Faults In Our Bus: Novel Bus Fault Attacks to Break ARM TrustZone

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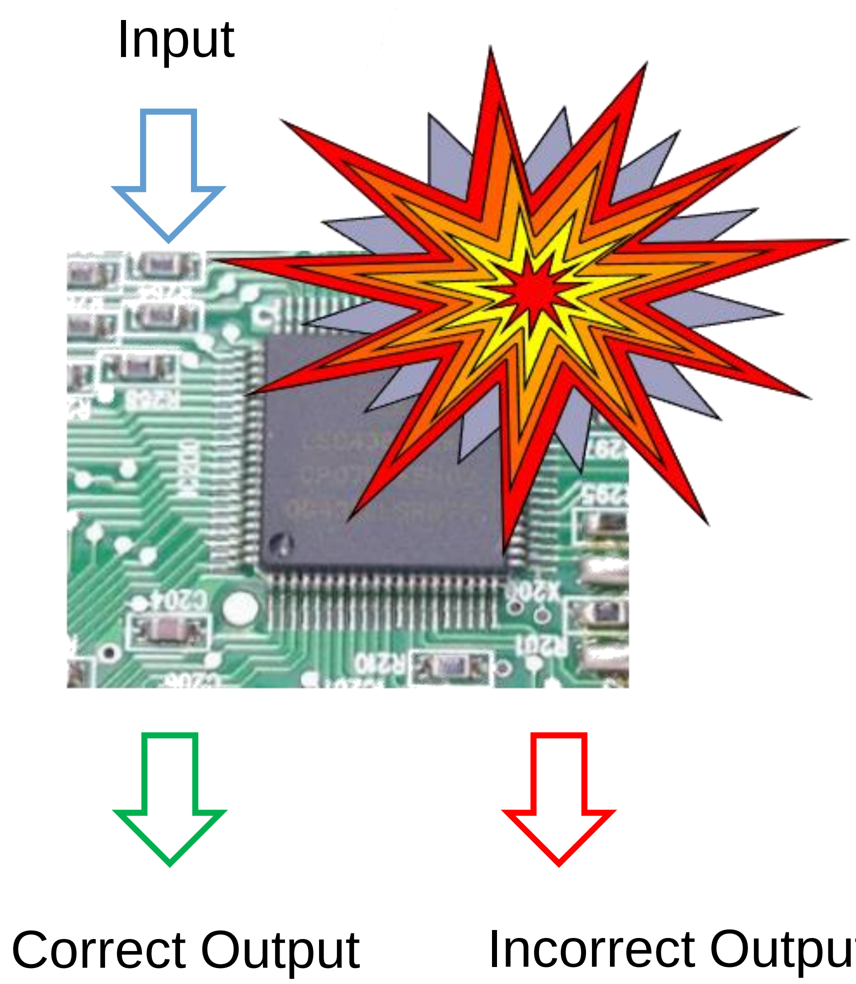
What are Faults?

- Actively perturb data or control-flow of a system and gain information about the secret through faulty system response

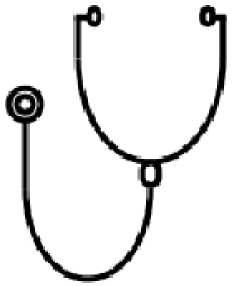


Fault Attack

- Fault causes error and error can be exploited to leak secret information

- Fault attack sometimes combined with side channel can lead to stronger attacks

Fault Injection



Side Channel Observation

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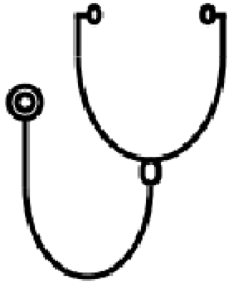
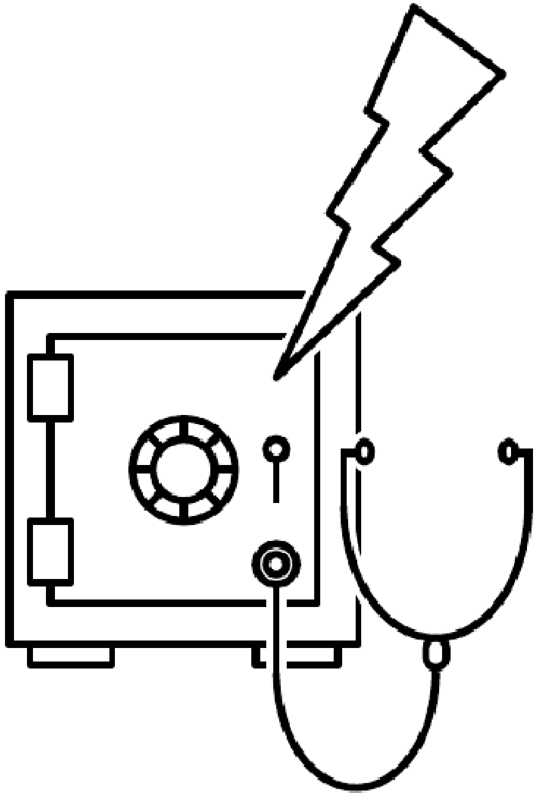




Fault Injection

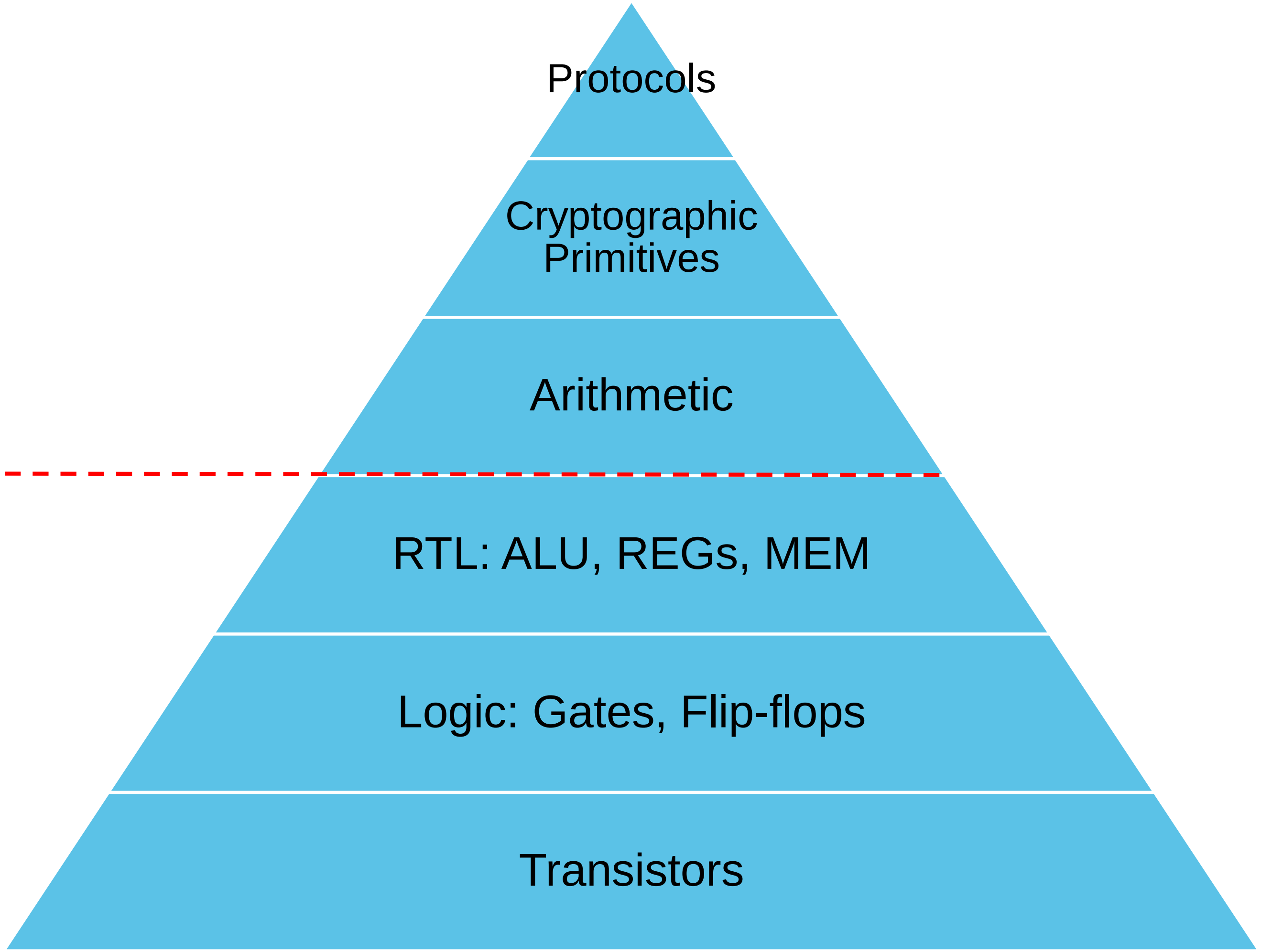
Side Channel Observation

The Fault Attack Jungle

Fault Attack on Embedded Systems

Fault Exploitation

Fault Injection



I. Verbauwhede, D. Karaklajid, and J.-M. Schmidt, “The Fault Attack Jungle - A Classification Model to Guide You”, FDTC, 2011

Fault Injection Attack Vectors

Fig: Electromagnetic Fault Injection (EMFI) Probe

- **WHAT**: Strategically modify execution environment of a system
- **HOW**: Through changes in external operational conditions

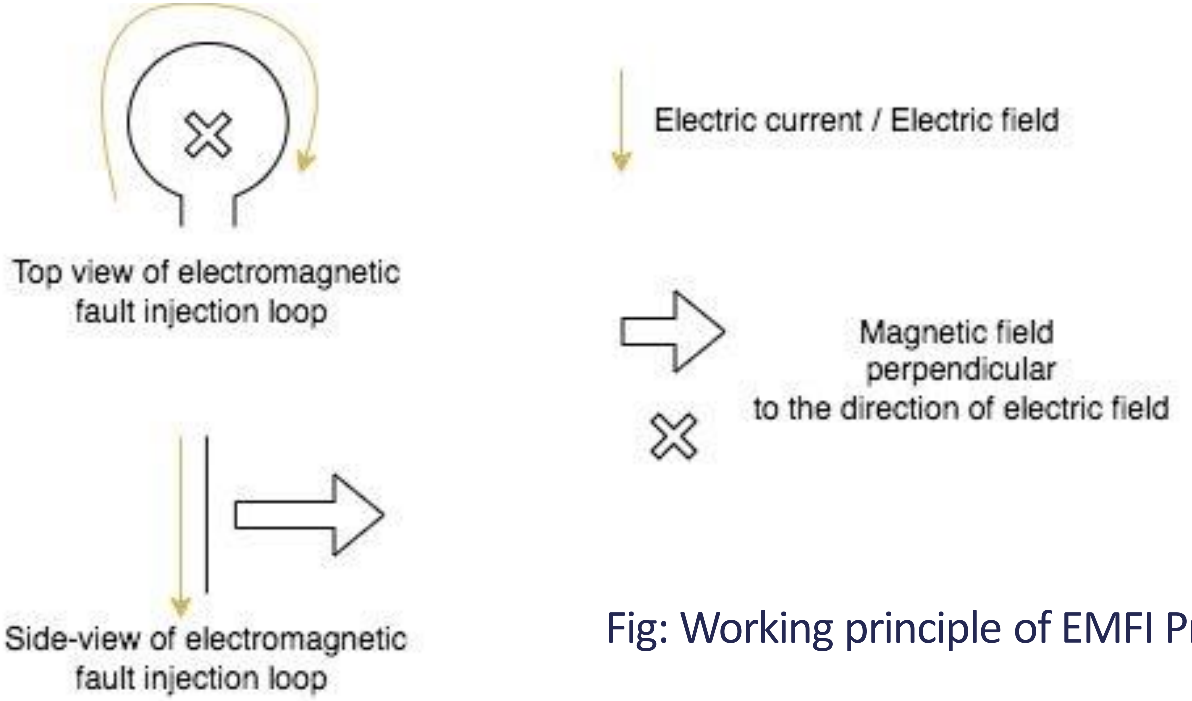


Fig: Working principle of EMFI Probe

Fault Injection Attack Vectors

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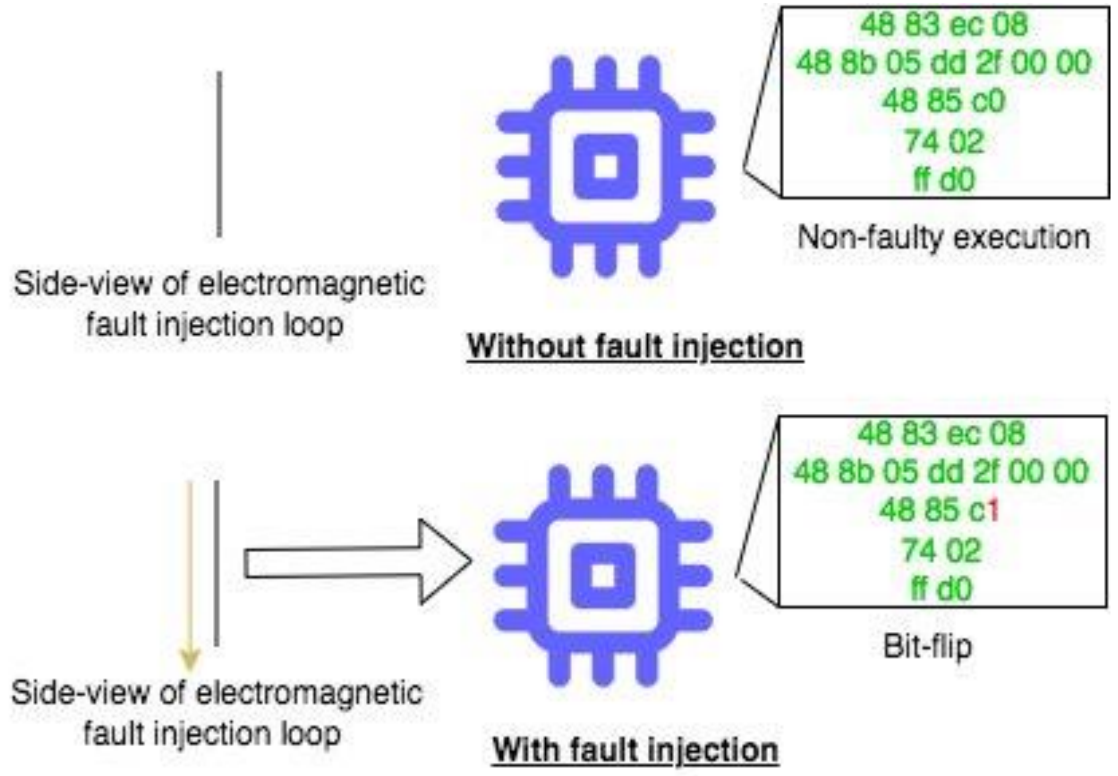
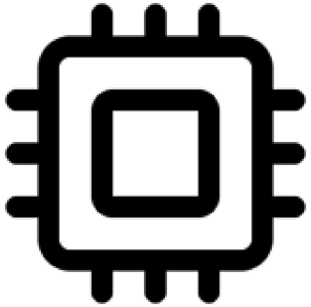
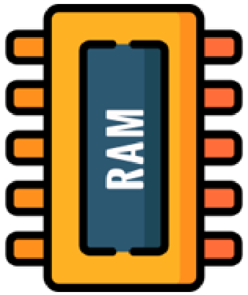
- **HOW**: Through changes in external operational conditions
- **WHY**: Bias software execution to adversarial advantage



Traditional Fault Injection Surfaces





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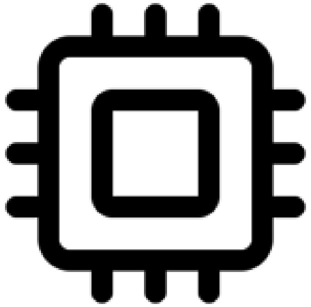

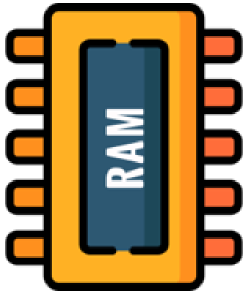

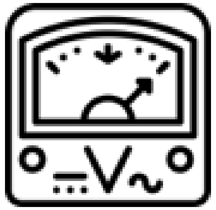

External interface
(voltage/clock glitch)

Dynamic Frequency and Voltage Scaling (DVFS)

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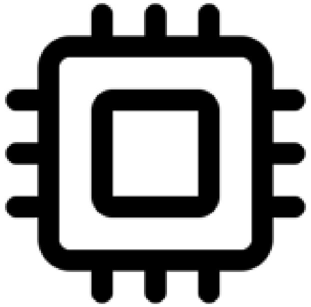

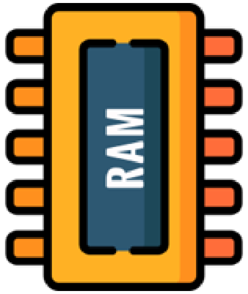

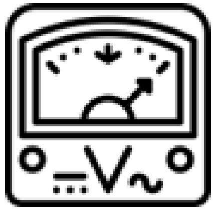

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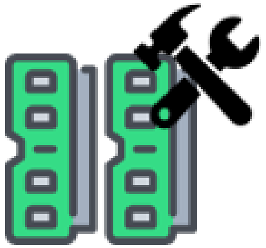
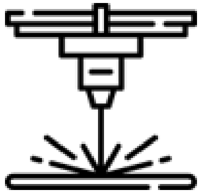
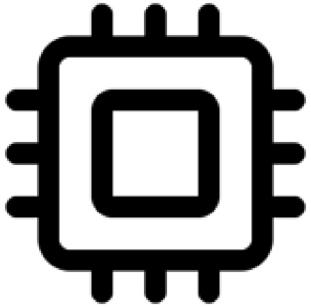


Rowhammer



Laser/EM Fault injection

Traditional Fault Injection Surfaces



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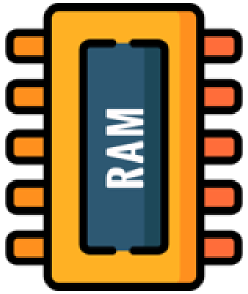
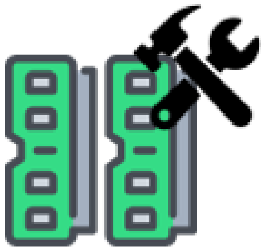
(in SoCs; ex RPi)

Privileged





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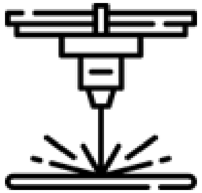

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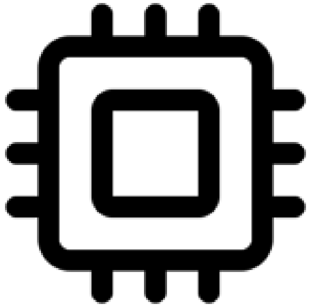

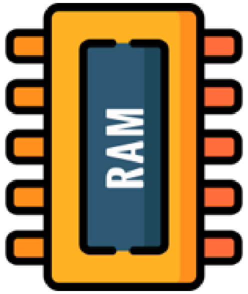

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Privileged

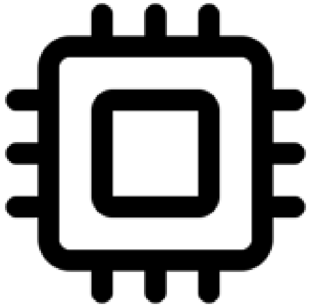
ECC checks,
Targeted Row
Refresh

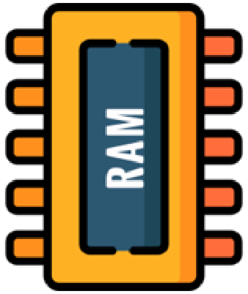
Casings
(requires invasive de
packaging)

Are there other **architectural aspects** that can be used for faults,

for which **no known defenses** are deployed yet?

A New Fault Injection Point for SoCs





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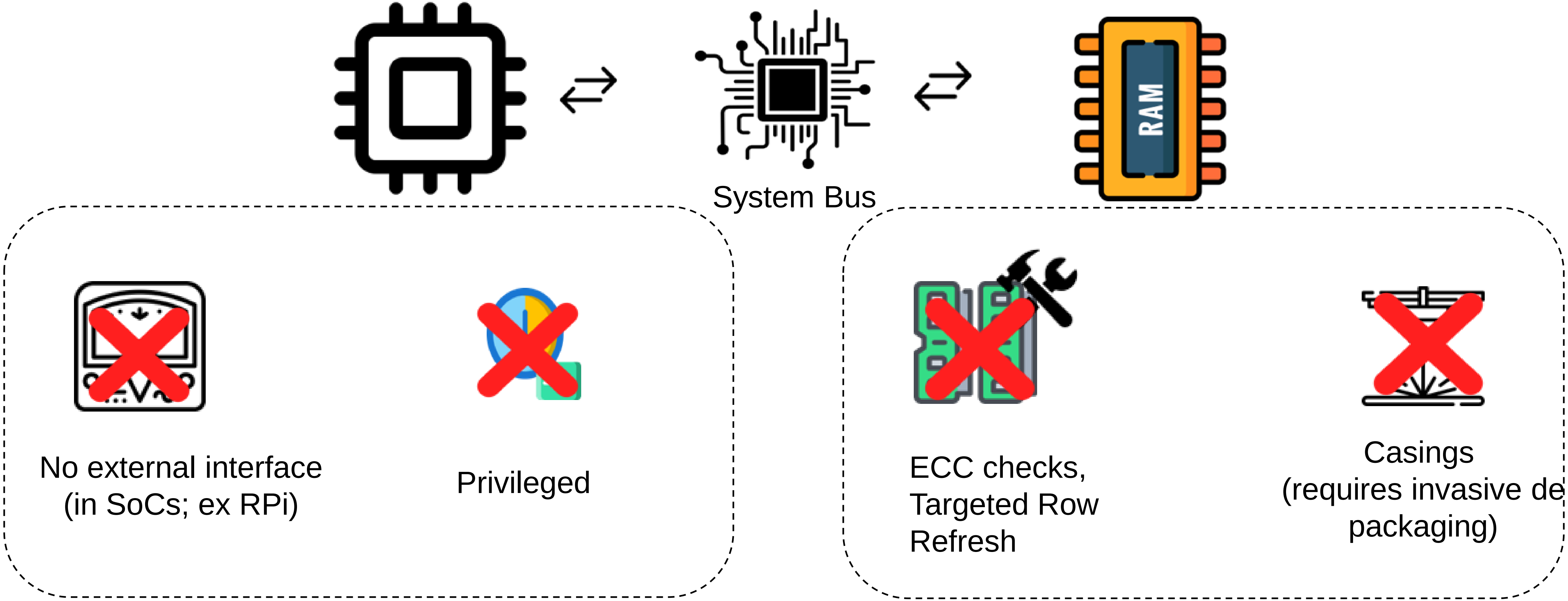


- Uncased and exposed
- Involved mainly with **load/store** instructions
- Prior works
  - Simulation of bus faults
  - External voltage glitches on PlayStation consoles to **skip** memory cycles

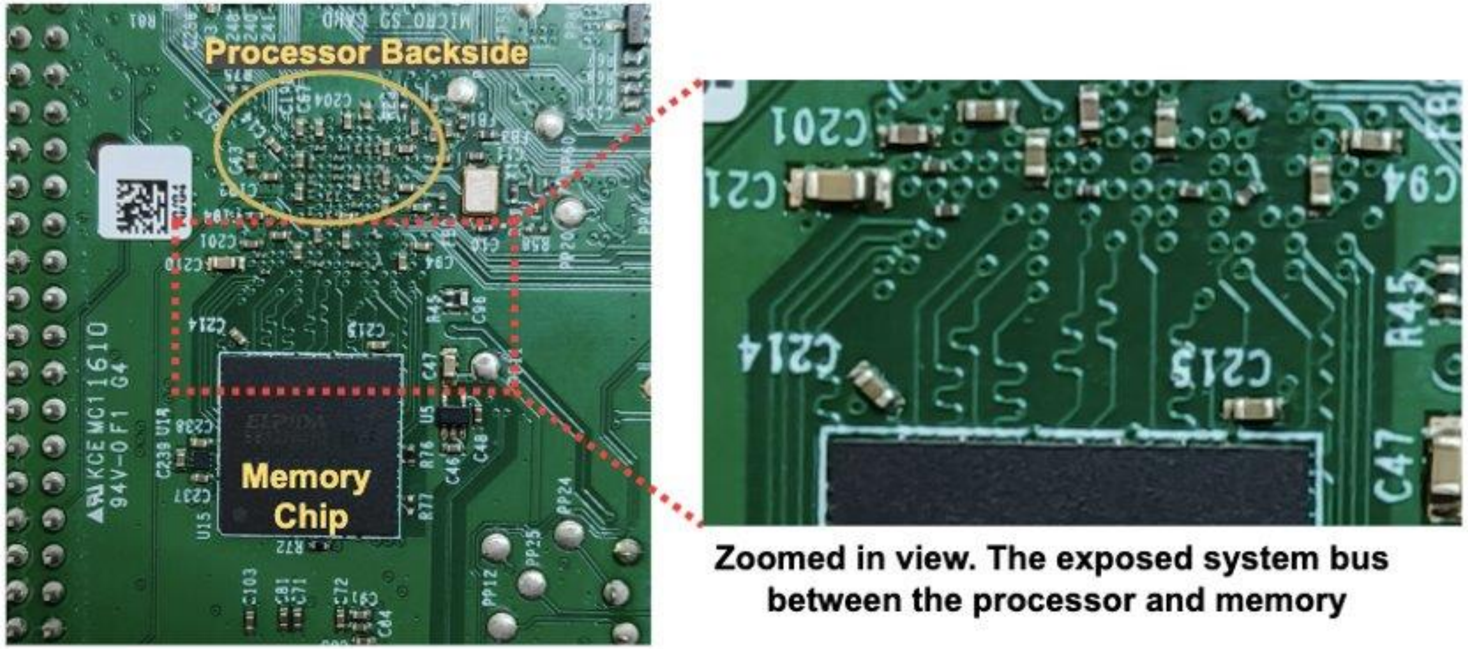


Fig: Exposed bus connections in RPi3

A New Fault Injection Point for SoCs

```
load   dest_reg,   [mem_addr]
```

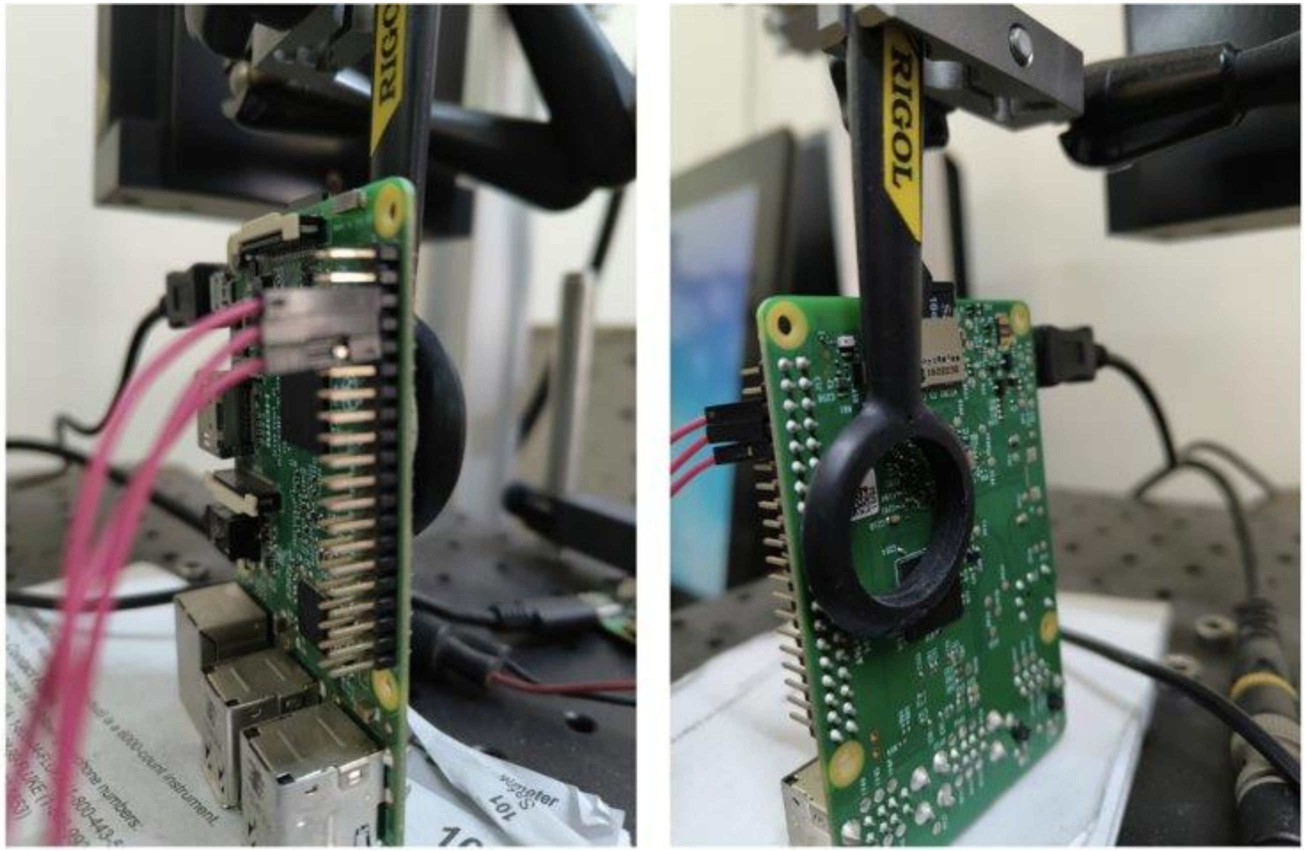
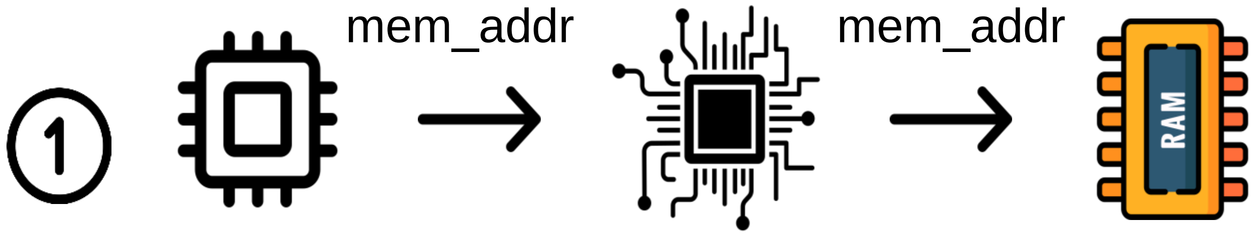
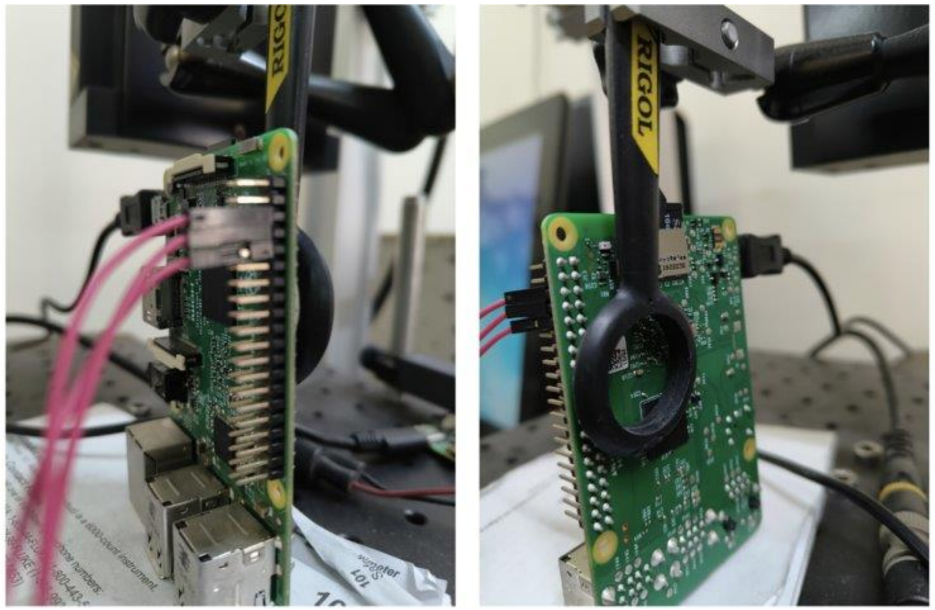


Fig: Electromagnetic Fault Injection probe positioned over the exposed system bus on a RPi3

A New Fault Injection Point for SoCs





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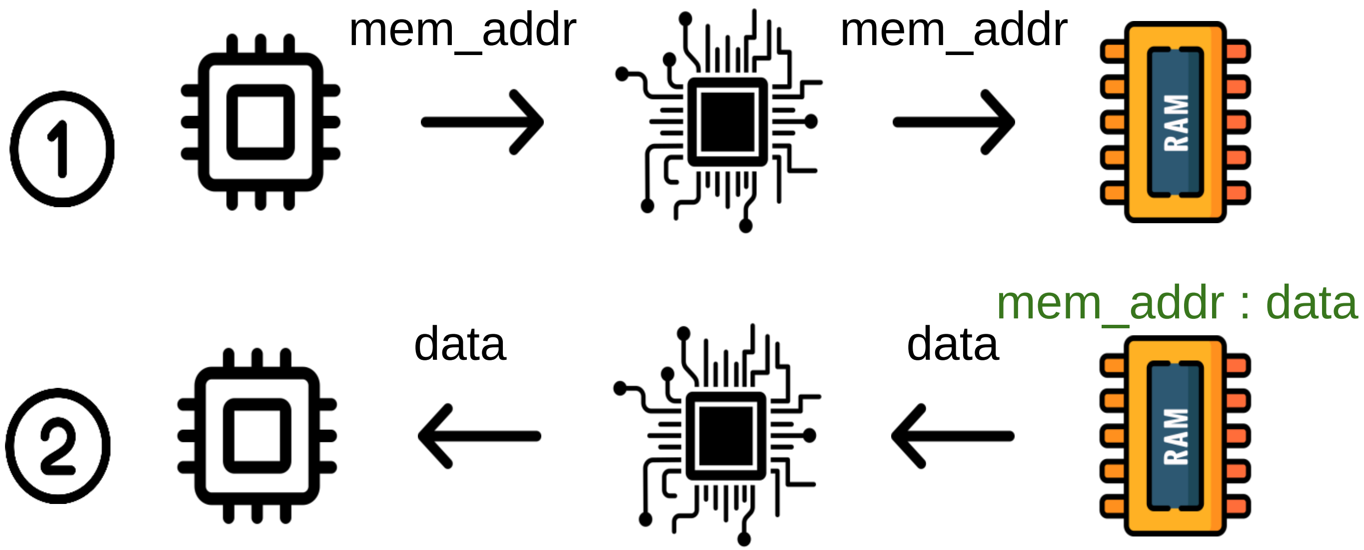

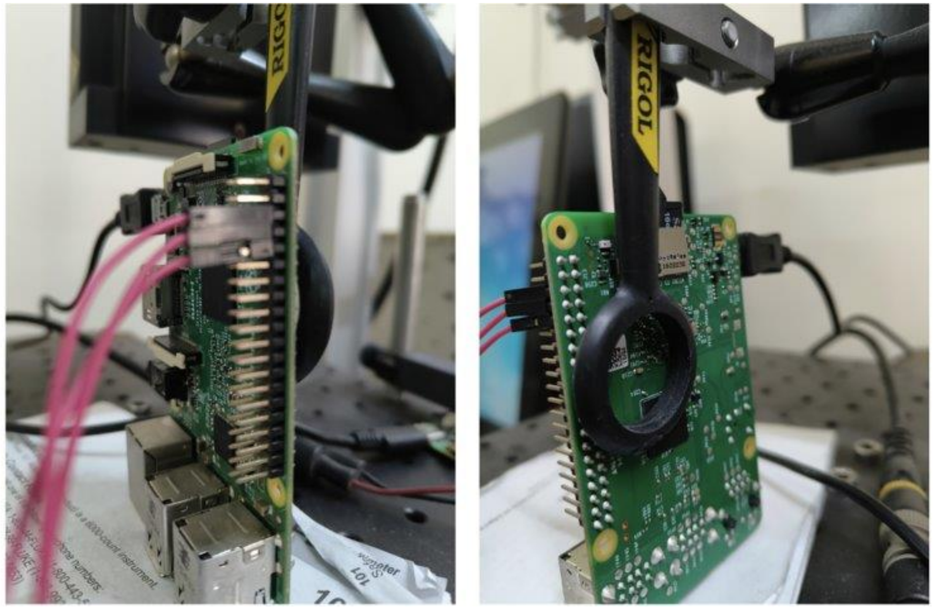

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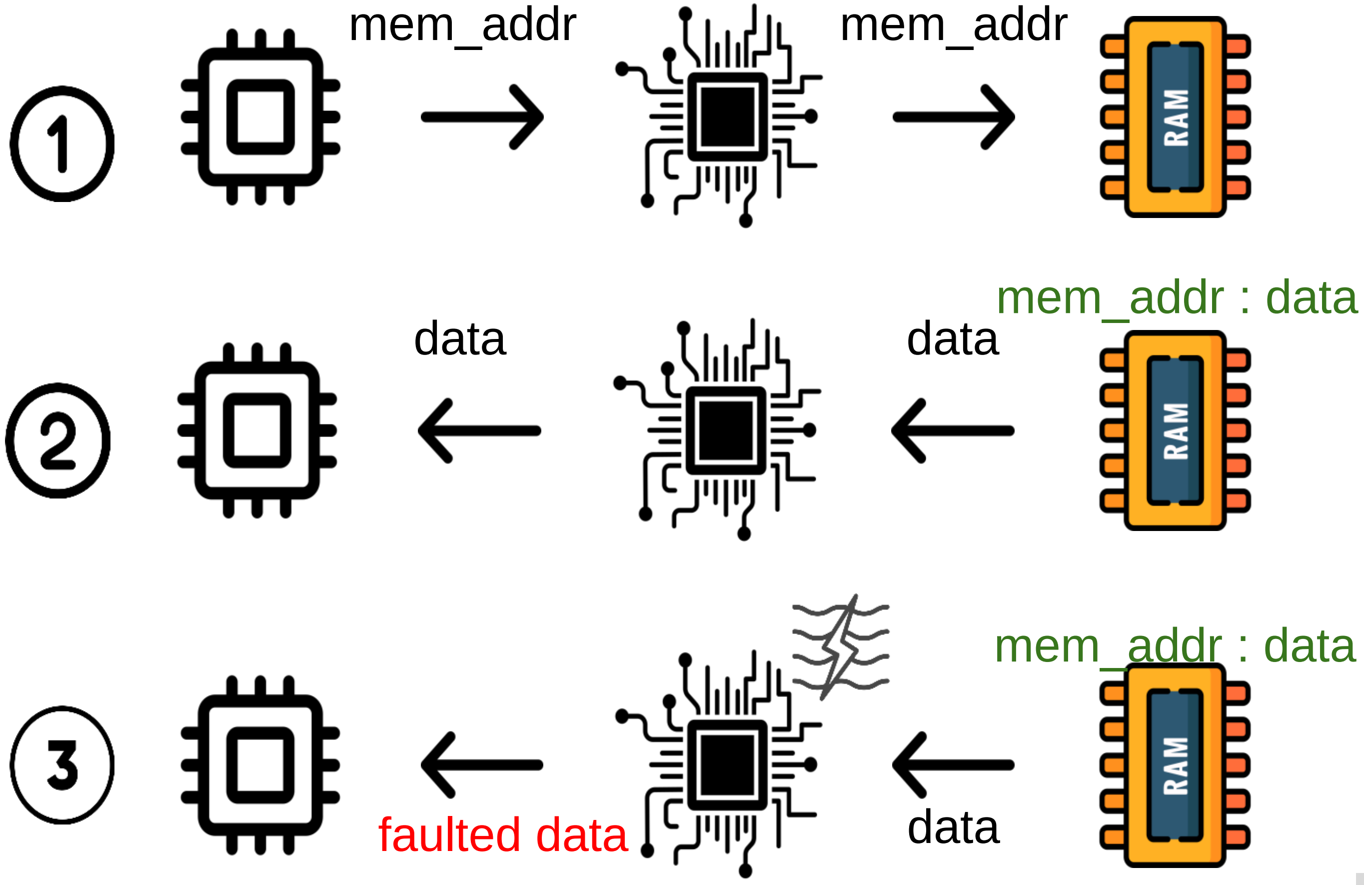

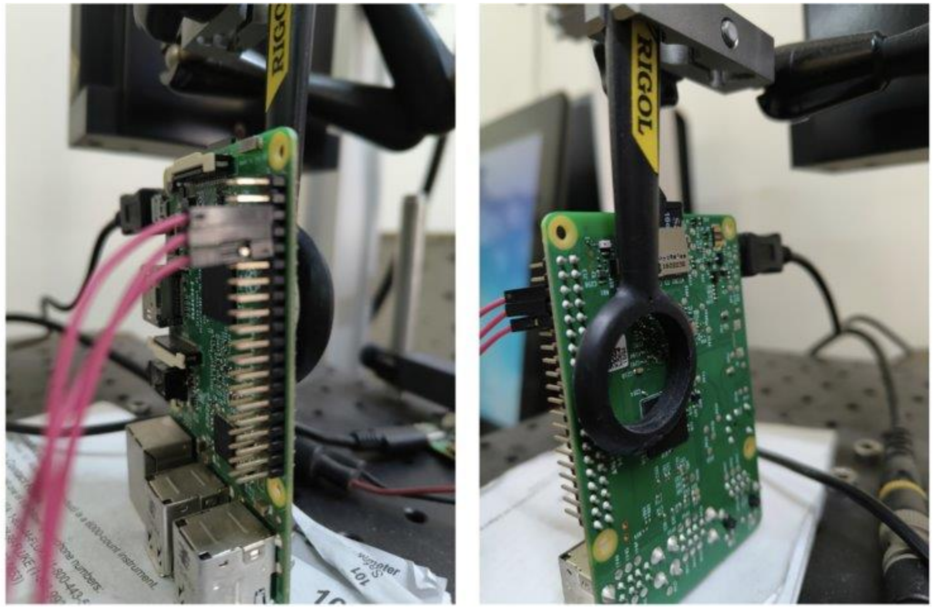

load dest_reg, [mem_addr]

FI on System Bus: Success Rates

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Data Bus Faults

- Result in **incorrect data**
- Success rate breakdown
  - **No fault**: 38%
  - **Fault to 0x0:** 35%
  - **Other cases**: 27%

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Data Bus Faults

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  - **Other cases**: 27%

Address Bus Faults

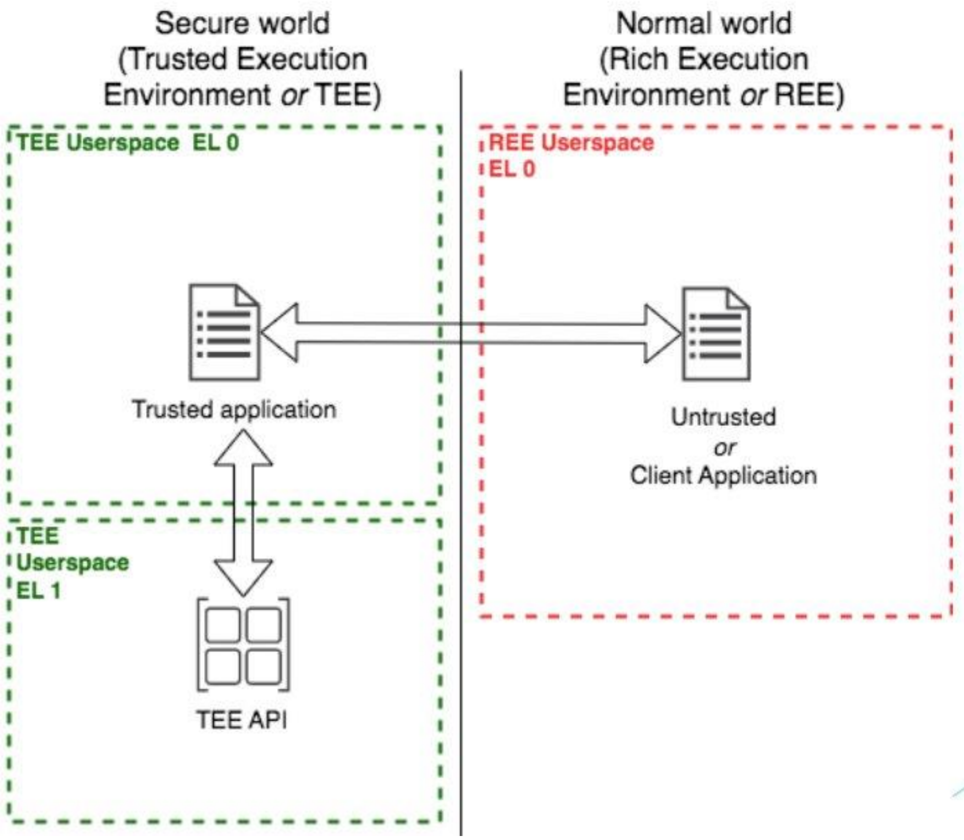
- Result in **SEGFAULT**
- Success rate breakdown
  - **SEGFAULT**: 31%
  - **Other cases**: 69%

Implication: Register sweeping to mount an end-to-end attack

on Open Portable Trusted Execution Environment (OP-TEE)

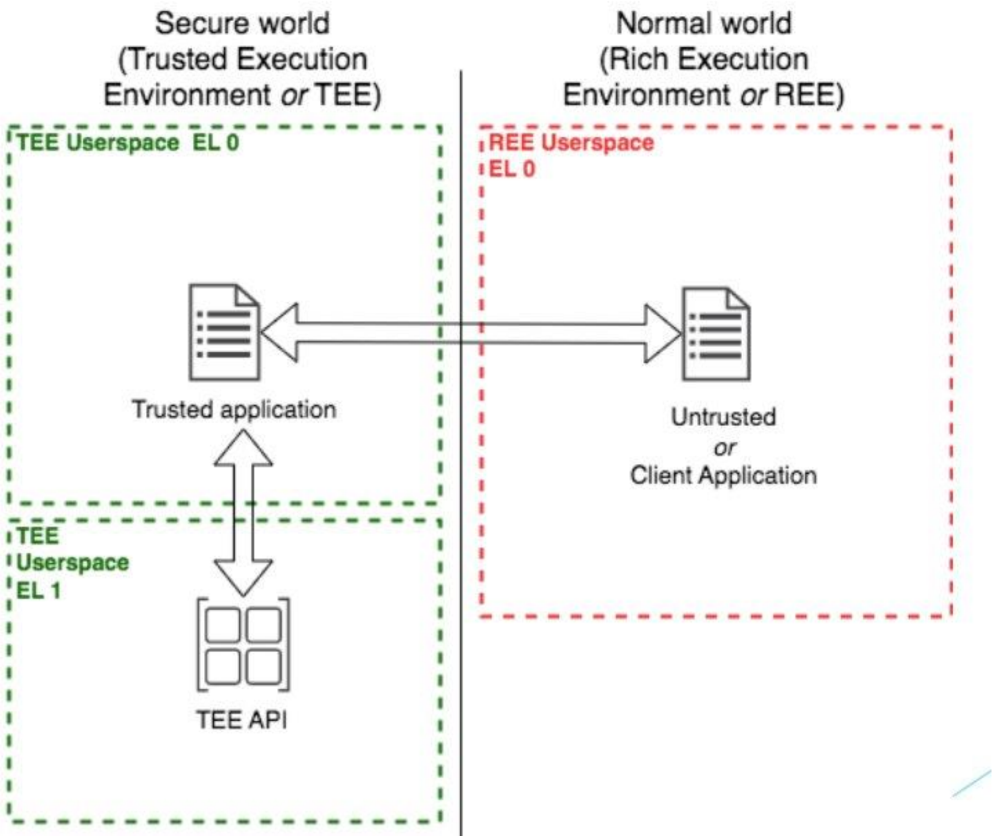
Open Portable Trusted Execution Environment

- open-source trusted execution environment (TEE) based on Arm TrustZone technology
- Hardware backed isolation of system resources
- Implementation of **GlobalPlatformAPI** specification for ARM TZ



Open Portable Trusted Execution Environment

- **Two main divisions**



Open Portable Trusted Execution Environment

- **Two main divisions**

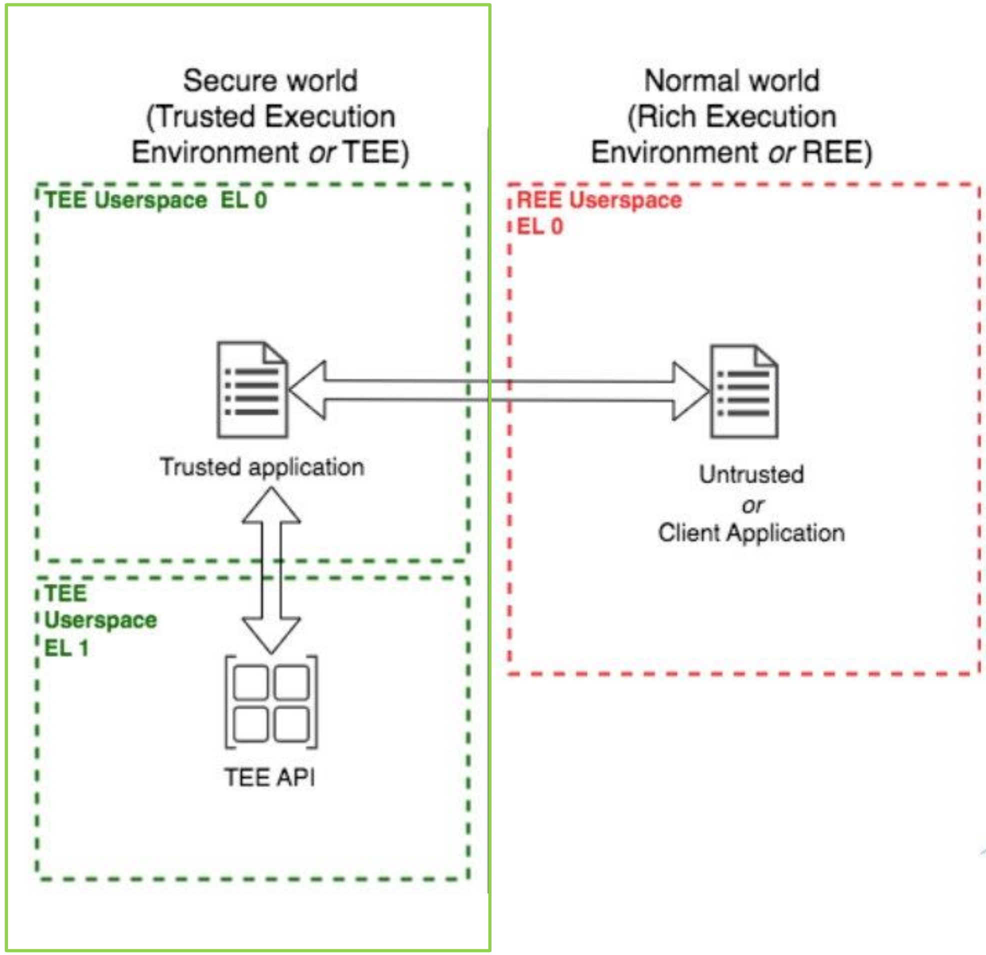
1. TEE or Trusted Execution Environment

Execution context where all the security critical operations reside. TEE has its own

a) secure/encrypted memory storage,

b) secure I/O peripherals,

c) secure context switching

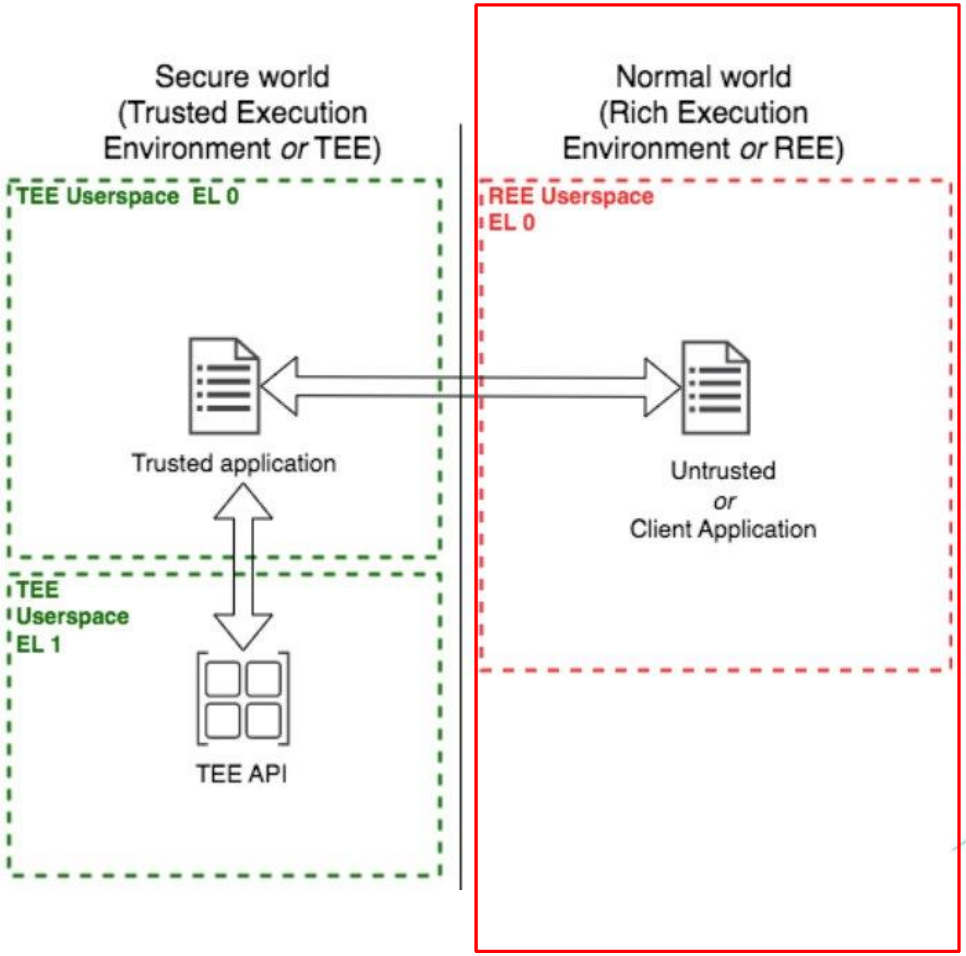


Open Portable Trusted Execution Environment

- **Two main divisions**

2. REE or Rich Execution Environment

Execution context where rest of the things run. REE invokes the services of TEE when required

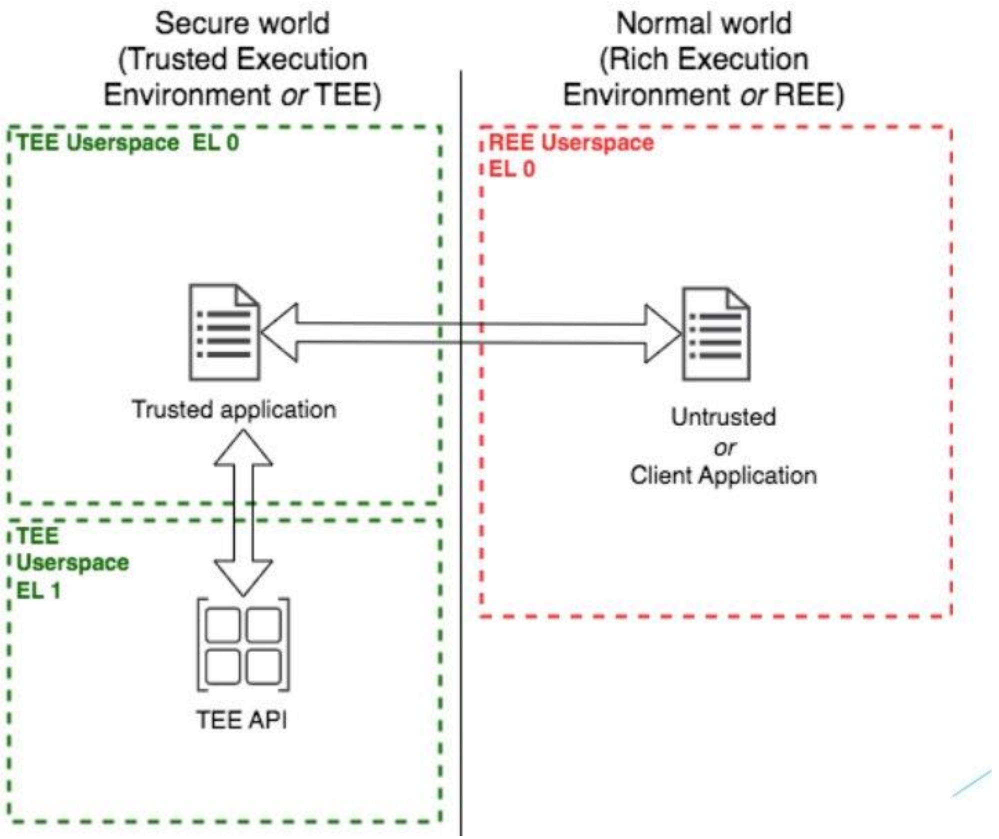


Open Portable Trusted Execution Environment

- **Two main divisions**

  1. **TEE or Trusted Execution Environment**
  2. **REE or Rich Execution Environment**

- All Trusted Applications (TAs) running in the TEE are checked for integrity
- No adversary having complete control over REE can execute arbitrary TEE code



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ADVERSARIAL GOAL!

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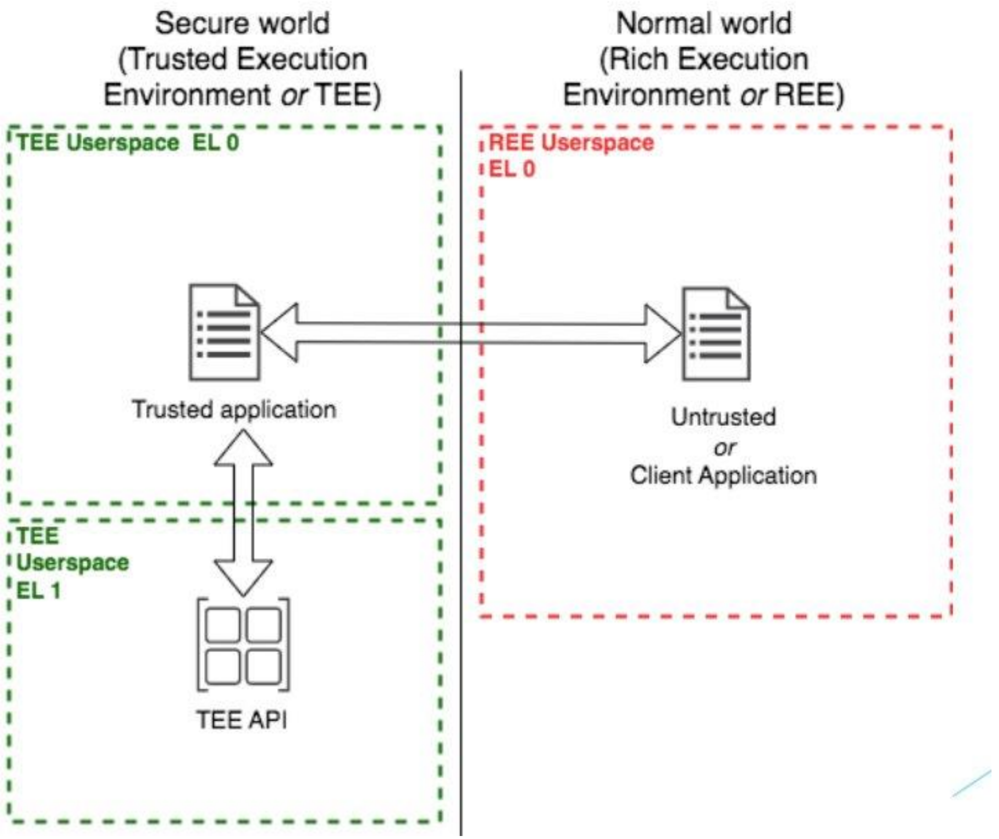

Adversarial Goals

- **Goal 1 :** Entire attack must be **online** (without taking the device offline)

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  - **Challenge 2 :** Cannot use **code-based** triggers (requires code modifications to the OP-TEE kernel)

    Our Solution : Construct a combined adversary (side-channel analysis + fault injection)

Adversarial Goals

Goal 2 : The attack must be non-invasive

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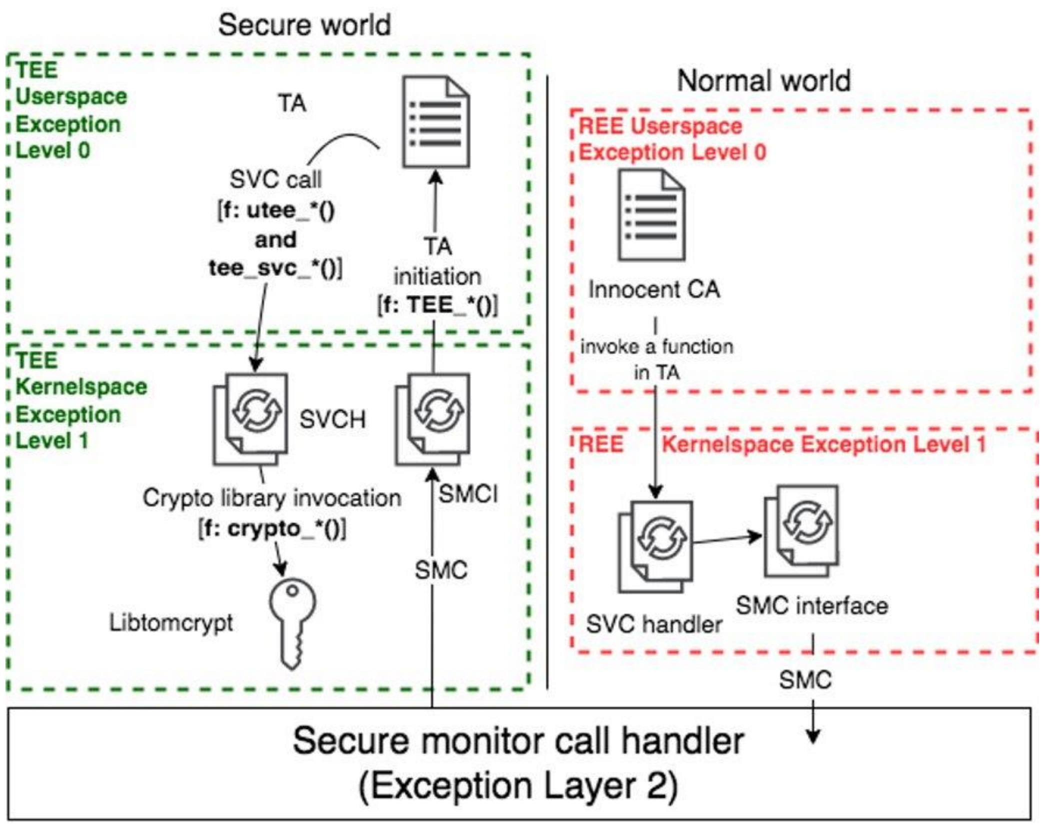
- **Challenge 3** : Cannot inject processor faults (requires depackaging). Trivial attacks like instruction skips cannot work

  Our Solution: Work with a new fault model (register sweeping) on the system-bus (requires no invasive alterations to the target device)

Fault Attack Target



Fault Attack Target

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#define TEE_ERROR_SECURITY 0xFFFF000F

TEE_Result verify_signature(char* ta_binary, uint8_t* signature){
    if(/*signature is valid*/)
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}

// load a TA referenced by a CA
void load_TA(...){
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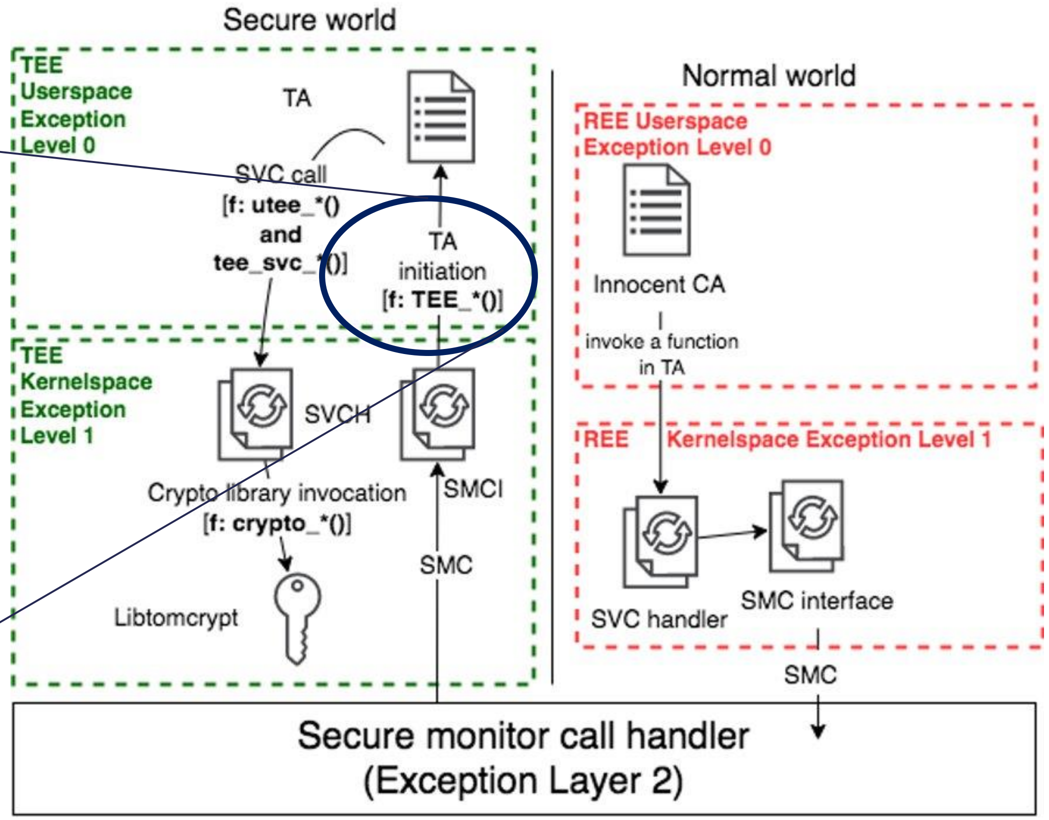

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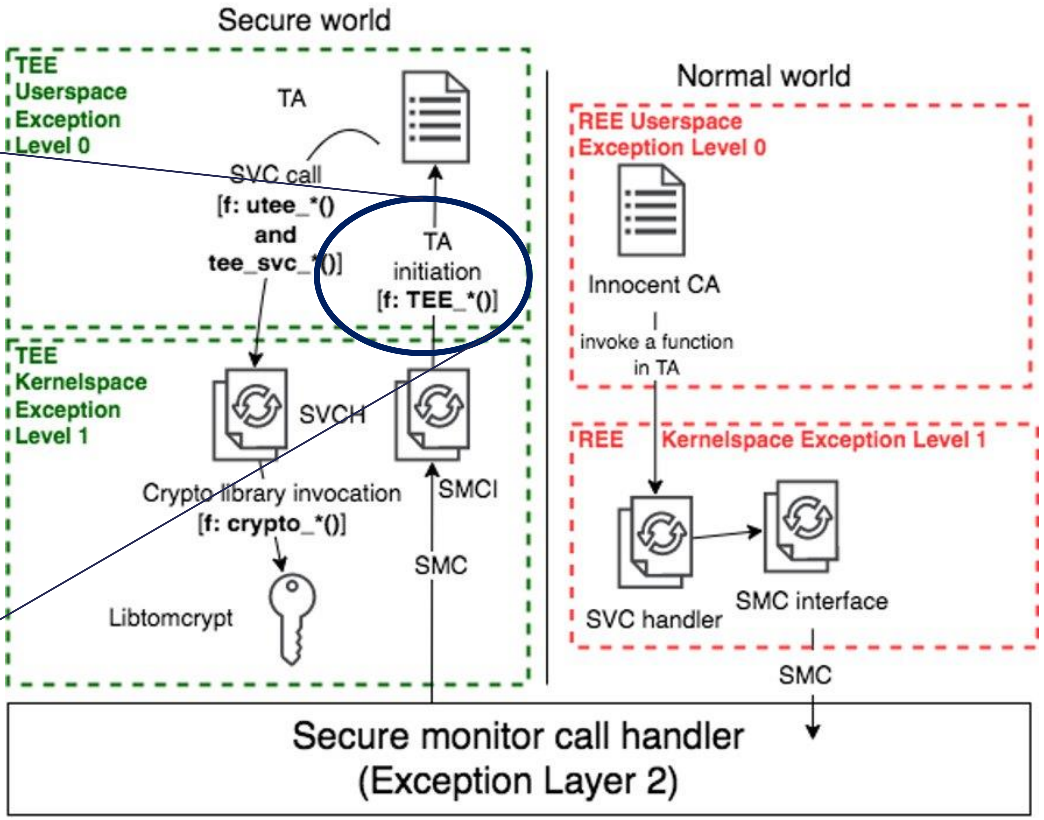

External glitch

DVFS

Rowhammer

Stealing signing key

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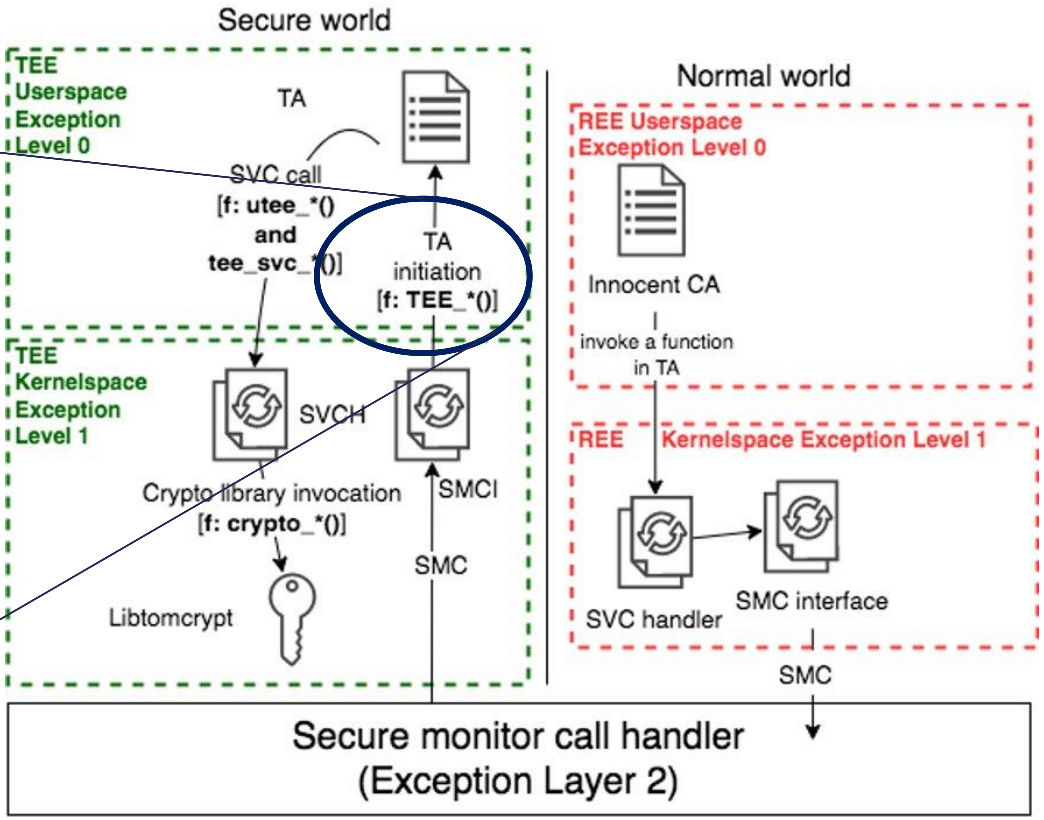

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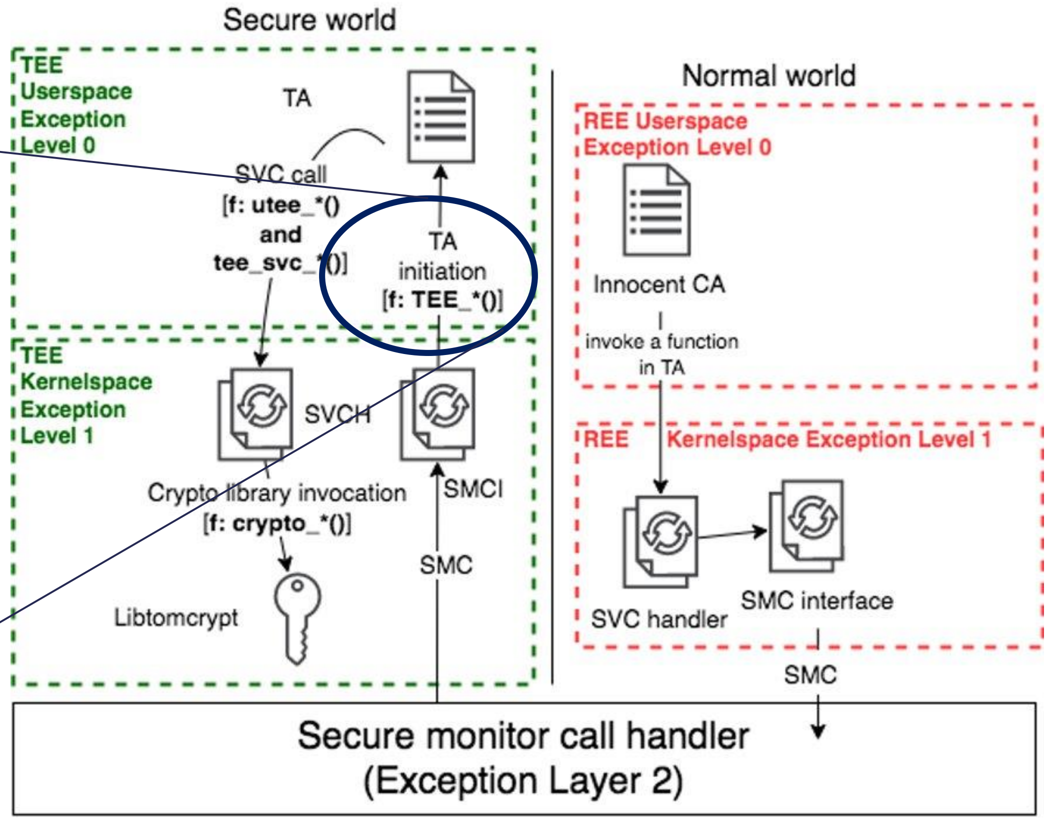


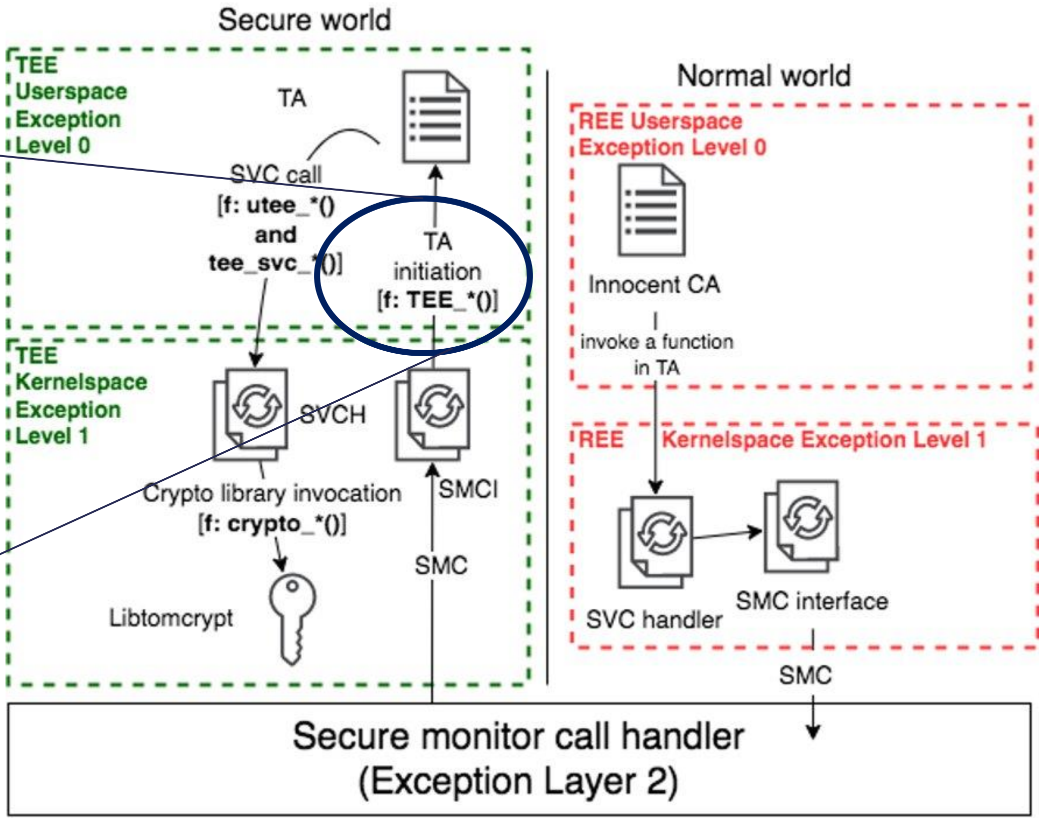
Register Sweeping: Fault the load to 0x0 through data bus faults

Fault Attack Target

```
bl      0 <crypto_acipher_rsassa_verify>
str     w0, [sp, #76]
```

FAULT INJECTION TARGET!

```
ldr     w0, [sp, #76]
cmp     w0, #0x0
b.eq    1e0 <shdr_verify_signature+0x1e0>  // b.none
mov     w0, #0xffff000f                   // #-65521
```

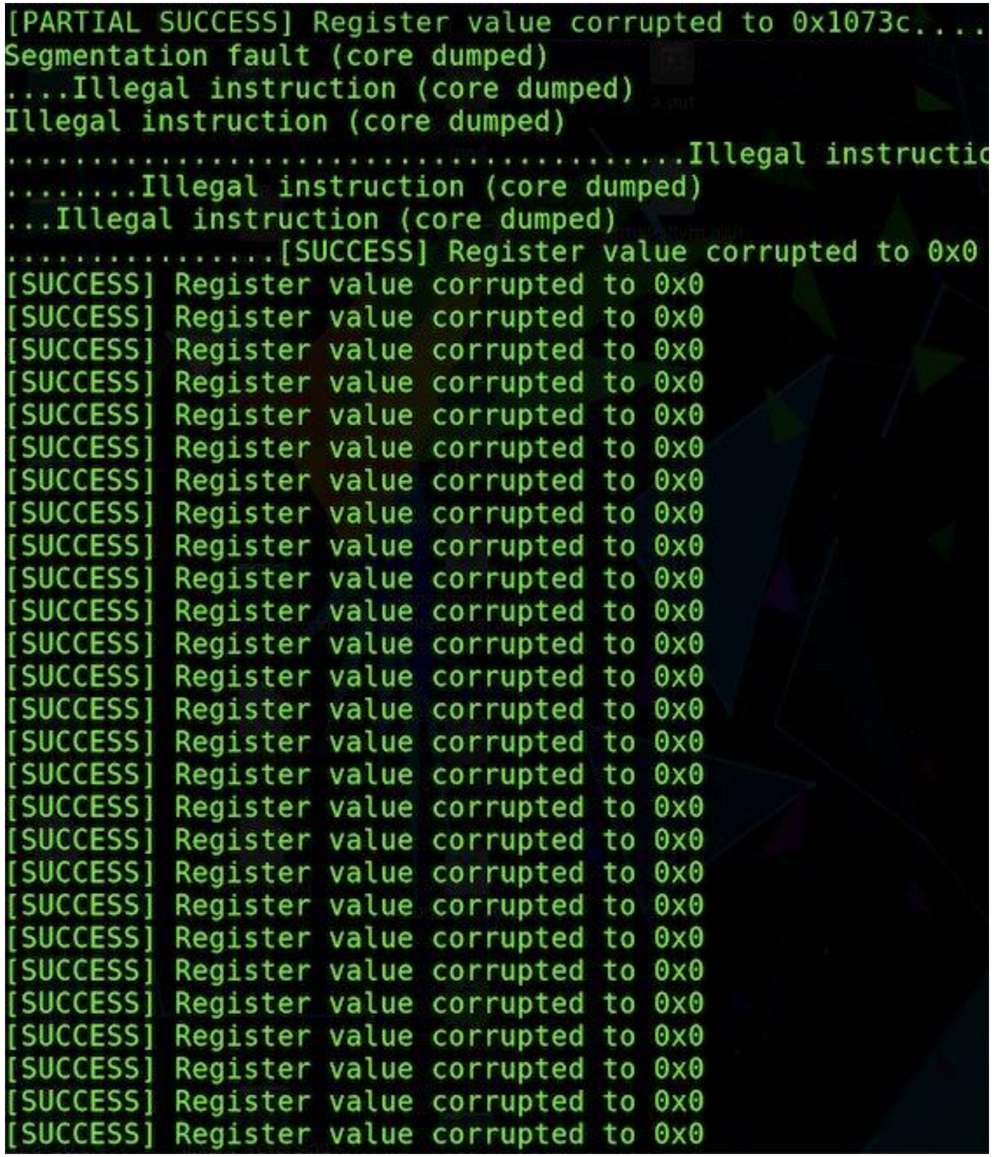


Register Sweeping: Fault the load to 0x0 through data bus faults

Fault Attack Result

- **No Effect** (denoted by a "dot") : No effect of the injected fault
- **Partial Success**: Injected fault changes the value of the load, but not to 0x0.

  Or causes SEGFAULT
- **Success** : Faults value of the load to 0x0.



End to End Attack

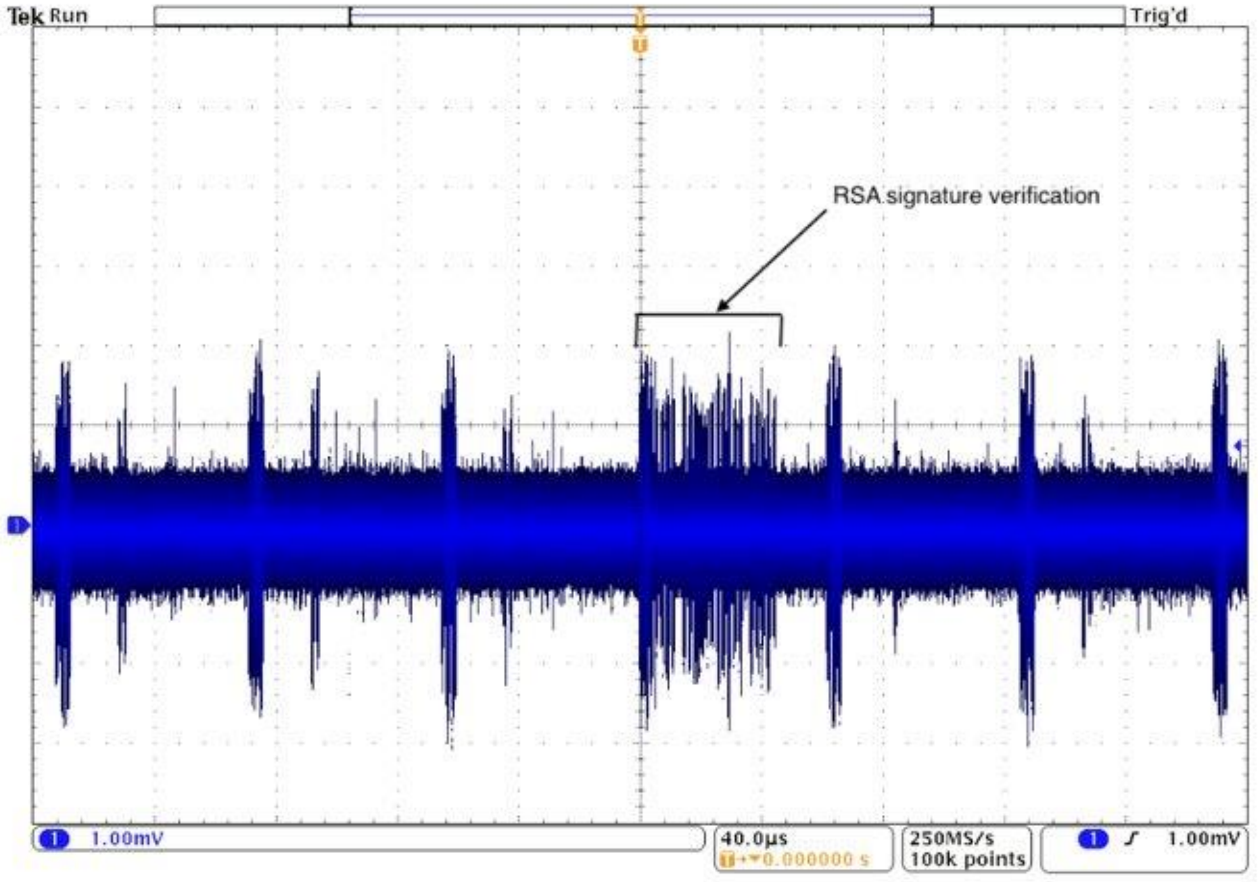
1. Load (adversarial) Trusted Applications through Faults

2. Redirect communication for other Trusted Applications

3. Decrypt (redirected) communication

Load (adversarial) Trusted Applications through Faults

Combined Adversary = Power of SCA + FI



Power side-channel as a trigger

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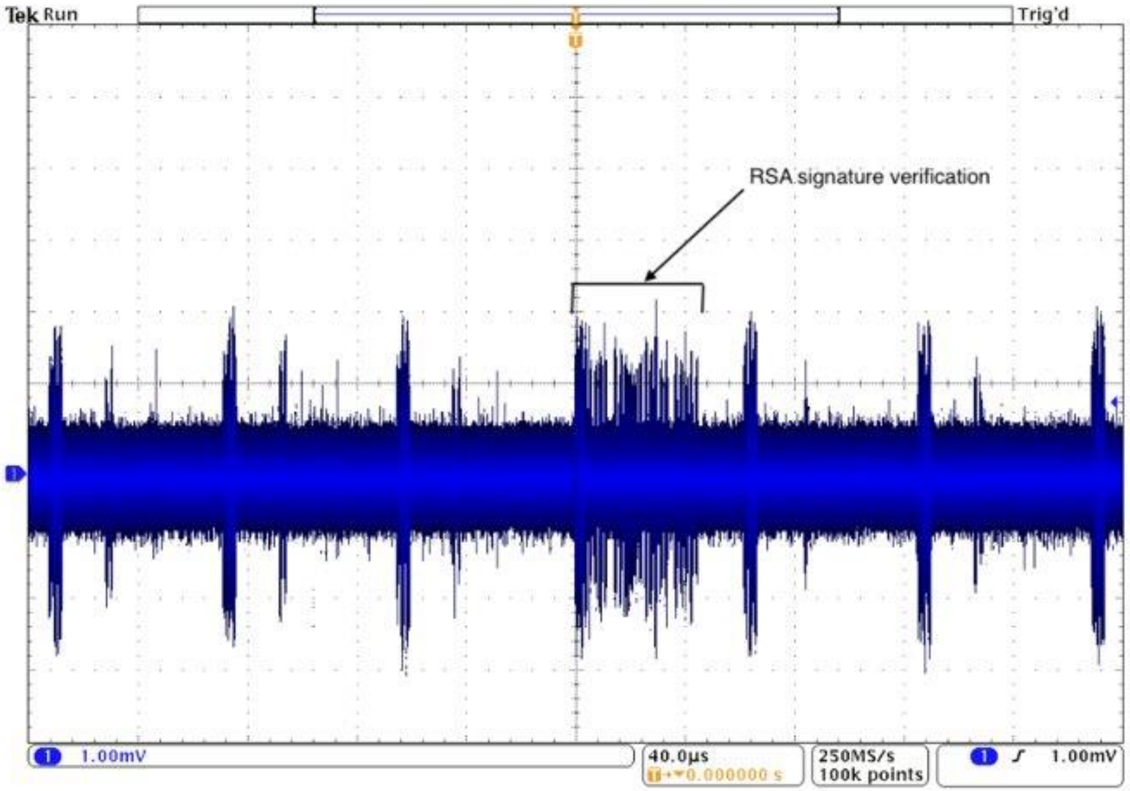
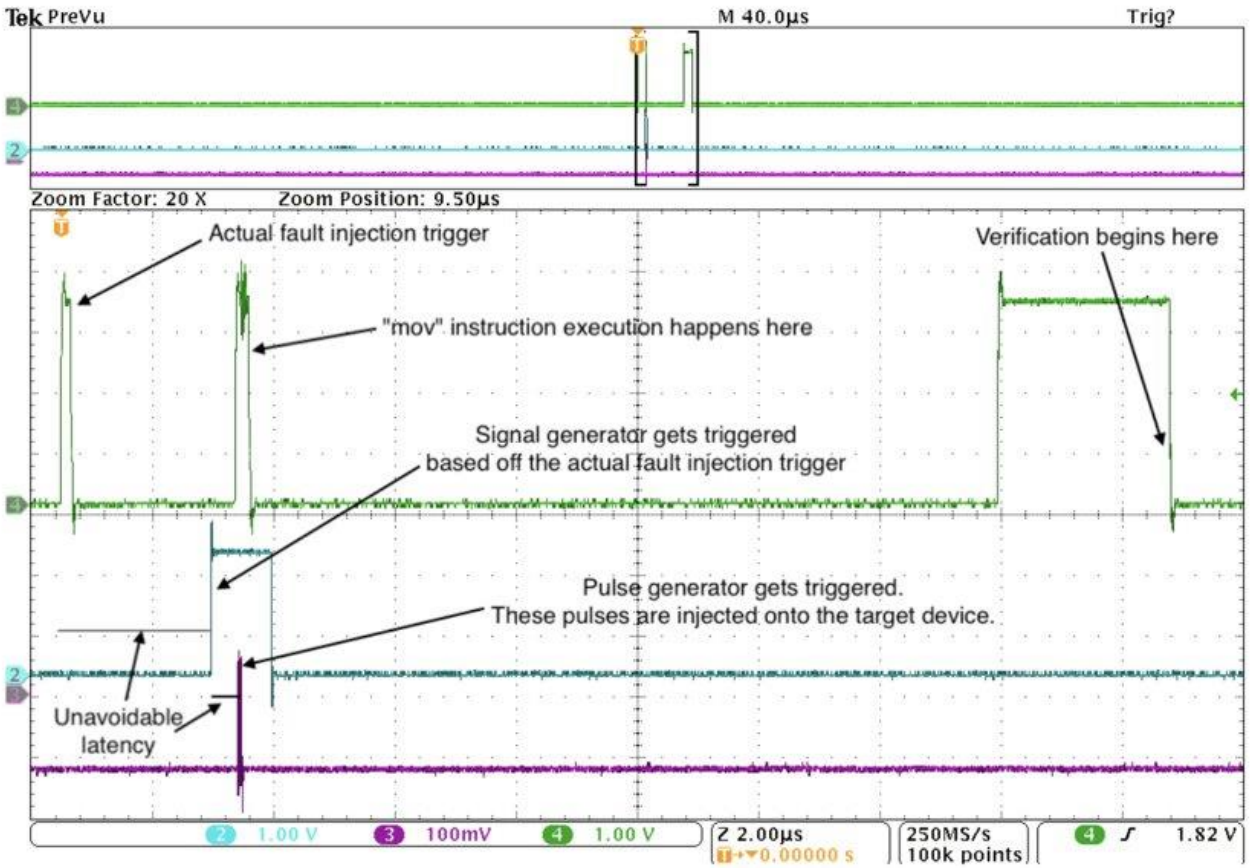


Power side-channel as a trigger fault injection in a non-invasive way
(no recompilation of OP-TEE necessary)

⊕



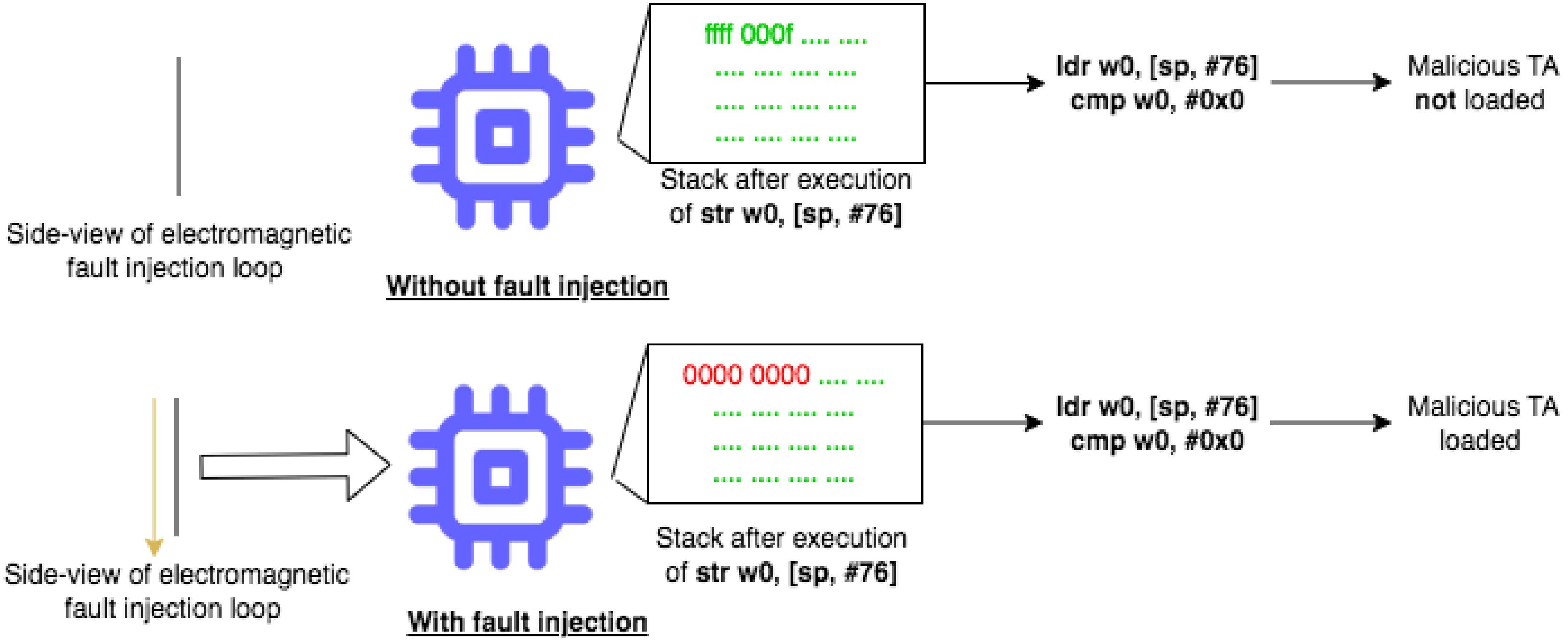
Actual Fault Injection on signature verification

Combined Adversary = Power of SCA + FI

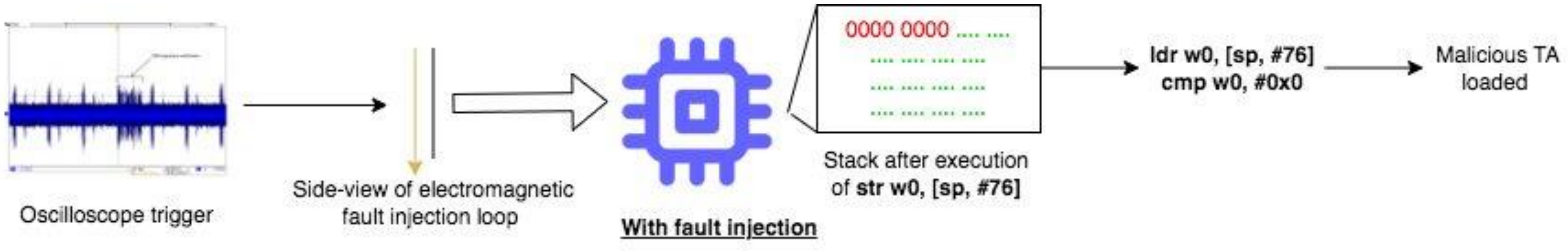
```
bl          0 <crypto_acipher_rsassa_verify>
str         w0, [sp, #76]
```

FAULT INJECTION TARGET!

```
ldr     w0, [sp, #76]
cmp     w0, #0x0
b.eq    1e0 <shdr_verify_signature+0x1e0>  // b.none
mov     w0, #0xffff000f                   // #-65521
```



Combined Adversary = Power of SCA + FI



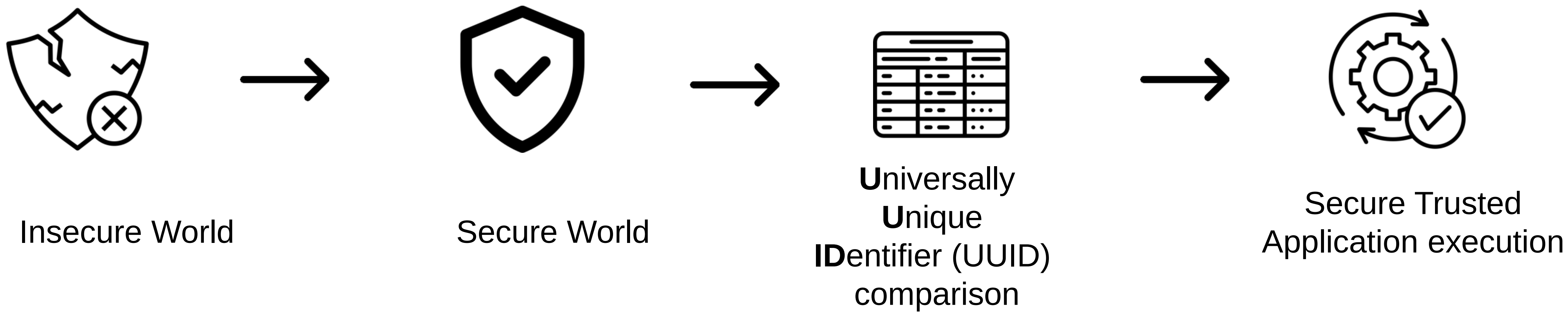
Fallout: Register sweeping fault attack loads a self-signed, adversarial controlled Trusted Application in the secure world of OP-TEE

Fallout: Register sweeping fault at[...] [...]lf-signed, adversarial controlled

Trusted Ap[...] [...]secure world of OP-TEE

Privilege Escalation !

Redirect communication for other Trusted Applications



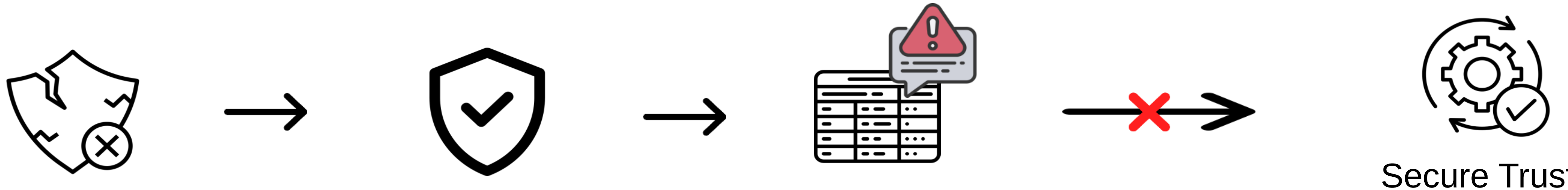
Redirect communication for other Trusted Applications

Observation: GlobalPlatform API specification (upon which OP-TEE is constructed) offloads the responsibility of choosing UUID to Original Equipment Manufacturer. It is the responsibility of **the OEM to ensure no two Trusted Applications (TA) share same UUID**

Redirect communication for other Trusted Applications

UUID confusion: Behavior of the system when UUID are non-unique is undefined. When UUIDs are shared, a non-persistent TA is preferred over a persistent TA.

Redirect communication for other Trusted Applications



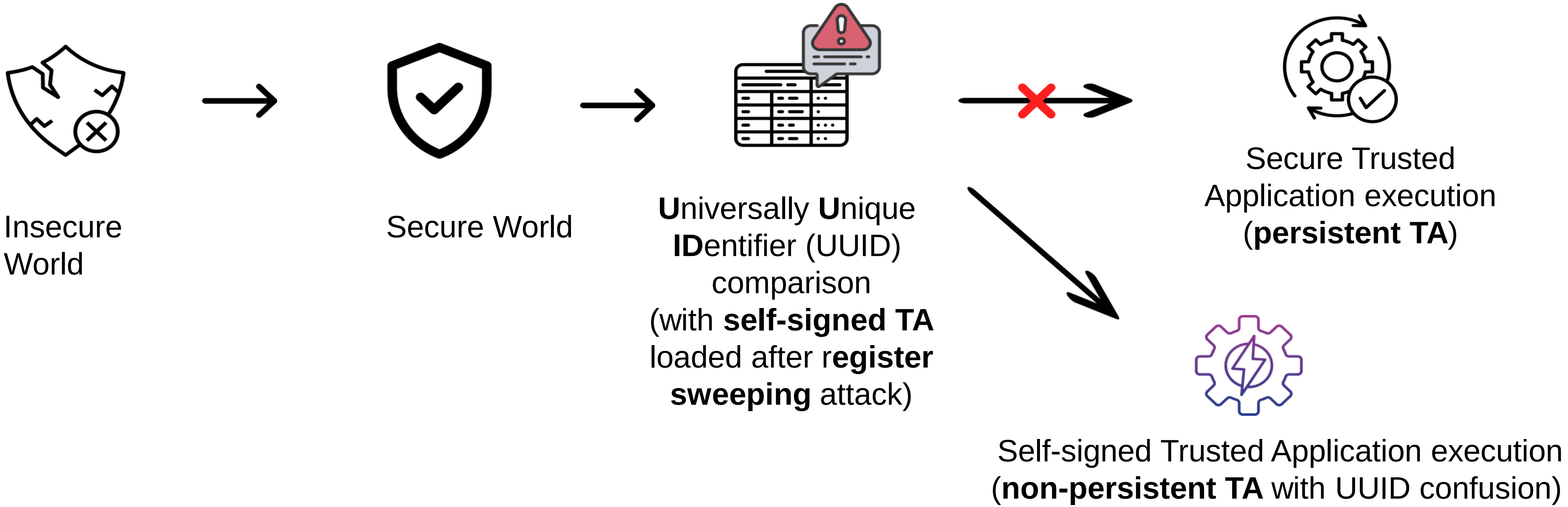
Insecure World

Secure World

Universally **U**nique **ID**entifier (UUID) comparison (with **self-signed TA** loaded after **register sweeping** attack)

Secure Trusted Application execution (**persistent TA**)

Redirect communication for other Trusted Applications

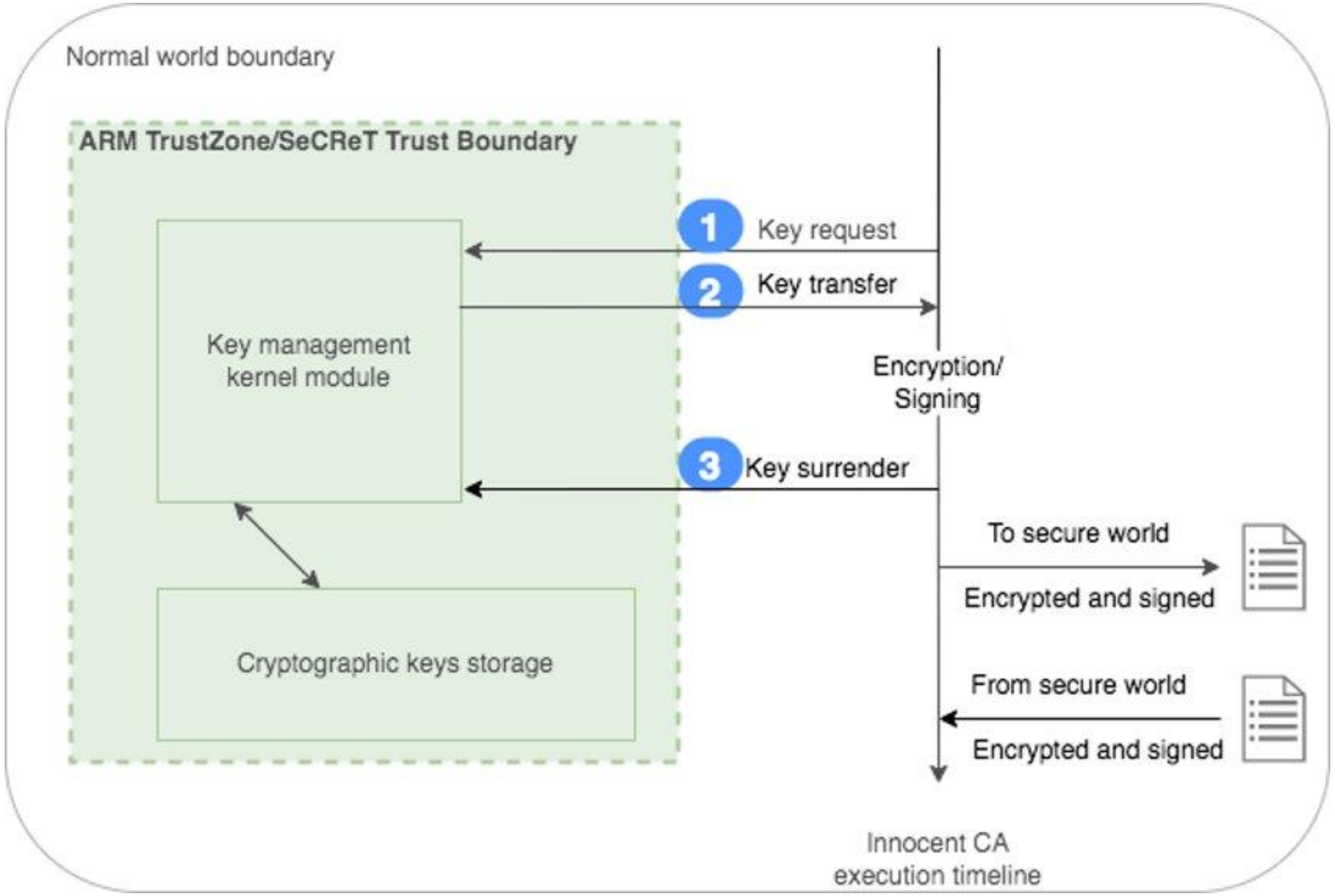


Decrypt (redirected) communication

Third Party extension: SeCReT

- Symmetric key management
- Blocks SIGTRAP
- Blocks unauthorized read to sensitive data pages

Decrypt (redirected) communication



Third Party extension: SeCReT

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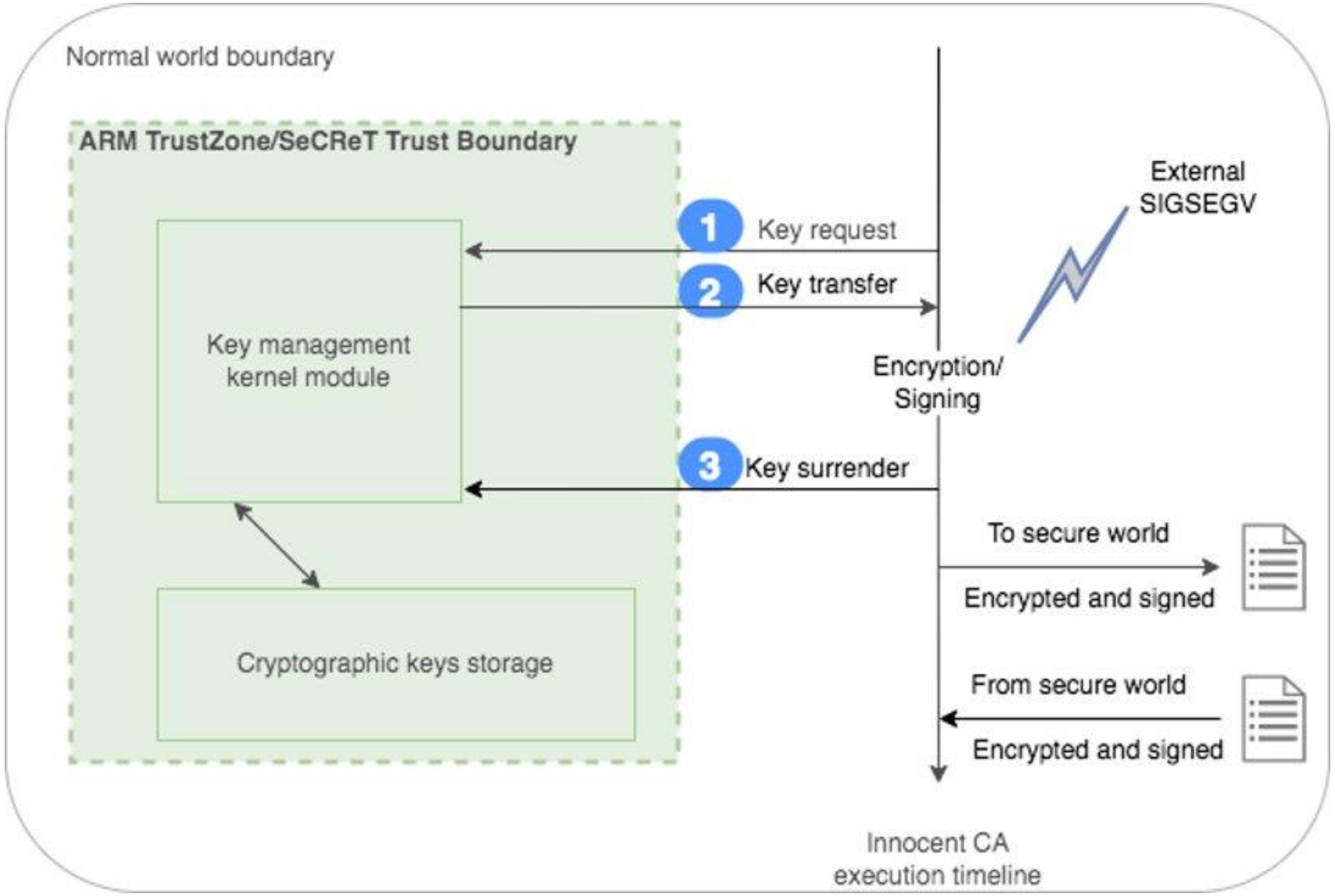
Decrypt (redirected) communication

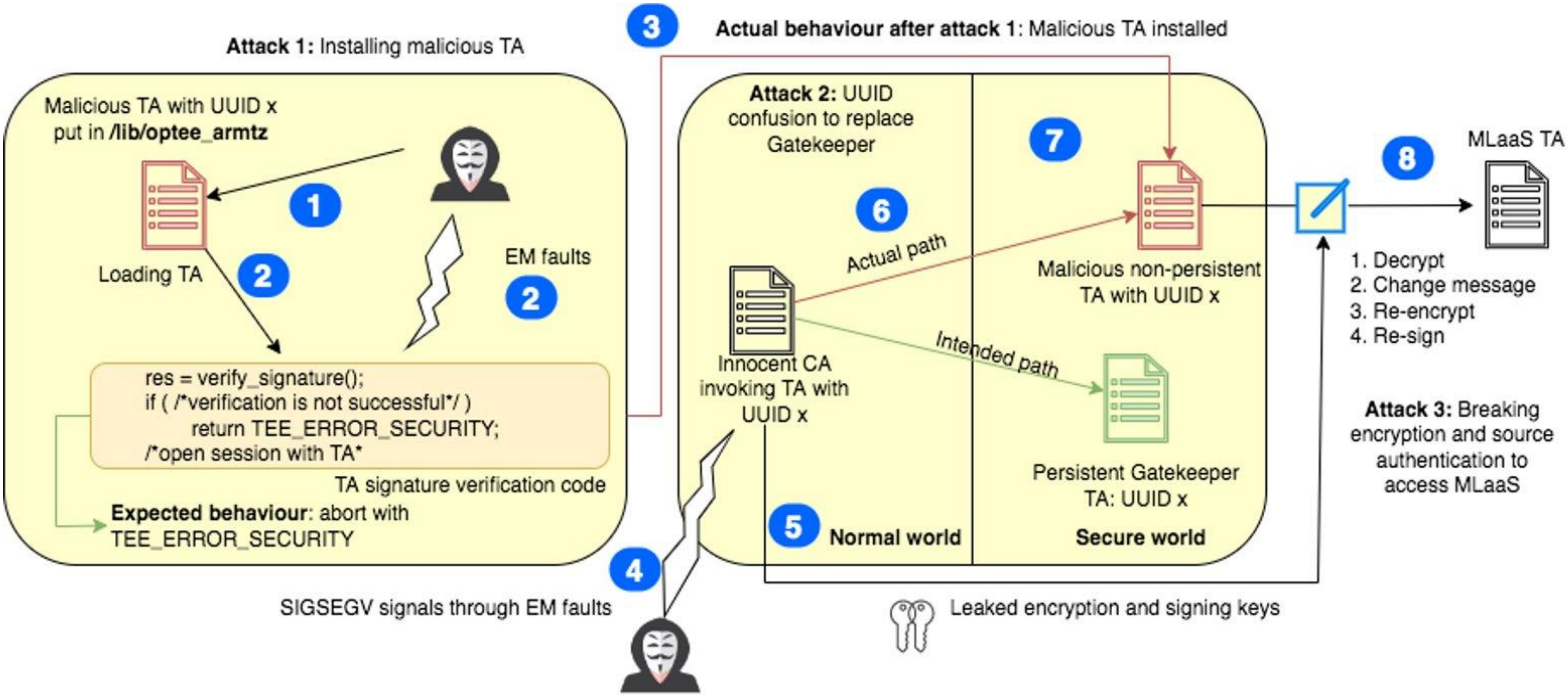


Third Party extension: SeCReT

- Symmetric key management
- Blocks SIGTRAP
- Blocks unauthorized read to sensitive data pages
- Does not block SIGSEGV. Leaks key through coredumps

Decrypt (redirected) communication

Bird's Eye View



Impact

- CVE 2022-47549
- Worked together with Linaro to deploy countermeasure in OP-TEE kernel

```
-        res = crypto_acipher_rsassa_verify(shdr->algo, &key, shdr->hash_size,
-                                           SHDR_GET_HASH(shdr), shdr->hash_size,
-                                           SHDR_GET_SIG(shdr), shdr->sig_size);
+        FTMN_CALL_FUNC(res, &ftmn, FTMN_INCR0,
+                       crypto_acipher_rsassa_verify, shdr->algo, &key,
+                       shdr->hash_size, SHDR_GET_HASH(shdr), shdr->hash_size,
+                       SHDR_GET_SIG(shdr), shdr->sig_size);
+        if (!res) {
+                ftmn_checkpoint(&ftmn, FTMN_INCR0);
+                goto out;
+        }
+        err_incr = 1;
+ err:
+        res = TEE_ERROR_SECURITY;
+        FTMN_SET_CHECK_RES_NOT_ZERO(&ftmn, err_incr * FTMN_INCR0, res);
```

Other Implications

- Re-enable Differential Fault Attack (DFA) on T-table implementation of AES (on SoCs)

- Address Bus Faults to leak **all** shares of Masked PQC implementations (like Kyber-KEM)

  Observation: All shares encapsulated within a **single** memory structure

Takeaways

- System + Execution Environment, not *just* the System

- Register sweeping fault model on a (new) architectural aspect – System Bus

  - Implications for other systems?

- Rethinking protocol specifications for embedded systems in light of SCA+FI adversaries

Thank You

For more details, scan the QR code →

For any questions or concerns, please contact:

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NDSS

Symposium 2024

Faults in Our Bus: Novel Bus Fault Attack to Break ARM TrustZone

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