Radboud University

Keyed Sponges

Applied Cryptography – Spring 2024

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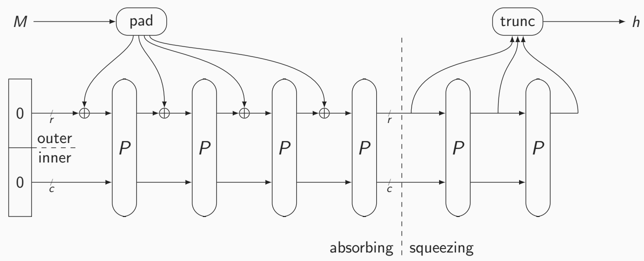
Last Lectures

- Permutations appear to be powerful primitives in cryptography
- Most importantly, sponge hash functions



- This lecture will be fully devoted to keyed versions of the sponge
  - Stream encryption
  - Authentication
  - . . .
- In addition, we will discuss Pseudorandom Number Generators (PRNGs)

Outline

Keying Sponges

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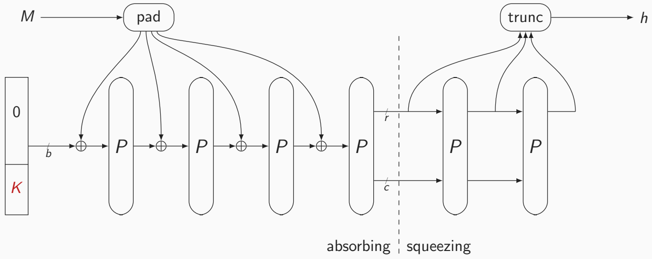
Keyed Sponge

- $\text{PRF}(K, M) = \text{Sponge}(K \parallel M)$
- Message authentication with tag size t: $\text{MAC}(K, M, t) = \text{Sponge}(K \parallel M, t)$
- Keystream generation of length ℓ: $\text{Stream}(K, D, \ell) = \text{Sponge}(K \parallel D, \ell)$
- (All assuming K is fixed-length)

Keyed Duplex

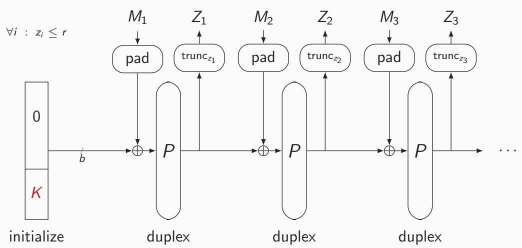
- Authenticated encryption
- Multiple CAESAR and NIST LWC submissions

Evolution of Keyed Sponges



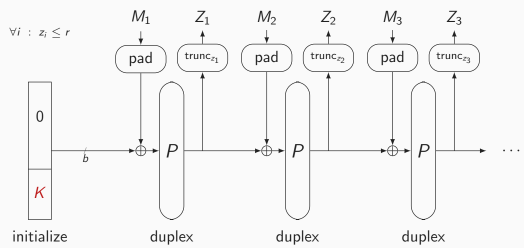
- Outer-Keyed Sponge [BDPV11,ADMV15,NY16,Men18]
- Inner-Keyed Sponge [CDHKN12,ADMV15,NY16]
- Full-Keyed Sponge [BDPV12,GPT15,MRV15]
- Generic security does not degrade: all can be used for PRF or MAC

Evolution of Keyed Duplexes



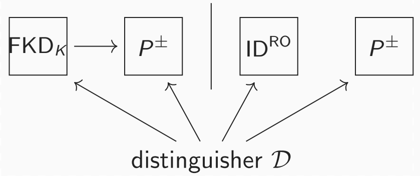
- Unkeyed Duplex [BDPV11]
- Outer-Keyed Duplex [BDPV11]
- Full-Keyed Duplex [MRV15,DMV17,DM19]
- Generic security does not degrade: both can be used for authenticated encryption

Security Model for Duplexes (1/2)



- For each duplex call, we can specify a path
  - In above picture, $\text{path}_1 = M_1$, $\text{path}_2 = M_1 \| M_2$, $\text{path}_3 = M_1 \| M_2 \| M_3$
- Ideally, output is random for each path: $Z_i \overset{?}{\sim} \mathcal{RO}(\text{path}_i, z_i)$
- Call such a function an ideal duplex (ID)

Security Model for Duplexes (2/2)

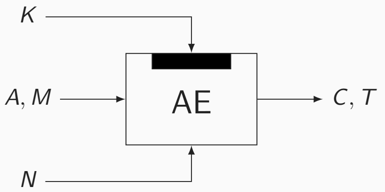


- Two oracles: FKD_K (for secret key K) and $\mathrm{ID}^{\mathrm{RO}}$ (for secret RO)
  - Both with initialize and duplex interface
- Distinguisher $\mathcal{D}$ has query access to one of these, plus the random permutation P
- $\mathcal{D}$ tries to determine which oracle it communicates with
- Its advantage is defined as:

$$\mathbf{Adv}^{\mathrm{duplex}}_{\mathrm{FKD}}(\mathcal{D}) = \Delta_{\mathcal{D}}\left(\mathrm{FKD}_K, P^{\pm}\ ;\ \mathrm{ID}^{\mathrm{RO}}, P^{\pm}\right) = \left|\mathbf{Pr}\left(\mathcal{D}^{\mathrm{FKD}_K, P^{\pm}} = 1\right) - \mathbf{Pr}\left(\mathcal{D}^{\mathrm{ID}^{\mathrm{RO}}, P^{\pm}} = 1\right)\right|$$

Authenticated Encryption Using the Duplex

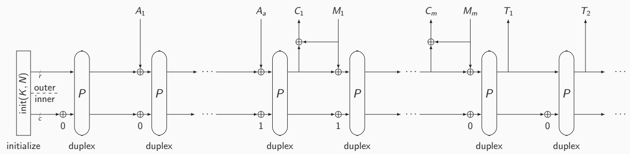
Recap: Authenticated Encryption



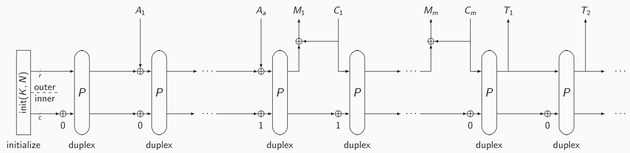
- Using key K:
  - Message M is encrypted in ciphertext C
  - Associated data A and message M are authenticated using T
- Nonce N randomizes the scheme
- Key, nonce, and tag are typically of fixed size
- Associated data, message, and ciphertext could be arbitrary length

SpongeWrap [BDPV11]

Authenticated Encryption

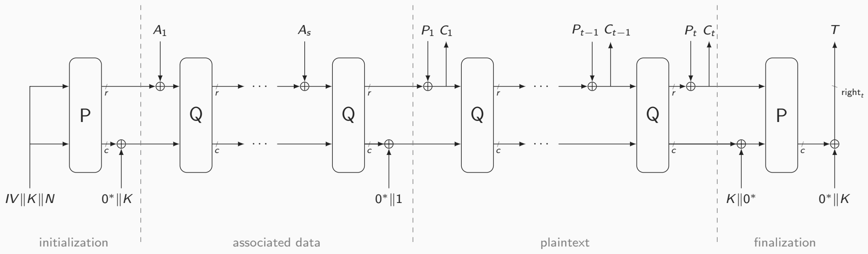


Authenticated Decryption



- Now: slight variant of original design
- SpongeWrap embeds generalization of duplex
- Note the domain separation (why?)
- Decryption similar
- Variations:
  - Absorb A full-state or alongside M?
  - Intermediate tags?
  - Misuse resistance?
- Popular approach (a.o. 3 NIST LWC finalists)

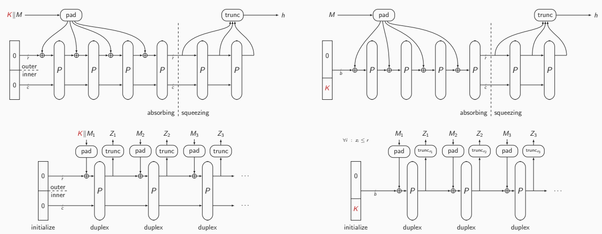
Ascon Authenticated Encryption



- Winner of the NIST Lightweight Cryptography competition in 2023
- Inspired by SpongeWrap but with some changes:
  - Key blinding: extra robustness against state recovery
  - Different permutations: outer ones are stronger than inner ones

Provable Security of Full-Keyed Sponge Construction

Simplified Security Bound



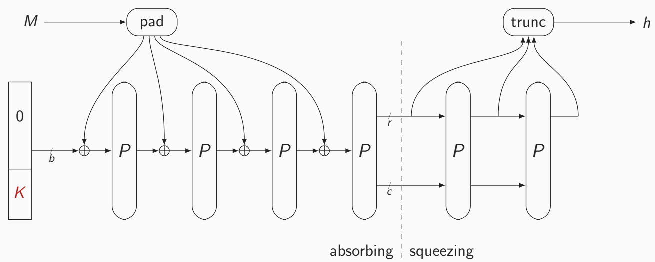
- $F \in \{\text{OKS}, \text{FKS}, \text{OKD}, \text{FKD}\}$
- M: data (construction) complexity
- N: time (primitive) complexity

Drastically Simplified Security Bound

$$\frac{M^2}{2^c} + \frac{MN}{2^c} + \frac{N}{2^k}$$

Now: rough idea how security of FKS is argued

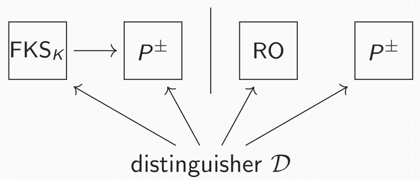
Full-Keyed Sponge Construction



Setting

- Assume random b-bit permutation P
- Key size k; rate r and capacity c with $b = r + c$
- FKS should behave like a random oracle

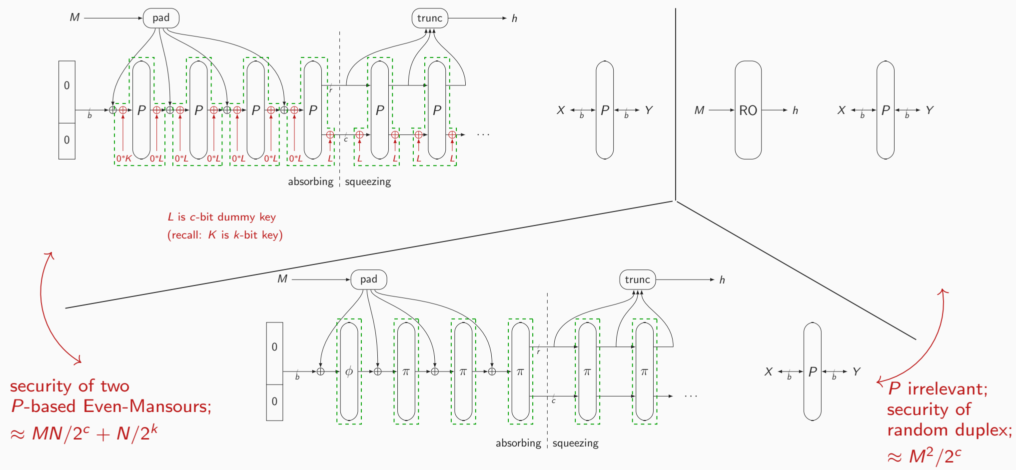
PRF Security



- Two oracles: FKS_K (for secret key K) and RO (secret)
- Distinguisher $\mathcal{D}$ has query access to one of these, plus the random permutation P
- $\mathcal{D}$ tries to determine which oracle it communicates with
- Its advantage is defined as:

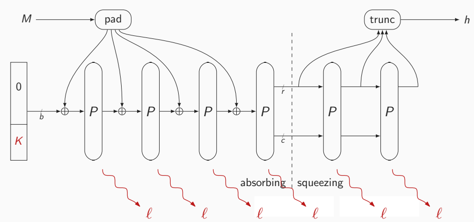
$$\mathbf{Adv}^{\mathrm{prf}}_{\mathsf{FKS}}(\mathcal{D}) = \Delta_{\mathcal{D}}\left(\mathsf{FKS}_K, P^\pm \,;\, \mathsf{RO}, P^\pm\right) = \left|\mathbf{Pr}\left(\mathcal{D}^{\mathsf{FKS}_K,P^\pm} = 1\right) - \mathbf{Pr}\left(\mathcal{D}^{\mathsf{RO},P^\pm} = 1\right)\right|$$

Hybrid Argument



Suffix Keyed Sponge

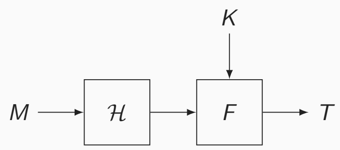
Leakage Resilience of Keyed Sponges



- Permutation P repeatedly evaluated on secret state
- Any evaluation of P may leak information

Minimizing leakage of keyed sponge?

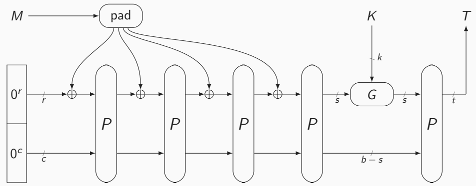
Hash-then-MAC



Typical Approach

- Hash function is unkeyed → nothing to be protected
- Keyed function F applied to fixed-size input
- Hash output (hence F input) must be at least $2k$ bits for k-bit security

Suffix Keyed Sponge



SuKS versus Full-Keyed Sponge

- No full-state absorption
- Side-channel leakage limited
- s, t arbitrary (typical: $s = t = c/2$)

SuKS versus Hash-then-MAC

- State of keyed function half as large
- G need not be cryptographically strong (a XOR suffices)
- Single cryptographic primitive needed

Conclusion

Overall Conclusion

Main Take-Away

- Unconditional security impossible!
- Security proofs are for modes and assume a strong building block
- Cryptanalysis, which is about investigating the actual strength of such building blocks, completes the picture
- Both provable security and cryptanalysis are active research areas

Concluding Remarks

- This last lecture concludes the symmetric cryptography part
- If you have any question on the lectures, or symmetric cryptography in general, you are always free to contact me