riscure black hat EUROPE 2016

Bypassing Secure Boot using Fault Injection

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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

Combining services and tools for fun and profit!

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

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

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Fault injection techniques¹



Remark

• All techniques introduce faults externally

¹The Sorcerers Apprentice Guide to Fault Attacks. - Bar-El et al., 2004

Fault injection techniques¹



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Voltage fault injection

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

Voltage glitch



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

Faults that affect hardware

- Registers
- Buses

Faults that affect hardware that does software^{2 3 4}

- Instruction corruption
- Data corruption

² Fault Model Analysis of Laser-Induced Faults in SRAM Memory Cells – Roscian et. al., 2015

³ High Precision Fault Injections on the Instruction Cache of ARMv7-M Architectures – Riviere et al., 2015

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When presented with code: instruction corruption.

Simple (MIPS)

Complex (ARM)

ldr w1, [sp, #0x8] 1011100101000000000101111100001 str w7, [sp, #0x20] 101110010<u>0</u>00000000<u>100</u>01111100<u>11</u>1

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



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Assures integrity (and confidentiality) of flash contents

- The chain of trust is similar to PKI⁵ found in browsers
- One root of trust composed of immutable code and key

⁵ Public Key Infrastructure



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Secure Boot – In reality ...



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

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Why use a hardware attack?

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

Bootloader vulnerabilities

- S5L8920 (iPhone)⁶
- Amlogic S905⁷

However

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

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

https://www.theiphonewiki.com/wiki/0x24000_Segment_Overflow

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- Invasive
- Physical access
- Expensive

Pros

- No logical vulnerability required
- Typical targets not properly protected

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Secure code

• Boot code (ROM⁸)

Secrets

• Keys (for boot code decryption)

Secure hardware

Cryptographic engines

⁸Read Only Memory

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Fault Injection – Intermezzo



Fault Injection – Tooling

Micah posted a very nice video using the ChipWhisperer-Lite⁹

By NewAE Technology Inc.¹⁰

⁹ https://www.youtube.com/watch?v=TeCQatNcF20 10 https://wiki newse.com/CW1173_ChinWhisperer-Lit

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Fault Injection – Setup



Target

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

Fault Injection – Setup



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Fault Injection – Setup



Characterization – Test application¹¹

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

Expected: 'too soft' counter = 00010000

Mute: 'too hard' counter =

Success: '\$\$\$' counter = 00009999 counter = 00010015 counter = 00008687

Remarks

Expected: 'too soft' counter = 00010000

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Remarks



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



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That was the introduction ...

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

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

- Applicable to all secure boot implementations
- Bypass of authentication

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

Source: https://tls.mbed.org/

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Multiple locations bypass the check with a single fault!



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Classic Bypass 01: Signature check call

```
/* glitch here */
if (mbedtls_pk_verify(&k, SHA256, h, hs, s, ss)) {
   /* do not boot up the image */
   no_boot();
} else {
   /* boot up the image */
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- Bypasses can happen on all levels
- Inside functions, inside the calling functions, etc.

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- Inside functions, inside the calling functions, etc.

- What to do when the signature verification fails?
- Enter an infinite loop!

```
/* glitch here */
if (mbedtls_pk_verify(&k, SHA256, h, hs, s, ss)) {
   /* do not boot up the image */
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} else {
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- Timing is not an issue!
- Classic smart card attack ¹²
- Better to reset or wipe keys

https://en.wikipedia.org/wiki/Unlooper



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Classic Bypass 03: Secure boot enable

- Secure boot often enabled/disabled based on OTP¹³ bit
- No secure boot during development; secure boot in the field
- Typically just after the CPU comes out of reset



¹³One-Time-Programmable memory

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

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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 optimizes out intended code!

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;
}</pre>
```

Compiler 'optimization' – Double check





Compiler 'optimization' – Double check

Compiled with optimizations

🛄 🚄 🖼
• int fastcall compare(unid *s2 size t n)
EXPORT compare
compare
PUSH (R3_LR)
MOU B2. B1 : n
MOV R1. R0 : 52
MOV R0, #aPassword ; s1
BLX memomp
ADDS R0, #0
IT NE
MOVNE R0, #1
NEGS RØ, RØ
POP {R3,PC}
; End of function compare

- Your compiler is smarter than you
- Use 'volatile' to prevent compiler problems
- Read the output of the compiler!

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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
EORPL.W	R0, R0, #1
MOVMI	R0, #0
BX	LR

Compiler 'optimization' – Pointer setup

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checkSecureBoot		
MOV	R3,	#0x20204000 🗲
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ITTTE PL		
LDRPL	RØ,	[R3] ; Second load from pointer
UBFXPL.W	RØ,	R0, #7, #1
EORPL.W	RØ,	R0, #1
MOVMI	RØ,	#0
BX	LR	

Combined Attacks

Those were the classics and their mitigations ..

... the attack surface is larger!¹⁷

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Combined Attacks

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

Before corruption

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

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

• Works when dedicated hardware is used (e.g. DMA¹⁸ engines)

¹⁸Direct Memory Access

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Remark

- Exploits an ARM32 characteristic
- PC¹⁹ register is directly accessible by most instructions

Multi-word copy

LDMIA r1!, {r3 - r10} STMIA r0!, {r3 - r10}

Controlling PC using LDMIA

LDMIA r1!, {r3-r10} 11101000101100010000011111111000 LDMIA r1!, {r3-r10, <u>PC</u>} 1110100010110001<u>1</u>000011111111000

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Combined attack - Controlling PC on ARM



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- 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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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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When to glitch?

- Not possible to use a signal originating from target
- Only reference point is power-on reset moment
- Use side-channels to obtain more information
- Compare behavior between valid image and an invalid image

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Boot profiling – Reset

Valid image



Invalid image



- No difference between a valid and invalid image
- Attack window spreads across the entire trace (~400 ms)

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Boot profiling – Flash activity Valid image



Invalid image



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

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Boot profiling – Power consumption



Remark

Measuring electromagnetic emissions using a probe²²

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Invalid image



- · Significant difference in the electromagnetic emissions
- Attack window reduced significantly (< 1 ms)
- Power profile at black arrow is flat: infinite loop



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Remark

Jitter during boot prevents effective timing (~150 μs)

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

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Glitch Timing – Power consumption



Remarks

· Jitter minimized using flash activity as a trigger

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- Fixed the glitch voltage to -2 V
- Randomize the glitch length



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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

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riscure Challenge your security

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