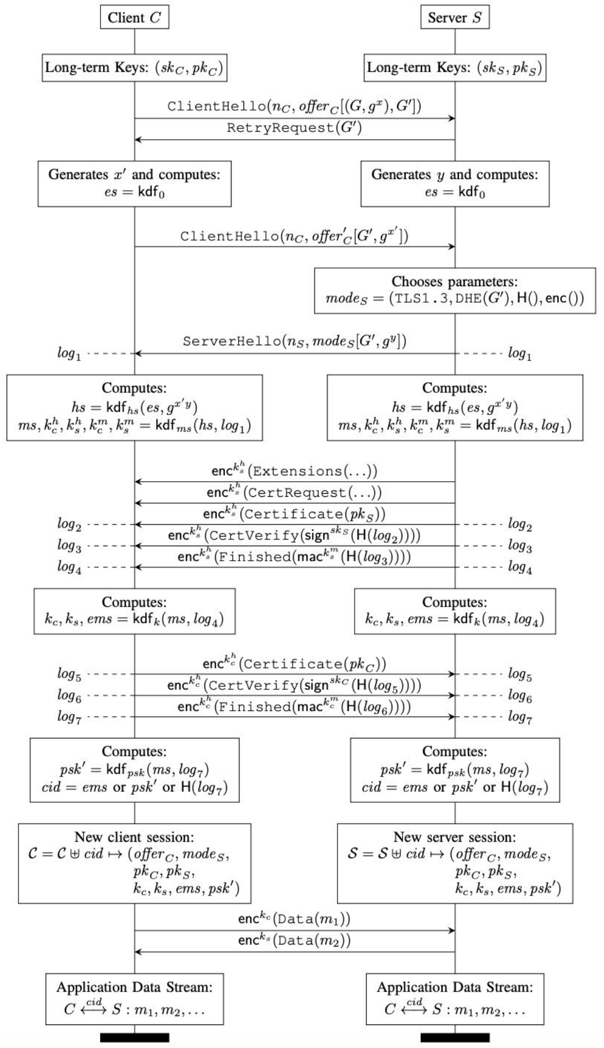
Formally Verifying TLS 1.3

TLS 1.3: Path to standardization

2014

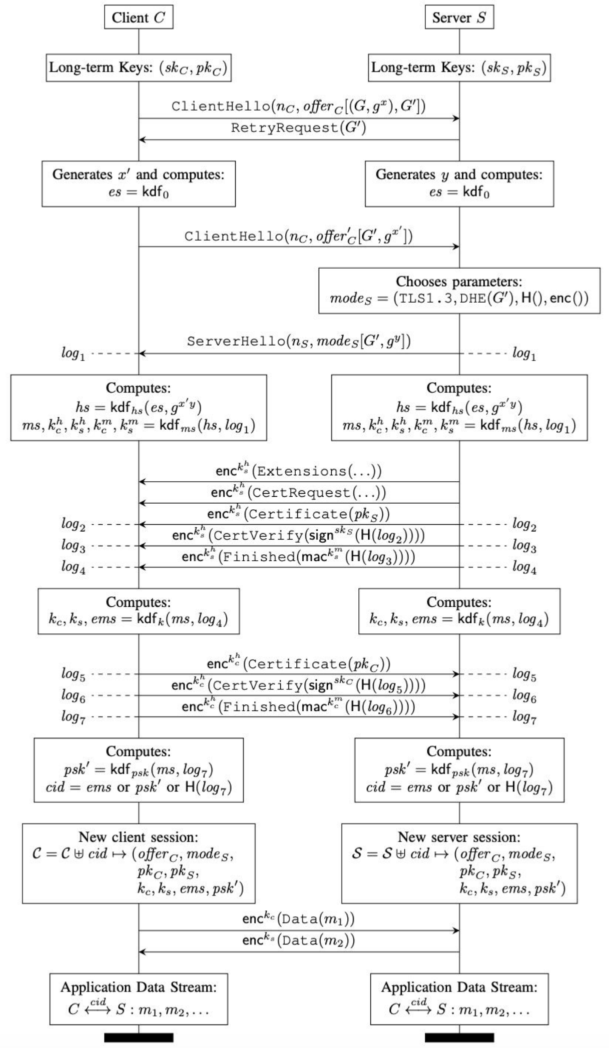
Draft 5	[Dowling, Fischlin, Günther, Stebila, 2015]
Draft 7	[Jager, Schwenk, Somorowsky, 2015]
Draft 9	[Krawczyk, Wee, 2016]
Draft 10	[Li, Xu, Zhang, Feng, Hu, 2016] [Fischlin, Günther, Schmidt, Warinschi, 2016] [Cremers, Horvat, Scott, van der Merwe, 2016]
Draft 12	[Bhargavan, Brzuska, Fournet, Green, Kohlweiss, Beguelin, 2016]
Draft 14	[Fischlin, Günther, 2017]
Draft 18	[Bhargavan, Delignat-Lavaud, Fournet, Kohlweiss, Pan, Protzenko, Rastogi, Swamy, Zanella-Béguelin, Zinzindohoué, 2017] [Bhargavan, Blanchet, Kobeissi, 2017]
Draft 21	[Cremers, Horvat, Hoyland, Scott, van der Merwe, 2017]

2018



TLS 1.3: Lessons and Impact

- Strong collaboration between WG and researchers
  - Many pen-and-paper proofs
  - Some machine-checked proofs in Tamarin, ProVerif, CryptoVerif, F*
  - Proofs now often required for new protocols
- IETF Working Groups
  - **LAKE**: Key exchange protocol for IoT
  - **TLS**: Encrypted Client Hello, KEM-TLS
  - **MLS:** Secure group messaging
- Industrial Protocols
  - PQ3 (iMessage), PQXDH (Signal), PQConnect (talk yesterday)

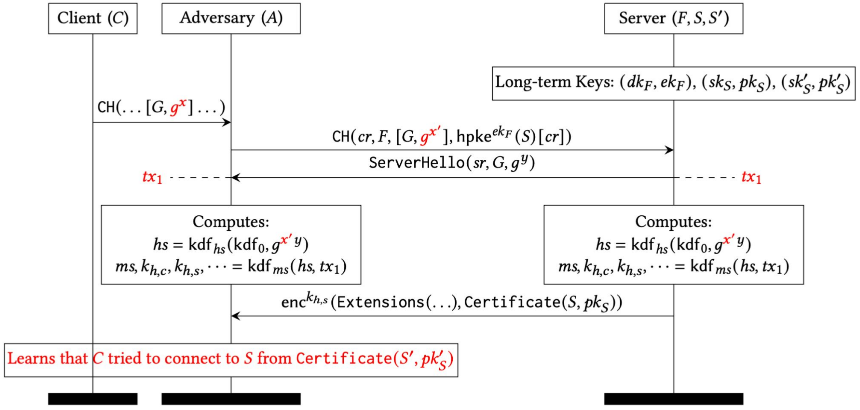


TLS 1.3+ECH: Improving privacy for TLS 1.3

- Stephen Farrell's talk today
- TLS 1.3 encrypts most handshake , message, but sends server name in the clear in the first message
- ECH privacy extension aims to fix this
  - many early proposals were broken
- Can we prove privacy for TLS+ECH?
  - Does ECH preserve TLS 1.3 security?
  - Yes! Formally verified with ProVerif
    [Cheval, Bhargavan, Wood, ACM CCS 2022]

Workgroup:	tls			
Internet-Draft:	draft-ietf-tls-esni-20			
Published:	5 August 2024			
Intended Status:	Standards Track			
Expires:	6 February 2025			
Authors:	E. Rescorla	K. Oku	N. Sullivan	C. A. Wood
	Independent	*Fastly*	*Cryptography Consulting LLC*	*Cloudflare*

TLS Encrypted Client Hello

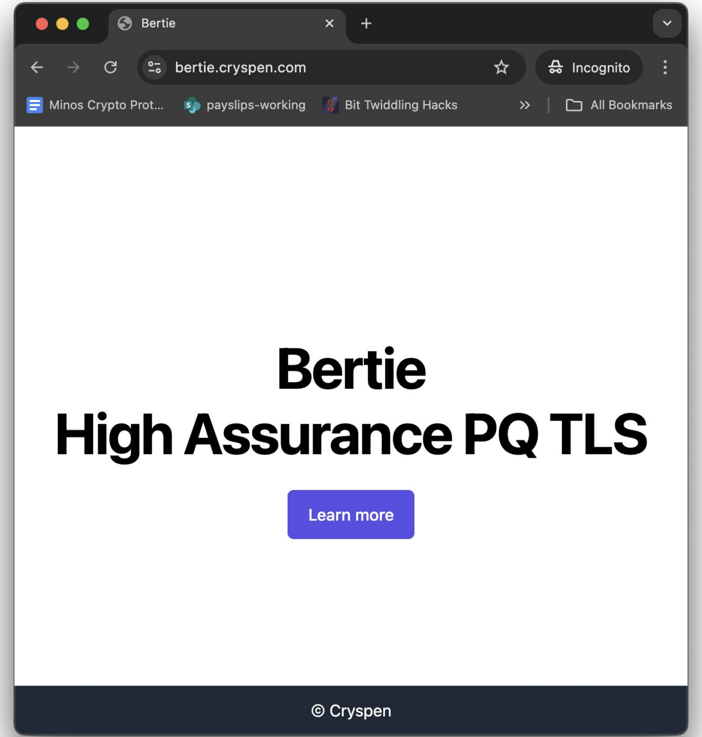


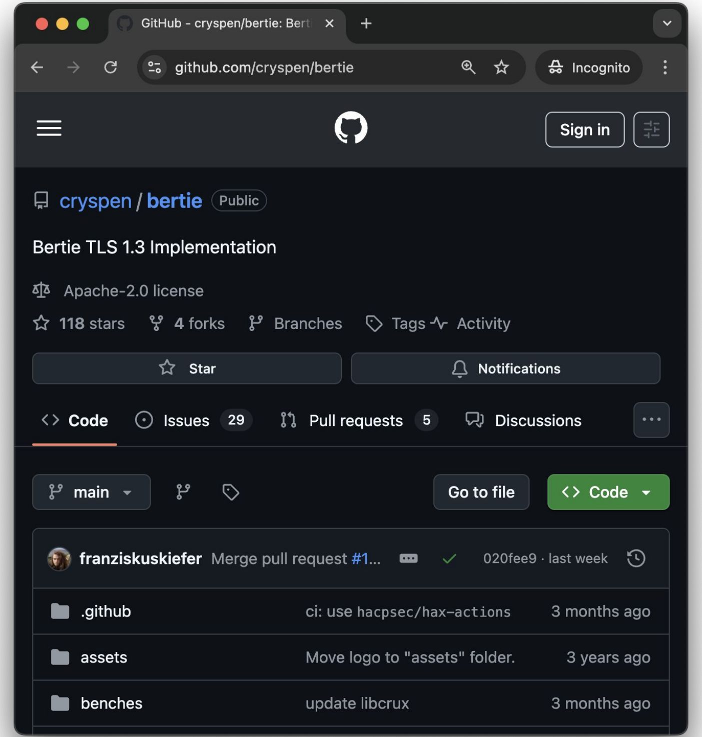
Verifying TLS 1.3 Implementations

- Many verified protocol components for TLS available today
  - Crypto libraries in C and asm: HACL*, Fiat-Crypto (more later)
  - Verified parsers for TLS, X.509 in C: EverParse, Comparse
  - Verified TLS and QUIC record layers: miTLS, EverQuic
- Too much effort to scale to all of OpenSSL
  - Each component needs many PhD student-years
  - 90% of time spent on proving memory safety for C and asm
  - Successful projects generate C (or assembly) from proof-oriented domain-specific languages
  - Can we verify a full TLS implementation in a mainstream language?

Project Everest: Perspectives from Developing Industrial-grade High-Assurance Software May, 2025.

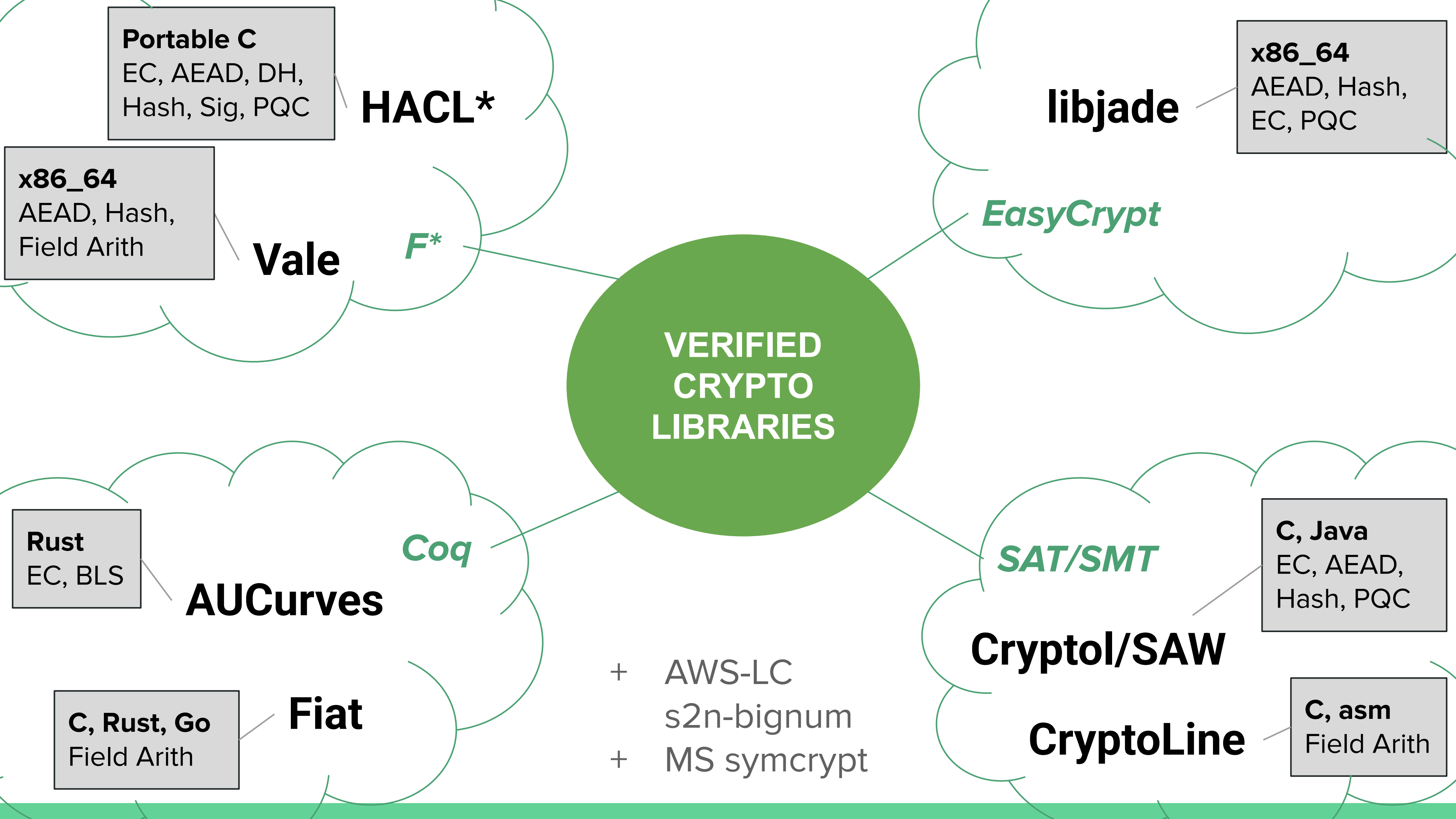
BERT13: Verified PQ-TLS 1.3 in Rust



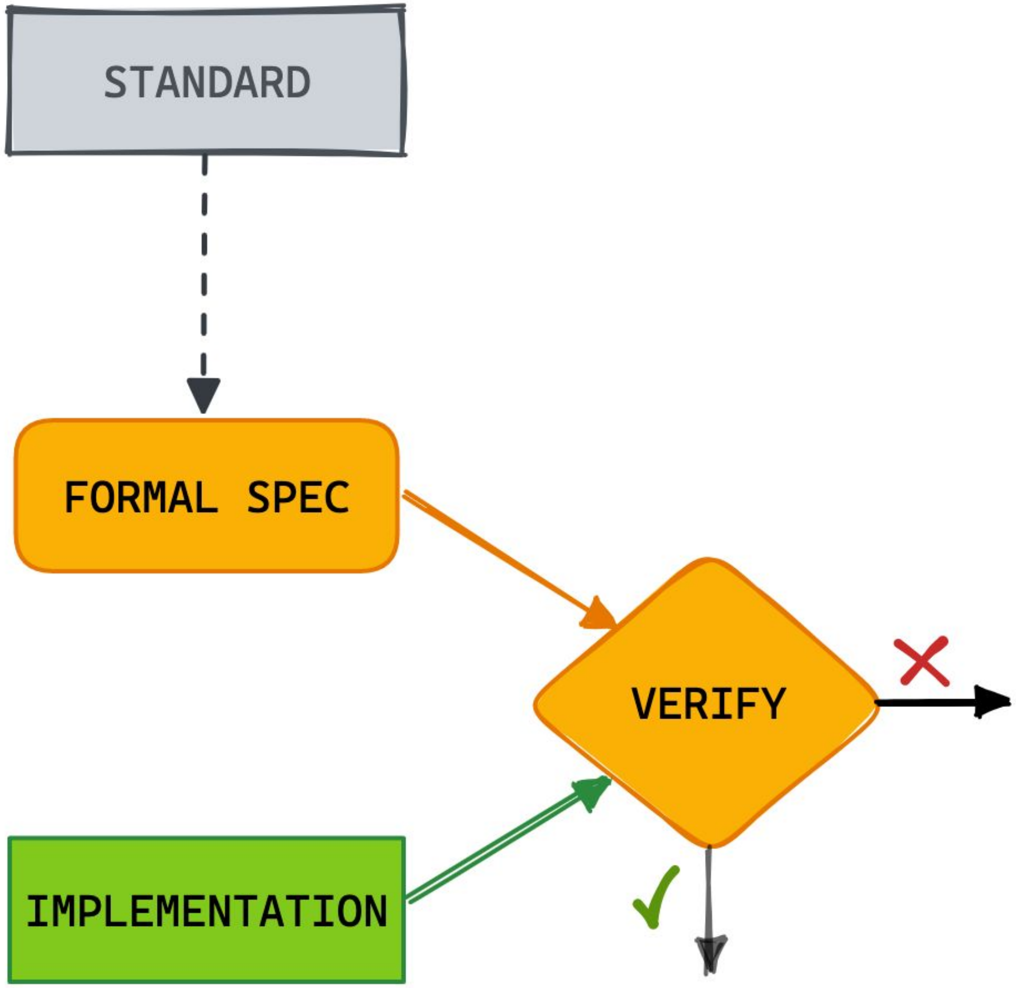


Formal Security and Functional Verification of Cryptographic Protocol Implementations in Rust.
ACM CCS 2025. Bhargavan, Hansen, Kiefer, Schneider-Bensch, Spitters.

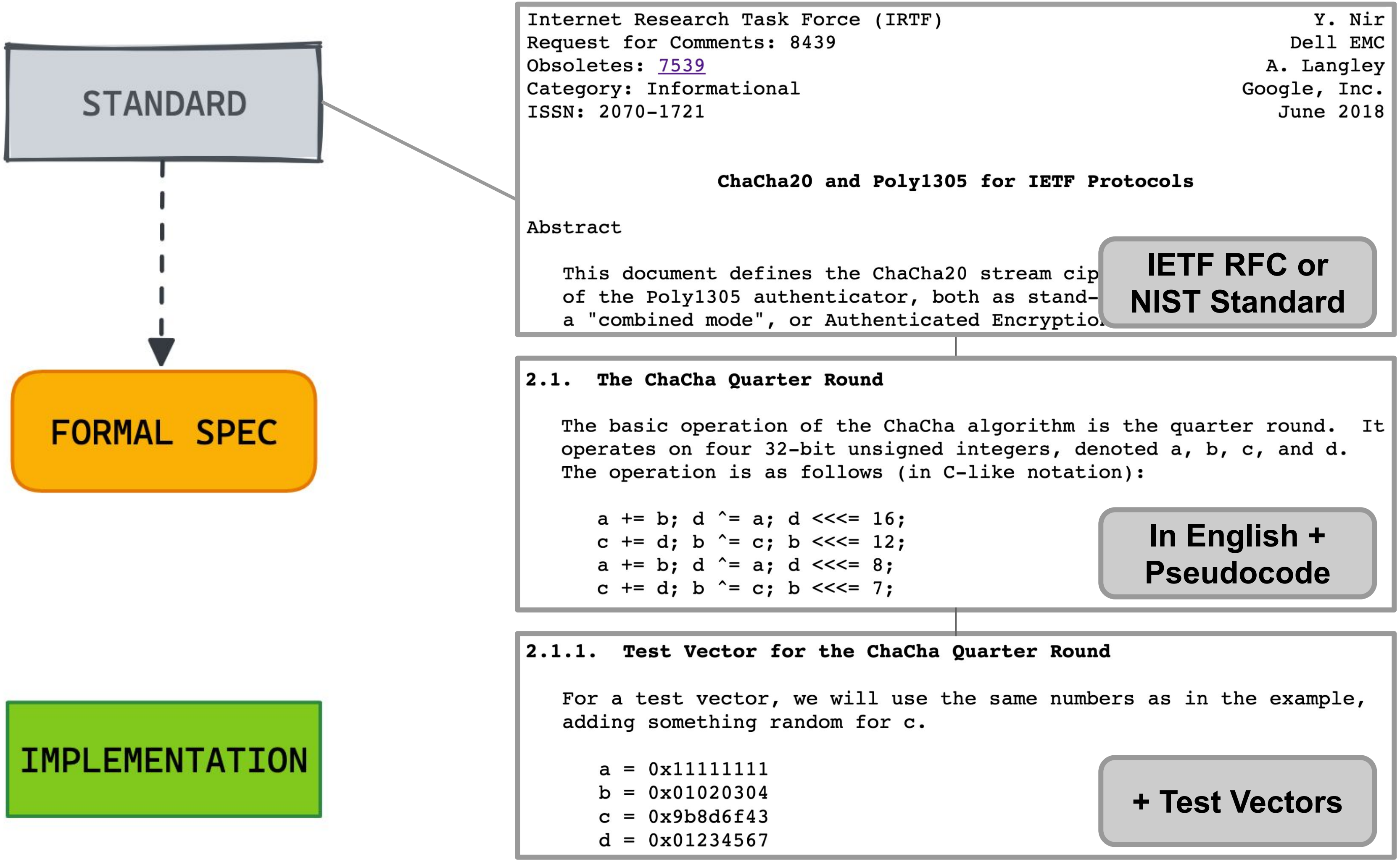
Verifying Cryptographic Libraries

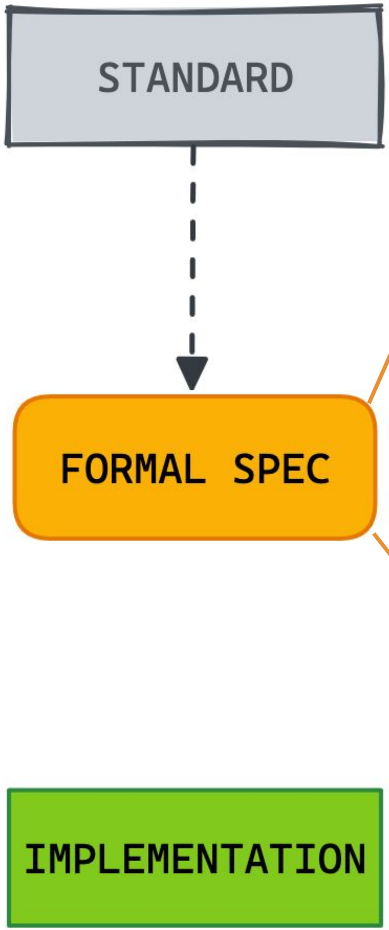


VERIFIED CRYPTO LIBRARIES
F*
HACL*
Portable C
EC, AEAD, DH, Hash, Sig, PQC
Vale
x86_64
AEAD, Hash, Field Arith
EasyCrypt
libjade
x86_64
AEAD, Hash, EC, PQC
Coq
AUCurves
Rust
EC, BLS
Fiat
C, Rust, Go
Field Arith
SAT/SMT
Cryptol/SAW
C, Java
EC, AEAD, Hash, PQC
CryptoLine
C, asm
Field Arith
+ AWS-LC
s2n-bignum
+ MS symcrypt



Verified Cryptography Workflow


STANDARD
FORMAL SPEC
IMPLEMENTATION
Internet Research Task Force (IRTF)
Request for Comments: 8439
Obsoletes: 7539
Category: Informational
ISSN: 2070-1721
Y. Nir
Dell EMC
A. Langley
Google, Inc.
June 2018
ChaCha20 and Poly1305 for IETF Protocols
Abstract
This document defines the ChaCha20 stream cip
of the Poly1305 authenticator, both as stand-
a "combined mode", or Authenticated Encryptio
IETF RFC or NIST Standard
2.1. The ChaCha Quarter Round
The basic operation of the ChaCha algorithm is the quarter round. It operates on four 32-bit unsigned integers, denoted a, b, c, and d. The operation is as follows (in C-like notation):
a += b; d ^= a; d <<<= 16;
c += d; b ^= c; b <<<= 12;
a += b; d ^= a; d <<<= 8;
c += d; b ^= c; b <<<= 7;
In English + Pseudocode
2.1.1. Test Vector for the ChaCha Quarter Round
For a test vector, we will use the same numbers as in the example, adding something random for c.
a = 0x11111111
b = 0x01020304
c = 0x9b8d6f43
d = 0x01234567
+ Test Vectors



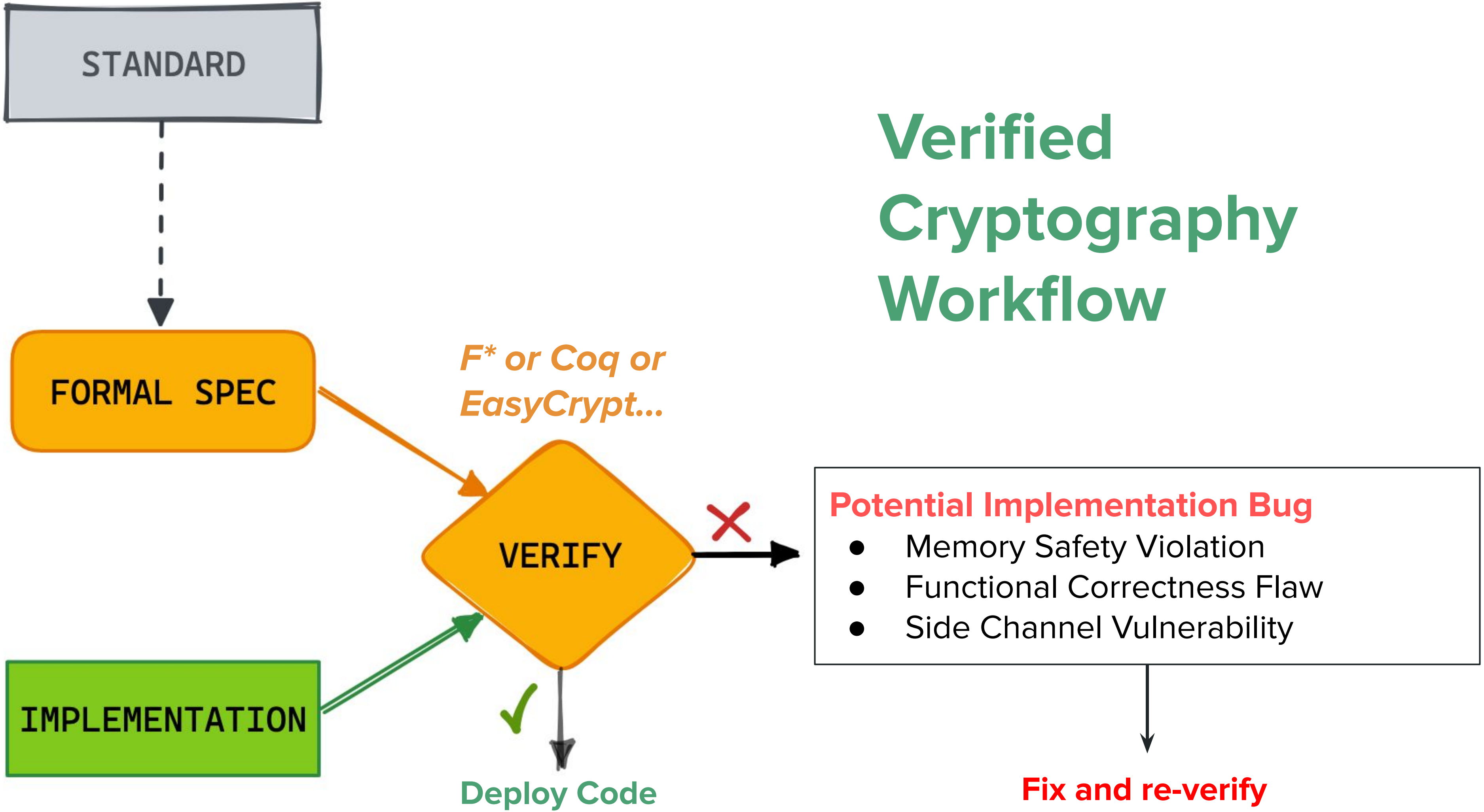

```
let line (a:idx) (b:idx) (d:idx) (s:rotval U32) (m:state) : Tot state =
  let m = m.[a] ← (m.[a] +. m.[b]) in
  let m = m.[d] ← ((m.[d] ^. m.[a]) <<<. s) in m

let quarter_round a b c d : Tot shuffle =
  line a b d (size 16) @
  line c d b (size 12) @
  line a b d (size 8)  @
  line c d b (size 7)
```

F* Spec
(HACL*)

```
proc chacha20_line(a : int, b : int, d : int, s : int, st : State) = {
  var state;
  state <- st;
  state.[a] <- ((state).[a]) + ((state).[b]);
  state.[d] <- ((state).[d]) `^` ((state).[a]);
  state.[d] <- rotate_left ((state).[d]) (s);
  return state;
}

proc chacha20_quarter_round(a : int, b : int, c : int, d : int, st : State) = {
  var state;
  state <@ chacha20_line (a, b, d, 16, st);
  state <@ chacha20_line (c, d, b, 12, state);
  state <@ chacha20_line (a, b, d, 8, state);
  state <@ chacha20_line (c, d, b, 7, state);
  return state;
}
```

EasyCrypt Spec
(libjade)

Verified Cryptography Workflow



Good news: For any modern crypto algorithm, there is probably a verified implementation

- You don’t have to sacrifice performance
- Mechanized proofs that you can run and re-run yourself
- You (mostly) don’t have to read or understand the proofs
- Formally verified crypto in NSS, BoringSSL, aws-lc, …

HACL* and EverCrypt [2017-2024]

Verified crypto library

- Multiple TLS 1.3 ciphersuites
- Fast C and assembly
- Deployed in NSS, WireGuard, Python, ...
- Proofs run on CI

Major verification effort

- 3 researchers, 4 Phds
- Code in proof-oriented F*
- Compiled to C, asm, Rust

- Too hard to verify C and multi-platform asm code written by crypto engineers like in OpenSSL

Algorithm	Portable C code	Arm A64	Intel x64			
		Neon	AVX	AVX2	AVX512	Vale
AEAD						
Chacha20-Poly1305	✓ [43] (+)	✓ (*)	✓ (*)	✓ (*)	✓ (*)	
AES-GCM						✓ [20]
Hashes						
SHA-224,256	✓ [43] (+)	✓ (*)	✓ (*)	✓ (*)	✓ (*)	✓ [20]
SHA-384,512	✓ [43] (+)	✓ (*)	✓ (*)	✓ (*)	✓ (*)	
Blake2s, Blake2b	✓ [34] (+)	✓ (*)	✓ (*)	✓ (*)		
SHA3-224,256,384,512	✓ [34]					
HMAC and HKDF						
HMAC (SHA-2,Blake2)	✓ [43]	✓ (*)	✓ (*)	✓ (*)	✓ (*)	
HKDF (SHA-2,Blake2)	✓ [43]	✓ (*)	✓ (*)	✓ (*)	✓ (*)	
ECC						
Curve25519	✓ [43]					✓ [34]
Ed25519	✓ [43]					
P-256	✓ [34]					
High-level APIs						
Box	✓ [43]					
HPKE	✓ (*)	✓ (*)	✓ (*)	✓ (*)	✓ (*)	✓ (*)

Verifying Post-Quantum Crypto in Rust

FIPS 203

Federal Information Processing Standards Publication

Module-Lattice-Based Key-Encapsulation Mechanism Standard

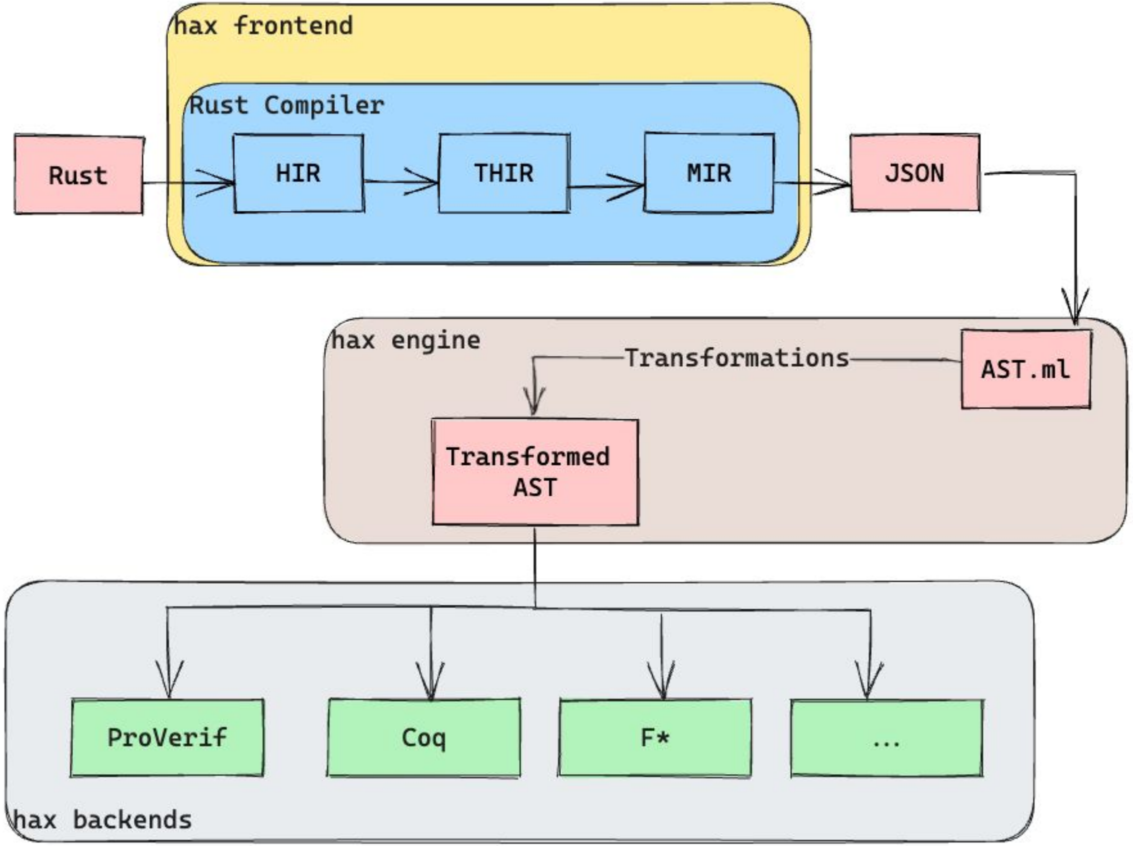
Category: Computer Security **Subcategory: Cryptography**

Information Technology Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8900

This publication is available free of charge from:
https://doi.org/10.6028/NIST.FIPS.203

Published August 13, 2024

hax: linking Rust code with proof backends

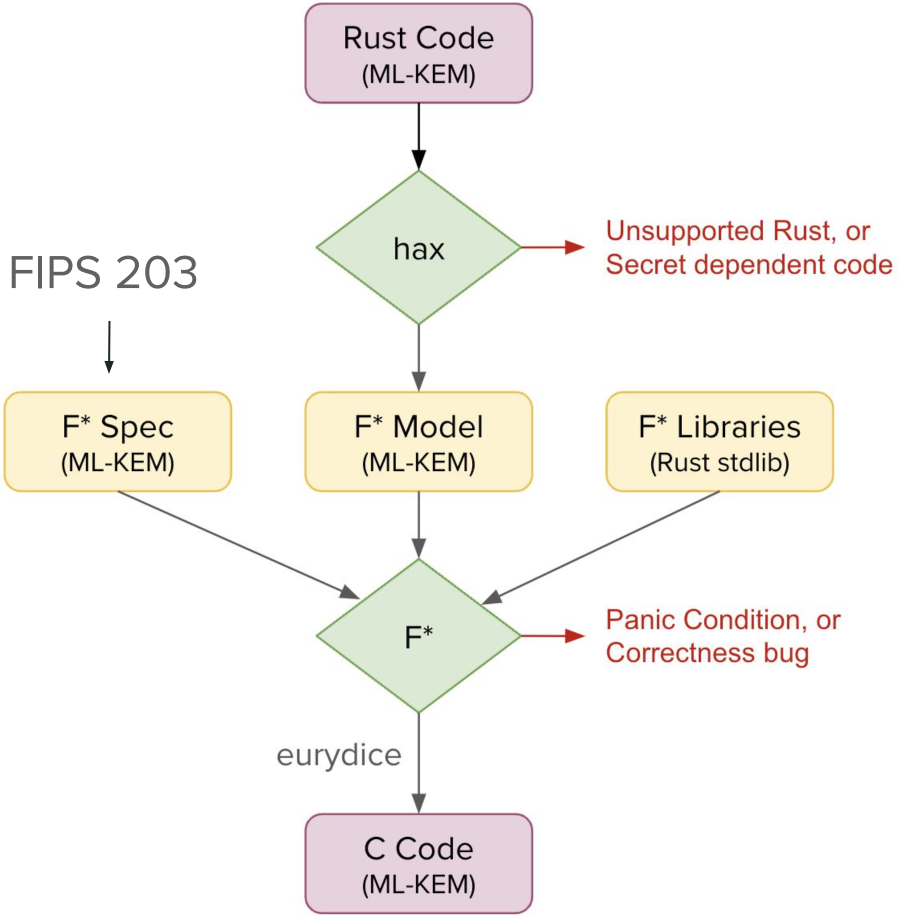


CRYSPEN

AARHUS UNIVERSITY

Inria

Verifying crypto code written in Rust and C using hax and F*



Writing Crypto Code in Rust

```rust
pub(crate) fn barrett_reduce(input: i32) -> i32 {
    let t = (i64::from(input) * 20159) + (0x4_000_000 >> 1);
    let quotient = (t >> 26) as i32;
    let remainder = input - (quotient * 3329);
    remainder
}
```

Barrett Reduction: computes **input % 3329**

(in constant time, so cannot directly use modulus)

Potential Panics in Rust Code

```rust
pub(crate) fn barrett_reduce(input: i32) -> i32 {
    let t = (i64::from(input) * 20159) + (0x4_000_000 >> 1);
    let quotient = (t >> 26) as i32;
    let remainder = input - (quotient * 3329);
    remainder
}
```

These arithmetic operations may overflow or underflow causing the code to panic at run-time

Proving Panic Freedom and Correctness in F*

```
val barrett_reduce (input: i32_b (v v_BARRETT_R))
    : Pure (i32_b 3328)
    (requires True)
    (ensures fun result ->
        v result % v Libcrux.Kem.Kyber.Constants.v_FIELD_MODULUS
      = v  input %v Libcrux.Kem.Kyber.Constants.v_FIELD_MODULUS)
```

Expected behaviour: `result % 3329 ≈ input % 3329`
`&& -3329 < result < 3329`

Enforcing Secret Independence

Type-based static analysis of forbidden operations

- **arithmetic operations** with input-dependent timing (e.g. division) over secret integers
- **comparison** over secret values
- **branching** over secret values
- **array** or vector **accesses** at secret indices

Prevents timing bugs at Rust source level.

Does not prevent compiler-induced leaks, micro-architectural attacks, ….

KyberSlash: a new timing vulnerability

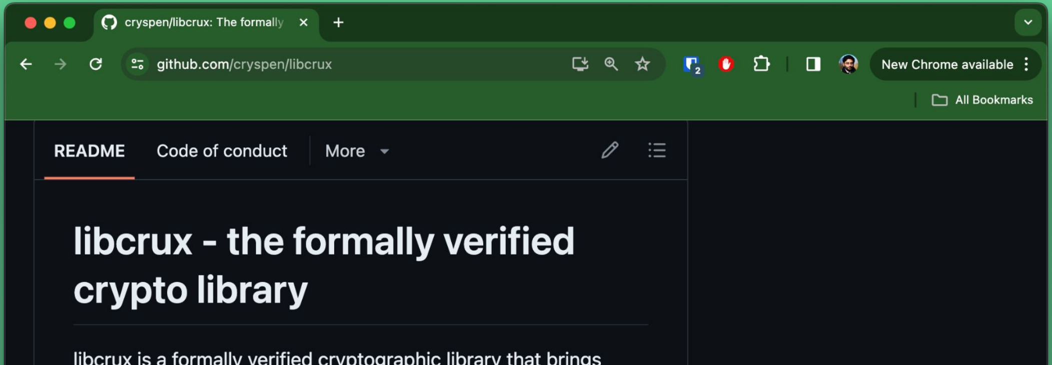
```
void poly_tomsg(uint8_t msg[KYBER_INDCPA_MSGBYTES], const poly *a)
{
  unsigned int i,j;
  uint16_t t;

  for(i=0;i<KYBER_N/8;i++) {
    msg[i] = 0;
    for(j=0;j<8;j++) {
      t  = a->coeffs[8*i+j];
      t += ((int16_t)t >> 15) & KYBER_Q;
      t  = (((t << 1) + KYBER_Q/2)/KYBER_Q) & 1;
      msg[i] |= t << j;
    }
  }
}
```

Bug present in PQ-Crystals, PQ-Clean, …

Bug found during Formal Verification of our Rust code!

KyberSlash: Exploiting secret-dependent division timings in Kyber implementations. CHES 2025.
Bernstein, Bhargavan, Bhasin, Chattopadhyay, Chia, Kannwischer, Kiefer, Paiva, Ravi, Tamvada.

Libcrux has an **optimized**, **portable**, formally **verified** implementation of ML-KEM and ML-DSA in **Rust and C**. Our ML-KEM code is now deployed in Firefox, OpenSSH, Signal, ...



Analyzing Post-Quantum Protocols

The (Classical) Signal Protocol

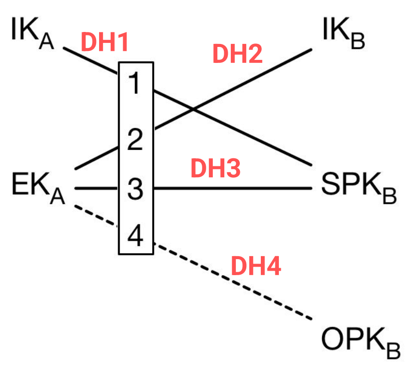
Two parts:

- **X3DH** handshake
- **Double Ratchet** for continuous key agreement

Important security guarantees:

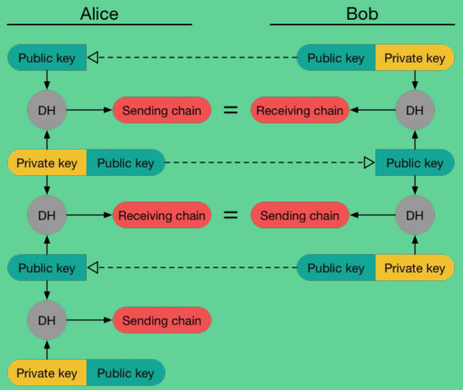
- Mutual authentication
- Post-compromise security
- Forward secrecy
- Deniability

X3DH

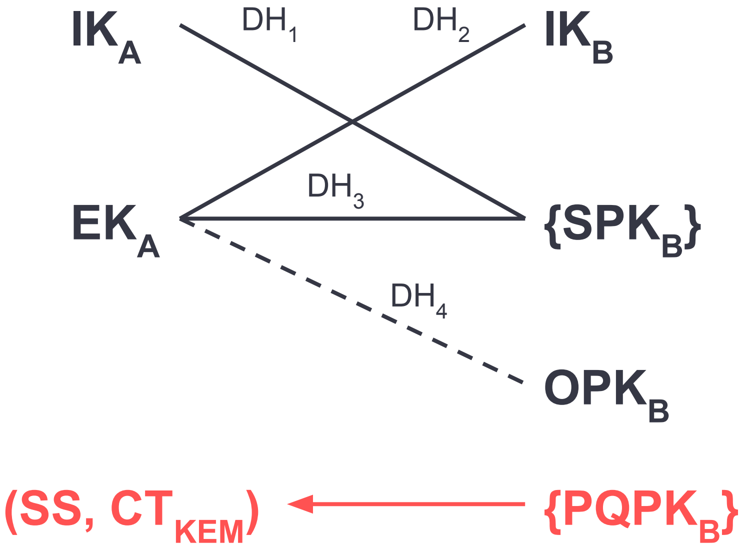


SK = KDF(**DH1** || **DH2** || **DH3** || **DH4**)

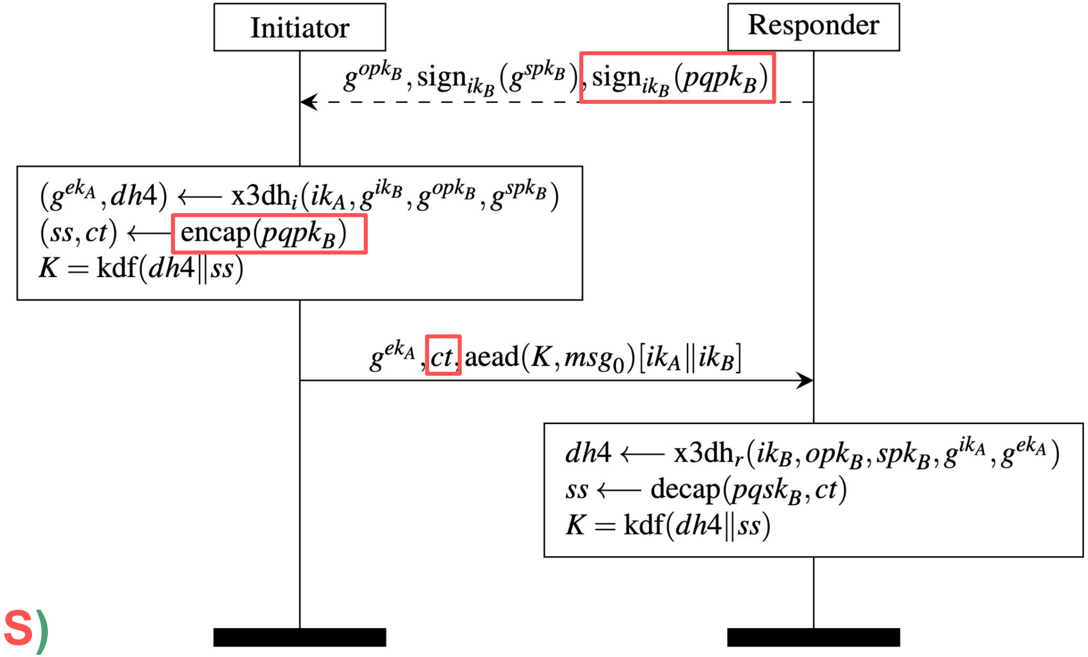
Double Ratchet



PQXDH Design: Add a PQ-KEM to X3DH



$SK = KDF(DH_1 \| DH_2 \| DH_3 \| DH_4 \| SS)$

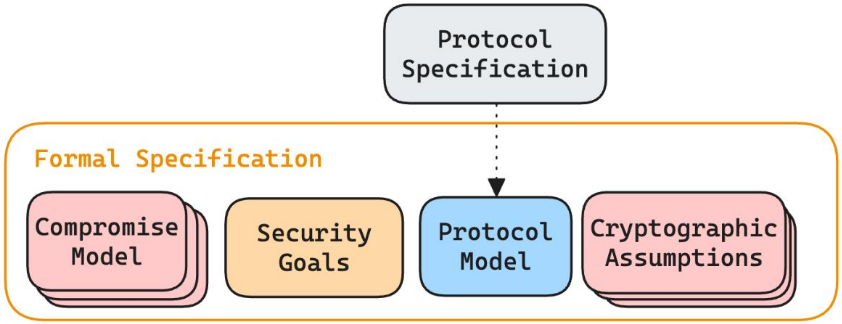


Analyzing PQXDH

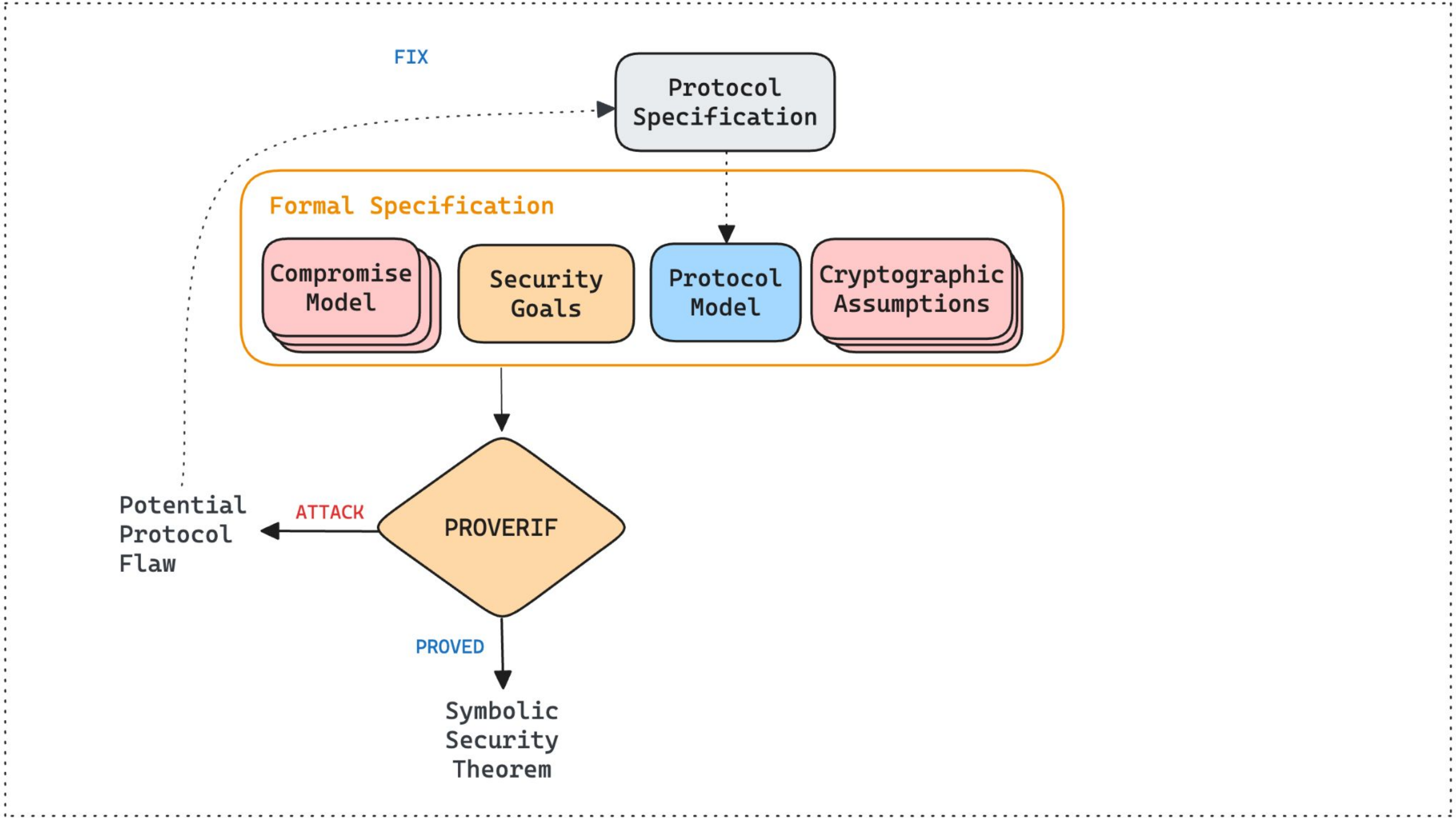
- PQXDH is a very small addition to X3DH.
- X3DH has been comprehensively analyzed in a variety of security models
  - Mutual Authentication, Confidentiality, (a form of) Forward Secrecy

- Is PQXDH as secure as X3DH?
- Is it secure against a Harvest-Now-Decrypt-Later quantum adversary?

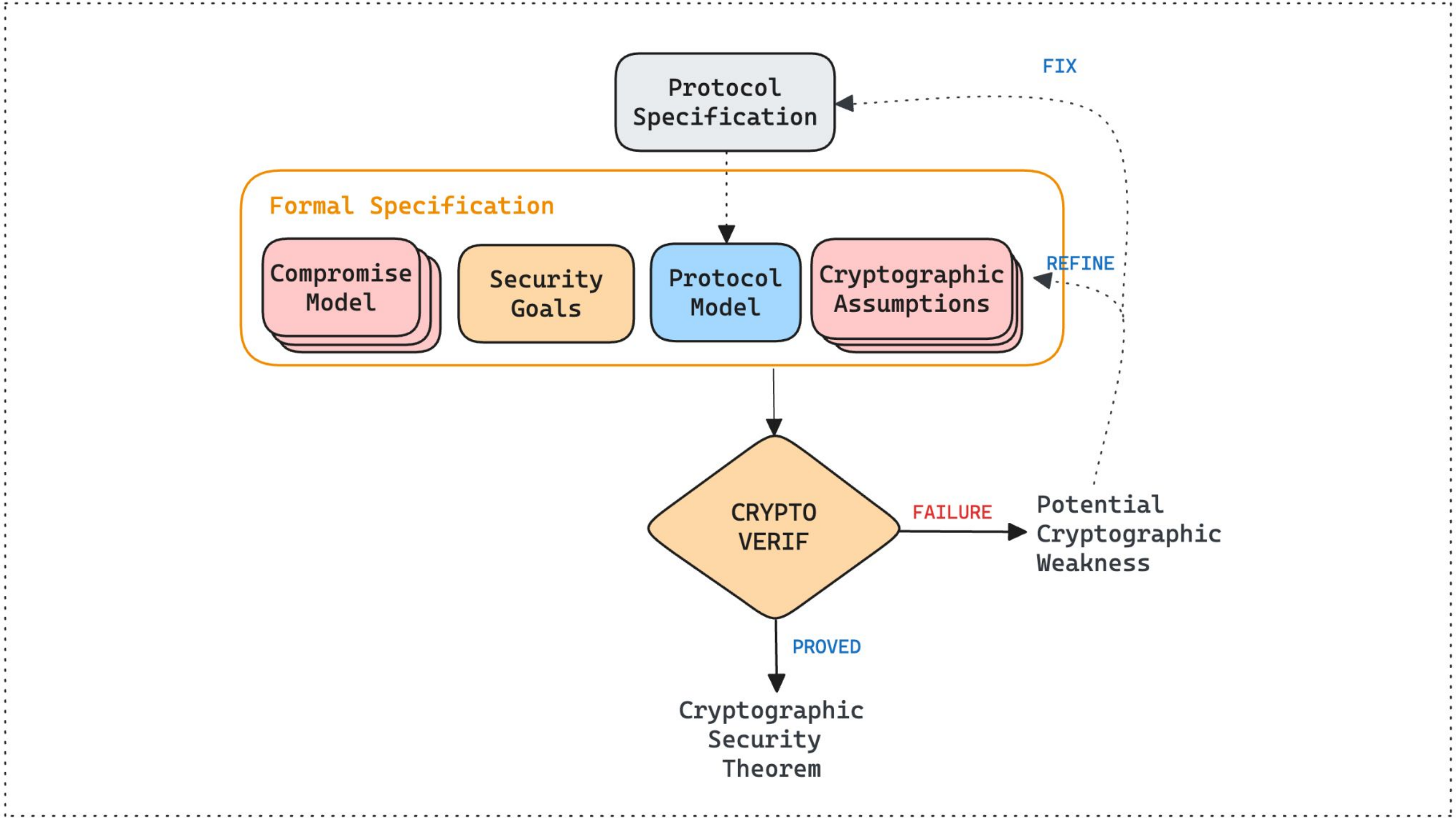
Our Formal Verification Methodology



Our Formal Verification Methodology



Our Formal Verification Methodology



Formally Specifying PQXDH

Single Message between Two Roles

- Arbitrary number of endpoints
- Any endpoint can play any role
- (Out-of-Band) Identity Key Verification
- Untrusted Key Distribution Server

Specification in Applied Pi Calculus

- Makes all computations precise.
- What is sent on the wire?
- What key encoding do we use?
- What exactly is signed/encrypted?
- How are all the keys derived?

```
let Initiator(i:client, IKA_s:scalar) =
    (* Download Responder Keys *)
    ...

    (* Verify the signatures *)
    if verify(IKB_p,encodeEC(SPKB_p),SPKB_sig) then
    if verify(IKB_p,encodeKEM(PQPKB_p),PQPKB_sig) then

    (* PQXDH Key Derivation*)
    let IKA_p = s2p(IKA_s) in
    let (CT:bitstring,SS:bitstring) =
        pqkem_enc(PQPKB_p) in (* PQ-KEM Encap *)
    new EKA_s:scalar;
    let EKA_p = s2p(EKA_s) in
    let DH1 = dh(IKA_s,SPKB_p) in
    let DH2 = dh(EKA_s,IKB_p) in
    let DH3 = dh(EKA_s,SPKB_p) in
    let DH4 = dh(EKA_s,OPKB_p) in
    let SK = kdf(concat5(DH1,DH2,DH3,DH4,SS)) in

    (* Send Message *)
    let ad = concatIK(IKA_p,IKB_p) in
    new msg_nonce: bitstring;
    let msg = app_message(i,r,msg_nonce) in
    let enc_msg = aead_enc(SK,empty_nonce,msg,ad) in

    out(server, (IKA_p,EKA_p,CT,OPKB_p,
                 SPKB_p,PQPKB_p,enc_msg))
```

Symbolic Analysis with ProVerif

Security goals as queries

- Secrecy, Authentication as trace properties about protocol events & attacker knowledge
- Indistinguishability, privacy stated as equivalence properties between processes

Fully automated analysis

- Finds attacks and produces traces
- If no attack found in model, establishes a symbolic security theorem
- Might not terminate!

```
(* Post-Quantum Forward Secrecy Query *)
query A, B, spk, pqpk, sk, i, j;
        event(BlakeDone(A,B,spk,pqpk,sk))@i
                ⇒ not(attacker(sk))
                  | (event(LongTermComp(A))@j & j < i)
                  | (event(QuantumComp)@j & j < i)
```

Attack Trace:

1. Using the function info_x25519_sha512_kyber1024 the attacker may obtain info_x25519_sha512_kyber1024.
attacker(info_x25519_sha512_kyber1024).

2. Using the function zeroes_sha512 the attacker may obtain zeroes_sha512.
attacker(zeroes_sha512).

3. We assume as hypothesis that
attacker(a).

4. We assume as hypothesis that
attacker(b).

5. The message b that the attacker may have by 4 may be received at input {2}.
So the entry identity_pubkeys(b,SMUL(IK_s_2,G)) may be inserted in a table at i
table(identity_pubkeys(b,SMUL(IK_s_2,G))).

…

Game-Based Proofs with CryptoVerif

Computational crypto model

- Standard cryptographic assumptions
- User-defined assumptions as equivalences
- Probabilistic polynomial-time adversary

Process, security query syntax like ProVerif

- Secrecy, authentication, indistinguishability

Proofs as a sequence of game transformations

- Requires some manual guidance
- Machine-checked transformations
- Computes concrete advantage formulas
- Proof failure may indicate attack, no trace

```
proof {
crypto uf_cma_corrupt(sign) signAseed;
out_game "g1.cv" occ;

insert before "EKSecA1 <-R Z" ...
insert after "RecvOPK(" ...
out_game "g11.cv" occ;

insert after "OH_1(" ...
crypto rom(H2);
out_game "g2.cv" occ;

insert before "EKSecA1p <-R Z" ...
insert after "RecvNoOPK(" ...
out_game "g12.cv"occ;

insert after "OH(" ...
crypto rom(H1);
out_game "g3.cv";

crypto gdh(gexp_div_8) ...
crypto int_ctxt(enc) *;
crypto ind_cpa(enc) **;
out_game "g4.cv";

crypto int_ctxt_corrupt(enc) r_23;
crypto int_ctxt_corrupt(enc) r_50;
success
}
```

Modeling the Quantum Adversary

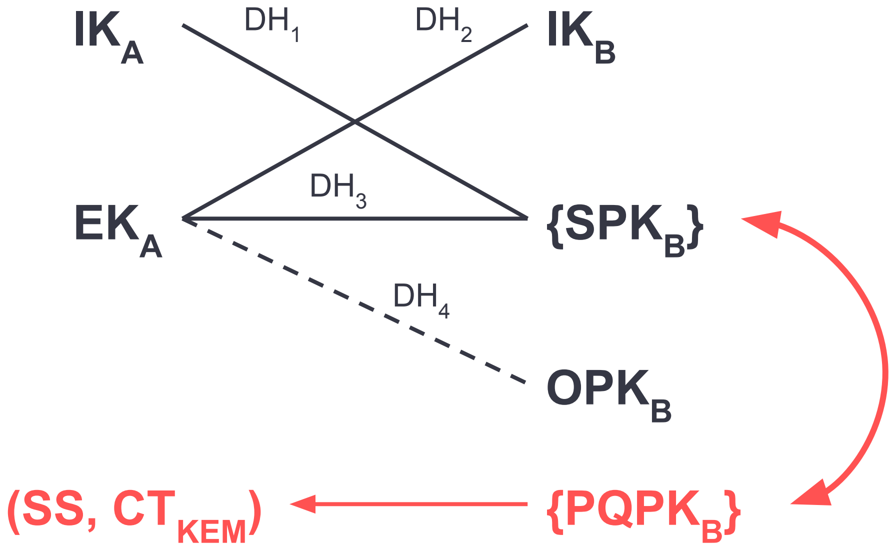
Passive Quantum Adversary Model (Harvest-Now-Decrypt-Later)

- We allow adversary to break certain crypto primitives (e.g. DH) *after* the session is over
- PQ primitives (e.g. PQ-KEM) remain secure

Symbolic and Computational Analysis

- ProVerif automatically searches for attacks that rely on broken primitives
- CryptoVerif checks that the classical game-based proof still holds against passive quantum attackers
    - *Post-quantum sound CryptoVerif and verification of hybrid TLS and SSH key-exchanges*, Blanchet, Jacomme, IEEE CSF 2024

Key Confusion Attack on PQXDH



$$SK = KDF(DH_1 \| DH_2 \| DH_3 \| DH_4 \| SS)$$

Attacker swaps keys and signatures to break PQ security of PQXDH

ProVerif finds this attack if:

- **the key encodings can collide, and**
- **public keys are not validated**

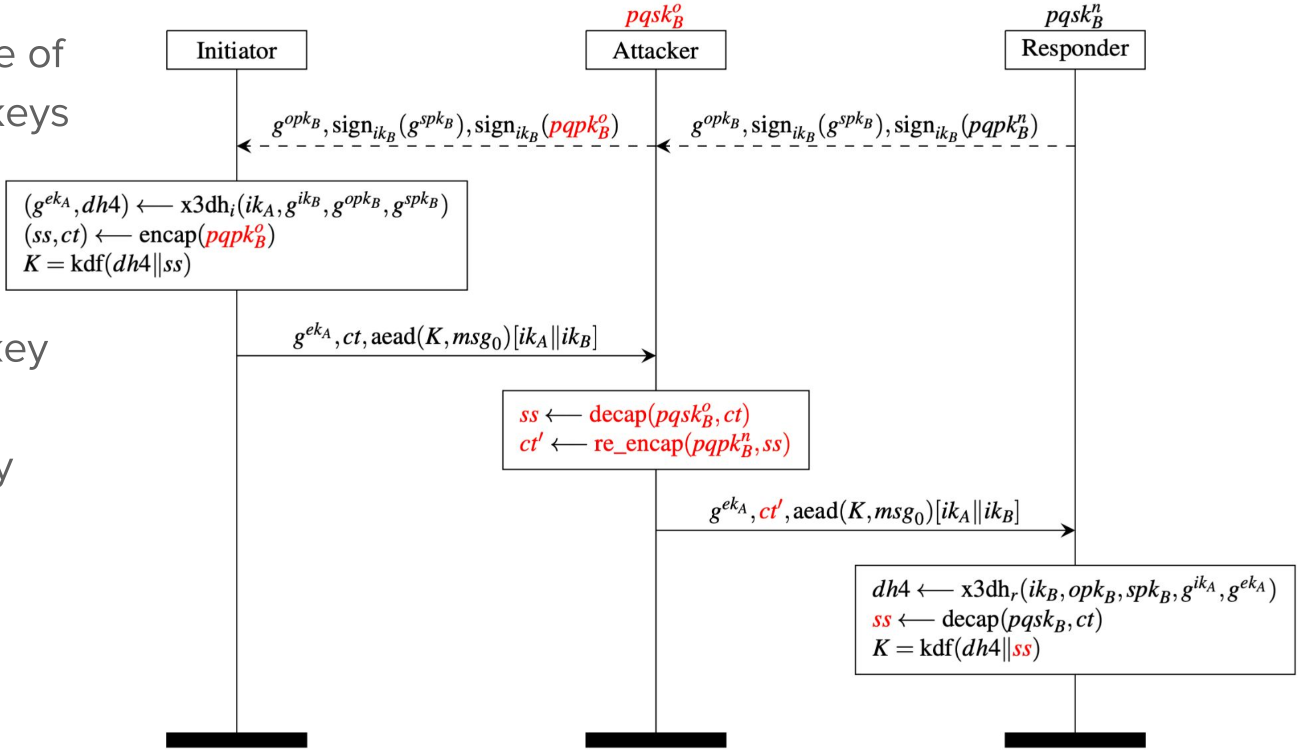
This is representative of a general class of cross-protocol attacks between classical modes and post-quantum crypto modes in the same protocol.

Easy Fix: Ensure all key/message/signature encodings have disjoint co-domains.

Signal implementation already does this

KEM Re-encapsulation Vulnerability in PQXDH

1. Attacker compromises one of responder's old PQ-KEM keys
2. Attacker provides old PQ-KEM key to initiator
3. Initiator encapsulates *SS* to (compromised) old key
4. Attacker re-encapsulates *SS* to responder's new key
5. Responder thinks initiator used new PQ public key



Breaks agreement query

(non-matching transcripts)

PQXDH Revision and Security Theorems

The findings and discussions with Signal team led to a new revision of the protocol:

- We required **AEAD** to be post-quantum **IND-CPA** and **INT-CTXT**
- Restricted the ranges of encodings to be disjoint
- Added **$PQPK_B$** to AD when it isn't already bound within the KEM

With these changes we can prove that PQXDH meets its classical and PQ security requirements in the symbolic, computational, and HNDL quantum models.

This whole process: spec, analysis, fix, proof, new spec took 1 calendar month.

Formal Analysis for the Full PQ Signal Protocol

New PQ ratcheting protocol (SPQR)

- Uses chunked messages
- Requires a new streaming API for ML-KEM

Formally verified protocol design

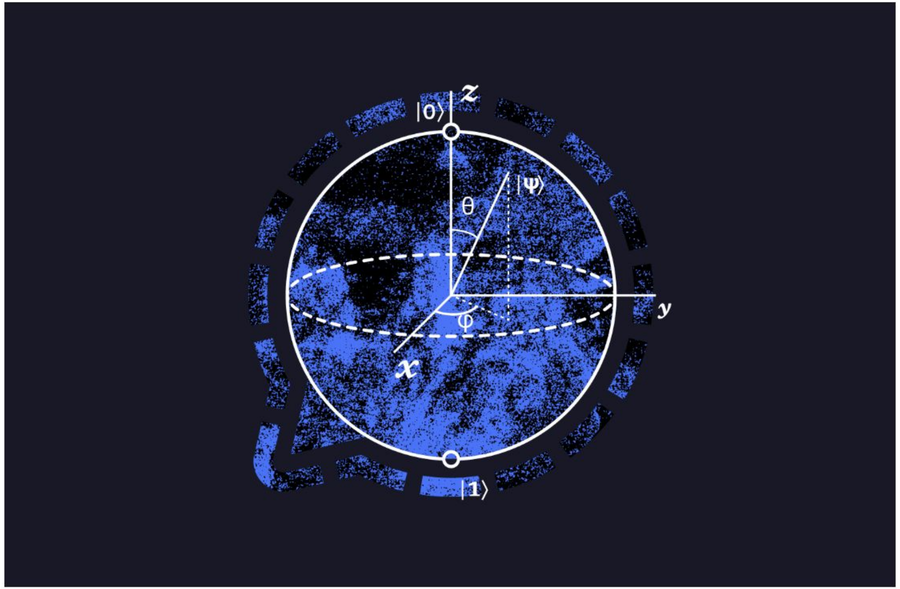
- Symbolic analysis with ProVerif
- Dozen variants analyzed

Formal verification for protocol code

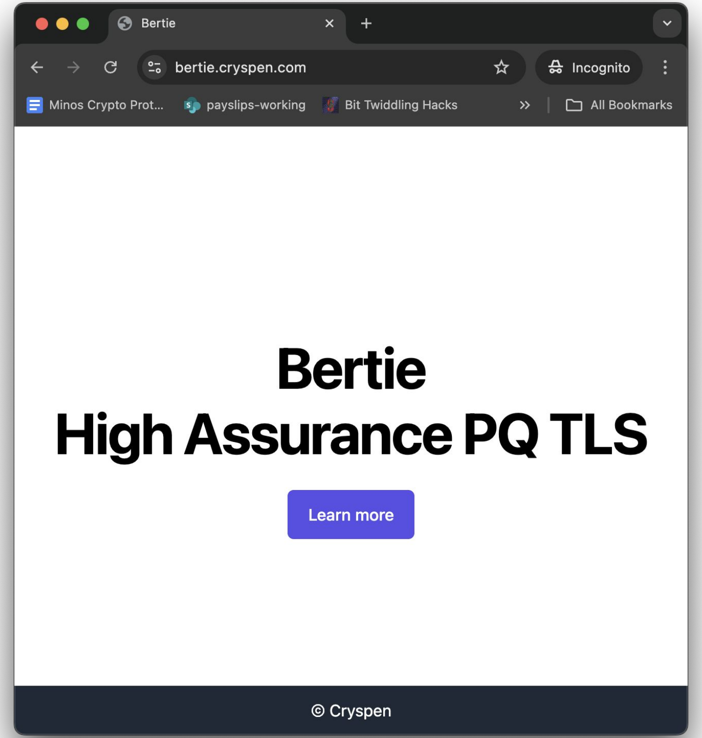
- Libcrux implementation of ML-KEM
- Proofs of panic-freedom and correctness using hax under CI

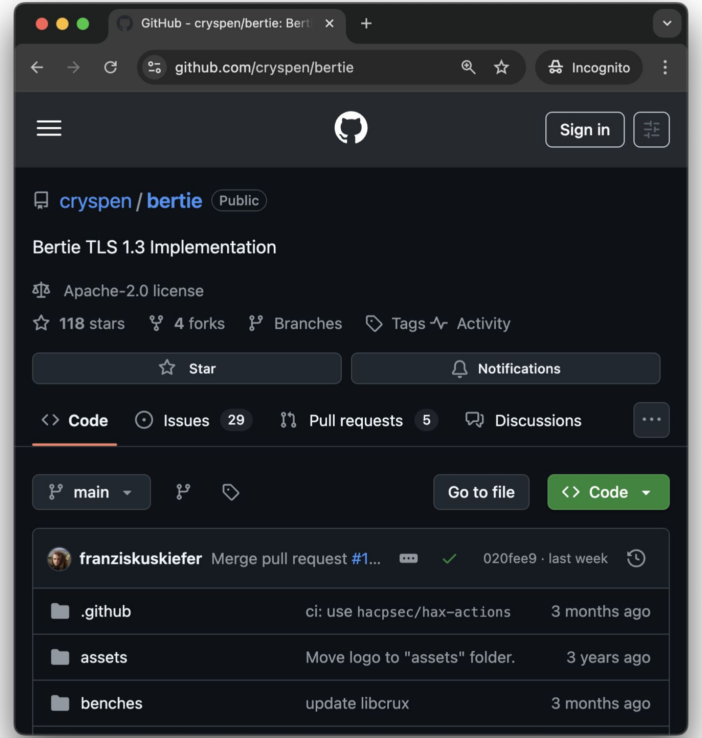
Signal Protocol and Post-Quantum Ratchets

Graeme Connell and Rolfe Schmidt on 02 Oct 2025

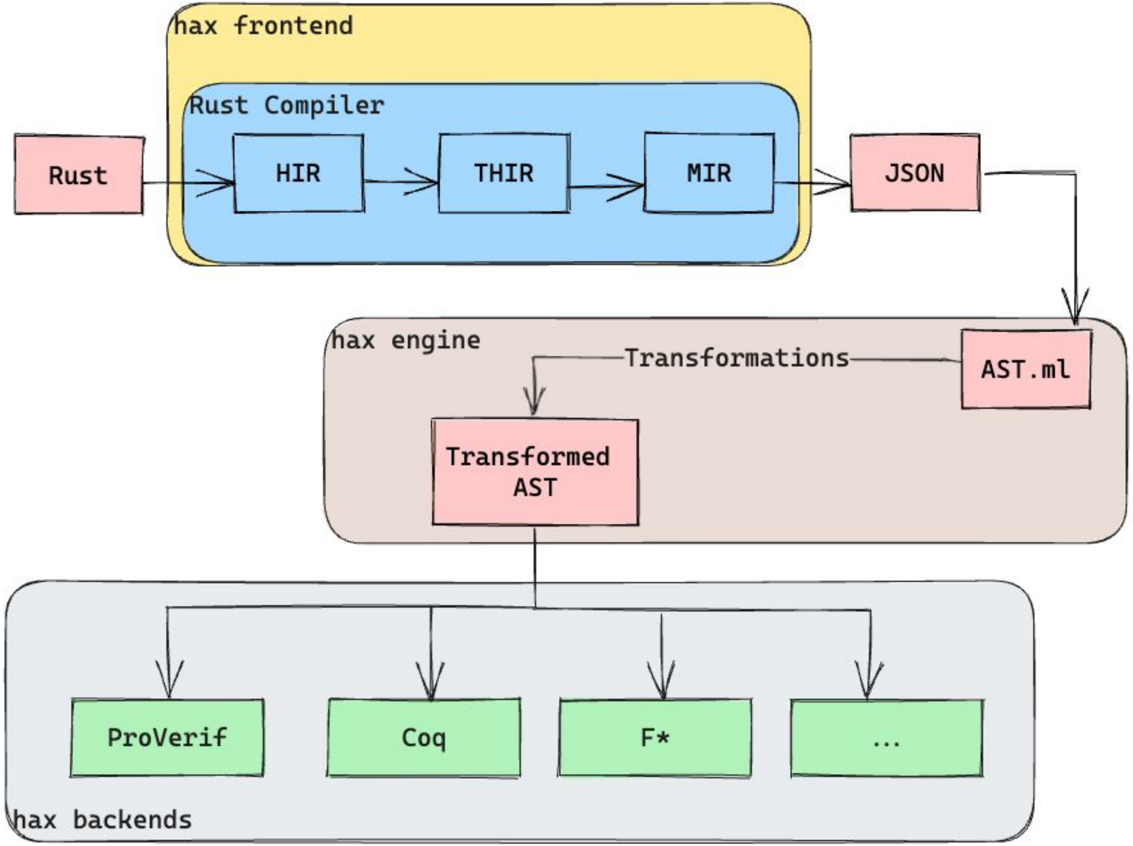


BERT13: Verified PQ-TLS 1.3 in Rust

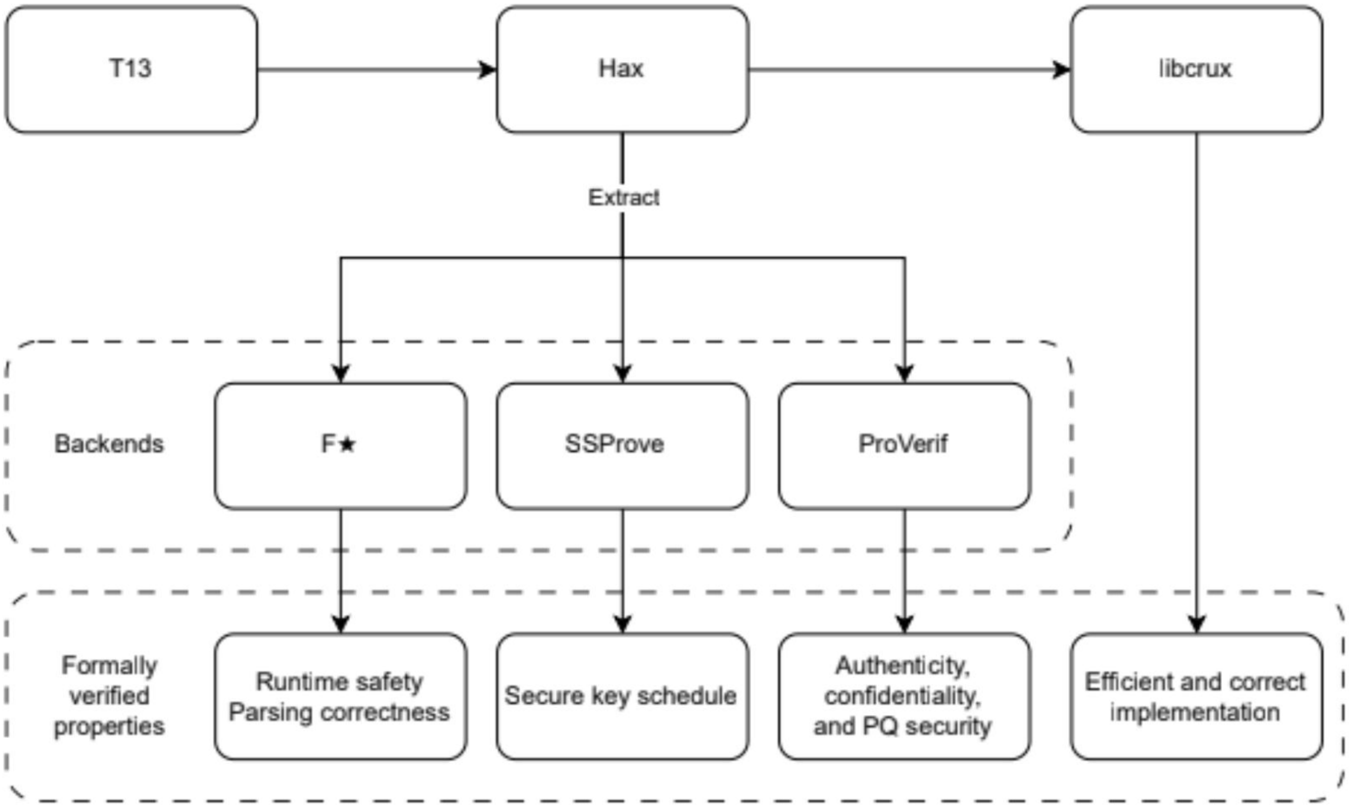




hax: bridging the gap between code and proof



Verifying BERT13 with hax



Verifying BERT13 using hax

- We use the Rust type system to enforce state machine invariants
- We use libcrux for verified cryptography
- We use F* for properties like parsing correctness and panic-freedom
- We use ProVerif to prove protocol security for the TLS 1.3 implementation
- We use SSProve to cryptographically verify the key schedule implementation

Table 2: Formal Verification Results for Bert13

Backend Prover	Rust Modules	Rust LoC	Translated LoC	Properties Proven	Time Taken for Proofs (s)
SSProve	1	425	815	Core Key Schedule Security	11m17s
ProVerif	3	1723	5980	Forward Secrecy, Authentication	20s
				HNDL Post-Quantum Security	
F⋆	8	3264	10964	Runtime Safety, Unambiguous Formats	1m21s

Formal Security and Functional Verification of Cryptographic Protocol Implementations in Rust.
ACM CCS 2025. Bhargavan, Hansen, Kiefer, Schneider-Bensch, Spitters.

Conclusion

Fast, verified crypto is available and already widely deployed

- See NSS, BoringSSL, AWS-LC, MS Symcrypt, …
- Verifying legacy C and asm is hard, generating them from DSLs is easier
- Verifying developer-friendly Rust code offers a sweet spot

Transitioning to post-quantum protocols requires new formal analysis

- More than just switching the crypto to ML-KEM
- Beware of downgrade and cross-protocol attacks

Verifying protocol code can find and prevent large classes of bugs

- Needs formal tools that protocol developers can use themselves
- New Rust-based verification frameworks are becoming practical to use

Questions?

- Papers: https://cryspen.com/research/
- Code:
  - Hax: https://github.com/cryspen/hax
  - Libcrux: https://github.com/cryspen/libcrux
  - Bertie: https://github.com/cryspen/bertie