From Gray-box to White-box Cryptography

Aleksei Udovenko

University of Innsbruck, May 17th 2023

SnT, University of Luxembourg

Outline

Plan

Symmetric-key Encryption

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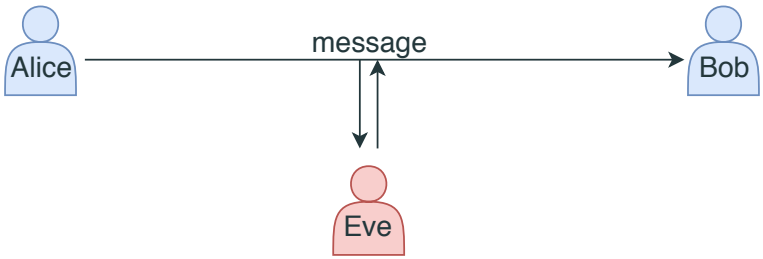

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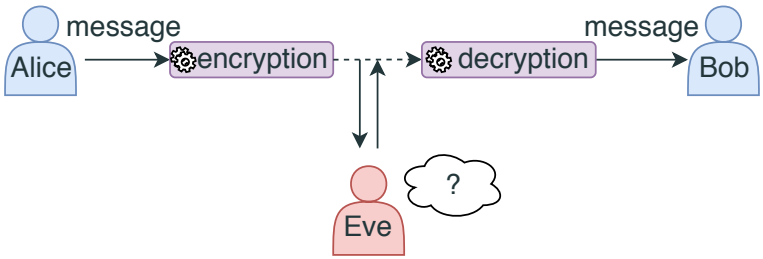

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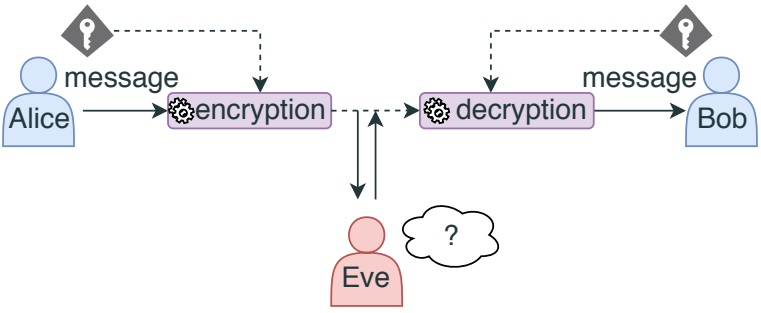
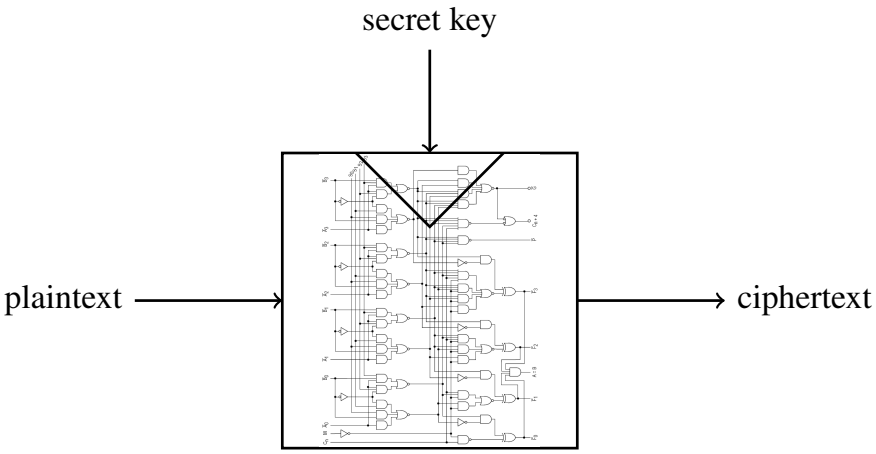
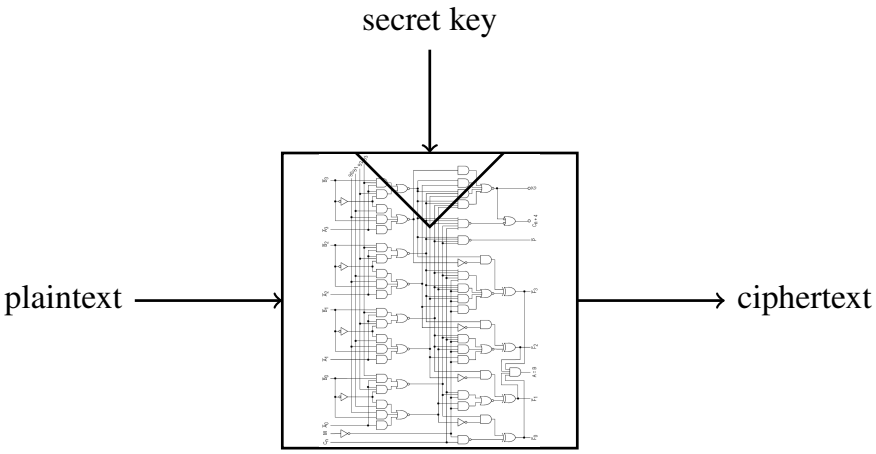


Block Cipher



Black-box Model



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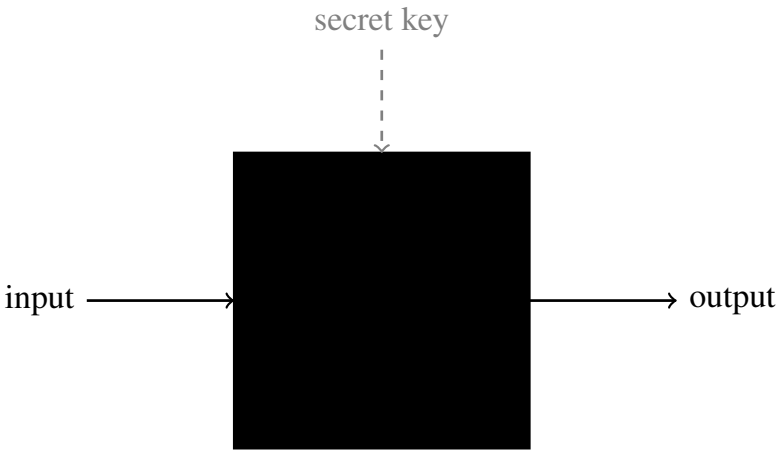
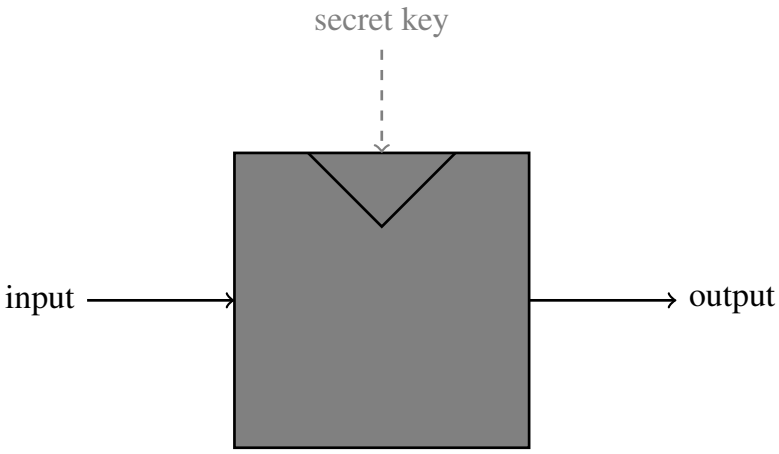


Gray-box Model (Side Channels)



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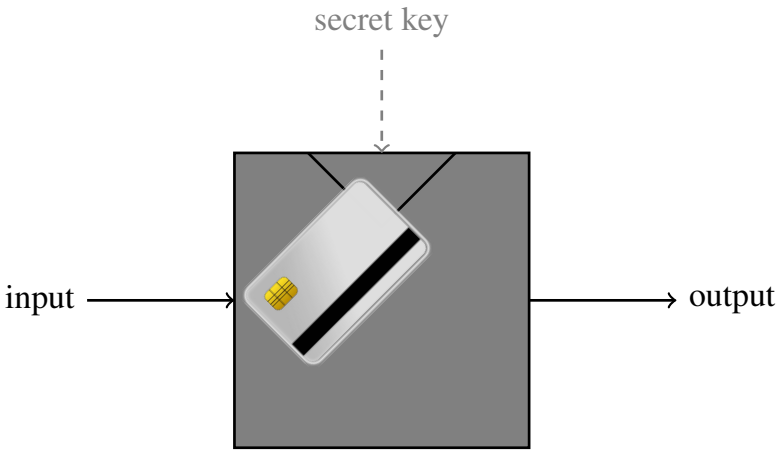

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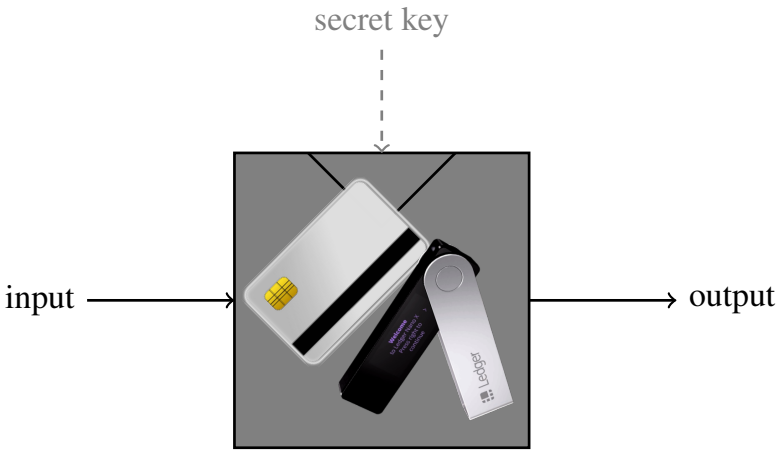

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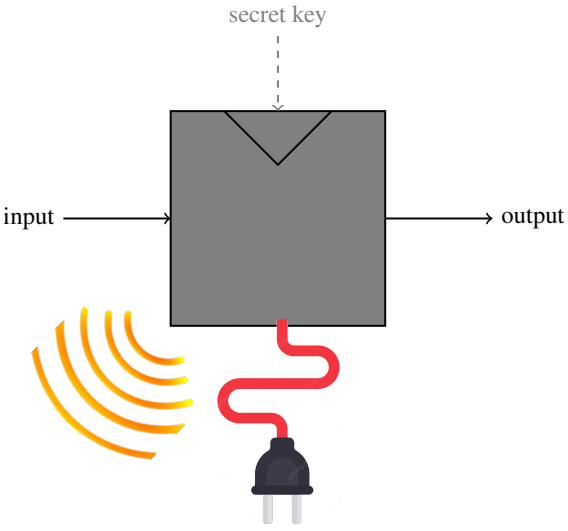

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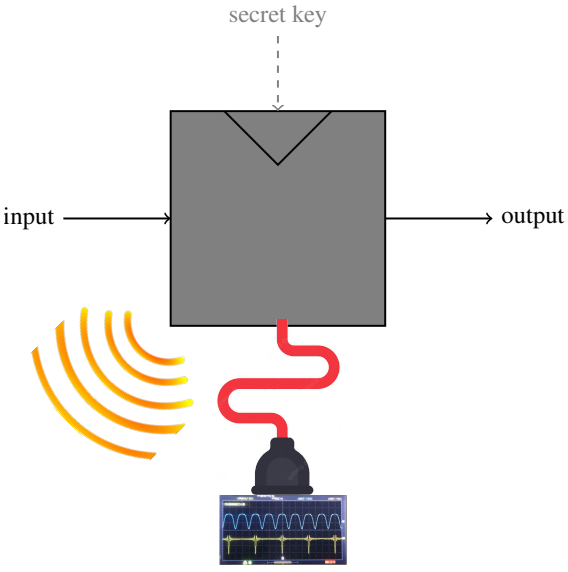

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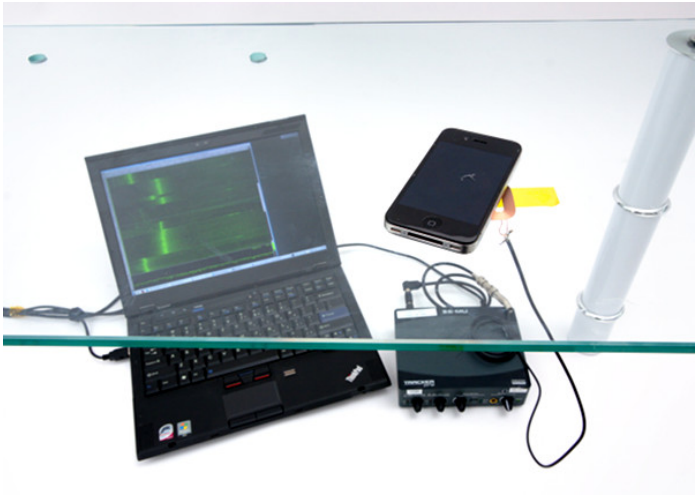
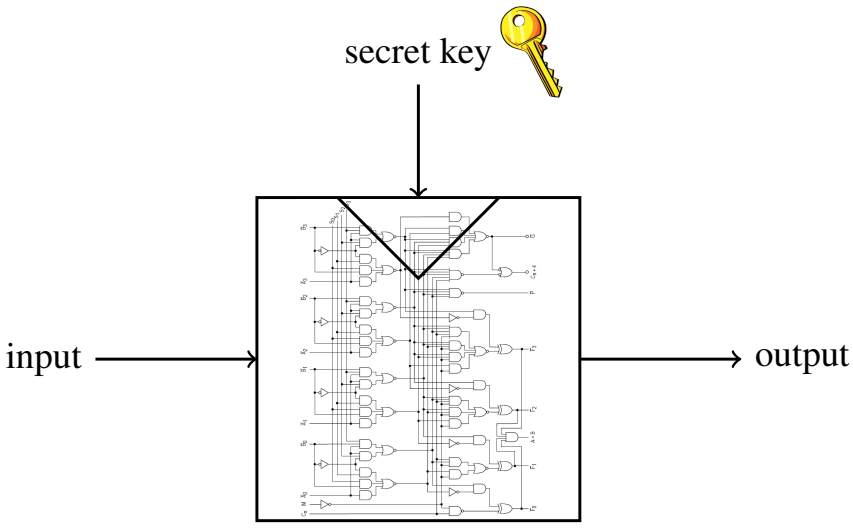


Breaking ECDSA on iPhone 4 using a $2 probe and a sound card. [GPPTY16]

White-box Model [ChoEisJohVOor02]



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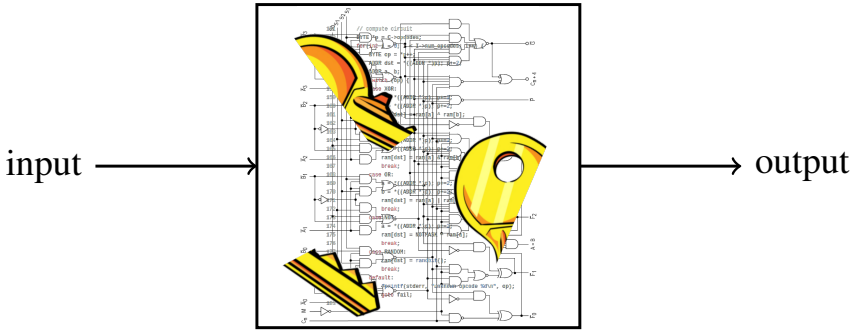

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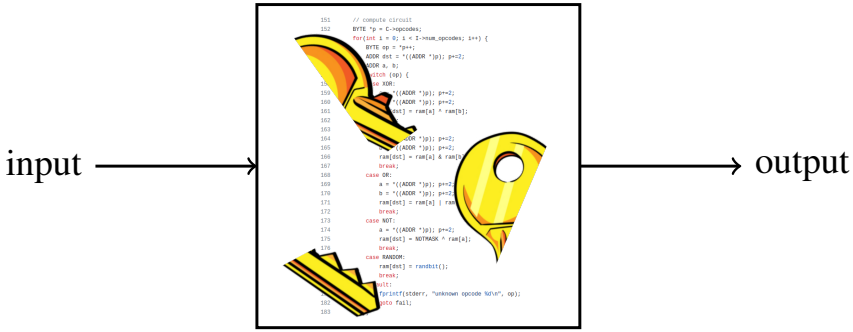

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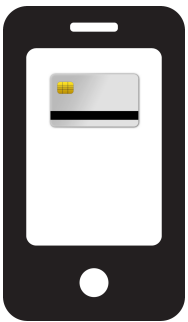

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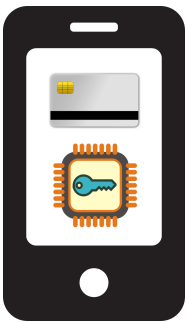

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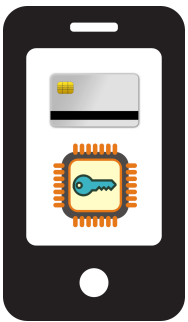
5. General cryptographic obfuscation: advanced protocols



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black-box gray-box white-box

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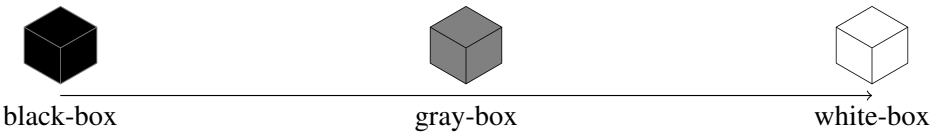

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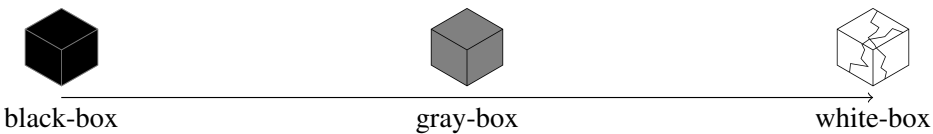

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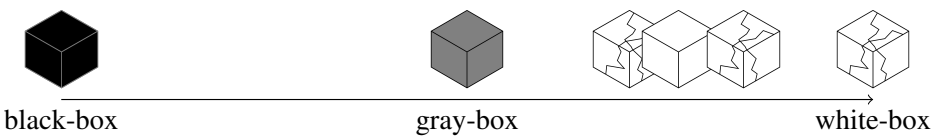

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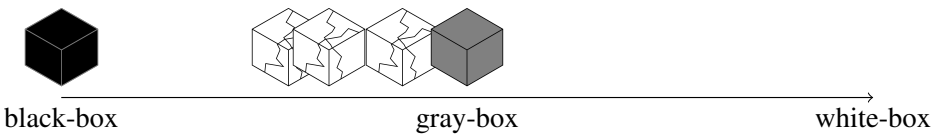

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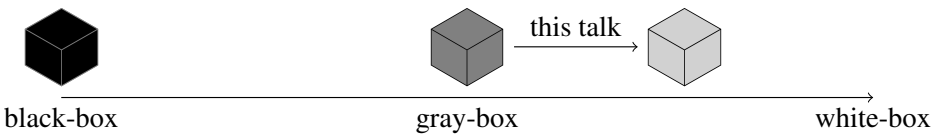
algebraic attacks and countermeasures (this talk)



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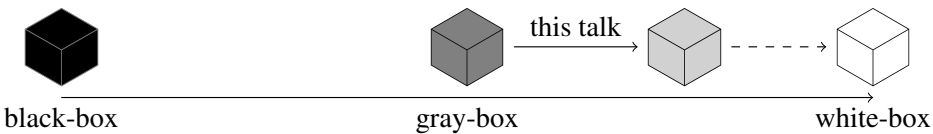

Plan

Differential Power Analysis [KocJafJun99]

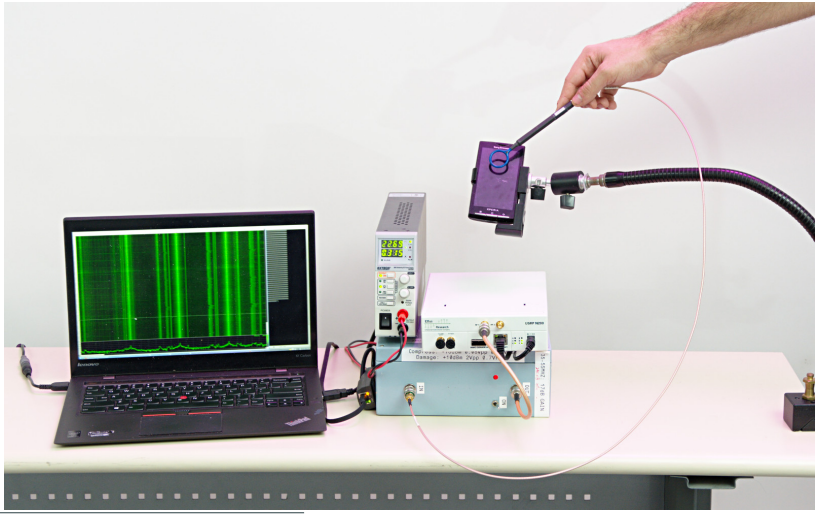

Figure: [GPPTY16] (CCS 2016)

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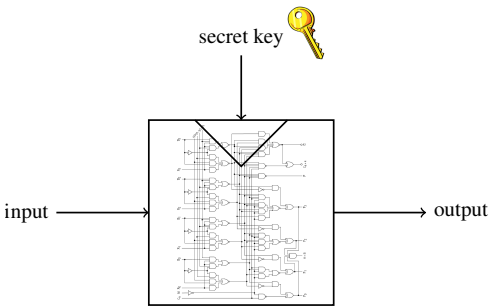

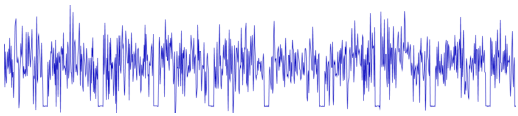

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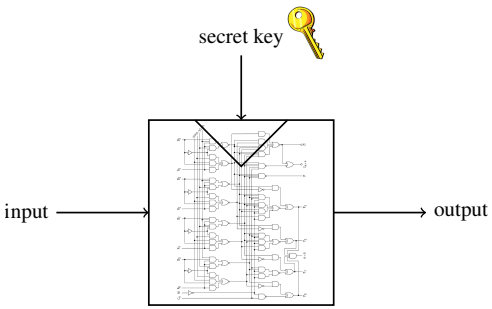

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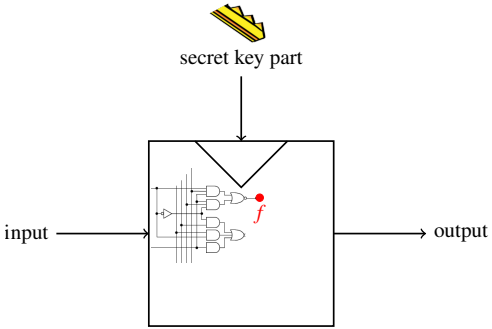

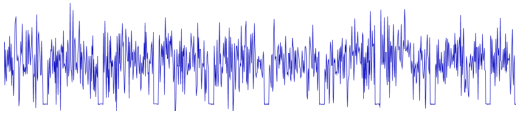

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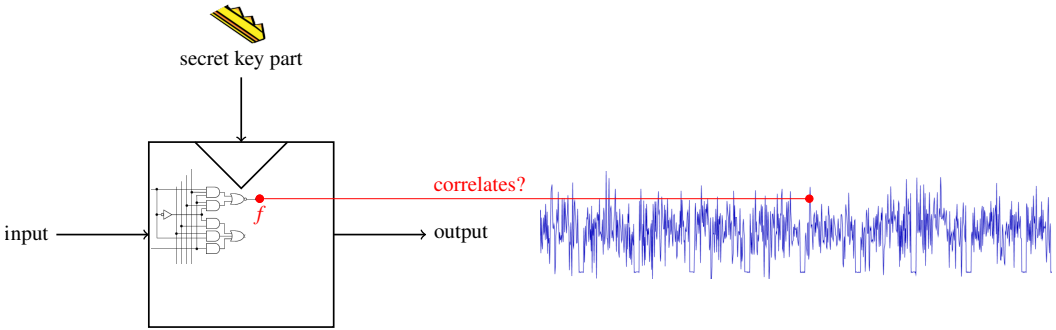

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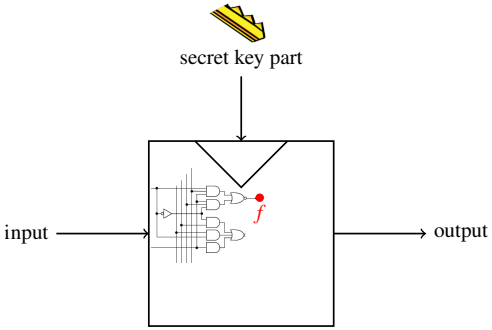
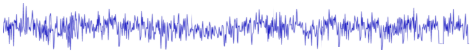


cor(power(t), f)



Wrong key guess

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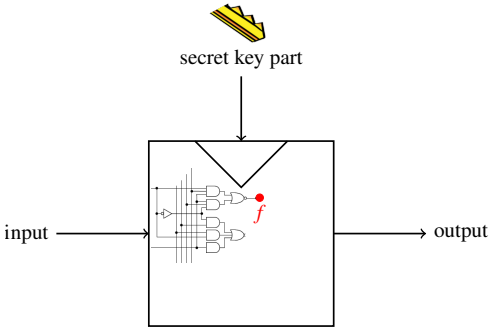

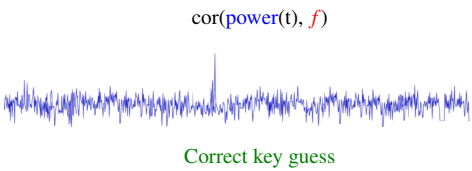

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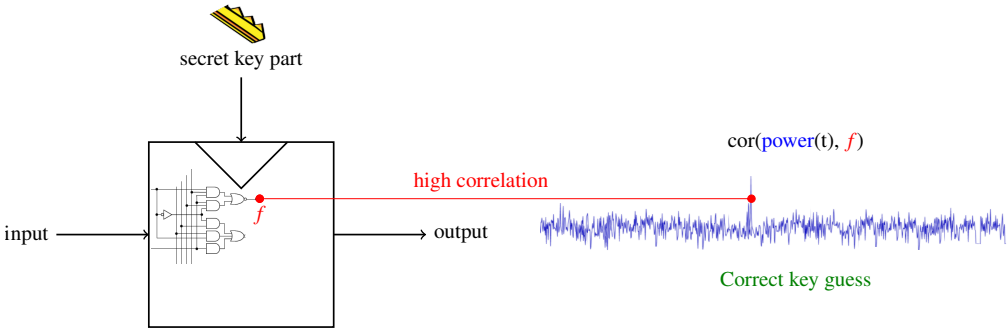

Countermeasure 1 - Linear Masking [ISW03]

- Based on *Secret Sharing*
- Every intermediate value f is represented as

$$f = x_1 + \ldots + x_n$$

- where $x_1, \ldots, x_{n-1}$ are sampled uniformly at random
- Computations on tuples $(x_1, \ldots, x_n)$

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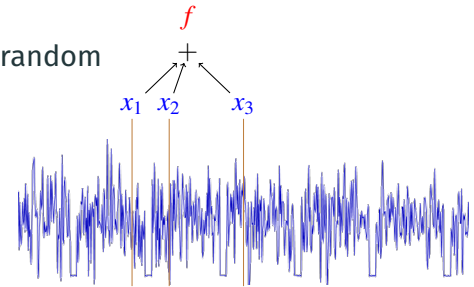


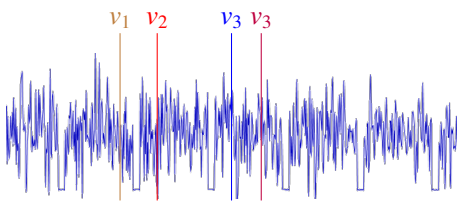
Effect 1: combinatorial explosion in locations

Effect 2: noise amplification

Countermeasure 2 - Shuffling [KocJafJun99; HOM06]

Program:

1. Operation 1
2. Operation 2
3. Operation 3
4. Operation 4



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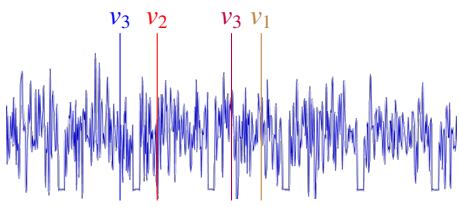

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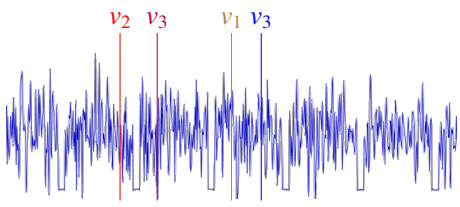

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Program:

1. Dummy operation
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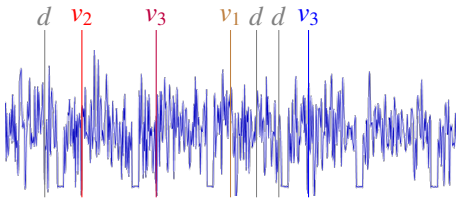
3. Operation 4
4. Operation 1
5. Dummy operation
6. Dummy operation
7. Operation 3



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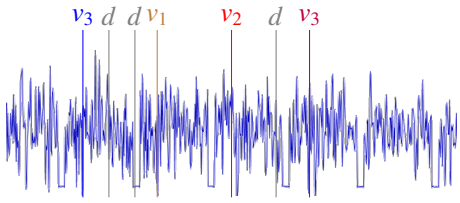

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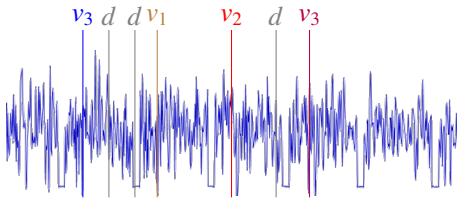

- **Effect:** (small) noise amplification (aid masking)

Algebraic Attack

- DPA breaks "White-box" designs [BHMT16]
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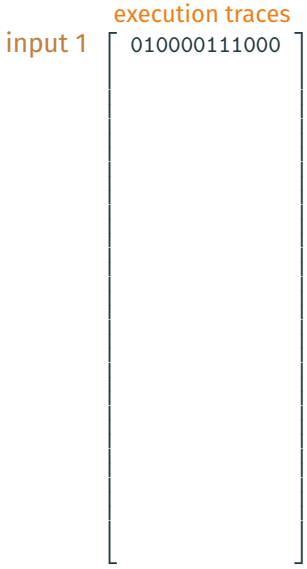
- Linear masking in white-box?
- Problem: no measurement noise!
- Only *locations* of shares $x_1, \ldots, x_n$ are unknown
- Find them using linear algebra [GPRW20; Bir**Udo**18]

Algebraic attack - Illustration



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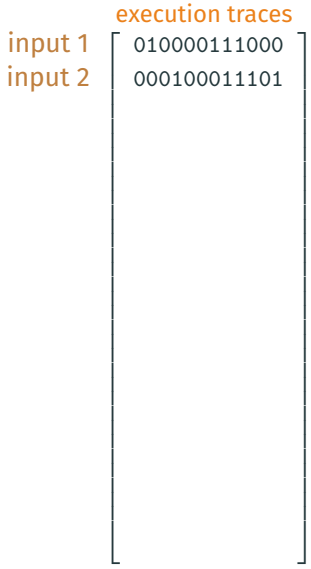

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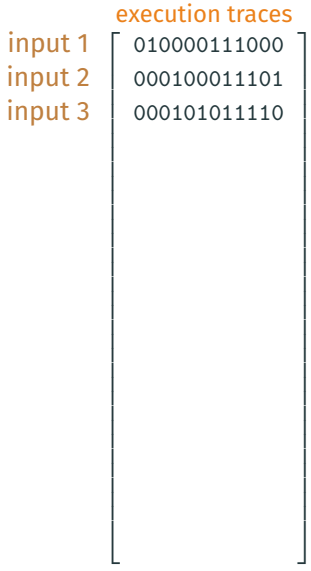
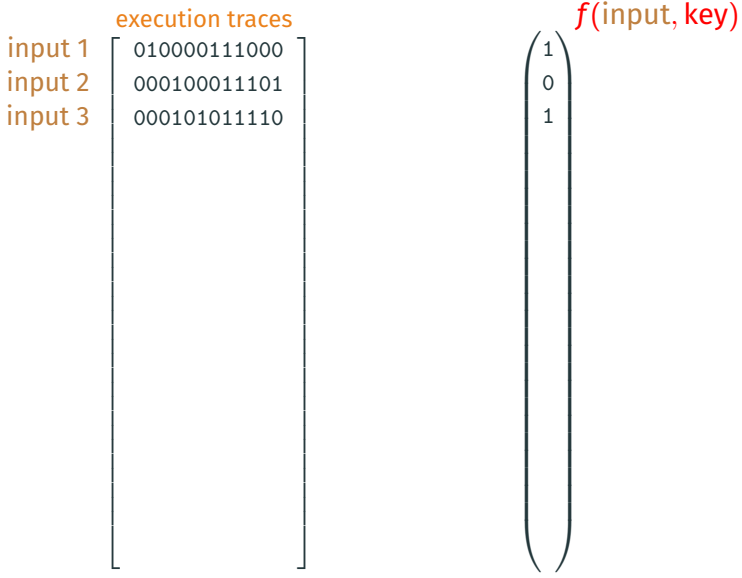


Algebraic attack - Illustration



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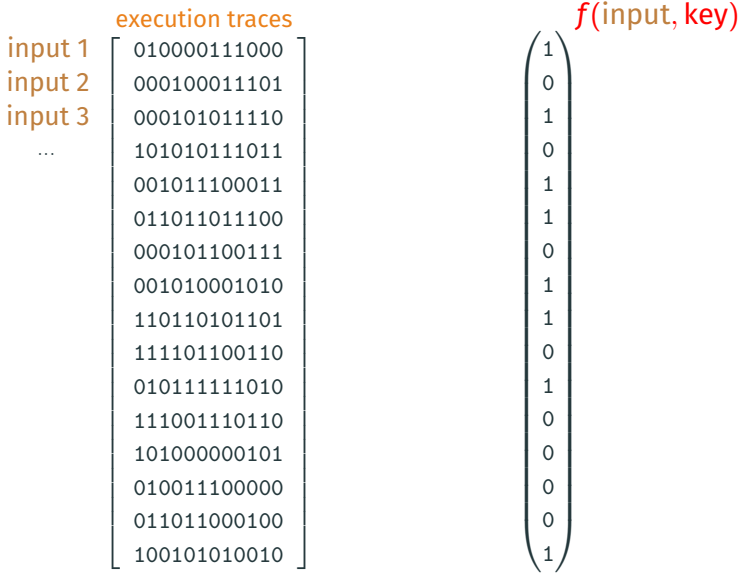

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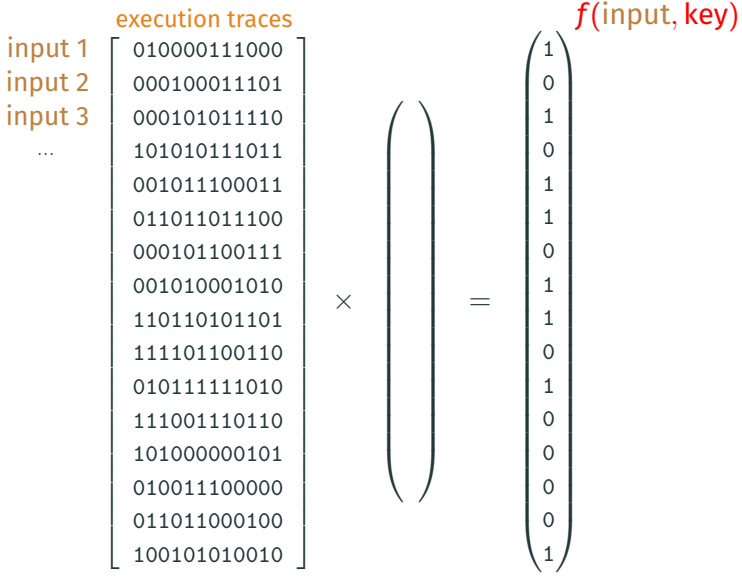

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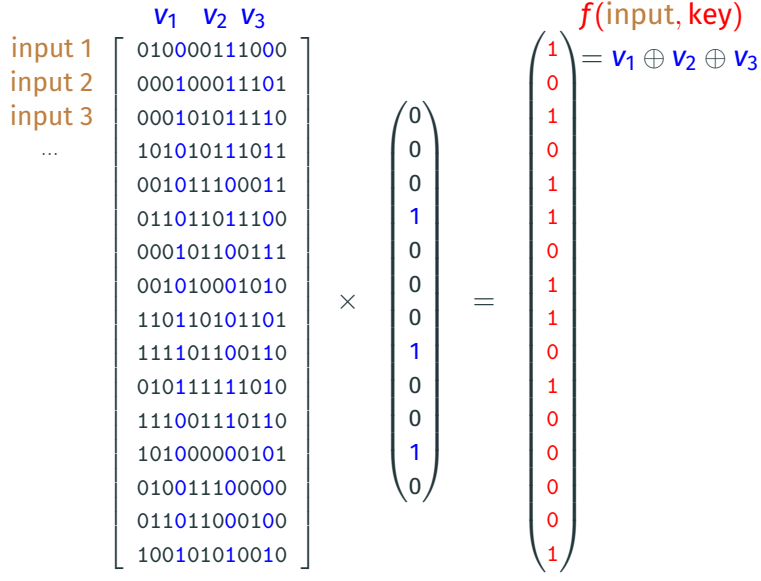

Nonlinear Masking [BirUdo18] (ASIACRYPT 2018)

- First security model against algebraic attacks (gray-box style)
- First nonlinear quadratic scheme:

$$f = ab + c$$

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Algorithm 3 Minimalist Quadratic Masking Scheme.

function Encode(x, r_a, r_b)
  return $(r_a, r_b, r_a r_b \oplus x)$

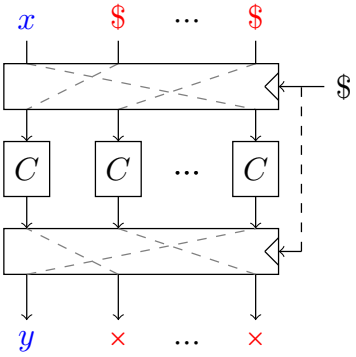
function Decode(a, b, c)
  return $ab \oplus c$

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)

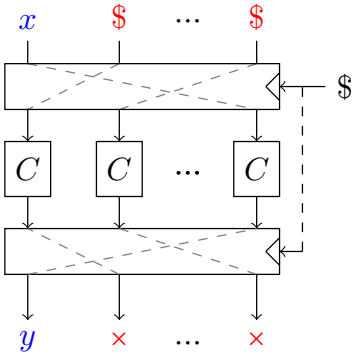
function Refresh$((a, b, c), (r_a, r_b, r_c))$
  $m_a \leftarrow r_a \cdot (b \oplus r_c)$
  $m_b \leftarrow r_b \cdot (a \oplus r_c)$
  $r_c \leftarrow m_a \oplus m_b \oplus (r_a \oplus r_c)(r_b \oplus r_c) \oplus r_c$
  $a \leftarrow a \oplus r_a$
  $b \leftarrow b \oplus r_b$
  $c \leftarrow c \oplus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

Dummy Shuffling [BirUdo21] (EUROCRYPT 2021)



- Extension of basic shuffling
- Dummy slots are essential!

Dummy Shuffling [BirUdo21] (EUROCRYPT 2021)



- Extension of basic shuffling
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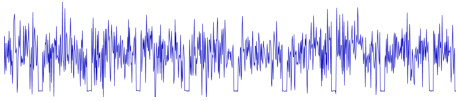
Resulting Protection:

- Very *efficient*
- Any-degree protection
- Provably secure (restricted) (Boolean functions framework)

Summary

1. DPA breaks ad-hoc white-box designs



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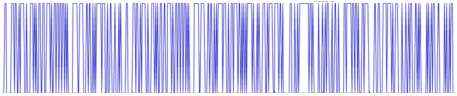

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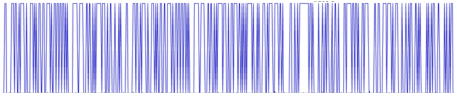

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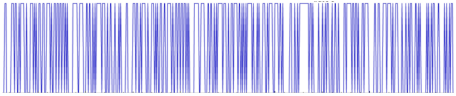

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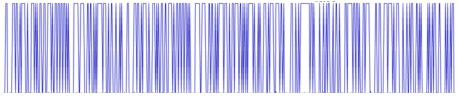

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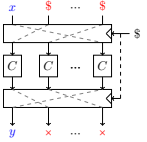
4. Countermeasures: nonlinear masking and dummy shuffling

$$f = ab + c$$



WhibOx competitions 2017, 2019 (white-box AES implementations)

Pseudonym	Identities	Score
cryptolux	Alex Biryukov, Aleksei Udovenko (University of Luxembourg)	406
grothendieck	Leandro Marin (University of Murcia and Philips)	78
sebastien-riou	Sébastien Riou	66

Pseudonym	Identities	Score
cryptolux	Alex Biryukov, Aleksei Udovenko (University of Luxembourg)	3308.28
white_mountain	*anonymous*	728.22
Mugiwara	Stéphane Cauchie	666.08

1. (Ongoing) Evaluation of mixed correlation-algebraic attacks (LPN)

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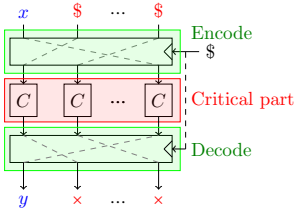

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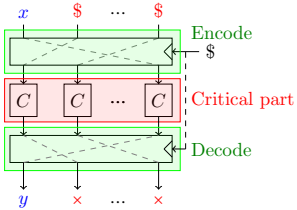

3. New nonlinear masking schemes? (degree ≥ 4 is still an open problem)

$$f = abcd + e?$$

Beyond Algebraic Attacks


Fault countermeasures (white-box specifics)


Pseudo-randomness protection


Combination of countermeasures


Structure-hiding methods

Beyond Algebraic Attacks


Fault countermeasures (white-box specifics)


Pseudo-randomness protection


Combination of countermeasures


Structure-hiding methods

Overall strategy: provably-secure components, *small* steps, scientific approach

Conclusions

White-box cryptography: 20-year-old challenging open problem

Should we try to extend the gray-box model first?

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