pace
Physical Analysis and Cryptographic Engineering

FDTC 2018
Fault Diagnosis and Tolerance in Cryptography

Breaking Redundancy-Based Countermeasures with Random Faults and Power Side Channel

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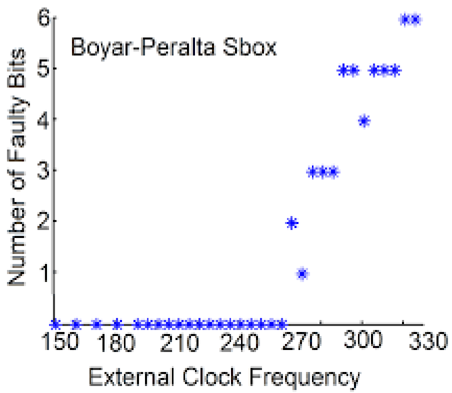
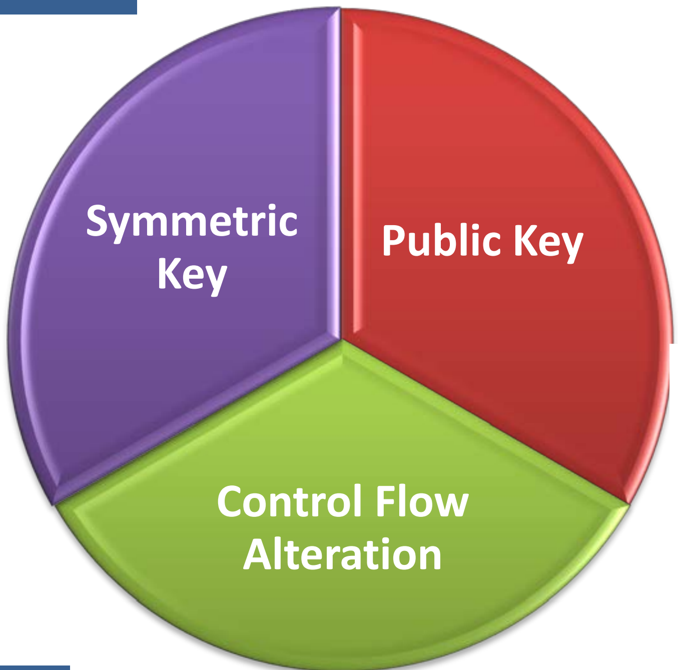
Introduction

Localized Random Faults

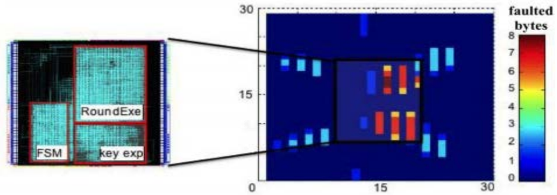


Biased Faults



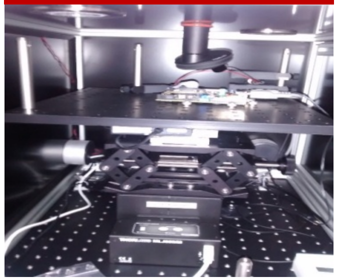
Instruction Skip/Modify

```
1 LDD  R24, Y+i   // load subkey
2 LD   R25, X     // load state
3 EOR  R24, R25   // ExclusiveOR
4 STD  Z+i, R24   // store result
```



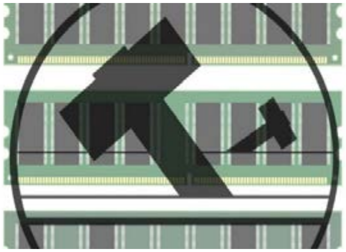
Cartographic view of internal registers

Laser-FI



EM-FI

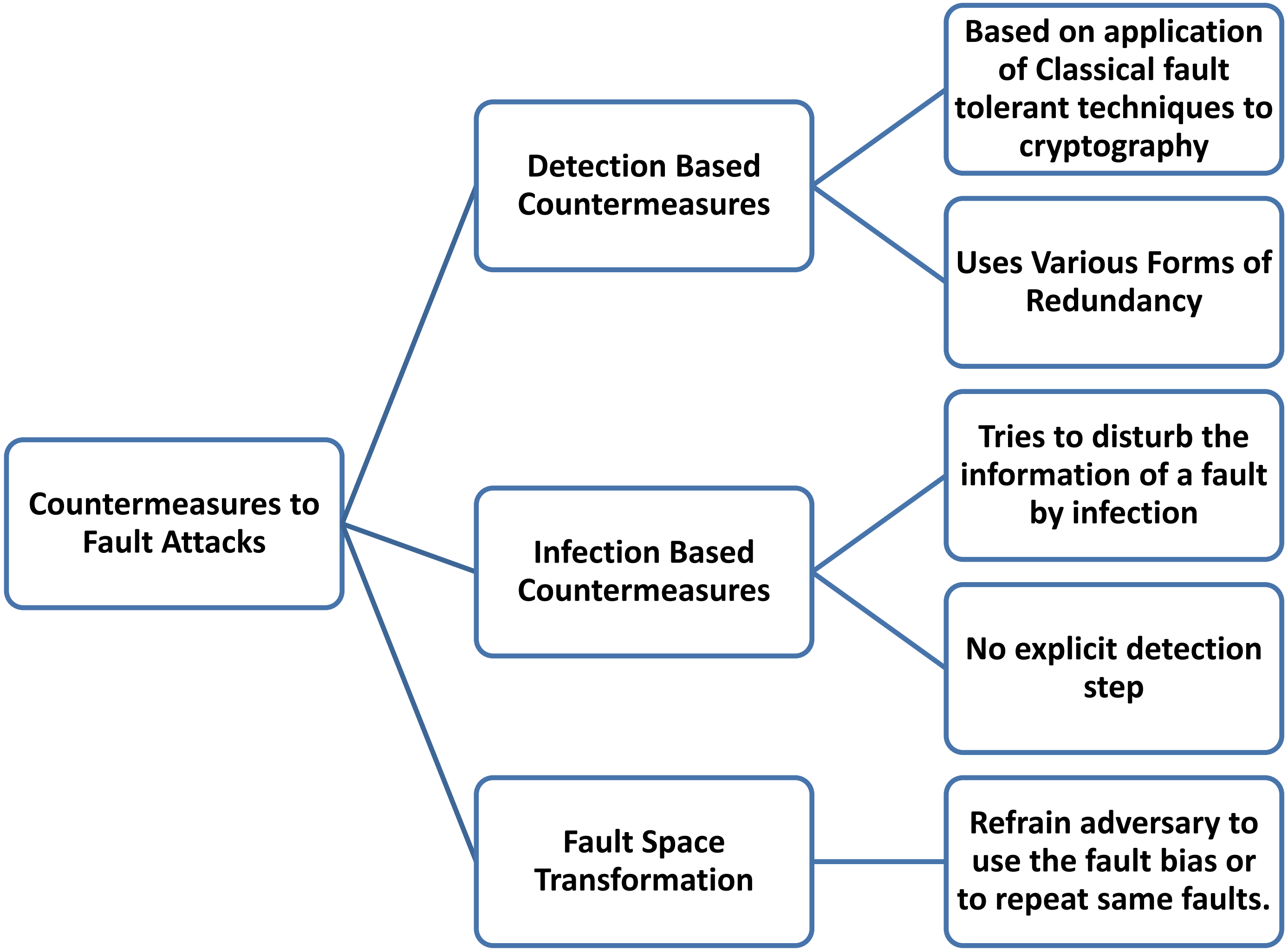
Row-Hammer



Voltage-Glitch

Clock-Glitch

Countermeasures Against Fault Attacks



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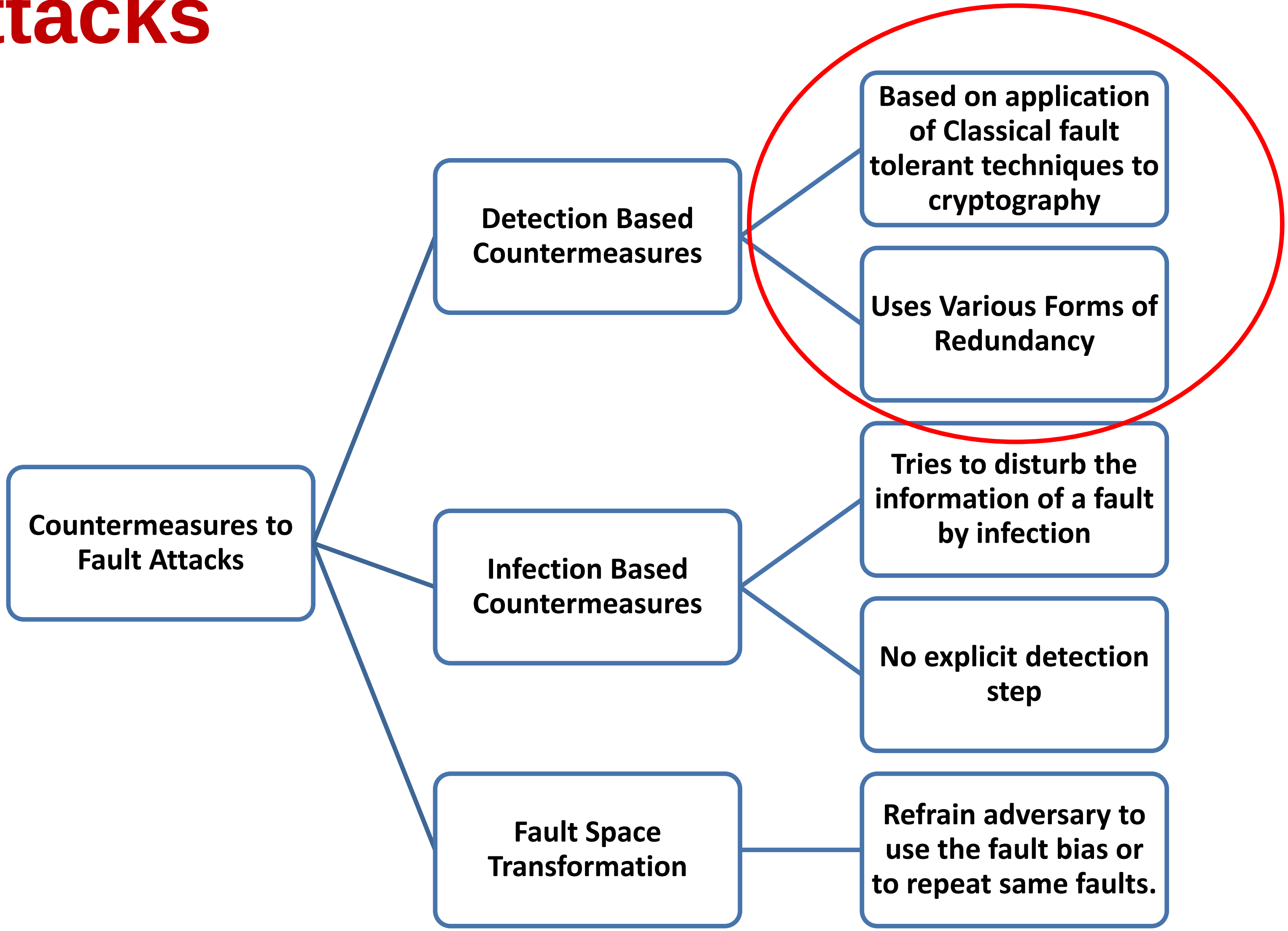
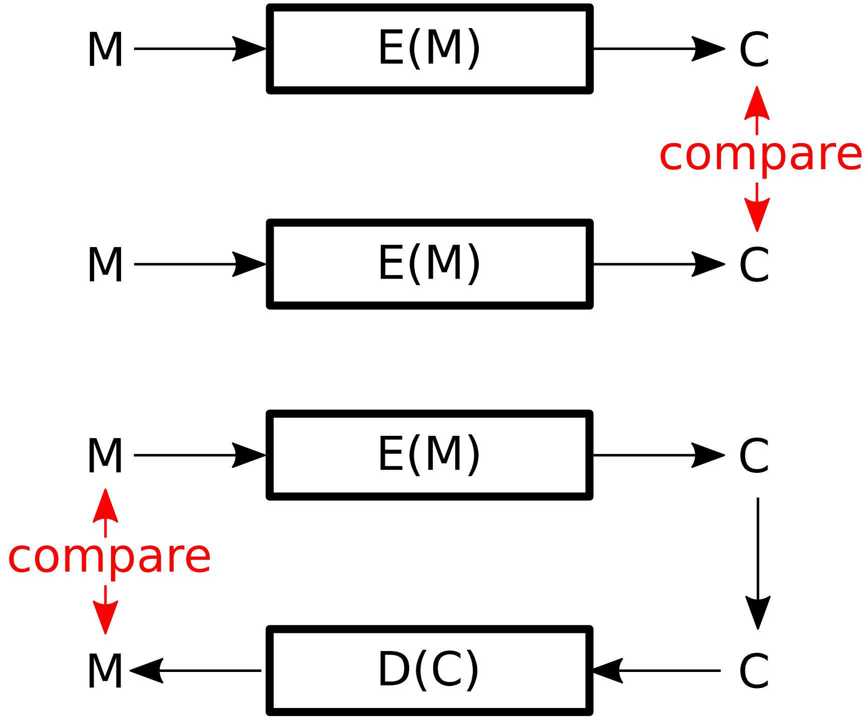
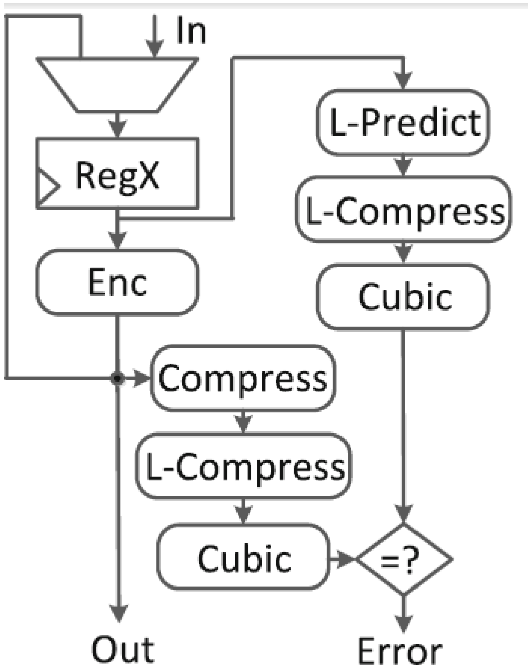


Redundancy Based Countermeasures

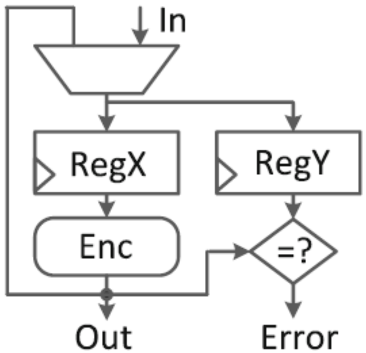


- Follows from classical fault tolerance.
- Simple redundancy executes the encryption twice and then compares the result.
- Another method is to execute the encryption, take the ciphertext, decrypt it, and compare the message.

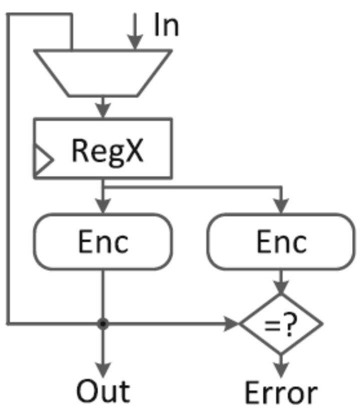
Redundancy Based Countermeasures



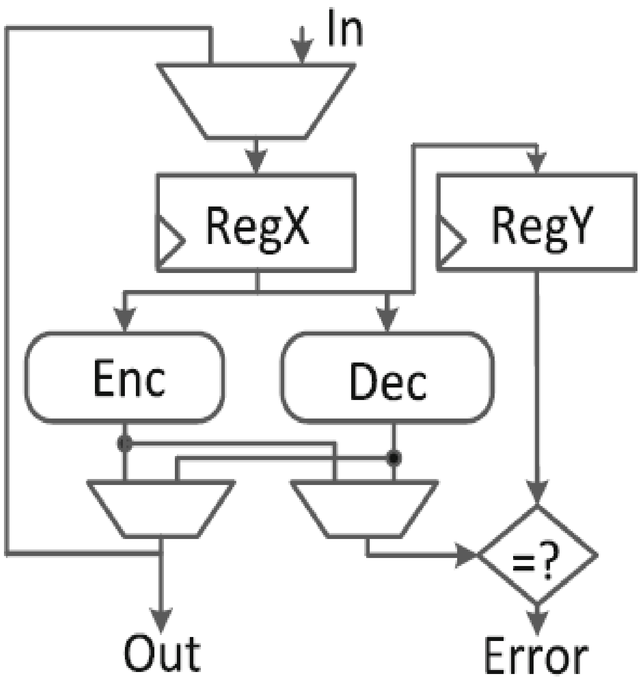
Information Redundancy – Robust Codes



Time Redundancy



Hardware Redundancy



Hybrid Redundancy - REPO

Source : Guo et. al. , Security analysis of concurrent error detection against differential fault analysis – Journal of Cryptographic Engineering, 2014

Simple is Best…

- Simplest form of Redundancy :
  - Execute the encryption twice and then compares the ciphertexts.
- Applications in safety and reliability
- Easy to implement
- Reasonably high fault coverage.
- Relatively low overhead.
- Used widely in industries.

Attacks on Redundancy

2014
- Guo et. al. (JCEN)
- Practically bypass concurrent error detection with biased faults.

2015
- Patranabis et. al. (COSADE)
- Biased faults to bypass time-redundancy.

2016
- Selmake et. al. (FDTC)
- Biased faults to bypass hardware-redundancy.

2017
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- Practically bypass information redundancy.

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- Wiersma et. al. (FDTC)
- Attack on commercial processors having ASIL-D security.

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Our Contributions

Previous Work	We Propose
➢ Bypass the countermeasures	➢ Use the countermeasure to leak
➢ Use Biased Faults	➢ Use Random Faults
➢ Corrupt all computation branches	➢ Corrupt single branch

Our Contributions

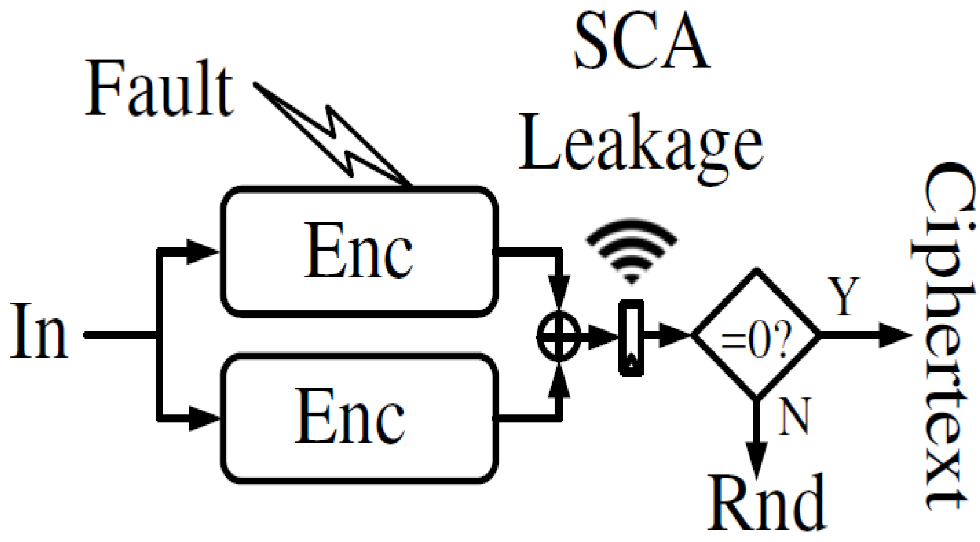
Previous Work	We Propose
➢ Bypass the countermeasures	➢ Use the countermeasure to leak
➢ Us	
➢ Corrupt all computation branches	➢ Corrupt single branch

Even Countermeasures Leak

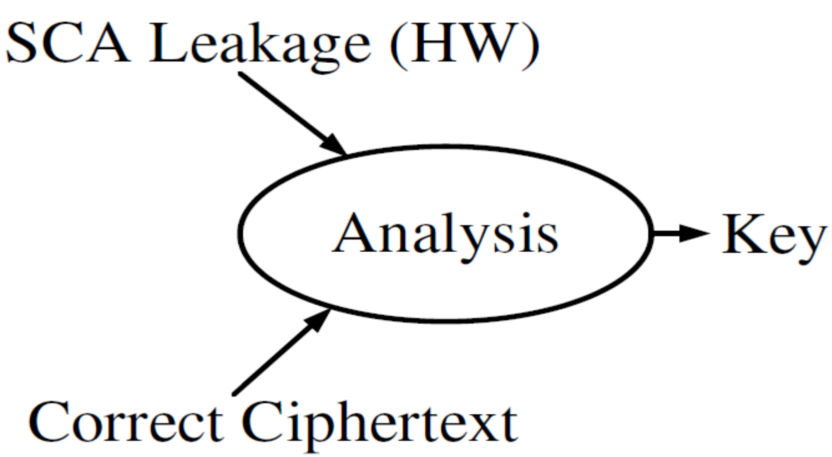
SCA Assisted DFA

- Proposed in FDTC 2017 by Patranabis et. al.
  - One Plus One is More than Two: A Practical Combination of Power and Fault Analysis Attacks on PRESENT and PRESENT-Like Block Ciphers.
- Uses side-channel to expose certain properties of bit permutation on fault injection
- Attacks on unprotected implementation of bit-permutation based ciphers
- Here we use side-channel to capture the leakage from countermeasures

SCA Assisted DFA: The Context of Countermeasures



- Assumptions:
  - Two or more redundant cipher computation and equality check of ciphertexts.
  - Side-channel measurement from the comparison operation
  - Random faults corrupting one single computation branch.



The Main Idea

- What we have and what we don't :
  - Correct ciphertexts: C → Known
  - Faulty Ciphertexts: C^* → Unknown
  - $HW(\delta) = HW(C \oplus C^*)$ → Known (bytewise)

With:

$HW(\delta) = w$

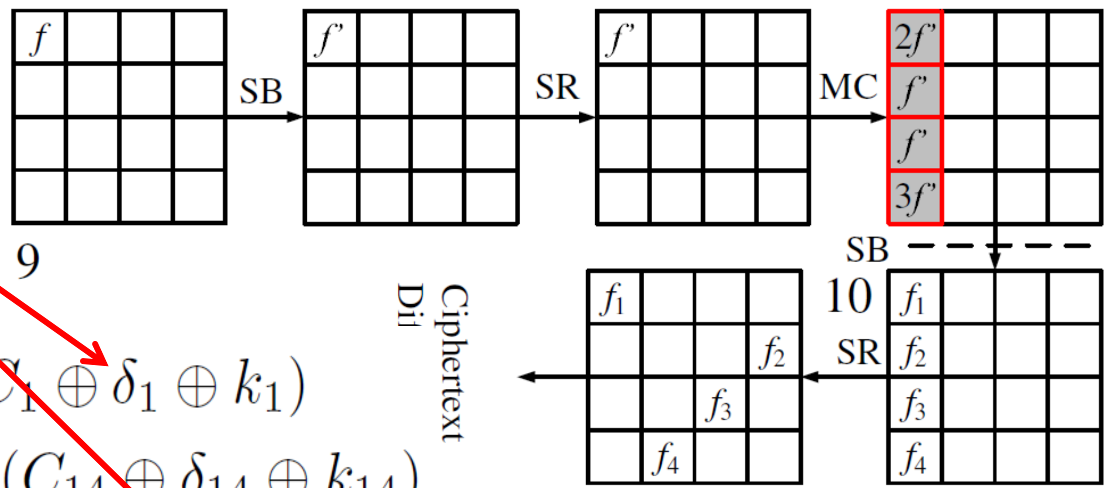
$\binom{8}{w}$ choices for C^*

Without:

2^8 choices for C^*

Can be low for certain choices of w

Case Study I: AES



$W(\delta_i)$

$$2f_1 = S^{-1}(C_1 \oplus k_1) \oplus S^{-1}(C_1 \oplus \delta_1 \oplus k_1)$$
$$f_1 = S^{-1}(C_{14} \oplus k_{14}) \oplus S^{-1}(C_{14} \oplus \delta_{14} \oplus k_{14})$$
$$f_1 = S^{-1}(C_{11} \oplus k_{11}) \oplus S^{-1}(C_{11} \oplus \delta_{11} \oplus k_{11})$$
$$3f_1 = S^{-1}(C_9 \oplus k_9) \oplus S^{-1}(C_9 \oplus \delta_9 \oplus k_9)$$

$$|\mathcal{R}| = 2^8 \times \prod_{i \in I} \binom{8}{W(\delta_i)}$$
$$|\mathcal{F}| = 1$$

- For each choice of $W(\delta_i)$ we have $2^8 \times \binom{8}{W(\delta_i)}$ choices for (k_i, δ_i)

Case Study I: AES

$$|\mathcal{R}| = 2^8 \times \prod_{i \in I} \binom{8}{W(\delta_i)}$$

$$|\mathcal{F}| = 1$$

For practical attack:

$$|\mathcal{R}| \leq 2^{32}$$

$$|\mathcal{F}| \leq 2^{32}$$

Worst Case

$$\binom{8}{W(\delta_i)} = \binom{8}{4} = 70$$

$$|\mathcal{R}| = 2^{32}$$

Best Case

$$\binom{8}{W(\delta_i)} = \binom{8}{8} = 1$$

$$|\mathcal{R}| = 2^8$$

Case Study I: AES

Wait and see…

$$S = \{1,2,3,4,5,6,7,8\}$$ → All possible HW values

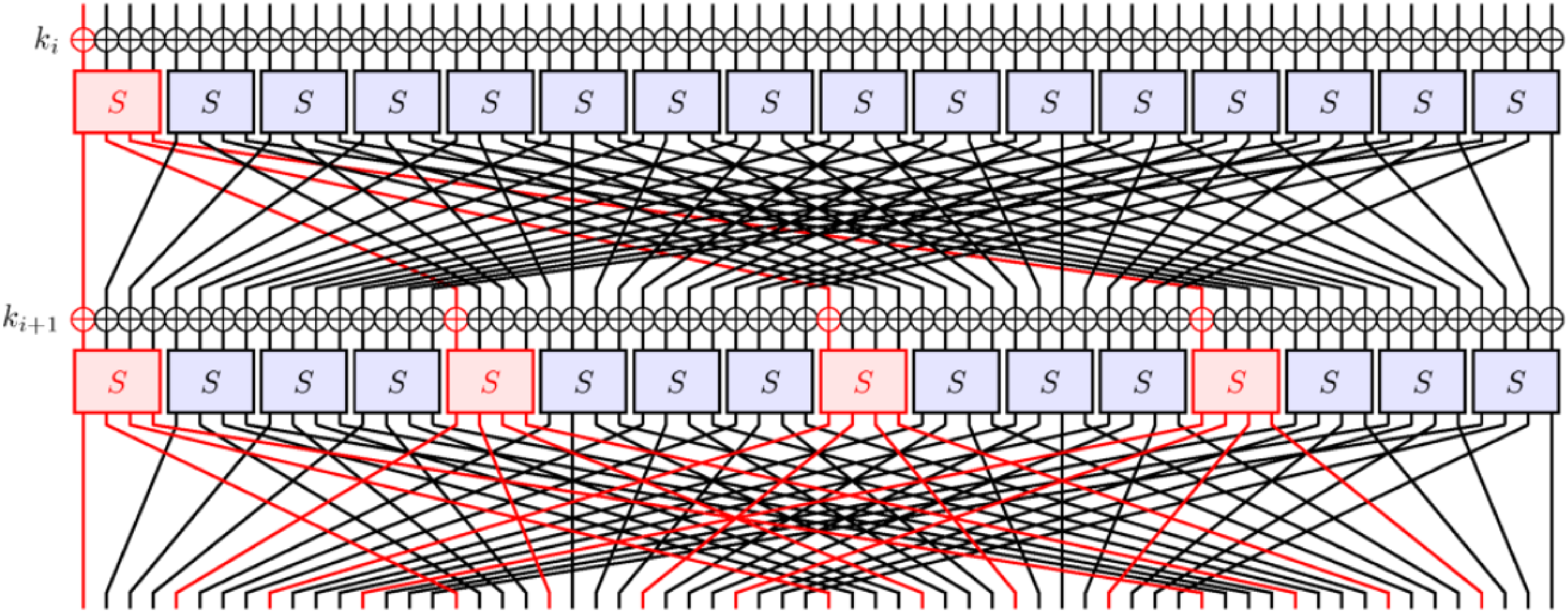
Let's just consider → $S - \{3,4,5\}$

Worst Case: $|\mathcal{F}| = \frac{2^{32}}{(28)^4} \approx \frac{2^{32}}{(2^5)^4} \approx 2^{12} \quad |\mathcal{R}| = 2^{18}$

Fairly Reasonable

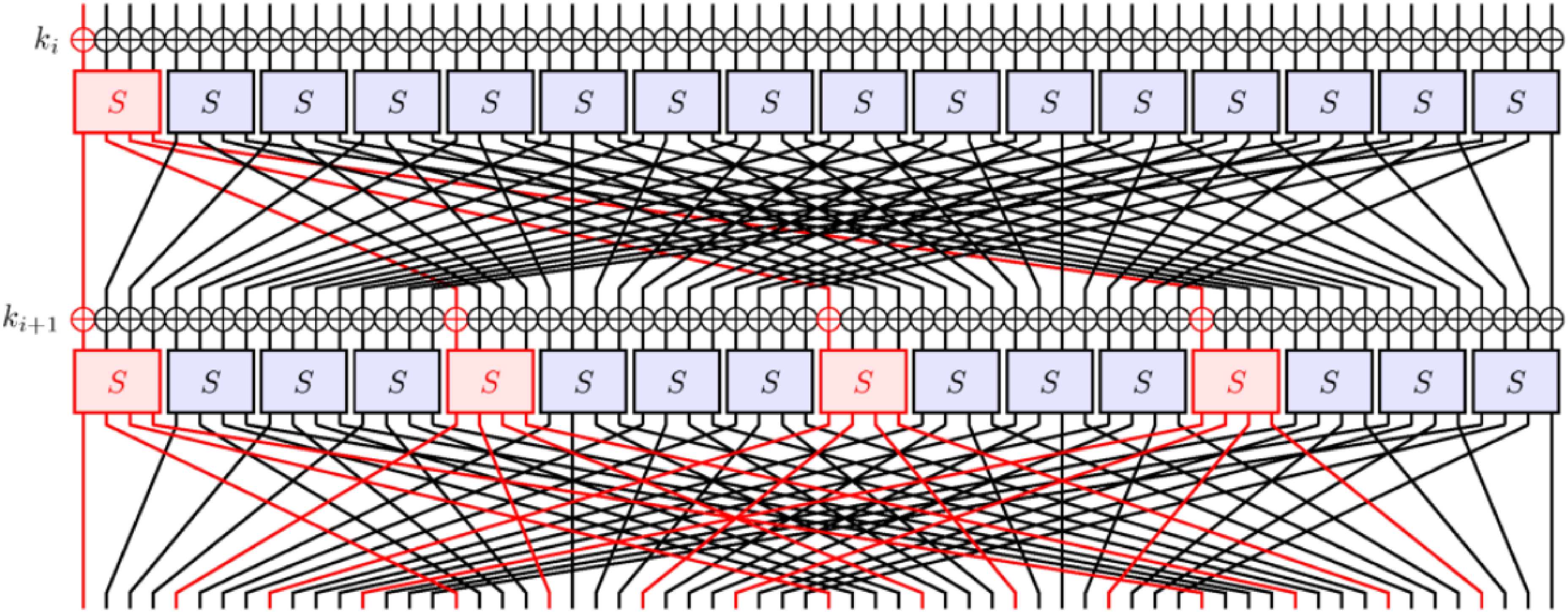
On average, the 128-bit AES key can be recovered with 2^{25} injections.

Case Study II: PRESENT



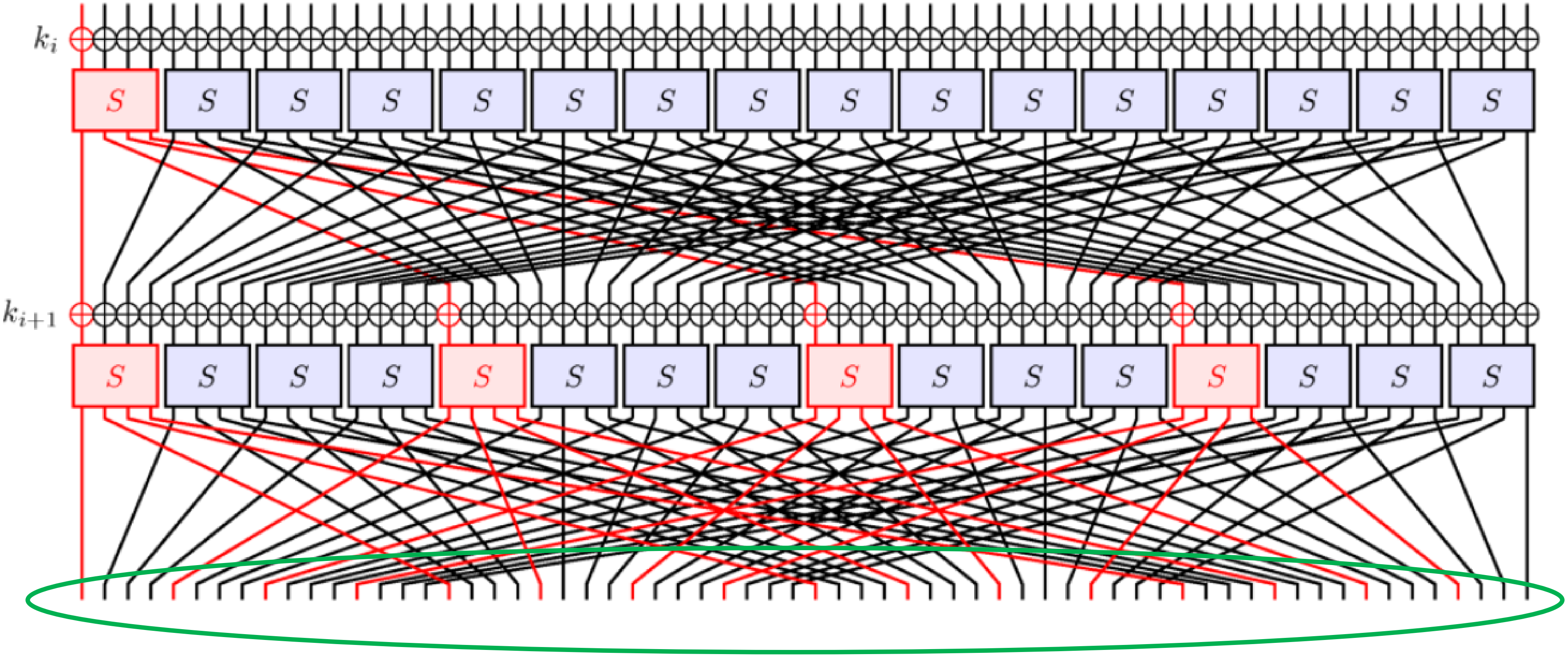
$$f_i = S^{-1}(C_i \oplus K_i) \oplus S^{-1}(C_i \oplus \delta_i \oplus K_i), \text{for } i \in [0, 15]$$

Case Study II: PRESENT



- We want nibble-wise Hamming weights
- We get byte-wise Hamming weights
- How to get nibble-wise values for byte-wise values???

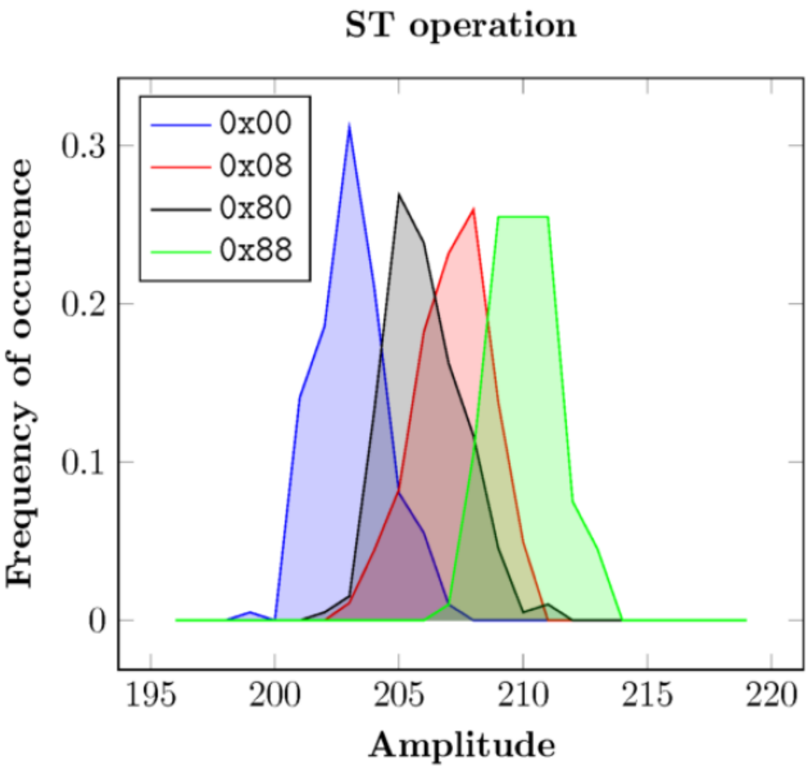
Case Study II: PRESENT



- No two consecutive nibbles in a byte are active simultaneously
- Only 3 byte-wise Hamming weights can be observed: 0, 1, 2

Case Study II: PRESENT

Templates: General approach for extracting nibble-wise Hamming weights

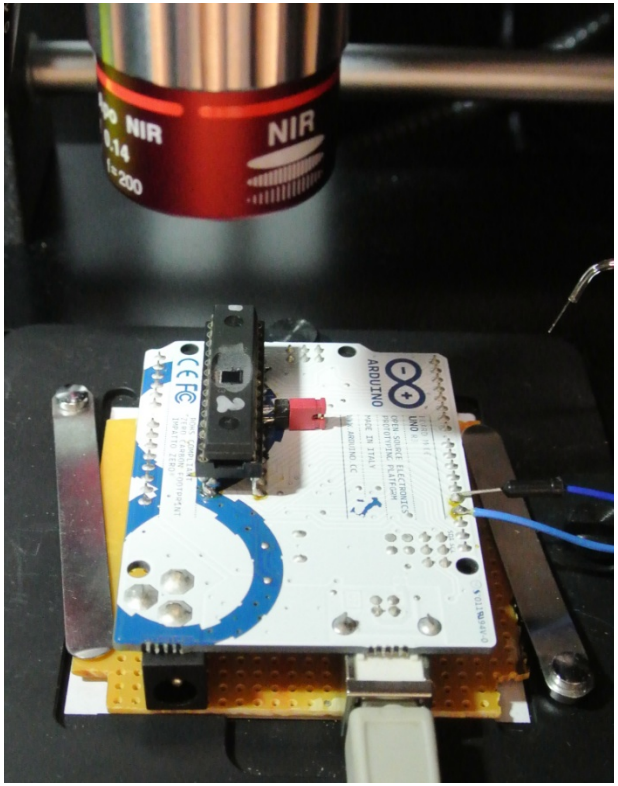


- 4 possible byte values: 00, 08, 80, 88
- All are clearly distinguishable from templates.
- Each nibble Hamming weight and nibble value has one-to-one correspondence.
  - We can uniquely extract the ciphertexts.

With 4 fault injections, the last round key can be determined uniquely

Practical Validation

Laser fault injection on an ATmega328P 8-bit microcontroller



- Near-infrared diode pulse laser
- Maximum output power of 20 W
- For the experiments, 20x magnifying objective lens was used
- As a DUT, ATmega328P was used – an 8-bit microcontroller running at 16 MHz
- Chip was depackaged from the backside to be accessible by the laser

Practical Validation

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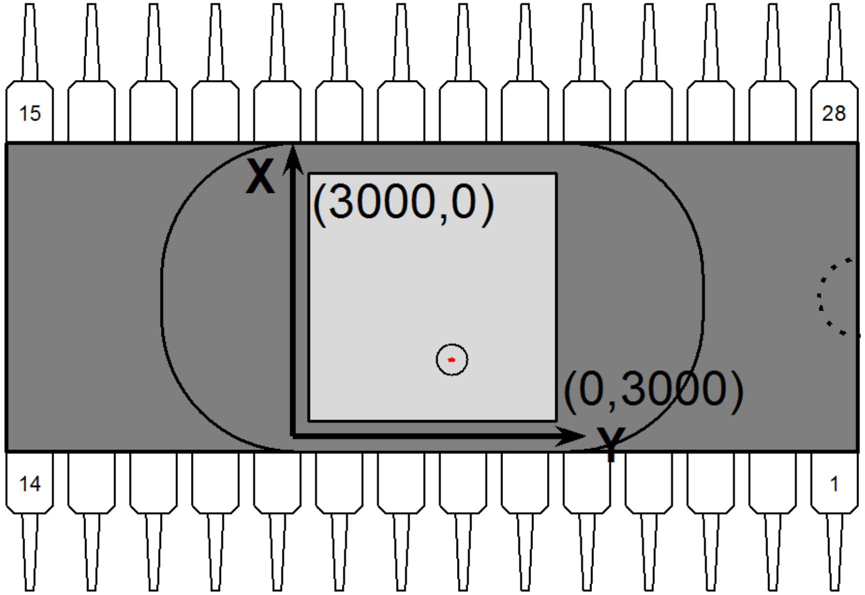
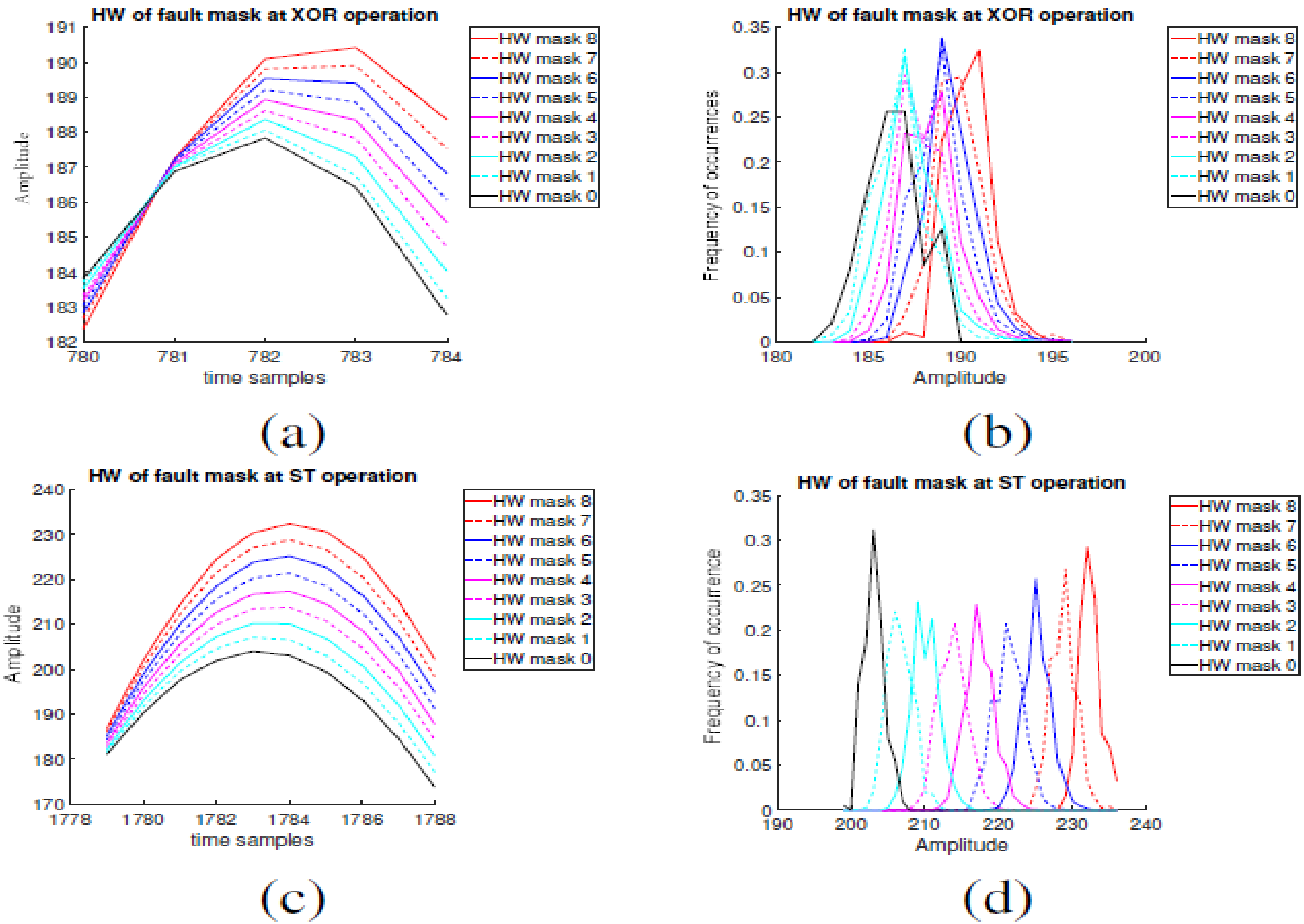
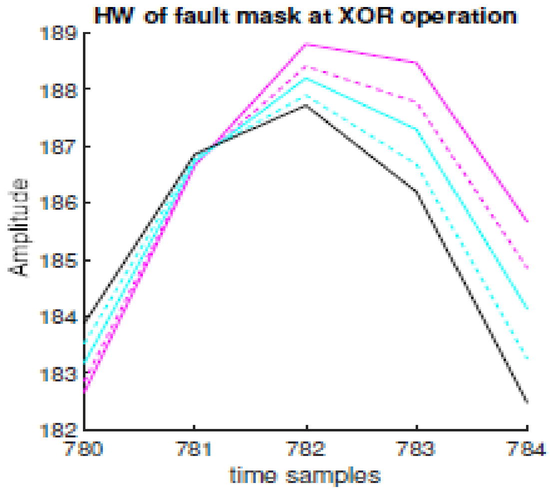


- Total area vulnerable to experiments was <1% of the entire chip area
- Reproducibility of faults was near to 100% with the same laser settings

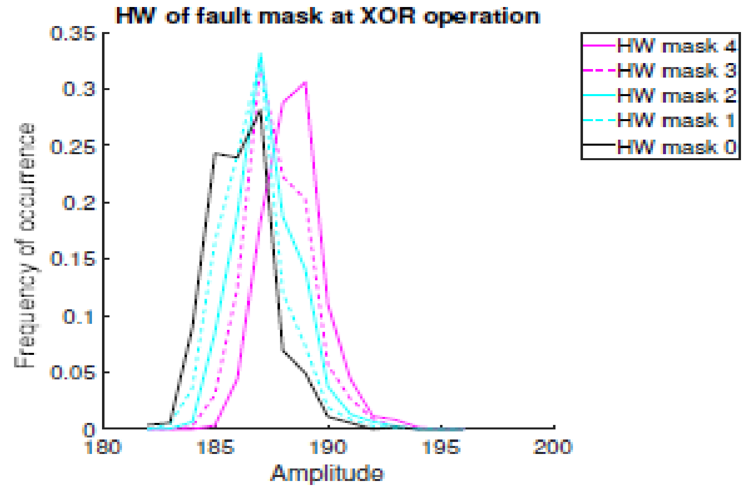
Practical Validation



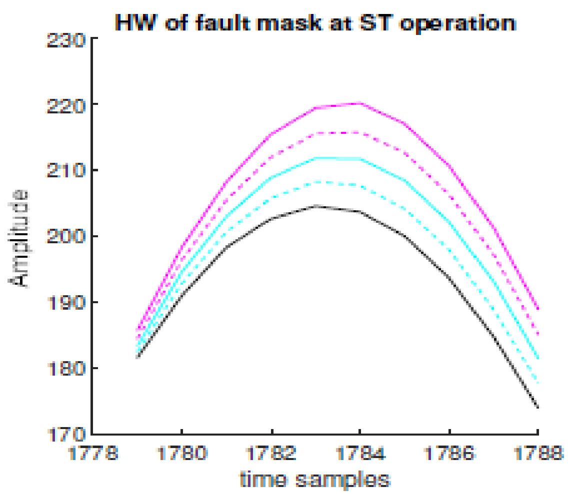
Practical Validation



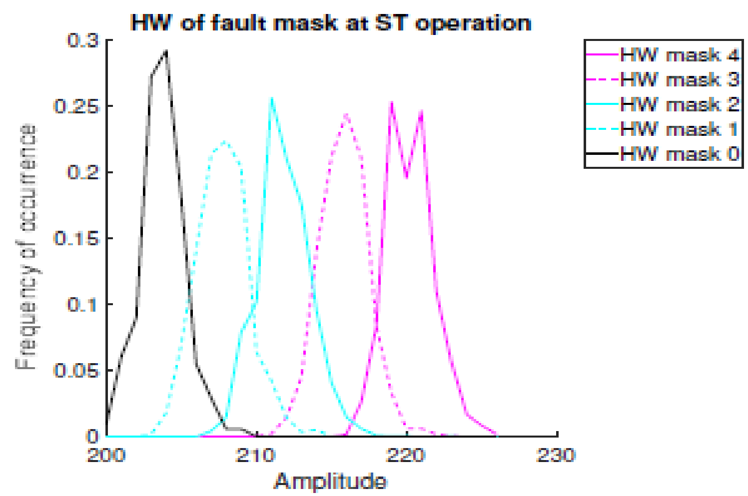
(a)



(b)



(c)



(d)

Practical Validation

Cipher	Code Size (bytes)	T_{ENC}	N_{EXP}	$(\|\mathcal{E}\|, \|\mathcal{F}\|, \|\mathcal{R}\|)$
AES-128	7570	0.326	$2^{26.98}$	$(2^{43}, 2^{25}, 1)$
PRESENT-80	7110	4.01	$2^{23.36}$	$(2^{4}, 4, 1)$

2^{25} injections can be performed within a day !!!

Summary

- Redundancy based countermeasures are simple and practical.
- Usage: very simple.
- Caution!!!
  - They leak unless properly constructed.

- Potential Solutions:
  - Mask the comparison block ⇒ Resource overhead
  - Redundancy at each round ⇒ May not be secured

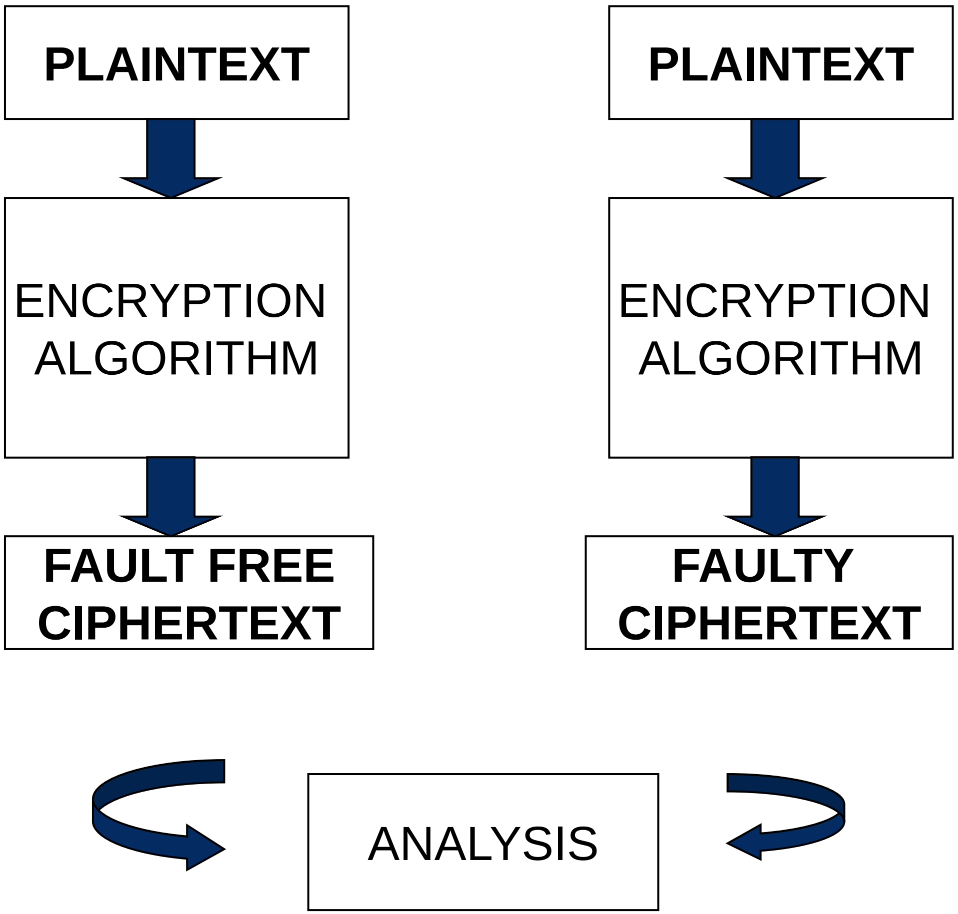
- Future works:
  - Extension for more general form of redundancies.
  - Low-cost but leakage-free countermeasure construction.

Thank you

Questions?

Introduction

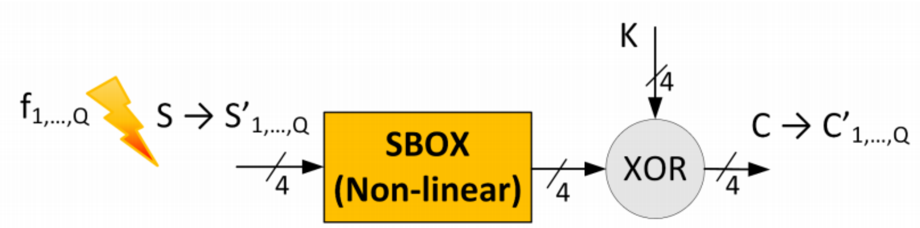
Differential Fault Analysis (DFA)



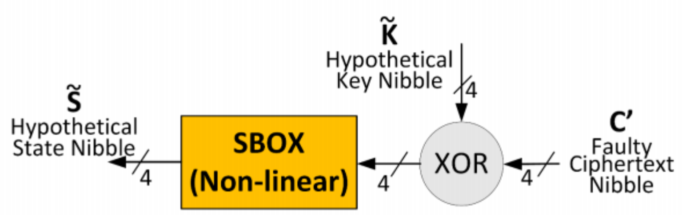
- Most widely explored
- Low fault complexity
- Complex analysis
- Fault Locations
  - Datapath
  - Key-schedule
- Fault models
  - Bit based
  - Nibble based
  - Byte based
  - Multiple byte based

Introduction

- Step 1: Biased Fault Injection
  - Apply Q different fault intensities ($f_{1,\ldots,Q}$)
  - Induce biased faults ($S'_{1,\ldots,Q}$)
  - Collect faulty ciphertexts ($C'_{1,\ldots,Q}$)



Step 2: Hypothesis Test with Biased Faults

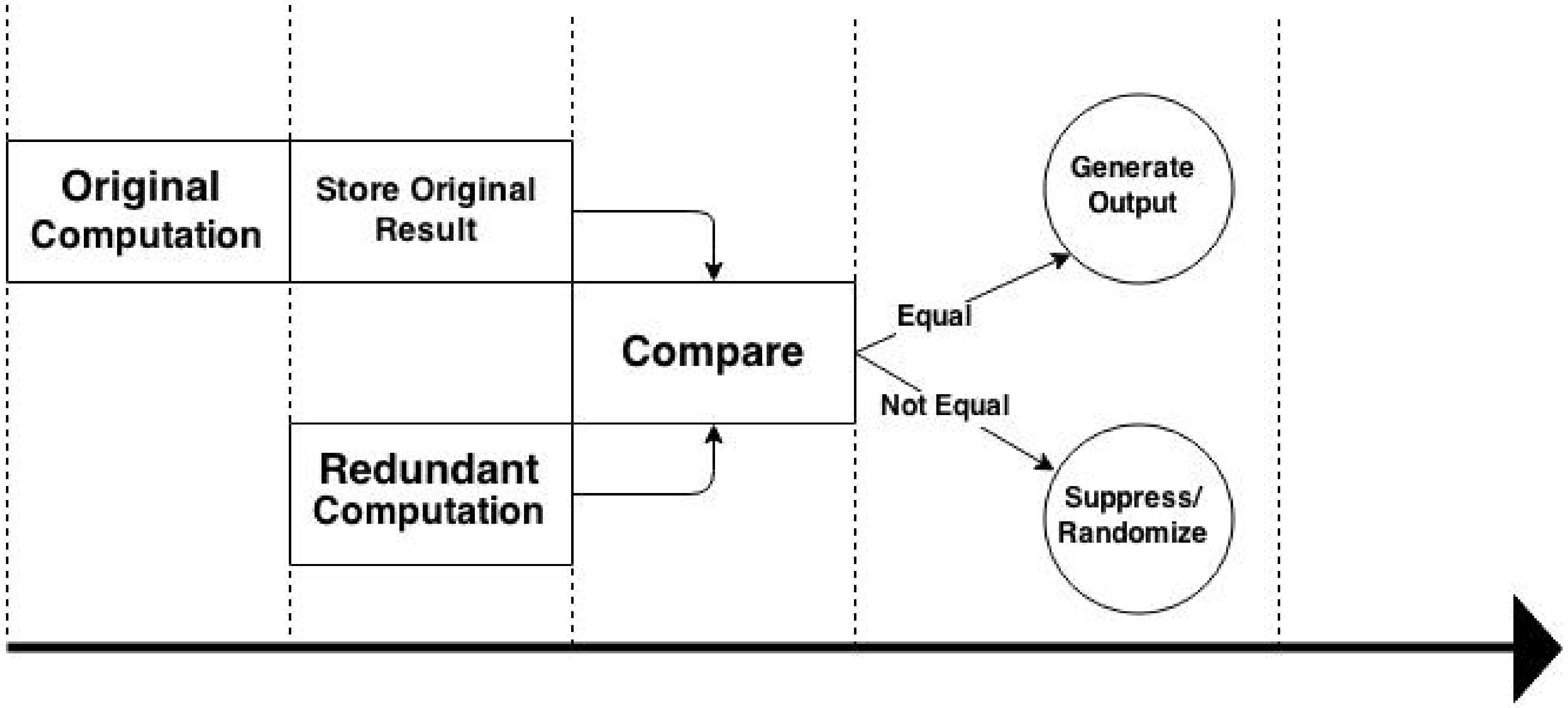


Given: C' and a KNOWN fault bias f
Find: Most likely key nibble $\tilde{K}$

For all $\tilde{K}$, find $\tilde{S} = SBOX^{-1}(C' \oplus \tilde{K})$
Accumulate $\rho_{\tilde{K}} = \sum HD(\tilde{S})$
Select K = argmin ρ

- **Biased Faults**: Distribution of the faulty values are non-uniform.
- Bias is exploited for key extraction by means of Hypothesis Testing.
- Utilizes device properties to the highest extent.
- Requires only faulty ciphertexts – But many of them.

Attacks on Redundancy



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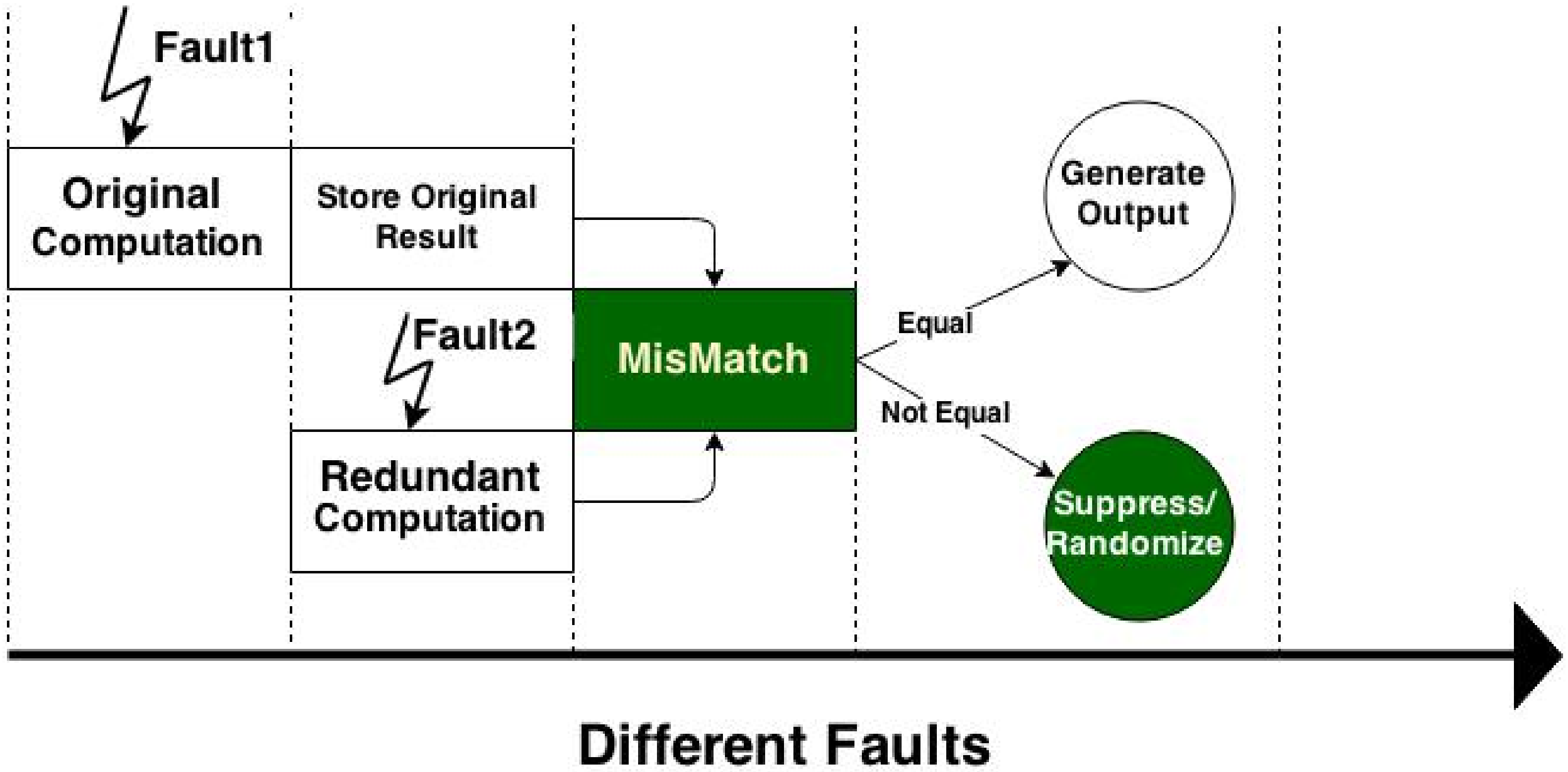

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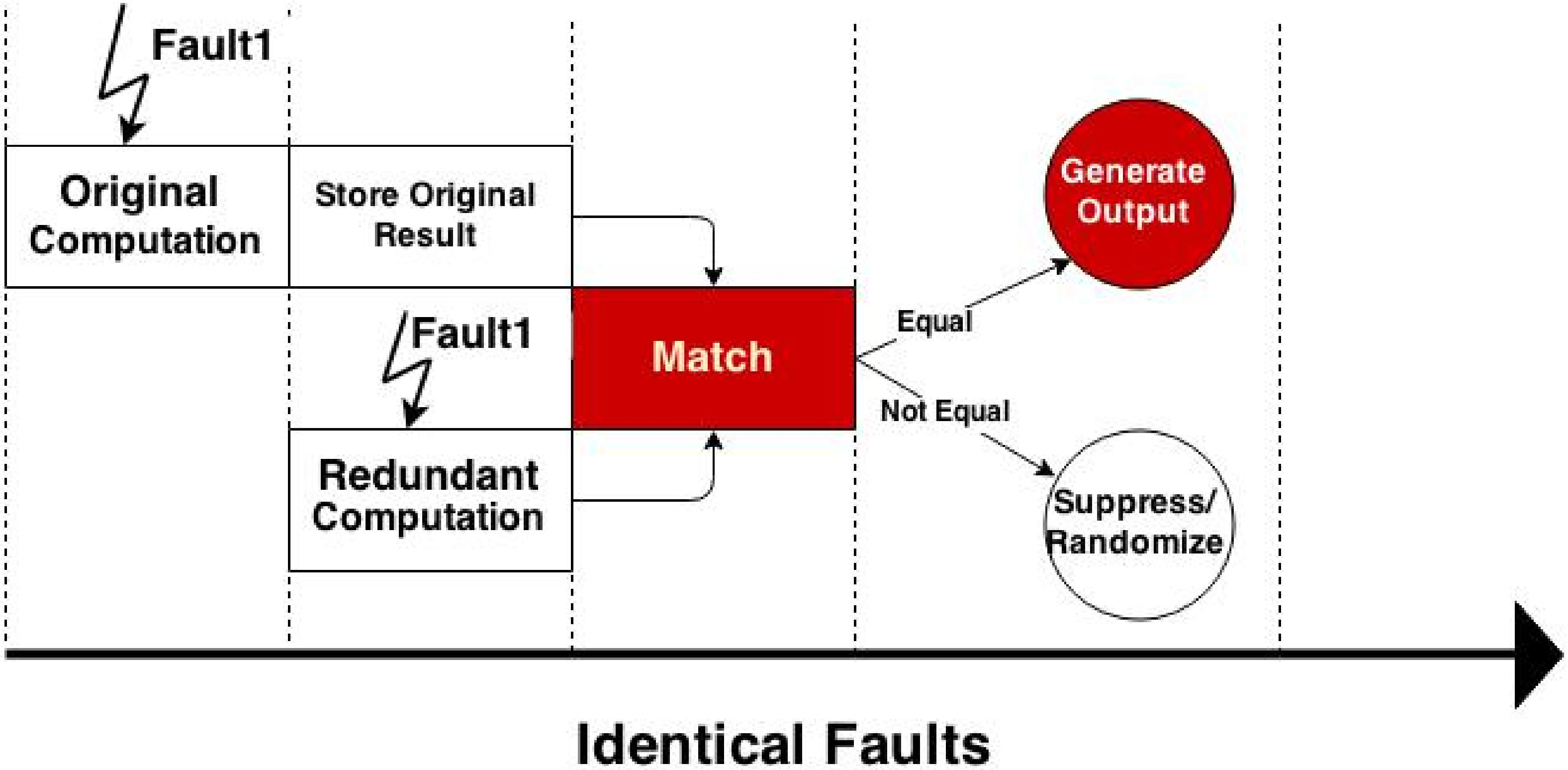

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