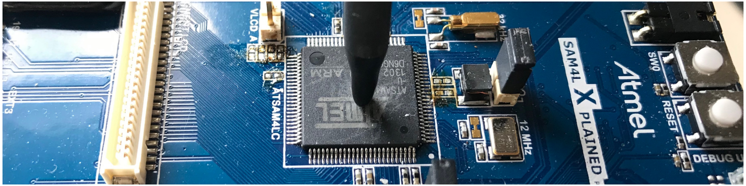


Side-channel Analysis of Cryptographic Implementations

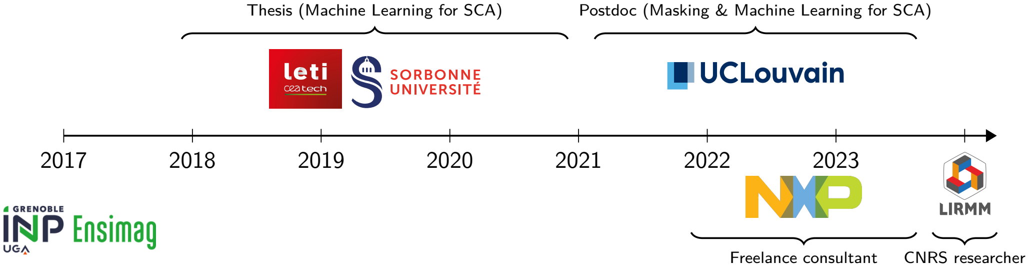
Evaluation & Counter-Measures

Loïc Masure (loic.masure@lirmm.fr)

Forum InCyber, 1 Avril 2025

cnrs LIRMM UNIVERSITÉ DE MONTPELLIER

Who am I?


Thesis (Machine Learning for SCA)
Postdoc (Masking & Machine Learning for SCA)
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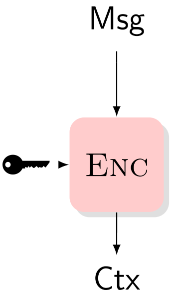
SORBONNE UNIVERSITÉ
UCLouvain
2017
2018
2019
2020
2021
2022
2023
GRENOBLE INP UGA Ensimag
LIRMM
Freelance consultant
CNRS researcher

Agenda

Content

Context : Side-Channel Analysis (SCA)



🔑: N bits ($\frac{N}{n}$ chunks of $n \ll N$ bits)

Black-box cryptanalysis: 2^N

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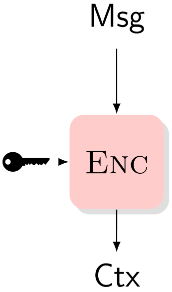
"Cryptographic algorithms don't run on paper,



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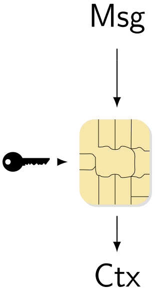

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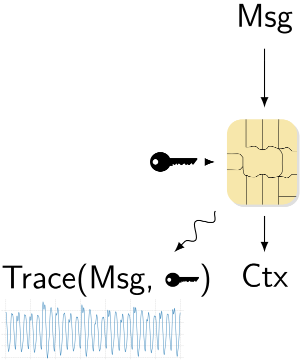

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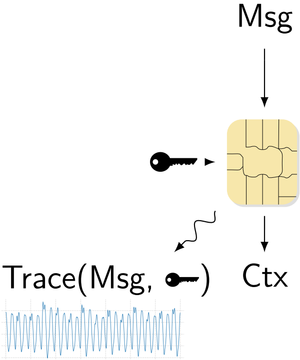

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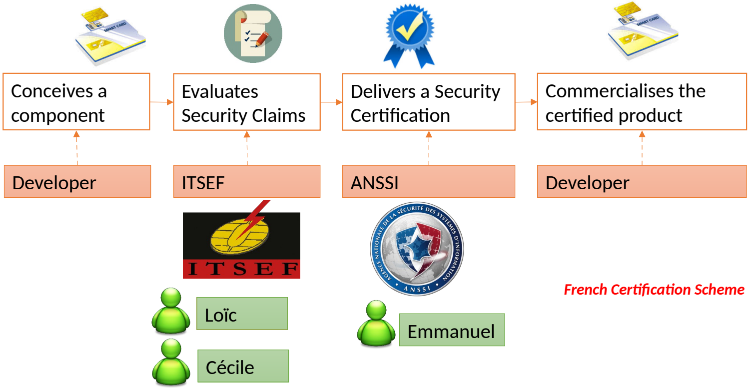
Black-box cryptanalysis: 2^N
Divide-and-conquer: $2^n \cdot \frac{N}{n}$
$\approx$ "quantum" break

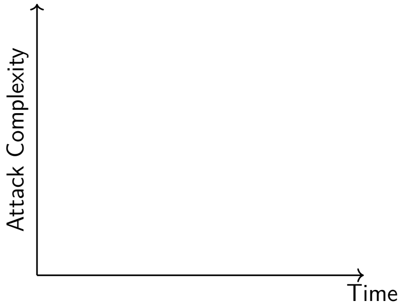
Content

Certification against SCA



Security graded w.r.t. attack complexity in terms of human, material, and financial means

Evaluate Security against Side-Channel Attacks



a

Attack approach (industry):

[a] Shamelessly stolen to O. Bronchain

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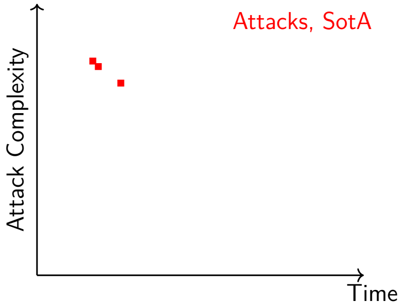

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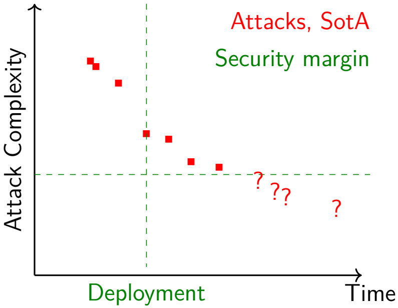

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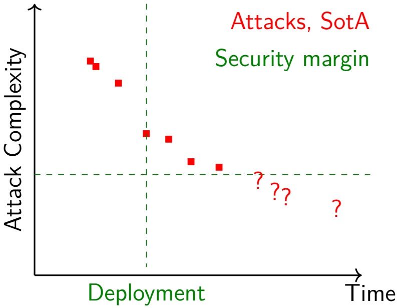

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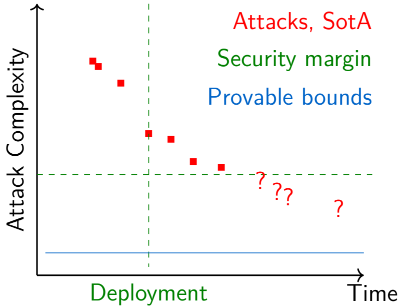

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- Potentially conservative ✗

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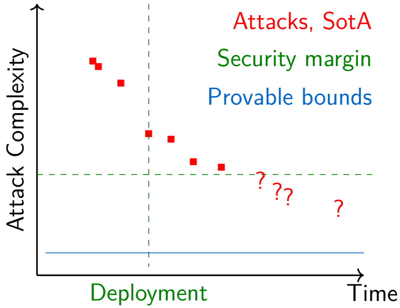

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Today's agenda: evaluation by proofs

Content

How to Evaluate Efficiently?

A good *evaluator* $\mathcal{E} \neq$ A good *adversary* $\mathcal{A}$

Security level:

- Design-dependent ✓

How to Evaluate Efficiently?

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Security level:

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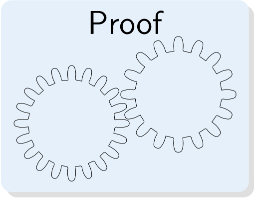
- Device-dependent ✓
- Adversary-dependent ✗

How to deal with this problem space?

Security Proofs



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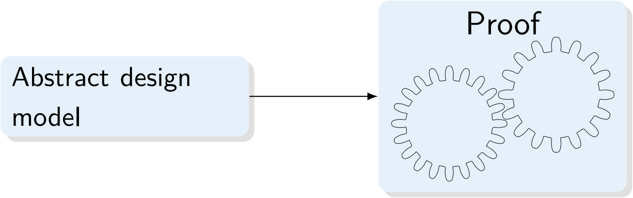
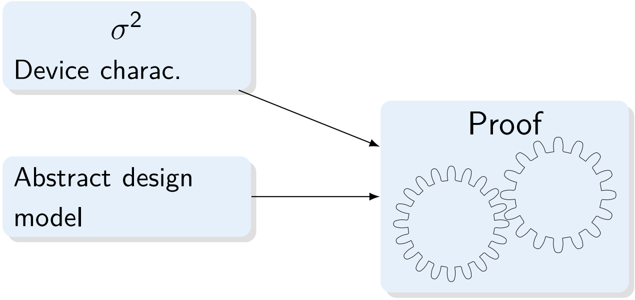


Security Proofs



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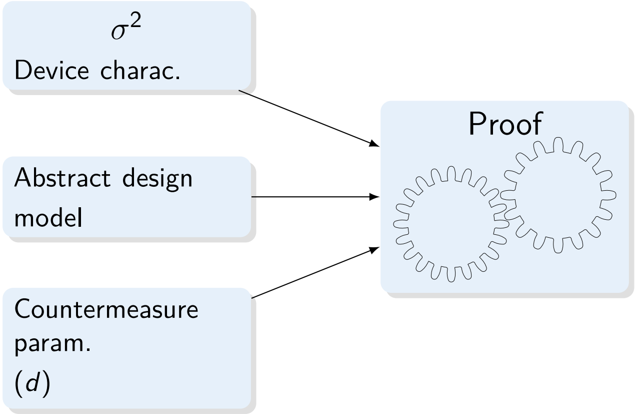

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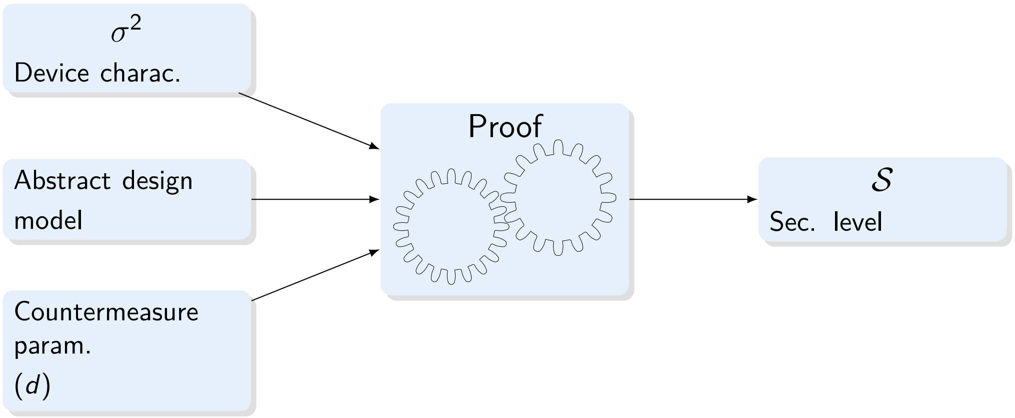

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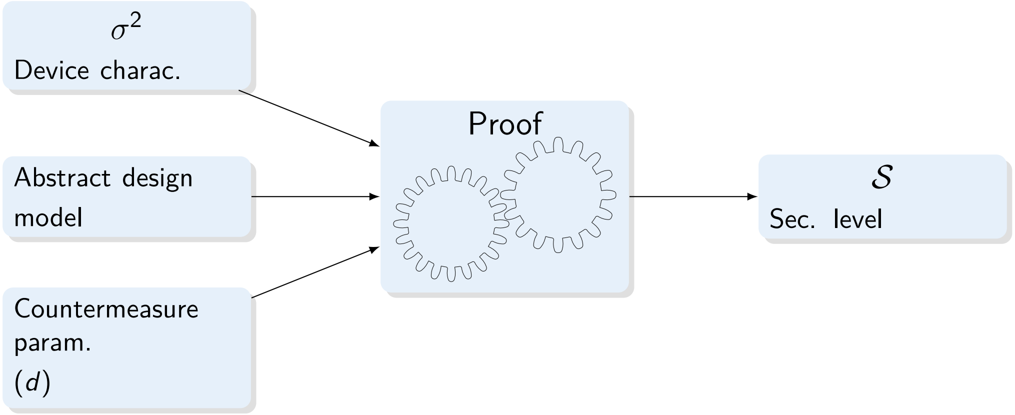

"Any SCA attack requires at least $\mathcal{S}$ queries"

Main Ingredient: Security Reductions

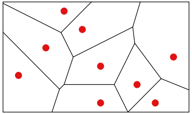

Figure: The set of all possible attacks : (adversary, leakages).

Reduction: "any attack from a given class is less powerful than the red-dot attack of the region".

Main Ingredient: Security Reductions

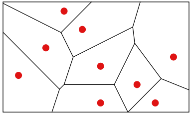

Figure: The set of all possible attacks : (adversary, leakages).

Reduction: "any attack from a given class is less powerful than the red-dot attack of the region".

Data-processing inequality & Simulatability: If two attacks $\mathcal{A}, \mathcal{B}$ are such that $\mathcal{A} = \mathcal{S}(\mathcal{B})$, then $\mathit{Success}(\mathcal{A}) \leq \mathit{Success}(\mathcal{B})$. Hence,

$$\max_{\mathcal{A} \in \mathcal{A}} \mathit{Success}(\mathcal{A}) \leq \max_{\mathcal{B} \in \mathcal{S}(\mathcal{A})} \mathit{Success}(\mathcal{B}).$$

Content

Masking: what is that ?

Masking, a.k.a. *MPC on silicon*:[12] secret sharing over a finite field $(\mathbb{F}, \oplus, \otimes)$

$$\mathrm{Y}(\text{secret})$$

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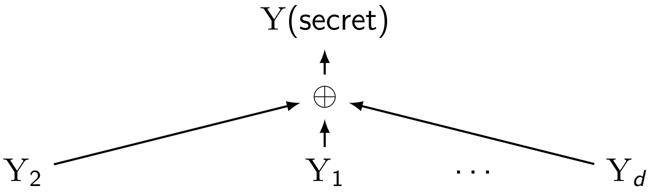
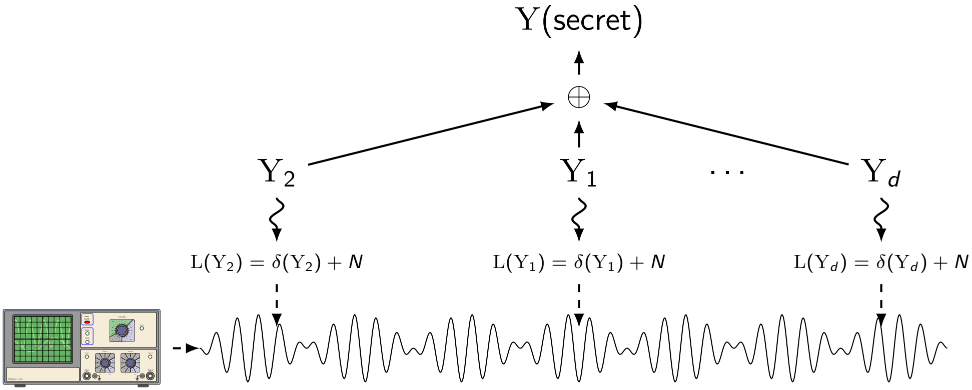


Masking: what is that ?

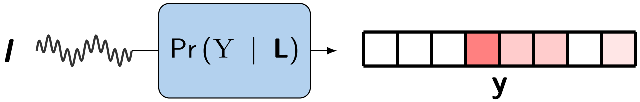
Masking, a.k.a. *MPC on silicon*:[1,2] secret sharing over a finite field $(\mathbb{F}, \oplus, \otimes)$



[1] Chari et al., "Towards Sound Approaches to Counteract Power-Analysis Attacks".
[2] Goubin and Patarin, "DES and Differential Power Analysis (The "Duplication" Method)".

The Noisy Leakage Model

In this model, for each intermediate computation, the adversary gets a probability distribution about its operands:



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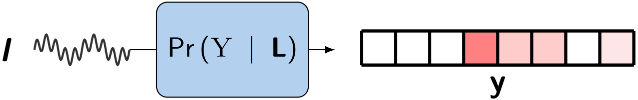
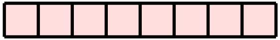


If, the adversary gets:



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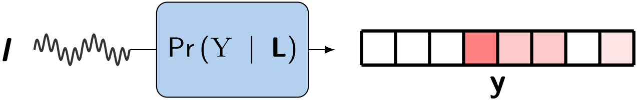

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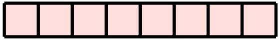
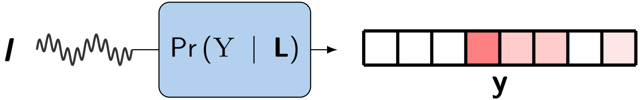


Very noisy
Sensitive computation unpredictable

The Noisy Leakage Model

In this model, for each intermediate computation, the adversary gets a probability distribution about its operands:



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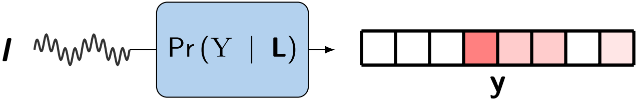


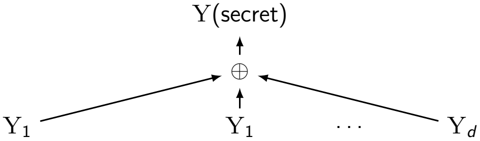
If, the adversary gets:

Low-noise
Exact prediction of the sensitive computation

The Effect of Masking

Y(secret)

The Effect of Masking



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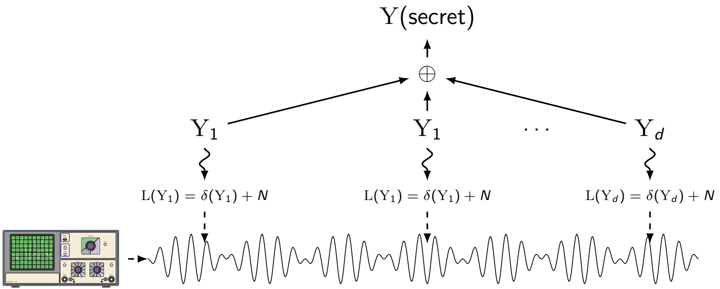

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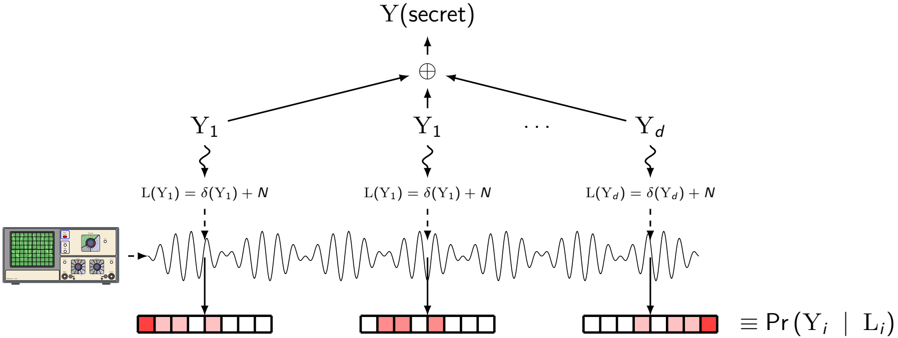

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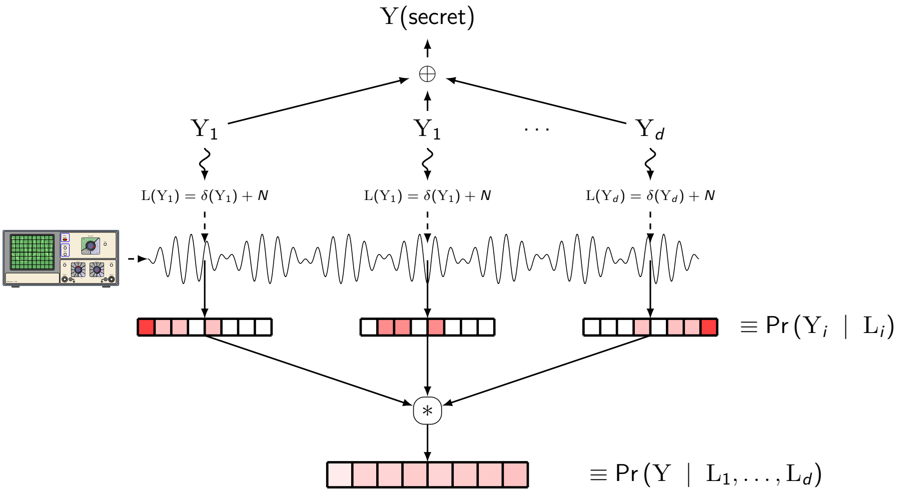

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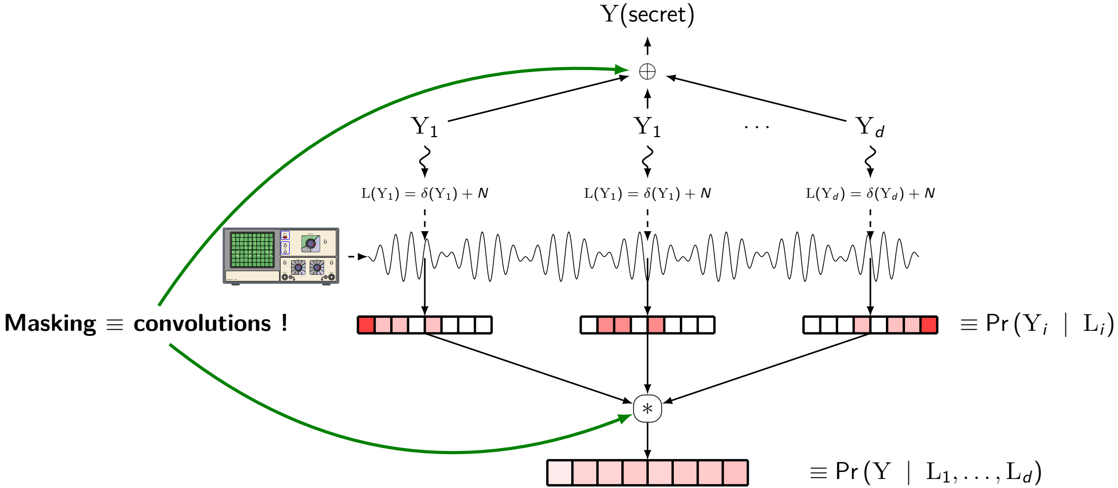


Convolution = Noise Amplification

Simulation, for $\mathbb{F}_{2^n}$: $L(Y_i) = hw(Y_i) + \mathcal{N}(0; \sigma^2)$, hw = Hamming weight

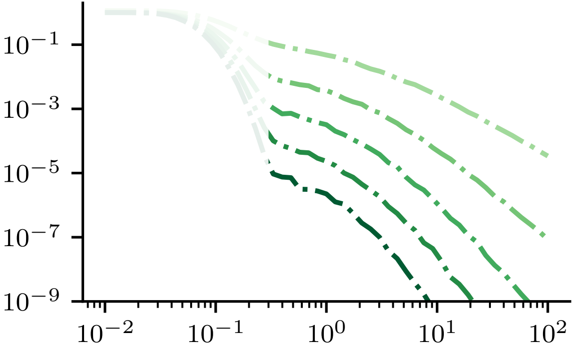
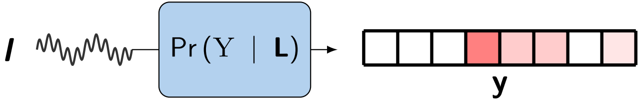


Figure: $\mathrm{MI}\left(\mathrm{Y}; \mathbf{L}\right)$ vs. σ^2, $2 \leq d \leq 6$

Content

Recall on Noisy Leakage Model



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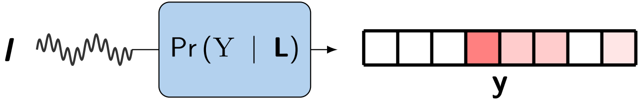

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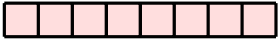

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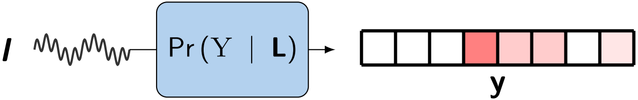

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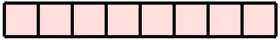
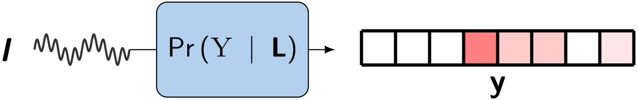


Very noisy leakage
Y indistinguishable from blind guess

Recall on Noisy Leakage Model



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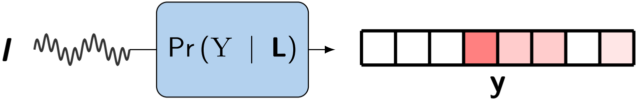

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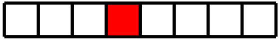
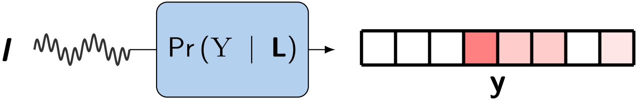


Low-noise leakage

Exact prediction for Y

Recall on Noisy Leakage Model



δ-noisy adversary

Any intermediate computation Y leaks $\mathrm{L}(\mathrm{Y})$ such that:

$$\mathsf{SD}(\mathrm{Y};\mathrm{L}) = \mathop{\mathbb{E}}_{\mathrm{L}}\left[TV\left(\underbrace{\cdots}_{\Pr(\mathrm{Y} \mid \mathrm{L})}, \underbrace{\cdots}_{\Pr(\mathrm{Y})} \right) \right] \leq \delta$$

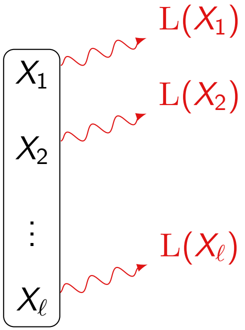
Security Proof for a Circuit

Consider a circuit with ℓ intermediate computations:

$$\begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_\ell \end{pmatrix}$$

Security Proof for a Circuit

Consider a circuit with ℓ δ-noisy intermediate computations:



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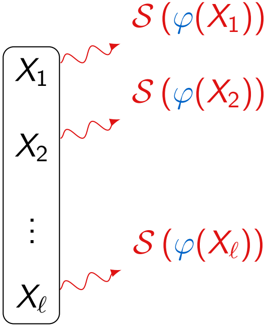


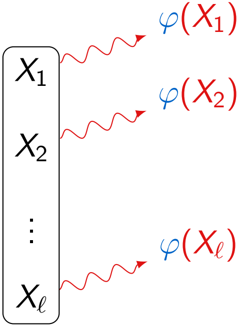
LEMMA (SIMULATABILITY)

The leakage function L *can be simulated from a random probing adversary:* $\varphi(x)$ *exactly reveals* x *with probability* $\epsilon = 1 - \sum_l \min_x \Pr(\mathrm{L}(x) = l) \leq \delta \cdot |\mathbb{F}|$.[a]

[a] Duc, Dziembowski, and Faust, "Unifying Leakage Models: From Probing Attacks to Noisy Leakage".

Security Proof for a Circuit

Consider a circuit with ℓ δ-noisy intermediate computations:



We may reduce to an adversary observing $\varphi(X)$ instead of $\mathcal{S}(\varphi(X))$ (Data Processing Inequality)

Security against a Random Probing Adversary

To succeed, at least d out of ℓ wires must be revealed to the adversary:

$$\Pr(\text{Adv. learns sth}) \leq \Pr(\text{At least } d \text{ wires revealed})$$

[3]Boucheron, Lugosi, and Massart, *Concentration Inequalities: A Nonasymptotic Theory of Independence*, P.24, and Ex. 2.11.

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THEOREM (CHERNOFF CONCENTRATION INEQUALITY[3])

If ℓ wires, each independently revealed with proba. ϵ:

$$\Pr(\textit{At least } d \textit{ wires revealed}) \leq \left(\frac{e \cdot \ell \cdot \epsilon}{d}\right)^d$$

[3] Boucheron, Lugosi, and Massart, *Concentration Inequalities: A Nonasymptotic Theory of Independence*, P.24, and Ex. 2.11.

Putting all Together

In our context, $\ell \leq \mathcal{O}\left(d^2\right)$, and $\epsilon \leq \delta \cdot |\mathbb{F}|$:

Theorem (Security Bound)

For a single computation with $\ell \leq \mathcal{O}\left(d^2\right)$ gates:

$$\mathsf{SD}(k; \mathbf{L}) \leq (\mathcal{O}(d) \cdot \delta \cdot |\mathbb{F}|)^d$$

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For the whole circuit $\mathbb{C}$, (work in progress),

$$\mathsf{SD}\left(k; \mathbf{L}\right) \leq \left(\mathcal{O}\left(|\mathbb{C}| d\right) \cdot \delta \cdot |\mathbb{F}|\right)^d$$

Putting all Together

In our context, $\ell \leq \mathcal{O}\left(d^2\right)$, and $\epsilon \leq \delta \cdot |\mathbb{F}|$:

Theorem (Security Bound)

For a single computation with $\ell \leq \mathcal{O}\left(d^2\right)$ gates:

$$\mathsf{SD}\left(k; \mathbf{L}\right) \leq \left(\mathcal{O}\left(d\right) \cdot \delta \cdot |\mathbb{F}|\right)^d$$

For the whole circuit $\mathbb{C}$, (work in progress),

$$\mathsf{SD}\left(k; \mathbf{L}\right) \leq |\mathbb{C}| \left(\mathcal{O}\left(d\right) \cdot \delta \cdot |\mathbb{F}|\right)^d$$

Wrap-Up of the Proof

δ-NL

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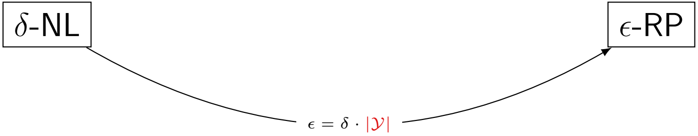
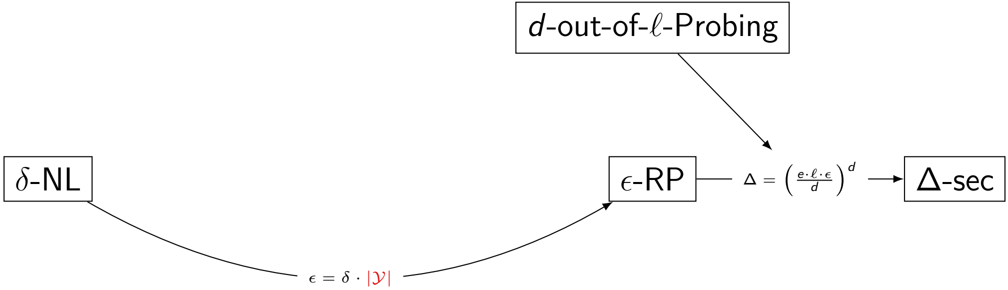


Wrap-Up of the Proof



[4] Brian, Dziembowski, and Faust, "From Random Probing to Noisy Leakages Without Field-Size Dependence".

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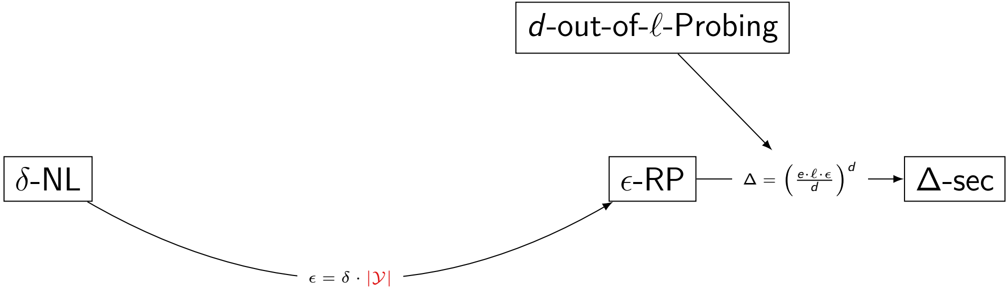
Bad *leakage rate* $\approx d \cdot |\mathbb{F}|$ ✗...



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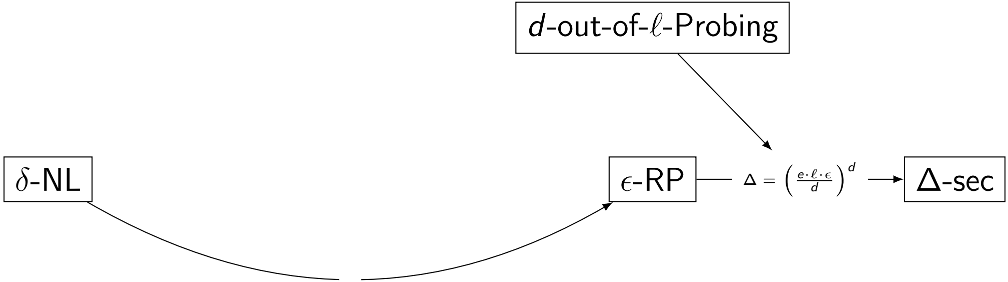
Wrap-Up of the Proof

Bad *leakage rate* $\approx d \cdot |\mathbb{F}|$ ✗... but new perspectives[4] ✓



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Perspectives

- Improving the reduction from Noisy Leakages to Random Probing

[5] Belaïd, Rivain, and Taleb, "On the Power of Expansion: More Efficient Constructions in the Random Probing Model".

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    $\implies$ wider gap between d-probing and ϵ-RP ✗
  - ⋆ Masking-friendly schemes, *e.g.*, Raccoon ? ✓

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