Introduction to Side Channel Attacks

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Summary

Introduction

Applications with Security Requirements

- medical devices, *e*-health
- { home | building | factory } automation
- *e*-commerce
- transports
- communications: cell. phones, Internet, industrial networks, ...
- IOT, WSN, RFID...
- embedded systems
- { cloud | fog | edge | ... } computing
- smart { grids | cars | cities | buildings | ... }
- defense
- digital administration
- *etc.*

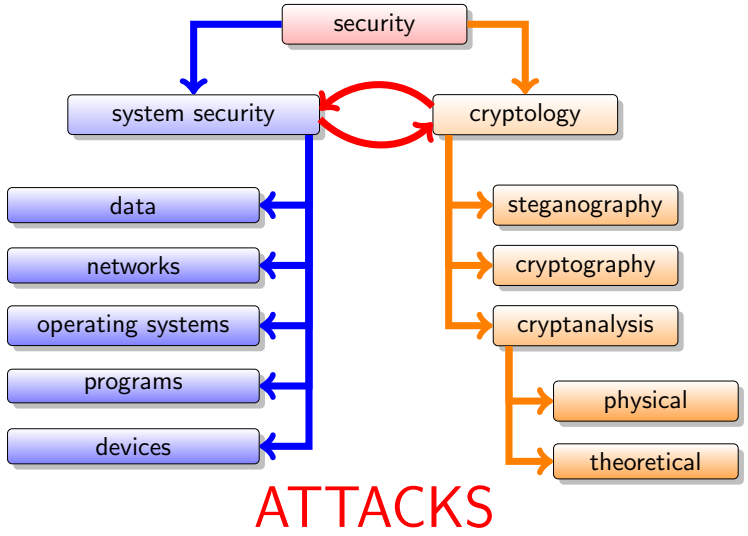
Security and Embedded Systems

Integrated circuits perform security tasks, somewhere in the system...

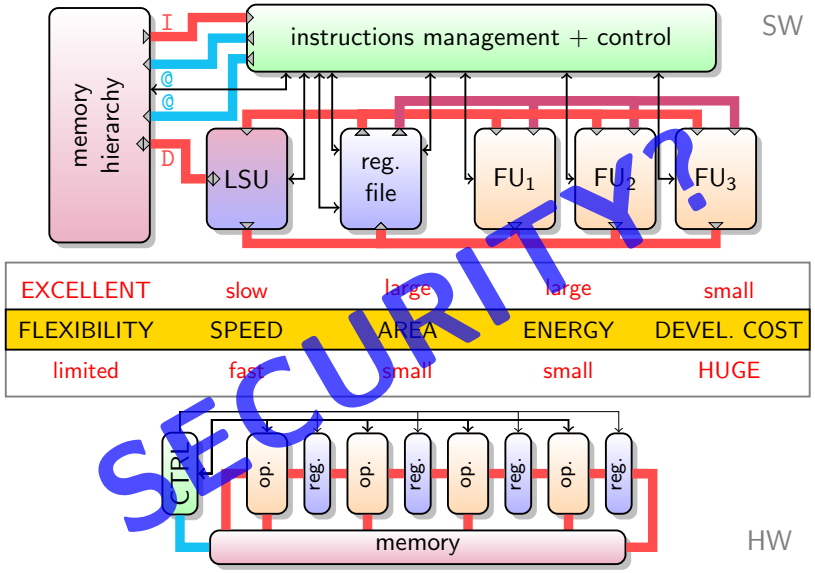
Examples where a close access is difficult:

Examples where a close access can be possible:

Security Aspects



Software vs Hardware Support



Crytographic Background

Cryptographic Features

Objectives:

- Confidentiality
- Integrity
- Authenticity
- Non-repudiation
- ...

Cryptographic primitives:

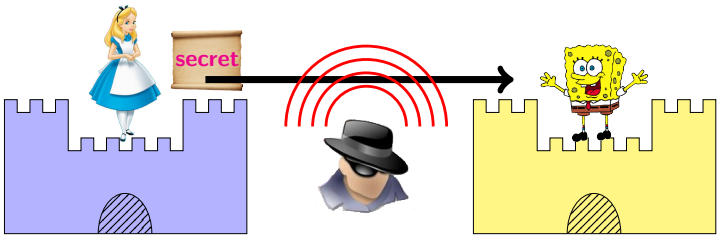
- Encryption
- Digital signature
- Hash function
- Random numbers generation
- ...

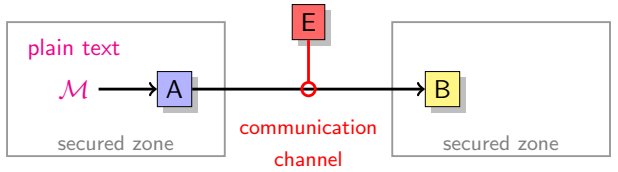
Implementation issues:

- Performances: speed, delay, throughput, latency
- Cost: device (memory, size, weight), low power/energy consumption, design
- Security: protection against attacks

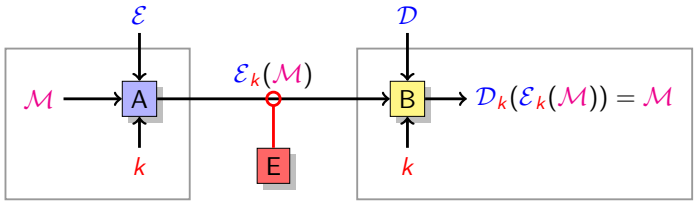
Basic Cyphering

Alice wants to secretly send a message to Bob in such a way Eve (eavesdropper/spy) **does not** get any information



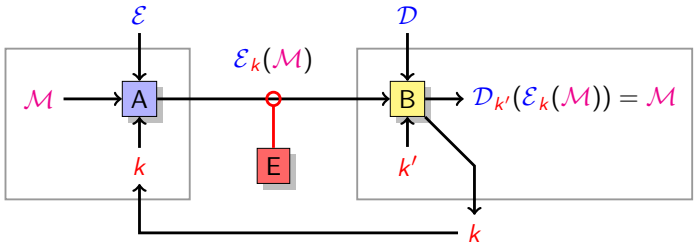


Symmetric / Private-Key Cryptography



- A: Alice, B: Bob
- $\mathcal{M}$: plain text/message
- $\mathcal{E}$: encryption/ciphering algorithm, $\mathcal{D}$: decryption/deciphering algorithm
- k: secret key to be shared by A and B
- $\mathcal{E}_k(\mathcal{M})$: encrypted text
- $\mathcal{D}_k(\mathcal{E}_k(\mathcal{M}))$: decrypted text
- E: eavesdropper/spy

Asymmetric / Public-Key Cryptography



- k: B's public key (known to everyone including E)
- $\mathcal{E}_k(\mathcal{M})$: ciphered text
- k': B's private key (must be kept secret)
- $\mathcal{D}_{k'}(\mathcal{E}_k(\mathcal{M}))$: deciphered text

Symmetric or Asymmetric Cryptography?

Private-key or symmetric cryptography:

- simple algorithms
  - → fast computation
  - → limited cost (silicon area, energy)
- ☹ requires a key exchange
- ☹ key distribution problem for n persons

Public-key or asymmetric cryptography:

- no key exchange required
- only 2 keys per person (1 private, 1 public)
- allows digital signature
- ☹ more complex algorithms
  - → slower computation
  - → higher cost

Advanced Encryption Standard (AES)

Established by NIST in 2001

Symmetric encryption

Block size: 128 bits

key length	#round
128	10
192	12
256	14

Based on substitution-permutation network

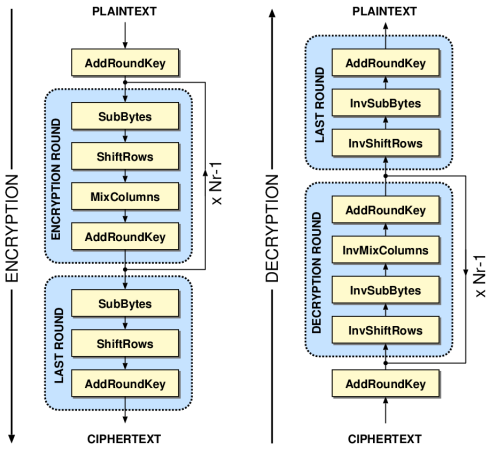
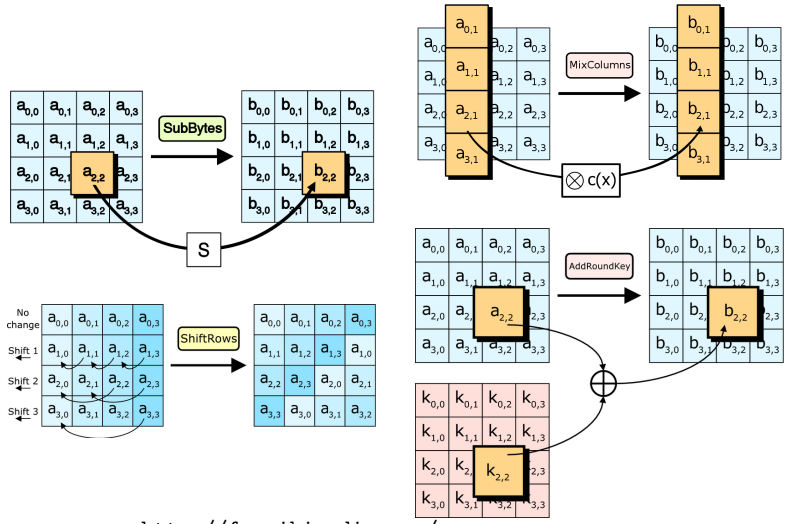


Image source: `http://fr.wikipedia.org/`

NIST: National Institute of Standards and Technology

AES Round Operations



Images source: `http://fr.wikipedia.org/`

RSA Asymmetric Cryptosystem (1/2)

Published in 1978 by Ron Rivest, Adi Shamir and Leonard Adleman [12]

Key generation (Alice side)

- Choose two large prime integers p and q
- Compute the modulus $n = pq$
- Compute $\varphi(n) = (p-1)(q-1)$
- Choose an integer e such that $1 < e < \varphi(n)$ and $\gcd(e, \varphi(n)) = 1$
- Compute $d = e^{-1} \bmod \varphi(n)$
- Private key (kept secret by Alice): d and also $p, q, \varphi(n)$
- Public key (published): (n, e)

RSA Asymmetric Cryptosystem (2/2)

Private key (Alice): d Public key (all): (n, e)

Encryption (Bob side):

- convert the message `M` to an integer m $(1 < m < n$ and $\gcd(m, n) = 1)$
- compute the cipher text $c = m^e \bmod n$

Decryption (Alice side):

- compute $m = c^d \bmod n$
- convert the integer m to the message `M`

Theoretical security: integer factorization, *i.e.* computing (p, q) knowing n, is not possible when n is large enough

Modular Exponentiation

Computation of operations such as : $a^b \bmod n$

$$a^b = \underbrace{a \times a \times a \times a \times \ldots \times a \times a \times a}_{a \text{ appears } b \text{ times}}$$

Order of magnitude of exponents: $2^{\text{size of exponent}} \rightsquigarrow 2^{1024} \ldots 2^{2048} \ldots 2^{4096}$

Fast exponentiation principle:

$$\begin{aligned} a^b &= (a^2)^{\frac{b}{2}} && \text{when } b \text{ is even} \\ &= a \times (a^2)^{\frac{b-1}{2}} && \text{when } b \text{ is odd} \end{aligned}$$

Least significant bit of the exponent: `bit` $= 0 \rightsquigarrow$ even and `bit` $= 1 \rightsquigarrow$ odd

Square and Multiply Algorithm

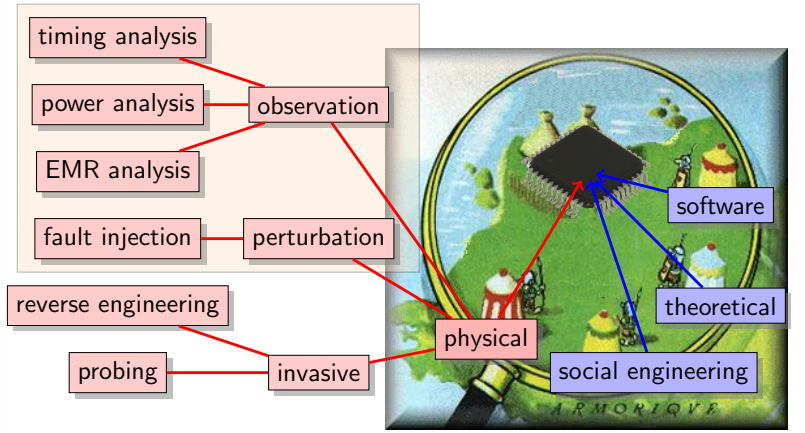
input: a, b, n where $b = (b_{t-1} b_{t-2} \ldots b_1 b_0)_2$
output: $a^b \bmod n$

```
r = 1
for i from 0 to t-1 do
    if b_i = 1 then
        r = r · a  mod n
    endif
    a = a^2  mod n
endfor
return r
```

This is the right to left version (there exists a left to right one)

Side Channel Attacks

Main Types of Attacks



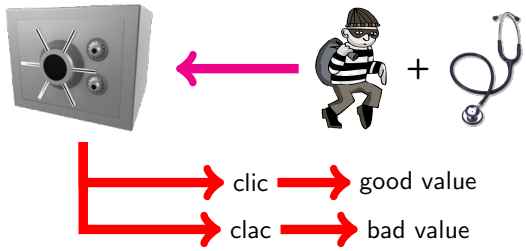
EMR = Electromagnetic radiation

Side Channel Attacks (SCAs) (1/2)

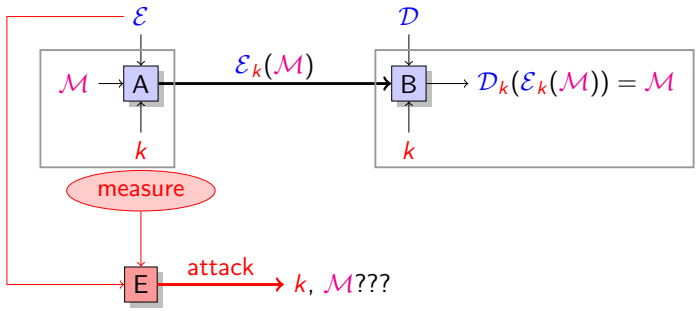
Attack: attempt to find, without any knowledge about the secret:

- the message (or parts of the message)
- informations on the message
- the secret (or parts of the secret)

"Old style" side channel attacks:



Side Channel Attacks (SCAs) (2/2)



General principle: measure external parameter(s) on a running device in order to deduce internal (secret) informations

What Should be Measured?

Answer: everything that can "enter" and/or "get out" in/from the device

- time
- power consumption
- electromagnetic radiation
- temperature
- sound
- number of cache misses
- number and type of error messages
- ...

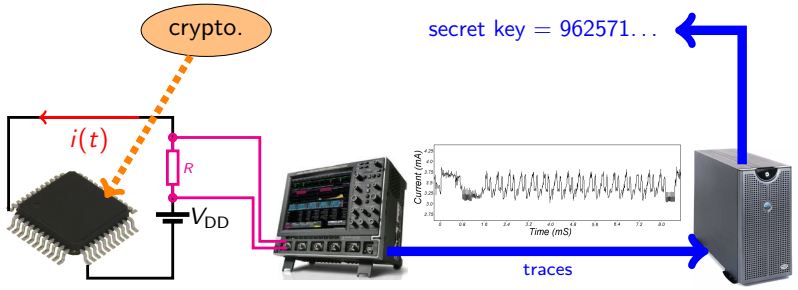
The measured parameters may provide informations on:

- global behavior (temperature, power, sound...)
- local behavior (EMR, # cache misses...)

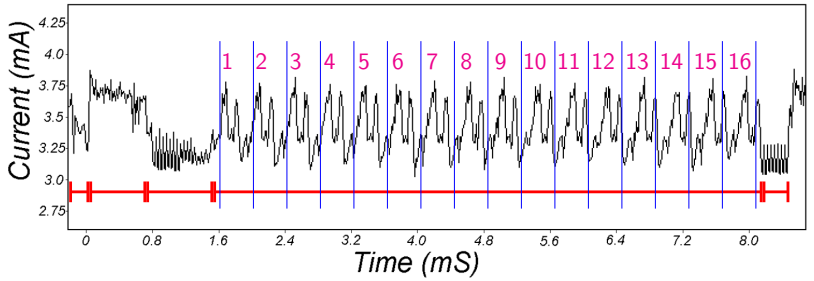
Power Consumption Analysis

General principle:

1. measure the current $i(t)$ in the cryptosystem
2. use those measurements to "deduce" secret informations



"Read" the Traces



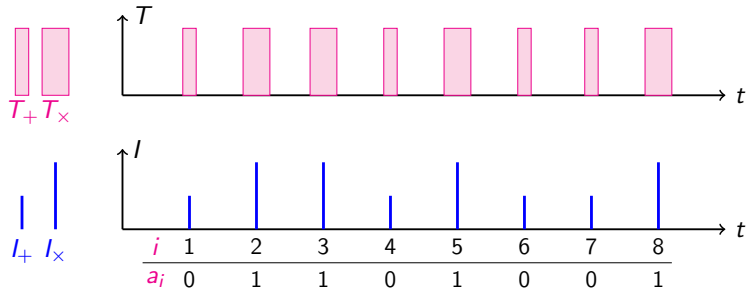
- algorithm → decomposition into steps
- detect loops
  - constant time for the loop iterations
  - non-constant time for the loop iterations

Source: [6] Kocher, Jaffe and Jun. **Differential Power Analysis**, Crypto99

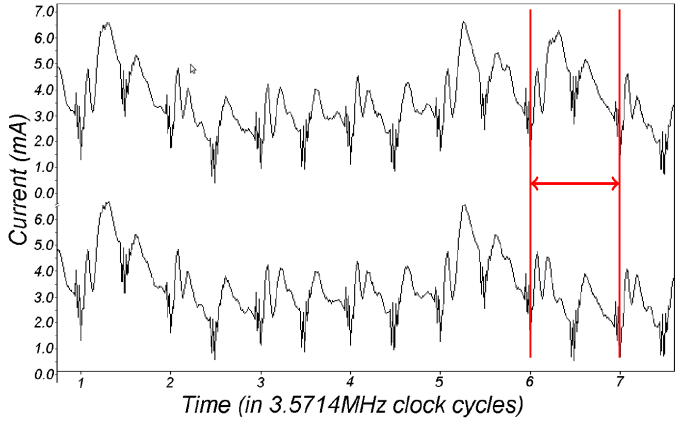
Differences & External Signature

An algorithm has a current signature and a time signature:

```
r = c0
for i from 1 to n do
    if ai = 0 then
        r = r+c1
    else
        r = r×c2
```



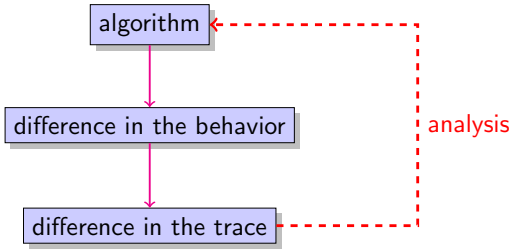
Simple Power Analysis (SPA)



Source: [6]

SPA in Practice

General principle:

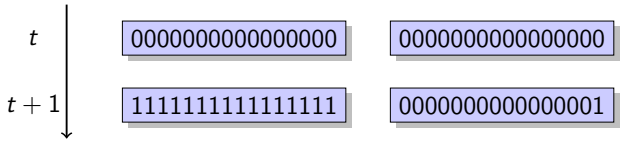


Methods: interpretation of the differences in

- control signals
- computation time
- operand values
- ...

Limits of the SPA

Example of behavior difference: (activity into a register)

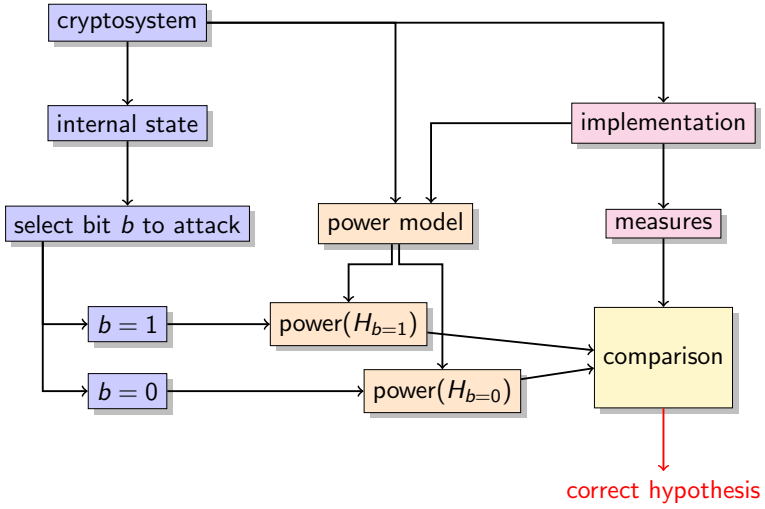


Important: a small difference may be evaluated has a noise during the measurement → traces cannot be distinguished

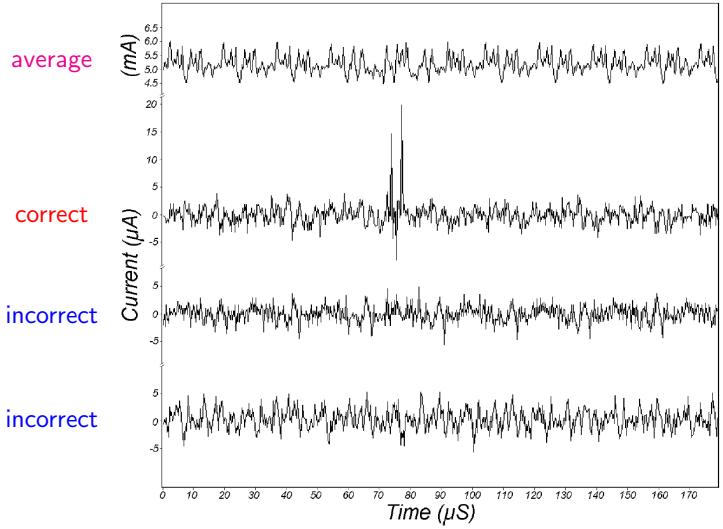
Question: what can be done when differences are too small?

Answer: use statistics over several traces

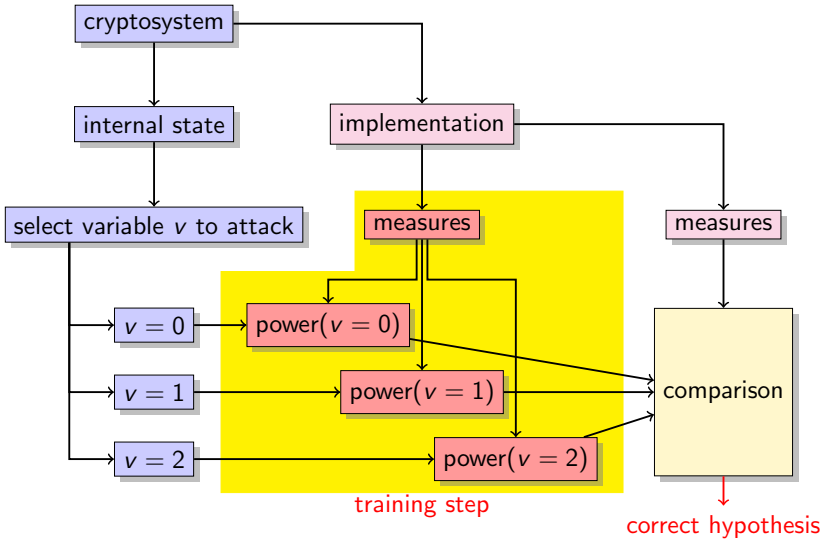
Differential Power Analysis (DPA)



Differential Power Analysis (DPA) Example

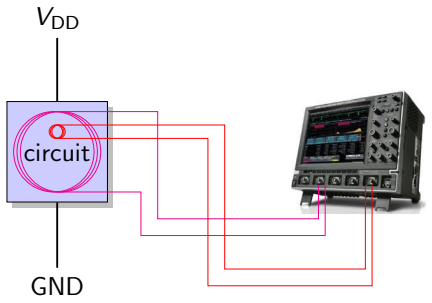


Template Attack



Electromagnetic Radiation Analysis (1/2)

General principle: use a probe to measure the EMR



EMR measurement:

- global EMR with a large probe
- local EMR with a micro-probe

Electromagnetic Radiation Analysis (2/2)

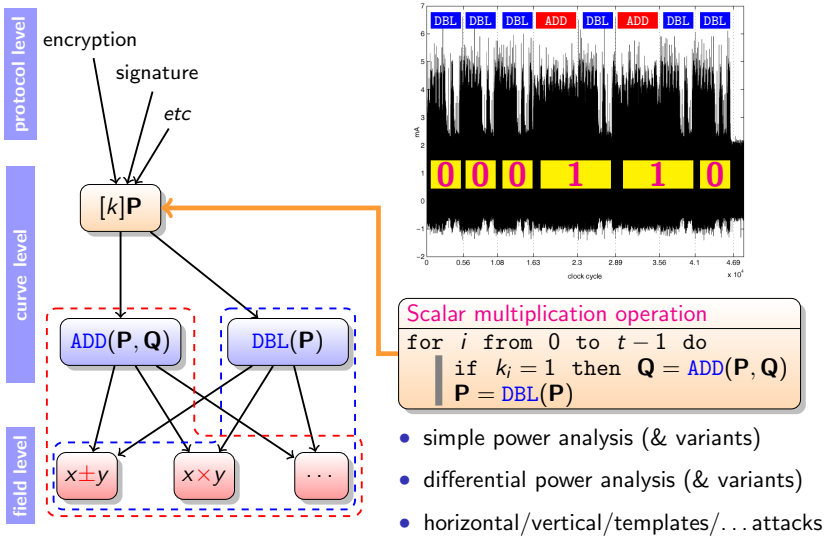
EMR analysis methods:

- simple electromagnetic analysis: SEMA
- differential electromagnetic analysis: DEMA

Local EMR analysis may be used to determine internal architecture details, and then select weak parts of the circuit for the attack

→ X-Y table

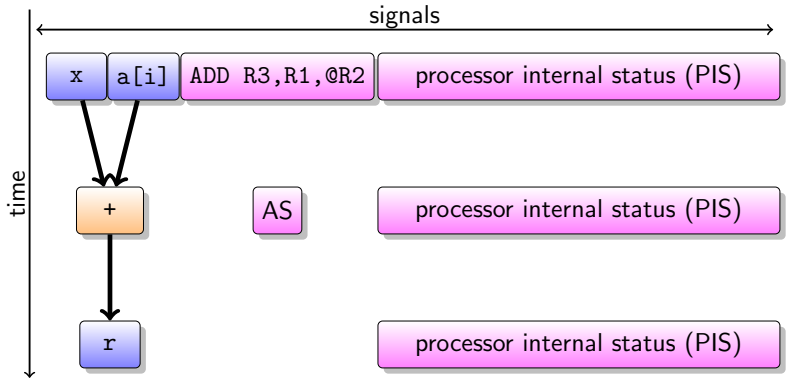
Side Channel Attack on Elliptic Curve Crypto



- simple power analysis (& variants)
- differential power analysis (& variants)
- horizontal/vertical/templates/... attacks

Activity in a Processor

Operation to be executed: `r ← x + a[i]`



- AS: ALU status
- PIS: pipeline management, bypasses, memory hierarchy, branch predictor, monitoring, etc)

Protections

Protections, Countermeasures

Principles for preventing attacks:

- embed additional protection blocks
- modify the original circuit into a secured version
- application levels: circuit, architecture, algorithm, protocol...

Countermeasures:

- electrical shielding
- detectors, estimators, decoupling
- use uniform computation durations and power consumption
- use detection/correction codes (for fault injection attacks)
- provide a random behavior (algorithms, representation, operations...)
- add noise (e.g. masking, useless instructions/computations)
- circuit reconfiguration (algorithms, block location, representation of values...)

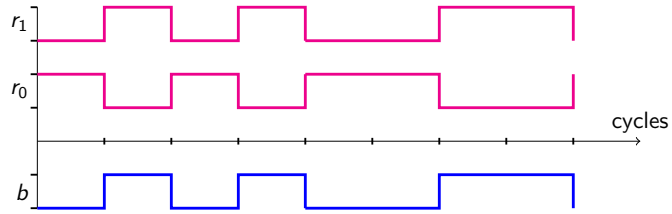
Low-Level Coding and Circuit Activity

Assumptions:

- b is a bit (i.e. $b \in \{0,1\}$, logical or mathematical value)
- electrical states for a wire ▬ : V_{DD} (logical 1) or GND (logical 0)

Low-level codings of a bit:

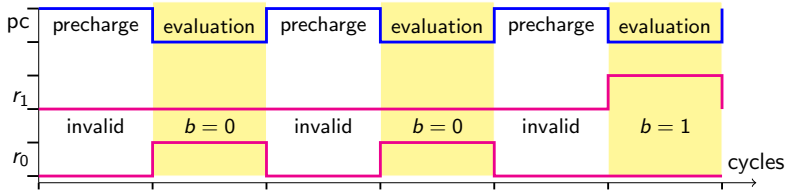
	$b=0$	$b=1$
standard	▬ GND	▬ V_{DD}
dual rail	r_0 = V_{DD}, r_1 = GND ⎤ $(1,0)_{DR}$	r_0 = GND, r_1 = V_{DD} ⎤ $(0,1)_{DR}$



Circuit Logic Styles

Countermeasure principles: uniformize circuit activity and exclusive coding

Solution based on precharge logic and dual-rail coding:



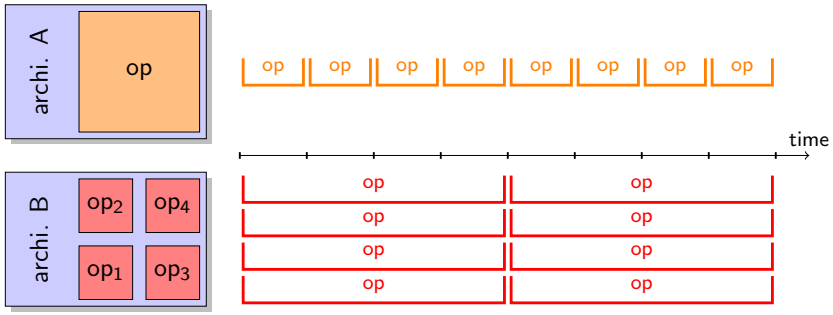
Solution based on validity line and dual-rail coding:

Important overhead: silicon area and local storage (registers)

Countermeasure: Architecture

Increase internal parallelism:

- replace one fast but big operator
- by several instances of a small but slow one



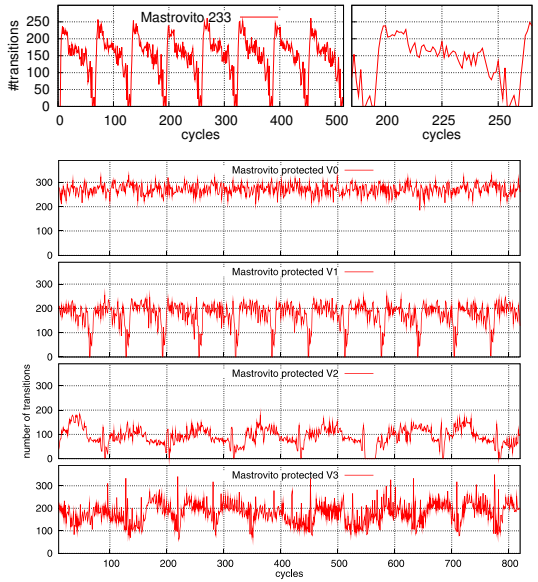
Protected Multipliers

Unprotected

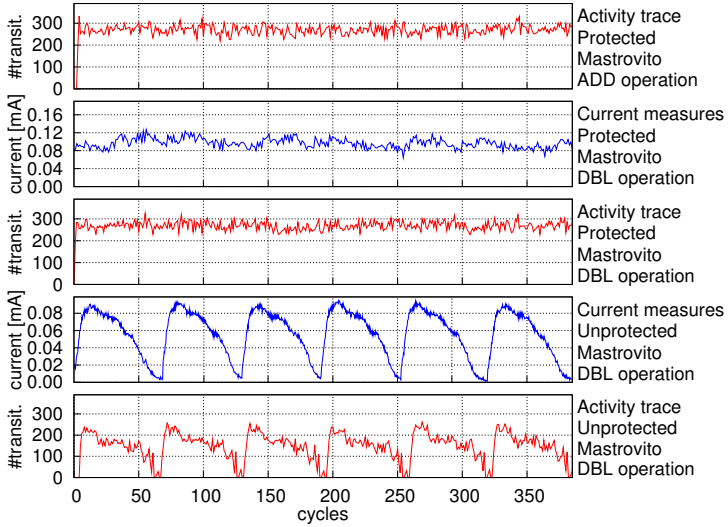
Protected

Overhead:
Area/time $< 10\,\%$

References:
PhD D. Pamula [8]
Articles: [11], [10], [9]



Protected (Old) Accelerator

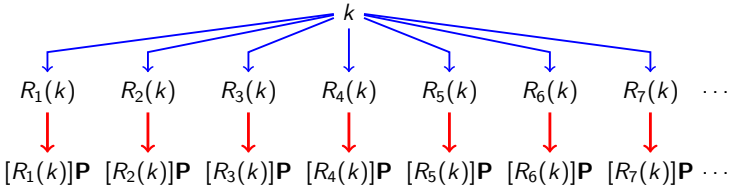


Warning: old dedicated accelerator (similar behavior is expected for our new one)

Arithmetic Level Countermeasures

Redundant number system =

- a way to improve the performance of some operations
- a way to represent a value with different representations



Important property: $\forall i \quad [R_i(k)]\mathbf{P} = [k]\mathbf{P}$

Proposed solution: use random redundant representations of k

Double-Base Number System

Standard radix-2 representation:

$$k = \sum_{i=0}^{t-1} k_i 2^i =$$

2^{t-1}	2^{t-2}	...	2^2	2^1	2^0	implicit weights
k_{t-1}	k_{t-2}	$\cdots$	k_2	k_1	k_0	t explicit digits

Digits: $k_i \in \{0, 1\}$, typical size: $t \in \{160, \ldots, 600\}$

Double-Base Number System (DBNS):

$$k = \sum_{j=0}^{n-1} k_j 2^{a_j} 3^{b_j} =$$

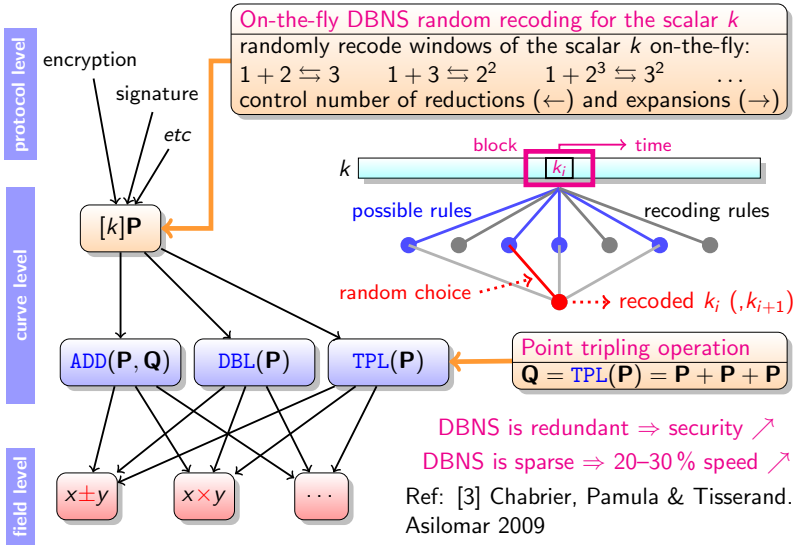
k_{n-1}	$\cdots$	k_1	k_0	n $(2,3)-$terms
a_{n-1}	$\cdots$	a_1	a_0	explicit "digits"
b_{n-1}	$\cdots$	b_1	b_0	explicit ranks

$a_j, b_j \in \mathbb{N}$, $k_j \in \{1\}$ or $k_j \in \{-1, 1\}$, size $n \approx \log t$

DBNS is a very redundant and sparse representation: $1701 = (11010100101)_2$

$$\begin{array}{rcccl} 1701 & = & 243 + 1458 & = & 2^0 3^5 + 2^1 3^6 \quad = \quad (1,0,5),(1,1,6) \\ & = & 1728 - 27 & = & 2^6 3^3 - 2^0 3^3 \quad = \quad (1,6,3),(-1,0,3) \\ & = & 729 + 972 & = & 2^0 3^6 + 2^2 3^5 \quad = \quad (1,0,6),(1,2,5) \\ & \ldots & & & \end{array}$$

Randomized DBNS Recoding of the Scalar k



DBNS is redundant ⇒ security ↗

DBNS is sparse ⇒ 20–30 % speed ↗

Ref: [3] Chabrier, Pamula & Tisserand. Asilomar 2009

Conclusion

Conclusion

- Physical attacks are very serious threats
- Attacks are more and more efficient (many variants, AI, DL)
- Security analysis and integration is mandatory at all levels (specification, algorithm, operation, implementation, test, ...)
- Security = *function*(secret value, attacker capabilities)
- Security = trade-off between performances, robustness and cost
- Security = computer science + microelectronics + mathematics

Current works examples:

- Secure processors and accelerators
- Hardware operators/accelerators with reduced activity variations
- Representation of numbers with error detection/correction features
- Circuit reconfiguration (representations, algorithms)
- Design space exploration with security objectives/metrics
- Methods/tools for automating security analysis
- CAD tools with security improvement capabilities

Resources: Conferences, Workshops, Journals, etc

- International Association for Cryptologic Research (IACR) Eprint Archives
- ACM Special Interest Group on Security, Audit and Control (SIGSAC)
- IEEE Computer Society's Technical Committee on Security and Privacy (TCSP)
- French national working group on Code & Crypto (C2) of the GDR IM
- French national working group on Security of Embedded Systems of the GDR SoC
- Conferences, workshops: CHES, FDTC, COSADE, CARDIS, CryptArchi ...
- Journals: TCHES, Journal of Cryptographic Engineering, IEEE Trans. on Computers, Circuits and Systems, VLSI Systems, ...
- `http://www.crypto.ruhr-uni-bochum.de/en_sclounge.html`
- `http://www.schneier.com/`

References I

[1] H. Bar-El, H. Choukri, D. Naccache, M. Tunstall, and C. Whelan.
The sorcerer's apprentice guide to fault attacks.
Proceedings of the IEEE, 94(2):370–382, February 2006.

[2] A. Barenghi, L. Breveglieri, I. Koren, and D. Naccache.
Fault injection attacks on cryptographic devices: Theory, practice, and countermeasures.
Proceedings of the IEEE, 100(11):3056–3076, November 2012.

[3] T. Chabrier, D. Pamula, and A. Tisserand.
Hardware implementation of DBNS recoding for ECC processor.
In *Proc. 44rd Asilomar Conference on Signals, Systems and Computers*, pages 1129–1133, Pacific Grove, California, U.S.A., November 2010. IEEE.

[4] D. Karaklajic, J.-M. Schmidt, and I. Verbauwhede.
Hardware designer's guide to fault attacks.
IEEE Transactions on Very Large Scale Integration (VLSI) Systems, 21(12):2295–2306, December 2013.

[5] P. C. Kocher.
Timing attacks on implementations of Diffie-Hellman, RSA, DSS, and other systems.
In *Proc. Advances in Cryptology (CRYPTO)*, volume 1109 of *LNCS*, pages 104–113. Springer, August 1996.

[6] P. C. Kocher, J. Jaffe, and B. Jun.
Differential power analysis.
In *Proc. Advances in Cryptology (CRYPTO)*, volume 1666 of *LNCS*, pages 388–397. Springer, August 1999.

[7] F. Koeune and F.-X. Standaert.
A tutorial on physical security and side-channel attacks.
In *5th International School on Foundations of Security Analysis and Design (FOSAD)*, volume 3655 of *LNCS*, pages 78–108. Springer-Verlag, 2005.

[8] D. Pamula.
Arithmetic Operators on GF(2^m) for Cryptographic Applications: Performance - Power Consumption - Security Tradeoffs.
Phd thesis, University of Rennes 1 and Silesian University of Technology, December 2012.

References II

[9] D. Pamula, E. Hrynkiewicz, and A. Tisserand.
Analysis of GF(2^{233}) multipliers regarding elliptic curve cryptosystem applications.
In *11th IFAC/IEEE International Conference on Programmable Devices and Embedded Systems (PDeS)*, pages 271–276, Brno, Czech Republic, May 2012.

[10] D. Pamula and A. Tisserand.
GF(2^m) finite-field multipliers with reduced activity variations.
In *4th International Workshop on the Arithmetic of Finite Fields*, volume 7369 of *LNCS*, pages 152–167, Bochum, Germany, July 2012. Springer.

[11] D. Pamula and A. Tisserand.
Fast and secure finite field multipliers.
In *Proc. 18th Euromicro Conference on Digital System Design (DSD)*, pages 653–660, Madeira, Portugal, August 2015.

[12] R. L. Rivest, A. Shamir, and L. Adleman.
A method for obtaining digital signatures and public-key cryptosystems.
Communications of the ACM, 21(2):120–126, February 1978.

Good Books (in French)

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Simon Singh
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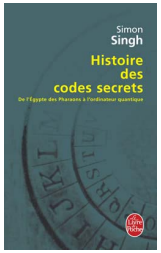
Livre de poche



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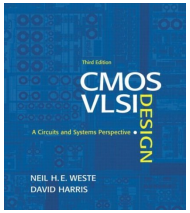

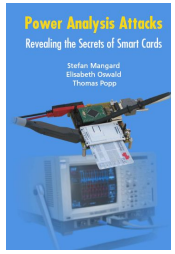

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Springer
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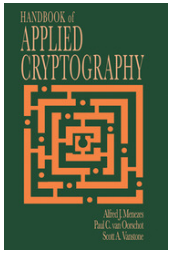

The end, questions ?

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Thank you