Design and Cryptanalysis of Symmetric-Key Algorithms in Black and White-box Models

Aleksei Udovenko

SnT, University of Luxembourg

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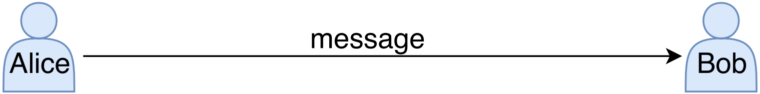
PhD Defense

UNIVERSITÉ DU LUXEMBOURG

securityandtrust.lu

Luxembourg National Research Fund


message
Alice
Bob


Alice
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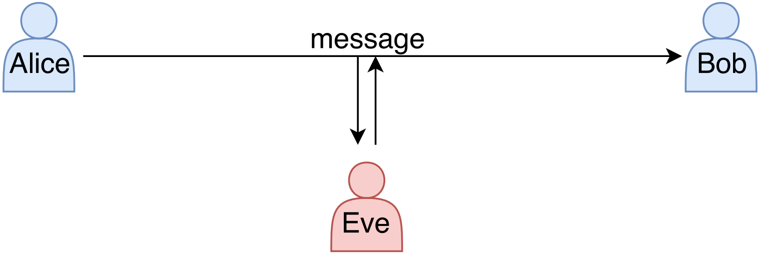
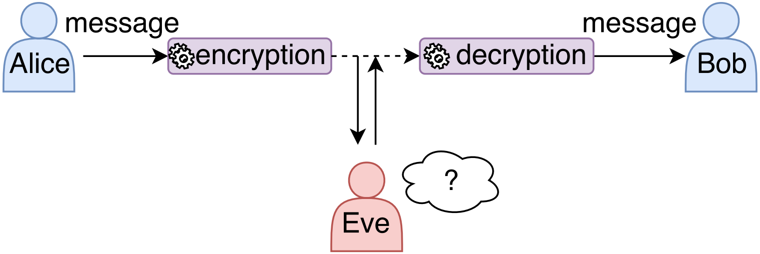

Alice
message
Bob
Eve


message
Alice
encryption
decryption
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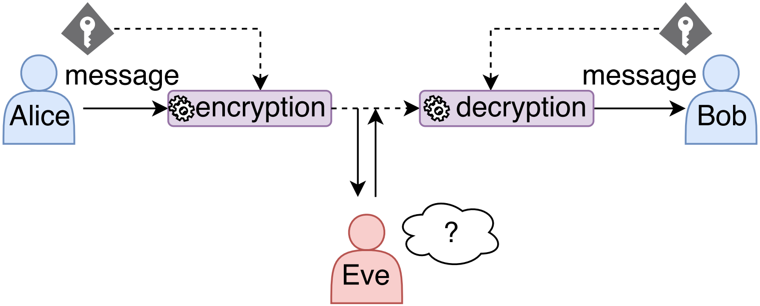
Bob
Eve
?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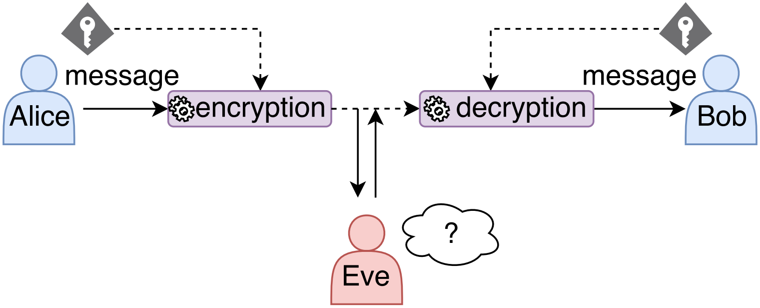
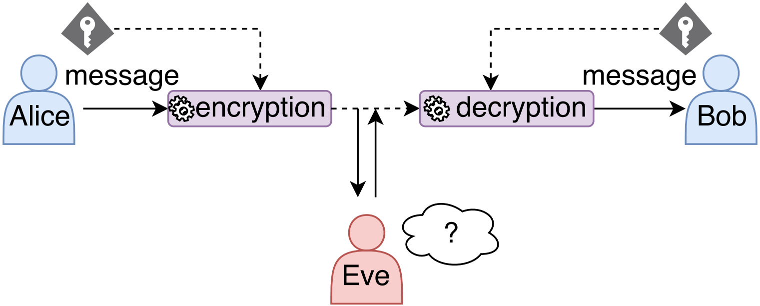


Symmetric-key Cryptography



Symmetric-key Cryptography

ensures that the message is:

1. secret (confidentiality)
2. unmodified (integrity)
3. from the correct person (authenticity)

$$\left.\begin{array}{l}\text{(confidentiality)}\\ \text{(integrity)}\\ \text{(authenticity)}\end{array}\right\}$$

$$\left.\begin{array}{l}\text{(confidentiality)}\\\text{(integrity)}\\\text{(authenticity)}\end{array}\right\} \Longleftrightarrow \begin{array}{c}\text{Authenticated}\\\text{Encryption}\end{array}$$

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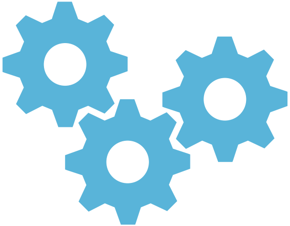
The main goal of
symmetric-key cryptography!

How does it work?



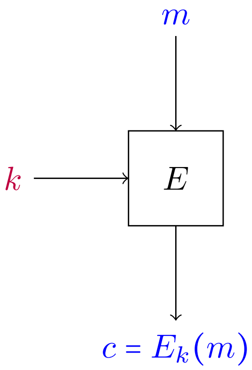
Construction 1:

Block Cipher + Mode of Operation

Block Cipher

An *Algorithm* E_k:

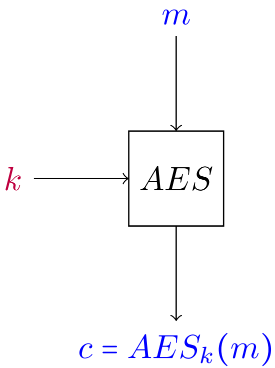
- n-bit message m
- κ-bit key k
- n-bit ciphertext c
- E_k is invertible



Example: Advanced Encryption Standard

AES Algorithm:

- 128-bit message m
- 128/192/256-bit key k
- 128-bit ciphertext c
- designed in 1998
  by V. Rijmen and J. Daemen



Mode of Operation

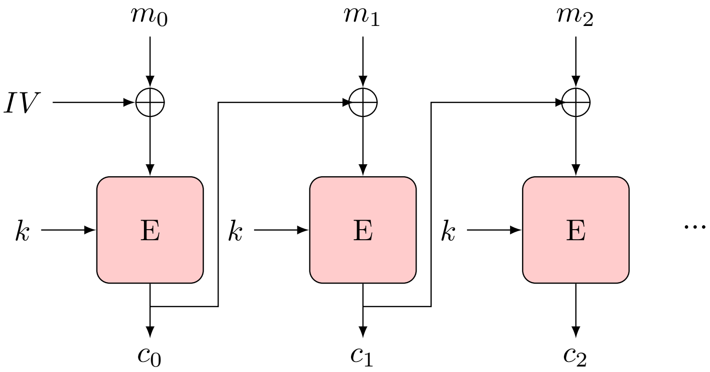


Figure credits: TikZ for Cryptographers

Example: COLM Mode of Operation

One of CAESAR competition winners (2019)

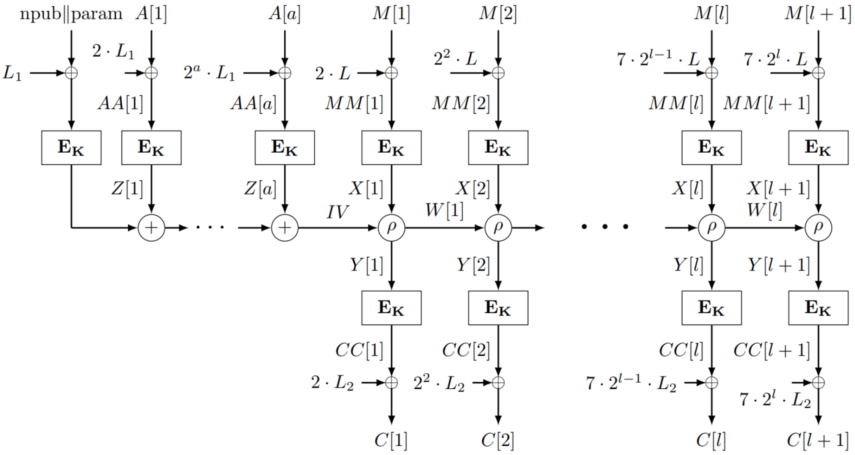
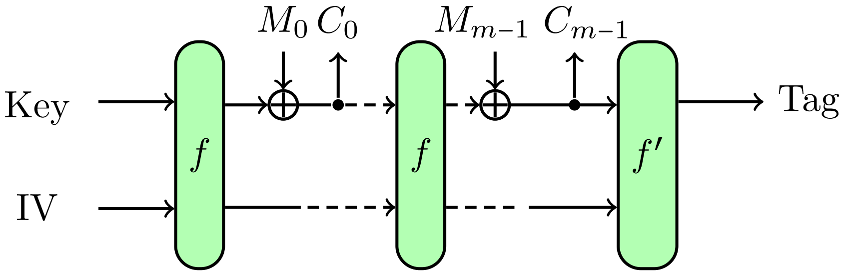


Figure credits: COLM v1 Specification

Construction 2:
Sponge Structure

(Duplexed) Sponge Structure



f: *keyless* invertible function (permutation)

Figure credits: TikZ for Cryptographers

Plan

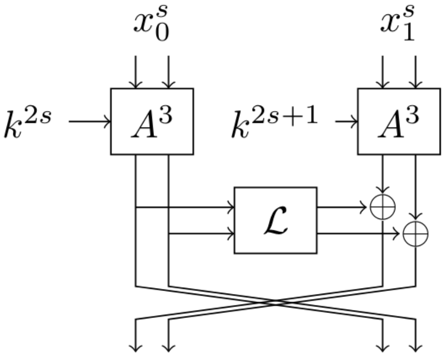
1. Introduction
2. Thesis Overview
   - Design of Symmetric-key Algorithms
   - Structural and Decomposition Cryptanalysis
   - Nonlinear Invariant Cryptanalysis
   - White-box Cryptography
3. White-box Cryptography

Design of Symmetric-key Algorithms

Lightweight Cryptography:

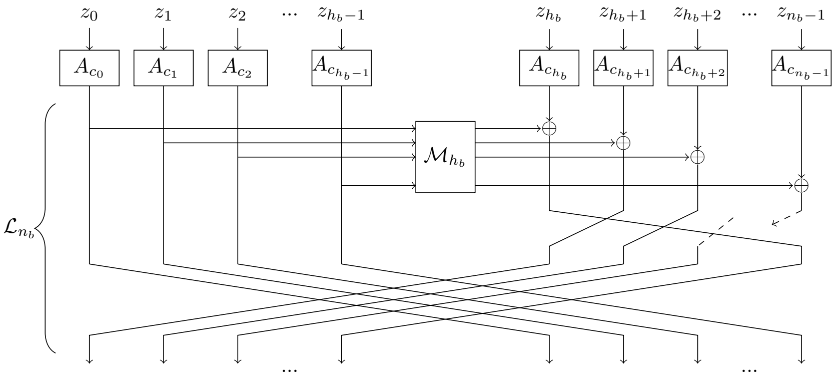
Cryptography for resource-constrained devices
(Internet of Things)

Design of Symmetric-key Algorithms



Sparx: a *lightweight* block cipher
based on a new design strategy

Design of Symmetric-key Algorithms



Sparkle, **Esch** and **Schwaemm**:
cryptographic permutations, hash functions
and authenticated encryption

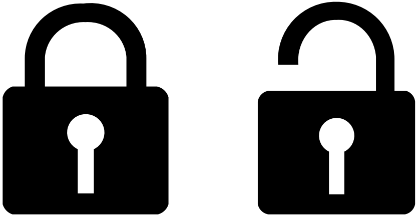
Design of Symmetric-key Algorithms

Daniel Dinu, Léo Perrin, Aleksei Udovenko, Vesselin Velichkov, Johann Großschädl, and Alex Biryukov.
Design Strategies for ARX with Provable Bounds: Sparx and LAX.
In *Advances in Cryptology - ASIACRYPT 2016*, pages 484–513.
https://www.cryptolux.org/index.php/SPARX.

Christof Beierle, Alex Biryukov, Luan Cardoso dos Santos, Johann Großschädl, Léo Perrin, Aleksei Udovenko, Vesselin Velichkov, and Qingju Wang.
Schwaemm and Esch: Lightweight Authenticated Encryption and Hashing using the Sparkle Permutation Family, 2019.
https://www.cryptolux.org/index.php/Sparkle.

How to make sure

that an encryption scheme is secure?



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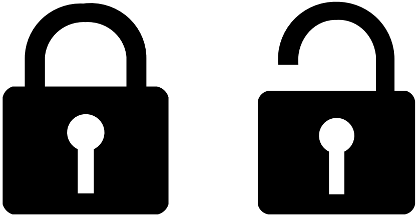
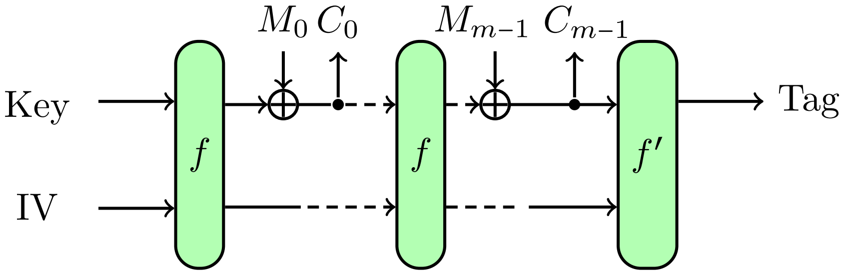


Security Proofs and Cryptanalysis!

Security Proofs: Modes and Structures



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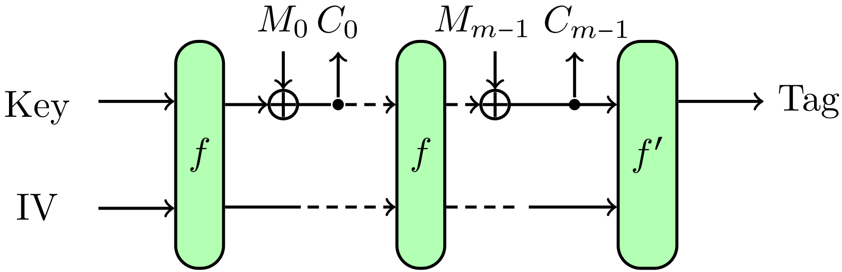

secure **if** the permutation f is secure (random)

Cryptanalysis:

an attempt to invalidate
security claims of a cryptosystem
by developing an attack

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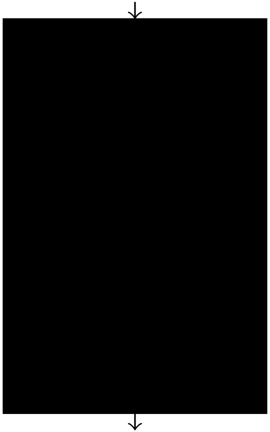
- a large variety of methods: differential, linear, integral, ...
- attacks on simplified versions
- analysis of components

Structural and Decomposition Cryptanalysis

Distinguishing structures and recovering components

Structural and Decomposition Cryptanalysis

x

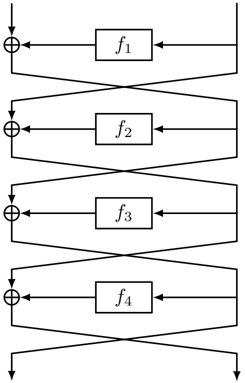


$E(x)$

Structural and Decomposition Cryptanalysis

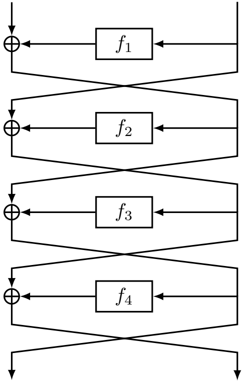
x	$E(x)$
0	182
1	210
2	78
3	251
4	97
...	
252	112
253	19
254	224
255	74

Structural and Decomposition Cryptanalysis



Feistel Networks

Structural and Decomposition Cryptanalysis



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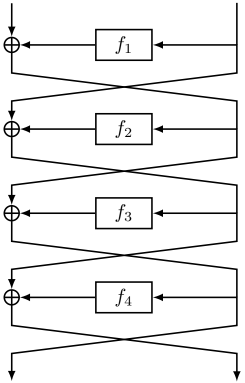

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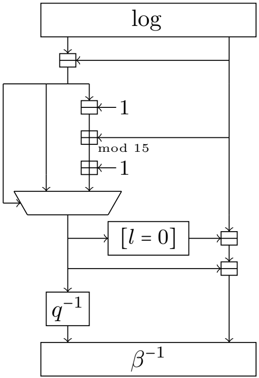
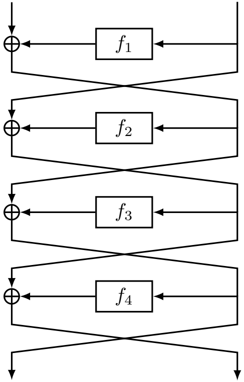


GOST S-Box

Structural and Decomposition Cryptanalysis



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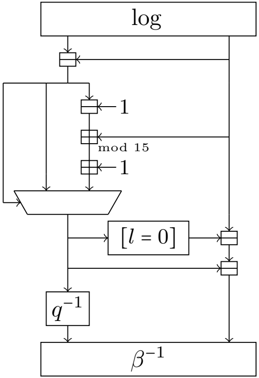

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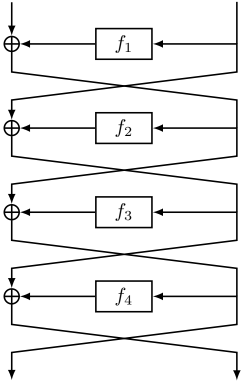

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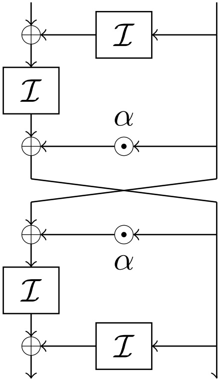
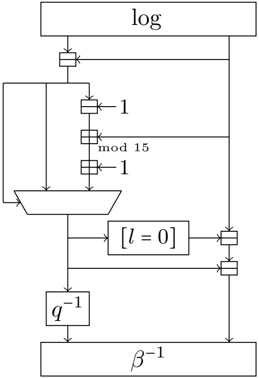


6-bit APN Permutation



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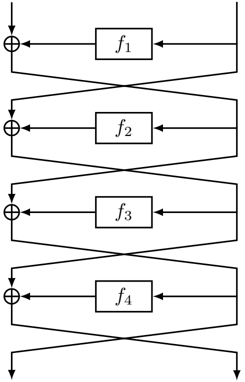

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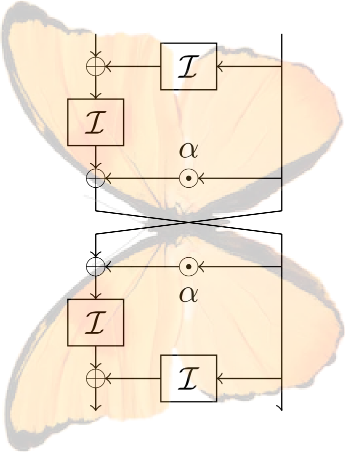
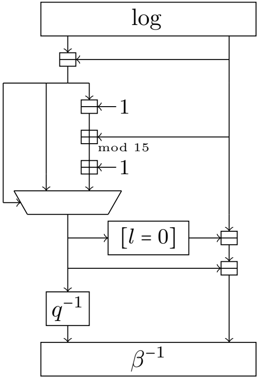


6-bit APN Permutation



GOST S-Box

Structural and Decomposition Cryptanalysis

Léo Perrin and Aleksei Udovenko.
Algebraic Insights into the Secret Feistel Network.
In *Fast Software Encryption - FSE 2016*, pages 378–398.

Léo Perrin, Aleksei Udovenko, and Alex Biryukov.
Cryptanalysis of a Theorem: Decomposing the Only Known Solution to the Big APN Problem.
In *Advances in Cryptology - CRYPTO 2016*, pages 93–122.

Alex Biryukov, Léo Perrin, and Aleksei Udovenko.
Reverse-Engineering the S-Box of Streebog, Kuznyechik and STRIBOBr1.
In *Advances in Cryptology - EUROCRYPT 2016*, pages 372–402.

Léo Perrin and Aleksei Udovenko.
Exponential S-Boxes: a Link Between the S-Boxes of BelT and Kuznyechik/Streebog.
IACR Trans. Symmetric Cryptol., 2016(2):99–124.

Nonlinear Invariant Cryptanalysis

Properties of messages that are preserved through encryption

Nonlinear Invariant Cryptanalysis

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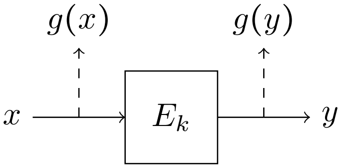
$$x \longrightarrow \boxed{E_k} \longrightarrow y$$

Nonlinear Invariant Cryptanalysis

Properties of messages that are preserved through encryption



Nonlinear Invariant Cryptanalysis

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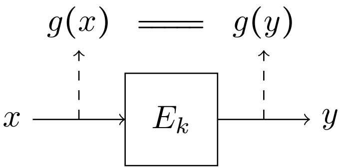


Nonlinear Invariant Cryptanalysis

Properties of messages that are preserved through encryption

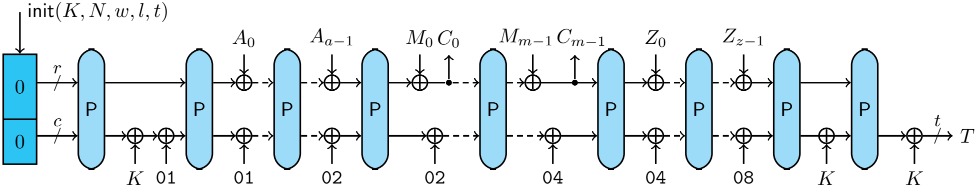
$$\texttt{a9a9} \longrightarrow \boxed{E_k} \longrightarrow \texttt{2727}$$

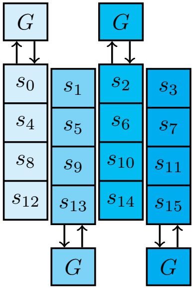
Nonlinear Invariant Cryptanalysis

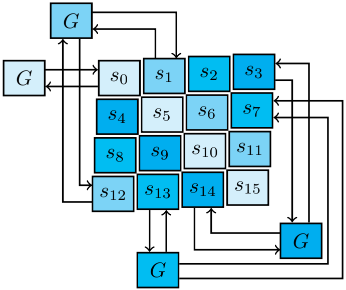
Properties of messages that are preserved through encryption

$$\texttt{4747} \longrightarrow \boxed{E_k} \longrightarrow \texttt{cfcf}$$

Nonlinear Invariant Cryptanalysis







Analysis of the NORX Authenticated Encryption

Figure credits: TikZ for Cryptographers

Nonlinear Invariant Cryptanalysis

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

Theoretical study of linear layers
preserving degree-d invariants

Nonlinear Invariant Cryptanalysis

Alex Biryukov, Aleksei Udovenko, and Vesselin Velichkov.
Analysis of the NORX Core Permutation.
Cryptology ePrint Archive, Report 2017/034, 2017.
https://eprint.iacr.org/2017/034.

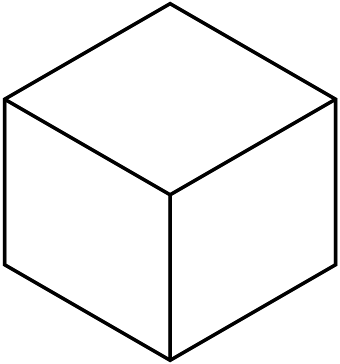
Christof Beierle, Alex Biryukov, and Aleksei Udovenko.
On Degree-d Zero-Sum Sets of Full Rank.
Cryptology ePrint Archive, Report 2018/1194, 2018.
https://eprint.iacr.org/2018/1194.

Plan

White-box Cryptography

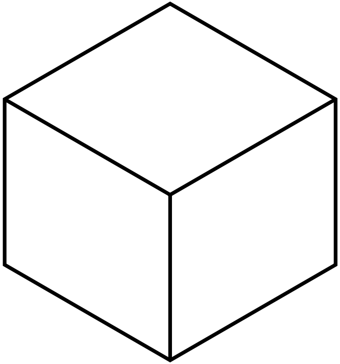
Alex Biryukov and Aleksei Udovenko.
Attacks and Countermeasures for White-box Designs.
In *Advances in Cryptology - ASIACRYPT 2018 II*, pages 373–402.

White-box model



White-box model

- implementation is fully available to an adversary
- secret key should be unextractable
- **extra**: one-wayness, incompressibility, traitor traceability, ...



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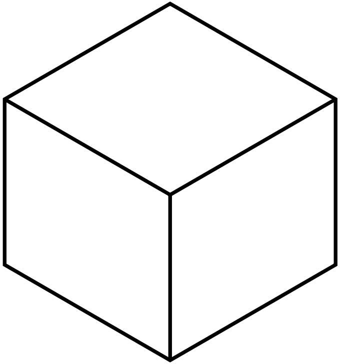

- The most **challenging** direction (this work):
  white-box implementations of
  existing symmetric primitives,
  e.g. the AES block cipher

Example: Secure White-box

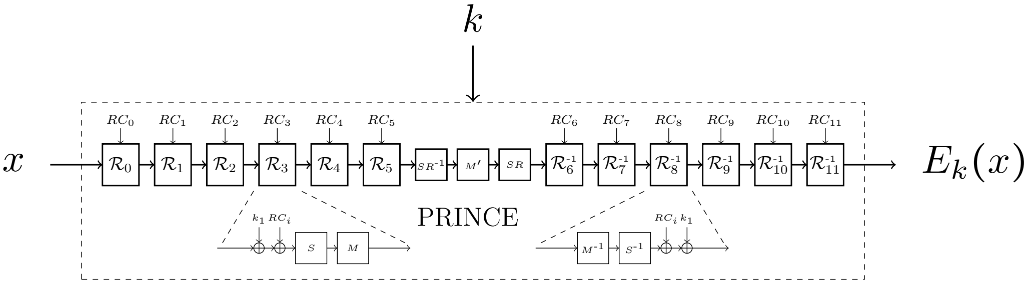

Figure credits: TikZ for Cryptographers

Example: Secure White-box

x	$E(x)$
0000000000000000	9333dd078833edd3
0000000000000001	7072b89243c84359
0000000000000002	7838040f2b7f9af6
0000000000000003	0b502e4231f42da3
0000000000000004	c39ea8c9434252aa
...	
fffffffffffffffb	8f1a82bc7af09497
fffffffffffffffc	9aaf33009a8e9a2f
fffffffffffffffd	5cd335922f9f0236
fffffffffffffffe	39d0e8b9a0eded09
ffffffffffffffff	daf2ced4ab8fc658

Figure credits: TikZ for Cryptographers

Example: Secure White-box

x	$E(x)$
0000000000000000	9333dd078833edd3
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0000000000000004	c39ea8c9434252aa
...	
fffffffffffffffb	8f1a82bc7af09497
fffffffffffffffc	9aaf33009a8e9a2f
fffffffffffffffd	5cd335922f9f0236
fffffffffffffffe	39d0e8b9a0eded09
ffffffffffffffff	daf2ced4ab8fc658

Impractical! 128 exbibytes for a 64-bit cipher!

Figure credits: TikZ for Cryptographers

White-box: Industry vs Academia

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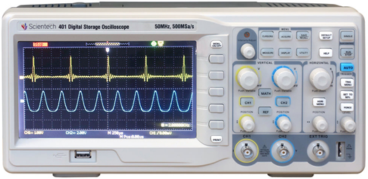
- WB has many applications
- strong need for *efficient* WB
- industry **does** WB:
  hidden designs

White-box: Industry vs Academia

- WB has many applications
- strong need for *efficient* WB
- industry **does** WB:
  hidden designs

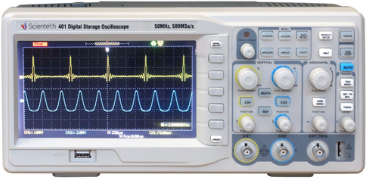
- **theory**: approaches using iO/FE, currently *impractical*
- **practical WB-AES**:
  few attempts (2002-2017),
  all broken
- powerful DCA attack (CHES 2016)

White-Box: Differential Computation Analysis (DCA)



- **DCA = Differential Power Analysis (DPA)** applied to white-box implementations
- Most of the implementations broken automatically

White-Box: Differential Computation Analysis (DCA)



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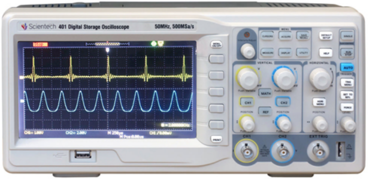
- Side-channel protection: **masking schemes**

White-Box: Differential Computation Analysis (DCA)



- **DCA = Differential Power Analysis (DPA)** applied to white-box implementations
- Most of the implementations broken automatically
- Side-channel protection: **masking schemes**

this work:

Can we apply the masking protection for white-box impl.?

General Setting

- Boolean **circuits**
- **obfuscated** reference implementation

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- **predictable values**: computations from ref. impl., e.g.

$$s = Bit_1(SBox(pt_1 \oplus k_1))$$

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- **obfuscated** reference implementation
- **predictable values**: computations from ref. impl., e.g.

$$s = Bit_1(SBox(pt_1 \oplus k_1))$$

- **masking**: $\exists v_1, \ldots, v_t$ nodes (*shares*), $f : \mathbb{F}_2^t \to \mathbb{F}_2$ s.t. for any encryption

$$f(v_1, \ldots, v_t) = s$$

Masking Schemes

- **Example** Boolean masking: linear decoder $f = \bigoplus_i v_i$
- **Example** FHE: complex non-linear decoder f

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- Aim for efficient schemes: relatively small t (number of shares)

$\Rightarrow$ can be secure only if
the locations of the shares in the circuit are unknown!

this work: exploring this possibility

Plan

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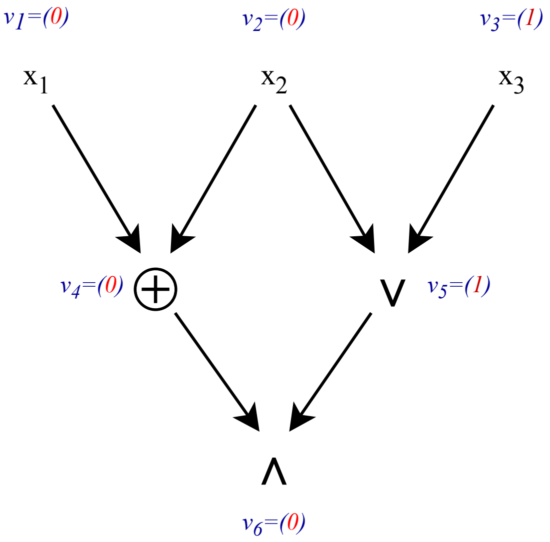
   - Introduction
   - Attack Methods
   - Countermeasures

(Generalized) Differential Computation Analysis (DCA)



$x^{(1)} = (0,0,1)$

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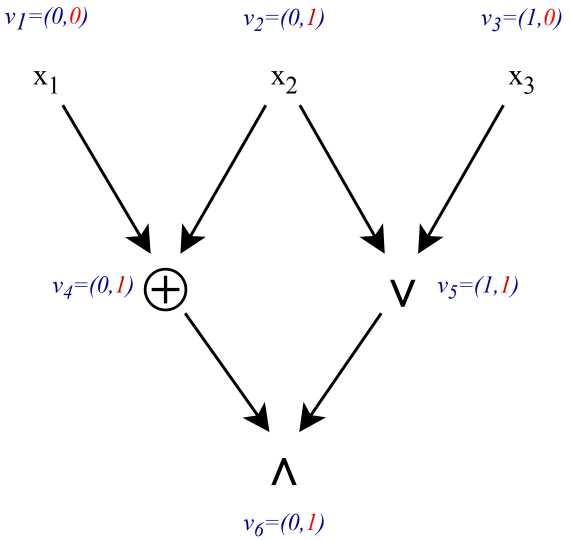

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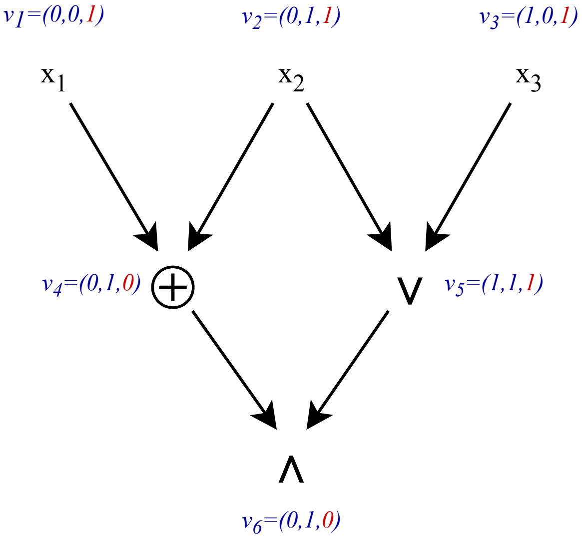

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The Linear Algebra Attack

- consider Boolean masking (**linear** decoder)
- matching with a predictable value s:
  a basic linear algebra problem:

$$M \times z = s, \qquad M = [v_1 \mid \ldots \mid v_n]$$

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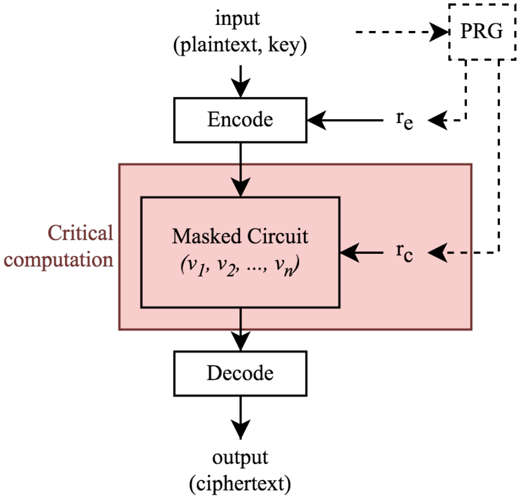
Goubin et al: How to Reveal the Secrets of an Obscure White-Box Implementation. (ePrint 2018/098)

Plan

Algebraic Security (1/3)

Security Model:

1. random bits allowed
   - as in classic masking
   - model unpredictability
   - in WB impl. as **pseudorandom**



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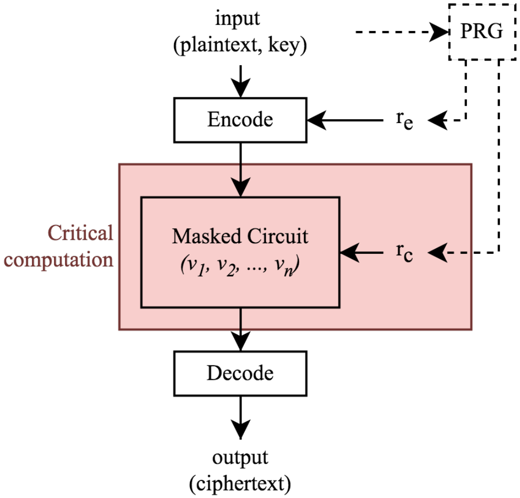

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   - in WB impl. as **pseudorandom**
2. **Goal:**
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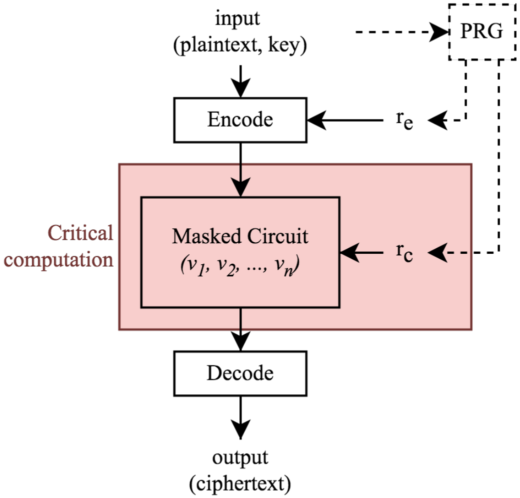
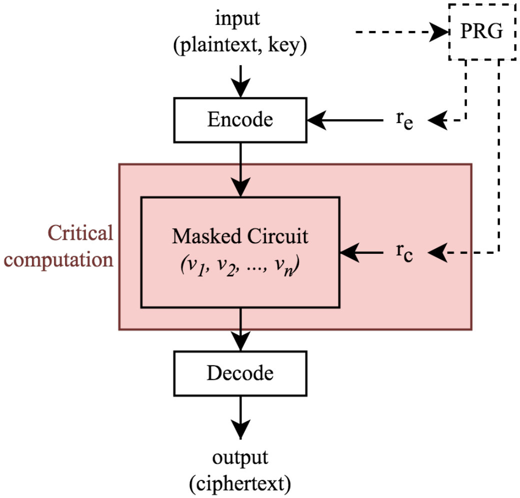
3. **isolated** from obfuscation problems



Algebraic Security (2/3)

Adversary:

1. chooses plaintext/key pairs



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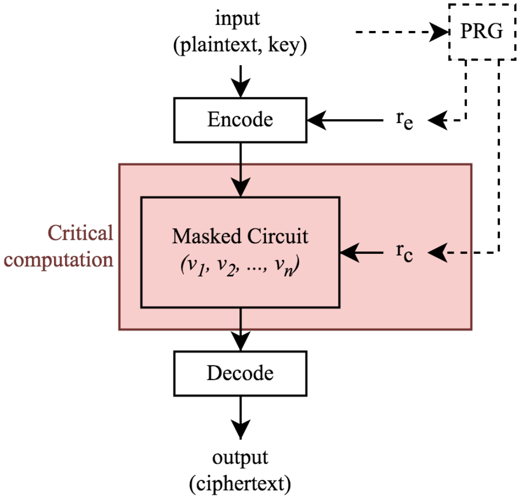
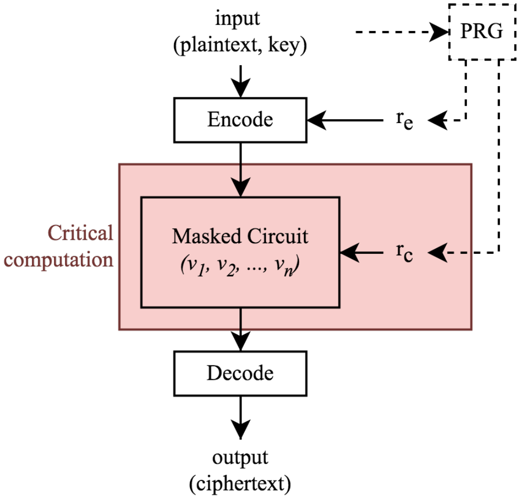


Algebraic Security (2/3)

Adversary:

1. chooses plaintext/key pairs
2. chooses $f \in span\{v_i\}$
3. tries to **predict** values of this function
   (i.e. before random bits are sampled)



Algebraic Security (3/3)

Proposition

Let $F = \{f(x, \cdot, \cdot) \mid f(x, r_e, r_c) \in span\{v_i\},\ x \in \mathbb{F}_2^N\}$.
Let $e = -\log_2\left(1/2 + \max_{f \in F} bias(f)\right)$.
Then for any adversary $\mathcal{A}$ choosing Q inputs

$$\mathrm{Adv}[\mathcal{A}] \leq min(2^{Q-|r_c|}, 2^{-eQ}).$$

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Corollary

Let k be a positive integer. Then for any adversary $\mathcal{A}$

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Information-theoretic security!

Minimalist Quadratic Masking Scheme

Masking scheme

- quadratic decoder: $(a, b, c) \mapsto ab \oplus c$
- set of **gadgets**
- provably secure **composition**

function EvalXOR$((a, b, c), (d, e, f), (r_a, r_b, r_c), (r_d, r_e, r_f))$
  $(a, b, c) \leftarrow$ Refresh$((a, b, c), (r_a, r_b, r_c))$
  $(d, e, f) \leftarrow$ Refresh$((d, e, f), (r_d, r_e, r_f))$
  $x \leftarrow a \oplus d$
  $y \leftarrow b \oplus e$
  $z \leftarrow c \oplus f \oplus ae \oplus bd$
  return (x, y, z)

function EvalAND$((a, b, c), (d, e, f), (r_a, r_b, r_c), (r_d, r_e, r_f))$
  $(a, b, c) \leftarrow$ Refresh$((a, b, c), (r_a, r_b, r_c))$
  $(d, e, f) \leftarrow$ Refresh$((d, e, f), (r_d, r_e, r_f))$
  $m_a \leftarrow bf \oplus r_c e$
  $m_d \leftarrow ce \oplus r_f b$
  $x \leftarrow ae \oplus r_f$
  $y \leftarrow bd \oplus r_c$
  $z \leftarrow am_a \oplus dm_d \oplus r_c r_f \oplus cf$
  return (x, y, z)

function Refresh$((a, b, c), (r_a, r_b, r_c))$
  $m_a \leftarrow r_a \cdot (b \oplus r_c)$
  $m_b \leftarrow r_b \cdot (a \oplus r_c)$
  $r_c \leftarrow m_a \oplus m_b \oplus (r_a \oplus r_c)(r_b \oplus r_c) \oplus r_c$
  $a \leftarrow a \oplus r_a$
  $b \leftarrow b \oplus r_b$
  $c \leftarrow c \oplus r_c$
  return (a, b, c)

Minimalist Quadratic Masking Scheme

Security

1. algorithm to verify that bias $\neq 1/2$
2. max. degree on r: 4

```
function EvalXOR((a, b, c), (d, e, f), (r_a, r_b, r_c), (r_d, r_e, r_f))
    (a, b, c) ← Refresh((a, b, c), (r_a, r_b, r_c))
    (d, e, f) ← Refresh((d, e, f), (r_d, r_e, r_f))
    x ← a ⊕ d
    y ← b ⊕ e
    z ← c ⊕ f ⊕ ae ⊕ bd
    return (x, y, z)

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    y ← bd ⊕ r_c
    z ← a m_a ⊕ d m_d ⊕ r_c r_f ⊕ cf
    return (x, y, z)

function Refresh((a, b, c), (r_a, r_b, r_c))
    m_a ← r_a · (b ⊕ r_c)
    m_b ← r_b · (a ⊕ r_c)
    r_c ← m_a ⊕ m_b ⊕ (r_a ⊕ r_c)(r_b ⊕ r_c) ⊕ r_c
    a ← a ⊕ r_a
    b ← b ⊕ r_b
    c ← c ⊕ r_c
    return (a, b, c)
```

Minimalist Quadratic Masking Scheme

Security

1. algorithm to verify that bias $\neq 1/2$
2. max. degree on r: 4

$\Rightarrow$ bias $\leq 7/16$

for 80-bit security we need $|r_c| \geq 940$

function EvalXOR($(a, b, c), (d, e, f), (r_a, r_b, r_c), (r_d, r_e, r_f)$)
    $(a, b, c) \leftarrow$ **Refresh**($(a, b, c), (r_a, r_b, r_c)$)
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    $y \leftarrow b \oplus e$
    $z \leftarrow c \oplus f \oplus ae \oplus bd$
    return (x, y, z)

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    return (a, b, c)

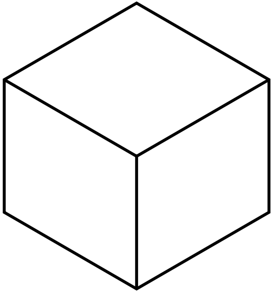
Proof-of-concept masked AES-128

1. MQMS + 1-st order Boolean masking
2. 31,783 $\rightarrow$ 2,588,743 gates expansion (x81)
3. 16 Mb code / 1 Kb RAM / 0.05s per block on a laptop
4. (unoptimized)

github.com/cryptolu/whitebox

Conclusions

1. new attack methods $\Rightarrow$ new constraints on a white-box impl.
2. new results on provable security for white-box model
3. new links with side-channel research



Design and Cryptanalysis of Symmetric-Key Algorithms in Black and White-box Models

Aleksei Udovenko
aleksei.udovenko@uni.lu

- Design of Symmetric-key Algorithms
- Structural and Decomposition Cryptanalysis
- Nonlinear Invariant Cryptanalysis
- White-box Cryptography