# 15-213/15-513/14-513 Recitation: Attack Lab

Your TAs

Friday, Sep 22nd, 2023

# Agenda

- Attack Lab Overview
- Stacks Review
- Activity 1
- Procedure Calling Review
- Activity 2

# Quick Reminders

- Attack Lab is due next Thursday
  - You can use one grace day
- Written 3 is due next Wednesday
- Written 2 peer reviews are due next Wednesday

# Learning objectives

By the end of this recitation, we want you to know:

- Stack discipline and calling conventions
- How to perform a simple buffer overflow attack

Refer to Lecture from Tuesday:
*Machine-Level Programming V: Advanced Topics*

# Structure Alignment Review

# Primitive Types

- char = 1 byte
- short = 2 bytes
- int = 4 bytes
- long = 8 bytes
- double = 8 bytes
- pointer = 8 bytes

*(on Linux under x86_64, machine dependent)

# Alignment Principles

- A structure has the alignment of its largest field/element.
- The initial address and size of the struct must be a multiple of it’s alignment.

# What’s the Size?

```
struct x {
    int a;
    char *b;
    char c[4];
    struct {
        short d;
        double e;
    } y;
};
```

- What is struct y’s alignment?
- What is the size of y in bytes? i.e what would sizeof(y) return?
- What is struct x’s alignment?
- What is the size of struct x in bytes?
- How could we arrange elements in the struct to save space?

# Lab Overview

# Attack Lab overview

- Attack programs by crafting buffer overflow attacks that hijack the control flow
- Provide inputs to the `rtarget` and `ctarget` programs that cause them to call certain functions
- Unlike in bomblab, the targets don't explode!

# Stacks Review

# Manipulating the stack

What instructions do we typically use to change the stack pointer, %rsp?

**Growing the stack:**

**Shrinking the stack:**

# Manipulating the stack

What instructions do we typically use to change the stack pointer, %rsp?

**Growing the stack:**

- `sub $0x28, %rsp`
- `push %rbx`
- `callq my_function`

**Shrinking the stack:**

# Manipulating the stack

What instructions do we typically use to change the stack pointer, %rsp?

**Growing the stack:**

- `sub $0x28, %rsp`
- `push %rbx`
- `callq my_function`

**Shrinking the stack:**

- `add $0x28, %rsp`
- `pop %rbx`
- `retq`

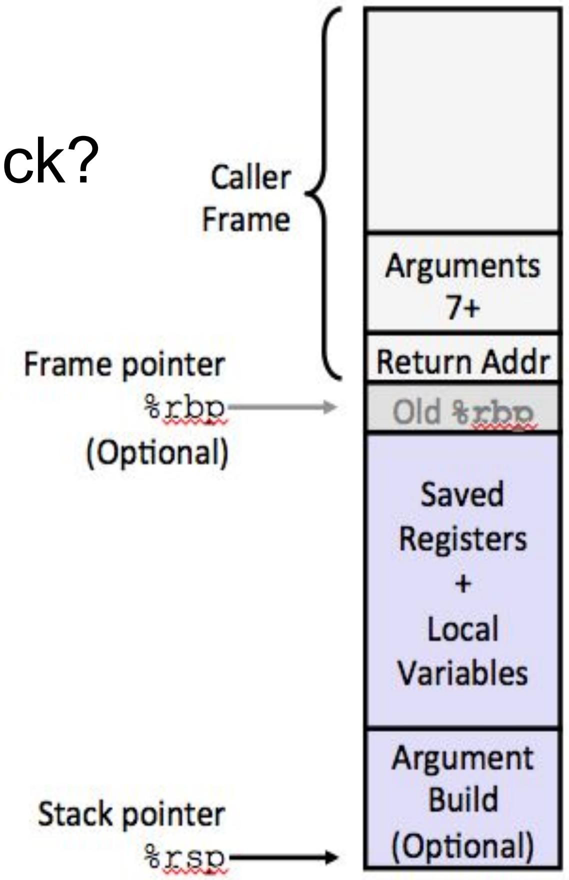
# x86-64 Stack Frames

What kinds of data are stored on the stack?

# x86-64 Stack Frames

What kinds of data are stored on the stack?

- Saved registers
- Local variables
- Arguments (7+)
- Saved return address



# Which way does the stack grow?

- Up?
- Down?
- Left?
- Right?

# Which way does the stack grow?

- Up?
- Down?
- Left?
- Right?

It depends on how you draw it!

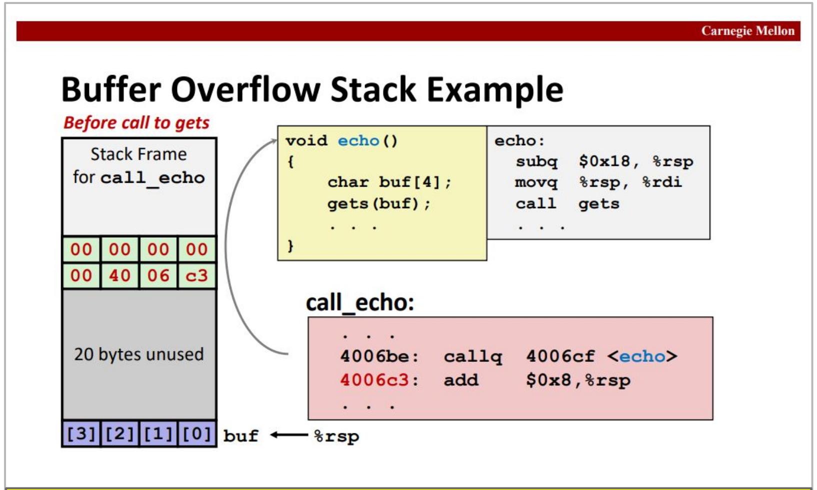
The stack always grows towards **lower addresses** in x86-64.

(Informally, this usually means "down".)

Be aware of this possible ambiguity when reading diagrams.

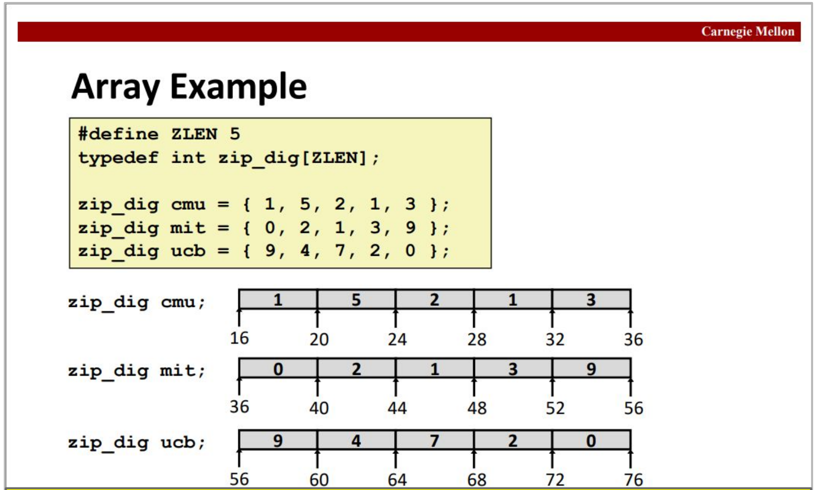
# Drawing memory

## Stack diagrams




Addresses are displayed increasing to the **left**, and then **upwards**.

## Everything else




Addresses are displayed increasing to the **right**, and then **downwards**.

# Endianness

- Describes how integers are represented as bytes.
- Little-endian means that the least-significant 8 bits of an integer are stored at the lowest address.

32-bit integer

`0x01020304`

"Big end" "Little end"

| | A[0] | A[1] | A[2] | A[3] |
|---|---|---|---|---|
| Little-endian | | | | |
| Big-endian | | | | |

# Endianness

- Describes how integers are represented as bytes.
- Little-endian means that the least-significant 8 bits of an integer are stored at the lowest address.

32-bit integer

0x01020304

"Big end" "Little end"

| | A[0] | A[1] | A[2] | A[3] |
|---|---|---|---|---|
| Little-endian | 0x04 | 0x03 | 0x02 | 0x01 |
| Big-endian | 0x01 | 0x02 | 0x03 | 0x04 |

# But wait - types are a lie

- Bytes in memory are just bytes: typing is just a way for the compiler to specify how they should be treated.
- E.g. use x/ 8i (addr) vs x/ 8gx (addr). They’re different!

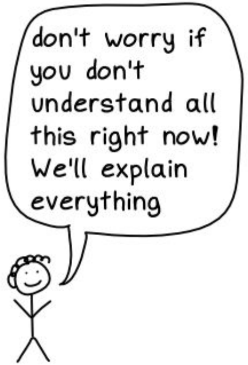
Julia Evans
@b0rk

# 8 bytes, many meanings

The same bytes can mean many different things. Here are 8 bytes and a bunch of things they could potentially mean:

0x.....0 … 0x....7

| 8 bytes → | 63 | 6f | 6d | 70 | 75 | 74 | 65 | 72 | |
|---|---|---|---|---|---|---|---|---|---|
| | c | o | m | p | u | t | e | r | 8 ASCII characters |
| | 99 | 111 | 109 | 112 | 117 | 116 | 101 | 114 | 8 8-bit integers |
| | 28515 | | 28781 | | 29813 | | 29285 | | 4 unsigned 16-bit integers |
| | 1886220131 | | | | 1919251573 | | | | 2 unsigned 32-bit integers |
| | 8243122740717776739 | | | | | | | | 1 unsigned 64-bit integer |
| | 0x72657475706d6f63 | | | | | | | | a 64-bit pointer |
| | 99.111.109.112 | | | | 117.116.101.114 | | | | 2 IPv4 addresses |
| | arpl WORD PTR [edi+0x6d],bp | | | jo 0x7a | | je 0x6c | | .byte 0x72 | x86 machine code |
| | c | o | m | p | u | t | 29285 | | 6 ASCII characters + 1 16-bit integer |
| | 2.93930e+29 | | | | 4.54482e+30 | | | | 2 32-bit floating point numbers |
| | 1.144493e+243 | | | | | | | | 1 64-bit floating point numbers |
| | rgba(99, 111, 109, 0.44) | | | | rgba(117, 116, 101, 0.45) | | | | 2 RGBA colours |




https://social.jvns.ca/@b0rk/109825092938649658

# Activity 1

# Part 1: Introduction to solve()

Let's look at `solve()` in the `src/activity.c` file.

What is it doing?

Is it possible for the program to call `win()`?

```
void solve(void) {
    long before = 0xb4;
    char buf[16];
    long after = 0xaf;

    Gets(buf);

    if (before == 0x3331323531)
        win(0x15213);

    if (after == 0x3331323831)
        win(0x18213);
}
```

# Part 1: The gets() function

```
char *gets(char *s);
```

- `gets()` reads from standard input and writes characters into `s` until it reaches a newline.
- Since it has no information about the **size** of the buffer `s`, its design is fundamentally flawed. **Never use `gets()` yourself!**
- `Gets()` is a CS:APP wrapper function that checks for errors, and exits if it encounters any.

# Part 1: Activity setup

- Split up into groups of 2-3 people
- One person needs a laptop
- Log in to a Shark machine, and type:

```
$ wget https://www.cs.cmu.edu/~213/activities/rec5.tar
$ tar xvf rec5.tar
$ cd rec5
```

- Take a look at the code in `src/activity.c`.

# Part 1: Diving into assembly

- Look at the disassembly of `solve()`.
- Try drawing a stack diagram.
  - How large is the stack frame?
  - Where is the saved return address?
  - Where are `before`, `buf`, and `after`?
- **Which variable will be overwritten if we perform a buffer overflow, `before` or `after`?**

# Part 1: Drawing the stack diagram

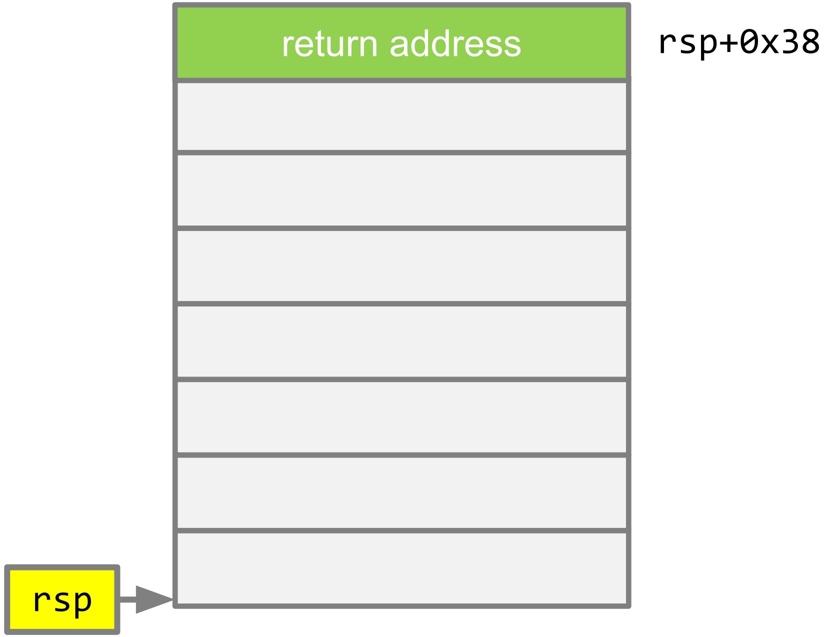
```
=> 0x4006b5 <+0>:     sub    $0x38,%rsp
```


Addresses
increase towards
the top of the slide

# Part 1: Drawing the stack diagram

```
   0x4006b5 <+0>:     sub    $0x38,%rsp
=> 0x4006b9 <+4>:     movq   $0xb4,0x28(%rsp)
```

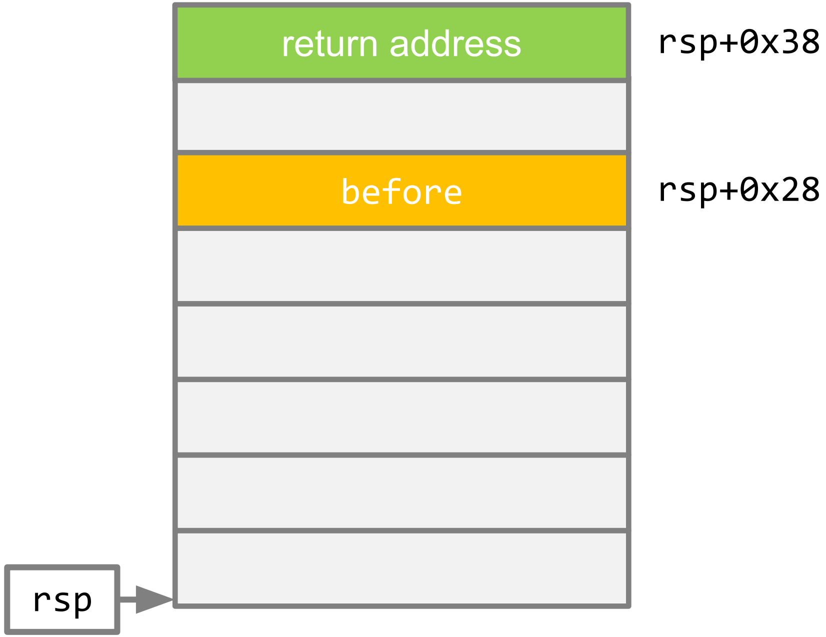
Addresses increase towards the top of the slide



# Part 1: Drawing the stack diagram

```
   0x4006b5 <+0>:     sub    $0x38,%rsp
   0x4006b9 <+4>:     movq   $0xb4,0x28(%rsp)
=> 0x4006c2 <+13>:    movq   $0xaf,0x8(%rsp)
```

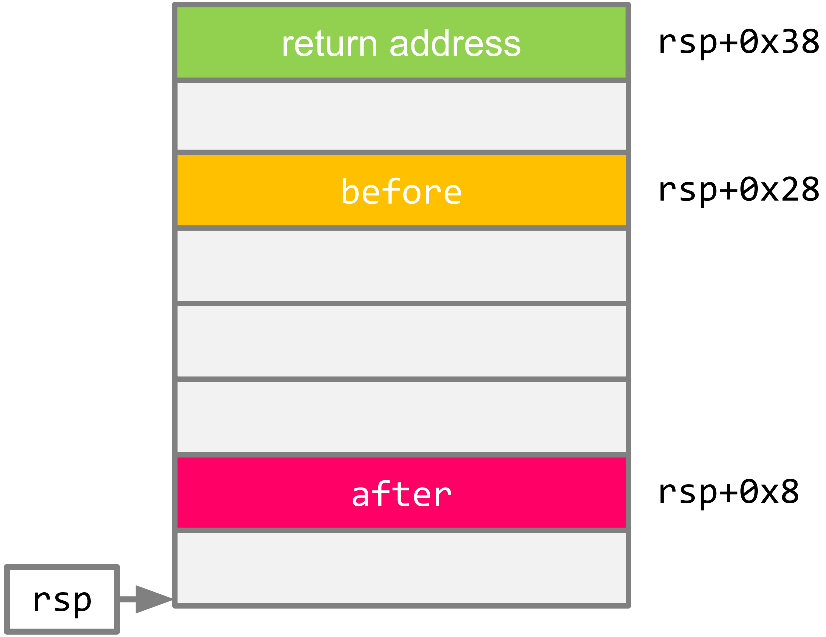
Addresses increase towards the top of the slide



# Part 1: Drawing the stack diagram

```
   0x4006b5 <+0>:     sub    $0x38,%rsp
   0x4006b9 <+4>:     movq   $0xb4,0x28(%rsp)
   0x4006c2 <+13>:    movq   $0xaf,0x8(%rsp)
   0x4006cb <+22>:    lea    0x10(%rsp),%rdi
=> 0x4006d0 <+27>:    callq  0x40073f <Gets>
```

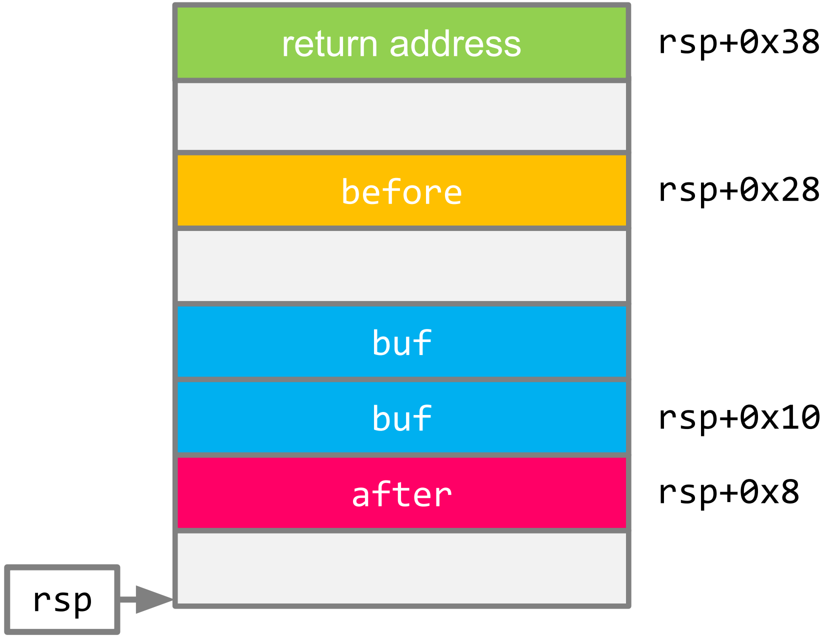
Addresses
increase towards
the top of the slide



# Part 1: Drawing the stack diagram

```
   0x4006b5 <+0>:     sub    $0x38,%rsp
   0x4006b9 <+4>:     movq   $0xb4,0x28(%rsp)
   0x4006c2 <+13>:    movq   $0xaf,0x8(%rsp)
   0x4006cb <+22>:    lea    0x10(%rsp),%rdi
   0x4006d0 <+27>:    callq  0x40073f <Gets>
=> 0x4006d5 <+32>:    mov    0x28(%rsp),%rdx
```

Addresses increase towards the top of the slide

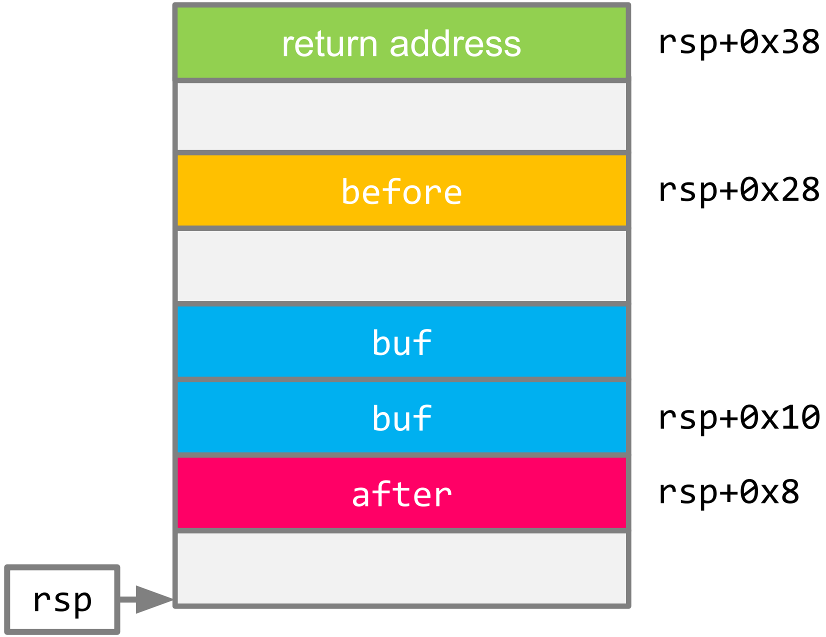


# Part 1: Comparing with GDB output

Let's compare the stack diagram we drew with the actual values on the stack after `Gets()` returns.

```
   0x4006d0 <+27>:    callq  0x40073f <Gets>
=> 0x4006d5 <+32>:    mov    0x28(%rsp),%rdx
```

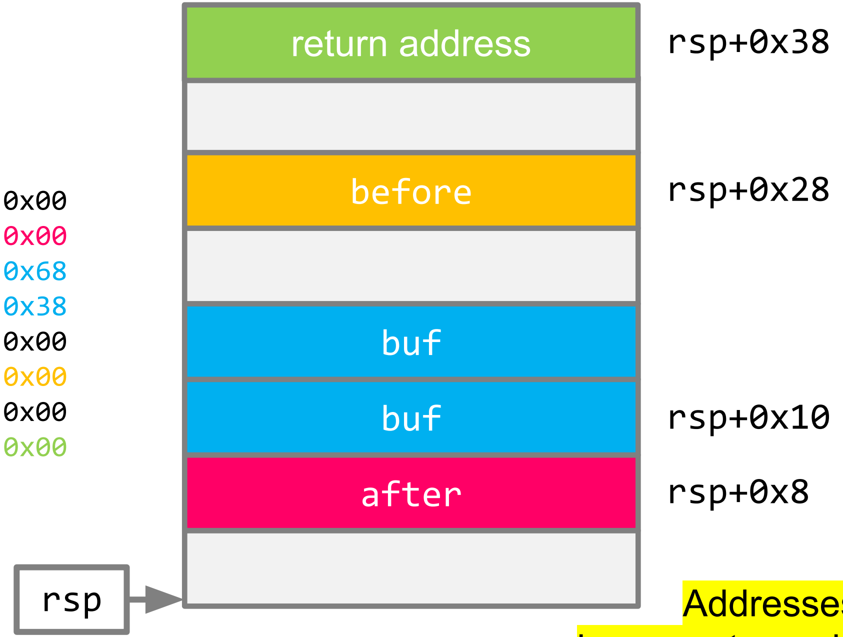
```
(gdb) break *0x4006d5
(gdb) run
Starting program: act1
abcdefgh12345678
(gdb) x/8gx $rsp
(gdb) x/64bx $rsp
```



# Part 1: Comparing with GDB output

```
(gdb) x/8gx $rsp
0x602020:    0x0000000000000000    0x00000000000000af
0x602030:    0x6867666564636261    0x3837363534333231
0x602040:    0x0000000000000000    0x00000000000000b4
0x602050:    0x0000000000000000    0x0000000000400783

(gdb) x/64bx $rsp
0x602020:  0x00  0x00  0x00  0x00  0x00  0x00  0x00  0x00
0x602028:  0xaf  0x00  0x00  0x00  0x00  0x00  0x00  0x00
0x602030:  0x61  0x62  0x63  0x64  0x65  0x66  0x67  0x68
0x602038:  0x31  0x32  0x33  0x34  0x35  0x36  0x37  0x38
0x602040:  0x00  0x00  0x00  0x00  0x00  0x00  0x00  0x00
0x602048:  0xb4  0x00  0x00  0x00  0x00  0x00  0x00  0x00
0x602050:  0x00  0x00  0x00  0x00  0x00  0x00  0x00  0x00
0x602058:  0x83  0x07  0x40  0x00  0x00  0x00  0x00  0x00
```




Addresses
increase towards
**bottom of the slide**

Addresses
increase towards
**top of the slide**

# Part 1: Exploitation

- Try to find an input string that wins 1 cookie!
  - What do we need to overwrite `before` with if we want to have `before == 0x3331323531`?
- Constructing an exploit
  - `gets()` stops reading once it sees a newline. In the buffer, it replaces the newline with a null terminator.
  - gets() does **not** stop reading at a null terminator.

# Part 1: Recap

- Buffer overflows can **overwrite** parts of the stack frame, including other local variables
- Stack frames may include **padding**, so looking at the assembly is crucial to drawing a correct diagram
- GDB prints output starting at the **lowest** address, whereas our stack diagrams start at the **highest**

# Procedure Calling Review

# Call and return instructions

Which registers do callq and retq change?

| |
|---|
| %rax |
| %rdi |
| %rsi |
| %rdx |
| %rcx |
| %r8 |
| %r9 |
| %r10 |
| %r11 |

| |
|---|
| %rbx |
| %r12 |
| %r13 |
| %r14 |
| %rbp |
| %rsp |
| %rip |

# Call and return instructions

Which registers do callq and retq change?

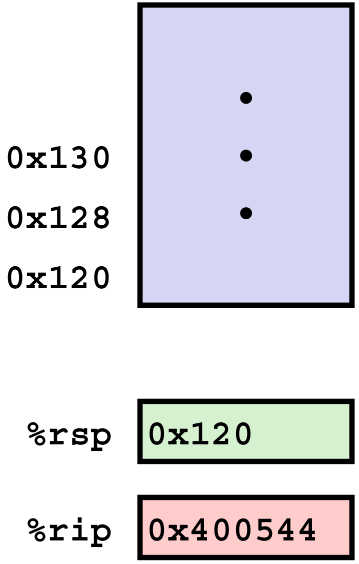
```
%rax
%rdi
%rsi
%rdx
%rcx
%r8
%r9
%r10
%r11
```

```
%rbx
%r12
%r13
%r14
%rbp
%rsp
%rip
```

# Stack/Procedure Review

```
0000000000400540 <multstore>:
  •
  •
=>400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

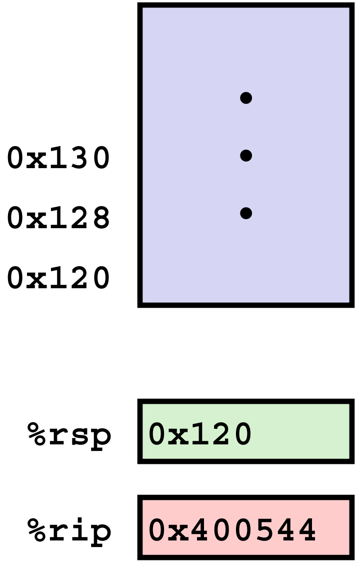
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



# Stack/Procedure Review

```
0000000000400540 <multstore>:
  •
  •
=>400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```

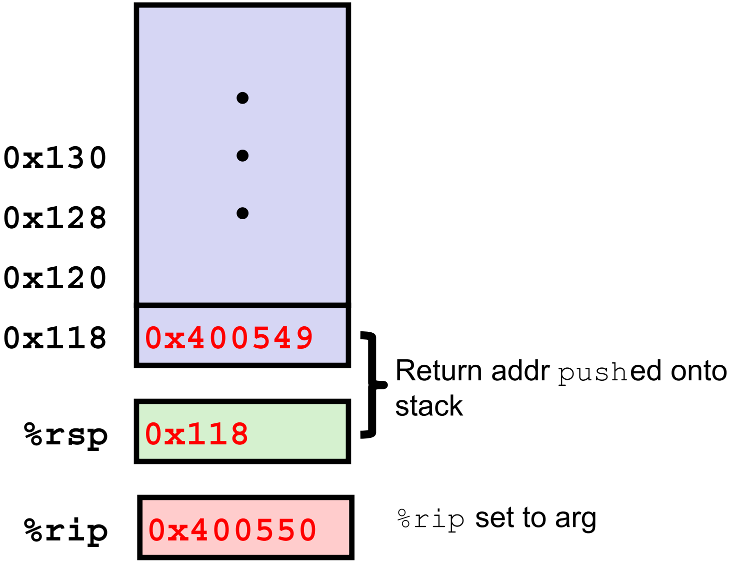



**What happens next?**

# Stack/Procedure Review

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

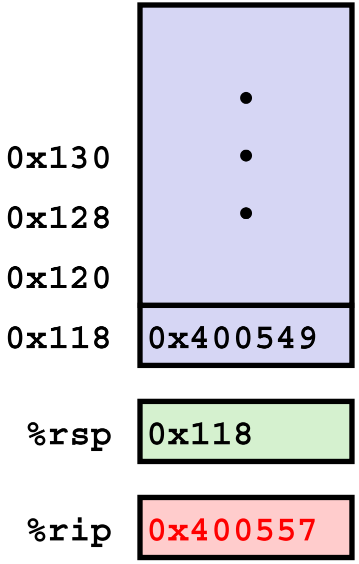
```
0000000000400550 <mult2>:
=>400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



# Stack/Procedure Review

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

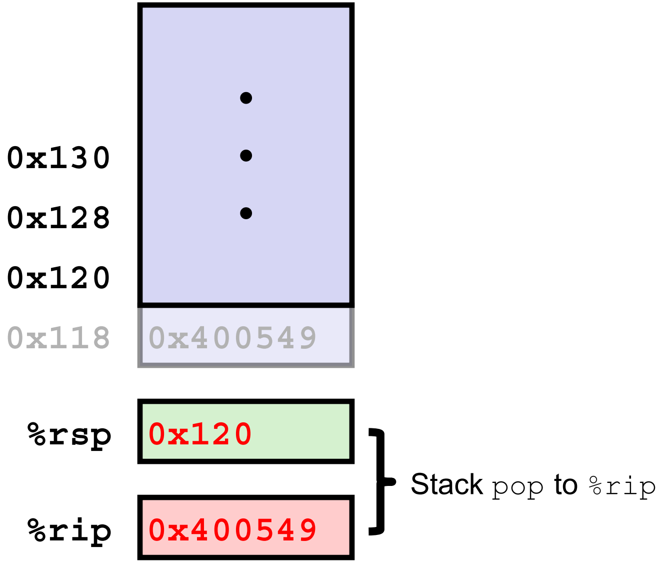
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
=>400557:  retq
```



# Stack/Procedure Review

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
=>400549: mov    %rax,(%rbx)
  •
  •
```

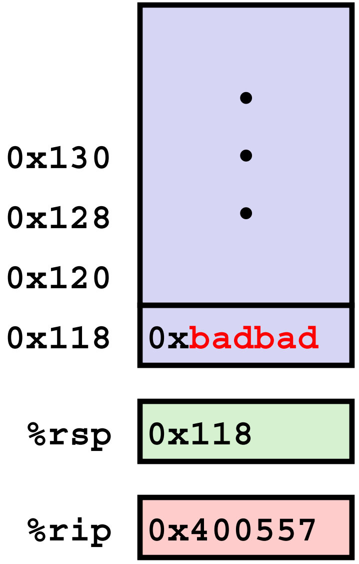
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



# Let's Rewind…

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  • ?????
  • ?????
=>400557:  retq
```




What if we mess up the return address?

# Attack Lab Tools

- ```
  $ gcc -c test.s
  $ objdump -d test.o
  ```
  Compiles the assembly code in test.s, then shows the disassembled instructions along with the actual bytes.

- ```
  (gdb) display /12gx $rsp
  (gdb) display /2i $rip
  ```
  Displays 12 elements on the stack and the next 2 instructions to run
  GDB is also useful to for tracing to see if an exploit is working.

# If you get stuck

- **Please read the writeup carefully.** Not everything will make sense on the first read-through.
- Other resources you can make use of:
  - CS:APP Chapter 3
  - Lecture slides and videos
  - x86-64 and GDB cheat sheets under Resources

# Appendix

# Activity 2

# Part 2: Exploitation

- Hijacking control flow
  - Is it possible to overwrite `after`? If not, what parts of the stack frame *can* we overwrite?
  - Is there anywhere we could jump to call `win(0x18213)`?
- Constructing an exploit

**inputs/input2.txt**

```
48 65 6c 6c 6f 20 31 35
32 31 33 21   # comment
```

→ **`make`** (runs `hex2raw`)

**inputs/input2.bin**

```
Hello 15213!
```

# Part 2: Recap

- `retq` always jumps to the **saved return address**, which it pops off the stack (at `rsp`).
- **Overwriting** the saved return address on the stack allows us to "fool" `retq`, and transfer control to an arbitrary instruction.