Maastricht University

The Theory of Permutation-Based Modes

Bart Mennink

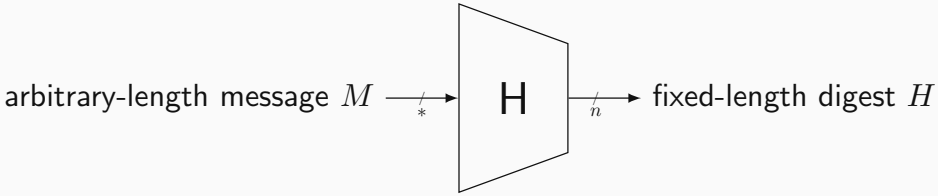
ProTeCS 2026 – Rome

May 9, 2026

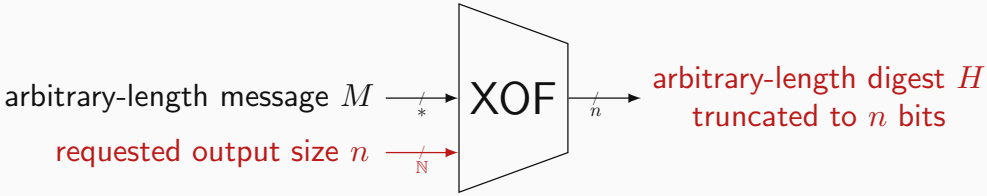
Outline

Introduction

Cryptographic Hash Function



eXtendable Output Function



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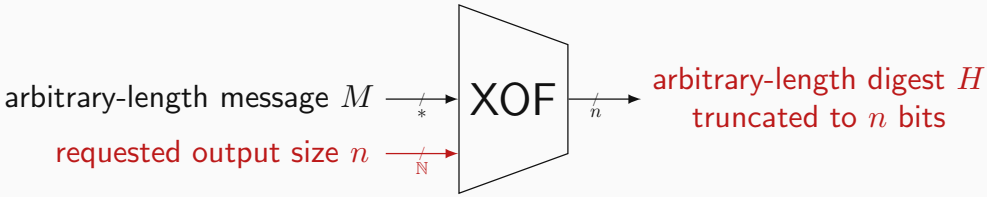

- Ideally behaves like a random oracle RO [BR93]

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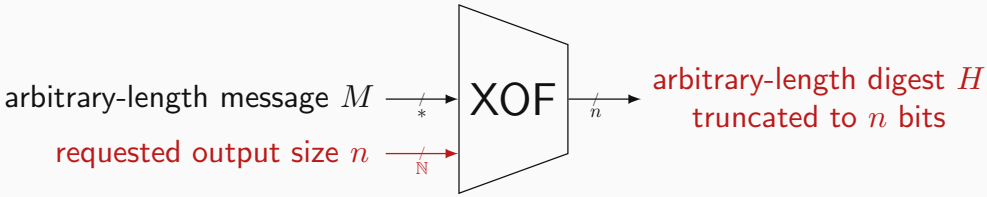

- Ideally behaves like a random oracle RO [BR93]
  - Different messages $\longrightarrow$ independent random-looking digests
  - Same message but different output sizes $\longrightarrow$ prefixed digests

Sponges [BDPV07]

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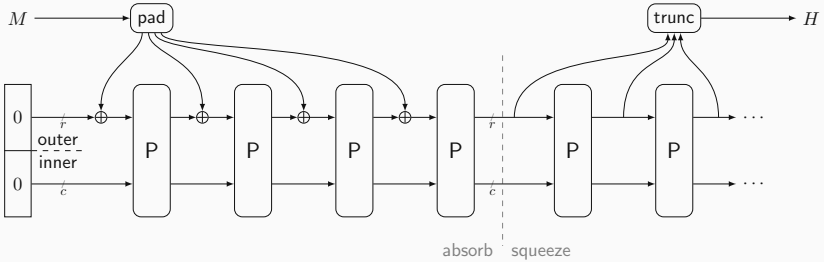

- P is a b-bit permutation, with $b = r + c$
  - r is the rate
  - c is the capacity (security parameter)

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- Assume that P is a random permutation
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Collision resistance:	$\mathcal{N}^2/2^c + \mathcal{N}^2/2^{n+1}$
Second preimage resistance:	$\mathcal{N}^2/2^c + \mathcal{N}/2^n$
Preimage resistance:	$\mathcal{N}^2/2^c + \mathcal{N}/2^n$

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- Generic security of Sponge truncated to n bits:
  - Collision resistance: $\min\{c/2, n/2\}$
  - First and second preimage resistance: $\min\{c/2, n\}$

Implications for Use Cases

Sponge Behaves Like a Random Oracle

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

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- ... indifferentiability bound is generic:
  - it does not distinguish between different types of complexities
  - dedicated analysis is often tighter
- ... adjustments to the mode sometimes lead to efficiency/security improvements

What Happened Next?

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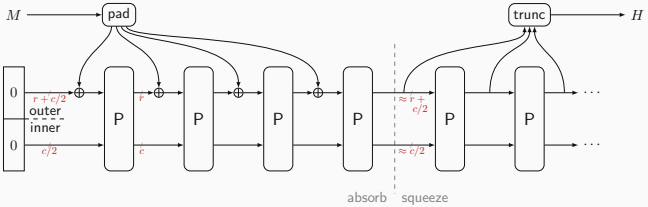

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FIPS PUB 202

FEDERAL INFORMATION PROCESSING STANDARDS PUBLICATION

SHA-3 Standard: Permutation-Based Hash and Extendable-Output Functions

CATEGORY: COMPUTER SECURITY SUBCATEGORY: CRYPTOGRAPHY

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

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August 2015

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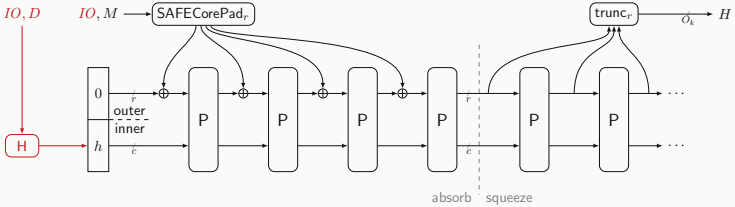

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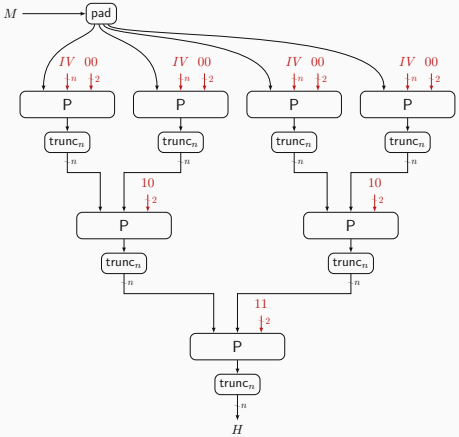

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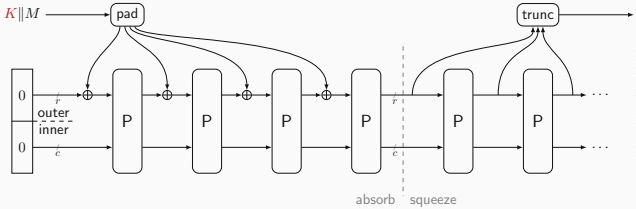

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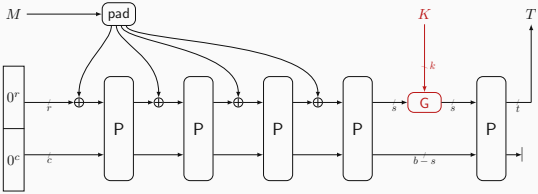

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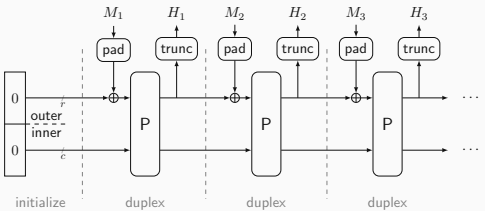

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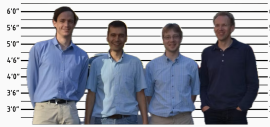

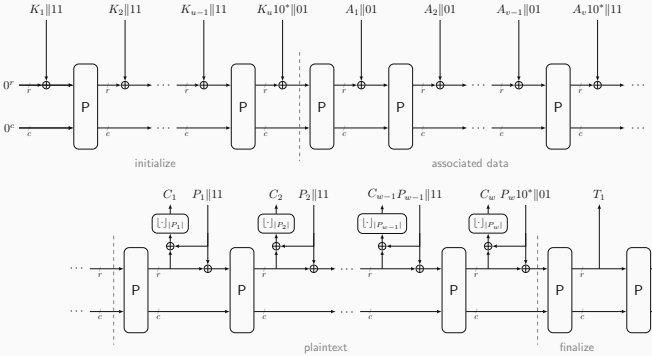

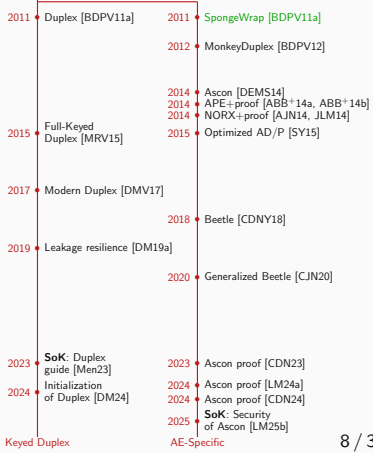

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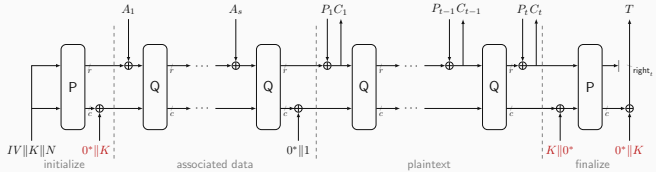

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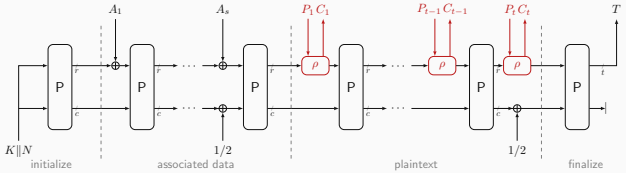

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2024 Double Sponge [LM24b]

2024 Leakage resilience of SuKS [BM24]

2025 Sponge-DM/ Sponge-EDM [SLZ+25]

Suffix-Specific

2011 Outer-Keyed Sponge [BDPV11b]

2012 Inner-Keyed Sponge [CDH+12]

2015 OKS/IKS analysis [ADMV15]

2015 Full-Keyed Sponge [MRV15]

2016 impr. OKS/IKS analysis [NY16]

2017 *Farfalle [BDH+17]*

2018 Key prediction [Men18]

2022 Asakey [DMP22]

2024 AsconPRF [DEMS24]

2025 MacaKey [LM25a]

Keyed Sponge

2011 Duplex [BDPV11a]

Full-Keyed Duplex

2015 Full-Keyed Duplex [MRV15]

2017 Modern Duplex [DMV17]

2019 Leakage resilience [DM19a]

2023 **SoK**: Duplex guide [Men23]

2024 Initialization of Duplex [DM24]

Keyed Duplex

2011 SpongeWrap [BDPV11a]

2012 MonkeyDuplex [BDPV12]

2014 Ascon [DEMS14]

2014 APE+proof [ABB+14a, ABB+14b]

2014 NORX+proof [AJN14, JLM14]

2015 Optimized AD/P [SY15]

2018 Beetle [CDNY18]

2020 Generalized Beetle [CJN20]

2023 Ascon proof [CDN23]

2024 Ascon proof [LM24a]

2024 Ascon proof [CDN24]

2025 **SoK**: Security of Ascon [LM25b]

AE-Specific

Hunt For Preimage Resistance

Generic Security of the Sponge (Cont.)

- Assume that P is a random permutation
- Sponge behaves like a random oracle RO up to bound $\mathcal{N}^2/2^c$ [BDPV08]

- Security of Sponge truncated to n bits against classical attacks [AMP10]:

Collision resistance:	$\mathcal{N}^2/2^c + \mathcal{N}^2/2^{n+1}$
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- Attacks already described in [BDPV07]
- Tightened preimage resistance bound by Lefevre and Mennink [LM22]:

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Application to Ascon-Hash and Ascon-(C)XOF Parameters [SMK+25]

- $(b, c, r, n) = \begin{cases} (320, 256, 64, 256) \text{ for Ascon-Hash} \\ (320, 256, 64, \infty) \text{ for Ascon-XOF} \\ (320, 256, 64, \infty) \text{ for Ascon-CXOF} \end{cases}$

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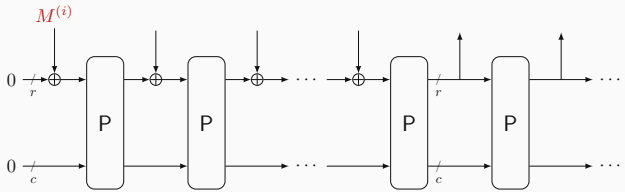
Can We Beat First and Second Preimage Bounds?

Intermezzo: Collision Attack [BDPV07]



- Absorb $2^{c/2}$ different messages $M^{(i)}$

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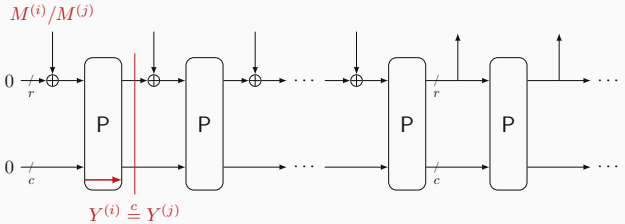

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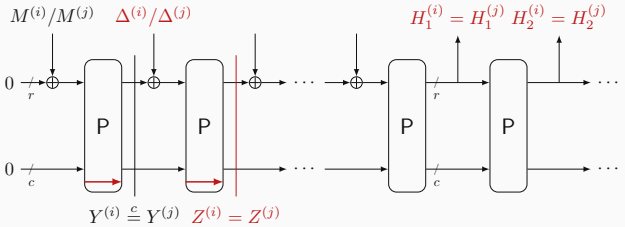
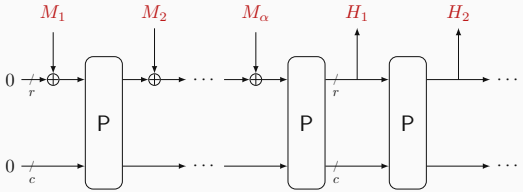


- Absorb $2^{c/2}$ different messages $M^{(i)}$
- With high probability, there exist $Y^{(i)} \neq Y^{(j)}$ that collide on their inner part
- Compensate the difference in next absorb call
- Triggers a full state collision and hence digest collision

Intermezzo: Second Preimage Attack [BDPV07]



- Let $M_1 \| M_2 \| \cdots \| M_\alpha$ be the first preimage

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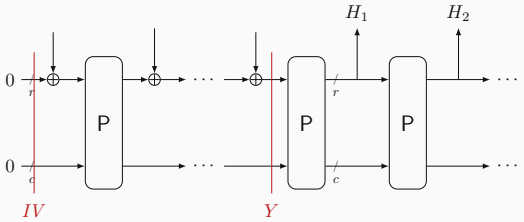

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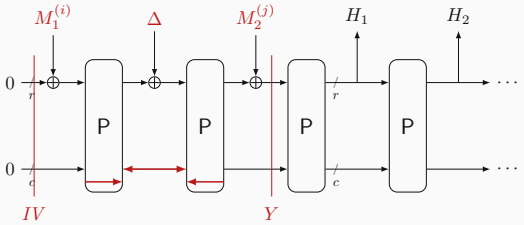

- Let $M_1 \| M_2 \| \cdots \| M_\alpha$ be the first preimage
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- Attack in $\approx 2^{c/2}$ queries

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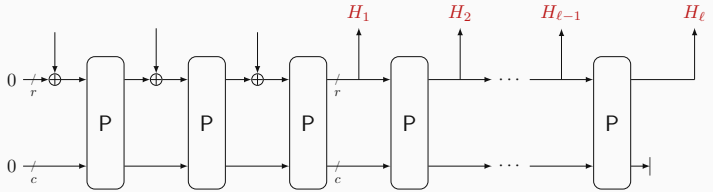

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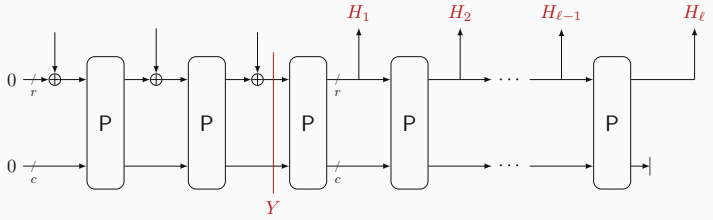

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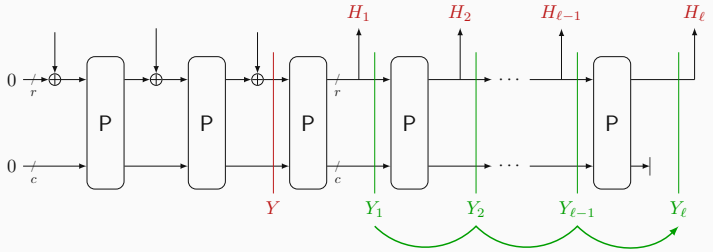

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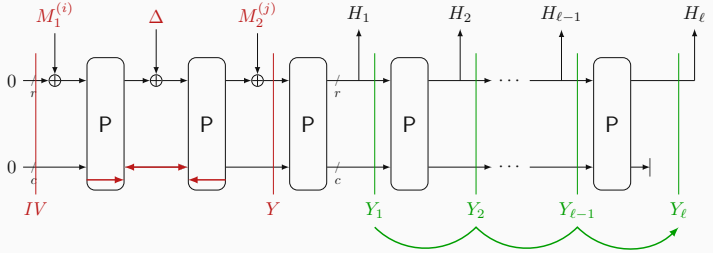

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Crux Observation

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Sponge With Transformation

- Analyzed by our Foekens in 2023 [Foe23]
  - Preimage resistance up to $\approx 2^n$ queries
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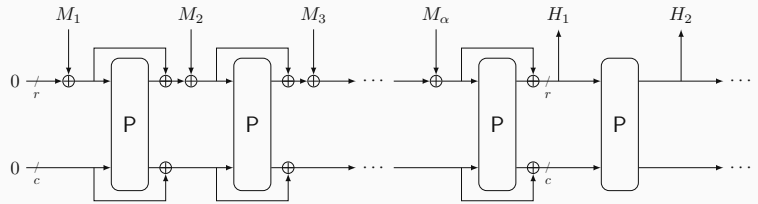

- Sponge-DM adds a feed-forward during absorption*

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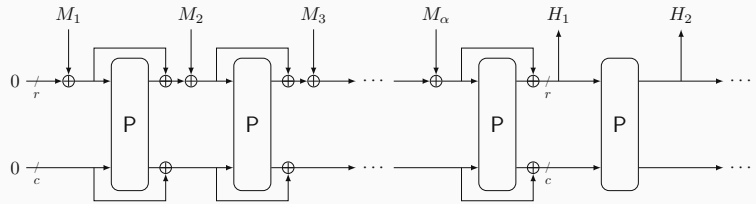

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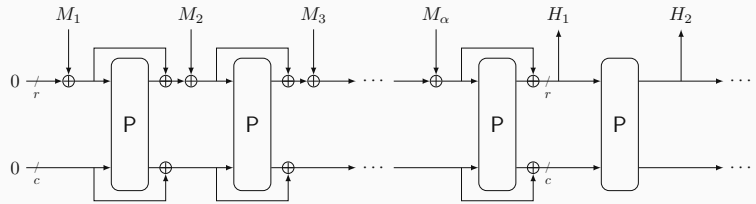

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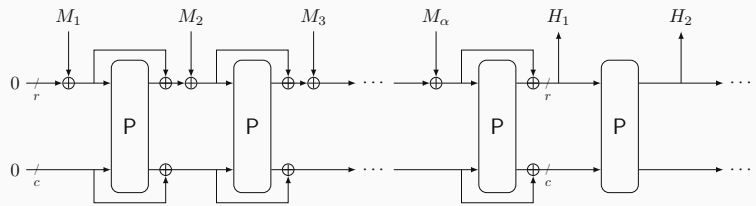

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Can We Reduce Feed-Forward Size?

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Sponge-EDM^a for $a \in \{0, \ldots, b\}$ [SLZ$^+$25]

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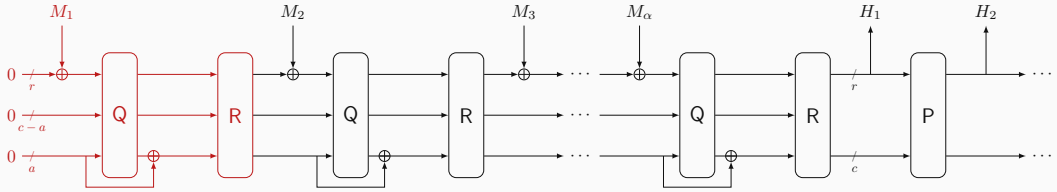

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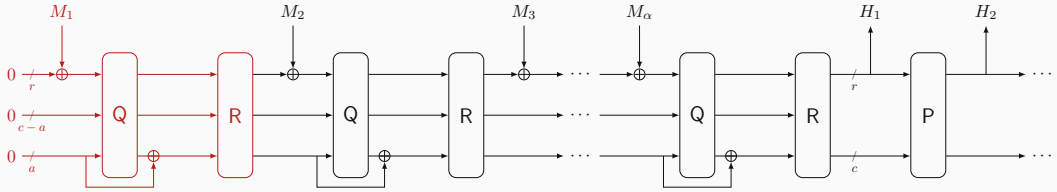
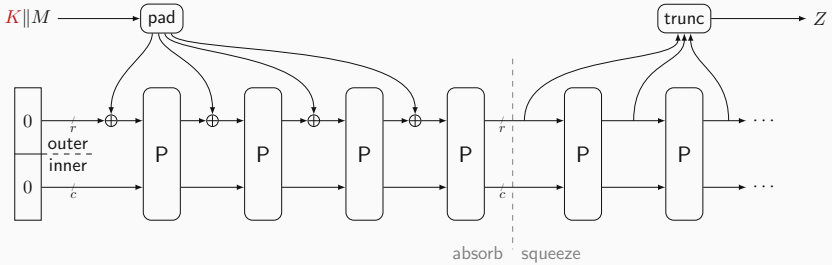


- Security ranges from that of Sponge-DM (for $a = b$) to Sponge (for $a = 0$)

From Outer- to Full-Keyed Sponge

Evolution of Keyed Sponges



- Outer-Keyed Sponge [BDPV11b, ADMV15, NY16, Men18]

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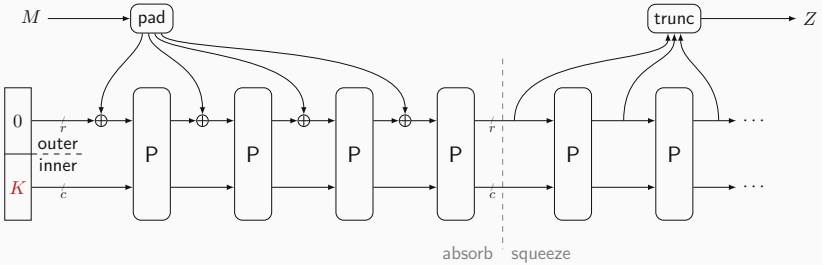

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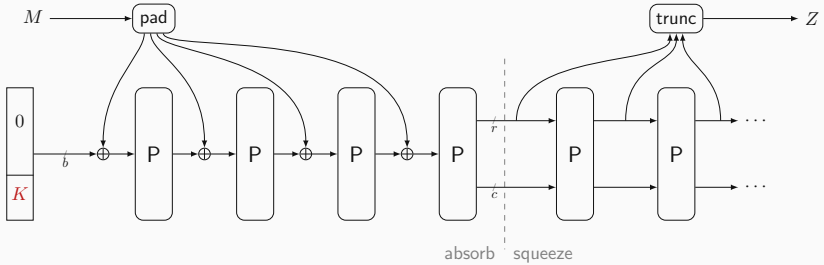

- Outer-Keyed Sponge [BDPV11b, ADMV15, NY16, Men18]
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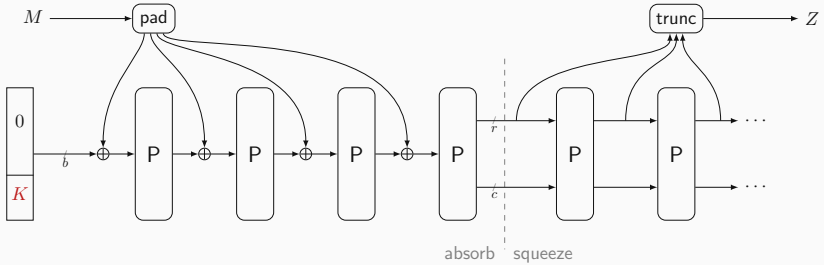

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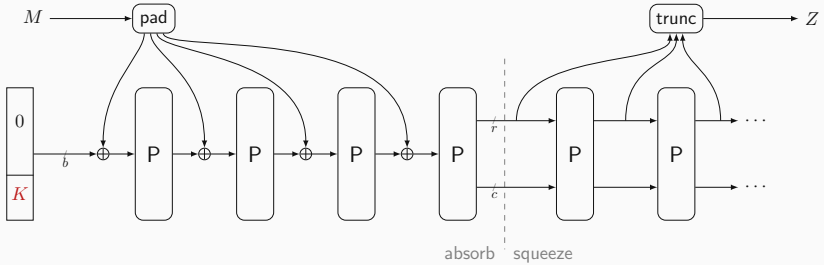
- Inner-Keyed Sponge [CDH+12, ADMV15, NY16]
- Full-Keyed Sponge [BDPV12, GPT15, MRV15]
- Generic security does not degrade: all can be used for PRF or MAC

Security of Full-Keyed Sponge (1/3)



Setting

- Assume random b-bit permutation P
- Rate r and capacity c with $b = r + c$; key size $k \leq c$

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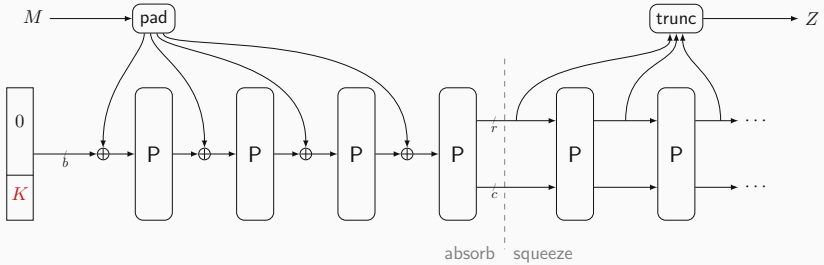

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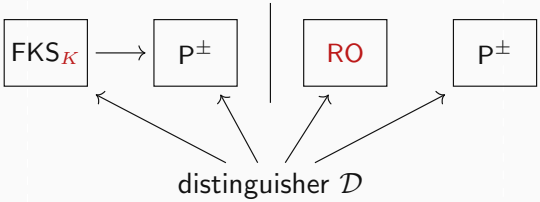
- FKS_K should behave like a random oracle RO

Security of Full-Keyed Sponge (2/3)



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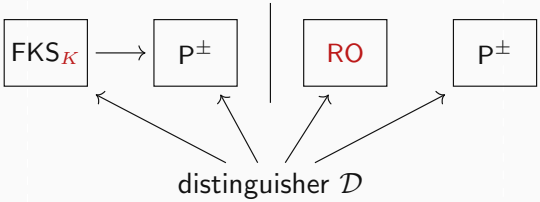

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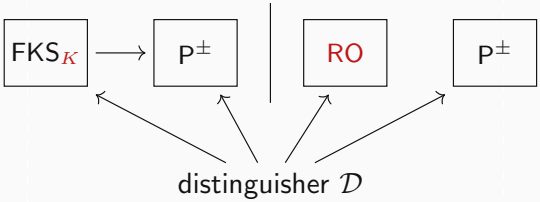

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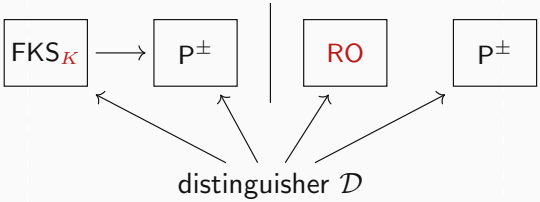
Security of Full-Keyed Sponge (2/3)



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

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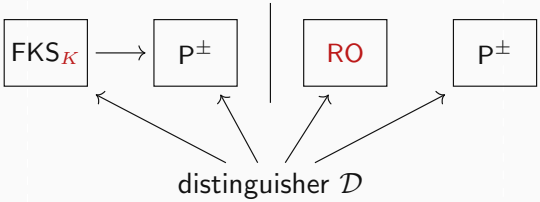

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scheme behaves randomly as long as this distance is $\ll 1$

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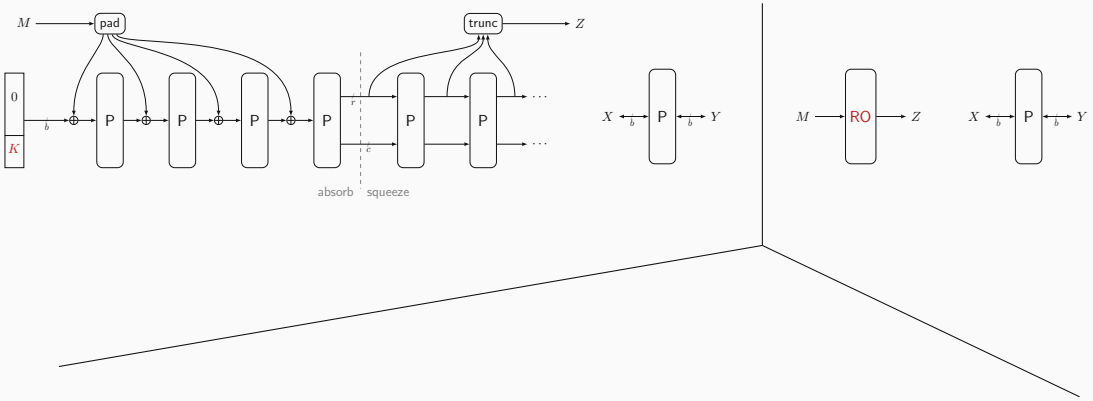

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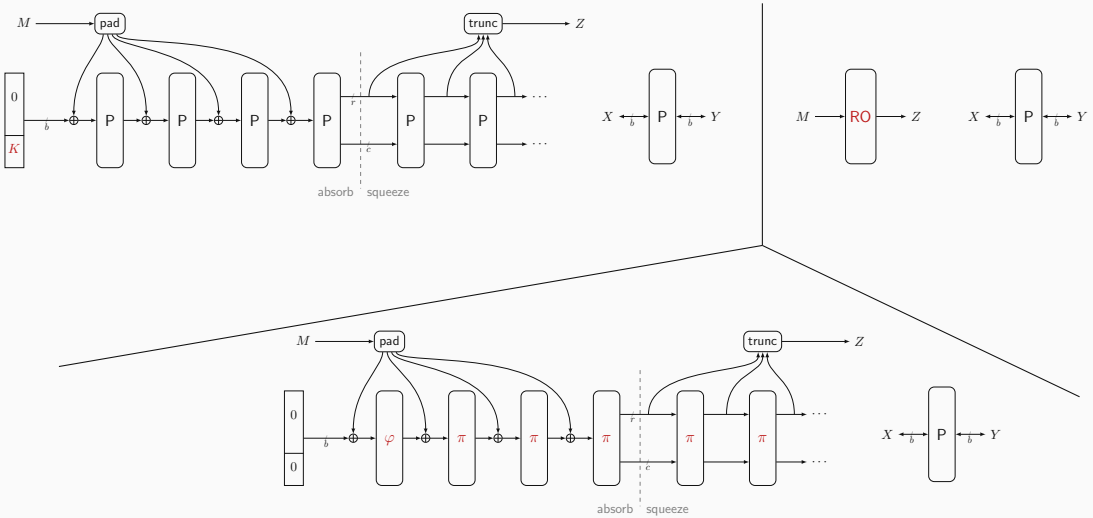

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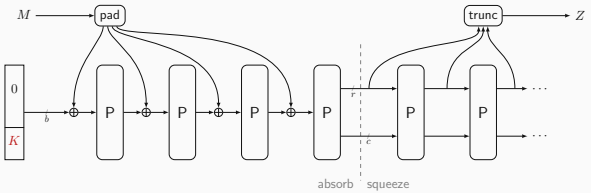

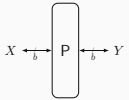

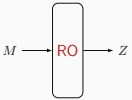

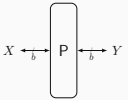

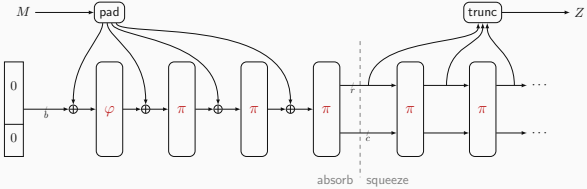

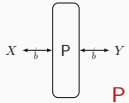

P irrelevant; security of random Sponge; $\approx \mathcal{M}^2/2^c$

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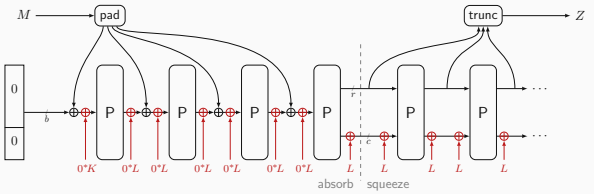

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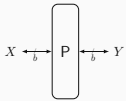

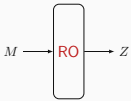

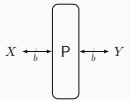

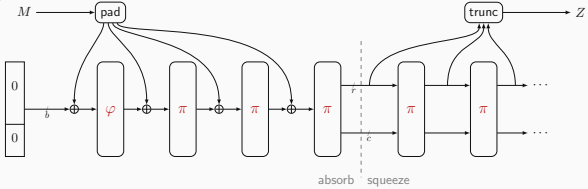

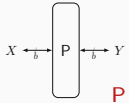

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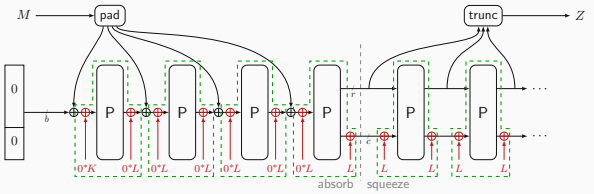

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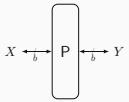

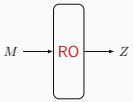

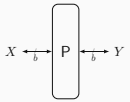

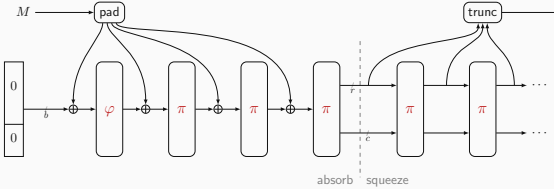

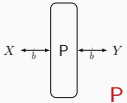

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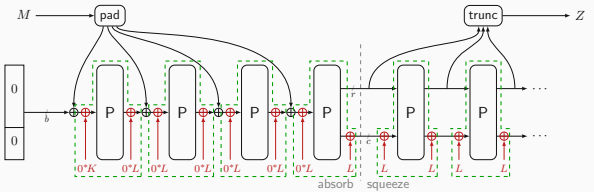

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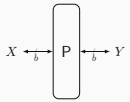
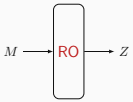
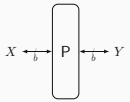
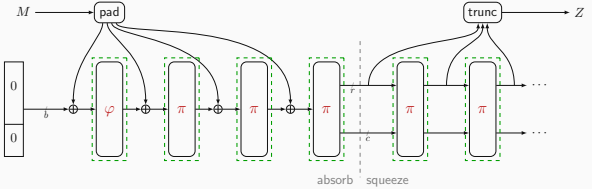
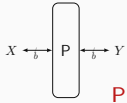






security of two
P-based Even-Mansours;
$\approx \mathcal{MN}/2^c + \mathcal{N}/2^k$





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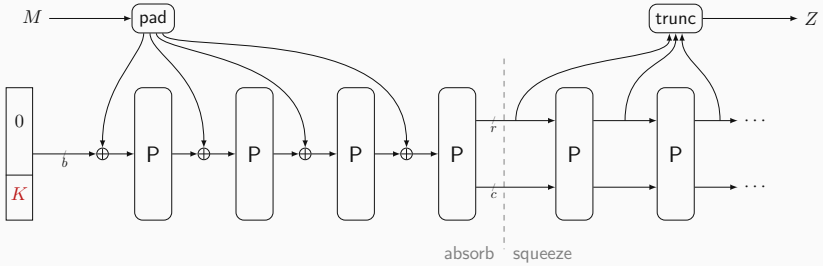
We Optimized Absorbing, Can We Optimize Squeezing?



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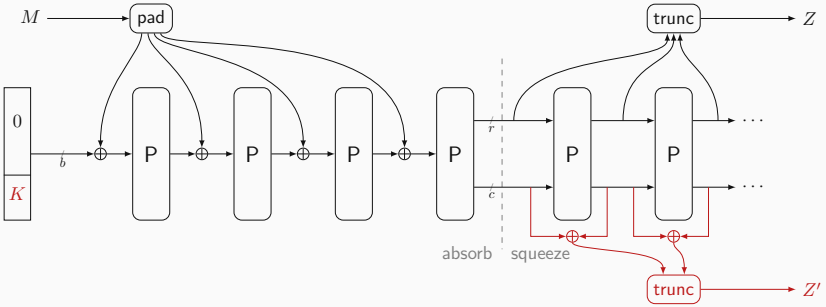
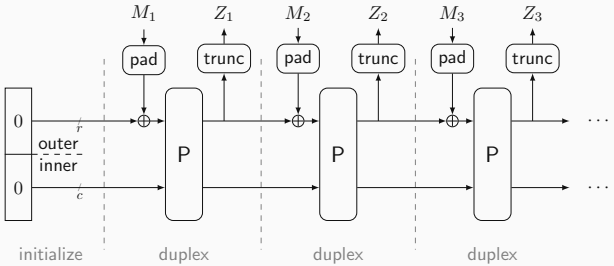


MacaKey-Style Squeezing [LM25a]

- Elegant combination of Sponge with summation-truncation hybrid [GM20]
  - Follow-up work by Bhaumik et al. [BCD26]
- Generic security does not degrade by b-bit squeezing

From Original to Full-Keyed Duplex

Evolution of Keyed Duplexes



- Unkeyed Duplex [BDPV11a]

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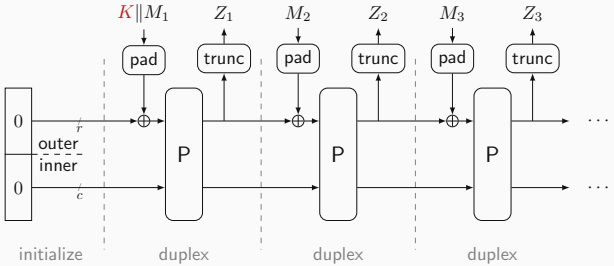

- Unkeyed Duplex [BDPV11a]
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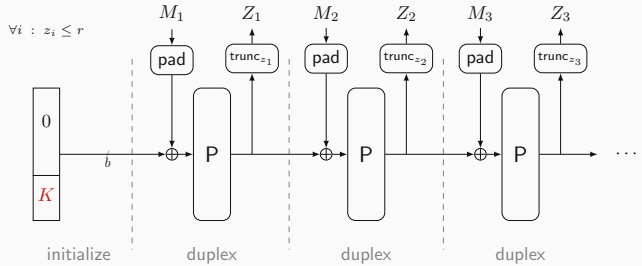

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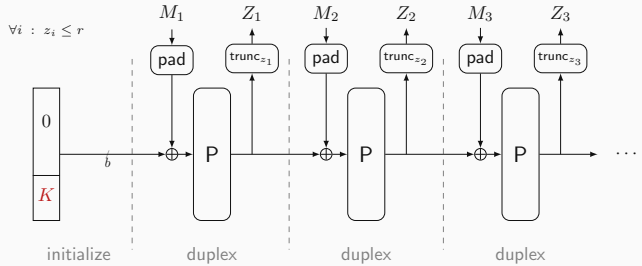

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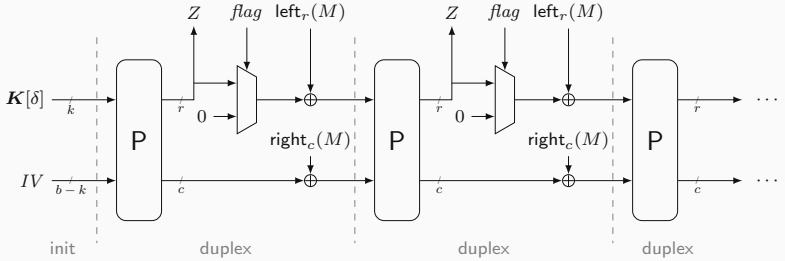
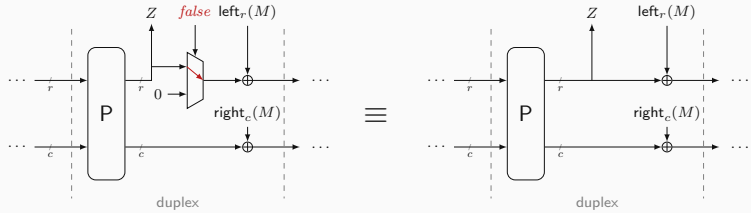
Generalized Keyed Duplex [DMV17, DM19a, Men23]



Generalized Keyed Duplex: Flag (1/2)



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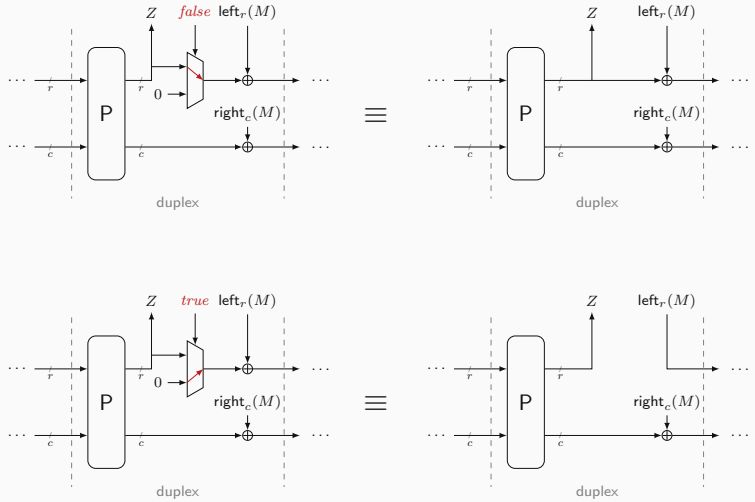

Generalized Keyed Duplex: Flag (2/2)

Extremely Simplified SpongeWrap

- Key K, plaintext P, ciphertext C, and tag T all r bits; nonce N c bits

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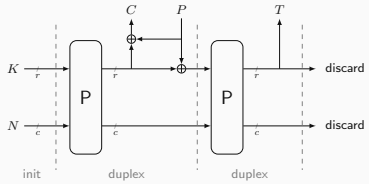

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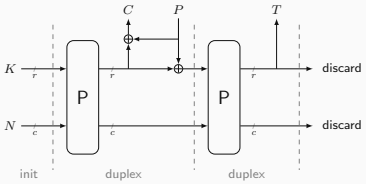
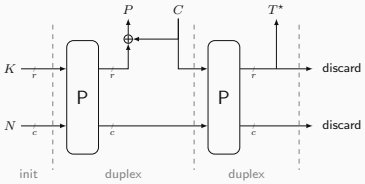


Decryption



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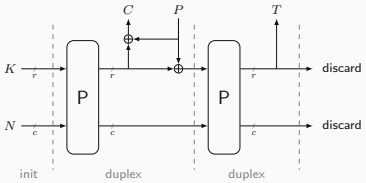

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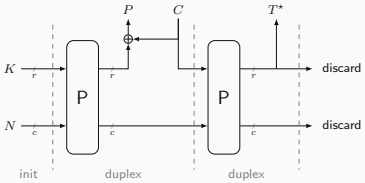

- Duplex call with $\mathit{flag} = \mathit{true}$ upon decryption
- Adversary can choose C and thus fix outer part to value of its choice

Generalized Keyed Duplex: Security Model

Algorithm Keyed Duplex construction $\mathsf{KD}[\mathsf{P}]_{\boldsymbol{K}}$

Interface: KD.init
Input: $(\delta, IV) \in \{1, \ldots, \mu\} \times \mathcal{IV}$
Output: $\varnothing$
  $S \leftarrow \boldsymbol{K}[\delta] \parallel IV$
  return $\varnothing$

Interface: KD.duplex
Input: $(\mathit{flag}, M) \in \{\mathit{true}, \mathit{false}\} \times \{0,1\}^b$
Output: $Z \in \{0,1\}^r$
  $S \leftarrow \mathsf{P}(S)$
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  $S \leftarrow S \oplus [\mathit{flag}] \cdot (Z \| 0^{b-r}) \oplus M$
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Algorithm Ideal extendable input function IXIF[RO]

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Input: $(\delta, IV) \in \{1, \ldots, \mu\} \times \mathcal{IV}$
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$$\mathbf{Adv}_{\mathsf{KD}}(\mathcal{D}) = \left| \mathbf{Pr}\left(\mathcal{D}^{\mathsf{KD}[\mathsf{P}]_{\boldsymbol{K}}, \mathsf{P}^{\pm}} = 1\right) - \mathbf{Pr}\left(\mathcal{D}^{\mathsf{IXIF}[\mathsf{RO}], \mathsf{P}^{\pm}} = 1\right) \right|$$

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Input: $(\delta, IV) \in \{1, \ldots, \mu\} \times \mathcal{IV}$
Output: $\varnothing$
  $\mathit{path} \leftarrow \mathsf{encode}[\delta] \parallel IV$
  return $\varnothing$

Interface: IXIF.duplex
Input: $(\mathit{flag}, M) \in \{\mathit{true}, \mathit{false}\} \times \{0,1\}^b$
Output: $Z \in \{0,1\}^r$
  $Z \leftarrow \mathsf{RO}(\mathit{path}, r)$
  $\mathit{path} \leftarrow \mathit{path} \parallel ([\mathit{flag}] \cdot (Z \| 0^{b-r}) \oplus M)$
  return Z

$$\mathbf{Adv}_{\mathsf{KD}}(\mathcal{D}) = \left| \mathbf{Pr}\left(\mathcal{D}^{\mathsf{KD}[\mathsf{P}]_{\boldsymbol{K}}, \mathsf{P}^{\pm}} = 1\right) - \mathbf{Pr}\left(\mathcal{D}^{\mathsf{IXIF}[\mathsf{RO}], \mathsf{P}^{\pm}} = 1\right) \right|$$

- IXIF[RO] is basically random oracle in disguise

Generalized Keyed Duplex: Security Model

Algorithm Keyed Duplex construction $\mathsf{KD}[\mathsf{P}]_{\boldsymbol{K}}$

Interface: KD.init
Input: $(\delta, IV) \in \{1, \ldots, \mu\} \times \mathcal{IV}$
Output: $\varnothing$
  $S \leftarrow \boldsymbol{K}[\delta] \parallel IV$
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Interface: KD.duplex
Input: $(flag, M) \in \{true, false\} \times \{0,1\}^b$
Output: $Z \in \{0,1\}^r$
  $S \leftarrow \mathsf{P}(S)$
  $Z \leftarrow \mathsf{left}_r(S)$
  $S \leftarrow S \oplus [flag] \cdot (Z \| 0^{b-r}) \oplus M$
  return Z

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- We prove that $\mathsf{KD}[\mathsf{P}]_{\boldsymbol{K}}$ behaves like IXIF[RO] for certain bound on adversarial resources

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- IXIF[RO] is basically random oracle in disguise
- We prove that $\mathsf{KD}[\mathsf{P}]_{\boldsymbol{K}}$ behaves like IXIF[RO] for certain bound on adversarial resources
  - Bound on adversarial resources is in turn determined by use case!

Generalized Keyed Duplex: Security Bounds From [DMV17, DM19a]

- $\mathcal{M}$: data complexity (calls to construction)
- $\mathcal{N}$: time complexity (calls to primitive)
- $\mathcal{Q}$: number of init calls
- $\mathcal{Q}_{IV}$: max # init calls for single IV
- $\mathcal{L}$: # queries with repeated path (e.g., nonce-violation)
- Ω: # queries with overwriting outer part (e.g., RUP)
- $\nu_{r,c}^{\mathcal{M}}$: some multicollision coefficient (often small)

Simplified Security Bound

$$\frac{\mathcal{Q}_{IV}\mathcal{N}}{2^k} + \frac{(\mathcal{L} + \Omega + \nu_{r,c}^{\mathcal{M}})\mathcal{N}}{2^c}$$

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$$\mathbf{Adv}_{\mathsf{KD}}(\mathcal{D}) \leq \frac{(\mathcal{L}+\Omega)\mathcal{N}}{2^c} + \frac{2\nu_{r,c}^{2(\mathcal{M}-\mathcal{L})}(\mathcal{N}+1)}{2^c} + \frac{\binom{\mathcal{L}+\Omega+1}{2}}{2^c} + \frac{(\mathcal{M}-\mathcal{L}-\mathcal{Q})\mathcal{Q}}{2^b-\mathcal{Q}} + \frac{\mathcal{M}(\mathcal{M}-\mathcal{L}-1)}{2^b} + \frac{\mathcal{Q}(\mathcal{M}-\mathcal{L}-\mathcal{Q})}{2^{\min\{c+k,\max\{b-\alpha,c\}\}}} + \frac{\mathcal{Q}_{IV}\mathcal{N}}{2^k} + \frac{\binom{\mu}{2}}{2^k} \quad \text{[DMV17]}$$

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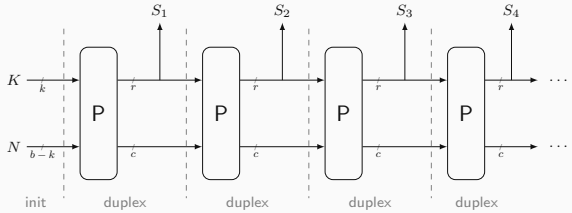
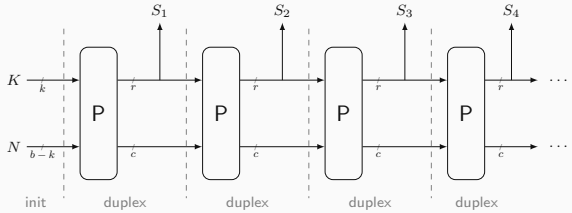
Bounds Simplify For Particular Applications!

Application to Keystream Generation



- Input: key K, nonce N
- Output: keystream S of requested length

Application to Keystream Generation



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  $S \leftarrow \varnothing$
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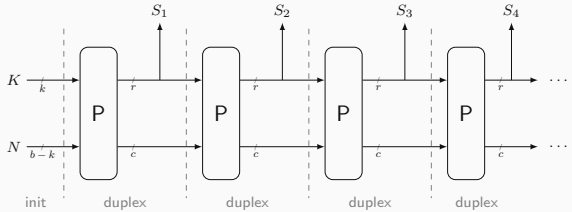

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- Strong simplified bound immediately follows:

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$$\mathbf{Adv}^{\mathrm{prf}}_{\mathsf{SC}}(\mathcal{D}) \leq \frac{2\nu_{r,c}^{2\mathcal{M}}(\mathcal{N}+1)}{2^c} + \frac{(\mathcal{M}-\mathcal{Q})\mathcal{Q}}{2^b-\mathcal{Q}} + \frac{2\binom{\mathcal{M}}{2}}{2^b} + \frac{\mathcal{Q}(\mathcal{M}-\mathcal{Q})}{2^{\min\{c+k,b\}}} + \frac{\mathcal{N}}{2^k}$$

Application to Keystream Generation: Security (1/2)

- Consider distinguisher $\mathcal{D}$ against PRF security of SC[P]

$$\mathbf{Adv}^{\mathrm{prf}}_{\mathsf{SC}}(\mathcal{D}) = \Delta_{\mathcal{D}}\left(\mathsf{SC}[\mathsf{P}]_K, \mathsf{P}^{\pm}\ ;\ \mathsf{R}, \mathsf{P}^{\pm}\right)$$

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&= \Delta_{\mathcal{D}}\left(\mathsf{SC}[\mathsf{KD}[\mathsf{P}]_K], \mathsf{P}^{\pm}\ ;\ \mathsf{R}, \mathsf{P}^{\pm}\right) \\
&\leq \Delta_{\mathcal{D}}\left(\mathsf{SC}[\mathsf{KD}[\mathsf{P}]_K], \mathsf{P}^{\pm}\ ;\ \mathsf{SC}[\mathsf{IXIF}[\mathsf{RO}]], \mathsf{P}^{\pm}\right) + \Delta_{\mathcal{D}}\left(\mathsf{SC}[\mathsf{IXIF}[\mathsf{RO}]], \mathsf{P}^{\pm}\ ;\ \mathsf{R}, \mathsf{P}^{\pm}\right)
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\end{aligned}$$

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\end{aligned}$$

$\leq \Delta_{\mathcal{D}'}\left(\mathsf{KD}[\mathsf{P}]_K, \mathsf{P}^{\pm}\ ;\ \mathsf{IXIF}[\mathsf{RO}], \mathsf{P}^{\pm}\right)$ $\quad = 0$

Application to Keystream Generation: Security (1/2)

- Consider distinguisher $\mathcal{D}$ against PRF security of $\mathsf{SC}[\mathsf{P}]$

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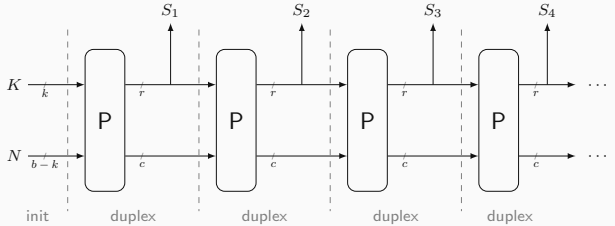
What Are the Resources of $\mathcal{D}'$?

Application to Keystream Generation: Security (2/2)



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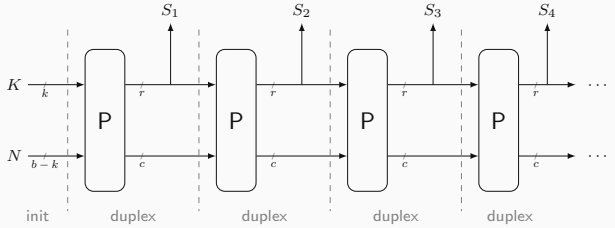

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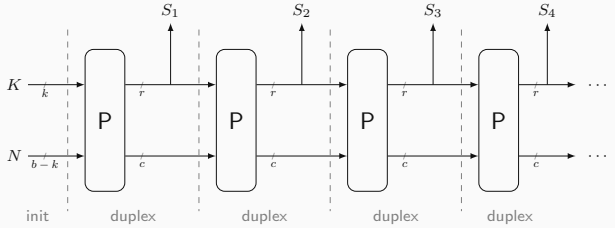

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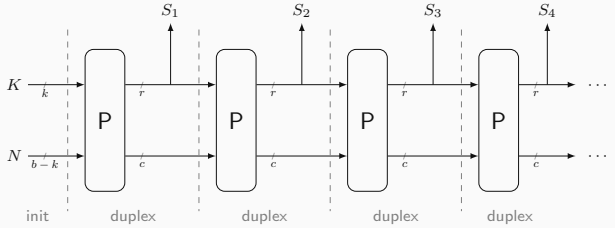

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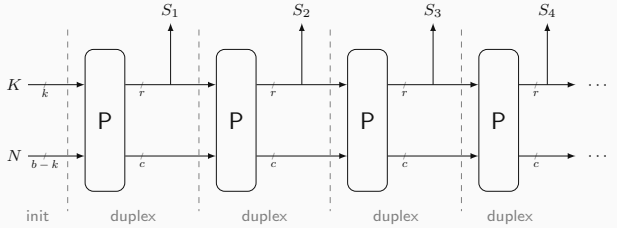
Application to Keystream Generation: Security (2/2)



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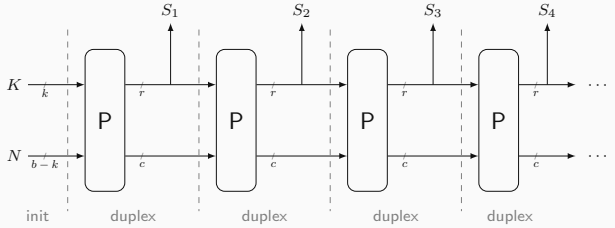
Application to Keystream Generation: Security (2/2)



Algorithm Keystream generation SC[P]

Input: $(K, N, \ell) \in \{0,1\}^k \times \{0,1\}^{b-k} \times \mathbb{N}$
Output: $S \in \{0,1\}^\ell$
  $S \leftarrow \varnothing$
  KD.init$(1, N)$
  for $i = 1, \ldots, \lceil \ell / r \rceil$ **do**
    $S \leftarrow S \,\|\, \mathsf{KD.duplex}(\mathit{false}, 0^b)$
  return $\mathsf{left}_\ell(S)$

resources of $\mathcal{D}'$	in terms of	resources of $\mathcal{D}$
$\mathcal{M}$: data complexity (calls to construction)	$\longrightarrow$	$\mathcal{M}$
$\mathcal{N}$: time complexity (calls to primitive)	$\longrightarrow$	$\mathcal{N}$
$\mathcal{Q}$: number of init calls	$\longrightarrow$	$\mathcal{Q}$
$\mathcal{Q}_{IV}$: max # init calls for single IV	$\longrightarrow$	1
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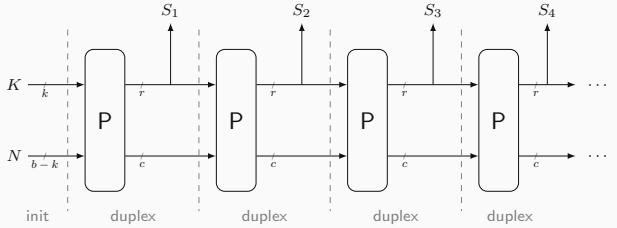

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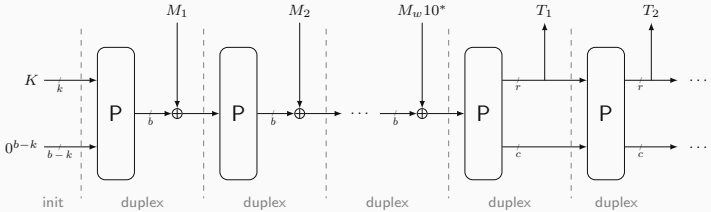
From [DMV17] (single-user setting): $\mathbf{Adv}_{\mathsf{KD}}(\mathcal{D}') \leq \frac{2\nu_{r,c}^{2\mathcal{M}}(\mathcal{N}+1)}{2^c} + \frac{(\mathcal{M}-\mathcal{Q})\mathcal{Q}}{2^b-\mathcal{Q}} + \frac{2\binom{\mathcal{M}}{2}}{2^b} + \frac{\mathcal{Q}(\mathcal{M}-\mathcal{Q})}{2^{\min\{c+k,b\}}} + \frac{\mathcal{N}}{2^k}$

Application to Full-Keyed Sponge [BDPV12, GPT15, MRV15]



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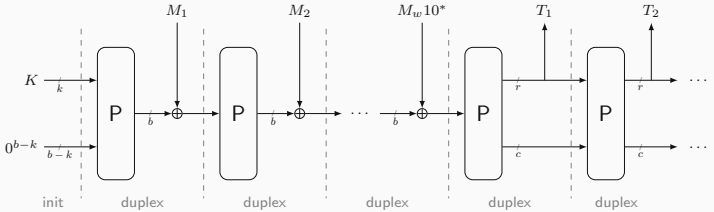

- Input: key K, message M
- Output: tag T
- Can be described using Duplex

Algorithm Full-Keyed Sponge FKS[P]

Input: $(K, M) \in \{0,1\}^k \times \{0,1\}^*$
Output: $T \in \{0,1\}^t$
  $(M_1, M_2, \ldots, M_w) \leftarrow \mathrm{pad}_b^{10^*}(M)$
  $T \leftarrow \varnothing$
  KD.init$(1, 0^{b-k})$
  for $i = 1, \ldots, w$ **do**
    KD.duplex(false, M_i) ▷ discard output
  for $i = 1, \ldots, \lceil t/r \rceil$ **do**
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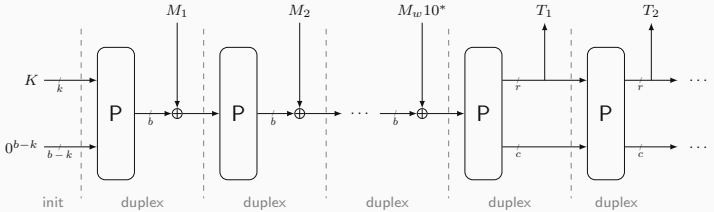
Application to Full-Keyed Sponge [BDPV12, GPT15, MRV15]



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- Analysis of [MRV15] applies...
- ... but better bound follows from Duplex:

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$$\mathbf{Adv}^{\mathrm{prf}}_{\mathsf{FKS}}(\mathcal{D}) \leq \frac{2\nu_{r,c}^{2\mathcal{M}}(\mathcal{N}+1)}{2^c} + \frac{(\mathcal{Q}-1)\mathcal{N}+\binom{\mathcal{Q}}{2}}{2^c} + \frac{(\mathcal{M}-\mathcal{Q})\mathcal{Q}}{2^b-\mathcal{Q}} + \frac{2\binom{\mathcal{M}}{2}}{2^b} + \frac{\mathcal{Q}(\mathcal{M}-\mathcal{Q})}{2^{\min\{c+k,b\}}} + \frac{\mathcal{N}}{2^k}$$

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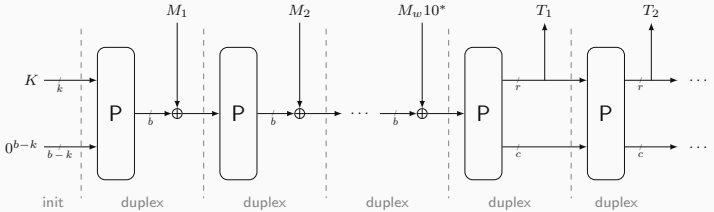

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influence of repeated paths

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Application to Full-Keyed Sponge: Power of Influencing Outer Part

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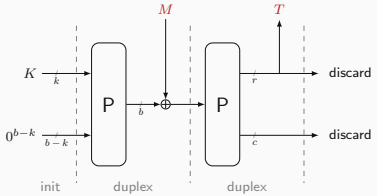
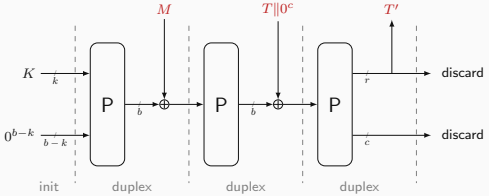
- Distinguisher makes two queries: $M \mapsto T$ and $M \| T \| 0^c \mapsto T'$





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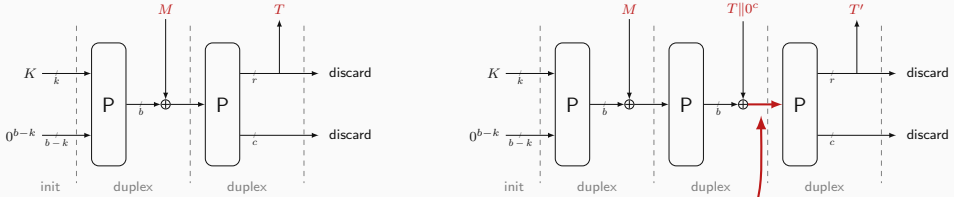

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Application to Full-Keyed Sponge: Power of Influencing Outer Part

- Repeated paths can seriously affect security
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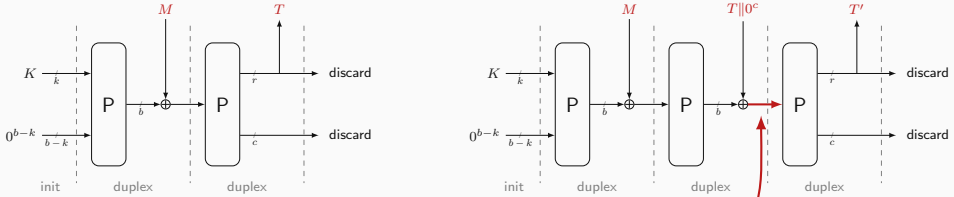
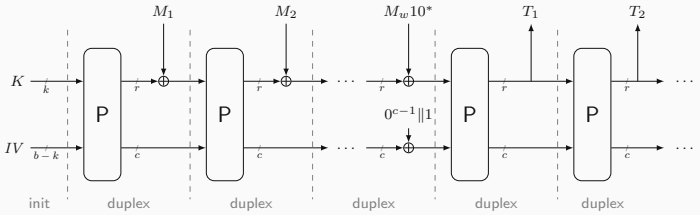


- State of second query before squeezing equals $0^r\|*^c$
- Key recovery attack:
  - Make $\mathcal{Q}$ twin queries as above and $\mathcal{N}$ primitive queries of form $0^r\|*^c$
  - Construction-primitive collision (likely if $\frac{\mathcal{Q}\cdot\mathcal{N}}{2^c} \approx 1$) $\longrightarrow$ derive K

Application to Ascon-PRF [DEMS24]



- Input: key K, initial value IV, message M
- Output: tag T

Algorithm Ascon-PRF[P]

Input: $(K, IV, M) \in \{0,1\}^k \times \mathcal{IV} \times \{0,1\}^*$
Output: $T \in \{0,1\}^t$
$(M_1, M_2, \ldots, M_w) \leftarrow \mathrm{pad}_r^{10^*}(M)$
$T \leftarrow \varnothing$
KD.init$(1, IV)$
for $i = 1, \ldots, w-1$ **do**
  KD.duplex(false, M_i) ▷ discard output
KD.duplex$(\mathit{false}, M_w\|0^{c-1}1)$
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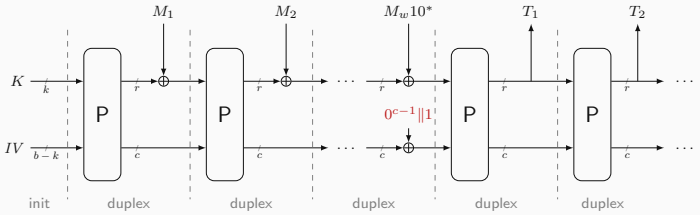
Application to Ascon-PRF [DEMS24]



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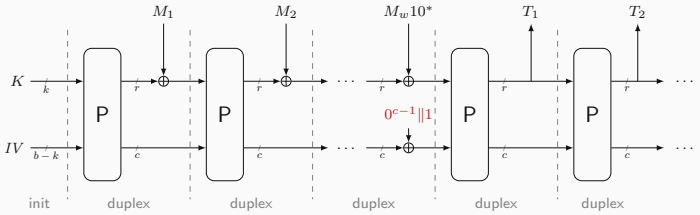

- Input: key K, initial value IV, message M
- Output: tag T

- Domain separation solves problem of repeated paths
  - Repeated paths may still occur...
  - ... but adversary cannot exploit them

Algorithm Ascon-PRF[P]

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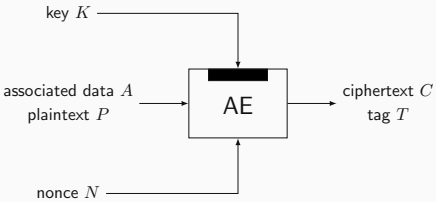
Application to AE: Model



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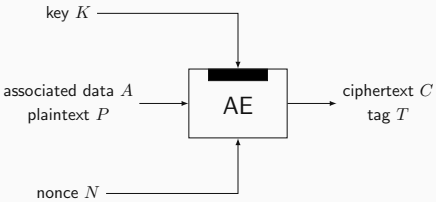

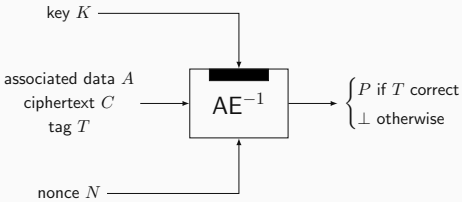

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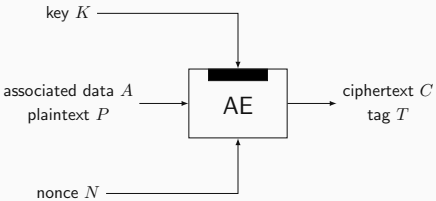
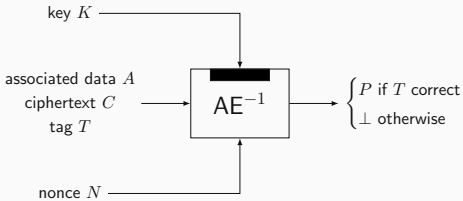
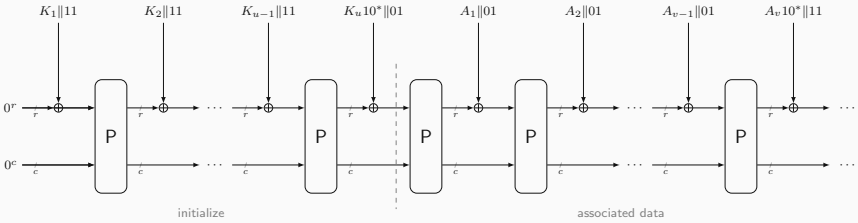


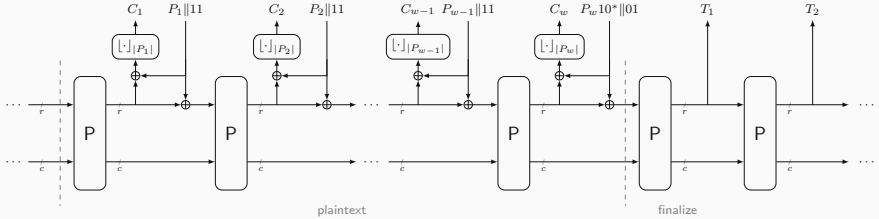


Role of Duplex

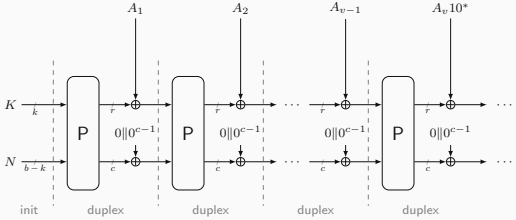
- Blockwise construction allows for processing different types of in-/output
- Usage of flag makes Duplex-style encryption decryptable

Application to AE: SpongeWrap [BDPV11a]

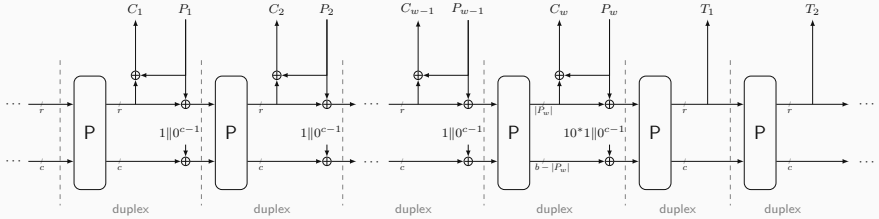




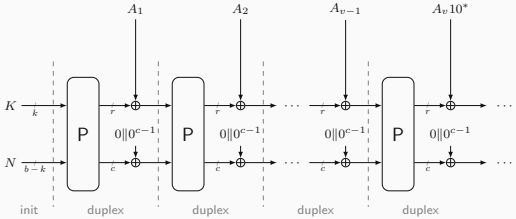
Application to AE: MonkeySpongeWrap: Encryption [Men23]



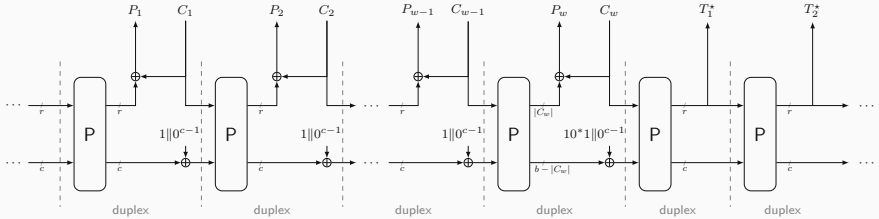
- Evolved version of SpongeWrap [BDPV11a]
  - State initialized using key and nonce
  - No block-wise padding
  - Domain separation spilled over



Application to AE: MonkeySpongeWrap: Decryption [Men23]



- Decryption similar to encryption
- Notable difference:
  - Processing of C
  - Duplexing with $flag = true$
- Impacts security bound



Application to AE: MonkeySpongeWrap: Security [Men23]

- Can be described using Duplex

Algorithm MonkeySpongeWrap[P]: ENC

Input: $(K, N, A, P) \in \{0,1\}^k \times \{0,1\}^{b-k} \times \{0,1\}^* \times \{0,1\}^*$
Output: $(C, T) \in \{0,1\}^{|P|} \times \{0,1\}^t$

$(A_1, A_2, \ldots, A_v) \leftarrow \mathrm{pad}_r^{10^*}(A)$
$(P_1, P_2, \ldots, P_w) \leftarrow \mathrm{pad}_r^{10^*}(P)$
$C \leftarrow \varnothing$
$T \leftarrow \varnothing$
KD.init$(1, N)$
for $i = 1, \ldots, v$ **do**
  KD.duplex$(\mathit{false}, A_i \| 0 \| 0^{c-1})$ ▷ discard output
for $i = 1, \ldots, w$ **do**
  $C \leftarrow C \parallel$ KD.duplex$(\mathit{false}, P_i \| 1 \| 0^{c-1}) \oplus P_i$
for $i = 1, \ldots, \lceil t/r \rceil$ **do**
  $T \leftarrow T \parallel$ KD.duplex$(\mathit{false}, 0^b)$
return $(\mathsf{left}_{|P|}(C), \mathsf{left}_t(T))$

Algorithm MonkeySpongeWrap[P]: DEC

Input: $(K, N, A, C, T) \in \{0,1\}^k \times \{0,1\}^{b-k} \times \{0,1\}^* \times \{0,1\}^* \times \{0,1\}^t$
Output: $P \in \{0,1\}^{|C|}$ or $\perp$

$(A_1, A_2, \ldots, A_v) \leftarrow \mathrm{pad}_r^{10^*}(A)$
$(C_1, C_2, \ldots, C_w) \leftarrow \mathrm{pad}_r^{10^*}(C)$
$P \leftarrow \varnothing$
$T^\star \leftarrow \varnothing$
KD.init$(1, N)$
for $i = 1, \ldots, v$ **do**
  KD.duplex$(\mathit{false}, A_i \| 0 \| 0^{c-1})$ ▷ discard output
for $i = 1, \ldots, w$ **do**
  $P \leftarrow P \parallel$ KD.duplex$(\mathit{true}, C_i \| 1 \| 0^{c-1}) \oplus C_i$
for $i = 1, \ldots, \lceil t/r \rceil$ **do**
  $T^\star \leftarrow T^\star \parallel$ KD.duplex$(\mathit{false}, 0^b)$
return $\mathsf{left}_t(T) = \mathsf{left}_t(T^\star)\ ?\ \mathsf{left}_{|C|}(P) : \perp$

Application to AE: MonkeySpongeWrap: Security [Men23]

- Can be described using Duplex

Algorithm MonkeySpongeWrap[P]: ENC

Input: $(K, N, A, P) \in \{0,1\}^k \times \{0,1\}^{b-k} \times \{0,1\}^* \times \{0,1\}^*$
Output: $(C, T) \in \{0,1\}^{|P|} \times \{0,1\}^t$
$(A_1, A_2, \ldots, A_v) \leftarrow \mathrm{pad}_r^{10^*}(A)$
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  $T \leftarrow T \parallel$ KD.duplex$(\mathit{false}, 0^b)$
return $(\mathsf{left}_{|P|}(C), \mathsf{left}_t(T))$

Algorithm MonkeySpongeWrap[P]: DEC

Input: $(K, N, A, C, T) \in \{0,1\}^k \times \{0,1\}^{b-k} \times \{0,1\}^* \times \{0,1\}^* \times \{0,1\}^t$
Output: $P \in \{0,1\}^{|C|}$ or $\perp$
$(A_1, A_2, \ldots, A_v) \leftarrow \mathrm{pad}_r^{10^*}(A)$
$(C_1, C_2, \ldots, C_w) \leftarrow \mathrm{pad}_r^{10^*}(C)$
$P \leftarrow \varnothing$
$T^* \leftarrow \varnothing$
KD.init$(1, N)$
for $i = 1, \ldots, v$ **do**
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for $i = 1, \ldots, w$ **do**
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for $i = 1, \ldots, \lceil t/r \rceil$ **do**
  $T^* \leftarrow T^* \parallel$ KD.duplex$(\mathit{false}, 0^b)$
return $\mathsf{left}_t(T) = \mathsf{left}_t(T^*)\ ?\ \mathsf{left}_{|C|}(P) : \perp$

- Security bound for MonkeySpongeWrap immediately follows:

$$\mathbf{Adv}^{\mathrm{ae}}_{\mathsf{MonkeySpongeWrap}}(\mathcal{D}) \leq \frac{2\nu_{r,c}^{2\mathcal{M}}(\mathcal{N}+1)}{2^c} + \frac{\mathcal{M}_d\mathcal{N} + \binom{\mathcal{M}_d}{2}}{2^c} + \frac{(\mathcal{M}-\mathcal{Q})\mathcal{Q}}{2^b - \mathcal{Q}} + \frac{2\binom{\mathcal{M}}{2}}{2^b} + \frac{\mathcal{Q}(\mathcal{M}-\mathcal{Q})}{2^{\min\{c+k,b\}}} + \frac{\mathcal{N}}{2^k} + \frac{\mathcal{Q}_d}{2^t}$$

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- Lots of research activity... and I did not even cover everything:
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Thank you!

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