SPN-Hash: Improving the Provable Resistance Against Collision Attacks

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What is SPN Hash?

- A Hash Function based on well-studied SPN structure.
- Generalized the optimal diffusion of SPN structure
  - So that more block sizes with good differential bounds can be constructed.
- First provable bound for true differential collision probability.
- Speed comparable to Grostl in software.
- Much lighter than SHA-3 candidates in hardware

Motivation

Hash	Proof of Security	Speed
PKC-based , e.g. VSH (very smooth hash)	Collision can be reduced to solving hard problems	Very Slow

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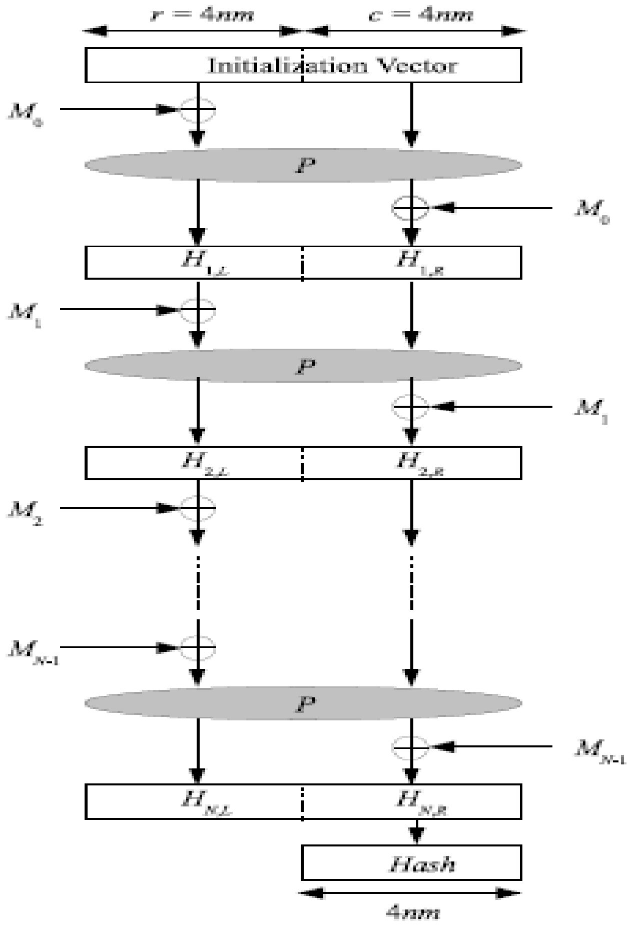
	Sponge-like (KECCAK, JH)	Low characteristic DC, correspond to collision resistance	Fast
SPN Hash		Low (true) DC, Provable collision resistance	Fast

SPN Hash – Mode of Operation



1. Uses the JH mode of operation.
2. It is a sponge variant.
3. (a) **Sponge:**M_i only XORed to input.

   (b) **JH:** M_i is XORed to both input and output.
4. Reason for using JH:
   (a) DC of $P \Rightarrow$ collision resistance (similar to sponge).

   (b) Pre-image resistant (similar to sponge).

   (c) 2nd pre-image attack on sponge. No effective 2nd pre-image attack on JH.

SPN Hash - Permutation P

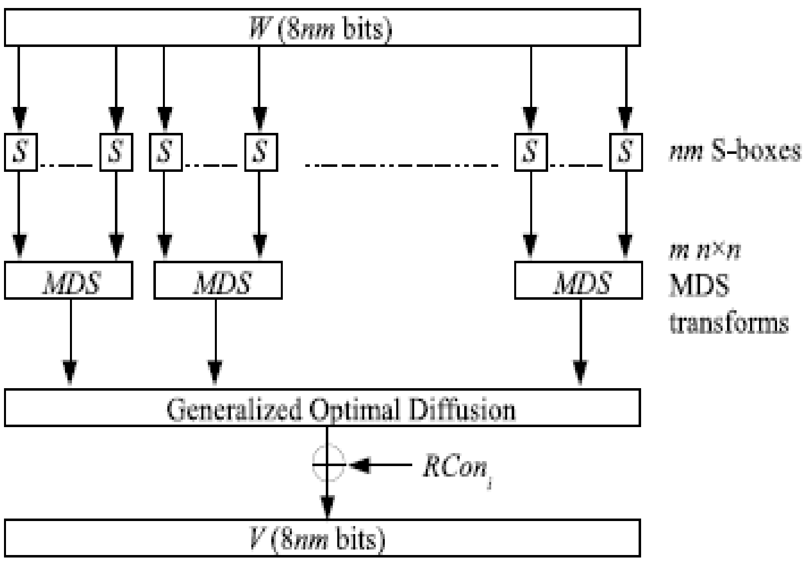


Fig. 4. The round function in permutation *P*

1. *P iterates SPN structure* **10 rounds.**

2. The substitution layer uses the AES S-box.

3. SPN similar to that used in AES:
   (a) There are *m* MDS's
   (b) Each MDS takes in *n* S-boxes

3. Known AES result, *m*=*n*.

4. In SPN hash, *m* divides *n*.

   We design new component **Generalized Optimal Diffusion** to achieve non-square block size.

SPN Hash - Permutation P

- **Q:** Why consider SPN design with non-square block size?
  A: So that we can design more block sizes.

MDS Size (n)	Block Size ($n \times n$) AES-like SPN	Hash Size
8 bytes	8×8 = 64 bytes = 512 bit	256 bit
16 bytes	16×16=256 bytes = 2048 bit	1024 bit

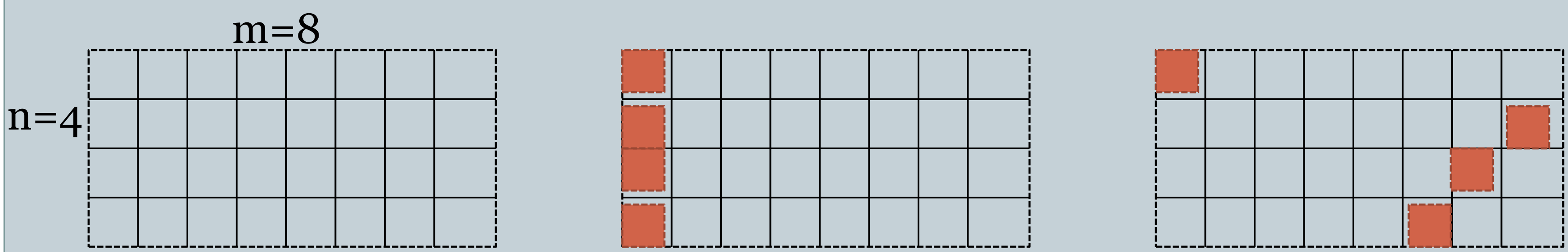
SPN Hash - Permutation P

- **Q:** Why consider SPN design with non-square block size?
  A: So that we can design more block sizes.

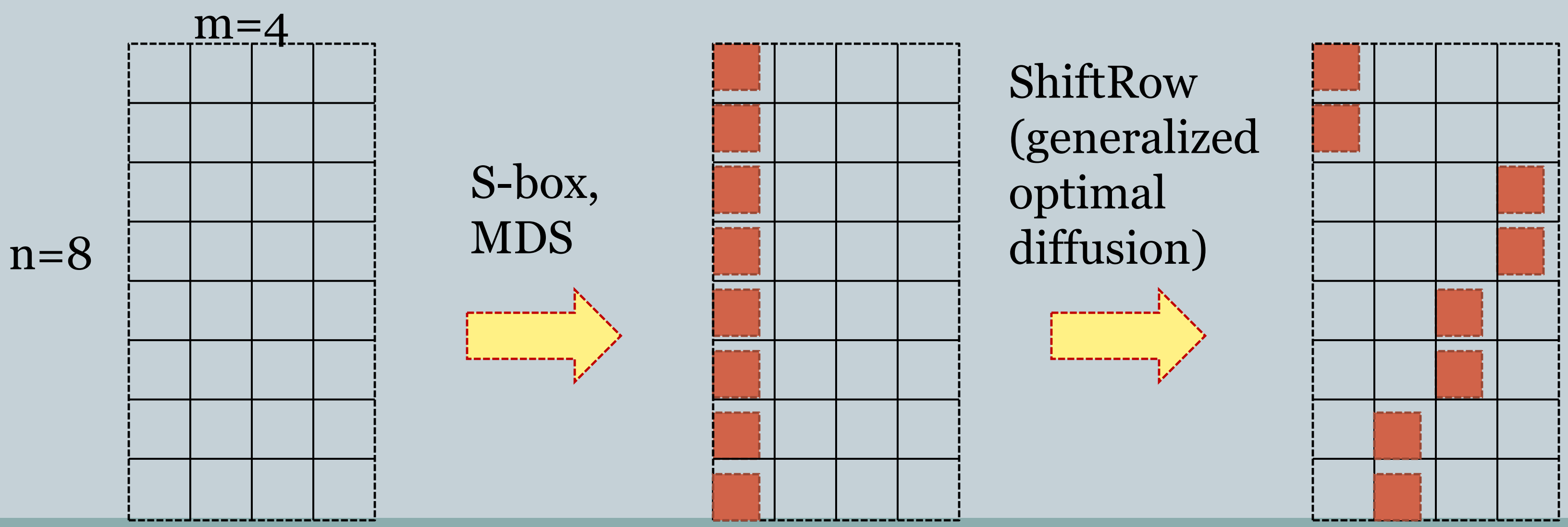
MDS Size (n)	Block Size ($n \times n$) Square SPN	Hash Size	Block Size ($m \times n$), m divides n Our SPN	Hash Size
8 bytes	8×8 = 64 bytes = 512 bit	256 bit	2×8 = 16 bytes=128 bit	64 bit
			4×8 = 32 bytes=256 bit	128 bit
			8×8 = 64 bytes=512 bit	256 bit
16 bytes	16×16=256 bytes = 2048 bit	1024 bit	2×16 = 32 bytes=256 bit	128 bit
			4×16 = 64 bytes=512 bit	256 bit
			8×16 = 128 bytes=1024 bit	512 bit
			16×16 = 256 bytes=2048 bit	1024 bit

How to Construct Non-Square Block Size

Rijmen-Daemen's Construction (optimal diffusion)



Our Construction (generalized optimal diffusion)



Differential Results on our SPN

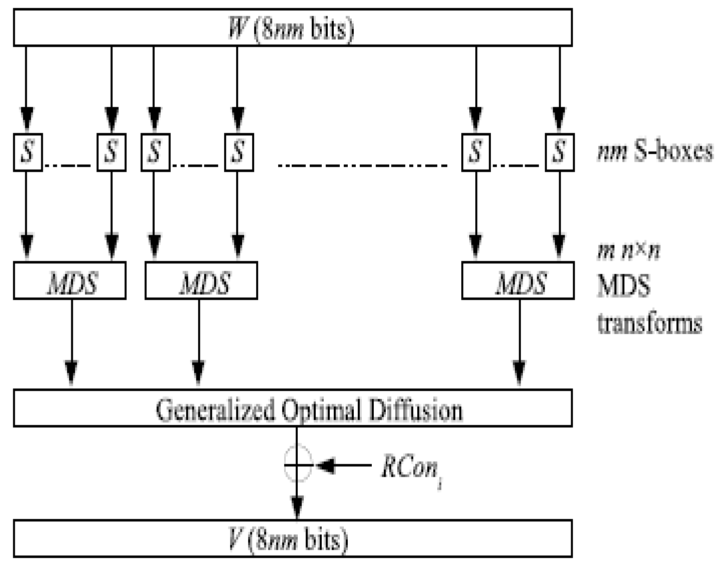


Fig. 4. The round function in permutation P

- **Q:** Why care about differential probability?

  A: Collision ⇔ Zero Output Differential.

- **Rijmen-Daemen result:** $m \geq n$.

  Every 4 rounds ⇔ $(n+1)^2$ active S-boxes

- **Our construction:** m divides n.

  Every 4 rounds ⇔ $(m+1)\times(n+1)$ active S-boxes

- **Example:** Construct 32-byte block.
  - AES Result(m=8,n=4): **25 active S-box.**
  - Our Result (m=4,n=8): **45 active S-box**

Differential Results on our SPN

- Counting Active S-boxes ⇔ Characteristic Differential Probability (Uses Wide-trail strategy of Rijmen-Daemen in [IMA Conference on Crypto and Coding 2001, Springer LNCS 2260, pp.222])

- We want:

  True Differential Probability ⇔ Actual Collision Probability (Uses Park et al.'s SDS result [FSE 2003, Springer LNCS 2887, pp. 247])

True Differential of SPN Hash

- **SPN Hash-128:** Block size = 256 bit. Hash output = 128-bit.
  - n=8, m=4 [32 AES S-box , Four 8×8 MDS].
  - True differential probability (256-bit block) ≤ $2^{-214.7}$.
  - Differential collision probability ≤ $2^{128} \times 2^{-214.7} = 2^{-86.7} < 2^{-64}$.

- **SPN Hash-256:** Block size = 512 bit. Hash output = 256-bit.
  - n=8, m=8 [64 AES S-box, Eight 8×8 MDS]
  - True differential probability (512-bit block) ≤ $2^{-429.5}$.
  - Differential collision probability ≤ $2^{256} \times 2^{-429.5} = 2^{-173.5} < 2^{-128}$.

- **SPN Hash-512:** Block size = 1024 bit. Hash output = 512-bit.
  - n=16, m=8 [128 AES S-box, Eight 16×16 MDS].
  - True differential probability (1024-bit block) ≤ 2^{-816}.
  - Differential collision probability ≤ $2^{512} \times 2^{-816} = 2^{-304} < 2^{-256}$.

Comparison with Existing Hash

- Among SHA-2 and SHA-3 hashes, only one have true differential bound and that is ECHO.

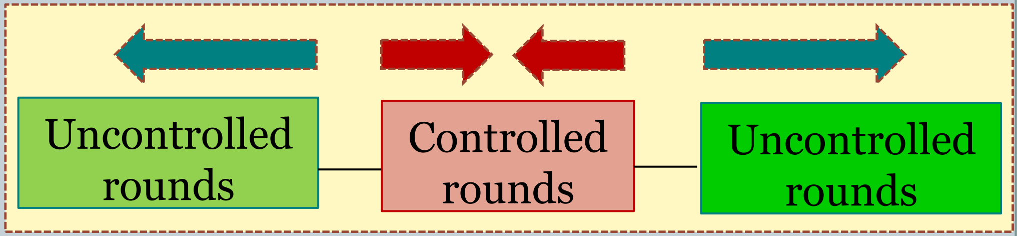
	SPN Hash-512	ECHO-512
Block Size	1024 bit	2048 bit
True Diff Probability of Block	2^{-816}	2^{-452}
Output (after truncation)	512 bit	512 bit
True Differential Collision Probability (after truncation)	2^{-304} (truncate 1024→512)	- (truncate 2048→512)

- True differential of ECHO block worse than SPN-hash block.
- ECHO truncate more bits, differential probability suffer even more.

Why no collision prob for ECHO?

Rebound Attack – Overview

- Divide an attack into two phases: Controlled rounds and Uncontrolled rounds

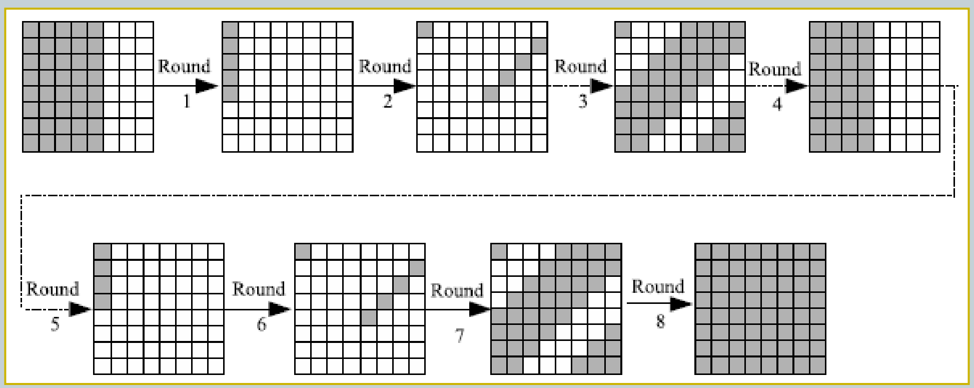


- Controlled rounds
  - Efficient meet-in-the-middle
  - Exploits available freedom degrees in the middle of a differential path
  - Non Full Super-Sbox Analysis
- Uncontrolled rounds
  - Mainly probabilistic
  - Solutions of the controlled rounds are computed backwards and forwards
- Can result in a **distinguishing attack**

Rebound Attack

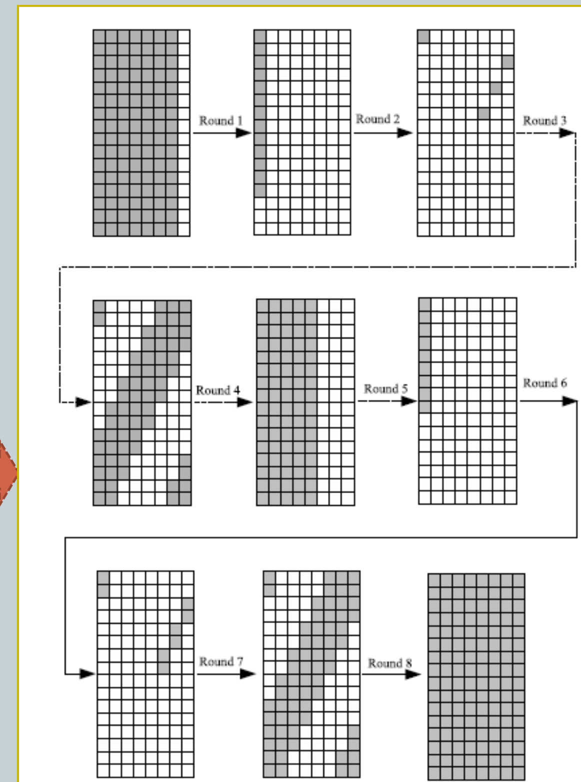
- View 512-bit and 1024-bit internal state of P as a 8×8 and 16×8 matrix of bytes
- 8-round differential paths
- Coloured cell: active byte;

  White cell: passive byte



512-bit P

1024-bit P

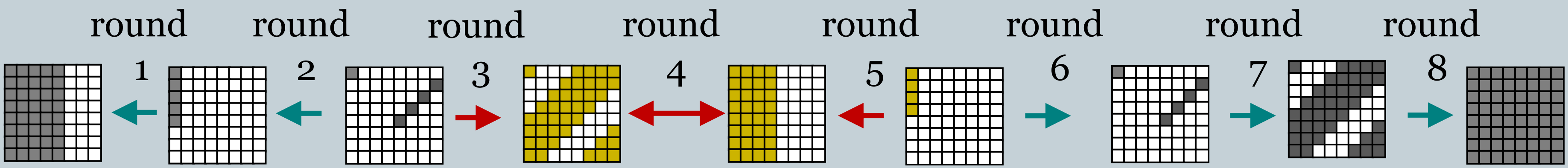


Rebound Attack- Non-Full Active Super-Sbox

- The non-full active Super-Sbox method allows attacker to **control 3 rounds in the middle** (**controlled rounds**): A starting point can be obtained with time 1 on average and 2^8 memory (512-bit P) / 2^{16} memory (1024-bit P)

- The rest of the path is fulfilled probabilistically (**uncontrolled rounds**): In the example of 512-bit P below, we have to pay a probability of approximately 2^{-48}

- Need to ensure **enough freedom degrees** to find a pair of values following the path: In example, need 2^{48} starting points but can choose 2^{72} differences at the start of controlled rounds



8-round differential path for 512-bit P

Rebound Attack

- **Q**: How does this translate to a distinguishing attack?

  A: We obtained distinguishers:
  - 512-bit P: Finding a valid pair for the whole 8-round path requires 2^{48} operations and 2^{8} memory. Ideal case requires 2^{96} computations.
  - 1024-bit P: Finding a valid pair for the whole 8-round path requires 2^{88} operations and 2^{16} memory. Ideal case requires 2^{256} computations.

$\Rightarrow$ Secure against rebound attack since P comprises 10 round functions.

Hardware Implementation

- Implement lightweight SPN Hash 128-bit and 256-bit.
- **Optimization:** Serialize the 8 by 8 MDS matrix over GF(2^8).
- **Problem:** Not easy to find byte-based serialized 8 by 8 MDS matrix, by using method of PHOTON hash design.
- **Our Solution:** Use parallel copies of the PHOTON 8 by 8 MDS matrix over GF(2^4).

Serialized matrix over GF(2^8)

$$Q = (A_{256})^8 = \begin{pmatrix} 0&1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&1 \\ 2&4&2&11&2&8&5&6 \end{pmatrix}^8 = \begin{pmatrix} 2&4&2&11&2&8&5&6 \\ 12&9&8&13&7&7&5&2 \\ 4&4&13&13&9&4&13&9 \\ 1&6&5&1&12&13&15&14 \\ 15&12&9&13&14&5&14&13 \\ 9&14&5&15&4&12&9&6 \\ 12&2&2&10&3&1&1&14 \\ 15&1&13&10&5&10&2&3 \end{pmatrix}$$

$$X = (X_1 || X_2) \rightarrow (Q \cdot X_1 || Q \cdot X_2),$$

where $X \in GF(2^8), X_1, X_2 \in GF(2^4)$

Lightweight implementation

- Besides Serialized MDS, we also use other optimizations like compact AES S-box, efficient use of registers, etc…
- Comparison with SHA-3 candidates:

Digest size	Alg.	Ref.	Msg. size	Technology	Area [GE]	Latency [clk]	T'put@100KHz [kbps]	FOM [nbps/GE^2]
128	SPN-Hash-128		256	UMC 0.18	2 777	710	36.1	2 338
	SPN-Hash-128		256	*estimate*	4 600	230	55.7	2 627
256	SPN-Hash-256		512	UMC 0.18	4 625	1 430	35.8	837
	SPN-Hash-256		512	*estimate*	8 500	230	111.3	1 541
	BLAKE-32	[23]	512	UMC 0.18	13 575	816	62.8	340
	GROSTL-224/256	[34]	512	AMS 0.35	14 622	196	261.2	1 222
	SKEIN-256-256	[34]	256	AMS 0.35	12 890	1 034	24.8	149

Software Implementation

- Expect speed of SPN-Hash 256 comparable to Grostl-256 (22 cycles/byte).
  - Use same number of AES S-boxes.
  - T-Table implementation independent of MDS coefficients.
  - ShiftByte is done implicitly in T-table look-up.
  - SPN-Hash process 256-bit message in 10 rounds compared to Grostl-256 which process 512-bit message in 20 rounds.
- SPN-Hash 128 should run at similar speed.
  - Takes half the message bit, process half the operations.

Conclusion

- We have designed new hash function SPN-hash.
  - Output Sizes: 128-bit, 256-bit, 512-bit
- Provable differential collision bound for all these sizes.
- Also secure against pre-image, 2^{nd} pre-image and rebound attacks.
- Much lighter than existing SHA-3 candidates in Hardware.
- Efficiency comparable to Grostl in Software.

Thank You!

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