Security Analysis of BLAKE2's Modes of Operation

Atul Luykx, Bart Mennink, Samuel Neves

KU Leuven (Belgium) and Radboud University (The Netherlands)

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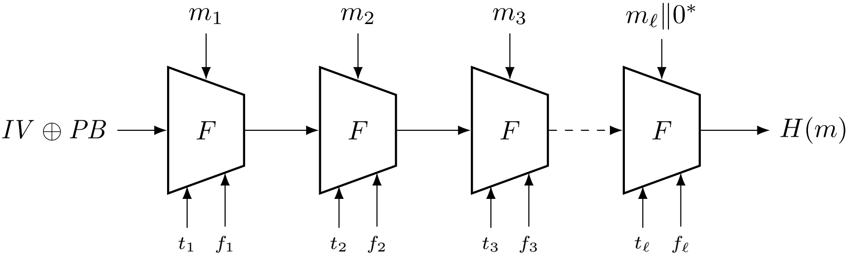
BLAKE2



- Cryptographic hash function
- Aumasson, Neves, Wilcox-O'Hearn, Winnerlein (2013)
- Simplification of SHA-3 finalist BLAKE

BLAKE2

Use in Password Hashing

- Argon2 (Biryukov et al.)
- Catena (Forler et al.)
- Lyra (Almeida et al.)
- Lyra2 (Simplício Jr. et al.)
- Rig (Chang et al.)

Use in Authenticated Encryption

- AEZ (Hoang et al.)

Applications

- Noise Protocol Framework (Perrin)
- Zcash Protocol (Hopwood et al.)
- RAR 5.0 (Roshal)

Security Inheritance?

	BLAKE
cryptanalysis	Aumasson et al. 2010 Biryukov et al. 2011 Dunkelman&K. 2011
generic	Andreeva et al. 2012 Chang et al. 2012

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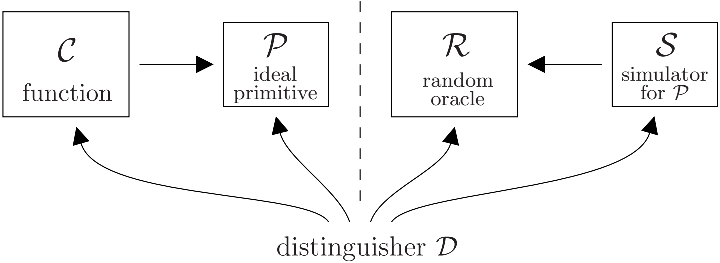
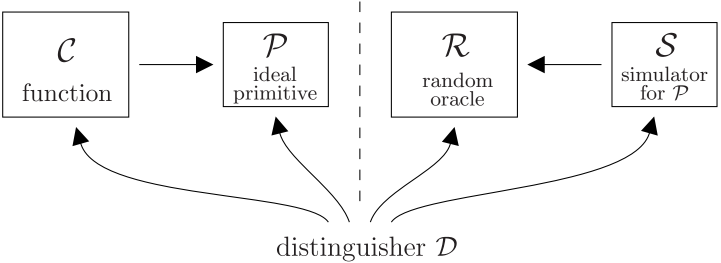
Even slight modifications may make a scheme insecure!

Indifferentiability



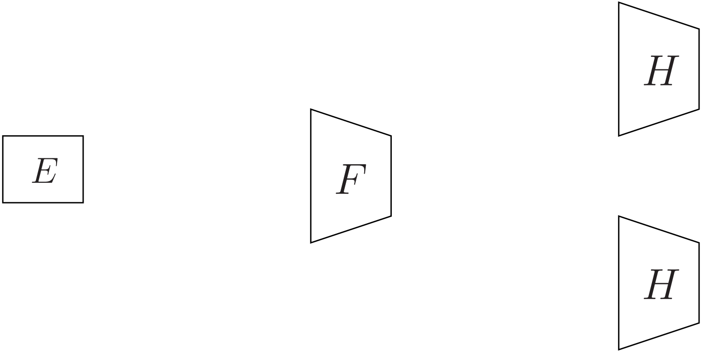
- Indifferentiability of function $\mathcal{C}$ from a random oracle
- $\mathcal{C}^{\mathcal{P}}$ is indifferentiable from $\mathcal{R}$ if $\exists$ simulator $\mathcal{S}$ such that $(\mathcal{C}, \mathcal{P})$ and $(\mathcal{R}, \mathcal{S})$ indistinguishable

Indifferentiability



- Indifferentiability of function $\mathcal{C}$ from a random oracle
- $\mathcal{C}^{\mathcal{P}}$ is indifferentiable from $\mathcal{R}$ if $\exists$ simulator $\mathcal{S}$ such that $(\mathcal{C}, \mathcal{P})$ and $(\mathcal{R}, \mathcal{S})$ indistinguishable
- No structural design flaws
- Well-suited for composition

Composition



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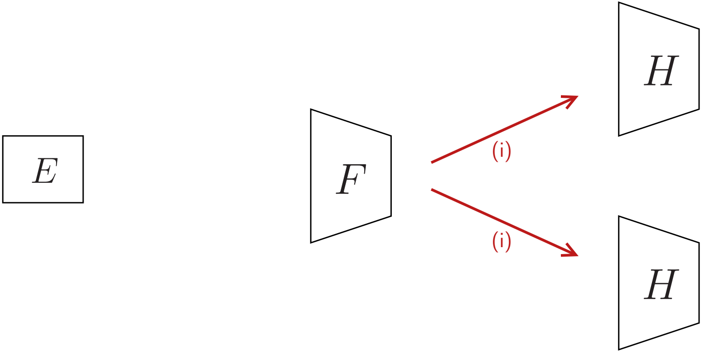

(i) First hash-function indifferentiability results

- Chop-/PF-MD with ideal $F \longrightarrow$ indifferentiable

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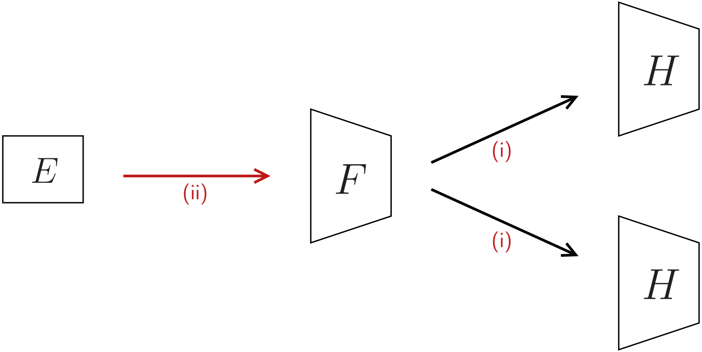

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(ii) Most obvious second step (composition)
- But (e.g.) Davies-Meyer with ideal $E \longrightarrow$ differentiable

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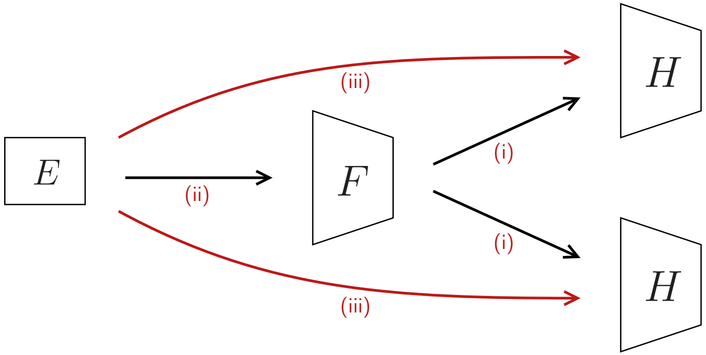

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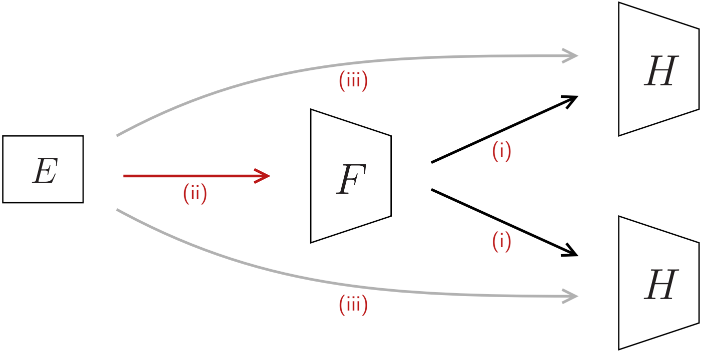

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Our Results

Compression Level Indifferentiability

- BLAKE2 indifferentiable at compression function level
- Immediately implies
  - indifferentiability of sequential hash mode
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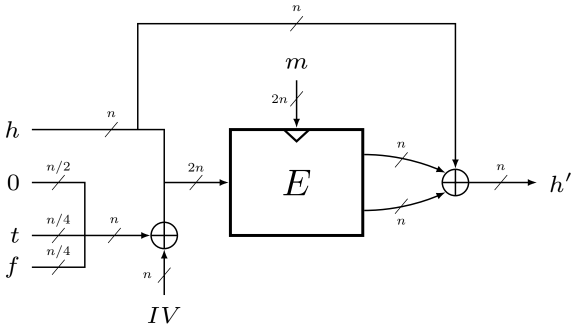
Weakly Ideal Cipher Model

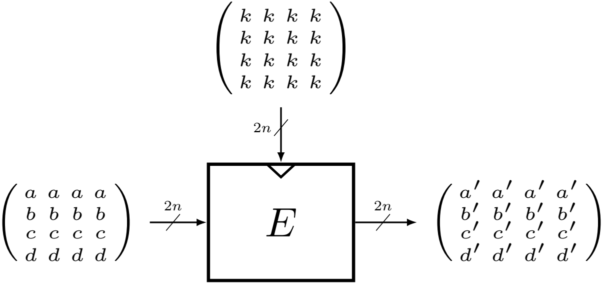
- BLAKE2 cipher has known, but harmless, properties
- Analysis tolerates these properties

BLAKE2 Compression Function



- h is state, m is message, t is counter, f is flag
- IV is initialization value

Underlying Block Cipher



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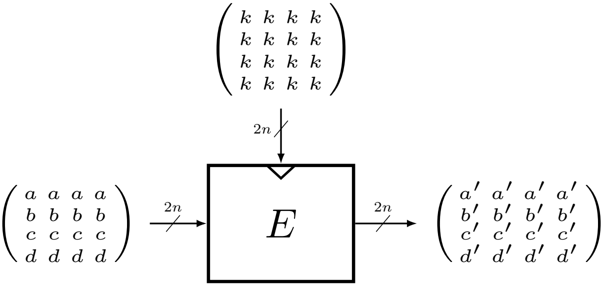

Weakly Ideal Cipher Model

- E is an ideal cipher modulo above property

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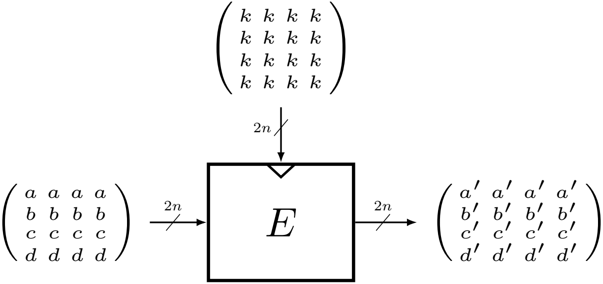

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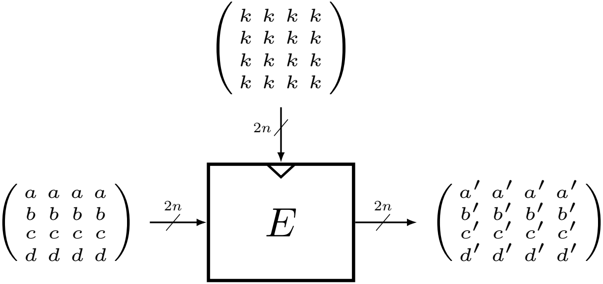
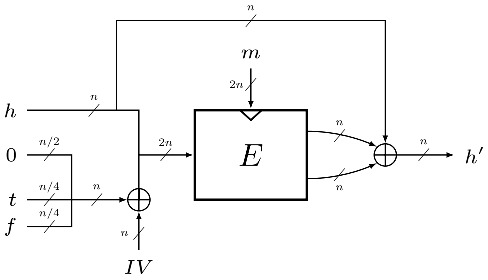


Weakly Ideal Cipher Model

- E is an ideal cipher modulo above property
- Weak- and strong-subspace invariance for weak keys
- Evaluation of E in BLAKE2 is never weak
  (as left half of IV is not of the form $cccc$)

Proof Idea

Construction F^E:



Simulator $\mathcal{S}$:

Proof Idea

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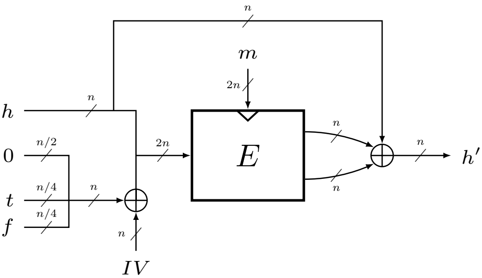

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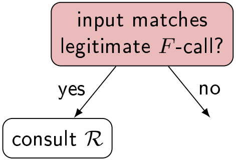

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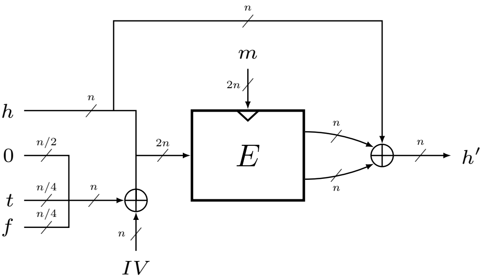

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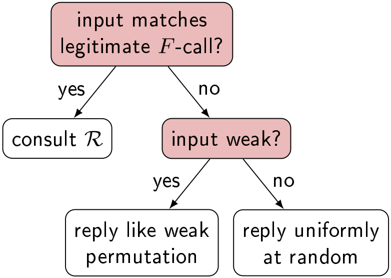

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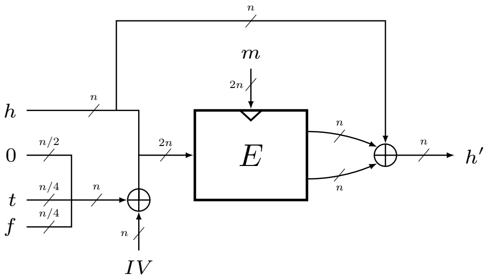

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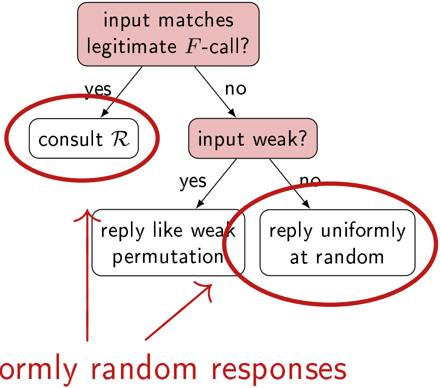

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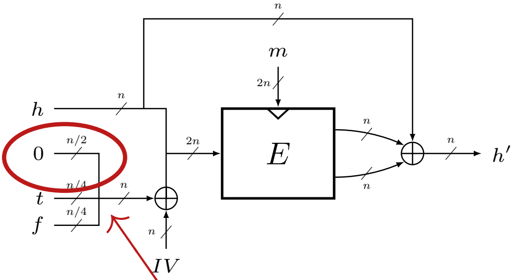
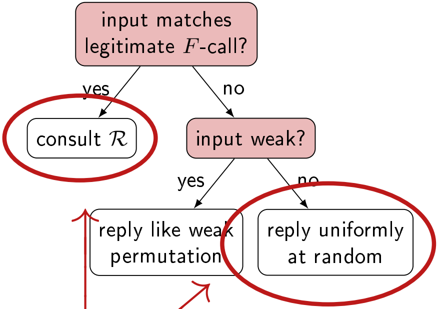


inverse query hits 0-block

Simulator $\mathcal{S}$:



collision in uniformly random responses

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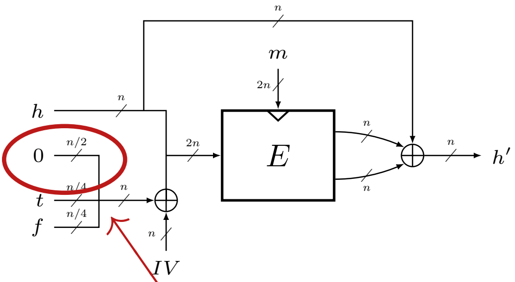

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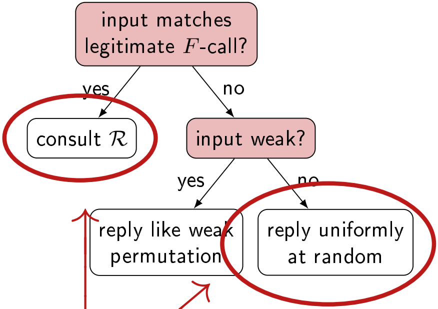

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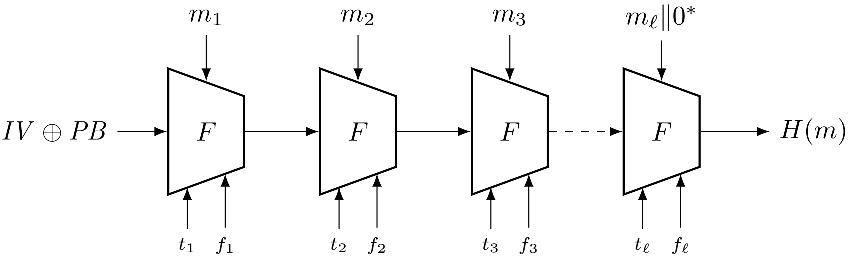
$$\mathsf{Indiff}_{F^E,\mathcal{S}}(q) = \Theta\left(\frac{q}{2^{n/2}}\right)$$

BLAKE2 Hashing Modes



- Message m padded into $m_1 \| \cdots \| m_\ell$
- $t_1 \| \cdots \| t_\ell$ are counter values, $f_1 \| \cdots \| f_\ell$ are flags
- PB is a parameter block

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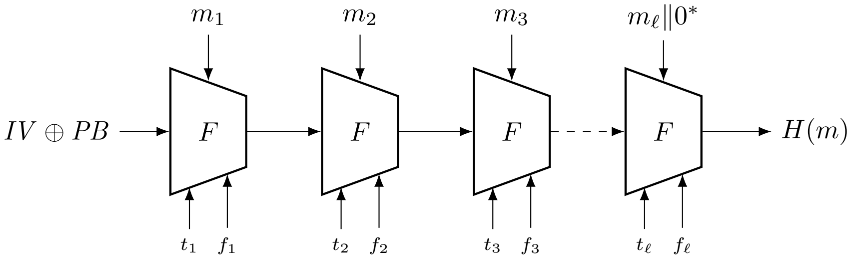

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Prefix-Free Merkle-Damgård?

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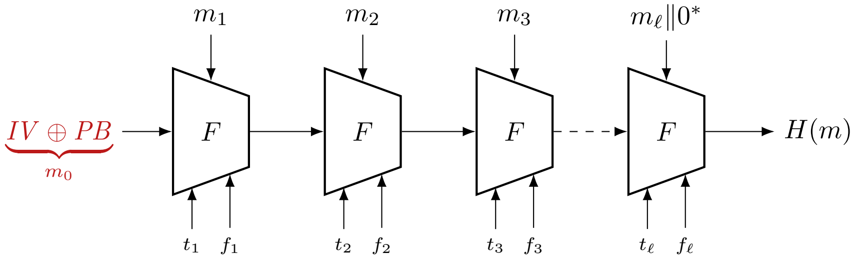

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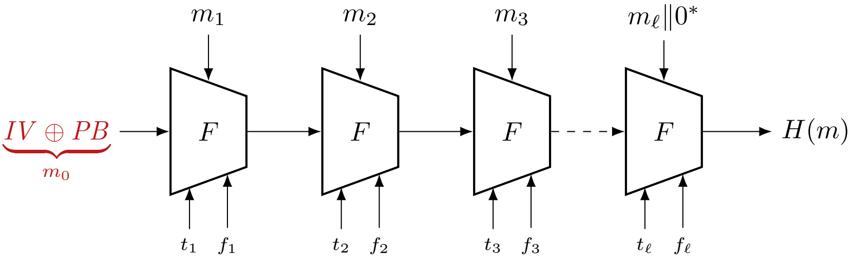

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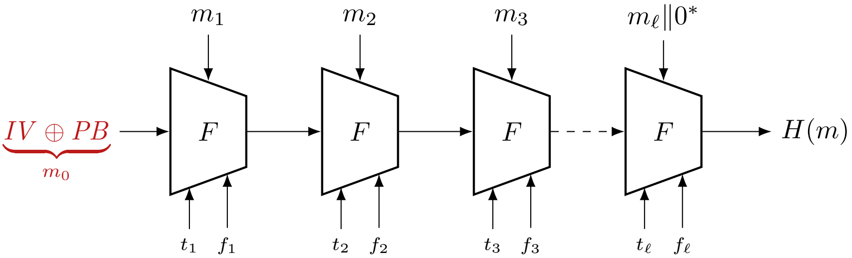

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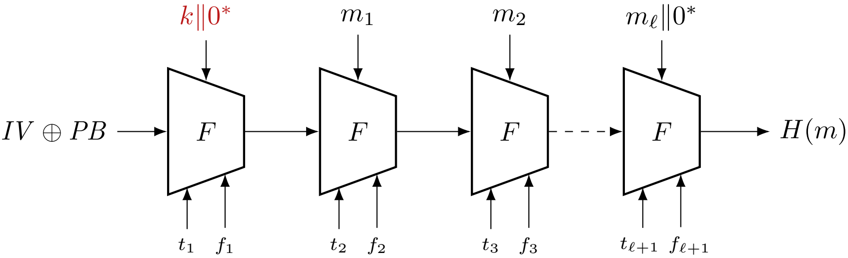
- Same reasoning for tree and parallel modes of BLAKE2

Keyed BLAKE2 Mode



- Key k as first message block, rest unchanged

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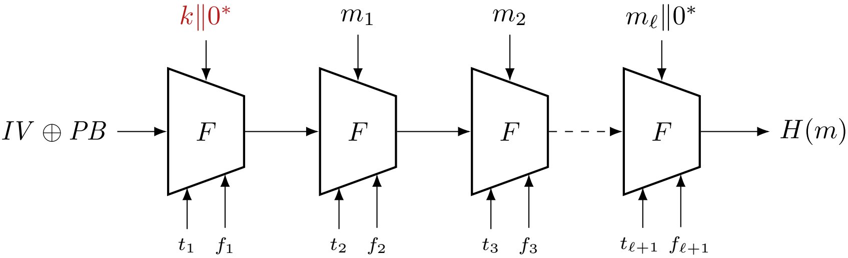

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1. Multi-key PRF security if BLAKE2 is random oracle

$$\mathsf{Prf}_{KH^E}(q) = \frac{\mu q}{2^\kappa} + \frac{\binom{\mu}{2}}{2^\kappa}$$

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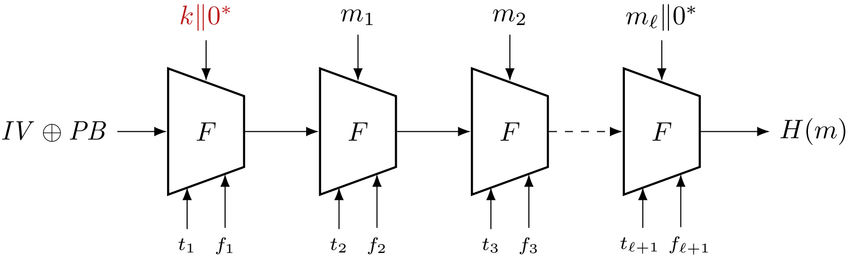

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1. Multi-key PRF security if BLAKE2 is random oracle
2. Indifferentiability of BLAKE2 with weakly ideal cipher

$$\mathsf{Prf}_{KH^E}(q) = \frac{\mu q}{2^\kappa} + \frac{\binom{\mu}{2}}{2^\kappa} + \Theta\left(\frac{q}{2^{n/2}}\right)$$

Conclusion

Indifferentiability of BLAKE2

- Short compression function indifferentiability proof
- Security of hashing modes due to composition

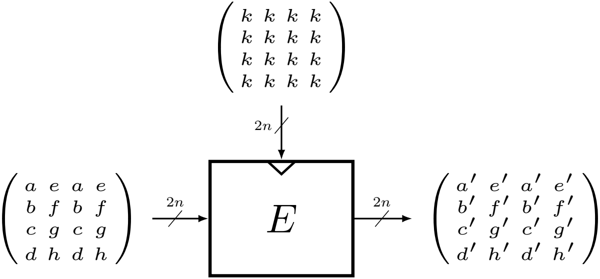
Optimality?

- Birthday bound security in the end
- Improved analysis for (second) preimage resistance?
- PRF security: direct analysis could give better result

Thank you for your attention!

Supporting Slides

Underlying Block Cipher



"Cryptanalysis of NORX v2.0" by Chaigneau et al.

- An unexpected structural property of E
- Analysis easily extends to this property
- Left half of IV is not of the form $cgcg$ either