Symmetric Key Cryptography

PQCRYPTO Summer School on Post-Quantum Cryptography 2017

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June 20th, 2017

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Introduction to Symmetric Key Cryptography

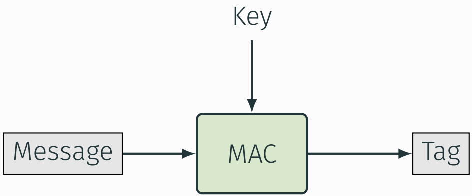
What can we do?

- Encryption
- Authentication (MAC)
- Hashing
- Random Number Generation
- Digital Signature Schemes
- Key Exchange

Authentication

Authentication

Message Authentication Code (MAC)



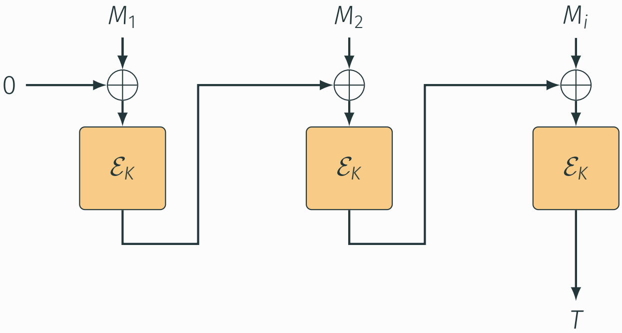
- Produces a tag
- Provide both *authenticity* and *integrity*
- It should be *hard* to forge a valid tag.
- Similar to hash but has a key
- Similar to digital signature but same key

Authentication

MAC Algorithm

- Block Cipher Based (CBC-MAC)
- Hash-based (HMAC, Sponge)
- Universal Hashing (UMAC, Poly1305)

CBC-MAC



Authentication

Hash-based:

- $H(k \mid\mid m)$
  - Okay with Sponge, fails with MD construction.
- $H(m \mid\mid k)$
  - Collision on H allows to construct Tag collision.
- HMAC: $H(k \oplus c_1 \mid\mid H(k \oplus c_2 \mid\mid m))$

Authentication

Universal Hashing (UMAC, Poly1305, ...)

- We need a universal hash function family $\mathcal{H}$.
- Parties share a secret member of $\mathcal{H}$ and key k.
- Attacker does not know which one was chosen.

Definition

A set $\mathcal{H}$ of hash functions $h : U \to N$ is universal iff $\forall x, y \in U$:

$$\Pr_{h \in H}(h(x) = h(y)) \leq \frac{1}{|N|}$$

when h is chosen uniformly at random.

Authenticated Encryption

In practice we **always** want Authenticated Encryption

- Encryption **does not** protect against malicious alterations.
- WEP [TWP07]
- Plaintext recovery OpenSSH [APW09]
- Recover TLS cookies [DR11]

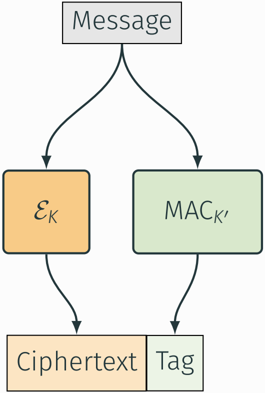
Problem

Lot of things can go wrong when combining encryption and authentication.

Note: This can allow to recover plaintext, forge messages…

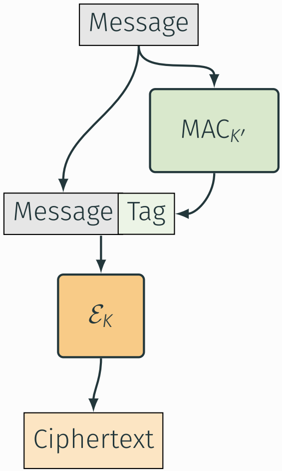
Authenticated Encryption [BN00]

Encrypt-and-MAC



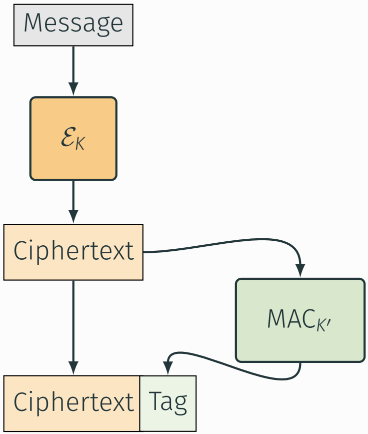
Authenticated Encryption [BN00]

MAC-then-Encrypt



Authenticated Encryption [BN00]

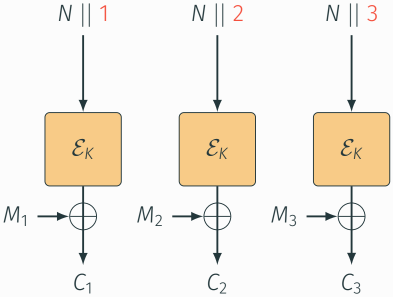
Encrypt-then-MAC



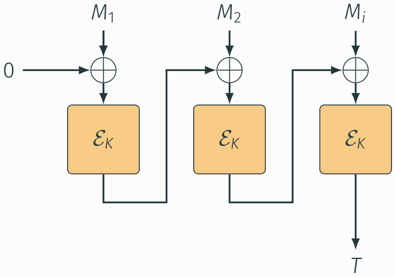
Authenticated Encryption

You have to be careful!

CTR-Mode



CBC-MAC

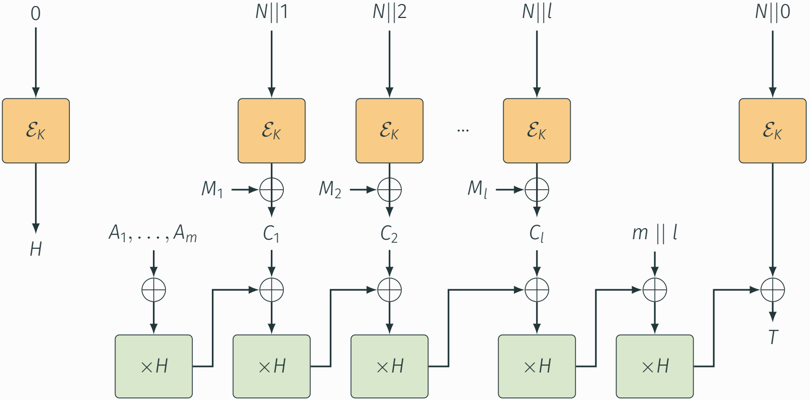


Authenticated Encryption

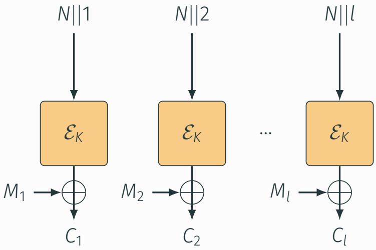
Authenticated Encryption with Associated Data (AEAD)

- Associcated Data A (e.g. packet header)
- Nonce N (unique number)

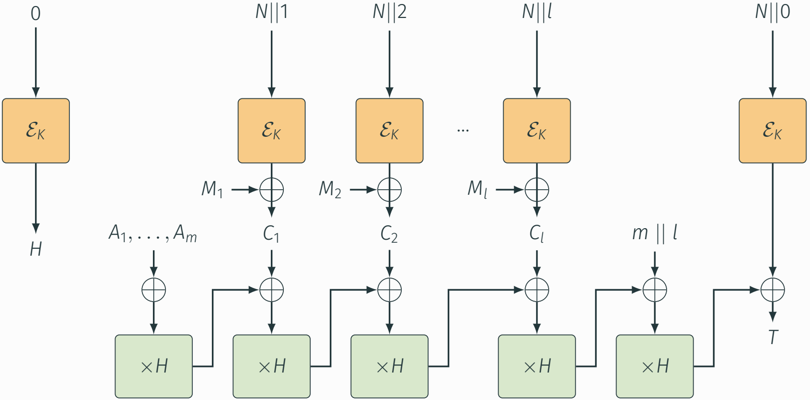
Galois/Counter Mode (GCM)



Galois/Counter Mode (GCM)



Galois/Counter Mode (GCM)



Authenticated Encryption

AES-GCM

- Widely used (TLS)
- Reusing nonce compromises security
- Weak keys for $\times H$
- Hardware support for AES + `PCLMULQDQ`
- AES-GCM-SIV?

Authenticated Encryption

CAESAR[1]: Competition for Authenticated Encryption: Security, Applicability, and Robustness

- Initially 57 submissions.
- Third round: 15 Submissions left
- Goal is to have a portfolio of AE schemes

Summary

Most applications need Authenticated Encryption!

[1] https://competitions.cr.yp.to/caesar.html

Quantum Attacks

Quantum Attacks

Attack Model

- Attacker listens to communication over classical channel.
- Can query a classic blackbox with the secret key.
- Attacker has large quantum computer.
- Only limited set of quantum algorithms available.

Quantum Attacks

Encryption / MACs

- Recover Key in $O(2^{k/2})$ with Grover's.

Hash Function

- Find Preimage in $O(2^{n/2})$ with Grover's.
- Find Collisions in $O(2^{n/3})$ [BHT97] ... but needs $O(2^{n/3})$ hardware.

Quantum Attacks

The costs are not so simple

- Costs of quantum operation vs. classic operations
- Collision finding not really faster [Ber09].

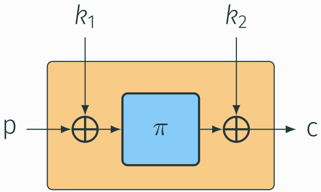
There is some work on better understanding this:

- Preimage SHA-256: 2^{166} *logical-qubit-cycles* [Amy+16].
- Preimage SHA3-256: 2^{166} *logical-qubit-cycles* [Amy+16].

Quantum Attacks

Even-Mansour

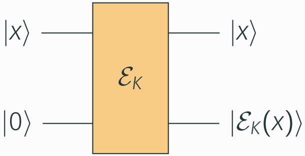
- Two keys k_1, k_2.
- Uses public permutation π.



Classic Security

- D queries to $\mathcal{E}$
- T queries to π
- *Proof* for upper bound on attack success $O(DT/2^n)$

Quantum Oracle Access to encryption algorithm



- Very strong model for adversary.

Simon's Algorithm

Given

$$f : \{0,1\}^n \to \{0,1\}^n$$

with promise that there exists

$$s \in \{0,1\}^n$$

such that

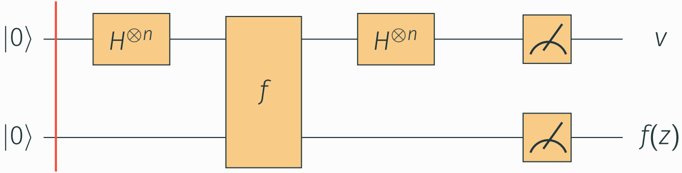
$$\forall (x,y) \in \{0,1\}^n : f(x) = f(y) \iff x \oplus y \in \{0^n, s\}$$

Output: s

Only needs $O(n)$ quantum queries.

Simon's Algorithm

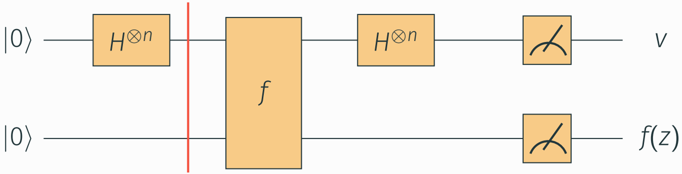
Circuit



$$|0^n\rangle|0^n\rangle$$

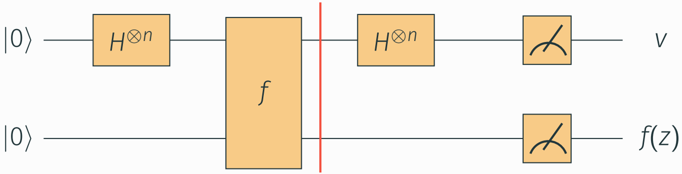
Simon's Algorithm

Circuit



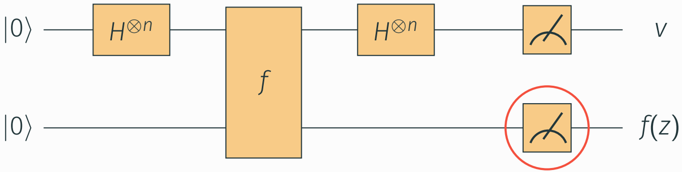
$$\frac{1}{\sqrt{2^n}}\sum_x |x\rangle|0^n\rangle$$

Circuit



$$\frac{1}{\sqrt{2^n}} \sum_x |x\rangle |f(x)\rangle$$

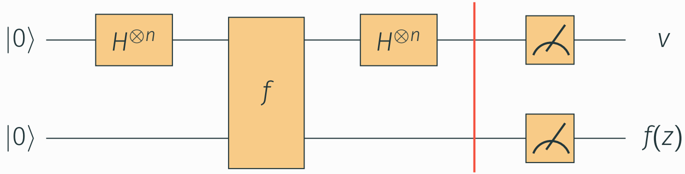
Circuit



$$\frac{1}{\sqrt{2}}|z\rangle + \frac{1}{\sqrt{2}}|z \oplus s\rangle$$

Simon's Algorithm

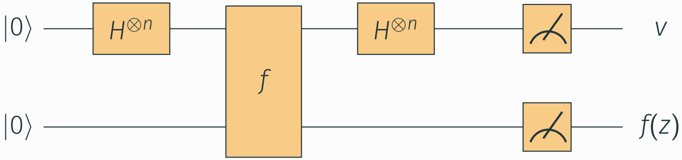
Circuit



$$\frac{1}{\sqrt{2}}\frac{1}{\sqrt{2^n}}\sum_y(-1)^{y\cdot z}(1+(-1)^{y\cdot s})|y\rangle$$

Simon's Algorithm

Circuit



$$\frac{1}{\sqrt{2}}\frac{1}{\sqrt{2^n}}\sum_y (-1)^{y\cdot z}(1+(-1)^{y\cdot s})|y\rangle$$

Result

One steps finds a vector such that $y \cdot s = 0$.

Breaking Even-Mansour [KM12]

$$\mathcal{E}_{k_1,k_2}(x) = \pi(x \oplus k_1) \oplus k_2$$

Construct:

$$\begin{aligned} f : \{0,1\}^n &\to \{0,1\}^n \\ x &\to \mathcal{E}_{k_1,k_2}(x) \oplus \pi(x) = \pi(x \oplus k_1) \oplus k_2 \oplus \pi(x) \end{aligned}$$

This function fulfills Simon's promise:

$$\begin{aligned} f(x) &= \pi(x \oplus k_1) \oplus k_2 \oplus \pi(x) \\ f(x \oplus k_1) &= \pi(x \oplus k_1 \oplus k_1) \oplus k_2 \oplus \pi(x \oplus k_1) \end{aligned}$$

Quantum

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Quantum

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Recover k_1 with $O(n)$ quantum queries.

Quantum Attacks

Similar attacks [Kap+16] apply to

- Block Cipher Modes
- MACs
- Authenticated Encryption
- Improving Slide Attacks

Quantum Attacks

Similar attacks [Kap+16] apply to

- Block Cipher Modes
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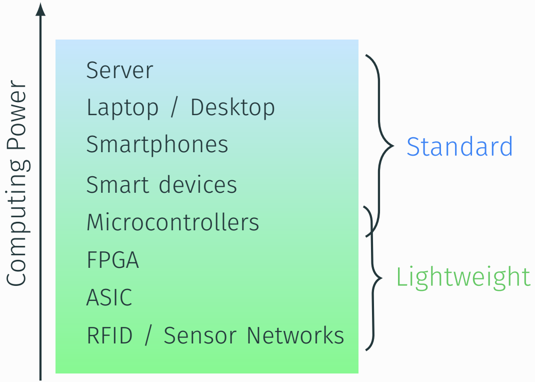
Goal

Construct f such that $f(x) = f(x \oplus s)$ for some secret s.

Current Directions in Symmetric Key Cryptography

Lightweight Cryptography

- Resource constraint
  - Chip area
  - Memory
  - Computing Power
  - Power/Energy
- NIST Project[5]
- Many designs exists



[1] https://beta.csrc.nist.gov/projects/lightweight-cryptography

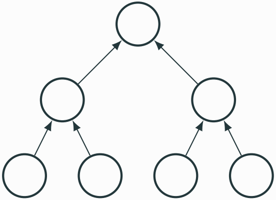
Symmetric Key Cryptography

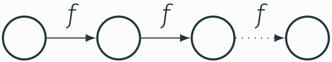
Hash-based Signatures:

- Many calls to a hash function...
- ...but only very short inputs.
- No collision resistance required

Current Designs:

- Often slow on short inputs.
- Too conservative for this restricted setting?
- Designs: ChaCha in SPHINCS, Haraka [Köl+]





Symmetric Key Cryptography

Multiparty Computation, Zero Knowledge, Fully Homomorphic Encryption

- Multiplications in primitives very costly for these applications.
- Signature size directly relates to number of ANDs (for ZK).

Symmetric Key Primitives which:

- Minimize number of ANDs
- Minimize circuit depth
- Examples: LowMC [Alb+15], MiMC [Alb+16], Kreyvium [Can+16], Flip [Méa+16]

Conclusion

Symmetric Key Cryptography

- Encryption: AES-CTR
- Hash: SHA-2, SHA-3
- Authenticated Encryption: AES-GCM, ChaCha20-Poly1305, CAESAR

Quantum Attacks

- Mostly fine with double the parameter sizes.
- Improve cryptanalytic attacks with quantum algorithms.

[1] Thanks to `https://www.iacr.org/authors/tikz/` for some of the figures.

Questions?

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