Smart cards attacks and protections

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UE « Calcul Sécurisé »

1ère partie

La sécurité logique est une abstraction

- L'attaquant échange des messages avec le système :
  - Messages connus: adversaire passif (écoute)
  - Messages choisis (de façon adaptative) : adversaire actif

- Puis utilise ces messages pour mettre en défaut des objectifs de sécurité :
  - Confidentialité : e-mails, numéros de cartes, voix, …
  - Integrité : téléchargement de logiciels, …
  - Authenticité : contrôle d'accès, signature électronique, …
  - Anonymat : paiement anonyme, vote électronique, …
  - …

Sécurité au niveau cryptographique

- Algorithmes cryptographiques = composants de base de la sécurité
  - Chiffrement, signature, authentification, …
  - S'appuient fortement sur les mathématiques : probabilités, combinatoire, théorie des codes, théorie de nombres, réseaux euclidiens, corps finis, courbes (hyper)elliptisues, géométrie algébrique, graphes, …
  - Secret = Clé (*principe de Kerckhoff*, 1883)

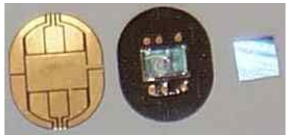
  - Les attaques utilisent des techniques de cryptanalyse
  - Preuves of securité (partielles), sous l'hypothèse de la difficulté d'un certain problème mathématique (théorie de la complexité)

Securité au niveau des protocoles

- Procotoles = Sur un réseau, supposé hostile
  - Des intrus peuvent lire, modifier et effacer le trafic, peuvent prendre le contrôle d'un ou plusieurs éléments du réseau.
  - Des attacks souvent non-intuitives :
    - Attaques de base : utilisent les fonctionnalités de base, dans un ordre arbitraire.
    - Attaques plus complexes : utilisent également des proprités subtiles des algorithmes cryptographiques, ou l'analyse statistique du trafic…
  - Preuves de sécurité pour les protocoles :
    - Modèle mathématique/logique du système & des objectifs de sécurité
    - Procédure effective pour vérifier la preuve (méthodes formelles).

Sécurité physique

- Modèle de sécurité plus général : utilise les aspects physiques du calcul.
- Menace potentielle pour tout dispositif portable/embarqué (spécialement les cartes à puce)
- Attaques invasives vs non invasives
  - Attaques invasives ➔ « dépackager » le circuit pour avoir un accès direct à ses composents (*e.g.* connecter un fil sur un bus de données pour écouter les données transférées)
  - Attaques non-invasives ➔ utilisent uniquement les informations disponibles de façon externe (temps de calcul, consommation de courant, …)



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The RSA Algorithm

RSA Cryptosystem (1977)

de facto standard of public-key cryptosystems

p, q: primes, $n = pq$, $ed = 1 \bmod (p-1)(q-1)$,

e, n: public key, d: secret key, (factoring, n: 1024 bits)
M: message, $M \in \{0,1,2,\ldots,n-1\}$.

$$\boxed{\textbf{Encryption: } C = M^e \bmod n}$$

e: small ($2^{16}+1$)

$$\boxed{\textbf{Decryption: } M = C^d \bmod n}$$

d: large ($d>n^{1/2}$)

Fast Exponentiation

The binary representation of d $=d[k-1]2^{k-1} + d[k-2]2^{k-2} + \ldots + d[1]2^{1} + d[0]2^{0}$, where $d[k-1]=1$.

Left-to-right binary method

Input **C, n, d**

Output $\mathbf{C^{d}}$ **mod n**

```
X= C;
For i=k-2 to 0
   X = X^2 mod n;
  if d[i]=1, then X=X*C mod n;
Return X
```

cubic complexity $O((\log n)^3)$.

- we need about 1500 modular multiplications for 1024-bit n,d on average.

d = 179769313486231590772930519078902473361797697894230657273430081157732639445209167262771634937140456477800995856
4863673560357494227785840418926558467439899258695049140360821770965996851973903412635215659390188627764072341203
1668285970266526289737711820513944871376325649575655785893257302729658745304709432808

RSA Decryption using Chinese Remainder Theorem

$M = C^d \bmod n$ n

$2^3 = 8$ time faster

dp = d mod (p-1)

$C_p = C \bmod p$

$M_p = C_p^{dp} \bmod p$ p

dq = d mod (q-1)

$C_q = C \bmod q$

$M_q = C_q^{dq} \bmod q$ q

$M = M_p + pv \bmod n, \quad v = (M_q - M_p)\, p^{-1} \bmod q$ n

Garner's algorithm

RSA decryption using the CRT can be computed about 4 times faster than the original decryption.

RSA with CRT

```
Algorithm RSA_Decryption_CRT (n=pq)
Input C, n, p, q, dp, dq, p_inv_q
Output M

1:   Mp = C^dp mod p;
2:   Mq = C^dq mod q;
3:   v =(Mq − Mp) p_inv_q mod q;
4:   M = Mp + pv;
5:   Return M
```

Pre-computation avoiding inversion

PKCS #1, http://www.rsasecurity.com/rsalabs/pkcs/

Crypto FAQ
CryptoBytes
RSA Algorithm
PKCS
RFID
Tech Notes
Staff & Associates
Bulletins
Challenges

PKCS #1 - RSA Cryptography Standard

This document provides recommendations for the implementation of public-key cryptography based on the RSA algorithm, covering the following aspects: cryptographic primitives; encryption schemes; signature schemes with appendix; ASN.1 syntax for representing keys and for identifying the schemes.

Version 2.1

- PKCS #1: RSA Cryptography Standard: MS-Word, Acrobat PDF.
- ASN Module for PKCS #1 v2.1
- Errata for PKCS #1 v2.1 (txt)
- NOTE: A new OID has been defined for the combination of the v1.5 signature scheme and the SHA-224 hash function:

  sha224WithRSAEncryption OBJECT IDENTIFIER ::= { pkcs-1 14 }

  Like the other sha*WithRSAEncryption OIDs in PKCS #1 v2.1, this OID has NULL parameters. The DigestInfo encoding for SHA-224 (see Section 9.2, Note 1) is:

  (0x)30 2d 30 0d 06 09 60 86 48 01 65 03 04 02 04 05 00 04 1c || H

Version 2.0

- PKCS #1 RSA Cryptography Standard: MS-Word, ASCII. View changes to previous draft.
- PKCS #1 Amd. 1: Multi-Prime RSA: MS-Word, Adobe Acrobat, PostScript.

Version 1.5

- RSA Encryption Standard: ASCII, MS-Word, PostScript and Gzip PostScript

Related Documents

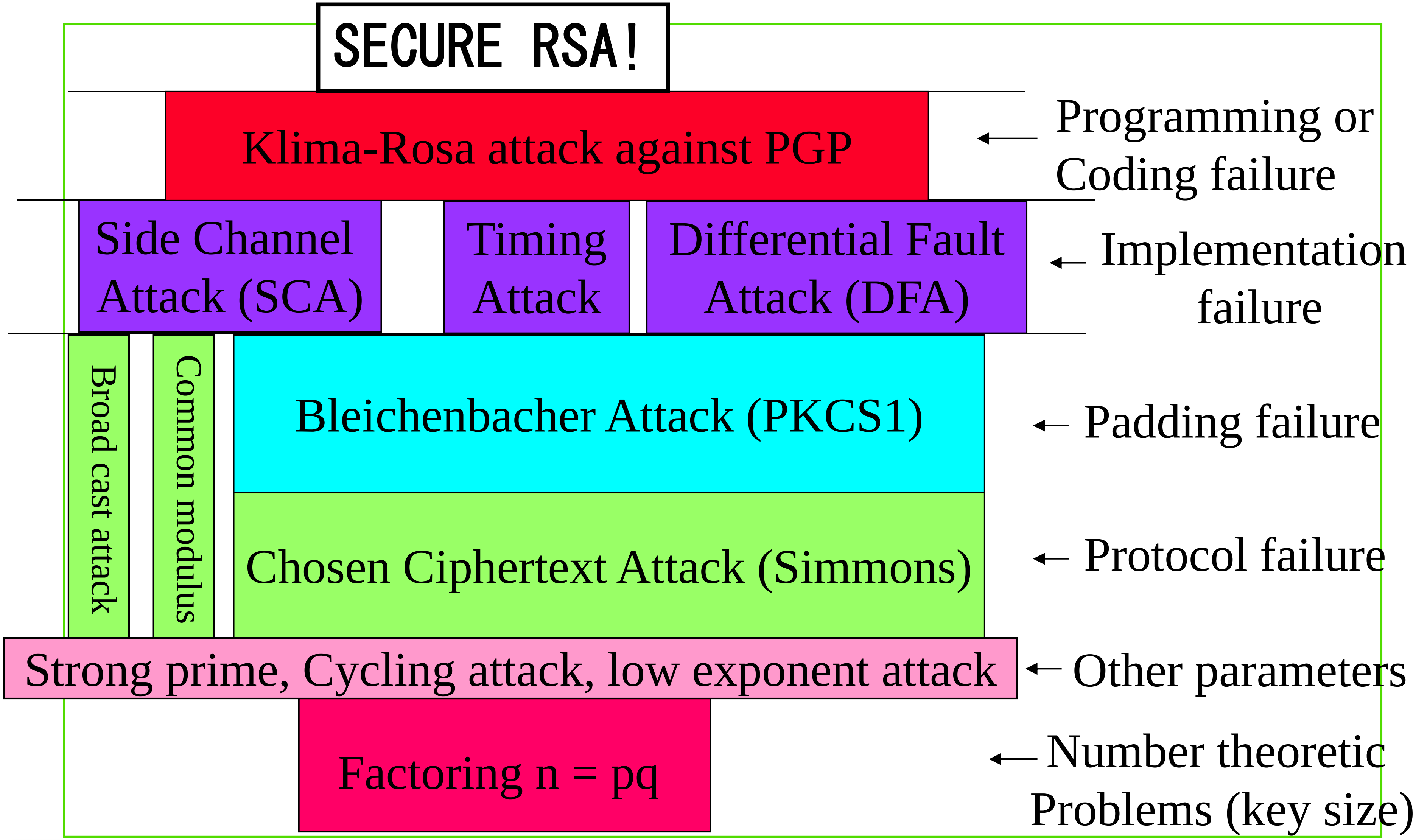
- Corrected: ASN.1 module for PKCS #1 v2.0
- Presentation of v 2.0 (PowerPoint) from the '98 Workshop
- PKCS #1 Informational RFC (3447): ASCII

Test Vectors

- RSA-OAEP and RSA-PSS test vectors (.zip file)

Questions and comments can be submitted via our contact form.

Security Analysis of RSA Cryptosystem



Timing Attacks

What are Timing Attacks ?

- The term “Timing Attack” was first introduced at CRYPTO'96 in Paul Kocher's paper
- Few other theoretical approaches without practical experiments up to the end of 97’
- Theory was put into practice in early 98’
- Timing attacks belong to the large family of "side channel" attacks

What are Timing Attacks ?

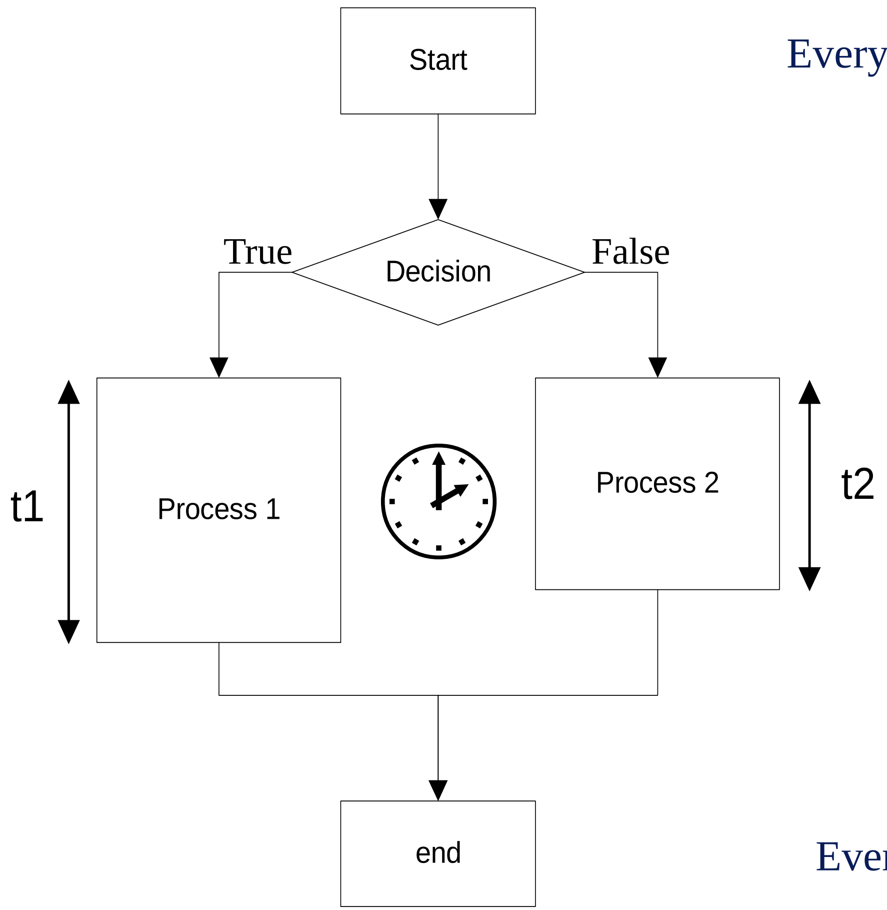
❍Principle of Timing Attacks :

- Secret data are processed in the card
- Processing time
  - depends on the value of the secret data
  - leaks information about the secret data
  - can be measured (or at least their differences)

❍Practical attack conditions

- Possibility to monitor the processing of the secret data
- Have a way to record processing times
- Have basic computational & statistical tools
- Have some knowledge of the implementation

What are Timing Attacks ?



Everything performed unconditionally before the test

A test based on secret data is performed that leads to a boolean decision

Depending on the boolean condition, the process may be long (t1) or short (t2)

Everything performed unconditionally after the test

Timing attack on RSA

- **Timing Attacks:** by precisely measuring the time it takes the smartcard to perform an decryption, Marvin can discover d.
- "repeated squaring algorithm", compute $C=M^d \bmod N$. $d=d_n d_{n-1} \dots d_0$
  - Set z equals to M and C=1. For i=0,...n do:
  - if $d_i=1$ set $C=C*z \bmod N$
  - set z equal to $z^2 \bmod N$

  At the end, C has the value $M^d \bmod N$
- To mount attack, Marvin asks the smartcard to generate signatures on a large number of random messages $M_1,M_2,\dots M_k \in Z_N^*$ and measure the time T_i it takes to generate each signature.

Timing attack on RSA

- Timing Attack
- If d_1=1, smartcard computes $Cz=MM^2$ mod$N$ and, Otherwise it does not. Let t_i be the time it takes the smart card to compute $M_iM_i^2$ mod N. The t_i's differ from each other and depends on M_i. Marvin measures them offline.
- When d_1=1, the two ensembles $\{t_i\}$ and $\{T_i\}$ are correlated. when d_1=0, they behave as independent random variables. By measuring the correlation, Marvin can determine d_1=1 or 0.
- Continuing in this way, he can discover d_2,d_3... and so on.
- Solutions: 1) add appropriate delay s.t. modular exponentiation always takes a fixed amount of time. 2) Rivest's blinding trick.
- Kocher's Power cryptanalysis?

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Power Analysis Attacks

Power Analysis: Basic Principles

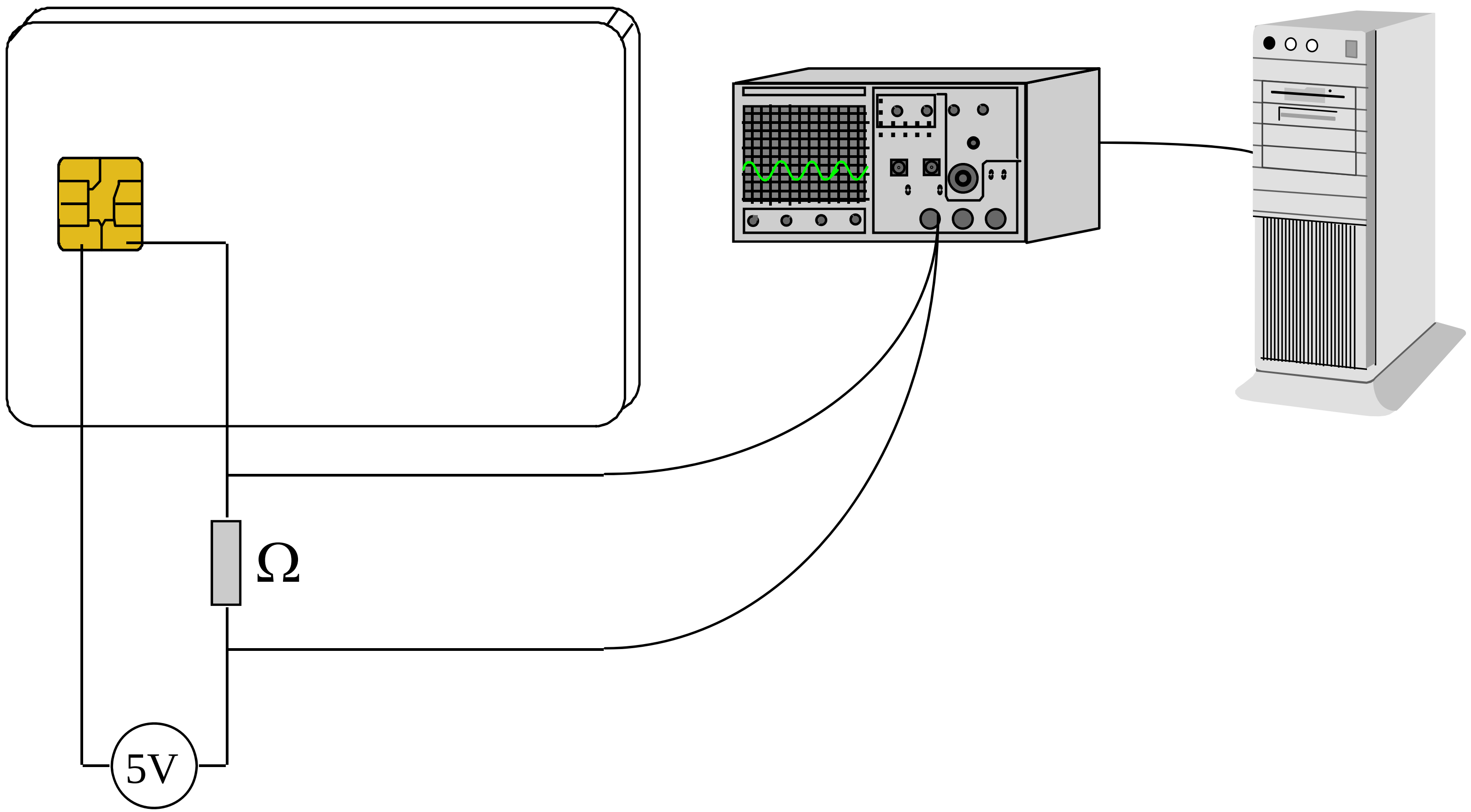
- ICC's Power Consumption leaks information about data processing
  - Power Consumption = f(processing, data)

- Deduce information about secret data and processing
  - empirical methods
  - statistical treatment

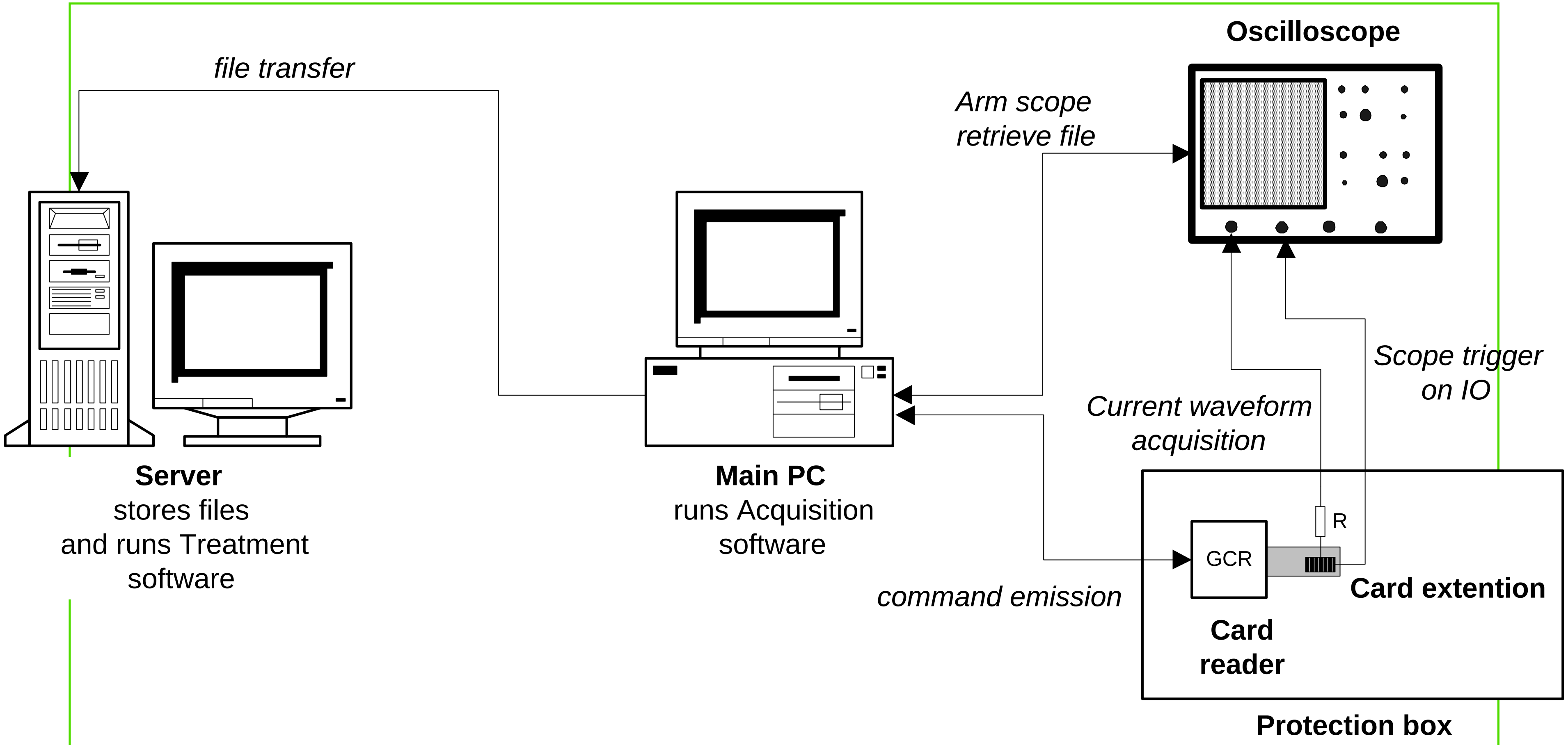
- Example : reverse engineering of an algorithm
  - The algorithm structure
  - Electrical signatures

- Single Power Analysis (SPA)
  - Attack against the DES key schedule
  - Attack against RSA

Power Analysis Tools



Experimental equipment



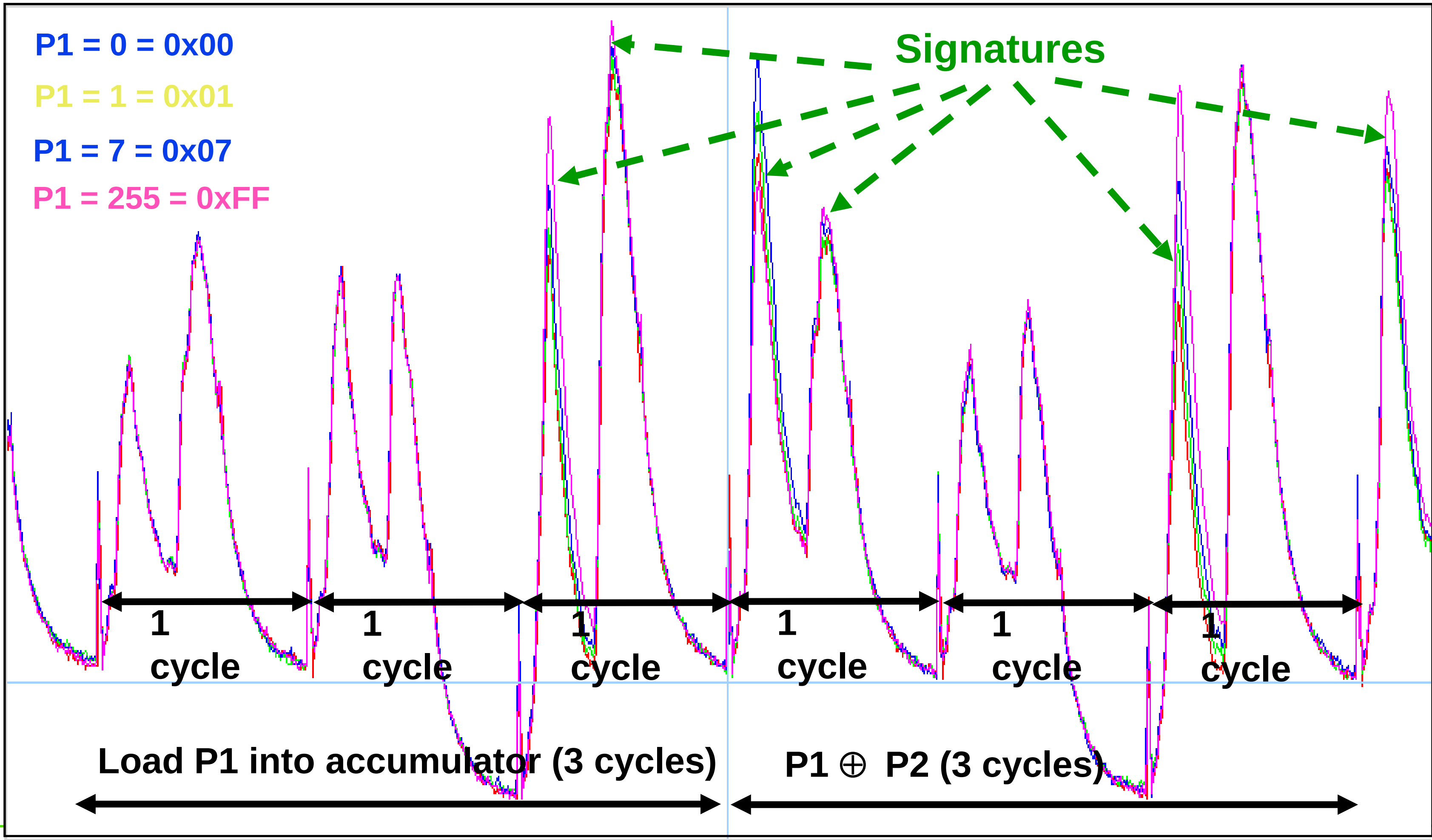
Devices for monitoring the current consumption of a chip

Information leakage

- The power consumption of a chip depends on
  - the manipulated data
  - the executed instruction
- Leakage models
  - Hamming Weight of the data, address, code Op
    - HW(0) = 0
    - HW(1) = HW(2) = HW(4) = HW(2^n) = 1
    - HW(3) = HW(5) = HW(6) = HW(9) = 2
    - …
    - HW(255) = HW(0xFF) = 8
  - Transitions weight (flipping bits on a bus state) :
    - HW ($state_i \oplus state_{i-1}$)
  - Other models, chips & technologies …

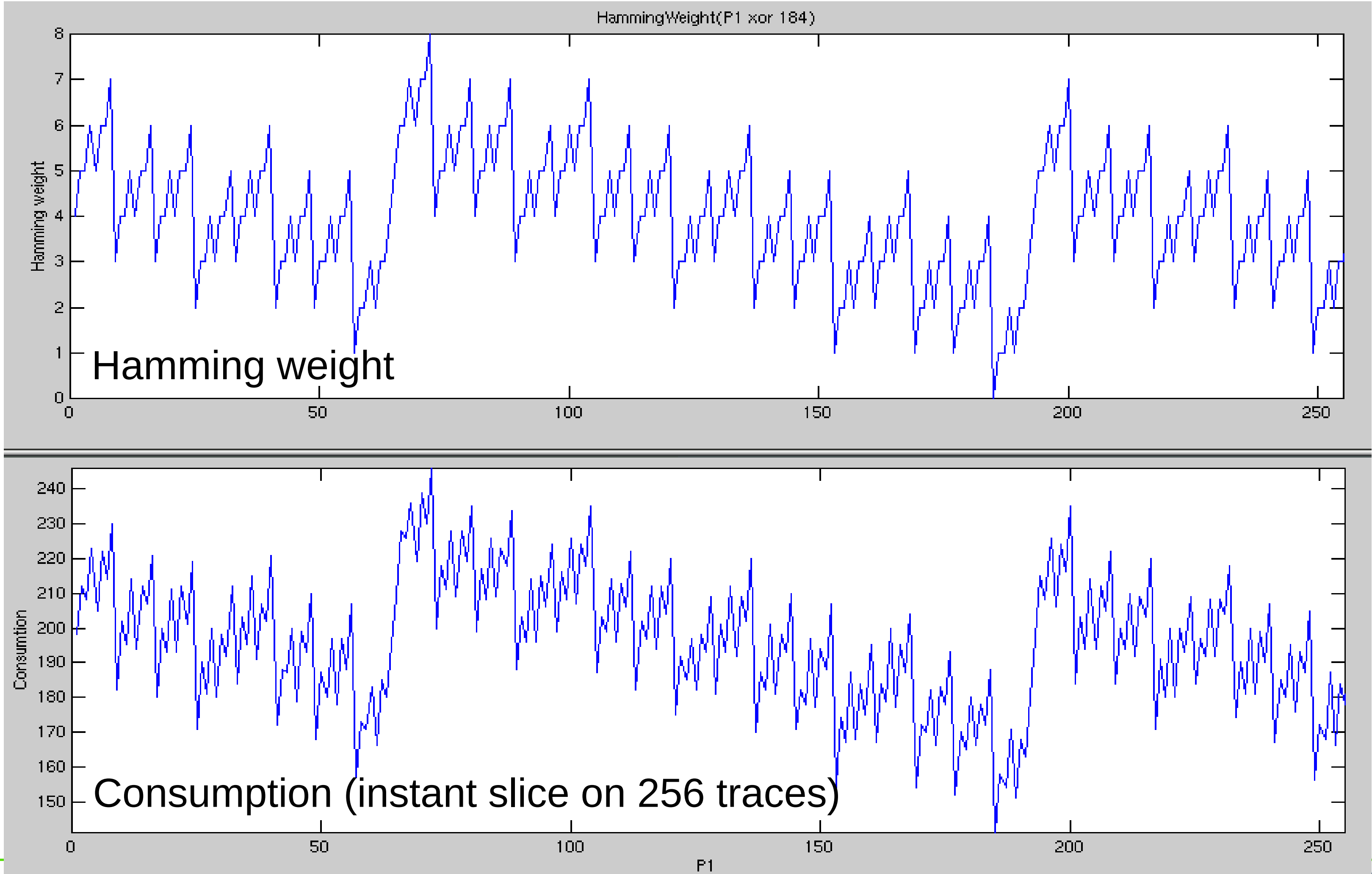
Information leakage

Load P1 and XOR with P2 = 0 (P1 ⊕ P2 with P1 = 0, 1, 7, 255)

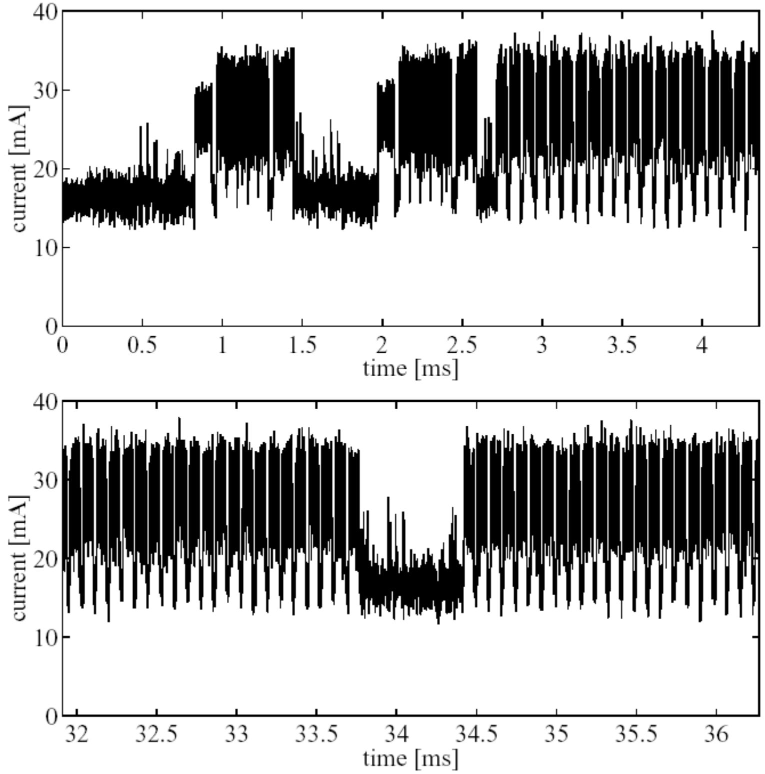


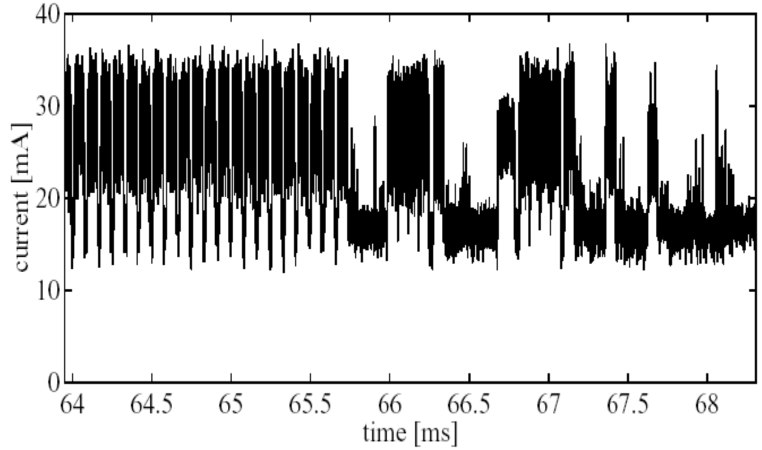
Information leakage

HW (P1 ⊕ 184), for P1 = 0, 255



Power Consumption of RSA-CRT





Cited from the paper: R.Novak, ``SPA-Based Adaptive Chosen Ciphertext Attack on RSA Implementation,'' PKC 2002, LNCS 2274, pp.252-262, 2002.

Side Channel Attacks

Left-to-right binary method

Input **M, n, d**

Output **M^d mod n**

X= M;

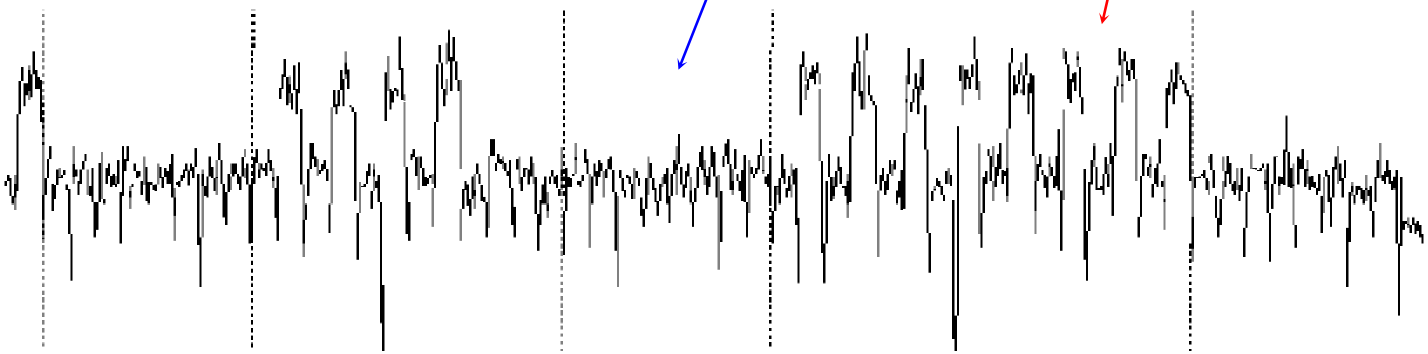
For i=k-2 to 0

  X = X*X mod n;

 if d[i]=1, then X=X*M mod n;

Return X

The time or the power to execute Squaring and Multiplication are different (side-channel information).



Cited from Clavier et. al, Universal exponentiation algorithm: A first step towards provable SPA-resistance, *CHES 2001*, LNCS 2162, pp. 300-308, 2001

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Simple Power Analysis

❍Simple (Single) Power Analysis context

- Find out a secret or private key
- Known algorithm
- Unknown implementation (*background culture recommended*)

❍Conditions

- 1 card available
- Learning phase required (*signature location*)
- Key inference on a single curve (*with relevant height of view)*
- Possibly known plain or ciphertext

SPA attack on RSA

- SPA against RSA private exponentiation

$$s = m^d \bmod n$$

  - n large modulus, say 1024 bits (n = p * q, with p & q large primes)
  - m message : slightly smaller than n (say 1023 bits)
  - s signature
  - d private exponent such that : e * d ≡ 1 mod (p-1)(q-1), with e public exponent

- The attacker aims at retrieving d

SPA attack on RSA

- basic "square and multiply" algorithm
- exponent bits scanned from MSB to LSB (left to right)

```
Let k = bitsize of d (say 1024)

Let s = m

For i = k-2 down to 0

  Let s = s*s mod n (SQUARE)

  If (bit i of d) is 1  then
   Let s = s*m mod n (MULTIPLY)
  End if

End for
```

Example :	$s = m^9 = m^{1001b}$
init (MSB 1)	$s = m$
round 2 (bit 0)	$s = m^2$
round 1 (bit 0)	$s = (m^2)^2 = m^4$
round 0 (bit 1)	$s = (m^4)^2 * m = m^9$

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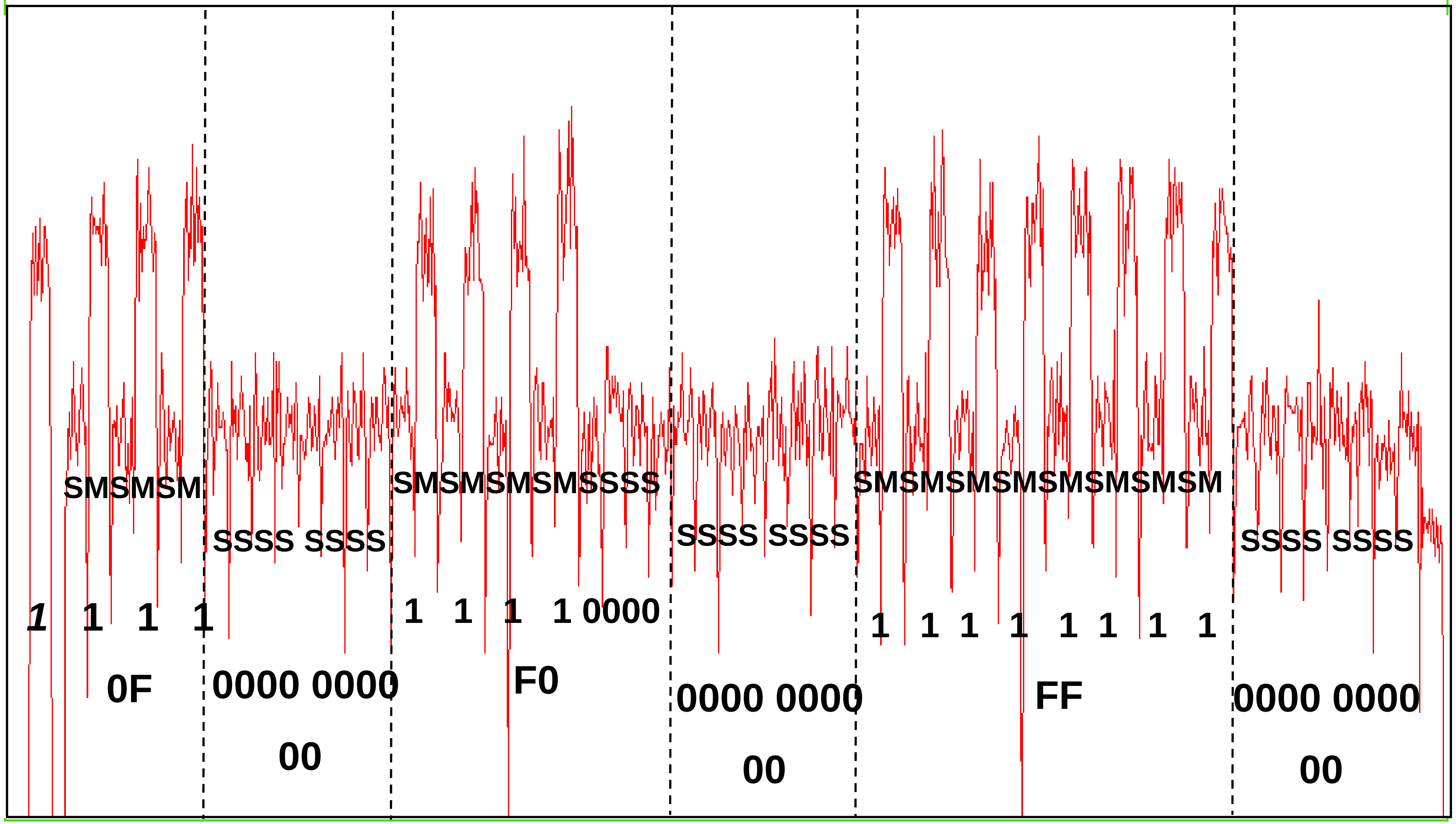
SPA attack on RSA

Test key value : 0F 00 F0 00 FF 00



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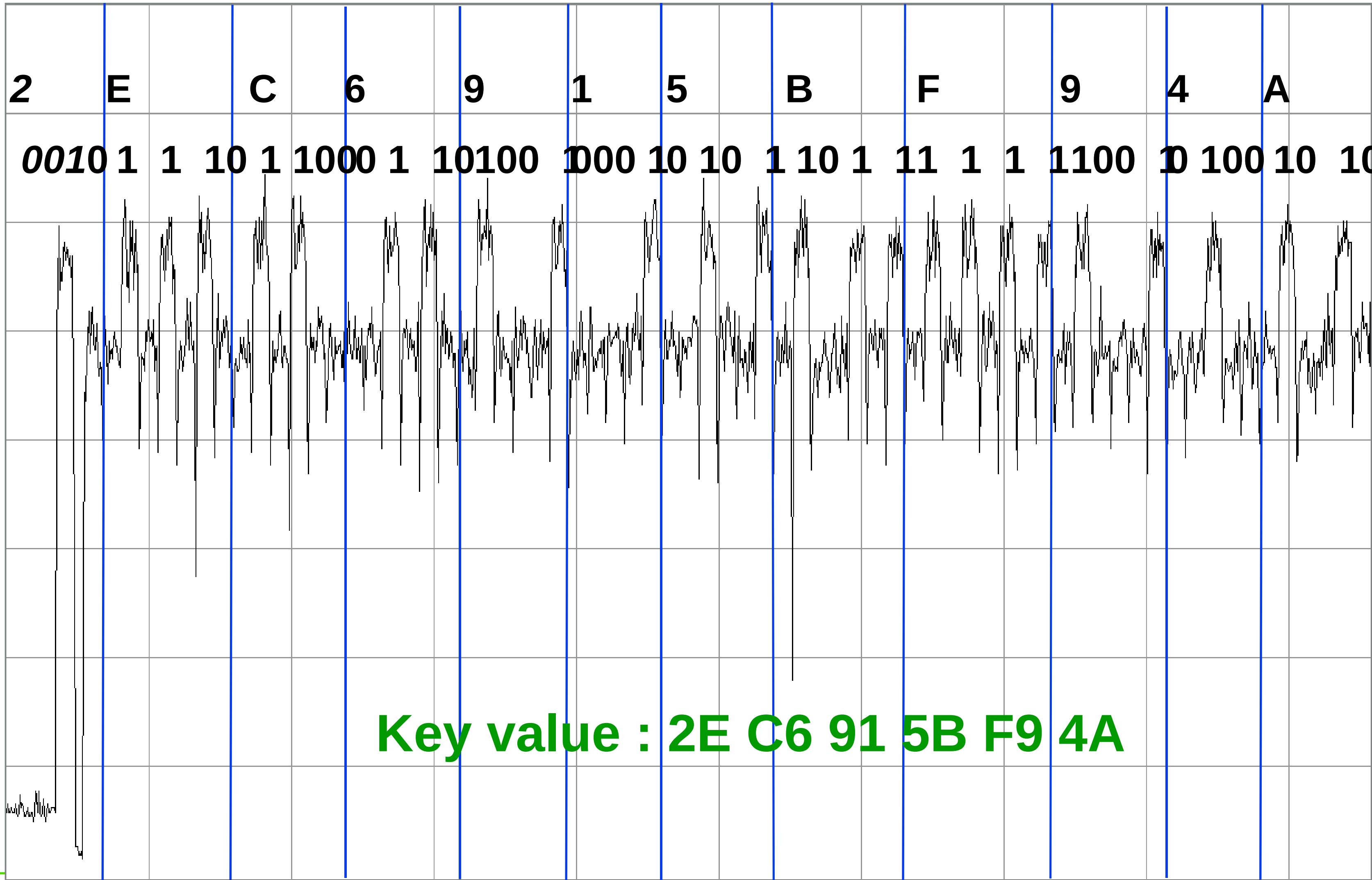
SPA attack on RSA



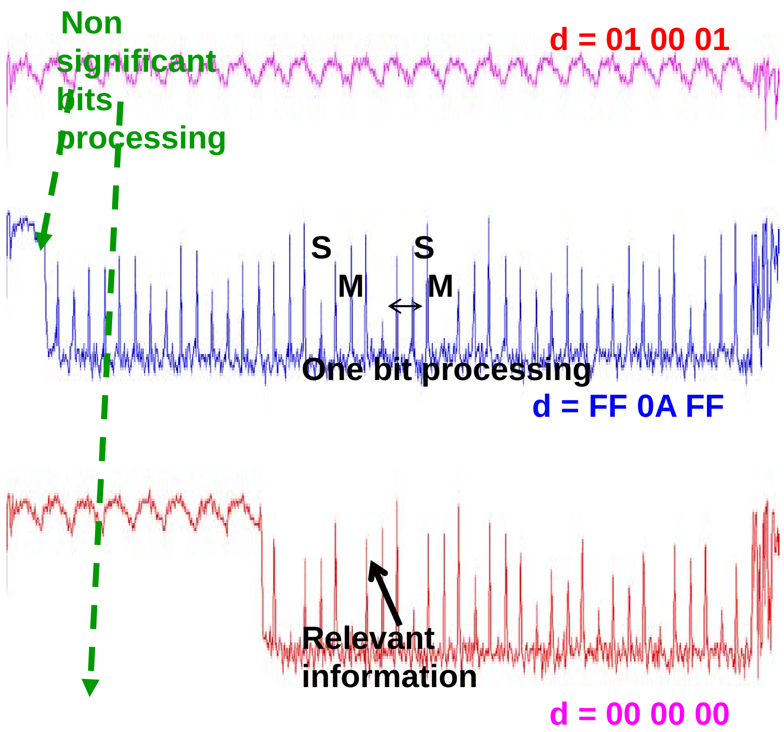
What you can do with SPA

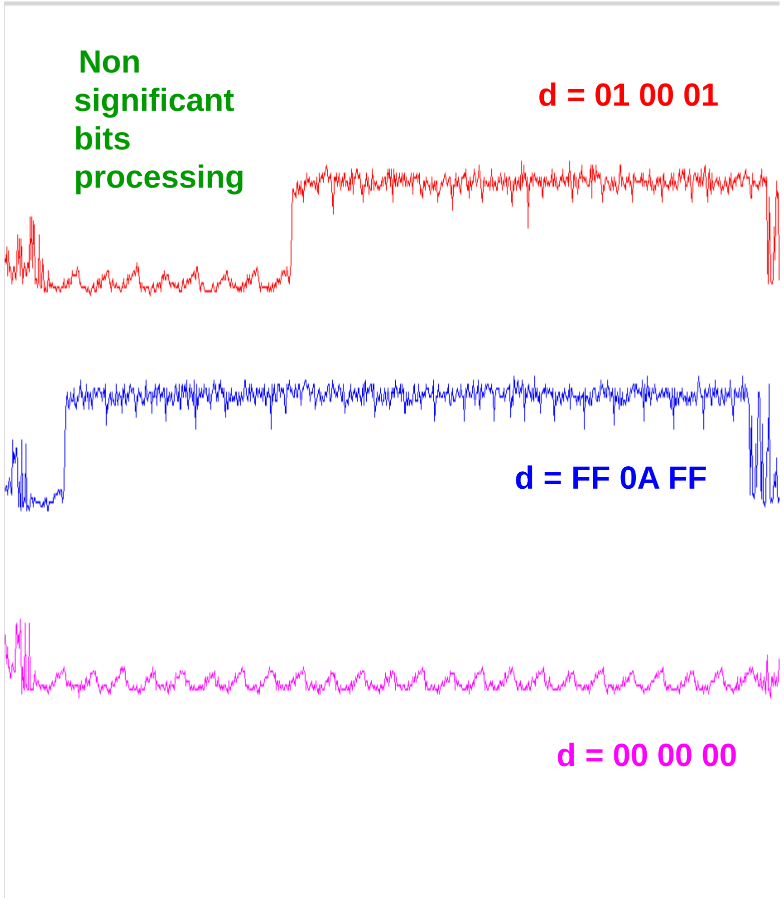
- SPA uses implementation related patterns
- SPA strategy
  - algorithm knowledge
  - reverse engineering phase (*signature location*)
  - representation tuning (*height of view*, *zoom, visualisation*)
  - then play with implementation assumptions...
- SPA is always specific due to
  - the algorithm implementation
  - the applicative constraints
  - the chip's technology (*electrical properties*)
  - possible counter-measures...

Counter-measures

- Counter-measure : anything that foils the attack !
- Trivial counter-measure
  - prohibit code branches conditioned by the secret bits
- Advanced counter-measures
  - algorithm specification refinement
    - code structure
    - data whitening
  - implementation design based on the chip's resources
    - play with instructions set
    - hardware electrical behaviour (current scrambler, desynchronisation, cryptoprocessor…)

Effects of Counter-measures





SPA possible

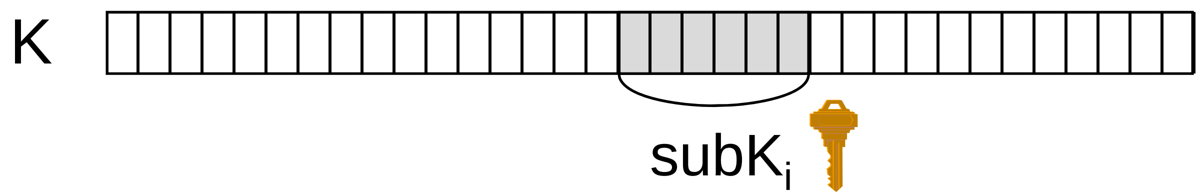
SPA resistant ! Although same specified RSA !

Differential Power Analysis

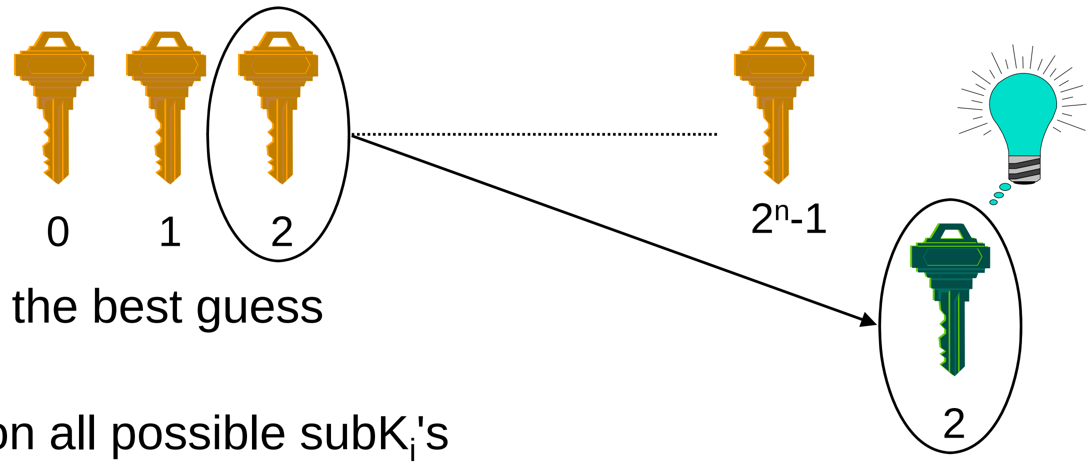
- required number of acquisitions : 500 to 10,000
- prerequisite
  - physical access to the card under attack
  - access to either plaintext M or ciphertext C
  - varying plaintext and constant key
  - algorithm specifications (MANDATORY)
- cost
  - A few dollars (to a few thousands)
  - A few days training
  - Average good level of expertise
  - Chip and implementation independent

Differential Power Analysis

- description :
  - choose a subset ($subK_i$) of n bits of K



  - perform a statistical test for each possible value of a $subK_i$

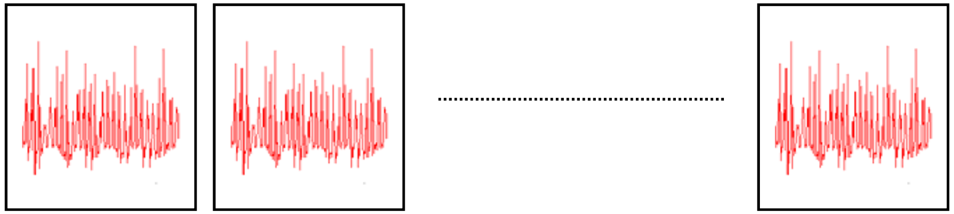


  - Choose the best guess
  - Iterate on all possible $subK_i$'s

Differential Power Analysis

❍DPA statistical test :

- a batch of data acquisitions for various messages M_k



0 1 k

- the corresponding plaintext M_k or the ciphertext C_k

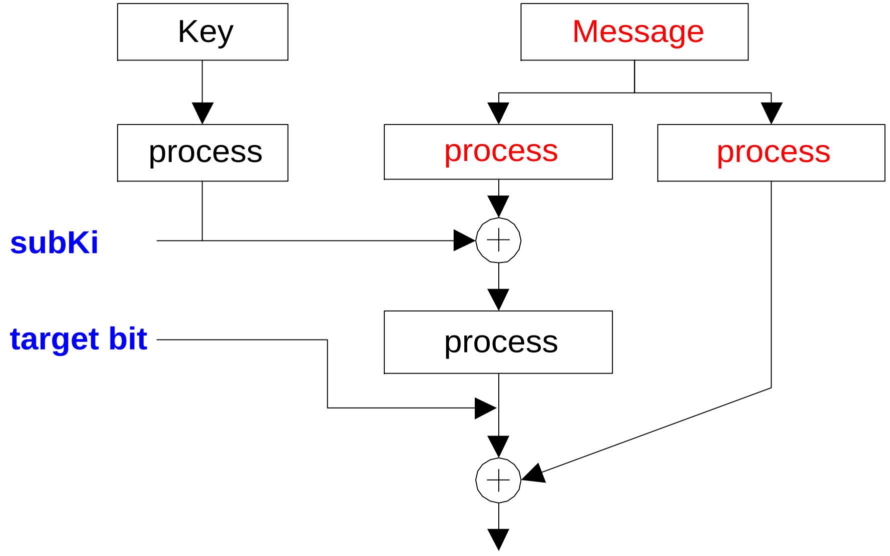
dfdsffb	fdgcxv	....	lklkjlsdq
M_0	M_1		M_k

- the values of the subK_i

0 1 2 2^n-1

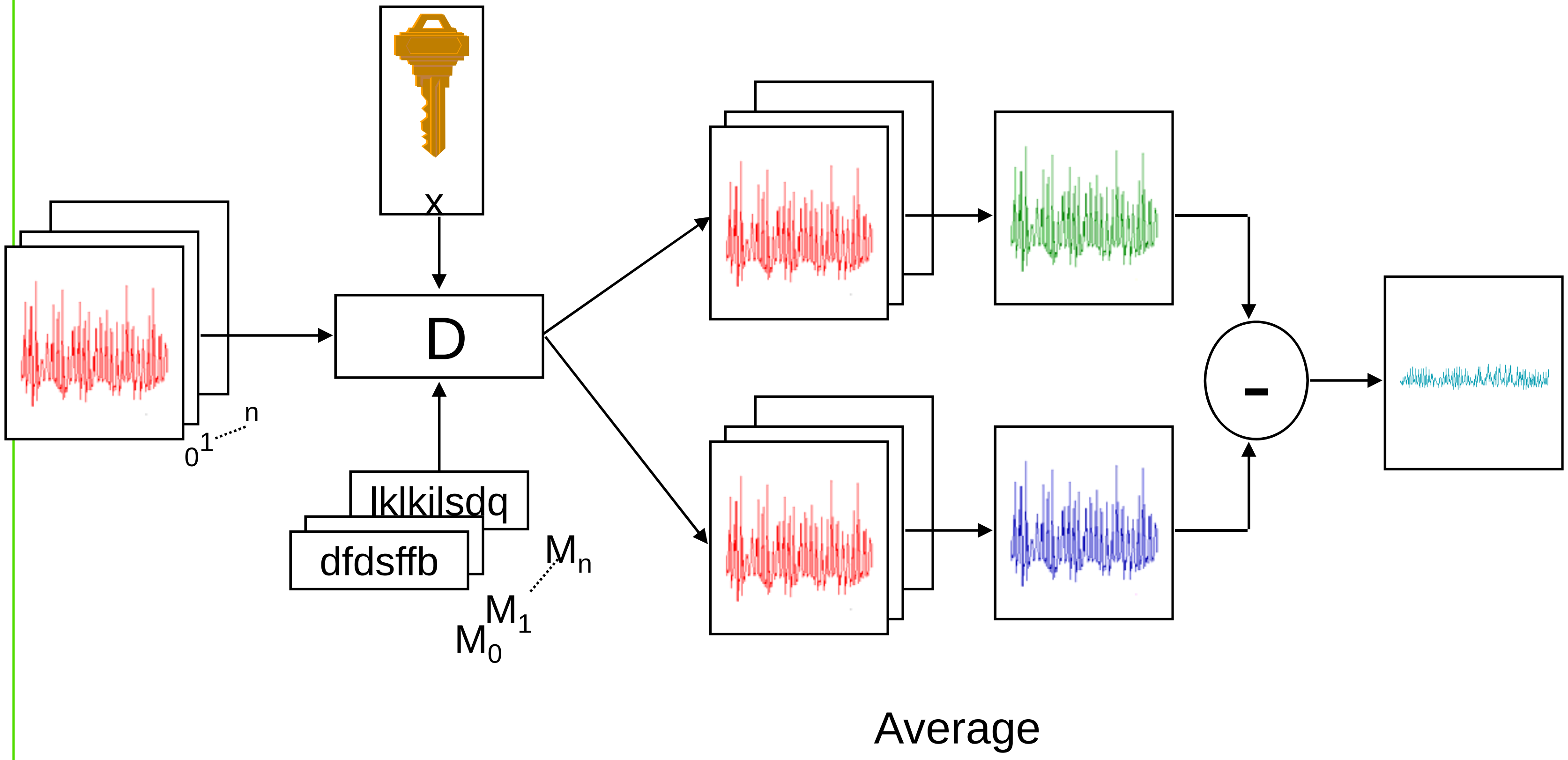
Differential Power Analysis

- DPA statistical test :
  - selection function D :
    - sort curves according to M_k or C_k for each value of a $subK_i$
    - output = image of a target bit of the algorithm



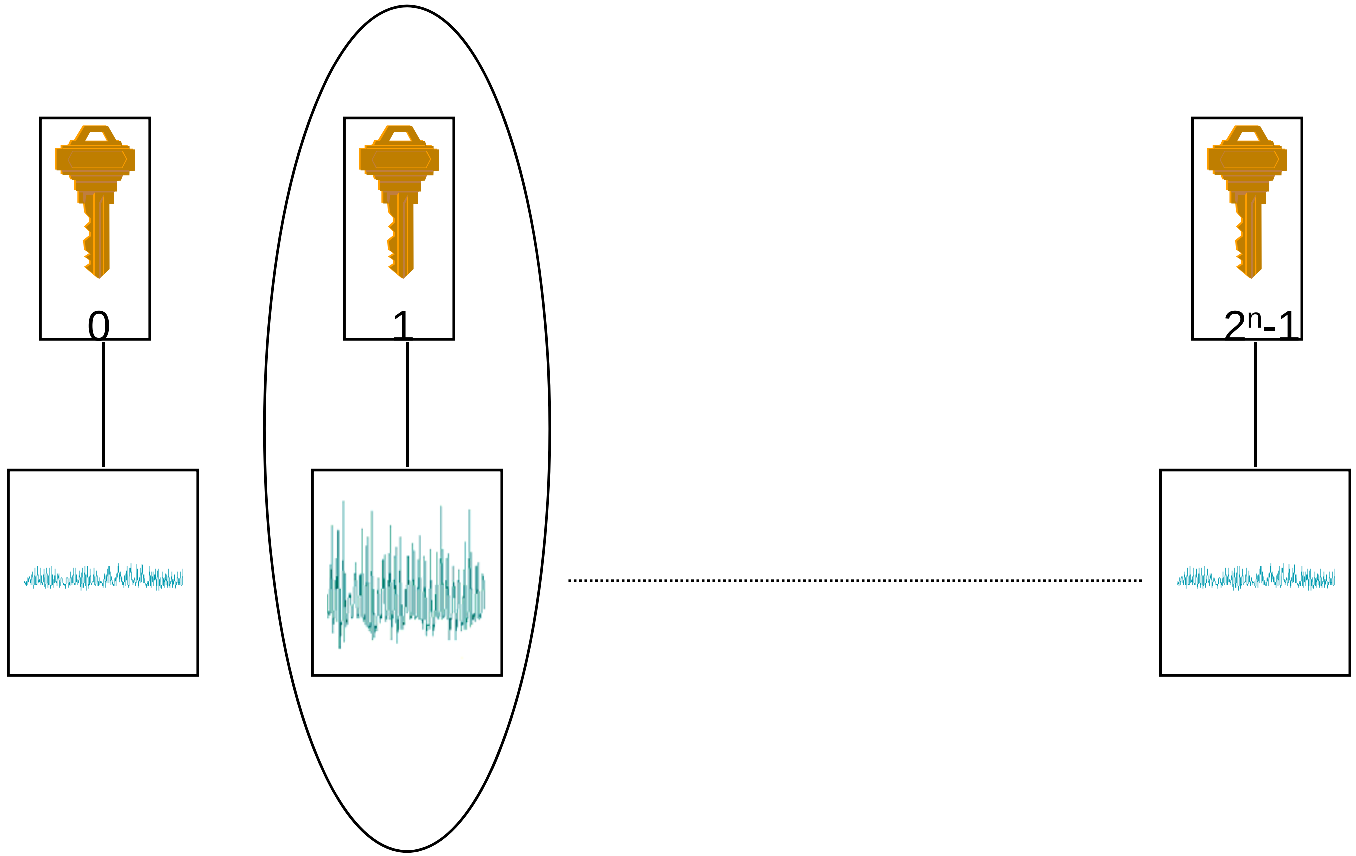
Differential Power Analysis

- data processing for a value x of a subK$_i$:



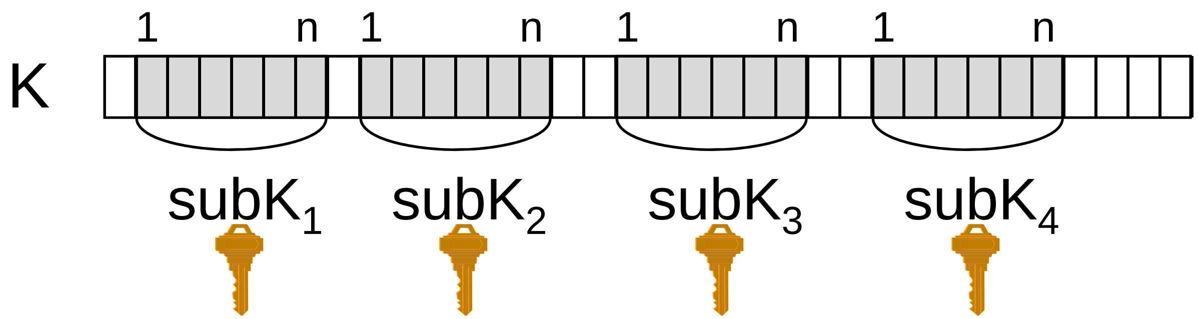
Differential Power Analysis

- Choosing the right guess

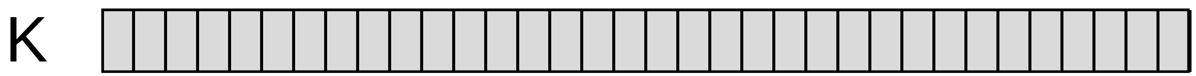


Differential Power Analysis

- iterate on all possible sub-keys :

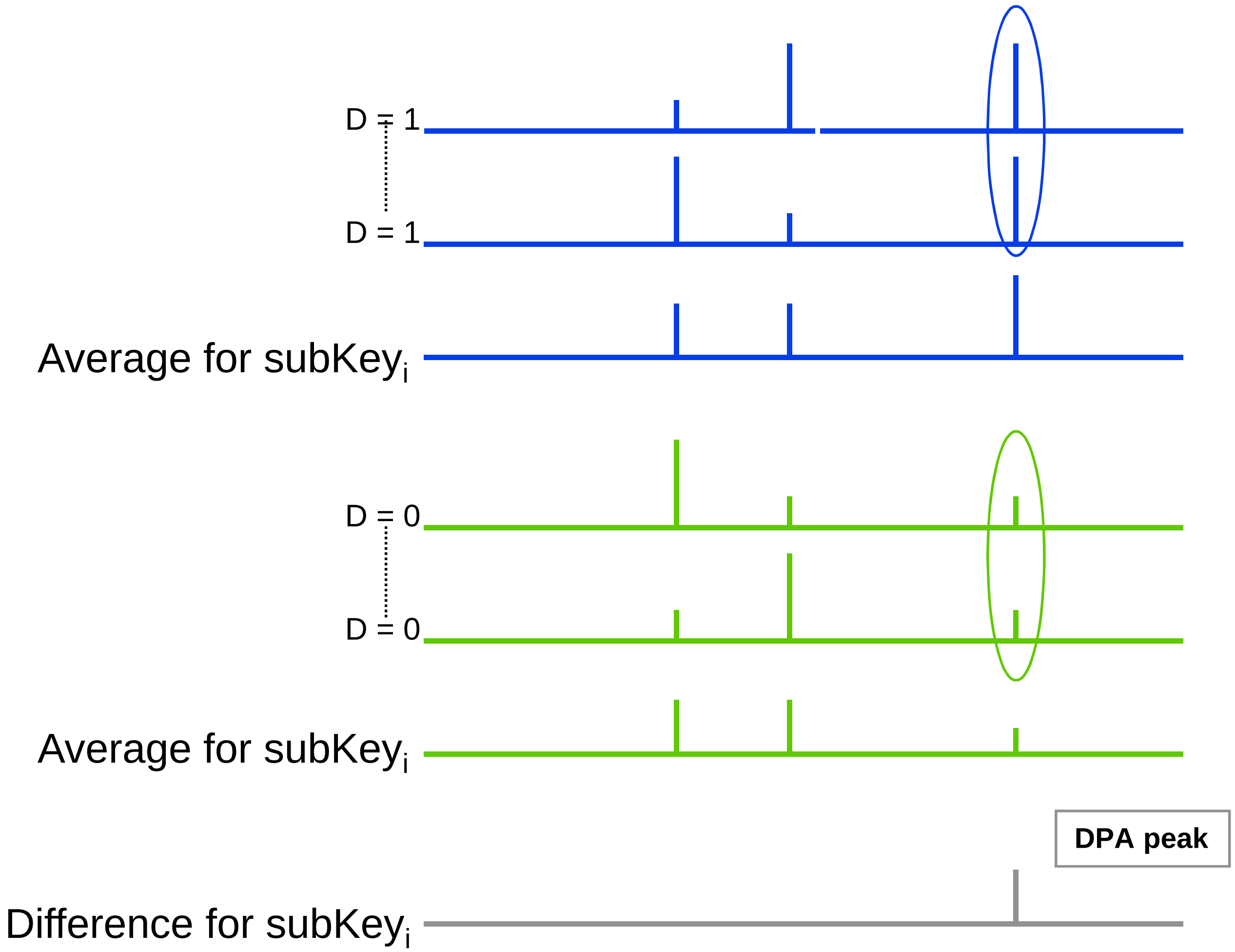


- find the remaining bits through exhaustive search



Differential Power Analysis

- How does it work ?



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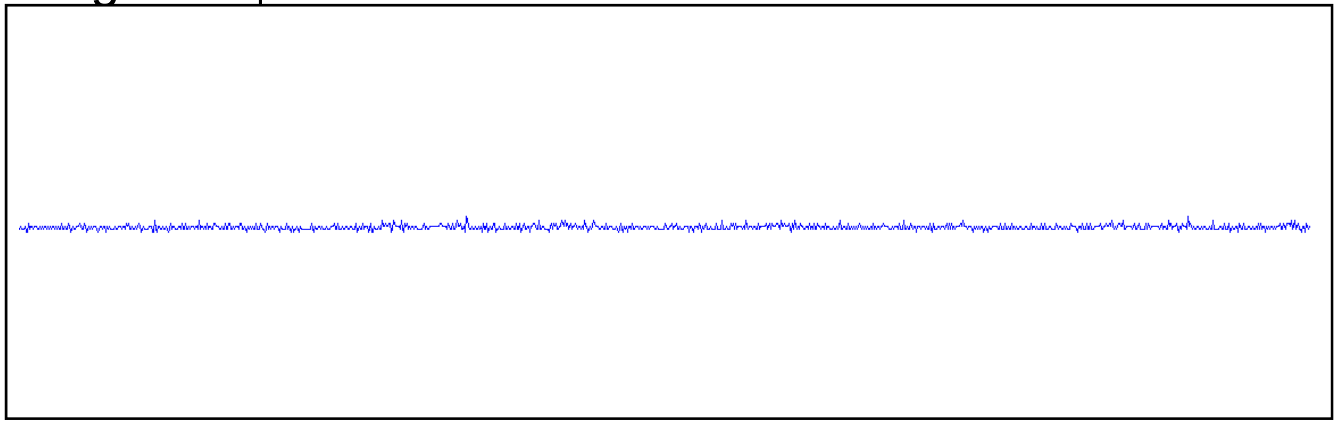
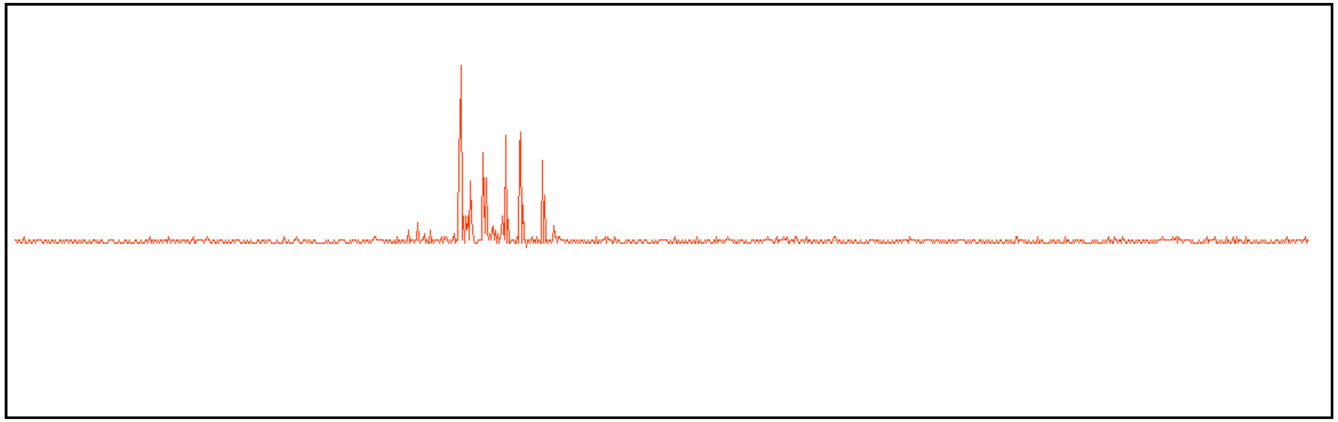
Differential Power Analysis

– wrong $subK_i$



– right $subK_i$



Counter-measures

- Add noise
- Scramble power consumption or stabilize it
- Randomize all sensitive data variables with a fresh mask for every execution of an algorithm

- Randomize, randomize, randomize …

  - Secret keys
  - Messages
  - Private exponents
  - Bases
  - Moduli

Example: DPA on RSA (1)

- DPA attacks on Modular exponentiation techniques [CHES'99 MDS]
- DPA - monobit exponentiation (« Square and Multiply » exponentiation algorithm 2):
- A(0) = 1
- for i = 0 to m-1
  - $A(0) = A(0)^2 \bmod N$
  - $A(1) = A(0)*X \bmod N$
  - $A(0) = A(d_i)$
- next
- return A(0)

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Example: DPA on RSA (2)

- Hypotheses:
  - – attacker has control of inputs to target device.
  - – attacker has some knowledge of the implementation hence can compute intermediate results using an offline simulation

- Secret exponent extracted bit by bit
- for i = 0 to m
  - – set d' = $d_0 \ldots d_{i-1} || 1$ and d' = $d_0 \ldots d_{i-1} || 0$
  - – accept d' which produces best correlation/match with the offline calculation.

Conclusion on Power Analysis Attacks

- Naïve smartcard implementations of cryptosystems can leak secret data.
- Power Analysis Attacks
  - – target symmetric and asymmetric cryptosystems
  - – practical, ‘fast’ and cheap
  - – difficult to circumvent
  - – countermeasures may impact efficiency.

First DPA Countermeasures

- Remove data dependent processing.
- Introduce 'noise' to reduce signal to noise ratio.
  - – Vertical noise in the CPU processing
  - – Horizontal noise - insertion of dummy cycles or instructions in the CPU processing may make synchronisation difficult.
  - – Concurrent processing.
  - – Hamming weight balancing.
- All of these can be circumvented given enough processing examples.

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DPA Countermeasures for RSA

- Algebraic approaches (power consumption is not directly correlated with sensitive data).
  - – Exponent Blinding
    - 'add' a random number, r, to the exponent.
      d → d + r * phi(N)
  - – Exponent splitting
    - E.g. represent $d = d_1 + d_2$ where $d_1 = r$, $d_2 = d-r$ and r is random.
  - – Message Blinding
    - M → r_1* M mod N (r_1 random).
  - – Modulus Blinding
    - N → r_2* N (r_2 random).
  - – Randomised exponentiation
    - numerous approaches.

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(Differential) Fault Attacks

Introduction

- Fault Attacks where first published as a way of jeopardising computations of cryptographic algorithms (RSA, DSA, DES).

- However, you can imagine to implement fault attacks on other processes inside a microprocessor.

- Fault attacks are real industrial security concern:
  - To pass some certification, like FIPS140-1 level 3 (US government security certification), you should prove that your system resists to fault attacks.

Different types of faults

❍ Transients Faults.

– Appear randomly in a system, have various unpredictable causes.

❍ Latent or Internal Faults.

– Are the result of hardware or low level software default (floating point unit on Pentium chips,...).
– Rarely controllable

❍ Induced Faults.

– Appear after intentional stress (E^2) or hardware "mutilation”, can be transient or permanent.
– Sometimes controllable with knowledge of the physical/chemical/electrical behaviour of the chip.

The DFA crisis: 1996

September 96

- Attack on RSA CRT by Bellcore (*EuroCrypt'97*)
- Attack improvements by Lenstra

October 96

- *18:* DFA on DES by Biham et Shamir
- *29:* Attack on RSA and ElGamal
- *30:* DFA on unknown cryptosystems by Biham & Shamir. *«Differential Fault Analysis of Secret Key Cryptosystems» (Crypto'97)*

November 96

- Attack of CRT on LUC and Demytko by Marc Joye and JJ Quisquater

Attack on standard signature

- Hypothesis:
  - the message m and its signature $s = m^d$ are known
  - a fault is injected on one bit i of d
  - this results in a wrong signature $s' = m^{d'}$

- **Then :**
- $s'/s = m^{d'-d} = m^{2^i}$ **mod n if bit *i* was 0**
- **or**
- $s'/s = m^{d'-d} = m^{-2^i}$ **mod n if bit *i* was 1**

- One bit in random position of the secret exponent is discovered every round.

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Attack on standard signature

- Faults can be induced on more than one bit, making analysis slightly more difficult.

- This attack is compatible with transient or permanent faults.

Recall on CRT

- The Chinese Remainder Theorem is used in RSA in order to speed up exponentiation by a factor of 4.

- Exponentiation is performed in three steps
  – $s_p = m^d \bmod p$ is computed (in fact, d_p is used)
  – $s_q = m^d \bmod q$ is computed (in fact, d_q is used)
  – the signature is recombined with CRT as

$$s = a.s_p + b.s_q \bmod n,$$

- The constants a and b are precomputed such that

$$a = 1 \bmod p, \qquad b = 0 \bmod p,$$
$$a = 0 \bmod q, \qquad b = 1 \bmod q.$$

Attack on CRT exponentiation

- This attack was first published by Lenstra.

- Hypothesis:
  - *s*, signature of a message *m* is known.
  - a fault is injected in the exponentiation mod *p.*

- Due to error injection, s_p becomes s_p'

$$s' = a.s_p' + b.s_q \bmod n,$$

- $$s'-s = (a.s_p' + b.s_q) - (a.s_p + b.s_q) \bmod n$$
- $$s'-s = a.(s_p' - s_p) \bmod n$$

- **the prime *q* divides *a* and can be retrieved by Gcd.**

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Summary of the Differential Fault Attack (DFA)

An attacker obtains a decryption which is computed in a wrong way.

$M = C^d \bmod n$

n

Fault

$dp = d \bmod (p-1)$

$Mp = C^{dp} \bmod p$

p

$dq = d \bmod (q-1)$

$Mq' = C^{dq} \bmod q$

q

$M' = Mp + pv \bmod n,\ v = (Mq' - Mp)\, p^{-1} \bmod q$

n

In the RSA using the CRT, if an attacker can cause a fault for the computation of Mq, then n can be factored by gcd(M-M',n)=p.

Counter-measures on RSA

❍ Applicative counter-measures

– Use a random padding with sufficient variability

– Compute the result twice and compare

– Verify that $s^e = m \bmod n$ when e is known

- *e* is usually a small number, verification is very fast

❍ Algorithmic counter-measures

– One possible counter-measure on RSA-CRT intends to protect both half-exponentiations by:

- choosing a small random number r
- computing $s_{pr} = m^d \bmod pr$ et $s_r = m^d \bmod r$
- checking whether $s_{pr} \bmod r = s_r$

Hardware aspects of fault attacks

- Flaw injection in this case is a hardly controllable and reproducible process.

- Implementation is not that easy:

– Stress on memories, during read/writing/retention
    - By means of variations on power supply, frequency
    - Through various types of radiation

– Modifications on hardware mechanism
    - Using probing or FIB
        - – Buses
        - – Random generators
        - – Crypto-coprocessors
        - – Hardware DES

Fault attacks and smart cards

- Need expertise in measurements and hardware to implement efficient fault attacks.

- Smart cards give many tools to defeat fault attacks:
  - Tamper-evidence
    - Security sensors, security mechanisms
  - Software counter-measures
    - On algorithms, on secret storage