Countermeasures

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Goal

- In this lecture some countermeasures will be presented that permits mitigating the impact of memory corruption attacks.

Prerequisites

- Lecture:
  - Basic knowledge of C

Outline

- Non eXecutable stack (NX)
- Stack Canaries
- Attacks against canaries
- Address Space Layout Randomization (ASLR)
- ASLR bypassing techniques
- Control Flow Integrity

Non eXecutable stack (NX)

- C*ode injection* attacks typically consist of two steps:
  - Add malicious code in the stack
  - Jump to it
- To contrast this kind of attacks, memory areas can be marked as *non executable*
- The command *readelf* can be used to check if a given section is executable or not

Non eXecutable stack (NX)

- Below the output of *readelf –e progname*

```
Program Headers:
  Type           Offset   VirtAddr   PhysAddr   FileSiz MemSiz  Flg Align
  PHDR           0x000034 0x08048034 0x08048034 0x00120 0x00120 R E 0x4
  INTERP         0x000154 0x08048154 0x08048154 0x00013 0x00013 R   0x1
      [Requesting program interpreter: /lib/ld-linux.so.2]
  LOAD           0x000000 0x08048000 0x08048000 0x0064c 0x0064c R E 0x1000
  LOAD           0x000f08 0x08049f08 0x08049f08 0x00118 0x0011c RW  0x1000
  DYNAMIC        0x000f14 0x08049f14 0x08049f14 0x000e8 0x000e8 RW  0x4
  NOTE           0x000168 0x08048168 0x08048168 0x00044 0x00044 R   0x4
  GNU_EH_FRAME   0x00052c 0x0804852c 0x0804852c 0x00034 0x00034 R   0x4
  GNU_STACK      0x000000 0x00000000 0x00000000 0x00000 0x00000 RWE 0x10
  GNU_RELRO      0x000f08 0x08049f08 0x08049f08 0x000f8 0x000f8 R   0x1
```

Non eXecutable stack (NX)


```
Program Headers:
  Type           Offset   VirtAddr   PhysAddr   FileSiz MemSiz  Flg Align
  PHDR           0x000034 0x08048034 0x08048034 0x00120 0x00120 R E 0x4
  INTERP         0x000154 0x08048154 0x08048154 0x00013 0x00013 R   0x1
      [Requesting program interpreter: /lib/ld-linux.so.2]
  LOAD           0x000000 0x08048000 0x08048000 0x0064c 0x0064c R E 0x1000
  LOAD           0x000f08 0x08049f08 0x08049f08 0x00118 0x0011c RW  0x1000
  DYNAMIC        0x000f14 0x08049f14 0x08049f14 0x000e8 0x000e8 RW  0x4
  NOTE           0x000168 0x08048168 0x08048168 0x00044 0x00044 R   0x4
  GNU_EH_FRAME   0x00052c 0x0804852c 0x0804852c 0x00034 0x00034 R   0x4
  GNU_STACK      0x000000 0x00000000 0x00000000 0x00000 0x00000 RWE 0x10
  GNU_RELRO      0x000f08 0x08049f08 0x08049f08 0x000f8 0x000f8 R   0x1
```

- Above we see that the stack is enabled for execution

Non eXecutable stack (NX)

- *gcc* allows us to *enable* or *disable NX flag* on building:

NX enabled

```
gcc -z noexecstack -o nxprogram myprogram.c -m32
```

NX disabled

```
gcc -z execstack -o nonxprogram myprogram.c -m32
```

Non eXecutable stack (NX)

- Pwntools can be also used to read ELF binary file and check the status of NX:

```
>>> elf = ELF('nxprogram')
[*] '/home/loreti/CC/SS3/nxprogram'
    Arch:     i386-32-little
    RELRO:    Partial RELRO
    Stack:    Canary found
    NX:       NX enabled
    PIE:      No PIE (0x8048000)
>>>
```

```
>>> elf = ELF('nonxprogram')
[*] '/home/loreti/CC/SS3/nonxprogram'
    Arch:     i386-32-little
    RELRO:    Partial RELRO
    Stack:    Canary found
    NX:       NX disabled
    PIE:      No PIE (0x8048000)
    RWX:      Has RWX segments
>>>
```

Non eXecutable stack (NX)

- The use of NX allow us to mitigate *code injection*
- However other form of ACE, like for instance *return-to-libc*, are not affected
- This because the malicious code (a function in the *Standard C Library*) is not stored in the stack

Stack Canaries

- Stack Canaries are secret values placed on the stack which change every time the program is executed.
- Prior to a function return, the stack canary is checked and if it appears to be modified, the program exits immediately
- The name is related to the birds used in the coal mines to check the presence of dangerous gases

Stack Canaries

- The *pseudocode* of a function that uses *canaries* is:

```
void afunction(...) {
   long canary = CANARY_VALUE; //Canary initialization
   ...
   ...
   if (canary != CANARY_VALUE) {
      exit(CANARY_DEAD);
   }
}
```

- Gcc compiler can generate a more efficient code for us
  - Option *–fstack-protector* must be used.

Stack Canaries

- The basic methodology is to place a filler word, the canary, between local variables, or buffer contents in general, and the return address
- The canary may consist of a mix of *random* and *terminator* values
- At the end of the function, just before the return instruction, the integrity of the canary is checked:
  - If no alteration is found, execution resumes normally
  - If an alteration is detected, program execution is terminated immediately

Stack Canaries

Without Canaries

```
0804843b <welcome>:
 804843b:       55                      push   %ebp
 804843c:       89 e5                   mov    %esp,%ebp
 804843e:       83 ec 18                sub    $0x18,%esp
 8048441:       83 ec 08                sub    $0x8,%esp
 8048444:       ff 75 08                pushl  0x8(%ebp)
 8048447:       8d 45 ee                lea    -0x12(%ebp),%eax
 804844a:       50                      push   %eax
 804844b:       e8 c0 fe ff ff          call   8048310 <strcpy@plt>
 8048450:       83 c4 10                add    $0x10,%esp
 8048453:       83 ec 08                sub    $0x8,%esp
 8048456:       8d 45 ee                lea    -0x12(%ebp),%eax
 8048459:       50                      push   %eax
 804845a:       68 20 85 04 08          push   $0x8048520
 804845f:       e8 9c fe ff ff          call   8048300 <printf@plt>
 8048464:       83 c4 10                add    $0x10,%esp
 8048467:       90                      nop
 8048468:       c9                      leave
 8048469:       c3                      ret
```

With Canaries

```
0804849b <welcome>:
 804849b:       55                      push   %ebp
 804849c:       89 e5                   mov    %esp,%ebp
 804849e:       83 ec 28                sub    $0x28,%esp
 80484a1:       8b 45 08                mov    0x8(%ebp),%eax
 80484a4:       89 45 e4                mov    %eax,-0x1c(%ebp)
 80484a7:       65 a1 14 00 00 00       mov    %gs:0x14,%eax
 80484ad:       89 45 f4                mov    %eax,-0xc(%ebp)
 80484b0:       31 c0                   xor    %eax,%eax
 80484b2:       83 ec 08                sub    $0x8,%esp
 80484b5:       ff 75 e4                pushl  -0x1c(%ebp)
 80484b8:       8d 45 ea                lea    -0x16(%ebp),%eax
 80484bb:       50                      push   %eax
 80484bc:       e8 af fe ff ff          call   8048370 <strcpy@plt>
 80484c1:       83 c4 10                add    $0x10,%esp
 80484c4:       83 ec 08                sub    $0x8,%esp
 80484c7:       8d 45 ea                lea    -0x16(%ebp),%eax
 80484ca:       50                      push   %eax
 80484cb:       68 a0 85 04 08          push   $0x80485a0
 80484d0:       e8 7b fe ff ff          call   8048350 <printf@plt>
 80484d5:       83 c4 10                add    $0x10,%esp
 80484d8:       90                      nop
 80484d9:       8b 45 f4                mov    -0xc(%ebp),%eax
 80484dc:       65 33 05 14 00 00 00    xor    %gs:0x14,%eax
 80484e3:       74 05                   je     80484ea <welcome+0x4f>
 80484e5:       e8 76 fe ff ff          call   8048360 <__stack_chk_fail@plt>
 80484ea:       c9                      leave
 80484eb:       c3                      ret
```

Stack Canaries

Without Canaries

```
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 8048450:       83 c4 10                add    $0x10,%esp
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 804845f:       e8 9c fe ff ff          call   8048300 <printf@plt>
 8048464:       83 c4 10                add    $0x10,%esp
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```

With Canaries

Initialization

```
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 80484b8:       8d 45 ea                lea    -0x16(%ebp),%eax
 80484bb:       50                      push   %eax
 80484bc:       e8 af fe ff ff          call   8048370 <strcpy@plt>
 80484c1:       83 c4 10                add    $0x10,%esp
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 80484e3:       74 05                   je     80484ea <welcome+0x4f>
 80484e5:       e8 76 fe ff ff          call   8048360 <__stack_chk_fail@plt>
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Stack Canaries

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 80484a4:       89 45 e4                mov    %eax,-0x1c(%ebp)
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 80484b2:       83 ec 08                sub    $0x8,%esp
 80484b5:       ff 75 e4                pushl  -0x1c(%ebp)
 80484b8:       8d 45 ea                lea    -0x16(%ebp),%eax
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 80484c7:       8d 45 ea                lea    -0x16(%ebp),%eax
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 80484ea:       c9                      leave
 80484eb:       c3                      ret
```

Test

Terminator Canaries

- Terminator Canaries are special sequence of bytes that *blocks* execution of functions such as *strcpy* or *gets:*
  - *NULL*, 0x00
  - *CR*, 0x0d
  - *LR*, 0x0a
  - *EOF*, 0xff
- The use of these 2-byte characters do terminate most string operations and makes the overflow attempt harmless

Random Canaries

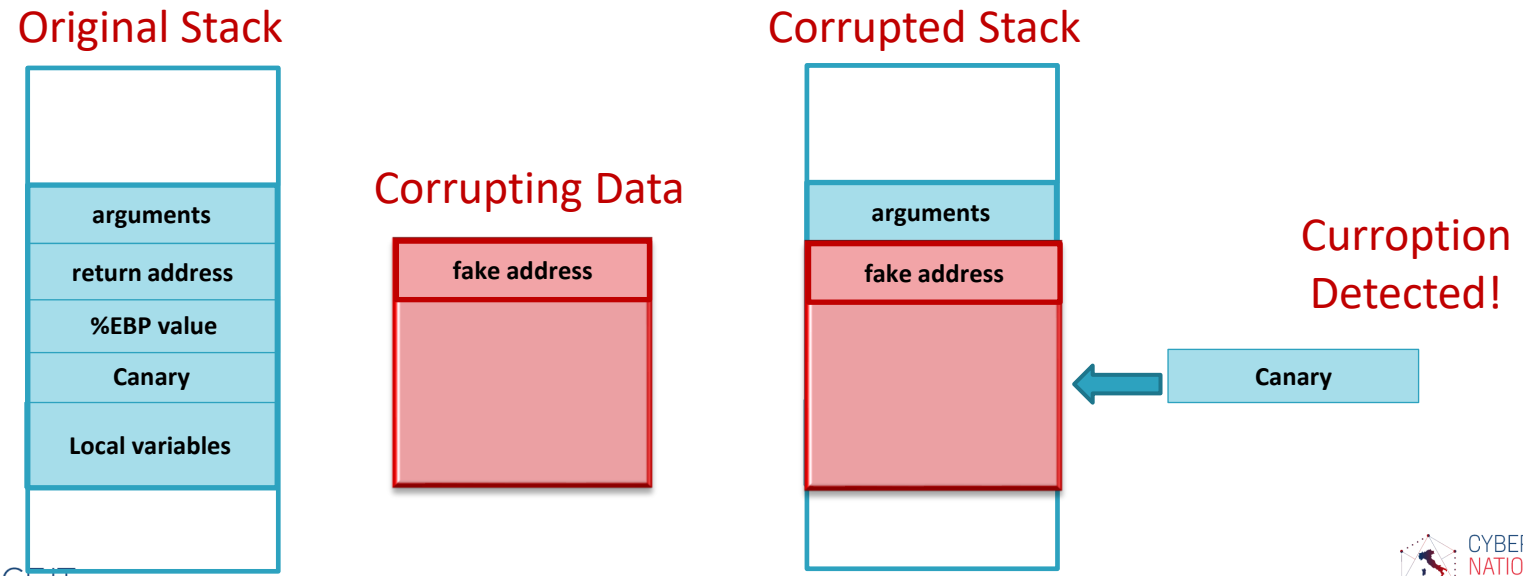
- Values are randomly selected with the goal of making it *exceedingly difficult* for attackers to find the right value
- The random value is taken from */dev/urandom* if available, otherwise by hashing the time of day
- The randomness is sufficient to prevent most prediction attempts

Bypass Canaries

- Stack Canaries seem an efficient mechanism to mitigate any stack smashing
- However, there are two techniques that can be used to bypass them:
  - Stack Canary Leaking
  - Bruteforcing attack

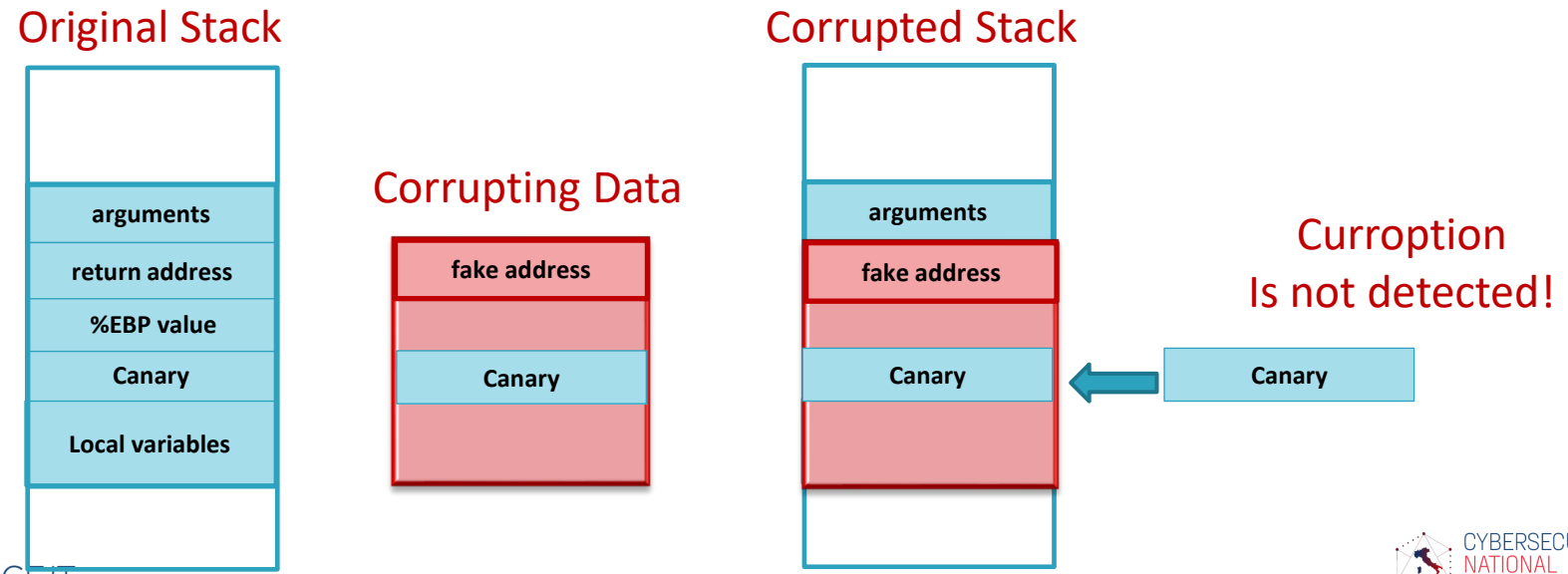
Stack Canary Leaking

- When stack canaries are used, we can check if data in the stack have been corrupted:



Stack Canary Leaking

- If an attacker knows or is able to read the data in the stack canary, that value can be used in the *corrupting* data:



Stack Canary Leaking

- When *terminator canaries* are used, their use in a corrupting data is not easy
  - For instance, the first byte of the stack canary could be NULL, meaning that string functions will stop when they hit it.
- In this case an attacker would perform two actions:
  - A first action to overwrite stack content
  - A second one to put the *termination canary* back

Bruteforcing a Stack Canary

- The canary is determined when the program starts up for the first time…
  - If the program forks, it keeps the same canaries in the child process
  - Each child is used as an *oracle* to test *one canary value*
  - The attack is replicated (with different values) on multiple children
  - This method can be used on fork-and-accept servers where connections are spun off to child processes

Address Space Layout Randomization

- The *Address Space Layout Randomization* (ASLR) is a computer security technique which involves randomly positioning:
  - the base address of an executable
  - the position of libraries, heap, and stack, in a process's address space

Address Space Layout Randomization

- Operating Systems may support different kinds of ASLRs
- Linux OS offers three ASLR modes:
  - No randomization, everything is static;
  - Conservative randomization, main process components (shared libraries, stack, mmap,…) are randomized;
  - Full randomization.

Address Space Layout Randomization

- Let us consider the following simple C program that just prints the address of a local variable:

```c
#include <stdio.h>

void main(int argc, char **argv) {

   int aVariable = 0;

   printf("Global is stored ad %p\n",&aVariable);

}
```

Address Space Layout Randomization

- This is the result of some executions with ASLR disabled:

```
[CC >echo 0 | sudo tee /proc/sys/kernel/randomize_va_space
 0
[CC >./testaslr
 Global is stored ad 0x7fffffffe4a4
[CC >./testaslr
 Global is stored ad 0x7fffffffe4a4
[CC >./testaslr
 Global is stored ad 0x7fffffffe4a4
[CC >./testaslr
 Global is stored ad 0x7fffffffe4a4
 CC >
```

Address Space Layout Randomization

- The same executions with ASLR enabled:

```
[CC >echo 2 | sudo tee /proc/sys/kernel/randomize_va_space
2
[CC >./testaslr
Global is stored ad 0x7ffc1d5666f4
[CC >./testaslr
Global is stored ad 0x7ffdd36e4bc4
[CC >./testaslr
Global is stored ad 0x7fffa73e9a34
[CC >./testaslr
Global is stored ad 0x7fffa8aa7e14
CC >
```

Bypassing ASLR

- Brute Force: the exploitation is repeated with different addresses until success
  - In some cases, like for *code injection*, extra *dummy instructions (NOP)* are used to increase the probability that the used address hits the injected code
- Information leakage: collected info can be used to instrument an attack based on ROP or JOP
- OS specific attack: since ASLR is specific for each OS, specific attacks and vulnerabilities can be used

Control-Flow Integrity (CFI)

- Control-Flow Integrity (CFI) is a technic that aims to prevent ACE attacks
- To control the *correct execution*, CFI uses a Control-Flow Graph (CFG) determined ahead of time (via static analysis)
- At runtime, it is checked that control flow remains within a given CFG

Control-Flow Integrity (CFI)

- Control-Flow Integrity (CFI) is an efficient defense against arbitrary code execution in general
- Unfortunately, it could be very costly or hard to implement.
- Details about CFI can be found in:

Control-flow integrity principles, implementations, and applications
Abadi, Budiu, Erligsson, Ligatti
ACM Transactions on Information and System Security, November 2009

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