15-213 Recitation
Attack Lab

Your TAs

Friday, February 7th

Reminders

- `bomblab` was due yesterday (February 6th)
- `attacklab` has been released, and is due on ***Thursday (February 13th)***

Announcement

- We are now using a new queue!
  - https://213ohq.com/ohq/
- Please view the Ed post for more guidance! (#280)

Agenda

- Review: Structs and Alignment
- Stacks
- Calling Procedures, Stack Frames
- Endianness
- Intro to Attack Lab
- Activity!

Review: `structs`

Alignment Requirements

- Badly aligned data can harm performance:
  - May need multiple memory accesses instead of just one.
- *Primitive* types have pre-determined alignments:
  - **`char`** = 1 byte
  - **`short`** = 2 bytes
  - **`int`** = 4 bytes
  - **`long`** = 8 bytes
  - **`double`** = 8 bytes
  - **`pointer`** = 8 bytes

Alignment : Compound Types

- Compound types:
  - Arrays
  - Structs
  - Unions
- Alignment rules for these types:
  1. Takes largest alignment requirement of its fields.
  2. Initial address and size must both be multiples of the alignment requirement.

Alignment Requirements: Example

```
double d;
```

- What is the alignment requirement for **d**?
  - *Primitive:* has pre-defined alignment requirement.
  - **Alignment: 8**
- What is its size?
  - **Size: 8 bytes**

Alignment Requirements: Example

```
struct y {
  double d;
}
```

- What is the alignment requirement for **`y`**?
  - **Rule (1):** struct alignment = max alignment of fields.
  - **Alignment: 8**
- What is its size?
  - **Size: 8 bytes**

Alignment Requirements: Example

```
struct y {
   short c;
   double d;
}
```

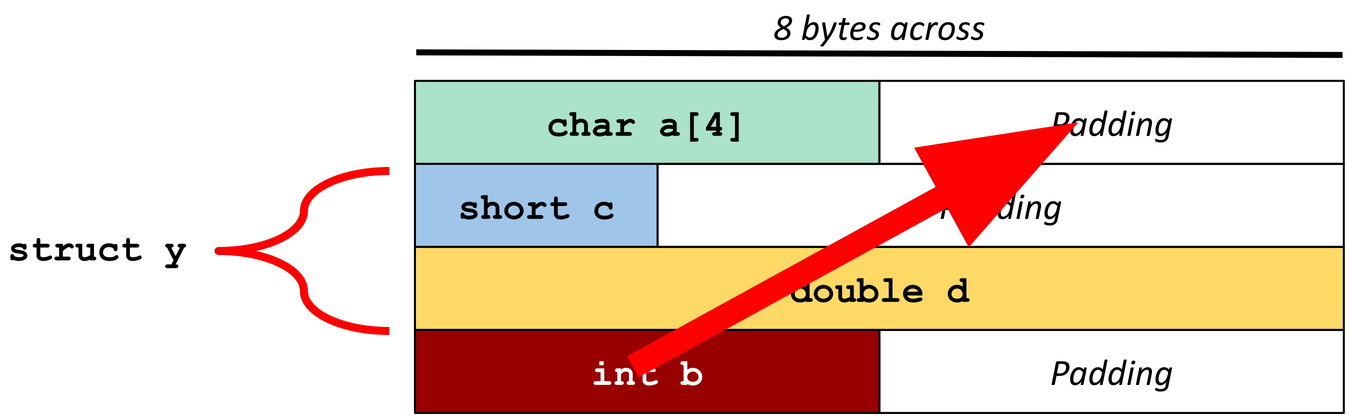
- What is the alignment requirement for **`y`**?
  - **Alignment: 8**
- What is its size?
  - **Rule (2):** have to add padding after **`c`** so that **`d`** is 8-byte aligned
  - **Size: 16 bytes**

Alignment Requirements: Example

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

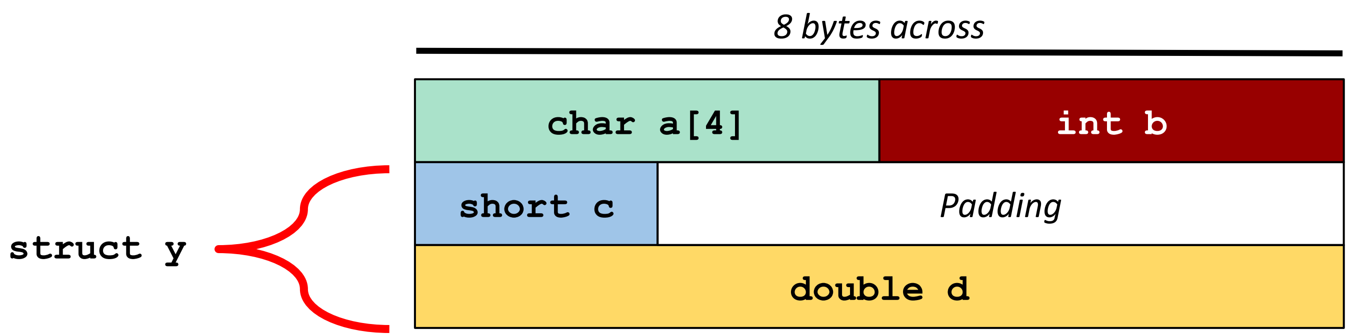
- What is the alignment requirement for **x**?
  - **Alignment: 8**
- What is its size?
  - Remember, the entire struct must also follow alignment rules
  - **Size: 32 bytes**

`structs`: Reordering Fields



- **`struct x`** takes up *32 bytes* to store *18 bytes* of data.
- Can we reorder the fields to do better?

`structs`: Reordering Fields



- **`struct x`** now takes up *24 bytes*!
- Compiler *cannot* do this optimization. It's up to the programmer (you!)
- *Note:* Can't move field into or out of **`y`** without also changing how you access those fields in your code.

Stacks

Manipulating the Stack

- Certain instructions ***grow*** the stack, and certain instructions ***shrink*** the stack:

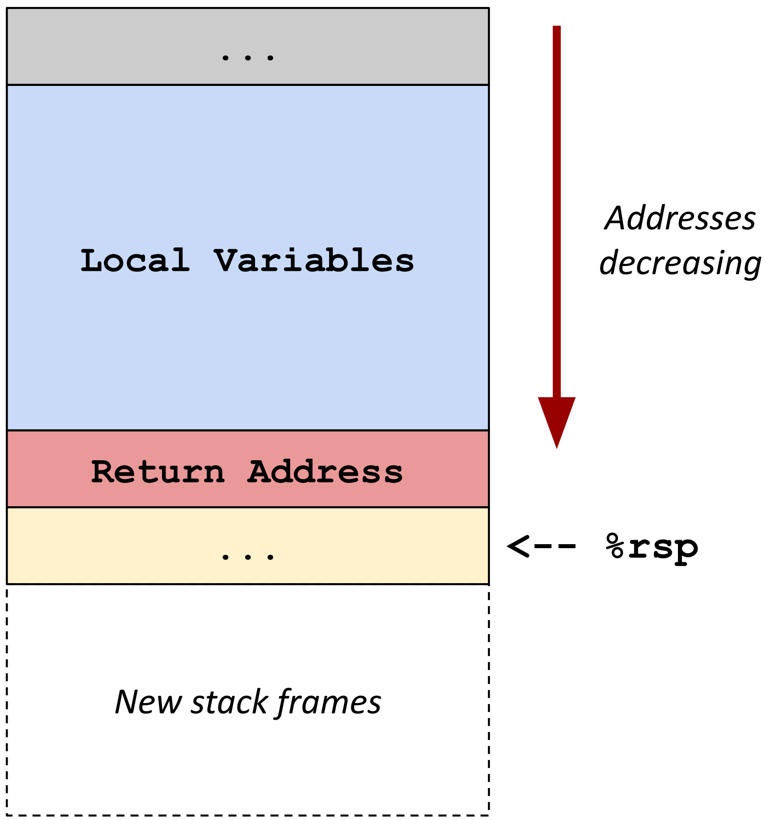
  Growing the stack
  - `sub 0x38, %rsp`
  - `push %rbp`
  - `call`

  Shrinking the stack
  - `add 0x38, %rsp`
  - `pop %rbp`
  - `ret`

- But what does this look like in memory?

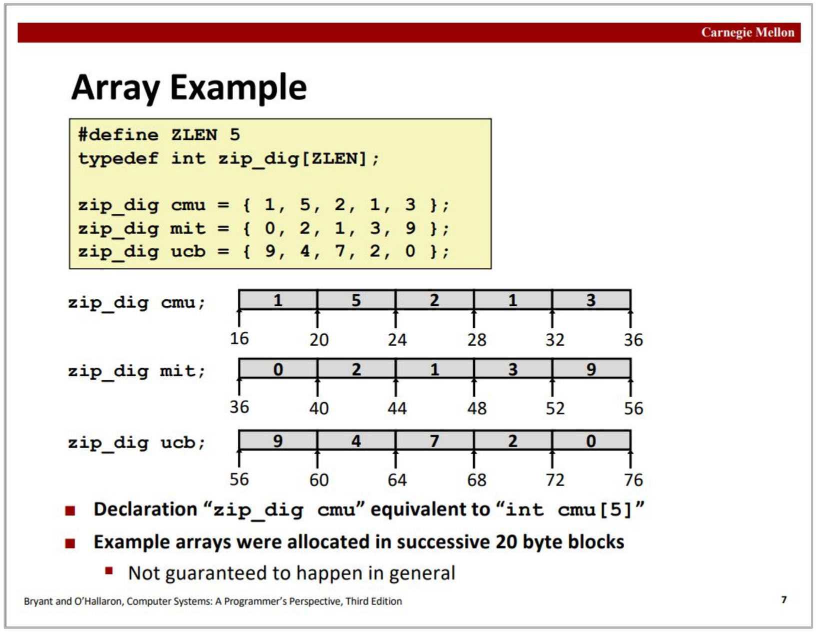
Which way does the stack grow?

- We say that the stack grows ***"down"*** because it grows towards ***lower addresses***:
  - e.g. **`sub 0x38, %rsp`**
- We will draw them this way in **`attacklab`** examples
  - But you can draw them in any way that makes sense to you!

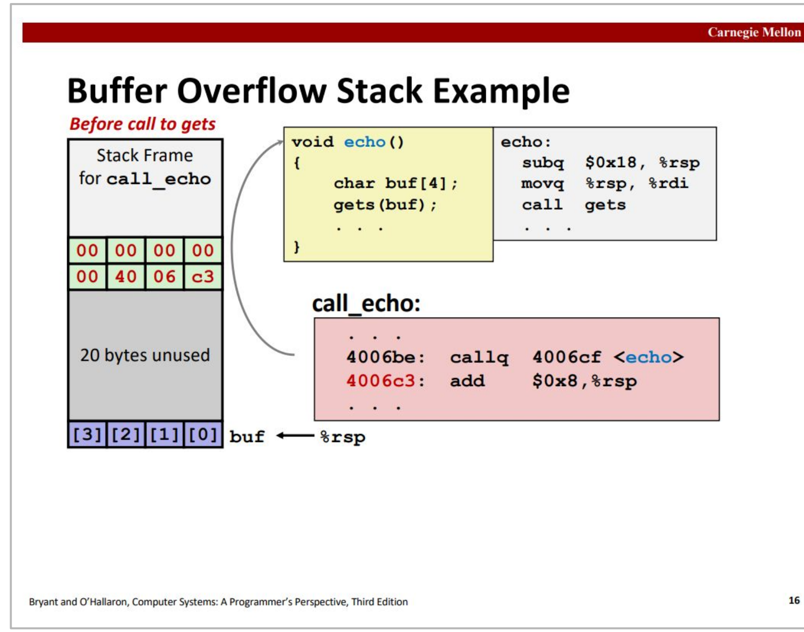


Drawing Memory

Conventional Memory Diagram



Stack Diagram



Addresses Increasing:

- Towards the <u>right</u>
- Then <u>downwards</u>

Addresses Increasing:

- Towards the <u>left</u>
- Then <u>upwards</u>

Calling Procedures, Stack Frames

Review: Calling Procedures

Procedure Call: **`call label`**

- Push *return address* onto the stack (so that we can pass control back to the caller!)
- Jump to **`label`**

Procedure Return: **`ret`**

- Pop address from stack
  - This is the address of the next instruction of the *caller*
- Jump to that address

Example

- Take a look at the following code snippet:

```
int outer_function() {
    int result = inner_function(1, 2, 3, 4, 5, 6, 7, 8, 9);

    return result + 1;
}
```

Lots of arguments!

- What would this look like in assembly? How would having many arguments affect the stack?

Example: `outer_function()`

- Here is the assembly for `outer_function`:

%rip

```
00000000004011ba <outer_function>:
...
4011c6:  push  $0x9
4011c8:  push  $0x8
4011ca:  push  $0x7

4011cc: mov $0x6,%r9d
4011d2: mov $0x5,%r8d
4011d8: mov $0x4,%ecx
4011dd: mov $0x3,%edx
4011e2: mov $0x2,%esi
4011e7: mov $0x1,%edi

4011ec: call 401136 <inner_function>
4011f1: add  $0x18,%rsp
...
```

Push extra arguments onto stack (note the order!)

Data for `outer_function()` <-- %rsp

Example: `outer_function()`

- Here is the assembly for **`outer_function`**:

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00000000004011ba <outer_function>:
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4011c6: push  $0x9
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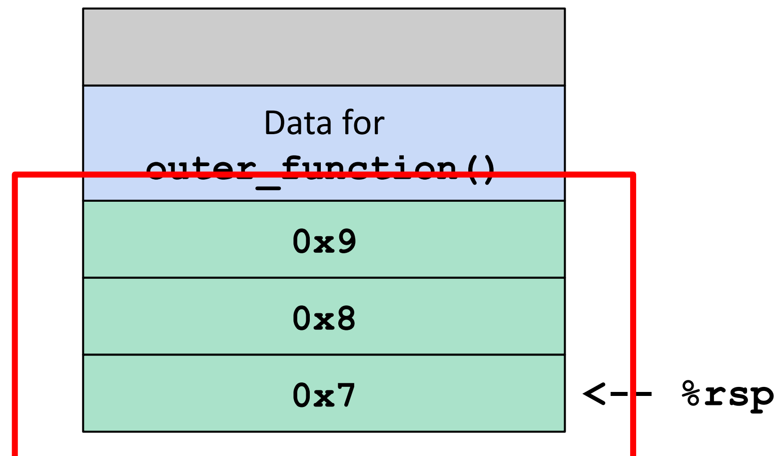
4011dd: mov $0x3,%edx
4011e2: mov $0x2,%esi
4011e7: mov $0x1,%edi

4011ec: call 401136 <inner_function>
4011f1: add  $0x20,%rsp
...
```

%rip

Push extra arguments onto stack (note the order!)



"Argument Build" space

Example: `outer_function()`

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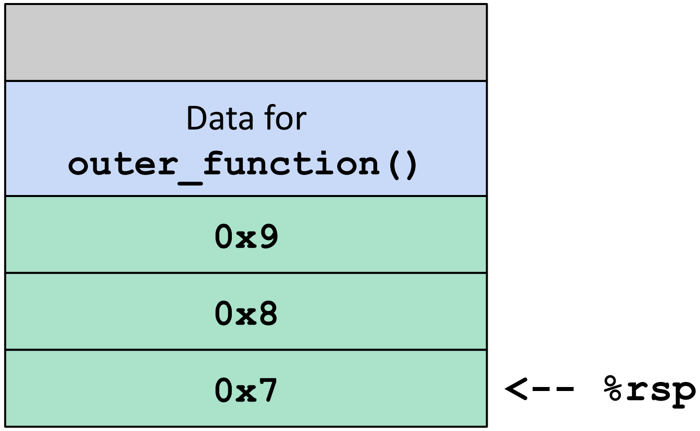
4011ec: call 401136 <inner_function>
4011f1: add  $0x20,%rsp
...
```

%rip

Load up first 6 arguments into argument registers



Example: outer_function()

- Remember, **call** loads the return address onto the stack

```
00000000004011ba <outer_function>:
...
4011c6:  push $0x9
4011c8:  push $0x8
4011ca:  push $0x7

4011cc: mov $0x6,%r9d
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4011e2: mov $0x2,%esi
4011e7: mov $0x1,%edi

4011ec: call 401136 <inner_function>
4011f1: add  $0x20,%rsp
...
```

Now we're ready to call!

Data for `outer_function()`	
`0x9`	
`0x8`	
`0x7`	
`??????`	`<-- %rsp`

Example: `outer_function()`

- What is the return address we should store? Let's inspect gdb to find out!

```
(gdb) x /4gx $rsp
0x7fffffffe3c8: 0x00000000004011f1      0x0000000000000007
0x7fffffffe3d8: 0x0000000000000008      0x0000000000000009
```

- Where does this value come from?

```
4011ec: call 401136 <inner_function>
4011f1: add $0x20,%rsp
...
```

- It's the address of the instruction we want to jump to after completing the call to **`inner_function`**

Example: outer_function()

- State of our program before starting **inner_function**

```
00000000004011ba <outer_function>:
...
4011c6:  push $0x9
4011c8:  push $0x8
4011ca:  push $0x7

4011cc: mov $0x6,%r9d
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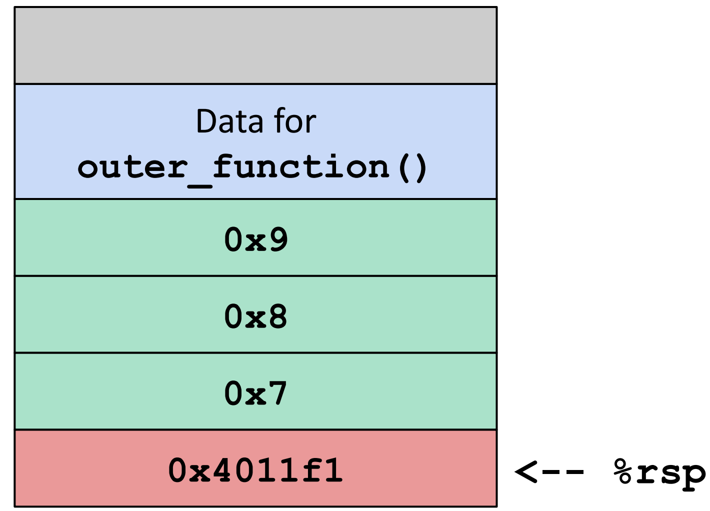
```



Pass control to **inner_function()**
=> Set **%rip** to **0x401136**

Example: inner_function()

- Here is the assembly for **inner_function**

```
            0000000000401136 <inner_function>:
%rip ──►    401136:   endbr64
            40113a:   push %rbp
            40113b:   mov %rsp,%rbp
            40113e:   sub $0x38,%rsp

            ...

            4011b9:   add $0x38,%rsp
            4011bd:   pop %rbp
            4011be:   ret
```

Example: `inner_function()`

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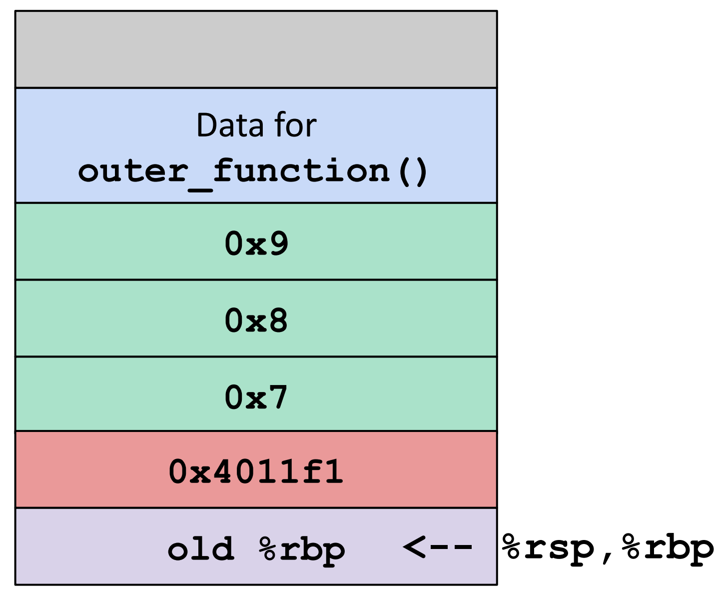
4011bd:   pop %rbp
4011be:   ret
```

%rip

Function store the original base pointer and repositions it for this stack frame



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...

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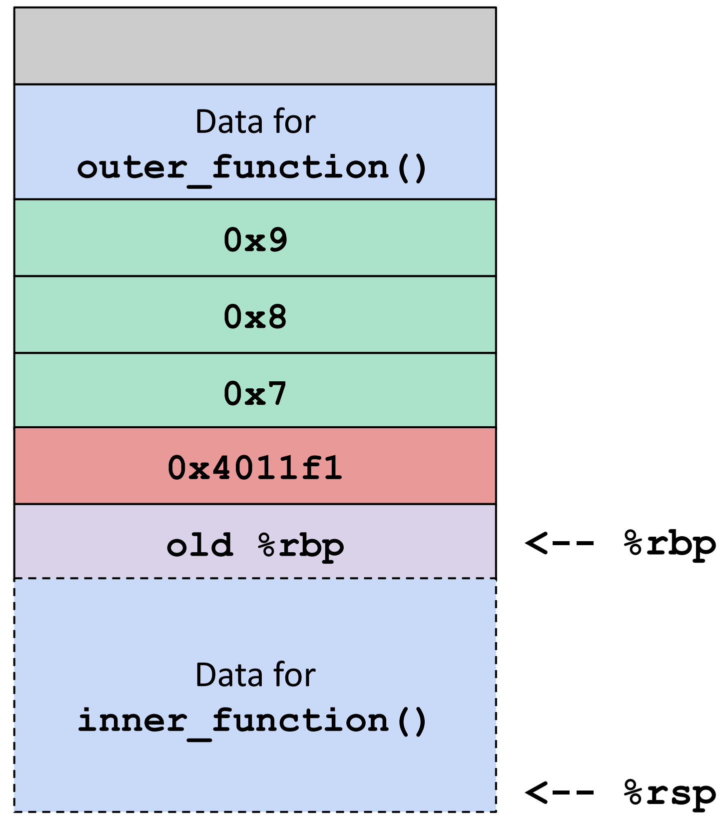
4011bd:   pop %rbp
4011be:   ret
```

%rip

Function allocates any space it needs



Example: inner_function()

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```
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401136:   endbr64
40113a:   push %rbp
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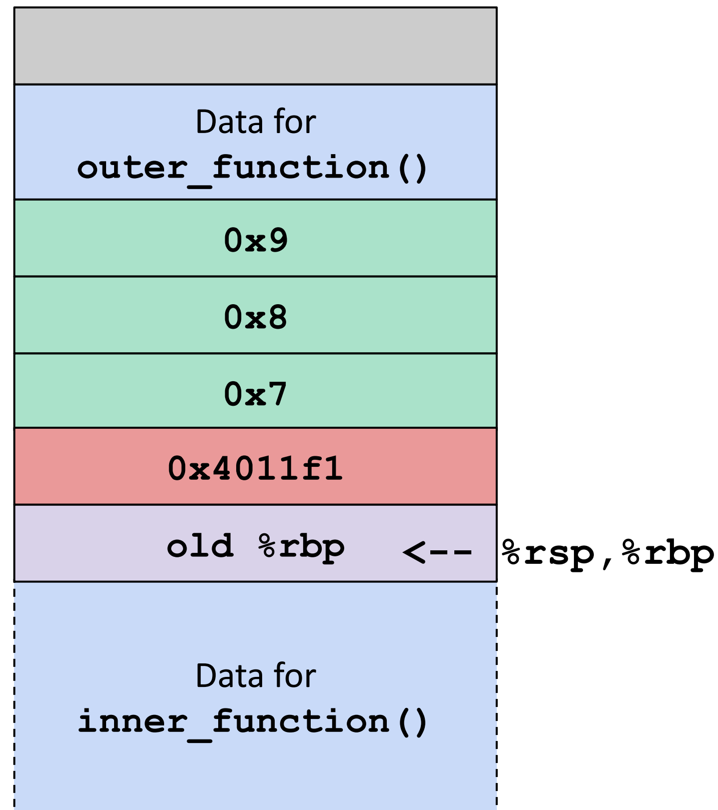
40113e:   sub $0x38,%rsp

...

4011b9:   add $0x38,%rsp
4011bd:   pop %rbp
4011be:   ret
```

%rip

De-allocate any stack space used by the function



Example: `inner_function()`

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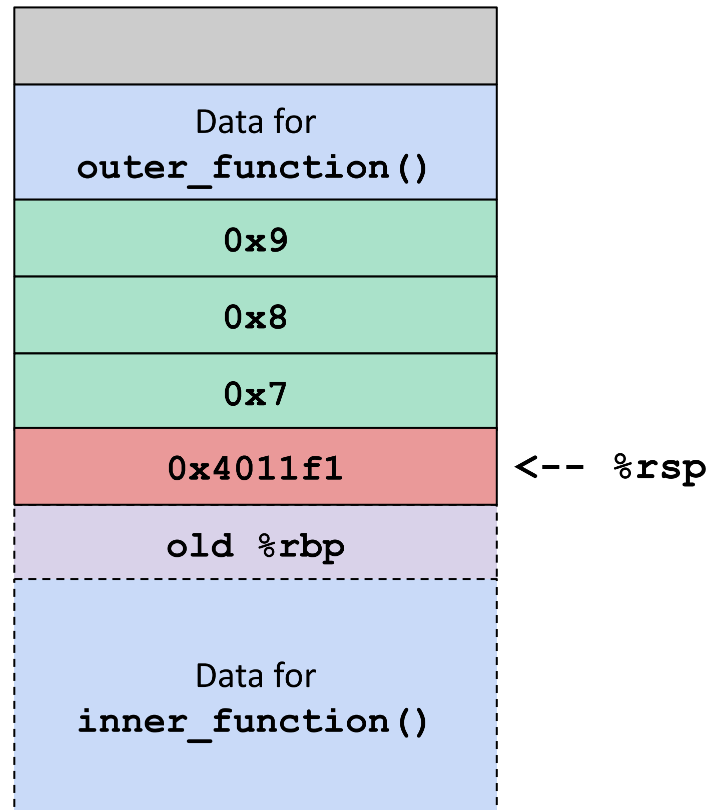
40113b:   mov %rsp,%rbp
40113e:   sub $0x38,%rsp

...

4011b9:   add $0x38,%rsp
4011bd:   pop %rbp
4011be:   ret
```

%rip → 4011be

Restore **%rbp** to prepare to return to original stack frame



Example: `inner_function()`

- Here is the assembly for **`inner_function`**

```
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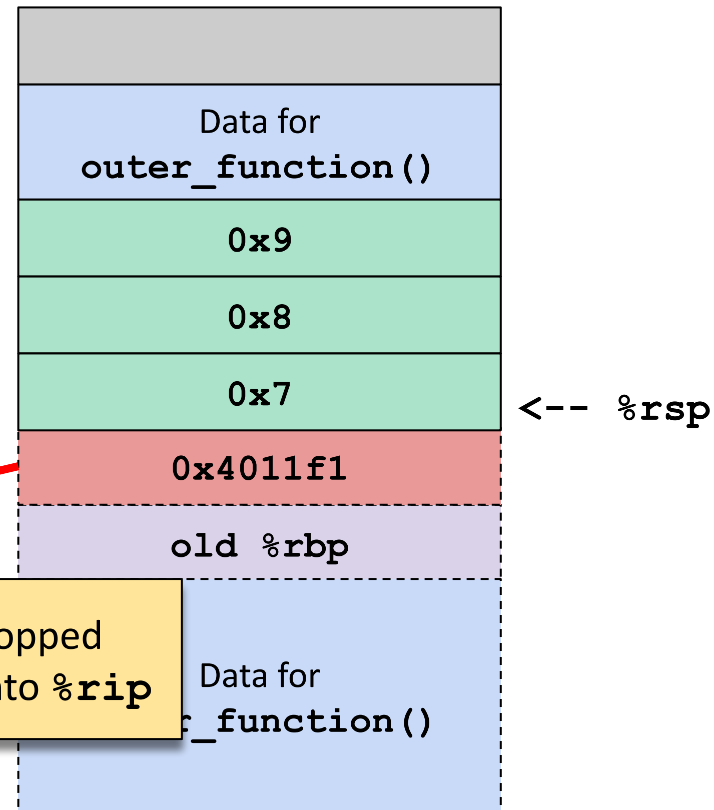
40113e:   sub $0x38,%rsp

...

4011b9:   add $0x38,%rsp
4011bd:   pop %rbp
4011be:   ret
```

Return! We pop the return address and jump




```
00000000004011ba <outer_function>:
...
4011ec: call 401136 <inner_functi
4011f1: add  $0x20,%rsp
...
```

%rip

Load popped address into **`%rip`**

Endianness

Endianness

- Under the hood, we represent everything as a series of contiguous *bytes.*
- ***Endianness*** refers to how we order the ***bytes*** for **"simple"** types (integers and floats).

Endianness

- ***Little-Endian***:
  - *Least* significant byte is stored at the *lowest* address.
  - Shark Machines are Little-Endian.
  - Assume everything in this class is **little-endian** unless otherwise stated.
- ***Big-Endian***:
  - *Most* significant byte is stored at the *lowest* address.

32-bit integer

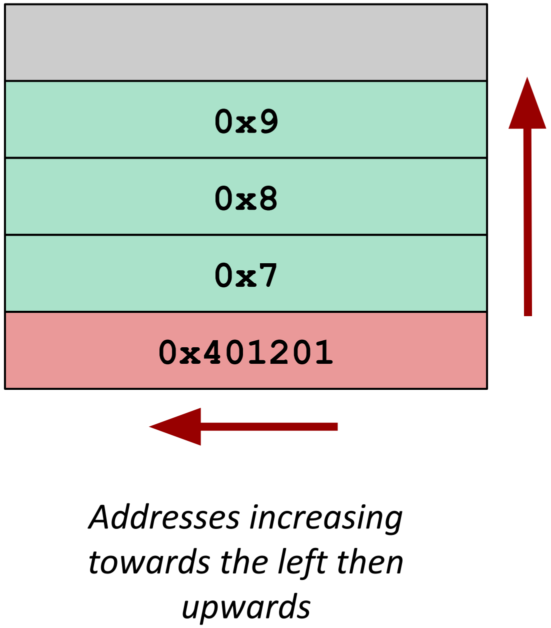
`0x01020304`

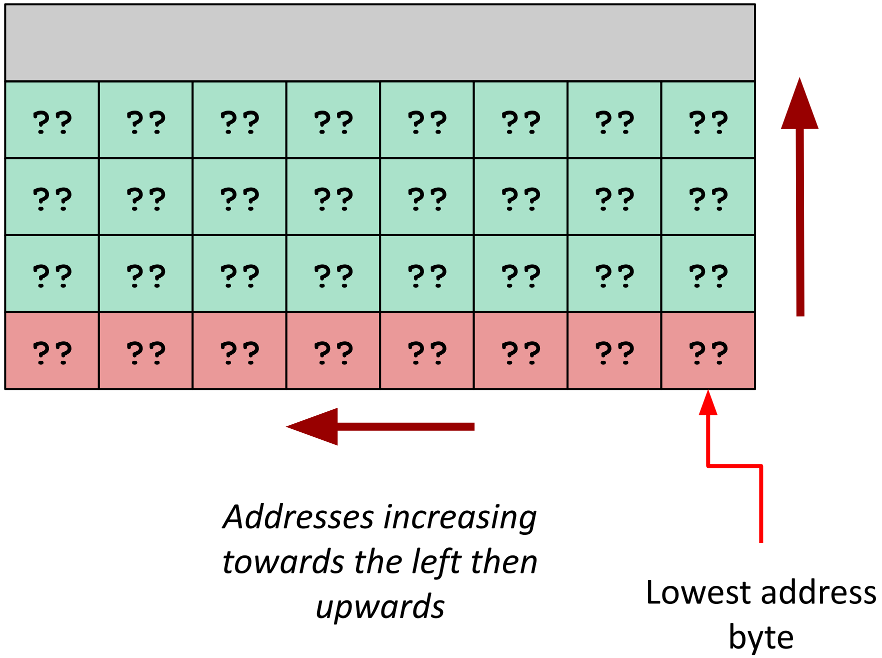
"Big end" "Little end"

	`Mem[0]`	`Mem[1]`	`Mem[2]`	`Mem[3]`
Little-Endian	`0x04`	`0x03`	`0x02`	`0x01`
Big-endian	`0x01`	`0x02`	`0x03`	`0x04`

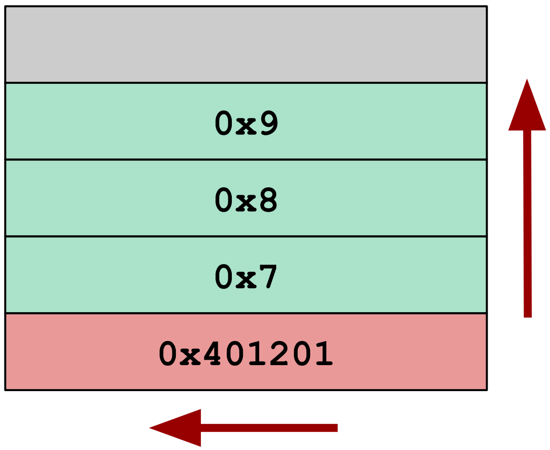
Endianness: Example

- Suppose we draw our diagram with addresses increasing towards the left, then upwards.
- How are the bytes ordered on a little endian machine?

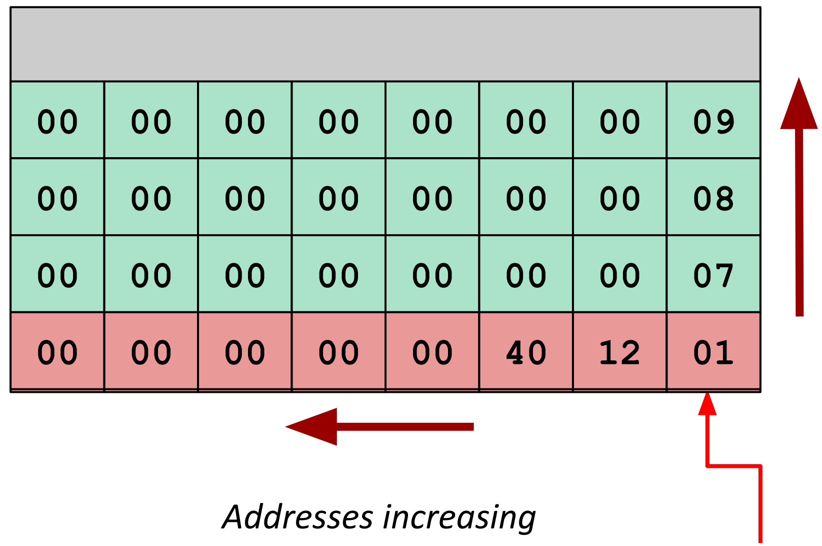




Endianness: Example



Addresses increasing towards the left then upwards



Addresses increasing towards the left then upwards

Lowest address byte

Endianness Example: Comparing with gdb

00	00	00	00	00	00	00	09
00	00	00	00	00	00	00	08
00	00	00	00	00	00	00	07
00	00	00	00	00	40	12	01

Addresses increasing towards the left then upwards

```
(gdb) x /32bx $rsp
0x7fffffffe3e8: 0x01 0x12 0x40 0x00 0x00 0x00 0x00 0x00
0x7fffffffe3f0: 0x07 0x00 0x00 0x00 0x00 0x00 0x00 0x00
0x7fffffffe3f8: 0x08 0x00 0x00 0x00 0x00 0x00 0x00 0x00
0x7fffffffe400: 0x09 0x00 0x00 0x00 0x00 0x00 0x00 0x00
```

Addresses increasing towards the right then downwards

- **gdb** draws its diagram with addresses increasing towards the right then downwards.
- Both diagrams are correct, and are still little-endian!

JULIA EVANS
@b0rk

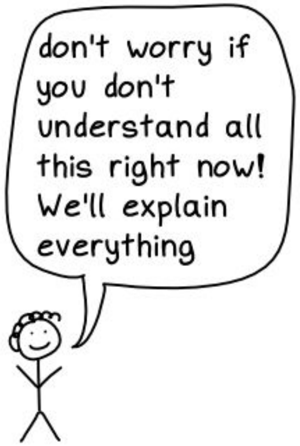
8 bytes, many meanings

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

Addresses increase towards the right

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



Attack Lab

Attack Lab: Overview

- Exploit vulnerabilities in target programs using the techniques you learned in lecture.
- Hijack their control flow and make them do something else!
- Targets do *not* explode like in **`bomblab`**.
- We'll get some practice right now!

Activity

Activity 1

- Download this week's handout from the *Schedule* page.
- For now:
  - Just open up the source code under **`src/activity.c`**.
  - We'll start by walking through the code together!

```
$ wget https://www.cs.cmu.edu/~213/activities/s25-rec4.tar
$ tar -xvf s25-rec4.tar
$ cd s25-rec4
```

Activity 1: `solve()`

```
void solve(void) {                              src/activity.c
     long before = 0xb4;
     char buf[16];
     long after = 0xaf;

     Gets(buf);

     if (before == 0x3331323531)
          win(0x15213);
     if (after == 0x3331323831)
          win(0x18213);
}
```

- Assume **`before`** and **`after`** are stored on the stack.
- Is there any way for **`solve()`** to call **`win()`**?
- Based on what you learned in lecture, are there any vulnerabilities we can exploit here?

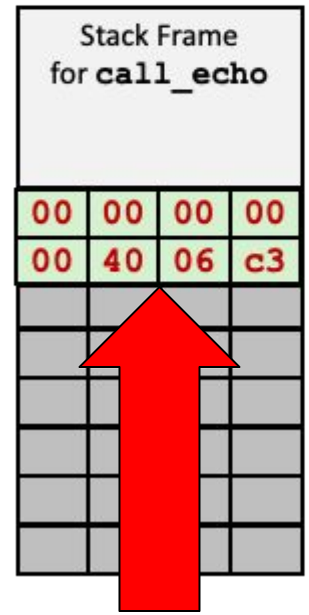
Recall: Unsafe Functions

- C standard library functions like **`gets()`** and **`strcpy()`** write to buffers, but have no length checks!
  - Enables *buffer overflow* attacks.

```
int echo() {
     char buf[4];
     gets(buf);
     ...
     return ...;
}
```

```
echo:
  subq   $0x18, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

Compiler making space
for buffer +
a little bit of padding



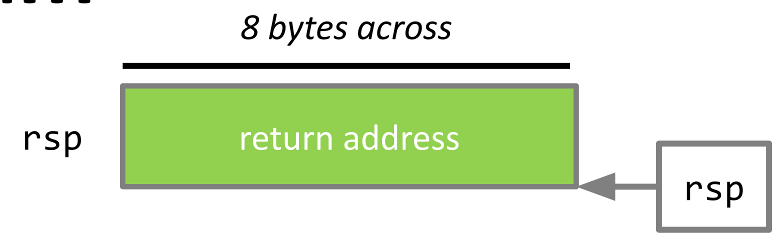
Can overwrite anything
before the buffer!

Activity 1: Back to `solve()`

- Let's see if we can find a similar vulnerability in **`solve()`** by looking at the assembly!
- Source code and assembly code are both reproduced on the back of the handout.
- Draw a stack diagram to see if you can answer the following:
  - What does the stack frame look like?
  - Where is the saved return address?
  - Where do we store **`buf`**, **`before`**, and **`after`** in relation to each other?

Activity 1: Stack diagram

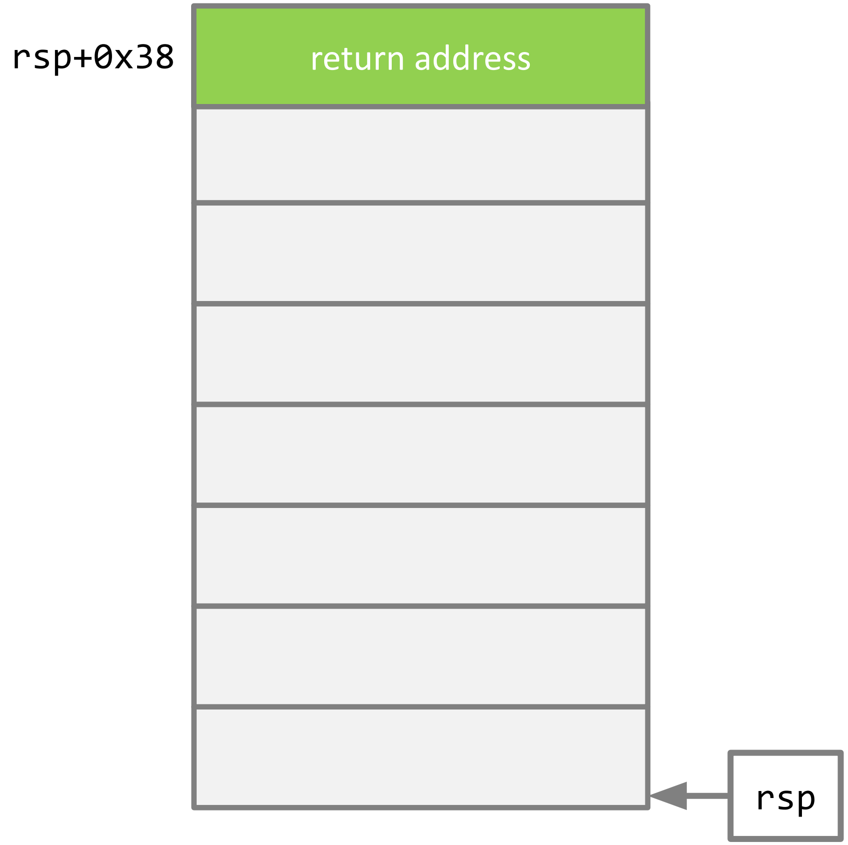
```
=> 0x4006b5 <+0>: sub    $0x38,%rsp
```



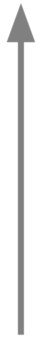
Addresses increase
towards the top of
the slide

Activity 1: Stack diagram

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

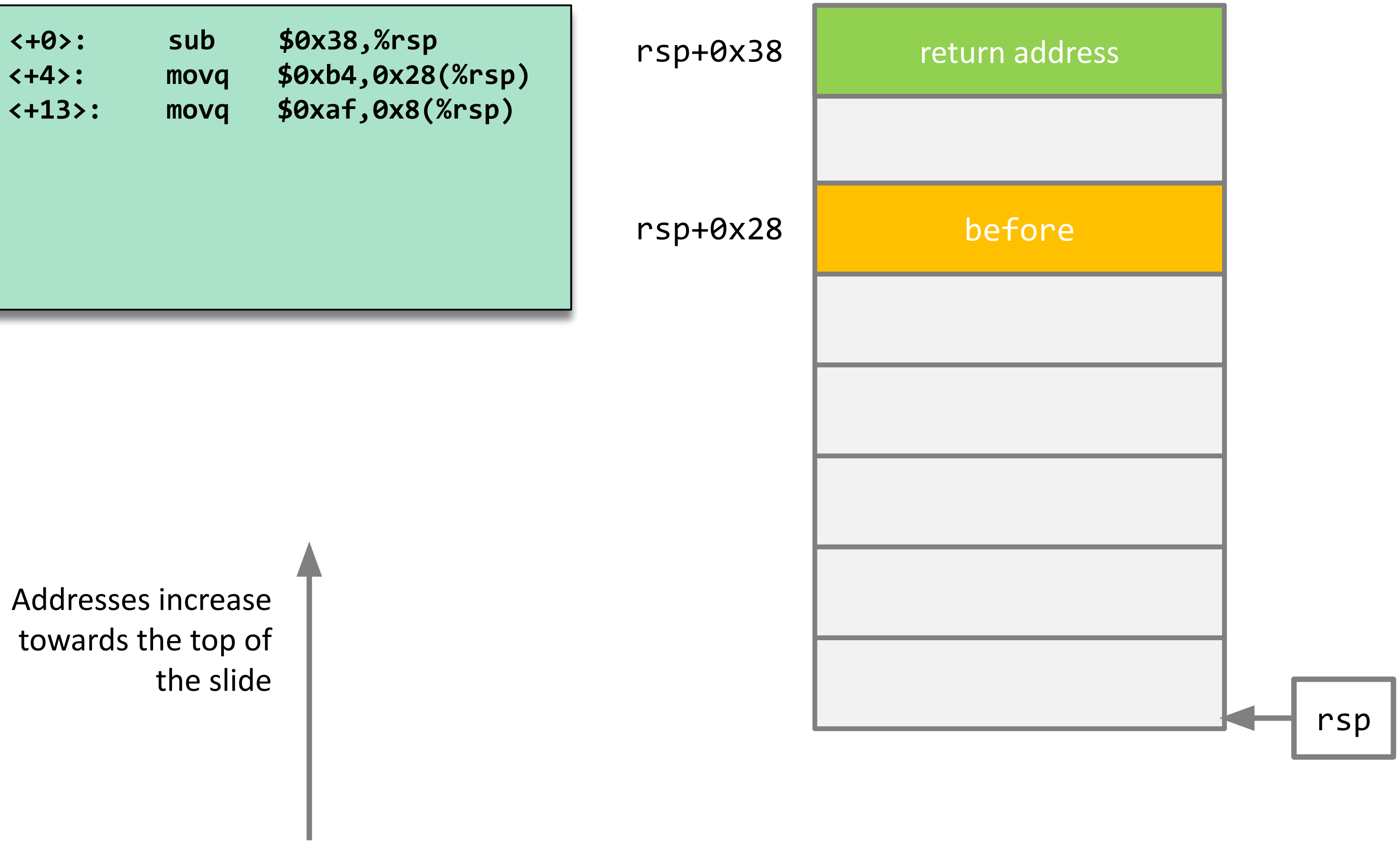


Addresses increase towards the top of the slide



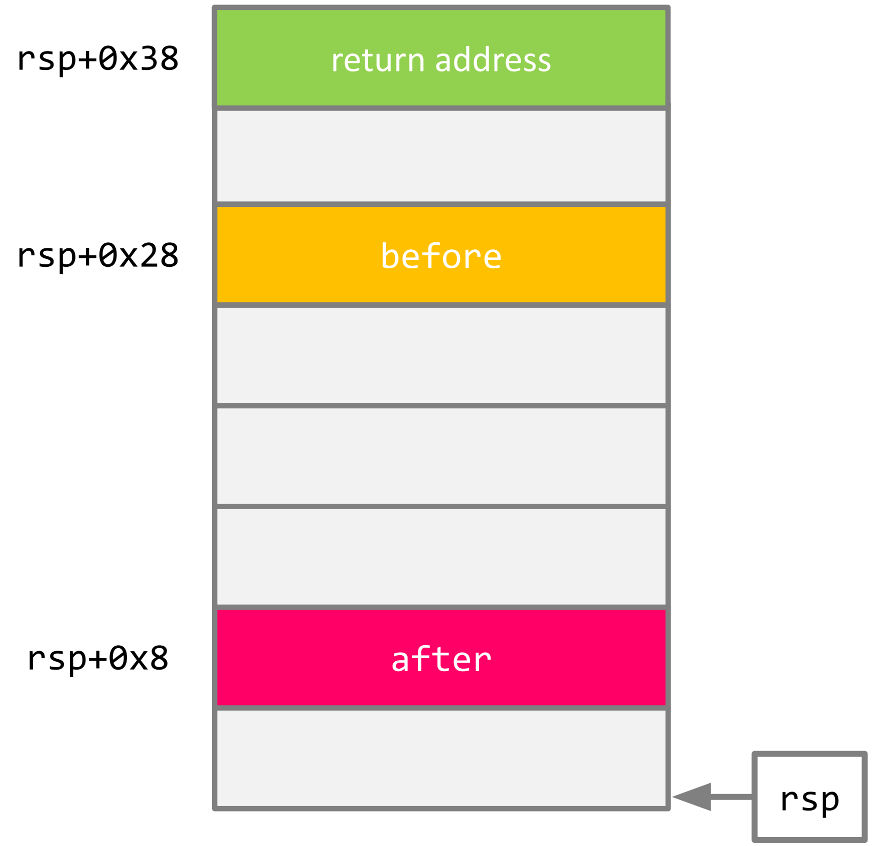
Activity 1: Stack diagram

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



Activity 1: 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
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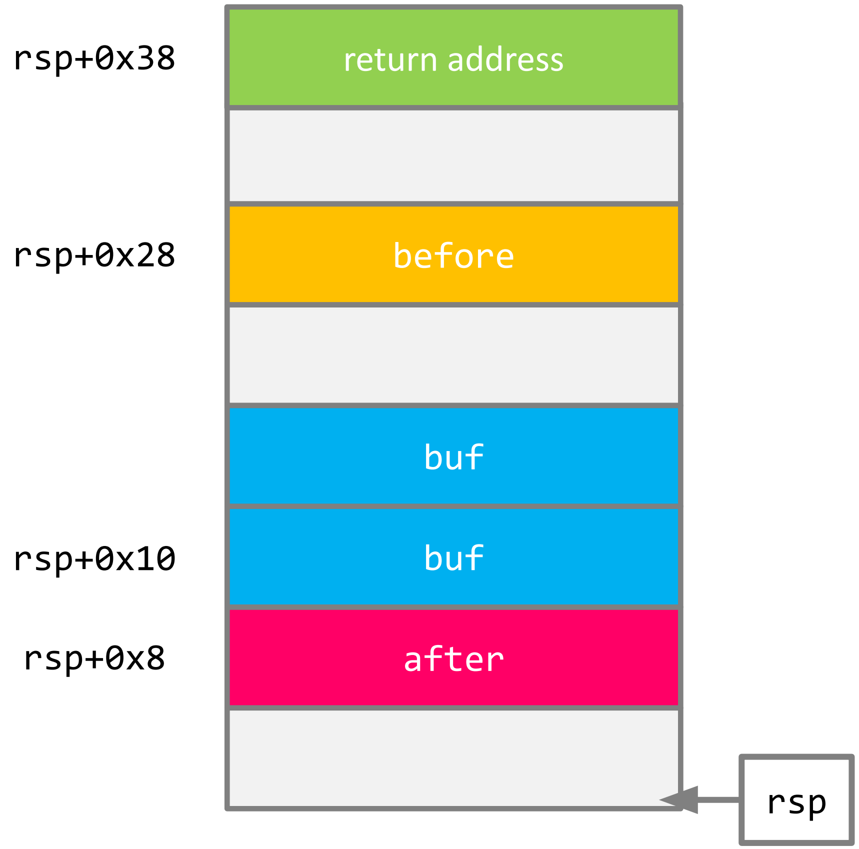
Activity 1: Stack diagram

```
   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
```



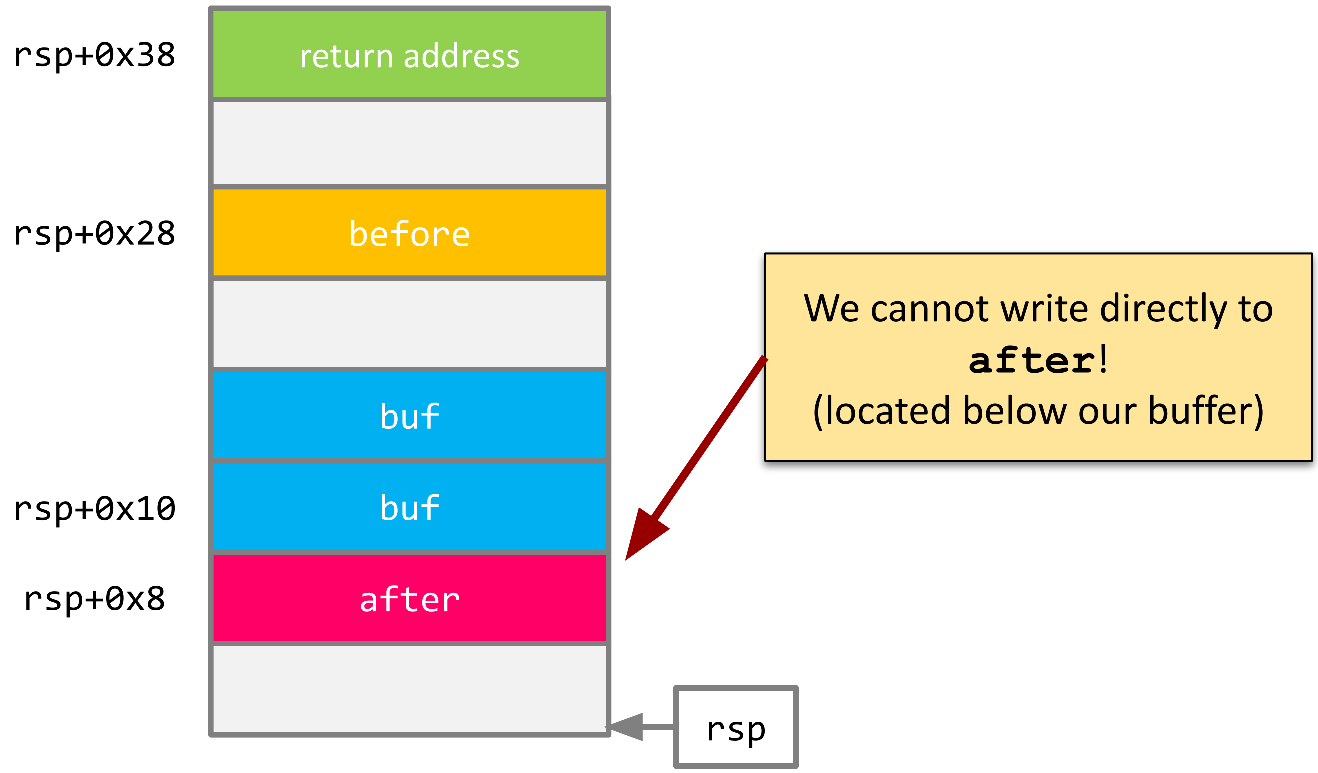
Addresses increase towards the top of the slide

Activity 1: Exploitation

- Goal: call `win(0x15213)`
- Take a few minutes to craft an exploit string!
- Crafting an exploit:
  - `gets()` stops reading once it sees a newline.
  - Will ***not*** stop reading when it sees a null terminator.

Activity 2

- Objective: call **`win(0x18213)`**
- How is activity 2 different from activity 1?

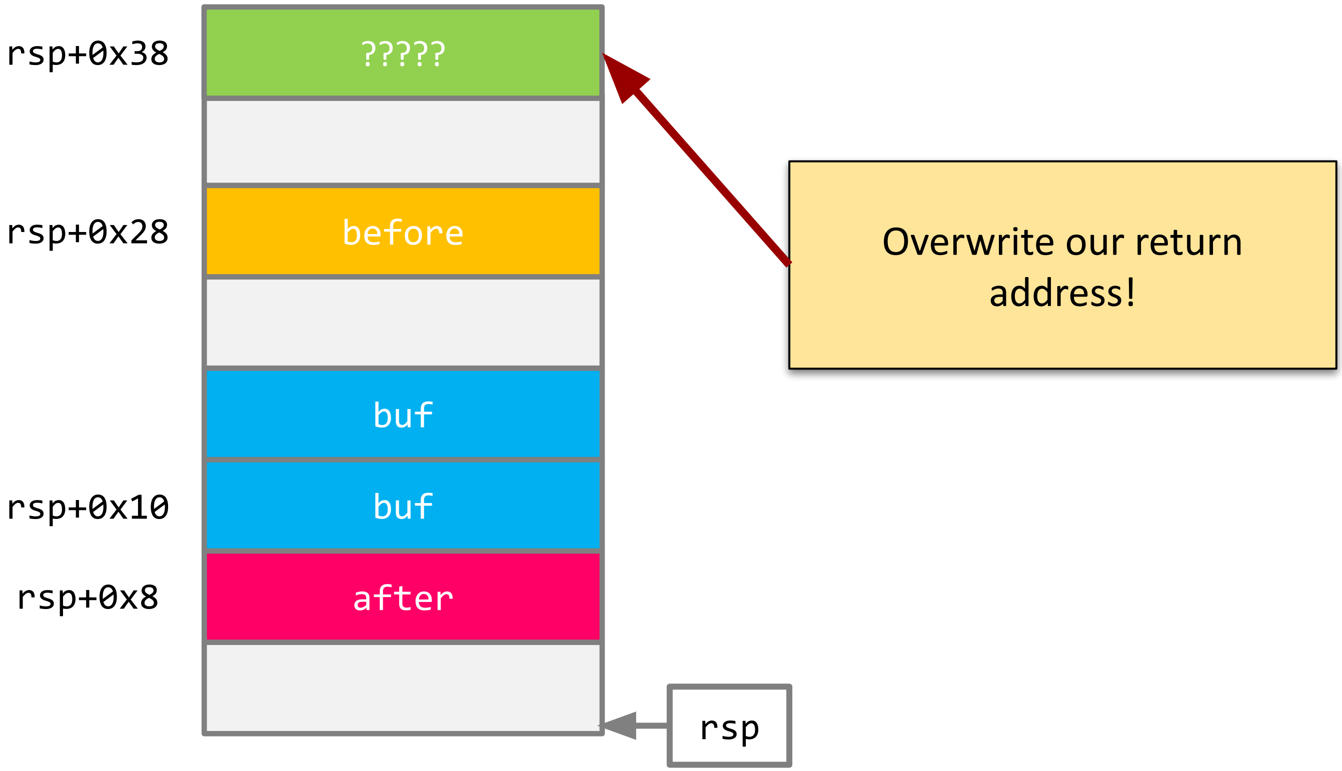


Activity 2: Exploitation

- If we cannot overwrite **`after`** in order to call **`win(0x18213)`**, what is another type of attack we can perform?
- *One possible solution:* Instead of setting local variables that result in calling **`win(0x18213)`**, we can jump to an instruction that directly calls **`win(0x18213)`**!

Activity 2

- Change the return address:



Activity 2: Reflection

- What address should we place in our return address?
- Use gdb to find this address!

Which one?

```
0x00000000004006b5 <solve>:
...
400707:  mov     $0x18213,%edi
40070c:  call    0x40064d <win>
...
```

Activity 2: Reflection

- What address should we place in our return address?
- Use gdb to find this address!

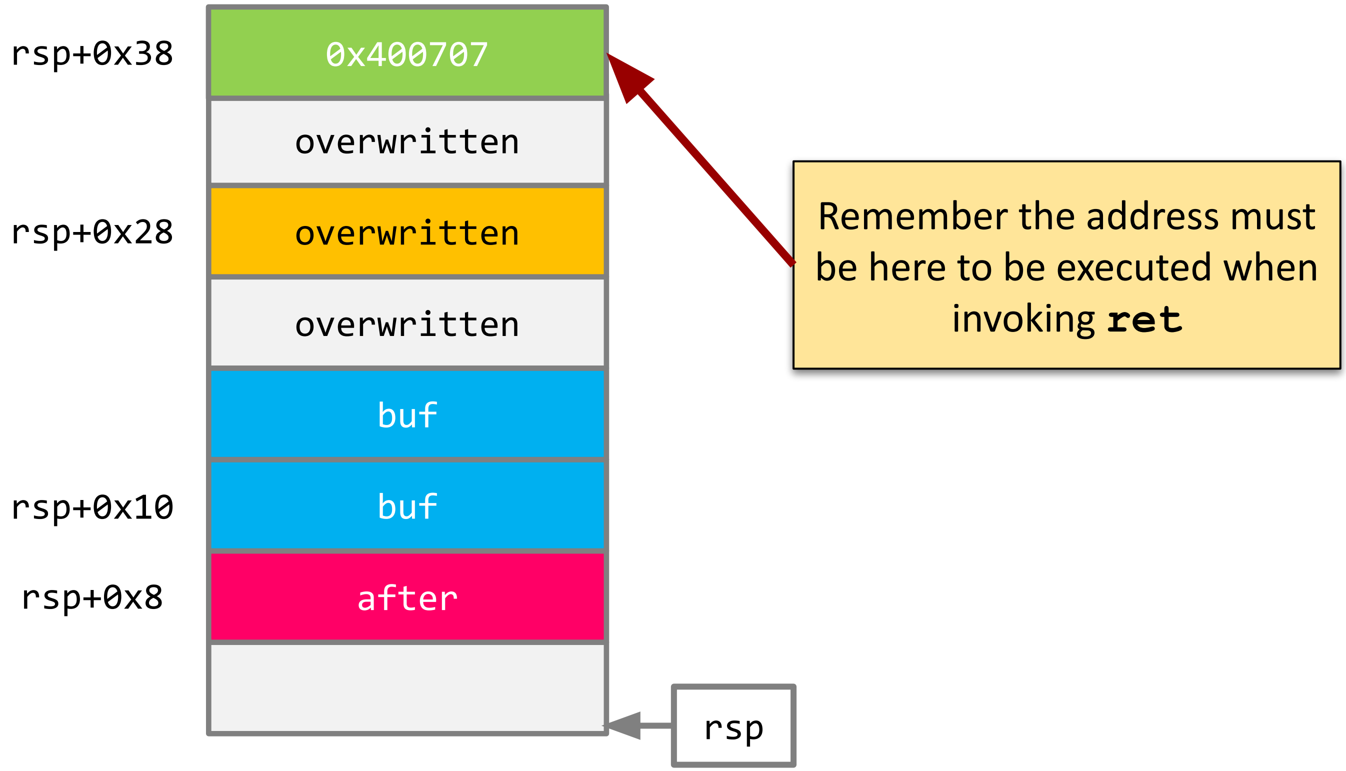
Correct!

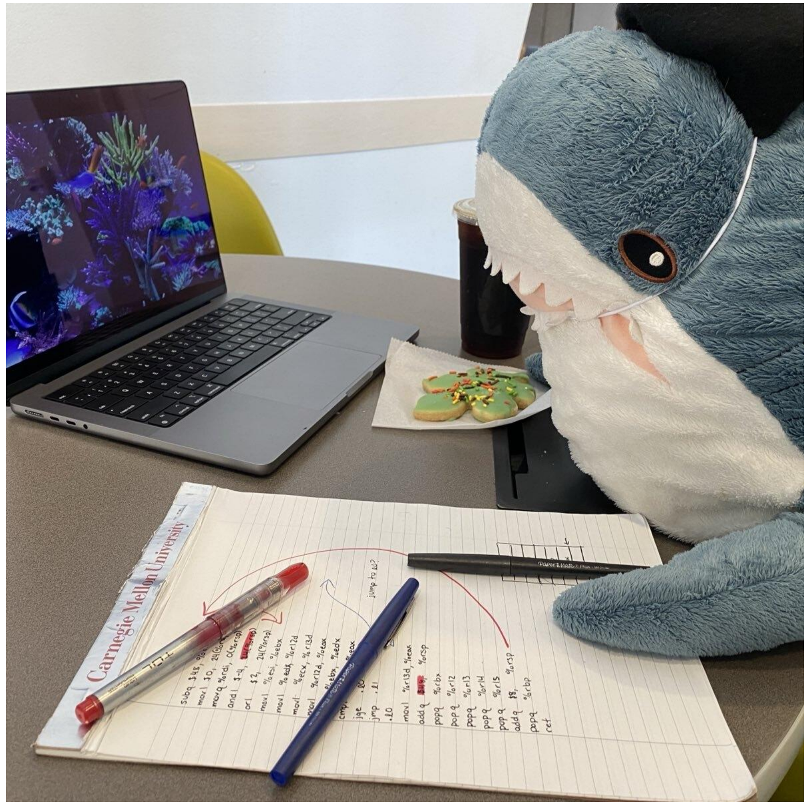
```
0x00000000004006b5 <solve>:
...
400707: mov    $0x18213,%edi
40070c: call   0x40064d <win>
...
```

- Remember that we can’t just call **`win()`**, we need to ensure that the first argument is set to **`0x18213`**.

Activity 2

- We write this address onto our stack:





The End