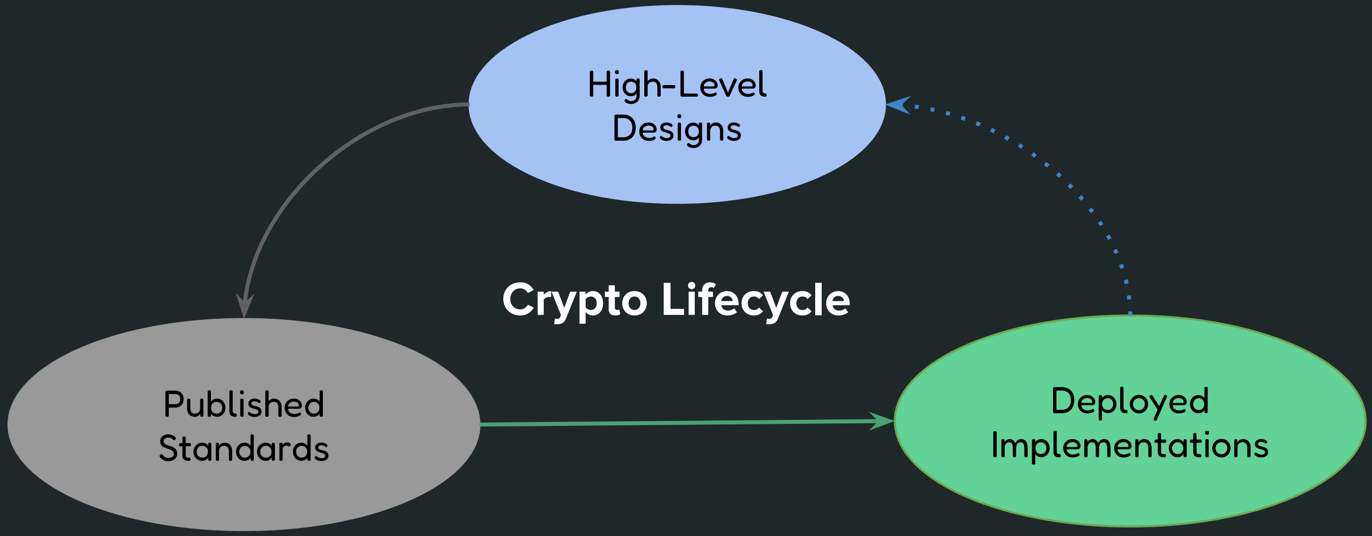
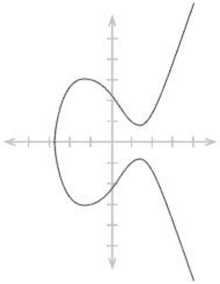
Provably Secure Protocols and High-Assurance Software for the Post-Quantum Transition

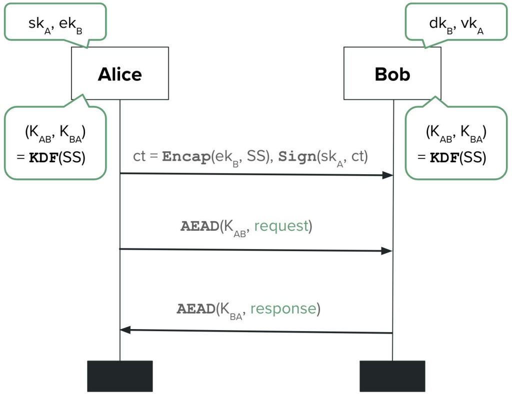
Karthikeyan Bhargavan


High-Level Designs
Crypto Lifecycle
Published Standards
Deployed Implementations

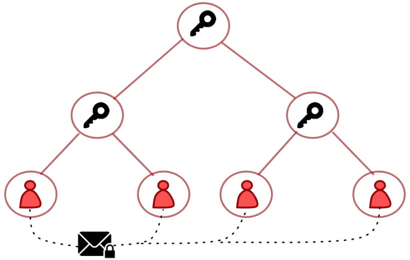
High-Level Cryptographic Design



- Novel constructions and protocols
- Abstract mathematical descriptions
- Security goals and threat models
- Is the math / proof correct?



- **Documentation:** white paper, publication
- **Evaluation**: **security proofs**, cryptanalysis
- **Examples:**
  - Elliptic Curves, **PQ KEMs**, Signatures
  - Key Exchange, Double Ratchet, TreeKEM



Published Standards

- Detailed technical specifications
- Algorithms, formats, data structures
- Enable interoperable implementations
- Is it ambiguous? Is it secure?

- **Documentation:** spec, standard
- **Evaluation**: public review, **formal analysis**
- **Examples:**
  - ECDSA, ML-KEM, HPKE
  - TLS, MLS, Signal, iMessage

FIPS 203

Federal Information Processing Standards Publication

Module-Lattice-Based Key-Encapsulation Mechanism Standard

Published:	February 2022			
ISSN:	2070-1721			
Authors:	R. Barnes	K. Bhargavan	B. Lipp	C. Wood
	Cisco	*Inria*	*Inria*	*Cloudflare*

RFC 9180

Hybrid Public Key Encryption

Signal

The PQXDH Key Agreement Protocol

Revision 3, 2023-05-24, Last Updated: 2024-01-23 [PDF]

Ehren Kret, Rolfe Schmidt

Deployed Implementations

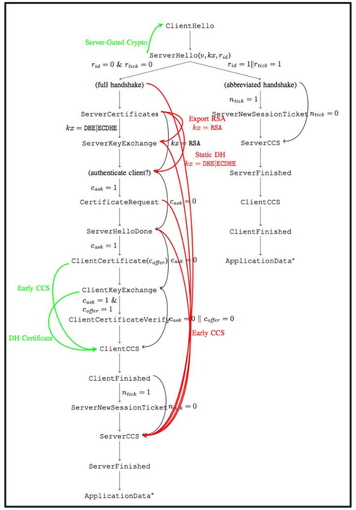
OpenSSL
Cryptography and SSL/TLS Toolkit

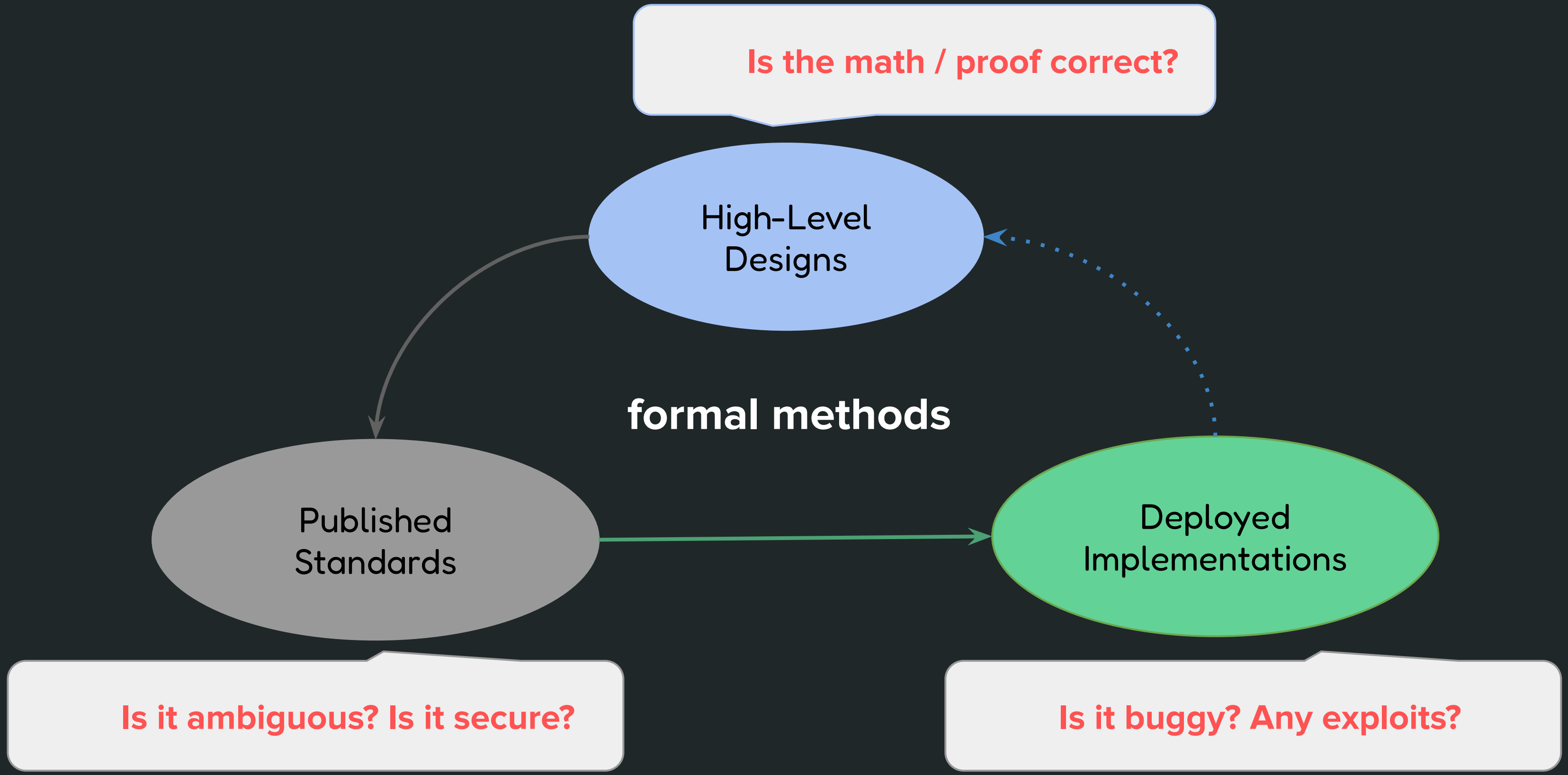
- Efficient code and hardware
- Usable APIs, side channel protections
- Integrate with real-world applications
- Is it buggy? Any exploitable attacks?

- **Documentation:** code, documentation
- **Evaluation**: testing, **software verification**
- **Examples:**
  - OpenSSL, boringssl, NSS, aws-lc, **libcrux**
  - Libsignal, miTLS, OpenMLS, **bertie**

```
for(i=0;i<KYBER_N/8;i++) {
  for(j=0;j<8;j++) {
    // map to positive standard representatives
    u  = a->coeffs[8*i+j];
    u += (u >> 15) & KYBER_Q;
    t[j] = ((((uint16_t)u << 4) + KYBER_Q/2)/KYBER_Q) & 15;
  }

  r[0] = t[0] | (t[1] << 4);
  r[1] = t[2] | (t[3] << 4);
  r[2] = t[4] | (t[5] << 4);
  r[3] = t[6] | (t[7] << 4);
  r += 4;
}
```




Is the math / proof correct?
High-Level Designs
formal methods
Published Standards
Deployed Implementations
Is it ambiguous? Is it secure?
Is it buggy? Any exploits?

Formal Methods for Crypto

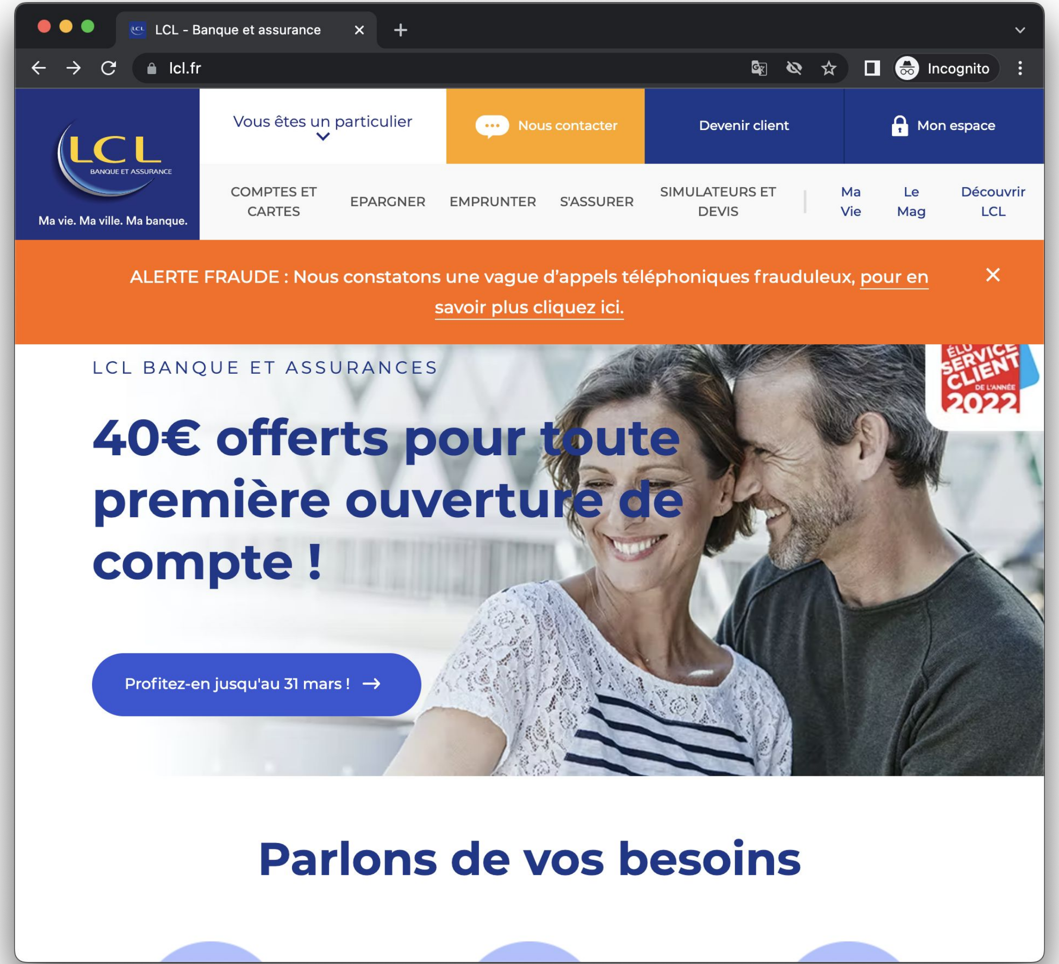
- Computer-Aided Cryptography, a.k.a. High Assurance Cryptography

  "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 vulnerabilities
- Comprehensively analyze **specifications** before publication
- Formally verify **implementations** to prevent bugs and attacks
- .... and **repeat** these steps over and over again as these artifacts evolve

TLS 1.3: An Instructive Example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Ma vie. Ma ville. Ma banque.
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Nous contacter
Devenir client
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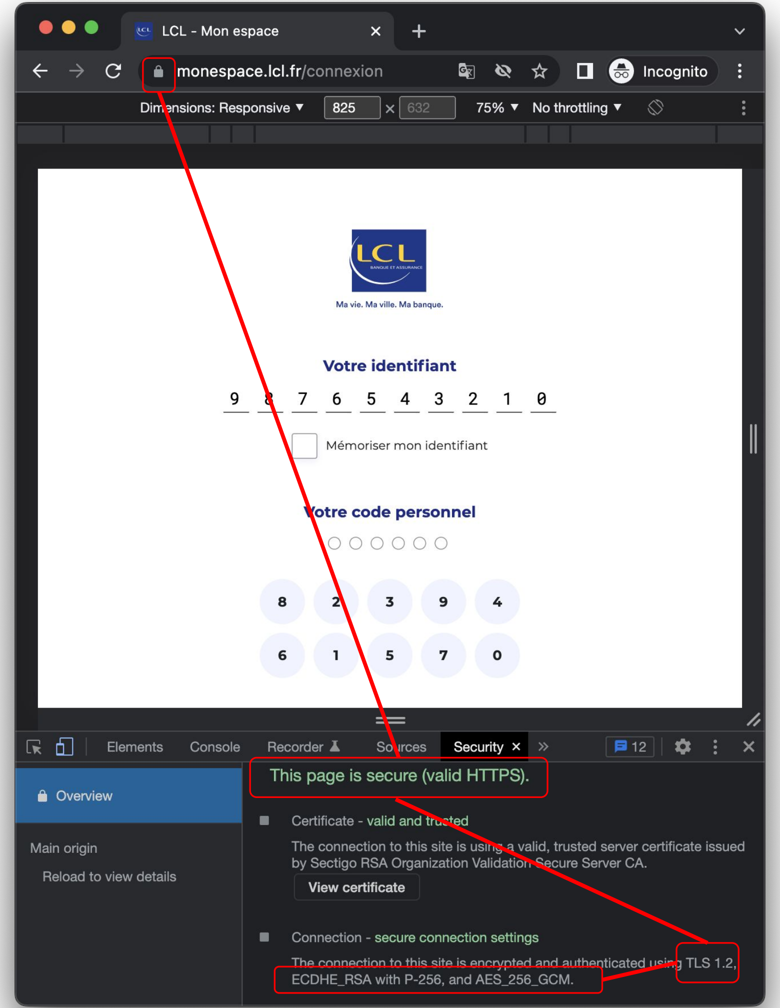
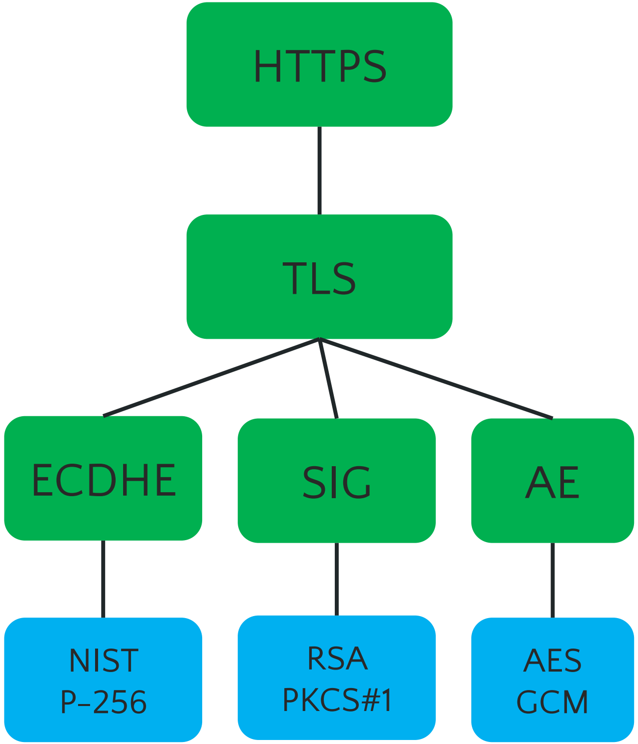




- Well-understood since 1994!
- So, is this a solved problem?

Many Practical Attacks on TLS (until TLS 1.3)

• BEAST	CBC predictable IVs	[Sep’11]
• CRIME	Compression before Encryption	[Sep’12]
• RC4	Keystream biases	[Mar’13]
• Lucky 13	MAC-Encode-Encrypt CBC	[May’13]
• 3Shake	Insecure resumption	[Apr’14]
• POODLE	SSLv3 MAC-Encode-Encrypt	[Dec’14]
• FREAK	Export-grade 512-bit RSA	[Mar’15]
• LOGJAM	Export-grade 512-bit DH	[May’15]
• SLOTH	RSA-MD5 signatures	[Jan’16]
• DROWN	SSLv2 RSA-PKCS#1v1.5	[Mar’16]
• SWEET32	3DES collisions	[May’16]
• …		

What goes wrong in protocols like TLS?

Crypto Weaknesses

- RC4, 3DES, MD5, PKCS#1 v1.5

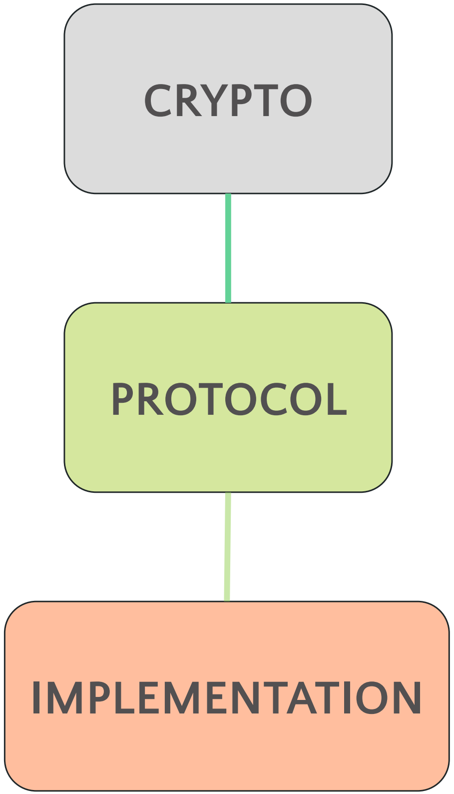
Protocol Design Flaws

- Downgrade attacks, Transcript collisions

Implementation Bugs

- Parsing, State machines, Memory safety

Often, a mix of all the above!

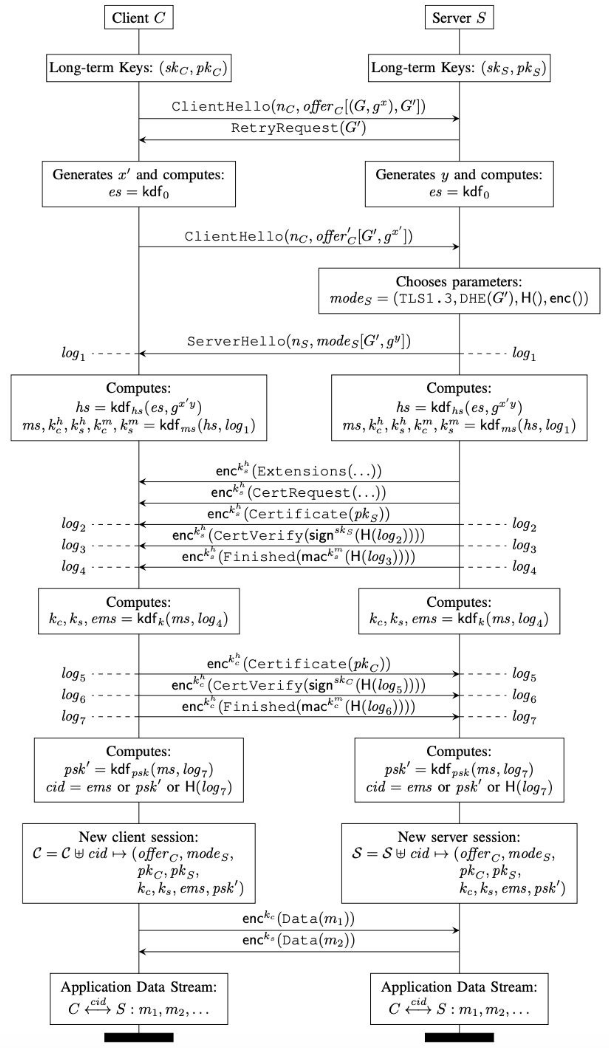


The TLS 1.3 Standardization Project

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

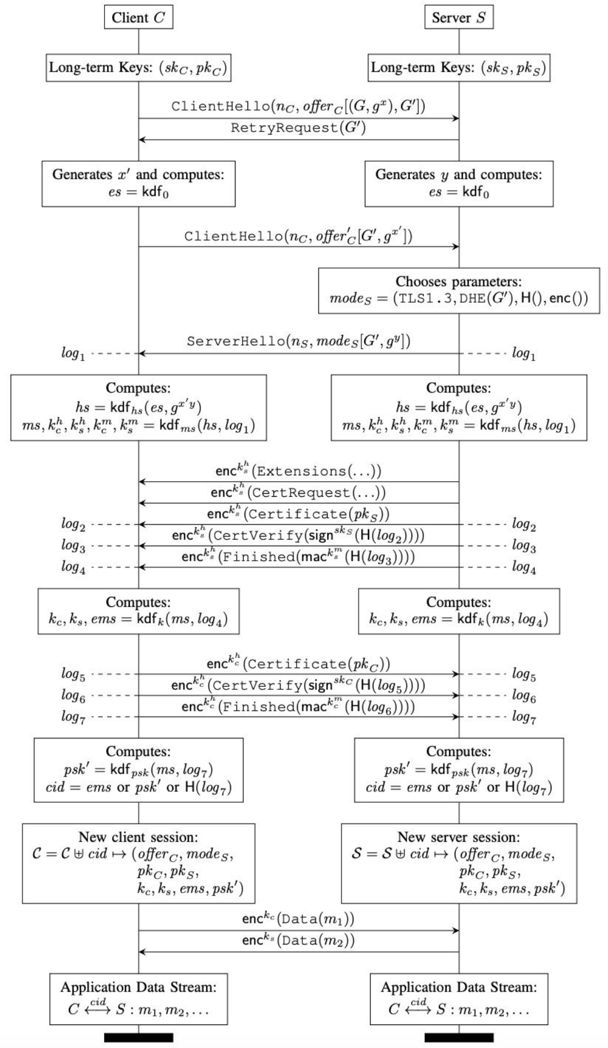


TLS 1.3: Impact on new protocols

- Proofs now often required for new designs
  - **Machine-checked proofs** preferred

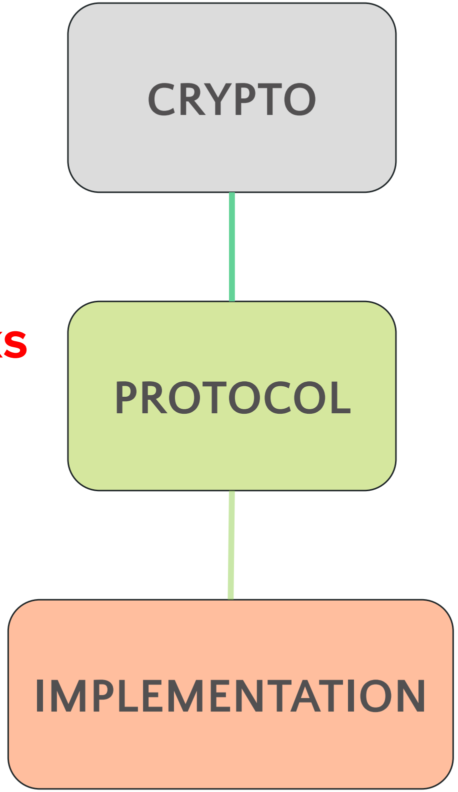
- IETF Working Groups
  - **LAKE**: Key exchange protocol for IoT
  - **TLS**: Encrypted Client Hello, KEM-TLS
  - **MLS:** Secure group messaging

- Industrial Protocols
  - PQ3 (iMessage), PQXDH (Signal)



Lessons from TLS 1.3

- Tight **Design** ↔ **Analysis** exchanges are crucial
- It's not just crypto, **low-level protocol details** matter
- Beware of composition flaws and **downgrade attacks**
- Prepare to address the **next threat** quickly
- **Formal methods** can give you an edge



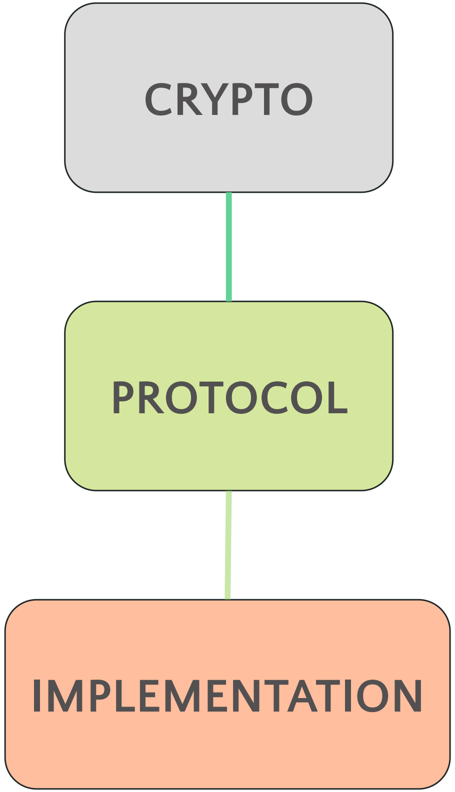
How can we apply these lessons to the PQC Migration?

Formal Methods for Post-Quantum Cryptography

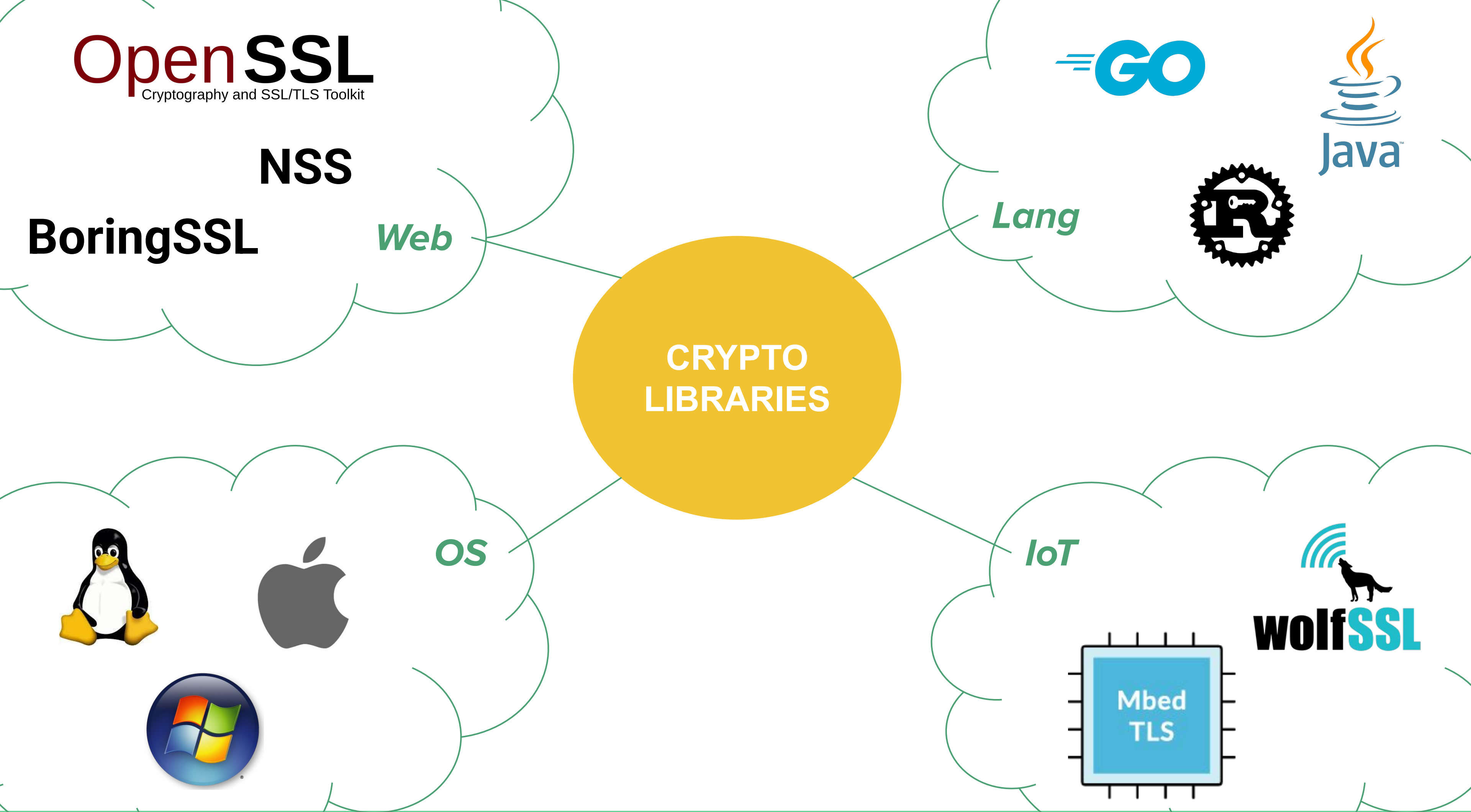
- Formally verifying PQC constructions and software
    - In this session: **Manuel Barbosa**

- Formally verifying real-world PQC protocols
    - In this session: **Rolfe Schmidt**

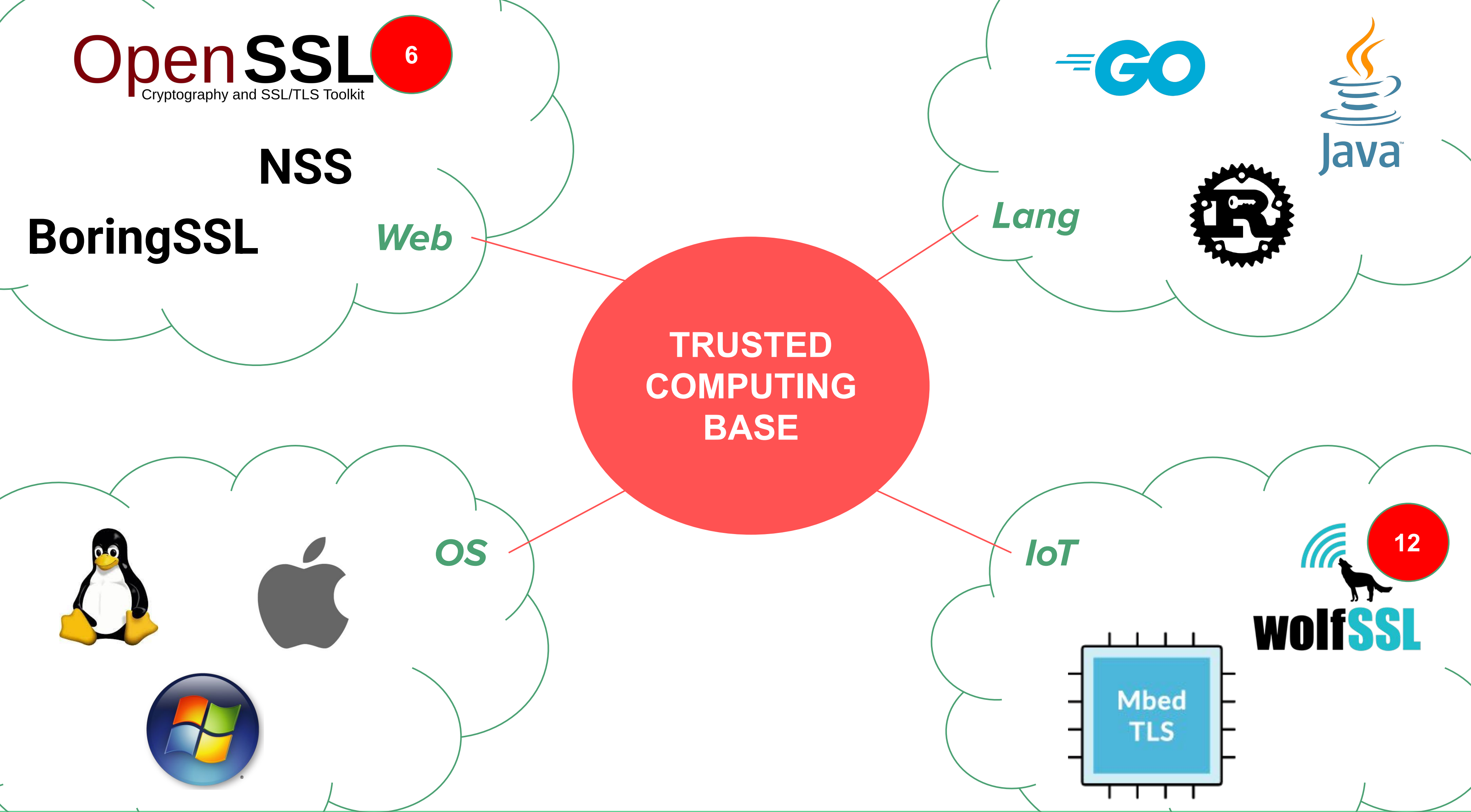
Rest of this talk: Verifying PQC software in Rust



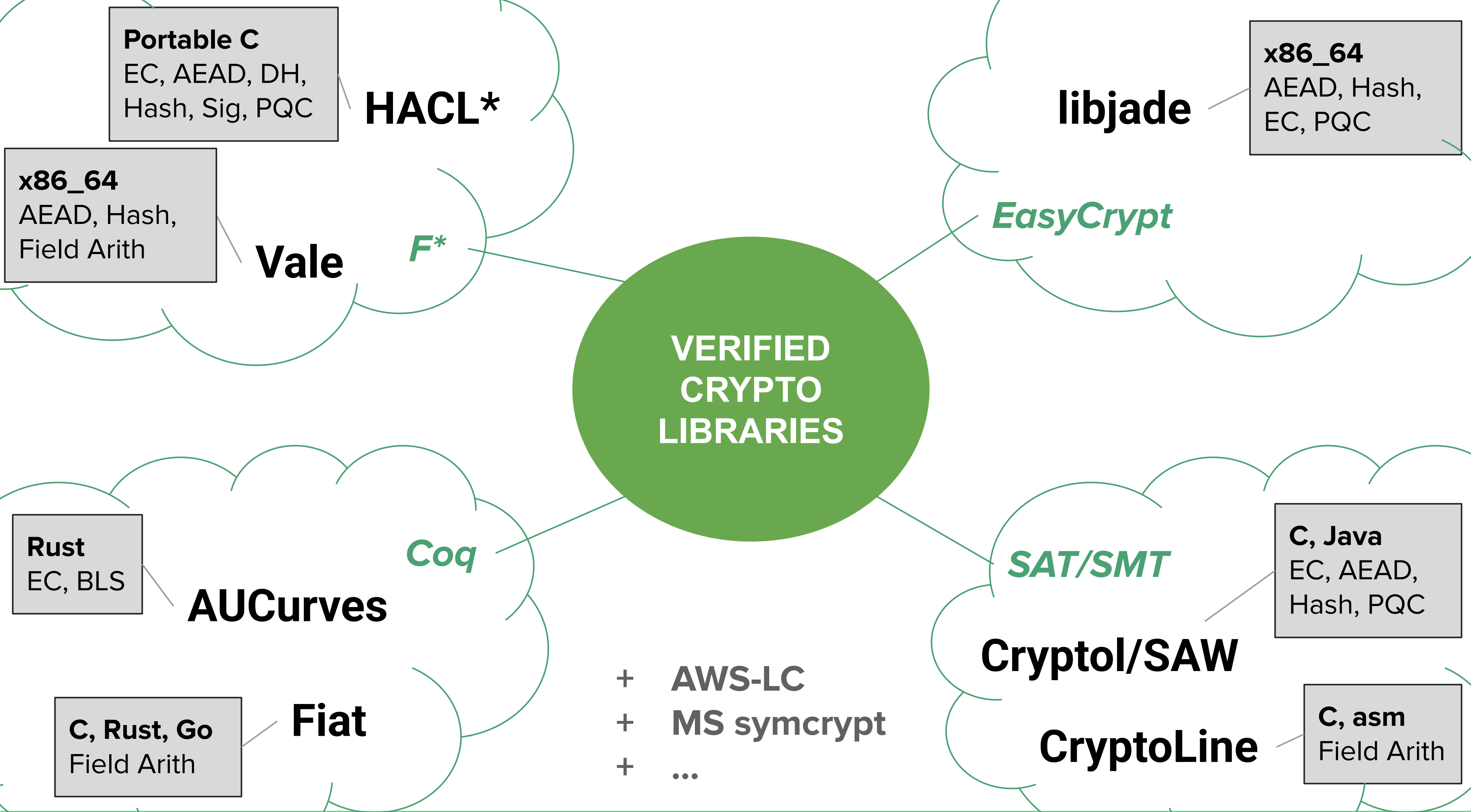
Verifying Post-Quantum Crypto Libraries



CRYPTO LIBRARIES
Web
OpenSSL
Cryptography and SSL/TLS Toolkit
NSS
BoringSSL
Lang
GO
Java
OS
IoT
wolfSSL
Mbed TLS



TRUSTED COMPUTING BASE
Web
OpenSSL
Cryptography and SSL/TLS Toolkit
6
NSS
BoringSSL
Lang
GO
Java
OS
IoT
12
wolfSSL
Mbed TLS



VERIFIED CRYPTO LIBRARIES
HACL*
Portable C
EC, AEAD, DH, Hash, Sig, PQC
Vale
x86_64
AEAD, Hash, Field Arith
F*
libjade
x86_64
AEAD, Hash, EC, PQC
EasyCrypt
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
+ MS symcrypt
+ ...

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
- Formally verified crypto in NSS, BoringSSL, aws-lc, ...

FIPS 203

Federal Information Processing Standards Publication

Module-Lattice-Based Key-Encapsulation Mechanism Standard

Category: Computer Security **Subcategory: Cryptography**

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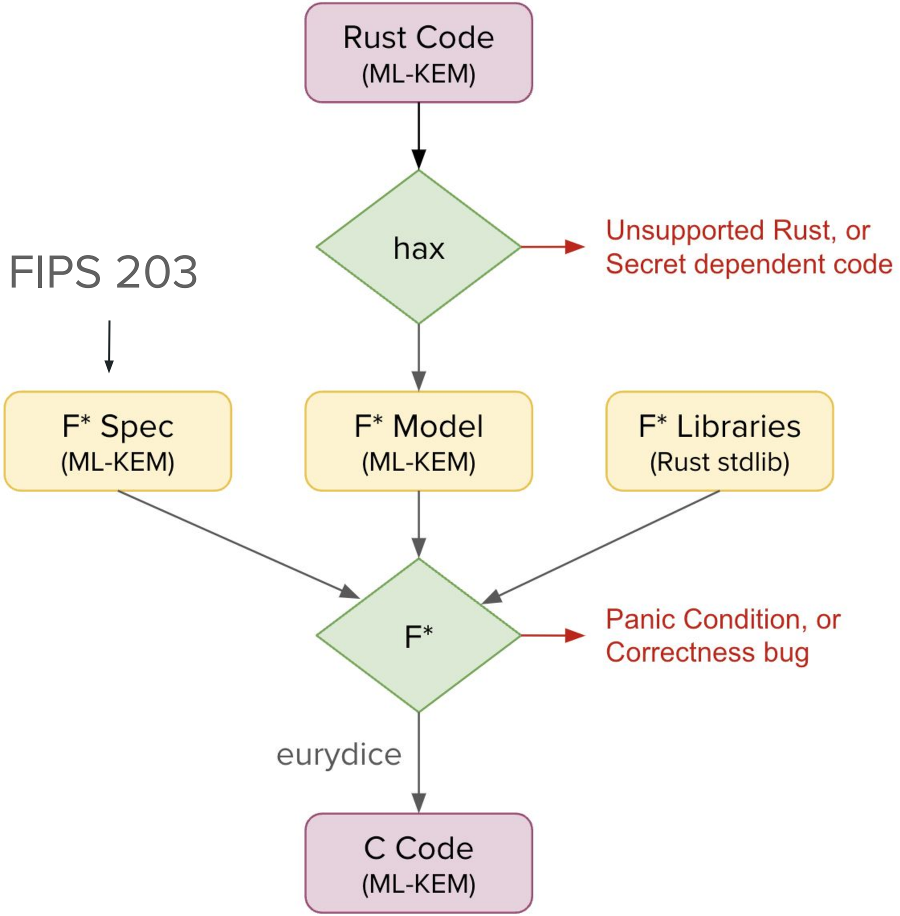
Verifying crypto code written in Rust using hax and F*



Writing Crypto Code in Rust

```rust
fn barrett_reduce(value: i32) -> i32 {
    let t = i64::from(value) * BARRETT_MULTIPLIER + (BARRETT_R >> 1);
    let quotient = (t >> BARRETT_SHIFT) as i32;
    let remainder = value - quotient * FIELD_MODULUS;
    remainder
}
```

Barrett Reduction Algorithm

(in constant time, so cannot directly use modulus operator)

Potential Panics in Rust Code

```rust
fn barrett_reduce(value: i32) -> i32 {
    let t = i64::from(value) * BARRETT_MULTIPLIER + (BARRETT_R >> 1);
    let quotient = (t >> BARRETT_SHIFT) as i32;
    let remainder = value - quotient * FIELD_MODULUS;
    remainder
}
```

These arithmetic operations may overflow or underflow causing the code to crash or compute wrong results

Proving Panic Freedom and Functional Correctness

```
#[requires(value >= -BARRETT_R && value <= BARRETT_R)]
#[ensures(|result| result > -FIELD_MODULUS && result < FIELD_MODULUS
                && result % FIELD_MODULUS == value % FIELD_MODULUS)]
fn barrett_reduce(value: i32) -> i32 {
    ...
    remainder
}
```

Specify pre-condition and post-condition
(Automatically verified using F*)

Enforcing Secret Independence

Type-based static analysis to avoid certain side channel attacks

- **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

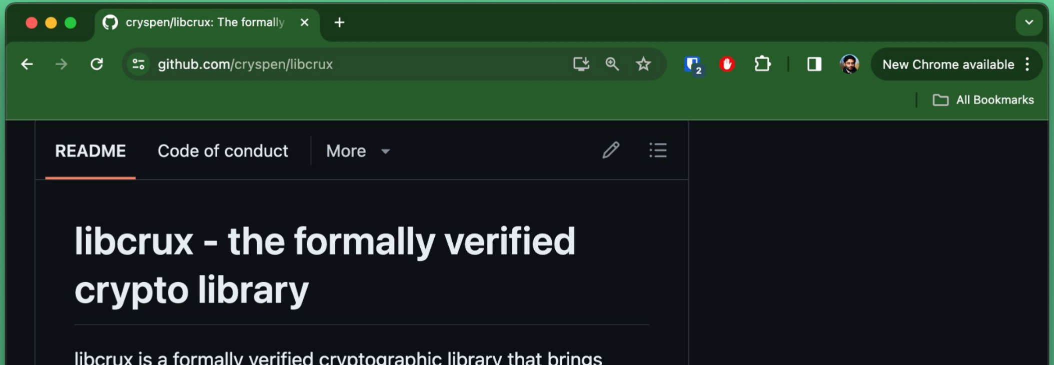
```c
void poly_tomsg(uint8_t msg[KYBER_INDCPA_MSGBYTES], const poly *a)
{
  unsigned int i,j;
  uint16_t t;

  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!

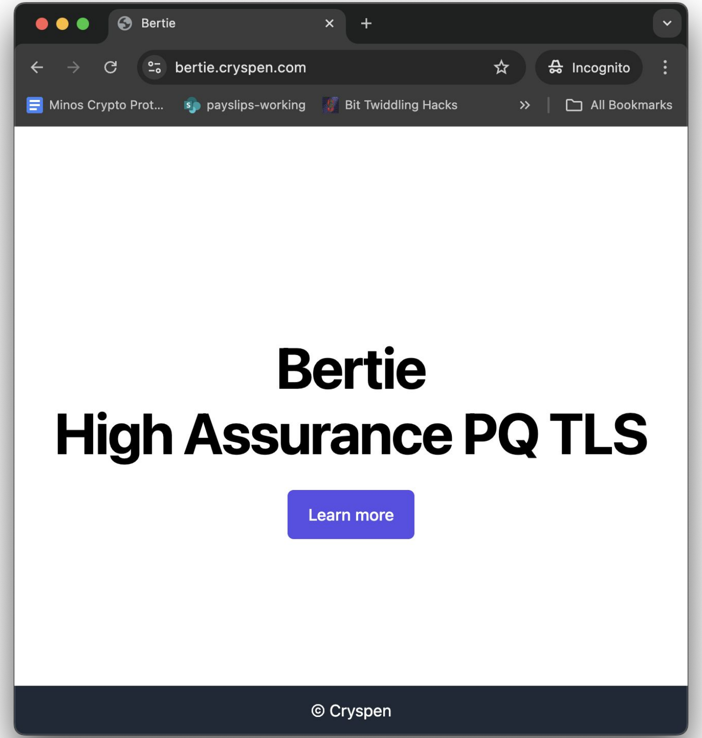
KyberSlash: Exploiting secret-dependent division timings in Kyber implementations. CHES 2025.
Bernstein, Bhargavan, Bhasin, Chattopadhyay, Chia, Kannwischer, Kiefer, Paiva, Ravi, Tamvada.

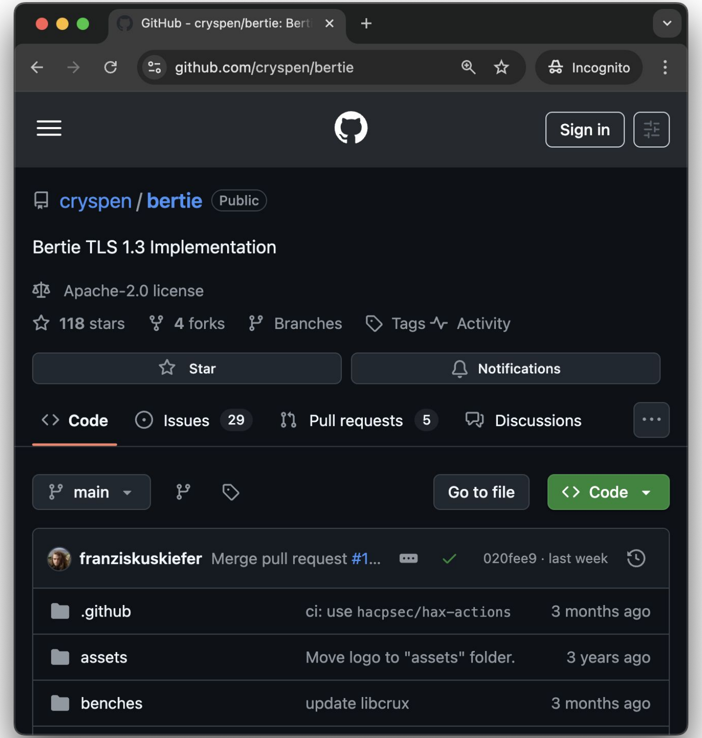
Libcrux has an **optimized**, **portable**, formally **verified** implementation of ML-KEM and ML-DSA in **Rust and C**. Our ML-KEM code is now deployed in Firefox, OpenSSH, Signal, ...



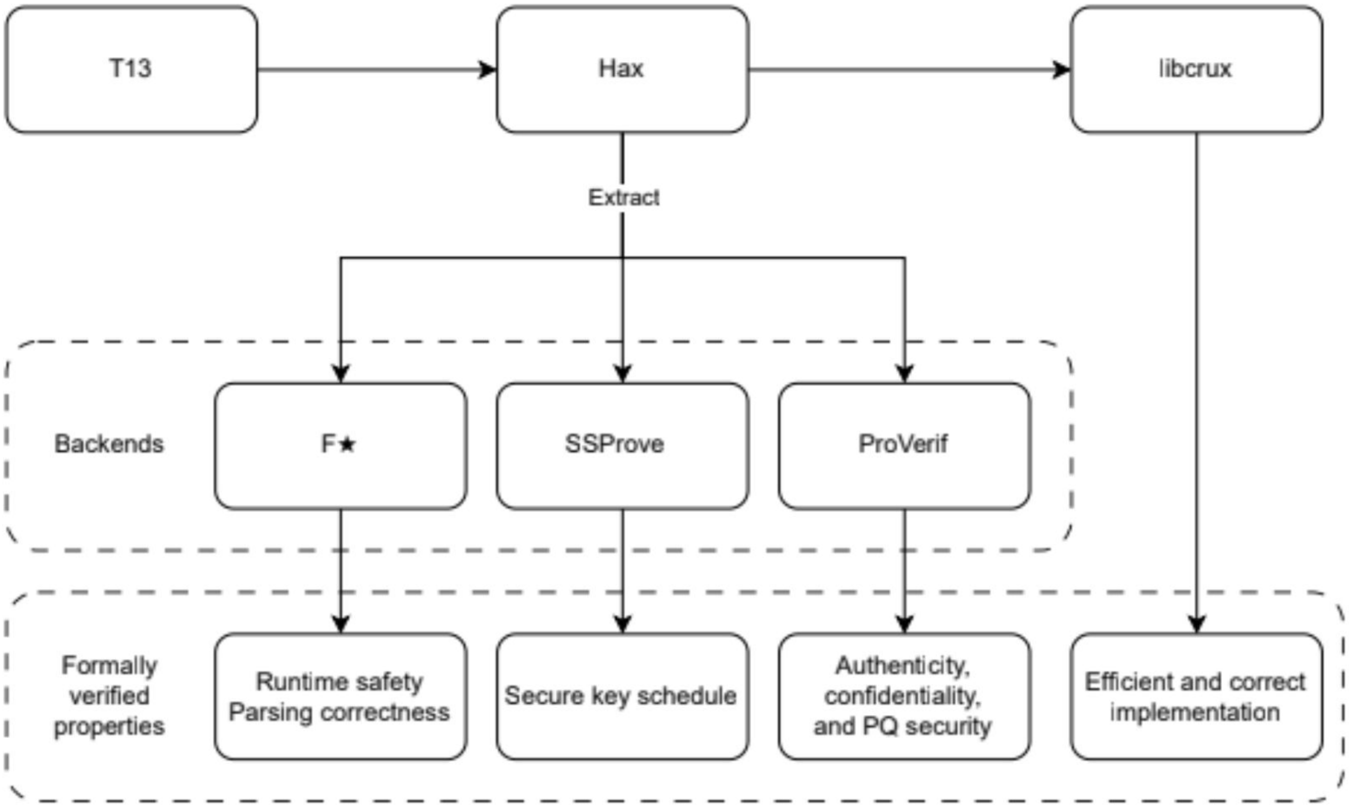
Verifying Post-Quantum Protocol Code

Bertie: Verified PQ-TLS 1.3 in Rust





Verifying Bertie for Security and Correctness



Verifying Bertie 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

Transitioning to PQC is about more than just switching crypto algorithms

- New security models, new attacks, new software bugs
- We should **require machine-checked proofs** for all new protocols

Fast, verified post-quantum crypto is available and already deployed

- See Signal, Formosa, NSS, BoringSSL, AWS-LC, MS Symcrypt, …
- We should **require software verification** for all PQC libraries

PQC is a unique opportunity to upgrade the security of the Internet

- Provably improve security for long-lived hardware and software
- Leverage cutting-edge EU research on formal security verification

Questions?

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

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

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https://cryspen.com