Simpira v2: A Family of Efficient Permutations Using the AES Round Function

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I'm Joint Author Of:

APE (PRIMATEs) (FSE 2014)

- Lightweight permutation-based authenticated encryption
- On-line misuse resistance, Releasing Unverified Plaintext (RUP) security
- PRIMATEs: Second-round CAESAR competition

Chaskey (SAC 2014)

- MAC algorithm for microcontrollers
- # 1 according to FELICS figure of merit
- ISO/IEC 29192-6 (draft)

Simpira (ASIACRYPT 2016)

- Family of permutations based on AES round function
- This presentation...

Background

AES Instructions

- Introduced by Intel (later AMD, recently ARM)
- On Intel Skylake: `AESENC` (1 round of AES)
  - Latency: 4 cycles
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- Requires parallelizable mode or independent data
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Example to Motivate `AESENC`: Google Chrome

- Recent 64-bit processors: AES-128-GCM
- If no AES instructions: ChaCha20-Poly1305

Limitations of AES

Key Schedule: Round Keys

- Calculate on-the-fly or store securely
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Block Size: Always 128 Bits

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Alternatives?

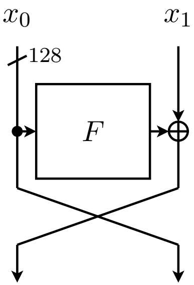
- Rijndael with 256-bit block size? SHA-2? ...?
- Faster solution: Simpira

Design of Simpira

Family of Permutations

- $128 \times b$ bits, $b \in \mathbb{N}^+$

Design of Simpira



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Building Block

- $b \geq 2$: (generalized) Feistel structure

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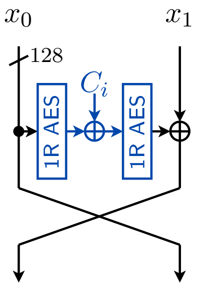

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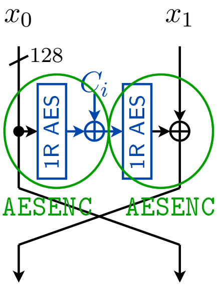

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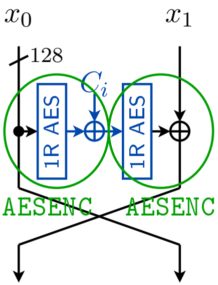

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Design Goal

- Secure up to 2^{128} queries, very easy analysis
- Throughput: # cycles ≈ # `AESENC` instructions

Design Requirements

Number of Rounds

- $\geq$ (# rounds: 25 active S-boxes) $\times 3$
- $\geq$ (# rounds: full bit diffusion) $\times 3$
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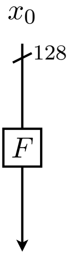
Extra

- Multiple options: choose simplest design!

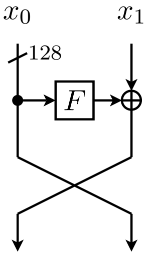
Simpira: $b = 1$



AES Permutation

- Rounds: 6
- # `AESENC`: 12

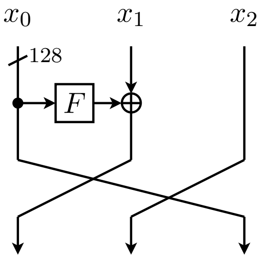
Simpira: $b = 2$



Feistel

- Rounds: 15
- # `AESENC`: 30

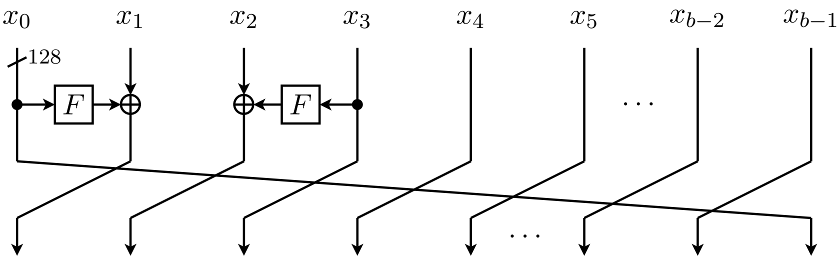
Simpira: $b = 3$



Type-1 GFS (Zheng et al.)

- Rounds: 21
- # `AESENC`: 42

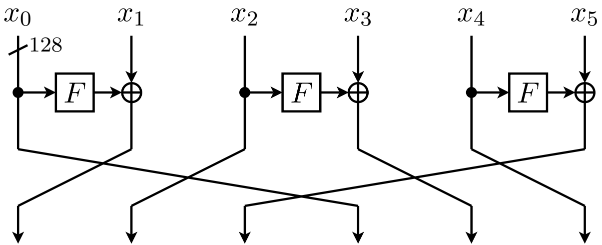
Simpira: $b \geq 4$ (except $b = 6$ and $b = 8$) v1



Yanagihara-Iwata: Type 1.x (b,2) GFS

- Feistel rounds: $6b - 9$
- # `AESENC`: $24b - 36$

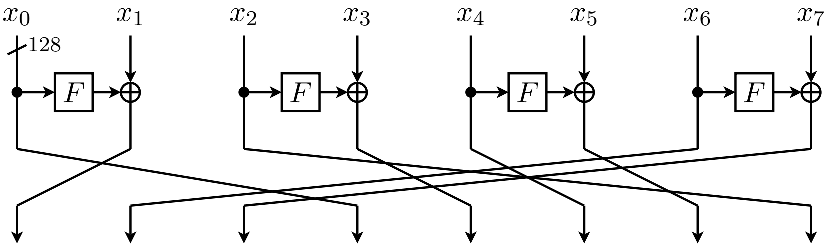
Simpira: $b = 6$



Suzaki-Minematsu Improved Type-2 GFS

- Feistel rounds: 15
- # `AESENC`: 90

Simpira: $b = 8$



Suzaki-Minematsu Improved GFS

- Feistel rounds: 18
- # `AESENC`: 144

Attack on Simpira v1

Dobraunig et al. (SAC 2016)

- Collision on Simpira-based hash function ($b = 4$)
- Full-round attack, complexity 2^{83} ($<2^{128}$)

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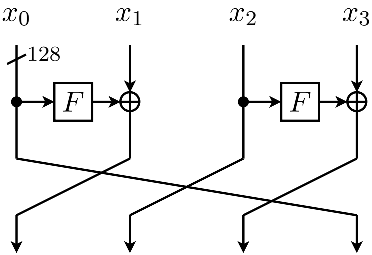
Underlying Problem: Yanagihara-Iwata Type 1.x GFS

- Careful with independences! Cryptographic permutation $\neq$ Markov cipher with independent subkeys
- Invariant subspace attacks: often overlooked
- Fix: strengthen round constants, replace Type 1.x GFS

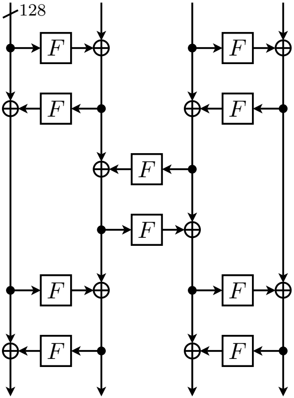
Simpira: $b = 4$ v2



Type-2 GFS (Zheng et al.)

- Feistel rounds: 15
- # `AESENC`: 60

Simpira: $b \geq 5$ (except $b = 6$ and $b = 8$) v2



Dedicated Construction

- Iterate this three times
- # `AESENC`: $24b - 36$

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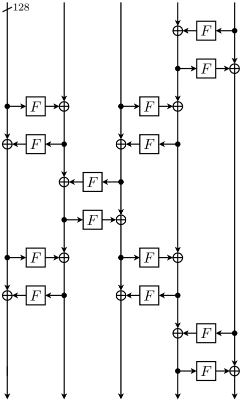

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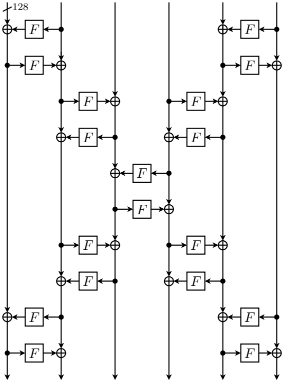

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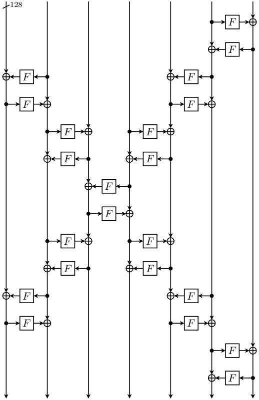

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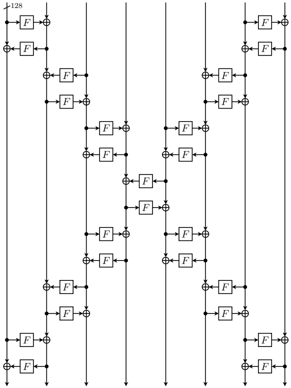

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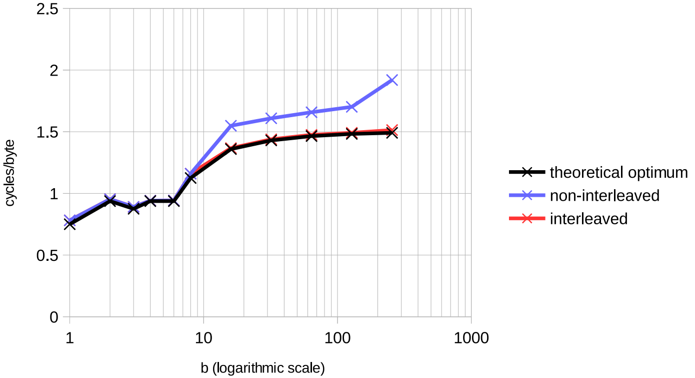
- # `AESENC`: $24b - 36$

Benchmarks (π and π^{-1})

Speed

- Theory: up to 512 bits: < 1 c/B, large b: 1.5 c/B
- Non-interleaved inputs: up to 1024 bits: overhead $< 3\%$
- Interleaved inputs: overhead $< 3\%$, even for 4 kB inputs



Some Applications

Permutation-based Hashing

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(Tweakable) Even-Mansour Block Cipher

- $E_K = \mathsf{Simpira}_b(P \oplus K \cdot T) \oplus K \cdot T$
- Tweak: $T \geq 1$, no tweak: $T = 1$
- Permutation size larger than $K \cdot T$: zero padding

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Robust Authenticated Encryption

- Encode-then-encipher with Even-Mansour
- Encoding: multiple of 128 bits

Conclusion

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Speed

- Theoretical optimum: one `AESENC` every clock cycle
- Short inputs: 1 cycle/byte, large inputs: 1.5 cycles/byte
- Benchmarks: negligible overhead (<3%)

Questions?

Supporting Slides

Algorithm 1 `AESENC`

procedure `AESENC`(state, key)
  tmp $\leftarrow$ state
  tmp $\leftarrow$ `ShiftRows`(tmp)
  tmp $\leftarrow$ `SubBytes`(tmp)
  tmp $\leftarrow$ `MixColumns`(tmp)
  state $\leftarrow$ tmp $\oplus$ key
  return state
end procedure

Algorithm 2 $F_{c,b}(x)$

procedure $F_{c,b}(x)$
  $C \leftarrow$ `SETR_EPI32`$(c, b, 0, 0)$
  return `AESENC`(`AESENC`$(x, C), 0)$
end procedure

Algorithm 3 Simpira ($b = 1$)

```
procedure Simpira(x_0)
    R ← 6
    for c = 1, ..., R do
        x_0 ← F_{b,c}(x_0)
    end for
    InvMixColumns(x_0)
    return x_0
end procedure
```

Algorithm 4 Simpira^{-1} ($b = 1$)

```
procedure Simpira(x_0)
    R ← 6
    MixColumns(x_0)
    for c = R, ..., 1 do
        x_0 ← F_{b,c}^{-1}(x_0)
    end for
    return x_0
end procedure
```