Expanding the Scope, Security and Efficiency of Classical Symmetric Primitives

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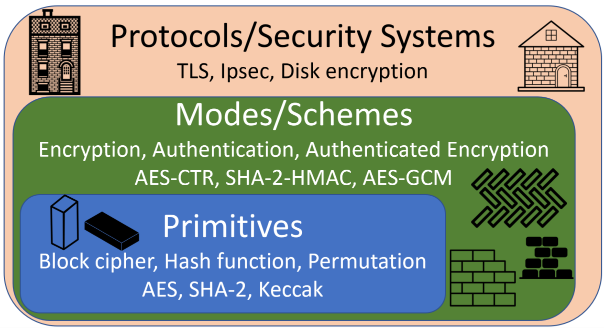
GAPs Workshop, Singapore

Modular Approach to Building Cryptographic Systems

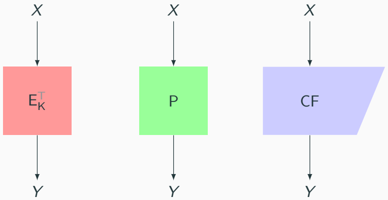
Modular aka Provable Approach



- \+ Bottom-up approach
- \+ **Primitives** over blocks $\Rightarrow$ **Schemes** on long data $\Rightarrow$ **Systems**
- \+ Reductionist security
- \+ Proofs allow to estimate min. adversarial attack resources (time, number/length of messages)

Symmetric-Key Primitives (Fixed-Size Block)

1. **Block cipher:** $\mathcal{K} \times \mathcal{X} \mapsto \mathcal{Y}$ where $|\mathcal{X}| = |\mathcal{Y}|$
   3-DES, AES
2. **Permutation:** $\mathcal{X} \mapsto \mathcal{Y}$ where $|\mathcal{X}| = |\mathcal{Y}|$
   Keccak in SHA3
3. **Compression function:** $\mathcal{X} \mapsto \mathcal{Y}$ where $|\mathcal{X}| > |\mathcal{Y}|$
   SHA2



Symmetric-Key (SK) Schemes for Secure Systems

SK primitives used for **classical**:

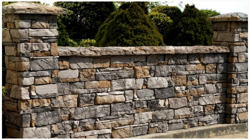
- **Encryption**
- **Message authentication**
- **Authenticated Encryption (AE)**

Modern security systems/protocols require SK primitives and modes with advanced and diverse security (NMR, BBB, RUP, MUS, CS, etc.), performance, cost requirements:

- TLS, IPSec, WiFi, DiskEnc, Key derivation, Multi-party Computation, Zero-Knowledge proofs, Blockchains, Messaging protocols (e.g, Signal, WhatsApp), etc.

Central Questions

1. Are we using the best-suited SK primitives in **modern** cryptographic systems?

 OR 

2. Are we not designing primitives/modes largely **in isolation**?

Why the Questions?

- Legacy: DES → 3-DES → AES (main application encryption)
  MD5 → SHA1 → SHA2 (main application integrity)

- More recent: SKINNY , DEOXYS TBCs, PRINCE, etc.
- Typical security in schemes:
  - AES 128-bit block → 64-bit security
  - PRINCE 64-bit block → 32-bit security
  + DEOXYS 128-bit block, 128-bit tweak → 128-bit security
  - Robust security harder with classical primitives
- Cost and suitability
  - DEOXYS vs AES → 14 vs 10 internal AES rounds
  - Typical AE overhead: 1BC per block to encrypt + 2 extra BC or 1 multiply per block for authentication
  - Hash function (HKDF) for randomness extraction ...

Goal: Primitives that are suited to modern system functionalities with adequate security at minimal cost

Towards Novel Primitives

1. Tweaks and innate **robustness** features – BBB, RUP, NMR, MUS, length-independence, block-wise atks or SC resistance, etc.
2. **Well-cryptanalyzed** structure – SPN, Tweakey, IEM, Sum of Ps
3. **Expansion** better-suited for $ Extraction/Enc/AE/etc.
4. **Improved performance**: internal/external parallelism, optimized for long/short M, high throughput, etc.
5. αn-bit expansion need be more **efficient** than α TBCs of n-bit

Forkcipher
Fixed-Output-Length (FOL)
Tweakable Expanding Function[a]

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[a]E. Andreeva, V. Lallemand, A. Purnal, R. Reyhanitabar, A. Roy, D. Vizàr
ForkAE, second round in NIST LW Standardization, 2019
Forkcipher: A New Primitive for Authenticated Encryption of Very Short Messages, ASIACRYPT'19

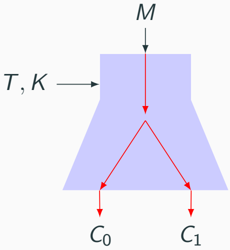
Forkcipher: FOL Tweakable Expanding Function

$FC : \mathcal{K} \times \mathcal{T} \times \mathcal{M} \mapsto \mathcal{C}_0 \times \mathcal{C}_1$ with $|M| = |C_0| = |C_1| = n$

K: secret and random

T: public tweak

Forward execution ($2n$-bit output)



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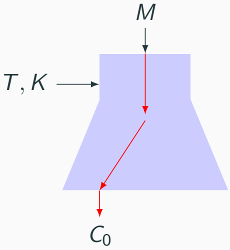
Output selection C_0 (left n-bit output = TBC)



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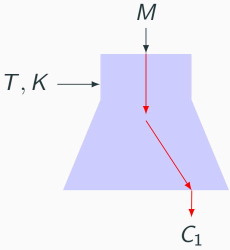
Output selection C_1 (right n-bit output = TBC)



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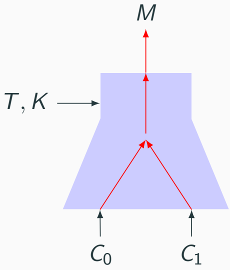
K: secret and random

T: public tweak

Inversion from either one or both C_0 and C_1



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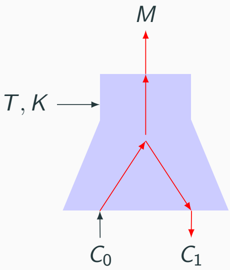
Reconstruction from C_0 to C_1 through forking point



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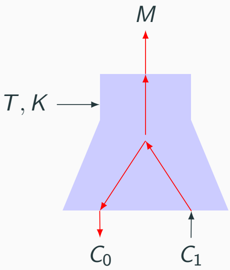

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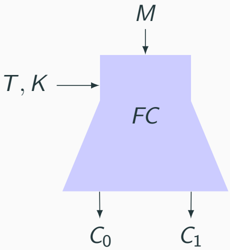
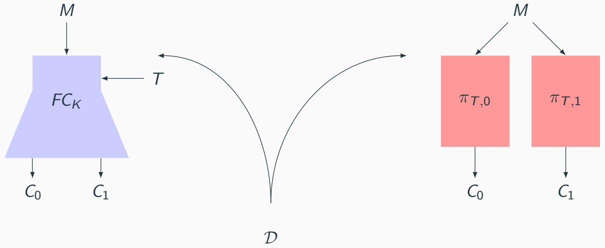


- ✓ Primitive generalizes to muti-forkcipher MFC
- ✓ Each branch is invertible $\Rightarrow$ output **invertible**
- ✓ Target *good* **definition** for secure randomness generation for Enc/AE/key derivation, etc.)?

Forkcipher Security Target



PseudoRandom Tweaked Forked Permutation PRTFP

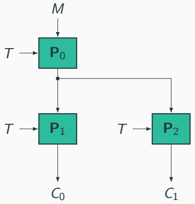
Indistinguishability from a pair of random, tweaked π_0, π_1 under chosen ciphertext attack

$$Adv_{FC}^{prtfp}(\mathcal{D}) = \Pr[K \xleftarrow{\$} \mathcal{K} : \mathcal{D}^{FC_K} \Rightarrow 1] - \Pr[\mathcal{D}^{\pi_0,\pi_1} \Rightarrow 1].$$

IFI: Iterate-Fork-Iterate Modular Forkcipher Framework

n-to-$2n$-bit **IFI** : $\mathcal{K} \times \mathcal{T} \times \{0,1\}^n \rightarrow \{0,1\}^{2n}$

- ✓ $\mathbf{P_0}, \mathbf{P_1}, \mathbf{P_2}$ independent, random $\Rightarrow$ $2n$-**bit expansion**
- ✓ $\mathbf{P_0} \rightleftarrows \mathbf{P_1}$ and $\mathbf{P_0} \rightleftarrows \mathbf{P_2}$ **invertibility**



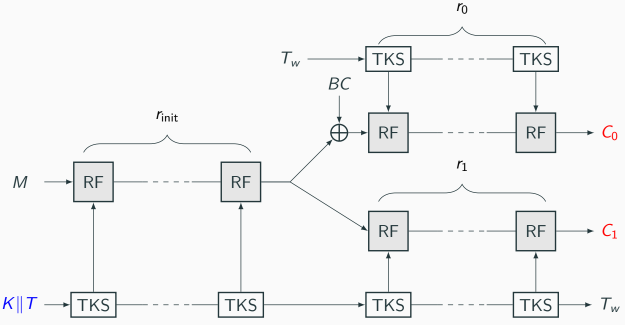
IFI is indistinguishable from independent, random π_1, π_2

$$Adv_{\mathbf{IFI}}^{\mathbf{PRTFP}}(\mathcal{D}) = 0.$$

Forkcipher Instance: ForkSkinny

Based on ISO/IEC 18033-7 standard SKINNY TBC components

$2n$-bit ciphertext of 1 FORKSKINNY $\approx$ 1,6 SKINNY (not 2)



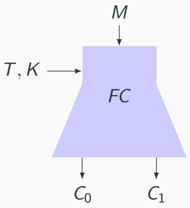
RF: round function; TKS: tweakey schedule; BC: branch constant; r_{init}, $r_0 = r_1$: nr rounds before and after fork.

Primitive	block	tweak	tweakey	r_{init}	r_0	r_1
FORKSKINNY-64-192	64	64	192	17	23	23
FORKSKINNY-128-192	128	64	192	21	27	27
FORKSKINNY-128-256	128	128	256	21	27	27
FORKSKINNY-128-288	128	128	288	25	31	31

Generic Designs of FOL Expanding Functions

- Forkcipher[n-to-$2n$] from IFI as FOL-PRF with $n/2$-bit security
- ForkSTH[n-to-$n+s$] [Dutta et al.'22] from STH as FOL-PRF with $(n - s/2)$-bit security
- FTEM[n-to-$2n$] with $r = 2$ [Kim et al.'20] is $2n/3$-bit PRTFP
- F1 and F2 [Mandal'25] full n-bit security
- FEM[n-to-$2n$] for any r is $rn/(r+1)$-bit secure PRFP and FTEM-ITS[n-to-$2n$] for any r is $rn/(r+1)$-bit secure PRTFP [Andreeva et al.'25]

Forkciphers Contd



– Reconstruction ⇒ Partial or full **inversion not always needed** for Enc and Dec, randomness generation, etc.

\+ VOL-PRF: MFC, ForkEDMD, ForkCENC, Hydra, Ciminion, Farfalle, etc.

\+ Benefits of tweak and >**2-block** expansion ⇒ Butterknife VOL-TPRF

ButterKnife VOL-Tweakable Expanding Function[a]

[a]E. Andreeva, B. Cogliati, V. Lallemand, M. Minier, A. Purnal, A. Roy
Masked Iterate-Fork-Iterate: A New Design Paradigm for Tweakable Expanding Pseudorandom Function, ACNS, 2024

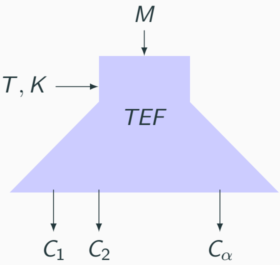
VOL-Tweakable Expanding Function

$TEF : \mathcal{K} \times \mathcal{T} \times \mathcal{M} \mapsto \mathcal{C}_1 \times \mathcal{C}_2 \times \ldots \times \mathcal{C}_\alpha$

$|K| = |T| = |M| = |C_1| = \ldots = |C_\alpha| = n$

K: secret and random T: public tweak

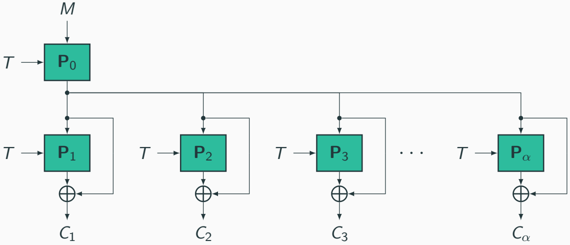
Forward-only evaluation



mIFI: Masked IFI Modular VOL-TPRF Framework

n-to-αn-bit **TEF** : $\mathcal{K} \times \mathcal{T} \times \{0,1\}^n \to \{0,1\}^{\alpha n}$

- ✓ $\mathbf{P_0} \ldots \mathbf{P}_\alpha$ independent, random $\Rightarrow$ αn-**bit expansion**
- ✓ $\mathbf{P_0}$ state $\oplus$ masks all output branches $\Rightarrow$ **no invertibility**



A TEF following mIFI is n-bit secure VOL-TPRF

mIFI is indistinguishable from a uniformly random αn-bit string

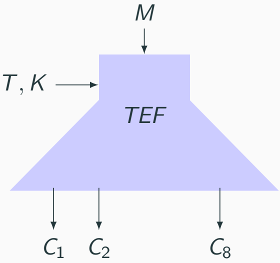
$$Adv^{\textbf{VOL-TPRF}}_{\textbf{mIFI}}(\mathcal{D}) \leq \frac{\sqrt{2\alpha} q}{2^n}.$$

ButterKnife mIFI Instance

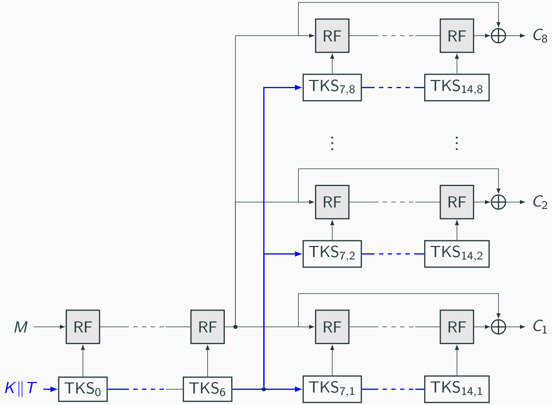
$$\text{BUTTERKNIFE} : \mathcal{K} \times \mathcal{T} \times \mathcal{M} \mapsto \mathcal{C}_1 \times \mathcal{C}_2 \times \ldots \times \mathcal{C}_8$$

$$|K| = |T| = |M| = |C_1| = \ldots = |C_8| = 128$$

- Based on AES-based DEOXYS-TBC-256 (ISO standard)
- 7 DEOXYS-TBC-256 rounds until state forks
- 8 more rounds after fork in each $\alpha = 8$ **parallel** branches
- **$8n$-bit ciphertext** for 1 BUTTERKNIFE $\approx$ 5 DEOXYS (not 8)



ButterKnife Structure



RF: round function; TKS: tweakey schedule; r_{init}, $r_1 = \ldots = r_8$: nr rounds before and after fork, resp.

Primitive RF&TKS	block	tweak	tweakey	r_{init}	$r_1, \ldots r_8$
Deoxys-256	128	128	256	7	8

Security and Performance Advantages of (FOL/VOL-)TEFs for

1. ForkAE: 2nd round in LW **AEAD** NIST standardization, 2019
2. Forkcipher: New Primitive for **AEAD** of Very Short Ms, ASIACRYPT'19
3. SAEF: **AEAD** Mode with OAE and RUP-OAE security, SAC'21, SCN'24
4. Let's Go Eevee! A Friendly and Suitable Family of **AEAD** Modes for IoT-to-Cloud Secure Computation, ACM CCS'23
5. Masked Iterate-Fork-Iterate: A New Design Paradigm for Tweakable Expanding Pseudorandom Function, Deterministic **AE**, ACNS'24
6. 1,2,3,Fork: CTR **Encryption** Variants Based on Generalized FC, ToSC'21
7. PAE: Towards More Efficient&BBB-secure **AE** From a Single Public Permutation, ICICS 2023 8. Forkcipher-Based **PRNG**, ACNS'23
9. Skye: Fast **KDF** from Expanding PRF& Application to Signal, AsiaCCS'24
10. Light**MAC**, Adv. in Mathematics of Communications'23
11. Sonikku: Gotta Speed, Keed! Family of Fast&Secure **MAC**s, CANS'25
12. FEDT: Forkcipher-based **Leakage-resilient** BBB-secure **AE**, CiC'24
13. Authenticity **AE**&**MAC** in Presence of **Leakage** using Forkcipher, CiC'25
14. **TEM** - in progress, 2025

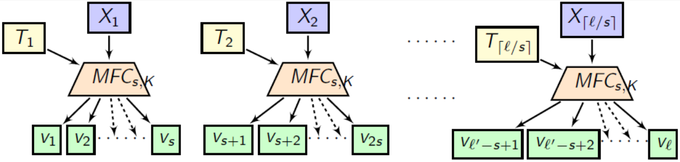
TEF $\underset{\text{Proof}}{\Longrightarrow}$ LW/Cloud/Det AEAD, ENC, PRNG, KDF, MAC, SC resistance, ...

Encryption (GCTR) [a]

[a] E. Andreeva, Bhati, D. Vizár
1,2,3,Fork: CTR Encryption Variants Based on Generalized Forkcipher, ToSC'21

Towards Encryption with TEF via TCTR

1. Apply TEF on inputs (X_j, T_j) where:
   - (X_j, T_j) are output by $f_X(N, R, j)$ and $f_T(N, R, j)$
   - f_X, f_T: simple f-ns $\{\|, \oplus, \mathrm{copy}\}$, N is nonce, R random value and j counter
2. TCTR generates random key-stream V

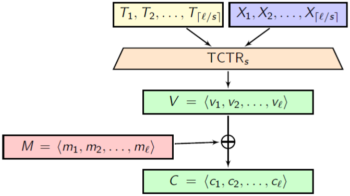


vs

Random key stream

General Tweakable Counter Mode (GCTR) Encryption

Apply the random key-stream V on M



GCTR$_s$ Encryption: $\mathcal{E}_K(N, R, M)$

```
for j ← 1 to ⌈ℓ/s⌉ do
    X_j = f_X(N, R, j)
    T_j = f_T(N, R, j)
T, X ← ⟨T_1, ..., T_⌈ℓ/s⌉⟩, ⟨X_1, ..., X_⌈ℓ/s⌉⟩
V ← TCTR_{s,K}(T, X)
C ← M ⊕ V
return C
```

- 22 variants with security from $n/2$ to **full** n**-bit** + **NMR**
- Recommend: GCTR-3 with $T_j = R \oplus j$, $X_j = N$, and GCTR-7 with $T_j = N \| j$, $X_j = R$

GCTR-ForkSkinny Efficiency

- The cost to compute 1 keystream n-bit block with GCTR-ForkSkinny is ≈ **0.8** of cost with GCTR-Skinny
- GCTR-ForkSkinny becomes **twice** faster than GCTR-Skinny using primitive level parallelism
- TEF evaluated *only* forward: possible instances with ButterKnife

AE(AD) [a]

[a] E. Andreeva, V. Lallemand, A. Purnal, R. Reyhanitabar, A. Roy, D. Vizàr
ForkAE, second round in NIST LW Standardization, 2019
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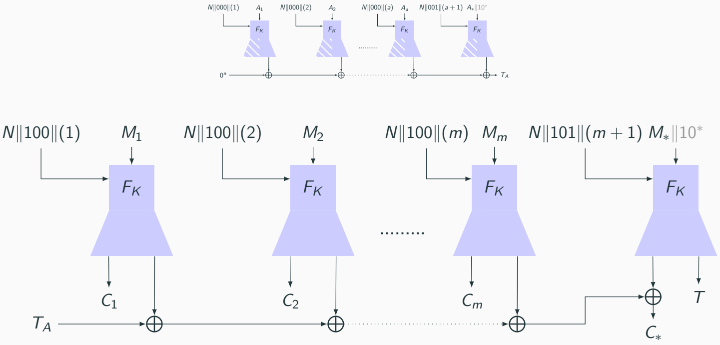
ForkAE

ForkAE family of AEAD schemes:

- Parallel mode: **PAEF** and **rPAEF**
- Sequential mode: **SAEF**

- **Rate-1**: 1 primitive call to Enc and Auth 1 block and no authentication overhead $\Rightarrow$ well-suited for short data

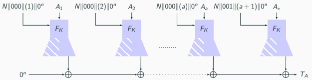


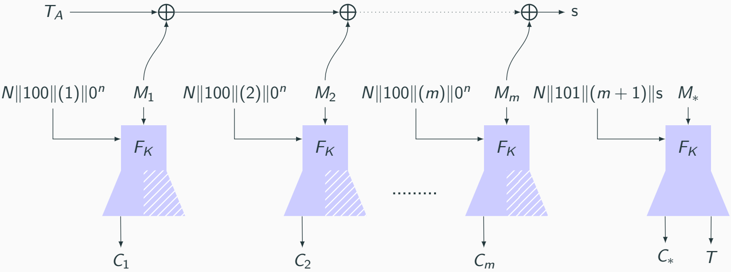
n-bit AE security

$$Adv_{PAEF}^{privacy}(\mathcal{A}) \leq Adv_{FC}^{PRTFP}(\mathcal{D})$$

$$Adv_{PAEF}^{auth}(\mathcal{A}) \leq Adv_{FC}^{PRTFP}(\mathcal{D}) + \frac{q_v \cdot 2^n}{(2^n - 1)^2}$$

Reduced Parallel AEAD from a Forkcipher: rPAEF

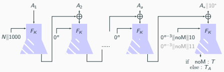


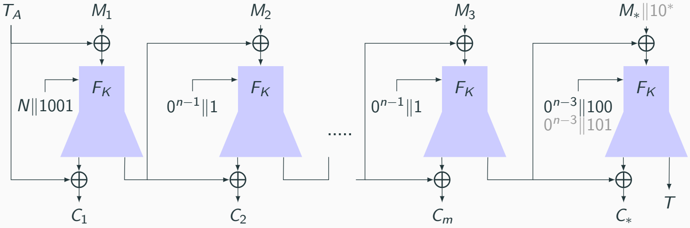


n-bit AE security

$$Adv^{privacy}_{rPAEF}(\mathcal{A}) \leq Adv^{PRTFP}_{FC}(\mathcal{D})$$

$$Adv^{auth}_{rPAEF}(\mathcal{A}) \leq Adv^{PRTFP}_{FC}(\mathcal{D}) + \frac{q_v \cdot 2^n}{(2^n - 1)^2}$$





$n/2$-bit AE security but also NMR and and OAE-RUP secure

$$Adv^{privacy}_{SAEF}(\mathcal{A}) \leq Adv^{PRTFP}_{FC}(\mathcal{D}) + 2\frac{(\sigma - q)^2}{2^n}$$

$$Adv^{auth}_{SAEF}(\mathcal{A}) \leq Adv^{PRTFP}_{FC}(\mathcal{D}) + \frac{2(\sigma - q + 1)^2}{2^n} + \frac{\sigma(\sigma - q)}{2^n} + \frac{q_v(q+2)}{2^n}$$

ForkAE Family Performance

- Rate-1: 1 ForkSkinny call per data block
- Excellent performance for **short messages**: ($\leq$ 4 blocks) (r)PAEF and SAEF 25% to 58% better in SW than Skinny-AEAD
- rPAEF better than Skinny-AEAD in SW for **all data sizes**
- Multiple **trade-offs in speed-resource design space** and excellent throughput per area in HW
- (r)PAEF: ***n*-bit** secure
- SAEF: **OAE-RUP** and **NMR** secure
- (r)PAEF further speed-up possible with ButterKnife

Deterministic Authenticated Encryption (DAE)

Authenticity, **Confidentiality** + **Same** $K, M \Rightarrow$ **Same** C

- Key wrap, search on encrypted data, LW etc.

  Challenges: Increase speed & security with classical primitives: 2 data passes (1 Enc and 1 Auth) GCM-SIV, SCT, ZAE, etc.

  SAFE = ButterKnife-CTR Enc + Polynomial-based hash

  ZAFE = ButterKnife-CTR Enc + ZMAC

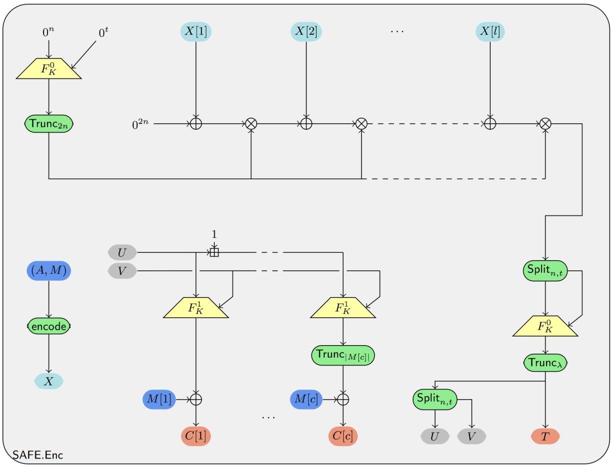
✓ Prallelizable and full 128-bit security

✓ **Best performance** among *equally* 128-bit secure existing DAE schemes ($>$ 25% ZAE and $>$ 50% Enc speed-up)

✓ **Comparable performance** with *less* 64-bit secure DAE

SAFE Deterministic Authenticated Encryption

SAFE: fast TPRF-based CTR encrypt. + polynomial-based hash



$\frac{n+\min(n,t)}{2}$**-bit DAE security**

DAE SW Implementations

Table 1: DAE implementations in cycles per byte (c/B) for long M (64KiB), decoupled **Auth** and **Enc**, and **Total**=**Enc**+**Auth**

		Skylake 3.2 GHz			Cascade Lake SP 2.7 GHz		
	Sec	**Auth**	**Enc**	**Total**	**Auth**	**Enc**	**Total**
AES-GCM-SIV	64	**0.30**	0.63	$\boxed{\mathbf{0.93}}$	**0.31**	0.63	$\boxed{\mathbf{0.94}}$
SCT	64	0.87	0.87	1.74	0.87	0.87	1.74
ZAE (256)	128	0.61	0.87	1.48	0.61	0.87	1.48
ZAE (384)	128	0.59	0.99	1.58	0.59	0.99	1.58
ZAE (256-384)	128	0.59	0.87	1.46	0.59	0.87	1.46
SAFE	128	0.63	$\boxed{\mathbf{0.55}}$	$\boxed{\mathbf{1.18}}$	0.62	$\boxed{\mathbf{0.55}}$	$\boxed{\mathbf{1.17}}$
ZAFE	128	0.60	$\boxed{\mathbf{0.55}}$	$\boxed{\mathbf{1.15}}$	0.60	$\boxed{\mathbf{0.55}}$	$\boxed{\mathbf{1.15}}$

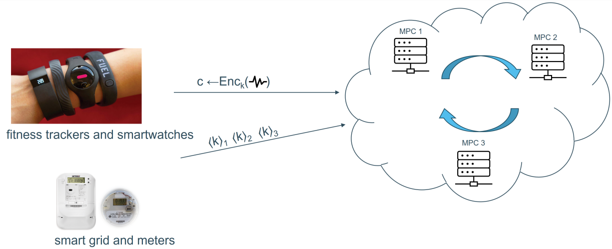
Throughput increase:

- ✓ $\approx$ 58% over ZAE **Enc** due to ButterKnife TPRF
- ✓ $\approx$ 24% over ZAE **Total**
- ✓ ButterKnife in CTR mode faster than AES (0.55 vs 0.63 c/B)

IoT-to-Cloud AEAD[a]

[a] A. Bhati, E. Pohle, A. Abidin, E. Andreeva, B. Preneel, Let's Go Eevee! A Friendly and Suitable Family of AEAD Modes for IoT-to-Cloud Secure Computation, ACM CCS'23

IoT-to-Cloud Setting



IoT: Client encrypts data (AEAD) and sends key shares

- AEAD: small area, small state, RAM, energy/power-efficient

- Large attack surface ⇒ NMR, block-wise, BBB security

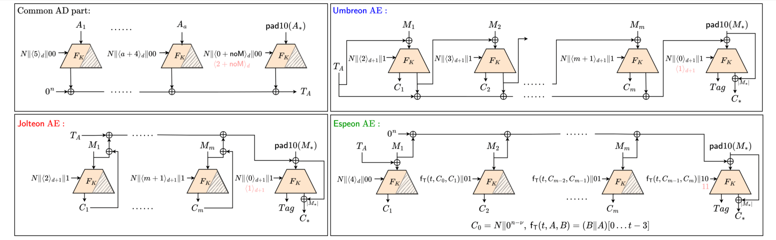
Cloud: MPC servers jointly decrypt and compute f-n F over data

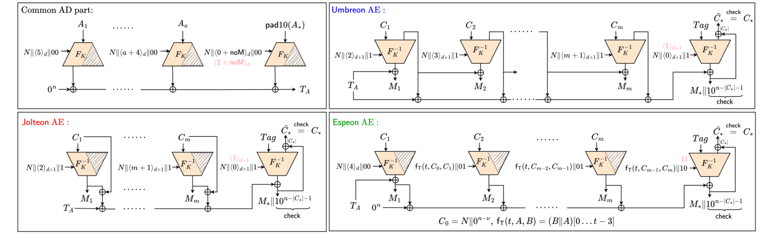
- Low-depth circuit & **parallelizable** Dec (to reduce communication cost)

- Independent of party shares

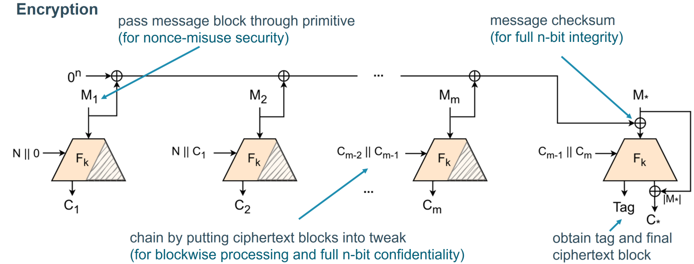
- CTR-PMAC, CTR-HtMAC for Cloud, (Rotaru et al., ToSC'18)

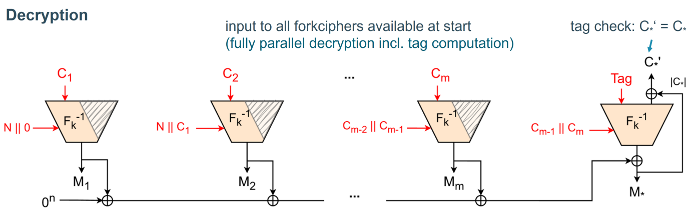
Eevee AEAD Family for IoT-to-Cloud Computation



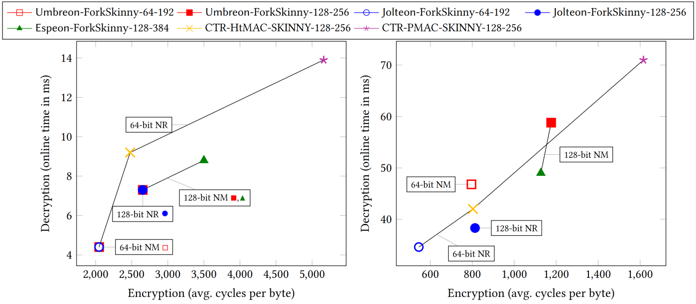


Espeon AEAD Family for IoT-to-Cloud





Eevee AEAD: Performance



(a) Message length = 8 byte. **(b) Message length ≥ 100 byte.**

Setting: 3 parties, < 1 ms latency, Cortex-M4

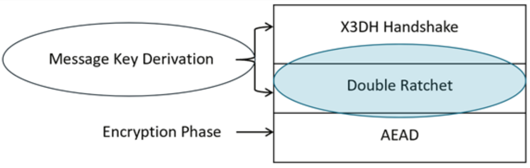
- Jolteon compared to CTR-HtMAC: 32% to 45% speed-up IoT-Enc 16% to 66% MPC-Dec throughput for 8B/100B data, no NMR
- Espeon: similar performance but with tweak-size-dependent NMR
- Umbreon: strongest security guarantees - full *n*-bit OAE security

Key Derivation [a]

[a] A.S. Bhati, A. Dufka, E. Andreeva, A. Roy, B. Preneel Skye: An Expanding PRF based Fast KDF and its Applications, AsiaCCS'24

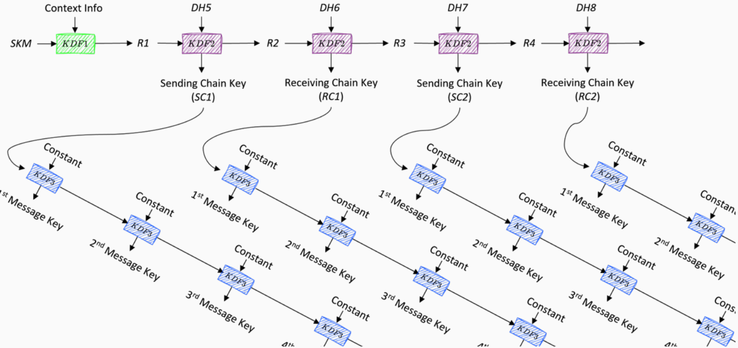
Key Derivation Function in Signal

- KDF generates uniform&random stream from weakly random K
- Singal uses HKDF



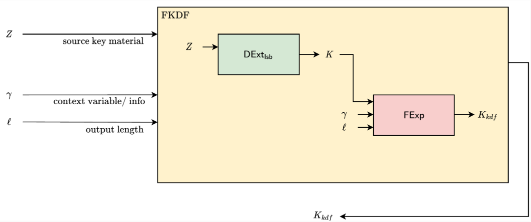
HKDF in Signal

- HKDF follows extract-then-expand paradigm
- HKDF is defined for general sources, not optimal for source-specific derivation, e.g. Diffie-Hellman in Signal
- HKDF is hghly sequential
- Proof relies on RO (SHA-2)



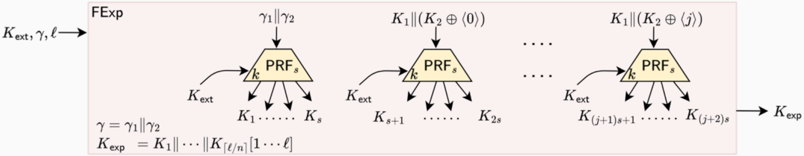
The Skye Key Derivation Function

1) Dedicated **source-specific randomness extractor**: DExt
2) **Randomness expansion** with TEF (ButterKnife): FExp



The Skye Key Derivation Function: Expansion

1) Dedicated **source-specific randomness extractor** : DExt
2) **Randomness expansion** with TEF (ButterKnife): FExp



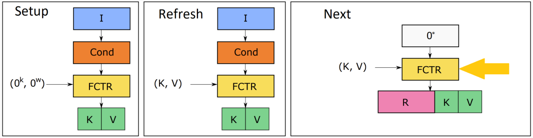
- parallelizable, 128-bit security in standard model

- Skye in Signal: 38% to 64% speed-up in unidirectional messaging, and 12-36% when 10 messages are sent and received at once

PRNG (FCRNG) [a]

[a] E. Andreeva and A. Weninger
A Forkcipher-Based Pseudo-Random Number Generator, ACNS'23

- NIST existing RNG standard CTR-DRBG, SP 800-90A
- Work with GCTR-style (FCTR) for randomness derivation
- Security proof *does not* degrade with the length of random inputs nor amount of requested pseudorandom bits
- 33% to 50% faster than CTR-DRBG standard with ForkSkinny and ButterKnife, resp.



Conclusions and Open Questions

Tweakable Expanding Primitives:

- More efficient and secure replacement for many classical symmetric schemes
- But also well-suited for modern and emerging applications
- Will benefit from new instances (low-latency, no tweak, algebraic, etc.), new design frameworks and cryptanalysis
- Can TEF support different design functionalities than PRF, PRTFP, or emerging privacy-friendly applications?

Thank you!

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