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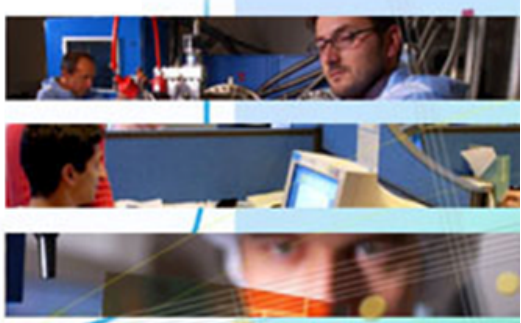
Analyse cryptographique des altérations d'algorithmes : Applications au RSA

Alexandre Berzati

CEA-LETI Minatec et Université de Versailles

20 Janvier 2009



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Outline

Introduction on RSA | Attack on "R2L" exp. | Attack on "L2R' exp. | Conclusion

1 Introduction on RSA

2 Attack on "R2L" exp.

3 Attack on "L2R' exp.

4 Conclusion

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Introduction

Description

Fault analysis on a standard RSA implementation by perturbating the public modulus

Motivation

Emphazing the importance of securing RSA public elements

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Outline

1 Introduction on RSA
- Fault Analysis Principle
- Previous work
- Overview of our attack

2 Attack on "R2L" exp.

3 Attack on "L2R' exp.

4 Conclusion

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RSA Cryptosystem

- Public Key
  - Modulus N such that $N = p \cdot q$, p and q prime and kept secret
  - The exponent e such that $\gcd(e, \varphi(N)) = 1$, where $\varphi(.)$ denotes Euler's totient function and $\varphi(N) = (p-1) \cdot (q-1)$

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  - The exponent d such that $e \cdot d \equiv 1 \bmod \varphi(N)$

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- RSA functions
  - Encryption of a message $m \Rightarrow C \equiv m^e \bmod N$

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  - Decryption of the cyphertext $C \Rightarrow \tilde{m} \equiv C^d \equiv m^{e \cdot d} \bmod N$
  - Signature of a message $m \Rightarrow S \equiv \dot{m}^d \bmod N$

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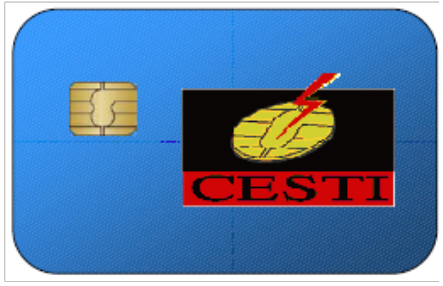
Fault Analysis Principle

- Differential Fault Analysis (*DFA*)
  - Identify the perturbation
  - Model faults
  - Differentiate correct and faulty outputs

Smart card input:
00101101 ... $\Longrightarrow$

Smart card output:
01010001 ... $\Longleftarrow$



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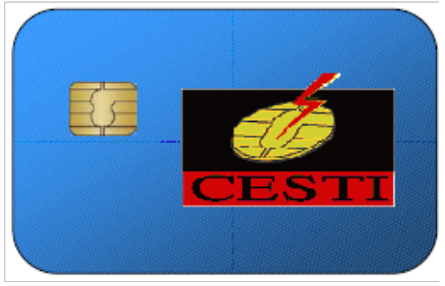

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2 Attack on "R2L" exp.

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DFA on RSA Public Elements

- *On authenticated computing and RSA-based authentication* (Sei05), ACM-CCS 2005

- *Is it wise to publish your Public RSA Keys ?* (GS06), FDTC 2006
  - Corrupt the RSA signature scheme without recovering the secret exponent *d*
  - Rely on a specific fault model

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- *Why One Should Also Secure RSA Public Key Elements* (BCMCC06), CHES 2006
  - Recover the secret exponent *d*
  - In a variant the analysis doesn't rely on any fault model

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  - Modification during the exponentiation

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- Our attack works by only modifying the public modulus *N*
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- Provides both partial and full secret key recovery:
  - Each faulty execution analysis makes the attacker recover a part of *d*
  - Cascading partial results leads to a full recovery of *d*

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- Applies on Standard RSA functions that handles the secret key
  - Signature (with deterministic padding)
  - Decryption

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- Applies on Standard RSA functions that handles the secret key
  - Signature (with deterministic padding)
  - Decryption
- Provides a faster attack algorithm

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RSA Exponentiation Algorithm

"Right-to-Left" Algorithm

Input: m, d, N
Output: $A = m^d \bmod N$

```
1 : A:=1;
2 : B:=m;
3 : for i from 0 upto (n − 1)
4 :     if (d_i == 1)
5 :         A := (A · B) mod N;
6 :     end if
7 :     B := B^2 mod N;
8 : end for
9 : return A;
```

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Fault model

- Perturbation of the Standard RSA signature
  - Transient byte fault on the public modulus *N*
  - Fault injected on a square *j* steps before the end of the exponentiation
  - The time location of the fault is known by the attacker

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$$\hat{N} = N \oplus \varepsilon$$

where $\varepsilon = R_8 \cdot 2^{8i}$, R_8 is a random byte value and $i \in [\![0; \frac{n}{8} - 1]\!]$

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- Then, the end of the exponentiation is executed with a faulty modulus $\hat{N}$

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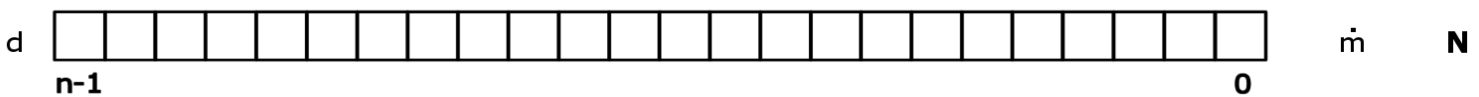
Faulty Execution of the *"Right-to-Left"* Algorithm



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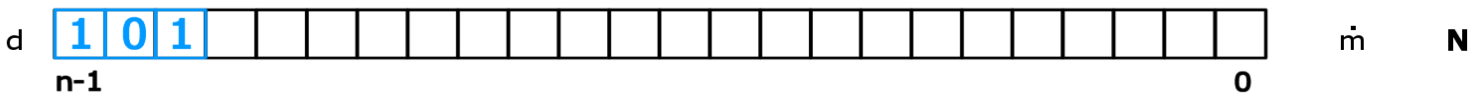

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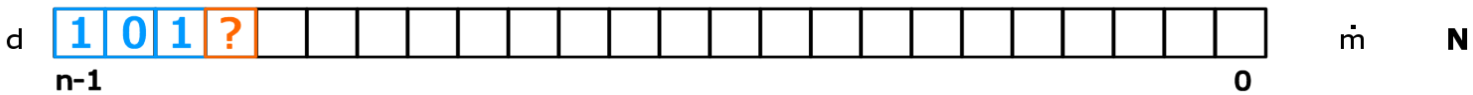
Faulty Execution of the *"Right-to-Left"* Algorithm

- A part of *d* is already known
- The attacker wants to recover *l* bits of *d*
  - *l* is a window length parameter



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Faulty Execution of the *"Right-to-Left"* Algorithm

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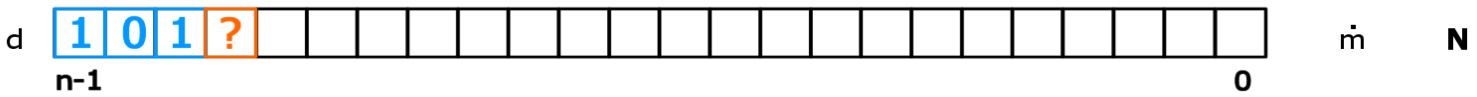
- The attacker wants to recover *l* bits of *d*
  - *l* is a window length parameter
  - For this example $l = 1$



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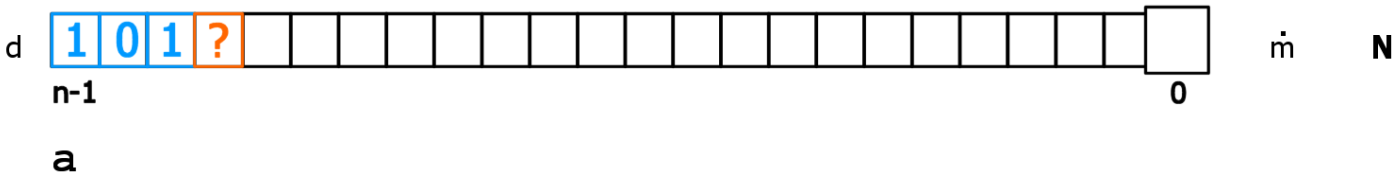

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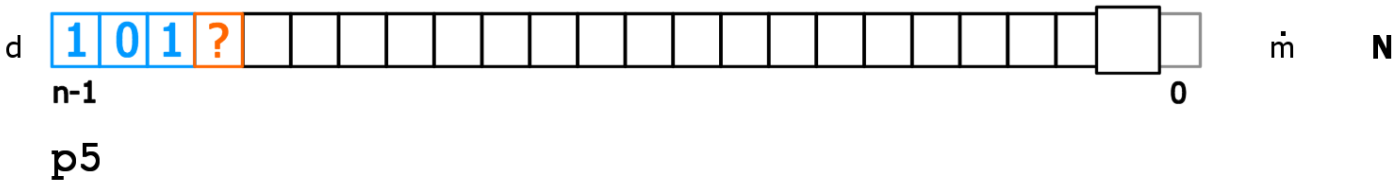

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Faulty Execution of the *"Right-to-Left"* Algorithm

- Example of a faulty execution

Ŝ 10th anniversary of CHES

- Consequences of the fault
  - The fault injection splits the faulty signature $\hat{S}$ into a correct part and a faulty one:

$$\hat{S} \equiv [(\dot{m}^{\sum_{i=0}^{(n-j-1)} 2^i \cdot d_i} \bmod N) \cdot (\dot{m}^{2^{(n-j-1)}} \bmod N)^{\sum_{i=(n-j)}^{n-1} 2^{[i-(n-j)+1]} \cdot d_i}] \bmod \hat{N}$$

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Fault Analysis

- Result of the faulty execution

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Fault Analysis

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- Attack principle

s r54_Correc+_519n4+ur3

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Faulty Execution of the *"Left-to-Right"* Algorithm

- Under the same fault model the result of the perturbation is:

$$\hat{S} \equiv [(\dot{m}^{\sum_{i=j}^{(n-1)} 2^i \cdot d_i} \bmod N)^{2^j} \cdot (\dot{m}^{2^{(n-j-1)}} \bmod N)^{\sum_{i=0}^{j-1} 2^i \cdot d_i}] \bmod \hat{N}$$

- The extra squares modulo $\hat{N}$ defeat the *"Right-to-Left"* analysis

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- The extra squares modulo $\hat{N}$ defeat the *"Right-to-Left"* analysis

- Square roots are computable if $\hat{N}$ is prime or *B*-smooth

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Faulty Execution of the *"Left-to-Right"* Algorithm

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- The extra squares modulo $\hat{N}$ defeat the *"Right-to-Left"* analysis
- Square roots are computable if $\hat{N}$ is prime or *B*-smooth
- We have to study the consistency of considering only prime faulty moduli

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Study of the new fault model

- Assumptions on the perturbation of the modulus
  - Transient fault on the public modulus N:

$$\hat{N} = N \oplus \varepsilon$$

    where $\varepsilon = R_{8k} \cdot 2^{8k \cdot i}$, R_{8k} is a k-byte random value and $i \in [\![0; \frac{n}{8k} - 1]\!]$
  - We consider only prime $\hat{N}$

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- Results obtained

Archi.	n bits	# of $\hat{N}$	# of prime $\hat{N}$	# of exp.	# of primes		
					Min.	Avg.	Max.
8-bit	1024	2^{15}	46.186	114890	18	46.26	79
8-bit	2048	2^{16}	46.176	57170	22	46.19	80
16-bit	1024	2^{22}	5911.83	17725	5621	5919.08	6212
32-bit	1024	2^{37}	$\approx 1,94 \cdot 10^8$				

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32-bit	1024	2^{37}	$\approx 1,94 \cdot 10^8$				

- $\hat{N}$ has one chance over 709 to be prime on an 8-bit architecture

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Fault Analysis

- Attack principle
  - Precomputation of a dictionnary of prime faulty moduli
  - Choose a candidate pair $(d'_{(k)}, \hat{N}')$ and compute
    1. $S' \equiv \hat{S} \cdot \dot{m}^{-d'_{(k)}} \bmod \hat{N}'$
    2. Test if S' is a k-th quadratic residue modulo $\hat{N}'$, else the pair is rejected
    3. Check if $S \equiv (S')^{2^k} \cdot \dot{m}^{d'_{(k)}} \bmod N$ is satisfied to validate the candidate pair
  - Cascade the resolution using the already recovered part of d

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Fault Number

- Fault number

$$\#fault = \mathcal{O}\left(\frac{n^2}{1.441 \cdot l}\right) \text{ tries}$$

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- Additional Remark
  - The probability for $\hat{N}$ to be prime depends on the byte location of the fault

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Possible countermeasures

- Random mask on the exponent
  - The private exponent d is masked such that:

$$d_{mask} = d + k \cdot \varphi(N)$$

where k is a random value longer than the resolution window length l

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- Error detecting mechanism (Hardware or Software)

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Conclusion

- Work in progress
  - Applications to elliptic curve cryptography

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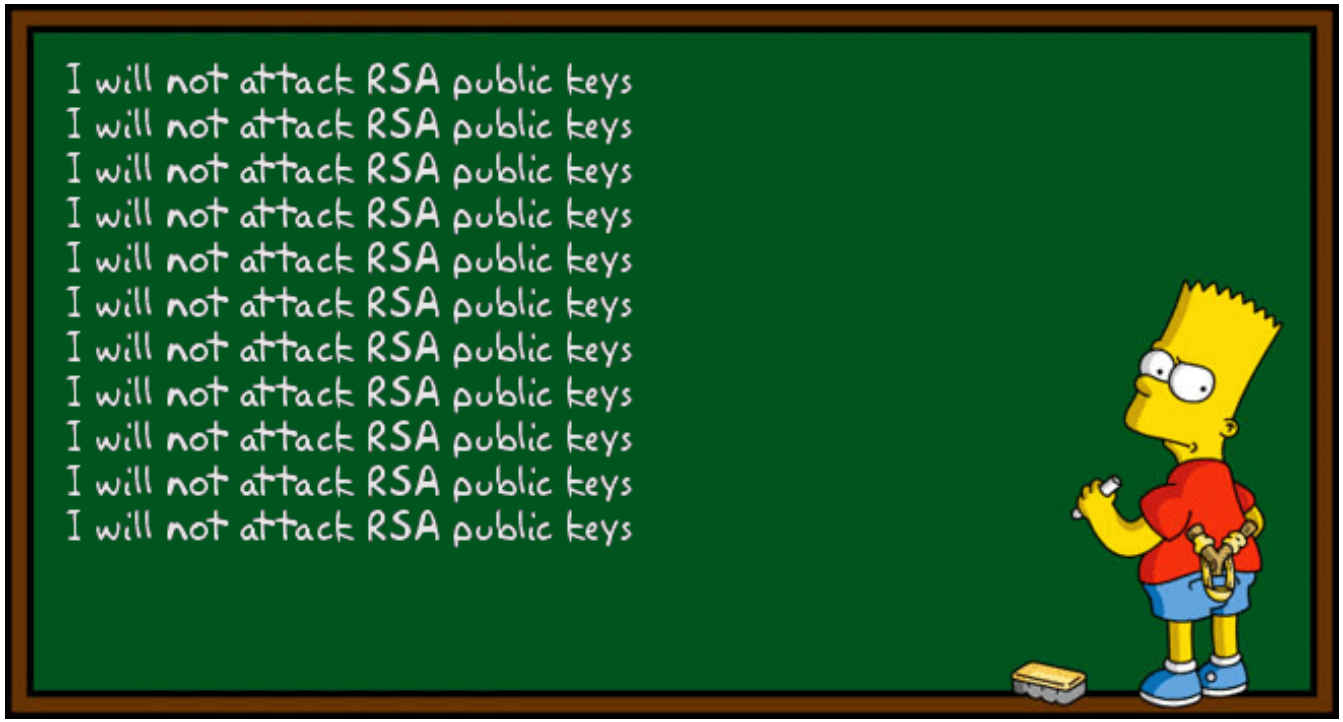
Conclusion

- Work in progress
  - Applications to elliptic curve cryptography
- Thank you for your attention !



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