Buffer Overflows

CSE 351 Winter 2020

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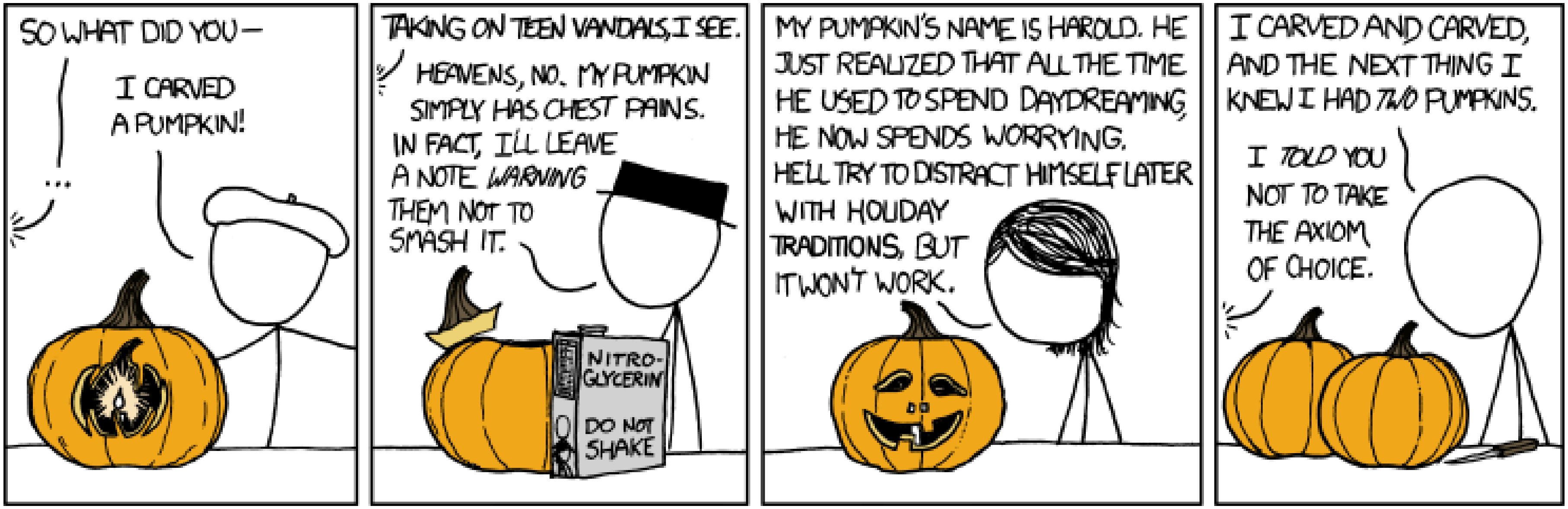

SO WHAT DID YOU—
I CARVED A PUMPKIN!
...
TAKING ON TEEN VANDALS, I SEE.
HEAVENS, NO. MY PUMPKIN SIMPLY HAS CHEST PAINS.
IN FACT, I'LL LEAVE A NOTE WARNING THEM NOT TO SMASH IT.
NITRO-GLYCERIN
DO NOT SHAKE
MY PUMPKIN'S NAME IS HAROLD. HE JUST REALIZED THAT ALL THE TIME HE USED TO SPEND DAYDREAMING HE NOW SPENDS WORRYING. HE'LL TRY TO DISTRACT HIMSELF LATER WITH HOLIDAY TRADITIONS, BUT IT WON'T WORK.
I CARVED AND CARVED, AND THE NEXT THING I KNEW I HAD TWO PUMPKINS.
I TOLD YOU NOT TO TAKE THE AXIOM OF CHOICE.

http://xkcd.com/804/

Administrivia

- Mid-quarter survey due Thursday (2/13)
- hw13 due Friday (2/14)
- Lab 3 released after class, due next Monday (2/24)
  - You will have everything you need by the end of this lecture
- Section Tomorrow:
  - Bring laptop and lab3 downloaded and untar-ed already
- Midterm grades coming soon
  - Solutions posted on website soon
  - Graded exam will be found on Gradescope
  - Regrade requests will be open for a short time after grade release

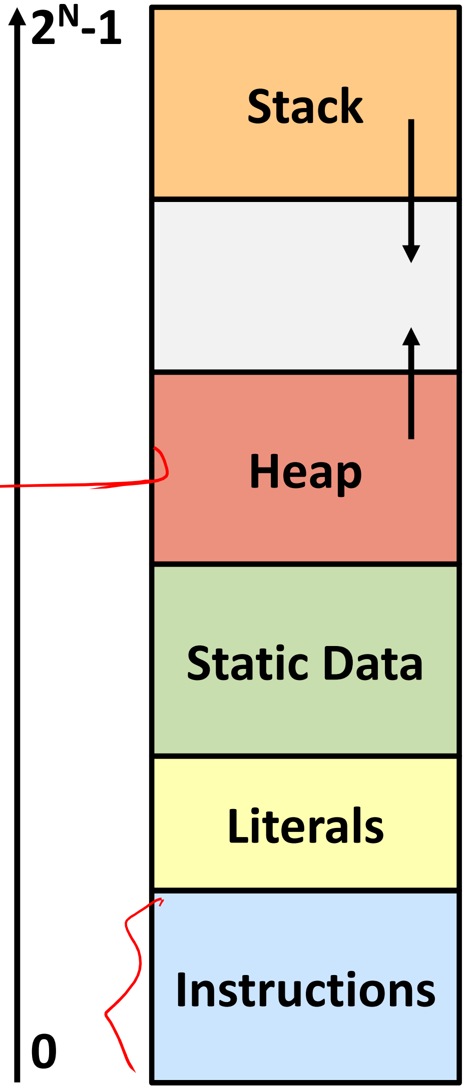
Buffer Overflows

- 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

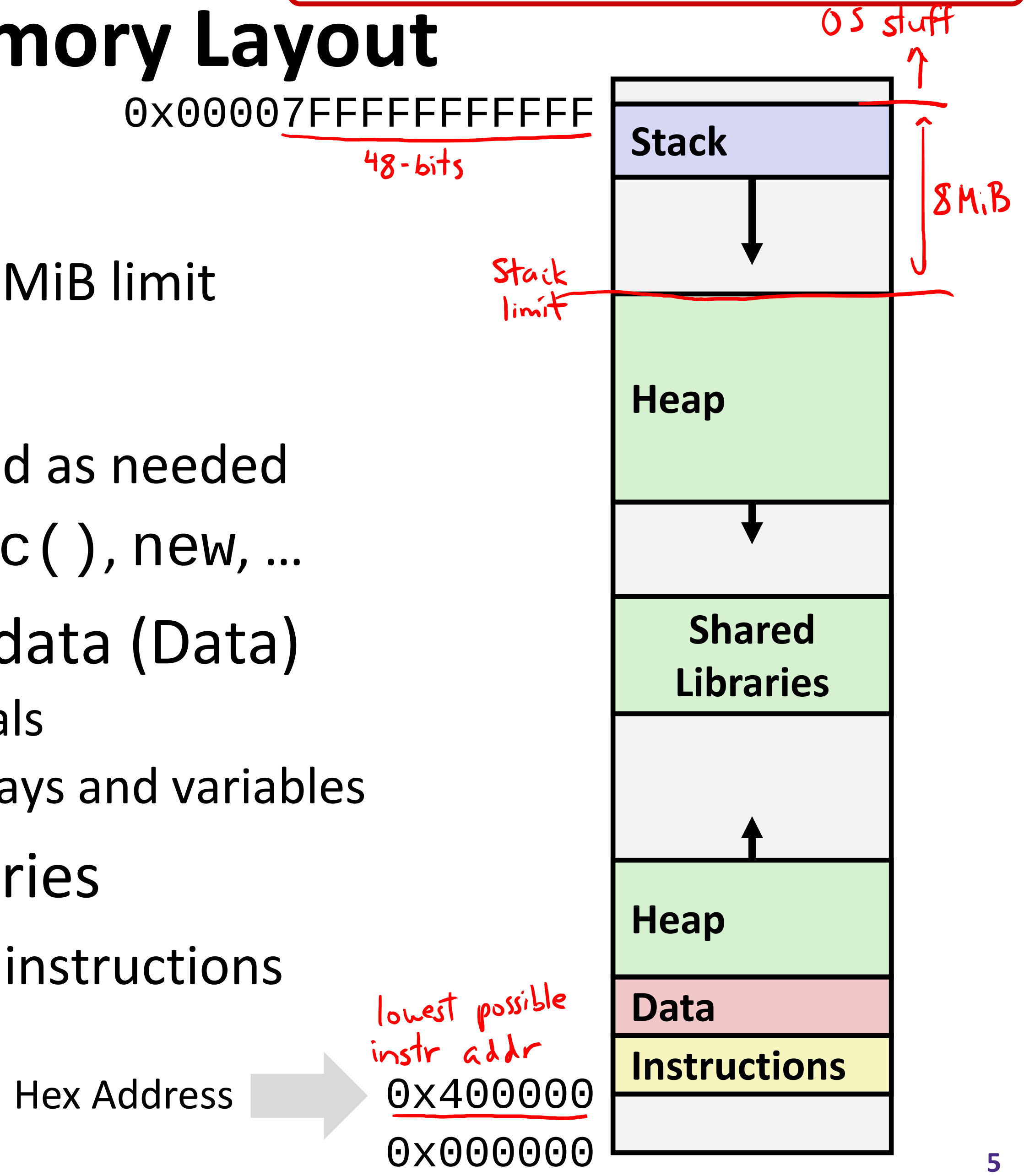
- Stack
  - Local variables (procedure context)
- Heap
  - Dynamically allocated as needed
  - `malloc()`, `calloc()`, new, …
- Statically allocated Data
  - Read/write: global variables (Static Data)
  - Read-only: string literals (Literals)
- Code/Instructions
  - Executable machine instructions
 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



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)

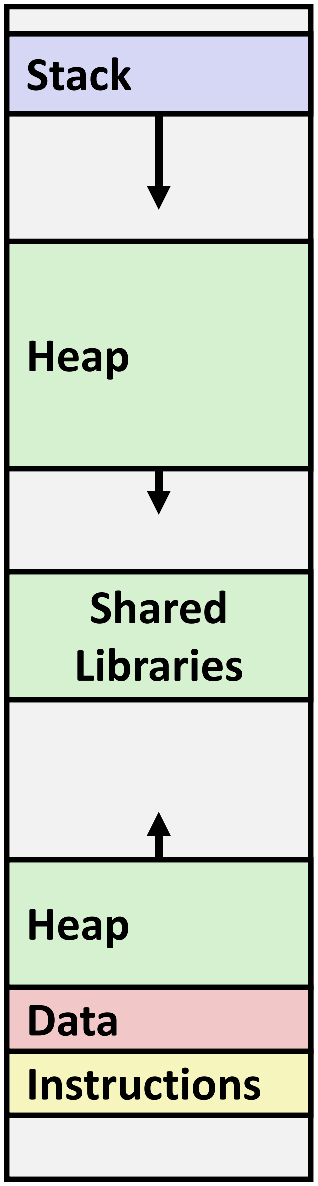
dynamically-allocated memory (Heap)

Where does everything go?

p1 → stack address

*p1 → heap address

not drawn to scale



not drawn to scale

Memory Allocation Example

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char big_array[1L<<24];  /* 16 MB */
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int global = 0;

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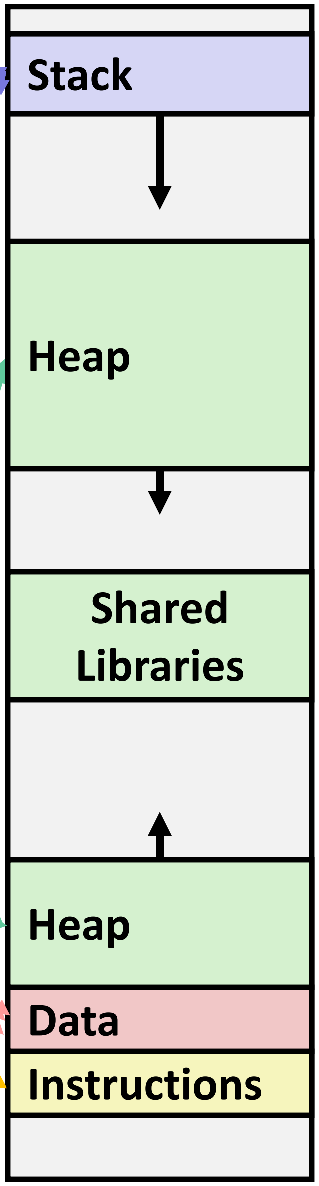
int main()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8);  /* 256  B */
    p3 = malloc(1L << 32); /*   4 GB */
    p4 = malloc(1L << 8);  /* 256  B */
    /* Some print statements ... */
}
```



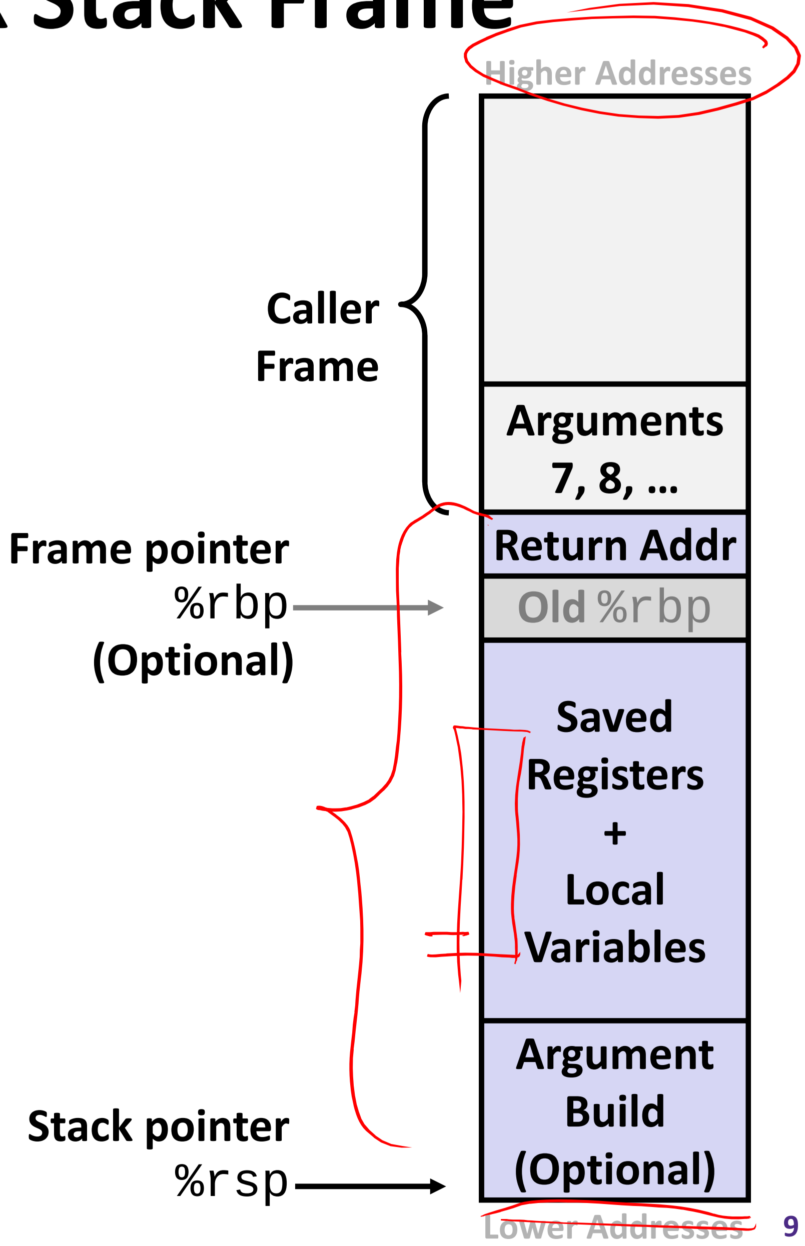
Where does everything go?

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

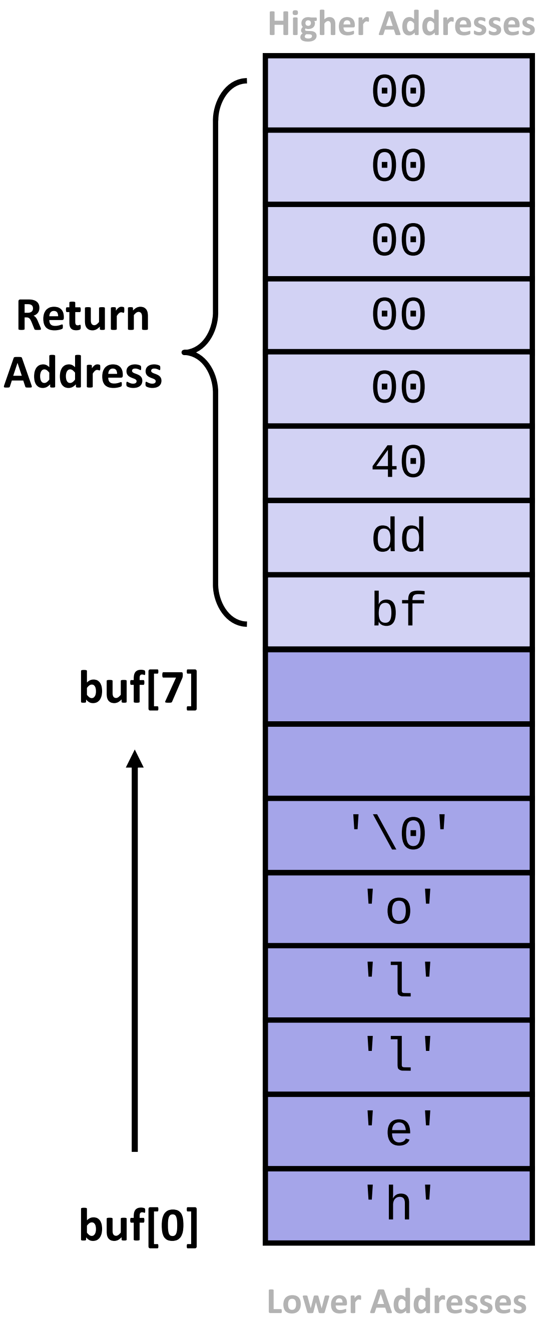
- Characteristics of the traditional Linux memory layout provide opportunities for malicious programs
  - Stack grows “backwards” in memory
  - Data and instructions both stored in the same memory

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 ☺



Higher Addresses

Return Address

00
00
00
00
00
40
dd
bf

buf[7]

'\0'
'o'
'l'
'l'
'e'
'h'

buf[0]

Lower Addresses

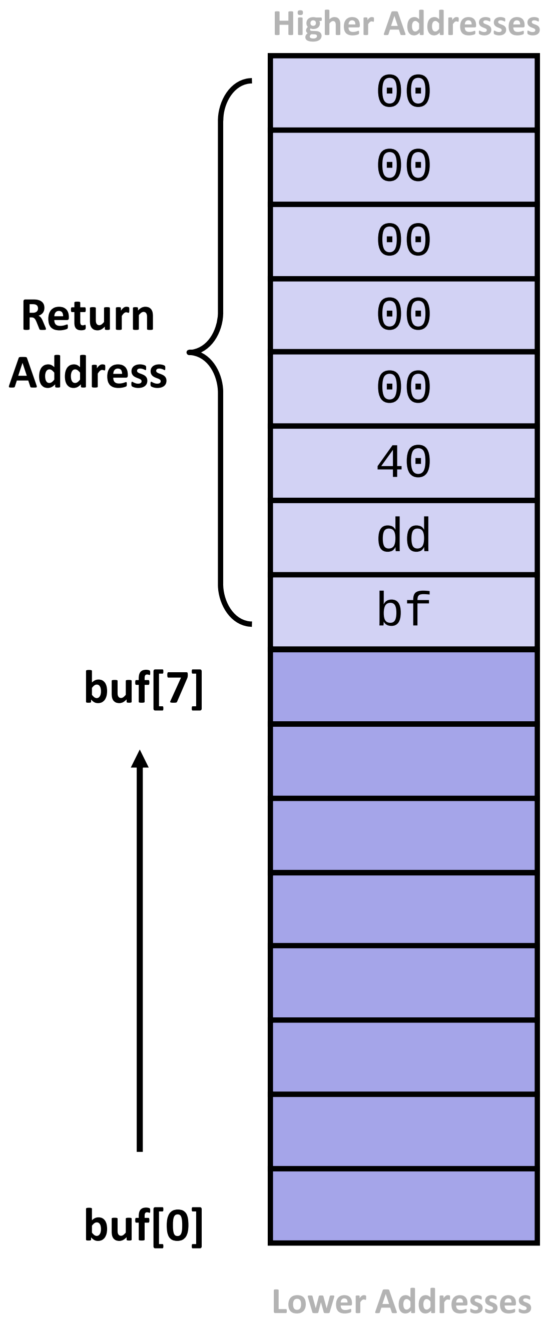
Buffer Overflow in a Nutshell

- 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
```

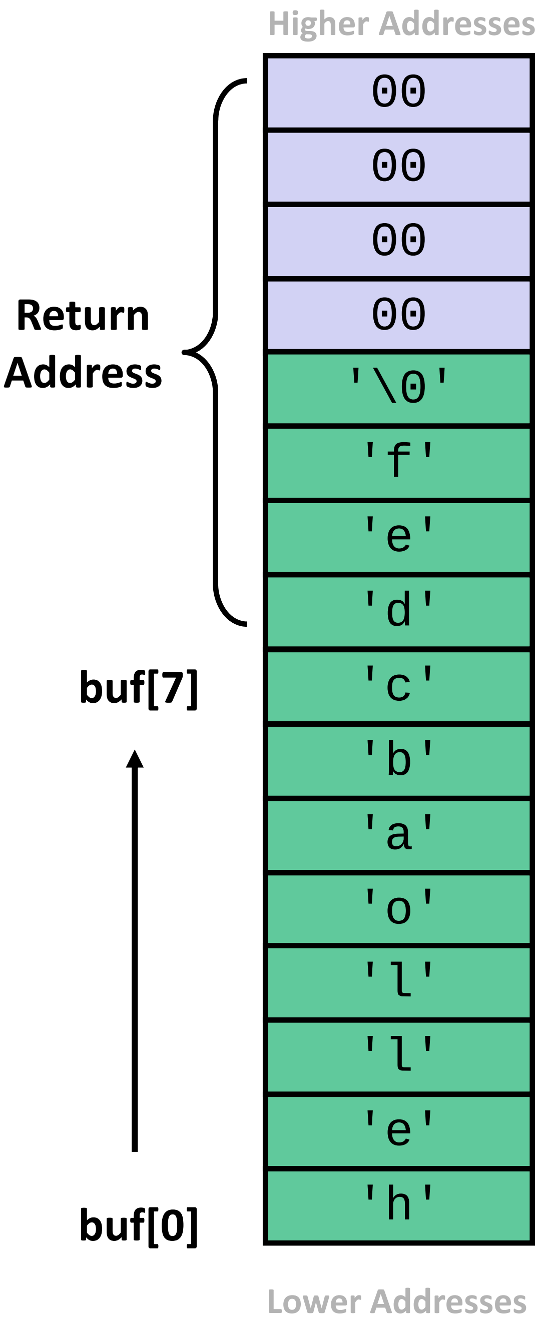


Buffer Overflow in a Nutshell

- 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() {          ↙ input buffer
    char buf[8];  /* Way too small! */
    gets(buf); ← read input into buffer
    puts(buf); ← 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:

```
                                                       24
 0000000000400597 <echo>:
  400597:  48 83 ec 18          sub    $0x18,%rsp   compiler choice
    ...                          ... 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
```

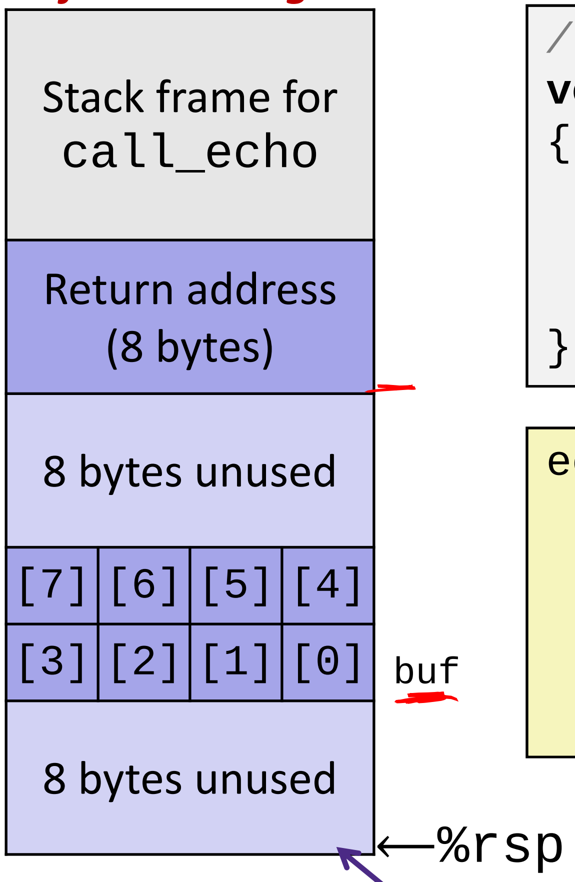
call_echo:

```
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



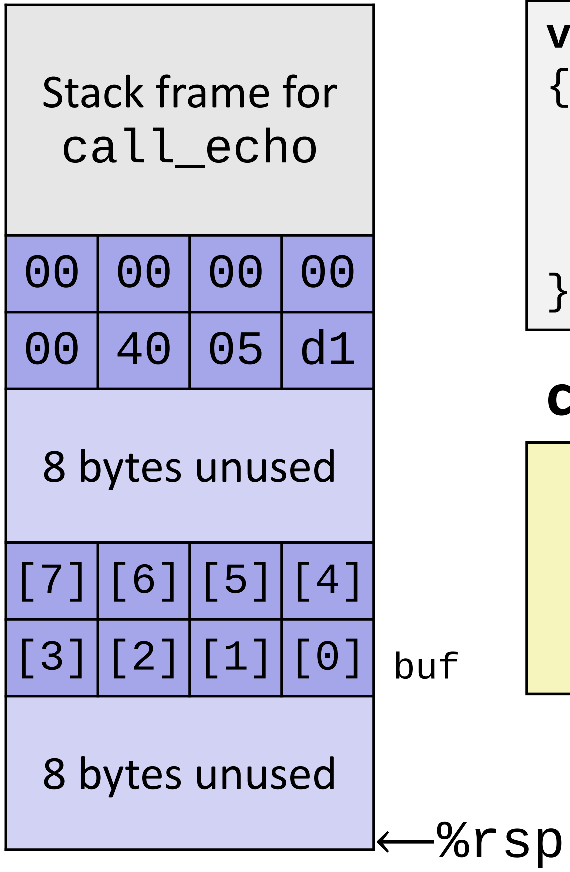
```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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);
    . . .
}
```

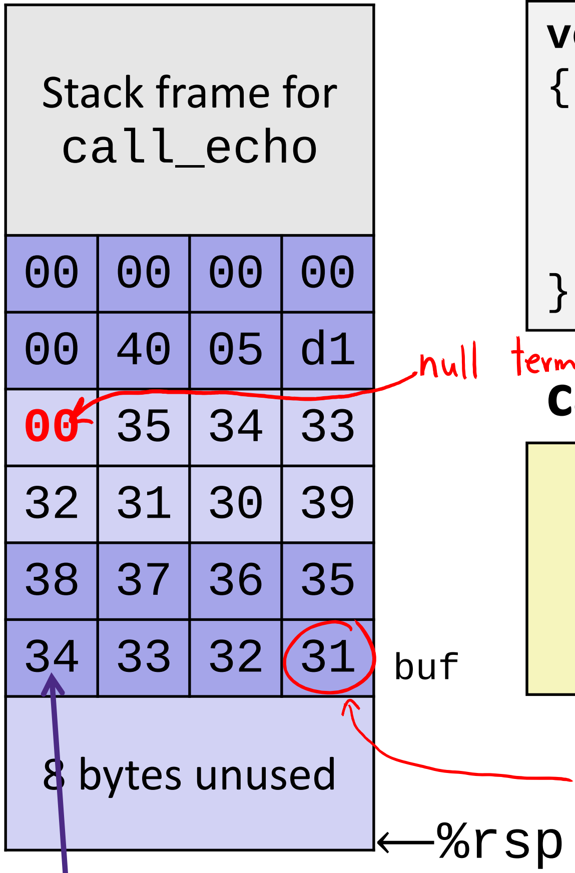
```
echo:
  subq  $24, %rsp
   ...
  leaq  8(%rsp), %rdi
  call  gets
   ...
```

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

8 bytes unused

```
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'

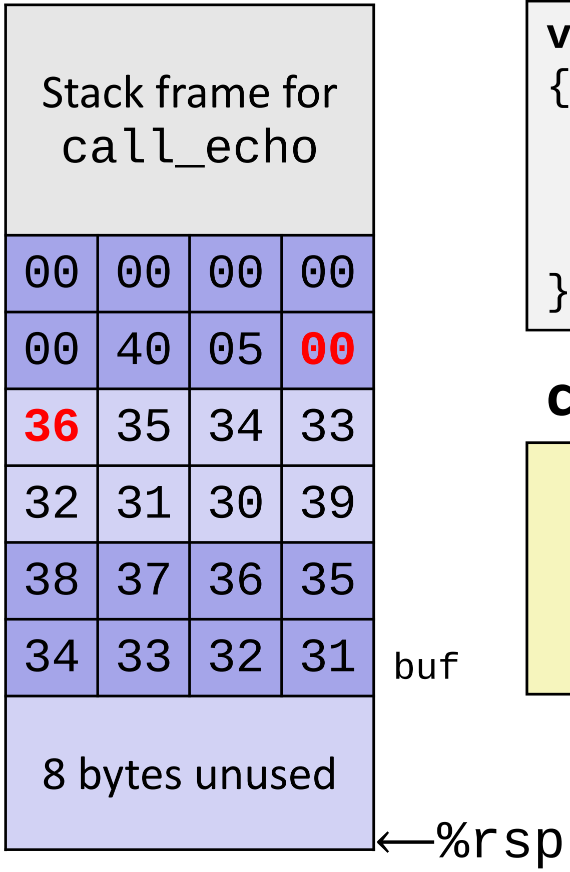
```
unix> ./buf-nsp
Enter string: 123456789012345
123456789012345
```

Overflowed buffer, but did not corrupt state

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 05 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
  call  gets
   ...
```

call_echo:

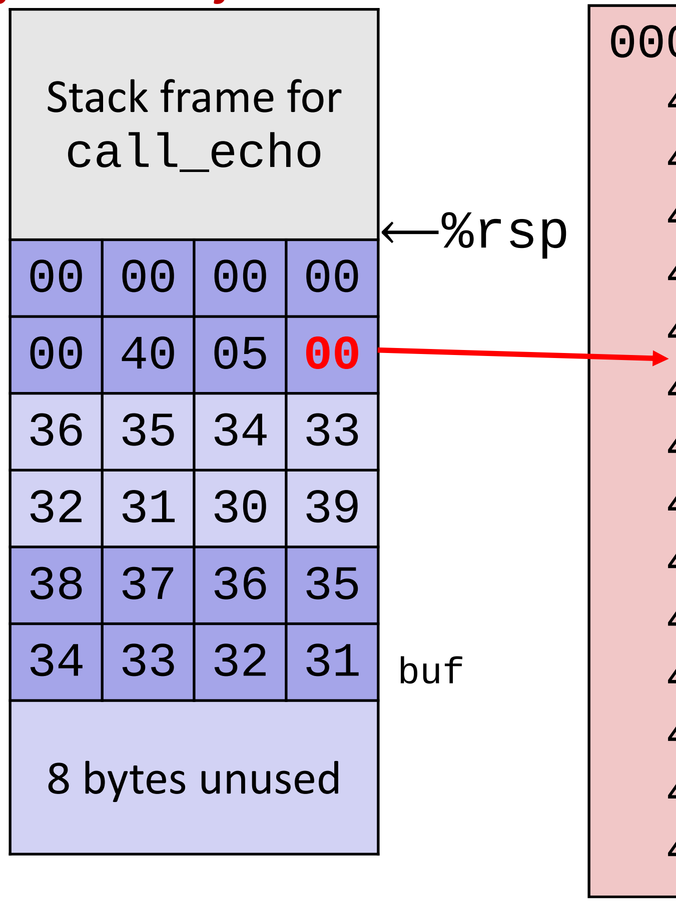
```
  . . .
  4005cc:  callq  400597 <echo>
  4005d1:  add    $0x8,%rsp
  . . .
```

```
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`

←%rsp

00	00	00	00
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`

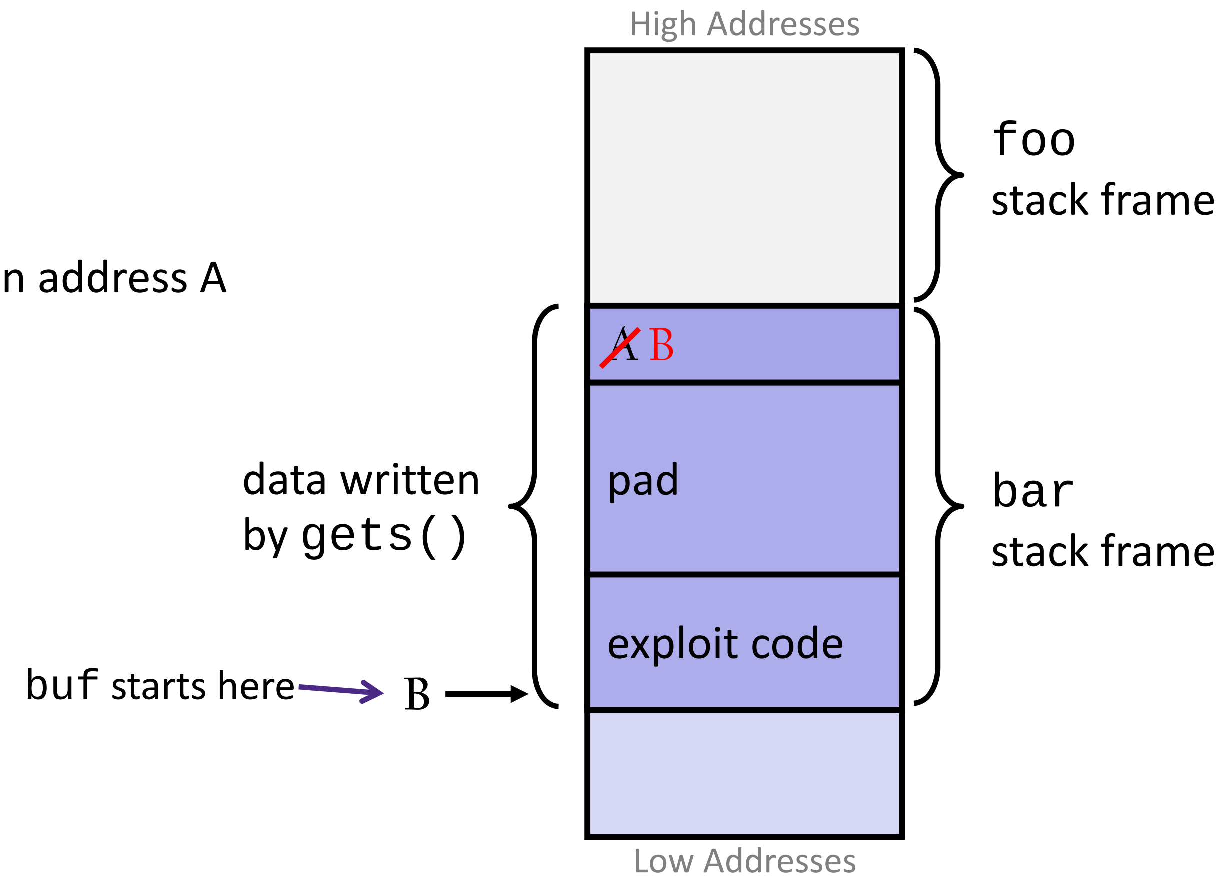
Malicious Use of Buffer Overflow: Code Injection Attacks

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

return address A

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

Stack after call to gets()



High Addresses

foo stack frame

~~A~~ B

pad

exploit code

bar stack frame

data written by gets()

buf starts here → B

Low Addresses

- 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

- `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)

Previous stack frame			
00	00	00	00
00	40	05	d1
. . .			
			[0]

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

A. 27

B. 30

C. 51

D. 54

E. We're lost…

Exploits Based on Buffer Overflows

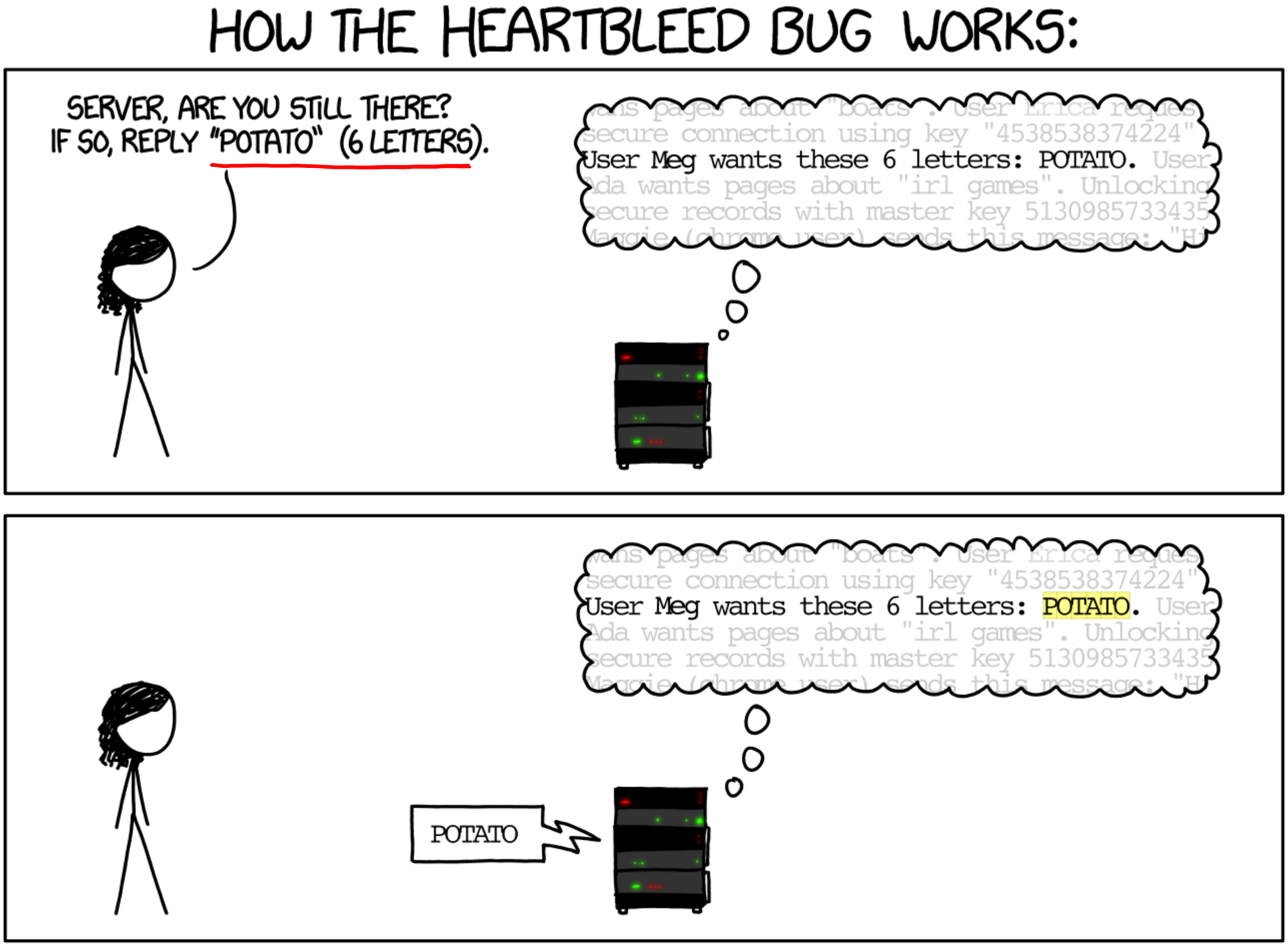
Buffer overflow bugs can allow attackers to execute arbitrary code on victim machines

- 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

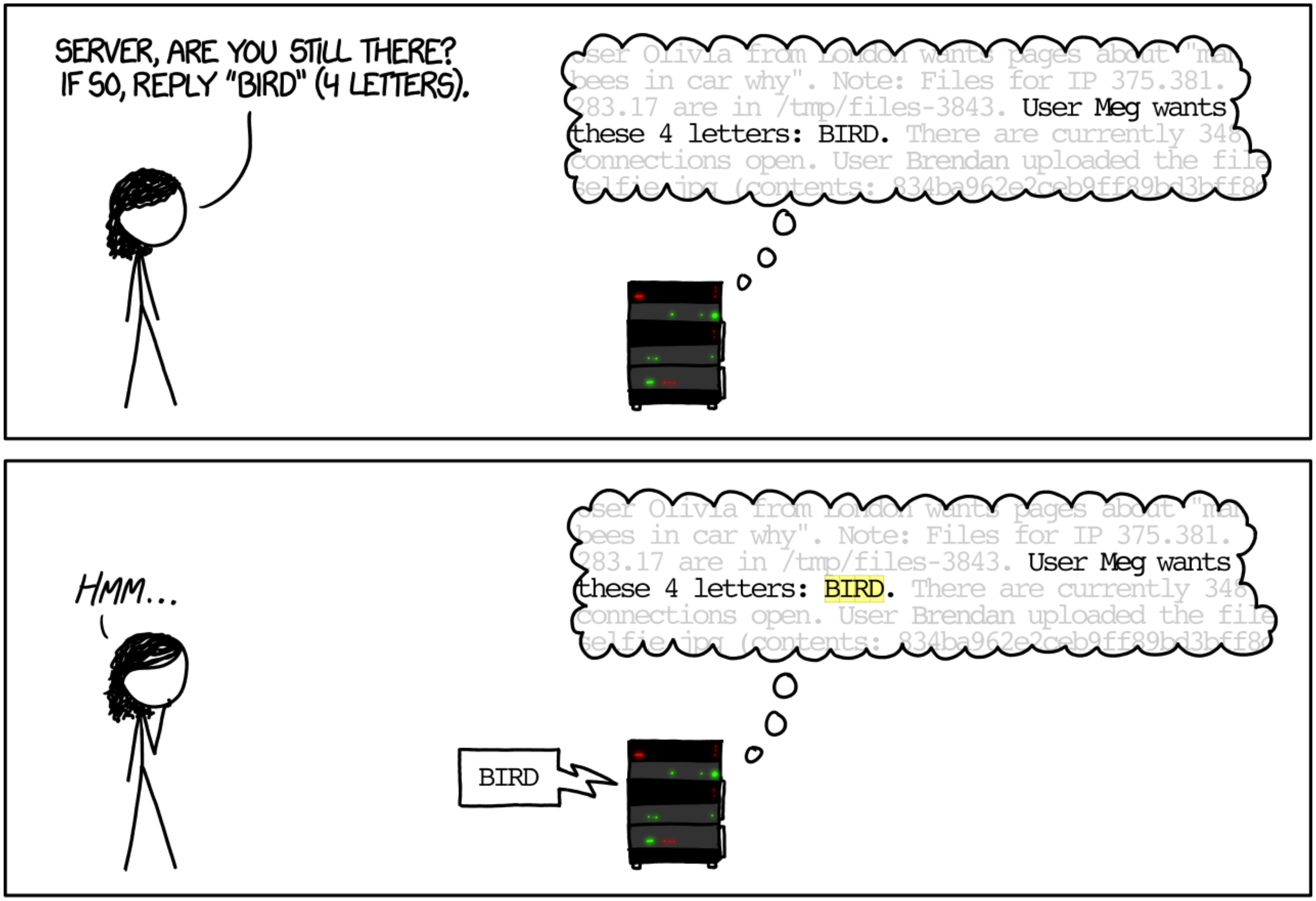
Example: the original Internet worm (1988)

- 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…

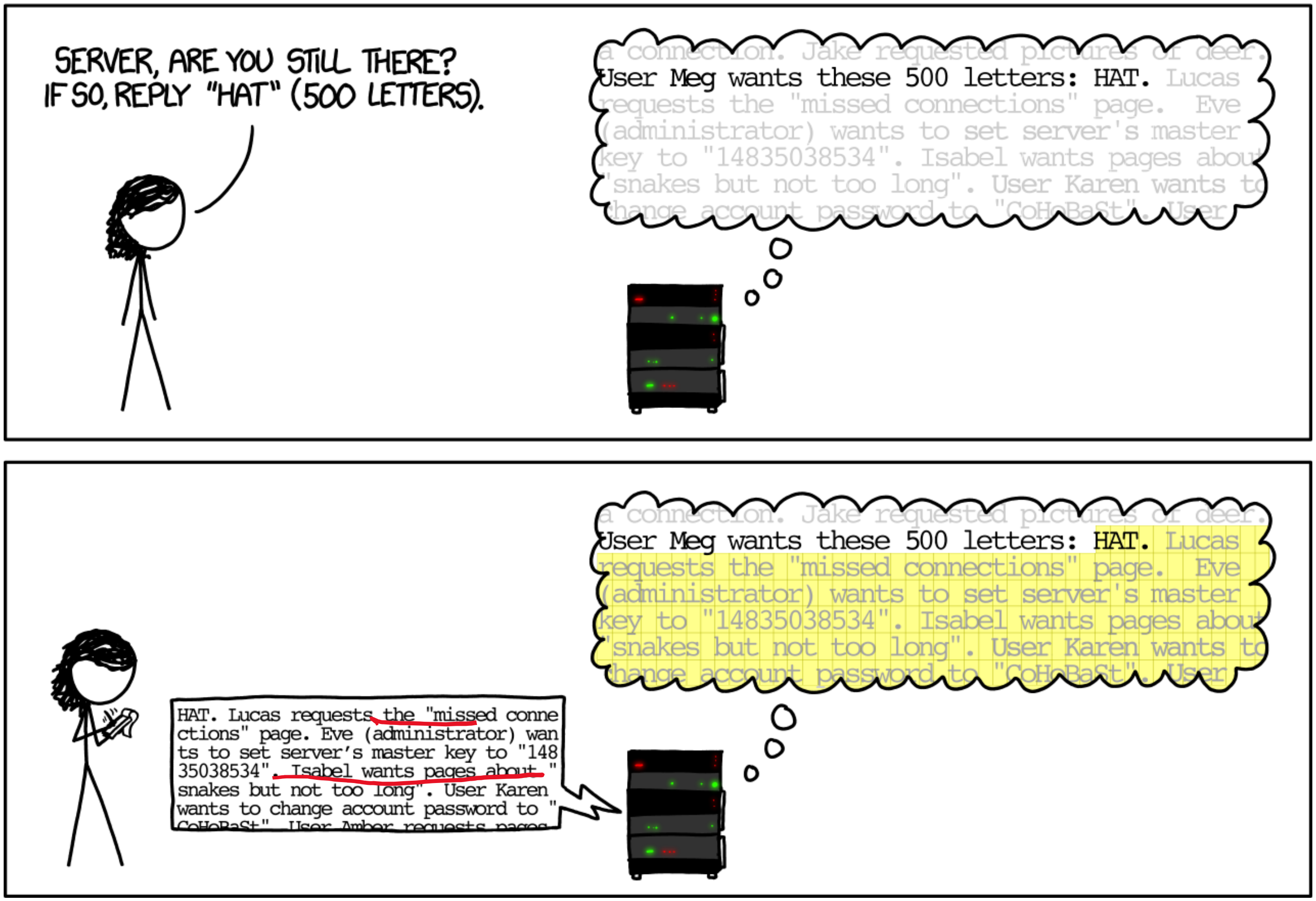
Example: Heartbleed


HOW THE HEARTBLEED BUG WORKS:
SERVER, ARE YOU STILL THERE? IF SO, REPLY "POTATO" (6 LETTERS).
ants pages about "boats". User Erica reques
secure connection using key "4538538374224"
User Meg wants these 6 letters: POTATO. User
Ada wants pages about "irl games". Unlocking
secure records with master key 5130985733435
Maggie (chrome user) sends this message: "H
POTATO

Example: Heartbleed

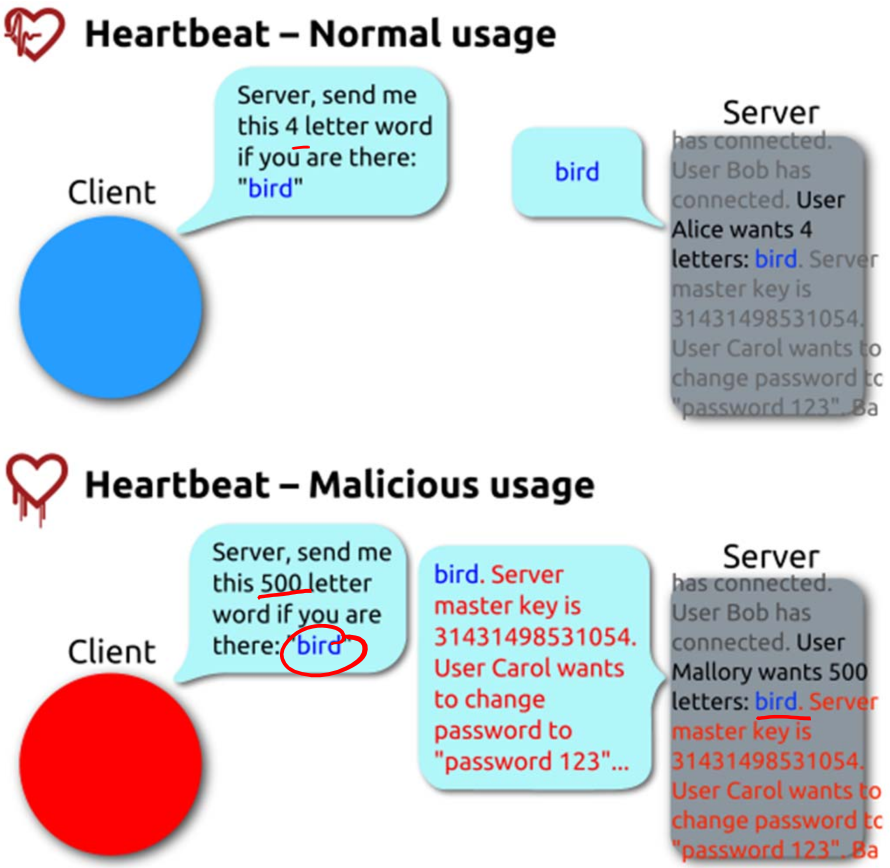

SERVER, ARE YOU STILL THERE? IF SO, REPLY "BIRD" (4 LETTERS).
User Olivia from London wants pages about "mar bees in car why". Note: Files for IP 375.381.283.17 are in /tmp/files-3843. User Meg wants these 4 letters: BIRD. There are currently 348 connections open. User Brendan uploaded the file selfie.jpg (contents: 834ba962e2ceb9ff89bd3bff8
HMM...
User Olivia from London wants pages about "mar bees in car why". Note: Files for IP 375.381.283.17 are in /tmp/files-3843. User Meg wants these 4 letters: BIRD. There are currently 348 connections open. User Brendan uploaded the file selfie.jpg (contents: 834ba962e2ceb9ff89bd3bff8
BIRD

Example: Heartbleed


SERVER, ARE YOU STILL THERE? IF SO, REPLY "HAT" (500 LETTERS).
a connection. Jake requested pictures of deer. User Meg wants these 500 letters: HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about "snakes but not too long". User Karen wants to change account password to "CoHoBaSt". User
a connection. Jake requested pictures of deer. User Meg wants these 500 letters: HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about "snakes but not too long". User Karen wants to change account password to "CoHoBaSt". User
HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about " snakes but not too long". User Karen wants to change account password to " CoHoBaSt". User Amber requests pages

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, ...


Heartbeat – Normal usage
Client
Server, send me this 4 letter word if you are there: "bird"
bird
Server
has connected. User Bob has connected. User Alice wants 4 letters: bird. Server master key is 31431498531054. User Carol wants to change password to "password 123". Ba
Heartbeat – Malicious usage
Client
Server, send me this 500 letter word if you are there: "bird"
bird. Server master key is 31431498531054. User Carol wants to change password to "password 123"...
Server
has connected. User Bob has connected. User Mallory wants 500 letters: bird. Server master key is 31431498531054. User Carol wants to change password to "password 123". Ba

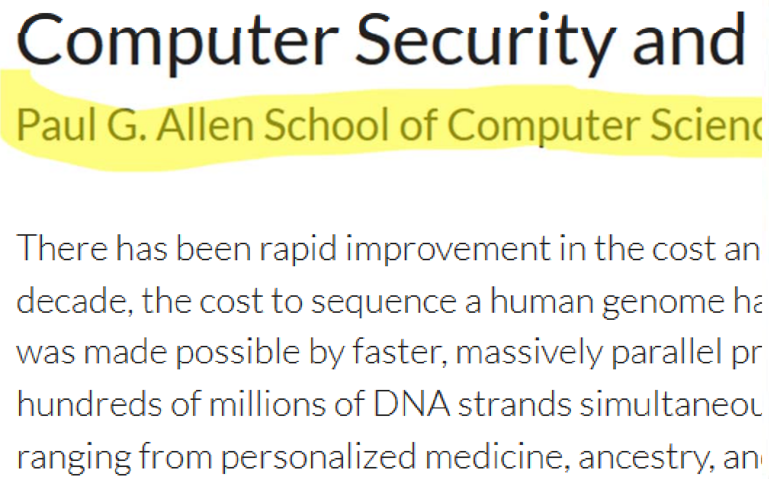
By FenixFeather - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=32276981

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

Hacking DNA Sequencing Tech

- 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.washi



Computer Security and

Paul G. Allen School of Computer Scienc

There has been rapid improvement in the cost an
decade, the cost to sequence a human genome ha
was made possible by faster, massively parallel pr
hundreds of millions of DNA strands simultaneou
ranging from personalized medicine, ancestry, an

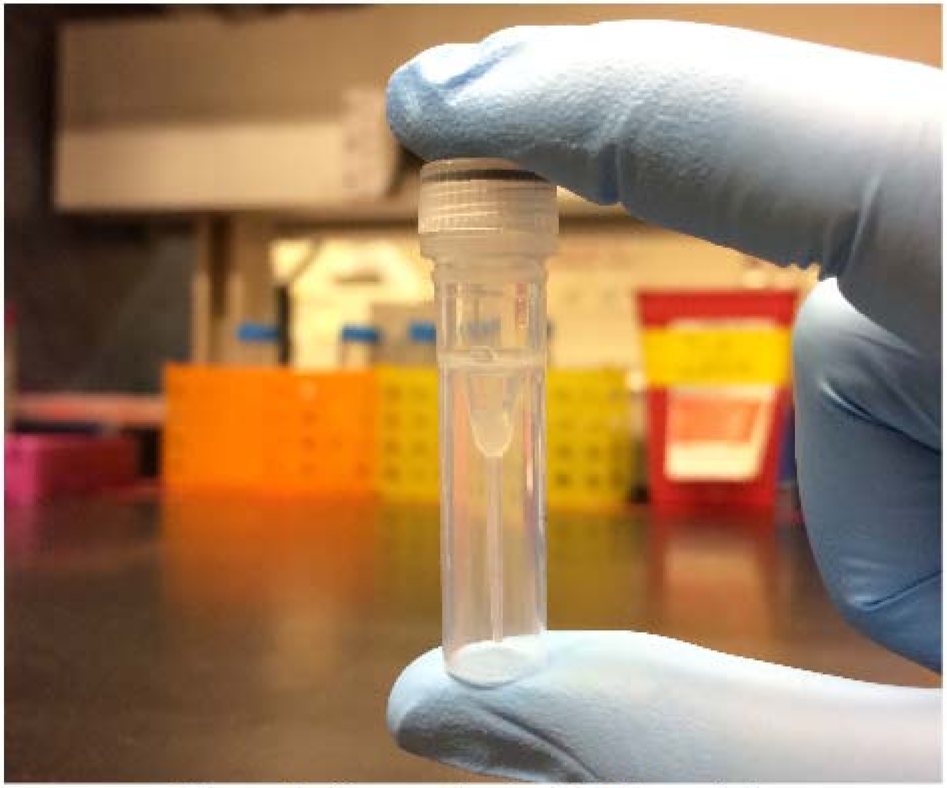


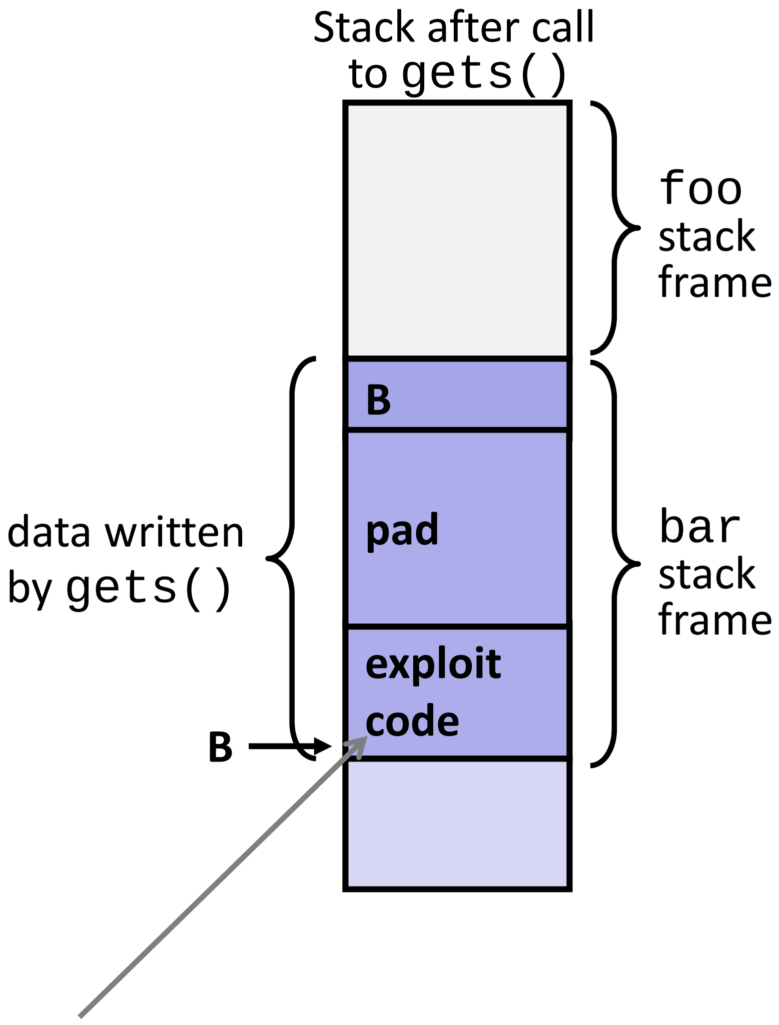
Figure 1: Our synthesized DNA exploit

Dealing with buffer overflow attacks

1) Employ system-level protections
2) Avoid overflow vulnerabilities
3) Have compiler use “stack canaries”

1) System-Level Protections

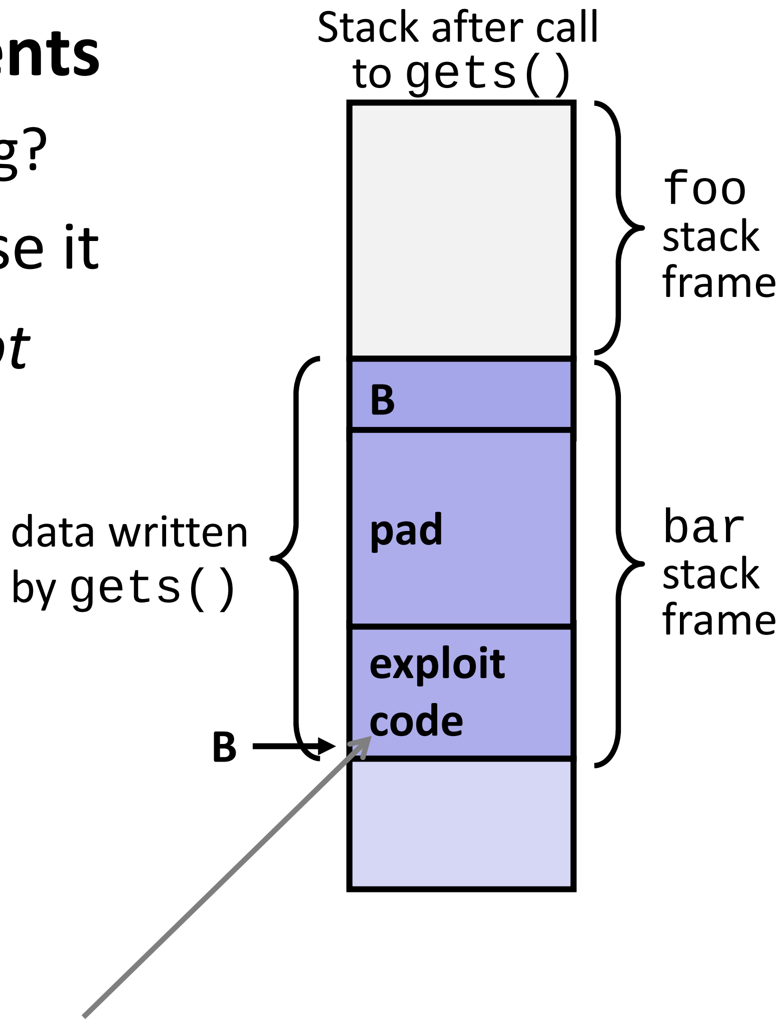
- **Non-executable code segments**
- In traditional x86, can mark region of memory as either "read-only" or "writeable"
  - Can execute anything readable
- x86-64 added explicit "execute" permission
- Stack marked as non-executable
  - Do *NOT* execute code in Stack, Static Data, or Heap regions
  -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



Any attempt to execute this code will fail

1) System-Level Protections

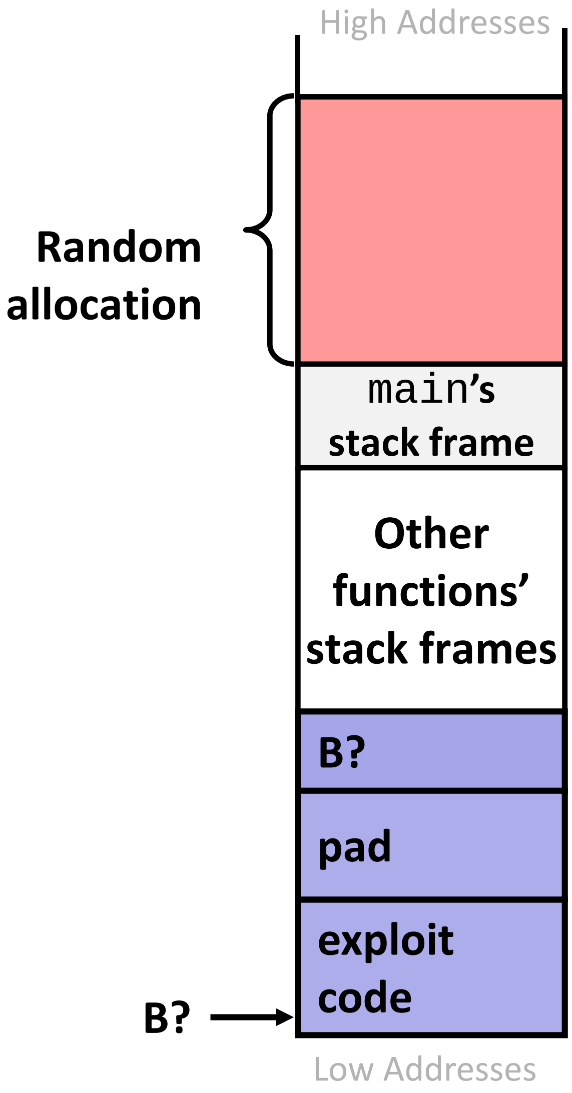
- **Non-executable code segments**
  - Wait, doesn't this fix everything?
- Works well, but can't always use it
- Many embedded devices *do not* have this protection
  - Cars
  - Smart homes
  - Pacemakers
- Some exploits still work!
  - Return-oriented programming
  - Return to libc attack
  - JIT-spray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

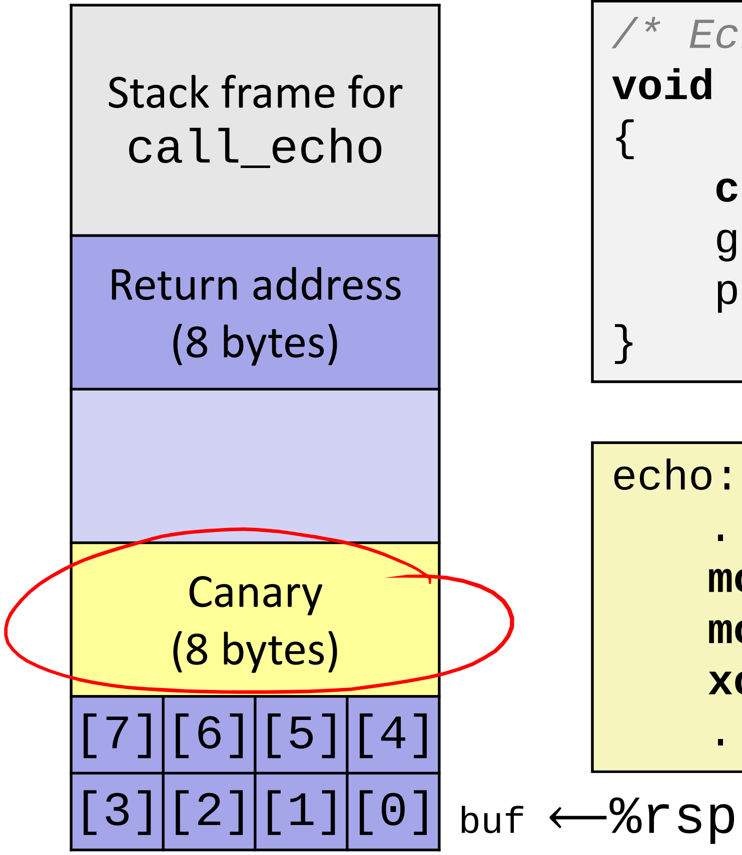
```
  400607:  sub    $0x18,%rsp
  40060b:  mov    %fs:0x28,%rax     # read canary value
  400614:  mov    %rax,0x8(%rsp)    # store canary on Stack
  400619:  xor    %eax,%eax         # erase canary from register
   ...     ... call printf ...
  400625:  mov    %rsp,%rdi
  400628:  callq  400510 <gets@plt>
  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);
}
```

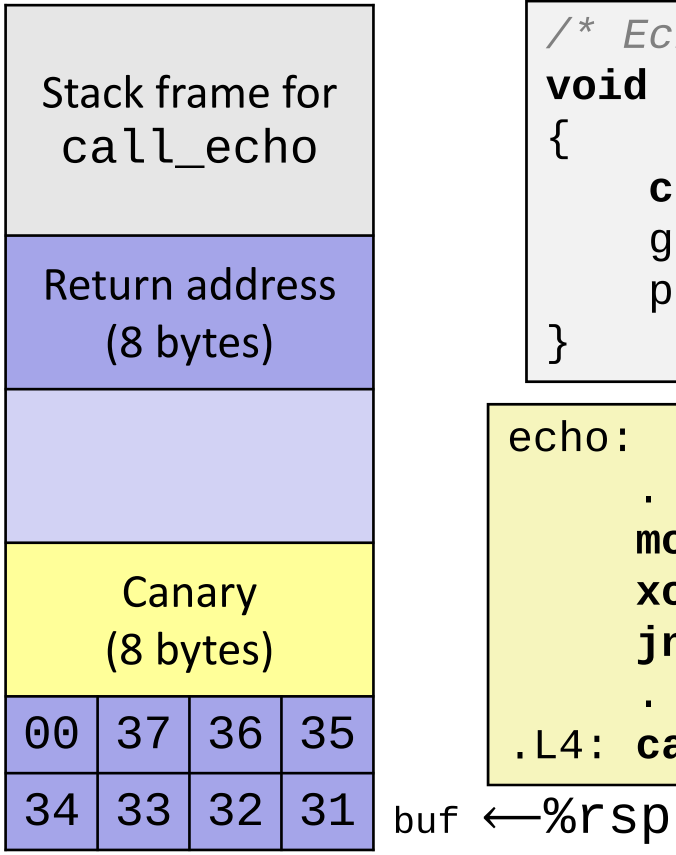
Segment register *(don't worry about it)*

```
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



Stack frame for `call_echo`

Return address (8 bytes)

Canary (8 bytes)

00	37	36	35
34	33	32	31

buf ←%rsp

```
/* 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`