Introduction to physical attacks against embedded devices

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Safety VS Security

Safety

protects against unintentional accidents as:

- human mistake,
- perturbations,
- failures.

Security

protects against malicious behaviour as:

- spy,
- tampering,
- destruction,
- usurpation (identity fraud).

Cryptology

The **cryptology** (science of secrets) regroups the **cryptography** and the **cryptanalysis**.

Modern cryptography:

- **confidentiality**: limits data access to authorized persons;
- **integrity**: ensures that the information cannot be altered;
- **authentication**: validates the origin of some data;
- **non-repudiation**: allows a person to take part in a contract without the possibility to denounce it later.

AES and Galois field $\mathbb{F}_{2^8}$

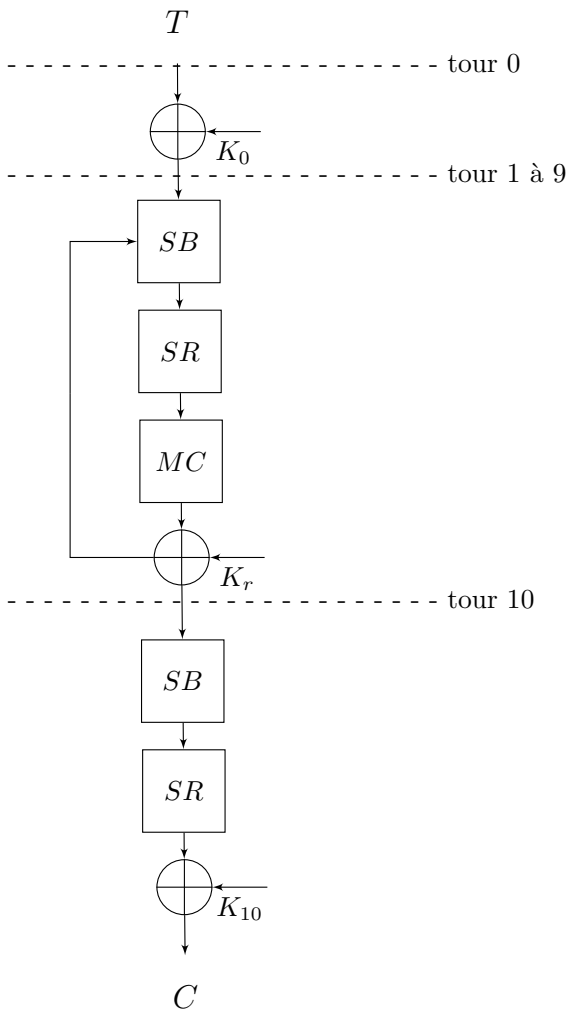
- AES(Advanced Encryption Standard).
- AES is the current block cipher standard.
- The AES work on the Galois field $\mathbb{F}_{2^8}$ with:

$$P(X) = X^8 + X^4 + X^3 + X + 1.$$

as irreducible polynomial .
The intern laws are: $\oplus$ and $\otimes$

AES [1]

- Mapping the plaintext M of 128 bits into an array of $4 \cdot 4 = 16$ bytes, called the State.
- Exists in different key size versions: 128, 192 or 256 bits.
- Substitution Permutation Network.
- The round function is composed of:
  - SubBytes: non-linear transformations, working independently on individual bytes of the State.
  - ShiftRows: a byte-shifting operation on each row of the State.
  - MixColumns: a linear matrix multiplication on $GF(2^8)$, applied on each column.
  - AddRoundKey: $\oplus$ a xor with the round-key.



SubBytes AES

$$SB(68) = 45$$

x \ y	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	63	7c	77	7b	f2	6b	6f	c5	30	01	67	2b	fe	d7	ab	76
1	ca	82	c9	7d	fa	59	47	f0	ad	d4	a2	af	9c	a4	72	c0
2	b7	fd	93	26	36	3f	f7	cc	34	a5	e5	f1	71	d8	31	15
3	04	c7	23	c3	18	96	05	9a	07	12	80	e2	eb	27	b2	75
4	09	83	2c	1a	1b	6e	5a	a0	52	3b	d6	b3	29	e3	2f	84
5	53	d1	00	ed	20	fc	b1	5b	6a	cb	be	39	4a	4c	58	cf
6	d0	ef	aa	fb	43	4d	33	85	45	f9	02	7f	50	3c	9f	a8
7	51	a3	40	8f	92	9d	38	f5	bc	b6	da	21	10	ff	f3	d2
8	cd	0c	13	ec	5f	97	44	17	c4	a7	7e	3d	64	5d	19	73
9	60	81	4f	dc	22	2a	90	88	46	ee	b8	14	de	5e	0b	db
a	e0	32	3a	0a	49	06	24	5c	c2	d3	ac	62	91	95	e4	79
b	e7	c8	37	6d	8d	d5	4e	a9	6c	56	f4	ea	65	7a	ae	08
c	ba	78	25	2e	1c	a6	b4	c6	e8	dd	74	1f	4b	bd	8b	8a
d	70	3e	b5	66	48	03	f6	0e	61	35	57	b9	86	c1	1d	9e
e	e1	f8	98	11	69	d9	8e	94	9b	1e	87	e9	ce	55	28	df
f	8c	a1	89	0d	bf	e6	42	68	41	99	2d	0f	b0	54	bb	16

illustration : http://freestudy9.com/aes-transformation-function/

MixColumns AES

- The **MixColumn** is a linear transformation in $GF(2^8)$ to the column of the state.
- $\otimes$ between a column vector of the state and a matrix.

$$\begin{pmatrix} 2 & 3 & 1 & 1 \\ 1 & 2 & 3 & 1 \\ 1 & 1 & 2 & 3 \\ 3 & 1 & 1 & 2 \end{pmatrix}$$

Figure: Matrix of **MixColumn** *MC*

$$1 \otimes a = a \quad .$$

$$2 \otimes a = \begin{cases} 2 \cdot a, & \text{if } a < 80. \\ FF\&((2 \cdot a) \oplus 1B), & \text{else.} \end{cases}$$

$$3 \otimes a = 2 \otimes a \oplus a \quad .$$

AES: Key generation

- The **master key** K is the round key 0, K_0.
- K_{r+1} is computed with the previous round key K_r,
- according the function **KeyExpansion** :

$$\begin{cases} K_{r+1}^{l,0} = SB\left(K_r^{(l+1) \bmod 4,3}\right) \oplus rcon(l,r) \oplus K_r^{l,0} & \forall l \in [\![0,3]\!] \\ K_{r+1}^{l,c} = K_r^{l,c} \oplus K_{r+1}^{l,c-1} & \forall l \in [\![0,3]\!] \text{ and } c \in [\![1,3]\!] \end{cases} \quad (1)$$

with SB the SubBytes function and $rcon$ a constant matrix of size 4×10.

A good link to summarize :
https://www.youtube.com/watch?v=H2LlHOw_ANg

Enigme

illustration: Pixabay

Different abstraction levels

1. Algorithm: the theory.
2. Programming language (C, java, python, etc.).
3. Architecture and micro-architecture.
4. Logic device.
5. Transistors.

Physical attacks are at level: logic device / transistors.

illustration: pixabay

Physical attacks

- Even if an encryption algorithm is proved secure mathematically, its implementation can open the gate to physical attacks.
- They exploit the fact that some physical states of a device depend on intermediate values of the computation.
- Two families two main types of physical attach
  1. **side channel analysis** (SCA)
  2. **fault injections attacks** (FIA)

Targets

the main target of physical attacks are small devices because of the below features

- small devices
- embedded device
- IoT
- physical access

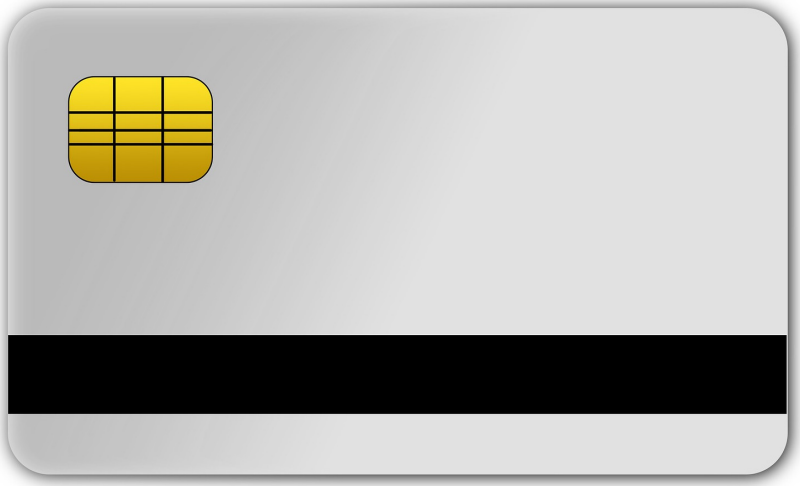
Embedded device features of embedded devices

1. specific function, Process limitation
2. space constraints, memory limitation
3. energy constraints. Battery limitation

Targets

Example: smart card

1. years 70-80.
2. dads: Kunitaka Arimura, Roland Moreno, Helmut Gröttrup and Jürgen Dethloff



Smart carts is a great target for physical attacks

illustration: Pixabay

Use cases

we attack the physical device to find passwords, pins, … in order to …

Find secret

- Cryptanalysis.
- Find a code PIN.

In order to

- steal personnal data,
- control a system,
- misuse identity
- privilege elevation ...

Use cases

It's a use case of physical attacks

Reverse engineering

The activity of studying an device to determine its inner workings.

- industrial spy.

Leakage analysis

Someone put something hidden somewhere

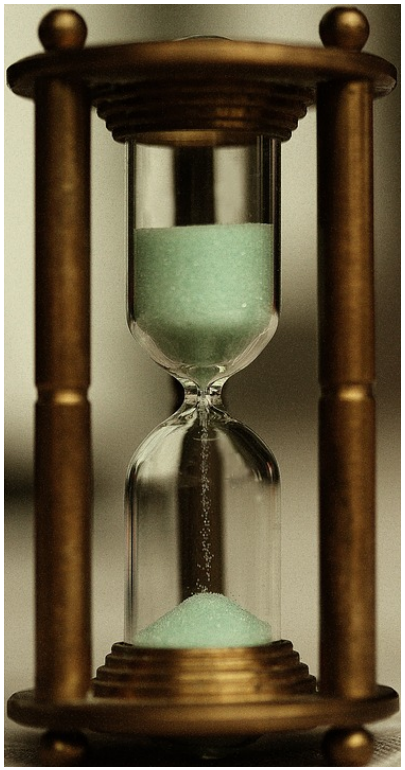
- SCA exploit the fact that some physical states of a device depend on intermediate values of the computation, called leakage.

Examples of physical leakage

- Timing [2]. more calculation needs more time
- Temperature [3].
- Power consumption [4].
- Electromagnetic radiations [5].
- Photons emission [6].

Timing

the first attack was a timing attack using Timing



Time as a leakage

- First leakage exploited.
- **Idea**: measure the execution time.
- Example: during a conditional branching.
- Exmaple of target: PIN code comparison.

illustrations: Pixabay

Code PIN

Code is for auth with crypto (with signature)

authentication

combines 2 of the 3 elements

- something we have, smart card
- something we know, the code pin
- something we are. the biometry

code PIN (Personnal Identifiant Number)

- confidential code
- to authenticate user of a smart card.
- smart card = login (we have)
- code PIN = password (we know)

Exercise

1. How many 4-digit PIN codes are there? 10^4 = 10000
2. If we test digit by digit, how many possibilities are there? 4*10 = 40
3. Find the weakness of this code PIN comparison algorithm.

pin.c

```
1 bool compare_arrays(const uint8_t* a, const uint8_t*
  ↪  b, size_t len) {
2     for(size_t i = 0; i < len; i++) {
3         if (a[i] != b[i]) {
4             return false;
5         }
6     }
7     return true;
8 }
```

4. Suggest a new version.

Correction

- How many 4-digit PIN codes are there?
  10^4

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  The comparison is not in constant time.
- Suggest a new version.

Correction

Fake good idea

pin.c

```
1  bool compare_arrays(const uint8_t* a, const uint8_t* b,
   ↪  size_t len) {
2      uint8_t result = true;
3      uint8_t  fake = true;
4      for(size_t i = 0; i < len; i++) {
5          if(a[i] != b[i]){
6              result = false;
7          }
8          else {
9              fake = false;
10         }
11     }
12     return result;
13 }
```

Correction

Correction for the exercise.

pin.c

```
1 bool compare_arrays(const uint8_t* a, const uint8_t* b,
  ↪  size_t len) {
2     uint8_t result = 0;
3     for(size_t i = 0; i < len; i++) {
4         result |= a[i] ^ b[i];
5     }
6     return result == 0;
7 }
```

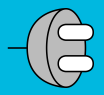
we can also write this line as:
result = a[i] = b[j]

Correction

Real good correction

pin.c

```
1  bool compare_arrays(const uint8_t* a, const uint8_t* b,
   ↪  size_t len) {
2      uint8_t encoded_candidate[HMAC_SHA256_DIGEST_SIZE];
3      hmac_sha256(encoded_candidate, a, len, secret_key,
   ↪  KEY_LEN);
4
5      uint8_t result = 0;
6      for(size_t i = 0; i < HMAC_SHA256_DIGEST_SIZE; i++) {
7          result |= encoded_candidate[i] ^ b[i];
8      }
9      return result == 0;
10 }
```

Power consumption 

That's what we do in March

Principe

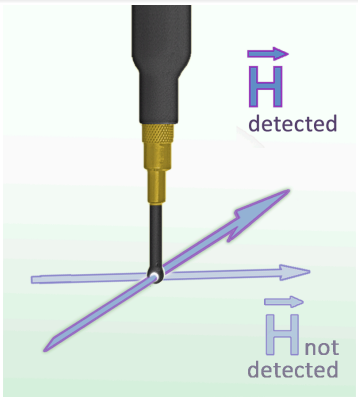
- Connection on the device.
- An integrated device is made up of a set of logic gates.
- The instantaneous device power consumption is the sum of the power consumptions of each of its logic gates.
- Possibility to distinguish a transition from 0 to 1 from a transition from 1 to 0.

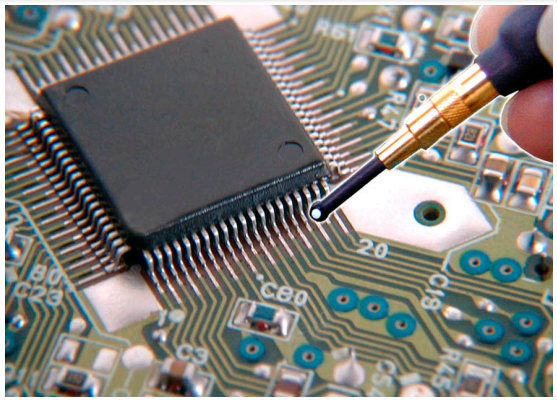
I can use a voltmeter to measure the electro magnetics

Electromagnetic radiations

Principe

- The variation of the power consumption is accompanied by a variation of the magnetic field.
- An EM probe is used for the measurements.
- Advantage: the device cannot detect that it is being observed.
- Weakness: less precise measurements.





illustrations: Langer EMV Tecknik `https://www.langer-emv.com/en/index`

Electromagnetic radiations

EMA, side channel bench of laboratory high security (LHS) d'INRIA Rennes.

Simple power analysis (SPA) [7, 8]

Idea

determine directly, from an observation of the power consumption, during a normal execution of an algorithm, information on the calculation performed or the data manipulated.

Example: Algorithm Square and Multiply

$$x^e \mod n$$

```
1:  procedure SQUARE AND MULTIPLY(x,e,n)
2:      r = 1
3:      b = (e)_2
4:      for i bit de poids fort au bit de poids faible do
5:          if b[i] = 1 then
6:              r = r^2 · x mod n
7:          else
8:              r = r^2 mod n
9:          end if
10:     end for
11:     return r
12: end procedure
```

Example: Algorithm Square and Multiply

long is for square
short is for mulitpication

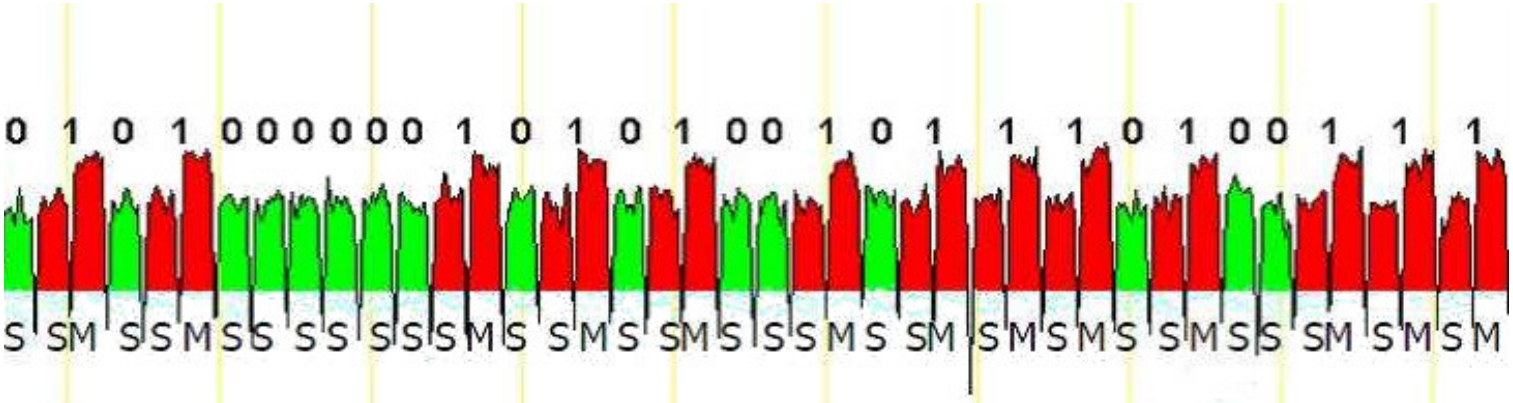


illustration from Cryptography Research, Inc.

Attacks by characterization or template attacks [9]

Advantages and weakness

- Most effective attacks.
- Need a device of the target

profiling or learning phase,

you need 2 devices one for attacking one for computation

- Characterization of the profiling device.
- The attacker can choose and change secrets.
- Learning significant leakage and noise characteristics.

attack or inference phase

- Get traces on the targeted device
- Confront the target traces with profiling traces.

Étape 1: Campaign, the target

what is the target? the secret key of an AES
but first round key

- Starting to define precisely the target $\mathcal{K} = \hat{k}$.
- Example: first round key of AES.
- **Divide and conquer**.
  Split the target in small pieces.
  Idea: make guess on the different part of the secret.
- Example: one **byte** AES round key (256 possible values).

we attack byte by byte

illustration: pixabay

Step 1: Campaign, the observables

Acquisitions de données et mesures

- A **campaign** collects data and measurements, called **observables**
- Examples:power consumption, cipher text, ...

illustration: pixabay

Step 1: Campaign, attack path

- The **attack path** $\mathcal{R}$ is a relation between observables (O_S, O_R) and the target $\mathcal{K} = \hat{k}$.
  $\mathcal{R}(\hat{k}, O_S) = O_R$
  It is composed by:
  - algorithm functions,
  - **physical function(s)**.

Physical function

- It represent a physical behaviour.
- It doesn't has a mathematical expression.
- It is called**leakage function** in SCA.

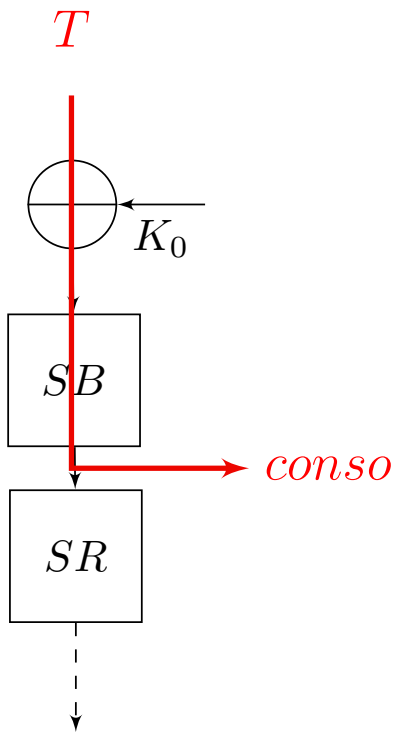
In my attack path I have my secret with my function of algo and phy func

Example (see in TP)

Example on AES: The correlation power analysis (CPA) [10])

- $\mathcal{K} = K_0^{l,c}$, a byte of the first round AES key.
- $O_S = T$, plain text
- $O_R = pow$, power consumption
- $\mathcal{R}(T, K) = f(SB(T \oplus K_0)) = pow$;
- with f the leakage function power consumption.

this is the physical function



Step 2: Predictions, model

Definition

A **model** is a mathematical function allowing to approach a physical function.

Examples

- *HW*, Hamming weight
- *HD*, Hamming distance

Step 2: Predictions, guesses

Theoretical attack path

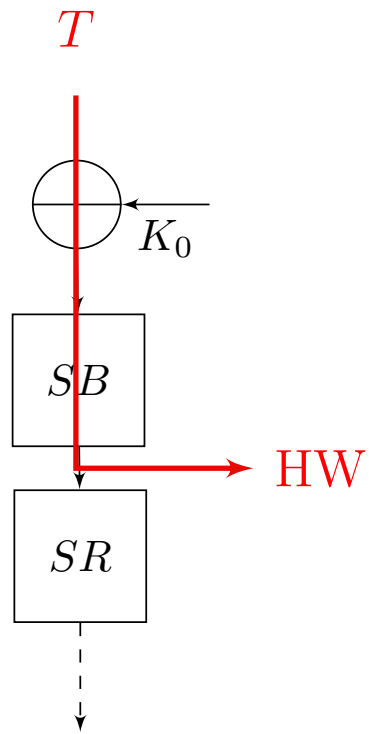
- The second step consist in build **predictions**.
- Choosing one or sevralmodels m to replace the physical function(s) in the attack path.
- The new relation is the theoretical attack path.
- With a divide and conquer approach, it is possible to compute a prediction $P_{m,k}$
  - for each guess k,
  - and each observable O_S,
- $\mathcal{R}_m(k, O_s) = P_{m,k}$.

Example (see in TP)

Example on AES: The correlation power analysis (CPA) [10])

- Hamming weight replaces the physical function f.
- For each first round AES key byte:

$$\begin{aligned} \mathcal{R}_m(k, O_s) &= \mathcal{R}_{HW}(k, T) \\ &= HW(SB(T \oplus k)) \\ &= P_{HW,k} \quad . \end{aligned}$$



Step 3: Confrontation

distinguisher

- To confront the prediction $P_{m,k}$ with observables O_R, a statistic tool is used **distinguisher**;
- It brings out one guess k_d.
- If $\hat{k} = k_d \Rightarrow$, the attack is a success.
- The distinguisher

Examples of distinguisher

sieve [11], counter [12], difference of mean [13], correlation [10], entropy [14], mutual information [15], principal component [16],linear discriminant [17]...

Example (see in TP)

Pearson Correlation

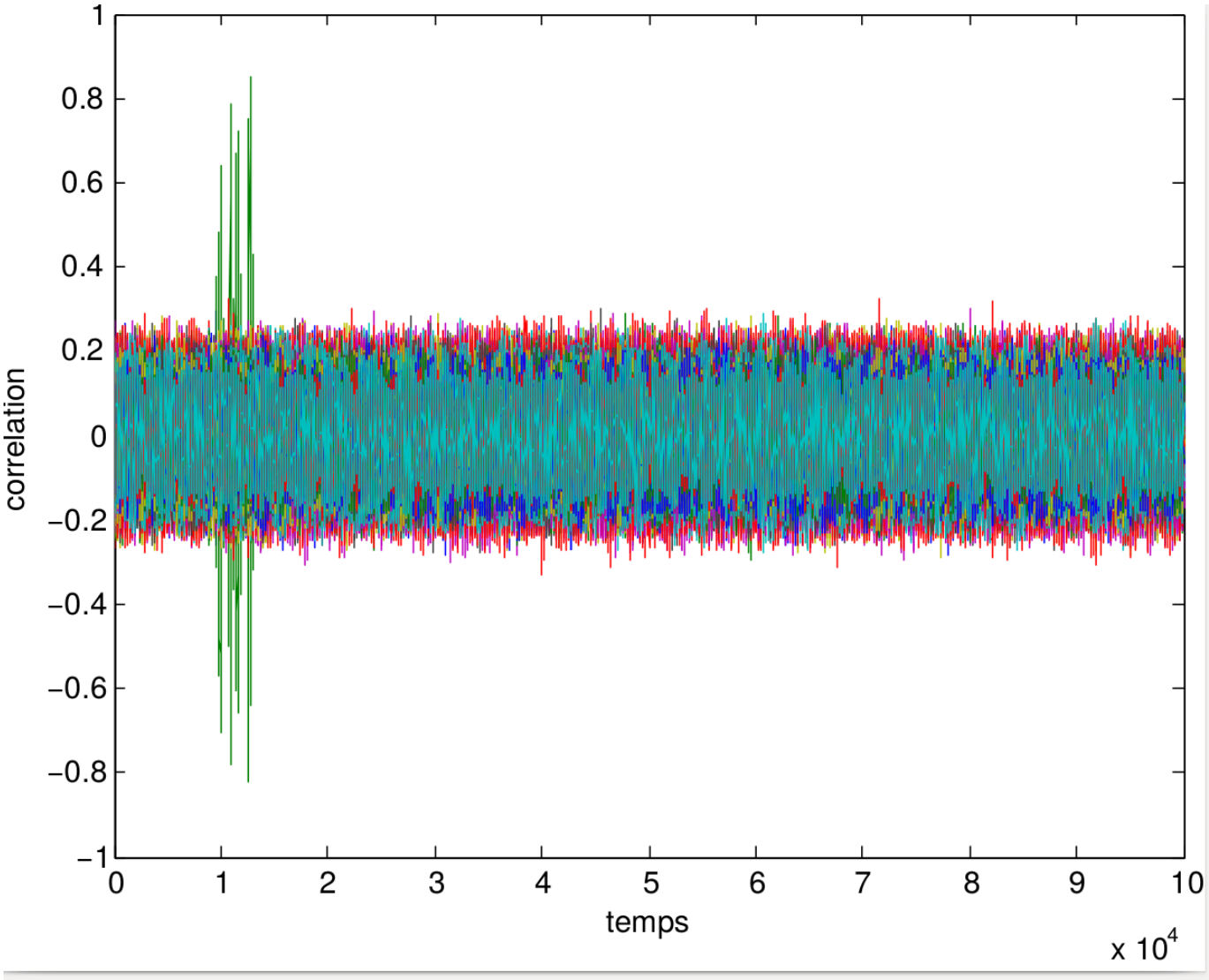
- The Pearson correlation between tow variables $O_R = X$ and $P_{m,k} = Y$ is defined as:

$$\mathrm{Cor}(X, Y) = \frac{\mathrm{Cov}(X, Y)}{\sqrt{\mathrm{Var}(X) \cdot \mathrm{Var}(Y)}} \quad .$$

Correlation Power Analysis [10]

- In our example the prediction matrix $P_{m,k}$ is correlated with the matrix of traces O_R.
- One curve is obtained for each guess.
- The returned guess k_d is the one with the maximum pic value.

Example (see in TP)



Example (see in TP)

Results in the curves

- A curve = one guess key byte.
- 256 curves.
- Here the correct key is associated to the green trace.
- The **points of interest** are the moment when the secret is manipulated.
- Pertinence of the model.
  Here, the correlation is 0.8, it is a good model.

Noise and desynchronisation

- Adding factice instructions/operations.
- Using analogue noise generators.
- Using a variable period clock.

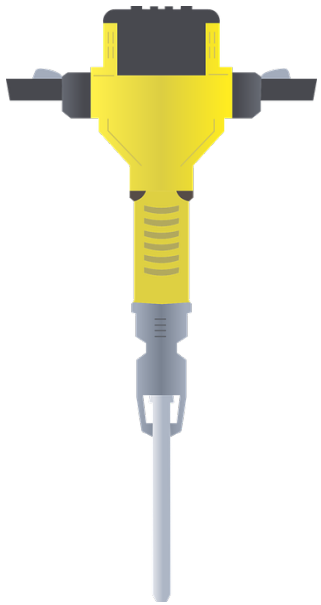
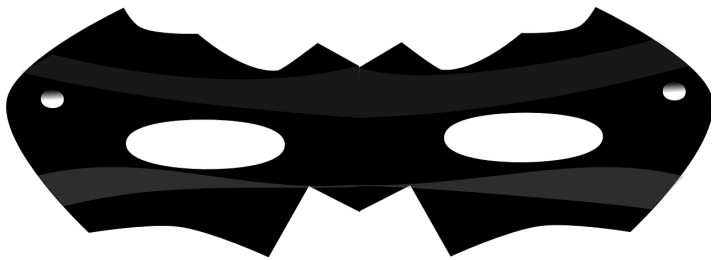


illustration: Pixabay

Mask

Let $f : \mathbb{F}_{2^m} \Rightarrow \mathbb{F}_{2^l}$ be a function which needs protection.
If it cannot possible to avoid an information leakage on x during $f(x)$ computation:

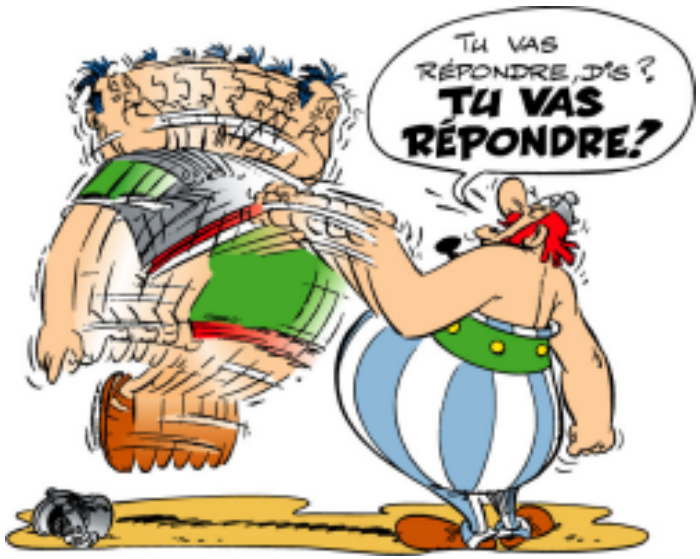
- if f is **linear**,
  we can use a random mask m:
  $f(x) = f(x \oplus m) \oplus f(m)$.
- if f is **not linear**.
  we can generates a function f_m such as:
  $f_m(x \oplus m) = f(x) \oplus m$.



Origin

illustrations : Pixabay

Physical fault



The **fault injection attacks** (FIA) disrupt the normal operation of a device, with the aim of obtaining information or hijacking it.

Examples of way to inject physical faults

- Laser fault injection [18].
- Electromagnetic fault injection [19].
- Clock glitch [20].
- Power glitch [21].
- ...

illustrations: Pixabay

Laser fault injection

Laser

- The energy of the light radiation is absorbed by the silicon of the circuit.
- Pairs electron hole are then created along the light beam.
- They can lead to the appearance of a photoelectric current at the level of a transistor.
- A voltage peak is propagated in combinatorial logic blocks.

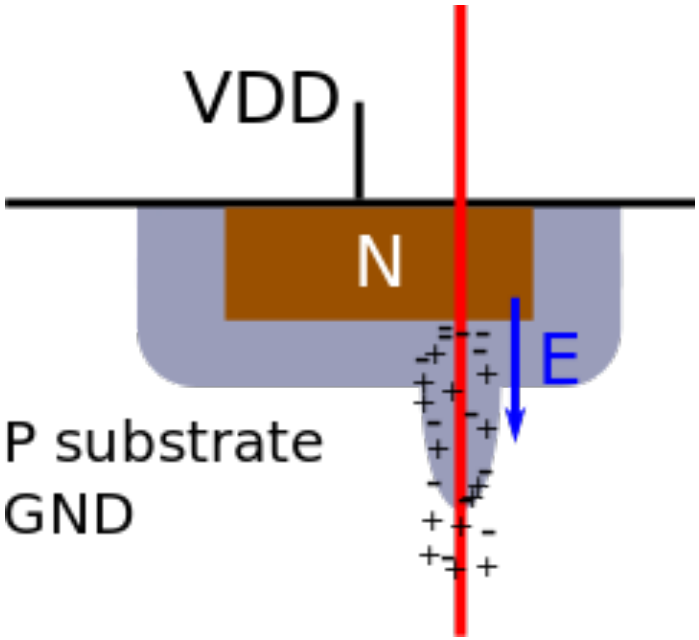
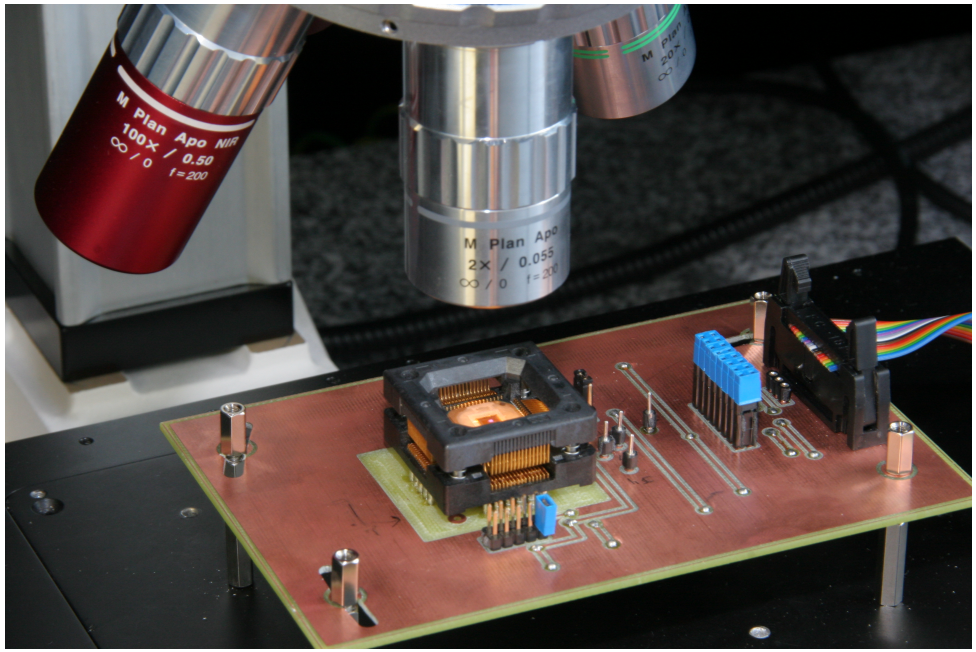


illustration: PhD of Roscian [18]

Laser fault injection



Micropacs laser bench, at "centre de Microélectronique de Provence", of "L'École des Mines de Saint-Étienne"

the most expensive device for testing

MINES Saint-Étienne

Micro-PackS CIM PACA

Electromagnetic fault injection

unlike laser, where you could inject the attack where exactly you wanted, EM is not that exact, but way less expensive

EM

- The attacked circuit is placed under a near-field antenna.
- A very strong current to flow for a very short time.
- By electromagnetic coupling, part of this energy is transmitted in the metal at the surface of the chip.
- The generated power in the chip can therefore generate errors.

Electromagnetic fault injection

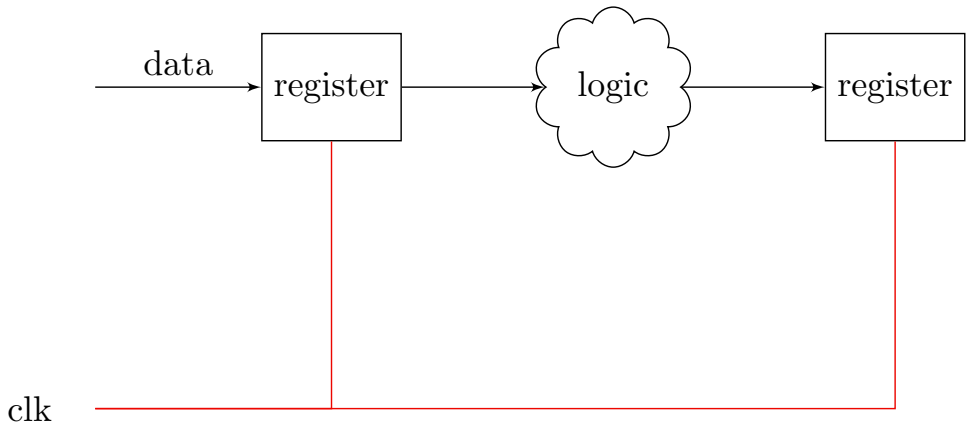
Faustine, of laboratory high security of INRIA Rennes [22].

Clock glitch

that's the attack that we are going to imply

Internal clock

- A synchronous circuit is composed by logic doors and registers managed by a common **internal clock** denoted `clk`.
- At each rising edge of the clock, data are updated in the registers.

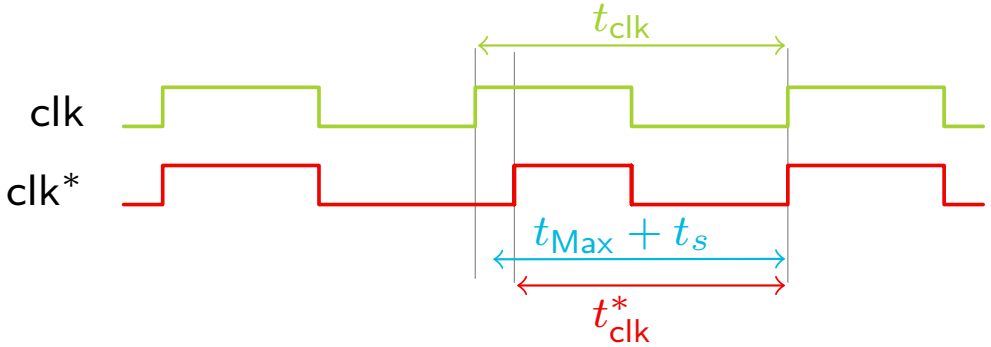


Clock glitch

Internal clock

- t_{clk}: clock period.
- t_{Max}: the time at which the last change in value of the data at the input of the registers takes place before being stable.
- t_s : the time during the data must remain stable in registers to be sampled correctly.

$$t_{clk} > t_{Max} + t_s$$



Clock glitch

- In TP we will use clock glitch.
- We will xor a signal with the internal clock.

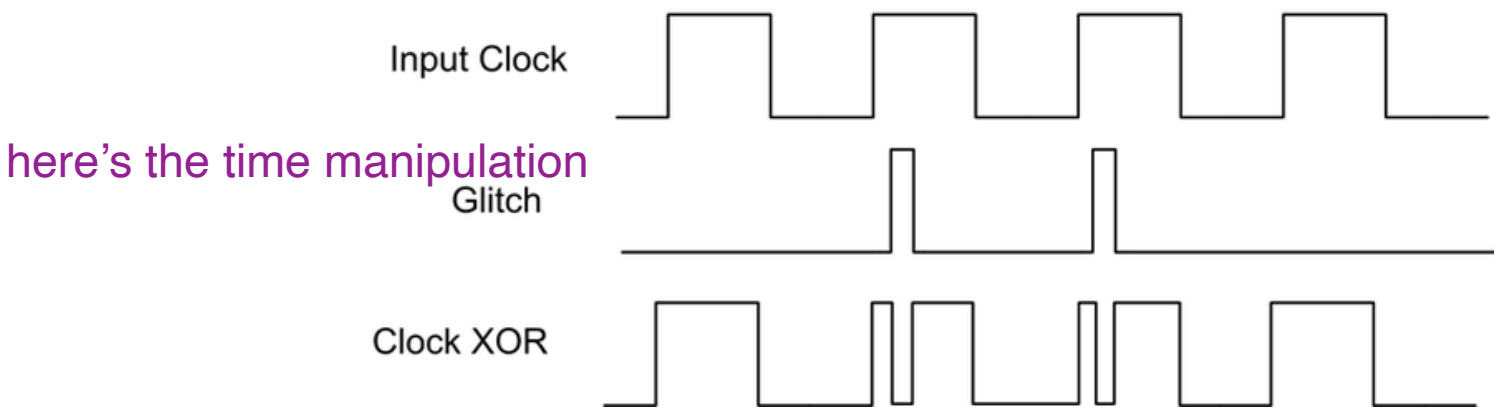


illustration: wiki ChipWhisperer [23]

Effects of Attack

- **No influence.**
- **Modifications of data.**
  - **Bonding**: at the binary or assembler level, this is the setting to 0 or 1 of some bits in the memory or in a register.
  - **Bit-flip**: this pattern represents a change in the assignment value of a variable or an intermediate value.
- **Modification of the instructions.**
  - **Instruction jump**: the instruction is not executed.

In fault injection we can't change the program

  - **Instruction replacement**: the instruction is replaced by another.
    Example: to modify a conditional test before a connection
- And sometimes...

Effects

Destroy the device !

illustration: Pixabay

DFA by Piret-Quisquater [24]

Fault model:

- 1 faulty byte in one input column of MixColumns.
- The model of the error is the function $\oplus e$.
- $4 \cdot 255 = 1020$ possible faults (4 bytes positions, 255 non-zero values).

for 4 byte we have
256-1 = 255
1 is for all zero

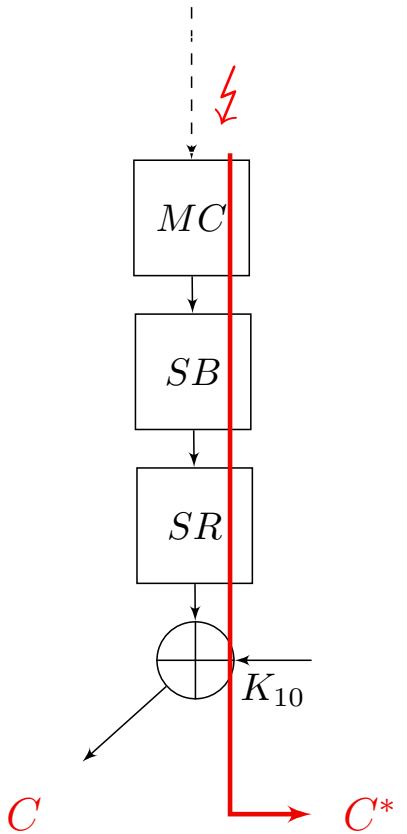
DFA by Piret-Quisquater [24]

Propagation of the fault

- 1020 possible faults at output of MixColumns.
- 1020 possible faults at output of final AddRoundKey.
- We can retrieve a part of the key with doing guesses on the 4 bytes key according to the faulty column.

e = error

$$\begin{pmatrix} 2 & 3 & 1 & 1 \\ 1 & 2 & 3 & 1 \\ 1 & 1 & 2 & 3 \\ 3 & 1 & 1 & 2 \end{pmatrix} \cdot \begin{pmatrix} e \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 2e \\ e \\ e \\ 3e \end{pmatrix}$$



DFA by Piret-Quisquater [24]

The attacker has the cipher text and the faulty text (which is 4 bytes here) C, $C*$
If error is in II we keep that
otherwise we eliminate it.

Sieve

1. For each guess $\hat{k}$ (among the 2^{32} possibilities) of the K_{10} bytes $0, 7, 10$ and 13.
2. Compute:

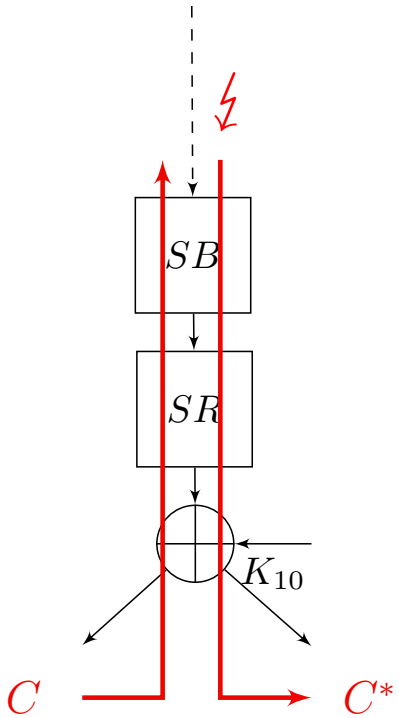
$$\Delta = \left(SB^{-1} \circ SR^{-1}\left(K_{10} \oplus C\right)\right) \oplus \left(SB^{-1} \circ SR^{-1}\left(K_{10} \oplus C^{*}\right)\right)$$

3. If Δ is equal to one of the 1020 fault possibilities, keep the guess.
4. While different guesses are possibles, start gain with an other pair(C, C^{*}).

DFA non uniform error value analysis (NUEVA) [14]

Fault model and campaign

- The fault has a statistical bias.
- Fault at the input of the last SubBytes.
- Repeat the process to have n pairs of (C, C^*).

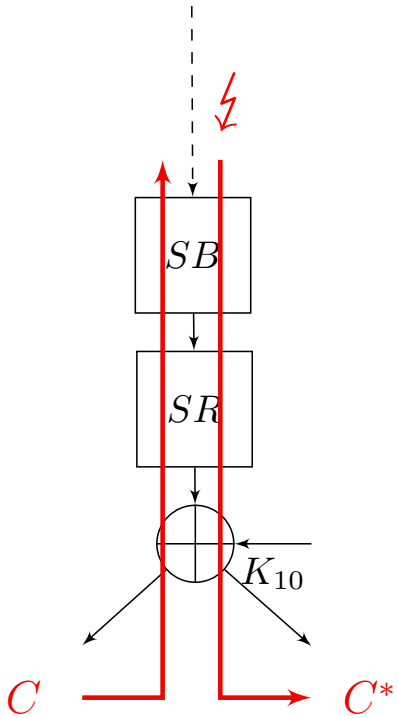


DFA non uniform error value analysis (NUEVA) [14]

Predictions:

- Divide and conquer approach byte per byte.
- For each guess $\hat{k}$ on a faulty byte $K_{10}[i]$ and each pair (C, C^*), compute the error. The error model is a $\oplus e$

$$e = \left(Sbox^{-1}(\hat{k} \oplus C)\right) \oplus \left(Sbox^{-1}(\hat{k} \oplus C^*)\right)$$



DFA non uniform error value analysis (NUEVA) [14]

n / $\hat{k}$	0	1	$\cdots$	255
0	$e_{0,0}$	$e_{0,1}$	$\cdots$	$e_{0,255}$
1	$e_{1,0}$	$e_{1,1}$	$\cdots$	$e_{1,255}$
2	$e_{2,0}$	$e_{2,1}$	$\cdots$	$e_{2,255}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$n-1$	$e_{n-1,0}$	$e_{n-1,1}$	$\cdots$	$e_{n-1,255}$

DFA non uniform error value analysis (NUEVA) [14]

Distinguisher

- In the table with n lines and 256 columns:
- Only one column corresponds to the real effect of our fault.
- It is the correct byte key guess.
- For a wrong guess, by property of confusion in the of SubBytes function, the distribution is random.
- Compute the **Shannon entropy** of each distribution.

$$H(X) = -\sum_{x \in \mathcal{X}} P(X = x) \cdot \log_2(P(X = x)) \quad .$$

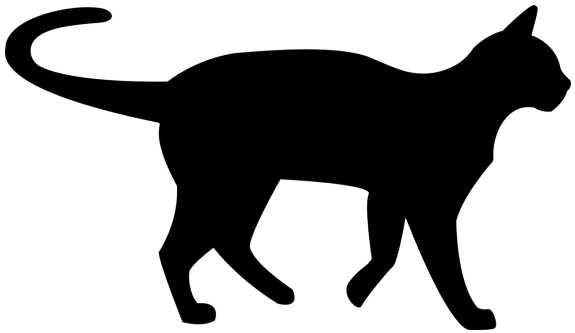
- Return the guess with smallest entropy.
- If the attack success it is the correct guess.

Vérification du code

Redundancy

- spatial,
- temporal,
- detectors/correctors codes.

Comparison between the results.



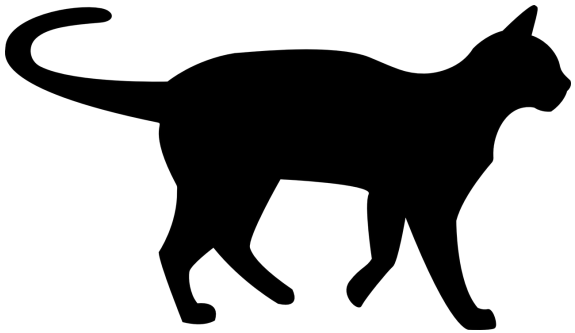


illustration: Pixabay

Protection of the chip

Shield

- metallic piste
- protection electromagnetic passive,
- or active: data is sent to these pistes and checked.

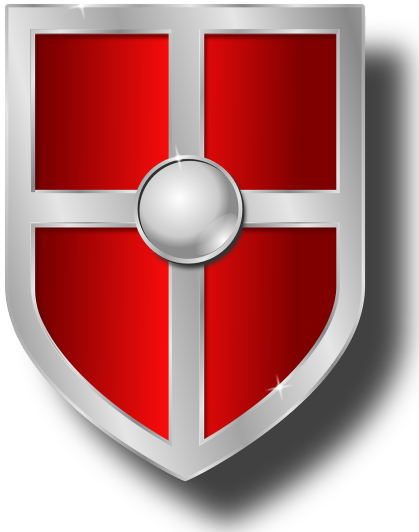
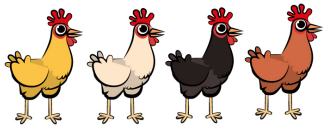


illustration: Pixabay

Les acteurs

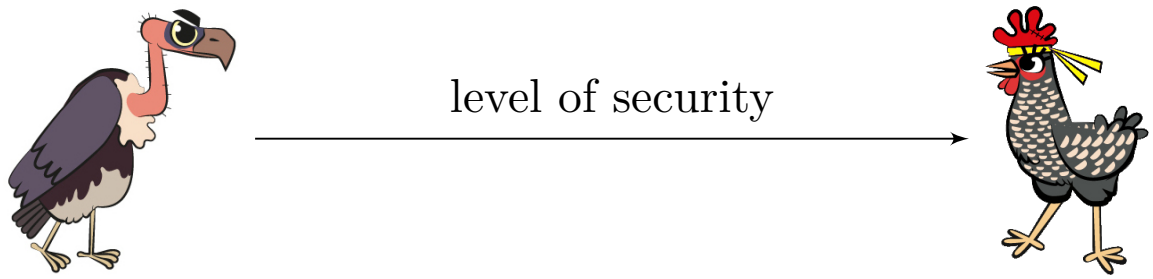
- The product for a specific utilization (ex smart cart for payment) 
- The customer of the products(ex: a bank) 
- The final clients or user sof the product 
- The insurer 
- The product maker 
- A material CESTI  to test the material
- The ANSSI   defence of the state we have follow the rules

In France ANSSI is for defence and the Army of France is for offense

illustrations: studios MoonCat

The different steps

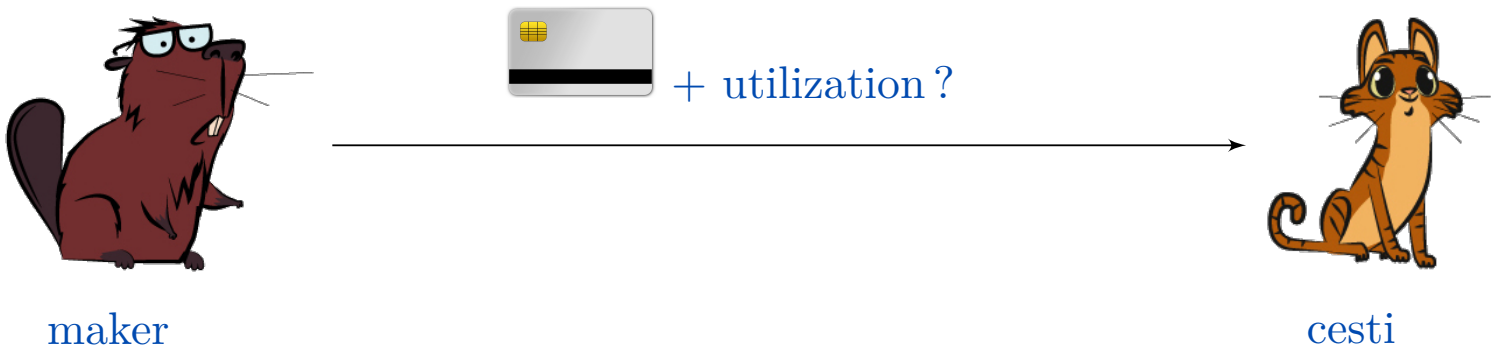
- The insurer asks a level of security.



illustrations: studios MoonCat

The different steps

- The maker asks a quote for the evaluation of pair (product, utilisation) to the cesti.



maker ask the cesti to test the device with specific config

illustrations: studios MoonCat

The different steps

- The CESTI suggests an evaluation for a level of certification given by ANSSI

illustrations: studios MoonCat

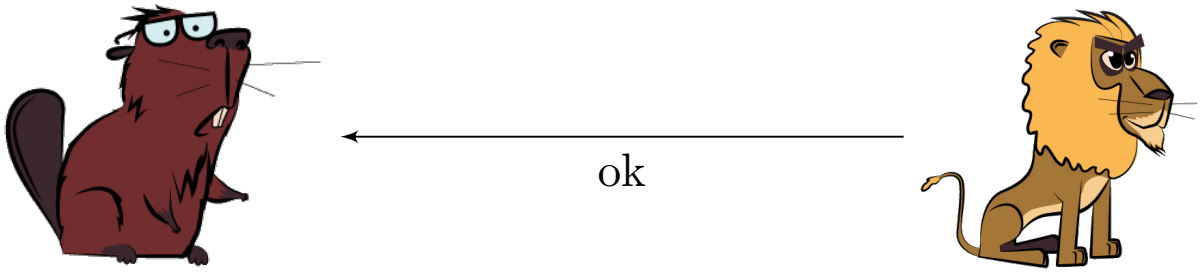
The different steps

- The maker sends this proposition to the ANSSI.

illustrations: studios MoonCat

The different steps

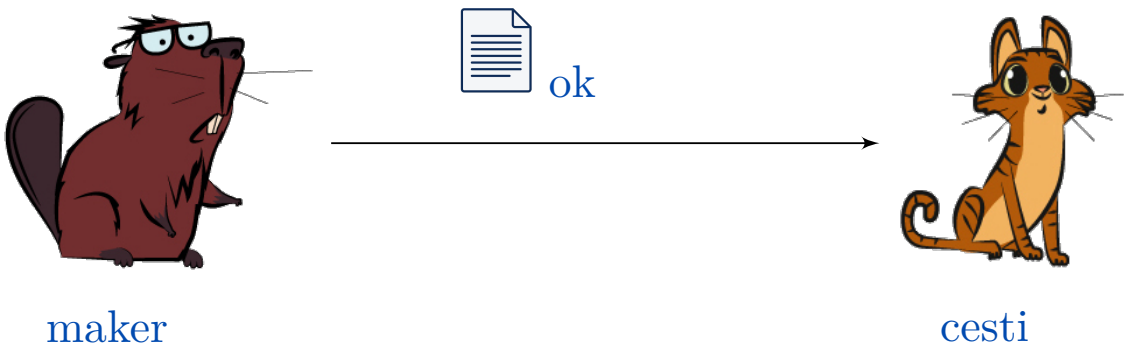
- ANSSI checks.



illustrations: studios MoonCat

The different steps

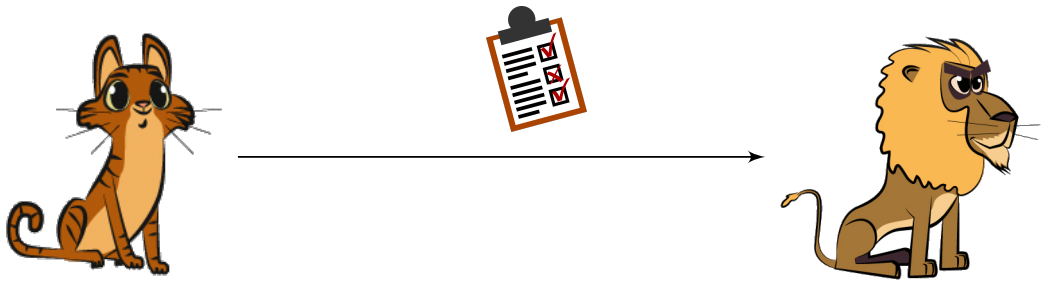
- The maker and the CESTI make a deal.



illustrations: studios MoonCat

The different steps

- The CESTI makes the product evaluation. All results are send to the ANSSI.



illustrations: studios MoonCat

The different steps

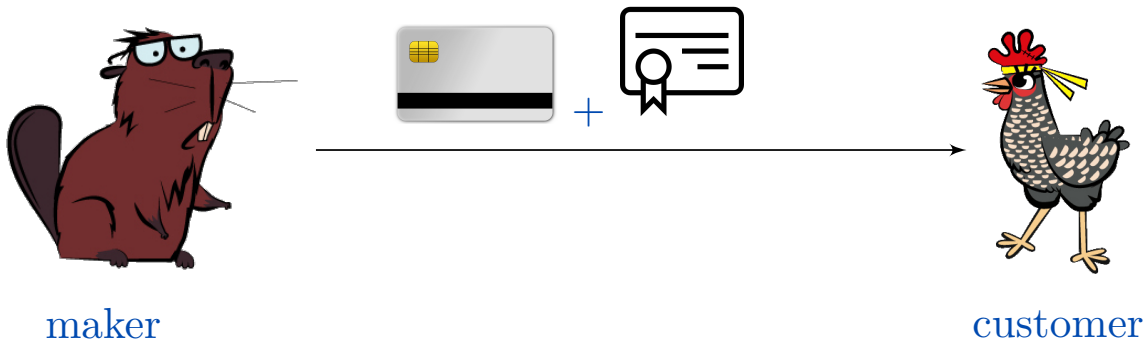
- The ANSSI check the compliance of the evaluation, then sends a certificate to the maker.

ANSSI gives the certificate to maker and not CESTI

illustrations: studios MoonCat

The different steps

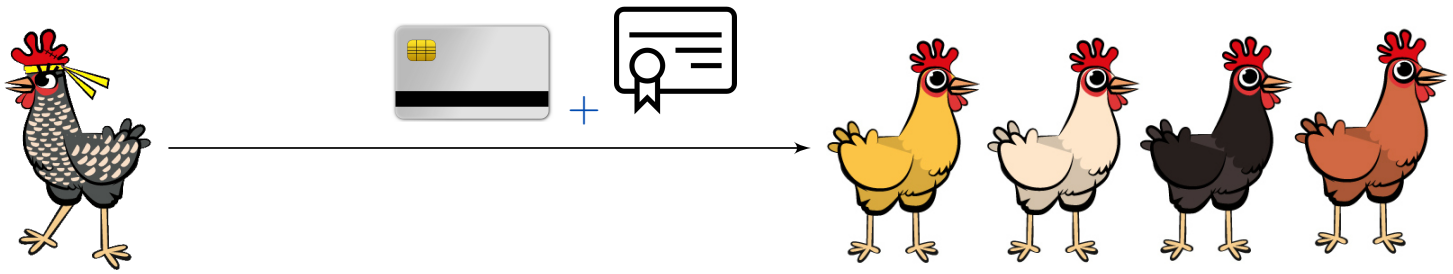
- The maker sends a product with a certificate.



illustrations: studios MoonCat

The different steps

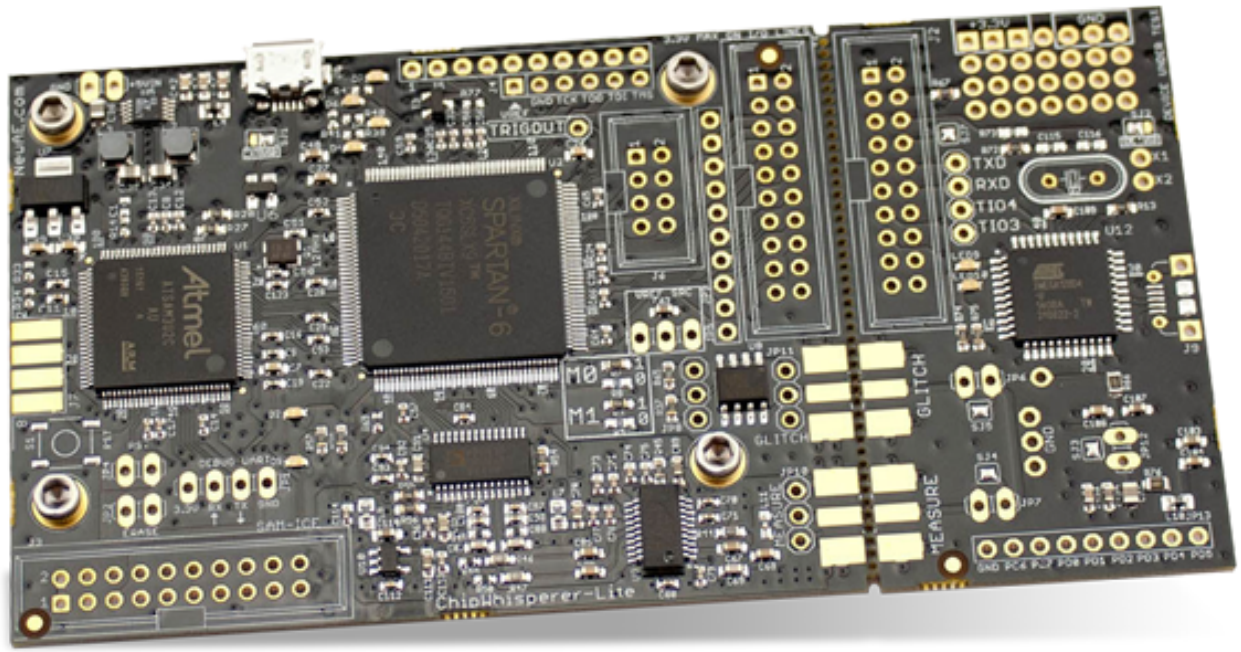
- The customer delivers the products to the final clients/ users.



customer users/final clients

illustrations: studios MoonCat

We use a ChipWhisperer-Lite from NewAE Technology [23].



La ChipWhisperer-Lite:

- is composed by a targeted device (programming in C): a ATxmega128D4,
- A FPGA use to realise attacks;
- communication in python.

The analysis of data is with programming language: julia.

You have to realize 2 attacks:

1. CPA,
2. DFA.

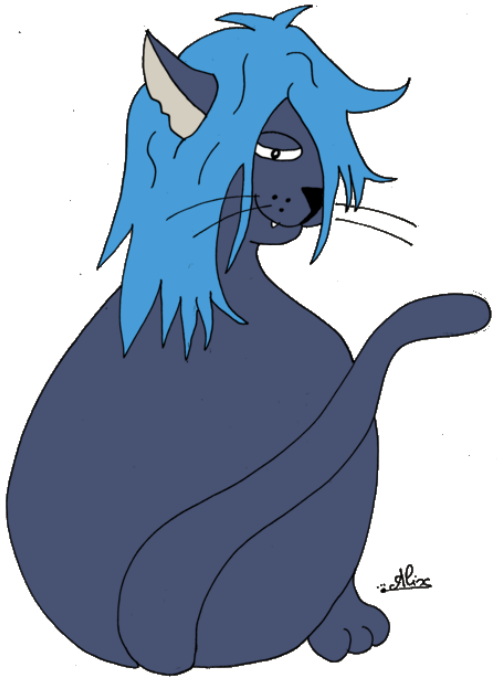
Conclusion:

- Physical attacks are a real threat.
- Do not implement your security in software, if your device can be a target of physical attacks.
- Use dedicated hardware devices.

Fun references: [25, 26, 27].

Reference: [4, 18, 20, 28, 29, 30, 31, 32, 33, 34, 35, 36].

Do you have any quesstion?



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