Buffer Overflows

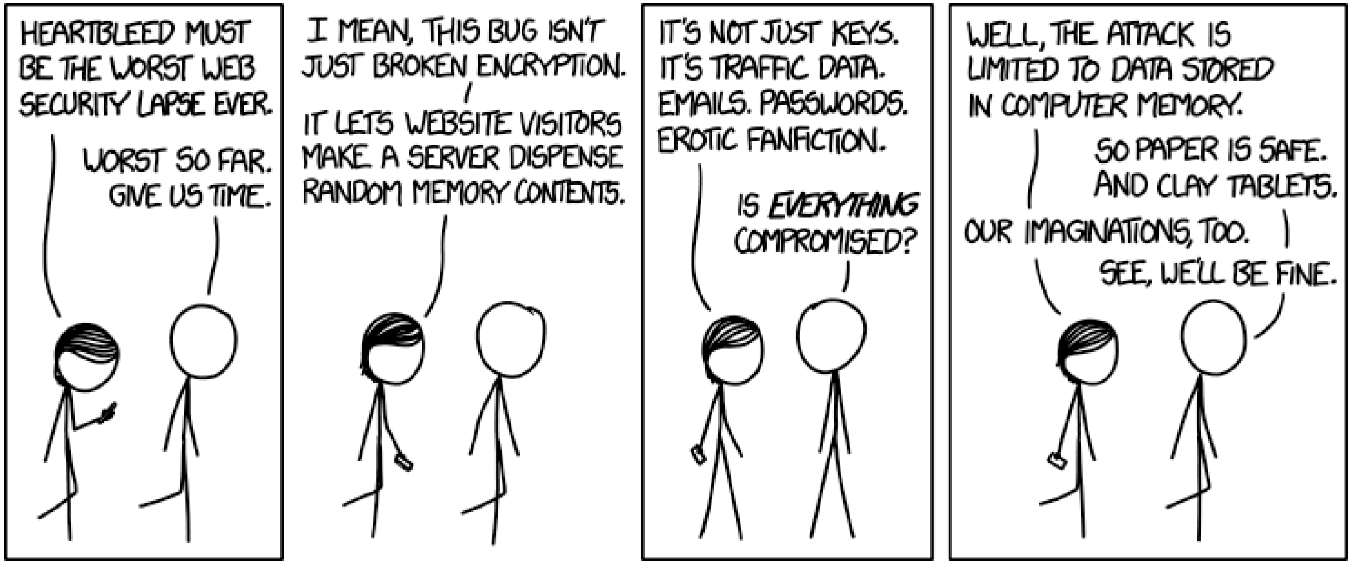
CSE 351 Autumn 2022

Instructor:

Justin Hsia

Teaching Assistants:

Angela Xu
Arjun Narendra
Armin Magness
Assaf Vayner
Carrie Hu
Clare Edmonds
David Dai
Dominick Ta
Effie Zheng
James Froelich
Jenny Peng
Kristina Lansang
Paul Stevans
Renee Ruan
Vincent Xiao



Alt text: I looked at some of the data dumps from vulnerable sites, and it was ... bad. I saw emails, passwords, password hints. SSL keys and session cookies. Important servers brimming with visitor IPs. Attack ships on fire off the shoulder of Orion, c-beams glittering in the dark near the Tannhäuser Gate. I should probably patch OpenSSL.

http://xkcd.com/1353/

Relevant Course Information

- hw13 due Wednesday (11/2)
- hw15 due Monday (11/7)

- Lab 3 released today, due next Friday (11/11)
  - You will have everything you need by the end of this lecture

- Midterm starts Thursday
  - Instructions will be posted on Ed Discussion
  - Gilligan's Island Rule: discuss high-level concepts and give hints, but not solving the problems together
  - We will be available on Ed Discussion (private posts, please) and office hours to answer clarifying questions

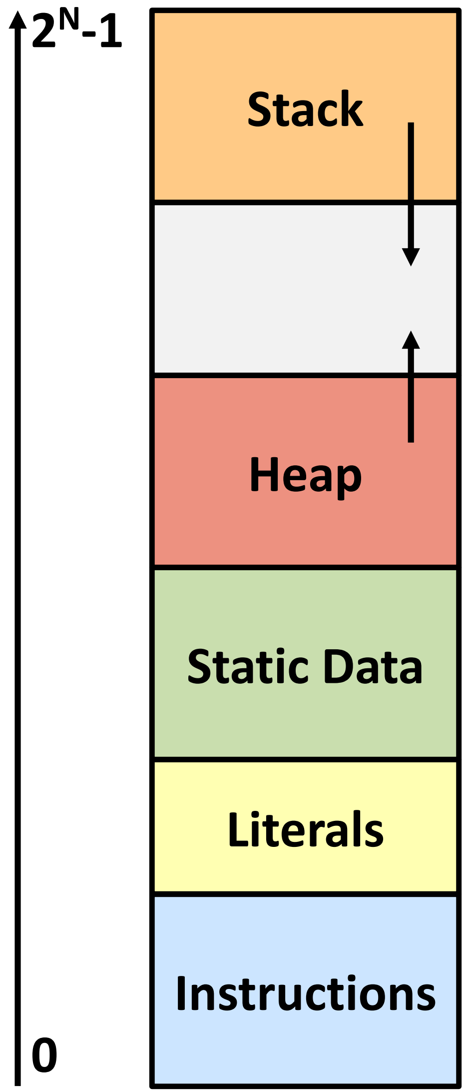
Buffer Overflows

- Address space layout review
- Input buffers on the stack
- Overflowing buffers and injecting code
- Defenses against buffer overflows

not drawn to scale

Review: General Memory Layout

- Stack
  - Local variables (procedure context)
- Heap
  - Dynamically allocated as needed
  - `new`, `malloc()`, `calloc()`, …
- Statically-allocated Data
  - Read/write: global variables (Static Data)
  - Read-only: string literals (Literals)
- Code/Instructions
  - Executable machine instructions
  - Read-only



not drawn to scale

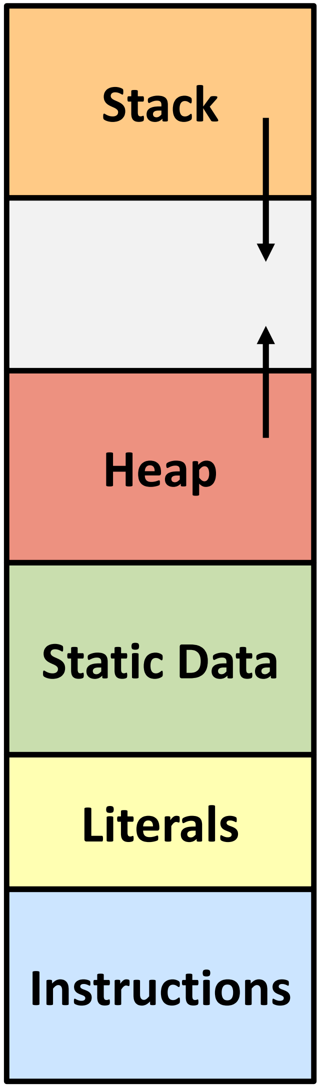
Memory Allocation Example

```
char big_array[1L<<24];  /* 16 MB */

int global = 0;

int useless() { return 0; }

int main() {
  void *p1, *p2;
  int local = 0;
  p1 = malloc(1L << 28); /* 256 MB */
  p2 = malloc(1L << 8);  /* 256  B */
  /* Some print statements ... */
}
```



Where does everything go?

not drawn to scale

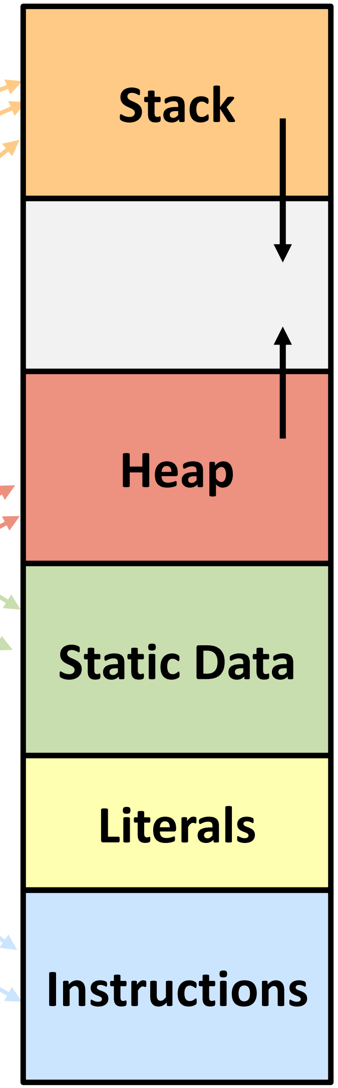
Memory Allocation Example

```
char big_array[1L<<24];   /* 16 MB */

int global = 0;

int useless() { return 0; }

int main() {
  void *p1, *p2;
  int local = 0;
  p1 = malloc(1L << 28); /* 256 MB */
  p2 = malloc(1L << 8);  /* 256  B */
  /* Some print statements ... */
}
```



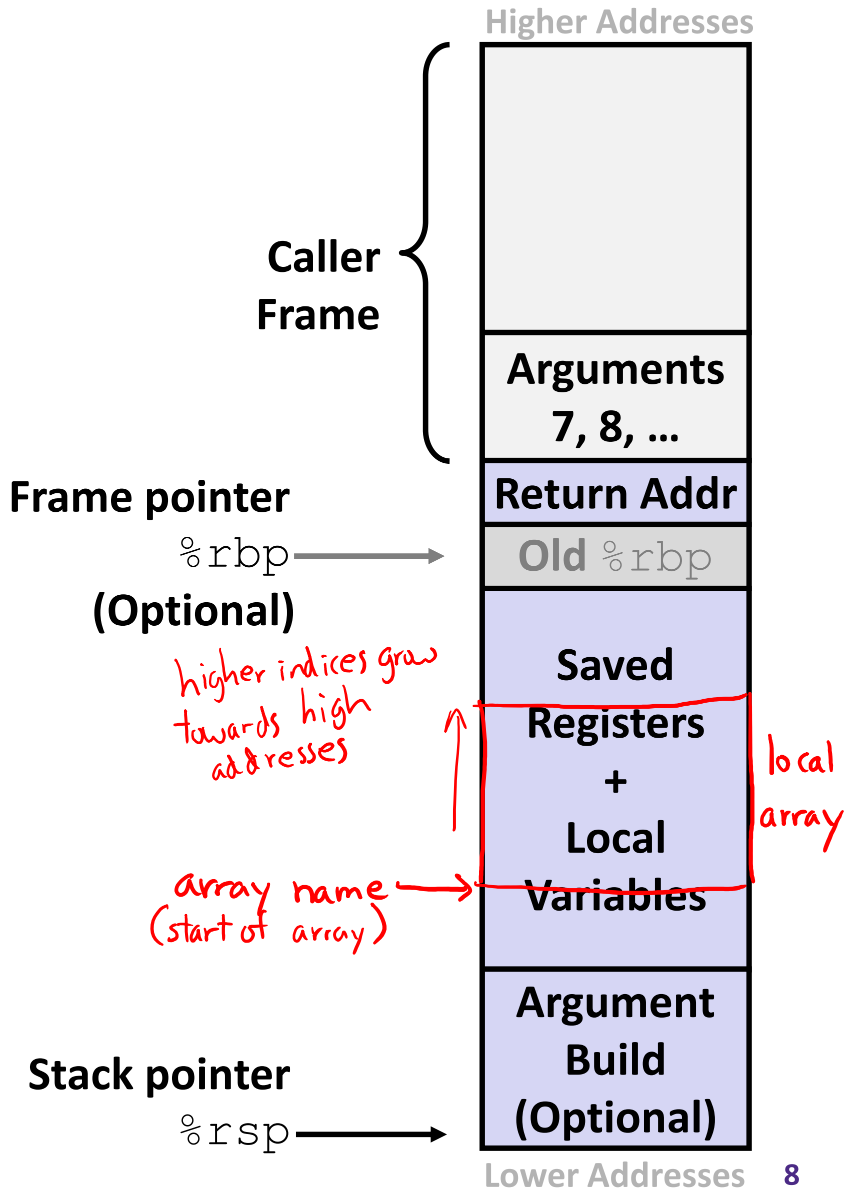
Where does everything go?

What Is a Buffer?

- A buffer is an array used to temporarily store data
- You've probably seen "video buffering…"
  - The video is being written into a buffer before being played
- Buffers can also store user input

Reminder: x86-64/Linux Stack Frame

- Caller's Stack Frame
  - Arguments (if > 6 args) for this call
- Current/ Callee Stack Frame
  - Return address
    - Pushed by `call` instruction
  - Old frame pointer (optional)
  - Caller-saved pushed before setting up arguments for a function call
  - Callee-saved pushed before using long-term registers
  - Local variables (if can't be kept in registers)
  - "Argument build" area (Need to call a function with >6 arguments? Put them here)



Buffer Overflow in a Nutshell

- C does not check array bounds
  - Many Unix/Linux/C functions don’t check argument sizes
  - Allows overflowing (writing past the end) of buffers (arrays)

- “Buffer Overflow” = Writing past the end of an array

- Characteristics of the traditional Linux memory layout provide opportunities for malicious programs
  - Stack grows “backwards” in memory
  - Data and instructions both stored in the same memory

Buffer Overflow in a Nutshell

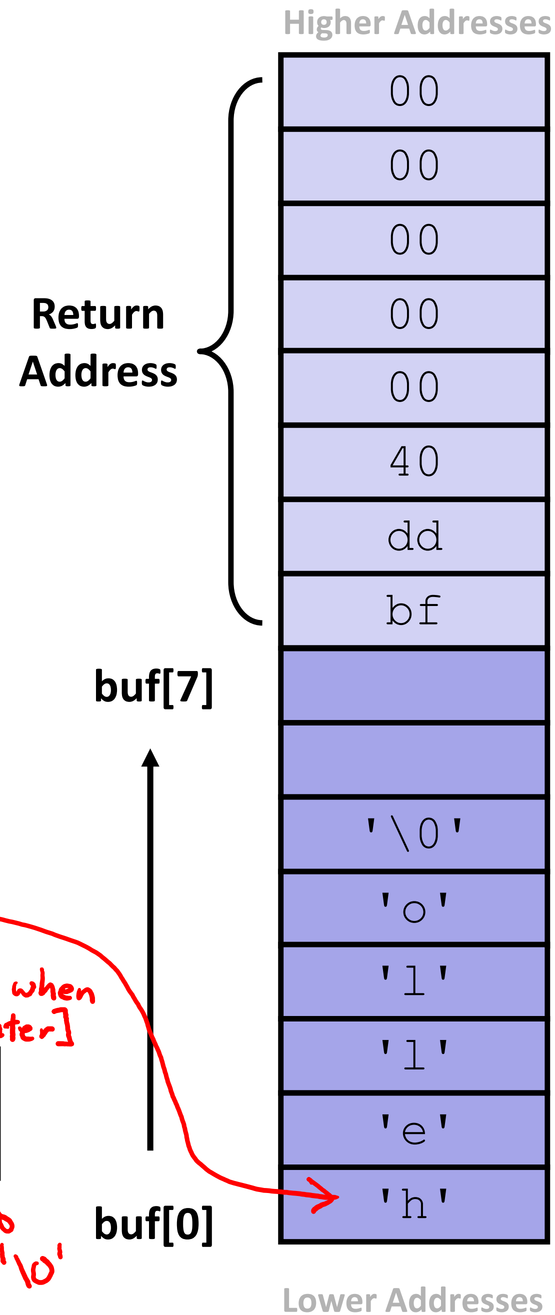
- Stack grows *down* towards lower addresses
- Buffer grows *up* towards higher addresses
- If we write past the end of the array, we overwrite data on the stack!

```
Enter input: hello
```
\n

newline inserted when user presses [Enter]

later converted to a null terminator '\0'

No overflow ☺

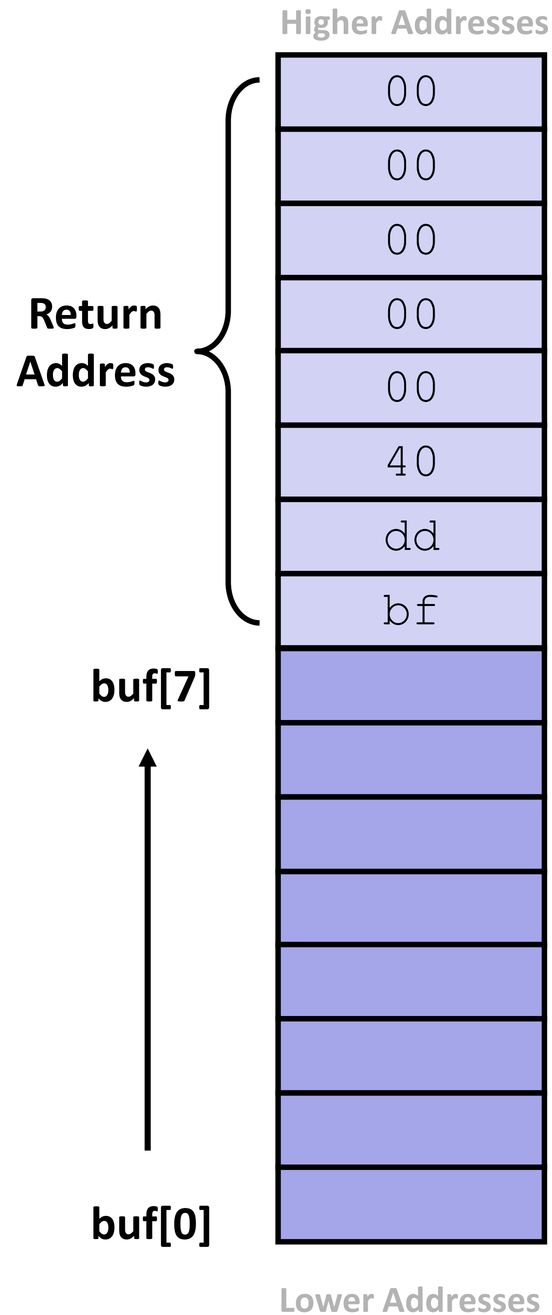


Buffer Overflow in a Nutshell

- Stack grows *down* towards lower addresses
- Buffer grows *up* towards higher addresses
- If we write past the end of the array, we overwrite data on the stack!

```
Enter input: helloabcdef
```

uh-oh!

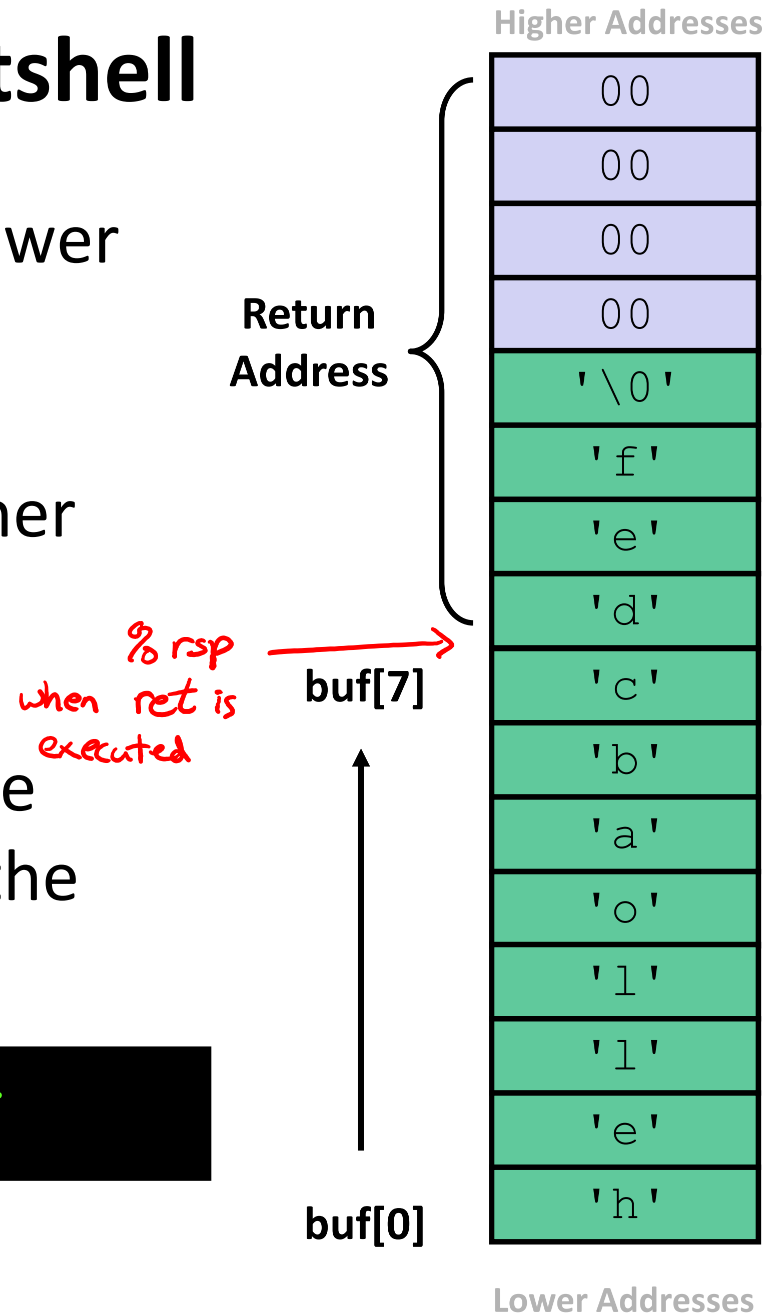


Buffer Overflow in a Nutshell

- Stack grows *down* towards lower addresses
- Buffer grows *up* towards higher addresses
- If we write past the end of the array, we overwrite data on the stack!

```
Enter input: helloabcdef
```

Buffer overflow! ☹



Buffer Overflow in a Nutshell

- Buffer overflows on the stack can overwrite "interesting" data
  - Attackers just choose the right inputs
- Simplest form (sometimes called "stack smashing")
  - Unchecked length on string input into bounded array causes overwriting of stack data
  - Try to change the return address of the current procedure
- Why is this a big deal?
  - It was the #1 *technical* cause of security vulnerabilities
    - #1 *overall* cause is social engineering / user ignorance

String Library Code

- Implementation of Unix function `gets()`

```
/* 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;
}
```

end of file

newline

reads character from input stream

pointer to start of an array (don't know size!)

same as:

```
*p = c;
p++;
```

  - What could go wrong in this code?

String Library Code

- Implementation of Unix function `gets()`

```
/* 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 way to specify **limit** on number of characters to read

stop condition looking for special characters

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

Vulnerable Buffer Code

```
/* Echo Line */
void echo() {
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

input buffer

read input into buffer

print output from buffer

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

```
unix> ./buf-nsp
Enter string: 123456789012345
123456789012345
```

```
unix> ./buf-nsp
Enter string: 1234567890123456
Segmentation fault (core dumped)
```

Buffer Overflow Disassembly (buf-nsp)

echo:

```
0000000000401146 <echo>:
 401146:  48 83 ec 18          sub    $0x18,%rsp
   ...                          ... calls printf ...
 401159:  48 8d 7c 24 08       lea    0x8(%rsp),%rdi
 40115e:  b8 00 00 00 00       mov    $0x0,%eax
 401163:  e8 e8 fe ff ff       callq  401050 <gets@plt>
 401168:  48 8d 7c 24 08       lea    0x8(%rsp),%rdi
 40116d:  e8 be fe ff ff       callq  401030 <puts@plt>
 401172:  48 83 c4 18          add    $0x18,%rsp
 401176:  c3                   retq
```

24

compiler choice

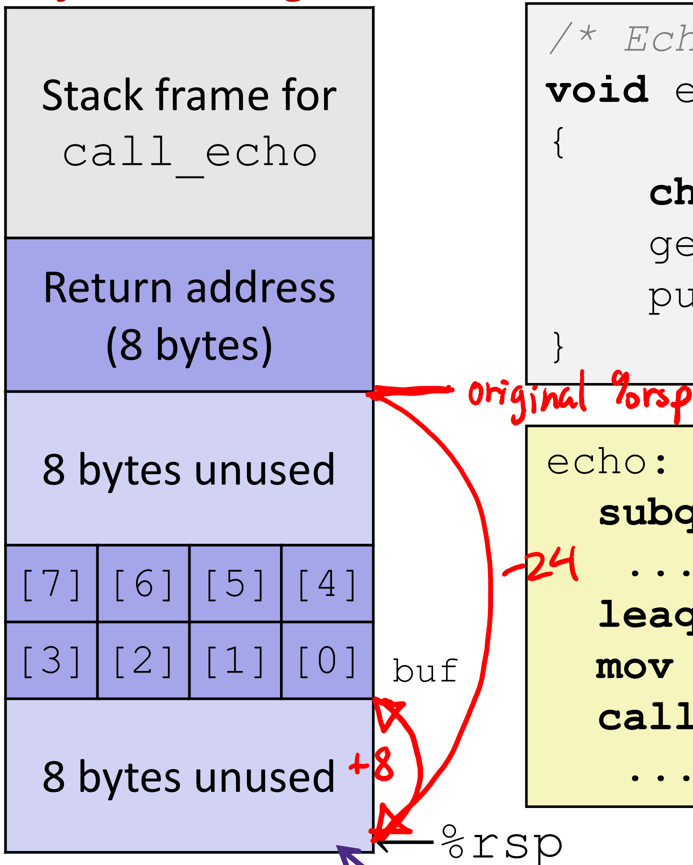
call_echo:

```
0000000000401177 <call_echo>:
 401177:  48 83 ec 08          sub    $0x8,%rsp
 40117b:  b8 00 00 00 00       mov    $0x0,%eax
 401180:  e8 c1 ff ff ff       callq  401146 <echo>
 401185:  48 83 c4 08          add    $0x8,%rsp
 401189:  c3                   retq
```

return address placed on stack

Buffer Overflow Stack

Before call to gets




```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

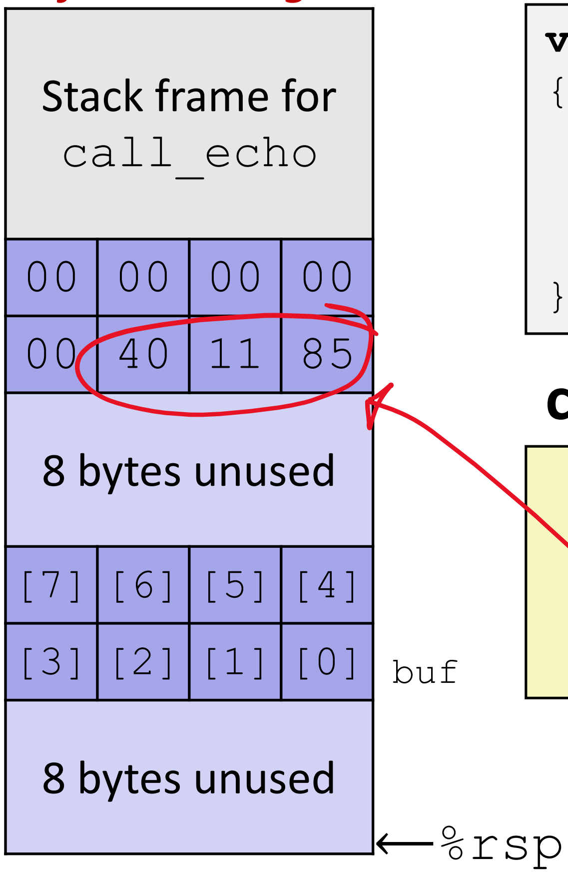
```
echo:
  subq   $24, %rsp
   ...
  leaq   8(%rsp), %rdi
  mov    $0x0,%eax
  call   gets
   ...
```

1st argument register

Note: addresses increasing right-to-left, bottom-to-top

Buffer Overflow Example

Before call to gets




```
void echo()
{
    char buf[8];
    gets(buf);
    . . .
}
```

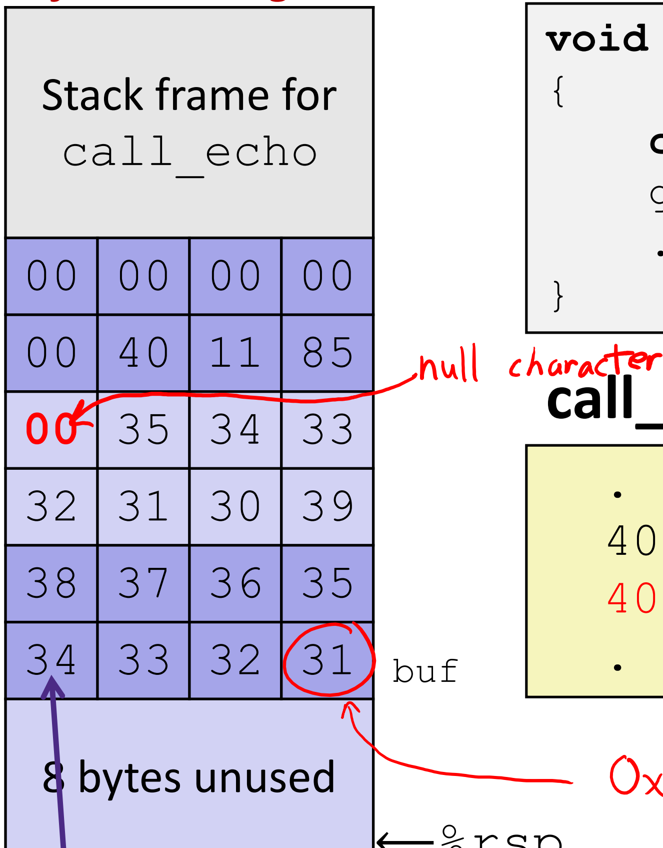
```
echo:
   subq   $24, %rsp
    ...
   leaq   8(%rsp), %rdi
   mov    $0x0,%eax
   call   gets
    ...
```

call_echo:

```
 . . .
 401180:   callq   401146 <echo>
 401185:   add     $0x8,%rsp
 . . .
```

Buffer Overflow Example #1

After call to gets




```
void echo()
{
    char buf[8];
    gets(buf);
    . . .
}
```

```
echo:
  subq  $24, %rsp
   ...
  leaq  8(%rsp), %rdi
  mov   $0x0,%eax
  call  gets
   ...
```

call_echo:

```
  . . .
  401180:  callq  401146 <echo>
  401185:  add    $0x8,%rsp
  . . .
```

0x31 = '1'

```
unix> ./buf-nsp
Enter string: 123456789012345
123456789012345
```

Overflowed buffer, but did not corrupt state

Note: Digit "*N*" is just 0x3*N* in ASCII!

Buffer Overflow Example #2

After call to gets

Stack frame for call_echo

00	00	00	00	
00	40	11	**00**	
36	35	34	33	
32	31	30	39	
38	37	36	35	
34	33	32	31	buf

8 bytes unused

←%rsp

```
void echo()
{
    char buf[8];
    gets(buf);
    . . .
}
```

```
echo:
  subq  $24, %rsp
   ...
  leaq  8(%rsp), %rdi
  mov   $0x0,%eax
  call  gets
   ...
```

call_echo:

```
  . . .
  401180:  callq  401146 <echo>
  401185:  add    $0x8,%rsp
  . . .
```

```
unix> ./buf-nsp
Enter string: 1234567890123456
Segmentation fault (core dumped)
```

Overflowed buffer and corrupted return pointer

Buffer Overflow Example #2 Explained

After return from echo

Stack frame for `call_echo`				
				← %rsp
00	00	00	00	
00	40	11	**00**	
36	35	34	33	
32	31	30	39	
38	37	36	35	
34	33	32	31	buf
8 bytes unused				

```
00000000004010d0 <register_tm_clones>:
  4010d0:  lea    0x2f61(%rip),%rdi
  4010d7:  lea    0x2f5a(%rip),%rsi
  4010de:  sub    %rdi,%rsi
  4010e1:  mov    %rsi,%rax
  4010e4:  shr    $0x3f,%rsi
  4010e8:  sar    $0x3,%rax
  4010ec:  add    %rax,%rsi
  4010ef:  sar    %rsi
  4010f2:  je     401108
  4010f4:  mov    0x2efd(%rip),%rax
  4010fb:  test   %rax,%rax
  4010fe:  je     401108
  401100:  jmpq   *%rax
  401102:  nopw   0x0(%rax,%rax,1)
  401108:  retq
```

"Returns" to a valid instruction, but bad indirect jump so program signals `SIGSEGV, Segmentation fault`

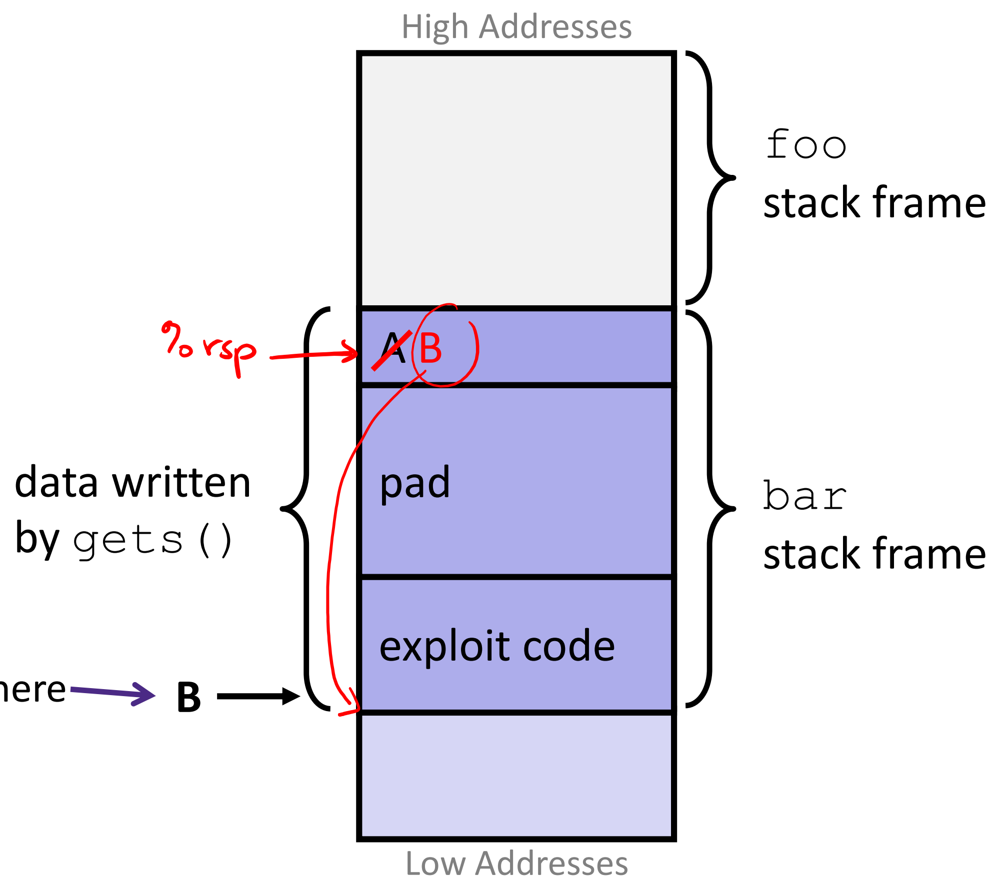
Malicious Use of Buffer Overflow: Code Injection Attacks

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

return address A

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

Stack after call to gets()



buf starts here → B

- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer B
- When bar() executes ret, will jump to exploit code

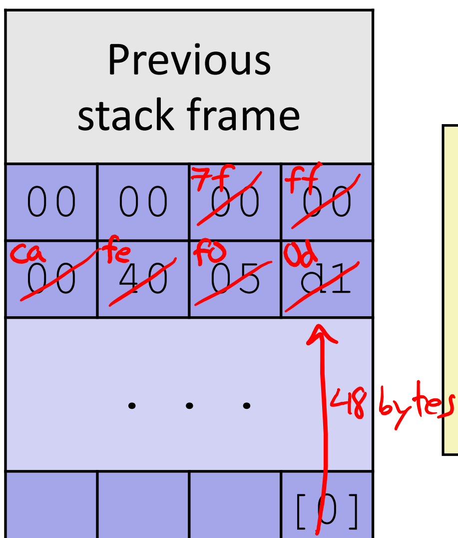
Practice Question

- `smash_me` is vulnerable to stack smashing!
- What is the minimum number of characters that `gets` must read in order for us to change the return address to a stack address?
  - For example: (0x00 00 7f ff ca fe f0 0d)

0x 00 00 7f ff ?? ?? ?? ??

always 0's

6 bytes of data



get to ret addr

$\underbrace{64\text{ bytes} - 16}_{\text{get to ret addr}} + \underbrace{6}_{\text{overwrite ret addr}}$

```
smash_me:
   subq   $0x40, %rsp
    ...
   leaq   16(%rsp), %rdi
   call   gets
    ...
```

overwrite ret addr

A. 27
B. 30
C. 51
D. $\boxed{54}$
E. We're lost…

Exploits Based on Buffer Overflows

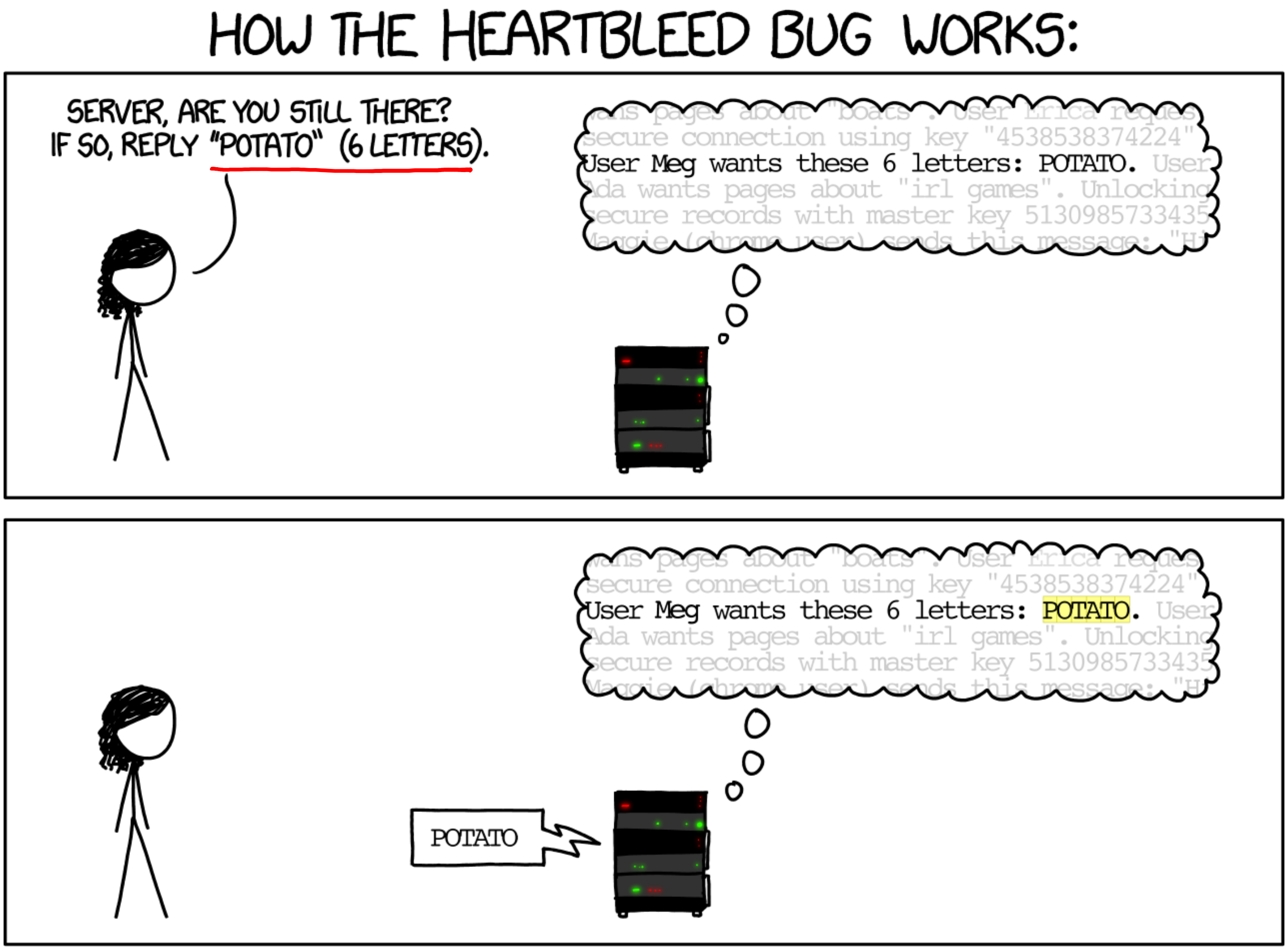
Buffer overflow bugs can allow attackers to execute arbitrary code on victim machines

- 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)
  - Heartbleed (2014, affected 17% of servers)
    - Similar issue in Cloudbleed (2017)
  - Hacking embedded devices
    - Cars, Smart homes, Planes

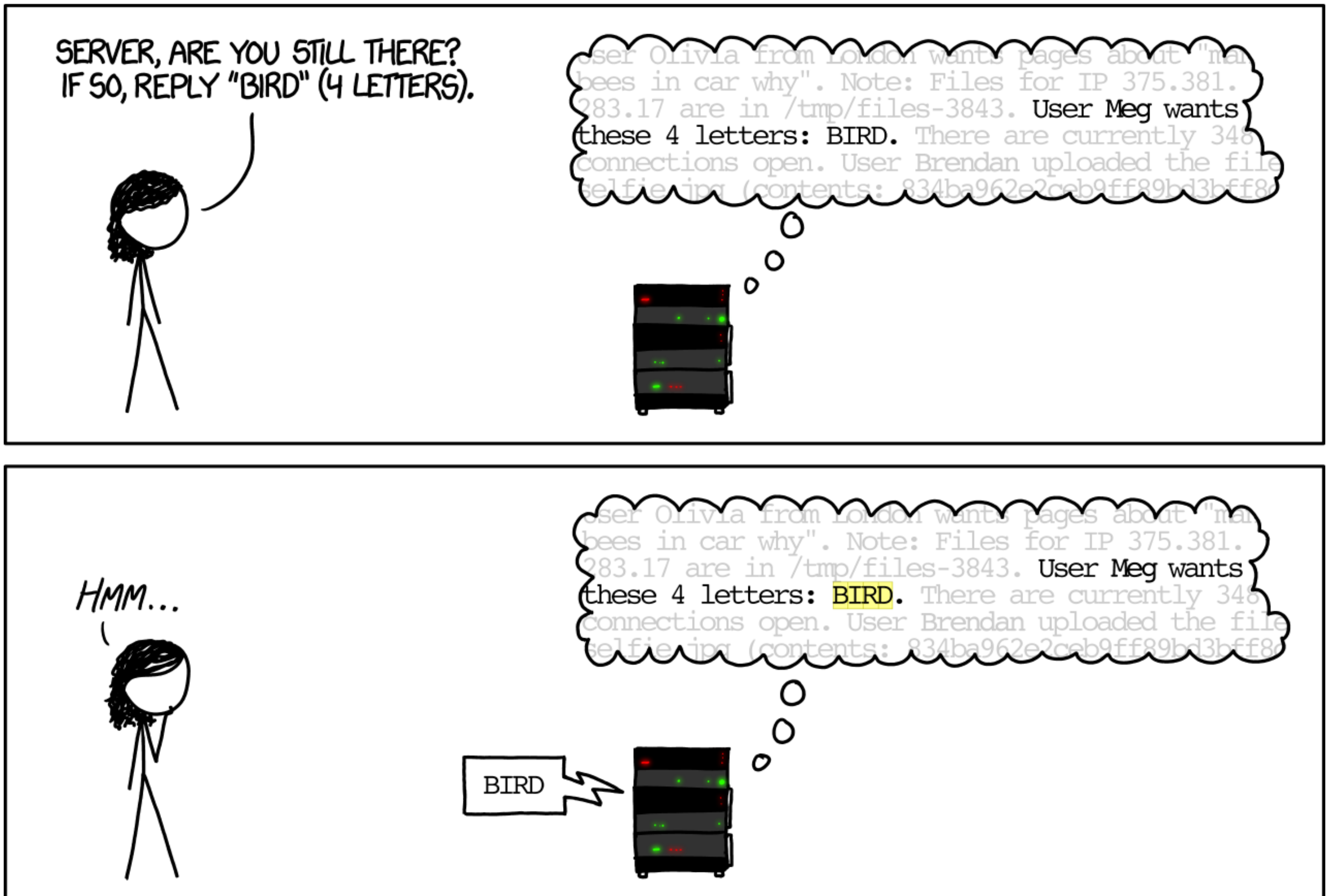
Example: the original Internet worm (1988)

- Exploited a few vulnerabilities to spread
  - Early versions of the finger server (`fingerd`) used `gets()` to read the argument sent by the client:
    - `finger droh@cs.cmu.edu`
  - Worm attacked `fingerd` server with phony argument:
    - `finger "`*`exploit-code padding new-return-addr`*`"`
    - Exploit code: executed a root shell on the victim machine with a direct connection to the attacker
- Scanned for other machines to attack
  - Invaded ~6000 computers in hours (10% of the Internet)
    - see June 1989 article in *Comm. of the ACM*
  - The author of the worm (Robert Morris*) was prosecuted…

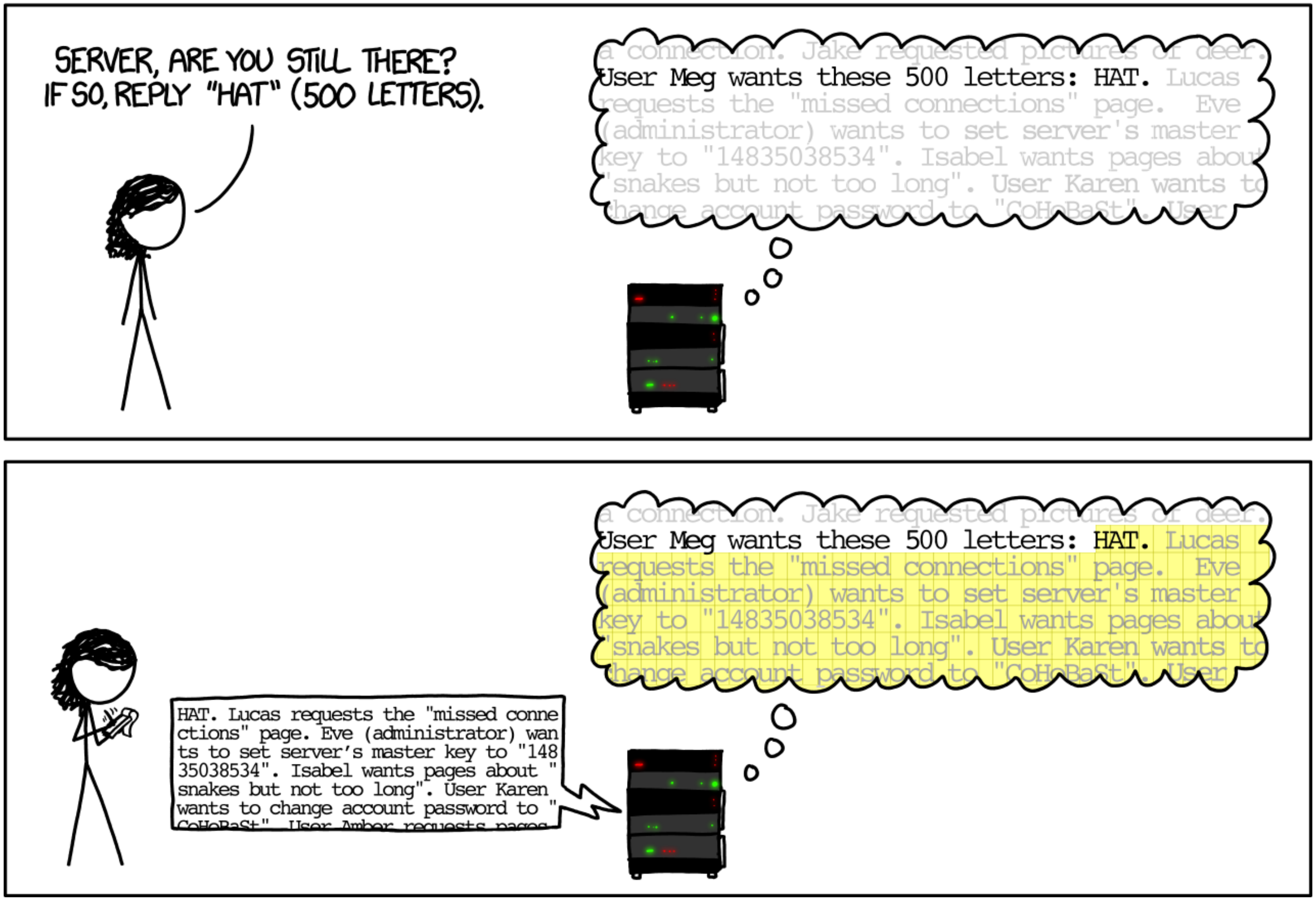
Example: Heartbleed (2014)



Example: Heartbleed (2014)

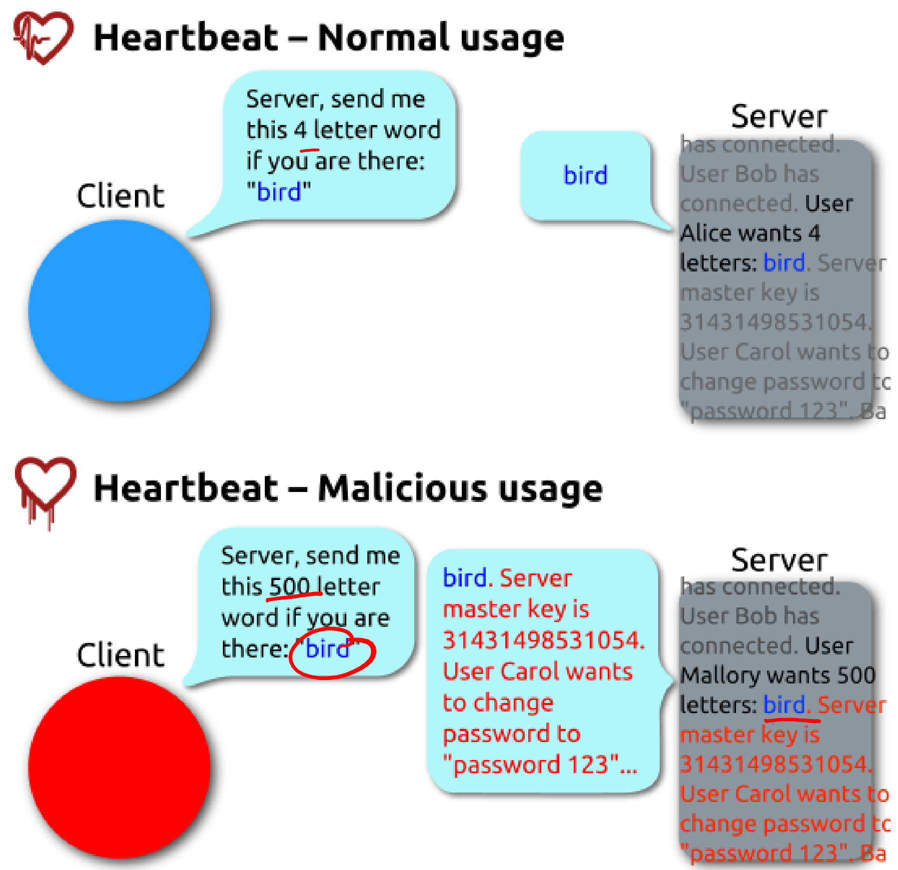


Example: Heartbleed (2014)



Heartbleed Details

- Buffer over-read in OpenSSL
  - Open source security library
  - Bug in a small range of versions
- "Heartbeat" packet
  - Specifies length of message
  - Server echoes it back
  - Library just "trusted" this length
  - Allowed attackers to read contents of memory anywhere they wanted
- Est. 17% of Internet affected
  - "Catastrophic"
  - Github, Yahoo, Stack Overflow, Amazon AWS, ...



By FenixFeather - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=32276981

Hacking Cars (2010)

- UW CSE research demonstrated wirelessly hacking a car using buffer overflow
  - http://www.autosec.org/pubs/cars-oakland2010.pdf
- Overwrote the onboard control system's code
  - Disable brakes, unlock doors, turn engine on/off

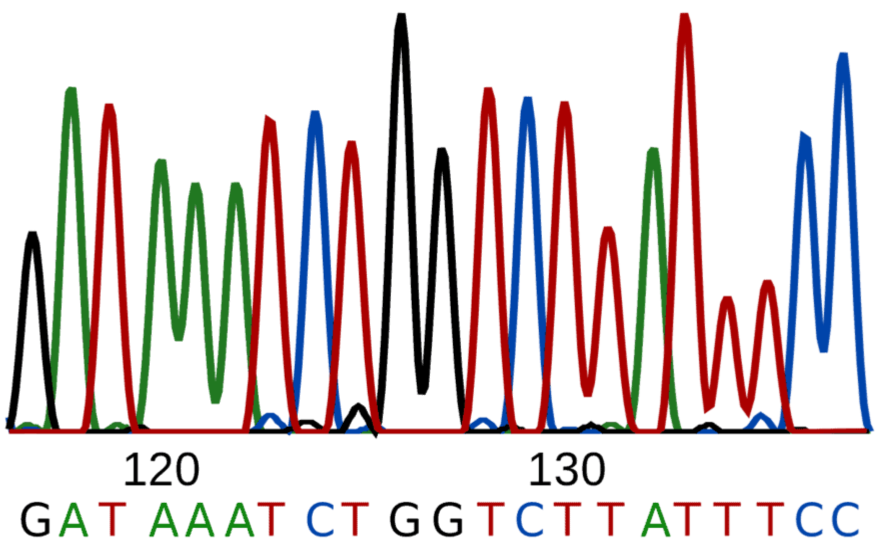
Hacking DNA Sequencing Tech (2017)

Computer Security and Privacy in DNA Sequencing

Paul G. Allen School of Computer Science & Engineering, University of Washington

- Potential for malicious code to be encoded in DNA!
- Attacker can gain control of DNA sequencing machine when malicious DNA is read
- Ney et al. (2017): https://dnasec.cs.washington.edu/

x86 in DNA!



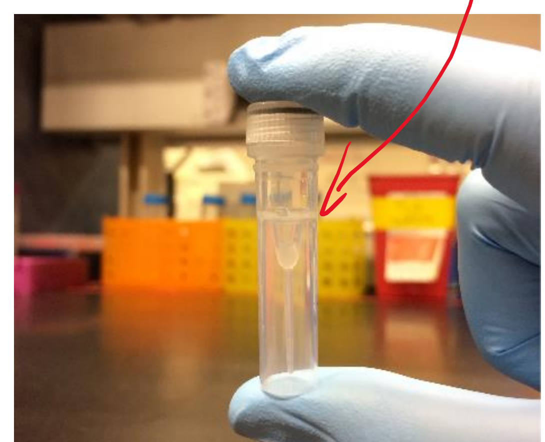


Figure 1: Our synthesized DNA exploit

Dealing with buffer overflow attacks

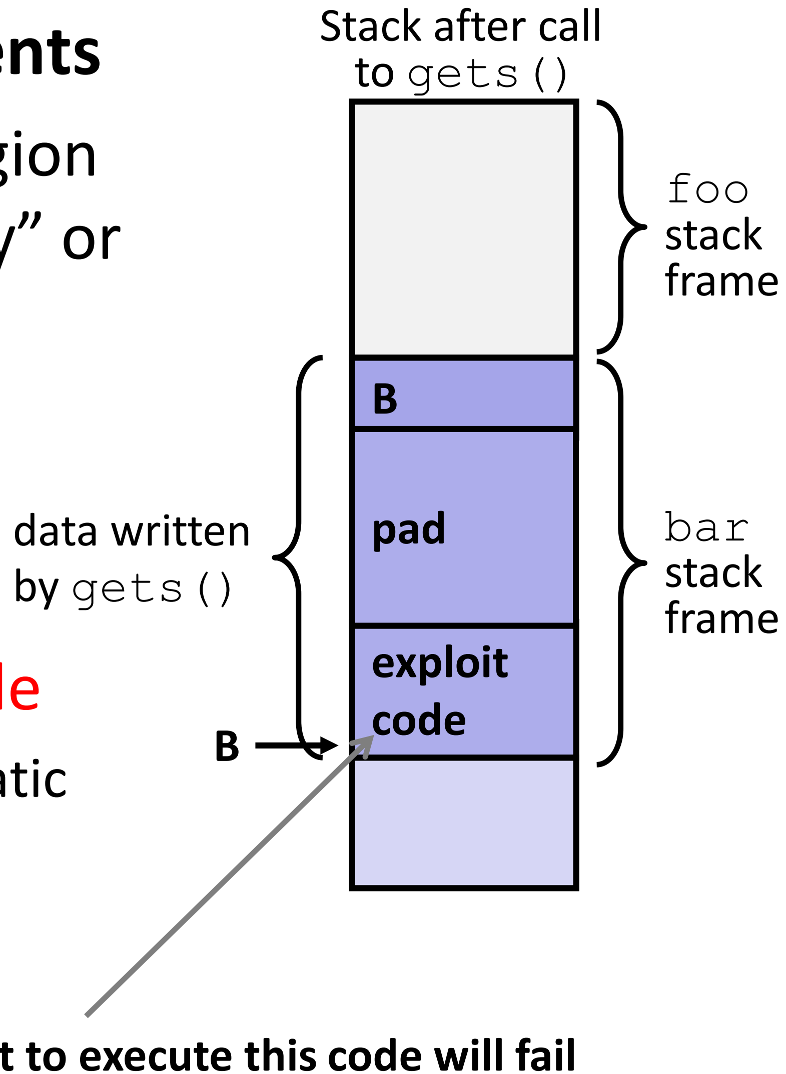
1) Employ system-level protections

2) Avoid overflow vulnerabilities

3) Have compiler use “stack canaries”

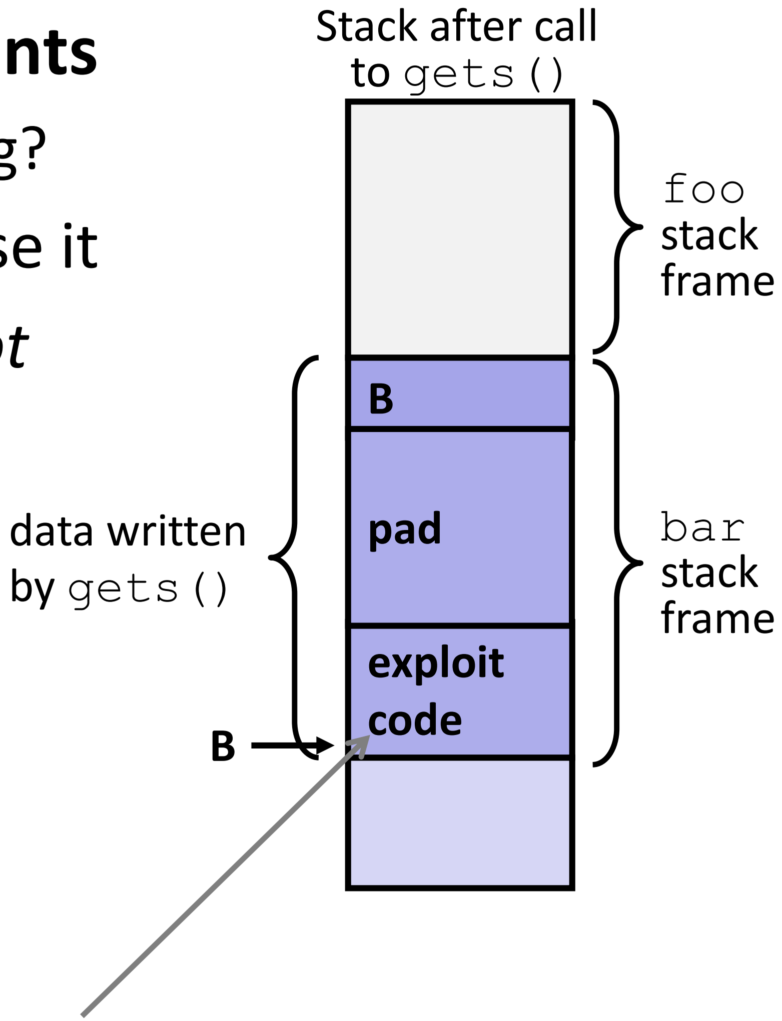
1) System-Level Protections

- **Non-executable code segments**
- In traditional x86, can mark region of memory as either "read-only" or "writeable"
  - Can execute anything readable
- x86-64 added explicit "execute" permission
- Stack marked as non-executable
  - Do *NOT* execute code in Stack, Static Data, or Heap regions
  - Hardware support needed



1) System-Level Protections

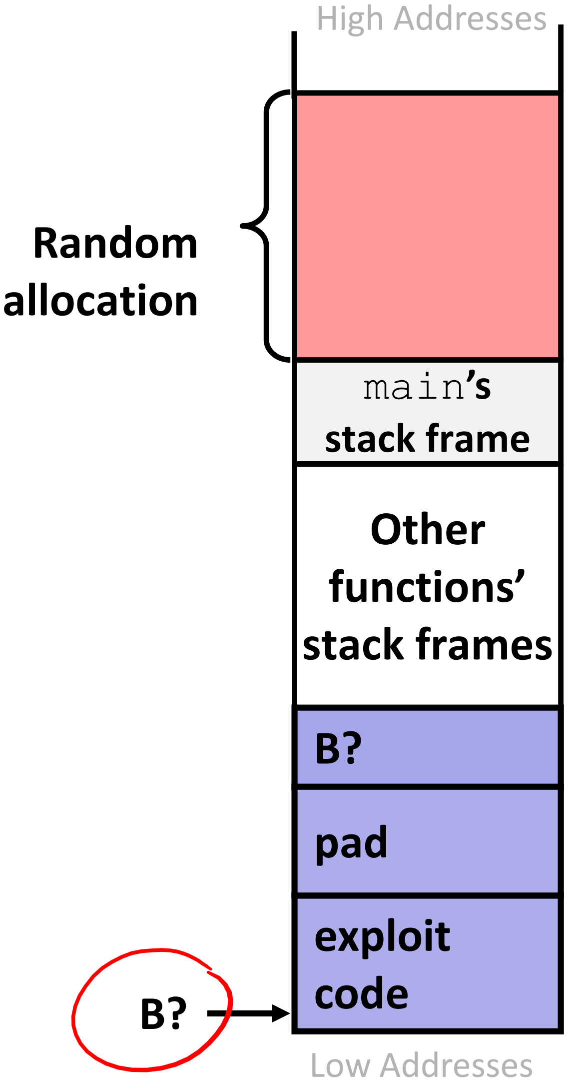
- **Non-executable code segments**
  - Wait, doesn't this fix everything?
- Works well, but can't always use it
- Many embedded devices *do not* have this protection
  - *e.g.*, cars, smart homes, pacemakers
- Some exploits still work!
  - Return-oriented programming
  - Return to libc attack
  - JIT-spray attack



Any attempt to execute this code will fail

1) System-Level Protections

- **Randomized stack offsets**
  - At start of program, allocate random amount of space on stack
  - Shifts stack addresses for entire program
    - Addresses will vary from one run to another
  - Makes it difficult for hacker to predict beginning of inserted code
- Example: Address of variable `local` for when Slide 5 code executed 3 times:
  - `0x7ffd19d3f8ac`
  - `0x7ffe8a462c2c`
  - `0x7ffe927c905c`
  - Stack repositioned each time program executes



2) Avoid Overflow Vulnerabilities in Code

```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    fgets(buf, 8, stdin);
    puts(buf);
}
```

character read limit

- Use library routines that limit string lengths
  - `fgets` instead of `gets` (2nd argument to `fgets` sets limit)
  - `strncpy` instead of `strcpy`
  - Don't use `scanf` with `%s` conversion specification
    - Use `fgets` to read the string
    - Or use `%ns` where `n` is a suitable integer

2) Avoid Overflow Vulnerabilities in Code

- Alternatively, don't use C - use a language that does array index bounds check
  - Buffer overflow is impossible in Java
    - ArrayIndexOutOfBoundsException
  - Rust language was designed with security in mind
    - Panics on index out of bounds, plus more protections

3) Stack Canaries

- Basic Idea: place special value ("canary") on stack just beyond buffer
  - *Secret* value that is randomized before main()
  - Placed between buffer and return address
  - Check for corruption before exiting function
- GCC implementation
  - `-fstack-protector`

```
unix>./buf
Enter string: 12345678
12345678
```

```
unix> ./buf
Enter string: 123456789
*** stack smashing detected ***
```

Protected Buffer Disassembly (buf)

This is extra (non-testable) material

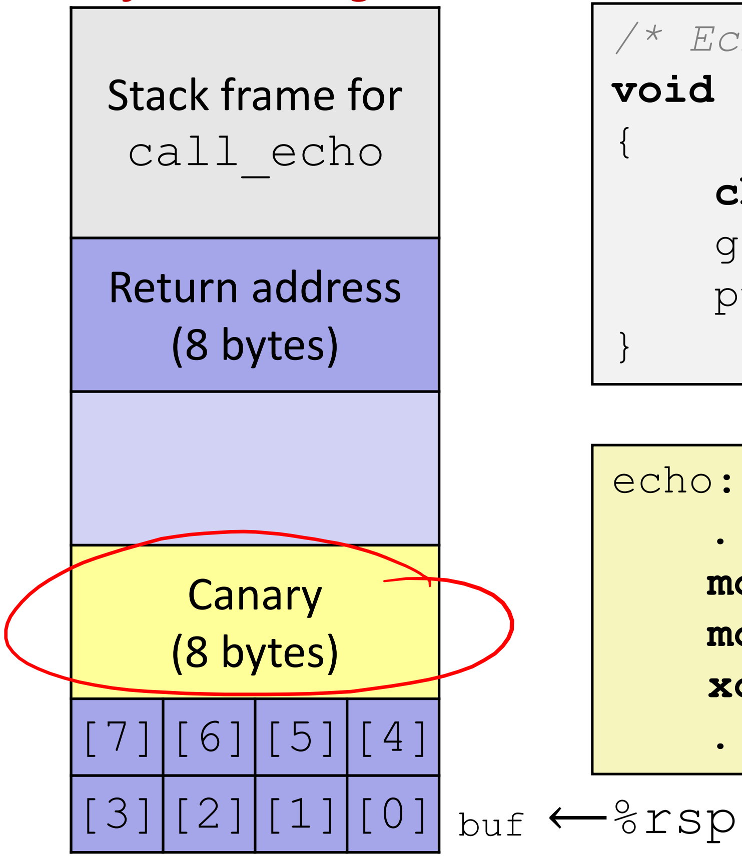
echo: try: diff buf-nsp.s buf.s

```
401156:  push   %rbx
401157:  sub    $0x10,%rsp
40115b:  mov    $0x28,%ebx
401160:  mov    %fs:(%rbx),%rax    # read canary value
401164:  mov    %rax,0x8(%rsp)     # store canary on Stack
401169:  xor    %eax,%eax          # erase canary from register
 ...     ... call printf ...
40117d:  callq  401060 <gets@plt>
401182:  mov    %rsp,%rdi
401185:  callq  401030 <puts@plt>
40118a:  mov    0x8(%rsp),%rax     # read current canary on Stack
40118f:  xor    %fs:(%rbx),%rax    # compare against original value
401193:  jne    40119b <echo+0x45> # if unchanged, then return
401195:  add    $0x10,%rsp
401199:  pop    %rbx
40119a:  retq
40119b:  callq  401040 <__stack_chk_fail@plt>  # stack smashing detected
```

Setting Up Canary

This is extra (non-testable) material

Before call to gets




```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

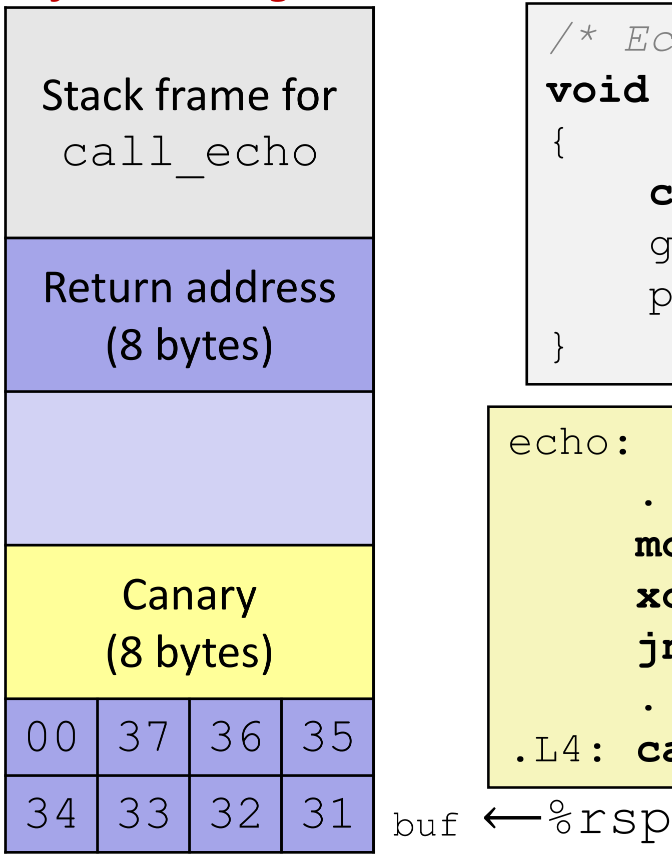
Segment register
(don't worry about it)

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

This is extra (non-testable) material

Checking Canary

After call to gets




```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
     . . .
     movq   8(%rsp), %rax     # retrieve from Stack
     xorq   %fs:40, %rax      # compare to canary
     jne    .L4               # if not same, FAIL
     . . .
.L4: call   __stack_chk_fail
```

Input: *1234567*

Summary of Prevention Measures

1) Employ system-level protections
   - Code on the Stack is not executable
   - Randomized Stack offsets

2) Avoid overflow vulnerabilities
   - Use library routines that limit string lengths
   - Use a language that makes them impossible

3) Have compiler use “stack canaries”

Think this is cool?

- You'll love Lab 3 😉
  - Released today, due next Friday
  - Some parts *must* be run through GDB to disable certain security features
- Take CSE 484 (Security)
  - Several different kinds of buffer overflow exploits
  - Many ways to counter them
- Nintendo fun!
  - Using glitches to rewrite code: https://www.youtube.com/watch?v=TqK-2jUQBUY
  - Flappy Bird in Mario: https://www.youtube.com/watch?v=hB6eY73sLV0

Discussion Questions

- In Lab 3, you will run a buffer overflow code injection attack; students love this lab because it "makes you feel like a hacker"
  - What connotations (*i.e.*, ideas or feelings evoked) does this statement carry for you and where do those come from?
  - While it is easy to say that you should not exploit security vulnerabilities, does the *target* of an attack change how you feel about it? Why?