Machine-checking post-quantum cryptography

Andreas Hülsing
Applied & Provable Security Group
Eindhoven University of Technology

How do you ensure that a cryptographic scheme is hard to break?

Traditional Answer: Cryptanalysis

Have many smart people try to break it.

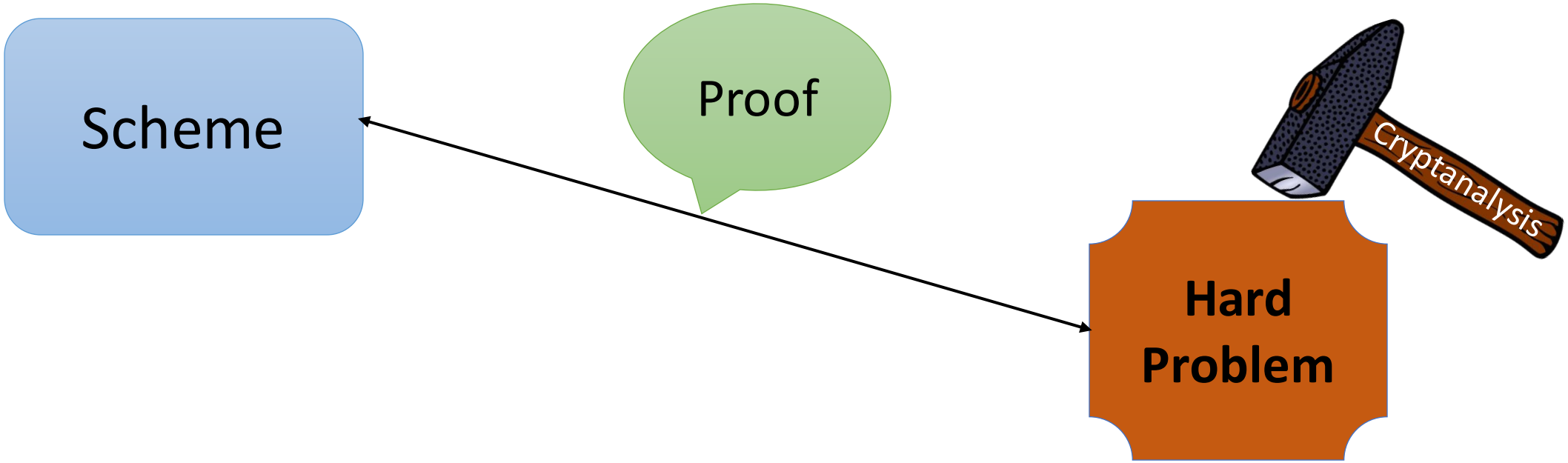
Does not scale!

- NIST: 64 candidates
- NIST signature on-ramp: 40 candidates
- KpqC: 16 candidates
- China, Russia, …

Who is supposed to cryptanalyze all of these?

What about protocols?

The Role of Security Proofs in Cryptography



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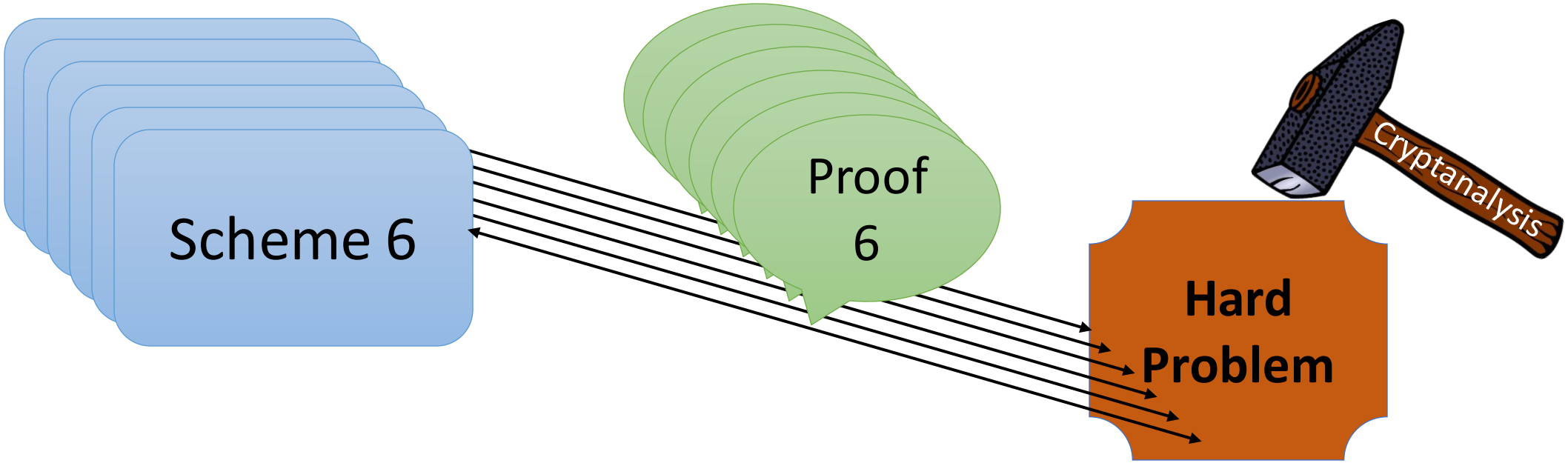
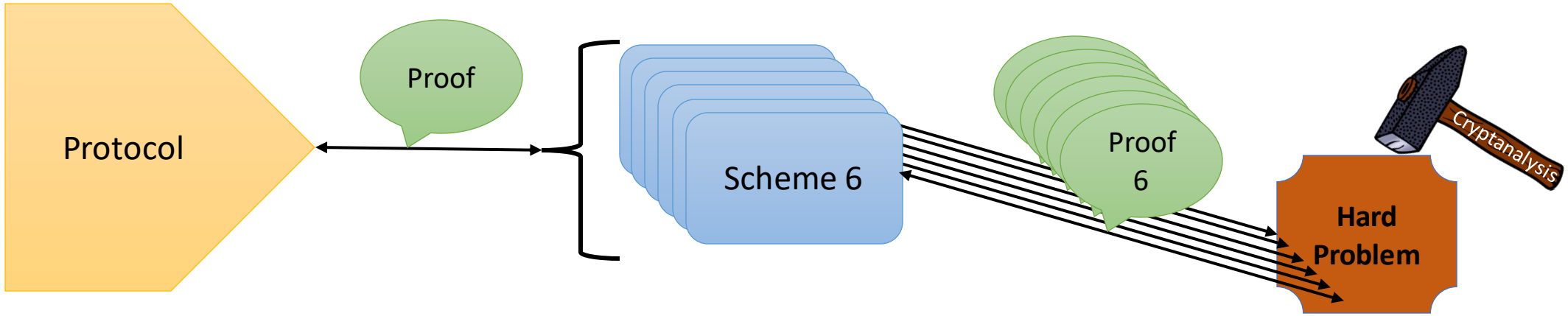


The Role of Security Proofs in Cryptography



Beautiful idea, but who checks the proofs?

- The reviewers?
  - Review load per reviewer at top tier IACR: 16+ papers, 30 pages main body, often 50+ pages with appendix
- The community?
  - eprint 2023:
    - **1703** papers, of which 512 tagged protocols, 264 tagged PKC (ignoring foundations, applications,…)
    - 2919 IACR members in 2023

Does that work?

Bugs in proofs / proof is wrong.

- XMSS & SPHINCS+:
  - Kudinov, Kiktenko, and Fedorov 2020: Bug in proof of tight security bound for SPHINCS+.
- Dilithium (and many other schemes):
  - Flaw in the HVZK proof step for Fiat-Shamir with aborts.
    [Barbosa, Barthe, Doczkal, Don, Fehr, Grégoire, Huang, Hülsing, Lee, and Wu. Fixing and Mechanizing the Security Proof of Fiat-Shamir with Aborts and Dilithium. CRYPTO 2023.]

All these are fixed now!

Does that work?

Bugs in instantiation / proof does not apply:

- XMSS & SPHINCS+:
  - Peickert 2018: Tight-security proof does not apply to instantiations.
  - Antonov 2022: SHA256 instantiation of SPHINCS+ does not achieve full conjectured security on required security properties.
- Kyber:
  - FO-transform used by Kyber is not the one with a security proof
  - Kyber round 1: Proof does not apply when using key compression

- **All these are fixed now!**

Proof failure modes

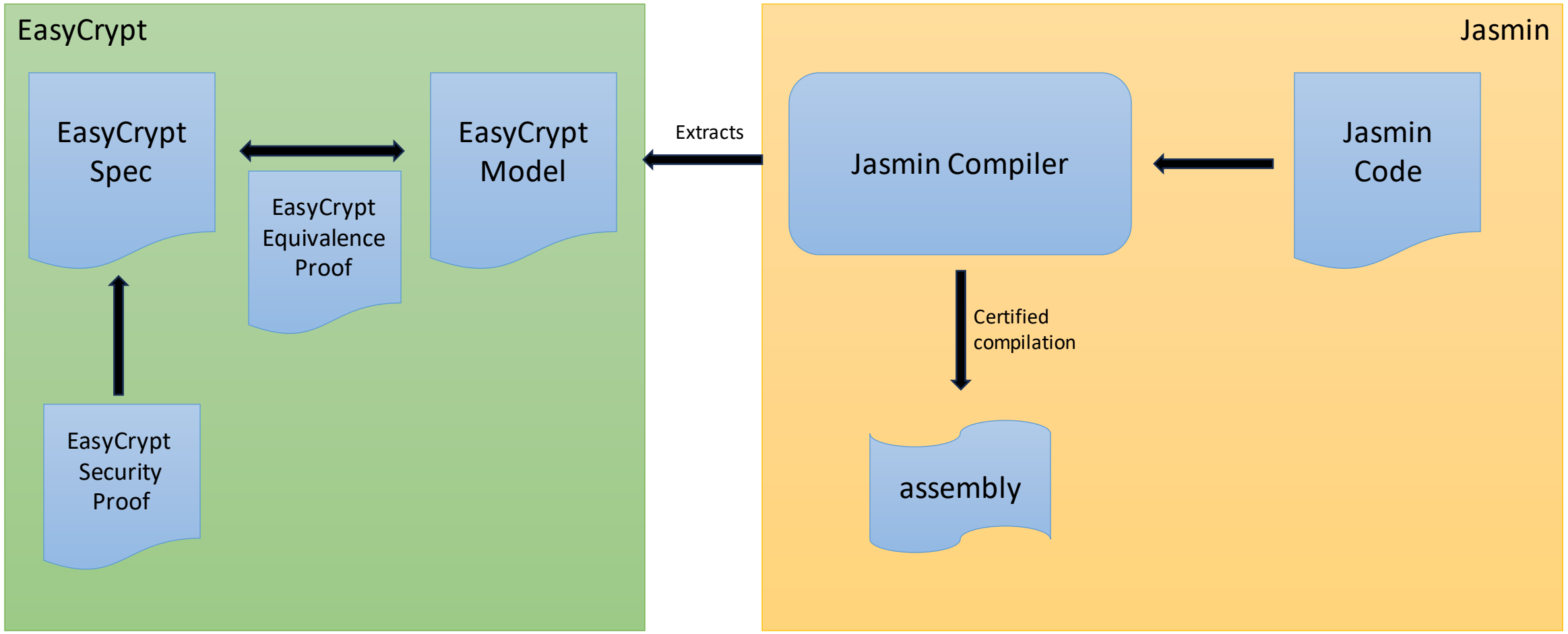
(Taken from Peter Schwabe)

- Proof is wrong
  - Theorem is correct
  - Theorem is also wrong
    - Scheme is still (possibly) secure
    - Scheme is efficiently broken
- Proof doesn’t apply to the scheme
  - Proof correct, but theorem “insufficient”
  - Example: attack hides in non-tightness
- Proof (and possibly theorem) too vague
- Theorem and proof correct, but not very useful
  - “A is secure if A is secure”

How to solve this?

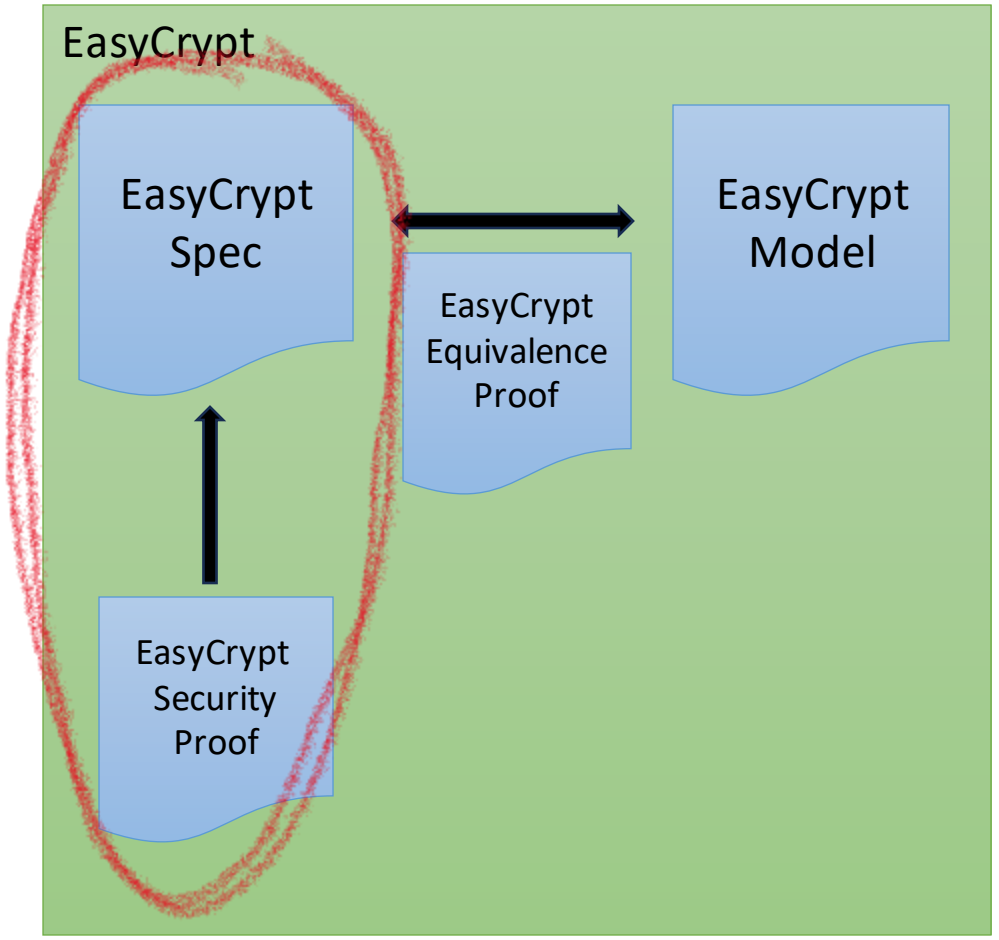
- Effort to formally verify crypto
- Goal: verified PQC ready for deployment
- Three main projects:
  - EasyCrypt proof assistant
  - Jasmin programming language
  - Libjade (PQ-)crypto library
- Core community of ≈ 30–40 people
- Discussion forum with >180 people

The toolchain



Results (Security proofs)

- Barbosa, Barthe, Fan, Grégoire, Hung, Katz, Strub, Wu, and Zhou. EasyPQC: Verifying Post-Quantum Cryptography. ACM CCS 2021
- Hülsing, Meijers, and Strub. Formal Verification of Saber's Public-Key Encryption Scheme in EasyCrypt. CRYPTO 2022
- Barbosa, Barthe, Doczkal, Don, Fehr, Grégoire, Huang, Hülsing, Lee, and Wu. Fixing and Mechanizing the Security Proof of Fiat-Shamir with Aborts and Dilithium. CRYPTO 2023
- Barbosa, Dupressoir, Grégoire, Hülsing, Meijers, and Strub. Machine-Checked Security for XMSS as in RFC 8391 and SPHINCS+. CRYPTO 2023



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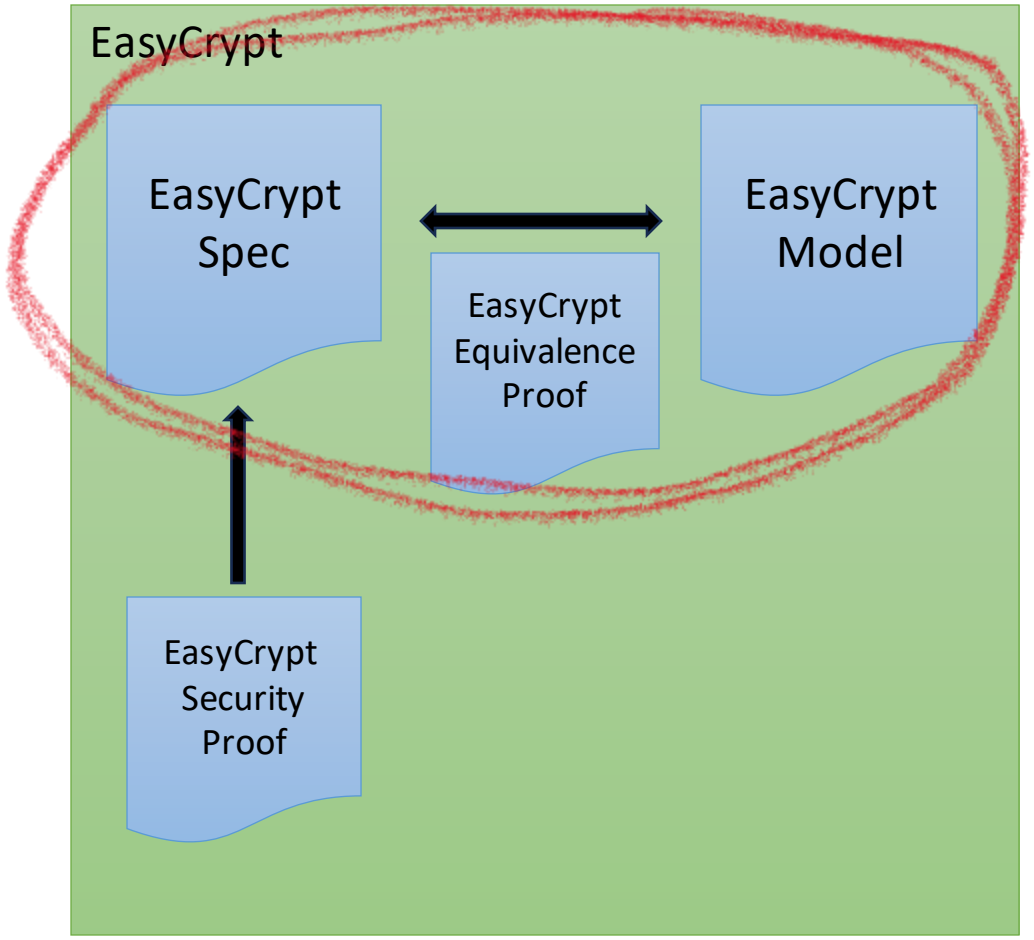
Results

- Almeida, Barbosa, Barthe, Grégoire, Laporte, Léchenet, Oliveira, Pacheco, Quaresma, Schwabe, Séré, Strub. Formally verifying Kyber Part I: Implementation Correctness.
  TCHES, 2023



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Manual effort!

What I did not talk about

- Implementation security (Jasmin part)
  - Side-Channel Attack Resistance
  - Speculative Execution Attack Mitigation
  - Memory Safety
  - …
  - See CHES 2023 invited talk by Peter Schwabe https://youtu.be/7uIabAwB92M?si=gdGWEwXlz9XGZUhm&t=944
- Other tools
  - Barbosa, Barthe, Bhargavan, Blanchet, Cremers, Liao, Parno. SoK: Computer-Aided Cryptography. S&P '21 https://eprint.iacr.org/2019/1393

Why does NIST not require machine-checked proofs for the signature round?

Results are great but

- Full workflow for Kyber took more than 3 years of many, many people! (Still not fully published!)
- Tools are "Expert Tools"
- New proofs often need help of tool developer
- Little automation
- Little integration with higher level tools (e.g., for protocols)

Summary

- We have the tools, we can achieve great results
- Verifying proofs is still research
- Usability still needs improvement
- There are many different tools for different use-cases

- We are working on a fully verified PQC library!
- Join the Formosa project (https://formosa-crypto.org/)