On the Practical Security of White-Box Cryptography

IEEE Information Theory Society

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CryptoExperts

White-Box Cryptography

* White-Box Security Model
* Historical White-Box Compilers
* Differential Computation Analysis Attack

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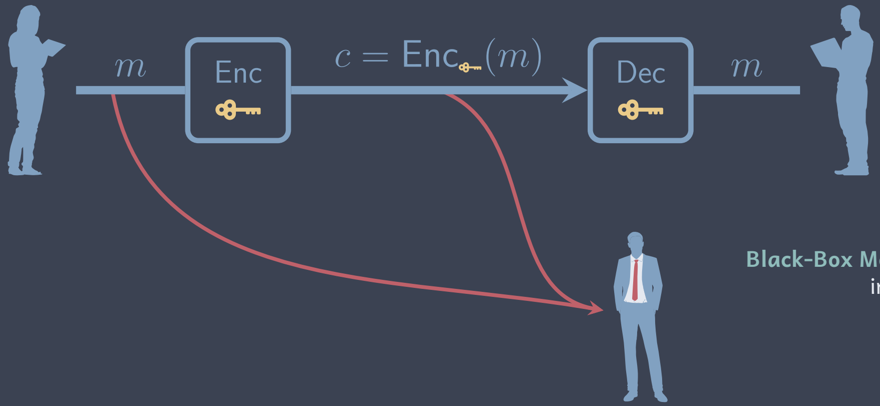
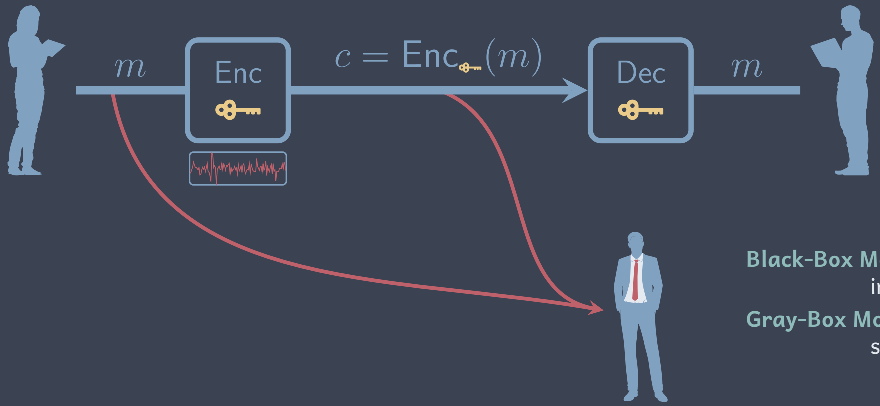
» Security Models: Shades of Gray



Black-Box Model:
input/output behavior

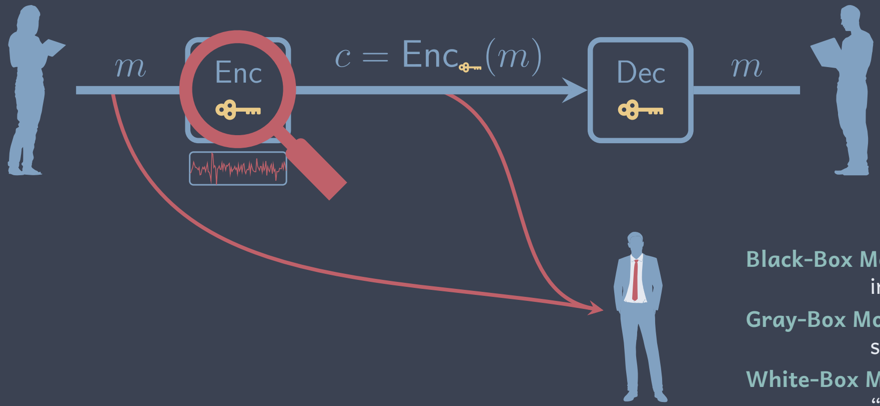
» Security Models: Shades of Gray



Black-Box Model:
input/output behavior

Gray-Box Model:
side-channel leakage

» Security Models: Shades of Gray



Black-Box Model:
input/output behavior

Gray-Box Model:
side-channel leakage

White-Box Model:
"full" control

» White-Box Threat Model

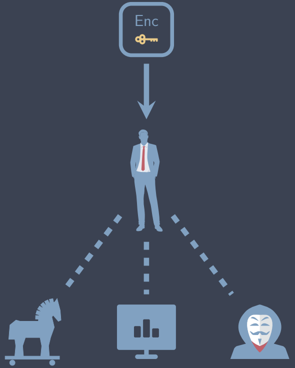
To extract a cryptographic key

Where from a software implementation of cipher

Whom by malwares, co-hosted applications, user themselves, $\cdots$

How by all kinds of means

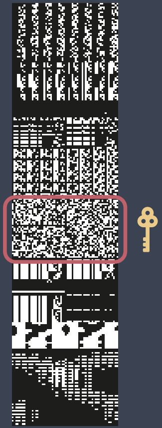
- analyze the code
- spy on the memory
- interfere the execution
- $\cdots$



» Motivation and Real-World Applications

- Why not using secure hardware ?
  - not always available
  - expensive (to produce, deploy, integrate, update)
  - usually has a long lifecycle
  - security breach is hard to mitigate

- Applications
  - Digital Content Distribution
  - Mobile Payment
  - Digital Contract Signing
  - Blockchains and cryptocurrencies



Credits to [Shamir, van Someren 99]

White-Box Cryptography

* White-Box Security Model
* Historical White-Box Compilers
* Differential Computation Analysis Attack

» White-Box Compiler

[Delerablée et al. 14]

A **white-box compiler** takes as input *a secret key* and generates a "white-box secure" program implementing some specific crypto. algo. with the specified secret key.

* White-box security notions
  * **Unbreakability** (hardness of key-extraction)
  * One-wayness
  * Incompressibility
  * Traceability

No provably secure unbreakable white-box compiler for standard block ciphers is known.

» Theoretical Progress: Cryptographic Obfuscation

An **obfuscator** makes programs “unintelligible” while preserving their functionalities.

* **Virtual Black-Box** (VBB) **Obfuscation**
  * Nothing is learned from the obfuscated programs except their I/Os.
  * (**Impossibility**) VBB is impossible in general!
  * VBB for point functions exist.
  * *Can we VBB obfuscate a block cipher ?*
* **Indistinguishability Obfuscation** (iO)
  * Literally, it hides the origin of an obfuscated program
  * Has many implications
  * Candidate constructions exist
  * *Does not imply unbreakability directly !*

» Historical White-Box Compilers

Transform a cipher into a series of randomized key-dependent lookup tables.

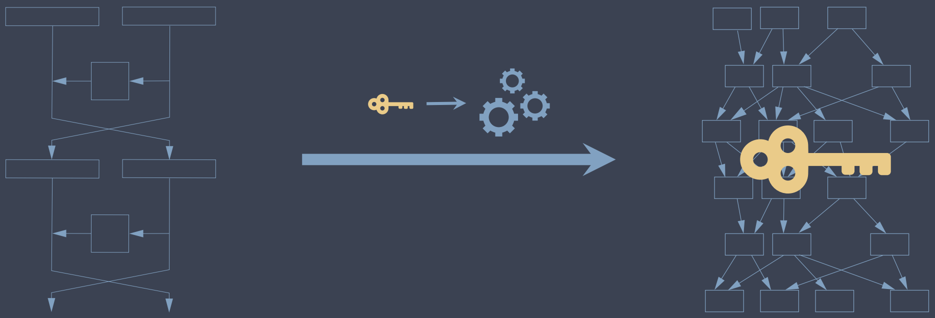
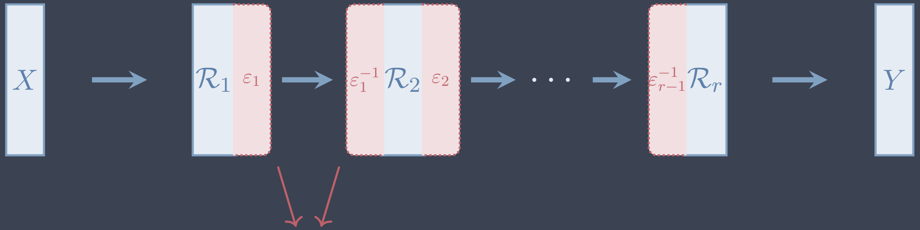


Illustration from [Wyseur12]

» Historical White-Box Compilers: Internal Encodings

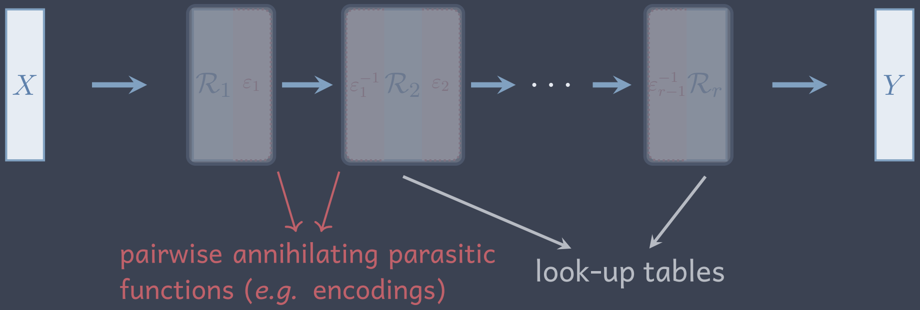
$$\boxed{X} \longrightarrow \boxed{\mathcal{R}_1} \longrightarrow \boxed{\mathcal{R}_2} \longrightarrow \cdots \longrightarrow \boxed{\mathcal{R}_r} \longrightarrow \boxed{Y}$$

» Historical White-Box Compilers: Internal Encodings

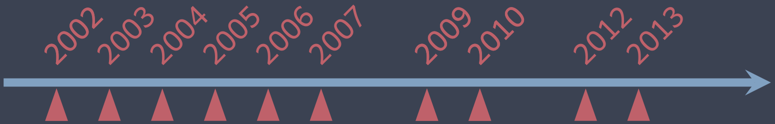


pairwise annihilating parasitic functions (*e.g.* encodings)

» Historical White-Box Compilers: Internal Encodings



» Timeline: A Cat-And-Mouse Game



- 2002: seminal wb-DES [Chow et al. 02]
- 2003: seminal wb-AES [Chow et al. 03]
- 2005: variant wb-DES [Link, Neumann 05]
- 2006: variant wb-AES [Bringer et al. 06]
- 2009: variant wb-AES [Xiao, Lai 09]
- 2010: variant wb-AES [Karroumi 10]
- . . .

- 2002: fault attack against wb-DES [Jacob et al. 02]
- 2004: BGE attack [Billet et al. 04]
- 2007: attack wb-DES [Goubin et al 07, Wyseur et al. 07]]
- 2009: attack wb-AES [Michiels et al. 09]
- 2010: attack Bringer et al. variant [De Mulder et al. 10]
- 2012: attack Xiao-Lai variant [De Mulder et al. 12]
- 2013: attack improvements and Karroumi variant [Lepoint et al .13]
- . . .

» Obscurity as a Solution

- All public designs are broken
- No provably secure solution

- Growing demand in industry
- Huge application potential

$$\Downarrow$$

Security through obscurity: home-made design + obfuscation

Time consuming reverse engineering + structural analysis

White-Box Cryptography

* White-Box Security Model
* Historical White-Box Compilers
* Differential Computation Analysis Attack

» Differential Computation Analysis (DCA)

[Bos et al. 2016, Sanfelix et al. 2015]

Differential power analysis (DPA) techniques on computational leakages.

gray-box model

side-channel leakages (noisy)

e.g. power / EM / time / $\cdots$

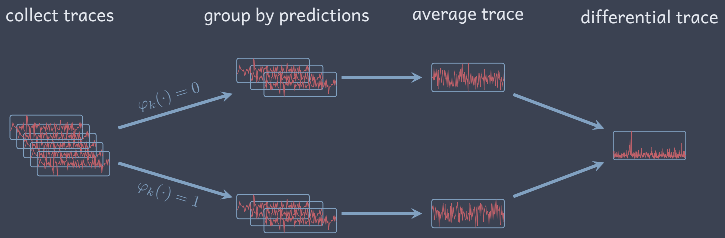
white-box model

computational leakages (noisy-free)

e.g. registers / accessed memory / $\cdots$

» Differential Computation Analysis (DCA) (cont.)

[Bos et al. 2016, Sanfelix et al. 2015]



Implying strong *linear correlation* between the sensitive variables φ_k and the leaked samples in the computational traces.

Many publicly available implementations are broken by DCA.

» WhibOx Competitions

* Organized as CHES CTF events

> *The competition gives an opportunity for researchers and practitioners to confront their (secretly designed) white-box implementations to state-of-the-art attackers*
>
> – WhibOx 2017

* Designer: to submit the C source codes of AES-128 with secret key
* Attacker: to reveal the hidden key
* No need to disclose identity or underlying techniques

» WhibOx Competitions (cont.)

* WhibOx 2017
  * 94 submissions were **all broken** by 877 individual breaks
  * most (86%) of them were alive for < 1 day
  * mostly broken by DCA [Bock and Treff 20]
* WhibOx 2019
  * New rules encourage designers to submit "smaller" and "faster" implementations
  * 27 submissions with 124 individual breaks
  * 3 implementations survived, but broken after the competition

» This Talk

* Analyze in-depth why DCA can break internal encodings and propose new efficient attacks against internal encodings
* Propose new different advanced gray-box attack paths
* Analyze advanced gray-box countermeasures against new attack paths
* Propose data-dependency analysis with substantially improved complexity over the existing attacks
* Break the winning challenges from two editions of WhibOx competitions

» Publications

[RW19] Rivain and Wang. "Analysis and Improvement of Differential Computation Attacks against Internally-Encoded White-Box Implementations". In: **TCHES 2019 Issue 2**.

[BRVW19] Bogdanov, Rivain, Vejre, and Wang. "Higher-Order DCA against Standard Side-Channel Countermeasures". In: **COSADE 2019**.

[GPRW20] Goubin, Paillier, Rivain, and Wang. "How to reveal the secrets of an obscure white-box implementation". In: **Journal of Cryptographic Engineering Volume 10 Issue 1**.

[GRW20] Goubin, Rivain, and Wang. "Defeating State-of-the-Art White-Box Countermeasures with Advanced Gray-Box Attacks". In: **TCHES 2020 Issue 3**.

» Passive Gray-Box Adversary Model [GRW20]

* For each of N chosen $(x^{(i)})_{1 \leq i \leq N}$, collect a computational trace of t samples

$$\boldsymbol{v} = (v_1, v_2, \cdots, v_t)$$

* Build a distinguisher D:

$$(\gamma_k)_{k \in \mathcal{K}} = \mathsf{D}\left((x^{(i)})_i \ , \ (\boldsymbol{v}^{(i)})_i\right)$$

* Choose key candidate: $\mathrm{argmax}_{k \in \mathcal{K}} \gamma_k$

* Number samples in attacked trace (window): t
* Required number traces: N

» Outline

White-Box Cryptography

DCA Analysis and Improvements against Internal Encodings

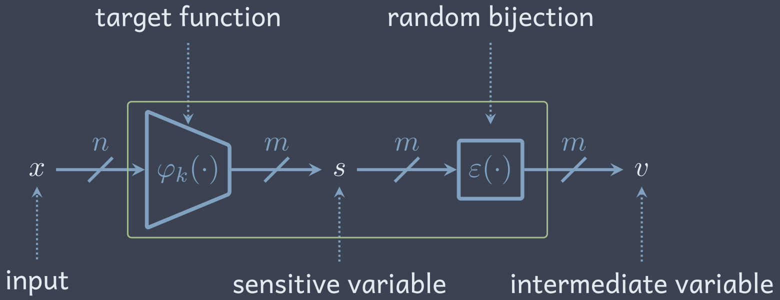
Advanced Gray-Box Countermeasures and Attacks

Data-Dependency Analysis

DCA Analysis and Improvements against Internal Encodings

* DCA against Internal Encodings
* Collision Attack

» Internal Encoding Leakage



* $\varepsilon \circ \varphi_k$, as a result of some **table look-ups**, is **leaked in the memory**
* To exploit the leakage of $\varepsilon \circ \varphi_k$, it is necessary that $n > m$

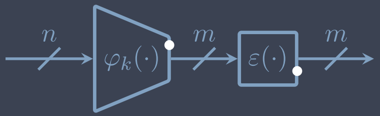
DCA Analysis and Improvements against Internal Encodings

* DCA against Internal Encodings
* Collision Attack

» DCA Analysis

Based on well-established theory – *Boolean correlation*, instead of *difference of means*: for any key guess k

$$\rho_k = \mathrm{Cor}\Big(\varphi_k(\cdot)[i] \ , \ \varepsilon \circ \varphi_{k^*}(\cdot)[j] \Big)$$



DCA success (roughly) requires:

$$|\rho_{k^*}| > \max_{k^\times} |\rho_{k^\times}|$$

» Distributions of ρ_{k^*} and $\rho_{k^\times}$

* **Ideal** assumption: $\left(\varphi_k\right)_k$ are mutually independent random (n, m) functions

Correct key guess k^*,

$$\rho_{k^*} = 2^{2-m} N^* - 1$$

where

$$N^* \sim \mathcal{HG}(2^m, 2^{m-1}, 2^{m-1}) \, .$$

Only depends on m.

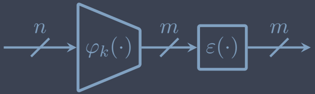
Incorrect key guess $k^\times$,

$$\rho_{k^\times} = 2^{2-n} N^\times - 1$$

where

$$N^\times \sim \mathcal{HG}(2^n, 2^{n-1}, 2^{n-1}) \, .$$

Only depends on n.



» Lemma

Lemma

Let $\mathcal{B}(n)$ be the set of balanced n-bit Boolean functions. If $f \in \mathcal{B}(n)$ and $g \xleftarrow{\$} \mathcal{B}(n)$ independent of f, then the balanceness of $f+g$ is $\mathrm{B}(f+g) = 4 \cdot N - 2^n$ where $N \sim \mathcal{HG}(2^n, 2^{n-1}, 2^{n-1})$ denotes the size of $\{x : f(x) = g(x) = 0\}$.

With

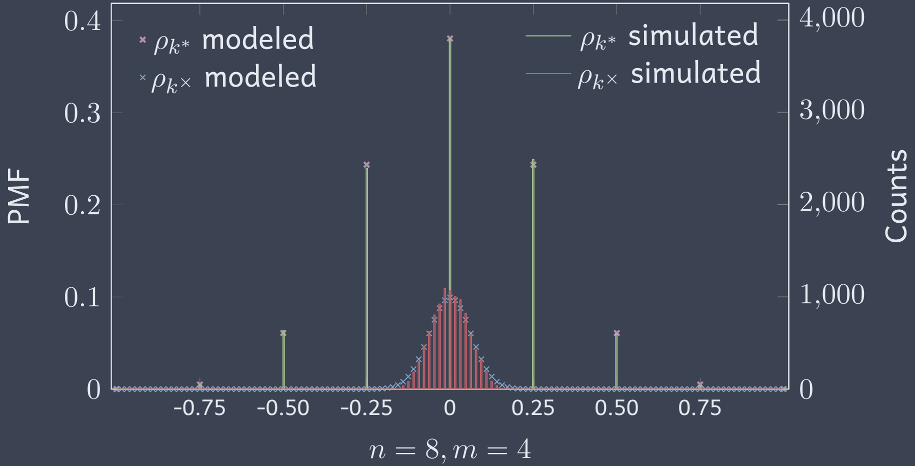
$$\mathrm{Cor}(f+g) = \frac{1}{2^n}\mathrm{B}(f+g)$$

$\Rightarrow$

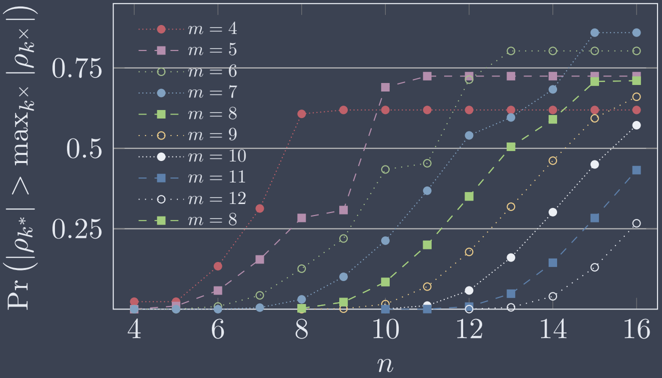
$$\rho_{k^*} = 2^{2-m} N^* - 1 \quad \text{and} \quad \rho_{k^\times} = 2^{2-n} N^\times - 1$$

where $N^* \sim \mathcal{HG}(2^m, 2^{m-1}, 2^{m-1})$ and $N^\times \sim \mathcal{HG}(2^n, 2^{n-1}, 2^{n-1})$.

» Distributions of ρ_{k^*} and $\rho_{k^\times}$



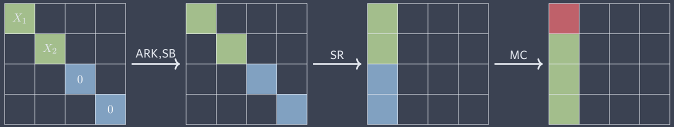
» DCA Success Rate: $|\rho_{k^*}| > \max_{k^\times} |\rho_{k^\times}|$



DCA success probability converges towards $\approx 1 - \Pr_{N^*}\left(2^{m-2}\right)$ for $n \geq 2m + 2$.

» Attack a NSC Variant: a White-Box AES

- *Byte* encoding protected AES
- DCA has failed to break it *before this work*
- Our approach: target an output byte of MixColumn in the first round



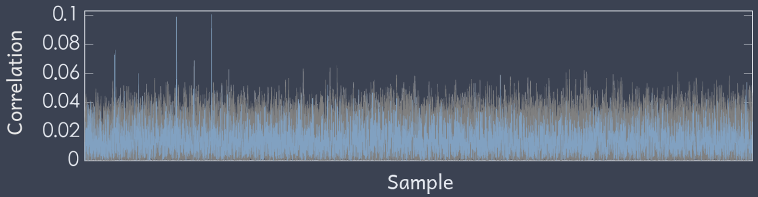
$$\varphi_{k_1||k_2}(x_1||x_2) = 2 \cdot \mathbf{Sbox}(x_1 \oplus k_1) \oplus 3 \cdot \mathbf{Sbox}(x_2 \oplus k_2) \oplus \mathbf{Sbox}(k_3) \oplus \mathbf{Sbox}(k_4) \quad c$$

$$\varepsilon' = \varepsilon \circ \oplus_c \,,$$

$$n = 16, m = 8 \,, |\mathcal{K}| = 2^{16}.$$

» Attack a NSC Variant: a White-Box AES

* Attack results: $\sim$ 1800 traces



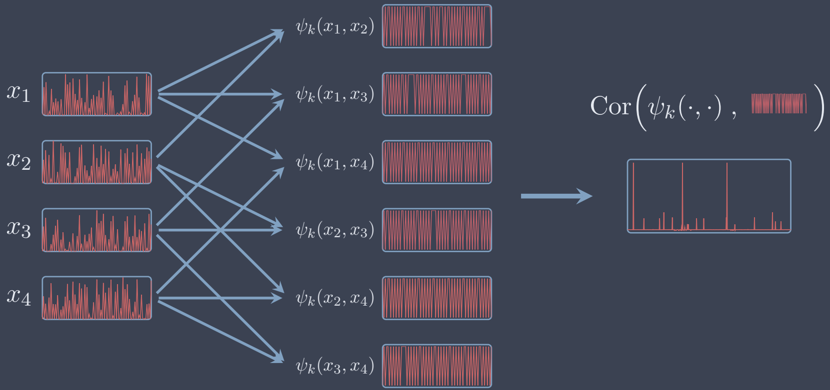
* Byte encoding can be efficiently broken

DCA Analysis and Improvements against Internal Encodings

* DCA against Internal Encodings
* Collision Attack

» Collision Attack

N inputs & raw traces $\binom{N}{2}$ collision predictions & traces



$$\psi_k(x_1, x_2) := \Big(\varphi_k(x_1) = \varphi_k(x_2)\Big)$$

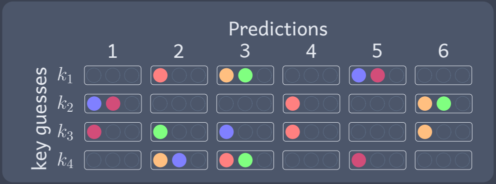
» Collision Attack Explanation

Based on the principle:

$$\varphi_k(x_1) = \varphi_k(x_2) \quad \Leftrightarrow \quad \varepsilon \circ \varphi_k(x_1) = \varepsilon \circ \varphi_k(x_2)$$

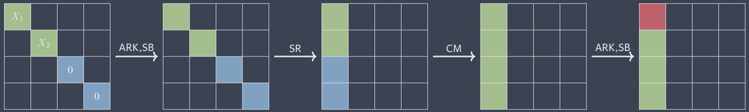
Trace Complexity:

$$N = \mathcal{O}\left(2^{\frac{m}{2}}\right)$$



» Attack the NSC Variant

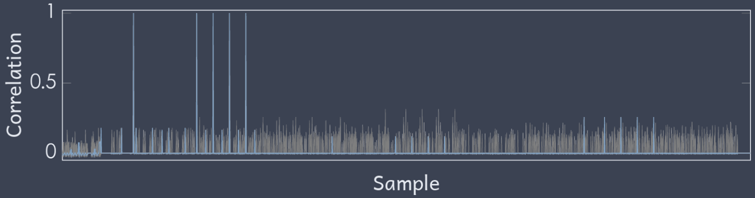
- Same to DCA: targeting at one 1-st round MixColumn output byte



$$\varphi_{k_1||k_2}(x_1||x_2) = 2 \cdot \mathbf{Sbox}(x_1 \oplus k_1) \oplus 3 \cdot \mathbf{Sbox}(x_2 \oplus k_2)$$

$$\varepsilon' = \varepsilon \circ \oplus_c \quad \text{or} \quad \varepsilon'' = \varepsilon \circ \mathbf{Sbox} \circ \oplus_{c \oplus k_1'}$$

- Attack results: 60 traces



» Contribution Summary

- DCA against internal encodings has been analysed in depth
  - Allows to attack wider encodings
- Propose new class of collision attacks with very low trace complexity
- Mutual information analysis with similar trace complexity but higher computation complexity
- Hence, protecting AES with internal encodings in the beginning rounds is insufficient

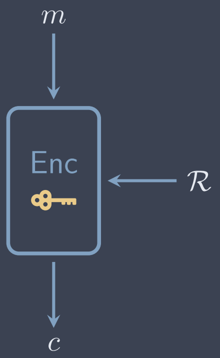
Advanced Gray-Box Countermeasures and Attacks

* Linear Masking, Higher-Order DCA, and Linear Decoding Analysis
* Algebraic Security and Non-Linear Masking
* Shuffling

» Random Source

[BRVW19]

* Countermeasures need randomness.

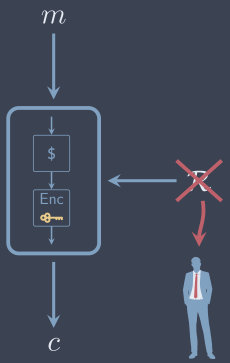


» Random Source

[BRVW19]

- Countermeasures need randomness.
- Plaintext is the only source of randomness
- Security criteria:

Pseudorandomness no statistical flaw
Obscurity the design should be kept secret
Obfuscation hard to distinguish from other intermediate variables



Advanced Gray-Box Countermeasures and Attacks

* **Linear Masking, Higher-Order DCA, and Linear Decoding Analysis**
* Algebraic Security and Non-Linear Masking
* Shuffling

» Linear Masking

[Ishai et al. 03]

- Intermediate value x is split into n shares

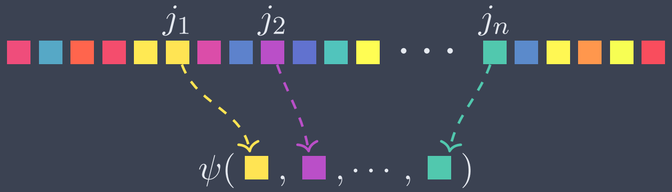
$$x = x_1 \oplus x_2 \cdots \oplus x_n$$

- Shares are manipulated separately such that any subset of at most $n-1$ shares is independent of x
- Resistant against $(n-1)$-th order DCA attacks

» Higher-Order DCA (HO-DCA)

[BVRW19]

- Trace **pre-processing**: an n-th order trace contains $q = \binom{t}{n}$ points:



- The natural combination function ψ is XOR sum
- Perform DCA attacks on the higher-order traces
- Linear masking can be broken
  - $\exists$ fixed n positions in which the shares are

$$\binom{1000}{5} \approx 2^{43}$$

» Linear Decoding Analysis (LDA)

[GPRW20]

- Assumption: there exists a linear decoding function

$$D(v_1, v_2, \cdots, v_t) = a_0 \oplus \left(\bigoplus_{1 \le i \le t} a_i \cdot v_i \right) = \varphi_k(x)$$

  for some sensitive variable φ_k and some fixed coefficients $a_0, a_1, \cdots, a_t$.

- Record the v_i's over N executions:

$$\begin{bmatrix} 1 & v_1^{(1)} & \cdots & v_t^{(1)} \\ 1 & v_1^{(2)} & \cdots & v_t^{(2)} \\ 1 & \vdots & \ddots & \vdots \\ 1 & v_1^{(N)} & \cdots & v_t^{(N)} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix} = \begin{bmatrix} \varphi_k(x^{(1)}) \\ \varphi_k(x^{(2)}) \\ \vdots \\ \varphi_k(x^{(N)}) \end{bmatrix}$$

» Linear Decoding Analysis (LDA) (cont.) [GPRW20]

* Record the v_i's over N executions:

$$\begin{bmatrix} 1 & v_1^{(1)} & \cdots & v_t^{(1)} \\ 1 & v_1^{(2)} & \cdots & v_t^{(2)} \\ 1 & \vdots & \ddots & \vdots \\ 1 & v_1^{(N)} & \cdots & v_t^{(N)} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix} = \begin{bmatrix} \varphi_k(x^{(1)}) \\ \varphi_k(x^{(2)}) \\ \vdots \\ \varphi_k(x^{(N)}) \end{bmatrix}$$

* Linear masking is vulnerable to LDA
  * system solvable for k^*
  * but not for incorrect key guess $k^\times$
* Trace Complexity $t + \mathcal{O}(1)$
* Computation complexity $\mathcal{O}\left(t^{2.8} \cdot |\mathcal{K}|\right)$

$$1000^{2.8} \approx 2^{28}$$

» Breaking WhibOx 2017 Winning Challenge with LDA [GPRW20]

* Small windows located for target variables
* The 3rd s-box $t = 35, \min(n) = 2 \quad \Longrightarrow \quad$ HO-DCA: 2^{18}, and LDA: 2^{22}

Bit	Encoding coefficients
1	0 0 0 0 0 0 1 0 1 0 1 1 1 0 0 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2	0 0 0 0 0 0 1 0 0 1 1 0 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3	0 0 0 0 0 0 0 0 1 0 1 0 0 0 1 1 1 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4	0 0 0 0 0 0 0 0 0 1 1 0 0 0 1 1 1 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
5	0 0 0 0 0 0 0 1 1 0 0 1 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
6	0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
7	0 0 0 0 0 0 1 0 0 0 1 0 0 1 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
8	0 0 0 0 0 0 0 1 0 0 0 0 1 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

The solution of the system of equations for each bit in the 3rd byte.

* The 14th s-box: $t = 45, \min(n) = 9 \quad \Longrightarrow \quad$ HO-DCA: 2^{49}, and LDA: 2^{23}

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» Algebraic Security and Non-Linear Masking

[Biryukov and Udovenko 18]

* Introduced by Biryukov and Udovenko at Asiacrypt 2018
* To capture LDA like algebraic attack

> A d-th degree algebraically-secure non-linear masking ensures that any function of up to d degree to the intermediate variables should not compute a “predictable” variable.

» First-Degree Secure Non-Linear Masking

[Biryukov and Udovenko 18]

* Quadratic decoding function

$$(a, b, c) \mapsto ab \oplus c$$

* Secure gadgets for bit XOR, bit AND, and refresh
* Provably secure composition
* But vulnerable to DCA attack

$$\mathsf{Cor}(ab \oplus c,\ c) = \frac{1}{2}$$

* Empirically, suggest using a combination of linear masking and non-linear masking to thwart both DCA (probing security) and LDA (algebraic security).

» Combination of Linear Masking and Non-linear Masking

[GRW20]

* Three possible natural combinations:
  1. apply linear masking on top of non-linear masking

$$x = (a_1 \oplus a_2 \oplus \cdots \oplus a_n)(b_1 \oplus b_2 \oplus \cdots \oplus b_n) \oplus (c_1 \oplus c_2 \oplus \cdots \oplus c_n)$$

  2. apply non-linear masking on top of linear masking

$$x = (a_1 b_1 \oplus c_1) \oplus (a_2 b_2 \oplus c_2) \oplus \cdots \oplus (a_n b_n \oplus c_n) \ .$$

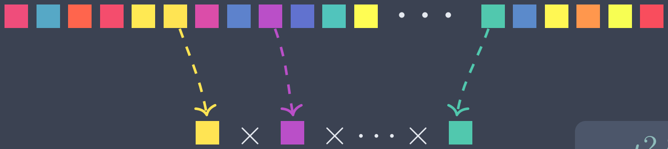
  3. merge the two maskings into a new encoding

$$x = ab \oplus c_1 \oplus c_2 \oplus \cdots \oplus c_n \ .$$

* For first two combinations, the combined masking gadgets can be simply derived from the original gadgets of both schemes.

» Higher-Degree Decoding Analysis (HDDA) [GPRW20]

- Assume the decoding function is of degree d
- Trace **pre-processing**: a d-th degree trace contains all monomials of degree $\leq d$



- Perform LDA attacks on the higher-degree traces
- Higher-degree trace samples: $\sum_{i=0}^{d} \binom{t}{d} = \binom{t+d}{d} \ll t^d$
- Complexity: $\mathcal{O}\left(t^{2.8d} \cdot |\mathcal{K}|\right)$, practical when t, d are small.

$$t^{2.8d} < 2^{50}$$

$$\Downarrow$$

$$d = 2 \quad \Rightarrow \quad t < 487$$
$$t = 100 \quad \Rightarrow \quad d \leq 5$$

Advanced Gray-Box Countermeasures and Attacks

* Linear Masking, Higher-Order DCA, and Linear Decoding Analysis
* Algebraic Security and Non-Linear Masking
* Shuffling

» Shuffling

* The order of execution is randomly chosen for each run of the implementation.
* To increase noise in the adversary's observation

» Shuffling (cont.)

[BRVW19]

- Not enough in white-box model: traces can be aligned by memory
- Thus, the memory location of shares has to be shuffled.

» HO-DCA and Integrated HO-DCA against Masking and Shuffling [BRVW19]

* $\nexists\, n$ fixed locations for all shares
* Shuffling degree is λ
  * correlation score decreased by a factor of λ
  * attack slow down by a factor of λ^2
* Integrate values from all λ slots
  * correlation score decreased by a factor of $\sqrt{\lambda}$
  * attack slow down by a factor of λ

» Multivariate HO-DCA

[BRVW19]

* The multivariate HO-DCA optimizes the attack by exploiting joint information of the higher-order samples on the secrets
* Based on a maximum likelihood distinguisher

$$\gamma_k = \Pr\left(K = k | (\boldsymbol{V}^{(i)})_i = (\boldsymbol{v}^{(i)})_i \wedge (X^{(i)})_i = (x^{(i)})_i\right)$$

* We show that

$$\gamma_k \propto \prod_{i=1}^{N} \mathsf{C}_k(\boldsymbol{v}^{(i)}, x^{(i)})$$

where *the counter*

$$\mathsf{C}_k(\boldsymbol{v}, x) := \text{the number of } n\text{-tuples} \quad \textit{s.t.} \quad v_{j_1} \oplus \cdots \oplus v_{j_n} = \varphi_k(x) \quad \text{in one trace.}$$

» Attack Comparison

	linear masking		linear + NL masking	
	trace	computation	trace	computation
without shuffling				
LDA / HDDA	$t + \mathcal{O}(1)$	$\mathcal{O}\left(\lvert\mathcal{K}\rvert \cdot t^{2.8}\right)$	$\mathcal{O}\left(t^2\right)$	$\mathcal{O}\left(\lvert\mathcal{K}\rvert \cdot t^{5.6}\right)$
HODCA	c	$\mathcal{O}(\lvert\mathcal{K}\rvert \cdot t^n)$	$4\,c$	$\mathcal{O}(\lvert\mathcal{K}\rvert \cdot t^n)$
with shuffling of degree λ				
HO-DCA	$c\,\lambda^2$	$\mathcal{O}\left(\lvert\mathcal{K}\rvert \cdot t^n \cdot \lambda^2\right)$	$4\,c\,\lambda^2$	$\mathcal{O}\left(\lvert\mathcal{K}\rvert \cdot t^n \cdot \lambda^2\right)$
Intg. HO-DCA	$c\,\lambda$	$\mathcal{O}(\lvert\mathcal{K}\rvert \cdot t^n \cdot \lambda)$	$4\,c\,\lambda$	$\mathcal{O}(\lvert\mathcal{K}\rvert \cdot t^n \cdot \lambda)$
MV HO-DCA	$\mathcal{O}(t^n)$	$\mathcal{O}\left(\lvert\mathcal{K}\rvert \cdot t^{2n}\right)$		

Note that c is some small empirical factor

Data-Dependency Analysis

* Data-Dependency Graph
* Data-Dependency Analysis against Masking Combinations

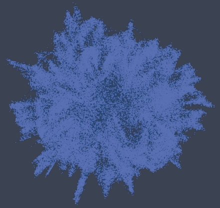
Data-Dependency Analysis

* Data-Dependency Graph
* Data-Dependency Analysis against Masking Combinations

» Data Dependency Graph

[GPRW20]

- White-box adversary also observes data-flow.
- Data-dependency graph (DDG) can visually reveal the structure of the implementation.



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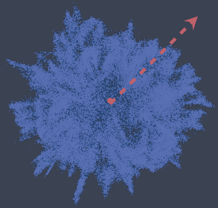

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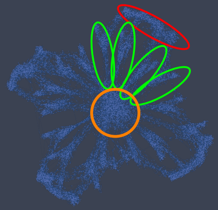

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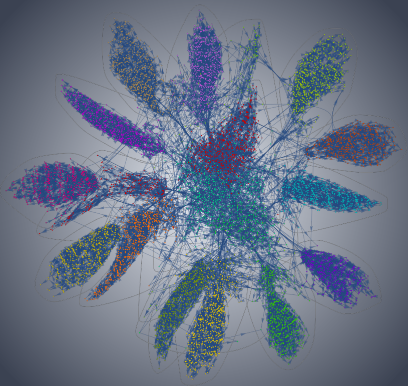
» Data Dependency Clusters

[GPRW20]

- Data-dependency can extract computation clusters and determines the location of sensitive computation
  - Round: $\sim$ 28 k nodes
  - S-box cluster: $\sim$ 500 nodes
  - Trace windows containing targets: $\sim$ 50 nodes



Data-Dependency Analysis

* Data-Dependency Graph
* Data-Dependency Analysis against Masking Combinations

» AND Gadget for Linear Masking

[Ishai et al. 03]

$$(x_1, x_2, \cdots, x_n), (y_1, y_2, \cdots, y_n) \mapsto (z_1, z_2, \cdots, z_n) \quad \text{s.t.} \bigoplus_i x_i \cdot \bigoplus_i y_i = \bigoplus_i z_i .$$

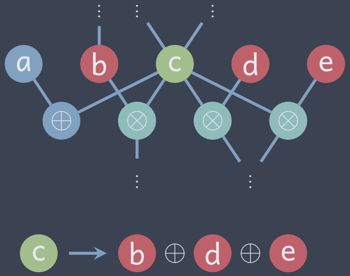
$$\begin{bmatrix} x_1y_1 & 0 & 0 \\ x_1y_2 & x_2y_2 & 0 \\ x_1y_3 & x_2y_3 & x_3y_3 \end{bmatrix} \oplus \begin{bmatrix} 0 & x_2y_1 & x_3y_1 \\ 0 & 0 & x_3y_2 \\ 0 & 0 & 0 \end{bmatrix}^T \oplus \begin{bmatrix} 0 & r_{1,2} & r_{1,3} \\ r_{1,2} & 0 & r_{2,3} \\ r_{1,3} & r_{2,3} & 0 \end{bmatrix} \xrightarrow{\text{sum rows}} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}$$

Each x_i is multiplied with all shares of y: $(y_j)_j$, vice versa.

» Data-Dependency Analysis against Masking Combinations

[GRW20]

- Find co-operands of each node for $\otimes$
- Collecting data-dependency (DD) traces
    - Sum co-operands values
- Launch HO-DCA attacks on DD traces
    - Biased variables can be covered in DD trace
- Computation complexity substantially improved
- Successfully applied to break WhibOx 2019 winning implementations



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HODCA	c	$\mathcal{O}(\lvert\mathcal{K}\rvert \cdot t^n)$	$4\,c$	$\mathcal{O}(\lvert\mathcal{K}\rvert \cdot t^n)$
DD-DCA	c	$\mathcal{O}(\lvert\mathcal{K}\rvert \cdot t)$	$4\,c$	$\mathcal{O}(\lvert\mathcal{K}\rvert \cdot t)$
with shuffling of degree λ				
HO-DCA	$c\,\lambda^2$	$\mathcal{O}\left(\lvert\mathcal{K}\rvert \cdot t^n \cdot \lambda^2\right)$	$4\,c\,\lambda^2$	$\mathcal{O}\left(\lvert\mathcal{K}\rvert \cdot t^n \cdot \lambda^2\right)$
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Intg. DD-DCA	$c\,\lambda$	$\mathcal{O}(\lvert\mathcal{K}\rvert \cdot t \cdot \lambda)$	$4\;\lambda$	$\mathcal{O}(\lvert\mathcal{K}\rvert \cdot t \cdot \lambda)$

Note that c is some small empirical factor

» Conclusion

* This talks covers practical security of white-box cryptography
  * Demonstrated the capabilities of gray-box adversary in white-box model
  * Understood why gray-box attacks work against internal encodings
  * Proposed new gray-box attacks
  * Quantified different gray-box attack performances against different countermeasures
* A good level of practical resistance against these attacks can be achieved
  * under an assumption of adversary's uncertainty on attacked window within a full computation trace
  * for some choice of the parameters for countermeasures
  * Stressed the importance to hide structural knowledge of implementation

On the Practical Security of White-Box Cryptography

IEEE Information Theory Society

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on July 1, 2020

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