Radbound University

Security of Permutation-Based Modes and Its Application to Ascon

Bart Mennink
Radboud University (The Netherlands)
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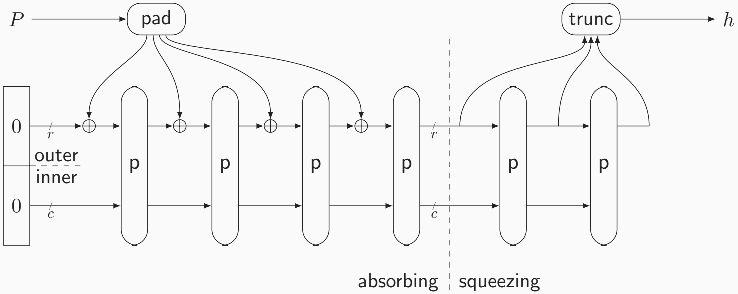
ESCADA

Sponges and Ascon-Hash Mode

Sponges [BDPV07]



- p is a b-bit permutation, with $b = r + c$
  - r is the rate
  - c is the capacity (security parameter)
- SHA-3, XOFs, lightweight hashing, ...

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Collision resistance:	$N^2/2^{c+1} + N^2/2^{n+1}$
Second preimage resistance:	$N^2/2^{c+1} + N/2^n$
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(N is # primitive evaluations)

classical attacks against RO
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Tightened Preimage Bound [LM22]

Tight Preimage Resistance

- Security proven up to $\approx \min \left\{2^{c/2}, 2^n \right.$ evaluations
- Best attack in $\approx \min\{2^{n-r} + 2^{c/2}, 2^n\}$ evaluations
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Implication for Ascon-Hash Mode with $(b, c, r, n) = (320, 256, 64, 256)$

- 128-bit collision resistance
- 128-bit second preimage resistance
- 192-bit preimage resistance

Keyed Sponges and Duplexes

Keyed Sponge

- $\text{PRF}(K, P) = \text{sponge}(K \| P)$
- Message authentication with tag size t: $\text{MAC}(K, P, t) = \text{sponge}(K \| P, t)$
- Keystream generation of length ℓ: $\text{SC}(K, D, \ell) = \text{sponge}(K \| D, \ell)$
- (All assuming K is fixed-length)

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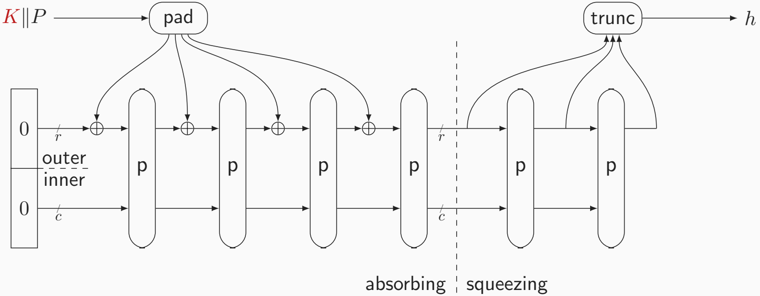
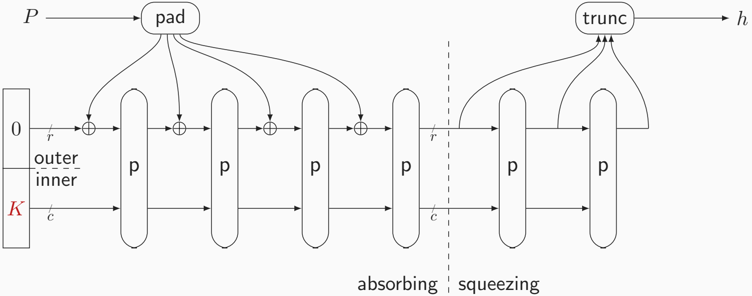
Keyed Duplex

- Authenticated encryption
- Multiple CAESAR and NIST LWC submissions



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

Evolution of Keyed Sponges



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- Inner-Keyed Sponge [CDH$^+$12, ADMV15, NY16]

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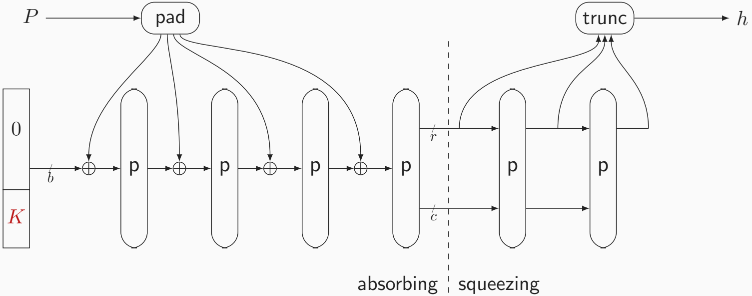
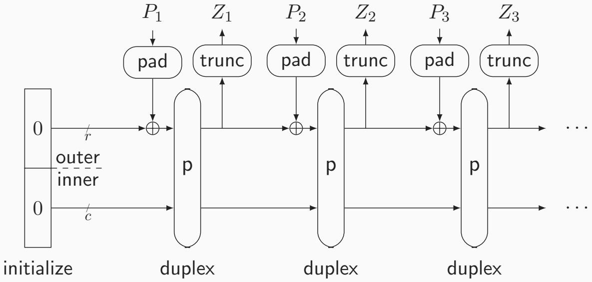


- Outer-Keyed Sponge [BDPV11b, ADMV15, NY16, Men18]
- Inner-Keyed Sponge [CDH$^+$12, ADMV15, NY16]
- Full-Keyed Sponge [BDPV12, GT16, MRV15]

Evolution of Keyed Duplexes



- Unkeyed Duplex [BDPV11a]

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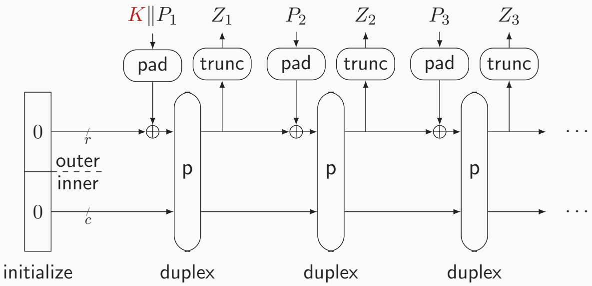

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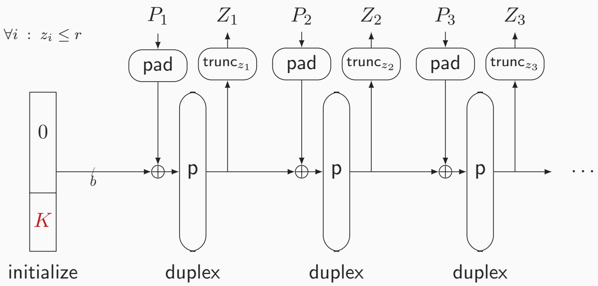
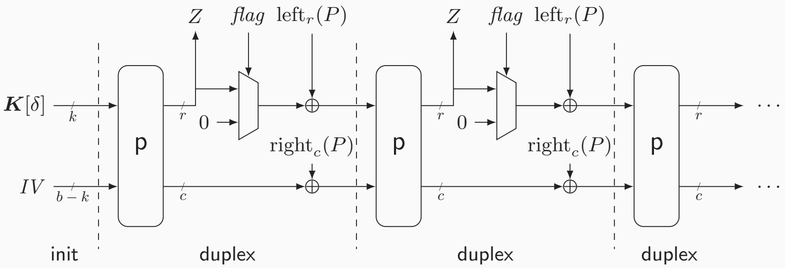


- Unkeyed Duplex [BDPV11a]
- Outer-Keyed Duplex [BDPV11a]
- Full-Keyed Duplex [MRV15, DMV17, DM19a, Men23]

Understanding the Duplex

Generalized Keyed Duplex ([DMV17, DM19a, Men23])



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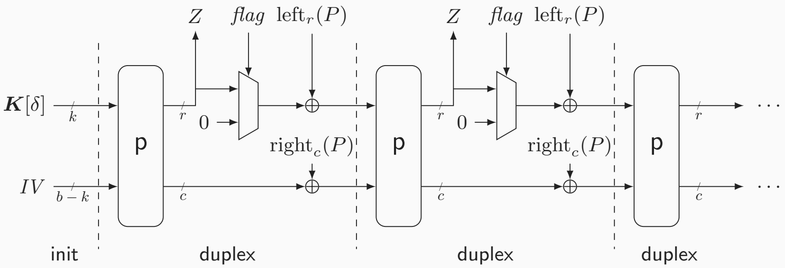
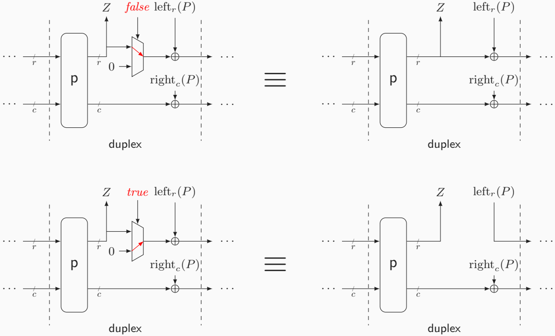


Features

- Multi-user by design: index δ specifies key in array
- Initial state: concatenation of $\boldsymbol{K}[\delta]$ and IV
- Full-state absorption, no padding
- Refined adversarial strength

Generalized Keyed Duplex: Flag (1)



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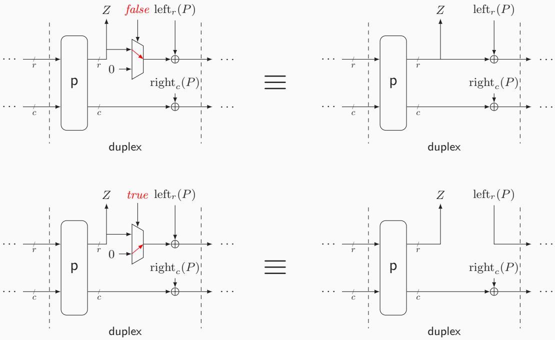

- Typical use case: authenticated encryption using duplex

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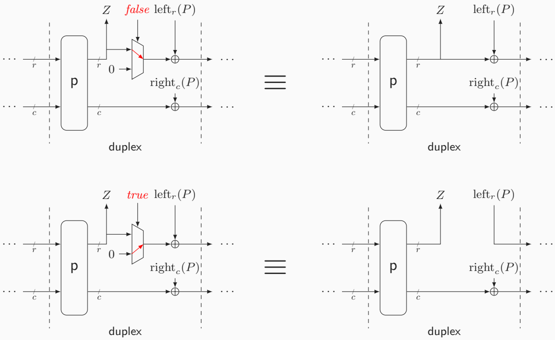

- Typical use case: authenticated encryption using duplex
- Security decreases for increasing number of calls with $\mathit{flag} = \mathit{true}$

- Consider extreme simplification of SpongeWrap authenticated encryption
- Key K, plaintext P, ciphertext C, and tag T all r bits; nonce U c bits
- General case will be discussed later in this presentation

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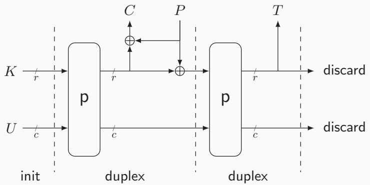

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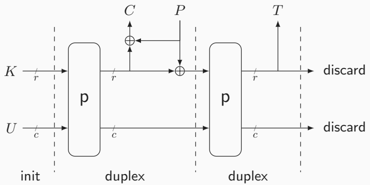
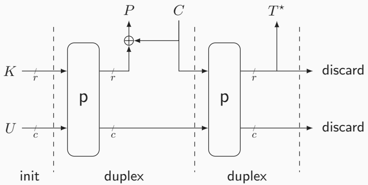


Decryption



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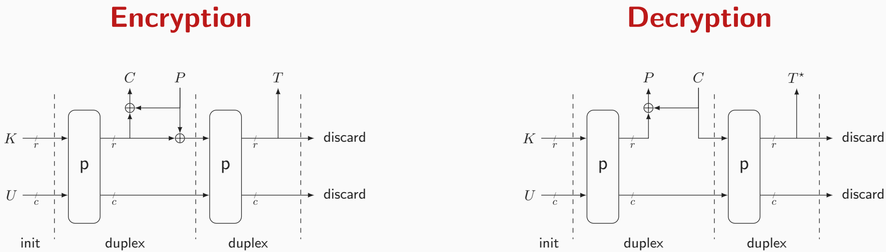

- Duplex call with $flag = true$ upon decryption
- Adversary can choose C and thus fix outer part to value of its choice

Security Model ([DMV17, DM19a, Men23])

Algorithm Keyed duplex construction $\mathsf{KD}[\mathsf{p}]_{\boldsymbol{K}}$

Interface: KD.init
Input: $(\delta, IV) \in \{1, \ldots, \mu\} \times \mathcal{IV}$
Output: $\varnothing$

$S \leftarrow \mathrm{rot}_\alpha(\boldsymbol{K}[\delta] \parallel IV)$
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Interface: KD.duplex
Input: $(\mathit{flag}, P) \in \{\mathit{true}, \mathit{false}\} \times \{0,1\}^b$
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- Bound on adversarial resources is in turn determined by use case!

Security Bounds From [DMV17] and [DM19a]

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

Simplified Security Bound

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

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Actual Security Bounds (Retained)

- [DMV17]:

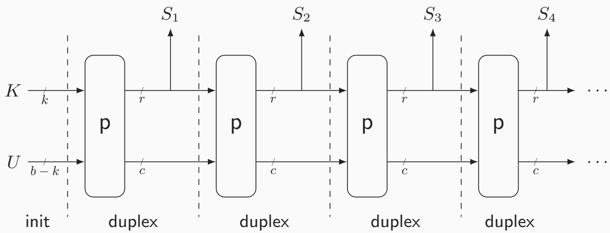
$$\mathbf{Adv}_{\mathsf{KD}}(\mathsf{D}) \leq \frac{(L+\Omega)N}{2^c} + \frac{2\nu_{r,c}^{2(M-L)}(N+1)}{2^c} + \frac{\binom{L+\Omega+1}{2}}{2^c} + \frac{(M-L-Q)Q}{2^b-Q} + \frac{M(M-L-1)}{2^b} + \frac{Q(M-L-Q)}{2^{\min\{c+k,\max\{b-\alpha,c\}\}}} + \frac{Q_{IV}N}{2^k} + \frac{\binom{\mu}{2}}{2^k}$$

- [DM19a] (with one simplification):

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

Duplex Application: Keystream Generation

Keystream Generation



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

Algorithm Keystream generation SC[p]

Input: $(K, U, \ell) \in \{0,1\}^k \times \{0,1\}^{b-k} \times \mathbb{N}$
Output: $S \in \{0,1\}^\ell$
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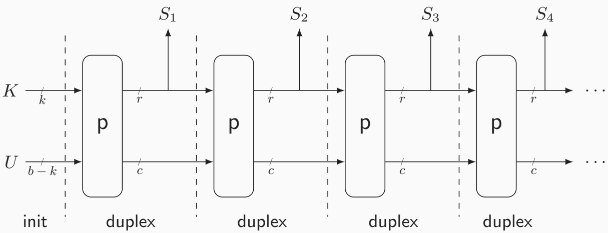

- Input: key K, nonce U
- Output: keystream S of requested length
- Keystream generation can be described using duplex

Algorithm Keystream generation SC[p]

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Underlying keyed duplex: $\mathsf{KD}[\mathsf{p}]_{(K)}$

```
S ← ∅
KD.init(1, U)
for i = 1, ..., ⌈ℓ/r⌉ do
    S ← S || KD.duplex(false, 0^b)
return left_ℓ(S)
```

Keystream Generation: Security (1)

- Consider distinguisher D against PRF security of SC[p]

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

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\end{aligned}$$

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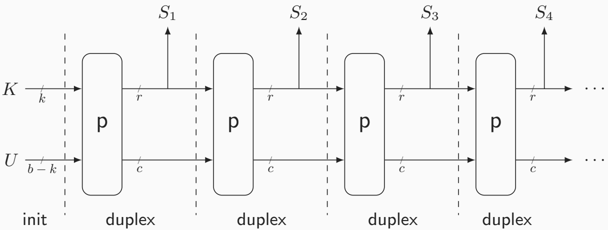
- What are the resources of D′?

Keystream Generation: Security (2)



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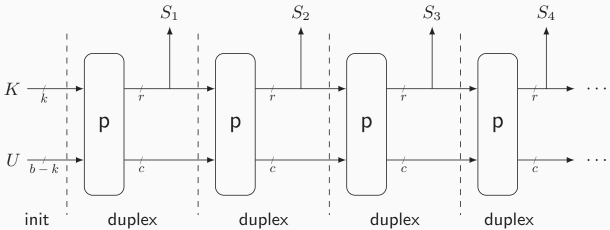

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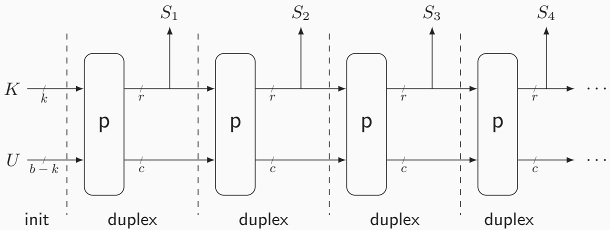

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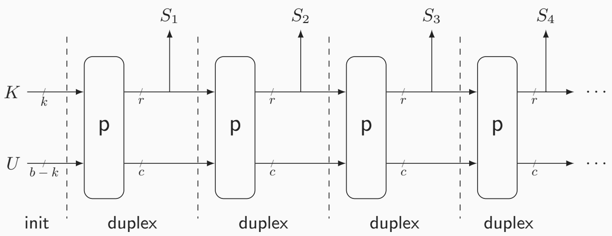

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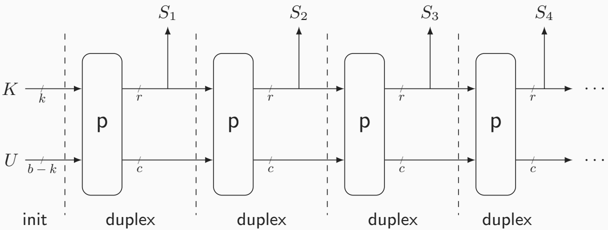

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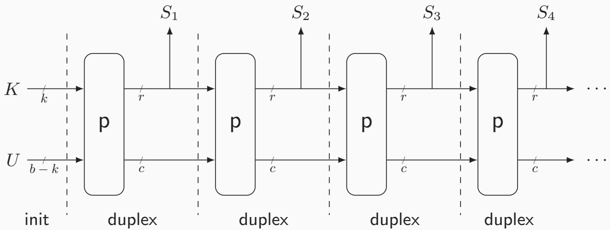

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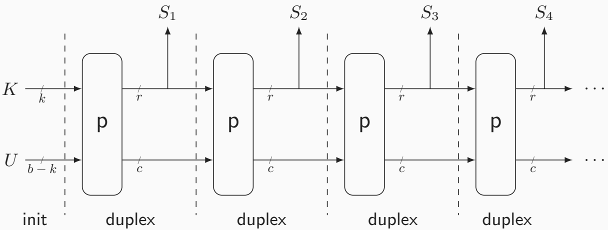

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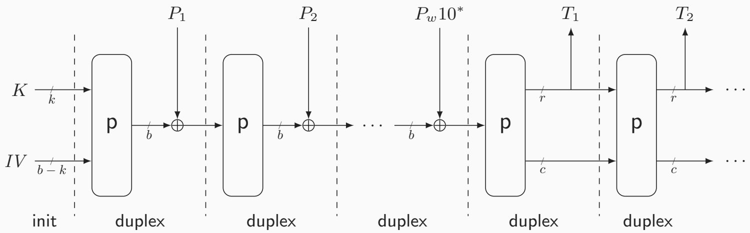
From [DMV17] (in single-user setting):

$$\mathbf{Adv}_{\mathsf{KD}}(\mathsf{D}') \leq \frac{2\nu_{r,c}^{2\sigma}(N+1)}{2^c} + \frac{(\sigma-q)q}{2^b-q} + \frac{2\binom{\sigma}{2}}{2^b} + \frac{q(\sigma-q)}{2^{\min\{c+k,b\}}} + \frac{N}{2^k}$$

Duplex Application: Message Authentication and Ascon-PRF

Full-State Keyed Sponge [BDPV12]



- Input: key K, initial value IV, message P
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Algorithm Full-state keyed sponge FSKS[p]

Input: $(K, IV, P) \in \{0,1\}^k \times \mathcal{IV} \times \{0,1\}^*$
Output: $T \in \{0,1\}^t$
Underlying keyed duplex: KD[p]$_{(K)}$

  $(P_1, P_2, \ldots, P_w) \leftarrow \mathrm{pad}_b^{10^*}(P)$
  $T \leftarrow \varnothing$
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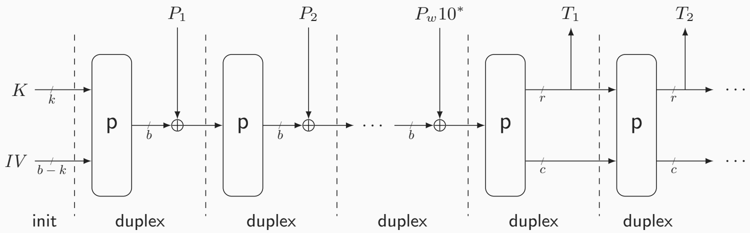

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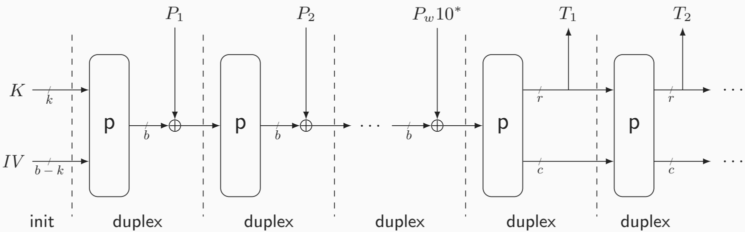

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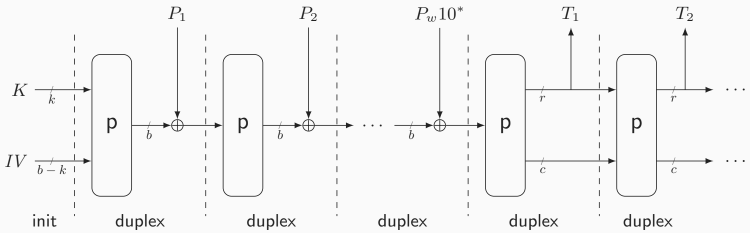

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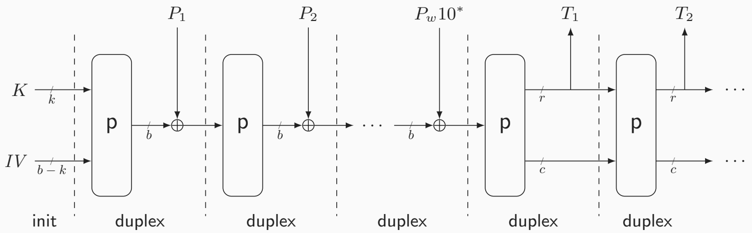

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influence of L

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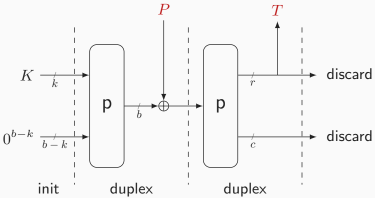

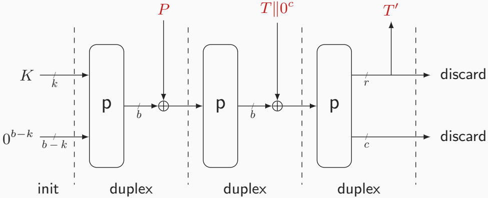

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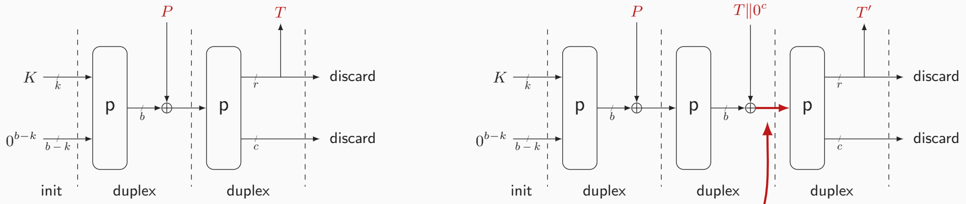

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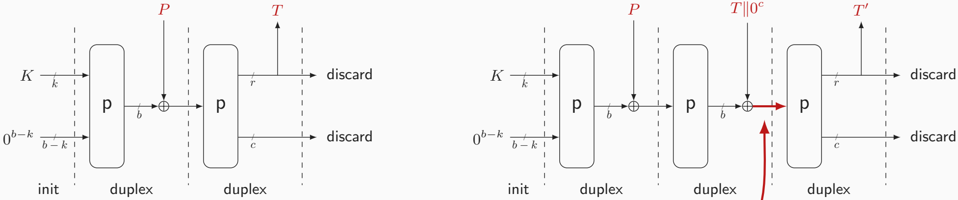
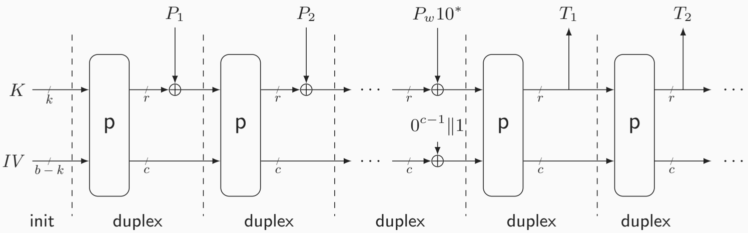


- State of second query before squeezing equals $0^r \| *^c$
- Key recovery attack:
  - Make q twin queries as above and N primitive queries of form $0^r \| *^c$
  - Construction-primitive collision (likely if $\frac{q \cdot N}{2^c} \approx 1$) $\longrightarrow$ derive K

Ascon-PRF [DEMS21]



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Input: $(K, IV, P) \in \{0,1\}^k \times \mathcal{IV} \times \{0,1\}^*$
Output: $T \in \{0,1\}^t$
Underlying keyed duplex: KD[p]$_{(K)}$

$(P_1, P_2, \ldots, P_w) \leftarrow \text{pad}_r^{10^*}(P)$
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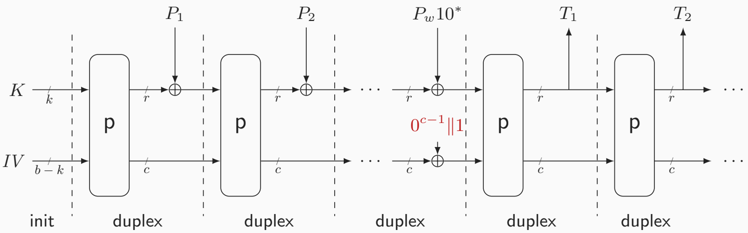

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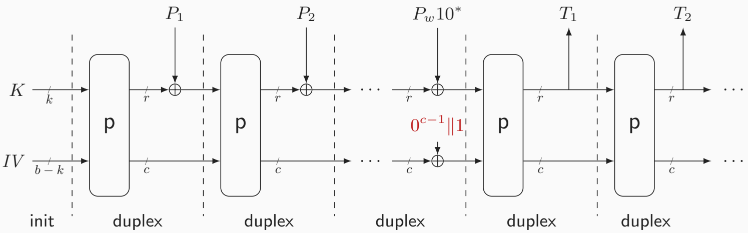

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for i = 1, ..., ⌈t/r⌉ do
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return left_t(T)
```

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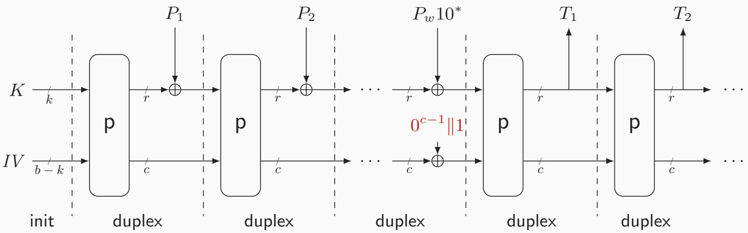

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  - . . . but adversary cannot exploit them

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- Improved bound from [DM19a]:
  - Defines additional parameter $\nu_{\text{fix}} \leq L + \Omega$
  - In most cases $\nu_{\text{fix}} = L + \Omega$; for current case $\nu_{\text{fix}} = 0$
  - Dominant term $\frac{(q-1)N+\binom{q}{2}}{2^c}$ never appears in the first place

Ascon-PRF: Implication

Multi-user bound from [DMV17]

$$\mathbf{Adv}^{\mu\text{-prf}}_{\mathsf{Ascon\text{-}PRF}}(\mathsf{D}) \leq \frac{2\nu_{r,c}^{2\sigma}(N+1)}{2^c} + \frac{(\sigma-q)q}{2^b-q} + \frac{2\binom{\sigma}{2}}{2^b} + \frac{q(\sigma-q)}{2^{\min\{c+k,b\}}} + \frac{\mu N}{2^k} + \frac{\binom{\mu}{2}}{2^k}$$

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- $(k, b, c, r) = (128, 320, 192, 128)$
- Assume online complexity of $q, \sigma \ll 2^{64}$ (could be taken higher)
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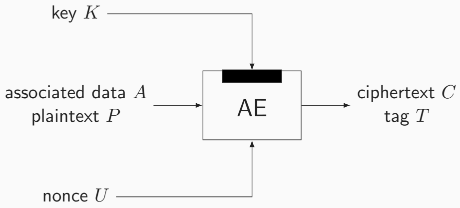
- Generic security as long as $N \ll 2^{128}/\mu$

Duplex Application: MonkeySpongeWrap

Authenticated Encryption



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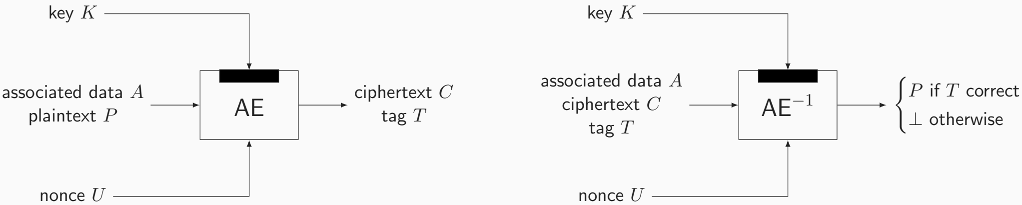
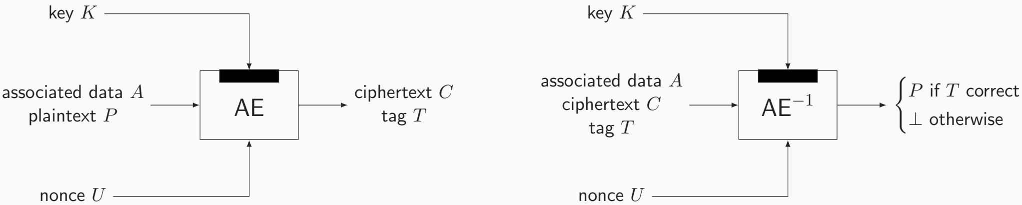
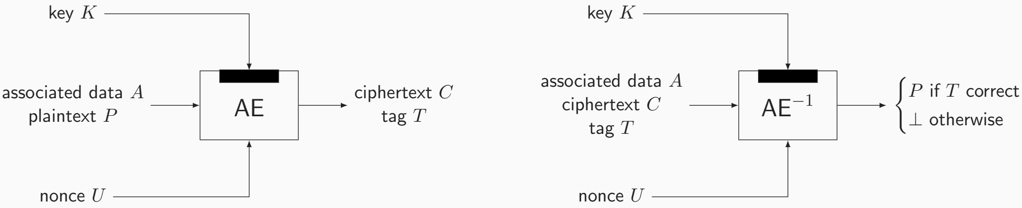




Role of Duplex

- Blockwise construction allows for processing different types of in-/output



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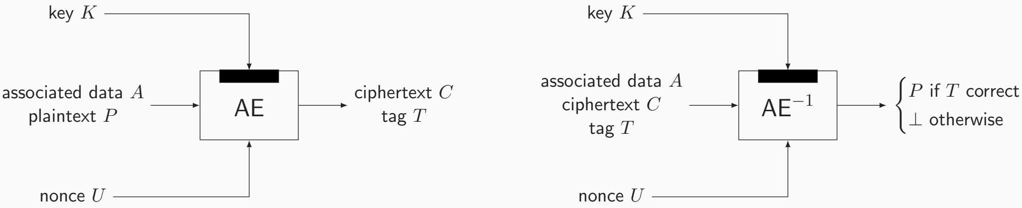

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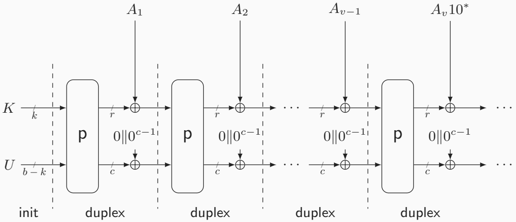
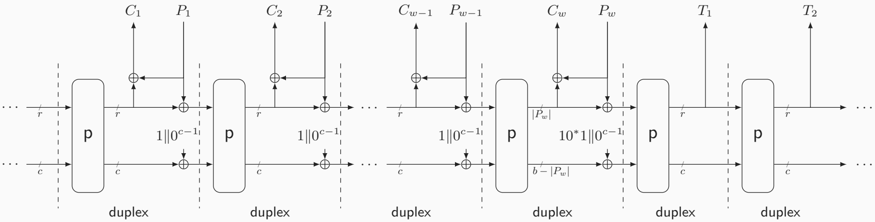
  (Although the flag is not a necessity for this)

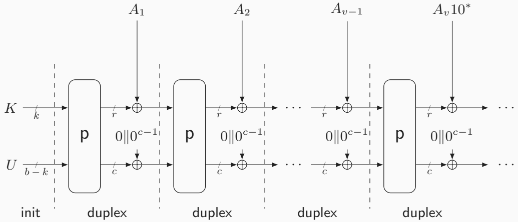
MonkeySpongeWrap: Encryption



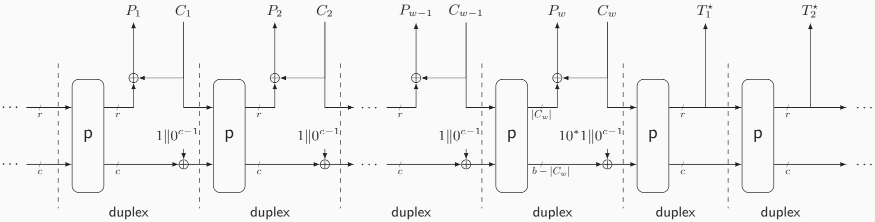
- Improvement over SpongeWrap [BDPV11a]
- State initialized using key and nonce
- Domain separation spill-over into inner part



MonkeySpongeWrap: Decryption



- Decryption similar to encryption
- Notable difference:
  - Processing of C
  - Duplexing with $\mathit{flag} = \mathit{true}$



MonkeySpongeWrap Versus Ascon-AEAD

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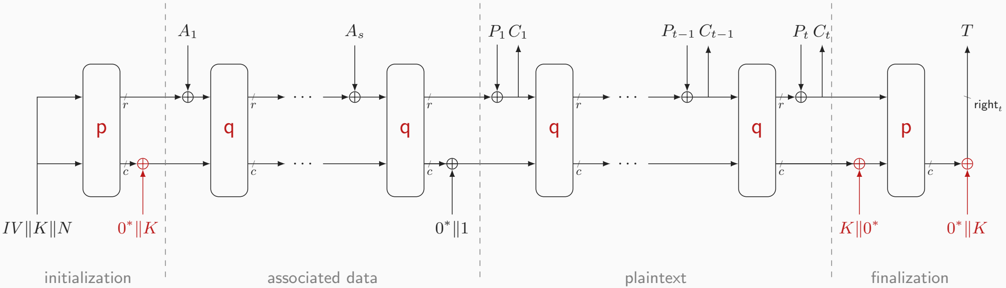
- Does not completely capture Ascon-AEAD
  - Additional key blindings at initialization and finalization
  - Outer and inner permutations p and q differ (minor)



Security of Ascon-AEAD Mode

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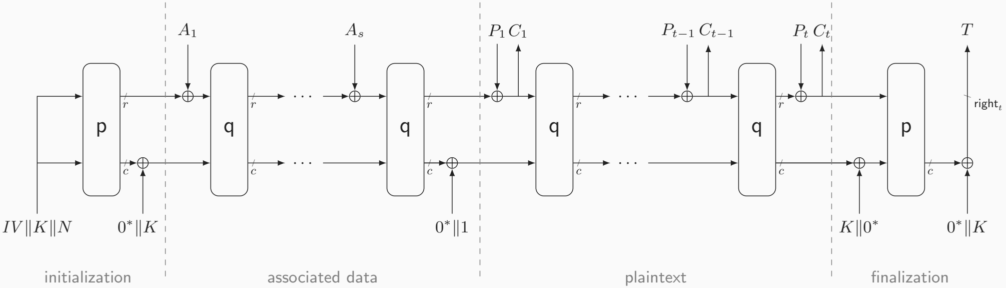

Two New Complementary Results on Ascon-AEAD

- Chakraborty et al. [CDN23]: tight bound on nonce-respecting confidentiality and authenticity in case p = q (next talk)
- Lefevre and Mennink [LM23]: general confidentiality and authenticity with main focus on role of key blindings (now)

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property	setting	security as long as (highly simplified)
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	nonce-misuse	
authenticity	nonce-respecting	
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	nonce-misuse	$N \ll \min\{2^k/\mu, 2^c/(\sigma_{\mathcal{E}} + \sigma_{\mathcal{D}})\}$

Application to Ascon-AEAD Parameters

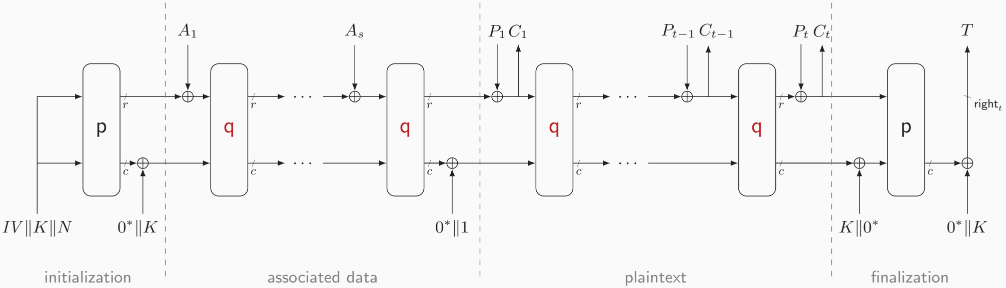
- $(k, b, c, r, t) = \begin{cases} (128, 320, 256, 64, 128) \text{ for Ascon-128} \\ (128, 320, 192, 128, 128) \text{ for Ascon-128a} \\ (160, 320, 256, 64, 128) \text{ for Ascon-80pq} \end{cases}$
- Assume online complexity of $q, \sigma \ll 2^{64}$ (could be taken higher)

Multi-User Security Under Typical Models

property	setting	security as long as (highly simplified)
confidentiality	nonce-respecting	$N \ll \min\{2^k/\mu, 2^{b/2}, 2^c\}$
	nonce-misuse	—
authenticity	nonce-respecting	$N \ll \min\{2^k/\mu, 2^b/\sigma_{\mathcal{E}}, 2^c/\sigma_{\mathcal{D}}\}$
	nonce-misuse	$N \ll \min\{2^k/\mu, 2^c/(\sigma_{\mathcal{E}} + \sigma_{\mathcal{D}})\}$

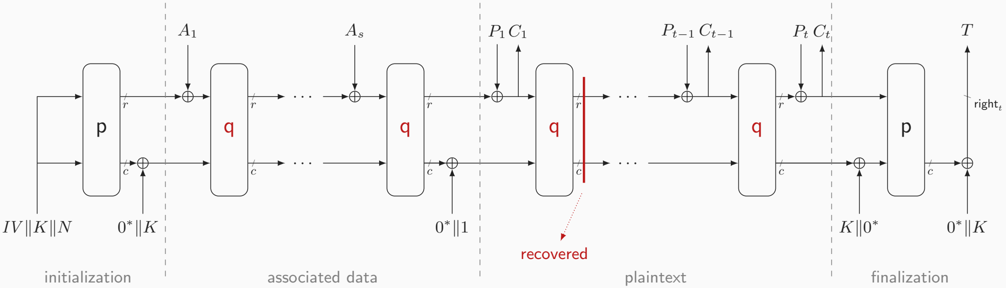
Application to Ascon-AEAD Parameters

- $(k, b, c, r, t) = \begin{cases} (128, 320, 256, 64, 128) & \text{for Ascon-128} \\ (128, 320, 192, 128, 128) & \text{for Ascon-128a} \\ (160, 320, 256, 64, 128) & \text{for Ascon-80pq} \end{cases}$
- Assume online complexity of $q, \sigma \ll 2^{64}$ (could be taken higher)
- Generic security as long as $N \ll 2^{128}/\mu$ (or $N \ll 2^{160}/\mu$ for Ascon-80pq)



Attack Setting

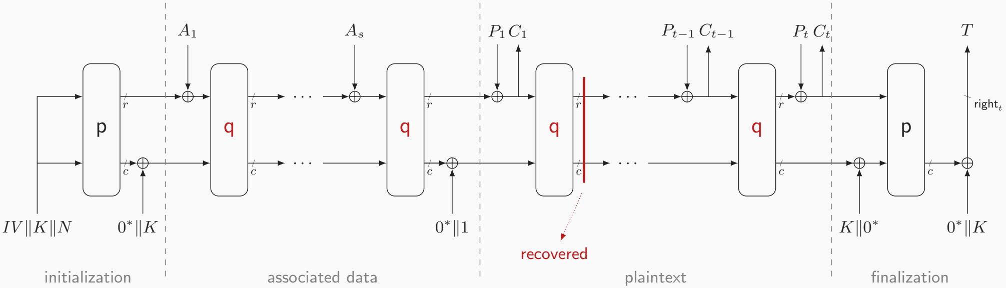
- Inner permutation q may get weaker protection than outer permutation



Attack Setting

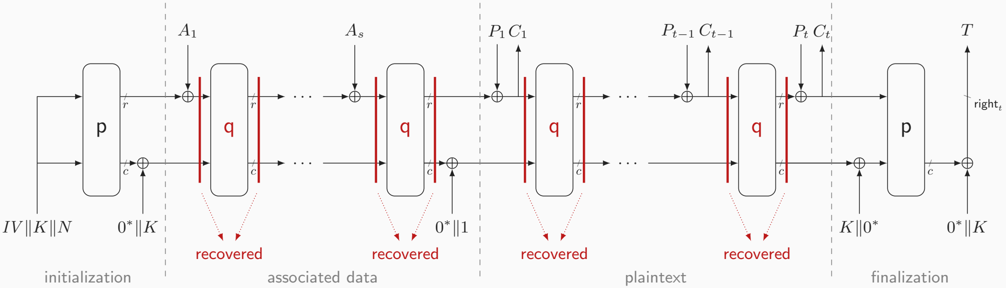
- Inner permutation q may get weaker protection than outer permutation
- Adversary may somehow recover any inner state

Authenticity Under State Recovery (1)



Attack Setting

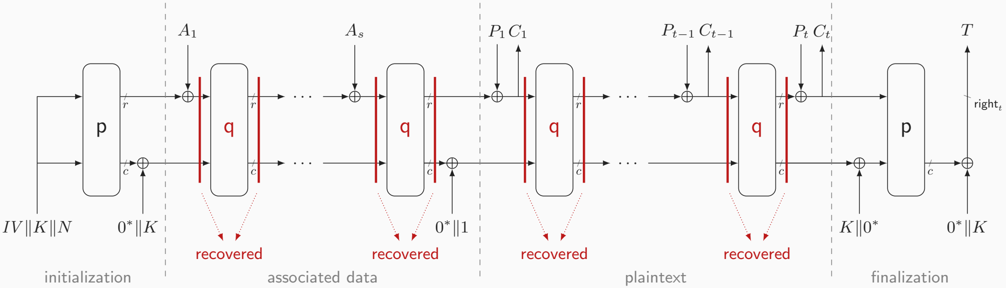
- Inner permutation q may get weaker protection than outer permutation
- Adversary may somehow recover any inner state
- Ascon-AEAD designed to still achieve authenticity in this setting



Model

- Without loss of generality: all evaluations of inner permutation q leak

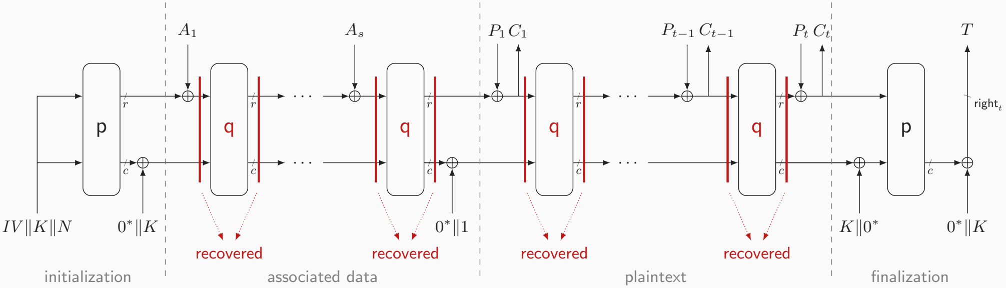
Authenticity Under State Recovery (2)



Model

- Without loss of generality: all evaluations of inner permutation q leak
- Model inspired by permutation-based leakage resilience [DM19a, DM19b]
- Adversary wins if it forges tag even under inner state recovery

Authenticity Under State Recovery (3)

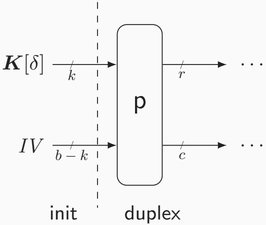


Results

- MonkeySpongeWrap-style AEAD does not achieve this property
- Ascon-AEAD mode achieves security as long as $N \ll \min\{2^k/\mu, 2^{c/2}\}$
- For Ascon-AEAD parameters: generic security as long as $N \ll 2^{128}/\mu$

Generalized Duplex Initialization

On the Power of Initialization



- Plain initialization: incurs term $\frac{\mu N}{2^k} + \frac{\binom{\mu}{2}}{2^k}$
  - Assumes that attacker has full control over IV

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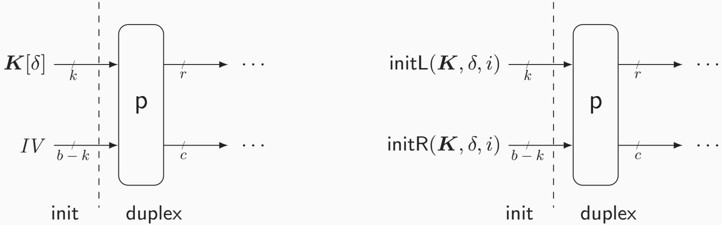
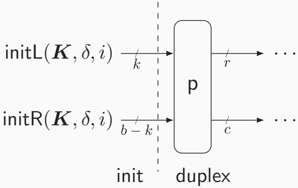


- Plain initialization: incurs term $\frac{\mu N}{2^k} + \frac{\binom{\mu}{2}}{2^k}$
  - Assumes that attacker has full control over IV
- Dobraunig and Mennink [DM23]: generalized analysis of initialization
  - Both inner and outer part may be keyed or depend on IV
  - i serves role of IV but also allows to formally capture random IV's

case	initL$(\boldsymbol{K}, \delta, i)$	initR$(\boldsymbol{K}, \delta, i)$
baseline	$\boldsymbol{K}[\delta]$	$\mathrm{encode}_{b-k}[i]$
global IV	$\boldsymbol{K}[\delta]$	$\mathrm{encode}_{b-k}[(\delta, i)]$
random IV	$\boldsymbol{K}[\delta]$	$RIV \Vert 0^{b-k-n}$
quasi-random IV	$\boldsymbol{K}[\delta]$	$(RIV_\delta \oplus \mathrm{encode}_n[i]) \Vert 0^{b-k-n}$
IV on key	$\boldsymbol{K}[\delta] \oplus \mathrm{encode}_k[i]$	0^{b-k}
global IV on key	$\boldsymbol{K}[\delta] \oplus \mathrm{encode}_k[i]$	$\mathrm{encode}_{b-k}[\delta]$



- Different types of initialization (see paper for side-conditions)
- RIV stands for random IV, RIV_δ unique random IV per user

Different Initializations

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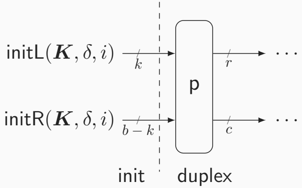
global IV on key	$\boldsymbol{K}[\delta] \oplus \text{encode}_k[i]$	$\text{encode}_{b-k}[\delta]$



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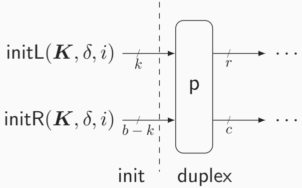

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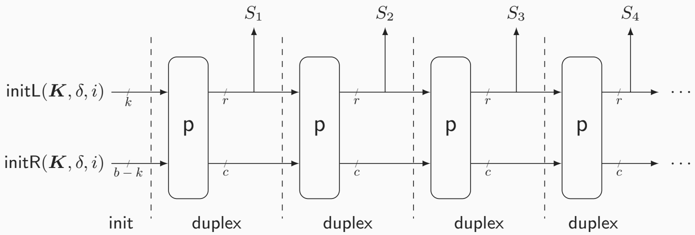
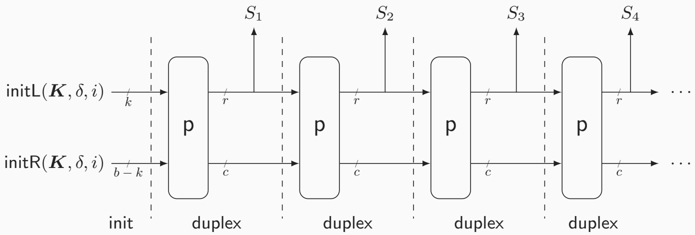
- Application to keystream and authenticated encryption


S_1
S_2
S_3
S_4
initL$(\boldsymbol{K}, \delta, i)$
initR$(\boldsymbol{K}, \delta, i)$
k
$b-k$
r
c
p
p
p
p
init
duplex
duplex
duplex
duplex

Application to Keystream Generation (Randomized IV in Paper)



case	initL$(\boldsymbol{K}, \delta, i)$	initR$(\boldsymbol{K}, \delta, i)$	initialization term (simplified)
baseline	$\boldsymbol{K}[\delta]$	$\mathrm{encode}_{b-k}[i]$	$\frac{\mu N}{2^k} + \frac{\binom{\mu}{2}}{2^k}$
global IV	$\boldsymbol{K}[\delta]$	$\mathrm{encode}_{b-k}[(\delta, i)]$	$\frac{N}{2^k}$
IV on key	$\boldsymbol{K}[\delta] \oplus \mathrm{encode}_k[i]$	0^{b-k}	$\frac{QN}{2^k} + \frac{\binom{Q}{2}}{2^k}$
global IV on key	$\boldsymbol{K}[\delta] \oplus \mathrm{encode}_k[i]$	$\mathrm{encode}_{b-k}[\delta]$	$\frac{Q_\delta N}{2^k} + \frac{\mu\binom{Q_\delta}{2}}{2^k}$

Q stands for # initializations, Q_δ initializations per user

Conclusion

Main Takeaways

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  - Versatile construction but application not always clear
  - Dedicated analysis sometimes more suited

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Acknowledgments

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Thank you for your attention!

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