Lecture 10
Buffer Overflows

CS213 – Intro to Computer Systems

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Slides adapted from:
St-Amour, Hardavellas, Bustamente (Northwestern), Bryant, O'Hallaron (CMU), Garcia, Weaver (UC Berkeley)

Northwestern

Administrivia

- Continue work on Bomb Lab

- Homework 3 releases late tonight or early tomorrow
  - Due on Tuesday, November 7th

- Attack Lab is out after class
  - Due on Wednesday, February 22nd

Today's Goals

- Introduce the domain of Computer Security

- Understand buffer overflows and return-oriented programming
  - What enables them
  - How they are used
  - How to protect against them

Why is computer security so important?

- Most public security happens at least in some portion on the honor system
  - Pretty easy to break a window
  - Keyed locks are easy to pick
  - Master keys can be determined and manufactured (Matt Blaze attack)
  - Laws apply after you've done it

Early computers didn’t have any security either

- Simple machines for doing computation do not have private files or contention

- Sometimes there were multiple users, but all were employees of the same company
  - Permissions needed to be as secure as a file in a locked drawer on a desk

“The act of breaking into a computer system has to have the same social stigma as breaking into a neighbor's house. It should not matter that the neighbor's door is unlocked.”
- Ken Thompson, Turing Award Lecture, 1984

Connectivity of computers makes security a top concern

- Security of physical items is dependent on the fact that only one person can possess a thing at a time
  - And it’s usually obvious when theft occurs
  - Not the case for private information on a computer!

- The internet makes security incredibly important
  - Usually not people breaking into computers manually, one at a time
  - Instead, it is computers breaking into computers by means of scripting
  - And you can access a computer from anywhere on Earth

- Breaking into or controlling one car is a crime
  - Controlling 100,000 cars remotely is a problem for the manufacturer

Outline

- **Buffer Overflows**
- Protecting Against Buffer Overflows
- Return-Oriented Programming
- Protecting Against Return-Oriented Programming

Memory Referencing Bug Example

```
typedef struct {
  int a[2];
  double d;
} struct_t;

double fun(int i) {
  volatile struct_t s; // volatile ≈ don’t optimize this away
  s.d = 3.14;
  s.a[i] = 1073741824; // Possibly out of bounds
  return s.d;
}
```

```
fun(0)  ⇒  3.14
fun(1)  ⇒  3.14
fun(2)  ⇒  3.1399998664856
fun(3)  ⇒  2.00000061035156
fun(4)  ⇒  3.14
fun(5)  ⇒  3.14
fun(6)  ⇒  Segmentation fault (core dumped)
```

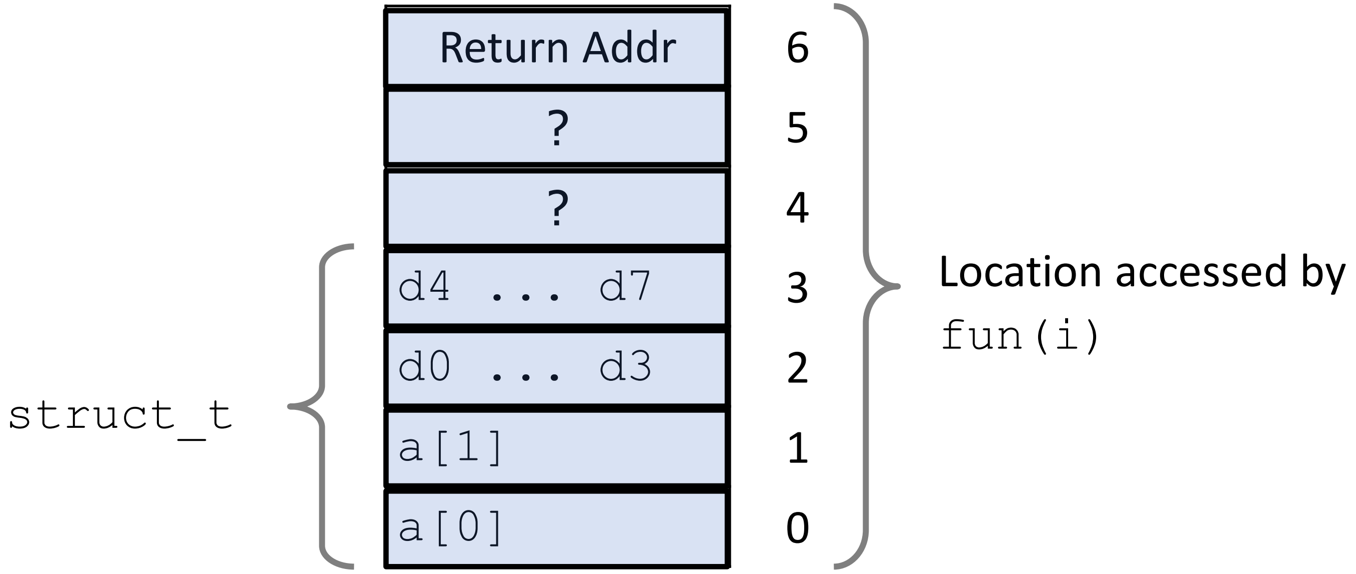
- Abuses undefined behavior
- Result is system specific

Memory Referencing Bug Example

```
typedef struct {
  int a[2];
  double d;
} struct_t;
```

fun(0)	→	3.14
fun(1)	→	3.14
fun(2)	→	3.1399998664856
fun(3)	→	2.00000061035156
fun(4)	→	3.14
fun(5)	→	3.14
fun(6)	→	Segmentation fault

Explanation:



Such problems are a ***BIG*** deal

- Generally called a “buffer overflow”
  - Going past end of memory allocated for an array (AKA buffer)

- Why is it a big deal?
  - #1 ***technical*** cause of security vulnerabilities
    - (#1 overall cause is social engineering)

- Most common form:
  - Unchecked lengths on string inputs
  - Particularly with character arrays on the stack
    - Sometimes referred to as “stack smashing”

String library code

- Implementation of Unix function `gets`
  - No way to specify limit on number of characters to read

```
/* Get string from stdin */
char *gets(char *dest)
{
    int c = getchar();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

No bounds checking!

- Similar problems with other Unix functions
  - **`strcpy`**, **`strcat`**: Copies string of arbitrary length
  - **`scanf`**, **`fscanf`**, **`sscanf`**, when given **`%s`** specifier

Vulnerable buffer code

```
int main(){
  printf("Type a string:");
  call_echo();
  return 0;
}
```

```
void call_echo() {
  echo();
}
```

```
/* Prints whatever is read */
void echo(){
  char buf[4]; /* Way too small! */
  gets(buf);
  puts(buf);
}
```

```
unix>./bufdemo-nsp
Type a string:012
012
```

```
unix>./bufdemo-nsp
Type a string: 000011112222333344445555
000011112222333344445555
```

Much more than 4 characters!

```
unix>./bufdemo-nsp
Type a string: 00001111222233334444555556
Segmentation Fault
```

Buffer Overflow Disassembly

echo:

```
0000000004006cf <echo>:
 4006cf:   48 83 ec 18               sub    $24,%rsp
 4006d3:   48 89 e7                  mov    %rsp,%rdi
 4006d6:   e8 a5 ff ff ff            callq  400680 <gets>
 4006db:   48 89 e7                  mov    %rsp,%rdi
 4006de:   e8 3d fe ff ff            callq  400520 <puts@plt>
 4006e3:   48 83 c4 18               add    $24,%rsp
 4006e7:   c3                        retq
```

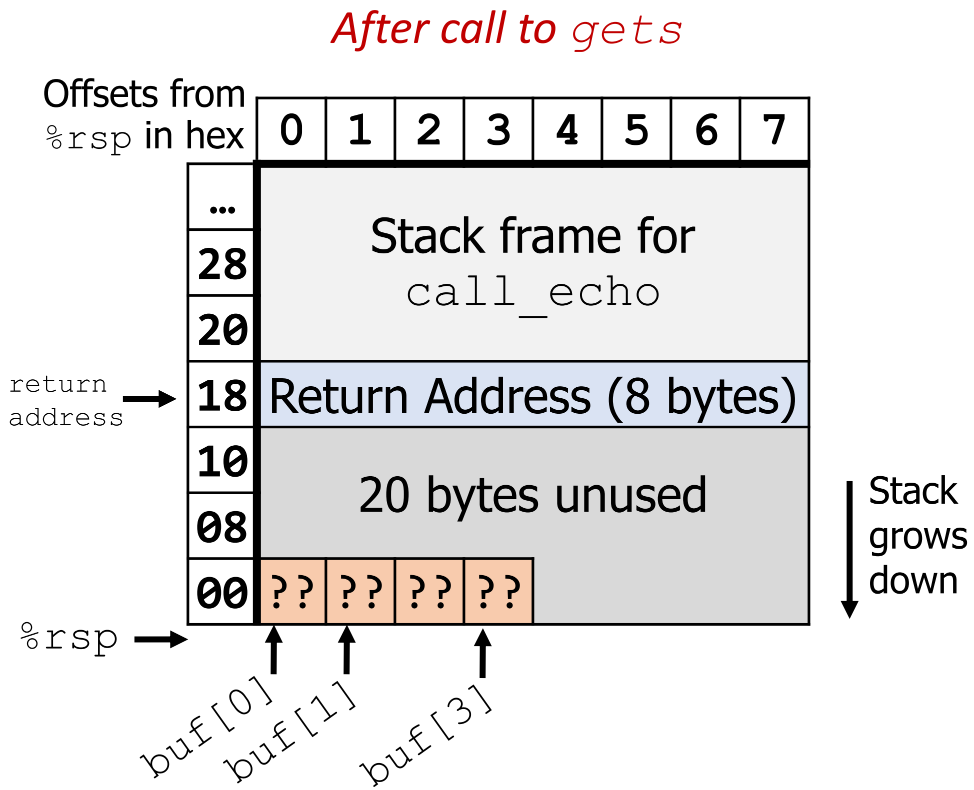
Sidebar: the compiler is optimizing here to use 8-byte alignment instead of 16-byte.

It knows no function this calls needs 16-byte alignment.

call_echo:

```
0000000004006e8 <call_echo>:
 4006e8:   48 83 ec 08               sub    $8,%rsp
 4006ec:   b8 00 00 00 00            mov    $0,%eax
 4006f1:   e8 d9 ff ff ff            callq  4006cf <echo>
 4006f6:   48 83 c4 08               add    $8,%rsp
 4006fa:   c3                        retq
```

Buffer Overflow Stack



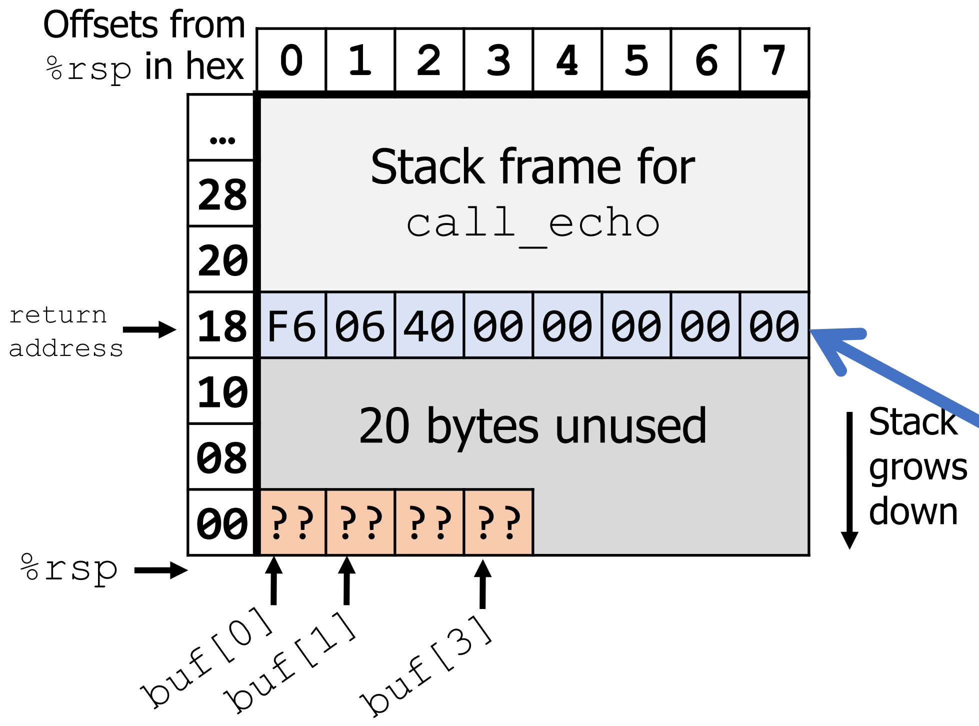

```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

```
echo:
  subq   $24, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

```
call_echo:
  . . .
  4006f1:  callq   4006cf <echo>
  4006f6:  add     $8,%rsp
  . . .
```

Buffer Overflow Stack Example

After call to `gets`

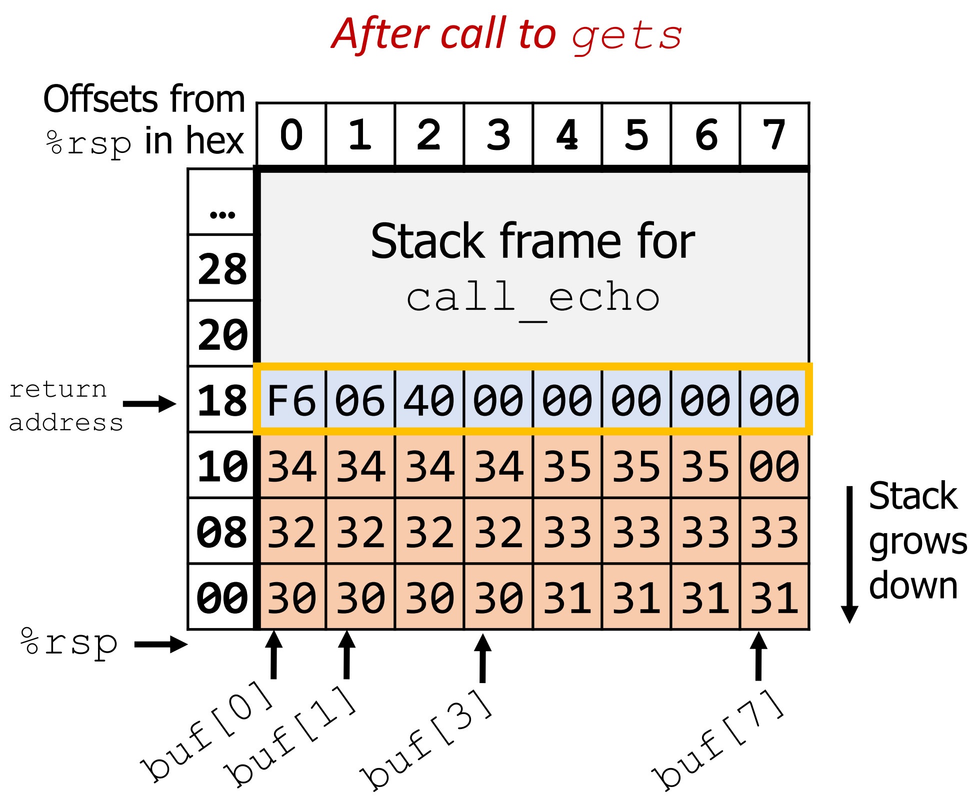



```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

```
echo:
  subq   $24, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

```
call_echo:
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $8,%rsp
  . . .
```

Buffer Overflow Stack Example #1




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

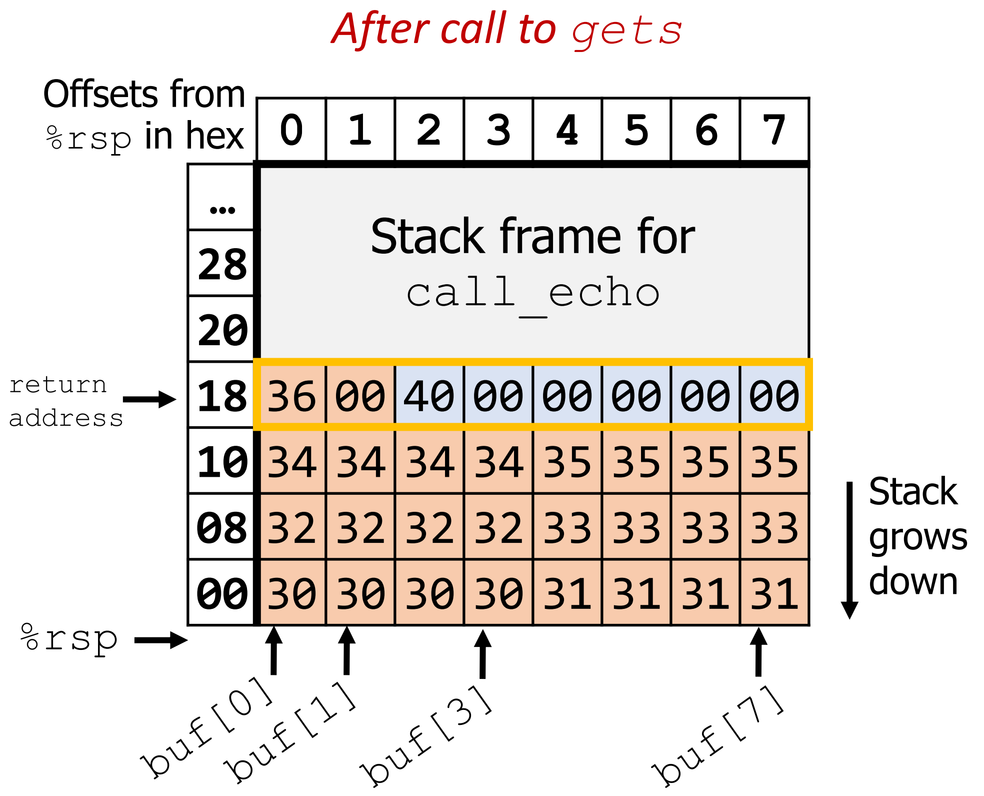
```
echo:
  subq   $24, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

```
call_echo:
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $8,%rsp
  . . .
```

```
unix>./bufdemo-nsp
Type a string: 000011112222333344445555
000011112222333344445555
```

Overflowed buffer, but did not corrupt state

Buffer Overflow Stack Example #2




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

```
echo:
  subq   $24, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

```
call_echo:
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $8,%rsp
  . . .
```

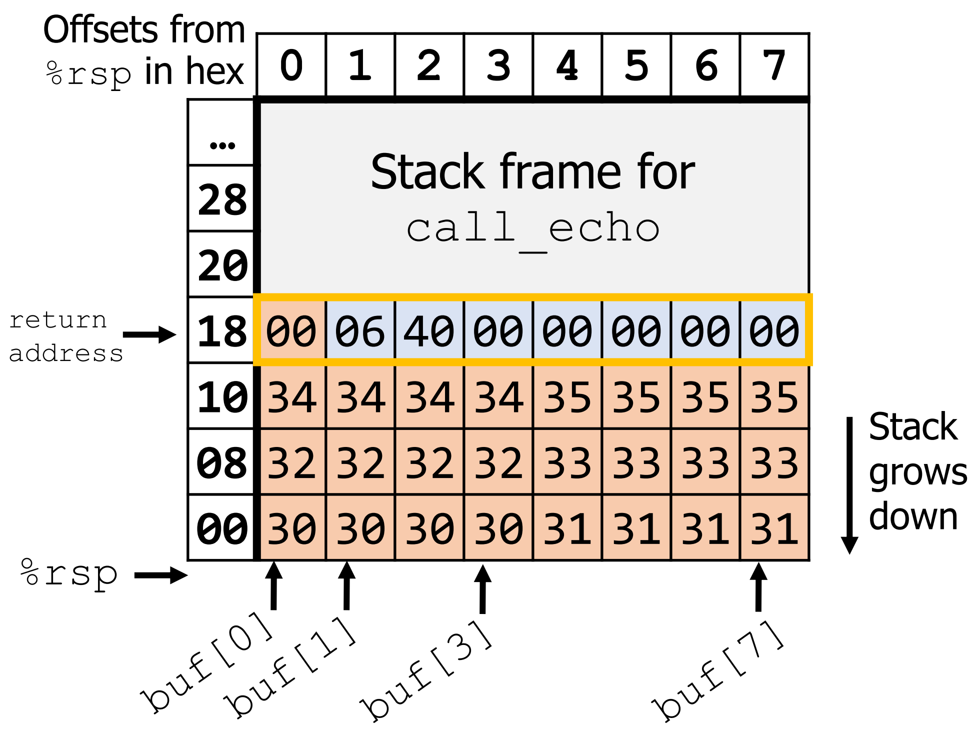
Is it a string?
Is it an address?
Depends on context!

```
unix>./bufdemo-nsp
Type a string: 000011112222333344445556
Segmentation Fault
```

Overflowed buffer and corrupted return address. Could point to unmapped memory, etc.

Buffer Overflow Stack Example #3

After call to `gets`




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

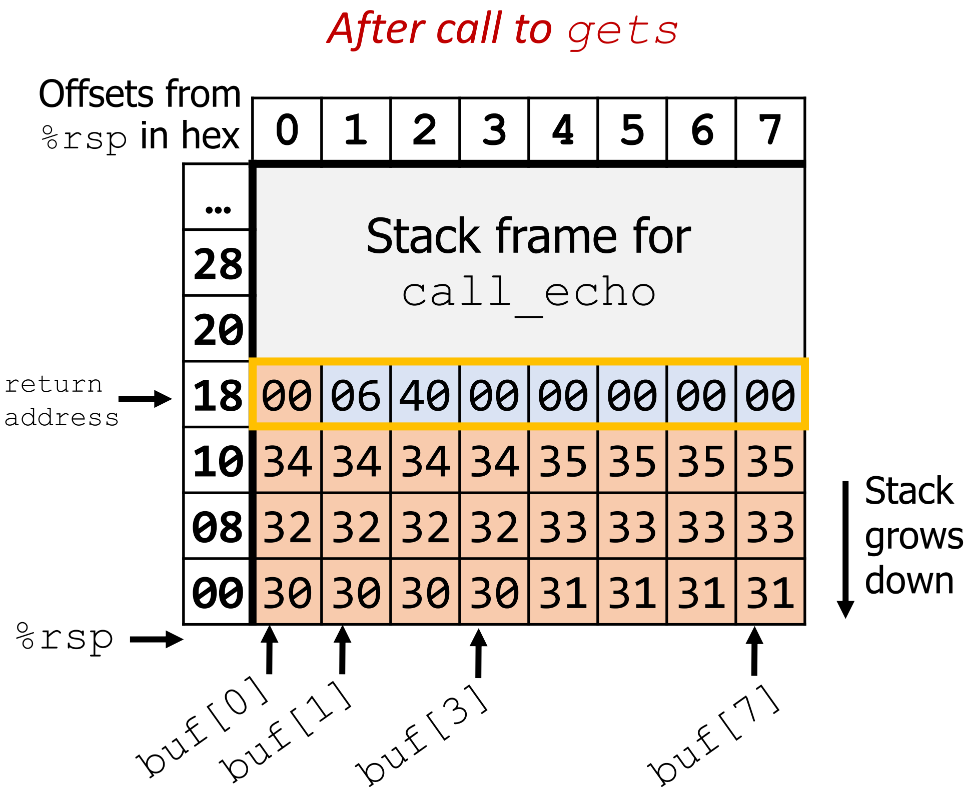
```
echo:
  subq   $24, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

```
call_echo:
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $8,%rsp
  . . .
```

```
unix>./bufdemo-nsp
Type a string: 000011112222333344445555
000011112222333344445555
```

Overflowed buffer, corrupted return address, but program *seems* to work! Latent bug!

Buffer Overflow Stack Example #3 Explained




```
register_tm_clones:
  . . .
  400600:  mov     %rsp,%rbp
  400603:  mov     %rax,%rdx
  400606:  shr     $0x3f,%rdx
  40060a:  add     %rdx,%rax
  40060d:  sar     %rax
  400610:  jne     400614
  400612:  pop     %rbp
  400613:  retq
```

"Returns" to unrelated code

Lots of things happen, without modifying critical state

Eventually executes `retq` back to `main` as if nothing happened...

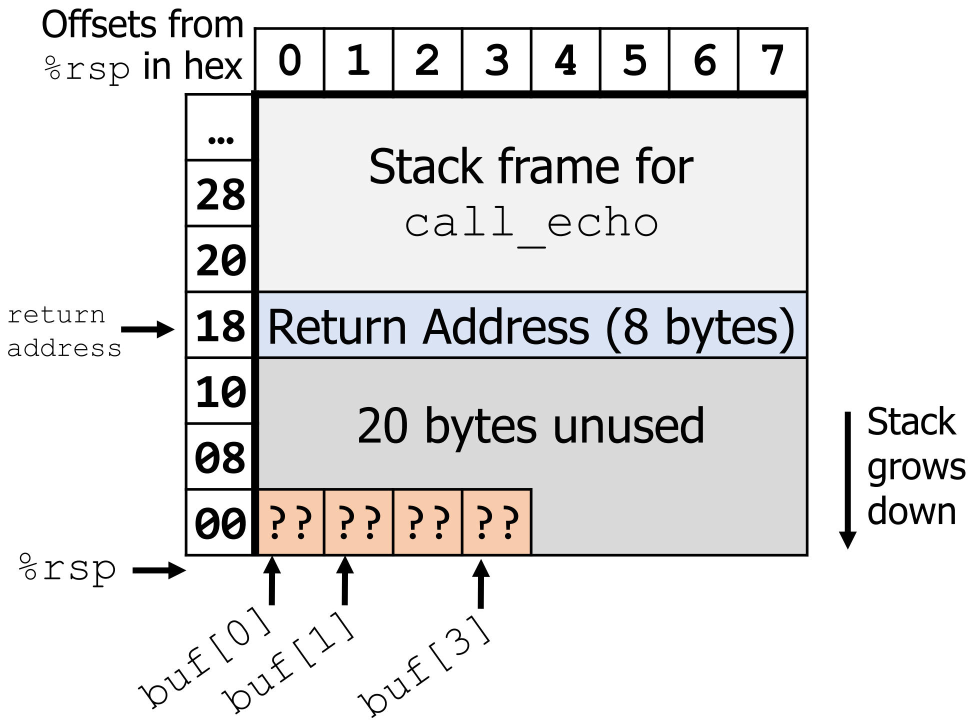
Break + Question

- Generally: How many bytes must be written to corrupt the return address? (assume `char buf[4];`)

- Is the answer the same for all programs?

- Is it the same each time the code runs?

After call to `gets`

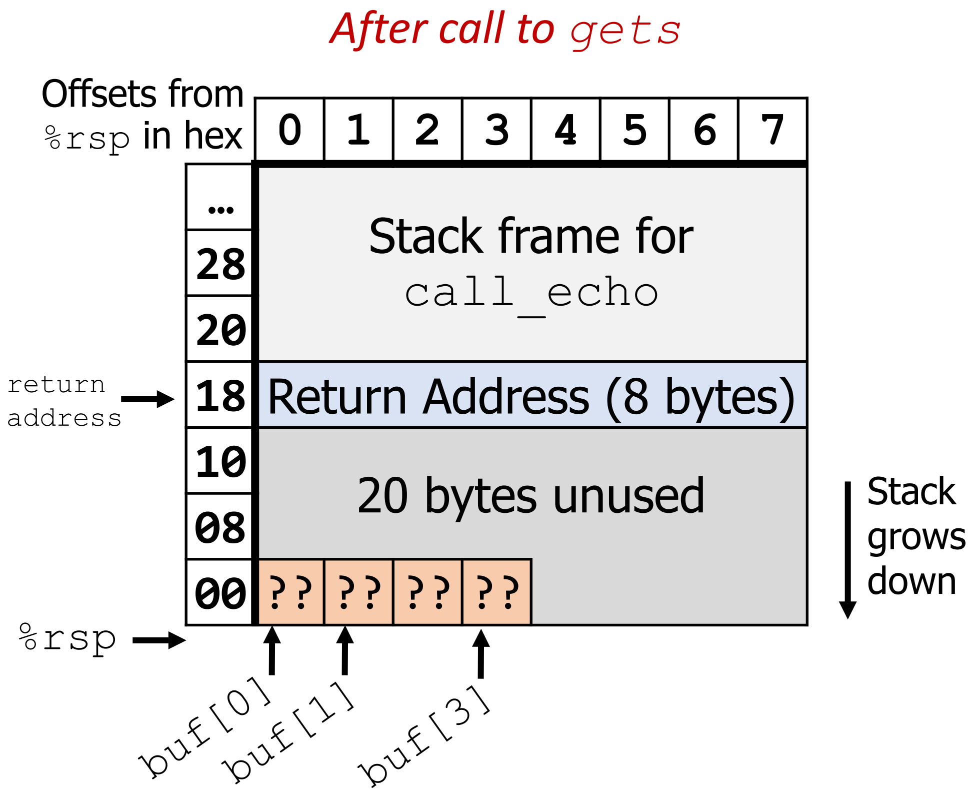


Break + Question

- Generally: How many bytes must be written to corrupt the return address? (assume `char buf[4];`) -> 25 bytes

- Is the answer the same for all programs?
  - No! Depends how much stack space the function uses

- Is it the same each time the code runs?
  - Almost certainly yes. Functions usually use the same amount of stack space each time



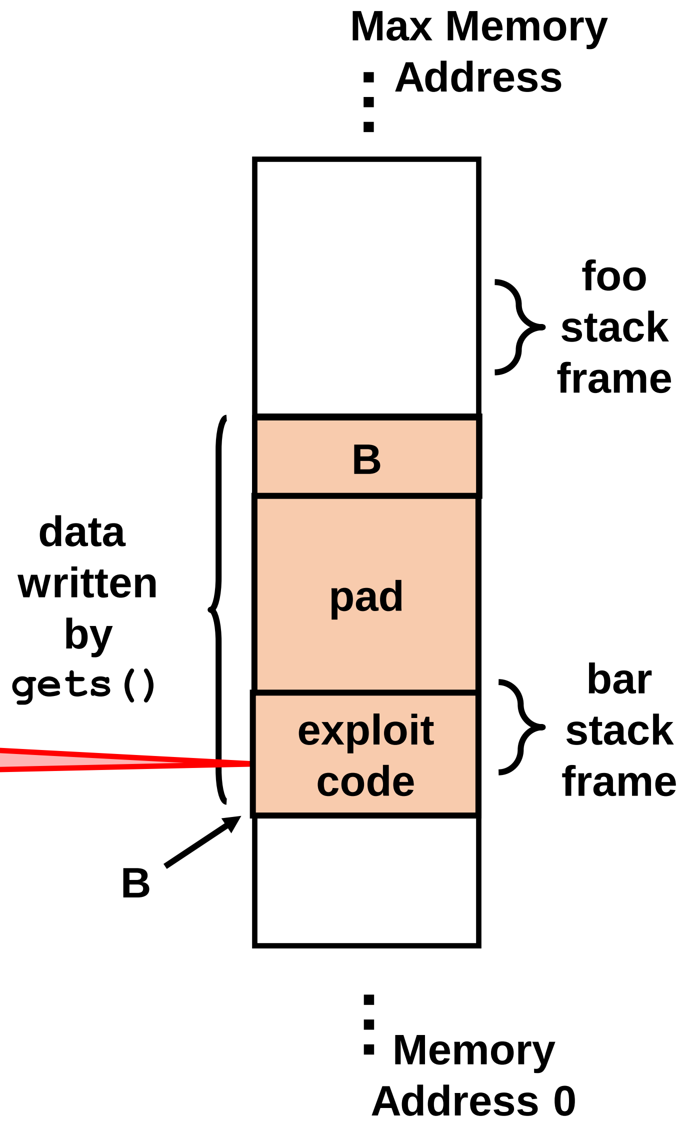
Malicious use of buffer overflow

return address A →

```
void foo(){
  bar();
  ...
}
```

```
void bar() {
  char buf[64];
  gets(buf);
  ...
}
```

```
08048444 <malicious_code>:
 8048444:    55               push   %ebp
 8048445:    89 e5            mov    %esp,%ebp
 8048447:    53               push   %ebx
 8048448:    83 ec 24         sub    $0x24,%esp
 804844b:    8d 5d f4         lea    -0xc(%ebp),%ebx
 804844e:    89 1c 24         mov    %ebx,(%esp)
 8048451:    e8 fa fe ff ff   call   8048350
 8048456:    89 1c 24         mov    %ebx,(%esp)
```



- Input string contains binary representation of executable code
- Overwrite return address with address of buffer
- When **`bar()`** returns, where do we go?
  - Into the beginning of **`malicious_code`** on the stack! 😱

Exploits based on buffer overflows

- Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines

- Distressingly common in real programs
  - Programmers keep making the same mistakes 😭
  - Recent measures make these attacks much more difficult

- Examples across the decades
  - Original "Internet worm" (1988)
    - Attacked **`fingerd`** server, replicated itself across the internet
  - Stuxnet (2010)
    - Attack on Iran nuclear program, malicious code destroyed centrifuges
  - … and many, many more

- You will learn some of these tricks with the attack lab
  - Hopefully convincing you to never leave such holes in your programs!

Outline

- Buffer Overflows
- **Protecting Against Buffer Overflows**
- Return-Oriented Programming
- Protecting Against Return-Oriented Programming

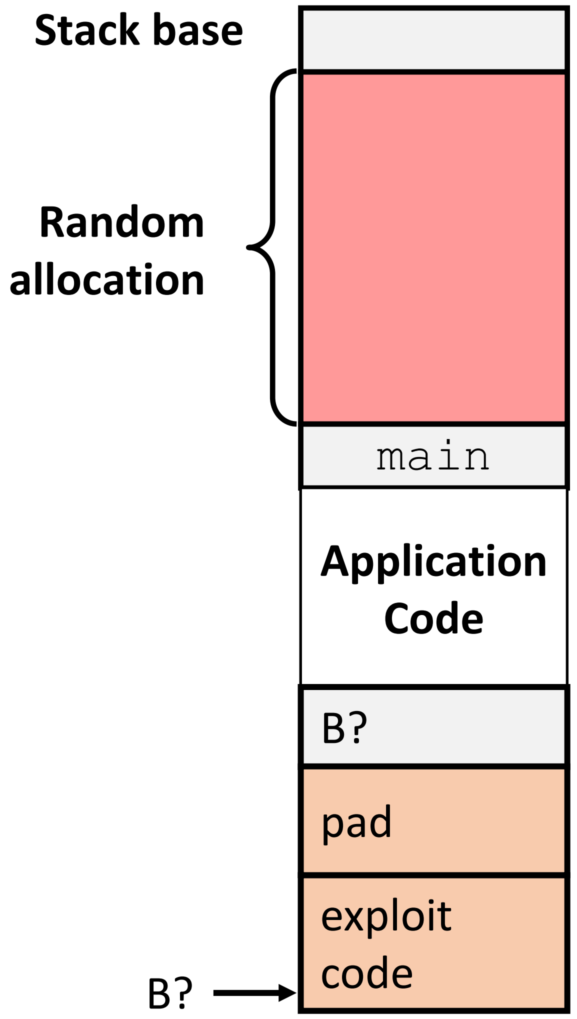
1. Avoiding Buffer Overflow Vulnerability

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin); /* length limit! */
    puts(buf);
}
```

- Use safe library routines that limit string lengths
  - **`fgets`** instead of **`gets`**
  - **`strncpy`** instead of **`strcpy`**
  - Don't use **`scanf`** with **`%s`** conversion specification
    - Use **`fgets`** to read the string
    - Or use format specifier **`%ns`** where **`n`** is a suitable integer
- Also: don't write your programs in C, when possible
  - Fundamental design of C is to be fast, not to be secure

2. System-Level Protection: Randomized Stack

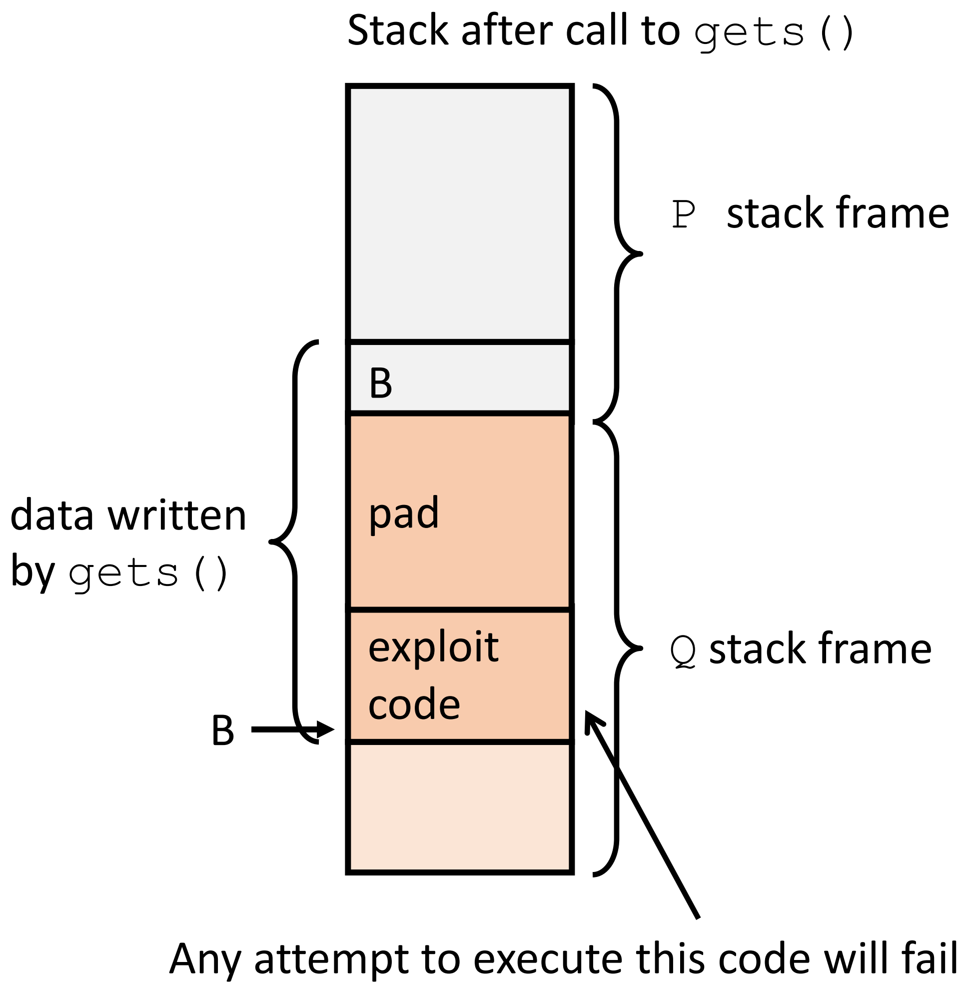
- Buffer overflow attack requires knowing the *absolute* address of the buffer
  - To overwrite return address to that
- At start of program, allocate a random amount of space on stack
  - Different every time the program runs
- Shifts stack addresses for entire program
  - Program still runs fine
  - Legitimate accesses to the stack are ***relative*** to `%rsp`
- But absolute addresses get randomly shifted
  - Don't know what return address should be!
  - Still not impossible to overcome (NOP sled)



3. System-Level Protection: Explicit Execute Page Permissions

- Non-executable stack
  - On x86-64, can mark a region of memory as “non-executable”
  - Trying to execute something in that region → crash
  - More about page permissions in the virtual memory lecture (later in class)

- OpenBSD goes further: W^X
  - A region of memory can be writeable or executable, but not both (xor!)
  - Causes trouble for JITs



Break + Open Question

- **Why is a buffer overflow in a web browser so bad?**

Break + Open Question

- **Why is a buffer overflow in a web browser so bad?**
  - The buffer overflow will exist in *at least* all instances of the same version of the web browser installed on the same OS and architecture
    - Possibly many other versions too
  - If it can be triggered from a website, then you could run malicious code on computers without any manual effort
    - Any website could be suspect
  - Scale is enormous: Chrome has roughly 3 billion users

Outline

- Buffer Overflows
- Protecting Against Buffer Overflows

- **Return-Oriented Programming**
- Protecting Against Return-Oriented Programming

How else are buffer overflows dangerous?

- Without the ability to write malicious code, our computers are safe, right??

1. Some computers won’t fix it: legacy hardware, forgot, etc.

2. Buffer overflows are definitely still happening
    - Can we take advantage of that in some way?

Finding a new way to abuse a vulnerability

- Buffer overflows can still write values to the stack
- Even if they can't place malicious code directly on the stack, they can always modify return addresses
- We can use that idea to build an attack from pieces of already existing program code that we reuse for malicious purposes
  - This is one of those ideas that sounds impossible to pull off in the real world
  - But actually, it totally works AND we'll have you do it in Attack Lab!

Return-Oriented Programming (ROP)

- Challenge (for would-be hackers)
  - Stack randomization → predicting buffer location is hard
    - So it's hard to know where to jump and start executing
  - Making stack non-executable → injecting code doesn't work
    - We can inject anything we want, but we can't run it
- Alternative strategy: Don't inject your own code!
  - Use code that's already in the program!
  - It's in a predictable location!
    - Otherwise, don't know where to call/jump
  - It's executable
    - Otherwise, the program wouldn't run at all…

Return-Oriented Programming (ROP)

- But wait, the code I want to run isn't in the program!
  - Unlikely that, e.g., a mail client includes code to, e.g., launch missiles

- Key idea: construct the code you want to run from pieces that you find in the program!
  - We'll call these pieces **gadgets**

- Strategy: find machine code fragments that do *one small step* of the malicious program you want to run, then return
  - Then we'll put these small steps together to get the whole program
  - These return instructions will be the glue that tie them together

- "The program" includes the standard library!
  - Things like **`printf`**, **`scanf`**, etc.
  - That's a lot of code! So, lots of gadgets to choose from

Gadget Examples

- Use the end of existing functions

```
long ab_plus_c
    (long a, long b, long c){
  return a*b + c;
}
```

```
00000000004004d0 <ab_plus_c>:
  4004d0: 48 0f af fe     imul %rsi,%rdi
  4004d4: 48 8d 04 17     lea  (%rdi,%rdx,1),%rax
  4004d8: c3              ret
```

Gadget: `rax ← rdi + rdx`
Address: `0x4004d4`

- Repurpose parts of instructions

```
void setval
     (unsigned *p) {

  *p = 3347663060u;
}
```

```
00000000004004d9 <setval>:
  4004d9: c7 07 d4 48 89 c7     movl $0xc78948d4,(%rdi)
  4004df: c3                    ret
```

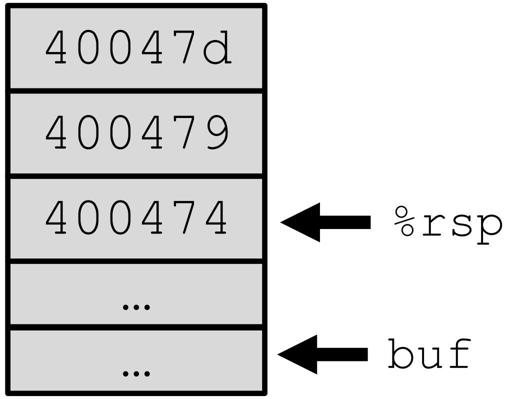
Encodes: `movq %rax, %rdi`
Gadget: `rdi ← rax`
Address: `0x4004dc`

Combining Gadgets

- Let's say our malicious program is this:
  `%rax = (%rbx * %rcx) + %rdi`
- And let's say we found the following gadgets in the standard library

```
0000000000400474 <g1>:
  400474: 48 0f af cb      imul %rbx,%rcx
  400478: c3               retq
0000000000400479 <g2>:
  400479: 48 01 cf         add %rcx,%rdi
  40047c: c3               retq
000000000040047d <g3>:
  40047d: 48 89 f8         mov %rdi,%rax
  400480: c3               retq
```

Given a large enough standard library, can find gadgets that do pretty much anything we want! Plenty of code to pick from.



- Combine gadgets by adding pointers to them to the stack
  - Arrange on the stack by overflowing a buffer, like before

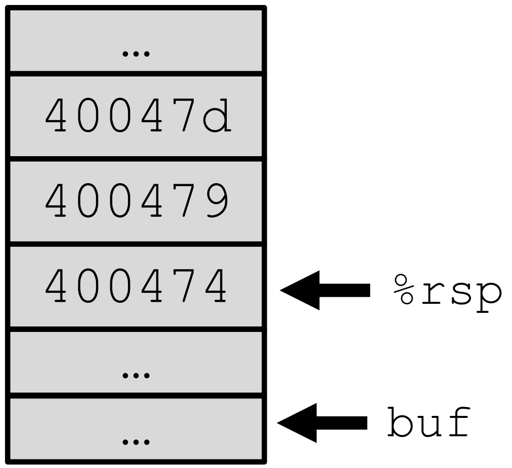
Gadget Execution

- Step 1: we overflowed the buffer, like before
  - We set up the stack with the gadget addresses, as on last slide
  - Now we're about to return from the vulnerable function (**`echo`**)

```
00000000004006cf <echo>:
  ...
  4006d6:  e8 a5 ff ff ff          callq  400680 <gets>
  ...
  4006e7:  c3                      retq
```

```
0000000000400474 <g1>:
  400474: 48 0f af cb     imul %rbx,%rcx
  400478: c3              retq
0000000000400479 <g2>:
  400479: 48 01 cf        add %rcx,%rdi
  40047c: c3              retq
000000000040047d <g3>:
  40047d: 48 89 f8        mov %rdi,%rax
  400480: c3              retq
```

%rip = 4006e7

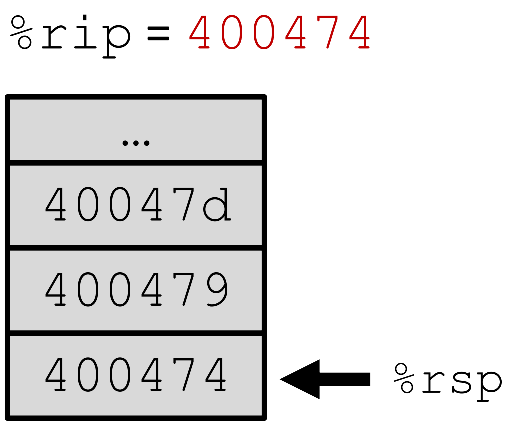


Gadget Execution

- Step 2: return from `echo`
  - Get the return address from **`%rsp`**
  - Oh, that's the address of the first gadget!

```
00000000004006cf <echo>:
  ...
  4006d6:   e8 a5 ff ff ff          callq   400680 <gets>
  ...
  4006e7:   c3                      retq
```

```
0000000000400474 <g1>:
  400474: 48 0f af cb     imul %rbx,%rcx
  400478: c3              retq
0000000000400479 <g2>:
  400479: 48 01 cf        add %rcx,%rdi
  40047c: c3              retq
000000000040047d <g3>:
  40047d: 48 89 f8        mov %rdi,%rax
  400480: c3              retq
```



Gadget Execution

- Step 3: run the first gadget
  - **%rcx = %rbx × %rcx**

```
0000000004006cf <echo>:
 ...
 4006d6:   e8 a5 ff ff ff          callq  400680 <gets>
 ...
 4006e7:   c3                      retq
```

```
0000000000400474 <g1>:
  400474: 48 0f af cb     imul %rbx,%rcx
  400478: c3              retq
0000000000400479 <g2>:
  400479: 48 01 cf        add %rcx,%rdi
  40047c: c3              retq
000000000040047d <g3>:
  40047d: 48 89 f8        mov %rdi,%rax
  400480: c3              retq
```

%rip = 400474

…
40047d
400479 ← %rsp

Gadget Execution

- Step 4: return from the first gadget
  - Get the return address from **`%rsp`**
  - **QUIZ**: where do we go next?

`400479`, that’s gadget 2!

```
0000000004006cf <echo>:
  ...
  4006d6:  e8 a5 ff ff ff          callq  400680 <gets>
  ...
  4006e7:  c3                      retq
```

```
0000000000400474 <g1>:
  400474: 48 0f af cb     imul %rbx,%rcx
→ 400478: c3              retq
0000000000400479 <g2>:
  400479: 48 01 cf        add %rcx,%rdi
  40047c: c3              retq
000000000040047d <g3>:
  40047d: 48 89 f8        mov %rdi,%rax
  400480: c3              retq
```

`%rip` = `400478`

…
40047d
400479 ← %rsp

Gadget Execution

- Step 5: run the second gadget
  - **`%rdi = (%rbx × %rcx) + %rdi`**

```
00000000004006cf <echo>:
 ...
 4006d6:  e8 a5 ff ff ff          callq  400680 <gets>
 ...
 4006e7:  c3                      retq
```

```
0000000000400474 <g1>:
  400474: 48 0f af cb     imul %rbx,%rcx
  400478: c3              retq
0000000000400479 <g2>:
  400479: 48 01 cf        add %rcx,%rdi
  40047c: c3              retq
000000000040047d <g3>:
  40047d: 48 89 f8        mov %rdi,%rax
  400480: c3              retq
```

%rip = 400479

Stack
…
40047d ← %rsp

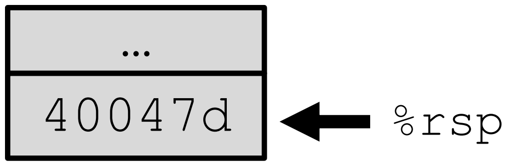
Gadget Execution

- Step 6: return from the second gadget
  - Get the return address from **`%rsp`**
  - Oh, that's the address of the third gadget!

```
00000000004006cf <echo>:
 ...
 4006d6:  e8 a5 ff ff ff          callq  400680 <gets>
 ...
 4006e7:  c3                      retq
```

```
0000000000400474 <g1>:
  400474: 48 0f af cb     imul %rbx,%rcx
  400478: c3              retq
0000000000400479 <g2>:
  400479: 48 01 cf        add %rcx,%rdi
  40047c: c3              retq
000000000040047d <g3>:
  40047d: 48 89 f8        mov %rdi,%rax
  400480: c3              retq
```

%rip = 40047d



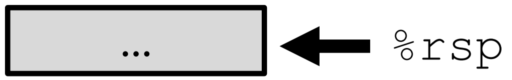
Gadget Execution

- Step 7: run the third gadget
  - **%rax = (%rbx × %rcx) + %rdi**
  - We’ve run the program we wanted to run. Our job is done.

```
00000000004006cf <echo>:
 ...
 4006d6:  e8 a5 ff ff ff          callq  400680 <gets>
 ...
 4006e7:  c3                      retq
```

```
0000000000400474 <g1>:
  400474: 48 0f af cb     imul %rbx,%rcx
  400478: c3              retq
0000000000400479 <g2>:
  400479: 48 01 cf        add %rcx,%rdi
  40047c: c3              retq
000000000040047d <g3>:
→ 40047d: 48 89 f8        mov %rdi,%rax
  400480: c3              retq
```

%rip = 40047d

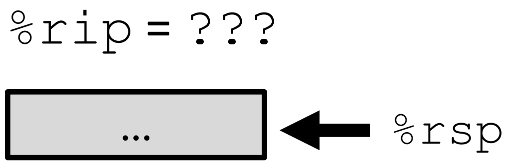


Gadget Execution

- Step 8: Return from the third gadget
  - At this point, return to whatever address we find on the stack.
  - That's past the data we put there ourselves, so it's whatever was there before. Maybe not meant to be an address! Could be anything!

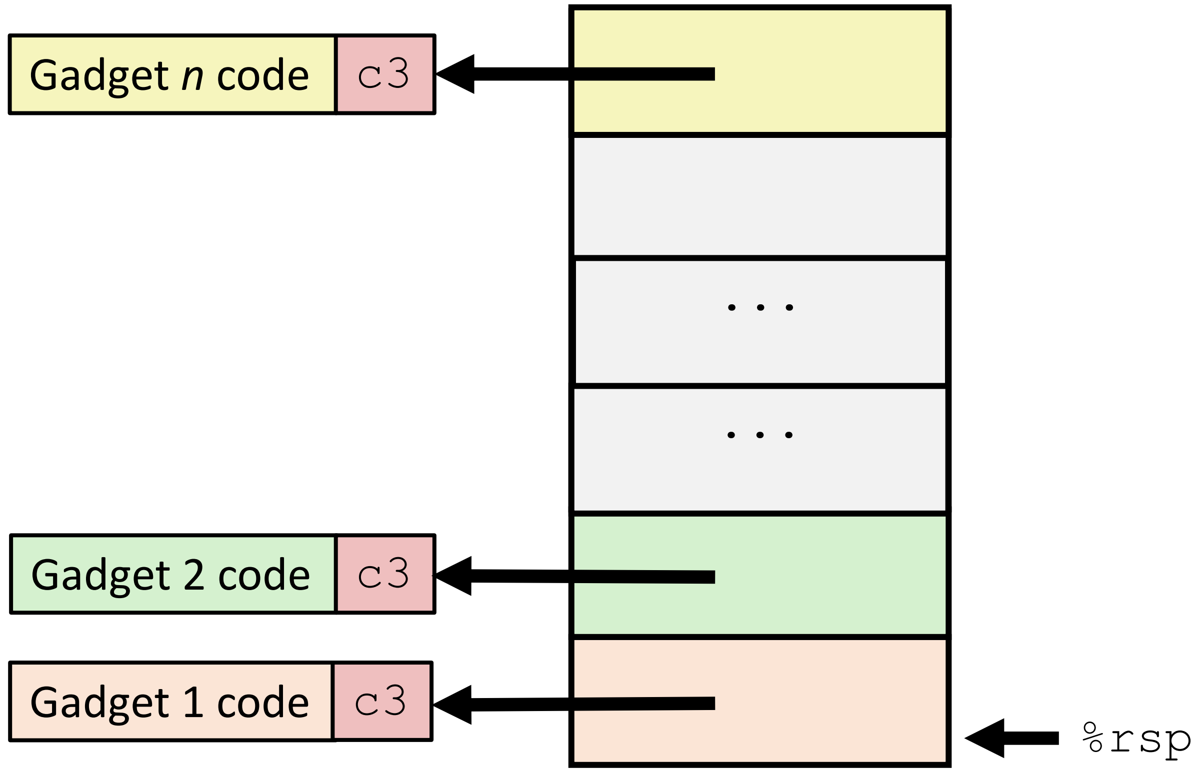
- But we don't care about what the program does anymore!
  - We've run the code we wanted to run, nothing else matters!
  - (Maybe we stole from bank accounts, launched missiles, etc.)

```
0000000000400474 <g1>:
  400474: 48 0f af cb     imul %rbx,%rcx
  400478: c3              retq
0000000000400479 <g2>:
  400479: 48 01 cf        add %rcx,%rdi
  40047c: c3              retq
000000000040047d <g3>:
  40047d: 48 89 f8        mov %rdi,%rax
  400480: c3              retq
```



Return-Oriented Programming Execution

- Trigger with `ret` instruction in the current function
- "Returns" to gadget 1, instead of to its caller
- Gadget 1 does its thing, then returns to gadget 2, etc.
  - Repeat as necessary
- Complete! You've "run" the "function" you wanted to run!



Outline

- Buffer Overflows
- Protecting Against Buffer Overflows

- Return-Oriented Programming
- **Protecting Against Return-Oriented Programming**

1. Avoiding buffer overflow vulnerabilities

- Write better code please

- Return-oriented programming starts with a buffer overflow
  - To set up gadget addresses on the stack

- No buffer overflow, no return-oriented programming!

2. Stack Canaries

- Idea
  - Place special value ("canary") on stack just beyond buffer
  - Check for corruption before exiting function
  - So we can detect buffer overflows ***before*** we run malicious code
    - Then just crash the program instead of doing bad things
  - Analogy: canary in a coal mine

- GCC Implementation
  - **`-fstack-protector`**
  - Now the default for potentially vulnerable functions
    - (disabled in attack lab to show the vulnerability)

```
unix>./bufdemo-sp
Type a string:0123456
0123456
```

```
unix>./bufdemo-sp
Type a string:01234567
*** stack smashing detected ***
```

2. Stack Canaries - Disassembly

echo:

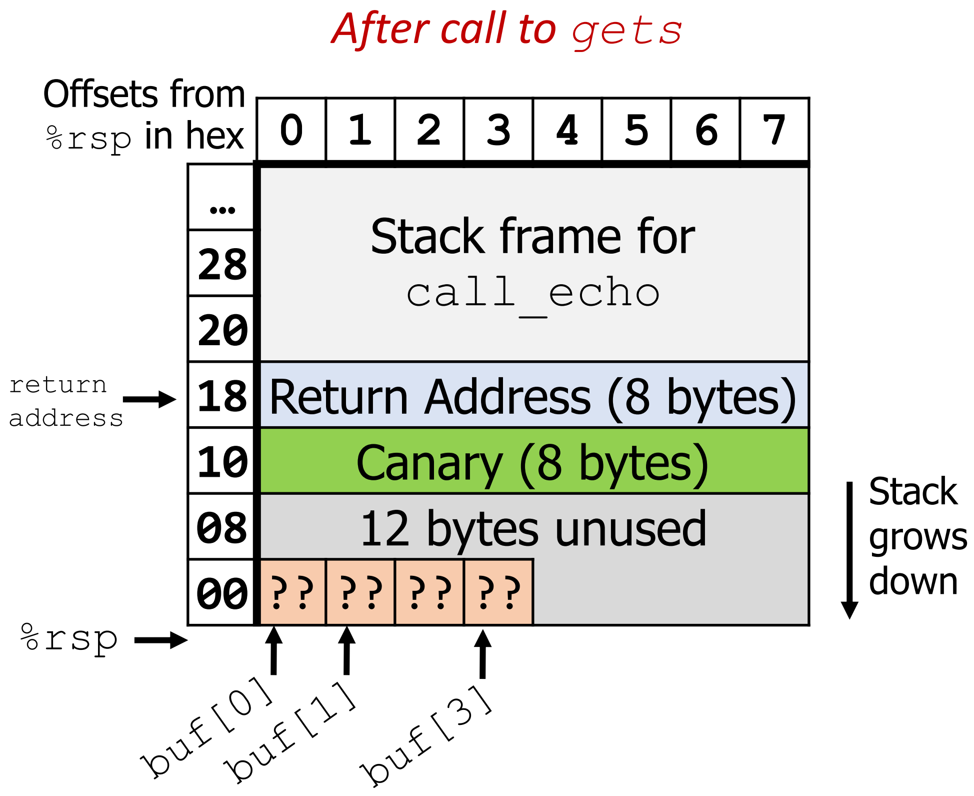
```
40072f:  sub    $0x18,%rsp
400733:  mov    %fs:0x28,%rax
40073c:  mov    %rax,0x8(%rsp)
400741:  xor    %eax,%eax
400743:  mov    %rsp,%rdi
400746:  callq  4006e0 <gets>
40074b:  mov    %rsp,%rdi
40074e:  callq  400570 <puts@plt>
400753:  mov    0x8(%rsp),%rax
400758:  xor    %fs:0x28,%rax
400761:  je     400768 <echo+0x39>
400763:  callq  400580 <__stack_chk_fail@plt>
400768:  add    $0x18,%rsp
40076c:  retq
```

Read value from a special, read-only segment in memory

Store it on the stack at offset 8 from `%rsp`

Check the canary is fine using `xorl` (0 if the two values are identical)

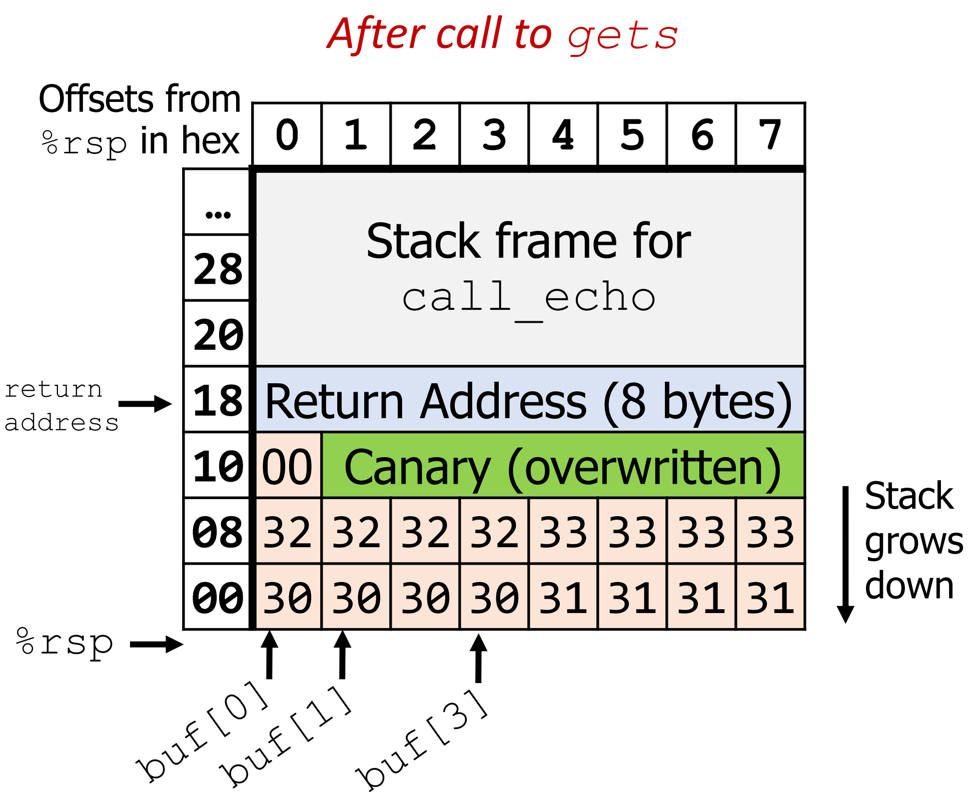
2. Stack Canaries - Setting up canary




```
/* Echo Line */
void echo()
{
    char buf[4];   /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movq    %fs:40, %rax   # Get canary
    movq    %rax, 8(%rsp)  # Place on stack
    xorl    %eax, %eax     # Erase canary
    . . .
```

2. Stack Canaries - Setting up canary




```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

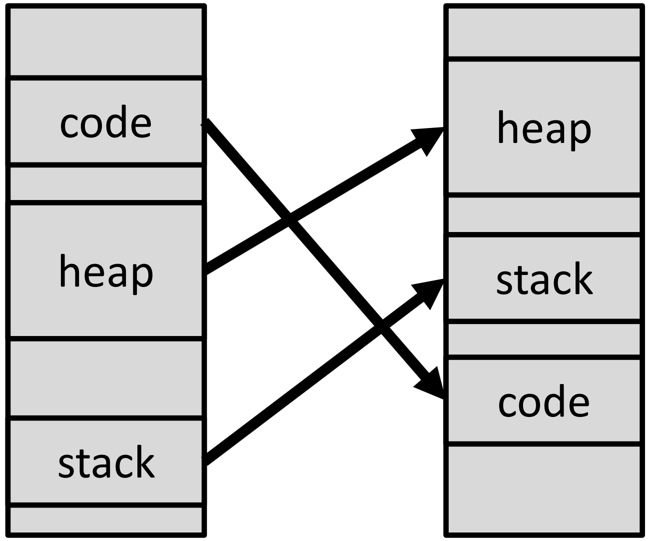
```
echo:
    . . .
    movq    8(%rsp), %rax       # Retrieve from stack
    xorq    %fs:40, %rax        # Compare to canary
    je      .L6                 # If same, OK
    call    __stack_chk_fail    # FAIL
.L6:        . . .
```

Input: *000111122223333*

Code crashes due to canary mismatch

3. Address space layout randomization (ASLR)

- Like stack randomization, generalized to all of memory
  - ***Especially***: executable code
- Code, stack, heap all start in random locations
  - Determined when program starts up
  - You know the gadget you want is at the end of **`ab_plus_c`**
  - But if you don't know where **`ab_plus_c`** ***is***, that's no use!
- Can be circumvented by clever side-channel attacks
  - But really hard! Much harder than ROP




```
???? <ab_plus_c>:
  ????: 48 0f af fe
  ????: 48 8d 04 17
  ????: c3
```

Security is an arms race

- There is no single fix for system security
  - New attacks are constantly being discovered
  - New solutions are constantly being applied

1. Find a vulnerability and how it can be exploited
2. Fix vulnerability
3. Go back to 1

- A good goal is to at least avoid all the simple known attacks
- Designing with security in mind can make vulnerabilities harder to find in the first place

Outline

- Buffer Overflows
- Protecting Against Buffer Overflows
- Return-Oriented Programming
- Protecting Against Return-Oriented Programming