Bypassing Secure Boot using Fault Injection

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November 4, 2016

What are the contents of this talk?

Keywords – *fault injection, secure boot, bypasses, mitigations, practicalities, best practices, demo(s) ...*

Who are we?

Albert & Niek

- (Senior) Security Analysts at Riscure
- Security testing of different products and technologies

Riscure

- Services (Security Test Lab)
  - Hardware / Software / Crypto
  - Embedded systems / Smart cards
- Tools
  - Side channel analysis (passive)
  - Fault injection (active)
- Offices
  - Delft, The Netherlands / San Francisco, USA

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Fault Injection – A definition...

"Introducing faults in a target to alter its intended behavior."

```
...
if( key_is_correct ) <-- Glitch here!
{
  open_door();
}
else
{
  keep_door_closed();
}
...
```

How can we introduce these faults?

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Fault injection techniques[1]

clock voltage e-magnetic laser

Remark

- All techniques introduce faults externally

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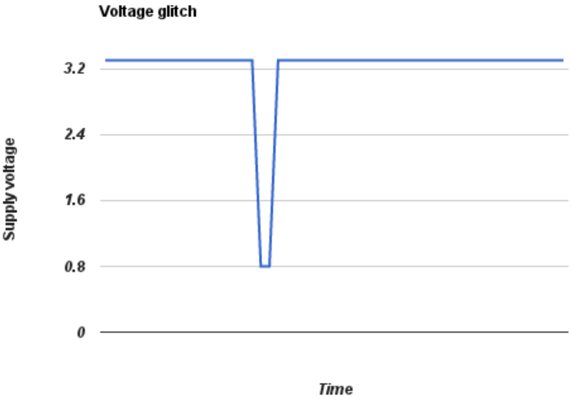
Voltage fault injection

- Pull the voltage down at the right moment
- Not 'too soft'; Not 'too hard'



Source: http://www.limited-entropy.com/fault-injection-techniques/

Fault models

Faults that affect hardware

- Registers
- Buses

Faults that affect hardware that does software[2] [3] [4]

- Instruction corruption
- Data corruption

*The **true fault model** is **hard to predict** or prove!*

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Fault Models – ”Our” choice ...

*When presented with code: **instruction corruption**.*

Simple (MIPS)

```
addi $t1, $t1, 8    00100001001010010000000000001000
addi $t1, $t1, 0    00100001001010010000000000000000
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Complex (ARM)

```
ldr w1, [sp, #0x8]  10111001010000000000101111100001
str w7, [sp, #0x20] 10111001000000000010001111100111
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Remarks

- Limited control over which bit(s) will be corrupted
- May or may not be the true fault model
- Other fault model behavior covered

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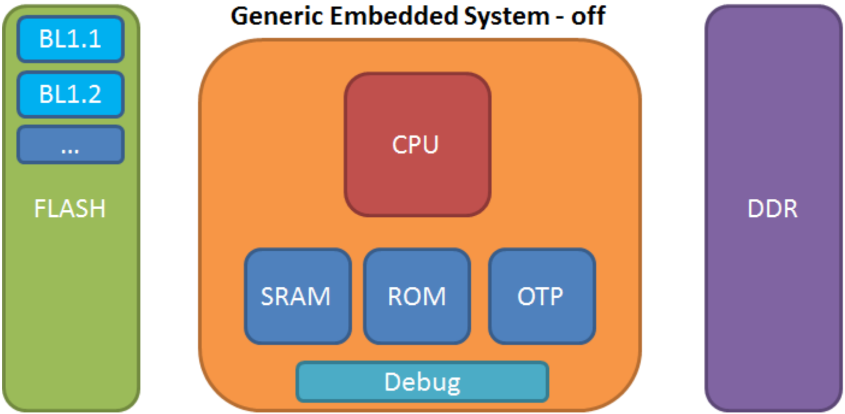

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- Integrity and confidentiality of flash contents are not assured!
- A mechanism is required for this assurance: **secure boot**

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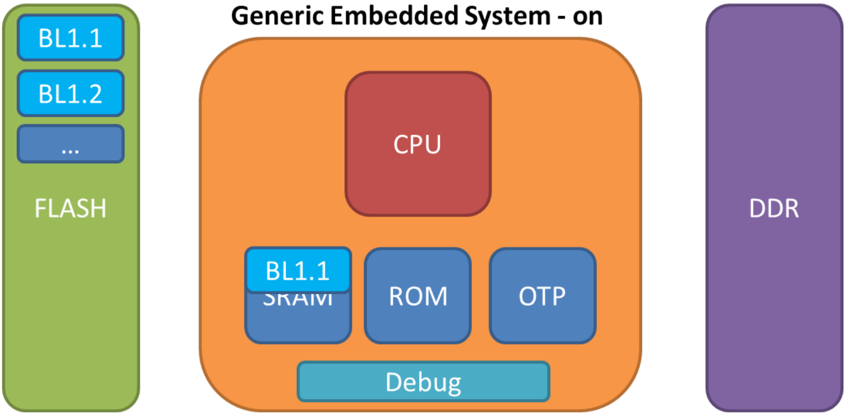

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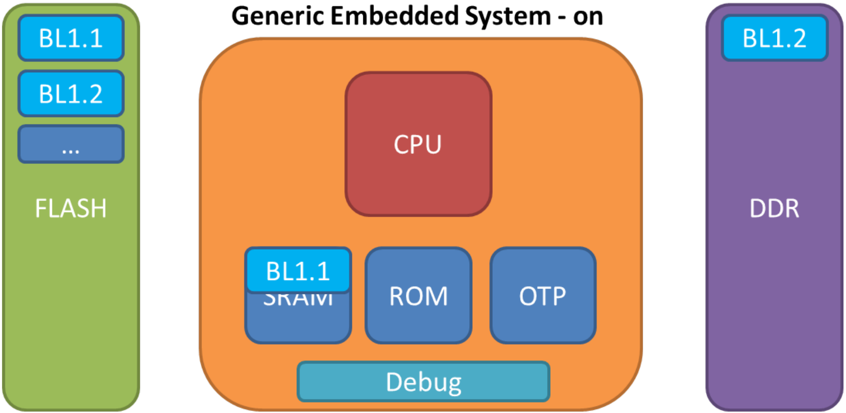

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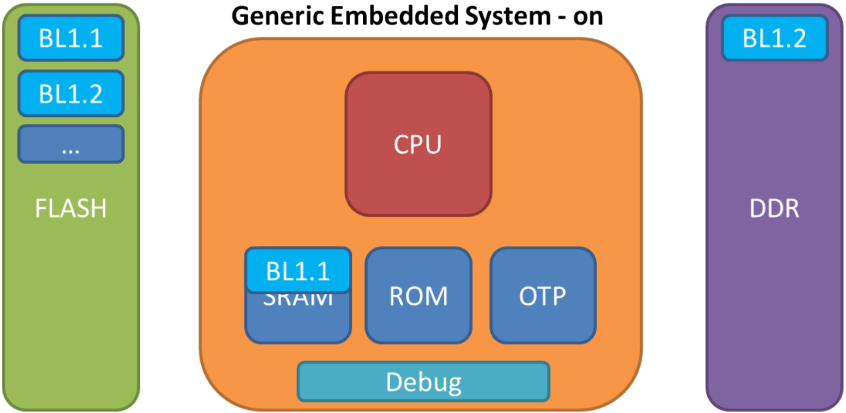

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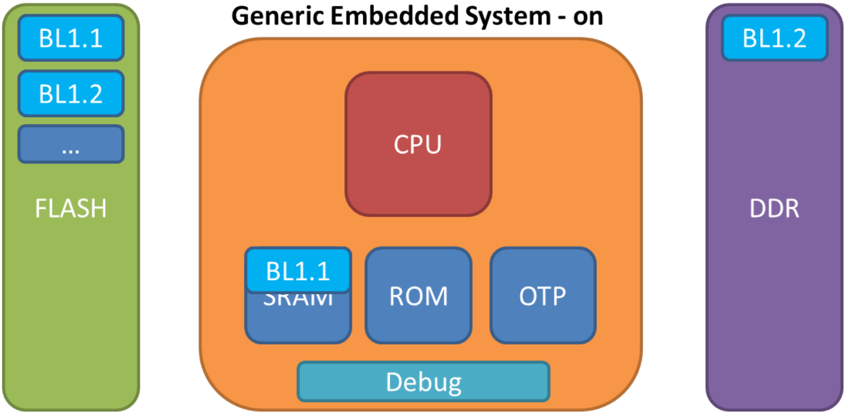

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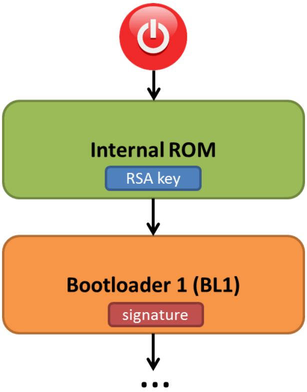

- Assures **integrity** (and **confidentiality**) of flash contents
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- One **root of trust** composed of immutable code and key

[5] Public Key Infrastructure

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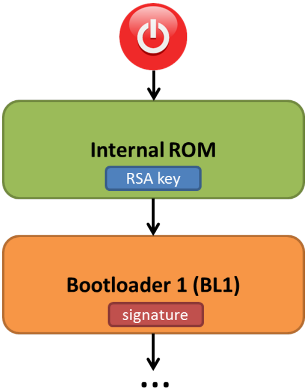

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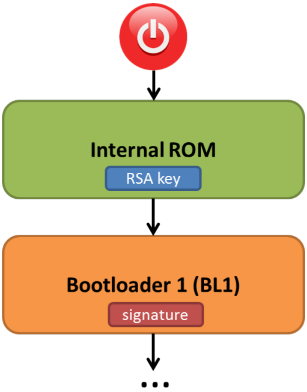

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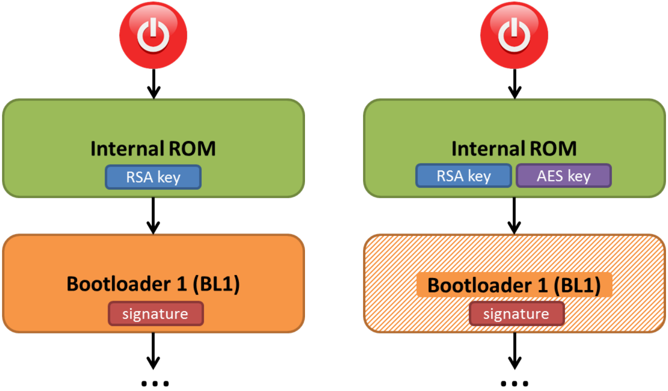

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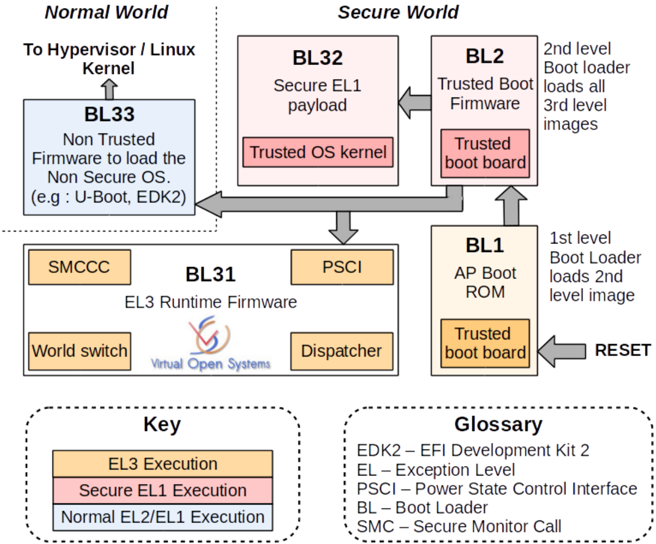

Source: http://community.arm.com/docs/DOC-9306

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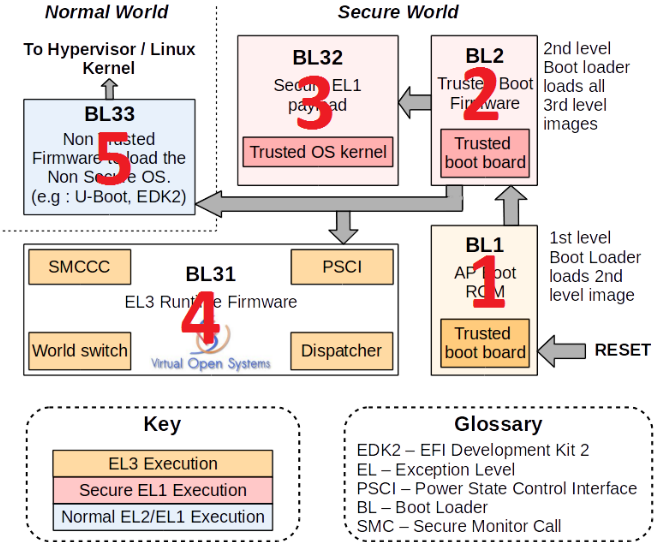

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Why use a hardware attack?

"Logical issues exist in secure boot implementations!!?"

Bootloader vulnerabilities

- S5L8920 (iPhone)[6]
- Amlogic S905[7]

However

- Small code base results in a small logical attack surface
- Implementations without vulnerabililties likely exist

Other attack(s) must be used when not logically flawed!

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Why (not) fault injection on secure boot?

Cons

- Invasive
- Physical access
- Expensive

Pros

- No logical vulnerability required
- Typical targets not properly protected

*Especially **relevant** when **assets** are not available after boot!*

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Typical assets

Secure code

- Boot code (ROM[8])

Secrets

- Keys (for boot code decryption)

Secure hardware

- Cryptographic engines

---

[8] Read Only Memory

Typical assets

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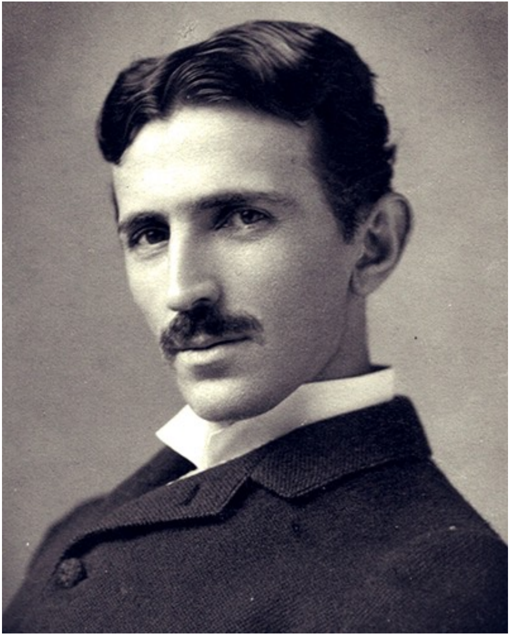
Fault Injection – Intermezzo



Fault Injection – Tooling

*Micah posted a very nice video using the **ChipWhisperer-Lite***[9]

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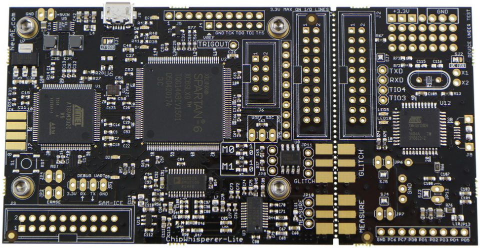

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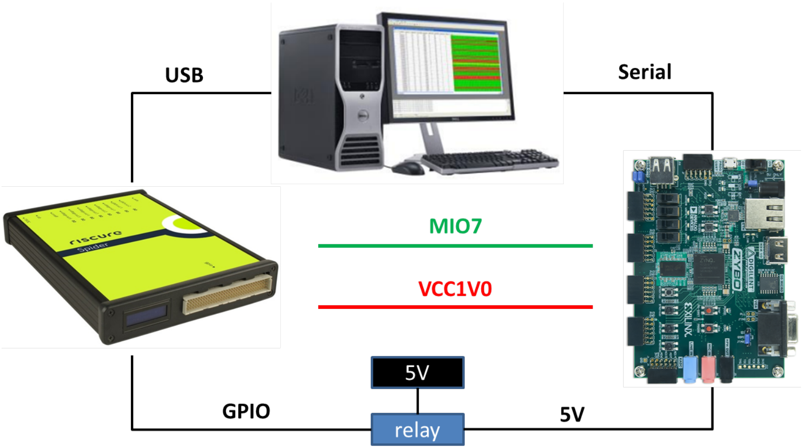

Target

- Digilent Zybo (Xilinx Zynq-7010 System-on-Chip)
- ARM Cortex-A9 (AArch32)

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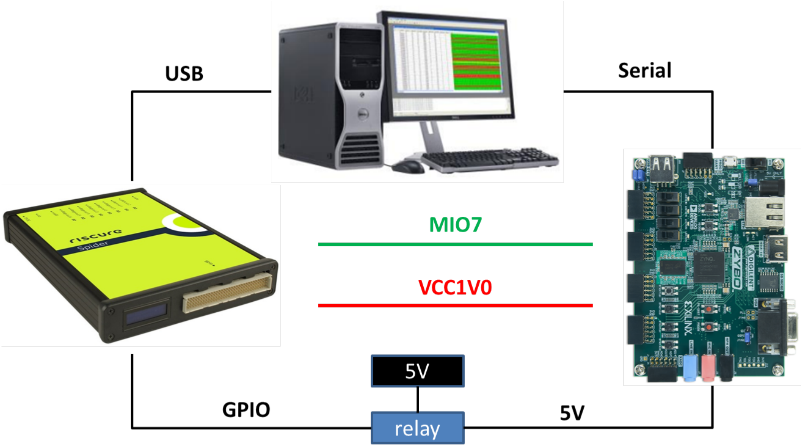

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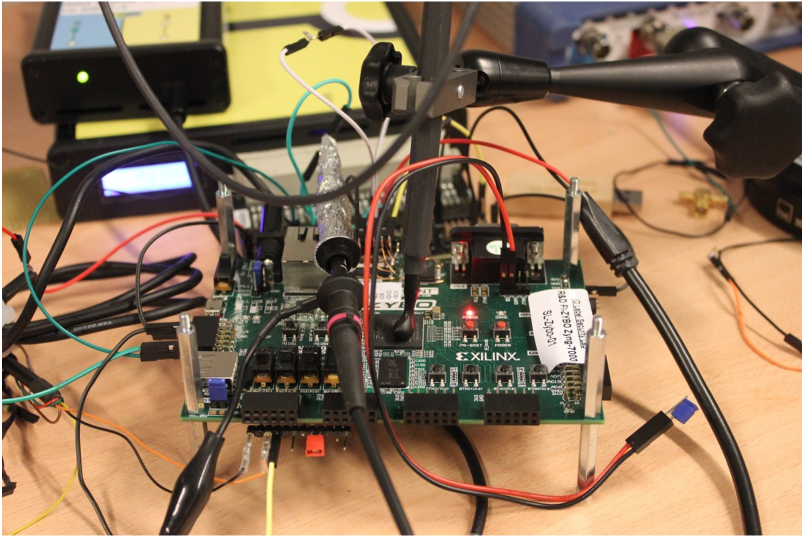

Characterization – Test application[11]

```
asm volatile
    (
        ...
        "add r1, r1, #1;"
        "add r1, r1, #1;"
        < repeat >          <-- glitch here
        "add r1, r1, #1;"
        "add r1, r1, #1;"
        ...
    );
```

Remarks

- Full control over the target
- Increasing a counter using ADD instructions
- Send counter back using the serial interface

[11] Implemented as an U-Boot command

Characterization – Possible responses

Expected: ’too soft’

counter = 00010000

Mute: ’too hard’

counter =

Success: ’$$$’

counter = 00009999

counter = 00010015

counter = 00008687

Remarks

- Glitching ’too hard’ may damage the target permanently

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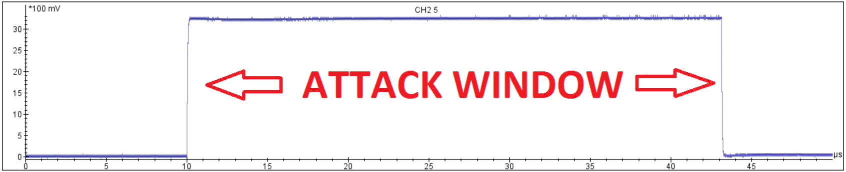

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- Randomize the glitch voltage
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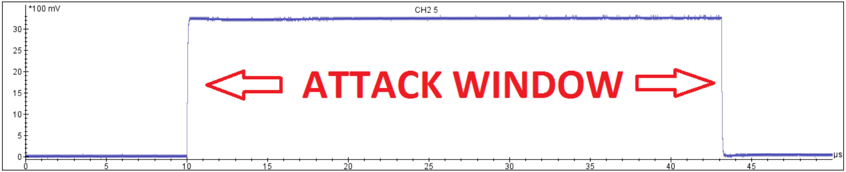

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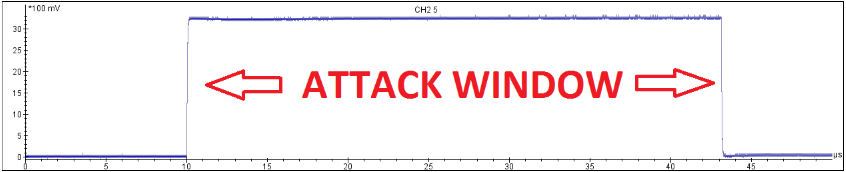

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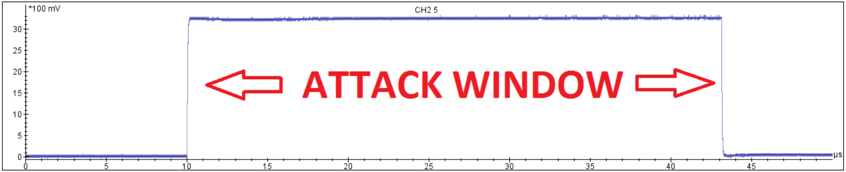
DEMO 1
PARAMETER SEARCH



Glitch parameters

- Randomize glitch delay within the attack window
- Randomize the glitch voltage
- Randomize the glitch length

That was the introduction ...

... let’s bypass secure boot: The Classics!

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Classic Bypass 00: Hash comparison

- Applicable to all secure boot implementations
- Bypass of authentication

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if( memcmp( p, hash, hashlen ) != 0 )
    return( MBEDTLS_ERR_RSA_VERIFY_FAILED );

p += hashlen;

if( p != end )
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return( 0 );
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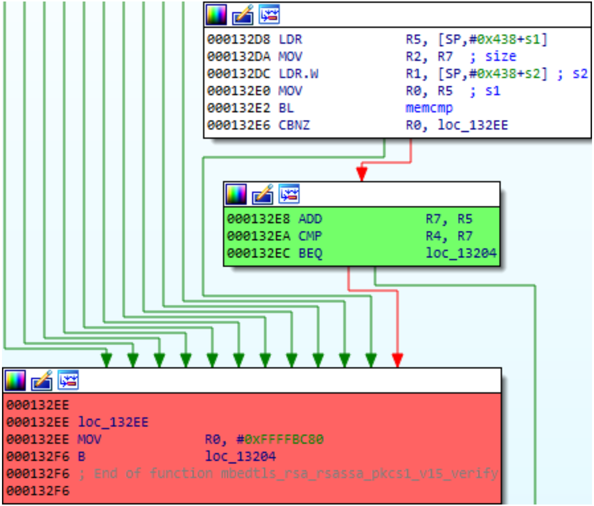

Multiple locations bypass the check with a single fault!

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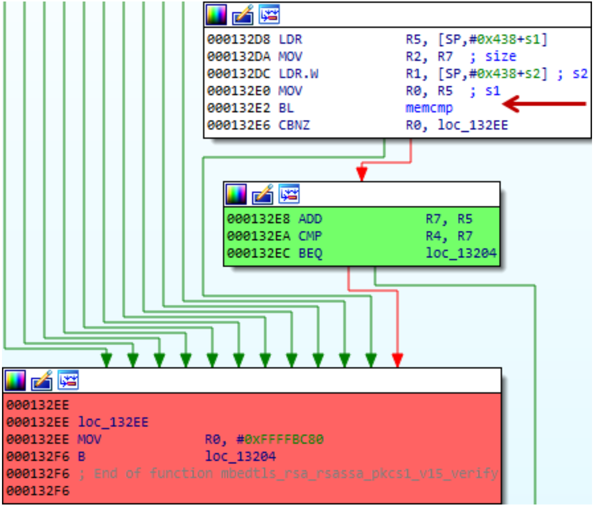

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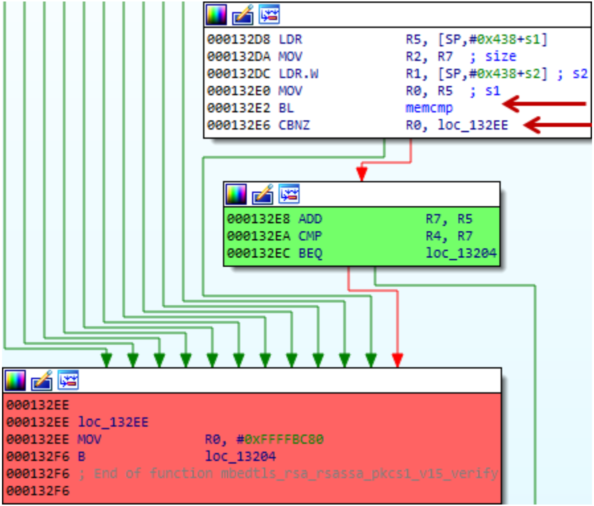

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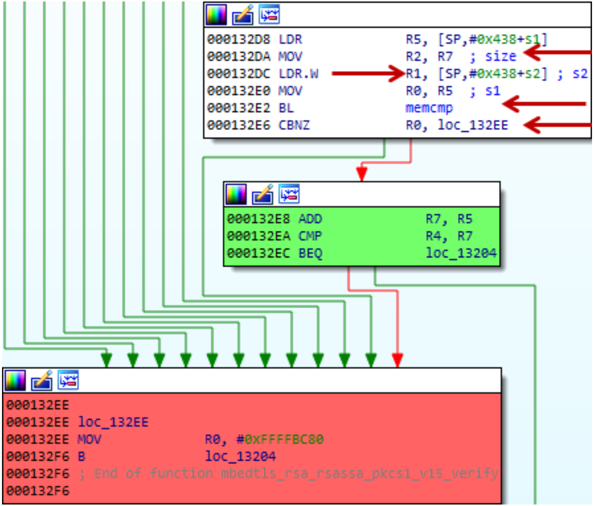

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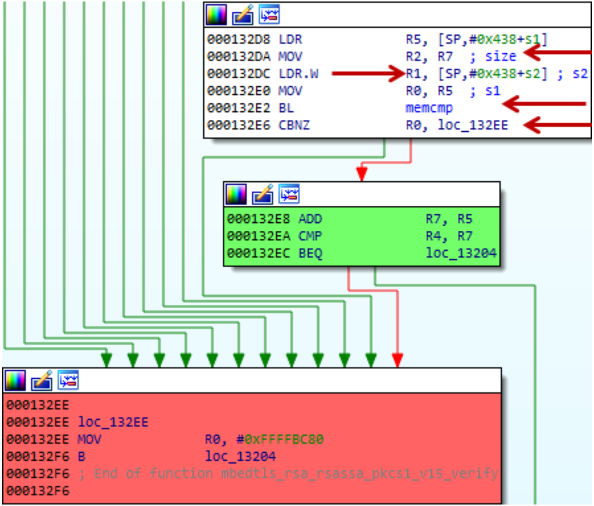

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Classic Bypass 01: Signature check call

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/* glitch here */
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} else {
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- Bypasses can happen on all levels
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- What to do when the signature verification fails?
- Enter an infinite loop!

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/* glitch here */
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Classic Bypass 02: Infinite loop

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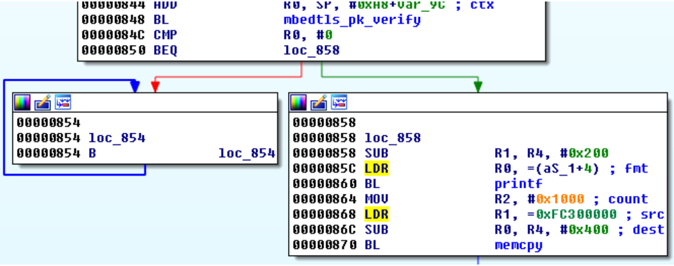

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- Classic smart card attack [12]
- Better to reset or wipe keys

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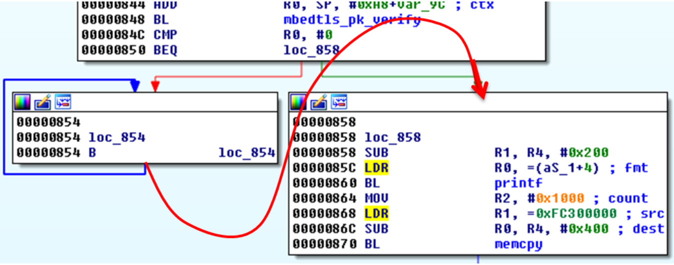

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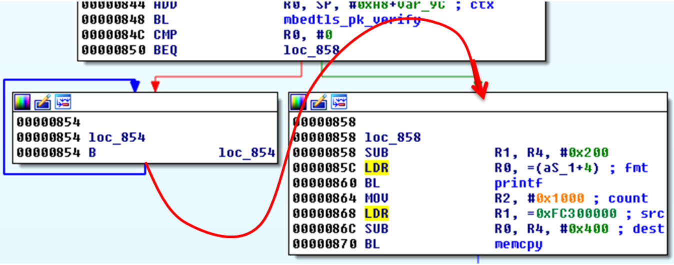

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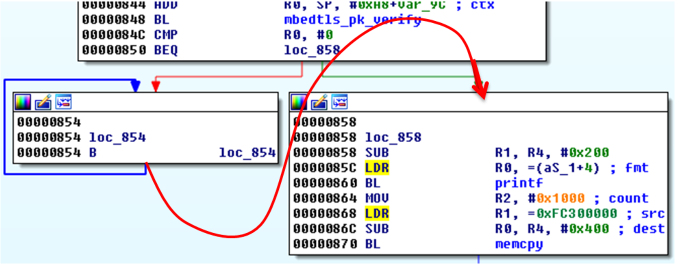

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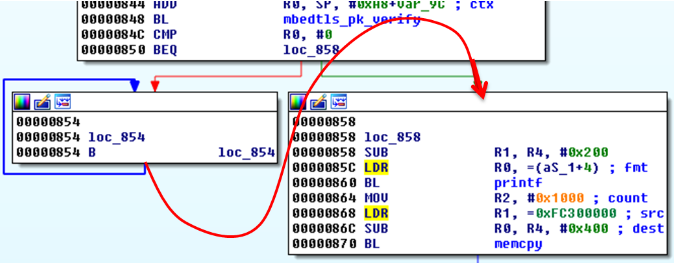

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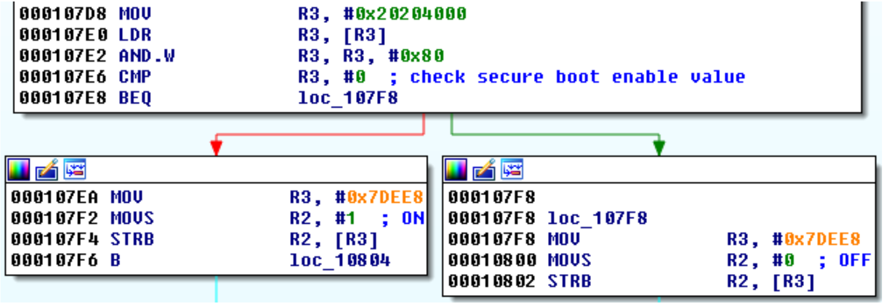
Classic Bypass 03: Secure boot enable

- Secure boot often enabled/disabled based on OTP[13] bit
- No secure boot during development; secure boot in the field
- Typically just after the CPU comes out of reset



[13] One-Time-Programmable memory

Fault Injection – Mitigations

Hardware countermeasures [14] [15]

- Detect the glitch or fault

Software countermeasures [16]

- Lower the probability of a successful fault
- Do not address the root cause

*You can **lower the probability** but not rule it out!*

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Compiler optimizations

Why?

- ROM memory size is limited
- Compiler optimizations decrease code size

*Compiler **optimizes out** intended code!*

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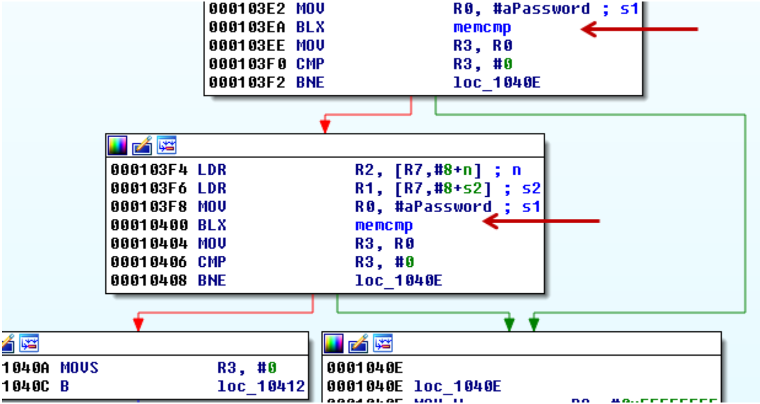
Compiler 'optimization' – Double check

Example of a double check

```
unsigned int compare(char * input, int len)
{
    if(memcmp(password, input, len) == 0)       <-- 1st
    {
        if(memcmp(password, input, len) == 0)   <-- 2nd
        {
            return TRUE;
        }
    }
    return FALSE;
}
```

Compiler 'optimization' – Double check

*Compiled **without** optimizations*



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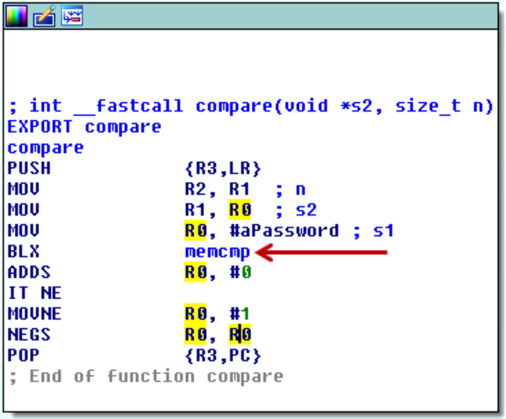

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- Your compiler is smarter than you
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Compiler 'optimization' – Pointer setup

*Example of a double check using '**volatile**'*

```
int checkSecureBoot( ){
    volatile int * otp_secure_boot = OTP_SECURE_BOOT;

    if( (*otp_secure_boot  >> 7) & 0x1 ){     <-- 1st
            return 0;
    }else{
        if( (*otp_secure_boot  >> 7) & 0x1 ){ <-- 2nd
            return 0;
        }else{
            return 1;
        }
    }
}
```

Compiler 'optimization' – Pointer setup

Compiled with optimizations

```
checkSecureBoot
MOV             R3, #0x20204000
LDR             R2, [R3] ; Load from pointer
LSLS            R2, R2, #0x18
ITTTE PL
LDRPL           R0, [R3] ; Second load from pointer
UBFXPL.W        R0, R0, #7, #1
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Combined Attacks

Those were the classics and their mitigations ..

... the attack surface is larger![17]

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Combined attack – Copy

- Introducing logical vulnerabilities using fault injection
  - Build your own buffer overflow!
- Easy approach: change *memcpy* the size argument

Before corruption

```
memcpy(dst, src, 0x1000);
```

After corruption

```
memcpy(dst, src, 0xCEE5);
```

Remark

- Works when dedicated hardware is used (e.g. DMA[18] engines)

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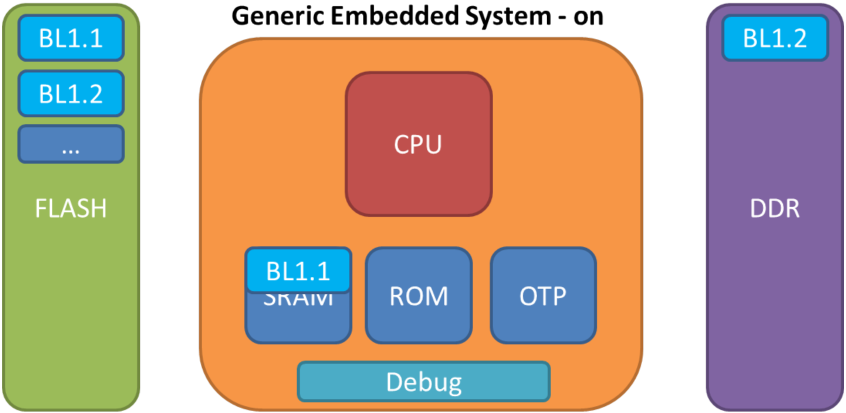

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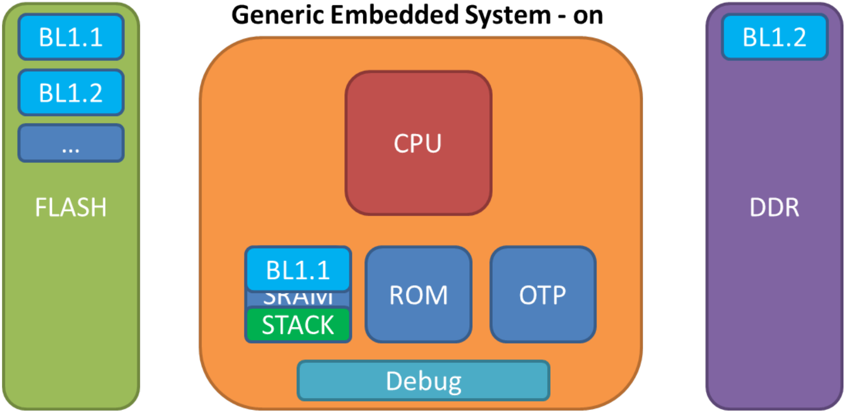

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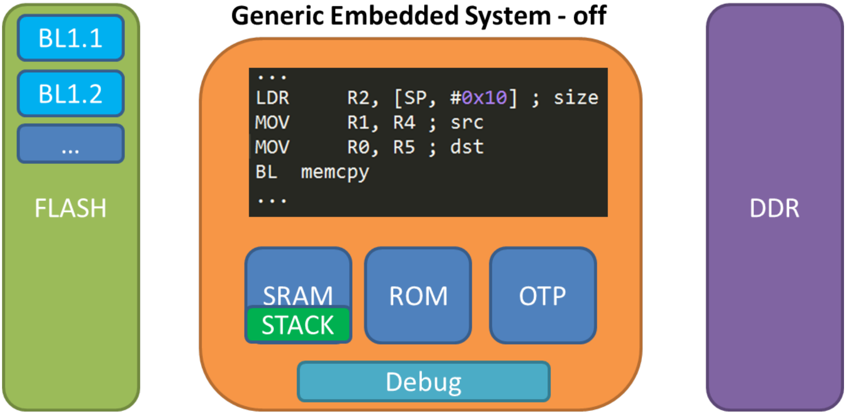

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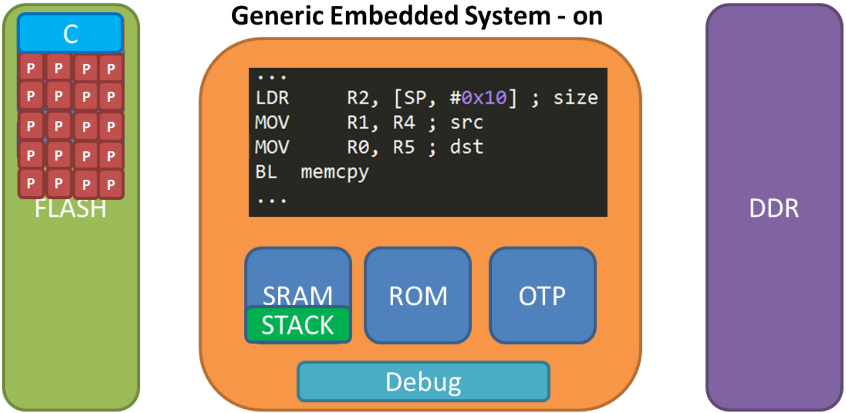

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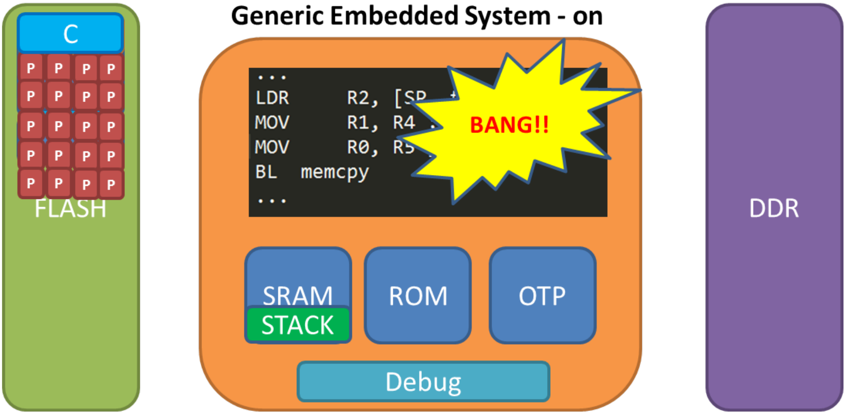

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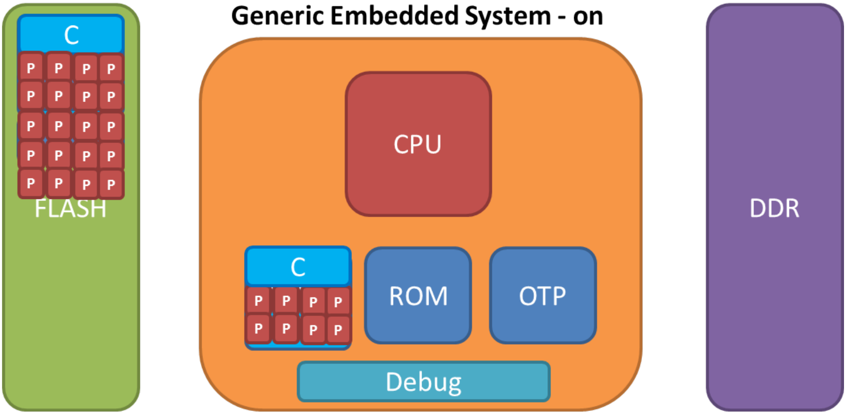

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Combined attack - Controlling PC on ARM[20]

- Exploits an ARM32 characteristic
- PC[19] register is directly accessible by most instructions

Multi-word copy

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LDMIA r1!, {r3 - r10}
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Controlling PC using LDMIA

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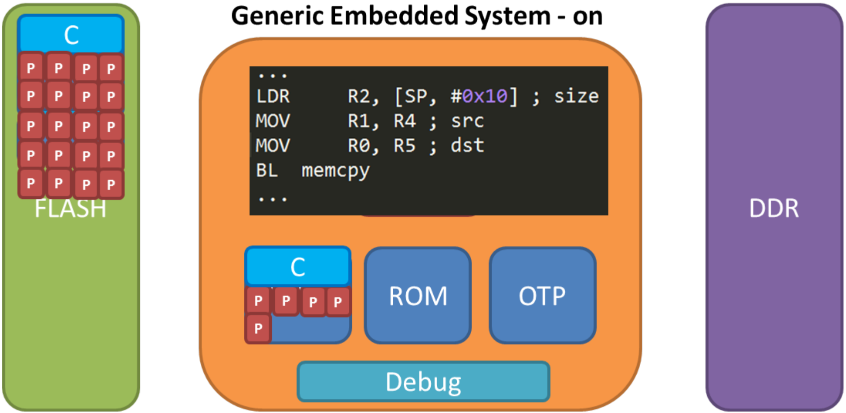

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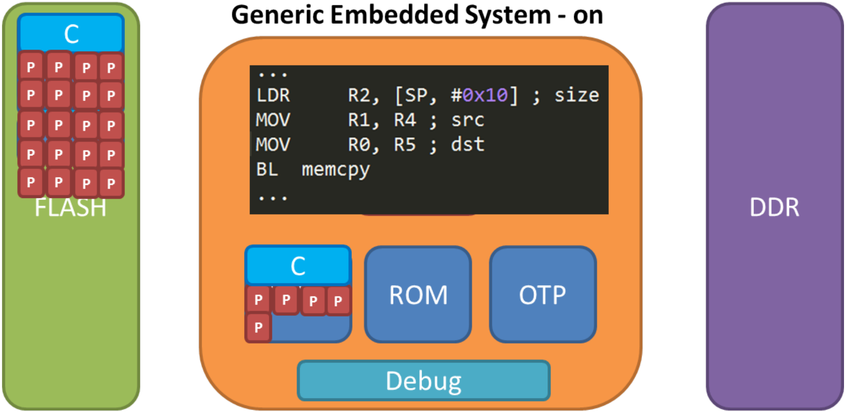

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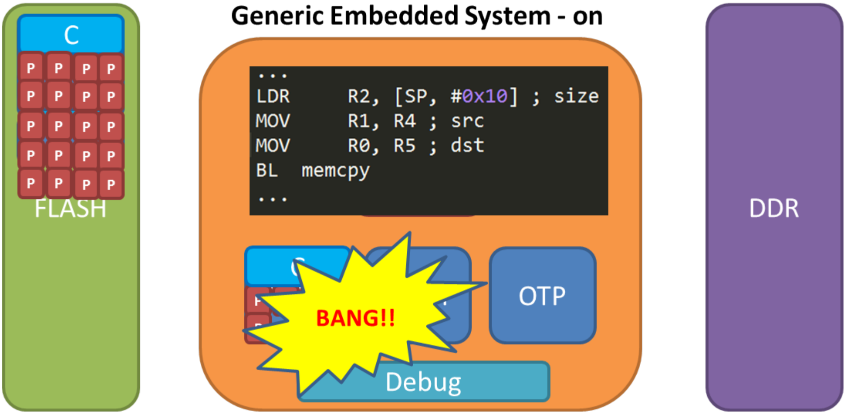

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- Start glitching while/after loading the image but before decryption
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- The more magic pointers, the higher the probability

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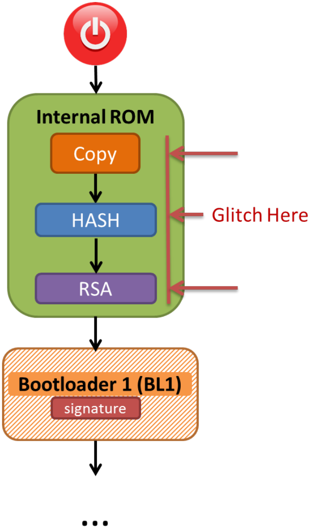

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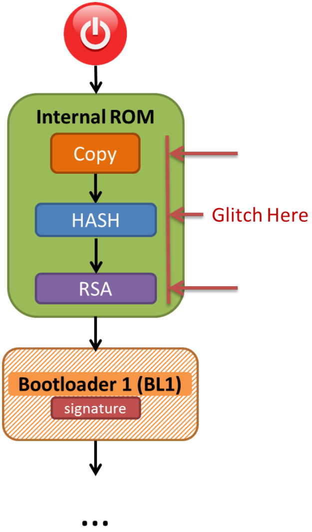

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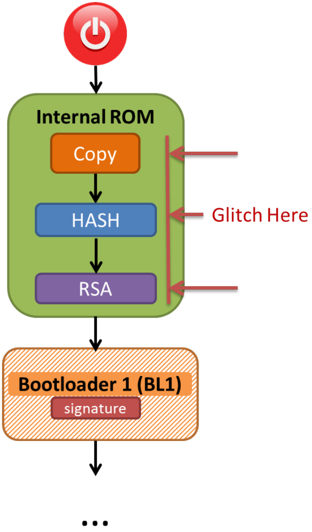
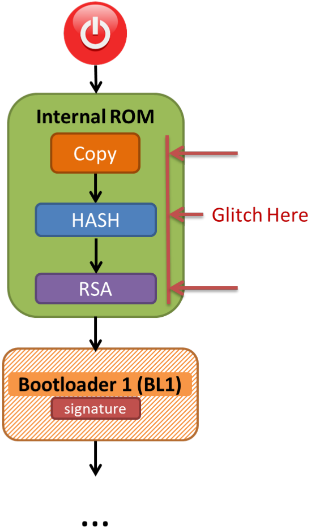


[21] Proving the wild jungle jump – Gratchoff, 2015

Combined attacks - Wild jungle jump[21]

- Start glitching while/after loading the image but before decryption
- Lots of 'magic' pointers around, which point close to the code
- Get them from: stack, register, memory
- The more magic pointers, the higher the probability



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Combined attack(s) – Summary

- Bypass of both authentication and decryption
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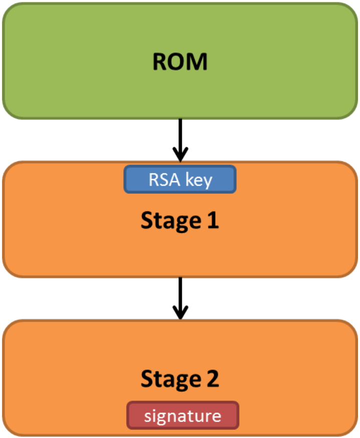
Secure Boot – Demo Design



Remark

- Stage 2 is invalided by changing the printed string
- Stage 1 enters an infinite loop when the signature is invalid

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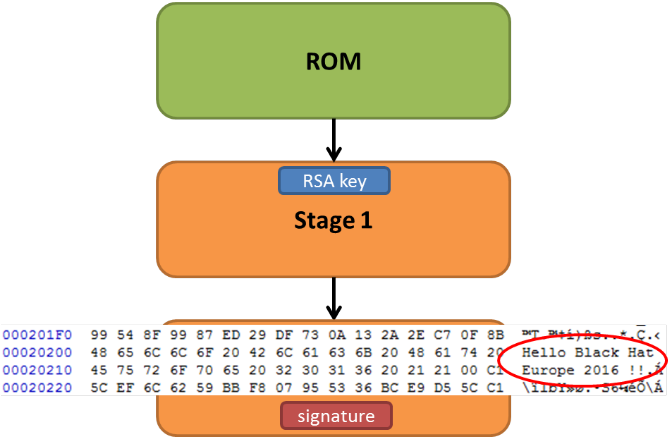

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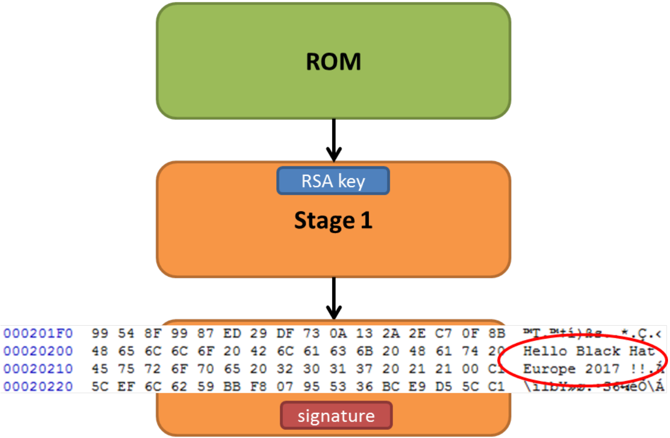

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When to glitch?

- Not possible to use a signal originating from target
- Only reference point is power-on reset moment
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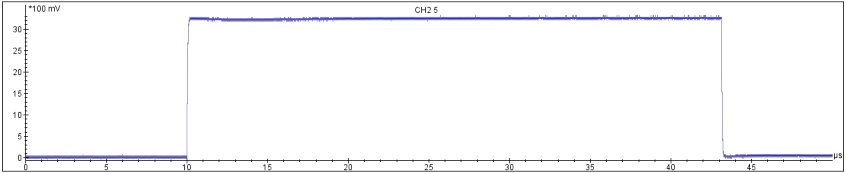

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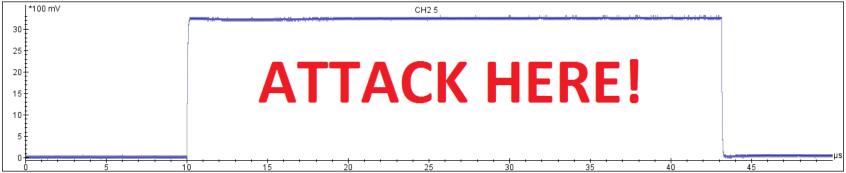

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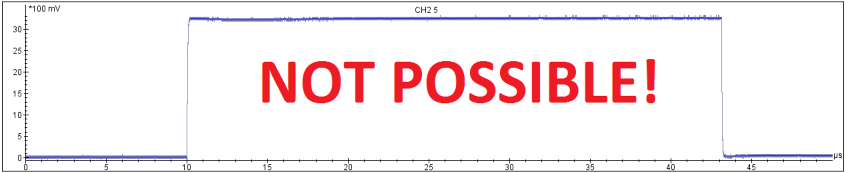

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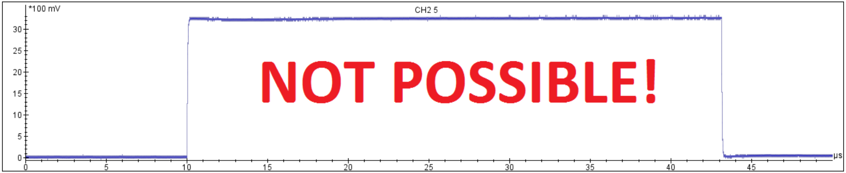

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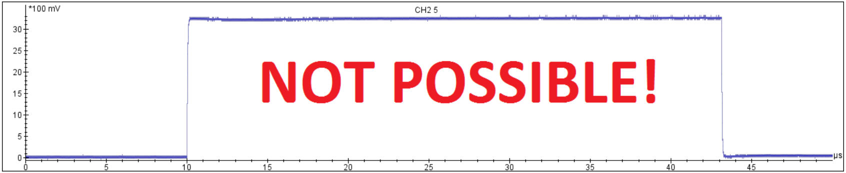

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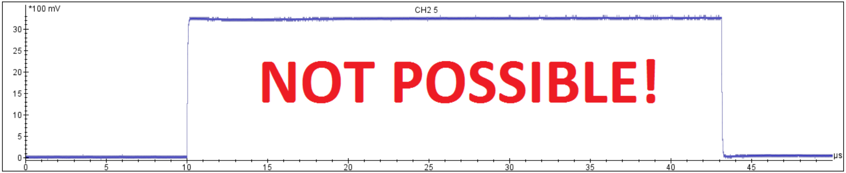

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Boot profiling – Reset

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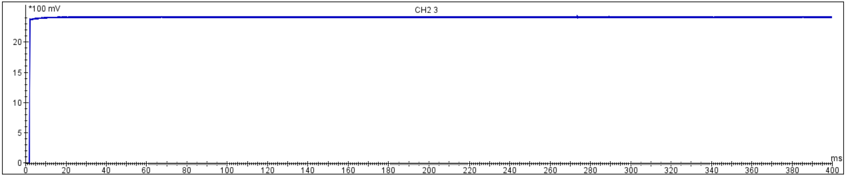
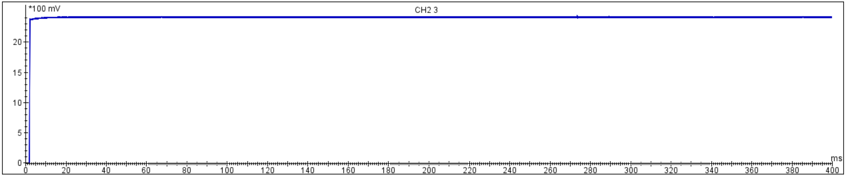


Invalid image



Remark

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- Attack window spreads across the entire trace (˜400 ms)

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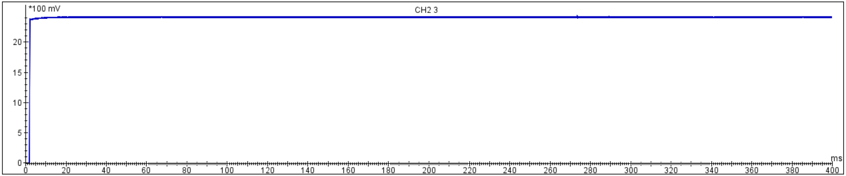

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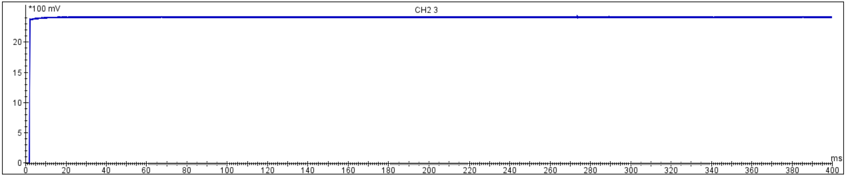

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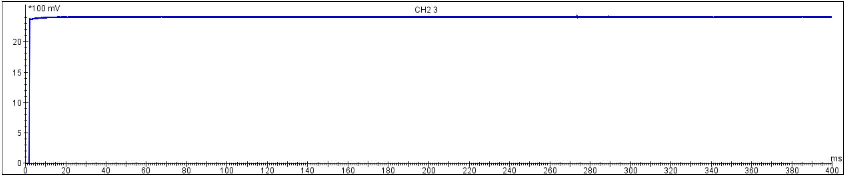

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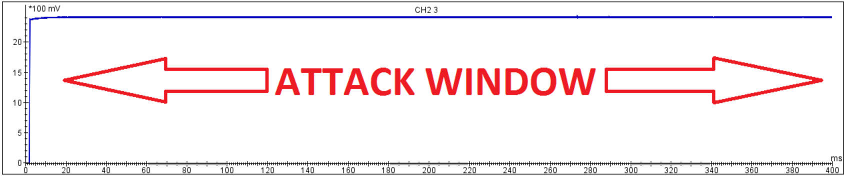

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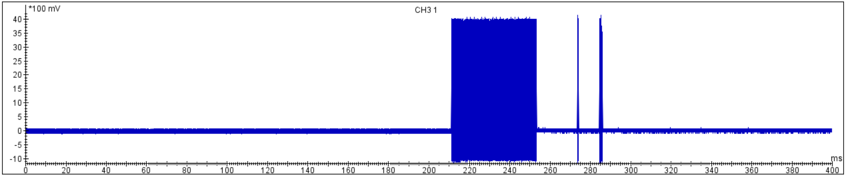
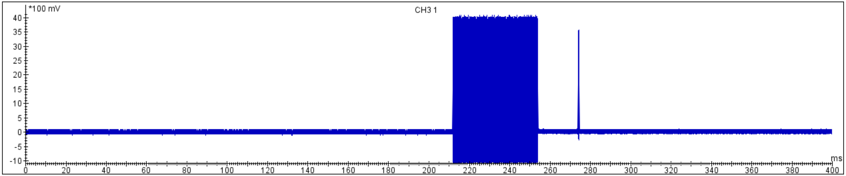
Boot profiling – Flash activity

Valid image



Invalid image

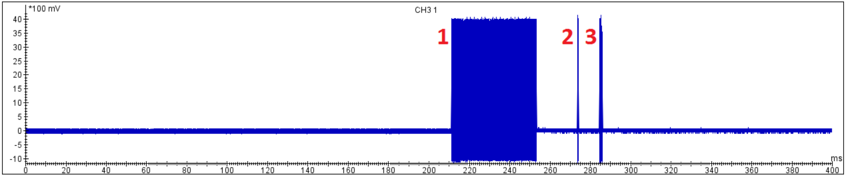


Remarks

- Flash activity 3 not present for the invalid image
- Attack window between flash activity 2 and 3 (˜10 ms)

Boot profiling – Flash activity

Valid image



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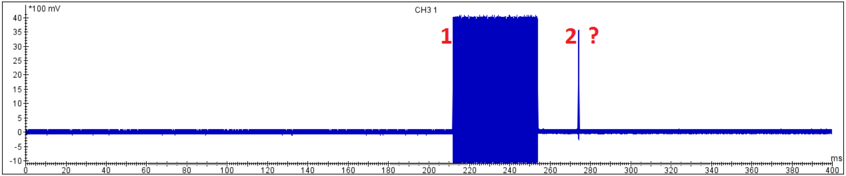

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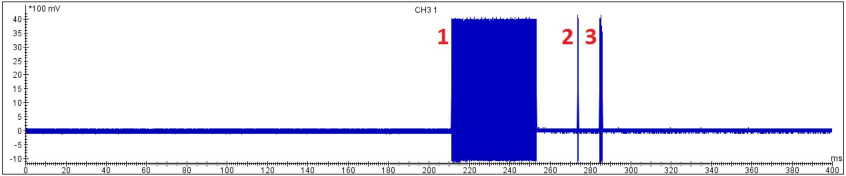

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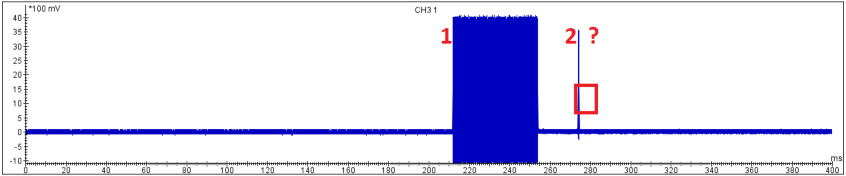

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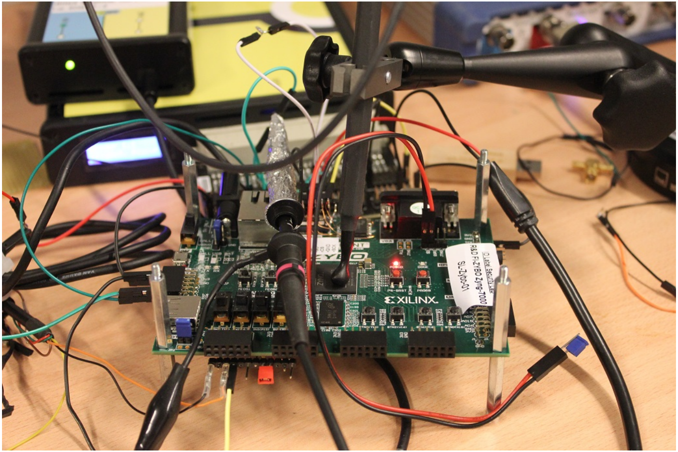

Remark

- Measuring electromagnetic emissions using a probe[22]

[22] https://www.langer-emv.de/en/product/rf-passive-30-mhz-3-ghz/35/rf1-set-near-field-probes-30-mhz-up-to-3-ghz/270

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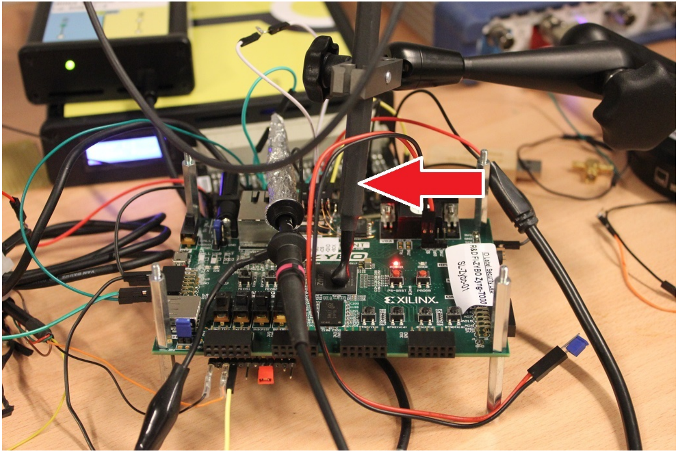

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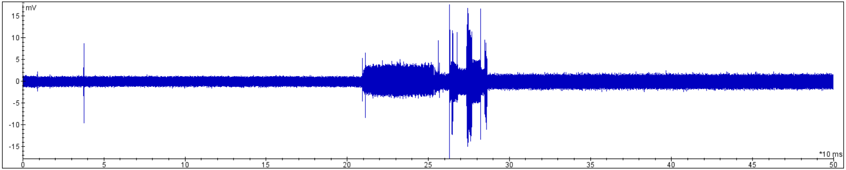

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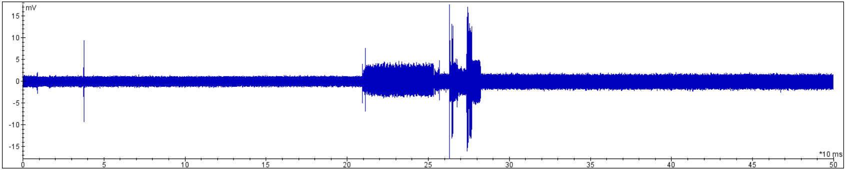

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- Attack window reduced significantly (< 1 ms)
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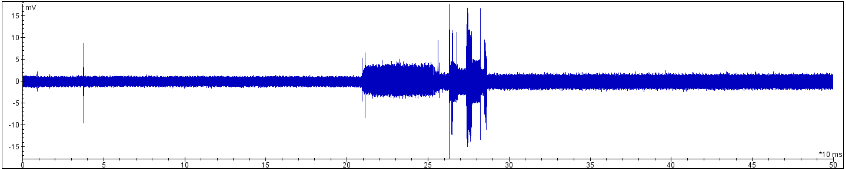

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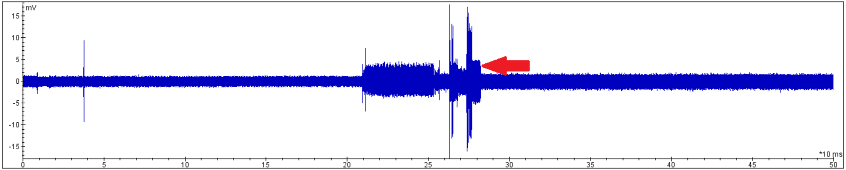

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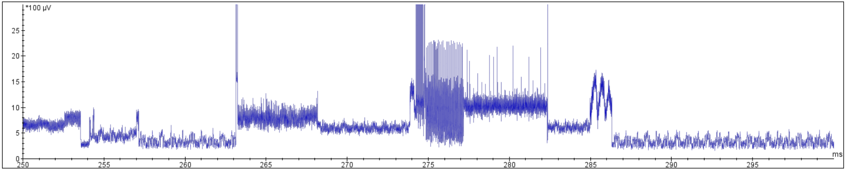

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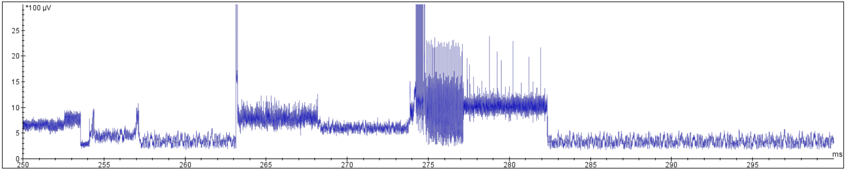

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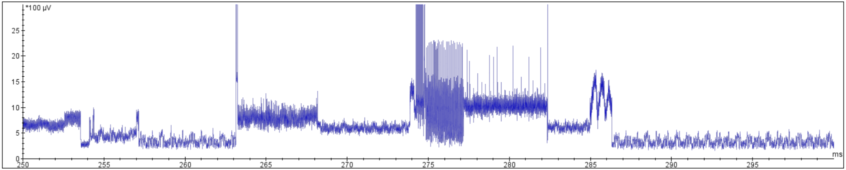

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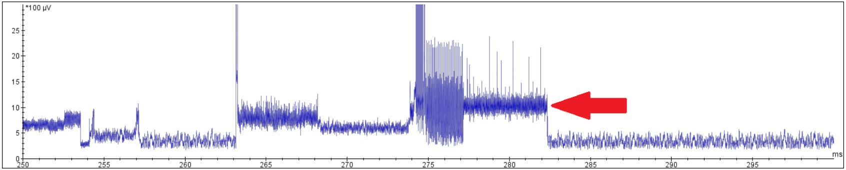

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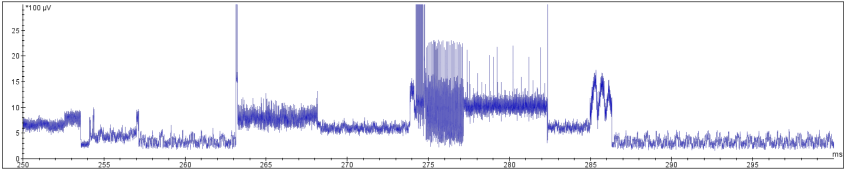

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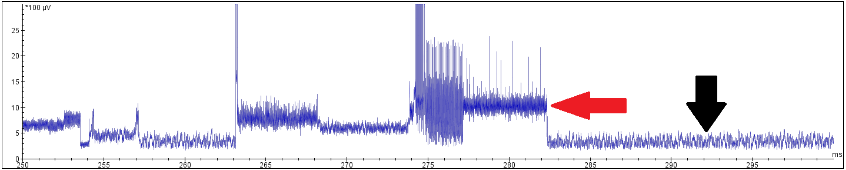

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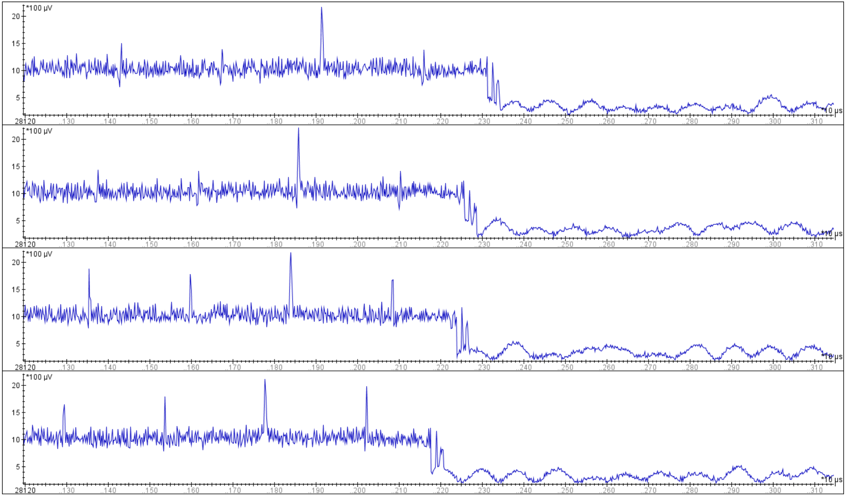

Remark

- Jitter during boot prevents effective timing (˜150 µs)

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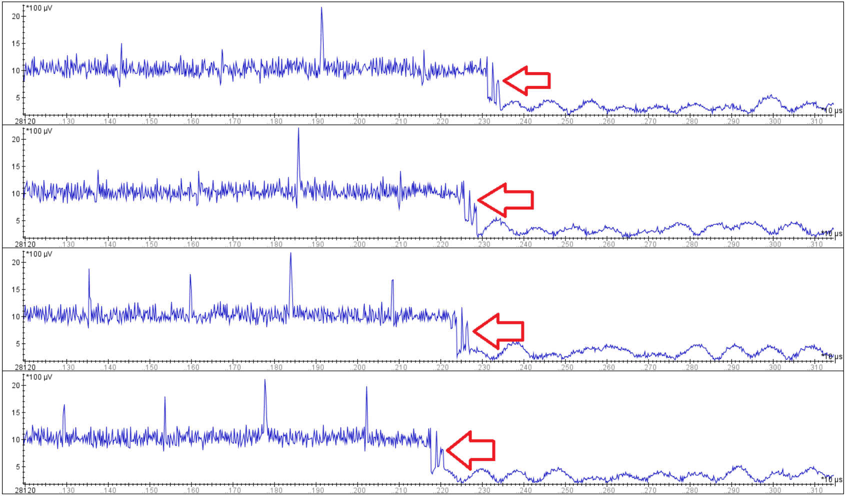

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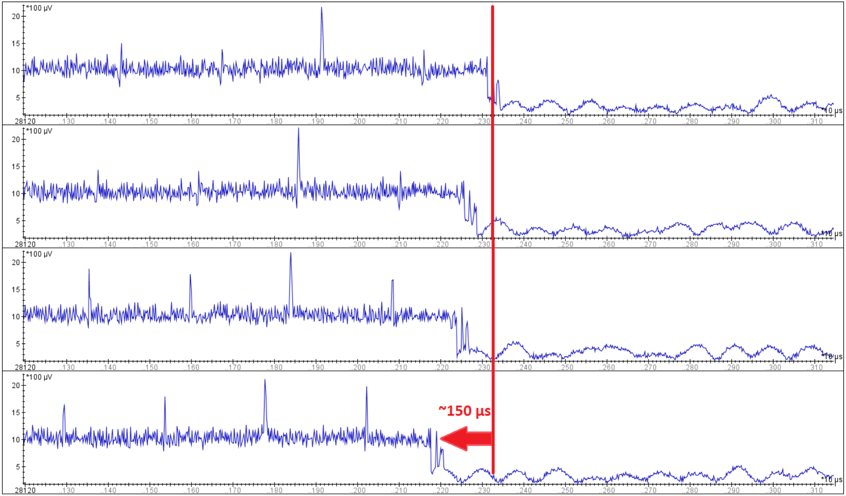

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- Power-on reset is too early
- Use a signal close to the ’glitch moment’

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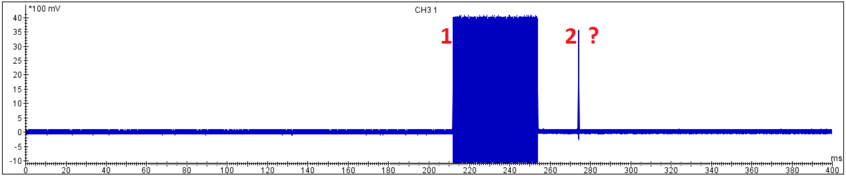

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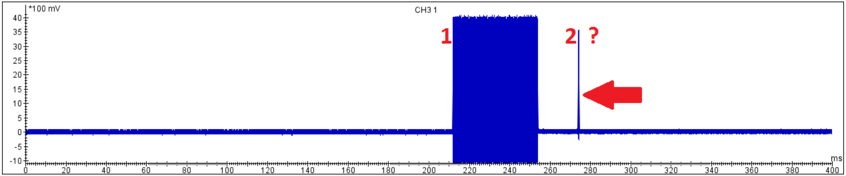

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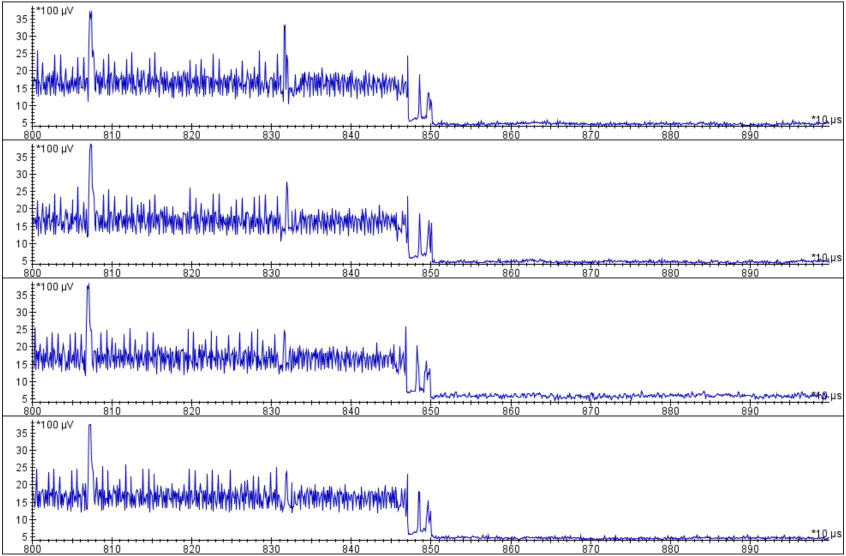

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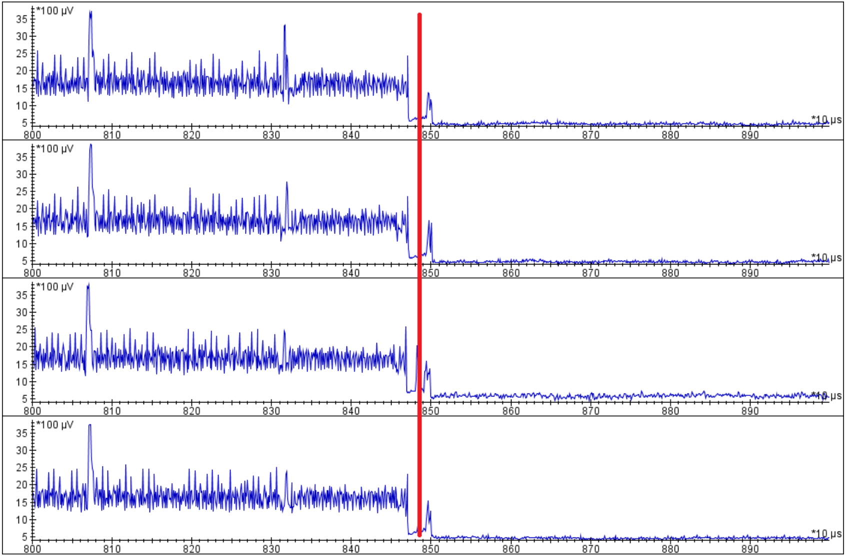

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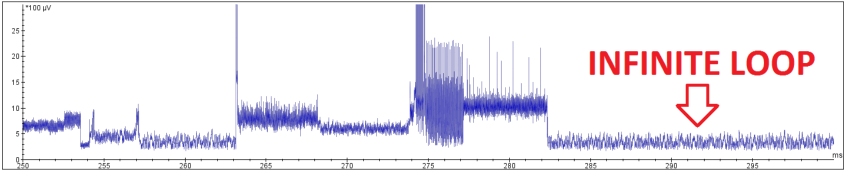
BYPASSING SECURE BOOT



Glitch parameter search

- Fixed the glitch delay to 300 ms
- Fixed the glitch voltage to -2 V
- Randomize the glitch length

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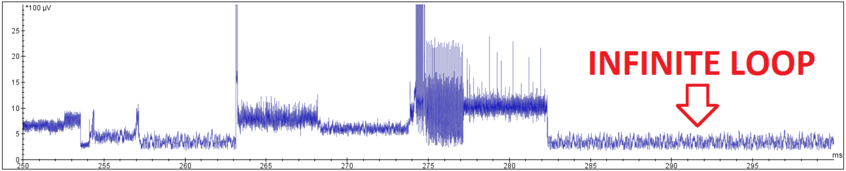

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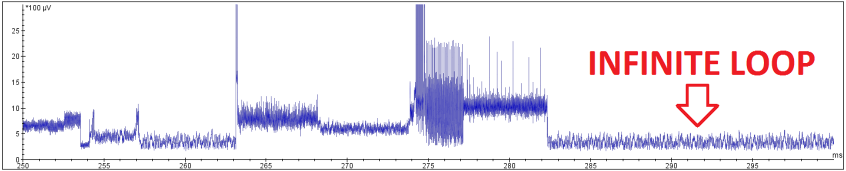

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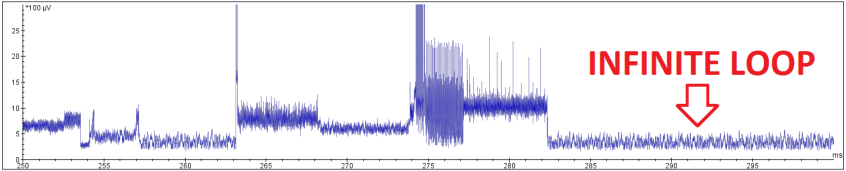

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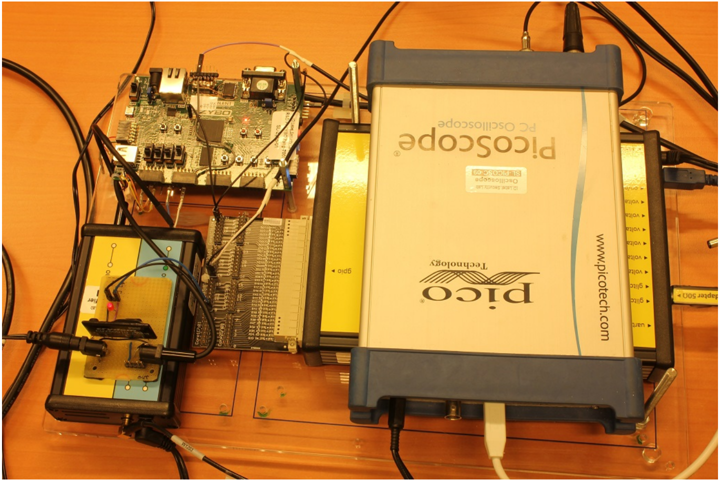

Secure Boot – Manufacturer Best practices

Minimize attack surface

- Authenticate all code and data
- Limit functionality in ROM code
- Disable memory when not required

Lower the probability

- Implement fault injection countermeasures
- Implement software exploitation mitigations

*Robustness can only be determined using **testing**!*

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riscure

Challenge your security

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