Symmetric-key Cryptography: an Engineering Perspective

Nicky Mouha

[1]ESAT/COSIC, KU Leuven and iMinds, Belgium
[2]Project-team SECRET, Inria, France

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Overview

Engineering Perspective

- Design, analysis, implementation
- Basic concepts and techniques

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Two Parts

- Hash functions
- MAC algorithms

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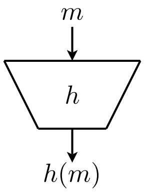
- Hash functions
- MAC algorithms

Simplified View

- Small inaccuracies, details missing
- Incomplete study: citations missing

Part I:
Hash Functions

Hash Function



Hash Function h

- Generates a short “fingerprint” of a message

Security Requirements

- One-way function:
  given Y, hard to find $m : h(m) = Y$
- Collision resistant function:
  hard to find $m \neq m' : h(m) = h(m')$
- ...

SHA-3 Competition (2008-2012)

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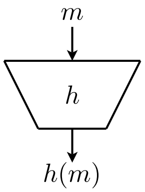

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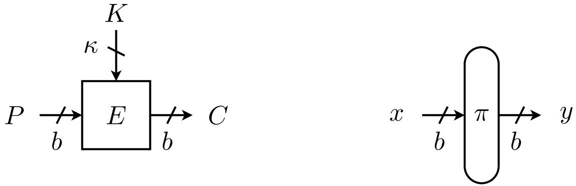
Permutation-Based Hash Functions

Hash Functions Based on Permutations

- Simpler to design: no key schedule
- Block-cipher-based: see later



(Cryptographic) Permutation

- Provable security: statistical object (random permutation)
- Cryptanalysis: deterministic algorithm (no "distinguishers")

Hash Function Rate

Hash Function Rate α

- $\alpha = \frac{\text{data processed per permutation call (in bits)}}{\text{permutation size (in bits)}}$
- Note: various definitions of "rate" exist!

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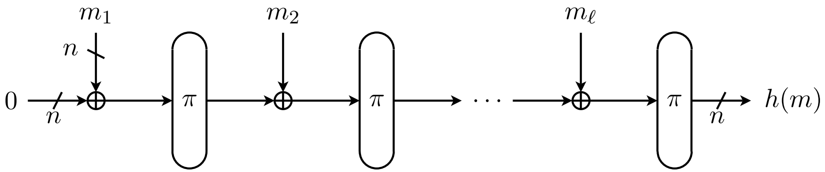
Ideal Construction

- Rate-1 hash function: $\alpha = 1$

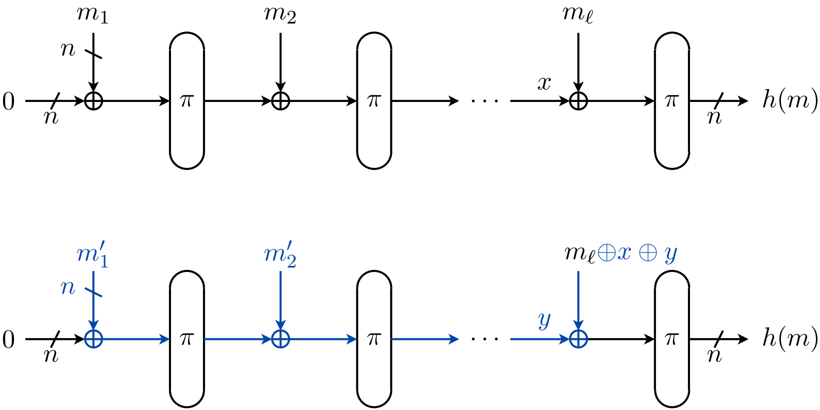
Rate-1 Hash Function: First Attempt

Simplest Rate-1 Hash Function



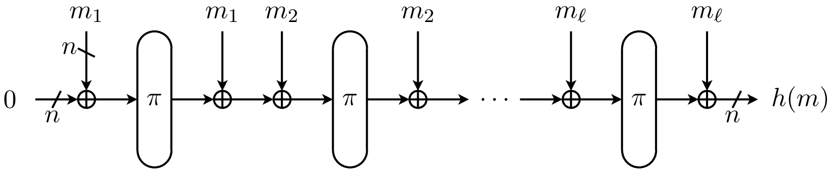
Rate-1 Hash Function: First Attempt

Collision: Correcting Block Attack



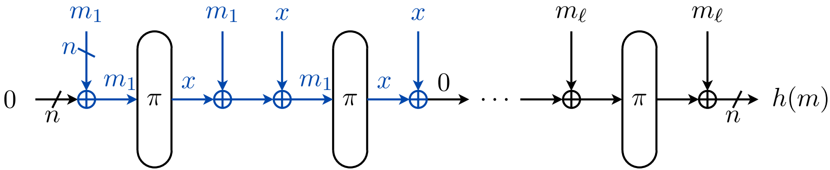
Rate-1 Hash Function: Second Attempt

Another Rate-1 Hash Function



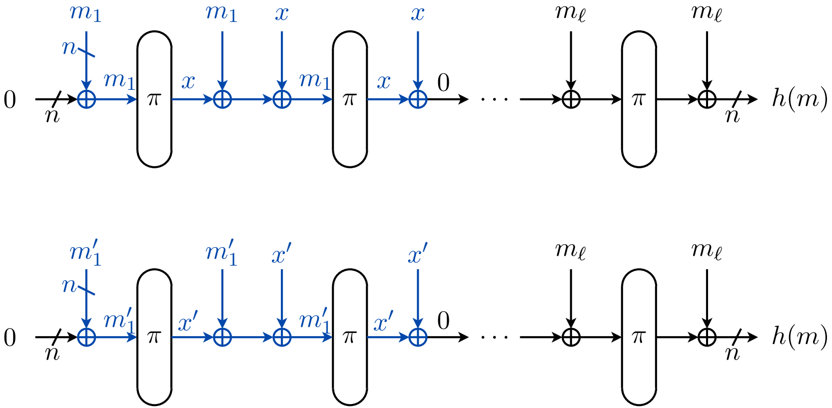
Rate-1 Hash Function: Second Attempt

Observation

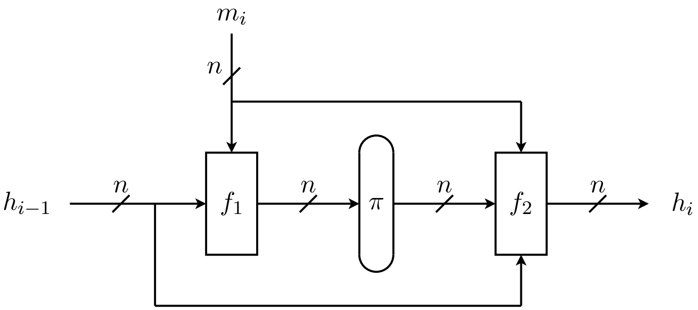


Rate-1 Hash Function: Second Attempt

Collision Attack (Black et al., Crypto '02)



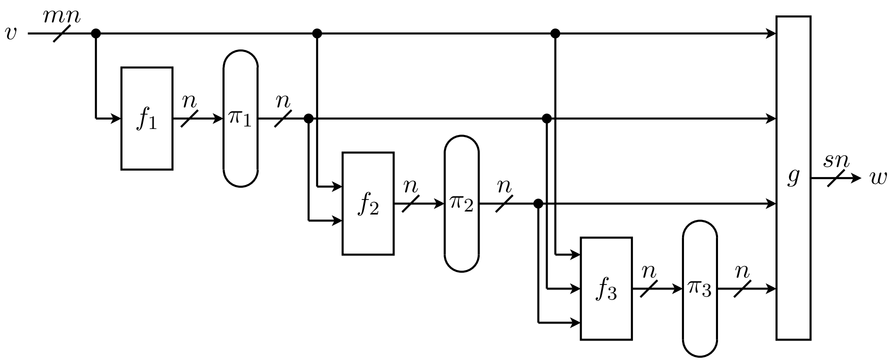
Impossibility Result



Black et al. (Eurocrypt '05)

- Compression function from n-bit permutation
- Information-theoretic: f_1, f_2 can be any function
- Generic collision attack: at most $n + \lceil \log_2(n) \rceil$ queries

Security/Efficiency Tradeoffs



Rogaway-Steinberger (Eurocrypt '08)

- Compression function from k n-bit permutations
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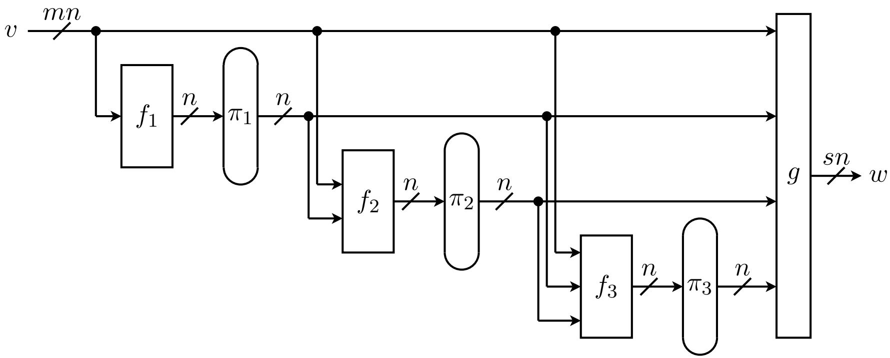
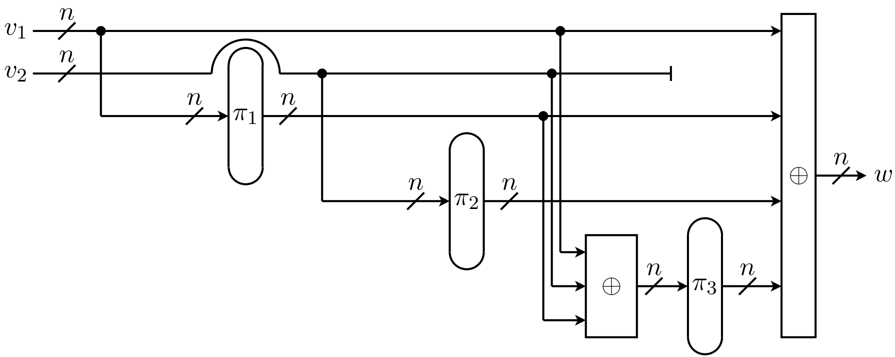
Security/Efficiency Tradeoffs



Rogaway-Steinberger (Eurocrypt '08)

- Compression function from $k = 3$ n-bit permutations
- Information-theoretic: f_i can be any function, $m = 2$, $s = 1$
- Generic collision attack: $2^{n[1-(2-0.5\cdot 1)/3]} = 2^{n/2}$

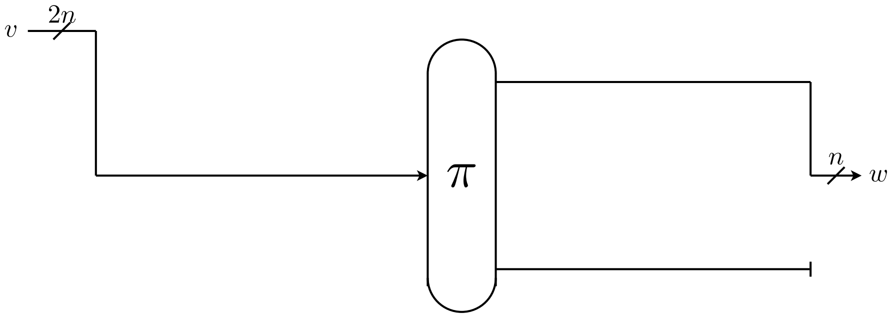
Security/Efficiency Tradeoffs



Mennink-Preneel (Crypto '12)

- Compression function from $k = 3$ n-bit permutations
- Constructions with only XORs, first systematic analysis
- Optimal collision resistance: $2^{n/2}$

Security/Efficiency Tradeoffs



Why Not One Big Permutation?

- $2n$-bit permutation instead of n-bit
- Same generic collision attack: $2^{n/2}$
- More efficient than three n-bit permutations?

Scaling Law

"When the input size of a symmetric-key primitive doubles, the number of operations (roughly) doubles as well".

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Remarks

- Not intuitive: $b \to b$ bits: $(2^b)^{2^b} = 2^{b2^b}$ functions
- Not rigorous: based on design choices and attacks
- How to count "operations"?

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Next Slides: Scaling Law Examples

Scaling Law: Fixed Word Size

PHOTON: 4-bit Words

- 100/144/196/256-bit permutation: 12 rounds
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Skein: 64-bit Words

- 256/512-bit block/key size: 72 rounds
- 1024-bit block/key size: 80 rounds
- Overdesign? Best (non-biclique) attack is on 36 rounds (Yu et al., SAC '13)

Scaling Law: Variable Word Size

BLAKE

- 960-to-256-bit: 14 rounds (32-bit words)
- 1920-to-512-bit: 16 rounds (64-bit words)

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Keccak

- 800-bit permutation: 22 rounds (32-bit words)
- 1600-bit permutation: 24 rounds (64-bit words)
- Note: zero-sum distinguisher for full-round 1600-bit permutation (Boura et al., Duan-Lai)

Scaling Law: Counterexamples?

Grøstl

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- 272-bit Spongent: 5x lower throughput than 256-bit PHOTON (Bogdanov et al., IEEE Trans. Comp. 2013)

Hash Functions with $2^{n/2}$ Collision Resistance

Rate-1 Hash Function $(\alpha = 1)$

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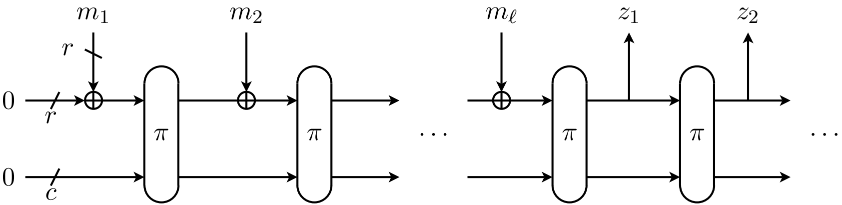
Higher Rate Possible? $(0.5 < \alpha < 1)$

- Yes, arbitrarily close to $\alpha = 1$!
- See next slide...

Sponge Function

Sponge Function

- $\alpha = \frac{r}{r+c}$



Example

- SHA3-256: $c = 512$, $r + c = 1600$, $\alpha = 0.68$

Concatenate-Permute-Truncate

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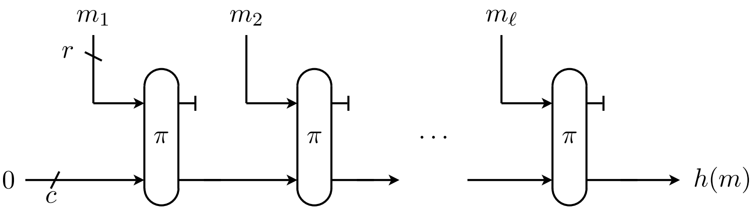
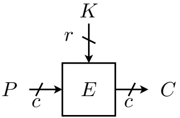


Example

- Grindahl-256: $r = 32$, $r + c = 416$, $\alpha = 0.08$
  (Note: low α, but compensated by weak π)

Merkle-Damgård with Davies-Meyer



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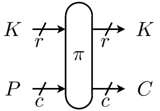

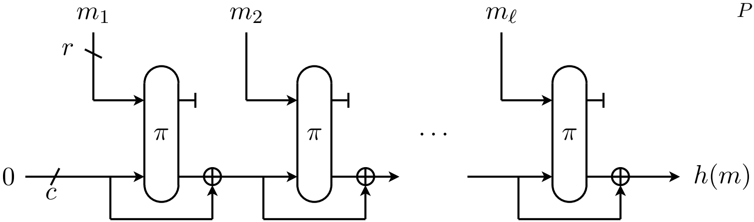

Example

- SHA256: $c = 256$, $r = 512$, $\alpha = 0.67$

Considerations

Lightweight

- Small hardware implementation
- Achieved by small permutation!
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Other Criteria

- Software: register pressure, instruction set, parallelism,...
- Hardware: throughput, latency, power, energy,...
- Both: message length, reuse of function/library, secure implementation, interoperability, standards compliance,...

Conclusion

Permutation-Based Hash Functions

- Engineering approach
- Tradeoffs for theory/cryptanalysis/implementation
- Simplified model: inaccuracies in figures, designs

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Goal

- Help to understand design choices
- No intention to critize certain designs!
- Feedback is welcome

Part II:
MAC Algorithms

Chaskey: An Efficient MAC Algorithm for 32-bit Microcontrollers

Nicky Mouha[1], Bart Mennink[1], Anthony Van Herrewege[1], Dai Watanabe[2], Bart Preneel[1], Ingrid Verbauwhede[1]

[1]ESAT/COSIC, KU Leuven and iMinds, Belgium
[2]Yokohama Research Laboratory, Hitachi, Japan

Presented at SAC 2014

MAC Algorithm for Microcontrollers

Message Authentication Code (MAC)

- $\text{MAC}_K(m) = \tau$
- Authenticity, no confidentiality
- Same key for MAC generation and verification

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Microcontroller

- Cheap 8/16/32-bit processor: USD 25-50¢
- Applications: home, medical, industrial,...
- Ubiquitous: 30-100 in any recent car

Design

Requirements

- Drop-in replacement for AES-CMAC
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Approach

- Dedicated design for microcontrollers

Commonly used MACs

Based on (cryptographic) hash function

- **Example:** HMAC, SHA3-MAC
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Based on block cipher

- **Example:** CMAC
- **Problem:** ten times too slow!

Our Approach

Every cycle counts!

- Avoid load/store: keep data in registers
- Avoid bit masking
- Make optimal use of instruction set

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Bridging the gap

- Cryptanalysis
- Provable security
- Implementation

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Which primitive?

- Cryptographic hash function ✗

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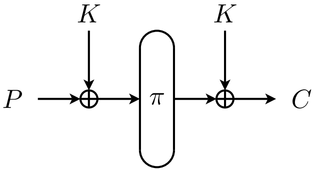

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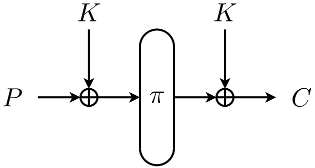
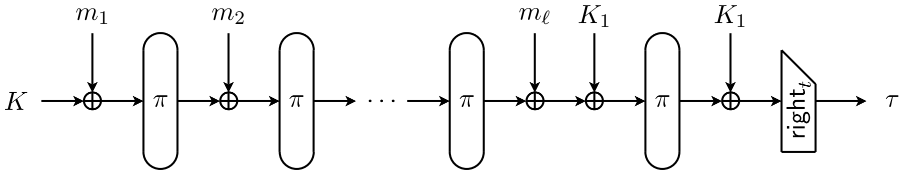


Related-key attacks

- Insecure: choose uniformly random keys!

Chaskey: Mode of Operation

- Split m into ℓ blocks of n bits
- Top: $|m_\ell| = n$
- $K_1 = 2K$



Chaskey: Mode of Operation

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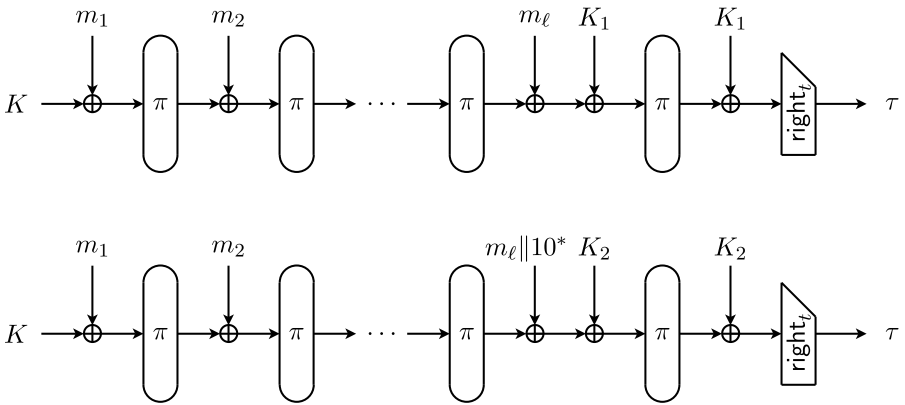

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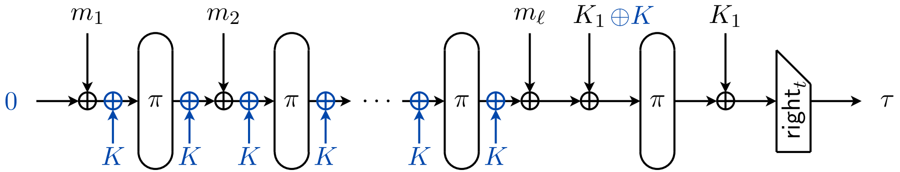

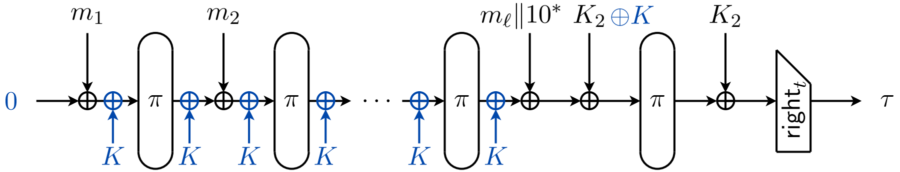

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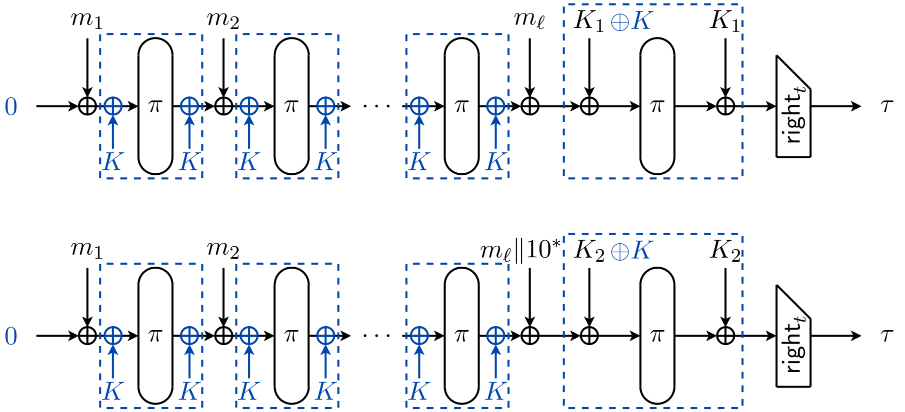

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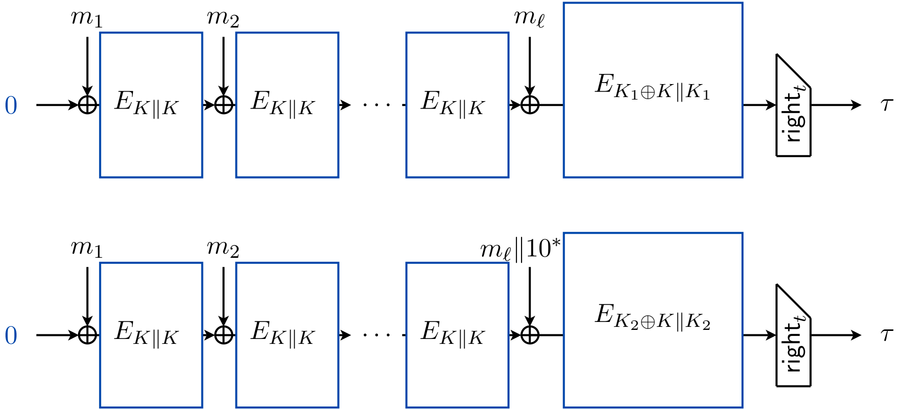

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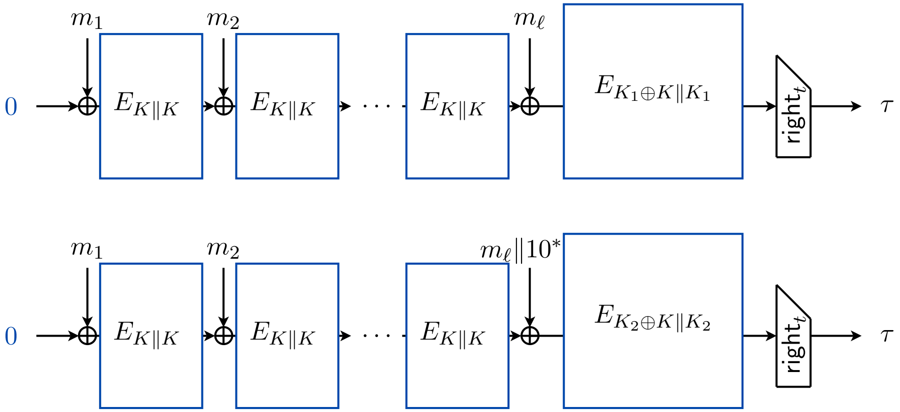
variant of FCBC [BR'00]



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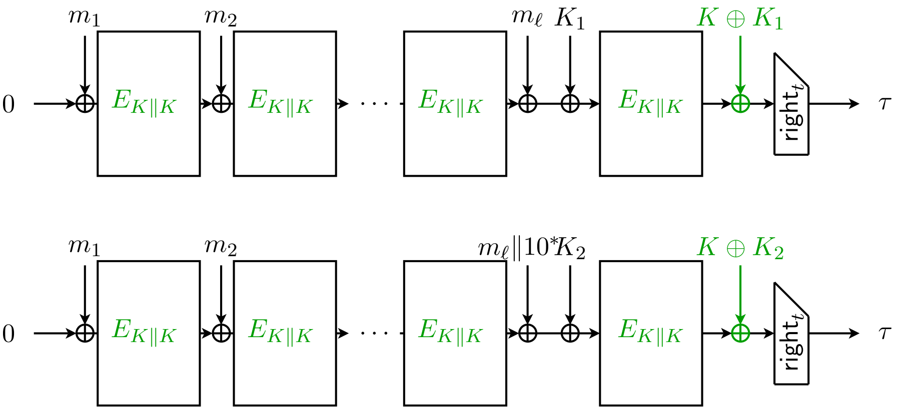

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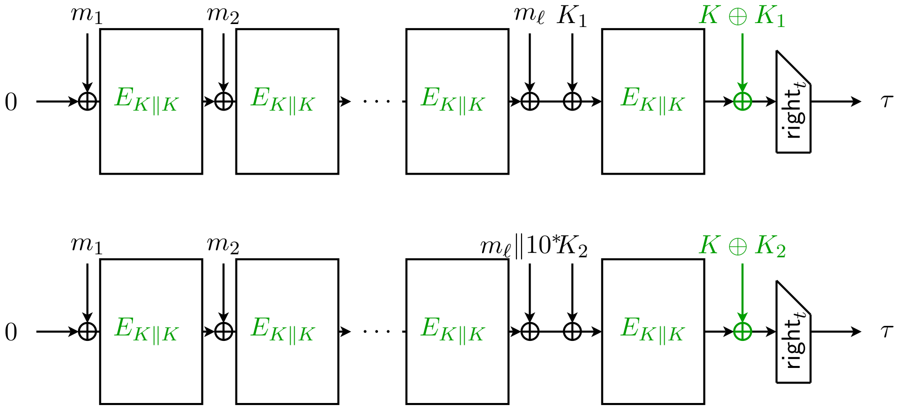

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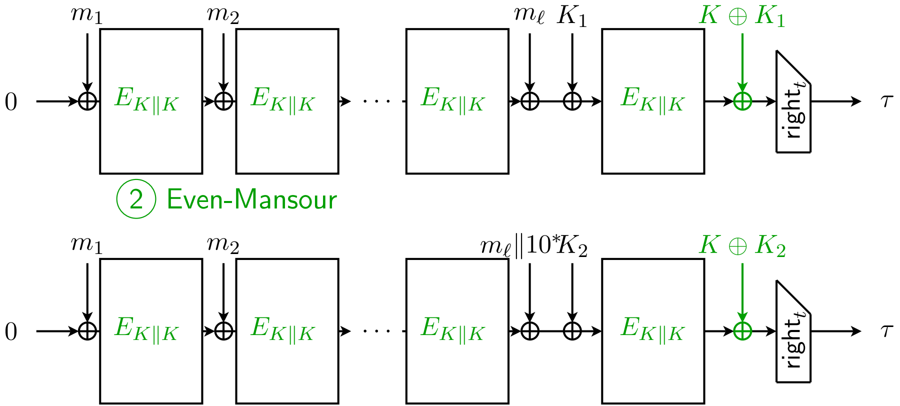
variant of CMAC [IK'03]

① $E_K(0^n) \rightarrow K$

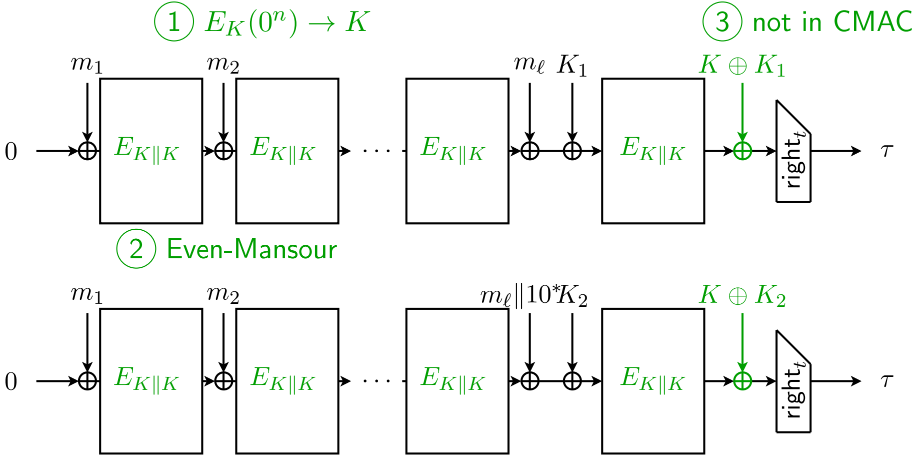
② Even-Mansour



Chaskey: Mode of Operation: Compared to CMAC

- Split m into ℓ blocks of n bits
- Top: $|m_\ell| = n$, bottom: $0 \leq |m_\ell| < n$
- $K_1 = 2K$, $K_2 = 4K$

variant of CMAC [IK'03]



Cryptanalysis

MAC forgery: find new valid (m, τ)

- D: data complexity (# chosen plaintexts)
- T: time complexity (# permutation eval.)

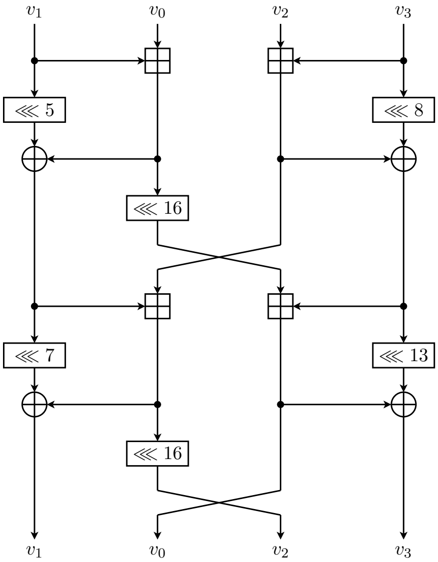
Attacks

- Internal collision: $D \approx 2^{n/2}$
- Key recovery: $T \approx 2^n / D$
- Tag guessing: $\approx 2^t$ guesses

Chaskey parameters

- Key size, block size: $n = 128$, tag length: $t \geq 64$

Permutation



Design

- Add-Rot-XOR (ARX)
- Inspired by SipHash
- 32-bit words
- 8 rounds

Properties

- Rotations by 8, 16:
  faster on 8-bit μC
- Fixed point: $0 \to 0$
- Cryptanalysis: rotational, (truncated) differential, MitM, slide,... see paper!

Chaskey: Speed Optimized (gcc -O2)

Microcontroller	Algorithm	Data [byte]	ROM [byte]	Speed [cycles/byte]
Cortex-M0	AES-128-CMAC	16	13 492	173.4
		128	13 492	136.5
	Chaskey	16	1 308	21.3
		128	1 308	18.3
Cortex-M4	AES-128-CMAC	16	28 524	118.3
		128	28 524	105.0
	Chaskey	16	908	10.6
		128	908	7.0

Chaskey: Size Optimized (gcc -Os)

Microcontroller	Algorithm	Data [byte]	ROM [byte]	Speed [cycles/byte]
Cortex-M0	AES-128-CMAC	16	11 664	176.4
		128	11 664	140.0
	Chaskey	16	414	21.8
		128	414	16.9
Cortex-M4	AES-128-CMAC	16	10 925	127.5
		128	10 925	89.4
	Chaskey	16	402	16.1
		128	402	11.2

Conclusion and Current Status

Chaskey:

MAC algorithm for 32-bit microcontrollers

- Addition-Rotation-XOR (ARX)
- Even-Mansour block cipher
- ARM Cortex-M: 7-15$\times$ faster than AES-128-CMAC

Conclusion and Current Status

Chaskey:

MAC algorithm for 32-bit microcontrollers

- Addition-Rotation-XOR (ARX)
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Standardization

- Chaskey: currently in study period
- ISO/IEC JTC1 SC27: MAC standardization
- ITU-T SG17: crypto for IoT, ITS

Questions?

Supporting Slides

Security Proof

MAC forgery: find new valid (m, τ)

- D: block cipher (PRP) queries
- T: permutation queries

Standard Model

- $\mathbf{Adv}^{\mathsf{mac}}_{\text{Chaskey-B}}(q, D, r) \leq \frac{2D^2}{2^n} + \frac{1}{2^t} + \mathbf{Adv}^{\mathsf{3prp}}_{E}(D, r)$

Ideal Permutation Model

- $\mathbf{Adv}^{\mathsf{mac}}_{\text{Chaskey}}(q, D, r) \leq \frac{2D^2}{2^n} + \frac{1}{2^t} + \frac{D^2 + 2DT}{2^n}$