MAX PLANCK INSTITUTE
FOR SECURITY AND PRIVACY

Formally verifying Kyber

Episode V: Machine-checked IND-CCA Security and Correctness of ML-KEM in EasyCrypt

José Bacelar Almeida, Santiago Arranz Olmos, Manuel Barbosa, Gilles Barthe, François Dupressoir, Benjamin Grégoire, Vincent Laporte, Jean-Christophe Léchenet, Cameron Low, Tiago Oliveira, Hugo Pacheco, **Miguel Quaresma**, Peter Schwabe, Pierre-Yves Strub

August 21, 2024

Summary

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- Motivation for formally verifying cryptography

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- ML-KEM correctness and security properties:
    - Machine-checked proofs
    - Optimized & verified implementations

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  - Targeted round 3 Kyber, not ML-KEM

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Derive that our implementations are an IND-CCA secure KEM at the assembly level

Motivation: relevance

- Kyber 2017 [BDK+18]
    - Public key compression invalidated assumption in security proof
    - Tweaked FO transform [FO99, FO13] broke (security) proof in QROM

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- KyberSlash: timing side-channel found when using `DIV` instruction [BBB+24]

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- Security proofs
- Functional correctness proofs
- Link the two:
  - Ensure the functional specification matches the one in the security proof
  - Derive that our implementations are secure

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- Proof of IND-CPA security with concrete bounds that consider low-level details:
    - compression
    - SHA3-based noise generation
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Concrete security bound for ML-KEM that considers low-level details

Kyber to ML-KEM - Kyber 2017

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- Lattice-based PKE scheme based on Module-LWE [BDK+18]
- Several optimizations: parameter choice + **public-key and ciphertext compression**
- Correctness and security implications:
  - Correctness bound is hard to compute: only heuristic results
  - Public-key compression not contemplated in security proof
  - Tweaked FO transform: ciphertext hashing

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  - Public keys transmitted in the NTT domain
  - Full specification of the scheme

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- Tweaked FO transform still in use: ciphertext hashing

Algorithm 8 KYBER.CCAKEM.Enc(pk)

Input: Public key $pk \in \mathcal{B}^{12 \cdot k \cdot n/8+32}$
Output: Ciphertext $c \in \mathcal{B}^{d_u \cdot k \cdot n/8 + d_v \cdot n/8}$
Output: Shared key $K \in \mathcal{B}^*$

$m \leftarrow \mathcal{B}^{32}$
$m \leftarrow \mathrm{H}(m)$
$(\bar{K}, r) := \mathrm{G}(m \| \mathrm{H}(pk))$
$c :=$ KYBER.CPAPKE.Enc(pk, m, r)
$K :=$ KDF$(\bar{K} \| \mathrm{H}(c))$
return (c, K)

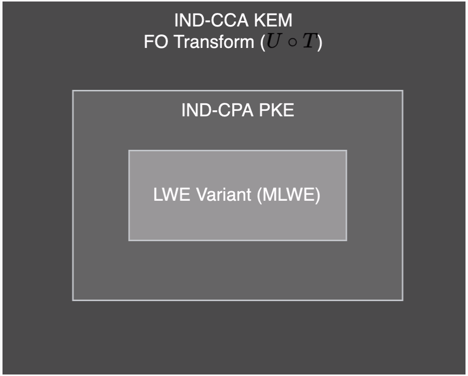
Algorithm 9 KYBER.CCAKEM.Dec(c, sk)

Input: Ciphertext $c \in \mathcal{B}^{d_u \cdot k \cdot n/8 + d_v \cdot n/8}$
Input: Secret key $sk \in \mathcal{B}^{24 \cdot k \cdot n/8+96}$
Output: Shared key $K \in \mathcal{B}^*$

$pk := sk + 12 \cdot k \cdot n/8$
$h := sk + 24 \cdot k \cdot n/8 + 32 \in \mathcal{B}^{32}$
$z := sk + 24 \cdot k \cdot n/8 + 64$
$m' :=$ KYBER.CPAPKE.Dec(sk, c)
$(\bar{K}', r') := \mathrm{G}(m' \| h)$
$c' :=$ KYBER.CPAPKE.Enc(pk, m', r')
if $c = c'$ **then**
    return $K :=$ KDF$(\bar{K}' \| \mathrm{H}(c))$
else
    return $K :=$ KDF$(z \| \mathrm{H}(c))$
end if
return K

Kyber to ML-KEM - ML-KEM “draft”

- Formerly CRYSTALS-Kyber
- Typical design of post-quantum KEMs
- IND-CPA PKE scheme from variant of LWE
- IND-CCA KEM using FO transform [FO99, FO13, HHK17]



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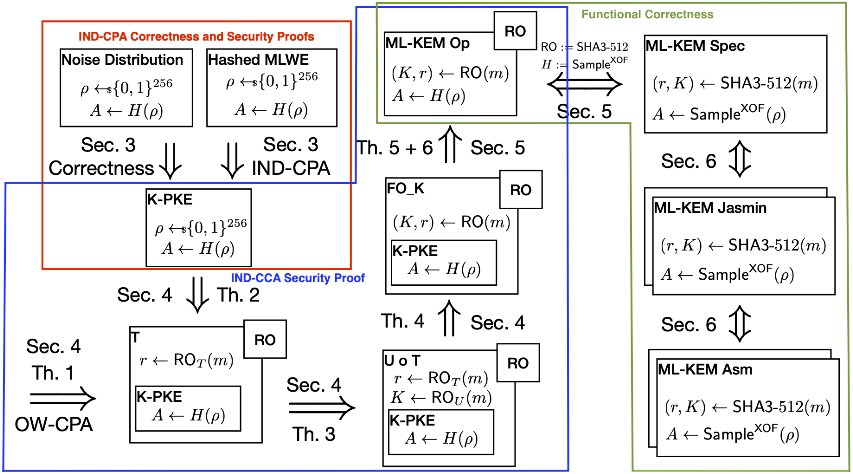

IND-CPA Correctness and Security Proofs
Noise Distribution
$\rho \leftarrow_{\$} \{0,1\}^{256}$
$A \leftarrow H(\rho)$
Hashed MLWE
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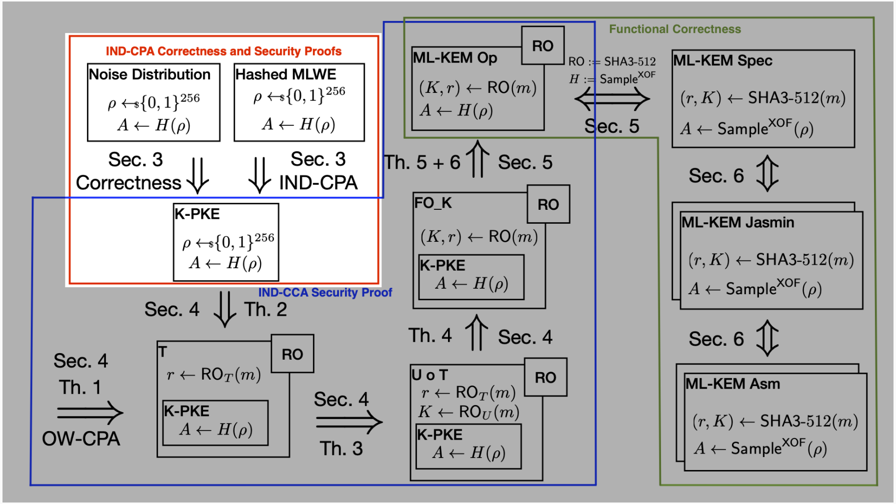
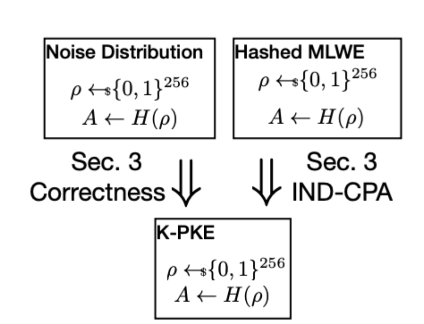
Overview: IND-CPA construction



Overview: IND-CPA construction

- IND-CPA security and correctness proof



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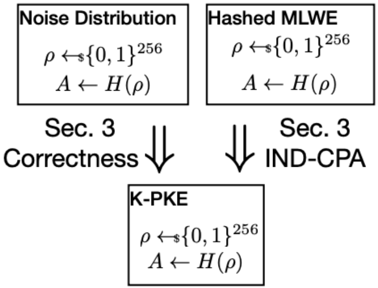
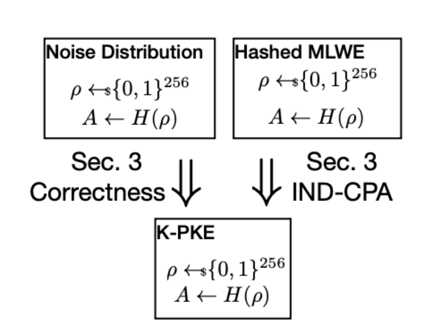


Overview: IND-CPA construction

- IND-CPA security and correctness proof
- K-PKE scheme underlies Kyber and ML-KEM
- Security proof under a variant of MLWE: Hashed MLWE
  - Replace sampling of matrix A with deterministic procedure H
- Correctness proof sets upper bound for a decryption failure



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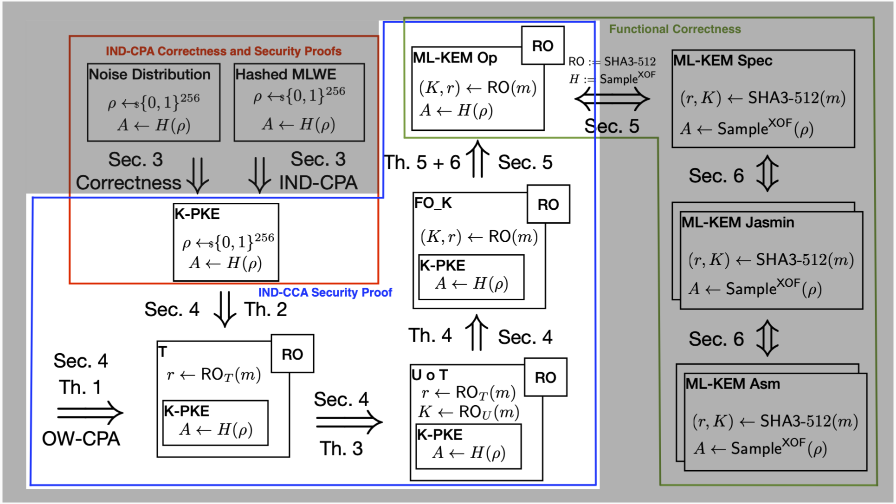

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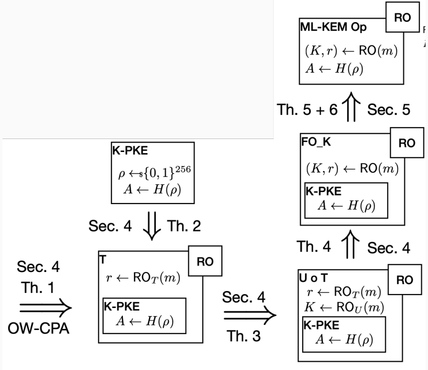

- Machine-checked security proofs for ML-KEM
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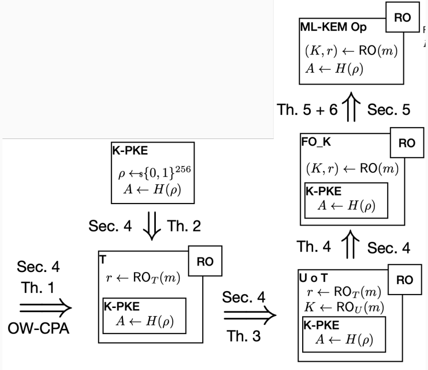

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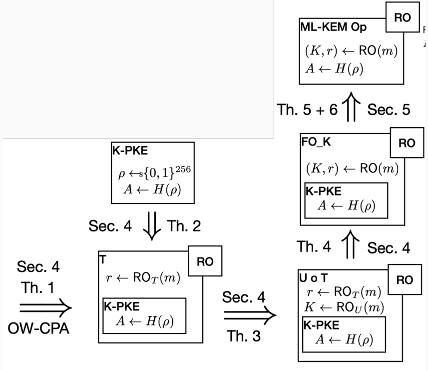
- IND-CCA security of FO_k derived from proof that shows security of the composition of T and U transforms



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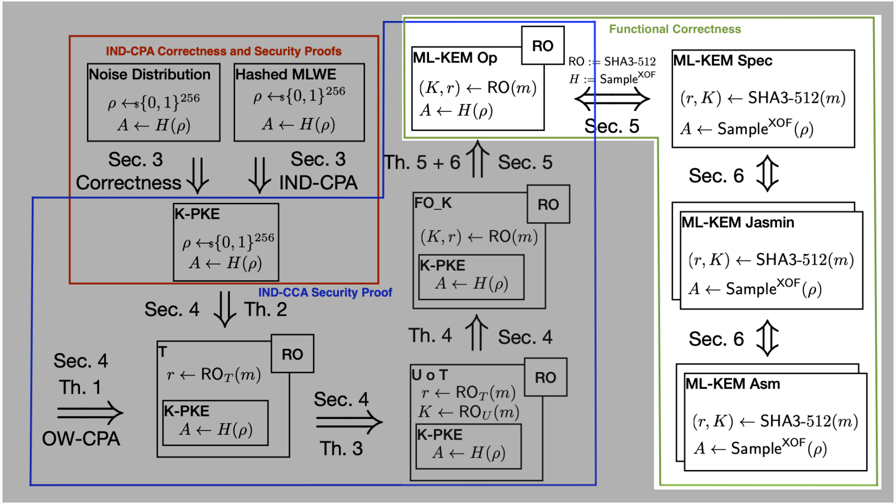

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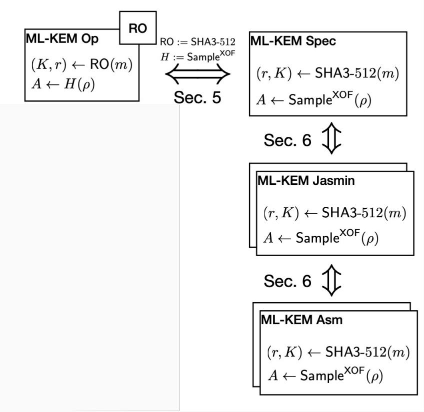

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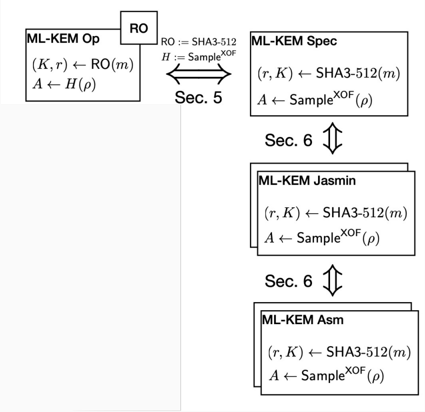

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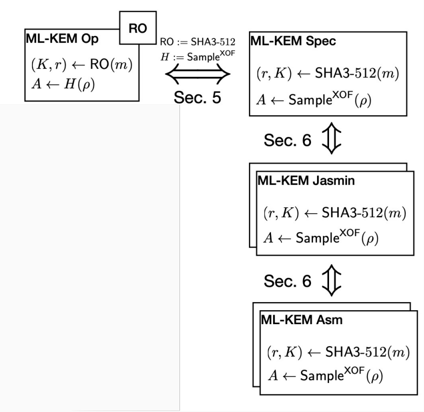
- Gap between security proof and assembly implementation:
  - Hash function (SHA3-512) is not a Random Oracle



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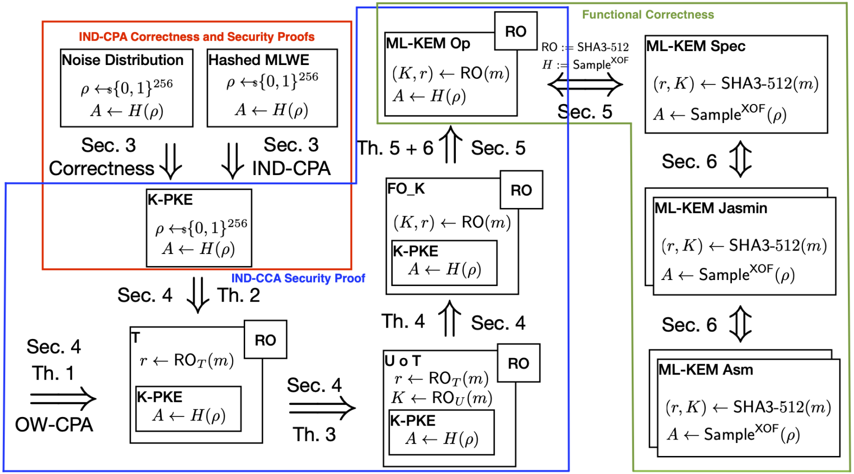

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  - Supports specifications, security proofs, implementations, functional correctness
- Drawbacks:
  - Proofs are not automatic and require significant effort
  - Theorems can be hard to read

Caveats/Limitations

- Large Trusted Code Base (TCB):
  - EasyCrypt (not formally verified)
  - EasyCrypt proof statements and specifications[1]
  - SMT solvers
- Classical security proof only: no security proof against quantum adversaries

[1] Machine-readable standards could provide a solution to the latter (future work)

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- Industry adoption of formally verified implementations

More online

https://formosa-crypto.org

- **High-assurance Kyber:**
  - Episode IV: https://eprint.iacr.org/2023/215
  - Episode V: https://eprint.iacr.org/2024/843
- **EasyCrypt specifications**: https://github.com/formosa-crypto/crypto-specs
- **Libjade:** https://github.com/formosa-crypto/libjade

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