Towards Optimally Secure Deterministic Authenticated Encryption Schemes

soft merge with

Making GCM Great Again: Toward Full Security and Longer Nonces

Ashwin Jha
RUB

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Eurocrypt 2025

6 May, 2025

Towards Optimally Secure Deterministic Authenticated Encryption Schemes

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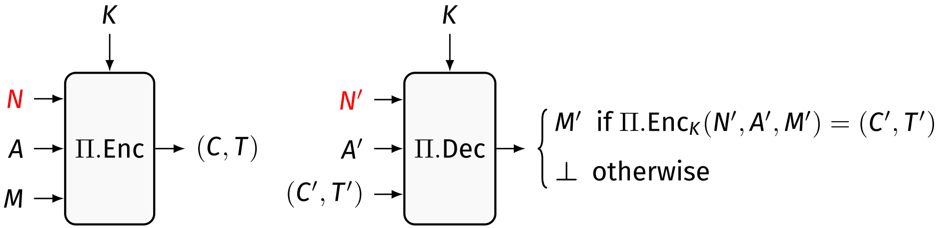
Authenticated Encryption with Associated Data



- AEAD *encrypts* the message M + *authenticates* the metadata & message (A, M)
- Widely deployed (TLS, IPsec, wireless standards)

GCM CCM ChaCha20-Poly1305 Ascon

- Nonce is supposed to be unique in encryption

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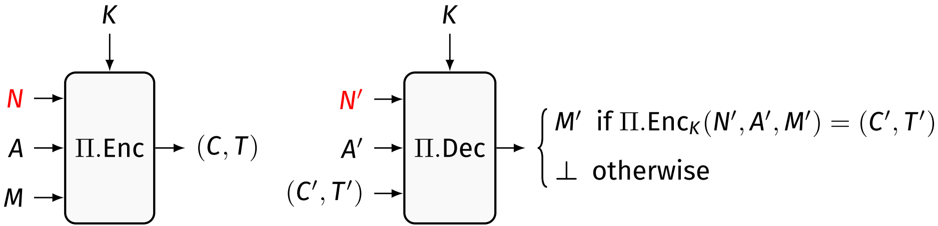

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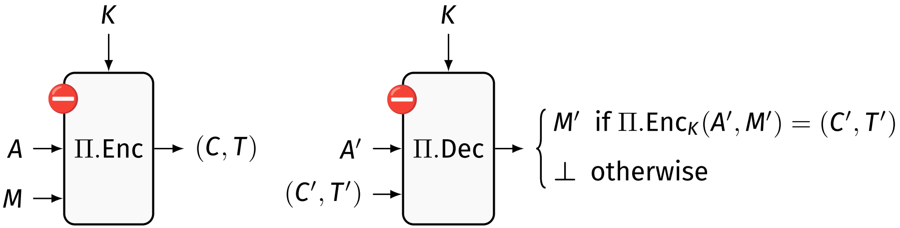
Deterministic AEAD [RS: EC '06]



- AEAD *without* a nonce [can be absorbed in the associated data]
- Encryption at rest (iCloud, AWS) and tokenization (PCI-compliant systems)

SIV GCM-SIV

Why Use a Nonce?

Uniqueness of nonce in encryption ensures security and efficiency

- Security:
  - DAEAD *leaks equality* when message + metadata repeat.
  - Nonce ensures *fresh* randomness per encryption query
- Efficiency:
  - DAEAD are inherently *two-pass* (rate[1] is capped at 0.5)
  - Nonce allows for *single-pass* schemes

[1] The ratio of number of n-bit blocks in the input to the number of primitive calls.

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⚠️ Nonce-reuse is *strictly* prohibited!

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The Curse of Nonce-Misuse

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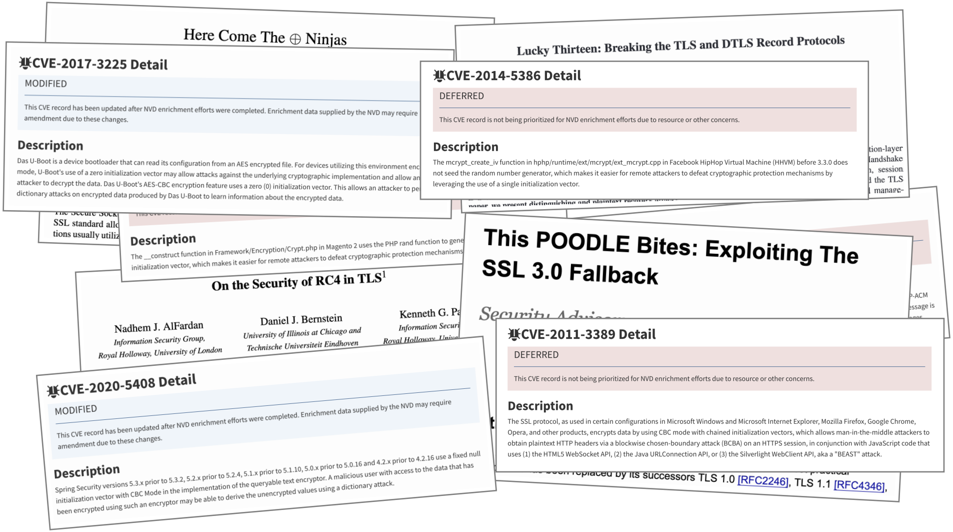

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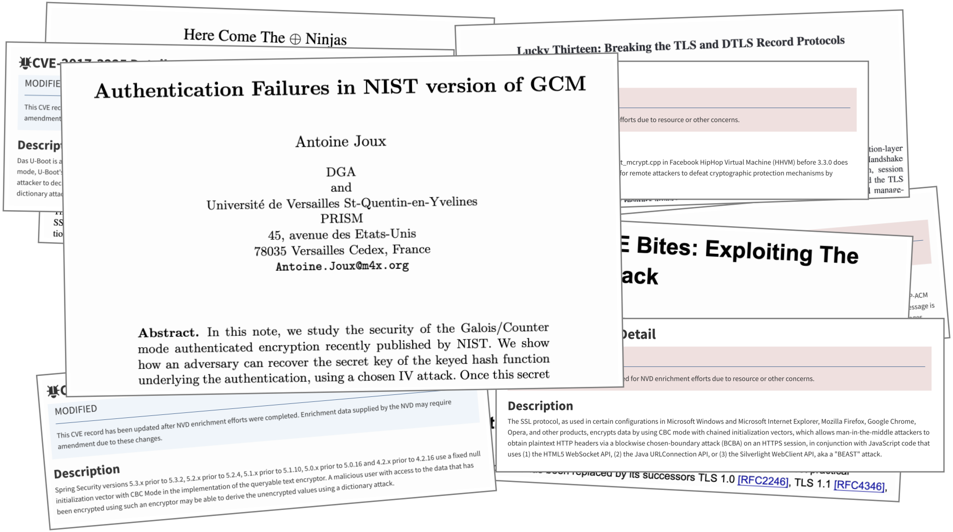

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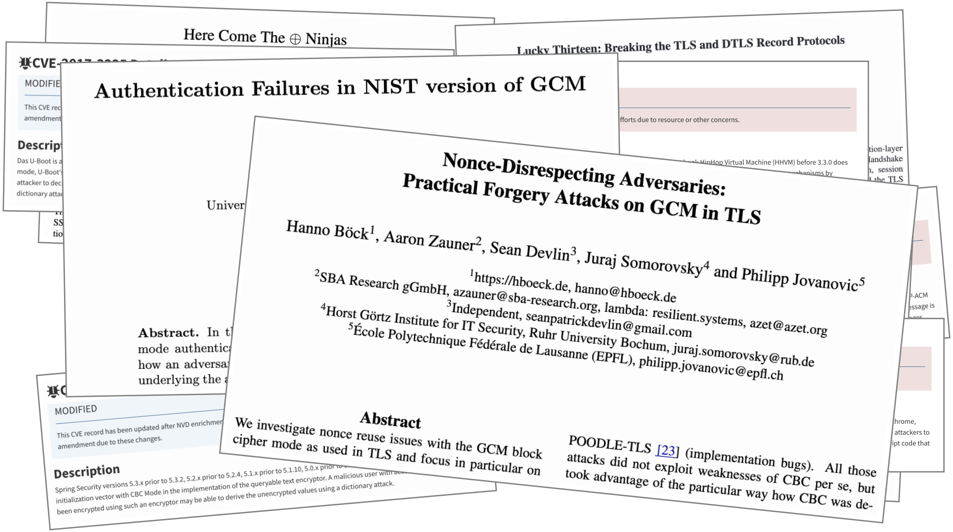

Need for Beyond-the-Birthday Bound Security

- GCM, CCM, and OCB† are *limited* to birthday bound security

  AES-{GCM,CCM,OCB†} is secure up to 2^{64} queries

- 64-bit security might be *insufficient*
  - exabyte-scale ($\simeq 2^{60}$) in use, zetabyte-scale ($\simeq 2^{70}$) expected
  - Limited *generic* multi-user security

- Standardise a bigger block cipher [an effective long term solution(?)]
  - Replacing AES-128 might not be viable
  - Noticeable setup time expected

- BBB secure (nonce-based) AEAD modes
  - CHM: full *n*-bit security
  - SCM: *graceful* degradation (*limited to $n/2$-bit security for arbitrary misuse*)
  - SIV$_r$: BBB nonce-misuse security (*highly inefficient*)

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The Goal

To solve two problems:

- *Unique* nonce requirement
- *Limited* security (birthday bound)

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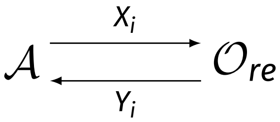
Design a block cipher-based efficient, misuse-resistant BBB-secure AEAD mode

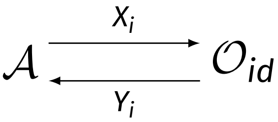
Security Notions: A Quick Recap

The Distinguishing Game

Real World (RW)



Ideal World (IW)

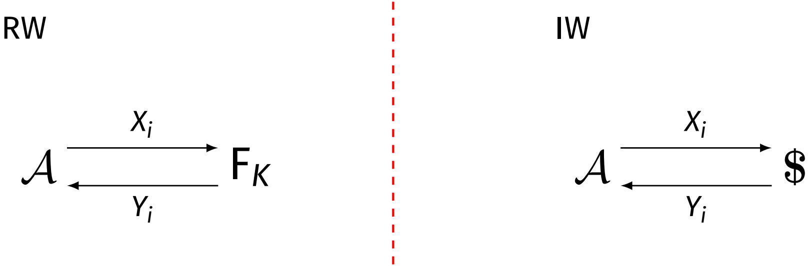


$$\mathbf{Adv}^{\text{game}}_{\mathcal{O}_{re}}(\mathcal{A}) := \left|\Pr\left(\mathcal{A} \text{ returns } 1 \text{ in RW}\right) - \Pr\left(\mathcal{A} \text{ returns } 1 \text{ in IW}\right)\right|$$

- Adversary's resources: q (query), ℓ (max. length), σ (total data) etc.
- Game: ideal world *functionality* + adversary's *power*

Security Notions: A Quick Recap

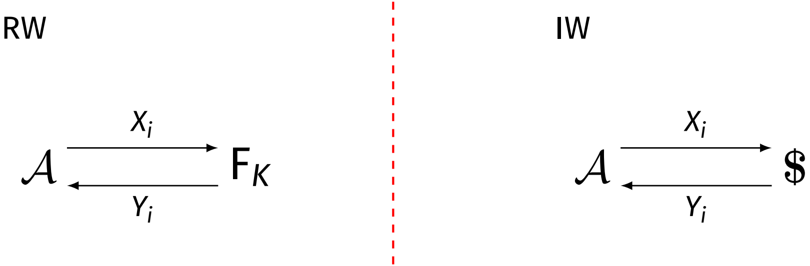
Pseudorandom Function (PRF)



- Ideal world: a uniform random function $\$$
- $\mathcal{A}$ makes *chosen* plaintext queries
- $\mathbf{Adv}_{\mathsf{F}}^{\mathsf{prf}}(\mathcal{A})$: the PRF advantage of $\mathcal{A}$ against F

Security Notions: A Quick Recap

Random IV-based PRF ($-PRF)



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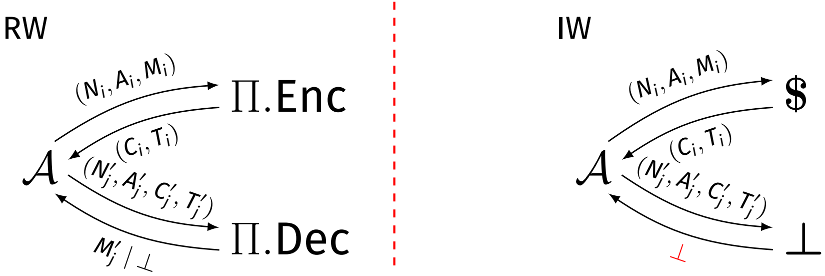
Misuse-resistant AE (MRAE)



- Ideal world: a uniform random function $\$$ and the *reject* oracle $\bot$
- $\mathcal{A}$'s queries must satisfy $(N'_j, A'_j, C'_j, T'_j) \neq (N_i, A_i, C_i, T_i)$
- $\mathbf{Adv}_{\Pi}^{\mathsf{mrae}}(\mathcal{A})$: the MRAE advantage of $\mathcal{A}$ against Π
- DAEADs achieve MRAE security naturally!

Security Notions: A Quick Recap

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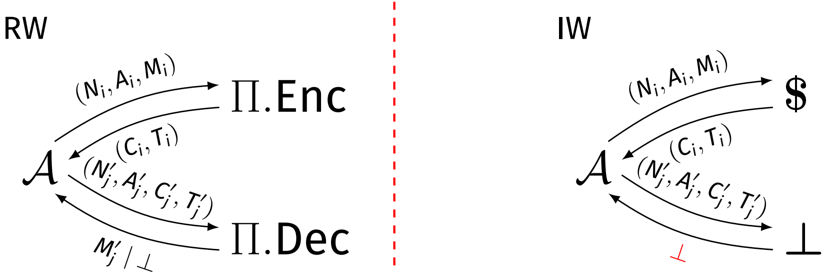

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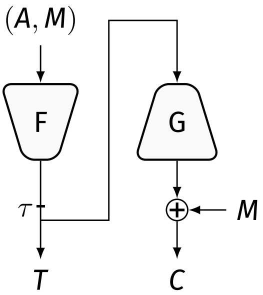
Synthetic IV [RS: EC '06]



- Two main components:
  - F: a PRF
  - G: a random IV-based PRF
- Inverse-free
- Parallelizable
- Composition Bound [RS: EC '06, IM: ToSC '16]:

$$\mathbf{Adv}^{\mathsf{mrae}}_{\mathsf{SIV}}(\mathcal{A}) \leq \mathbf{Adv}^{\mathsf{prf}}_{\mathsf{F}}(\mathcal{B}) + \mathbf{Adv}^{\$\text{-}\mathsf{prf}}_{\mathsf{G}}(\mathcal{C}) + \frac{q}{2^{\tau}}$$

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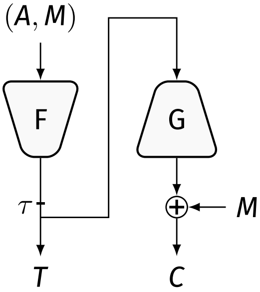

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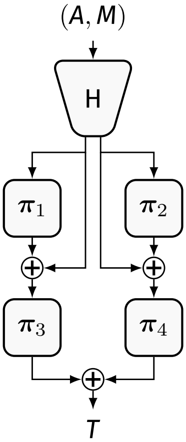
TODOs:

1. A BBB secure PRF component with $\tau > n$ bits of output
2. A BBB secure random IV-based PRF component

The PRF Component

Revisiting **HtmB-p2** [CJN: AC '20]



- Hashing solves two purposes:
  - Handling arbitrary length inputs
  - Inputs to $\pi_{\{1,2\}}$ have *controlled collisions*

  $\implies$ Optimal Security for HtmB

- HtmB-p2 PRF Bound [CJN: AC '20, CDNPS EC '23]:

$$\mathbf{Adv}^{\mathsf{prf}}_{\mathsf{HtmB\text{-}p2}}(\mathcal{A}) = O\left(\frac{q}{2^n} + q^2 \epsilon_{coll}\right)$$

- Limitation: only n-bit outputs

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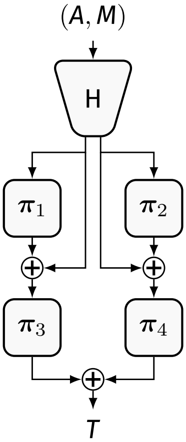

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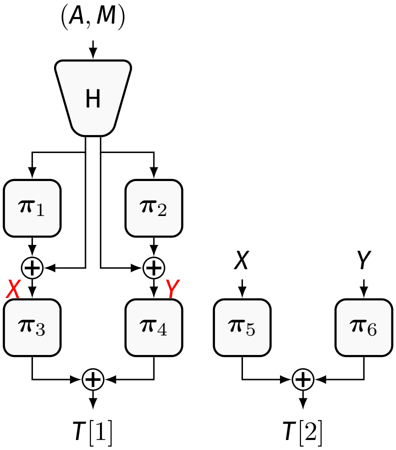
F^*: A BBB secure PRF with $2n$-bit outputs



- HtmB-p2*:
  - Duplicates the HtmB-p2 finalization
  - Additional n bits at the cost of two calls
- F*: HtmB-p2* with a PMAC+ like hash

F* is optimally secure [for lengths up to $\sqrt{2^n}$]

$$\mathbf{Adv}^{\mathsf{prf}}_{\mathsf{F}^*}(\mathcal{A}) = O\left(\frac{\sigma}{2^n}\right)$$

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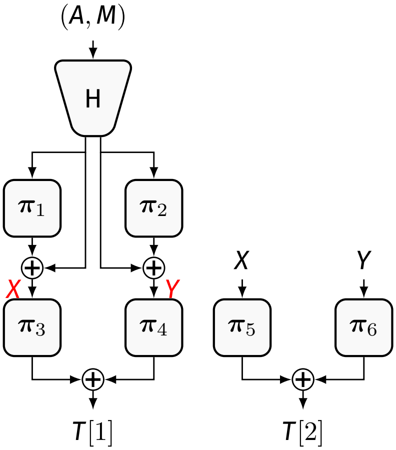

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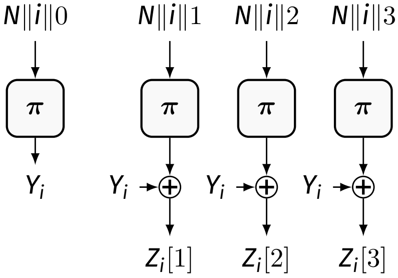
The Random-IV PRF Component (Option 1)

Revisiting CENC [Iwata: FSE '06]



The i-th chunk of keystream (r=3)

- Keystream is generated in chunks of r blocks
- Fully parallelizable
- Rate $\approx \left(\frac{r}{r+1}\right)$
- Optimally secure if IVs are *unique* [IMV: ePrint '16]
- Limitations:
  - $|N| < n$ (we require $\approx 2n$)
  - Only *birthday-bound* \$-PRF secure

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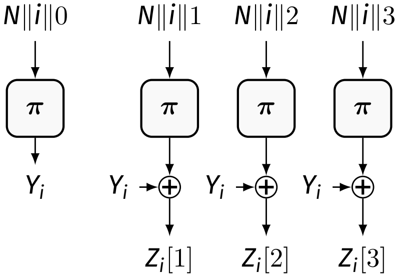

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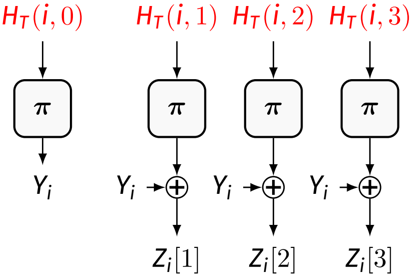
GiantStar: A BBB secure random IV-based PRF



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- CTR-based encoding $\rightarrow$ *lightweight* hash
  - Use the random IV as key
- Inherits all the the efficiency traits of CENC
- Secure if hash is 2-wise independent

GiantStar is BBB secure [for *moderately* large ℓ]

$$\mathbf{Adv}^{\$\text{-prf}}_{\text{GiantStar}}(\mathcal{A}) = O\left(\frac{r\sigma}{2^n} + \frac{r\sigma^2\ell}{2^{2n}}\right)$$

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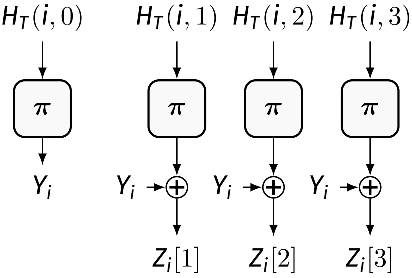

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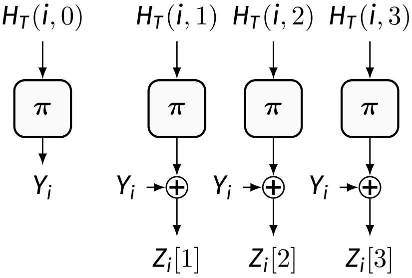

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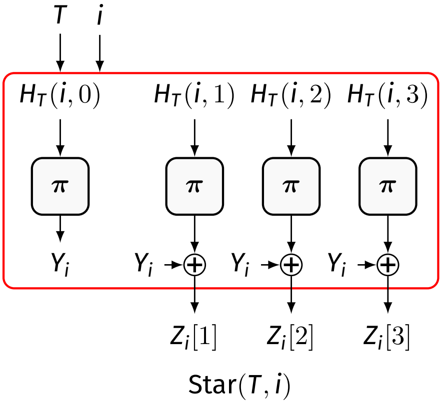
The Random-IV PRF Component (Option 2)

Star: A fixed-length BBB secure random IV-based PRF



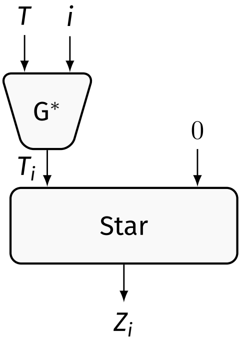
- Star $\equiv$ GiantStar with
  - Fixed chunk index i
  - Restricted to $\leq r$-block outputs

Star is optimally secure

$$\mathbf{Adv}^{\$\text{-prf}}_{\text{Star}}(\mathcal{A}) = O\left(\frac{rq}{2^n}\right)$$

The Random-IV PRF Component (Option 2)

Snowflake: A length-independent BBB secure random IV-based PRF



The i-th chunk of keystream

- Fresh $2n$-bit randomness per chunk

$$\mathbf{Adv}^{\text{\$-prf}}_{\text{Snowflake}}(\mathcal{A}) \leq \mathbf{Adv}^{\text{\$-prf}}_{\text{Star}}(\mathcal{B}) + \mathbf{Adv}^{\text{\$-prf}}_{\text{G}^*}(\mathcal{C})$$

- G* must have *length-independent* bound!
- G* can be relatively heavier
  - in the paper: 6 calls per chunk

Snowflake is optimally secure

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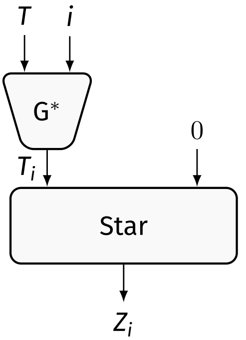

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Our Contributions

Two misuse-resistant BBB-secure AEAD modes

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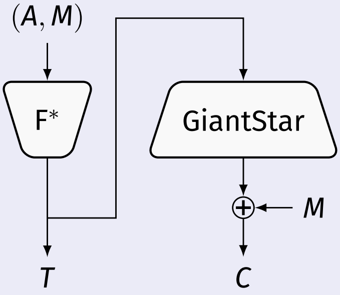
DENC1



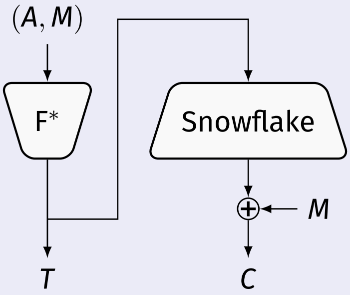
- Highly *parallelizable*
- Tag size $\tau = 2n$-bit
- Max. input length $\ell \leq \sqrt{2^n}$-block
- Rate $\geq \left(\frac{r}{2r+0.5}\right)$ (≈ 0.498 for $r = 64$)
- BBB secure for *moderate* message lengths

$$\mathbf{Adv}^{\mathsf{mrae}}_{\mathsf{DENC1}}(\mathcal{A}) = O\left(\frac{r\sigma^2\ell}{2^{2n}}\right)$$

Our Contributions

Two misuse-resistant BBB-secure AEAD modes

DENC2



- Highly parallelizable
- Tag size $\tau = 2n$-bit
- Max. input length $\ell \leq \sqrt{2^n}$-block
- Rate $\geq \left(\frac{r}{2r+3.5}\right)$ (≈ 0.486 for $r = 64$)
- Length-independent optimal security

$$\mathbf{Adv}^{\mathsf{mrae}}_{\mathsf{DENC1}}(\mathcal{A}) = O\left(\frac{r\sigma}{2^n}\right)$$

Making GCM Great Again: Toward Full Security and Longer Nonces

Woohyuk Chung[1] Seongha Hwang[1] Seongkwang Kim[2]
Byeonghak Lee[2] Jooyoung Lee[1]

[1]KAIST, Korea [2]Samsung SDS, Korea

Eurocrypt 2025

2025. 05. 06.

Same Motivation, Different Goal

Recall: We require BBB-secure AEAD with low nonce misusing risk.

1. Design a misuse-resistant AE
    - AES-GCM-SIV, DENC1, DENC2, ...
    - Best for security, but inherently two pass
2. Design a nonce-based AE with extended nonces
    - DNDK-GCM: requires carefully generated nonces and BC with 2n-bit key

Same Motivation, Different Goal

Recall: We require BBB-secure AEAD with low nonce misusing risk.

1. Design a misuse-resistant AE
   - AES-GCM-SIV, DENC1, DENC2, ...
   - Best for security, but inherently two pass
2. Design a nonce-based AE with extended nonces
   - DNDK-GCM: requires carefully generated nonces and BC with 2n-bit key

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Our Goal:

- Block cipher based AE with full security
  + Provably secure under standard PRP assumption
- Efficiency is comparable to GCM
- Support extended nonces or provide nonce misuse resistance
- Support arbitrary length message

Starting Point: CENC

Cipher-based ENCryption (CENC)

- CTR-type encryption mode with full security

$$\mathsf{Adv}^{\mathsf{prf}}_{\mathsf{CENC}[E,r]}(q,\sigma,l) \leq O\left(\frac{\sigma}{2^n}\right)$$

- limitation: $|\text{nonce}| + |\text{counter}| \leq n$
  $\Rightarrow$ still have nonce misusing risk and short length limitation

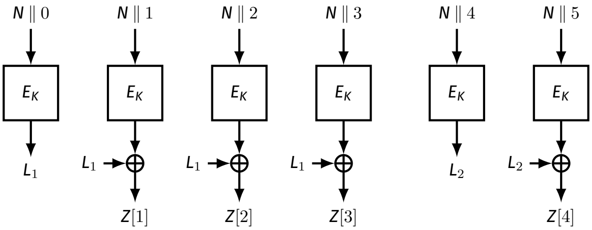


Figure: The first 4 keystream blocks from $\mathsf{CENC}[E_K, w](N, \cdot)$ with $w = 3$.

Building Blocks - eCTR

enhanced CTR (eCTR) ($\simeq$ GiantStar !)

- almost fully secure variable output length PRF (VOL-PRF) with 2n-bit random IV

$$\mathbf{Adv}^{\$\text{-prf}}_{\text{eCTR}[E,r]}(\mathcal{A}) \leq O\left(\frac{r\sigma}{2^n} + \frac{r\sigma^2 l}{2^{2n}}\right)$$

- limitation: requires random IV
  $\Rightarrow$ enough for iv-based AE, but we want nonce-based

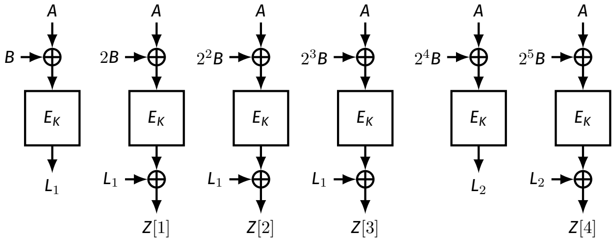


Figure: The first 4 blocks from eCTR$[E_K, w](A, B)$ with $w = 3$.

Building Blocks - HteC

Hash-then-eCTR (HteC)

- almost fully secure variable input/output length PRF (VIL-VOL-PRF)

$$\mathsf{Adv}^{\mathsf{prf}}_{\mathsf{HteC}[H,E,w]}(\mathcal{A}) \leq O\left(\frac{w\sigma}{2^n} + \frac{w\sigma^2 l}{2^{2n}}\right)$$

  where H is δ-universal hash (UH)
- UH-then-PRP outputs $(= A, B)$ are not fully random but enough for eCTR input

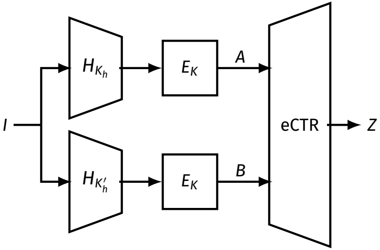
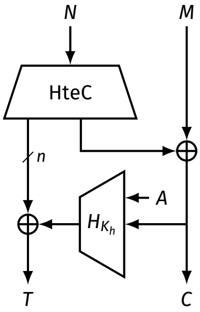


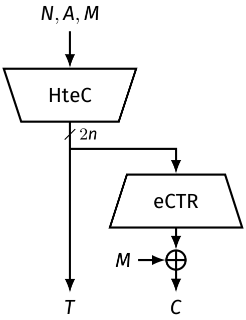
Figure: The HteC VIL-VOL pseudorandom function.

Our Contribution

eGCM/eGCM-SIV: enhanced variant of GCM/GCM-SIV



(a) Encryption of eGCM

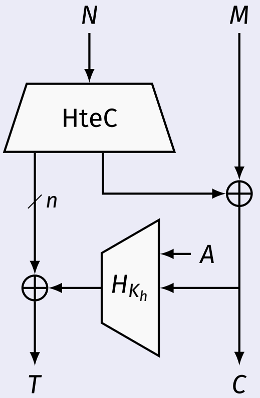


(b) Encryption of eGCM-SIV

Figure: The eGCM and eGCM-SIV AE schemes. A nonce, an associated data, and a message are denoted *N*, *A* and *M*, respectively

Our Contribution

eGCM

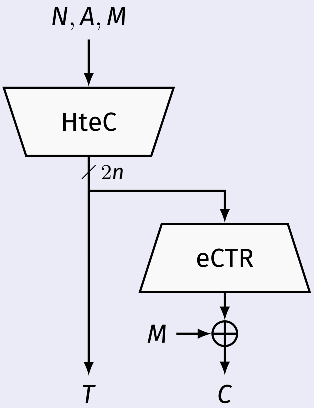


- Replace CTR to HteC
- Support extended nonces
- Support encrypting arbitrary length messages
- BBB secure for *moderate* message lengths

$$\mathrm{Adv}^{\mathrm{nae}}_{\mathrm{eGCM}}(\mathcal{A}) = O\left(\frac{r\sigma^2\ell}{2^{2n}}\right)$$

Our Contribution

eGCM-SIV



- Use HteC as PRF and replace CTR to eCTR
- Support encrypting arbitrary length messages
- BBB secure for *moderate* message lengths

$$\mathsf{Adv}^{\mathsf{dae}}_{\mathsf{eGCM\text{-}SIV}}(\mathcal{A}) = O\left(\frac{r\sigma^2\ell}{2^{2n}}\right)$$

Comparison

AEAD	Rate	Security	
		NR	NM
OCB3	1	$n/2$	-
GCM	1/2	$n/2$	-
CIP, CHM, mGCM, eGCM	$\lesssim 1/2^{\dagger}$	n	-
AES-GCM-SIV	1/2	n	$n/2$
SCM	1/2	n	$n/2$
CWC+	$\lesssim 1/2^{\dagger}$	$3n/4$	$n/2$ (auth only)
eGCM-SIV, DENC1, DENC2	$\lesssim 1/2^{\dagger}$	n	n

‡ Depends on the parameter w, while we write $\lesssim 1/2$ since the rate approaches $1/2$ as w increases and w can be set to a large enough value.

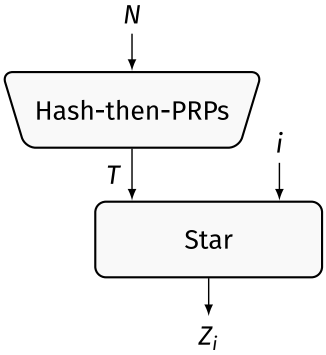
Table: Comparion of eGCM, eGCM-SIV, DENC1 and DENC2 and other block cipher based AE schemes. The maximum message length $(= l)$ is assumed to be a small constant. Note that DENC2 has length-independent security.

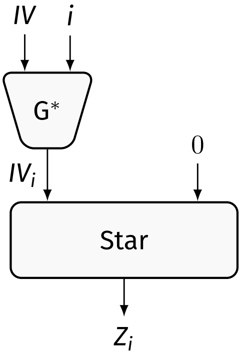
Benchmark

AEAD	Message		
	1KB	4KB	64KB
OCB3	0.52	0.47	0.45
GCM	1.65	1.02	0.83
eGCM	0.93	0.89	0.88
AES-GCM-SIV	1.33	1.07	0.99
SCM	1.19	1.11	1.07
eGCM-SIV	1.33	1.15	1.12
DENC1	1.31	1.20	1.18
DENC2	1.42	1.38	1.32

Table: Benchmark of eGCM, eGCM-SIV, DAE1 and DAE2 and other block cipher based AE schemes. Throughput is measured in cycles per byte, for empty associated data.

HteC vs SnowFlake

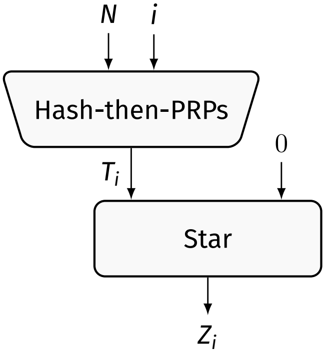




- Use arbitrary length nonces
- Simpler compressing function
- Length-dependent security

- Use random IVs (enough for SIV)
- Length-independent security
- G^* is heavy!

Combining Two Papers: **HteC + SnowFlake**



- G* is replaced by Hash-then-PRPs $\Rightarrow$ faster and support nonce!
- VIL-VOL-PRF with (output) length-independent security
- Can be used to construct fully secure NAE and DAE

Conclusion

Towards Optimally Secure DAEs

- DENC1: almost fully secure DAE
- DENC2: fully secure DAE (length-independent security)

Making GCM Great Again

- HteC: almost fully secure VIL-VOL-PRF
- eGCM: almost fully secure NAE with extended nonces
- eGCM-SIV: almost fully secure DAE

Our results can also be applied to:

- Accordion ciphers: Hash-CTR-Hash $\Rightarrow$ Hash-(eCTR/SnowFlake)-Hash
- Nonce-key derivation: HteC and HteC+SnowFlake are PRF

Thank you for your attention!