Radboud University

Authenticated encryption: state-of-the-art and beyond

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ESCADA

What do we want to do?

Protect the communication between Alice and Bob over an open channel that is controlled by a potentially very resourceful adversary Eve

- Confidentiality of the content of messages
- Authentication of the communication
  - Alice can check that any received message was effectively sent by Bob
  - ... and that it is not a *replay* of an old message by Eve
  - ... and that Bob sent it recently: *freshness*

We assume that Alice and Bob share a secret key K that Eve does not know

Confidentiality: encryption with the one-time pad (OTP)

Bob enciphers: $C \leftarrow M \oplus K$

$$
\begin{array}{rcccccccccccccccc}
M = & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & \\
K = & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & \oplus \\
\hline
C = & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 &
\end{array}
$$

Alice deciphers: $M \leftarrow C \oplus K$

$$
\begin{array}{rcccccccccccccccc}
C = & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & \\
K = & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & \oplus \\
\hline
M = & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 &
\end{array}
$$

Unconditional security of the one-time pad

Claude Shannon

Encryption is 100 % secure if ciphertext C gives no information on content of plaintext P

$$\forall p : \mathbf{Pr}(P = p|C) = \mathbf{Pr}(P = p)$$

Claude Shannon proved the security of OTP

- Unconditional: $\forall$ Eve
- Problem: key K must be as long as total amount of plaintext

From one-time pad to practical stream encryption

Stream encryption: bitwise add to the plaintext P a keystream of same length Z

$$C \leftarrow P + Z$$

Stream encryption made practical: generate Z from a short key K and a *diversifier* D

$$Z \leftarrow \mathrm{SC}_K(D) \quad \text{or for short} \quad C \leftarrow P + \mathrm{SC}_K(D)$$

Diversifier is there to generate multiple keystreams Z from a single key K

Stream encryption is secure if D is unique per message and stream cipher is secure

Stream encryption: beware of diversifier re-use!

- Say we use same diversifier D to encipher M_1 and M_2
- This gives same keystream $Z = \mathrm{SC}_K(D)$ for both messages, so:

$$C_1 = M_1 \oplus Z \text{ and } C_2 = M_2 \oplus Z$$

- Eve can compute difference between M_1 and M_2 from ciphertexts:

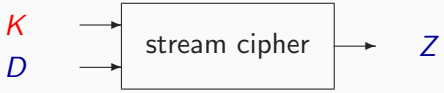
$$C_1 \oplus C_2 = M_1 \oplus Z \oplus M_2 \oplus Z = M_1 \oplus M_2$$

- (partial) knowledge of M_1 gives (partial) knowledge of M_2

Nonce

Diversifier D must be unique per message. We call this a *nonce*: number used once

When is a stream cipher secure?



- For an adversary that knows the algorithm but not the key K
  - $Z = \mathrm{SC}_K(D)$ must be hard to distinguish from a random sequence
  - for values of D freely chosen by the adversary
- You cannot prove this is satisfied
  - you can try to demonstrate this is *not* satisfied using *cryptanalysis*
  - security assurance of a function grows with amount of cryptanalysis it had
  - . . . as long as this does not result in a break

Concrete design requirements: Diffusion and Confusion (C. Shannon)

All bits of $Z = \mathrm{SC}_K(D)$ must be a **complicated** function of **all** bits of D en K

Authenticating a message using a MAC function

Encryption does not guarantee that Alice can detect message tampering by Eve

This can be done by appending an *authentication code* $T \leftarrow \mathrm{MAC}_K(M)$

- Bob computes over the message M an authentication code T (aka *tag*)
  - M can be long, T is short, e.g., 16 bytes
  - computation of T requires a secret key K
  - with key it is easy to compute T, without key not
- Bob sends (M, T) to Alice
  - Alice uses her key K to compute T' from M
  - if $T = T'$, she accepts the message as coming from Bob
- A *forgery* is a pair (M, T) not coming from Bob, accepted by Alice

Often Alice wants to authenticate more, requiring *active checks* from her part

Authenticating freshness

Alice wants to authenticate that the message from Bob is recent

	Bob		Alice
have:	K		K
		$\xrightarrow{\text{Bob}}$	$R \xleftarrow{\$} \{0,1\}^n$
		$\xleftarrow{R}$	
	$T \leftarrow \mathrm{MAC}_K(R; M)$	$\xrightarrow{M,T}$	$T \stackrel{?}{=} \mathrm{MAC}_K(R; M)$

Requires 3 passes:

- Bob announces he has a message
- Alice provides an unpredictable challenge R
- Bob computes tag and sends (M, T)

Protecting against replay

	Bob		Alice
have:	K, N_B		K, N_A
	$N_B \leftarrow N_B + 1$		
	$T \leftarrow \mathrm{MAC}_K(N_B; M)$	$\xrightarrow{\text{Bob}, N_B, M, T}$	$N_B \stackrel{?}{>} N_A$
			$T \stackrel{?}{=} \mathrm{MAC}_K(N_B; M)$
			$N_A \leftarrow N_B$

N_X: counter keeping track of the number of protocol runs started by Bob

- Requires only a single pass
- Stateful: Bob and must keep track of counters N
- Prevents replay but not *stalling* of messages by Eve

Note: this protocol allows *holes* in the counter sequence, variants exist

Intermezzo: finite field basics

A field is a set S with two operations: addition $+$ and multiplication $\cdot$

- $(S, +)$ forms a group
  - Associative, neutral element 0 and each element a has an inverse $-a$
- $(S \setminus \{0\}, \cdot)$ forms a group
  - Associative, neutral element 1 and each element a has an inverse a^{-1}
- Distributive: $a(b + c) = ab + ac$ and $(a + b)c = ac + bc$
- If S is finite we speak of a finite field
- There exists one finite field for any $\#S = p^n$ with p a prime. Special cases:
  - Prime fields $\mathbb{F}_p$: addition and multiplication modulo p
  - Binary fields $\mathbb{F}_{2^n}$: XOR and "carryless" modular multiplication

A polynomial of degree n in a finite field has at most n roots

Polynomial authentication codes

This type of code requires encoding message and keys as elements of finite field

- Message encoded as a sequence of elements of a finite field S: $M = m_1, m_2, \ldots m_\ell$
- Key K consists of a pair of subkeys, also in the finite field S: $K = z, k$.

Tag computation:

$$T \leftarrow z + \sum_{i=1}^{\ell} m_i k^i$$

This is

- secure if a fresh random key z, k is used for every message
- not secure if a key z, k is used for more than a single message

Re-use of keys for polynomial authentication codes

Consider two messages with length 1, m and m', and their tags T and T'

$$T = z + mk \quad \text{and} \quad T' = z + m'k$$

Subtracting gives

$$T - T' = (m - m')k$$

Solving for k:

$$k = \frac{T - T'}{m - m'}$$

And then determine $z = T - mk$

Re-use leaks the key allowing arbitrary forgery!

Security in case of unique key per message

Say Eve observes a valid pair (M, T)

If fresh keys z, k for each message, probability of successful forgery is $\leq \ell/\#S$

- successful forgery (M', T') would satisfy $T' = z + \sum_{i=1}^{\ell} m'_i k^i$
- subtraction from $T = z + \sum_{i=1}^{\ell} m_i k^i$ gives

$$T - T' + \sum_{i=1}^{\ell} (m'_i - m'_i) k^i = 0$$

Polynomial equation of degree ℓ in the unknown k, so at most ℓ solutions

For any choice of (M', T') the forgery is successful for at most ℓ out of $\#S$ keys k

MAC functions made practical

Problem: each message consumes 2 finite field elements

Solution 1: Carter-Wegman (example for $\mathbb{F}_{2^n}$)

- Generate z with a stream cipher: $z \leftarrow 0^n + \mathrm{SC}_K(D)$
- Requires D to be a nonce per message
- Re-use of D leaks k
- Secure if D is a nonce and stream cipher is secure

Solution 2: Dedicated MAC function $T \leftarrow \mathrm{MAC}_K(M)$

When is a MAC function secure?

- For an adversary that does not know the key K
  - $T = \mathrm{MAC}_K(M)$ must be hard to distinguish from a random sequence
  - for values of M freely chosen by the adversary
- You cannot prove this is satisfied
- But you can *claim* security, hope it is attacked and pray it is not broken

Concrete design requirements: Diffusion and Confusion (C. Shannon)

All bits of $T = \mathrm{MAC}_K(M)$ must be a **complicated** function of **all** bits of M en K

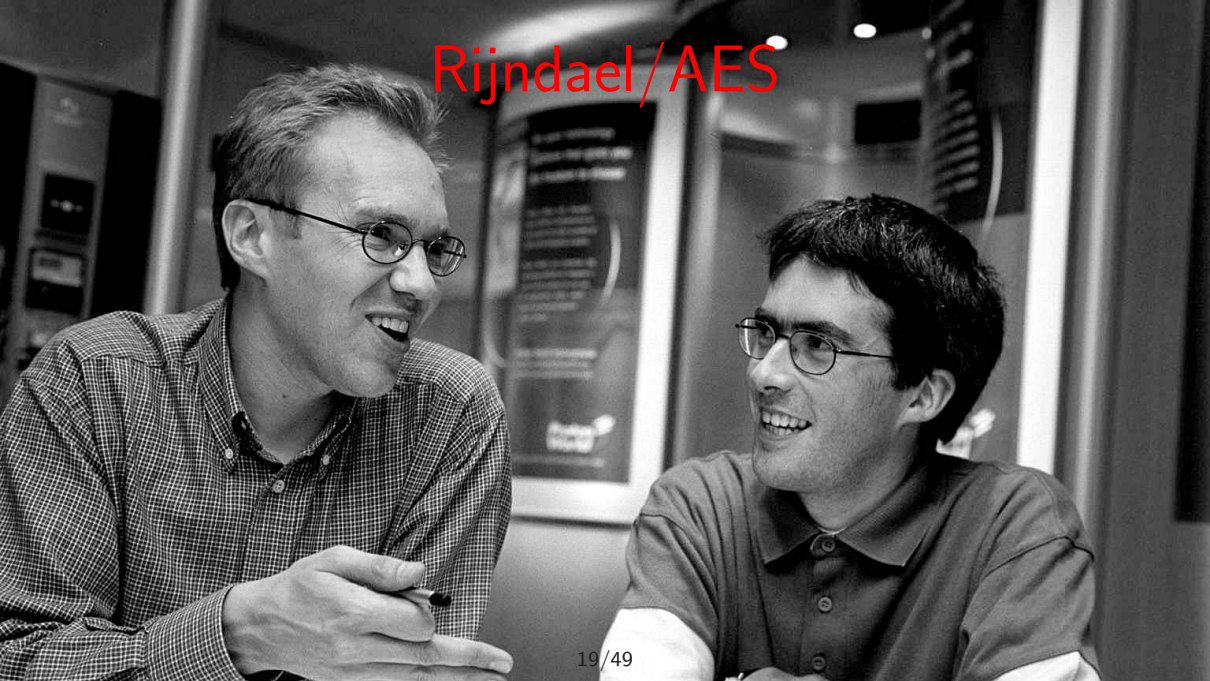
Example of encryption combined with message sequence authentication

Bob		Alice
K, N		K, N'
$N \leftarrow N + 1$		
$C_N \leftarrow M_N \oplus \mathrm{SC}_K(N)$		
$T \leftarrow \mathrm{MAC}_K(N; C_N)$	$\xrightarrow{\text{Bob}, N, C_N, T}$	$N \stackrel{?}{=} N' + 1$
		$T \stackrel{?}{=} \mathrm{MAC}_K(N; C_N)$
		$N' \leftarrow N$
		$M_N \leftarrow C_N \oplus \mathrm{SC}_K(N)$

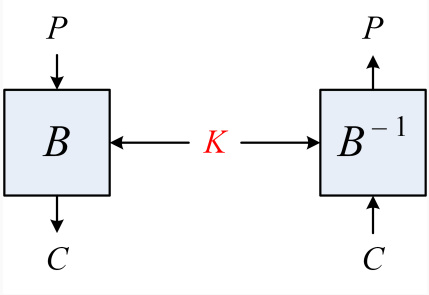
- N serves two purposes
  - encryption nonce incremented by Bob for each message
  - replay/omission prevention checked by Alice per message
- This protocol: no freshness and tolerates no message loss

But how do we build a secure stream cipher or MAC function?

Rijndael/AES

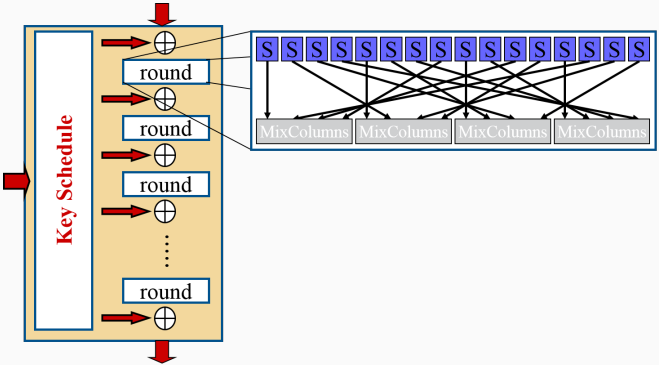


AES is a block cipher



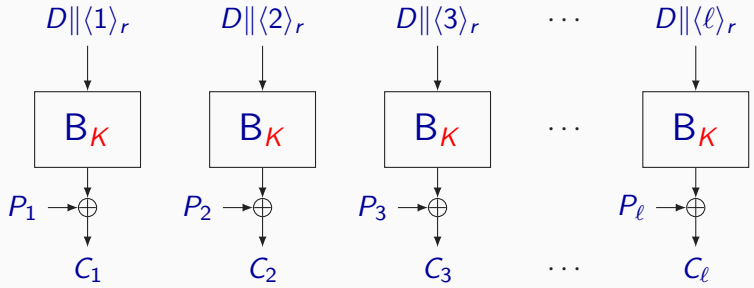
- B_K: encryption of a 16-byte plaintext P to an 16-byte ciphertext C
- Computation of $C = \mathrm{B}_K(P)$ of $P = \mathrm{B}_K^{-1}(C)$ must be
  - efficient for someone who knows the key K
  - . . . infeasible otherwise: B_K *must look like a random permutation*
- With some tinkering this can be made into a stream cipher and a MAC function: *modes of use*

AES in a nutshell



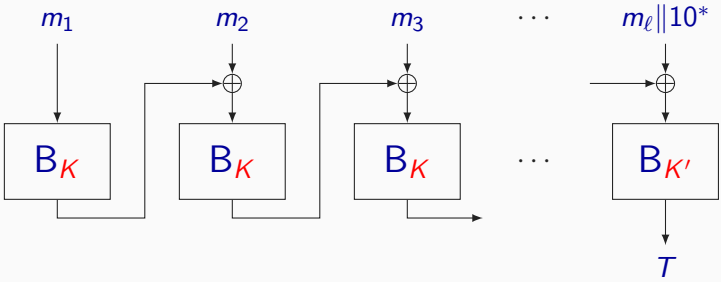
- 10 rounds for 128-bit key, 12 for 192-bit key and 14 for 256-bit key
- Selling point: table-lookup implementatie costs only 16 TLU en XORs per round.
- Best attack breaks reduced-round version of 7 rounds (out of 10)

Stream encryption with a block cipher: Counter mode



- You can prove this is reasonably secure if B_K behaves like a random permutation
- The diversifier D must be a nonce: unique per message
- Security breaks down after $2^{n/2}$ blocks: *birthday bound*

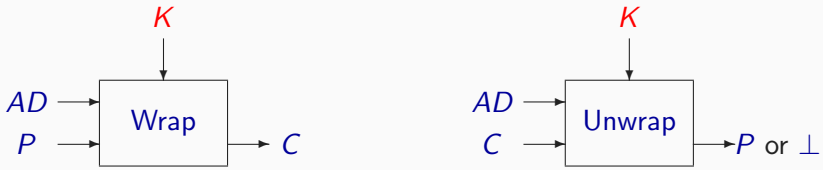
MAC function with a block cipher: CBC-MAC(-like)



- You can prove this is reasonably secure if B_K behaves like a random permutation
- Also here security breaks at the birthday bound: after $2^{n/2}$ blocks

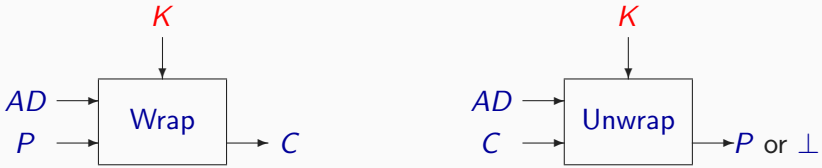
Authenticated encryption

Authenticated encryption (modern definition)



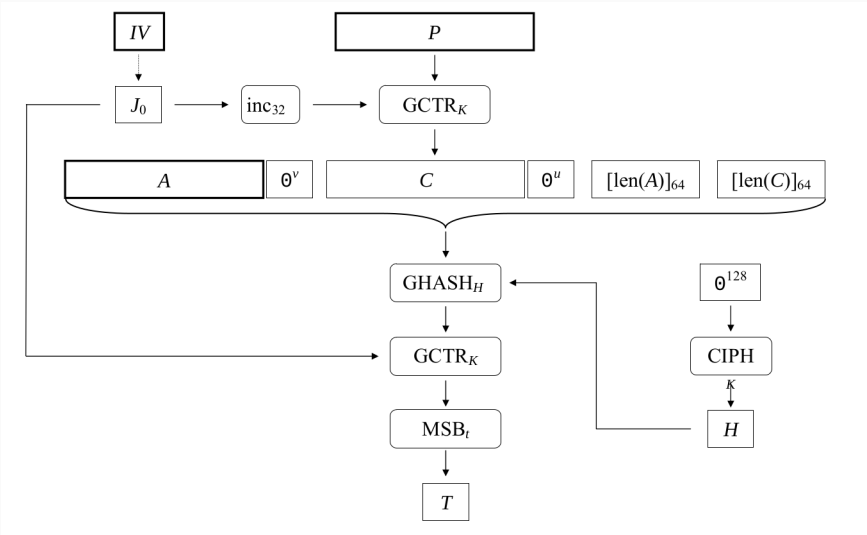
- Wrap: encryption of (var. length) plaintext P to ciphertext C under parameters:
  - (variable-length) associated data AD
  - secret key K
- Unwrap: decryption of C to P includes *authentication*
  - returns error $\perp$ if C is not a valid cryptogram
  - C contains redundancy: $|C| > |P|$
- Wrap and unwrap are deterministic

Authenticated encryption: security goal



- A scheme is secure if it is hard to distinguish from an ideal scheme
- Ideal scheme: the Jammin' cipher [Bacuieti et al., Asiacrypt '22]
  - ciphertexts C are random and independent per input (K, AD, P)
  - unwrap rejects all invalid ciphertexts C
- Limitation: encryption is deterministic
  - leakage: equal inputs (AD, P) give equal ciphertexts C
  - countermeasure: include nonce in AD
- Distinguishability may be conditional on AD uniqueness

Dominant AE standard: AES in Galois Counter Mode (GCM) [NIST SP800-38D]



Issues of AES-GCM

Combination of counter mode AES with Carter-Wegman polynomial MAC over $\mathbb{F}_{2^{128}}$

- In case the diversifier (called IV) repeats:
  - difference of plaintexts leaks
  - authentication key H leaks, so forgery becomes easy
- Diversifier is limited to 96 bits
- Taking a short tag may eventually leak authentication key H
- AES software implementations are vulnerable to **cache attacks**!
  - efficient AES code makes use of table-lookups (TLU)
  - presence/absence of table in cache makes TLU variable-time
  - can be used to recover the key [Page 2002], etc. etc ...

Later Intel and others added AES and GHASH instructions in their CPUs

ChaCha20-Poly1305 by Dan Bernstein

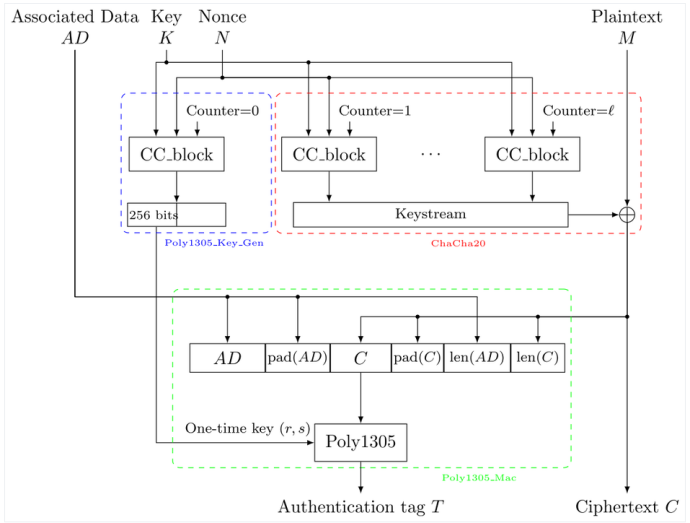


figure by Morz25

ChaCha20 explained

Initial state:

C	C	C	C
K	K	K	K
K	K	K	K
Ctr	D	D	D

Quarter round:

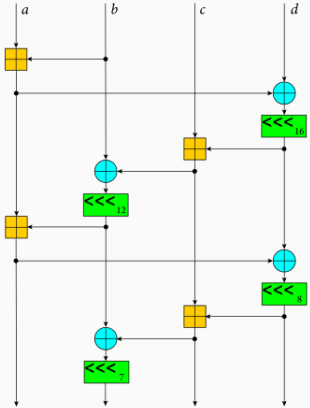


figure T. Arcieri

Odd round:

a	a	a	a
b	b	b	b
c	c	c	c
d	d	d	d

Even round:

a	a	a	a
b	b	b	b
c	c	c	c
d	d	d	d

Best attack breaks reduced-round version of 5/6 rounds (out of 20)

On ChaCha20-Poly1305

- No table-lookups so not vulnerable to cache attacks
  - ChaCha20 is an Addition-Rotation-XOR (ARX) cipher
  - security is based on the mess these operations create when combined
  - very efficient in software, less suited for hardware implementation
  - hard to protect against side channel attacks exploiting measurement of power consumption or electromagnetic emanations
- Poly1305 is a polynomial MAC function in $\mathbb{F}_p$ with $p = 2^{130} - 5$
- In case the diversifier (called N) repeats:
  - difference of plaintexts leaks
  - authentication key r, s leaks, so forgery with same N becomes easy
- Diversifier is limited to 96 bits

ChaCha20-Poly1305 is embraced by Big Tech and the cool crowd!

Deck functions and modes

Deck function based crypto

Refactoring of symmetric crypto, with a three-layer approach:

1. Build permutation f
2. Construct a *new kind of primitive* F_K on top of it
   - input and output of variable length (preferably arbitrary length)
   - output of $F_K(X)$ should look as a sequence of random bits
   - assurance: based on public scrutiny by cryptanalysts
3. Build modes on top of this function that are proven secure if F_K is secure

Definition of a deck function

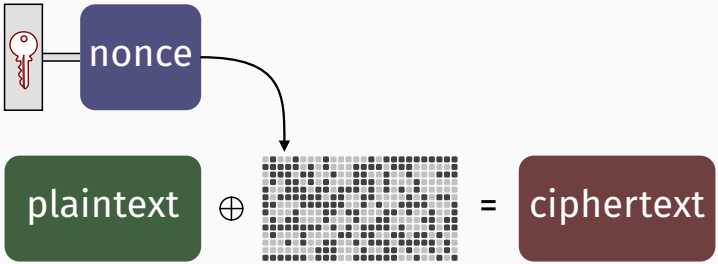
A deck function F_K

$$Z = 0^n + F_K\left(X^{(1)}; \ldots; X^{(m)}\right) \ll q$$

- Input: sequence of strings $X^{(1)}; \ldots; X^{(m)}$
- Output: potentially infinite output
  - **pseudo-random function of the input**
  - taking n bits starting from offset q

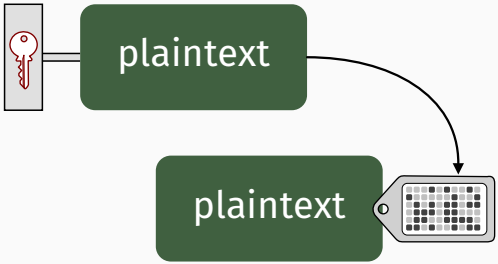
doubly extendable cryptographic keyed function

Stream encryption: short input, long output



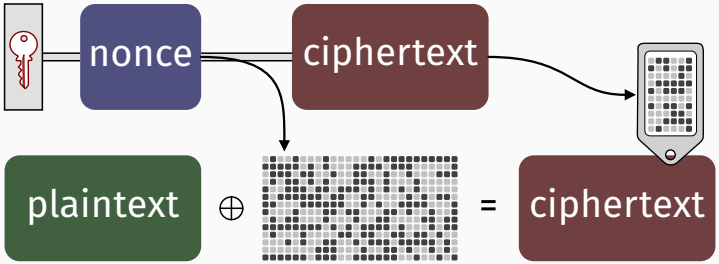
$$C \leftarrow P + F_K(N)$$

MAC computation: long input, short output



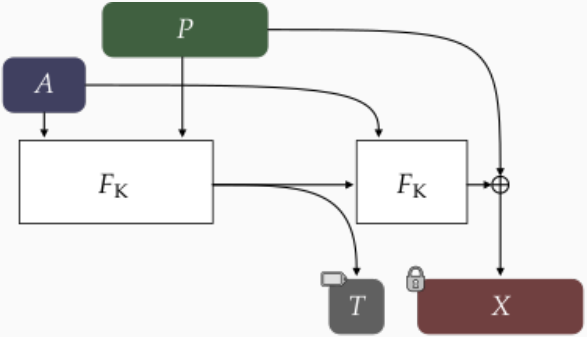
$$T \leftarrow 0^t + F_K(P)$$

Nonce-based authenticated encryption



$$X \leftarrow P + F_K(AD)$$
$$T \leftarrow 0^t + F_K(AD; X)$$
$$C \leftarrow X || T$$

AE without nonce requirement: variant of SIV [Rogaway, Shrimpton Eurocrypt '06]



$$T \leftarrow 0^t + F_K(AD; P||0)$$

$$X \leftarrow P + F_K(AD; T||1)$$

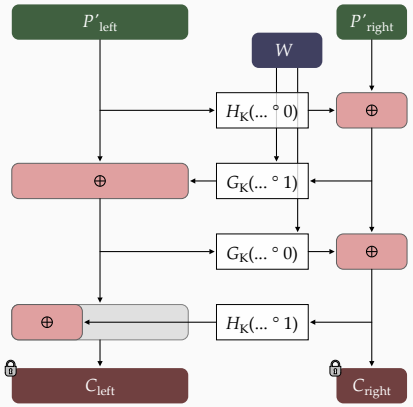
$$C \leftarrow X||T$$

Wide block cipher with double-decker, as Deck-WBC in [KT, eprint 2016/1188]

Encipher $P \in \mathbb{Z}_2^*$ with K and tweak $W \in \mathbb{Z}_2^*$

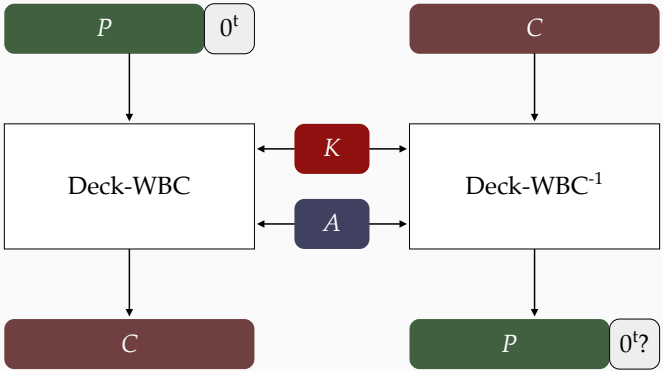
$$
\begin{array}{llll}
(L, R) & \leftarrow & & \mathrm{split}(P) \\
R_0 & \leftarrow R_0 & + & H_K(L||0) \\
L & \leftarrow L & + & G_K(W; R||1) \\
R & \leftarrow R & + & G_K(W; L||0) \\
L_0 & \leftarrow L_0 & + & H_K(R||1) \\
C & \leftarrow L & || & R
\end{array}
$$

return ciphertext C of length $|P|$



Security bound proven in [Gunsing et al, ToSC 2019/4]

Deck-WBC-AE: robust AE [Hoang, Krovetz and Rogaway, Eurocrypt '15]



. . . and much more

- Support for sessions
  - allow intermediate tags for *online* operation
  - allows integrated authentication of bidirectional communication
- Trade-off of efficiency vs robustness against misuse
- Support for *committing* authenticated encryption
- . . . and all their combinations

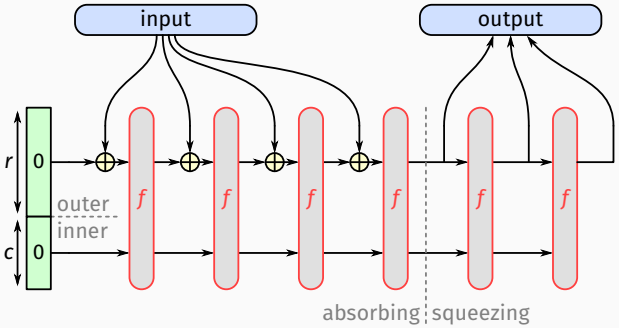
See

"Jammin' on the deck" [Bacuieti et al., Asiacrypt '22]

"Committing authenticated encryption based on SHAKE" [Eprint '23/1494]

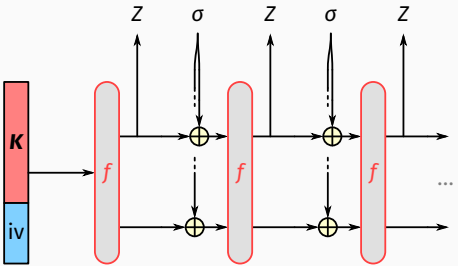
Building deck functions, serially

Sponge [Keccak Team, Ecrypt 2008]



Taking K as first part of input gives something close to a deck function

Keyed duplex object



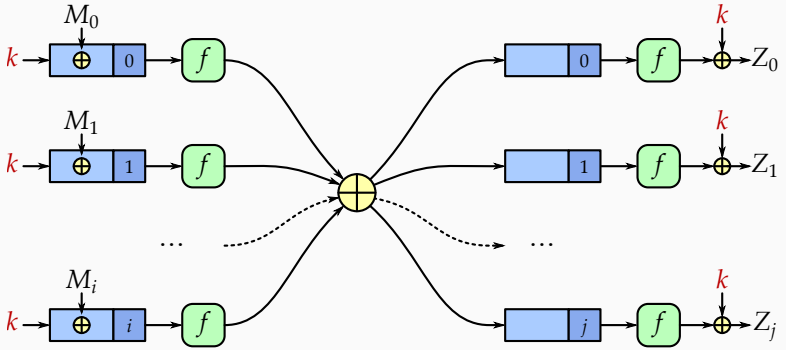
E.g., Strobe [Hamburg 2017], Xoodyak, Subterranean, ASCON [NIST lwc]

- Deck function with length-restricted input and output strings
- Restrictions can be circumvented with a thin input-encoding layer on top
- Cryptanalysis: plug in (round-reduced) permutation and try to break

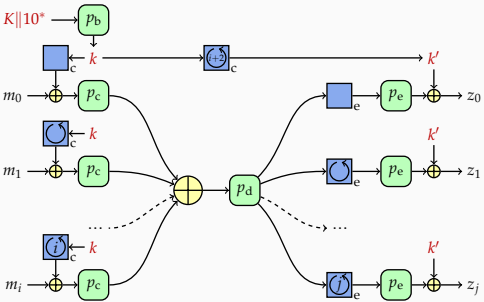
Parallel deck functions

How to build a parallelizable deck function?

Farfalle: early attempt [KT 2014-2016]



Farfalle as published in [Keccak Team + Seth Hoffert, ToSC 2018]



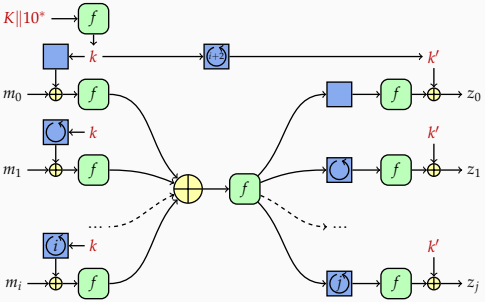
- Derivation of mask k from user key K using p_b
- Linear input mask rolling and p_c *to prevent collisions in state at input of* p_d
- Non-linear state rolling, p_e and mask against state retrieval from output
- Input-output attacks have to deal with $p_e \circ p_d \circ p_c$

Xoodoo and Xoofff

The permutation Xoodoo [Keccak team with Seth Hoffert, ToSC 2018]

- Inspired by 384-bit permutation Gimli [Bernstein et al., CHES 2017]
  - compact on low-end: fits registers of ARM Cortex M3/M4
  - fast on high-end: suitable for SIMD
  - not suited for Farfalle
- Xoodoo
  - 384-bit permutation Keccak *philosophy ported to Gimli shape*
  - main purpose: usage in Farfalle: Xoofff
  - efficient on wide range of platforms

Xoodoo + Farfalle = Xoofff



- $f = \textsc{Xoodoo}$[6]
- Input mask rolling with LFSR, state rolling with NLFSR

Xoofff performance

	ARM Cortex		Intel		
	M0	**M3**	**Skylake**	**SkylakeX**	
mask derivation	1985	781	168	74	cycles
less than 48 bytes	5658	2568	504	358	cycles
MAC computation use case:					
long inputs	26.0	8.8	0.90	0.40	cycles/byte
Stream encryption use case:					
long outputs	25.1	8.1	0.94	0.51	cycles/byte
AES-128 counter mode	121.4	33.2	0.65	0.65	cycles/byte

Conclusions

- There are many AE schemes
- In classical schemes
  - encryption usually done with block ciphers
  - tag computation usually done with polynomial hashes
  - AES-GCM and ChaCha20-Poly1305 dominate
- Secure deck functions are very powerful primitives
  - nonce-based (session) AE
  - SIV-based (session) AE
  - Wide block encryption
- Deck functions can be built from permutations
  - compact: keyed duplex
  - computationally efficient: Farfalle
- Using Xoodoo already gives very competitive deck function Xoofff

Thanks for your attention!