Dumbo, Jumbo, and Delirium: Parallel AEAD for the Lightweight Circus

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NIST Lightweight Cryptography Workshop 2019

November 6, 2019

Authenticated Encryption

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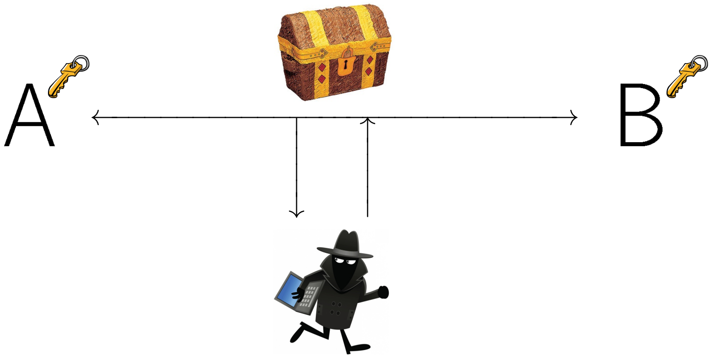

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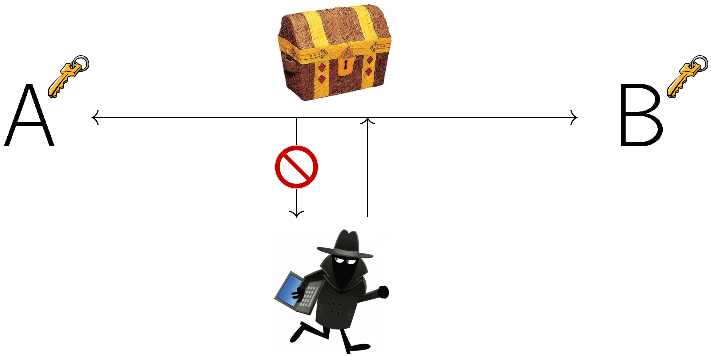

Encryption

- No outsider can learn anything about data

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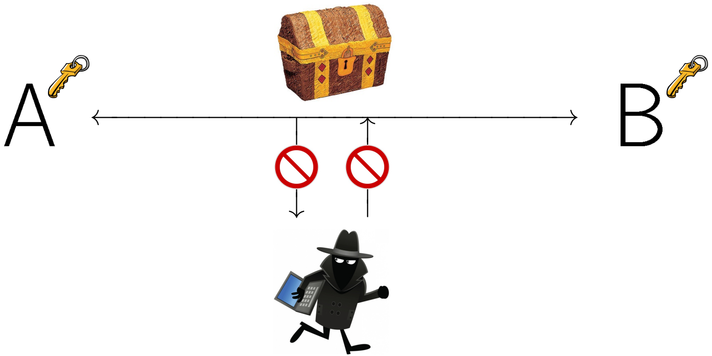


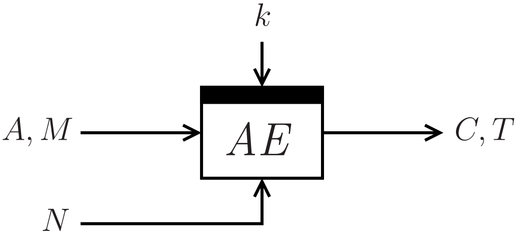
Encryption

- No outsider can learn anything about data

Authentication

- No outsider can manipulate data

Authenticated Encryption



- Ciphertext C encryption of message M
- Tag T authenticates associated data A and message M

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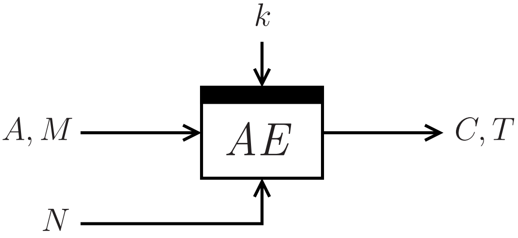
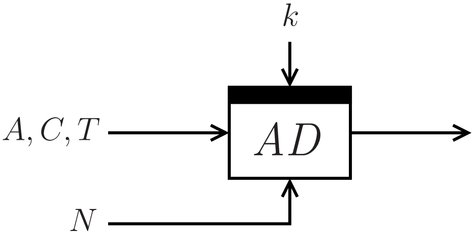


- Ciphertext C encryption of message M
- Tag T authenticates associated data A and message M
- Nonce N randomizes the scheme

Authenticated Decryption



- Authenticated decryption needs to satisfy that
  - Message disclosed if tag is correct
  - Message is not leaked if tag is incorrect

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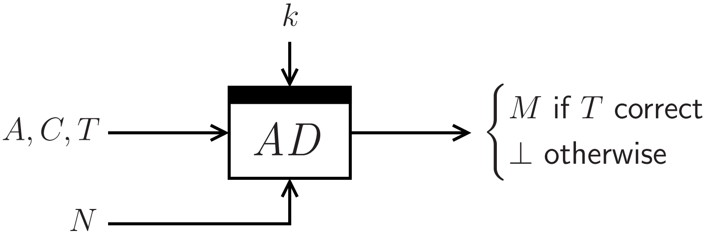

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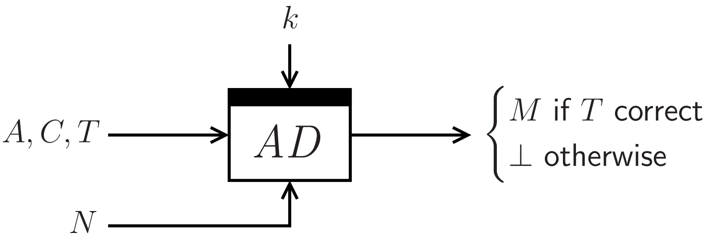
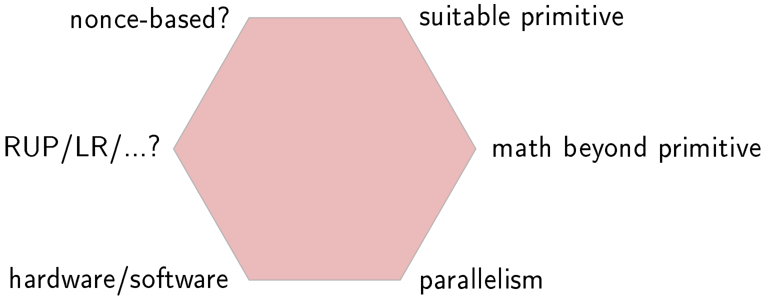
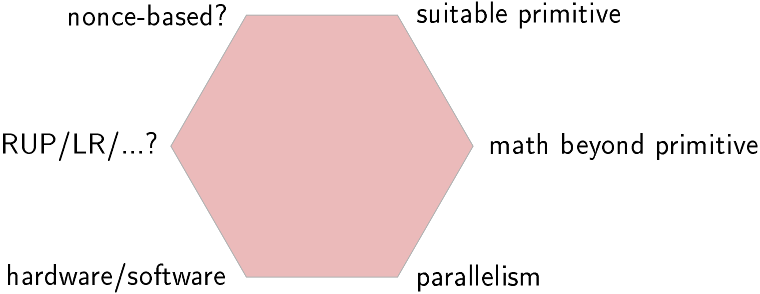


- Authenticated decryption needs to satisfy that
  - Message disclosed if tag is correct
  - Message is not leaked if tag is incorrect
- Correctness: $AD_k(N, A, AE_k(N, A, M)) = M$

Lightweight Authenticated Encryption



Lightweight Authenticated Encryption



Our goal: minimize state size and complexity of design while still meeting expected security strength 2^{112} and limit on online complexity 2^{50} bytes

What Primitive?

Tweakable Block Cipher

Block Cipher

Permutation

What Primitive?

Tweakable Block Cipher

Block Cipher

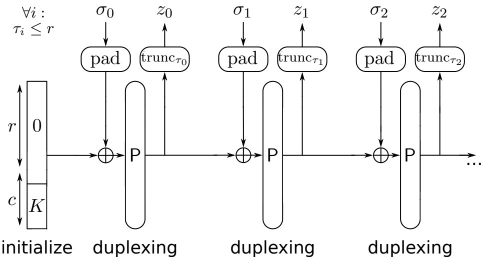
Permutation

Permutation is the best suited choice

What Mode?

Established Approach

- Keyed duplex/sponge [BDPV11,MRV15,DMV17]
- Inherently sequential



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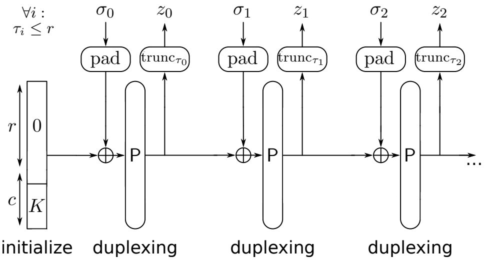
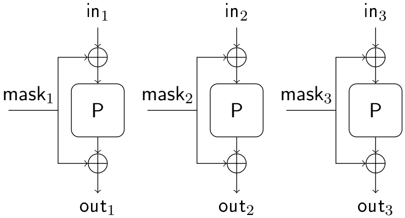


Our Approach

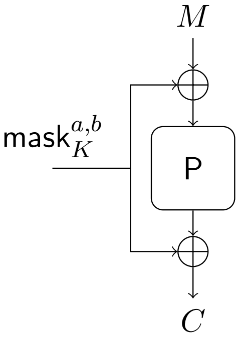
- Parallel evaluation of the permutation
  → requires proper masking
- Evaluating it in forward direction only
  → requires proper mode of use
- Goal: minimize permutation size



What Mask?

Simplified Version of MEM [GJMN16]

- φ_1 is fixed LFSR, $\varphi_2 = \varphi_1 \oplus \mathsf{id}$
- $\mathsf{mask}_K^{a,b} = \varphi_2^b \circ \varphi_1^a \circ \mathsf{P}(K \| 0^{n-k})$



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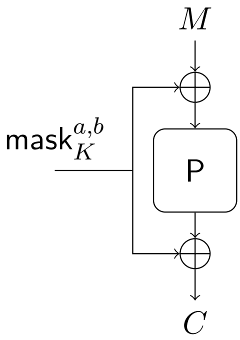
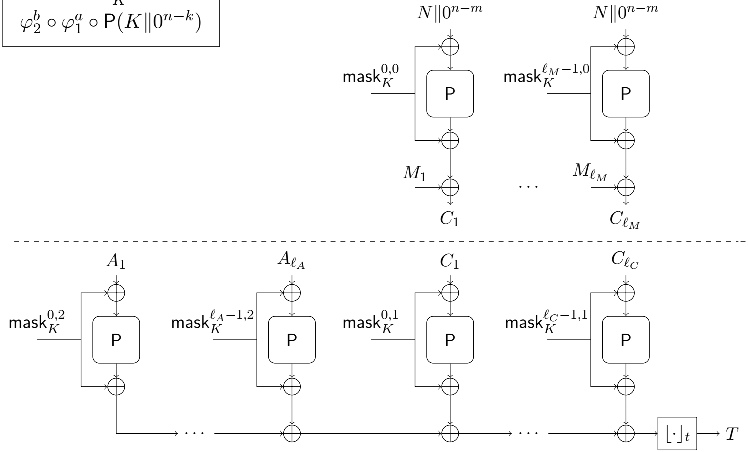


Features

- Constant-time
- Simple to implement
- More efficient than alternatives

Elephant Authenticated Encryption Mode

$$\mathsf{mask}_K^{a,b} = \varphi_2^b \circ \varphi_1^a \circ \mathsf{P}(K \| 0^{n-k})$$



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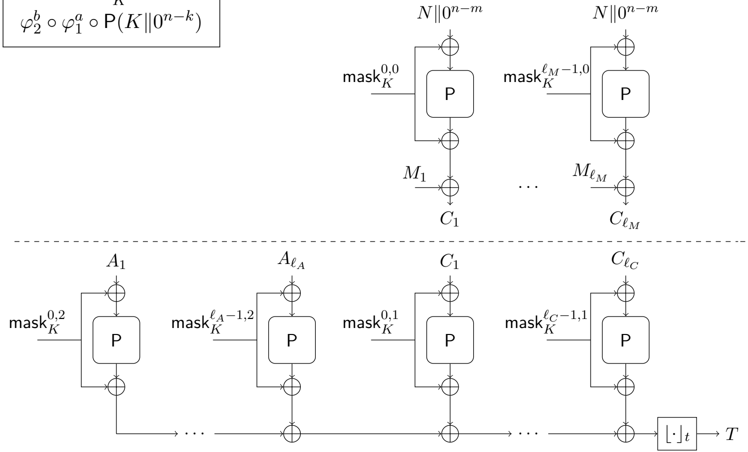

Encryption

- Nonce N input to all P calls
- K and counter in mask
- Padding $M_1 \dots M_{\ell_M} \xleftarrow{n} M$
- Ciphertext $C \leftarrow \lfloor C_1 \dots C_{\ell_M} \rfloor_{|M|}$

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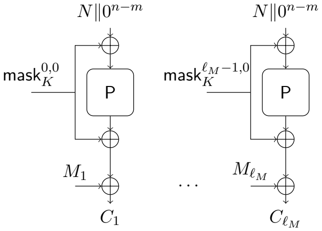

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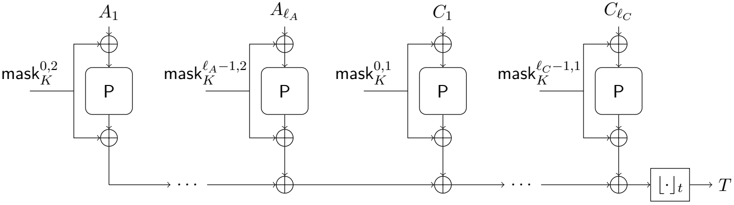

Authentication

- Padding $A_1 \dots A_{\ell_A} \xleftarrow{n} N\|A\|1$
- Padding $C_1 \dots C_{\ell_C} \xleftarrow{n} C\|1$
- K and counter in mask
- Tag T truncated to t bits

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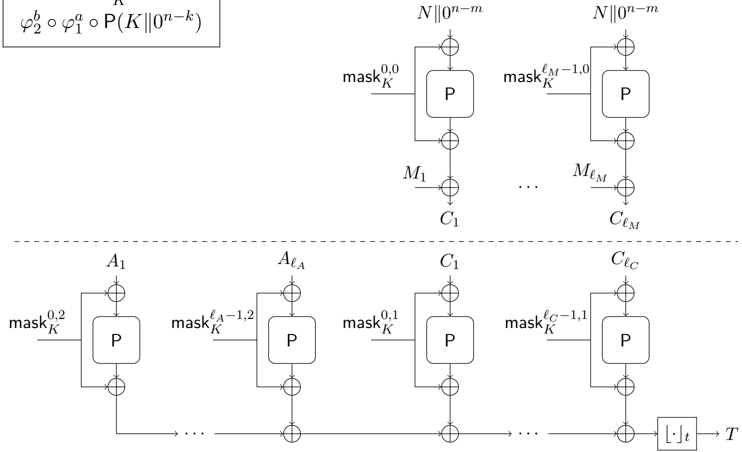

Mode Properties

- Encrypt-then-MAC
  - CTR encryption
  - Wegman-Carter-Shoup
- Fully parallelizable
- Uses single primitive P
- P in forward direction only

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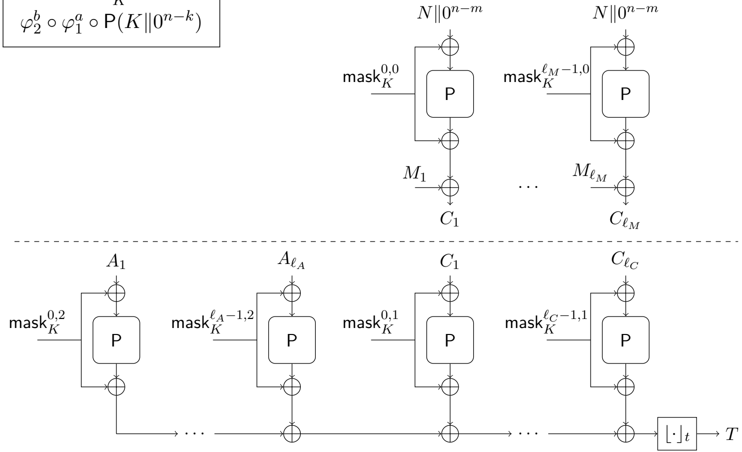

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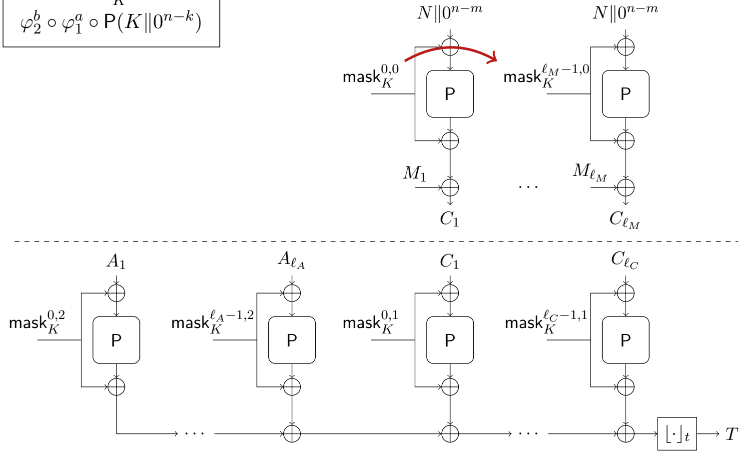

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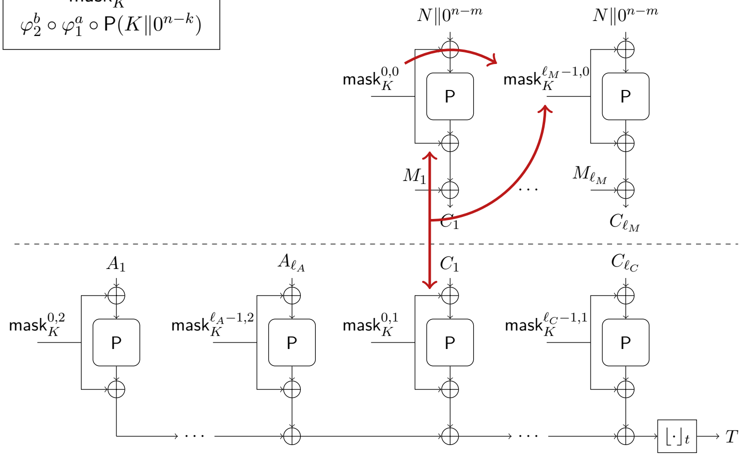

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- Mask can be easily updated
- $\text{mask}_K^{i,0} = \varphi_1 \circ \text{mask}_K^{i-1,0}$
- $\text{mask}_K^{i-1,0} \oplus \text{mask}_K^{i-1,1} = \text{mask}_K^{i,0}$

Security of Mode

$$\mathbf{Adv}^{\mathrm{ae}}_{\mathsf{Elephant}}(\mathcal{A}) \lesssim \frac{4\sigma p}{2^n}$$

- σ is online complexity, p is offline complexity
- Assumptions:
  - P is random permutation
  - φ_1 has maximal length and $\varphi_2^b \circ \varphi_1^a \neq \varphi_2^{b'} \circ \varphi_1^{a'}$ for $(a, b) \neq (a', b')$
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Parameters of NIST lightweight call
can be met with a 160-bit permutation!

Instantiation

Dumbo

- Spongent-$\pi[160]$
- Minimalist design
  - Time complexity 2^{112}
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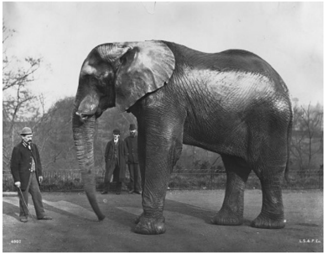

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- ISO/IEC standardized

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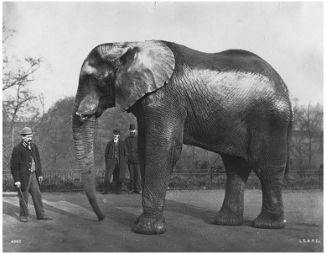

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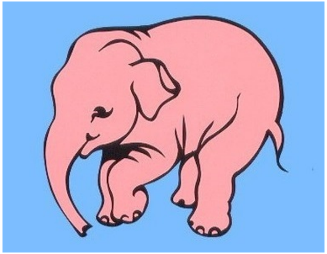

Delirium

- Keccak-$f[200]$
- High security
    - Time complexity 2^{127}
    - Data complexity 2^{70}
- NIST standardized

Technical Specification of Instances

instance	k	m	n	t	P	φ_1	expected security strength	limit on online complexity
Dumbo	128	96	160	64	80-round Spongent-$\pi[160]$	φ_{Dumbo}	2^{112}	$2^{50}/(n/8)$
Jumbo	128	96	176	64	90-round Spongent-$\pi[176]$	φ_{Jumbo}	2^{127}	$2^{50}/(n/8)$
Delirium	128	96	200	128	18-round Keccak-$f[200]$	$\varphi_{\text{Delirium}}$	2^{127}	$2^{74}/(n/8)$

- All LFSRs operate on 8-bit words:

$$\varphi_{\text{Dumbo}}: (x_0, \ldots, x_{19}) \mapsto (x_1, \ldots, x_{19}, x_0 \lll 3 \oplus x_3 \ll 7 \oplus x_{13} \gg 7)$$

$$\varphi_{\text{Jumbo}}: (x_0, \ldots, x_{21}) \mapsto (x_1, \ldots, x_{21}, x_0 \lll 1 \oplus x_3 \ll 7 \oplus x_{19} \gg 7)$$

$$\varphi_{\text{Delirium}}: (x_0, \ldots, x_{24}) \mapsto (x_1, \ldots, x_{24}, x_0 \lll 1 \oplus x_2 \lll 1 \oplus x_{13} \ll 1)$$

- All have maximal length and $\varphi_2^b \circ \varphi_1^a \neq \varphi_2^{b'} \circ \varphi_1^{a'}$ for $(a, b) \neq (a', b')$

Conclusion

Elephant

- Parallel lightweight AE with small state
- Mode: provably secure in random permutation model
- Primitives: standardized and well-studied
- Dumbo and Jumbo for hardware
- Delirium for software

Thank you for your attention!