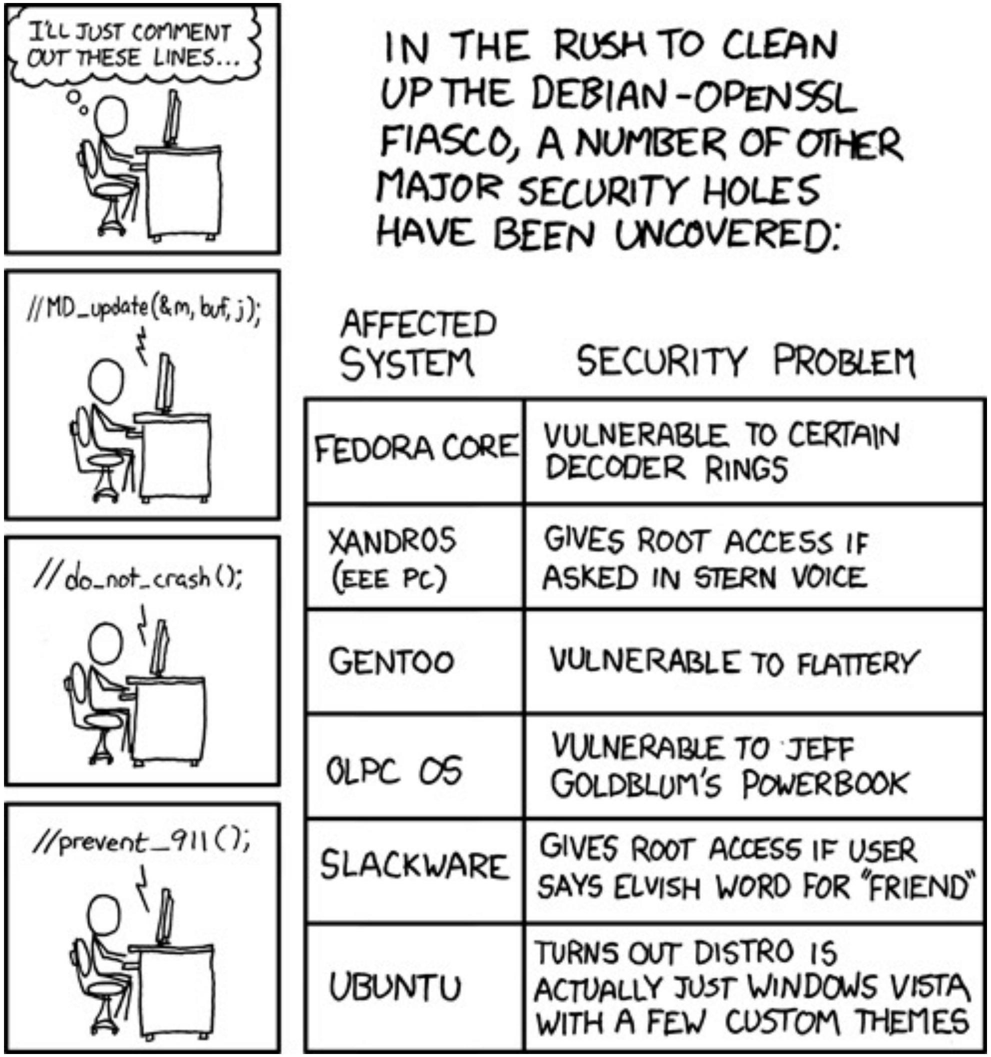
Buffer Overflows

CSE 351 Winter 2022

Instructor:
Sam Wolfson

Teaching Assistants:
Angela Xu
Anirudh Kumar
Catherine Guevara
Dara Stotland
Harrison Bay
Ian Hsiao
Kevin Wang
Mara Kirdani-Ryan
Nick Durand
Sanjana Sridhar



https://xkcd.com/424/

Relevant Course Information

- hw13 due Monday (2/7)
- hw15 due Wednesday (2/9)

- Lab 3 released today, due next Wednesday (2/16)
  - You will have everything you need by the end of this lecture

- Midterm starts Wednesday
  - 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

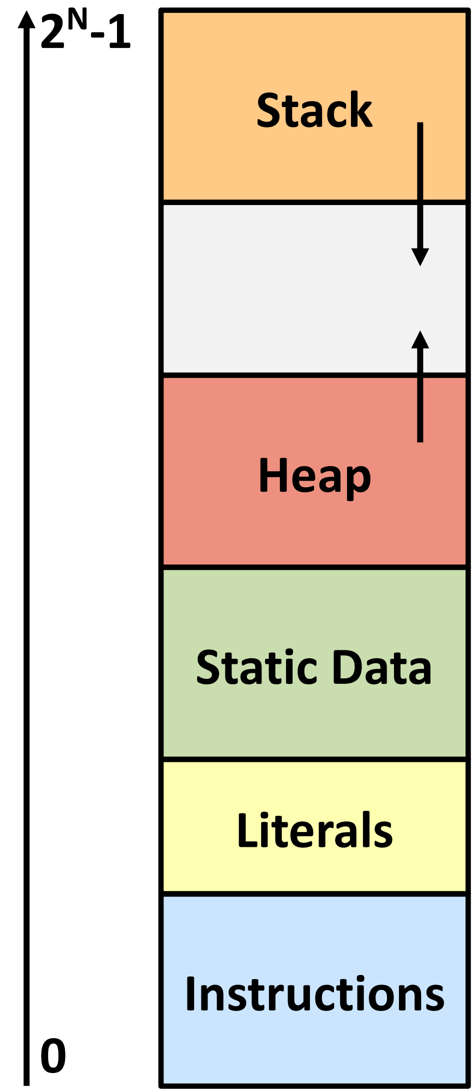
Buffer Overflows

- 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



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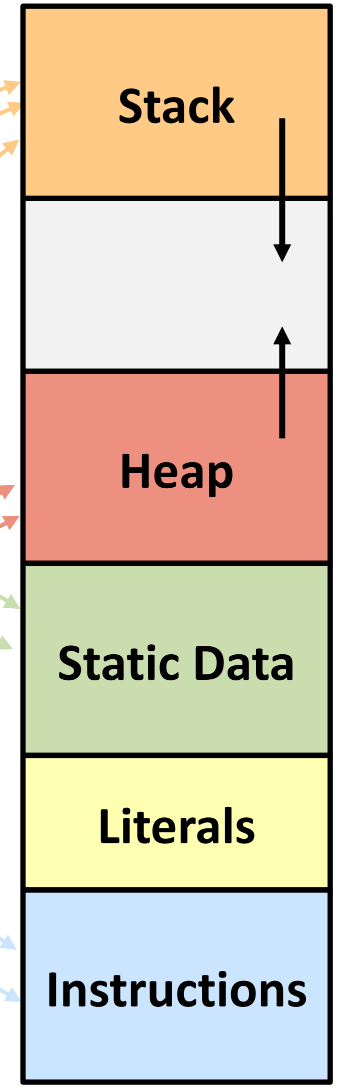
Memory Allocation Example

```
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 ... */
}
```



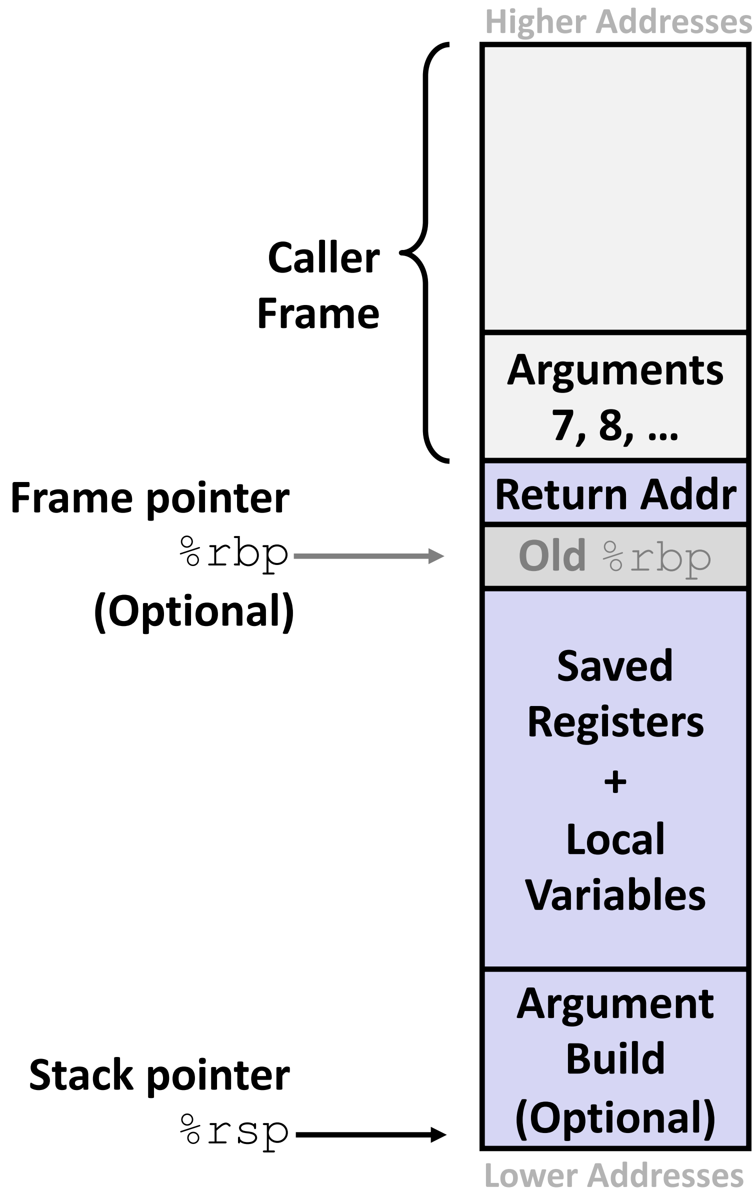
Where does everything go?

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

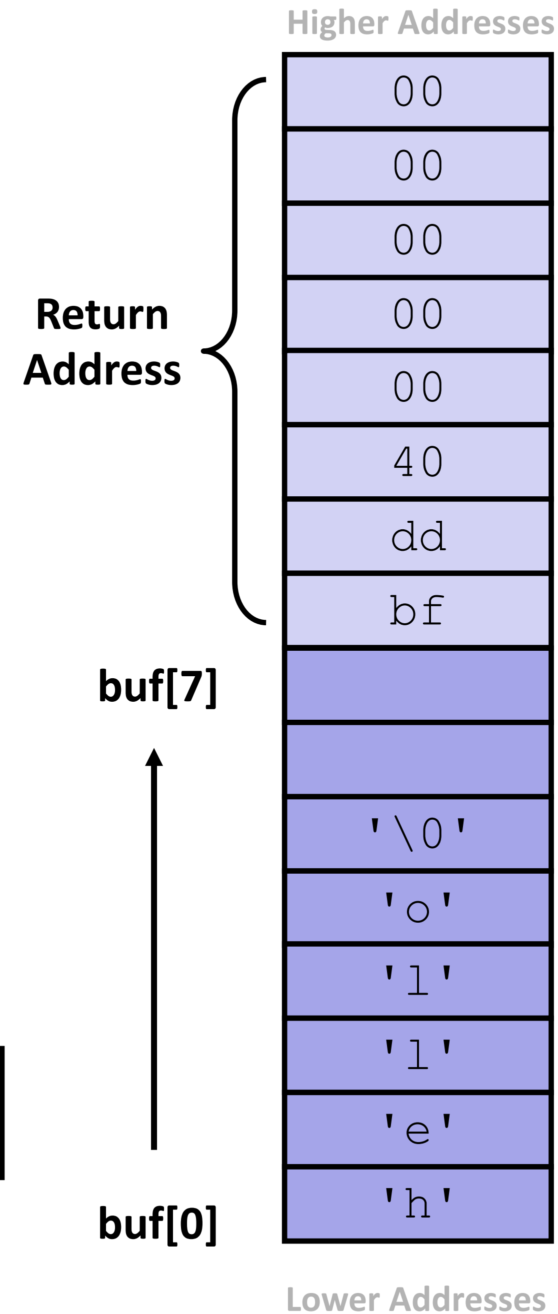
- C does not check array bounds
  - Many Unix/Linux/C functions don't check argument sizes
  - Allows overflowing (writing past the end) of buffers (arrays)
- "Buffer Overflow" = Writing past the end of an array
- Characteristics of the traditional Linux memory layout provide opportunities for malicious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

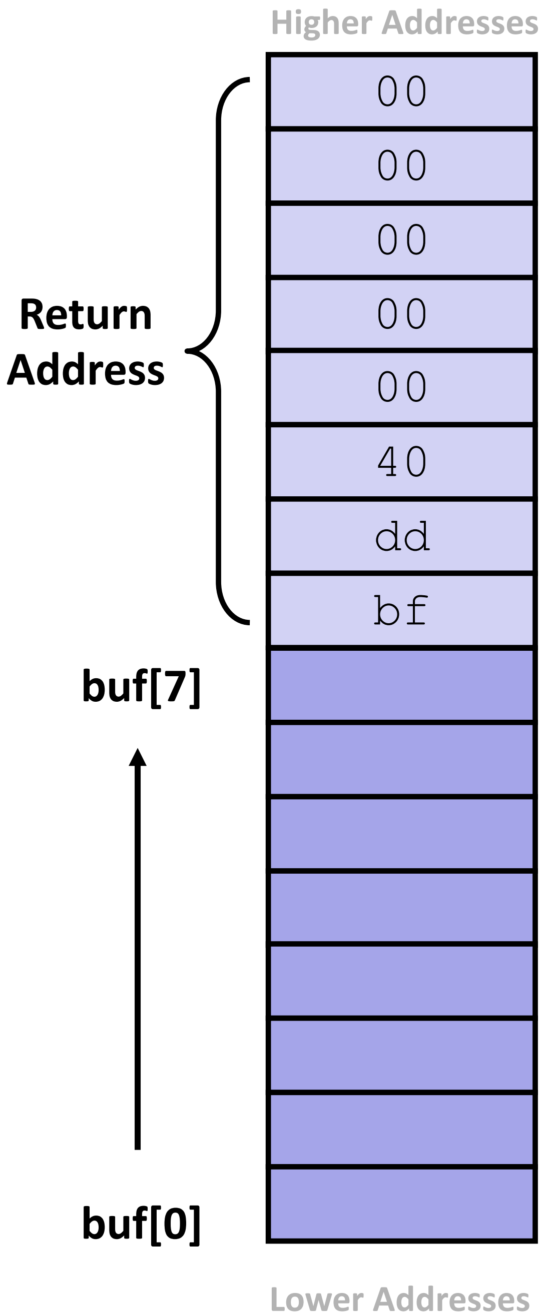
No overflow ☺



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
```

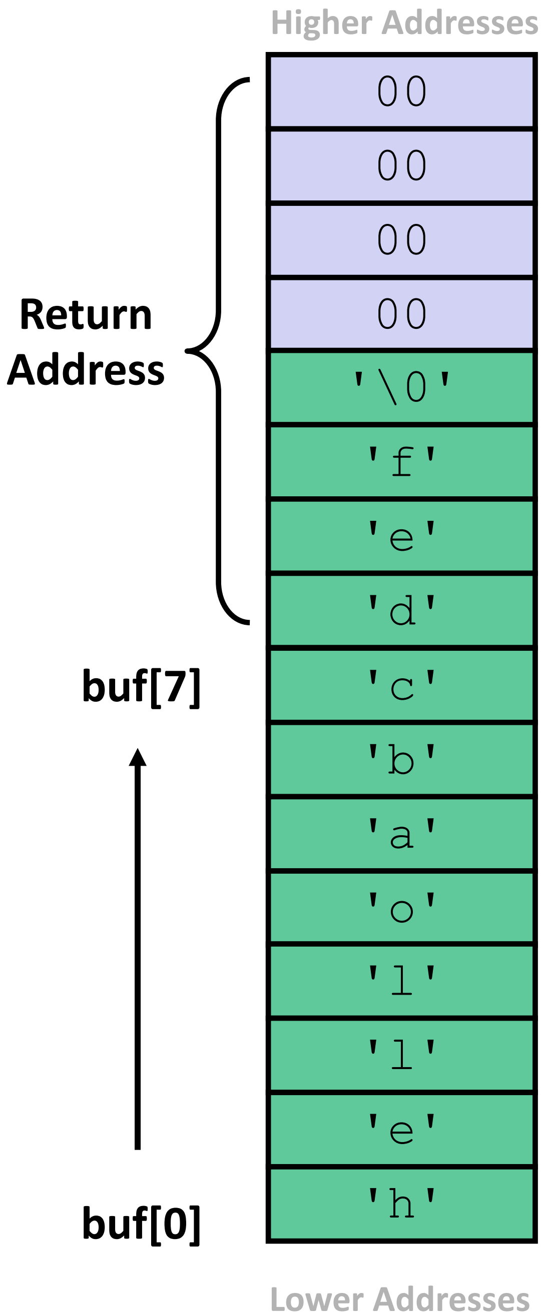


Buffer Overflow in a Nutshell

- 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;
}
```

pointer to start of an array

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);
}
```

```
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
```

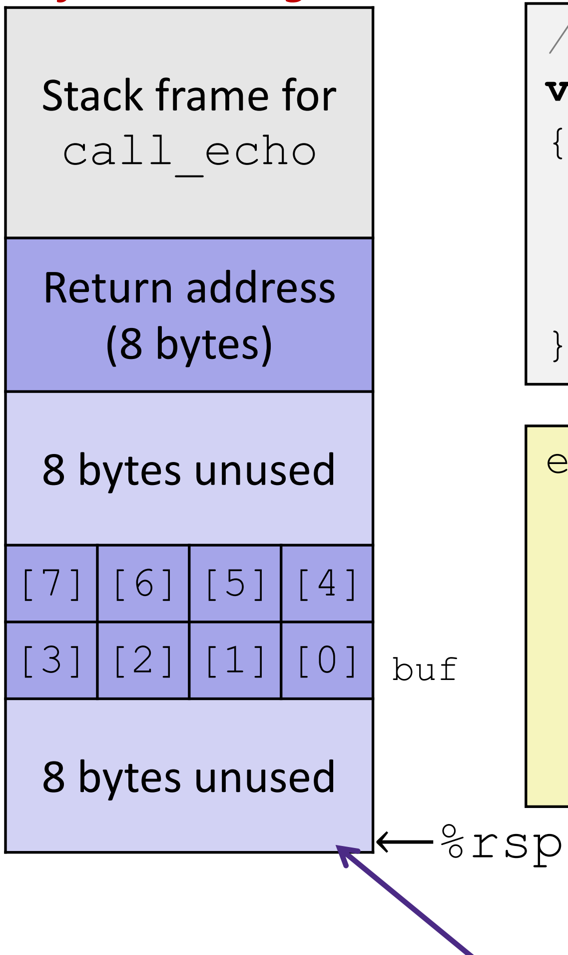
call_echo:

```
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 (pointing to 401185)

Buffer Overflow Stack

Before call to gets



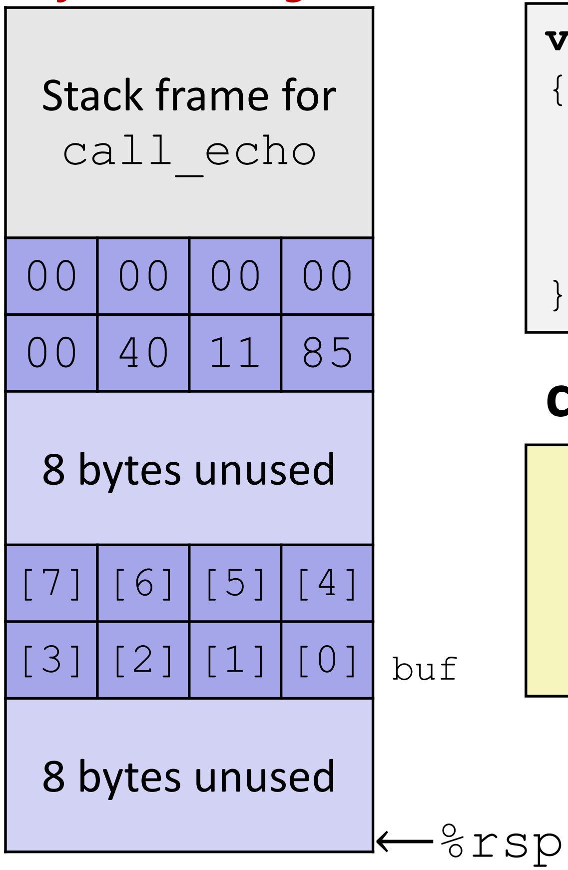

```c
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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

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

Buffer Overflow Example

Before call to gets




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

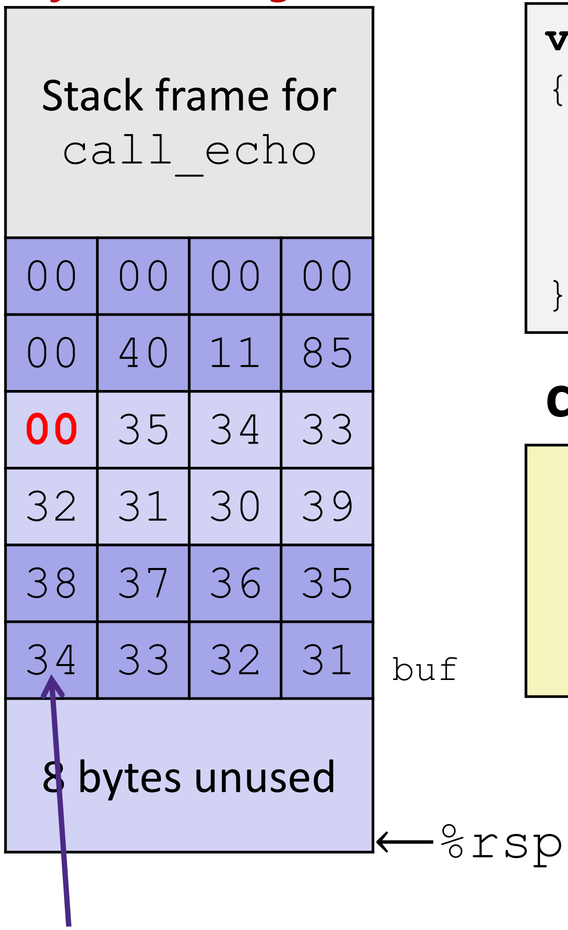
```
echo:
  subq   $24, %rsp
   ...
  leaq   8(%rsp), %rdi
  mov    $0x0,%eax
  call   gets
   ...
```

call_echo:

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

Buffer Overflow Example #1

After call to gets



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

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

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

call_echo:

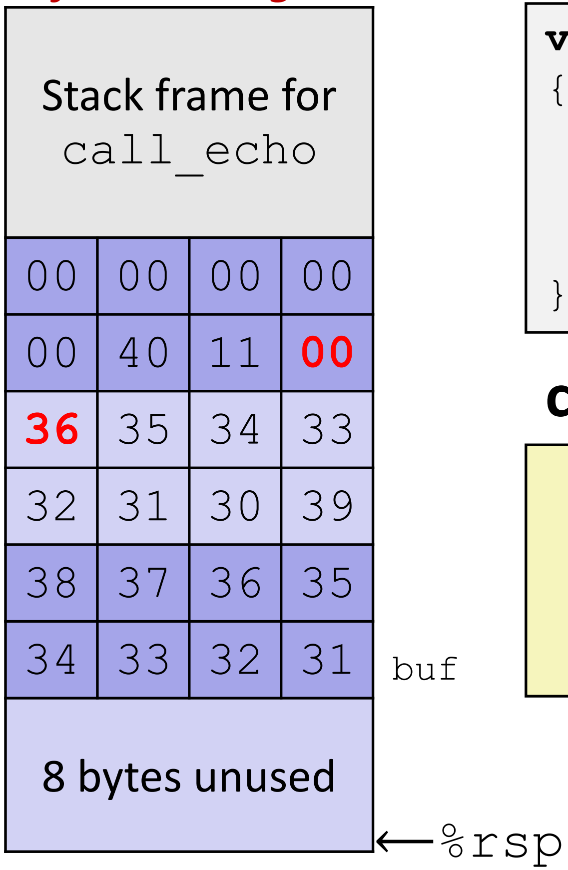
```
   . . .
   401180:   callq   401146 <echo>
   401185:   add     $0x8,%rsp
   . . .
```

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

Overflowed buffer, but did not corrupt state

Buffer Overflow Example #2

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:

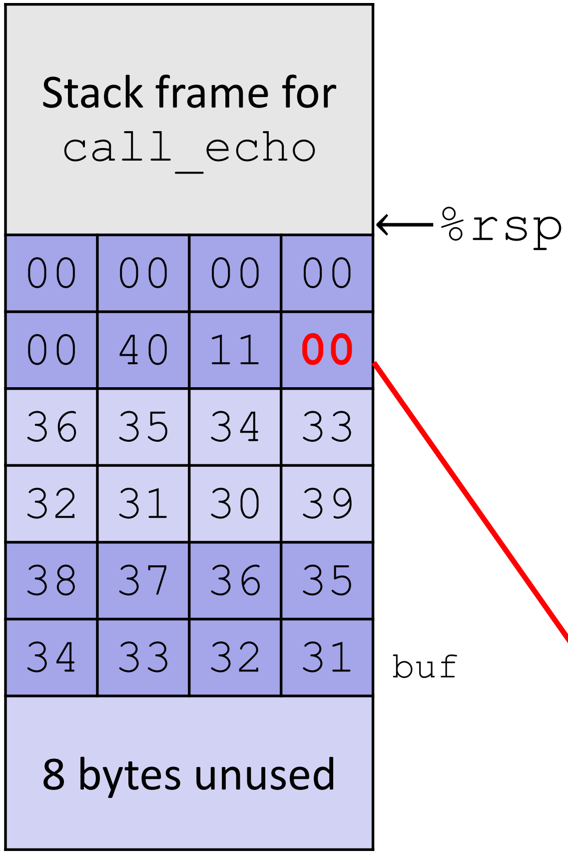
```
  . . .
  401180:   callq   401146 <echo>
  401185:   add     $0x8,%rsp
  . . .
```

```
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




```
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`

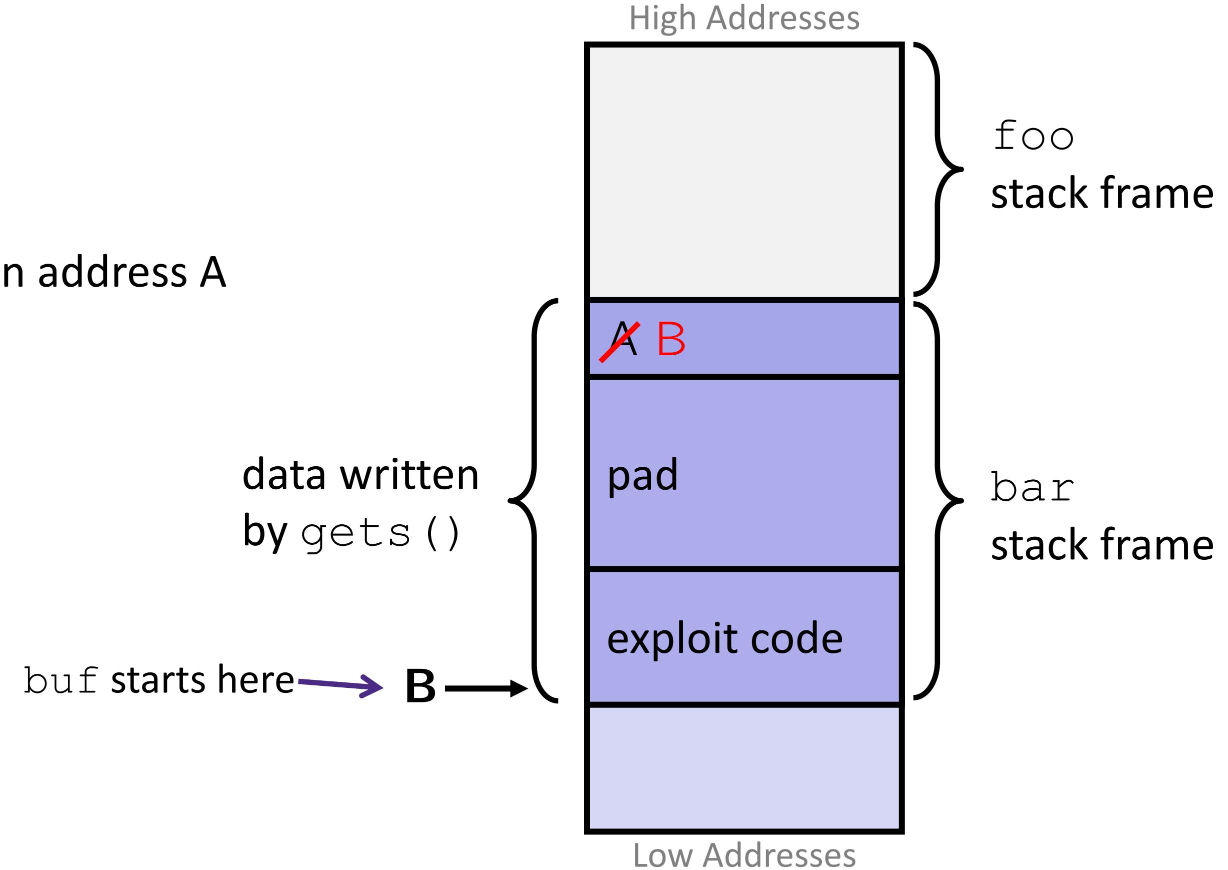
Malicious Use of Buffer Overflow: Code Injection Attacks

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

return address A

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

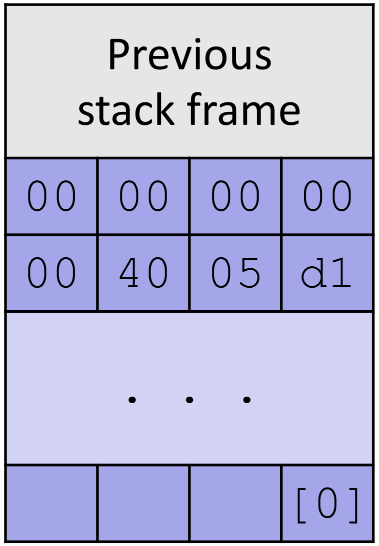
Stack after call to gets()



- 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 for us to change the return address to a stack address?
  - For example: (0x00 00 7f ff ca fe f0 0d)




```
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

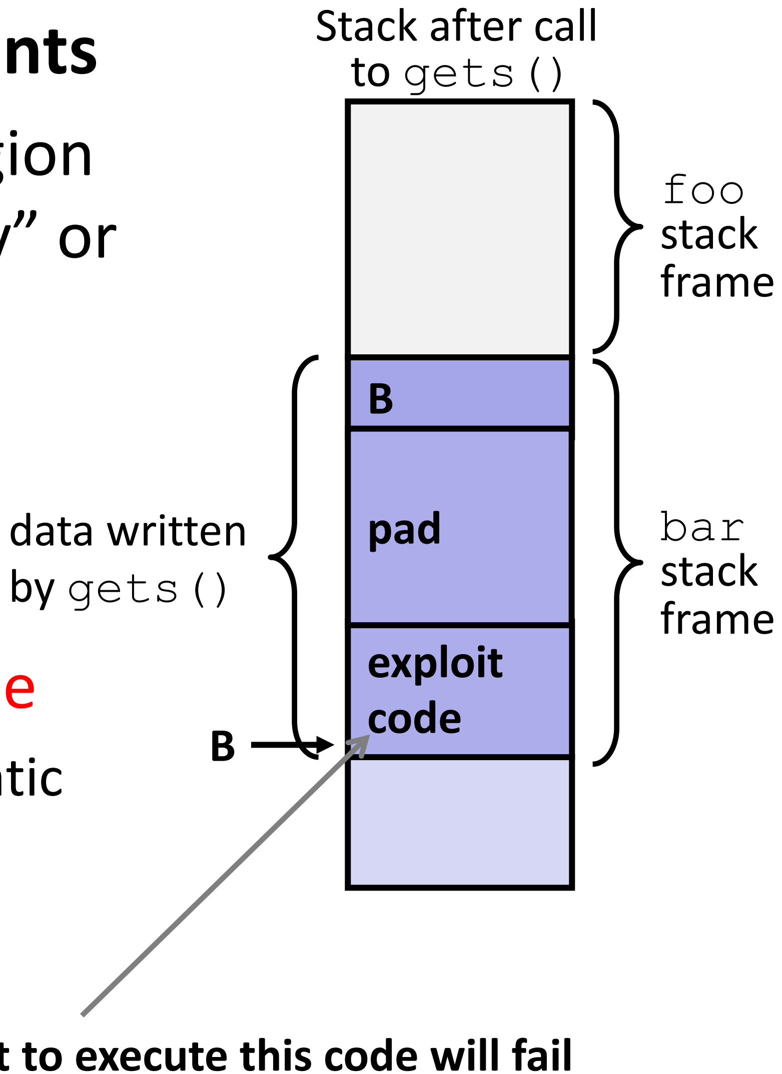
- Distressingly common in real programs
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- Examples across the decades
  - Original “Internet worm” (1988)
  - Heartbleed (2014, affected 17% of servers)
    - Similar issue in Cloudbleed (2017)
  - Hacking embedded devices
    - Cars, smart homes, planes (yikes)

Dealing with buffer overflow attacks

1) Employ system-level protections
2) Have compiler use “stack canaries”
3) Avoid overflow vulnerabilities in the first place…

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

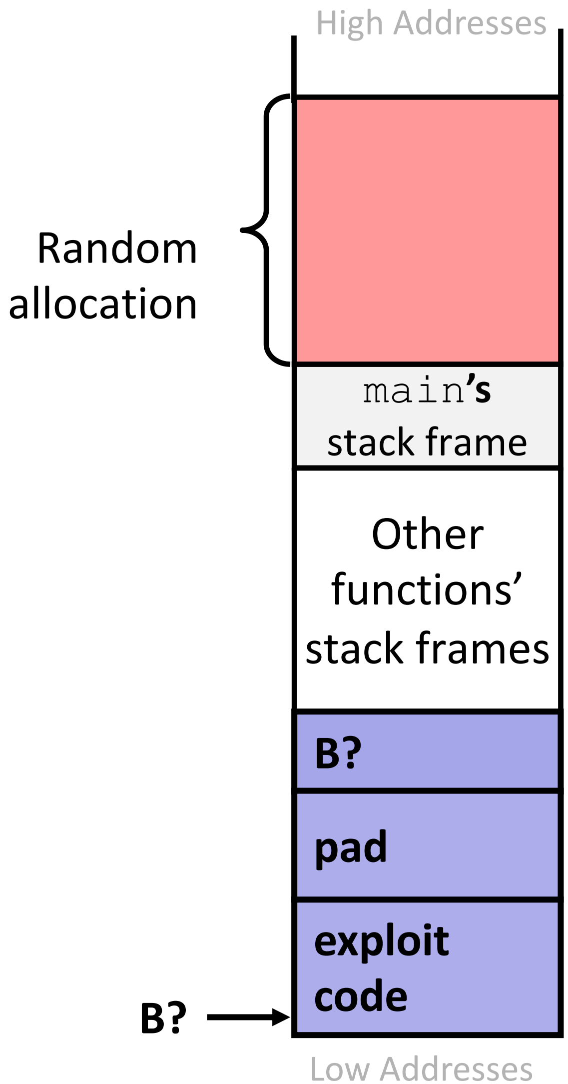


1) System-Level Protections

- **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

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) 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

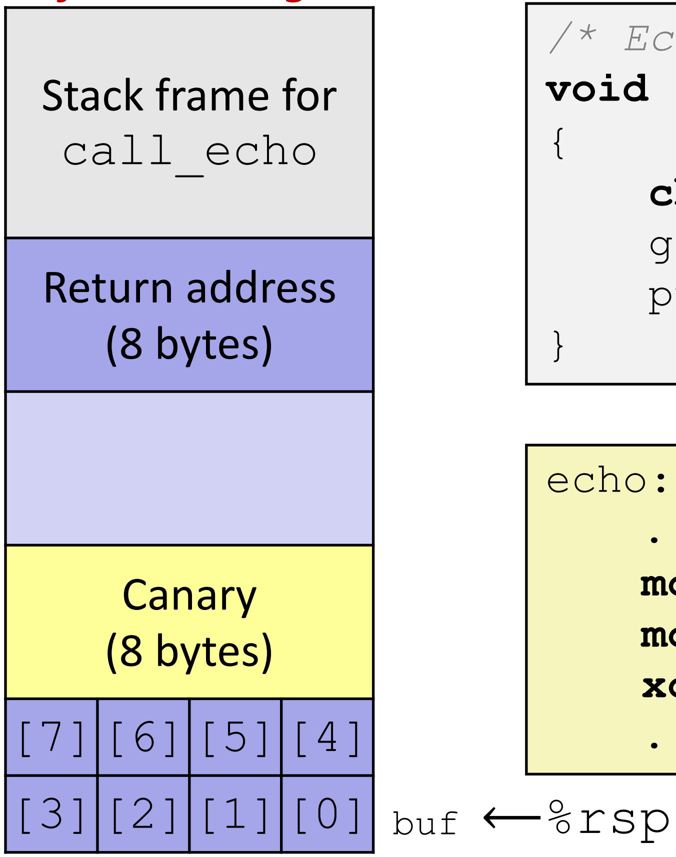
echo:

```
401156:  push   %rbx
401157:  sub    $0x10,%rsp
40115b:  mov    $0x28,%ebx
401160:  mov    %fs:(%rbx),%rax
401164:  mov    %rax,0x8(%rsp)
401169:  xor    %eax,%eax
 ...     ... call printf ...
40117d:  callq  401060 <gets@plt>
401182:  mov    %rsp,%rdi
401185:  callq  401030 <puts@plt>
40118a:  mov    0x8(%rsp),%rax
40118f:  xor    %fs:(%rbx),%rax
401193:  jne    40119b <echo+0x45>
401195:  add    $0x10,%rsp
401199:  pop    %rbx
40119a:  retq
40119b:  callq  401040 <__stack_chk_fail@plt>
```

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);
}
```

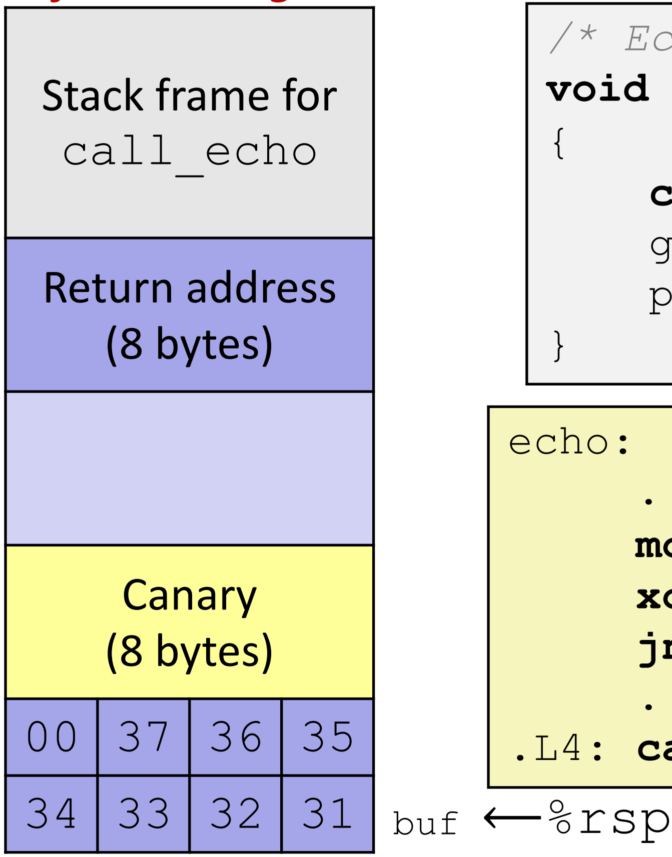
Segment register *(don't worry about it)*

```
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




```c
/* 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*

3) Avoid Overflow Vulnerabilities in Code

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

- 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

3) 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

Summary of Prevention Measures

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

2) Have compiler use "stack canaries"

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

Think this is cool?

- You'll love Lab 3 😉
  - Released Wednesday, due next Friday (11/13)
  - 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

Why doesn't C have bounds checks?

- Bounds checks would have prevented `gets` bug
  - And countless other vulnerabilities (see bonus slides)
- Considered **inefficient**
  - Prioritization of values: efficiency over safety
  - If C is like camping, then bounds checks are like hot water

Two Narratives in C

- "I think programmers should know enough to not access array elements out of bounds. It's a relatively simple check to insert at the language level, and if **you** can't remember to add it, **you** shouldn't write C."
  - Emphasis on the **individual**

- "C is an absolutely awful language; why on earth doesn't it implement bounds checking? It's an expense, but a relatively nominal one, and **the language** would be so much easier to use."
  - Emphasis on the **structure**

Two Narratives in Privacy

- "I think people should know enough to change the privacy settings on their phones. It's a relatively simple setting change and if **you** can't figure that out, **you** don't deserve privacy."
  - Emphasis on the **individual**

- "Phones are awful; why on earth aren't **they** private by default? Or why aren't the options presented to users? It's not a complicated check, and folks would have better relationships with phones because of it."
  - Emphasis on the **structure**

Two Narratives in Accessibility

- "I think people should know enough to change font sizes on their phone. It's a relatively simple settings change, and if **you** can't figure that out, **you** shouldn't use a phone."
  - Emphasis on the **individual**

- "It's bananas that phones do anything before checking font size. So many people are vision impaired, how do **manufacturers** expect anything from people before they can read what's on the screen?"
  - Emphasis on the **structure**

Individuals vs. Structure

- There's lots of examples, especially in tech
  - **You** shouldn't compare floats for equality
  - **You** must remember to check array bounds in C
  - **You** should know better than to click on ads
  - **Your** privacy can be bought and sold (up to you to prevent)
  - "If **you** can't access x, **you** shouldn't use x"
  - "**You're** a bad person if **you** don't recycle"
  - **You** should aim for zero-waste
  - …
- This tension comes up **everywhere!**

Neoliberalism, Defined

- Everything that happens to you is because of **your** actions. You're free to make your own decisions. Your access to anything (housing, medical care) is **your** responsibility.
  - Tends to ignore systemic/structural bias and inequity

- C: rugged, individualistic, minimalistic
  - Sound familiar?

Accessibility, Defined

- Narrowly: usable by people experiencing disabilities
  - Usually, around vision and mobility deficits
- More broadly: usable, **by anyone**, without causing harm, independent of physical or cognitive capabilities

- Inaccessibility is a structural issue, not a personal one
  - Not the fault of the individual

Accessibility and Computer Science

- Is C accessible?
  - "C is good for two things: being beautiful and creating catastrophic 0days in memory management."
  - So… not really.

OK, but, like, just don't use C?

- You don't have a choice!
  - You might work on legacy code (lots of C)
  - You might work in software systems (lots of C)
  - You might want to hack on Arduinos (C by default)
  - You might just be programming
    - 21% of developers indicated they did "extensive development work" in C last year (Stack Overflow 2021 Developer Survey)
    - 60% of C users indicated that they "dreaded" working in it
  - They really didn't think this through...

Accessibility and Computer Science

- Is C accessible?
  - "C is good for two things: being beautiful and creating catastrophic 0days in memory management."
  - So… not really.

```
/*
 * If the new process paused because it was
 * swapped out, set the stack level to the last call
 * to savu(u_ssav).  This means that the return
 * which is executed immediately after the call to aretu
 * actually returns from the last routine which did
 * the savu.
 *
 * You are not expected to understand this.
 */
if(rp->p_flag&SSWAP) {
        rp->p_flag =& ~SSWAP;
        aretu(u.u_ssav);
}
```

Unix 6th edition source code

- Is **programming** accessible?
  - A notoriously difficult task to do correctly (even for experts!)
  - But it's also impossible to avoid in modern society!
  - Ideological foundations tend to over-emphasize individuals
  - No real thought given to accessibility
    - "Cleverness" and performance implicitly valued
- **You** know how to program. What now?

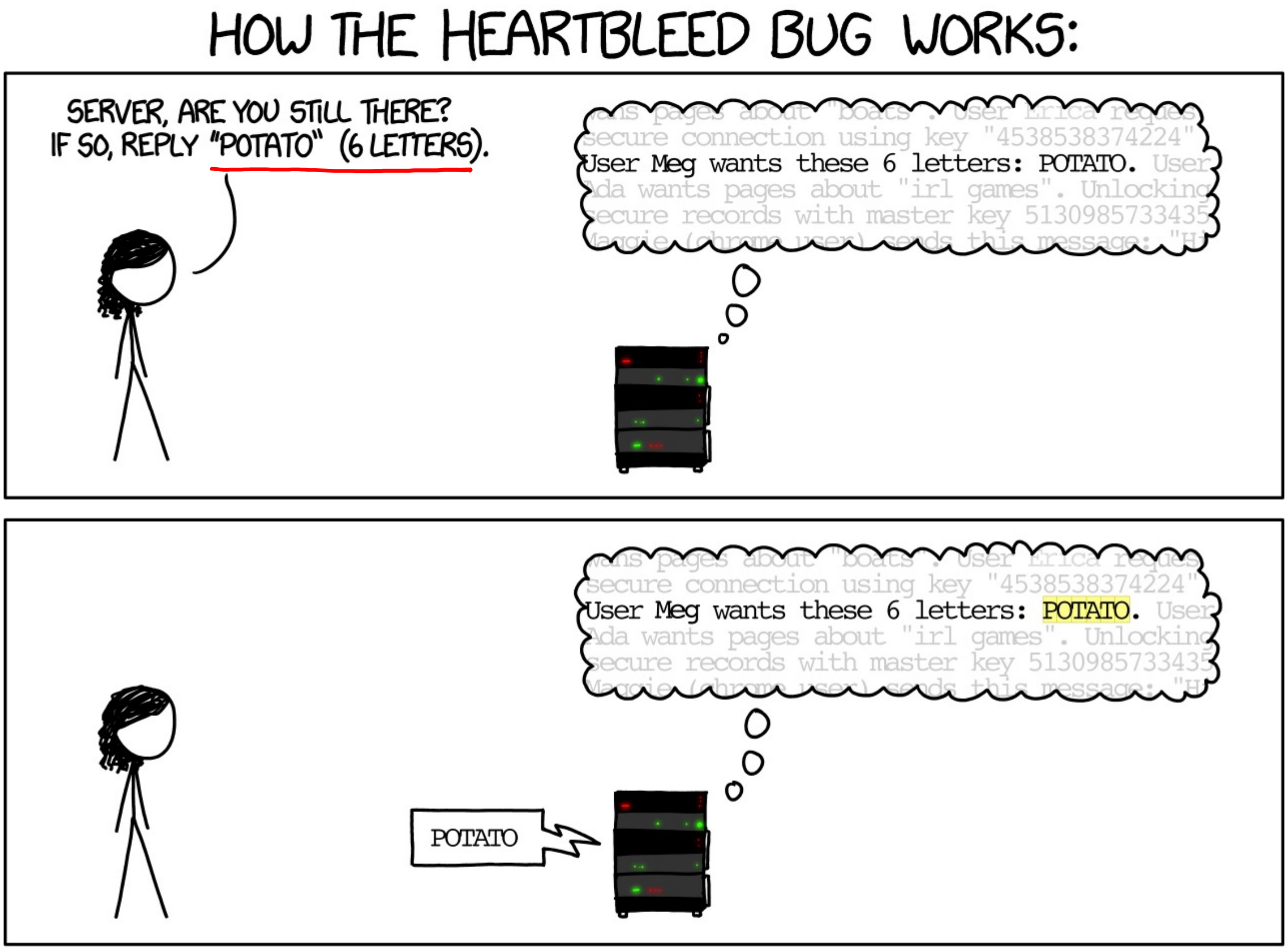
BONUS SLIDES

We won't test you on the specifics of the following material, but these are some examples of buffer overflow attacks that we think are particularly salient.

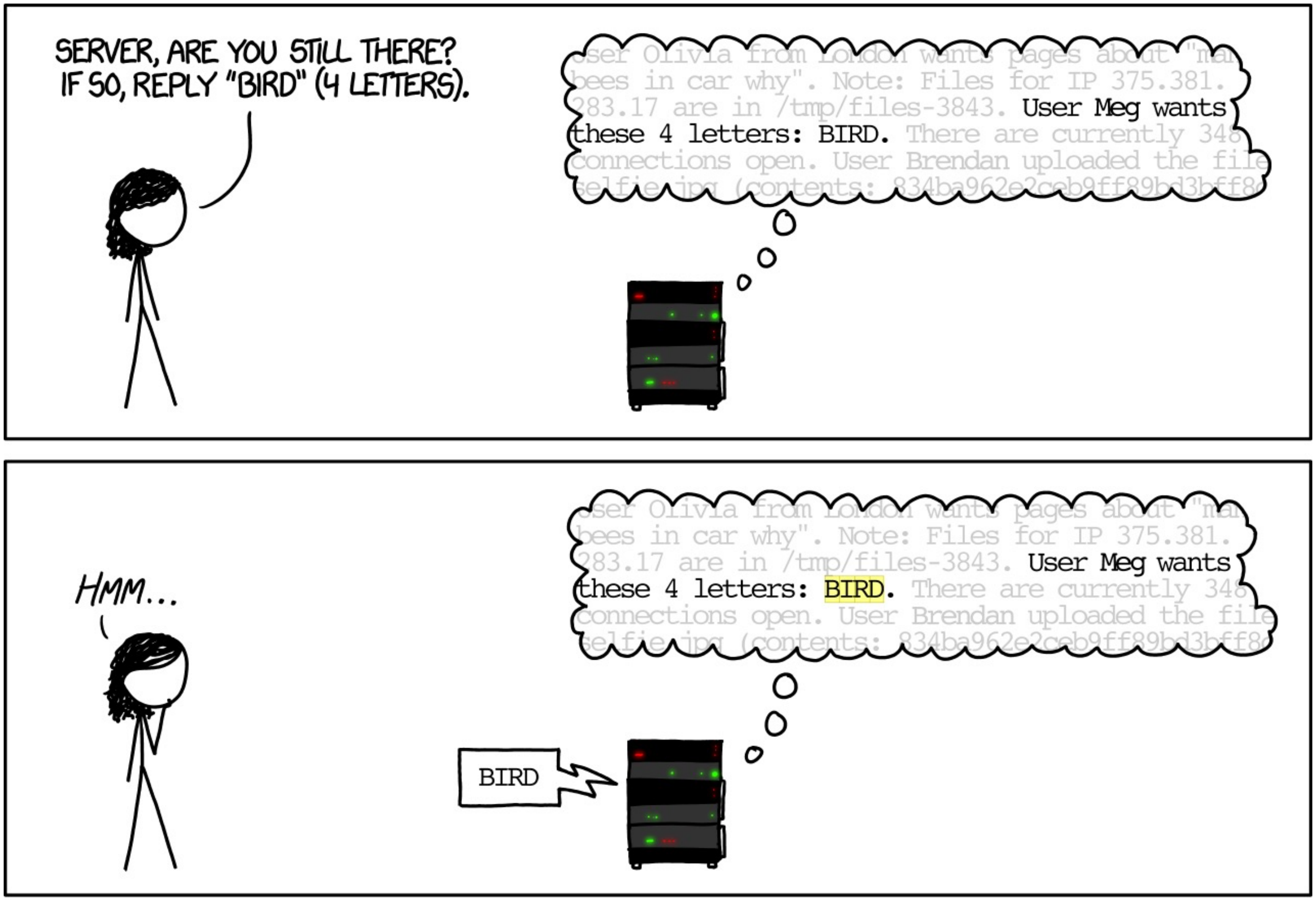
Example: the original Internet worm (1988)

- 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…

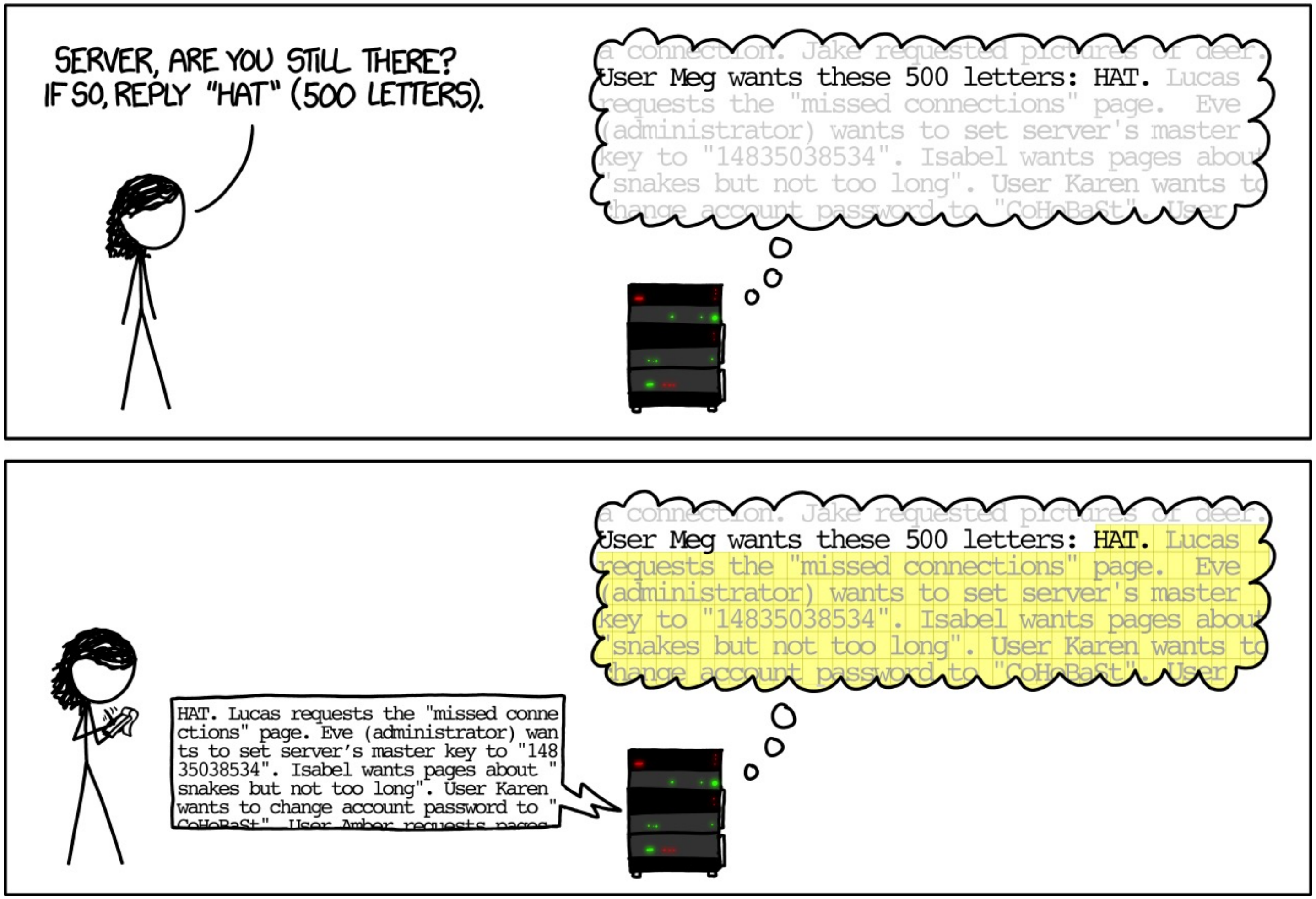
Example: Heartbleed (2014)



Example: Heartbleed (2014)

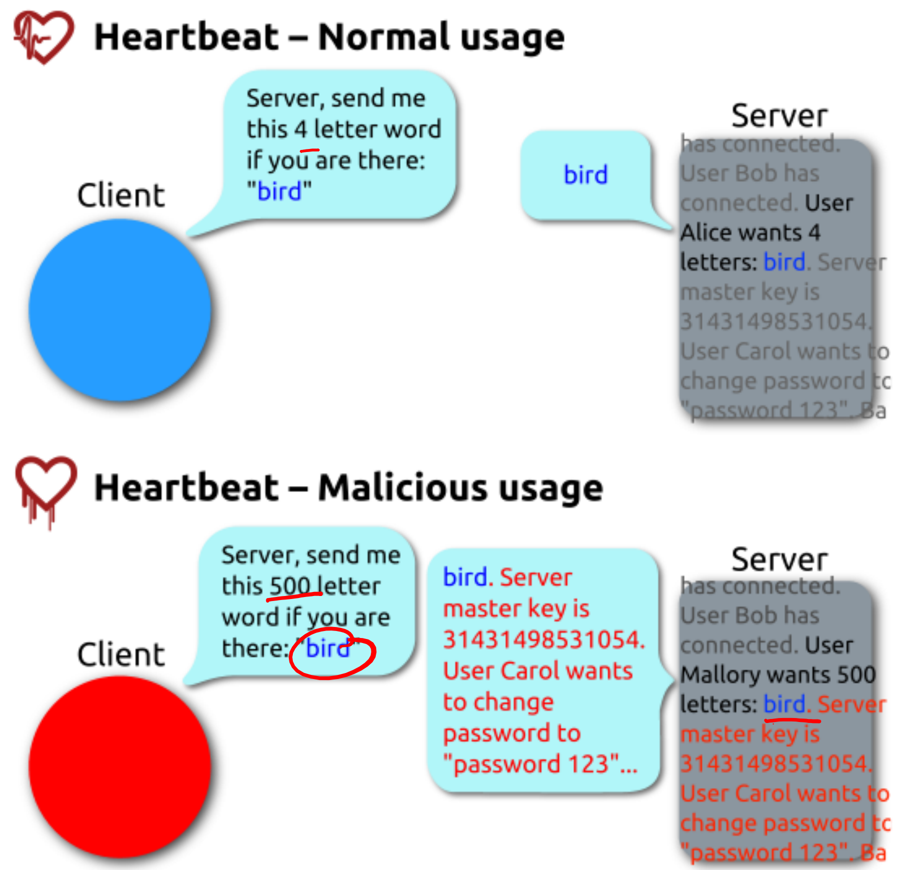


Example: Heartbleed (2014)



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

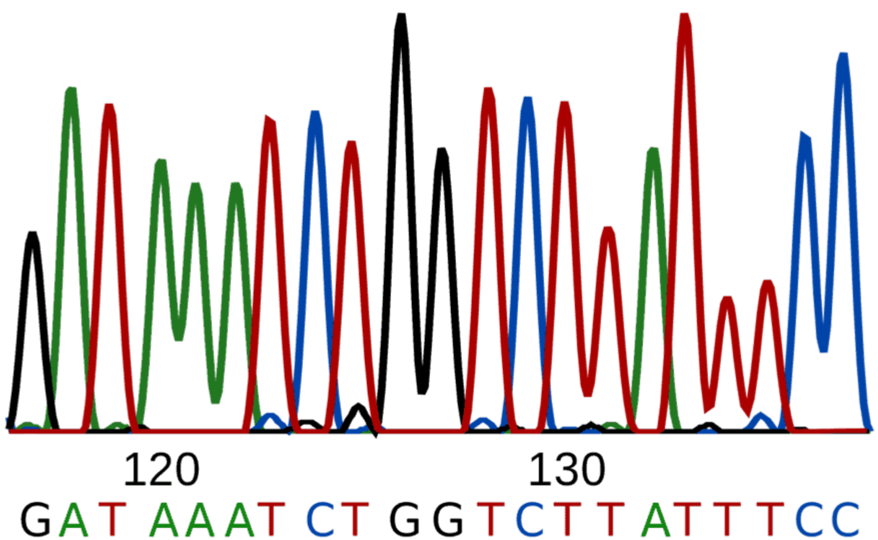
Hacking DNA Sequencing Tech (2017)

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!



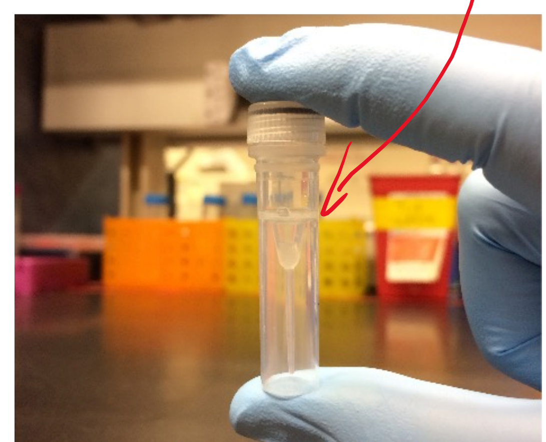


Figure 1: Our synthesized DNA exploit