Radboud University

Efficient Instances of Docked Double Decker With AES, and Application to Authenticated Encryption

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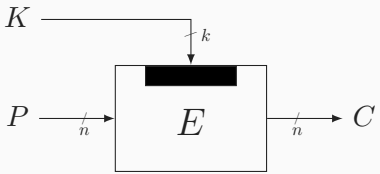
ASK 2024

December 16, 2024

ESCADA

Introduction

Blockciphers



- Plaintext P encrypted to ciphertext C with secret key K
- Fixed block size

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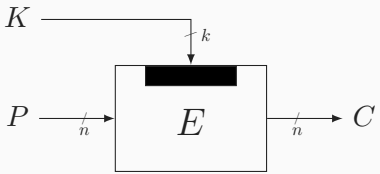
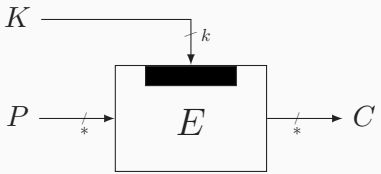


- Plaintext P encrypted to ciphertext C with secret key K
- Fixed block size
- In order to encrypt variable sized plaintexts, we need a mode of operation
  - These modes require a nonce

Wide Blockciphers



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- A wide block cipher is a block cipher with a variable block size

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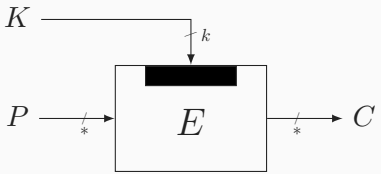
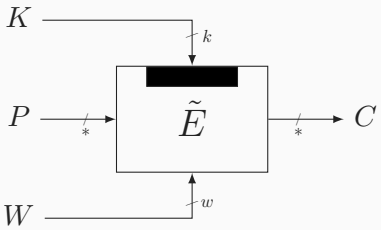


- Alternatively, we can design a wide block cipher
- A wide block cipher is a block cipher with a variable block size
- Every part of the output (ideally) depends on every part of the input

Tweakable Wide Blockciphers



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- Tweak W public, ciphertext completely changes with a different tweak

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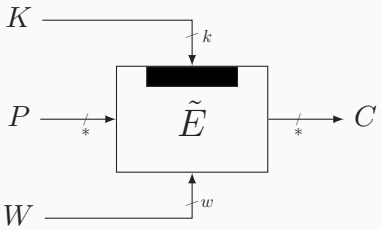

- A tweakable wide block cipher additionally has a tweak
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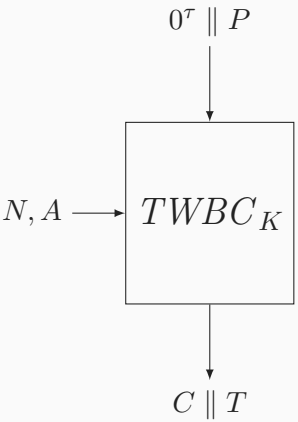
- Applications:
  - disk encryption, where every sector gets its own tweak
  - robust authenticated encryption

Application to Robust Authenticated Encryption [HKR15]



Robust Authenticated Encryption

- Encryption:
  - Prepend τ zeros to P
  - Evaluate with $TWBC_K$ to obtain $C \parallel T$
- Decryption:
  - Decrypt $C \parallel T$ using $TWBC_K^{-1}$
  - If result starts with τ zeros: output P

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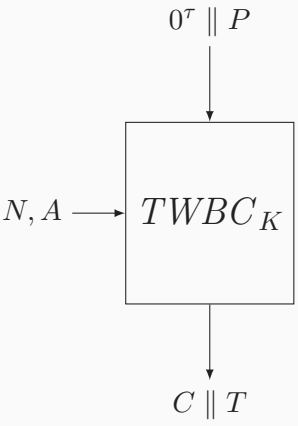

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- Solves many issues present in GCM...
- ... but we first need to design $TWBC$

NIST's Incentive to Develop Accordion Mode

- March 2024: US NIST announced quest for tweakable wide blockciphers
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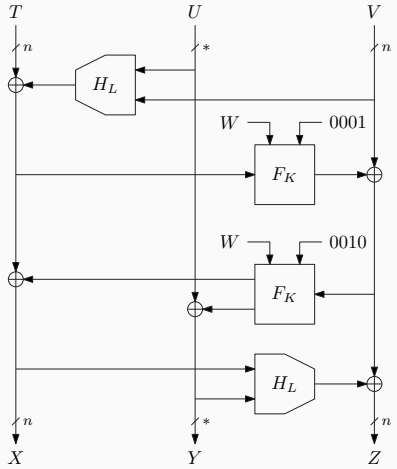
Now: high-level idea of our proposals

Docked Double Decker

Docked Double Decker [GDM19]



Building Blocks

- F_K: stream cipher
- H_L: universal hash

Construction

- Feistel-like structure
- Outer lanes of fixed size
- Inner lane of variable size

Generic Security

- Assume
  - F_K is PRF-secure
  - H_L is ϵ-XOR-universal
- Adversary makes q queries and at most q_W queries per tweak W
- Docked double decker is secure up to approximately

$$\sum_{W \in \{0,1\}^w} \binom{q_W}{2} \epsilon + \mathbf{Adv}_F^{\mathrm{prf}}(2q)$$

Security of Docked Double Decker [GDM19]

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Implications

- Birthday bound secure in n in general case
- Security significantly increases when tweaks are not used too often

Application to Disk Encryption on SSDs

- Docked double decker is very suitable for disk encryption
  - Disks are separated in sectors
  - Block size is equal to the sector size
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  - With tweak separation this improves to $N\binom{500}{2}\epsilon \ll 1$, i.e., $\epsilon \ll 2^{-45}$
- One could take weaker (and thus cheaper) H_L without security sacrifice!

Efficient Instantiation

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- Instantiation using components as used in NIST standardized schemes:
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Goals and Hurdles

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Hurdles

- AES is not a tweakable blockcipher
- AES is rather small (circular reasoning?)
- AES in typical stream cipher modes only gives birthday bound security

ddd-AES

- H_L instantiated using Polyval (sibling of GHASH)
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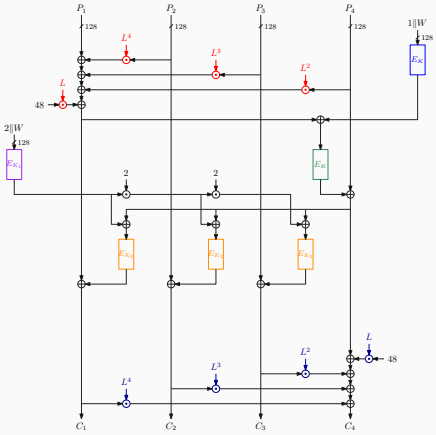
Instantiations turn out to be very competitive and well parallelizable

Efficiency

Implementation Design of $ddd\text{-}AES$ (512-Bit Message)



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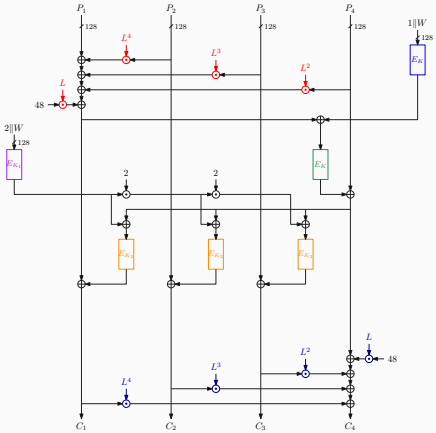

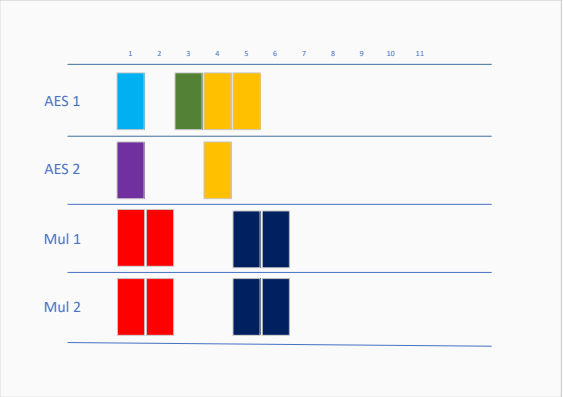

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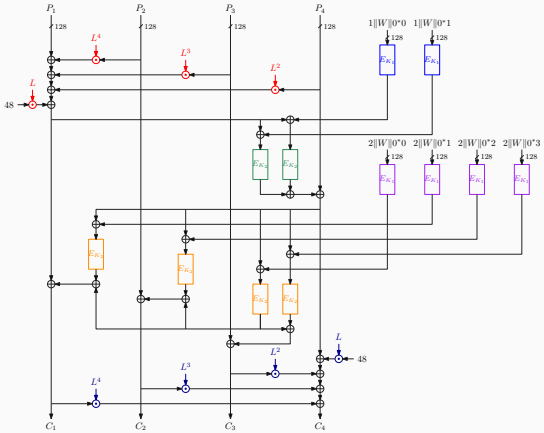

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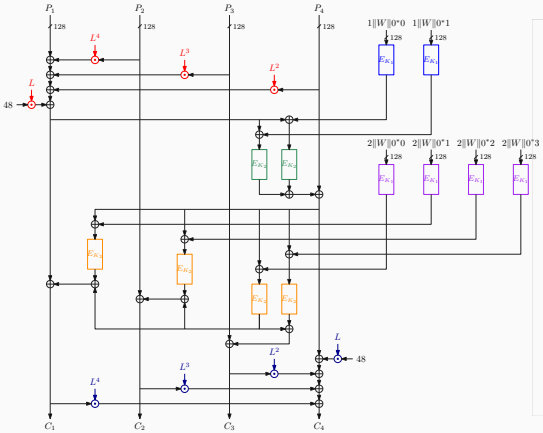

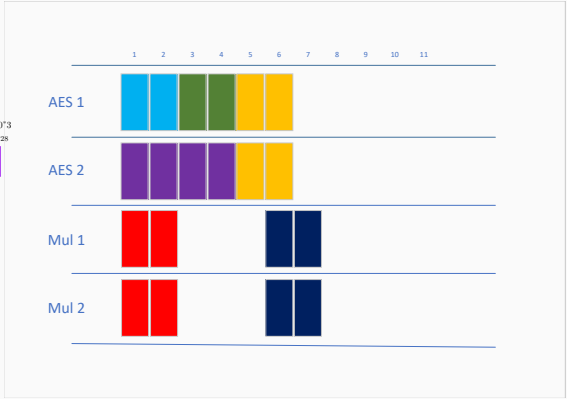

Benchmarks

- *ddd-AES* and *bbb-ddd-AES* on an Intel® Core™ i7-10610U
- C implementation using AES-NI and PCLMULQDQ

Message length (bytes)	32	48	64	96	128	256	512	1024	2048
ddd-AES x1	6	4.3	3.4	2.8	2.5	2.3	2.2	2.1	2.1
ddd-AES x2	6	3.9	3.2	2.5	2.0	1.7	1.5	1.3	1.3
ddd-AES x3	9	4.6	3.1	2.5	2.1	1.4	1.2	1.1	1.0
ddd-AES x4	7	4.3	3.5	2.6	2.3	1.6	1.3	1.1	1.0
bbb-ddd-AES x1	8	5.0	4.0	3.2	2.9	2.6	2.5	2.5	2.5
bbb-ddd-AES x2	9	5.1	3.9	3.0	2.6	1.9	1.6	1.4	1.3
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bbb-ddd-AES x4	8	5.0	4.1	3.0	2.8	1.9	1.4	1.2	1.1

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- For comparison, CBC encryption takes ≈ 1.4 cpb for 2048 byte messages

Conclusion

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- $ddd\text{-}AES$, $ddd\text{-}AES^{+}$, and $bbb\text{-}ddd\text{-}AES$
- Schemes come with security reduction to AES
- We also introduced authenticated encryption mode aaa for TWBCs
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Future Research

- Turning proposal to context committing ciphers (ccc)
- $\widetilde{XORP}$ is a tweakable blockcipher based PRF used in $bbb\text{-}ddd\text{-}AES$
- Only proven $2n/3$-bit secure under limited tweak-reuse $\rightarrow$ tightness?

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Thank you for your attention!

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Efficient Instantiation

Polyval [GLL17]

- Operates on finite field $GF(2^{128})[x]/(x^{128} + x^{127} + x^{126} + x^{121} + 1)$
- Defined as follows, for a padded message $(I_1, I_2, \ldots, I_s)$:

$$Polyval_L(I_1, I_2, \ldots, I_s) = \sum_{i=1}^{s} \left(L^{s-i+1} \cdot I_i \cdot x^{-128 \cdot (s-i+1)} \right)$$

- We use zero-padding with length encoding

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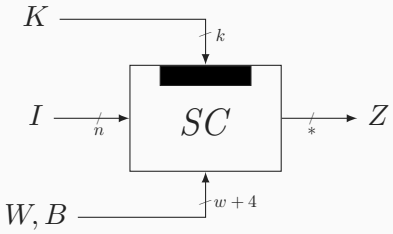
- We use zero-padding with length encoding
- $Polyval$ is ϵ-XOR-universal with $\epsilon = m_{\max}/2^{128}$ [GLL17]

Recall Goal



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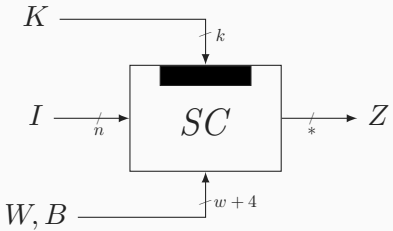

- Construction should be built on top of AES

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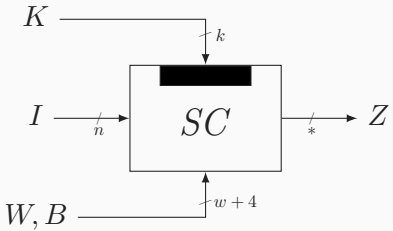
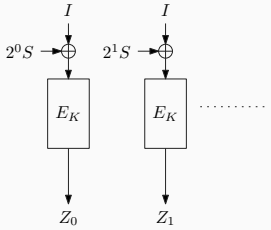


- Construction should be built on top of AES
- We give one construction with birthday bound security
  one construction with beyond birthday bound security

XE-style [Rog04] Tweakable Blockcipher in Counter Mode

- Let $S = E_K(B\|W)$



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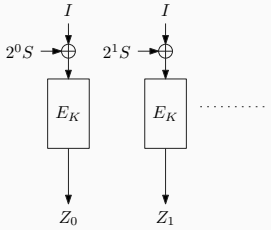

- Stream cipher (and thus $ddd\text{-}AES$) is $2^{n/2}$ PRF-secure

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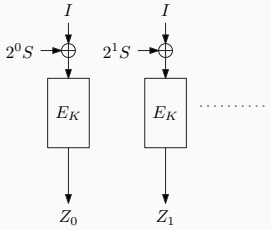

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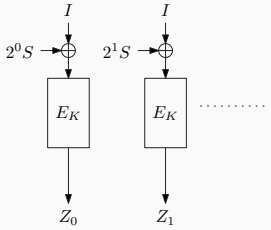
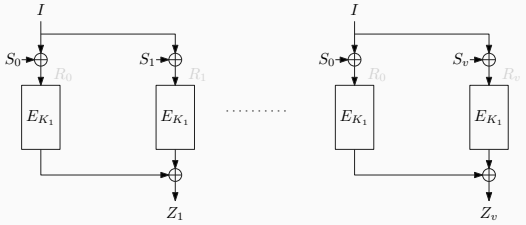


- Stream cipher (and thus $ddd\text{-}AES^+$) is $2^{n/2}$ PRF-secure

$\widetilde{XORP}$ PRF in Counter Mode

- $\widetilde{XORP}$: $XORP$ as used in CENC [Iwa06], and extended to include tweak
  - Introduction is new and comes with separate security proof
  - Let $S_j = E_{K_2}(B \| W \| c \| j)$



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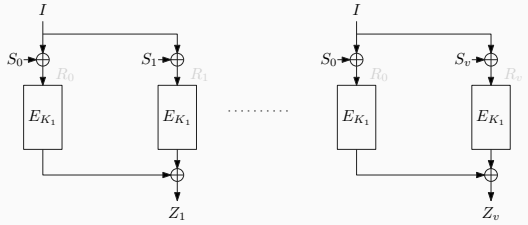
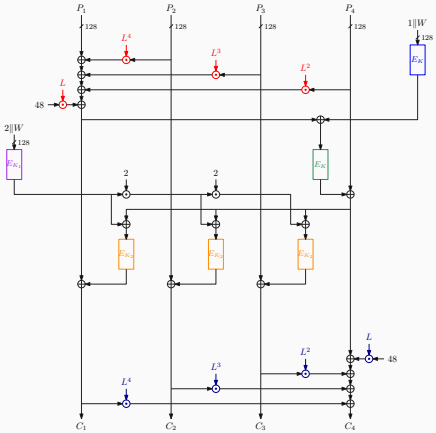
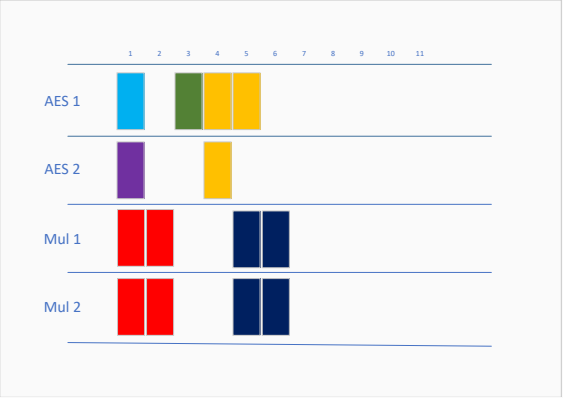


- Corresponding stream cipher runs $\widetilde{XORP}$ in counter mode
- Stream cipher (and thus $bbb\text{-}ddd\text{-}AES$) is $2^{2n/3}$ PRF-secure when tweaks are not used too often

Efficiency

Implementation Design of $ddd\text{-}AES$ (512-Bit Message)





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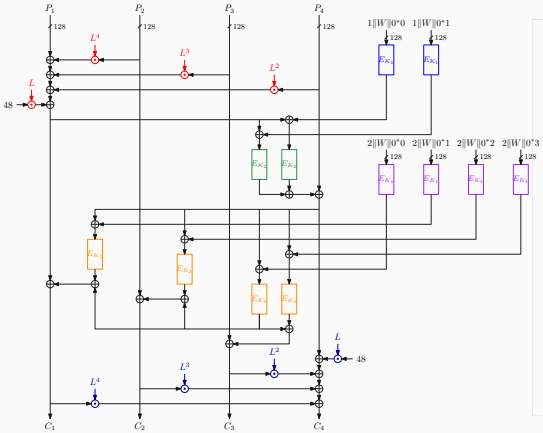
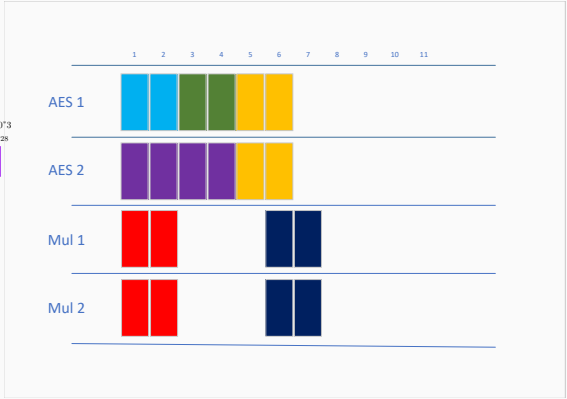
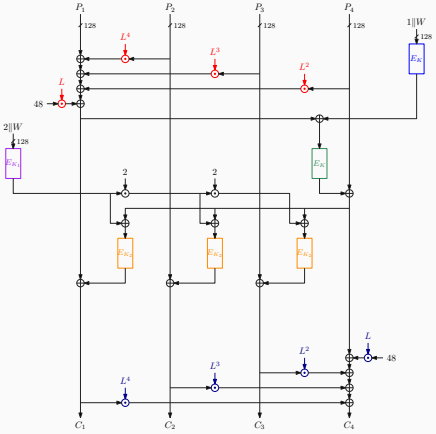
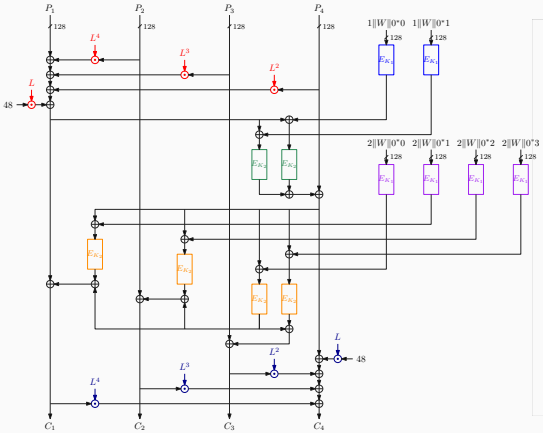




Implementation Design of $ddd\text{-}AES$ (1024-Bit Message)

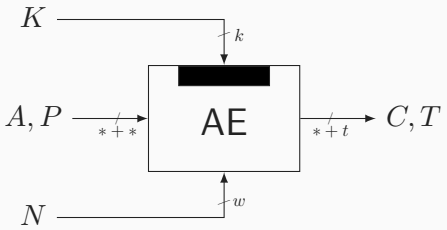


Implementation Design of $bbb\text{-}ddd\text{-}AES$ (1024-Bit Message)



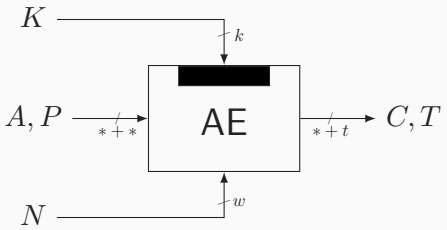
Application to Authenticated Encryption

Authenticated Encryption



- Using key K:
  - Plaintext P is encrypted in ciphertext C
  - Associated data A and plaintext P are authenticated using T

Authenticated Encryption



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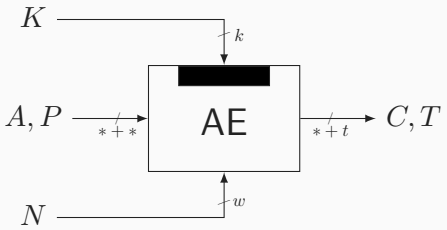

- Using key K:
  - Plaintext P is encrypted in ciphertext C
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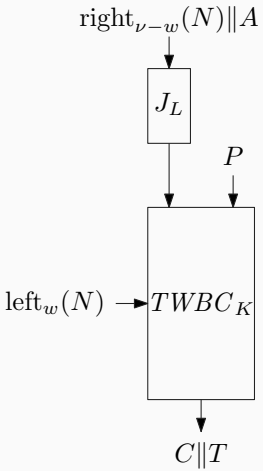
- Nonce N randomizes the scheme
- Decryption outputs message if and only if tag is correct

Advanced Authenticated Encryption with Associated Data (aaa)



Building Blocks

- $TWBC_K$: tweakable wide blockcipher
- J_L: universal hash

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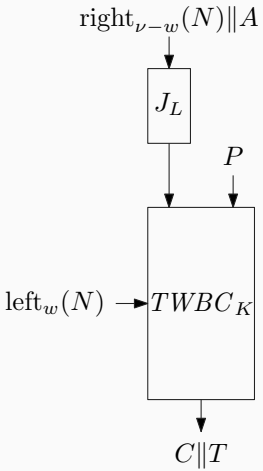
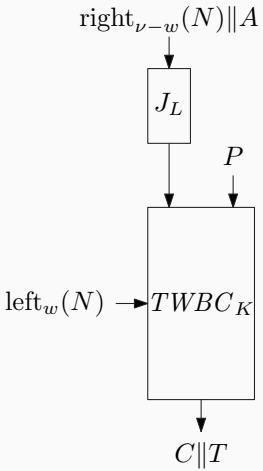


Building Blocks

- $TWBC_K$: tweakable wide blockcipher
- J_L: universal hash

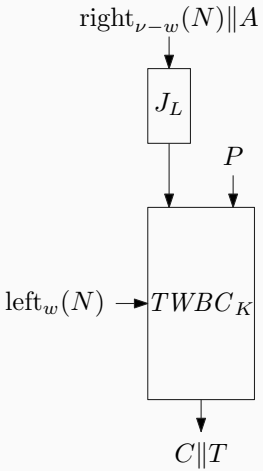
Rationale

- N partially entered into tweak
- Rest of N and A hashed into τ-bit string



Nonce-Respecting Setting

- $\mathrm{left}_w(N)$ unique for each *encryption* query
- Security analysis relies on fact that tweak to $TWBC_K$ is always new



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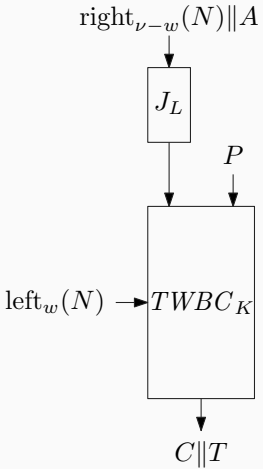
Advanced Authenticated Encryption with Associated Data (aaa): Security



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Nonce-Misusing Setting

- Birthday bound security retained