

Project 4: Application Security

This project is due on **Friday, Nov 17 at 11:59 p.m.** and counts for 9% of your course grade.

This is a group project; you may optionally work in **teams of two** and submit one project per team. Please find a partner as soon as possible. If have trouble forming a team, post to the #project-partner-finder in Slack.

The code and other answers your group submits must be entirely your own work, and you are bound by the Honor Code. You may consult with other students about the conceptualization of the project and the meaning of the questions, but you may not look at any part of someone else's solution or collaborate with anyone outside your group. You may consult published references, provided that you appropriately cite them (e.g., with program comments), as you would in an academic paper.

Solutions must be submitted electronically via Github Classroom (<https://classroom.github.com/a/tLBfKgX6>), following the submission checklist below.

Introduction

This project will introduce you to control-flow hijacking vulnerabilities in application software, including buffer overflows. We will provide a series of vulnerable programs and a virtual machine environment in which you will develop exploits.

Objectives

- Be able to identify and avoid buffer overflow vulnerabilities in native code.
- Understand the severity of buffer overflows and the necessity of standard defenses.
- Gain familiarity with machine architecture and assembly language.

Read this First

This project asks you to develop attacks and test them in a virtual machine you control. Attempting the same kinds of attacks against others' systems without authorization is prohibited by law and university policies and may result in *fines, expulsion, and jail time*. **You must not attack anyone else's system without authorization!** Per the course ethics policy, you are required to respect the privacy and property rights of others at all times, *or else you will fail the course*. See the "Ethics, Law, and University Policies" section on the course website.

Setup

Buffer-overflow exploitation depends on specific details of the target system, so we are providing two ways to run your attacks: a **Docker container** (recommended for non-M1 users) or a **Virtual Machine**.

Docker container (recommended for x86 computers)

Docker provides a lightweight container that makes it easy to run the same code with the same configurations on different machines. We recommend this route if your computer runs x86 (or x86_64 or amd64), but not if you run a Mac M1 (e.g. aarch64).

1. Download and install Docker Desktop for your operating system. You do not need a Docker account.
2. You can test if you have Docker installed correctly by running `docker run hello-world`
3. Accept the Github assignment and clone your repository
4. Within your repository, build the docker image: `docker build -t project4 .`
5. To start a container from that image, run:
`docker run -privileged -it -v ./:/home/ubuntu/project4 project4`
6. There should be a directory, `project4` in the home directory, mapped to your Github Classroom cloned repository.

Virtual Machine setup (needed for M1 Mac)

You do not need to do this if the Docker container works for you.

1. Download VirtualBox from <https://www.virtualbox.org/> and install it on your computer. VirtualBox runs on Windows, Linux, and Mac OS.
2. Get the VM file at <https://file.ecen4133.org/4133-vm.ova> (same as the Network project; you do not need to redownload). This file is 3 GB, so we recommend downloading it from campus.
3. Launch VirtualBox and select File > Import Appliance to add the VM.
4. Start the VM. There is a user named `ubuntu` with password `ubuntu`.
5. You may need to install `libcap` inside the VM: `sudo apt install libcap2-bin`
6. Clone your github repo (after accepting the Github Classroom assignment) inside the VM

Setup targets for attack

Whichever setup you did (Docker or virtual machine), you'll need to compile the targets. Each group's target will be slightly different based on your identikey. Personalize the targets by running:

1. `./setcookie identikey1 identikey2`
Double check that you have set both identikeys correctly.
2. Be sure to add the cookie file to your github repo (`git add cookie && git commit -m "add cookie"`), or the autograder will not work.
3. `sudo make`
4. You should now be able to run the targets. You can test with the first one to verify everything is working: `./target0`

Resources and Guidelines

No Attack Tools! You may not use special-purpose tools meant for testing security or exploiting vulnerabilities. You must complete the project using only general purpose tools, such as gdb.

Control Hijacking Before you begin this project, review the lecture slides from the control-hijacking lecture and attend discussion for additional details. Read "Smashing the Stack for Fun and Profit," available at https://ecen4133.org/static/stack_smashing.pdf

GDB You will make extensive use of the GDB debugger. Useful commands that you may not know are "disassemble", "info reg", "x", and "stepi". See the GDB help for details, and don't be afraid to experiment! This quick reference may also be useful: <http://users.ece.utexas.edu/~adnan/gdb-refcard.pdf>

x86 Assembly There are many good references for Intel assembly language, but note that this project targets the 32-bit x86 ISA. The stack is organized differently in x86 and x86_64. If you are reading any online documentation, ensure that it is based on the x86 architecture, not x86_64.

Targets

The target programs for this project are simple, short C programs with (mostly) clear security vulnerabilities. Your job is to come up with an exploit for each vulnerability, as described below. We have provided source code and a Makefile that compiles all the targets. Your exploits must work against the targets as compiled and executed within Docker/the provided VM.

target0: Overwriting a variable on the stack

(Difficulty: Easy)

This program takes input from `stdin` and prints a message. Your job is to provide input that makes it output: “Hi *identikay!* Your grade is A+.” (You can use either group member’s *identikay*.) To accomplish this, your input will need to overwrite another variable stored on the stack.

Here’s one approach you might take:

1. Examine `target0.c`. Where is the buffer overflow?
2. Start the debugger (`sudo gdb target0`) and disassemble `_main`: `(gdb) disas _main`
Identify the function calls and the arguments passed to them.
3. Draw a picture of the stack. How are `name[]` and `grade[]` stored relative to each other?
4. How could a value read into `name[]` affect the value contained in `grade[]`? Test your hypothesis by running `./target0` on the command line with different inputs.

What to submit Create a Python program named `sol0.py` that prints a line to be passed as input to the target. Test your program with the command line:

```
python3 sol0.py | ./target0
```

Hint: In Python, you can write strings containing non-printable bytes by using the escape sequence “`\xnn`”, where *nn* is a 2-digit hex value. To cause Python to repeat a character *n* times, you can do: `b"X"*n`.

target1: Overwriting the return address

(Difficulty: Easy)

This program takes input from `stdin` and prints a message. Your job is to provide input that makes it output: “Your grade is perfect.” Your input will need to overwrite the return address so that the function `vulnerable()` transfers control to `print_good_grade()` when it returns.

1. Examine `target1.c`. Where is the buffer overflow?
2. Disassemble `print_good_grade`. What is its starting address?
3. Set a breakpoint at the beginning of `vulnerable` and run the program:
`(gdb) break vulnerable`
`(gdb) run`

4. Disassemble `vulnerable` and draw the stack. Where is `input []` stored relative to `%ebp`? How long an input would overwrite this value and the return address?
5. Examine the `%esp` and `%ebp` registers: `(gdb) info reg`
6. What are the current values of the saved frame pointer and return address from the stack frame? You can examine two words of memory at `%ebp` using: `(gdb) x/2wx $ebp`
7. What should these values be in order to redirect control to the desired function?

What to submit Create a Python program named `sol1.py` that prints a line to be passed as input to the target. Test your program with the command line:

```
python3 sol1.py | ./target1
```

When debugging your program, it may be helpful to view a hex dump of the output. Try this:

```
python3 sol1.py | xxd -p
```

Remember that x86 is little endian. Use Python's `struct` module to output little-endian values:

```
from struct import pack
import sys
sys.stdout.buffer.write(pack("<I", 0xDEADBEEF))
```

target2: Redirecting control to shellcode

(Difficulty: Easy)

The remaining targets are owned by the `root` user and have the `suid` bit set. Your goal is to cause them to launch a shell, which will therefore have root privileges. This and later targets all take input as command-line arguments rather than from `stdin`. Unless otherwise noted, you should use the shellcode we have provided in `shellcode.py`. Successfully placing this shellcode in memory and setting the instruction pointer to the beginning of the shellcode (e.g., by returning or jumping to it) will open a shell.

1. Examine `target2.c`. Where is the buffer overflow?
2. Create a Python program named `sol2.py` that outputs the provided shellcode:


```
from shellcode import shellcode
import sys
sys.stdout.buffer.write(shellcode)
```
3. Set up the target in GDB using the output of your program as its argument:


```
gdb --args ./target2 $(python3 sol2.py)
```
4. Set a breakpoint in `vulnerable` and start the target.
5. Disassemble `vulnerable`. Where does `buf` begin relative to `%ebp`? What's the current value of `%ebp`? What will be the starting address of the shellcode?

6. Identify the address after the call to `strcpy` and set a breakpoint there:
`(gdb) break *0x08049d1b`
 Continue the program until it reaches that breakpoint.
`(gdb) cont`
7. Examine the bytes of memory where you think the shellcode is to confirm your calculation:
`(gdb) x/32bx 0xaddress`
8. Disassemble the shellcode: `(gdb) disas/r 0xaddress,+32`
 How does it work?
9. Modify your solution to overwrite the return address and cause it to jump to the beginning of the shellcode.

What to submit Create a Python program named `sol2.py` that prints a line to be used as the command-line argument to the target. Test your program with the command line:

```
./target2 $(python3 sol2.py)
```

If you are successful, you will see a root shell prompt (`#`). Running `whoami` will output “root”.

If your program segfaults, you can examine the state at the time of the crash using GDB with the core dump: `gdb ./target2 core`. The file `core` won't be created if a file with the same name already exists. Also, since the target runs as root, you will need to run it using `sudo ./target2` in order for the core dump to be created.

target3: Overwriting the return address indirectly *(Difficulty: Medium)*

In this target, the buffer overflow is restricted and cannot directly overwrite the return address. You'll need to find another way. Your input should cause the provided shellcode to execute and open a root shell.

What to submit Create a Python program named `sol3.py` that prints a line to be used as the command-line argument to the target. Test your program with the command line:

```
./target3 $(python3 sol3.py)
```

target4: Beyond strings *(Difficulty: Medium)*

This target takes as its command-line argument the name of a data file it will read. The file format is a 32-bit count followed by that many 32-bit integers. Create a data file that causes the provided shellcode to execute and opens a root shell.

What to submit Create a Python program named `sol4.py` that outputs the contents of a data file to be read by the target. Test your program with the command line:

```
python3 sol4.py > tmp; ./target4 tmp
```

target5: Bypassing DEP

(Difficulty: Medium)

This program resembles target2, but it has been compiled with data execution prevention (DEP) enabled. DEP means that the processor will refuse to execute instructions stored on the stack. You can overflow the stack and modify values like the return address, but you can't jump to any shellcode you inject. You need to find another way to run the command `/bin/sh` and open a root shell.

What to submit Create a Python program named `sol5.py` that prints a line to be used as the command-line argument to the target. Test your program with the command line:

```
./target5 $(python3 sol5.py)
```

For this target, it's acceptable if the program segfaults after the root shell is closed.

target6: Variable stack position

(Difficulty: Medium)

When we constructed the previous targets, we ensured that the stack would be in the same position every time the vulnerable function was called, but this is often not the case in real targets. In fact, a defense called ASLR (address-space layout randomization) makes buffer overflows harder to exploit by changing the position of the stack and other memory areas on each execution. This target resembles target2, but the stack position is randomly offset by 0–255 bytes each time it runs. You need to construct an input that always opens a root shell despite this randomization.

What to submit Create a Python program named `sol6.py` that prints a line to be used as the command-line argument to the target. Test your program with the command line:

```
./target6 $(python3 sol6.py)
```

target7: Heap-based exploitation [Extra credit]

(Difficulty: Hard)

This program implements a doubly linked list on the heap. It takes three command-line arguments. Figure out a way to exploit it to open a root shell. You may need to modify the provided shellcode slightly.

What to submit Create a Python program named `sol7.py` that print lines to be used for each of the command-line arguments to the target. Your program should take a single numeric argument that determines which of the three arguments it outputs. Test your program with the command line:

```
./target7 $(python3 sol7.py 1) $(python3 sol7.py 2) $(python3 sol7.py 3)
```

target8: Return-oriented programming [Extra credit]

(Difficulty: Hard)

This target is identical to target2, but it is compiled with DEP enabled. Implement a ROP-based attack to bypass DEP and open a root shell.

What to submit Create a Python program named `sol8.py` that prints a line to be used as the command-line argument to the target. Test your program with the command line:

```
./target8 $(python3 sol8.py)
```

You may find the `objdump` utility helpful.

For this target, it's acceptable if the program segfaults after the root shell is closed.

target9: Callback shell [Extra credit]

(Difficulty: Hard)

This target uses the same code as `target3`, but you have a different objective. Instead of opening a root shell, implement your own shellcode to implement a *callback shell*. Your shellcode should open a TCP connection to `127.0.0.1` on port `31337`. Commands received over this connection should be executed at a root shell, and the output should be sent back to the remote machine.

What to submit Create a Python program named `sol9.py` that prints a line to be used as the command-line argument to the target. Test your program with the command line:

```
./target9 $(python3 sol9.py)
```

For the remote end of the connection, use netcat:

```
nc -l 31337
```

To receive credit, you must include (as an extended comment in your Python file) a fully annotated disassembly on your shellcode that explains in detail how it works.

Submission Checklist

Submit the assignment through Github Classroom (<https://classroom.github.com/a/tLBfKgX6>). Make sure the following files are in your Github repository:

```
cookie [Generated by setcookie based on your identikays.]
sol0.py
sol1.py
sol2.py
sol3.py
sol4.py
sol5.py
sol6.py
sol7.py [Optional extra credit.]
sol8.py [Optional extra credit.]
sol9.py [Optional extra credit.]
```

Your files can make use of standard Python libraries and the provided `shellcode.py`, but they must be otherwise self-contained. Be sure to test that your solutions work correctly in the provided VM without installing any additional packages.

Like previous assignments, you will be able to see your grade and autograder feedback via the Github Actions tab in your repository.