Leakage Resilience of the ISAP Mode: a Vulgarized Summary

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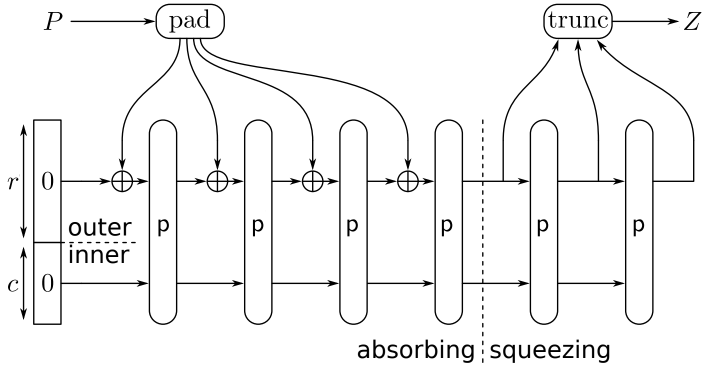
* Thanks to the ISAP team!

Sponges [BDPV07]



- Cryptographic hash function
- SHA-3, XOFs, lightweight hashing, . . .
- Behaves as RO up to query complexity $\approx 2^{c/2}$ [BDPV08]

Keying Sponges

Keyed Sponge

- $\text{PRF}(K, P) = \text{Sponge}(K \| P)$
- Message authentication
- Keystream generation

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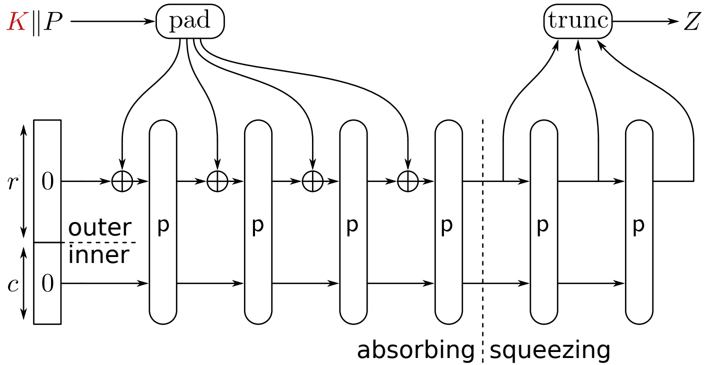
Keyed Duplex

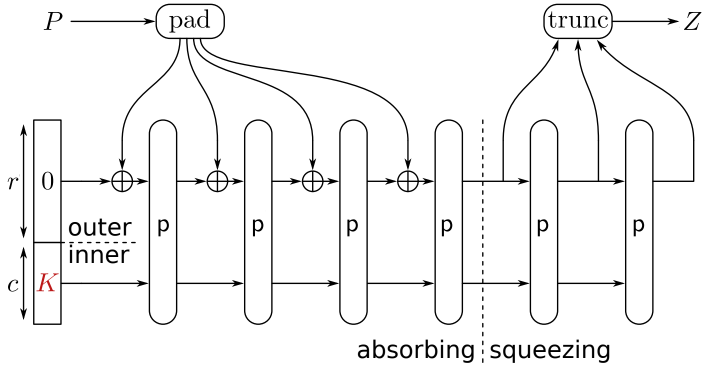
- Authenticated encryption
- Multiple CAESAR and NIST LWC submissions

Evolution of Keyed Sponges



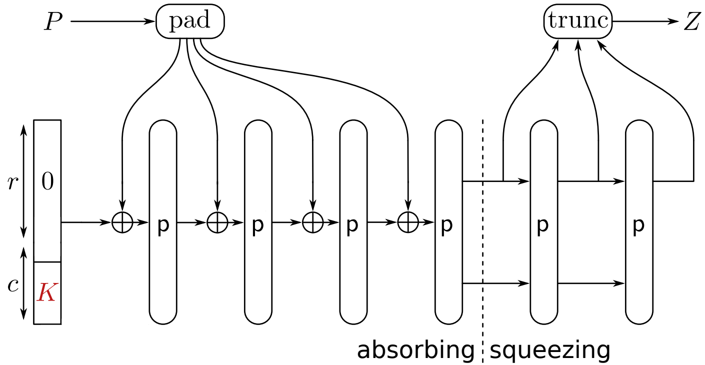
- Outer-Keyed Sponge [BDPV11,ADMV15,NY16,Men18]

Evolution of Keyed Sponges



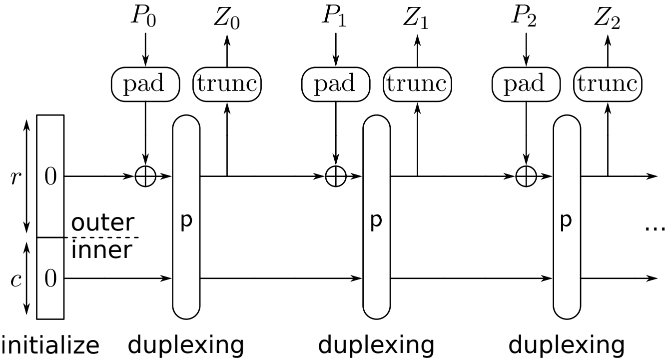
- Outer-Keyed Sponge [BDPV11,ADMV15,NY16,Men18]
- Inner-Keyed Sponge [CDHKN12,ADMV15,NY16]

Evolution of Keyed Sponges



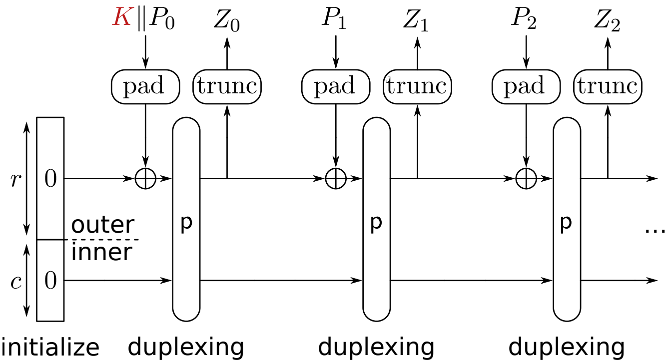
- Outer-Keyed Sponge [BDPV11,ADMV15,NY16,Men18]
- Inner-Keyed Sponge [CDHKN12,ADMV15,NY16]
- Full-Keyed Sponge [BDPV12,GPT15,MRV15]

Evolution of Keyed Duplexes



- Unkeyed Duplex [BDPV11]

Evolution of Keyed Duplexes



- Unkeyed Duplex [BDPV11]
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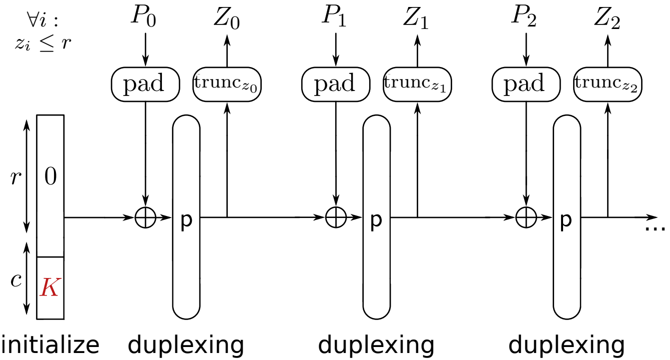
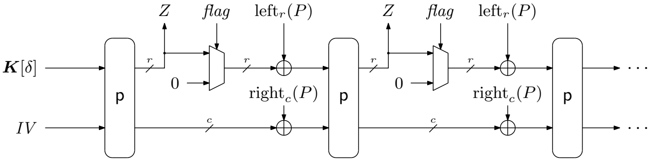
Evolution of Keyed Duplexes

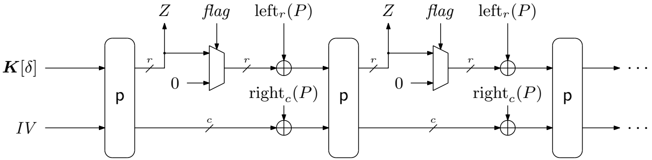


- Unkeyed Duplex [BDPV11]
- Outer-Keyed Duplex [BDPV11]
- Full-Keyed Duplex [MRV15,DMV17]

Security of Generalized Keyed Duplex [DMV17]



Security of Generalized Keyed Duplex [DMV17]



- M: data complexity (calls to construction)
- N: time complexity (calls to primitive)
- 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 $\rightarrow$ often small constant

Simplified Security Bound

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

Outline

Leakage Resilience of the Duplex Construction

Security of the Suffix Keyed Sponge

Application to ISAP

Conclusion

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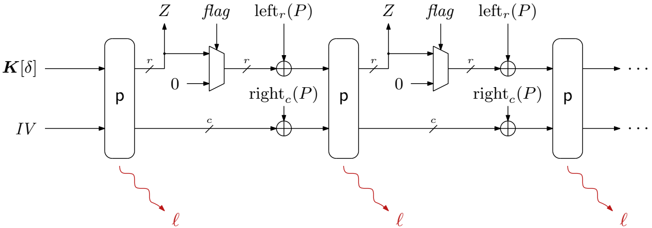
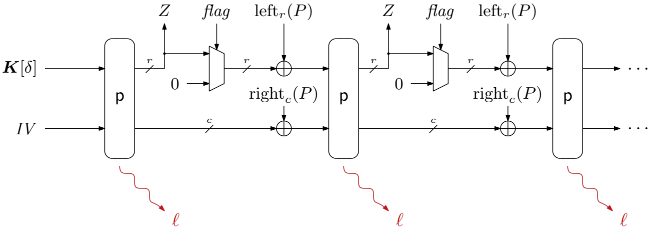
Leakage Resilience of Keyed Duplex



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

Leakage Resilience of Keyed Duplex



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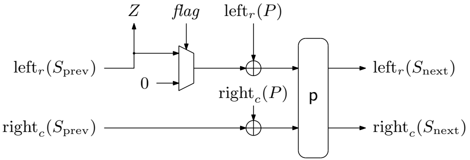
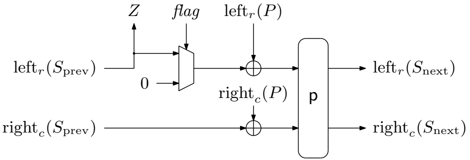
Is keyed duplex secure under leakage?

Formalizing Leakage



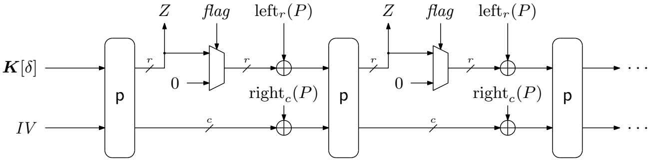
- L is any fixed leakage function (non-adaptive leakage)
- For each evaluation of p: L leaks λ bits of $(S_{\mathrm{prev}}, S_{\mathrm{next}})$

Influence of Leakage



- Suppose S_{prev} invoked at most R times
- At most $R+1$ leakages of S_{prev}
- Min-entropy of S_{prev}: at least $c-(R+1)\lambda$

Leakage Resilience of Keyed Duplex



- M: data complexity (calls to construction)
- N: time complexity (calls to primitive)
- q_{IV}: max # init calls for single IV
- q_δ: maximum # init calls for single δ
- L: # queries with repeated path (e.g., nonce-violation)
- Ω: # queries with overwriting outer part (e.g., RUP)
- R: max # duplexing calls for single non-empty subpath
- $\nu^M_{r,c}$: some multicollision coefficient $\rightarrow$ often small constant

Simplified Security Bound

$$\frac{q_{IV} N}{2^{k - q_\delta \lambda}} + \frac{(L + \Omega + \nu^M_{r,c}) N}{2^{c-(R+1)\lambda}}$$

Application: Managing Leakage

Simplified Security Bound

$$\frac{q_{IV} N}{2^{k - q_\delta \lambda}} + \frac{(L + \Omega + \nu_{r,c}^{M}) N}{2^{c - (R+1)\lambda}}$$

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Simplified Security Bound

$$\frac{q_{IV} N}{2^{k - q_\delta \lambda}} + \frac{(L + \Omega + \nu_{r,c}^{M}) N}{2^{c-(R+1)\lambda}}$$

$q_\delta \leq$ # **allowed** IV**'s**

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Simplified Security Bound

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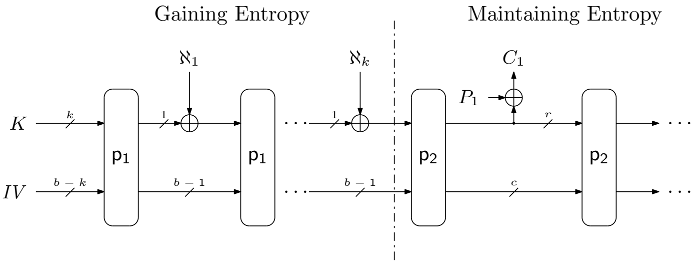
$q_\delta \leq$ # **allowed** IV**'s**

Limit $L + \Omega$ **or limit** R**?**

Application: Leakage Resilient Encryption (1)



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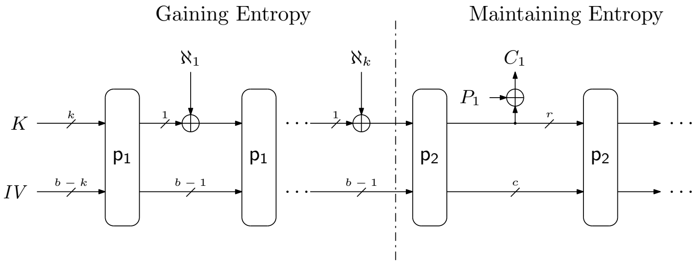

- Gain entropy in KD_1 from nonce at small rate

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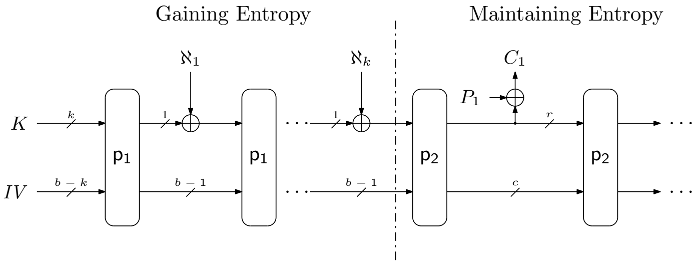

- Gain entropy in KD$_1$ from nonce at small rate
- Final state of KD$_1$ has high entropy (w.h.p.)

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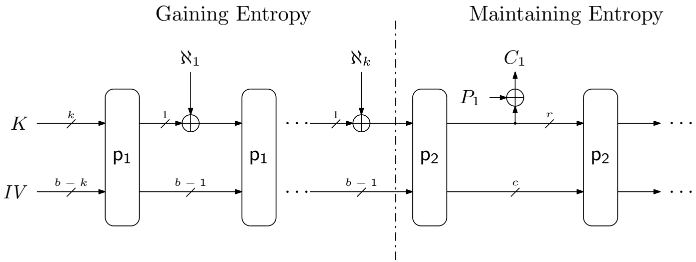

- Gain entropy in KD_1 from nonce at small rate
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- Inner part of state of KD_1 forms key to KD_2

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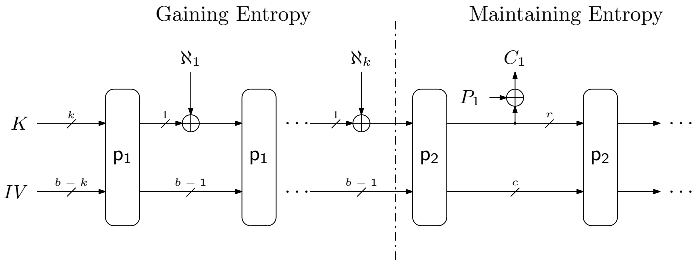
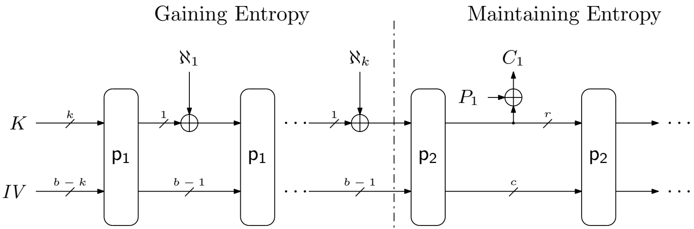


- Gain entropy in KD_1 from nonce at small rate
- Final state of KD_1 has high entropy (w.h.p.)
- Inner part of state of KD_1 forms key to KD_2
- Encrypt in KD_2 at high rate while maintaining high entropy (w.h.p.)

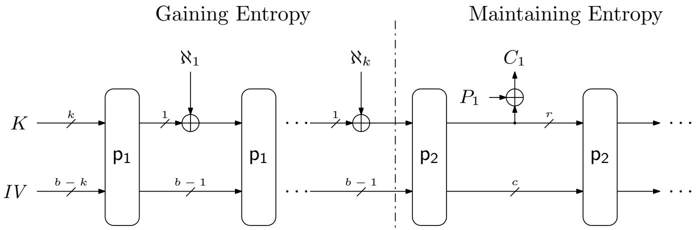
Application: Leakage Resilient Encryption (2)



- Paths may repeat: $L+\Omega$ arbitrary
- Small rate: $R+1 \leq 2^1+1 \leq 3$

- Unique paths: $L+\Omega=0$
- Large rate: $R+1=2$

Application: Leakage Resilient Encryption (2)



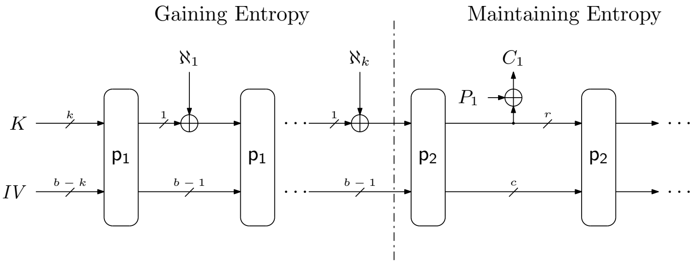
- Paths may repeat: $L + \Omega$ arbitrary
- Small rate: $R + 1 \le 2^1 + 1 \le 3$

$$\mathbf{Adv}^{\mathrm{nalr}}_{\mathsf{KD}_1}(\mathsf{D}) \lesssim \frac{QN}{2^{b-4\lambda}} + \frac{N^2}{2^b} + \frac{N}{2^{k-2\lambda}}$$

- Unique paths: $L + \Omega = 0$
- Large rate: $R + 1 = 2$

$$\mathbf{Adv}^{\mathrm{nalr}}_{\mathsf{KD}_2}(\mathsf{D}) \lesssim \frac{\nu^{M}_{r,c} N}{2^{c-2\lambda}} + \frac{QN}{2^{b-4\lambda}} + \frac{N^2}{2^b}$$

Application: Leakage Resilient Encryption (3)



$$\mathbf{Adv}_{\mathcal{E}}^{\text{nalr-cpa}}(\mathsf{D}) \leq 4 \cdot \mathbf{Adv}_{\mathsf{KD}_1}^{\text{nalr}}(\mathsf{D}') + 2 \cdot \mathbf{Adv}_{\mathsf{KD}_2}^{\text{nalr}}(\mathsf{D}'')$$

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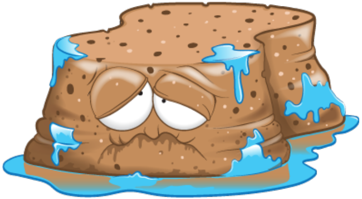
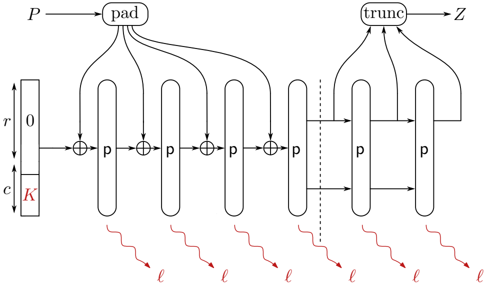
Leakage Resilience of Keyed Sponges





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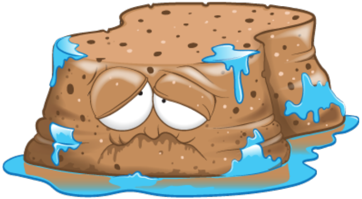

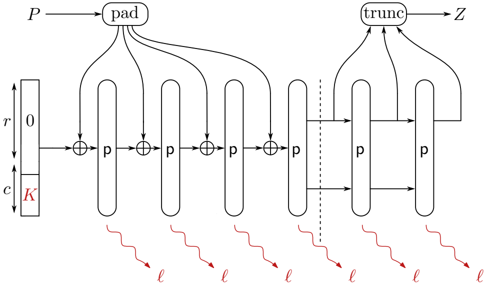

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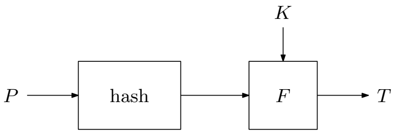
Minimizing leakage of keyed sponge?

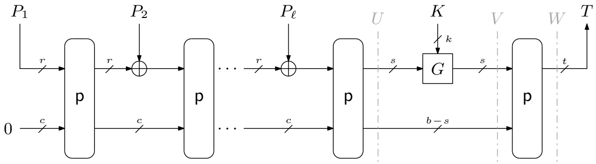
Hash-then-MAC



Typical Approach

- Hash function is unkeyed $\rightarrow$ 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



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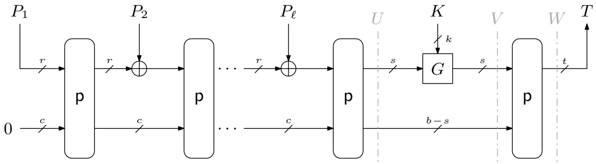

SuKS versus Full-Keyed Sponge

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

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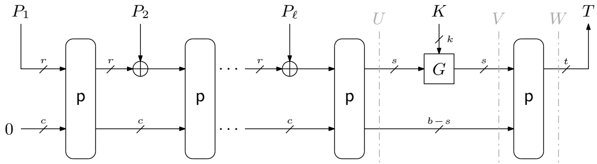

SuKS versus Full-Keyed Sponge

- No full-state absorption
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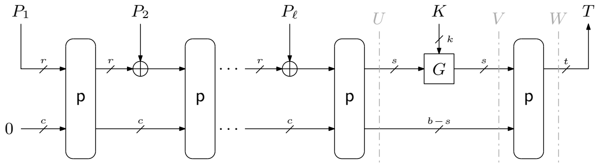
SuKS versus Hash-then-MAC

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

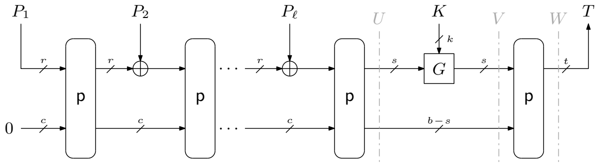
Security of SuKS



- $k, s, t \leq b$
- G is $2^{-\delta}$-uniform and $2^{-\epsilon}$-universal

$$\mathbf{Adv}_F^{\mathrm{prf}}(\mathsf{D}) \leq \frac{2N^2}{2^c} + \frac{\nu_{b-s,s}^{2(N-q)} \cdot N}{2^{\min\{\delta,\varepsilon\}}} + \frac{\nu_{t,b-t}^{q} \cdot N}{2^{b-t}}$$

Security of SuKS



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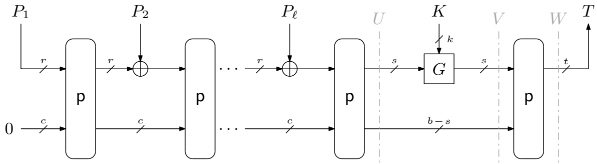
inner collision

Security of SuKS



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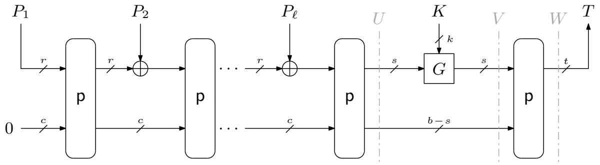
inner collision

"break at G", bounds primitive queries with same inner part

Security of SuKS



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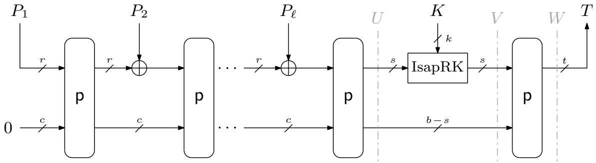
inner collision

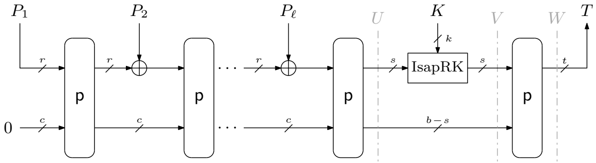
"break at T", bounds construction queries with same tag

"break at G", bounds primitive queries with same inner part

Application to MAC Part of ISAP [DEMMMPU19]



Application to MAC Part of ISAP [DEMMMPU19]

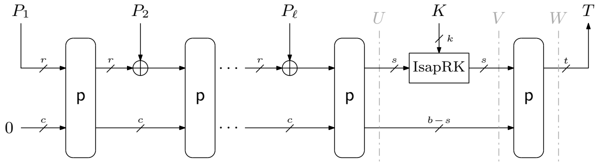


$$\boldsymbol{(b, c, r, k) = (400, 256, 144, 128)}$$

- $\nu_{b-s,s}^{2(N-q)} = \mu_{272,128}^{2^{129}} \leq 3$
- $\nu_{t,b-t}^{q} = \mu_{128,272}^{2^{128}} \leq 80$

$$\mathbf{Adv}_{\mathrm{IsapMAC}}^{\mathrm{prf}}(\mathsf{D}) \leq \frac{2N^2}{2^{256}} + \frac{3N}{2^{128}} + \frac{80N}{2^{272}}$$

Application to MAC Part of ISAP [DEMMMPU19]



$(b, c, r, k) = (400, 256, 144, 128)$

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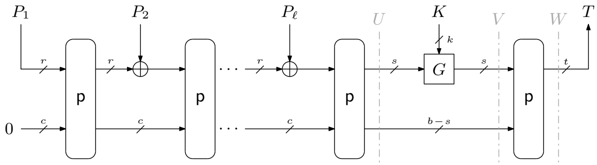
$$\mathbf{Adv}_{\text{IsapMAC}}^{\text{prf}}(\mathsf{D}) \leq \frac{2N^2}{2^{256}} + \frac{3N}{2^{128}} + \frac{80N}{2^{272}}$$

$(b, c, r, k) = (320, 256, 64, 128)$

- $\nu_{b-s,s}^{2(N-q)} = \mu_{192,128}^{2^{129}} \leq 5$
- $\nu_{t,b-t}^{q} = \mu_{128,192}^{2^{128}} \leq 67$

$$\mathbf{Adv}_{\text{IsapMAC}}^{\text{prf}}(\mathsf{D}) \leq \frac{2N^2}{2^{256}} + \frac{5N}{2^{128}} + \frac{67N}{2^{272}}$$

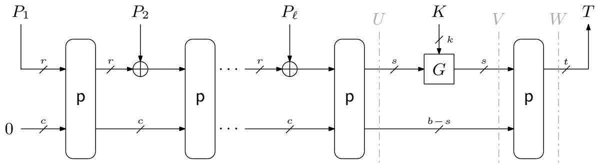
Leakage Resilience of SuKS



- $k, s, t \leq b$
- G is strongly protected, $2^{-\delta}$-uniform, and $2^{-\epsilon}$-universal

$$\mathbf{Adv}_F^{\text{nalr-prf}}(\mathsf{D}) \leq \frac{2N^2}{2^c} + \frac{\nu_{s,b-s}^{2(N-q)}}{2^{b-s}} + \frac{\nu_{b-s,s}^{2(N-q)} \cdot N}{2^{\min\{\delta,\varepsilon\} - \nu_{s,b-s}^{2(N-q)} \lambda}} + \frac{\nu_{t,b-t}^{2q} \cdot N}{2^{b-t-\lambda}}$$

Leakage Resilience of SuKS



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$$\mathbf{Adv}_F^{\text{nalr-prf}}(\mathsf{D}) \leq \frac{2N^2}{2^c} + \frac{\nu_{s,b-s}^{2(N-q)}}{2^{b-s}} + \frac{\nu_{b-s,s}^{2(N-q)} \cdot N}{2^{\min\{\delta,\varepsilon\}} + \nu_{s,b-s}^{2(N-q)}\lambda} + \frac{\nu_{t,b-t}^{2q} \cdot N}{2^{b-t-\lambda}}$$

bounds the number of repeated leakages on same $G(K, X)$

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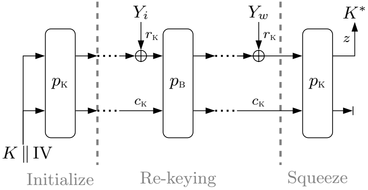
ISAP

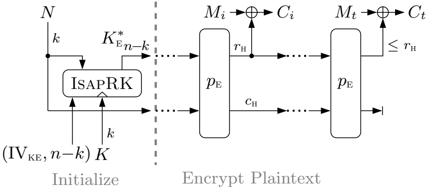
- LWC candidate [DEMMMPU19]

- Originally proposed at FSE 2017 [DEMMU17]
- Sponge/duplex-based authenticated encryption mode
- Instantiation:
  - Keccak-p$[400]$
  - Ascon-p
- Carefully selected capacities and rates:
  - Protection against DPA
  - Hardening against fault attacks: DFA, SFA, SIFA

Security of ISAP Mode



IsapRK



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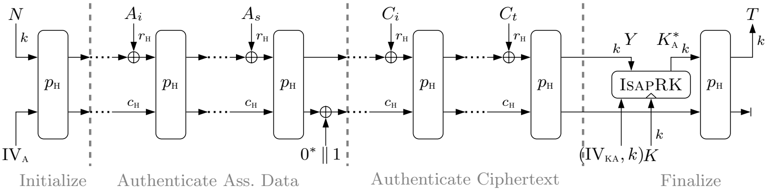
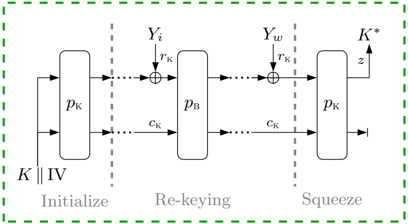


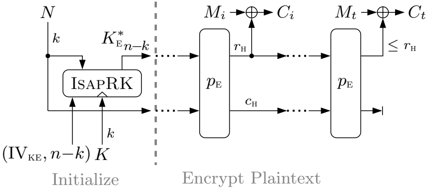
IsapMAC

Security of ISAP Mode

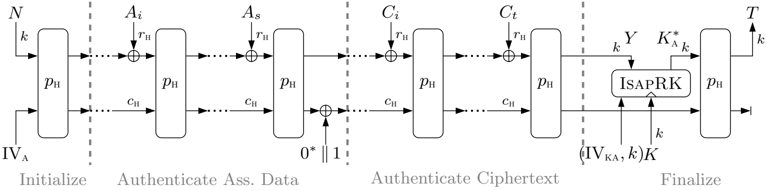


IsapRK

KD$_1$ with small rate

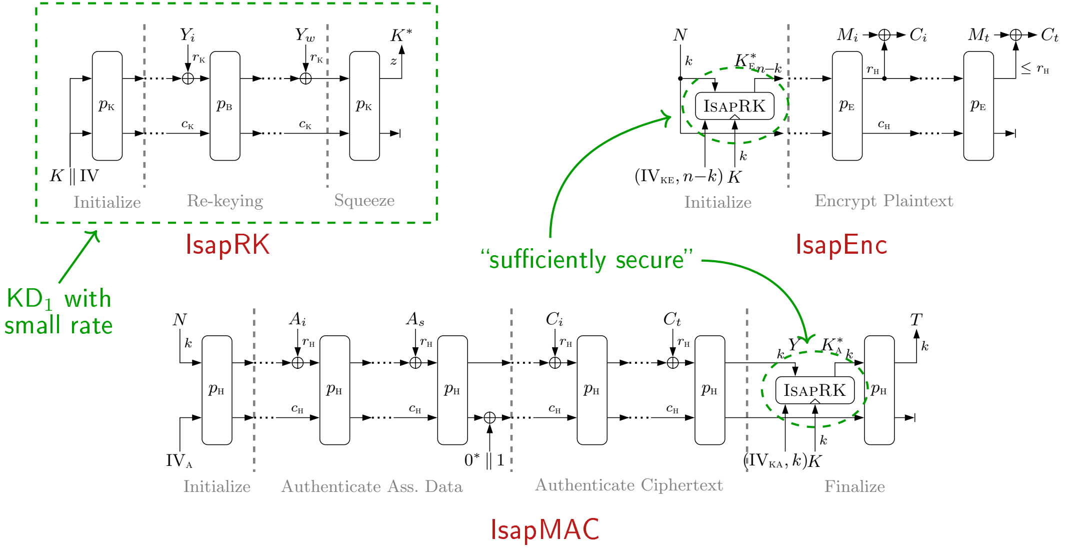


IsapEnc

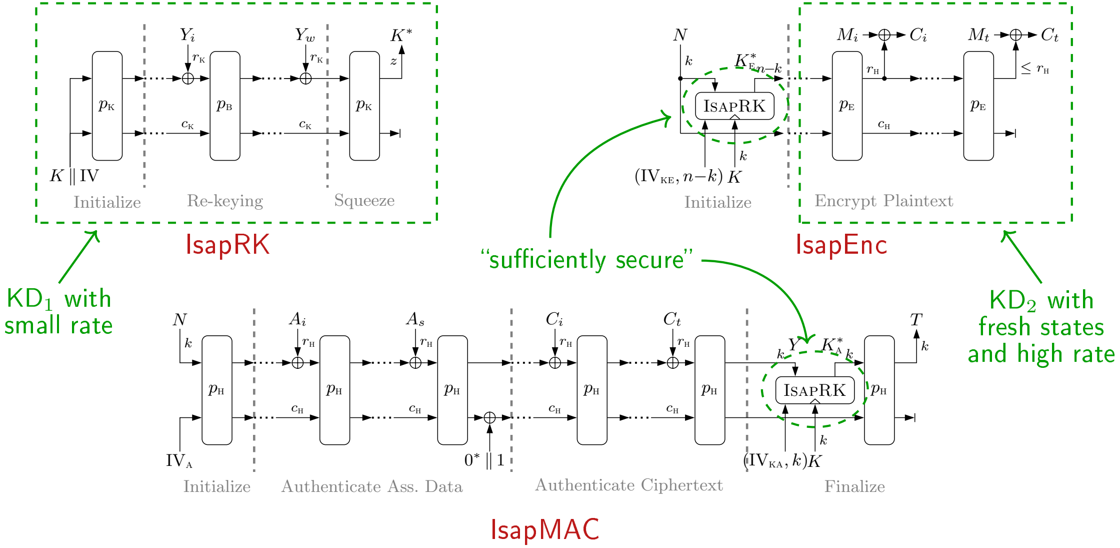


IsapMAC

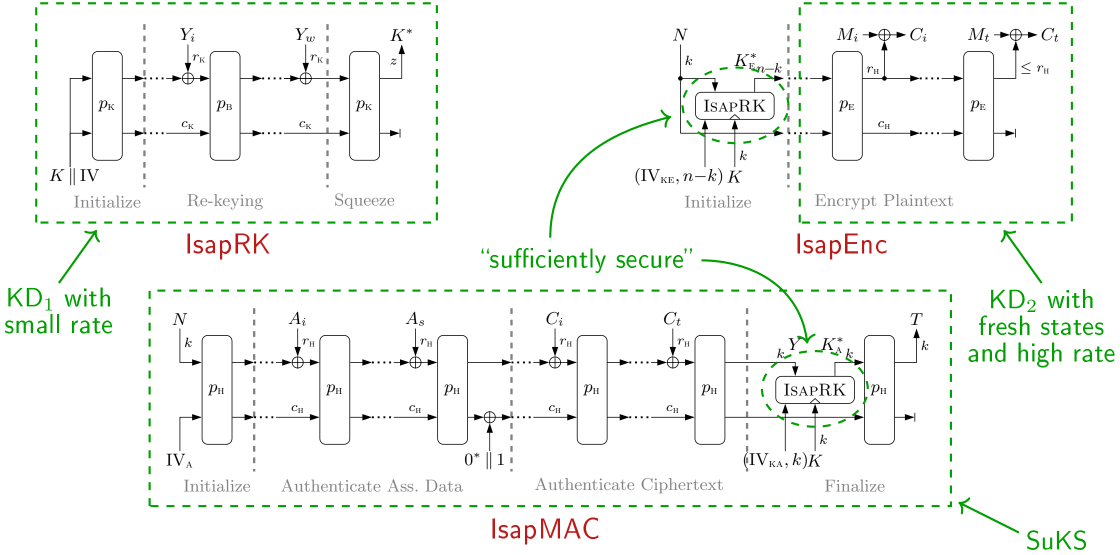
Security of ISAP Mode



Security of ISAP Mode



Security of ISAP Mode



Outline

Leakage Resilience of the Duplex Construction

Security of the Suffix Keyed Sponge

Application to ISAP

Conclusion

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ISAP

- Built-in security against side-channel and fault attacks
- Higher order security without higher order masking!

Conclusion

ISAP

- Built-in security against side-channel and fault attacks
- Higher order security without higher order masking!

Leakage Resilience

- Follows from:
    - Leakage resilience of Keyed Duplex [DM19a]
    - Leakage resilience of Suffix Keyed Sponge [DM19b]
- Proof in alternative model given by Guo et al. [GPPS19]

Thank you for your attention!