NOP-Oriented Programming: Should we Care?

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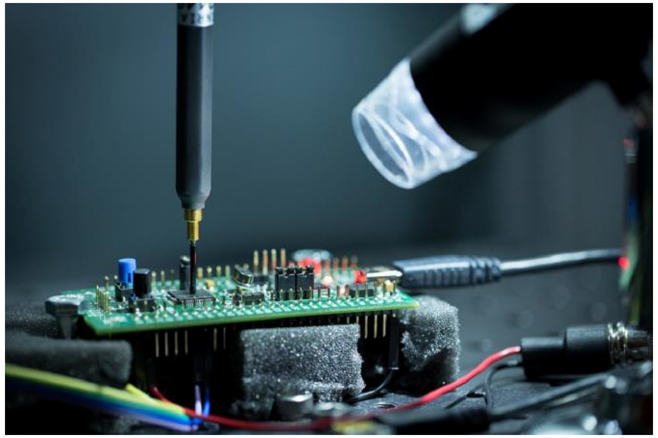
Introduction

- Fault injection nowadays
  - ElectroMagnetic Pulse (EMP)
  - Laser injection
  - Clock glitch
  - …



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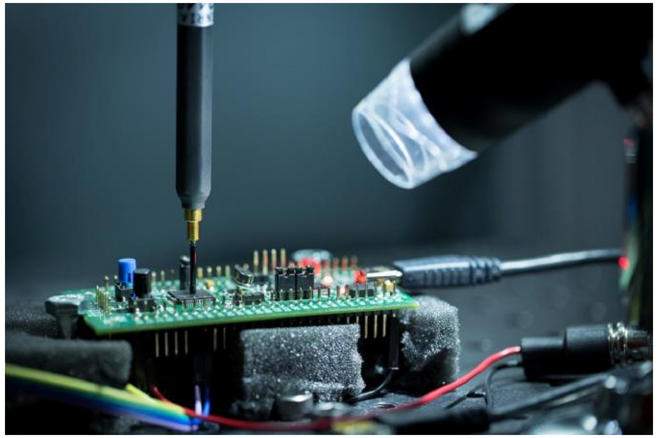
- Efficient but limited to 1 or few injections



Introduction

- Fault injection nowadays
  - ElectroMagnetic Pulse (EMP)
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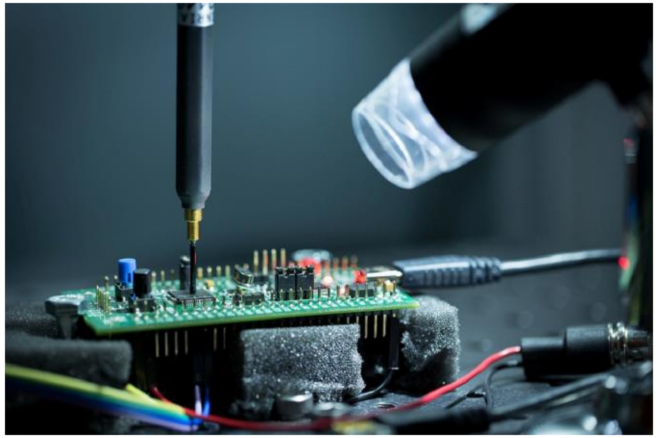
  - Clock glitch
  - …
- Efficient but limited to 1 or few injections
- Lack of precision
  - EMP/laser: unavoidable delay between 2 injections



Approach and questions

- What if an attacker can overcome these limitations?
  - No delay between injection
  - High precision (instruction-level)
  - Unlimited number of faults

- Questions:
  1. What are the possibilities for an attacker?
  2. Can we simulate this?

Fault model : NOP-Oriented programming

- Base fault model: instruction skip*
  - An attacker is able to entirely skips a specific instruction
  - Skipping an instruction replaces this instruction by a NOP

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  - Program mainly driven by NOP
  - Select which instruction you want to execute

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- Our model: instruction-skip by a factor of hundreds/thousands
  - Program mainly driven by NOP
  - Select which instruction you want to execute
- That’s what we call NOP-Oriented Programming

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Theoretical analysis

Possibilities with a NOP-Oriented programming model

Assumptions

- The binary contains a minimal set of instructions:
  - load/store
  - move
  - add
  - sub
- The binary is bug-free
- No backdoor is necessary
- ARM instruction set
  - Could be applied to other ISA

Control Flow Hijacking (attack 1)

- Any instruction can be skipped to reach any address
- From an address *A*, any address *A'* where *A'* > *A* can be reached

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```
@A     : inst. 1
@A+2   : inst. 2
          …
          …
@A'-1  : inst. n-1
@A'    : inst. n
```

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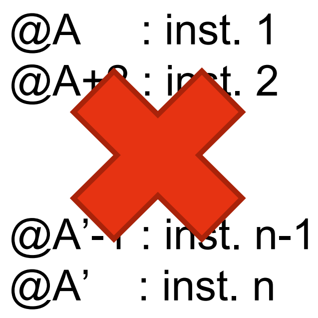

- With branches, almost any address could be reached
  - Starting from @A, how to reach @B?

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- Any instruction can be skipped to reach any address
- From an address *A*, any address *A'* where *A'* > *A* can be reached

@A : inst. 1
@A+[illegible] : inst. 2
@A'-1 : inst. n-1
@A' : inst. n

- With branches, almost any address could be reached
  - Starting from @A, how to reach @B?

@B : inst. n+1
…
@A : inst. 1
…
…
@A'-1 : inst. n-1
@A' : branch B

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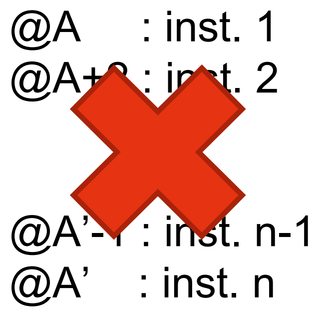

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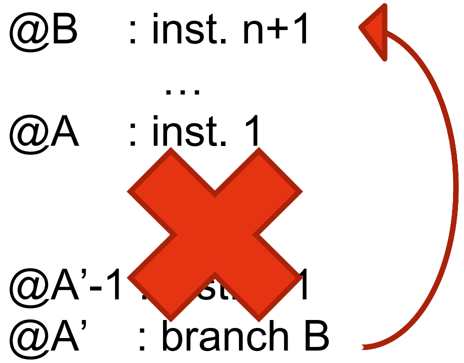

Control loop iteration (attack 2)

- Do fewer iterations by:

- Do more iterations by:

```
        …
  mov r4, #10
label:
        …
  sub r4, r4, #1
  cmp r4, 0
  bne label

endloop:
        …
```

Control loop iteration (attack 2)

- Do fewer iterations by:
  - Replace entire body by NOP

```
        …
   mov r4, #10
label:
        …
   su        #1
   cmp
   bne abe

endloop:
        …
```

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Control loop iteration (attack 2)

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  - NOP the conditional branch at the end and exit
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  - NOP the instruction which controls the loop condition

    Typically a subtraction on a counter

…
mov r4, #10
label:
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endloop:
…

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  - Replace entire body by NOP
  - NOP the conditional branch at the end and exit

- Do more iterations by:
  - NOP the instruction which controls the loop condition
    Typically a subtraction on a counter
  - NOP the compare instruction
    This relies on the current state of the control flags

…
mov r4, #10
label:
…
sub r4, r4, #1
~~cmp r4, 0~~
bne label

endloop:
…

Write any possible value in a register (attack 3)

- This relies on the presence of
  - Instruction(s) to increment a register
  - move or load

```
    …
    mov r0, #0
    mov r4, #10
label:
    …
    add r0, r0, #1
    …
    mov r3, r0
    …
    sub r4, r4, #1
    cmp r4, 0
    bne label

endloop:
    …
```

Write any possible value in a register (attack 3)

- This relies on the presence of
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1. Use a controlled loop (attack 2)
   - We control the number of iterations

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    …
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label:
    …
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    …
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2. Use a register *Rs* whose content is controlled

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label:
      …
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      …
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      …
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   bne label

endloop:
      …
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3. Use a move instruction from *Rs* into *Rd*

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label:
    …
  add r0, r0, #1
    …
  mov r3, r0
    …
  sub r4, r4, #1
  cmp r4, 0
  bne label

endloop:
    …
```

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3. Use a move instruction from *Rs* into *Rd*
4. Exit the loop (attack 1)

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endloop:
        …
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        …
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endloop:
        …
```

- This can be extended to a set of registers (see paper)

Load & store from a register (attack 4)

- *Rm* represents a memory address
- *Rs* represents a value to store

```
        …
    mov r0, #0
    mov r1, #0
    mov r4, #10
label:
        …
    add r0, r0, #1
    add r1, r1, #1
        …
    sub r4, r4, #1
    cmp r4, 0
    bne label

endloop:
        …
        …
    ldr r1, [r0]
        …
        …
    str r1, [r0]
```

Load & store from a register (attack 4)

- *Rm* represents a memory address
- *Rs* represents a value to store
- Both registers content are controlled (attack 3)

```
    …
  mov r0, #0
  mov r1, #0
  mov r4, #10
label:
    …
  add r0, r0, #1
  add r1, r1, #1
    …
  sub r4, r4, #1
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endloop:
    …
    …
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```

Load & store from a register (attack 4)

- *Rm* represents a memory address
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- To read in memory, reach a load that uses *Rm*
  - No need of *Rs* for reading

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mov r0, #0
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label:
…
add r0, r0, #1
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endloop:
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ldr rX, [r0]
…
…
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label:
…
add r0, r0, #1
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…
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endloop:
…
ldr
…
…
str r1, [r0]

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    - If no such instruction, use other registers with move (attack 3)

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mov r1, #0
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label:
…
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- This can be extended to a set of registers (see paper)

```
   …
  mov r0, #0
  mov r1, #0
  mov r4, #10
label:
   …
  add r0, r0, #1
  add r1, r1, #1
   …
  sub r4, r4, #1
  cmp r4, 0
  bne label

endloop:
   …
  ldr r
   …
   …
  str r1, [r0]
```

Jump to any address (attack 5)

- *Rd* represents the destination of a branch

```
        …
    mov r0, #0
    mov r4, #10
label:
        …
    add r0, r0, #1
        …
    sub r4, r4, #1
    cmp r4, 0
    bne label

endloop:
        …
        …
        …
    blx r0
```

Jump to any address (attack 5)

- *Rd* represents the destination of a branch
- *Rd* is a controlled register

…
mov r0, #0
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label:
…
add r0, r0, #1
…
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cmp r4, 0
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endloop:
…
…
…
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Jump to any address (attack 5)

- *Rd* represents the destination of a branch
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- Find an unconditional branch to *Rd*:
  blx *Rd*

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…
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- Use the stack:
  push *Rd*
  pop *pc*

…
mov r0, #0
mov r4, #10
label:
…
add r0, r0, #1
…
~~sub r4, r4, #1~~
cmp r4, 0
~~bne label~~

endloop:
…
blx r0

Summary of possibilities

1) CFG Hijacking
2) Control loop iteration
3) Control register(s) content

4) Load/Store from register(s)
5) Jump to any address

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Direct dependency

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This is Turing-Complete (proof in the paper)

Application to (almost) real life

NOP-Oriented programming in a nutshell

Disclaimer

- We present two attacks:
  1) How to retrieve the encryption key used in AES
  2) How to write user-defined data in memory
- However, this is **not specific to AES**

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- Our target: **ARM embedded systems**
  - No memory protection

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- We only need a minimum set of instructions
- Our target: **ARM embedded systems**
  - No memory protection

- Realised in the **gem5* simulator**
  - Replay fault model has been implemented
  - Few attacks tested on real board

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Adaptation of the fault model

- Theory: skipping an instruction **has no side-effect**
  - NOP-Oriented Programming

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```
ldr  r0, [pc, #-32]
add  r0, r0, r1
```

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```
ldr   r0, [pc, #-32]        ldr   r0, [pc, #-32]
add   r0, r0, r1       →    ldr   r0, [pc, #-32]
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ldr *r0*, [*pc*, #-32]
add *r0*, *r0*, *r1*

→

ldr *r0*, [*pc*, #-32]
ldr *r0*, [*pc*, #-32]

→

Possible side-effect on *r0*

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Base program

```
memset(cipher, 0, BUF_SIZE);
sprintf(plain, "%s", "thisisaplaintext");
sprintf(key, "%s", "0123456789ABCDEF");
```

Init phase

Base program

```
memset(cipher, 0, BUF_SIZE);
sprintf(plain, "%s", "thisisaplaintext");
sprintf(key, "%s", "0123456789ABCDEF");

AESEncrypt(cipher, plain, key);
printf("%s\n", cipher);
```

Init phase

Compute phase

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Init phase

Compute phase

- Goal: retrieve the key

Attack #1 : get the encryption key (1/2)

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- AESEncrypt(cipher, plain, key);
  → key is in r2 (function call convention)
- printf("%s\n", cipher);
  → String to print is in r1 (function call convention)
- Idea: move r2 into r1, then call printf()

Attack #1 : get the encryption key (2/2)

```
<abort>:
        ...
<main>:
        ...
```

```
<Encrypt>:
105d0: push {fp, lr}
105d4: add  fp, sp, #4
105d8: sub  sp, sp, #248
105dc: str  r0, [fp, #-240]
105e0: str  r1, [fp, #-244]
105e4: str  r2, [fp, #-248]
105e8: sub  r3, fp, #24
105ec: ldr  r1, [fp, #-248]
```

1) Move r2 into r1
2) Call printf()

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<abort>:
        ...
<main>:
        ...
```

1) Move r2 into r1
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key is in r2

```
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105e0: str  r1, [fp, #-244]
105e4: str  r2, [fp, #-248]
105e8: sub  r3, fp, #24
105ec: ldr  r1, [fp, #-248]
```

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```
<abort>:
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<main>:
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Store at $fp-248

Load into r1

1: inst. to reach

2: nop burst

3: jump

Attack #1 : get the encryption key (2/2)

```
<abort>:
        ...
<main>:
        ...
10594: ldr r2, [fp, #-16]
10598: ldr r1, [fp, #-8]
1059c: ldr r0, [fp, #-12]
105a0: bl  105d0 <Encrypt>
105a4: ldr r1, [fp, #-12]
105a8: ldr r0, [pc, #28]
105ac: bl 17cc4 <_IO_printf>
        ...
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4: nop burst

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1: inst. to reach

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1) Move r2 into r1
2) Call printf()

- Two bursts of nops are necessary
- More generic attacks to retrieve the key are presented in the paper

Attack #2: Write custom data in memory (in theory)

- Idea: hijack cipher buffer to write custom data
  → ASCII characters in this example

```
memset(cipher, 0, BUF_SIZE);
AESEncrypt(cipher, plain, key);
printf("%s\n", cipher);
```

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- How? Take control of a loop to:
  1) Re-create the address of cipher in register *Rm*
  2) Set the decimal value for a character in register *Rs*
  3) Find a store instruction that use *Rm* and *Rs*

Attack #2: Write custom data in memory (in practice)

- Illustration with “Hello World!”

1. Call AESEncrypt()

<AESEncrypt>:

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loop:






  cmp
  bne loop
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        …
   add r0, r0, #1      // Executed N times, with N = @cipher


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  add r1, r1, #1      // Executed 72 times (‘H’ character)
        …              // then always skipped
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Attack #2: Write custom data in memory (in practice)

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4. Store the value

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        …
  str r1, [r0]
```

Attack #2: Write custom data in memory (in practice)

- Illustration with “Hello World!”

1. Call AESEncrypt()
2. Do as many iteration as necessary
3. Exit the loop
4. Store the value
5. Restart

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  cmp
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        …
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Conclusion

Let’s try to summarize and answer our questions

Summary

- Q1. What are the possibilities for an attacker?
  - Hijack CFG
  - Control registers
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  → The attacker executes what he wants (full control)

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  - Hijack CFG
  - Control registers
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- Q2. Can we simulate this fault model?
  - gem5 simulator
    - Setup available at https://gitlab.inria.fr/gem5-nop/gem5
    - Simulator modifications + all source code and binaries
  - Successfully retrieve a key with AES
  - Successfully altered memory

Future Works

- More realistic use-cases
  - Proof of concept
  - Extends to real applications (embedded OS?)
- Fault model in gem5 has to be enhanced (on-going internship)
  - More realistic fault model (replay more than one inst.)
- Propose countermeasures
  - Hardware (could depend on how the injection is made)
  - Software (HW independent)

Thank You!

NOP-Oriented Programming: Should we Care?

Pierre-Yves Péneau, Ludovic Claudepierre, Damien Hardy, Erven Rohou