Return-to-libc Attack Lab

Updated on January 12, 2020

1 Lab Overview

Some of the main points from Chapter 5 are summarized in Section 3 of this document. Please review this section!

The learning objective of this lab is for students to gain the first-hand experience on an interesting variant of buffer-overflow attack; this attack can bypass an existing protection scheme currently implemented in major Linux operating systems. A common way to exploit a buffer-overflow vulnerability is to overflow the buffer with a malicious shellcode, and then cause the vulnerable program to jump to the shellcode stored in the stack. To prevent these types of attacks, some operating systems allow programs to make their stacks non-executable; therefore, jumping to the shellcode causes the program to fail.

Unfortunately, the above protection scheme is not fool-proof. There exists a variant of buffer-overflow attacks called *Return-to-libc*, which does not need an executable stack; it does not even use shellcode. Instead, it causes the vulnerable program to jump to some existing code, such as the `system()` function in the `libc` library, which is already loaded into a process's memory space.

In this lab, students are given a program with a buffer-overflow vulnerability; their task is to develop a Return-to-libc attack to exploit the vulnerability and finally to gain the root privilege. In addition to the attacks, students will be guided to walk through some protection schemes implemented in Ubuntu to counter buffer-overflow attacks. This lab covers the following topics:

- Buffer overflow vulnerability
- Stack layout in a function invocation and Non-executable stack
- Return-to-libc attack and Return-Oriented Programming (ROP)

Customization by instructor. Instructors should customize this lab by choosing a value for the `BUF_SIZE` constant, which is used during the compilation of the vulnerable program. Different values can make the solutions different. Please pick a value between `0` and `200` for this lab.

The `BUF_SIZE` value for this lab is: 116

Readings and related topics. Detailed coverage of the return-to-libc attack can be found in Chapter 5 of the SEED book, *Computer & Internet Security: A Hands-on Approach, 2nd Edition*, by Wenliang Du (`https://www.handsonsecurity.net`). A topic related to this lab is the general buffer-overflow attack, which is covered in a separate SEED lab, as well as in Chapter 4 of the SEED book.

Lab environment. This lab has been tested on our pre-built Ubuntu 16.04 VM, which can be downloaded from the SEED website.

2 Lab Tasks

2.1 Turning off countermeasures

You can execute the lab tasks using our pre-built `Ubuntu` virtual machines. `Ubuntu` and other Linux distributions have implemented several security mechanisms to make the buffer-overflow attack difficult. To simplify our attacks, we need to disable them first.

Address Space Randomization. `Ubuntu` and several other Linux-based systems use address space randomization to randomize the starting address of heap and stack, making guessing the exact addresses difficult. Guessing addresses is one of the critical steps of buffer-overflow attacks. In this lab, we disable this feature using the following command:

```
$ sudo sysctl -w kernel.randomize_va_space=0
```

The StackGuard Protection Scheme. The GCC compiler implements a security mechanism called *StackGuard* to prevent buffer overflows. In the presence of this protection, buffer overflow attacks do not work. We can disable this protection during the compilation using the *-fno-stack-protector* option. For example, to compile a program `example.c` with StackGuard disabled, we can do the following:

```
$ gcc -fno-stack-protector example.c
```

Non-Executable Stack. `Ubuntu` used to allow executable stacks, but this has now changed. The binary images of programs (and shared libraries) must declare whether they require executable stacks or not, i.e., they need to mark a field in the program header. Kernel or dynamic linker uses this marking to decide whether to make the stack of this running program executable or non-executable. This marking is done automatically by the recent versions of `gcc`, and by default, stacks are set to be non-executable. To change that, use the following option when compiling programs:

```
For executable stack:
$ gcc -z execstack  -o test test.c

For non-executable stack:
$ gcc -z noexecstack  -o test test.c
```

Because the objective of this lab is to show that the non-executable stack protection does not work, you should always compile your program using the `"-z noexecstack"` option in this lab.

Configuring `/bin/sh` (Ubuntu 16.04 VM only). In both Ubuntu 12.04 and Ubuntu 16.04 VMs, the `/bin/sh` symbolic link points to the `/bin/dash` shell. However, the `dash` program in these two VMs have an important difference. The `dash` shell in Ubuntu 16.04 has a countermeasure that prevents itself from being executed in a `Set-UID` process. If `dash` is executed in a `Set-UID` process, it immediately changes the effective user ID to the process's real user ID, essentially dropping its privilege. The `dash` program in Ubuntu 12.04 does not have this behavior.

Since our victim program is a `Set-UID` program, and our attack uses the `system()` function to run a command of our choice. This function does not run our command directly; it invokes `/bin/sh` to run our command. Therefore, the countermeasure in `/bin/dash` immediately drops the `Set-UID` privilege before executing our command, making our attack more difficult. To disable this protection, we link `/bin/sh` to another shell that does not have such a countermeasure. We have installed a shell program called `zsh` in our Ubuntu 16.04 VM. We use the following commands to link `/bin/sh` to `zsh` (there is no need to do these in Ubuntu 12.04):

```
$ sudo ln -sf /bin/zsh /bin/sh
```

It should be noted that the countermeasure implemented in `dash` can be circumvented. We will do that in a later task.

2.2 The Vulnerable Program

A copy of this program has been added to our course repo. You must use the retlib.c file!

Listing 1: The vulnerable program `retlib.c`

DO NOT COPY THIS CODE - THE CORRECT VERSION IS AVAILABLE IN OUR COURSE REPO!

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

/* Changing this size will change the layout of the stack.
 * Instructors can change this value each year, so students
 * won't be able to use the solutions from the past.
 * Suggested value: between 0 and 200 (cannot exceed 300, or
 * the program won't have a buffer-overflow problem). */
#ifndef BUF_SIZE
#define BUF_SIZE 12
#endif

int bof(FILE *badfile)
{
    char buffer[BUF_SIZE];

    /* The following statement has a buffer overflow problem */
    fread(buffer, sizeof(char), 300, badfile);

    return 1;
}

int main(int argc, char **argv)
{
    FILE *badfile;

    /* Change the size of the dummy array to randomize the parameters
       for this lab. Need to use the array at least once */
    char dummy[BUF_SIZE*5];  memset(dummy, 0, BUF_SIZE*5);

    badfile = fopen("badfile", "r");
    bof(badfile);

    printf("Returned Properly\n");
    fclose(badfile);
    return 1;
}
```

The above program has a buffer overflow vulnerability. It first reads an input of size `300` bytes from a file called `badfile` into a buffer of size `BUF_SIZE`, which is less than `300`. Since the function `fread()` does not check the buffer boundary, a buffer overflow will occur. This program is a root-owned `Set-UID` program, so if a normal user can exploit this buffer overflow vulnerability, the user might be able to get a root shell. It should be noted that the program gets its input from a file called `badfile`, which is provided by users. Therefore, we can construct the file in a way such that when the vulnerable program copies the file contents into its buffer, a root shell can be spawned.

Compilation. Let us first compile the code and turn it into a root-owned `Set-UID` program. Do not forget to include the `-fno-stack-protector` option (for turning off the StackGuard protection) and the `"-z noexecstack"` option (for turning on the non-executable stack protection). It should also be noted that changing ownership must be done before turning on the `Set-UID` bit, because ownership changes cause the `Set-UID` bit to be turned off.

```
// Note: N should be replaced by the value set by the instructor
$ gcc -DBUF_SIZE=N -fno-stack-protector -z noexecstack -o retlib retlib.c
$ sudo chown root retlib
$ sudo chmod 4755 retlib
```

For instructors. To prevent students from using the solutions from the past (or from those posted on the Internet), instructors can change the value for `BUF_SIZE` by requiring students to compile the code using a different `BUF_SIZE` value. Without the `-DBUF_SIZE` option, `BUF_SIZE` is set to the default value `12` (defined in the program). When this value changes, the layout of the stack will change, and the solution will be different. Students should ask their instructors for the value of `N`.

2.3 Task 1: Finding out the addresses of `libc` functions

In `Linux`, when a program runs, the `libc` library will be loaded into memory. When the memory address randomization is turned off, for the same program, the library is always loaded in the same memory address (for different programs, the memory addresses of the `libc` library may be different). Therefore, we can easily find out the address of `system()` using a debugging tool such as `gdb`. Namely, we can debug the target program `retlib`. Even though the program is a root-owned `Set-UID` program, we can still debug it, except that the privilege will be dropped (i.e., the effective user ID will be the same as the real user ID). Inside `gdb`, we need to type the `run` command to execute the target program once, otherwise, the library code will not be loaded. We use the `p` command (or `print`) to print out the address of the `system()` and `exit()` functions (we will need `exit()` later on).

```
$ touch badfile
$ gdb -q retlib     ← Use "Quiet" mode
Reading symbols from stack...(no debugging symbols found)...done.
gdb-peda$ run
......
gdb-peda$ p system
$1 = {<text variable, no debug info>} 0xb7e42da0 <__libc_system>
gdb-peda$ p exit
$2 = {<text variable, no debug info>} 0xb7e369d0 <__GI_exit>
gdb-peda$ quit
```

It should be noted that even for the same program, if we change it from a `Set-UID` program to a non-`Set-UID` program, the `libc` library may not be loaded into the same location. Therefore, when we debug the program, we need to debug the target Set-UID program; otherwise, the address we get may be incorrect.

2.4 Task 2: Putting the shell string in the memory

Our attack strategy is to jump to the system() function and get it to execute an arbitrary command. Since we would like to get a shell prompt, we want the system() function to execute the "/bin/sh" program. Therefore, the command string "/bin/sh" must be put in the memory first and we have to know its address (this address needs to be passed to the system() function). There are many ways to achieve these goals; we choose a method that uses environment variables. Students are encouraged to use other approaches.

When we execute a program from a shell prompt, the shell actually spawns a child process to execute the program, and all the exported shell variables become the environment variables of the child process. This creates an easy way for us to put some arbitrary string in the child process's memory. Let us define a new shell variable MYSHELL, and let it contain the string "/bin/sh". From the following commands, we can verify that the string gets into the child process, and it is printed out by the env command running inside the child process.

```
$ export MYSHELL=/bin/sh
$ env | grep MYSHELL
MYSHELL=/bin/sh
```

We will use the address of this variable as an argument to system() call. The location of this variable in the memory can be found out easily using the following program:

```
void main(){
   char* shell =  getenv("MYSHELL");
   if (shell)
      printf("%x\n", (unsigned int)shell);
}
```

A version of this program is available in the course repo: envaddr.c

If the address randomization is turned off, you will find out that the same address is printed out. However, when you run the vulnerable program retlib, the address of the environment variable might not be exactly the same as the one that you get by running the above program; such an address can even change when you change the name of your program (the number of characters in the file name makes a difference). The good news is, the address of the shell will be quite close to what you print out using the above program. Therefore, you might need to try a few times to succeed.

2.5 Task 3: Exploiting the buffer-overflow vulnerability

We are ready to create the content of badfile.

Using Python. We provide you with a skeleton of the code, with the essential parts left for you to fill out.

```
#!/usr/bin/python3
import sys

# Fill content with non-zero values
content = bytearray(0xaa for i in range(300))
```

A version of this program is available in the course repo: libc_exploit.py

```
sh_addr = 0x00000000       # The address of "/bin/sh"
content[X:X+4] = (sh_addr).to_bytes(4,byteorder='little')

system_addr = 0x00000000   # The address of system()
content[Y:Y+4] = (system_addr).to_bytes(4,byteorder='little')

exit_addr = 0x00000000     # The address of exit()
content[Z:Z+4] = (exit_addr).to_bytes(4,byteorder='little')

# Save content to a file
with open("badfile", "wb") as f:
  f.write(content)
```

You need to figure out the three addresses and the values of `X`, `Y`, and `Z`. If your values are incorrect, your attack might not work. In your report, you need to describe how you decide the values for `X`, `Y` and `Z`. Either show us your reasoning or, if you use a trial-and-error approach, show your trials.

```
$./libc_exploit.py // create the badfile
$./retlib          // launch the attack by running the vulnerable program
# <---- You've got a root shell!
```

Attack variation 1: Is the `exit()` function really necessary? Please try your attack without including the address of this function in `badfile`. Run your attack again, report and explain your observations.

Attack variation 2: After your attack is successful, change the file name of `retlib` to a different name, making sure that the length of the new file name is different. For example, you can change it to `newretlib`. Repeat the attack (without changing the content of `badfile`). Will your attack succeed or not? If it does not succeed, explain why.

2.6 Task 4: Turning on address randomization

In this task, let us turn on the Ubuntu's address randomization protection and see whether this protection is effective against the Return-to-libc attack. First, let us turn on the address randomization:

```
$ sudo sysctl -w kernel.randomize_va_space=2
```

Please run the same attack used in the previous task. Can you succeed? Please describe your observation and come up with your hypothesis. In the exploit program used in constructing `badfile`, we need to provide three addresses and the values for `X`, `Y`, and `Z`. Which of these six values are incorrect if the address randomization is turned on. Please provide evidence in your report.

If you plan to use `gdb` to conduct your investigation, you should be aware that `gdb` by default disables the address space randomization for the debugged process, regardless of whether the address randomization is turned on in the underlying operating system or not. Inside the `gdb` debugger, you can run "`show disable-randomization`" to see whether the randomization is turned off or not. You can use "`set disable-randomization on`" and "`set disable-randomization off`" to change the setting.

TASK 5 IS EXTRA CREDIT

2.7 Task 5: Defeat Shell's countermeasure

The purpose of this task is to launch the return-to-libc attack after the shell's countermeasure is enabled. Before doing the attack in Tasks 1 to 4, we relinked `/bin/sh` to `/bin/zsh`, instead of to `/bin/dash` (the original setting). This is because some shell programs, such as `dash` and `bash`, have a countermeasure that automatically drops privileges when they are executed in a `Set-UID` process. In this task, we would like to defeat such a countermeasure, i.e., we would like to get a root shell even though the `/bin/sh` still points to `/bin/dash`. Let us first change the symbolic link back:

```
$ sudo ln -sf /bin/dash /bin/sh
```

When `/bin/sh` points to `/bin/dash`, we cannot directly return to the `system()` function, because `system()` actually uses `/bin/sh` to execute commands, and `/bin/dash` will drop the privilege. There are many ways to solve this problem. One way is to return to a different function that does not depend on `/bin/sh`. Another way is to invoke `setuid(0)` before invoking `system()`. The `setuid(0)` call sets both real user ID and effective user ID to 0, turning the process into a non-`Set-UID` one (it still has the root privilege). It turns out that this is quite challenging to do using the return-to-libc technique.

There are two primary challenges: (1) how to chain multiple functions (with arguments) together, and (2) how to pass zeros as arguments without including any zero in the malicious input? In this task, we focus on addressing the first challenge; we are allowed to ignore the second challenge and put zeros in the input. In the vulnerable program, we intentionally used `fread()`, which, unlike `strcpy()`, is not affected by zeros.

TASK 6 IS EXTRA CREDIT

2.8 Task 6: Defeat Shell's countermeasure without putting zeros in input

In this task, we will address the second challenge in Task 5, i.e., we are not allowed to put any zero (binary zero) in the input (the `badfile`). In real-world attacks, copying data into buffer often uses functions like `strcpy()`, which terminates the copying when zero is encountered. To simulate the real-world situation, we added this constraint.

The main idea to circumvent this restriction is to first put a non-zero value in the place where the `setuid()` function gets its argument, but before `setuid()` is invoked, we invoke a sequence of functions, such as `sprintf()` to change the non-zero value to zero. After that, we invoke `setuid()`, but now its argument is already zero. Basically, we first put our payload on the stack (without zeros), and then use the return-to-libc technique to self-modify the data placed on the stack.

To achieve this goal, we need to be able to chain a sequence of functions together, some of which have multiple arguments. The basic return-to-libc technique used in Tasks 3 and 5 has a limit on the number of functions and their arguments. We need a more generic technique called *Return Oriented Programming (ROP)*, which allows us to chain arbitrary number of functions (with or without arguments) together. The return-to-libc attack conducted in Task 3 and 5 is just a special case of ROP.

Extra credit is "all or nothing" - your solution must be entirely correct to earn the extra credit.
No help is allowed on extra credit.
(Asking about clarifications of the problem is OK though.)
There is no harm in trying - no points will be taken away for an incorrect solution.

3 Guidelines: Understanding the Function Call Mechanism

The guidelines in this section only address Tasks 1 to 5. Guidelines for Task 6 are quite complicated, and the SEED book (2nd edition) spends 16 pages (Chapter 5.5) to explain how to do it. Please refer to the book for guidelines.

3.1 Understanding the stack layout

To know how to conduct Return-to-libc attacks, we need to understand how stacks work. We use a small C program to understand the effects of a function invocation on the stack. More detailed explanation can be found in the SEED book, *Computer & Internet Security: A Hands-on Approach, 2nd Edition*, by Wenliang Du.

```
/* foobar.c */
#include<stdio.h>
void foo(int x)
{
  printf("Hello world: %d\n", x);
}

int main()
```

```
{
  foo(1);
  return 0;
}
```

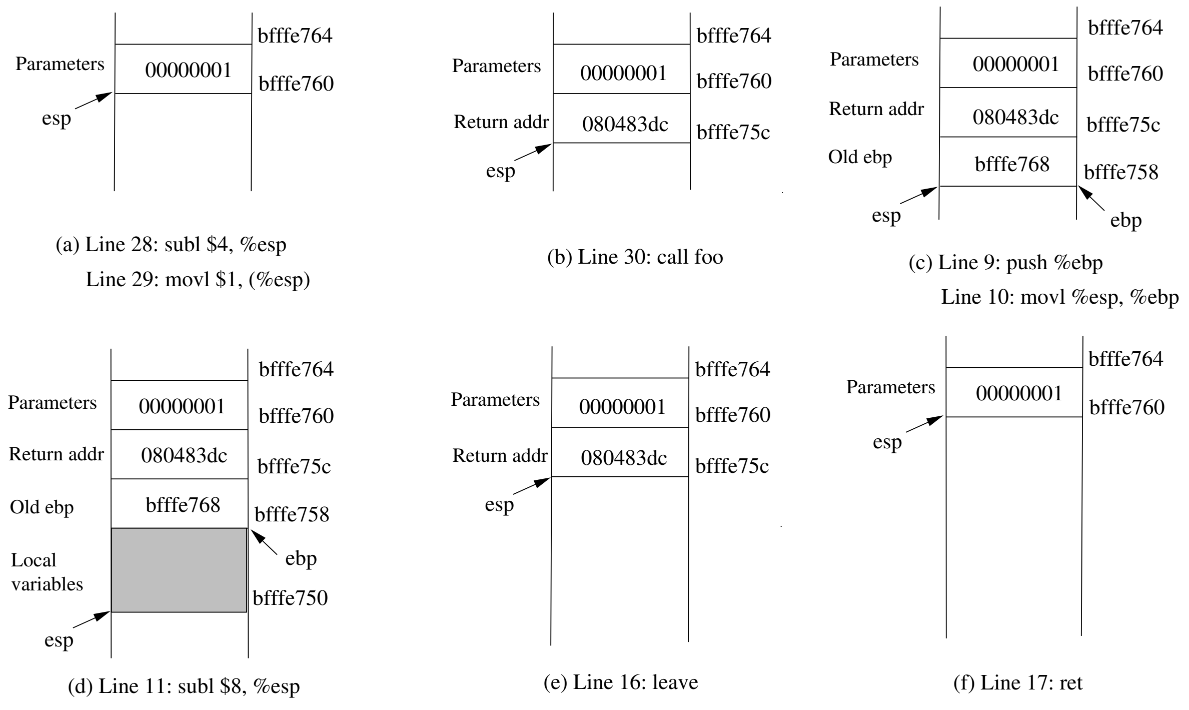
We can use "`gcc -S foobar.c`" to compile this program to the assembly code. The resulting file `foobar.s` will look like the following:

```
    ......
  8 foo:
  9         pushl   %ebp
 10         movl    %esp, %ebp
 11         subl    $8, %esp
 12         movl    8(%ebp), %eax
 13         movl    %eax, 4(%esp)
 14         movl    $.LC0, (%esp)   : string "Hello world: %d\n"
 15         call    printf
 16         leave
 17         ret
    ......
 21 main:
 22         leal    4(%esp), %ecx
 23         andl    $-16, %esp
 24         pushl   -4(%ecx)
 25         pushl   %ebp
 26         movl    %esp, %ebp
 27         pushl   %ecx
 28         subl    $4, %esp
 29         movl    $1, (%esp)
 30         call    foo
 31         movl    $0, %eax
 32         addl    $4, %esp
 33         popl    %ecx
 34         popl    %ebp
 35         leal    -4(%ecx), %esp
 36         ret
```

3.2 Calling and entering `foo()`

Let us concentrate on the stack while calling `foo()`. We can ignore the stack before that. Please note that line numbers instead of instruction addresses are used in this explanation.

- **Line 28-29:**: These two statements push the value 1, i.e. the argument to the `foo()`, into the stack. This operation increments `%esp` by four. The stack after these two statements is depicted in Figure 1(a).
- **Line 30: `call foo`**: The statement pushes the address of the next instruction that immediately follows the `call` statement into the stack (i.e the return address), and then jumps to the code of `foo()`. The current stack is depicted in Figure 1(b).
- **Line 9-10**: The first line of the function `foo()` pushes `%ebp` into the stack, to save the previous frame pointer. The second line lets `%ebp` point to the current frame. The current stack is depicted in Figure 1(c).



(a) Line 28: subl $4, %esp
Line 29: movl $1, (%esp)

(b) Line 30: call foo

(c) Line 9: push %ebp
Line 10: movl %esp, %ebp

(d) Line 11: subl $8, %esp

(e) Line 16: leave

(f) Line 17: ret

Figure 1: Entering and Leaving `foo()`

- **Line 11: `subl $8, %esp`**: The stack pointer is modified to allocate space (8 bytes) for local variables and the two arguments passed to `printf`. Since there is no local variable in function `foo`, the 8 bytes are for arguments only. See Figure 1(d).

3.3 Leaving `foo()`

Now the control has passed to the function `foo()`. Let us see what happens to the stack when the function returns.

- **Line 16: `leave`**: This instruction implicitly performs two instructions (it was a macro in earlier x86 releases, but was made into an instruction later):

```
mov  %ebp, %esp
pop  %ebp
```

  The first statement releases the stack space allocated for the function; the second statement recovers the previous frame pointer. The current stack is depicted in Figure 1(e).

- **Line 17: `ret`**: This instruction simply pops the return address out of the stack, and then jump to the return address. The current stack is depicted in Figure 1(f).

- **Line 32: `addl $4, %esp`**: Further restore the stack by releasing more memories allocated for `foo`. As you can see that the stack is now in exactly the same state as it was before entering the function `foo` (i.e., before line 28).

4 Submission

You need to submit a detailed lab report, with screenshots, to describe what you have done and what you have observed. You also need to explain the observations that are interesting or surprising. Please also list the important code snippets followed by an explanation. Simply attaching code without any explanation will not receive credits.