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Hardware Security

12. Physical side-channel attack defences 2 (active)

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Today

- Countermeasure principles
- Attacks & countermeasures

Fault attack

Kill chain

Cyber kill chain

1. Fault injection
   - Attacker manipulates the environment and creates a fault
   - EM pulse, voltage glitch, ...
2. Fault manifestation
   - Fault manifests as a logical effect in target execution
   - Bit flip, byte reset, ...
3. Fault propagation
   - Fault propagates and impacts execution further
   - Wrong branch taken, ...
4. Fault observation
   - Attacker is able to observe the result of the fault somehow
   - Wrong ciphertext output, wrong signature output, ...
5. Fault exploitation
   - Attacker exploits the fault to break some security property
   - Key recovery, verification bypass, ...

Stopping the attack at **any** step is sufficient.

Fault tolerant design

- Focus on naturally occurring faults
- No attacker control
- Space probes, hostile environments, radiation, solar flares
- Not enough against fault attacks
  - Attacker has a goal, natural faults do not
  - Some techniques will help

Countermeasure taxonomy

- **Level**: Where is it?
  - Algorithm
  - Software
  - Hardware / Logical
  - Physical / Electrical
- **Objective**: What does it do?
  - Prevention
  - Detection
  - Correction
  - Infection
- **Killchain step**: What does it eliminate?
  1. Fault injection
  2. Fault manifestation
  3. Fault propagation
  4. Fault observation
  5. Fault exploitation

Embedded Cryptography 1

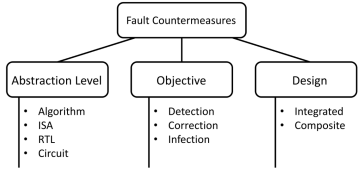


Figure 12.1. *Taxonomy of fault countermeasures along three dimensions*

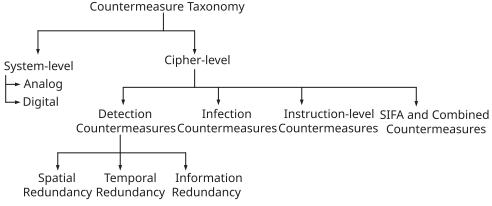


Figure 10.5. *Taxonomy of notable FA countermeasures*

Attack complexity

Attacker's goals

- Get the secret
- Bypass verification
- ...

Defender's goals

- There is no absolute security in hardware
- Make the attack *as hard as possible* (as costly as possible)
  - More faults required → harder to do *n* faults than one
  - More precise faults required → harder to fault a precise time/location
  - More repeatable faults required → harder to repeat the same fault
  - More specific faults required → harder to cause a specific value than a random one

- Random bit/byte fault in a large state processed over a long time
  - Easy
- Repeated same byte set fault several times at precise times
  - Hard

Countermeasure principles

- Prevention
- Detection + Response
- Redundancy
- Randomness
- Infection

Prevention

- EMFI: Shielding
  - Metallic package/coating
  - Can include a detector
- Clock glitching: Clock filtering/internal clock
  - Phase-locked loops (PLLs)
  - Glitch detectors (T_{clk} too short)
- Voltage glitching: Power filtering
  - Low-dropout regulators (LDOs)
  - Glitch detectors (voltage sensors)
- ...
- 👍 Prevents faults altogether
- 👍 Also prevents natural faults
- 👎 Can be bypassed using different injection technique

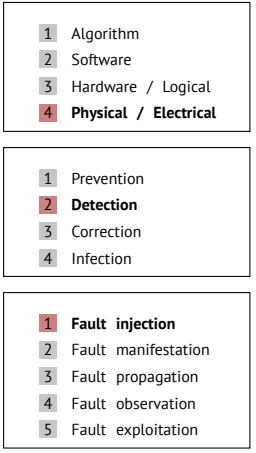
1. Algorithm
2. Software
3. Hardware / Logical
4. **Physical / Electrical**

1. **Prevention**
2. Detection
3. Correction
4. Infection

1. **Fault injection**
2. Fault manifestation
3. Fault propagation
4. Fault observation
5. Fault exploitation

Detection

- Sensors and detectors (physical level)
  - Can also be done at higher levels (through redundancy)
- Detect fault injection before manifestation
- 👍 Independent of target functionality
- 👎 Can be bypassed using different injection technique



Fault response

- Detection needs a response
- You detected a fault, what do you do?
  - Return error
  - Return random (plausible) data
  - Correct it (if you can)
  - Go silent (temporarily)
  - Go silent and delete all secrets (brick)
- Faults may occasionally happen naturally
  - Response should not be too aggressive
  - False positive ratio of detector
    - If low, response can be aggressive
    - If high, response needs to be softer
- Fault counters: Keep count of detected faults, take action after a few faults
  - Fault counter could also be faulted/teared

Redundancy

- Redundancy: Have reduntant element in the computation
- Why does redundancy help defend against fault attack?
  - How do you know you have the correct result if you only have one result?
  - Harder to inject more faults (into redundant copies)
- How do you add redundancy?
  - **Spatial**: Multiple parallel executions
  - **Temporal**: Repeat execution several times
  - **Information**: Encode values redundantly
- Requires checking and merging
  - Can also be faulted!

1. **Algorithm**
2. **Software**
3. **Hardware / Logical**
4. **Physical / Electrical**

1. Prevention
2. **Detection**
3. **Correction**
4. Infection

1. Fault injection
2. **Fault manifestation**
3. **Fault propagation**
4. **Fault observation**
5. Fault exploitation

Redundancy

Temporal

- $y_1 = f(x); y_2 = f(x); \ldots y_n = f(x)$
- $y_1 \stackrel{?}{=} y_2 \stackrel{?}{=} \ldots \stackrel{?}{=} y_n$
- Detects up-to $n - 1$ faults
- Can correct using majority vote
- Slow
- Check can be faulted
- May not detect semi-permanent fault

Redundancy

Spatial

- $y_1 = f(x) \mid y_2 = f(x) \mid \ldots \mid y_n = f(x)$
- $y_1 \overset{?}{=} y_2 \overset{?}{=} \ldots \overset{?}{=} y_n$
- Detects up-to $n - 1$ faults
- Can correct using majority vote
- Lots of space
- Check can be faulted

Redundancy

Information

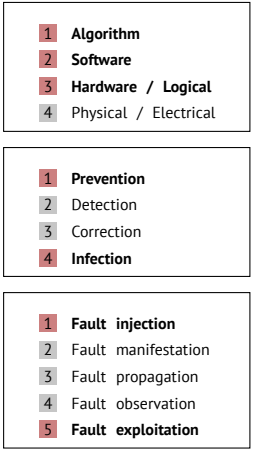
```
# bit in (0, 1)
if bit:
    # something
else:
    # something else
```

- What could be improved in this case?
  - Any non-zero value is truthy, zero is falsy
  - Gives attacker too much freedom to fault
  - Use values with redundancy

```
VAL_TRUE = 0xAA;  VAL_FALSE = 0x55
if bit == VAL_TRUE:
    # something
elif bit == VAL_FALSE:
    # something else
else:
    # Fault!
```

Randomness

- Redundancy not enough against many precise faults
- Unpredictable/unknown to the attacker
- How does randomness help?
  - Attacker needs to know what faults to do and where/when



Randomness

Misalignment

- Targets the SCA assistance to FA
- Attacker needs to time fault precisely
- 👍 Makes precise fault injection harder
- 👎 Attacker can try a lot and get lucky
- 👎 Real-time pattern matching

Randomness

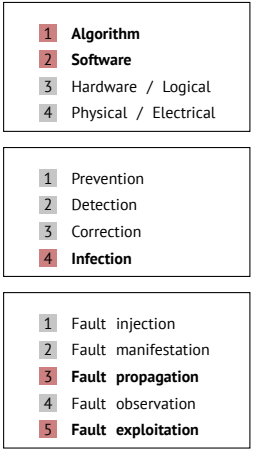
Redundancy

```
VAL_TRUE = rand()
VAL_FALSE = not(VAL_TRUE)
if bit == VAL_TRUE:
    # something
elif bit == VAL_FALSE:
    # something else
else:
    # Fault!
```

- Randomizes redundant representations
- $y_1 = f(\texttt{rerand}(x))$; $y_2 = f(\texttt{rerand}(x))$; ... $y_n = f(\texttt{rerand}(x))$
  $\texttt{derand}(y_1) \stackrel{?}{=} \texttt{derand}(y_2) \stackrel{?}{=} \ldots \stackrel{?}{=} \texttt{derand}(y_n)$
  - Only possible sometimes
- 👍 Makes specific fault injection harder
- 👎 Non-specific faults largely unaffected

Infection

- Detection: Target detects fault and response mitigates it
- Correction: Target detects fault and is able to correct it
- **Infection**: Detection and response *embedded* in the computation
  - Response makes the result useless by randomizing it (**infecting**)
  - Response always happens, is no-op if no fault is present
- Infected result has no relationship to the secret key or plaintext



Infection

Block cipher

Inputs: $P, K = k^j$ for $j \in \{1, \dots, n\}$, $(\beta, k^{\mathbf{0}})$ dummy plaintext and key s.t.; $RoundFunction(\beta, k^{\mathbf{0}}) = \beta$
Output: $C = \text{BlockCipher}(P, K)$

State $R_{\mathbf{0}} \leftarrow P$, Redundant state $R_{\mathbf{1}} \leftarrow P$, Dummy state $R_{\mathbf{2}} \leftarrow \beta$
$i \leftarrow 1, q \leftarrow 1$
$rstr \leftarrow \{0,1\}^t$ ▷ $\#1(rstr) = 2n$, $\#0(rstr) = t - 2n$
while $q \leq t$ **do**
    $\lambda \leftarrow rstr[q]$ ▷ $\lambda = 1$ real round, $\lambda = 0$ dummy round
    $\kappa \leftarrow (i \wedge \lambda) \oplus 2(\neg\lambda)$ ▷ κ selects the state
    $\zeta \leftarrow \lambda \cdot \lceil i/2 \rceil$ ▷ ζ is actual round counter, 0 for dummy
    $R_{\kappa} \leftarrow \text{RoundFunction}(R_{\kappa}, k^{\zeta})$ ▷ Do the round
    $\gamma \leftarrow \lambda(\neg(i \wedge 1)) \cdot IsNonZero(R_{\mathbf{0}} \oplus R_{\mathbf{1}})$ ▷ Was there a fault in $R_{\mathbf{0}}$ or $R_{\mathbf{1}}$?
    $\delta \leftarrow (\neg\lambda) \cdot IsNonZero(R_{\mathbf{2}} \oplus \beta)$ ▷ Was there a fault in $R_{\mathbf{2}}$?
    $R_{\mathbf{0}} \leftarrow (\neg(\gamma \vee \delta) \cdot R_{\mathbf{0}}) \oplus ((\gamma \vee \delta) \cdot R_{\mathbf{2}})$ ▷ Infect $R_{\mathbf{0}}$ if faulty
    $i \leftarrow i + \lambda$
    $q \leftarrow q + 1$
return $(R_{\mathbf{0}})$

Attacks & Countermeasures

Attacks & Countermeasures

DFA

- Attacker needs ≥ one correct encryption, ≥ one faulty encryption with an unknown (single byte) fault in a certain round, on a fixed plaintext

1. Fault injection
   - Prevent / Detect + abort
   - Dummy rounds
   - Misalignment
2. Fault manifestation
   - Detect + abort / Correct
3. Fault propagation
   - Infect / Correct
4. Fault observation
   - Detect + abort / correct
5. Fault exploitation
   - Do not allow repeated plaintexts (CBC with random IV)

Attacks & Countermeasures

SFA

1. Fault injection
2. Fault manifestation
3. Fault propagation
4. Fault observation
5. Fault exploitation

- Attacker needs many faulty ciphertexts, with an unknown biased fault in a certain round, the plaintext no longer needs to be fixed
- Same as DFA, disallowing repeated plaintexts no longer works
- Limiting key reuse prevents exploitation (only up to n encryptions per key)
- Detection can be more relaxed compared to DFA

Attacks & Countermeasures

SIFA

1. Fault injection
2. Fault manifestation
3. Fault propagation
4. Fault observation
5. Fault exploitation

- Attacker needs many correct ciphertexts, which had an ineffective (biased) fault in a certain round, the plaintext no longer needs to be fixed
- Prevention + detection on physical level still works
- Detection on a logical level no longer works
  - SIFA uses ineffective faults which do not manifest
  - Yet, running a SIFA attack will also cause effective faults
  - These can be detected before too much leaks
  - But, response must be permanent
- Correction still works

Attacks & Countermeasures

RSA-CRT Bellcore attack

1. Fault injection
2. Fault manifestation
3. Fault propagation
4. Fault observation
5. Fault exploitation

- Attacker needs any (unknown) fault in computation of:

$$s_1 \equiv m^{d_p} \bmod p$$
$$s_2 \equiv m^{d_q} \bmod q$$

- Resulting signature is invalid
- What can we do?
  - All of the generic prevention and detection
  - Sign-then-verify
- Shamir's countermeasure: Redundancy on algorithm level
  1. $r \leftarrow$ random prime (small)
  2. $s_1 \equiv m^{d \bmod \varphi(rp)} \bmod r \cdot p$
  3. $s_2 \equiv m^{d \bmod \varphi(rq)} \bmod r \cdot q$
  4. Check $s_1 \equiv s_2 \bmod r$

Attacks & Countermeasures

ECDSA (repeated nonces)

1. Fault injection
2. Fault manifestation
3. Fault propagation
4. Fault observation
5. Fault exploitation

- Attacker needs repeated use of nonce k for two different messages
- Hard to fix
  - There is no state that remembers past nonces
  - Nonces are (supposed to be) random
  - Many ways a repeat can happen: RNG stuck at 0, …
- Generic prevention and detection works
- Hedged nonce derivation: Deterministic + random
  - $k = H(m, d, rand())$
  - Deterministic part provides difference for $m_1 \neq m_2$

Attacks & Countermeasures

ECDSA (related nonces)

1. Fault injection
2. Fault manifestation
3. Fault propagation
4. Fault observation
5. Fault exploitation

- Attacker needs to know the relation between two nonces for the same message
- Generic prevention and detection works
- Hedged nonce derivation: Deterministic + random
  - $k = H(m, d, rand())$
  - Random part provides unguessable randomness

Attacks & Countermeasures

ECDH safe-error

- Attacker faults operation and detects whether it is a dummy or not
- Remove dummy operations
  - There should not be values that are used/unused based on key bits
- Problem: M safe-error attacks

Takeaways

- How to stop a fault attack by targeting a step in its kill chain
- How to push attacks into less practical territory
- There is a large variety of fault attack countermeasures

Tutorial

- Fault injection with ChipWhisperer-Nano

Next week

- Guest lecture by **Thomas Roche**
  - On Zoom at the *usual time*
  - Everyone please come if you can
  - You will have a chance to ask questions
- No tutorial

Recommended reading

- For **this** lecture
  - Read Embedded Cryptography 1 – Chapter 12 – Fault countermeasures
- For the **next** lecture (13th week)
  - Nothing
  - Thomas will talk about: A Side Journey to Titan and EUCLEAK
- For the **next next** lecture (14th week)
  - Nothing
  - Łukasz will talk about: SoK: SCA-secure ECC in software – mission impossible?
- For the **last** lecture (15th week)
  - Read Security Engineering – Chapter 28 – Assurance and Sustainability

References

- Secure Application Programming in the presence of Side Channel Attacks
- Infective Computation and Dummy Rounds: Fault Protection for Block Ciphers without Check-before-Output
- Destroying Fault Invariant with Randomization
- SIFA: Exploiting Ineffective Fault Inductions on Symmetric Cryptography
- A synthesis of side-channel attacks on elliptic curve cryptography in smart-cards
- A Systematic M Safe-error Detection in Hardware Implementations of Cryptographic Algorithms