ASLR Bypasses Lab #4

Learning Objectives

- Understand how address-space layout randomization protects software from memory corruption attacks.
- Learn how software prefetchers pose a security risk by revealing which pages are present in the address space.
- Leverage speculative execution once again to probe the address space to learn which pages are present.
- Understand buffer overflows/ code reuse attacks and implement a return-oriented programming attack from assembly instruction gadgets.
- Combine software and hardware attacks to defeat a victim binary using a return oriented programming attack with ASLR defeated via hardware techniques.

Description In this final security lab, students will put all the pieces together from throughout the course to create a full end to end attack against a vulnerable piece of software. Students will learn about modern memory corruption protections, and use hardware side channels to defeat them. Then, students will build a realistic return-oriented programming (ROP) chain using the information leaked through side channels to defeat a victim process.

Background

Long, long ago, programs used to be loaded at constant addresses. Every time you ran a program, every function was located at the exact same virtual address. This made it quite easy for attackers to jump to known locations in program memory as part of their exploits, as they knew that specific functions would be located at specific addresses every time.

Enter **Address-Space Layout Randomization**, or **ASLR**. This mitigation randomizes the address of the program at runtime so that attackers can't simply know the actual addresses of payloads or gadgets. ASLR makes information leaks, or the ability to leak contents of the victim's memory, a necessity for most memory corruption exploits. We will explore several means of creating information leaks using, you guessed it, microarchitectural side channels.

Luckily for us attackers, ASLR in Linux is applied not at the byte or word level, but at a page granularity. This means that on our `x86_64` machines with 4KB pages, the lower

12 bits of an address will always stay the same (as only the virtual page number changes from run to run).

ASLR is applied as a random constant, let's call it delta, added to every virtual page number in the program's address space. People usually use different delta values for different parts of memory. (So the stack gets its own delta, the heap gets its own delta, and the program code gets its own delta).

This means that distances are preserved under ASLR – Leaking just one pointer to a given structure is typically sufficient to find anything in the structure. For example, if my program binary has two methods- `MethodA` and `MethodB`, knowing the address of `MethodA` tells me where to find `MethodB`. The relative distance between `MethodA` and `MethodB` is unchanged under ASLR. The trick is finding the address of `MethodA` in the first place!

We declare ASLR defeated if we can leak just a single address.

In this lab, we will explore ASLR from a hardware perspective, and investigate techniques that can be used to reveal the address space layout by creating our own microarchitectural infoleaks.

Lab Codebase

This lab is divided into three distinct modules - parts 1, 2, and 3. The code for each is contained within the `part1`, `part2`, and `part3` folders respectively.

In Part 1, you will be modifying the files `part1A.c`, `part1B.c`, and `part1C.c`. You should not modify `main.c`.

In Part 2, you will be modifying `part2A.c` and `part2B.c`. The vulnerable method you will be exploiting is defined in `main.c`. The `win` and `call_me_maybe` methods are also defined in `main.c`. The gadgets to use for your ROP chain are defined in `gadgets.s`. You should not modify `main.c`.

In Part 3, you will be modifying `part3.c`. Just like in Part 2, `call_me_maybe` and `vulnerable` are defined in `main.c`. The gadgets you will be using are in `gadgets.o` (run `make` to get it), and are the same as the gadgets in `part2/gadgets.s`. You should not modify `main.c`.

For all three parts, you will build the lab by running `make`. Each subpart is a binary identified simply by the part letter. For example, Part 2 will contain:

```
a  b  build  gadgets.s  main.c  Makefile  part2A.c  part2B.c
```

`a` and `b` are your built programs. (`a` is your solution for Part 2A and `b` is your solution for Part 2B). You can run them with `./a` or `./b`.

In Part 3, the binary is simply called `part3`, as there is only one subsection for Part 3.

Here's a list of all files we will consider while grading:

```
- part1/part1A.c
- part1/part1B.c
- part1/part1C.c
- part2/part2A.c
- part2/part2B.c
- part3/part3.c
```

You are free to include whatever standard library header files you'd like anywhere in the lab. If you accidentally include something that uses an illegal syscall, you'll see the `seccomp-filter` complain.

Automated Checking

We provide a check script that can tell you whether your code was correct or not. The script is very similar to the autograder we used in the spectre lab #3.

Below are the options available with the check utility:

```
 % ./check.py -h
usage: check.py [-h] part

Check your lab code

positional arguments:
  part        Which part to check? 1a, 1b, 1c, 2a, 2b, or 3?

optional arguments:
  -h, --help  show this help message and exit
```

You can check a specific part by specifying the part to check:

```
 % ./check.py 1a
make: Nothing to be done for 'all'.
Checking part 1A...
100%|████████████████████████████████████████████████████| 1000/1000 [00:03<00:00,
251.72it/s]
You passed 1000 of 1000 runs (100.0%)
Success! Good job

Your score is 20 / 20
You scored 100.0% for this part!
```

You can also check the entire lab by running `./check.py all`. At the end the autograder will tell you your grade. In the above example, we scored 100% for Part 1A.

Jailing

During these exercises, you will be operating inside of a `chroot` and `seccomp-filter` jail. This jail will prevent your code from performing most system calls and file accesses, so you can't simply read `/proc/self/pagemap` to determine where our mystery page is.

Here's the system calls that we allow your code to execute:

Allowed Syscalls in this lab

`write` - Write to an already opened file descriptor.

`access` - See Part 1A.

`close` - Close a file descriptor.

`exit` / `exit_group` - Quit the program.

`fstat` - Needed by `printf`.

If your code tries to access an illegal syscall, you'll see the following message:

```
 % ./part1A
zsh: invalid system call  ./part1A
```

You can use `strace` to trace which system calls your program made.

```
 % strace ./part1A
...
execve(NULL, NULL, NULL)                = ?
+++ killed by SIGSYS +++
zsh: invalid system call  strace ./part1A
```

In this example, the program was terminated for trying to use `execve`.

You should not have to worry about the filter, as it is only there to prevent you from bypassing the lab assignment in a trivial manner, and to increase the immersion of the lab experience.

If you're curious about how the `seccomp` filter works, check out `setup_jail` in `main.c` of Part 1 or 3 (Part 2 doesn't use a jail).

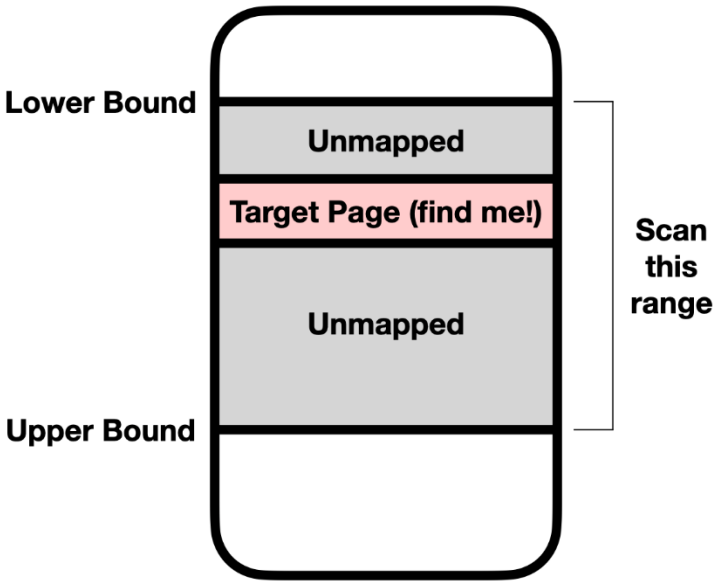
Part 1: Breaking ASLR

In this part we will explore 3 different ways to break ASLR – one simple method operating at the ISA level, and two of them relying on microarchitectural attacks.

In all three parts, you will be tasked with locating a single page of code within a given range. Your code will be given a lower and upper bound to scan. You will scan this range using three different techniques, and return the correct page as the return value of your function.

Before your code runs, we will `mmap` a random page into memory at a random location. We will then pass two bounds to your code to scan for this random page. Everywhere inside of these bounds except for the single page to find will be unmapped (no entry in the page table).

Your code will need to locate the random page.



Your code will operate as follows:

```
// Your code for each exercise in Part 1:
uint64_t find_address(uint64_t low, uint64_t high) {
    for (uint64_t addr = low; addr < high; addr += PAGE_SIZE) {
        // The implementation of is_the_page_mapped will be
        // different for Parts 1A, 1B, and 1C.
        if (is_the_page_mapped(addr)) {
            return addr;
        }
    }
    return NULL;
}
```

For now, all you need to do is locate the page. In later parts, we'll need the location of this page for conducting realistic code reuse attacks in Part 3!

Part 1A: Egghunter (20%)

Egghunters are a technique commonly used in binary exploitation where you have limited code execution and are trying to find a larger payload to execute. For example, you may be able to execute a small (on the order of 64 bytes) amount of code. You have also injected a larger code payload into the program but don't know where it is located. An "egg hunter" is a small chunk of code that is used to find the larger chunk of code.

In this lab, we will be writing an egg hunter in C to scan for a page in memory. We won't be looking for a particular value in memory (as most egg hunters do) – we will just look for the mapped page.

You may be wondering what the mechanism for egg hunting actually is. Typically, it is the kernel itself! To see what we mean by this, check out this exerpt from the `man` page for the `access` system call:

```
ERRORS

       EACCES The requested access would be denied to the file, or
              search permission is denied for one of the directories in
              the path prefix of pathname.  (See also
              path_resolution(7).)

       ...

       EFAULT pathname points outside your accessible address space.

       ...
```

The `access` syscall takes a path name and a mode, and returns whether the file can be accessed by our current process. It has the following declaration:

```
int access(const char *pathname, int mode);
```

We provide `access` a pointer to a string, and it will do something with it (what it does, we don't care). We won't be using `access` for its intended purpose- we will use it as an oracle for determining if an address is mapped into our address space.

Notice how `access` will return `EACCES` if the string points to valid memory (but describes an invalid file), and `EFAULT` if the string we provide doesn't belong to our address space. We can pass every address in the region to scan to `access`, and if `access` returns anything but `EFAULT`, we know the address is mapped!

KEY IDEA

If `access` returns `EFAULT`, our argument to `pathname` was unmapped.

Your code will need to run in **1 second or less** and should produce the correct answer 100% of the time. (If it ever gets the answer wrong, you will receive a 0 for this part).

EXERCISE #1.1

Implement an egg hunter using the `access` system call.

DISCUSSION QUESTION #1.2

Identify one other syscall that could be used for egg hunting.
Any syscall that returns `EFAULT` is likely to be useful for egg hunting.

Sadly, while this approach works great for userspace, it won't work on kernel addresses. For that, we need to move to the microarchitectural level. (Parts 1B and 1C are done in userspace, but the techniques have been shown to work on the kernel as well).

Part 1B: The `prefetch` Instruction (40%)

In this part, we will be implementing the Prefetch attack from *Prefetch Side-Channel Attacks* paper available on moodle.

The `prefetch` instruction provides a hint to the prefetcher to load a particular line into the cache. This instruction performs absolutely 0 access control checks. We will use the `prefetch` instruction to try and load every address into the cache. In particular, we will use the "Translation-Level Oracle" technique (described in their Section 3.2) to locate our hidden page.

The `prefetch` instruction will try to translate the given virtual address into a physical address and load it into the cache hierarchy. If the address is unmapped, it will require a full page table walk (which takes many cycles!). If the page is already present in the cache hierarchy, `prefetch` will stop early.

To be more precise, when we use `prefetch` on an address, if the corresponding page is unmapped, the page table entry will not appear in any micro architectural structures. So the processor ends up doing the following operations:

1. TLB lookup (miss)
2. Page cache lookup (miss)
3. Page table walk (traverse the page table tree)
4. Find the entry is invalid
5. Done

If the page is mapped and if it has been accessed before, the corresponding page table entry could exist in one or multiple of these structures and `prefetch` will stop much earlier.

By timing how long `prefetch` takes to run, we can determine whether the given address was present or not. If `prefetch` is slow, that means a full page table walk occurred, and therefore the address was not mapped. If it is fast, that means the address is likely to have already existed in the cache hierarchy, and so is very likely to be our address.

KEY IDEA
Prefetching a mapped address is faster than prefetching unmapped ones.

Timing the `prefetch` instruction is a little tricky due to CPU synchronization. We recommend you follow the instruction sequence approach used by the paper authors:

```
mfence
rdtscp
cpuid
prefetch
cpuid
rdtscp
mfence
```

While doing this exercise, you may find referring to the source code for the prefetch paper helpful. You can refer to this repo or past lab assignments for how to write inline assembly. Additionally, the GNU manual on inline assembly is quite handy.

For causing a `prefetch` instruction, you can either try the builtin `_mm_prefetch(address, _MM_HINT_T2)` function, or you can use the following wrapper (taken from the IAIK repo above):

```
void prefetch(void* p)
{
  asm volatile ("prefetchnta (%0)" : : "r" (p));
  asm volatile ("prefetcht2 (%0)" : : "r" (p));
}
```

Your code will need to run in **5 seconds or less** and should produce the correct result 90% of the time or better.

EXERCISE #1.3
Use the `prefetch` instruction to find the hidden page.

DISCUSSION QUESTION #1.4
Imagine you are the Intel engineer tasked with fixing this problem. How would you approach fixing it?

Bonus - Part 1C: Speculative Probing

This part is quite difficult, we suggest finishing the other parts before choosing to do this one!

Having access to the `prefetch` instruction makes things too easy. Additionally, not all architectures have such a convenient instruction for performing attacks. **Speculative Probing** (paper available on moodle) is a more general technique that has been shown to work on many architectures. We will be implementing a modified version of the Code Region Probing attack described in Section 5.1 of the Speculative Probing paper.

To conduct a speculative probing attack, you will write and exploit your *own* spectre gadget! Here's an overview of how it works.

First, you will write your own Spectre gadget (similar to the one you attacked in the spectre lab #3). Below is pseudocode you can use as a guide for your speculative probing gadget. Write this as a C function in `part1C.c`.

```
def speculative_probing_gadget(condition, guess, controlled_memory):
    if condition:
        # Access 1: Derefence the "guess" address (if it is mapped).
        idx = load(guess)

        # If guess was not mapped, we will crash here.
        # Hopefully all crashes happen under speculation so the program doesn't crash!

        # Access 2: Modify some controlled memory at an index dependent on the first load.
        # This only happens if the first load didn't crash, since the index is
        # a function of the contents of the first load.
        controlled_memory[idx] += 1
```

You'll notice that this gadget operates on a subtly different mechanism than the Spetre gadgets from the spectre lab. In the spectre lab, the goal was to learn the *contents* of the "guess" address (reveal the contents of the first load). Here, we don't actually care about the value of the first load. Instead, we only want to determine whether or not the load was *successful*.

There are two cases for our guess address: either our current guess is correct, or it isn't. If we have the right address, we can read freely from it without any issues. However, if it isn't mapped, reading from it will cause a page fault exception (that we will observe as a segfault). Just one segfault will crash the whole program.

So instead, let's have the crashes run under speculation, and use a side channel to learn whether or not a crash happened.

KEY IDEA

We suppress exceptions by causing them to happen *speculatively*, and then afterwords learn whether or not a crash happened using microarchitectural side channels.

After creating the gadget, you will need to control it. You can use the following as a high-level overview of a potential attack:

1. Allocate a chunk of memory to use.
2. Train the branch predictor for your `speculative_probing_gadget`.
3. Try an address with `speculative_probing_gadget`.
4. Learn whether or not a load occurred with `time_access` to your controlled memory.

There are a few engineering problems to solve here. Notably, the contents of the probed memory could be anything! How do you know what `idx`'s value was? Is there a way to make our attack access `controlled_memory` the same way regardless of what `idx` was?

EXERCISE #1.5
Use speculative probing to leak the address of the hidden page.

We will run your code 10 times and it should work at least once. We will kill each job after 2 minutes.

- You completely control the Spectre code, so you can write it any way you like.
- You may find revisiting the lab #3 or your lab #3 code helpful.
- Make sure that both memory accesses happen speculatively so that you don't crash the program!
- Don't forget you can `clflush` any address you'd like.

Part 1 Checklist

Before you move on to Part 2, make sure that you've:

- Completed the code for Exercises 1-1 and 1-3 (and 1-5 if you're taking the bonus).
- Checked your code with the check script and made sure it passes.
- Answered Discussion Questions 1-2 and 1-4.

Part 2: Code Reuse Attacks

In this part, we will explore what the consequences are for breaking ASLR. We will also get some practice constructing realistic code reuse attacks that attackers might use in the real world against vulnerable programs.

We will be exploiting a category of bugs known as **buffer overflows**. In a buffer overflow, the program reads more information than can fit into a particular buffer, overwriting memory past the end of the buffer.

Buffer Overflows

The most basic form of a buffer overflow is the **stack buffer overflow**.

```
/*
 * vulnerable
 * This method is vulnerable to a buffer overflow
 */
void vulnerable(char *your_string) {
    // Allocate 16 bytes on the stack
    char stackbuf[0x10];

    // Copy the attacker-controlled input into 'stackbuf'
    strcpy(stackbuf, your_string);
}
```

If `your_string` is larger than 16 bytes, then whatever is on the stack below `stackbuf` will be overwritten.

So, what's on the stack?

When a function is called, the return address is pushed to the stack. The return address is the next line of code that will be executed. Let's take a look at a hypothetical piece of assembly:

```
0x100: call vulnerable
0x101: nop
```

Immediately after `call vulnerable`, the next instruction to execute (in this case, `0x101`) will be pushed to the stack. When `vulnerable` is done, it will execute `ret`, which will pop the return address off the stack and jump to it.

Let's look at the disassembly of `vulnerable` to find out more:

```
vulnerable:
    # rdi contains 'your_string'
    # First, setup the stack frame for vulnerable
1   push   rbp
2   mov    rbp,rsp

    # Create some space for stackbuf on the stack
3   sub    rsp,0x10

    # Put 'your_string' into rsi (argument 2)
```

```
4   mov    rsi,rdi

    # Put 'stackbuf' into rdi (argument 1)
5   lea    rax,[rbp-0x10]
6   mov    rdi,rax

    # Call strcpy(stackbuf, your_string)
7   call   strcpy

    # Teardown our stack frame
8   mov rsp, rbp
9   pop rbp

    # Return from vulnerable (this is basically pop rip)
10  ret
```

Immediately upon entry to `vulnerable` (right before line 1), the stack will look like this:

```
Towards 0x0000000000000000

   Stack Growth
       /|\
        |
        |
+---------------+
|     0x101     | <- Return address!
+---------------+

Towards 0xFFFFFFFFFFFFFFFF
```

Next, the `rbp` register is pushed, and some more space is made for `stackbuf`. So, after line 3, the stack will look like this:

```
Towards 0x0000000000000000

   Stack Growth
       /|\
        |
        |
+---------------+
|     ?????     | <- Space for stackbuf
+---------------+
|    Old RBP    | <- Saved RBP
+---------------+
|     0x101     | <- Return address!
+---------------+

Towards 0xFFFFFFFFFFFFFFFF
```

Note that `stackbuf` sits *above* the return address on the stack. If we put more information into `your_string` than can fit into `stackbuf`, we will continue writing *down* the stack, and overwrite the return address!

That means we can change what happens when `vulnerable` concludes executing, effectively redirecting control flow in a way we desire!

Of course, in order to actually do this, we will need to know where the code we want to run is located. This is where ASLR bypasses come in handy. By breaking the

address randomization of a program, we can reveal where program instructions are located, and jump to them by overwriting return addresses (or any function pointers in a program).

You can read Stack Smashing in the 21st Century for more background on buffer overflows or revisit lecture #13 from Mamat (044101) course.

Part 2A: `ret2win` (10%)

In this activity we will perform a `ret2win` attack. In a `ret2win` attack, the attacker replaces the return address with the address of a `win` method that, when called, does everything the attacker wants. The attacker does not need to control any arguments passed to `win` – we only care that `win` gets executed.

The vulnerable method for this lab operates as follows:

```
void vulnerable(char *your_string) {
    // Allocate 16 bytes on the stack
    char stackbuf[16];

    // Copy the user input to the stack:
    strcpy(stackbuf, your_string);
}
```

Feel free to read the source code of `vulnerable` for a bit more info on how the stack works.

For now, you can get the `win` address manually (without needing to use your ASLR bypass techniques developped in Part 1) as follows:

```
// Cast win to a function pointer and then to a 64 bit int
uint64_t win_address = (uint64_t)&win;
```

After we run your code, we will print the resulting stack frame to the console so you can see how your attack worked. In this example, I've set `your_string` to 16 A's (`'A'` `== 0x41`) followed by a new line (`'\n'`). So we see 16 `0x41`'s repeated on the stack. The newline does not appear as our version of `strcpy` doesn't copy the ending new line byte.

```
This is what the stack looks like now:
      +-----------------------------------------+
0x00: | 0x00007FFE055628B0 = 0x4141414141414141 | <- stackbuf starts here
      +-----------------------------------------+
0x01: | 0x00007FFE055628B8 = 0x4141414141414141 |
      +-----------------------------------------+
0x02: | 0x00007FFE055628C0 = 0x00007FFE05562CE0 | <- Saved RBP
      +-----------------------------------------+
0x03: | 0x00007FFE055628C8 = 0x000055FEF9B4E91A | <- Return address!
      +-----------------------------------------+
```

We provide you some sample code to fill in the string you pass to `vulnerable`. For your convenience, we treat your "string" as an array of 64-bit integers. This way you can directly write to a specific slot on the stack by indexing the provided array. For example, to set the saved RBP position (index 2), you can use `your_string[2] = 0x0123456789abcdef`.

Note on strcpy: To allow `NULL` characters into your buffer, we use a different definiton of `strcpy` than the libc one. Our `strcpy` allows `NULL` characters, but stops at newlines (`0x0A`, or `'\n'`). This is to mirror the behavior of `gets`, which is commonly used in CTF stack overflow problems.

Note on rbp: The base pointer rbp is reset upon entry to a C function (see line 2 of the `vulnerable` disassembly above). So you can set it to whatever you like during your overflow and it won't make a difference (you will need to overwrite rbp to change the return address).

EXERCISE #2.1
Overwrite the return address in `vulnerable` with the address of `win`.

It's ok if your code segfaults on occasion for Part 2A (it doesn't have to work every time, so long as it works most of the time). This is because sometimes ASLR gives an address that has a new line in it, which means your overflow will stop early.

Part 2B: Return Oriented Programming (ROP) (20%)

In this part, we will perform a return oriented programming attack, or ROP. ROP is a technique devised to counteract data execution prevention (otherwise known as W^X), which is a security feature introduced to protect against simply writing your own code into the stack and jumping to it. DEP and ASLR are the foundation of all modern exploit mitigations. Just like how ASLR can be sidestepped with an information leak, DEP can be defeated by ROP.

The idea behind ROP is to construct a sequence of code by combining tiny "gadgets" together into a larger chain. ROP looks a lot like `ret2win`, except we add more things to the stack than just overwriting a single return address. Instead, we construct a chain of return addresses that are executed one after the other.

Let's take a look at two example ROP gadgets:

```
gadget_1:
    pop rdi
    ret

gadget_2:
    pop rsi
    ret
```

The above sequences of code will pop the top value off the stack into `rdi` or `rsi`, and then return to the next address.

We can combine them as follows to gain control of `rdi` and `rsi` by writing the following to the stack:

```
+---------------+
|  OVERWRITTEN  | <- Space for stackbuf
+---------------+
|  OVERWRITTEN  | <- Saved RBP
+---------------+
|    gadget_1   | <- Return address
+---------------+
| New rdi Value |
+---------------+
|    gadget_2   |
+---------------+
| New rsi Value |
+---------------+
| Next gadget...|
+---------------+
```

We can encode desired values for `rdi` and `rsi` onto the stack alongside our return addresses. Then, by carefully controlling where code execution goes, we can make the gadgets perform arbitrary computation.

In fact, it has been shown that ROP is Turing Complete for sufficiently large programs.

KEY IDEA
We can chain code sequences together by continuing to overflow the stack.

For this problem, you will need to combine ROP gadgets to cause `call_me_maybe` to return the flag. You will use the same buffer overflow as we used in Part 2A, and you can get the address of a given gadget the same way we got the address of the `win` function.

The gadgets are defined in `gadgets.s`. `call_me_maybe` is defined below:

```c
void call_me_maybe(uint64_t rdi, uint64_t rsi, uint64_t rdx) {
    if ((rdi & 0x02) != 0) {
        if (rsi == 2 * rdi) {
            if (rdx == 1337) {
                printf("MIT{flag_goes_here}\n");
                exit(0);
            }
        }
    }
    printf("Incorrect arguments!\n");
    printf("You did call_me_maybe(0x%lX, 0x%lX, 0x%lX);\n", rdi, rsi, rdx);
    exit(-1);
}
```

EXERCISE #2.2

Construct a ROP chain to call `call_me_maybe` with satisfactory arguments.

It's ok if your code segfaults on occasion for Part 2B (it doesn't have to work every time, so long as it works most of the time). This is because sometimes ASLR gives an address that has a new line in it, which means your overflow will stop early.

Part 2 Checklist

Before you move on to Part 3, make sure that you've:

- Completed the code for Exercises 2-1 and 2-2.
- Checked your code with the check script and made sure it passes.

Debugging - Reminder

If you are experiencing crashes and don't know why, you can use GDB to help figure out where your exploit is going wrong. Refresh your memory looking at gdb workshop of Mamat (044101) course.

Here's an example of running GDB on a non-working Part 2B (`./b`):

```
 % gdb ./b
...
Reading symbols from b...done.
(gdb) run
...
Program received signal SIGSEGV, Segmentation fault.
0xffffffffffffffff in ?? ()
(gdb)
```

You can inspect the state of your registers at the crash by running `info registers`:

```
(gdb) info registers
rax            0x4141414141 280267669825
rbx            0x0  0
rcx            0x0  0
...
rip            0xffffffffffffffff       0xffffffffffffffff
```

`rip` will contain the address your code tried to execute (in this case, `0xffffffffffffffff`), and the rest of the registers will show what your ROP chain managed to store into them before crashing. Additionally, `call_me_maybe` will report the arguments you called it with if you got them wrong. The listing above shows the register values both in hex and "decoded" (interpreted as whatever GDB thinks the value is). This sometimes will still be hex, decimal, or it could be a string.

Below is a "cheat-sheet" of the important commands to know in gdb.

GDB Cheat Sheet

`si` - Step over a single instruction.

`bt` - Show a stack backtrace (during buffer overflows this will get corrupted as we change the stack).

`b` - Set a breakpoint at a location (an example of this will be given later).

`c` - Continue until you hit a breakpoint.

`disas` - Disassemble a specific function.

`x` - Examine memory (an example of this will be given later).

Here's an example GDB workflow that might be useful for debugging your attack code.

```
(gdb) set disassembly-flavor intel
(gdb) b main.c:235
Breakpoint 2 at 0xa09: file main.c, line 235.
(gdb) run
...
Breakpoint 2, vulnerable (your_string=0x7fffffffdfb0 "\277") at main.c:235
235 }
(gdb)
```

First, I set the disassembly flavor to `intel` syntax (which is easier to read). Then, I set a breakpoint in `main.c` on line `235`, which is the last line of `vulnerable` (it is the line with the closing `}` on it- this number may be different for your `main.c`). Then, I run the program and stop on the breakpoint.

```
(gdb) x/3i $rip
=> 0x555555554a09 <vulnerable+337>: nop
   0x555555554a0a <vulnerable+338>: leave
   0x555555554a0b <vulnerable+339>: ret
```

I use the examine memory command as `x/3i`. This means print the next 3 instructions from a given address. I use the register `rip` (specified with a `$` before it) as the location to print from. This tells us what instructions the program will run next. The `=>` arrow points to the very next instruction to execute.

```
(gdb) si
(gdb) x/2i $rip
=> 0x555555554a0a <vulnerable+338>: leave
   0x555555554a0b <vulnerable+339>: ret
```

Using the `si` command I can step into the program, and when I print the next few instructions you'll see that we have moved forward by one. We can define a hook to print this automatically for us with the following:

```
(gdb) define hook-stop
Type commands for definition of "hook-stop".
End with a line saying just "end".
>x/3i $rip
>end
(gdb)
```

Now every time we step, we will automatically see the next few instructions. Let's keep stepping until we hit the `ret`.

```
(gdb) si
=> 0x555555554a0b <vulnerable+339>: ret
...
(gdb) si
=> 0x555555554ae5 <gadget1>:    pop    rax
   0x555555554ae6 <gadget1+1>:  ret
   ...
0x0000555555554ae5 in gadget1 ()
(gdb)
```

You can see that we landed on `gadget1`, which was the first gadget in my ROP sequence! Let's step one more time and see what gets loaded into `rax`.

```
(gdb) si
=> 0x555555554ade <gadget1+1>:  ret
   ...
(gdb) p/x $rax
$1 = 0x4141414141
```

I can print the value of `rax` using `p/x $rax` (or `info registers` if I want to see all the registers). Here we can see that `rax` was loaded with 0x41414141 (the string "AAAA"). Let's step one more time and see what happens next.

```
(gdb) si
=> 0xffffffffffffffff:  Error while running hook_stop:
Cannot access memory at address 0xffffffffffffffff
0xffffffffffffffff in ?? ()
```

Looks like this is where the crash comes from! So, from using GDB, I was able to determine that my load of `rax` with `gadget1` is successful, but the gadget after that is not correctly filled in.

You can quit `gdb` with `quit` (or just `q`).

You can learn more about GDB here.

Part 3: Putting it All Together (10%)

We are now going to combine the ASLR bypasses in Part 1 with the ROP chain you wrote in Part 2.

The random page from Part 1 will contain the same sequence of ROP gadgets that you had access to in Part 2B. Additionally, it will be marked executable so that it can be executed if you jump to it.

Dumping the gadgets

The hidden page from Part 1 will be filled with the code from the `gadgets.o` file (which is included in the part3 folder). Dump the contents of `gadgets.o` with the following:

```
objdump -d gadgets.o -M intel
```

Objdump will report something like the following:

```
Disassembly of section .text:

0000000000000000 <gadget1>:
   0:   5f                      pop    rdi
   1:   c3                      ret
        ...

0000000000000010 <gadget2>:
  10:   5e                      pop    rsi
  11:   c3                      ret
```

The line `0000000000000000 <gadget1>:` tells you the offset of `gadget1`. In this case, `gadget1` will be located at `hidden_page[0x0000]` and `gadget2` will be at `hidden_page[0x0010]` (where `hidden_page` is a `uint8_t *` that points to the page your Part 1 code found).

As ASLR slides everything together by applying a constant offset, `gadget2` will always be `0x10` bytes after `gadget1`, no matter where ASLR places them.

KEY IDEA

Relative distances between instructions are preserved under ASLR.

Performing the Attack

For Part 3, you will need to reconstruct your ROP chain using the gadgets dumped from `objdump`. Then, you will combine your code from Part 1 with the reconstructed Part 2 chain to complete a full ROP attack in the hidden page.

Your attack will do the following:

1. Locate the hidden `mmap` page with your choice of technique from Part 1.

2. Construct a ROP chain using the gadgets in the hidden page (with offsets calculated from `objdump`).
3. Call `vulnerable` with your payload configured.

EXERCISE #3.1

Combine your Part 1 and Part 2 attacks to defeat Part 3.

On success, you should see the success flag printed to the console.

A note on realism

You may be wondering why we bother with jumping to a sequence of ROP gadgets if we already have control of C code. This is to simulate attacking a real program without the ability to run code within the victim context (for example, attacking the kernel from userspace, or attacking a remote server over a `netcat` connection).

Part 3 Checklist

Before you submit this lab, make sure that you've:

- Completed the code for Exercise 3-1.
- Checked your code with the check script and made sure it passes.