PAEQ: Parallelizable Permutation-based Authenticated Encryption

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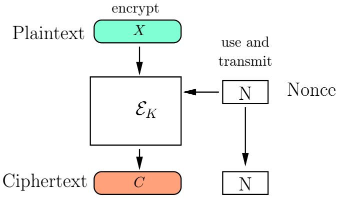
12 October 2014

Authenticated encryption

If you just want to protect confidentiality of your data, you use (simple) symmetric encryption:



- Agree on the key $\mathcal{K}$;
- Choose nonce N uniquely for each piece of data;
- Encrypt and send.

Good encryption scheme makes ciphertexts look random (even if plaintexts repeat).

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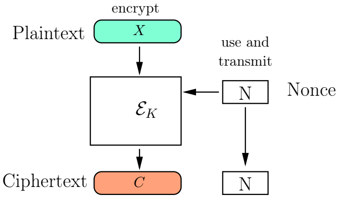

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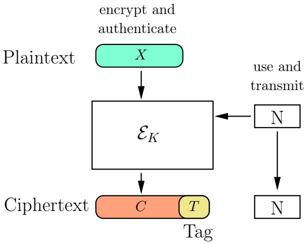
No integrity protection.

If you also want to protect integrity of your data (i.e. authenticate the message), you use *authenticated encryption*:



- Tag T is added to each ciphertext;
- Adversary can not modify $C||T$ without getting noticed.

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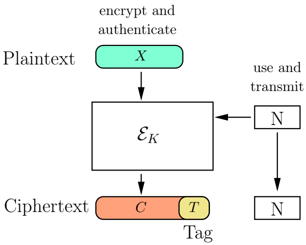

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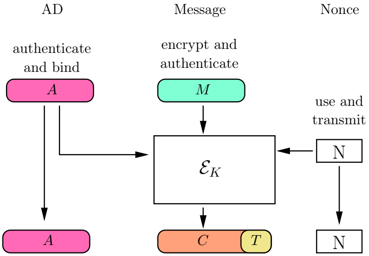
We might also want to authenticate some data without encrypting it (associated data).

Authenticated encryption with associated data



Confidentiality:

- Ciphertexts indistinguishable from random strings;

Data integrity:

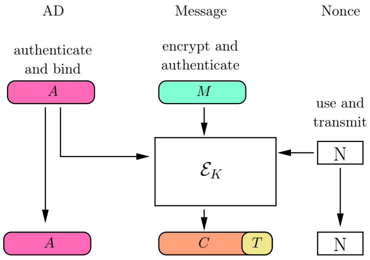
- Most of seemingly valid ciphertexts decrypt to $\perp$.

Desirable features

Non-exhaustive list of authenticated encryption features:

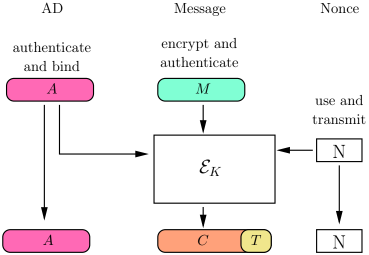
- Parallelizability to fully use multi-core CPU;
- Incremental tags to avoid recomputing the entire ciphertext;
- Security proof;
- Reasonable performance;
- Compact implementation.

What we also want



Some extra features:

- Easy to understand and implement.
- Security level equal to the key length (does not hold for AES-CBC/GCM/OCB).
- More compact and verifiable security proofs.
- No extra operations like key derivation, field multiplications etc. (makes the design more complex).



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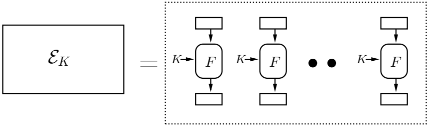
Solution: design a permutation-based mode, not a blockcipher one.

Permutation-based

How to construct a variable-length cipher:



- Each component is keyed function F_K;
- Security reduces to pseudorandomness of F (unpredictable under a random key).

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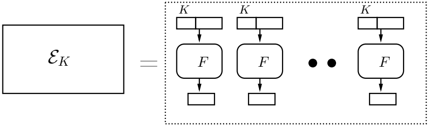

- Each component is a fixed public function F;
- Security proven if F is randomly chosen (while in fact it is not).

Why permutation-based?

- A wide permutation can take key, nonce, counter, intermediate values, or a message block altogether as input.
- Plenty of designs: different widths and optimizations;
- The underlying permutation is easier to design and analyze (no need to care of key schedule, mask generation, nonce formatting, etc.).

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Cons:

- Weaker security model (random permutation);
- Lower throughput (larger calls/byte ratio).

80- and 128-bit security

Most popular modes suggest using AES (128-bit block) as the underlying blockcipher.

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Beyond 64-bit security

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We want to offer a higher security margin.

PAEQ

Our new scheme **PAEQ** has

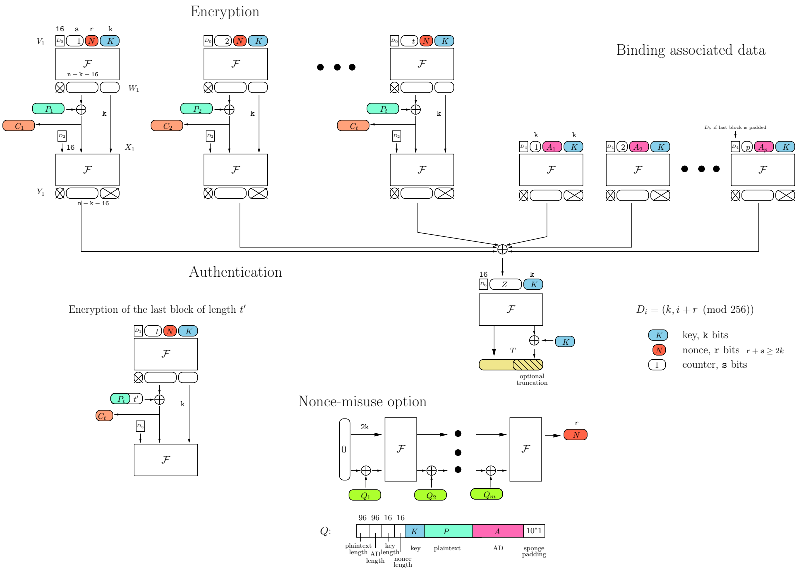
Basic features:

- Fully parallelizable;
- Handles associated data;
- Variable key/nonce/tag length;
- Patent-free;
- Online encryption and authentication, no length awareness;
- Byte-oriented.
- Incremental tag (for max tag length).

Extra features:

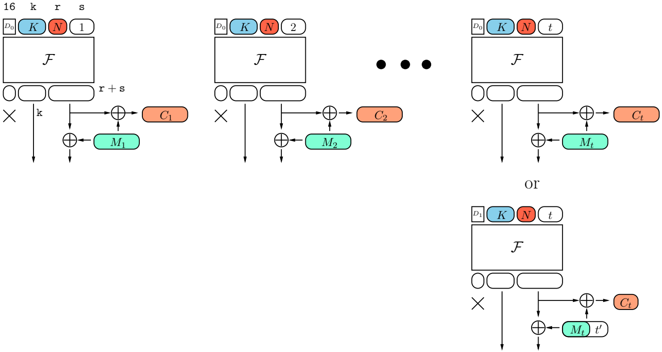
- Security level up to 128 bits and higher (up to $w/3$) and equal to the key length;
- Compact security proof in the random permutation setting;
- Permutation inputs and outputs are linked by only XORs and counters, no extra operations;
- Only forward permutation calls.

PAEQ



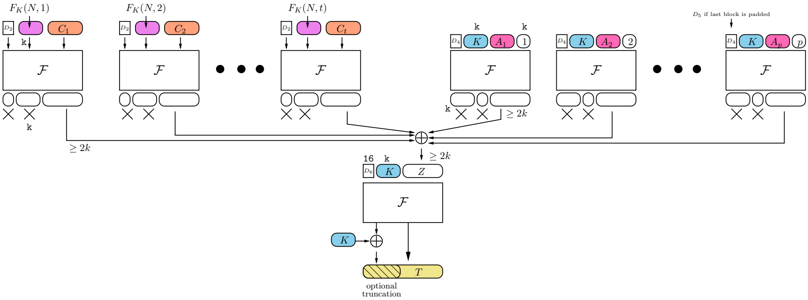
Encryption
Binding associated data
Authentication
Encryption of the last block of length t′
Nonce-misuse option
D_i = (k, i + r (mod 256))
key, k bits
nonce, r bits r + s ≥ 2k
counter, s bits
optional truncation
D₅ if last block is padded
Q:
plaintext length
AD length
key length
nonce length
key
plaintext
AD
sponge padding

Encryption:



- Counter mode with PRF;
- Confidentiality basically follows from the properties of CTR.

Authentication:

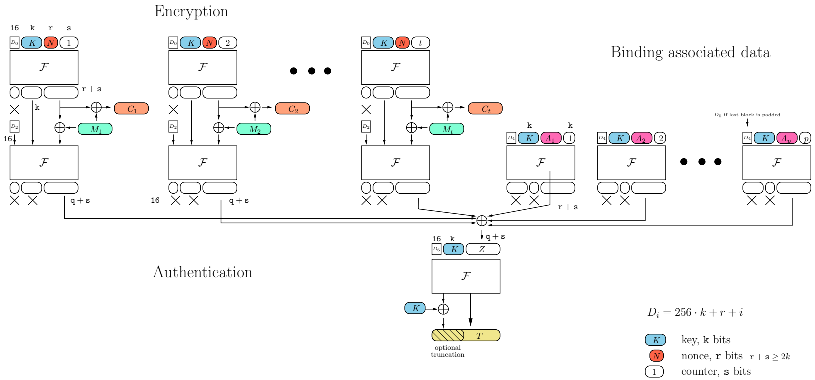


- PMAC style with additional input from the encryption part;
- If the tag has full length, it can be updated with a few extra calls.

PAEQ comes with several security proofs. Confidentiality and integrity are established up to 2^k total queries to $\mathcal{F}$:

$$\mathbf{Adv}_{\Pi}^{\mathrm{conf}}(\mathcal{A}) \leq \frac{3q}{2^k};$$
$$\mathbf{Adv}_{\Pi}^{\mathrm{int}}(\mathcal{A}) \leq \frac{q}{2^\tau} + \frac{4q}{2^k}.$$

where k — key length, τ — tag length, q — total number of queries to $\mathcal{F}$.
If the nonce is misused, integrity is still established up to $2^{k/2}$ queries.



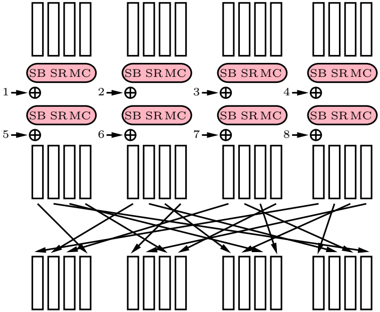
We use our own permutation — AESQ.

AESQ

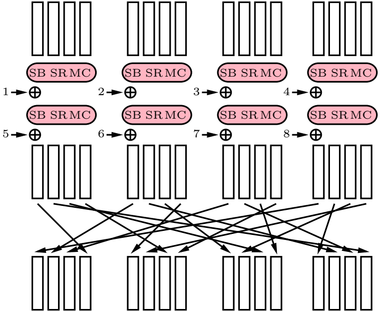
New 512-bit permutation aimed at modern CPUs:

- 4 parallel AES states;
- 2 AES rounds alternated with column shuffle;
- Simple round constants;
- 20 rounds in total.

2 rounds of AESQ:



Running two instances of AESQ in parallel yields highest throughput on Haswell processors.



Security of AESQ:

- Differential/linear properties disappear after 8 rounds;
- Rebound attacks stop at 12 rounds;
- Preimage/distinguishing attacks stop at 12-14 rounds.

Benchmarks on the Haswell CPU:

Security level / Key length	PAEQ (20 rounds, cycles per byte)
64	4.9
80	5.1
128	5.8
256	8.9

Questions?