Buffer Overflows

CSE 351 Spring 2020

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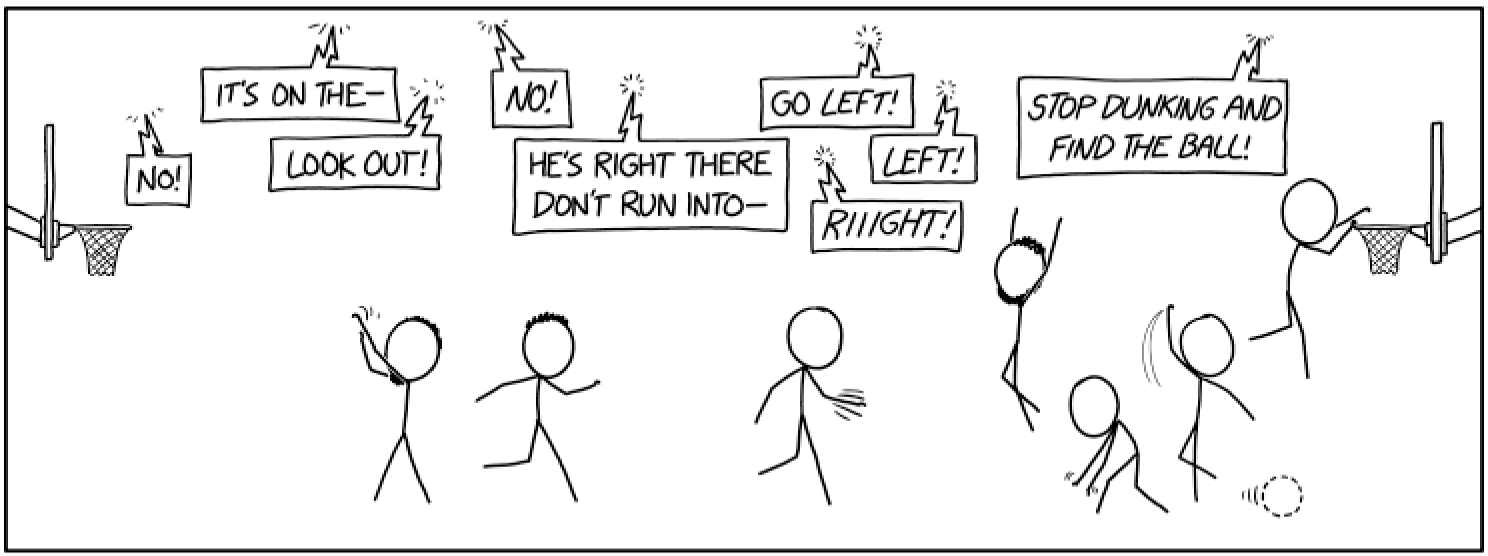


NO ONE LIKED MY NEW SPORTS SYSTEM, IN WHICH EACH PLAYER IS IN A SEPARATE ARENA SHARING A SINGLE VIRTUAL BALL THAT THEY CAN'T SEE WHILE ONLINE VIEWERS YELL INSTRUCTIONS, BUT IT WAS FUN TO WATCH WHILE IT LASTED.

http://xkcd.com/2291/

Administrivia

- Lab 2 (x86-64) due TONIGHT, Friday (5/01)
  - Since you are submitting a text file (`defuser.txt`), there won't be any Gradescope autograder output this time
  - Extra credit needs to be submitted to the extra credit assignment
- Unit Summary #2, due Friday (5/08)
- Lab 3 coming soon!
  - You will have everything you need by the end of this lecture
- **You must log on with your @uw google account to access!!**
  - **Google doc** for 11:30 Lecture: https://tinyurl.com/351-05-01A
  - **Google doc** for 2:30 Lecture: https://tinyurl.com/351-05-01B

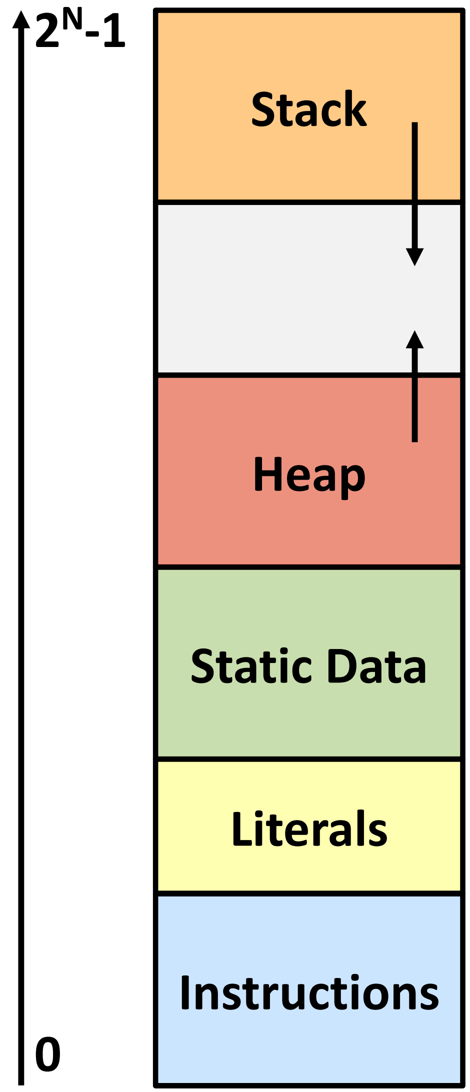
Buffer Overflows

- Address space layout (more details!)
- Input buffers on the stack
- Overflowing buffers and injecting code
- Defenses against buffer overflows

not drawn to scale

Review: General Memory Layout

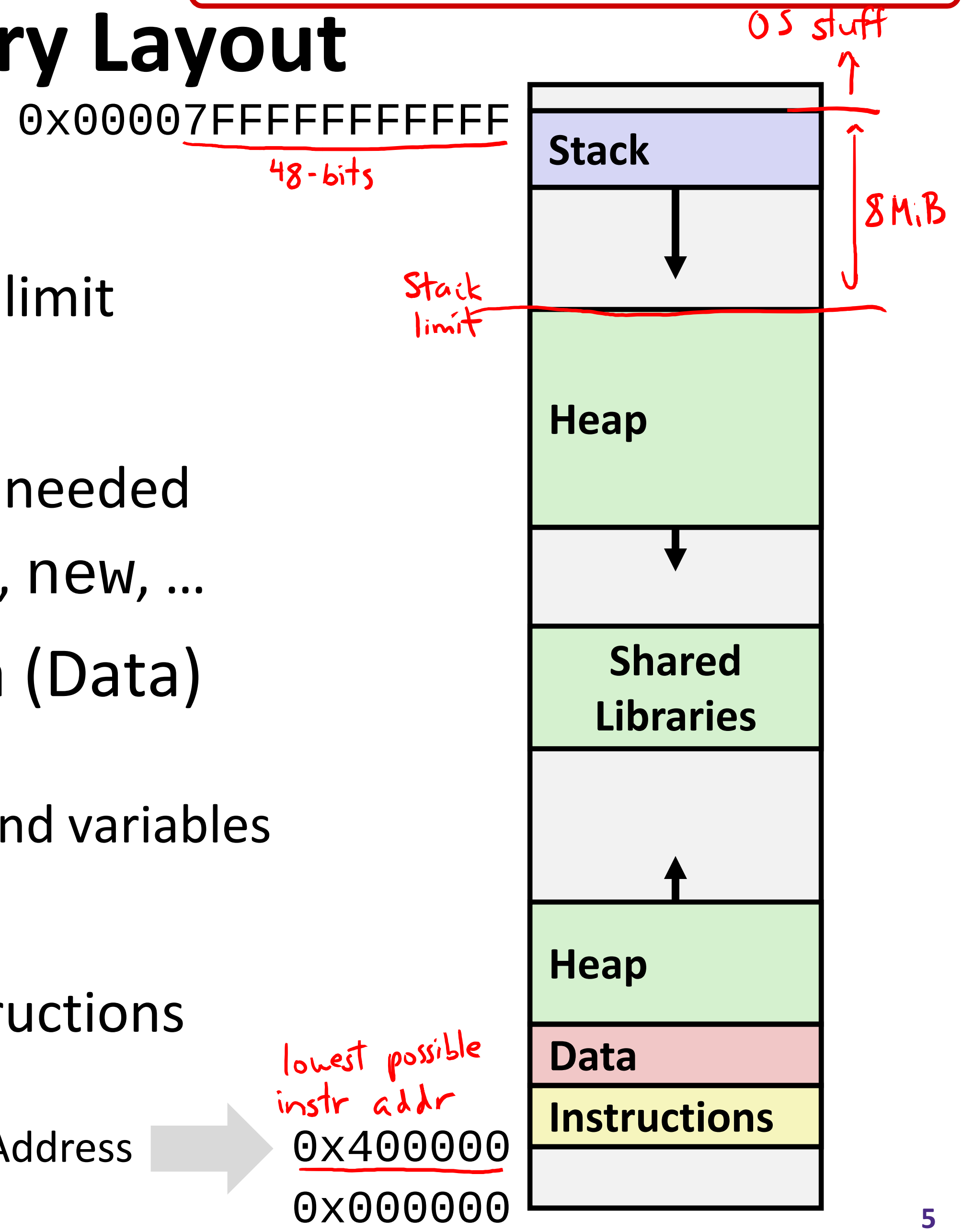
- Stack
  - Local variables (procedure context)
- Heap
  - Dynamically allocated as needed
  - `malloc()`, `calloc()`, new, …
- Statically allocated Data
  - Read/write: global variables (Static Data)
  - Read-only: string literals (Literals)
- Code/Instructions
  - Executable machine instructions
 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



This is extra (non-testable) material

x86-64 Linux Memory Layout

- Stack
  - Runtime stack has 8 MiB limit
- Heap
  - Dynamically allocated as needed
  - `malloc()`, `calloc()`, new, …
- Statically allocated data (Data)
  - Read-only: string literals
  - Read/write: global arrays and variables
- Code / Shared Libraries
  - Executable machine instructions
  - Read-only



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Memory Allocation Example

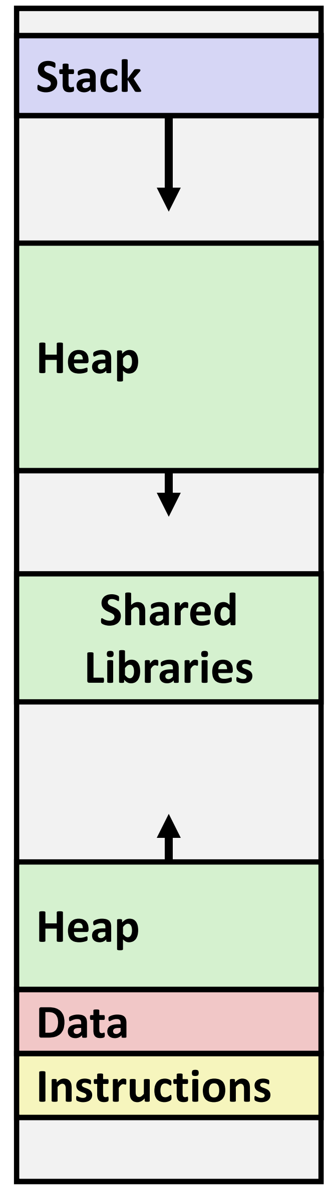
```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

int global = 0;

int useless() { return 0; }

int main()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8);  /* 256  B */
    p3 = malloc(1L << 32); /*   4 GB */
    p4 = malloc(1L << 8);  /* 256  B */
    /* Some print statements ... */
}
```

global (Data)

labels in code

local (Stack)

dynamically-allocated memory (Heap)



Where does everything go?

p1 → stack address

*p1 → heap address

not drawn to scale

Memory Allocation Example

```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

int global = 0;

int useless() { return 0; }

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    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
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    p4 = malloc(1L << 8);  /* 256  B */
    /* Some print statements ... */
}
```
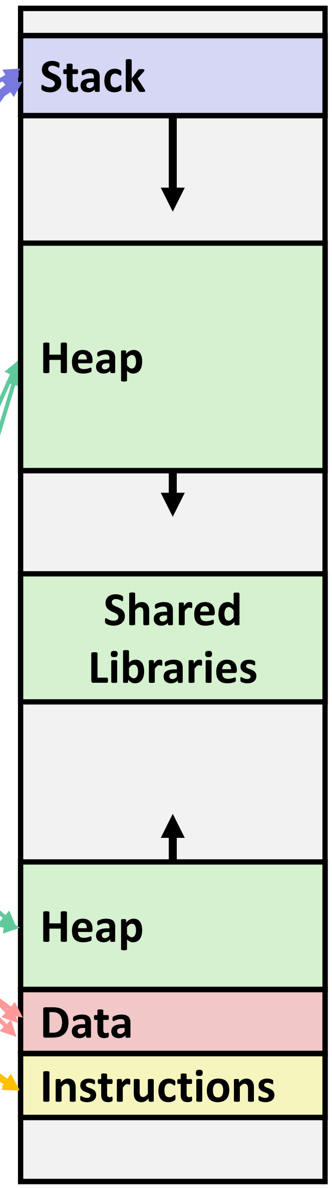



Where does everything go?

What Is a Buffer?

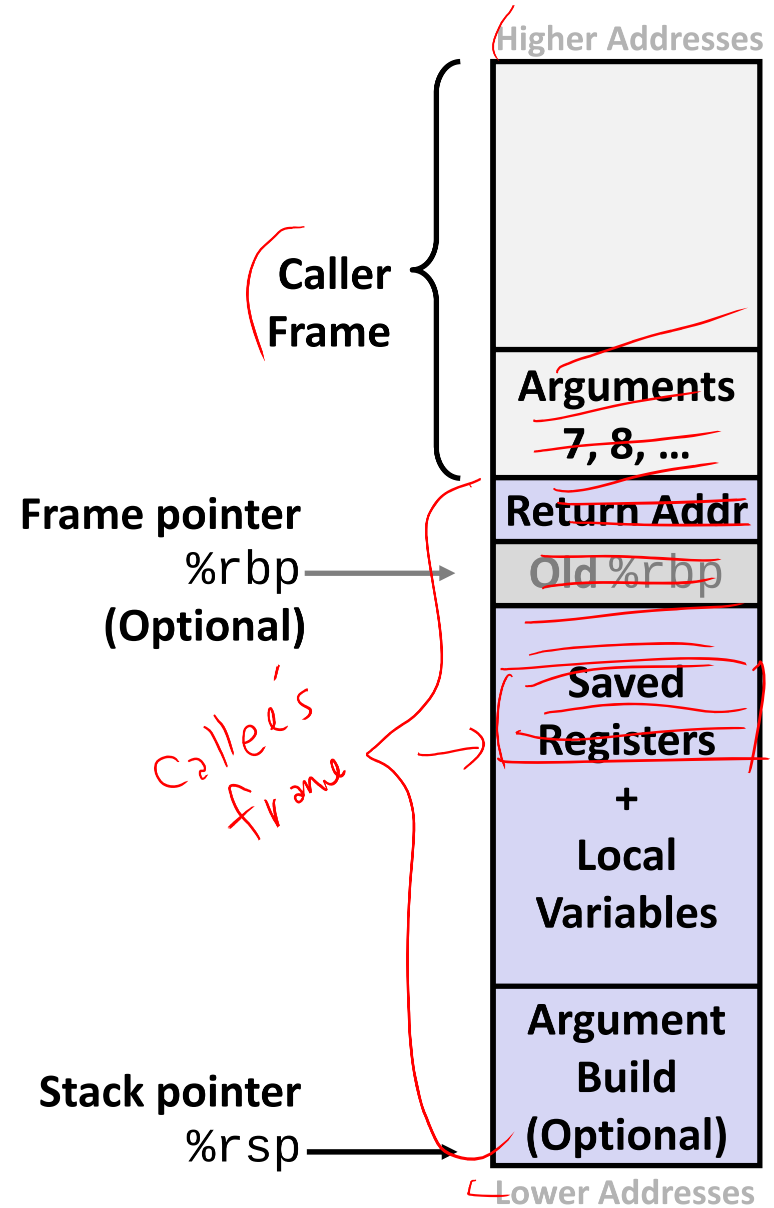
- A buffer is an array used to temporarily store data

- 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

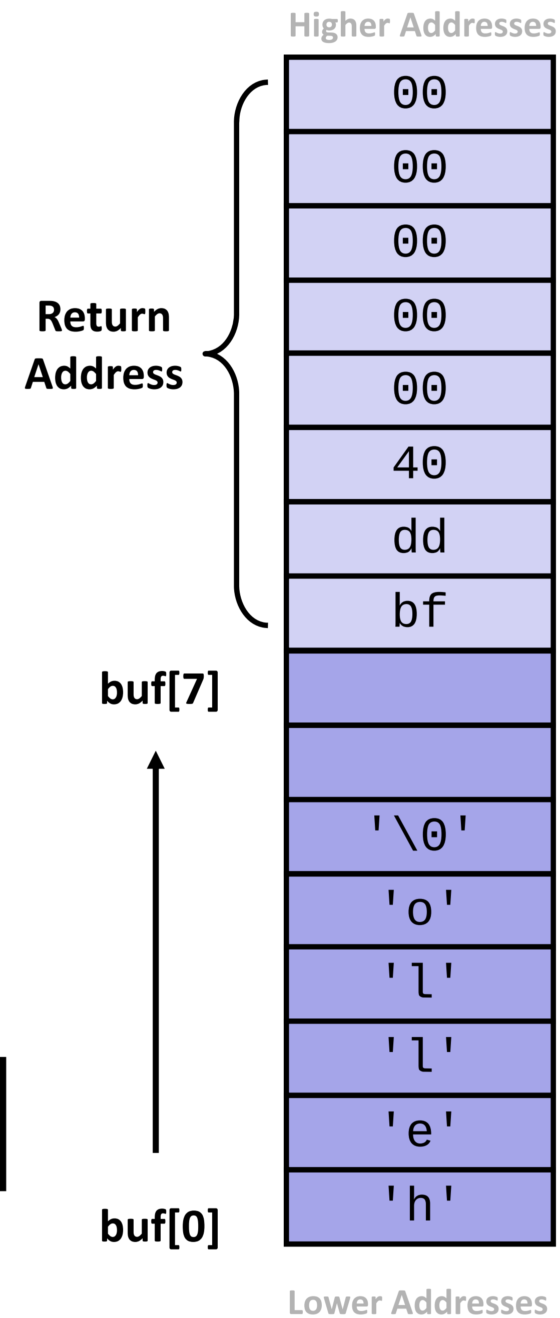
- C does not check array bounds
  - Many Unix/Linux/C functions don't check argument sizes
  - Allows overflowing (writing past the end) of buffers (arrays)
- "Buffer Overflow" = Writing past the end of an array
- Characteristics of the traditional Linux memory layout provide opportunities for malicious 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
```

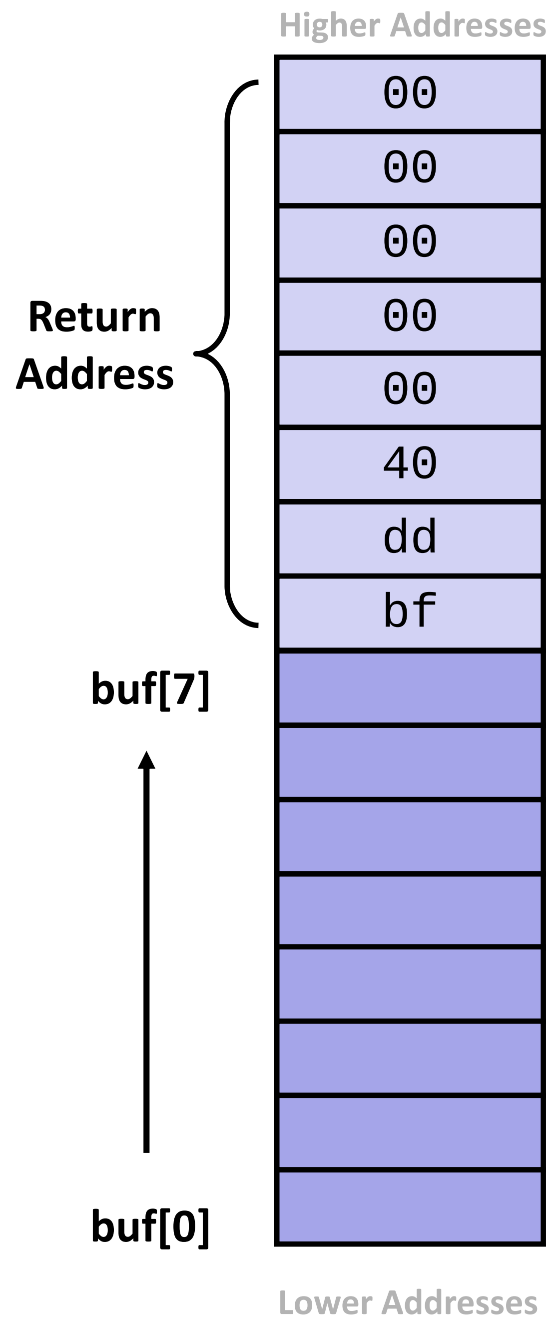
No overflow ☺



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
```

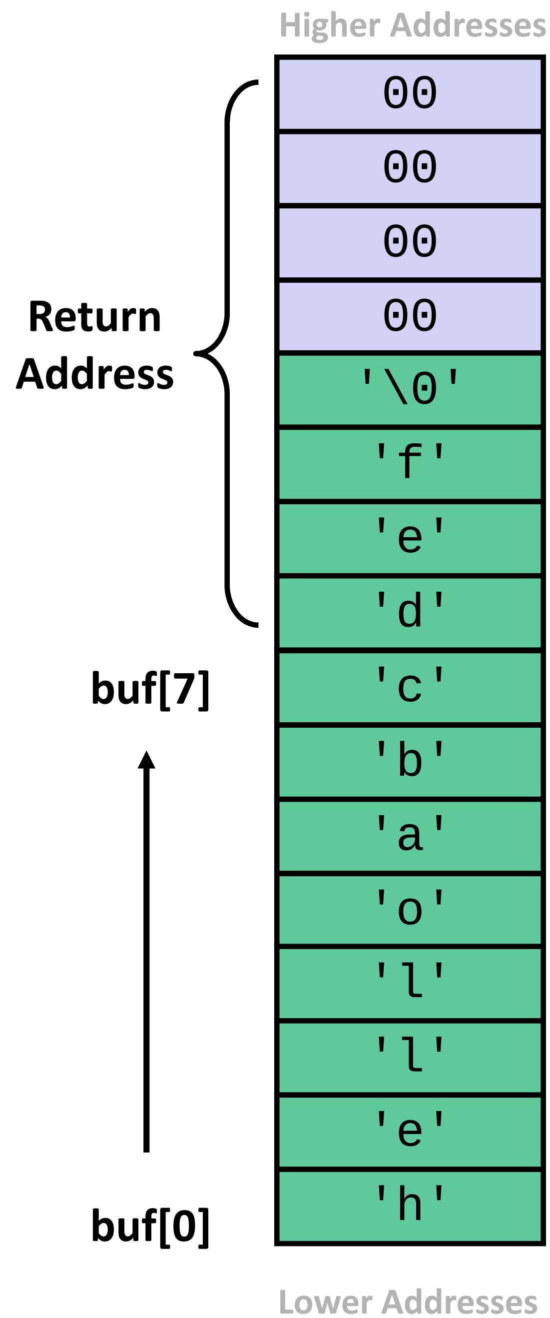


Buffer Overflow in a Nutshell

- 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

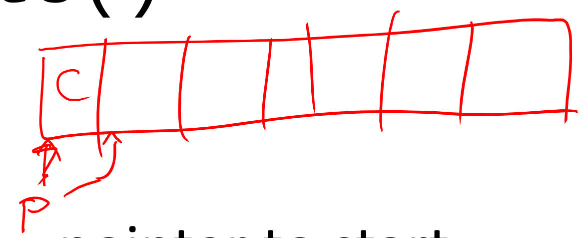
- Implementation of Unix function `gets()`

```
/* 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

- 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
Illegal instruction
```

```
unix> ./buf-nsp
Enter string: 12345678901234567
Segmentation Fault
```

Buffer Overflow Disassembly (buf-nsp)

echo:

```
0000000000400597 <echo>:
  400597:  48 83 ec 18          sub    $0x18,%rsp
    ...                          ... calls printf ...
  4005aa:  48 8d 7c 24 08       lea    0x8(%rsp),%rdi
  4005af:  e8 d6 fe ff ff       callq  400480 <gets@plt>
  4005b4:  48 89 7c 24 08       lea    0x8(%rsp),%rdi
  4005b9:  e8 b2 fe ff ff       callq  4004a0 <puts@plt>
  4005be:  48 83 c4 18          add    $0x18,%rsp
  4005c2:  c3                   retq
```

24

compiler choice

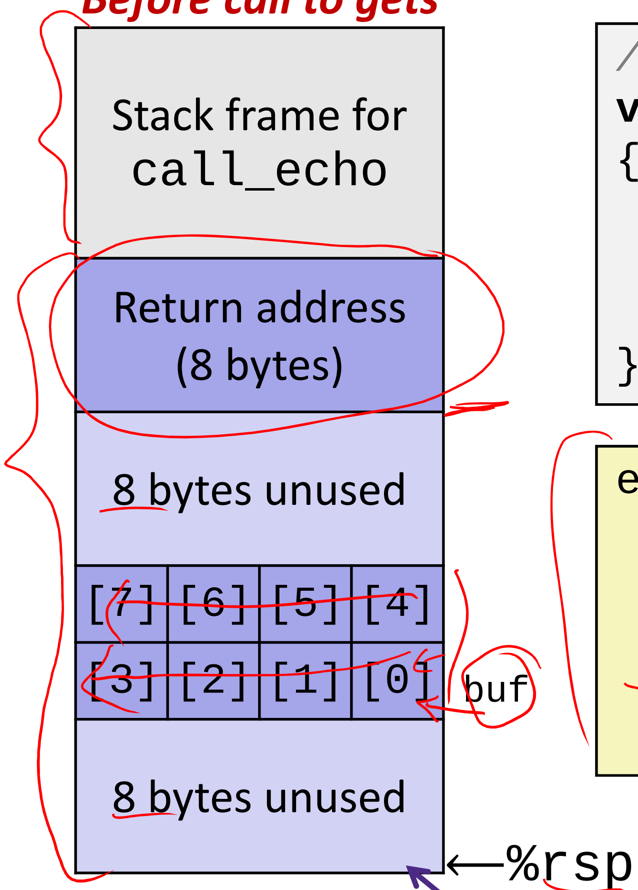
call_echo:

```
00000000004005c3 <call_echo>:
  4005c3:  48 83 ec 08          sub    $0x8,%rsp
  4005c7:  b8 00 00 00 00       mov    $0x0,%eax
  4005cc:  e8 c6 ff ff ff       callq  400597 <echo>
  4005d1:  48 83 c4 08          add    $0x8,%rsp
  4005d5:  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
  call   gets
   ...
```

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

Buffer Overflow Example

Before call to gets

Stack frame for `call_echo`			
00	00	00	00
00	40	05	d1
8 bytes unused			
[7]	[6]	[5]	[4]
[3]	[2]	[1]	[0] ← buf
8 bytes unused			

←%rsp

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

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

call_echo:

```
   . . .
   4005cc:  callq   400597 <echo>
   4005d1:  add     $0x8,%rsp
   . . .
```

Buffer Overflow Example #1

After call to gets

Stack frame for `call_echo`				
00	00	00	00	
00	40	05	d1	
00	35	34	33	
32	31	30	39	
38	37	36	35	
34	33	32	31	buf
8 bytes unused				←%rsp

null terminator

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

1

1

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

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

call_echo:

```
   . . .
   4005cc:  callq  400597 <echo>
   4005d1:  add    $0x8,%rsp
   . . .
```

0x31 = '1'

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

Overflowed buffer, but did not corrupt state

Buffer Overflow Example #2

After call to gets

Stack frame for call_echo			
00	00	00	00
00	40	05	00
36	35	34	33
32	31	30	39
38	37	36	35
34	33	32	31
8 bytes unused			

buf

←%rsp

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

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

call_echo:

```
   . . .
   4005cc:  callq   400597 <echo>
   4005d1:  add     $0x8,%rsp
   . . .
```

```
unix> ./buf-nsp
Enter string: 1234567890123456
Illegal instruction
```

Overflowed buffer and corrupted return pointer

Buffer Overflow Example #2 Explained

After return from echo

Stack frame for `call_echo`				
00	00	00	00	⟵%rsp
00	40	05	**00**	
36	35	34	33	
32	31	30	39	
38	37	36	35	
34	33	32	31	buf
8 bytes unused				

```
00000000004004f0 <deregister_tm_clones>:
  4004f0:  push   %rbp
  4004f1:  mov    $0x601040,%eax
  4004f6:  cmp    $0x601040,%rax
  4004fc:  mov    %rsp,%rbp
  4004ff:  je     400518
  400501:  mov    $0x0,%eax
  400506:  test   %rax,%rax
  400509:  je     400518
  40050b:  pop    %rbp
  40050c:  mov    $0x601040,%edi
  400511:  jmpq   *%rax
  400513:  nopl   0x0(%rax,%rax,1)
  400518:  pop    %rbp
  400519:  retq
```

2nd byte of this instruction

"Returns" to a byte that is not the beginning of an instruction, so program signals `SIGILL, Illegal instruction`

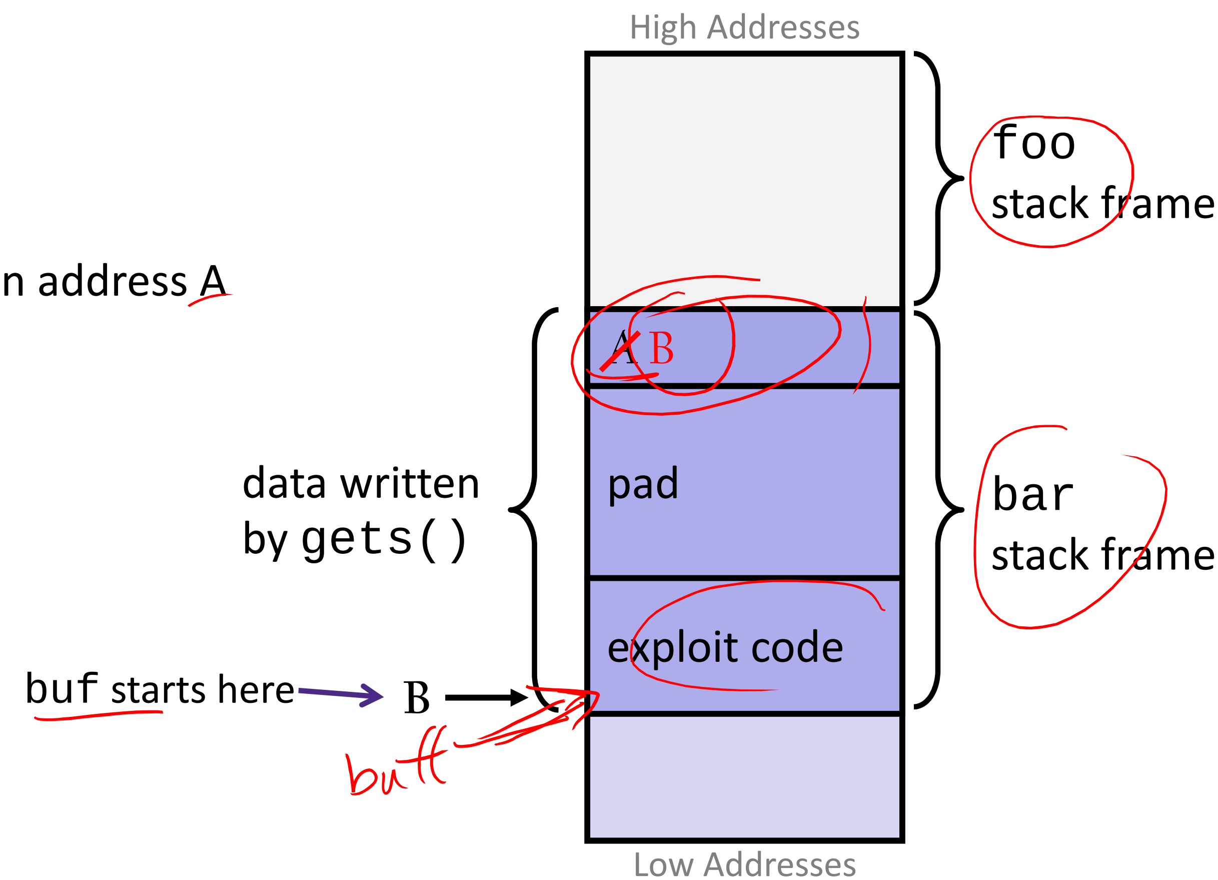
Malicious Use of Buffer Overflow: Code Injection Attacks

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

← return address A

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

Stack after call to `gets()`

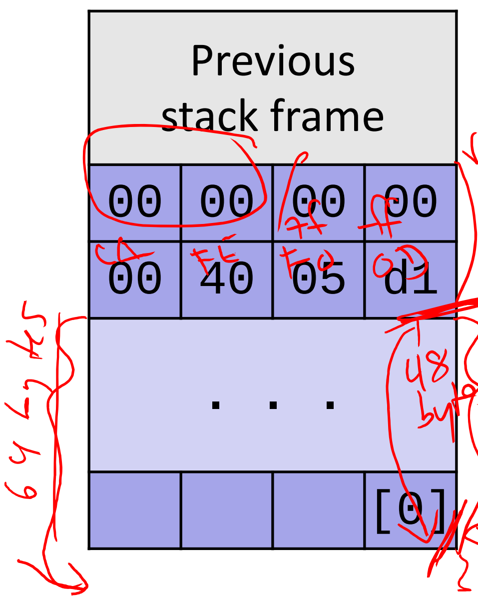


- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer B
- When `bar()` executes `ret`, will jump to exploit code

Peer Instruction Question [Buf]

- `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~~?
- Vote at http://PollEv.com/rea
  - For example: (0x00 00 7f ff CA FE F0 0D)

return addr



64 bytes

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

buff

64-16=48

16 bytes

- ~~A. 27~~
- ~~B. 30~~
- C. 51
- D. 54
- E. We're lost…

Exploits Based on Buffer Overflows

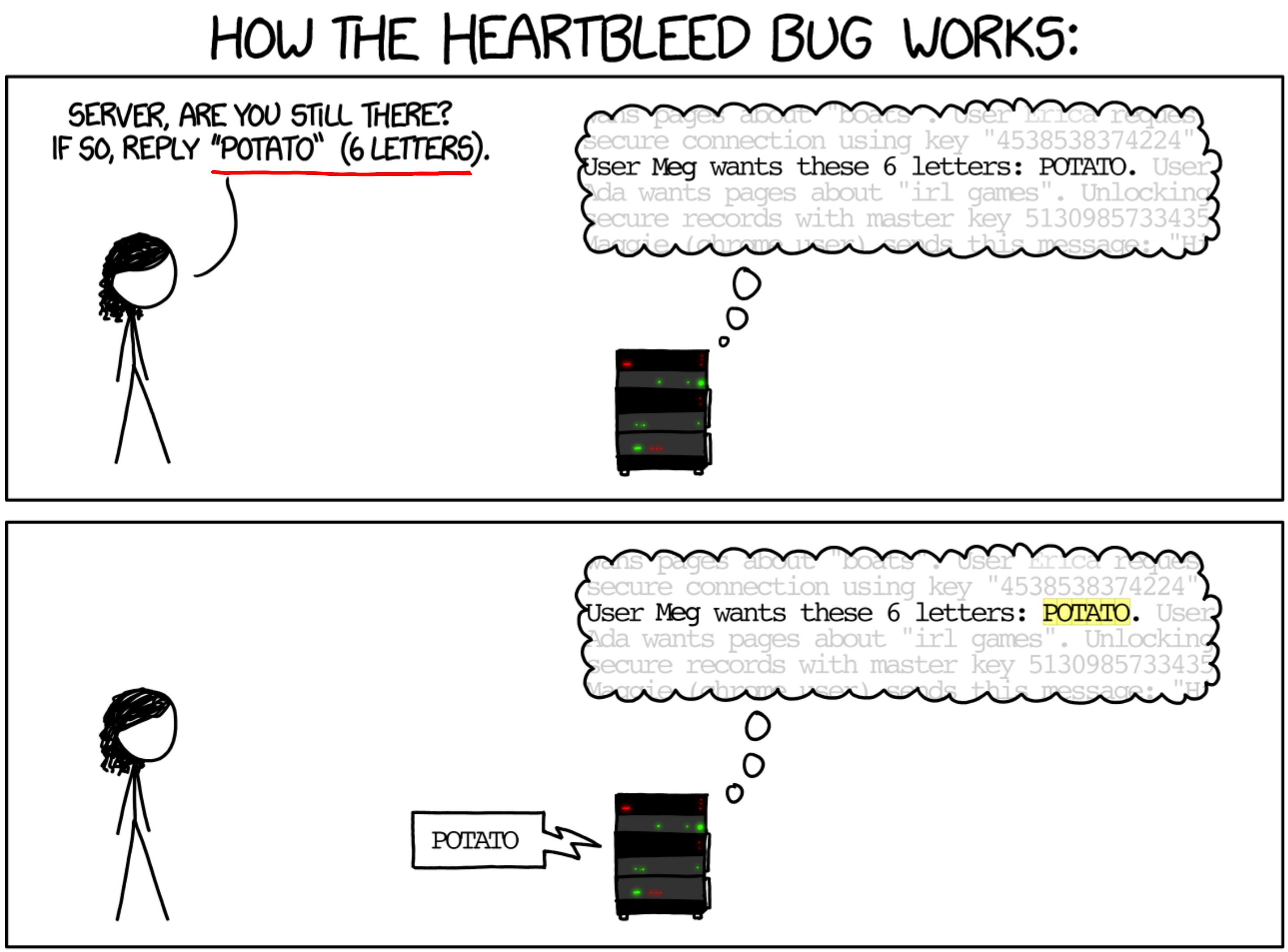
Buffer overflow bugs can allow attackers to execute arbitrary code on victim machines

- 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

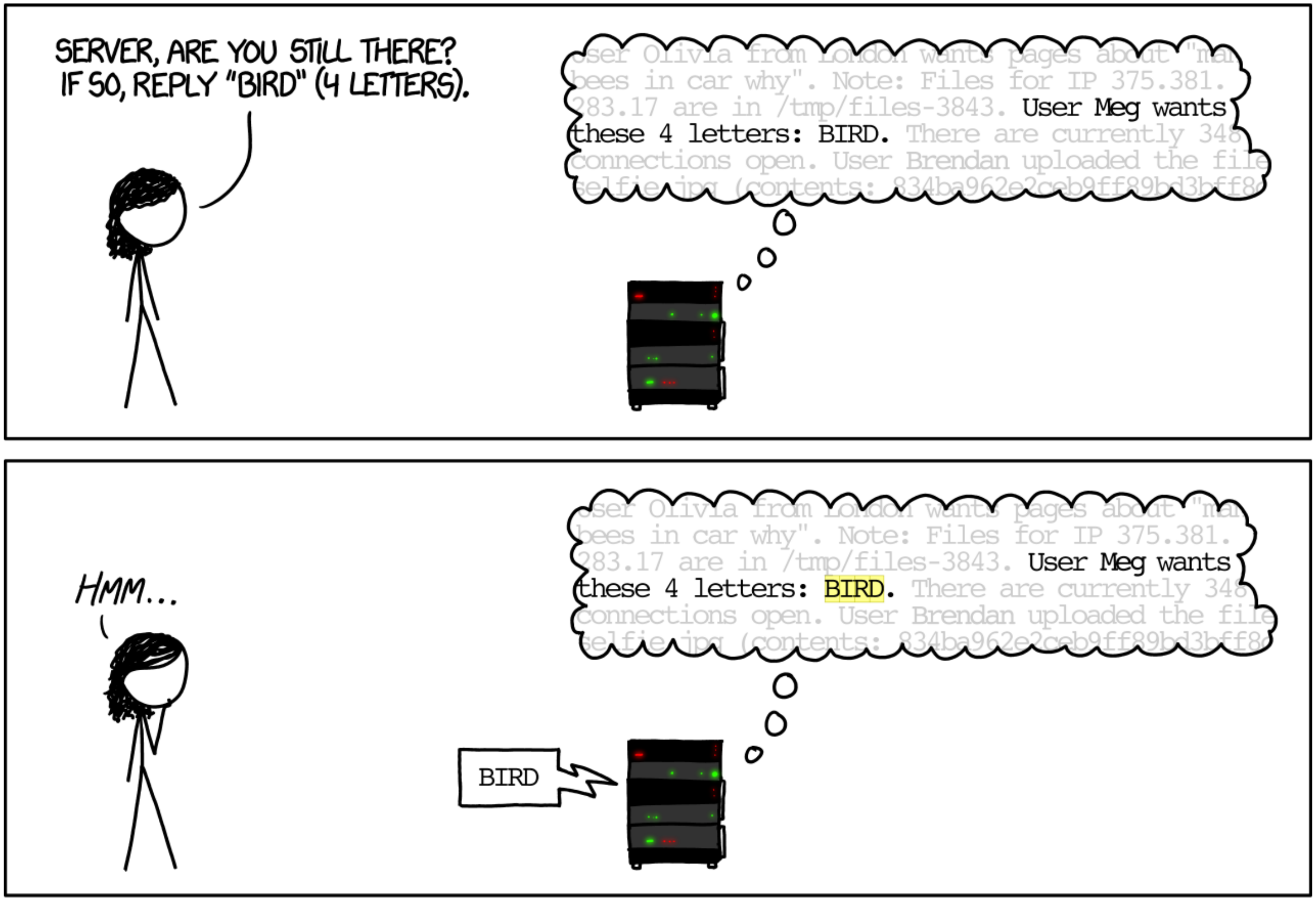
Example: the original Internet worm (1988)

- 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…

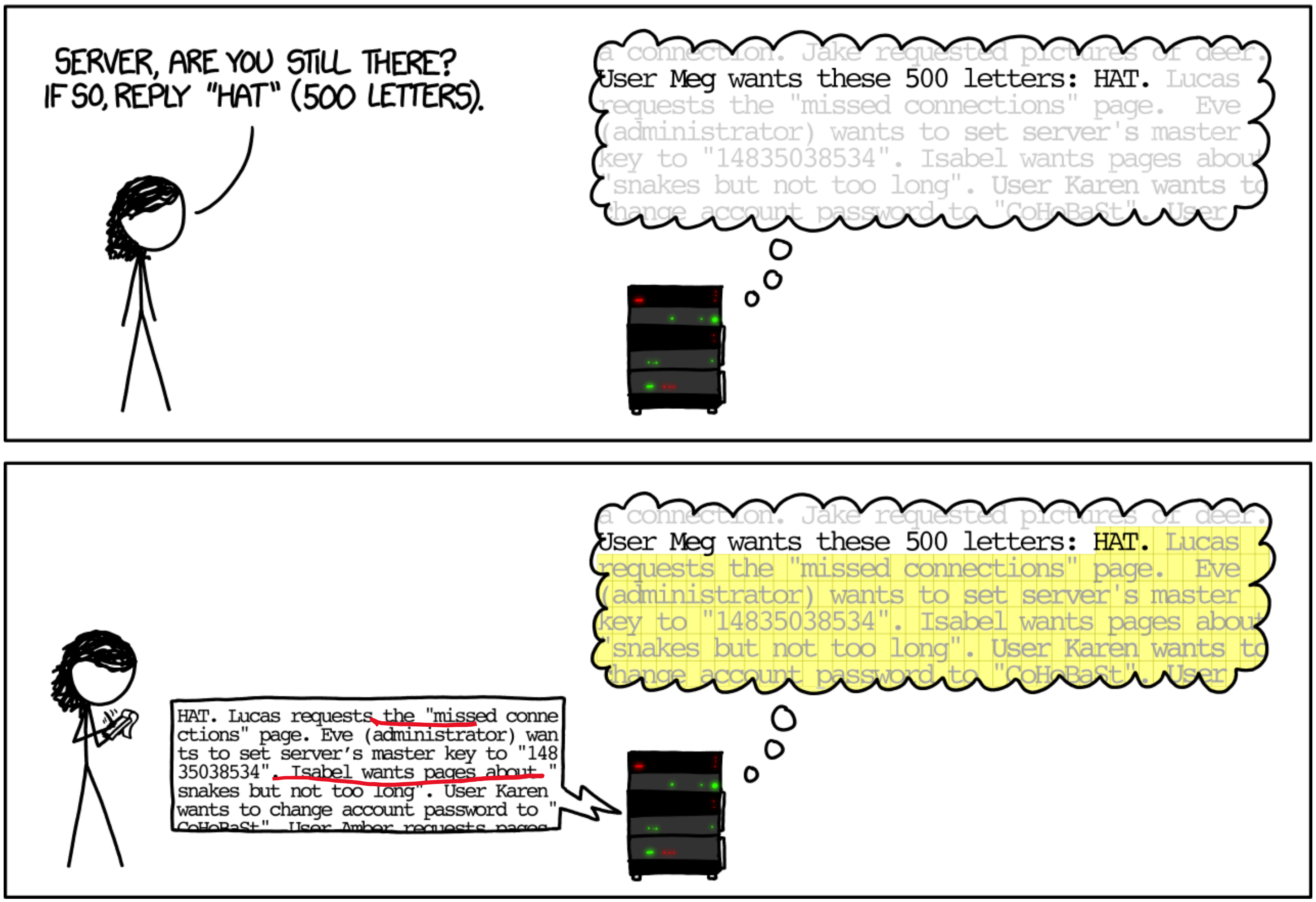
Example: Heartbleed



Example: Heartbleed

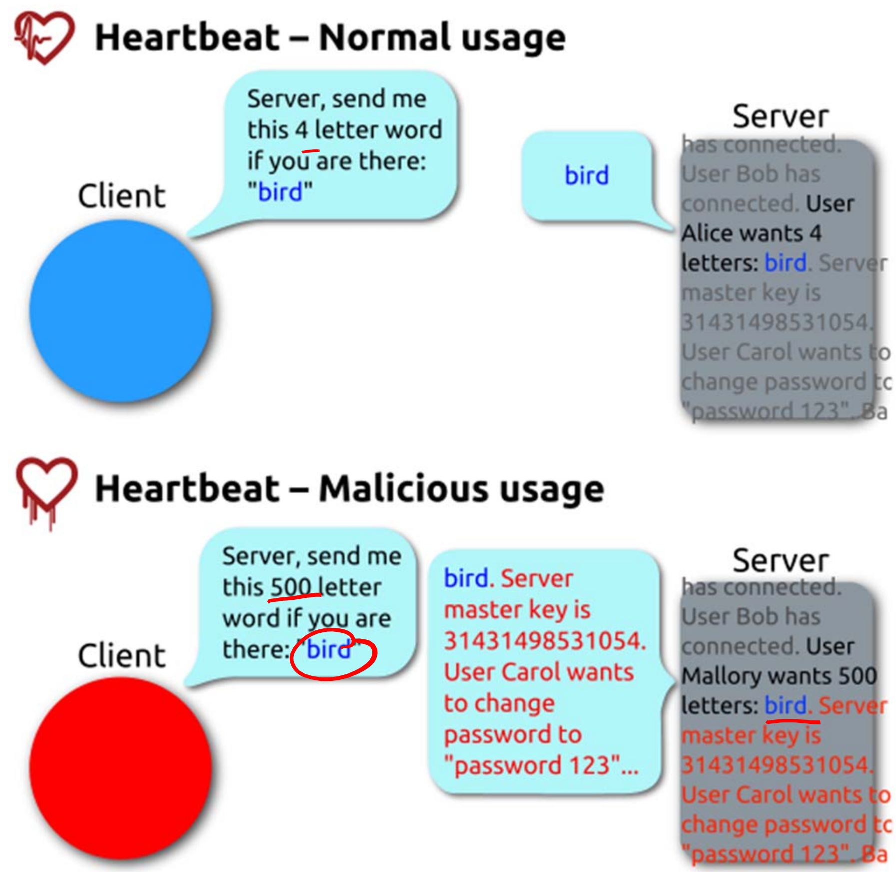


Example: Heartbleed



Heartbleed (2014)

- 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, ...



Hacking Cars

- UW CSE research from 2010 demonstrated wirelessly hacking a car using buffer overflow
- Overwrote the onboard control system's code
  - Disable brakes
  - Unlock doors
  - Turn engine on/off

Dealing with buffer overflow attacks

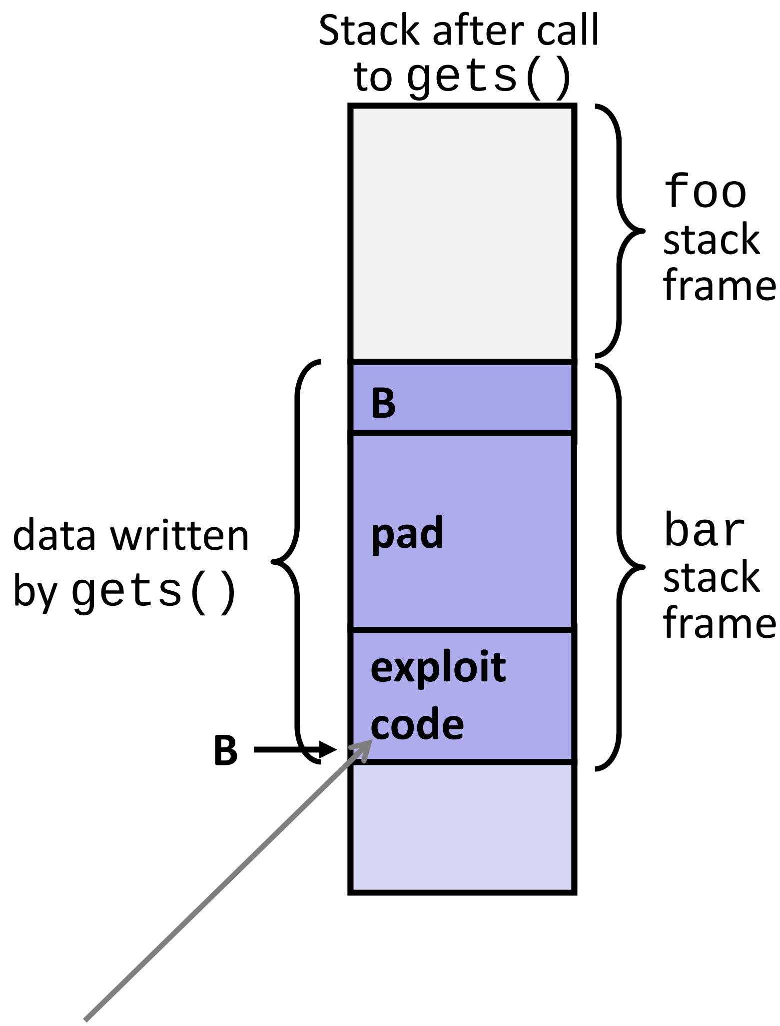
1) Employ system-level protections

2) Avoid overflow vulnerabilities

3) Have compiler use “stack canaries”

1) System-Level Protections

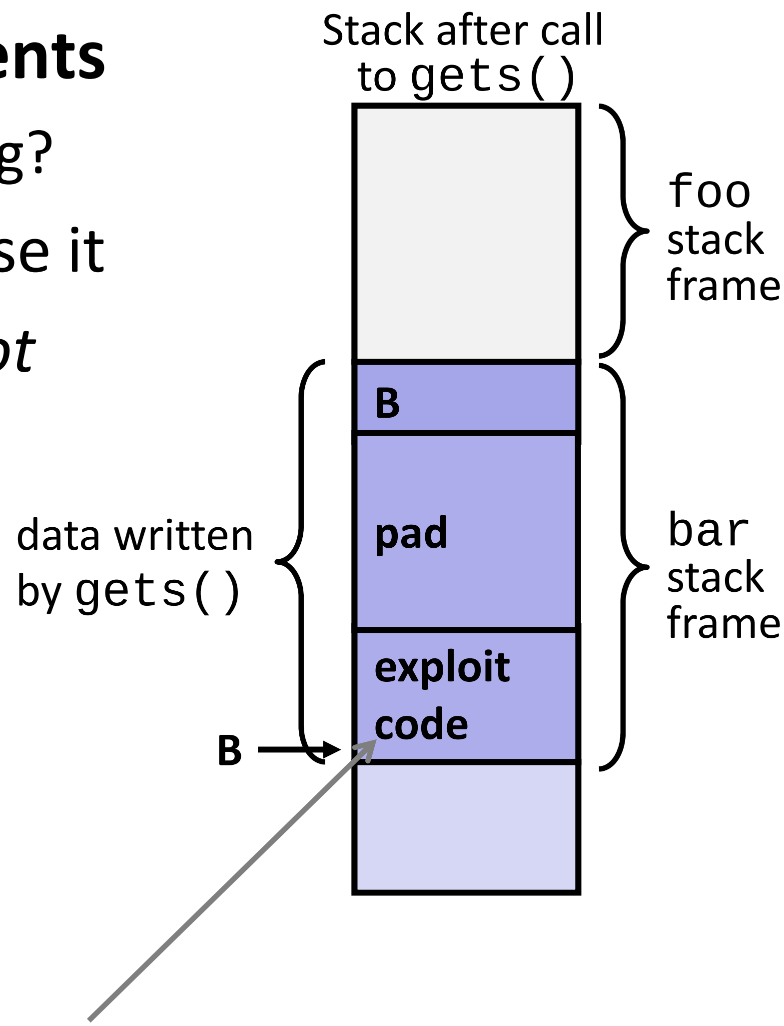
- **Non-executable code segments**
- In traditional x86, can mark region of memory as either "read-only" or "writeable"
  - Can execute anything readable
- x86-64 added explicit "execute" permission
- Stack marked as non-executable
  - Do *NOT* execute code in Stack, Static Data, or Heap regions
  -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



Any attempt to execute this code will fail

1) System-Level Protections

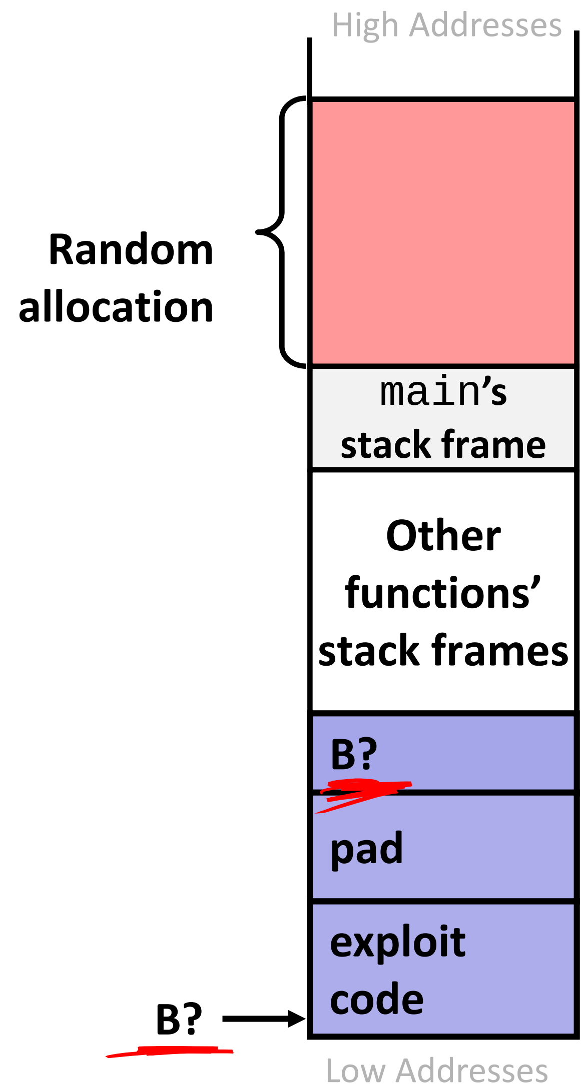
- **Non-executable code segments**
  - Wait, doesn't this fix everything?
- Works well, but can't always use it
- Many embedded devices *do not* have this protection
  - Cars
  - Smart homes
  - Pacemakers
- Some exploits still work!
  - Return-oriented programming
  - Return to libc attack
  - JIT-spray 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: Code from Slide 6 executed 5 times; address of variable `local` =
    - `0x7ffd19d3f8ac`
    - `0x7ffe8a462c2c`
    - `0x7ffe927c905c`
    - `0x7ffefd5c27dc`
    - `0x7fffa0175afc`
  - 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:

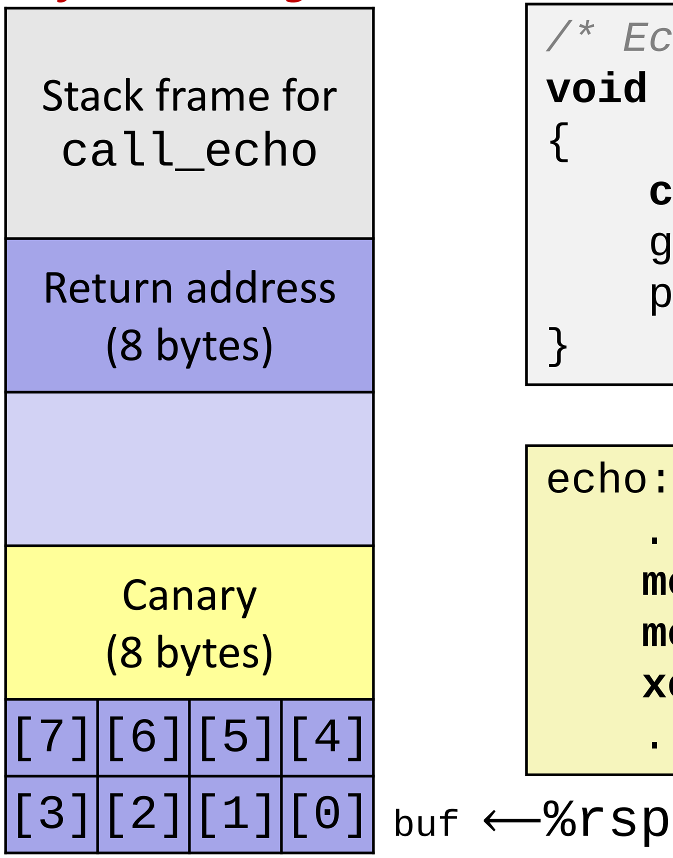
```
400607:  sub    $0x18,%rsp
40060b:  mov    %fs:0x28,%rax          # read canary value
400614:  mov    %rax,0x8(%rsp)         # store canary on Stack
400619:  xor    %eax,%eax              # erase canary from register
 ...      ... call printf ...
400625:  mov    %rsp,%rdi
400628:  callq  400510 <gets@plt>
40062d:  mov    %rsp,%rdi
400630:  callq  4004d0 <puts@plt>
400635:  mov    0x8(%rsp),%rax         # read current canary on Stack
40063a:  xor    %fs:0x28,%rax          # compare against original value
400643:  jne    40064a <echo+0x43>     # if unchanged, then return
400645:  add    $0x18,%rsp
400649:  retq
40064a:  callq  4004f0 <__stack_chk_fail@plt>   # stack smashing detected
```

try: diff buf-nsp.s buf.s

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);
}
```

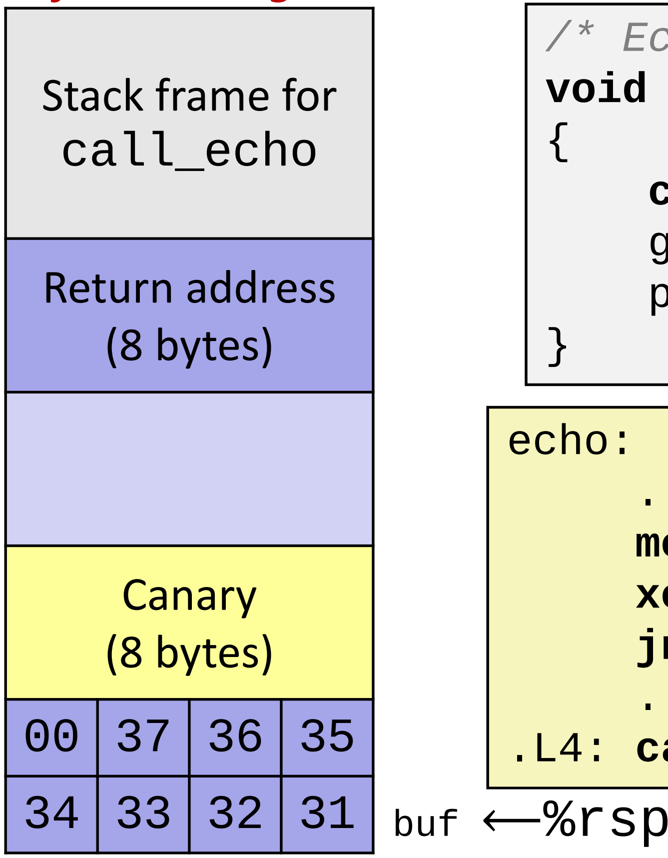
Segment register ***(don't worry about it)***

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

Checking Canary

This is extra (non-testable) material

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 ☺
  - Check out the buffer overflow simulator!
- 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=hB6eY73sLV

Extra Notes about %rbp

This is extra (non-testable) material

- `%rbp` is used to store the frame pointer
  - Name comes from “base pointer”
- You can refer to a variable on the stack as `%rbp+offset`
- The base of the frame will never change, so each variable can be uniquely referred to with its offset
- The top of the stack (`%rsp`) may change, so referring to a variable as `%rsp-offset` is less reliable
  - For example, if you need save a variable for a function call, pushing it onto the stack changes `%rsp`