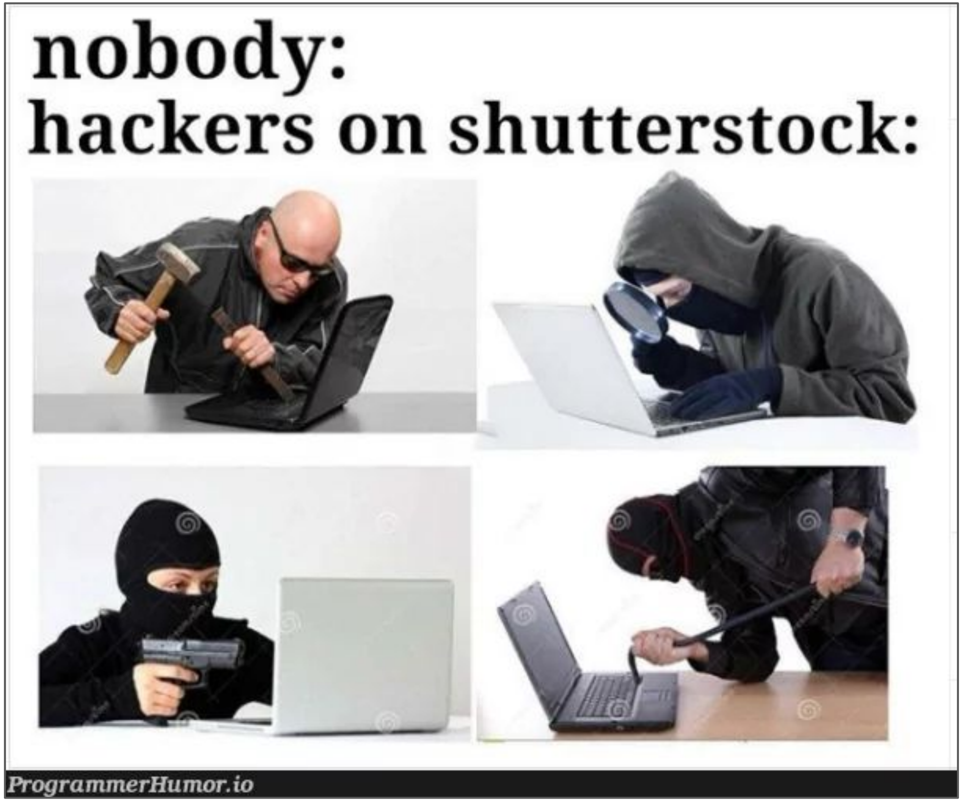
Buffer Overflow

CSE 351 Summer 2024

Instructor:
Ellis Haker

Teaching Assistants:
Naama Amiel
Micah Chang
Shananda Dokka
Nikolas McNamee
Jiawei Huang



Administrivia

- Today:
  - HW11 due (11:59pm)
  - **Mid-Quarter Survey due** (11:59pm)
  - Lab3 released! (due next Friday, 7/26)
- Friday, 7/19
  - RD14 due (1pm)
  - HW12 due (11:59pm)
  - **Lab2 due** (11:59pm)
    - Reminder: weekend counts as 1 late day
- **Quiz 1 released on Monday**

TA Applications are Open!

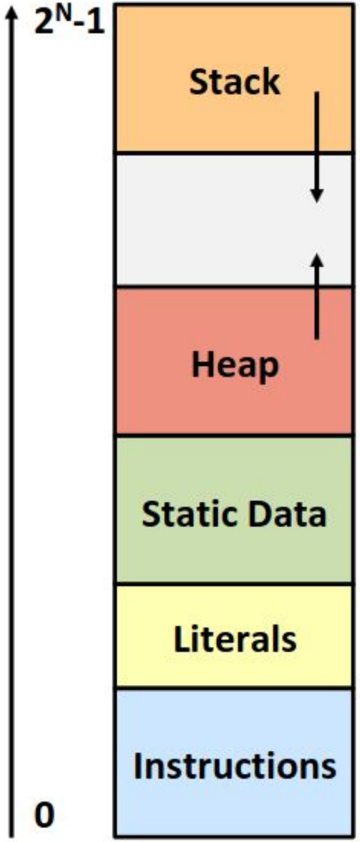
- Apply by Monday, 7/22 to TA for Fall
  - https://www.cs.washington.edu/students/ta
  - Same application for all CSE classes (besides intro)
- You are eligible to TA for 351 next quarter!
  - If interested, please also contact Ruth Anderson to let her know you’re interested

Lecture Topics

- **Memory Layout Review**
- Buffer overflow
  - Input buffers on the stack
  - Overflow attacks and code injection
- Exploits Based on Buffer Overflows
- Defenses against buffer overflow
- Societal Impact

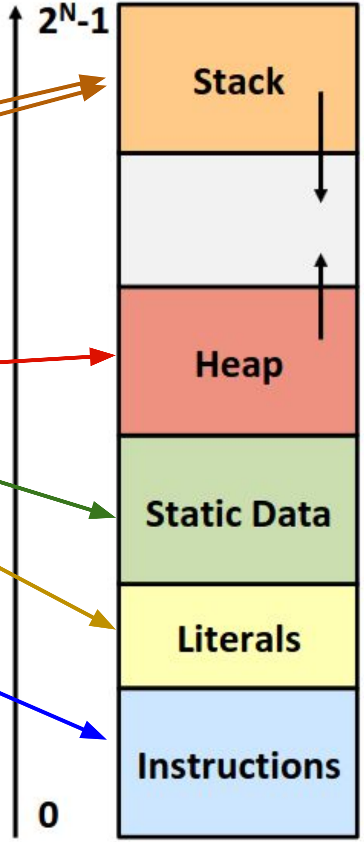
Review: Memory Layout

- **Stack**
  - Local variables, procedure context
- **Heap**
  - Dynamically allocated using `malloc()`
  - Future lecture topic!
- Statically-allocated data
  - Read/write: **Static Data**
  - Read-only: **Literals**
- **Instructions**
  - Machine code
  - Read-only



Memory Allocation Example

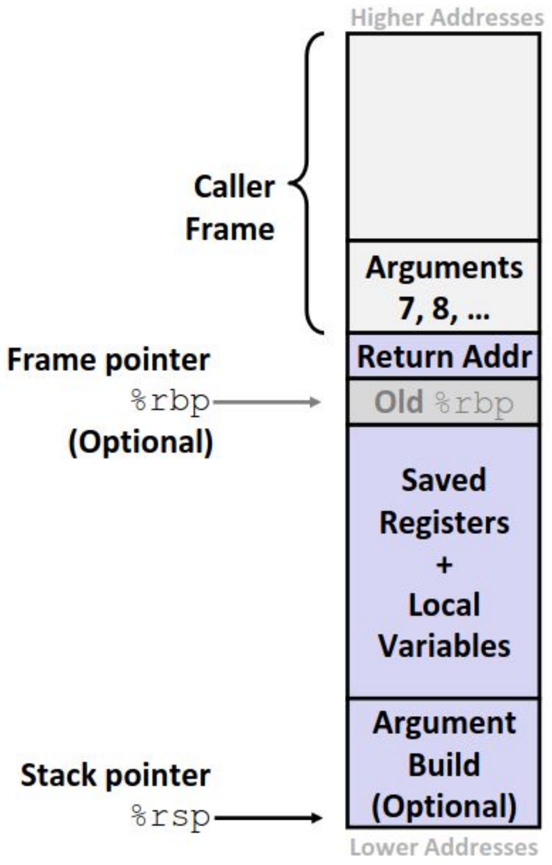
```
char* str = “hello!”;

int main() {
    void *p1;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    /* Some other code ... */
}
```



Where does everything go?

Review: x86 Stack Frame

- Caller's stack frame
  - Arguments 7+ for this call
- Current stack frame
  - Return address pushed by `call` instruction
  - Old frame pointer (optional)
  - Local data
    - Callee-saved registers pushed before using
    - Caller-saved registers pushed before calling another function
  - Argument build = arguments 7+ for the *next* function

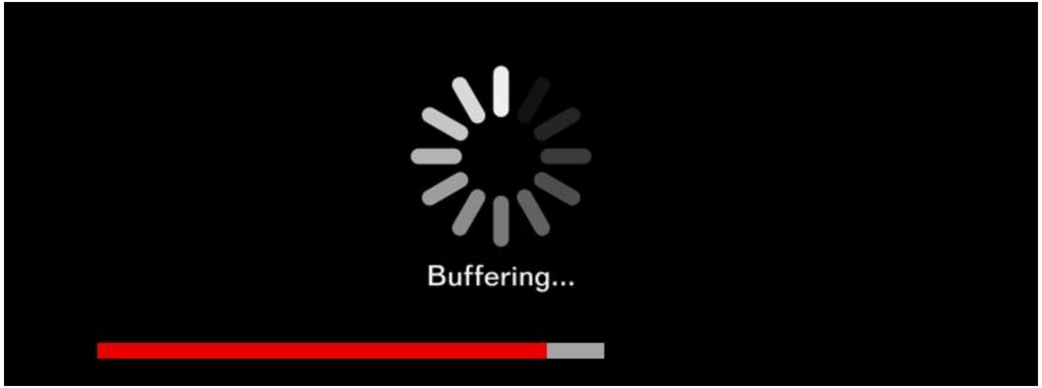


Lecture Topics

- Memory Layout Review
- **Buffer overflow**
  - **Input buffers on the stack**
  - **Overflow attacks and code injection**
- Exploits Based on Buffer Overflows
- Defenses against buffer overflow
- Societal Impact

What is a Buffer?

- An array used to temporarily store data
  - Typically some input or output
- Example: you've probably seen "video buffering"
  - Video data from the internet is written to a buffer before being played



Buffer Overflow in a Nutshell

- C does not check array bounds
  - **Buffer Overflow** = writing past the end of an array
- Characteristics of the Linux memory layout provide opportunities for malicious programs
  - Stack grows “backwards” in memory
  - Stack used for both data and control flow (return addresses)
  - Data and instructions both stored in memory

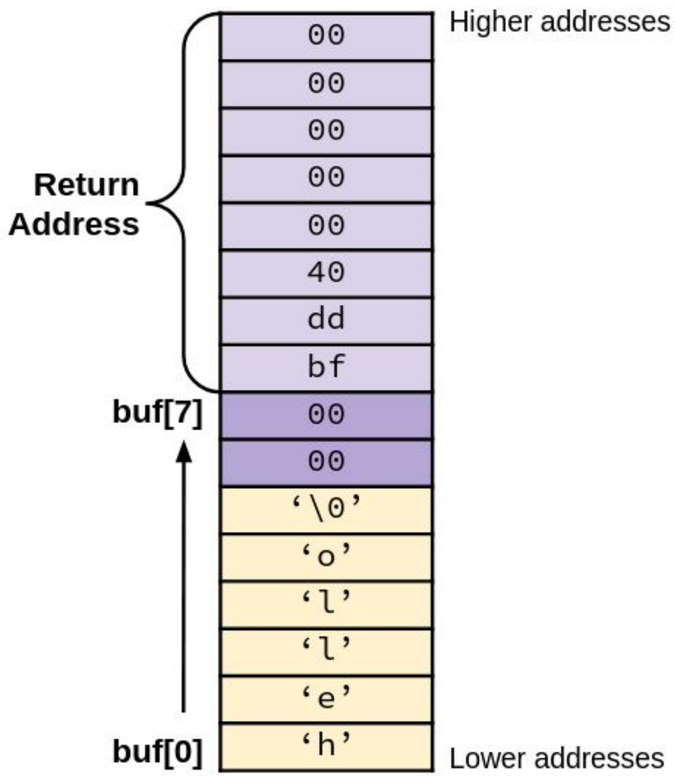
Buffer Overflow in a Nutshell (pt 2)

- Stack grows *down* towards lower addresses
- Buffer grows *up* towards higher addresses
- **Result**: if we overflow a buffer on the stack, we will overwrite other data!

<u>Example</u>:

```
Enter input: hello
```

No overflow :)



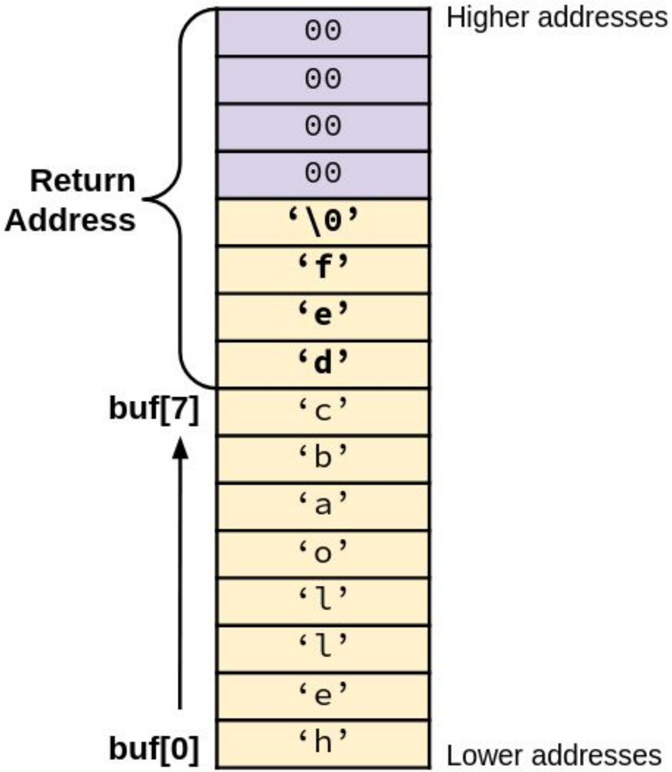
Buffer Overflow in a Nutshell (pt 3)

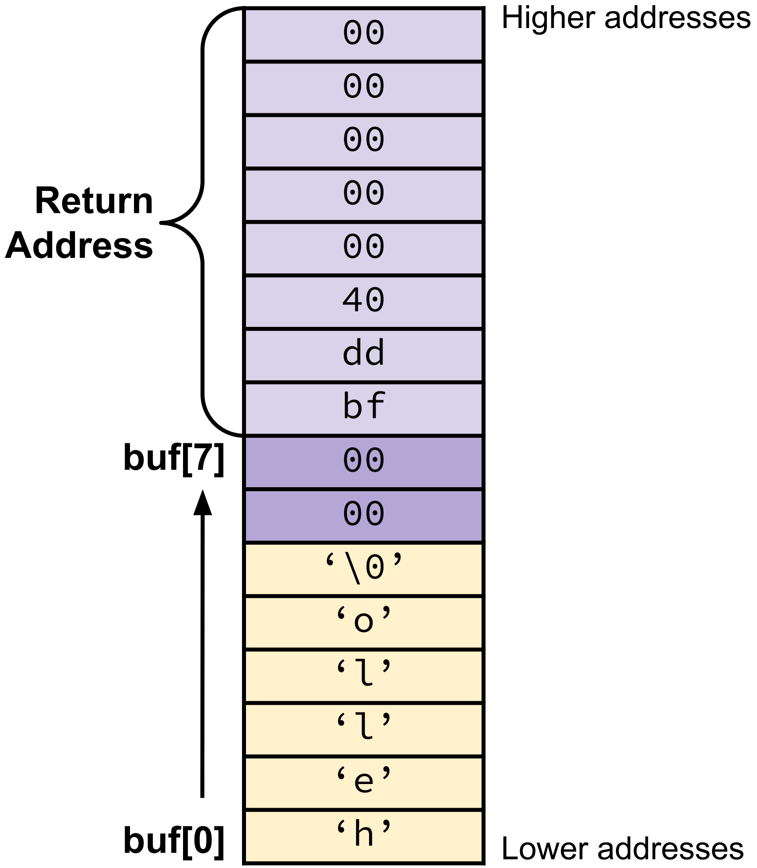
- Stack grows *down* towards lower addresses
- Buffer grows *up* towards higher addresses
- **Result**: if we overflow a buffer on the stack, we will overwrite other data!

Example:

```
Enter input: helloabcdef
```

Buffer overflow :(




Higher addresses
Return Address
00
00
00
00
00
40
dd
bf
buf[7]
00
00
'\0'
'o'
'l'
'l'
'e'
'h'
buf[0]
Lower addresses

Buffer Overflow in a Nutshell (pt 4)

- Buffer overflows on the stack can overwrite important data
  - *e.g.,* the return address
  - A clever attacker can use this to their advantage
- Simplest form is **stack smashing**
  - Overwrite return address to change how a program runs
- More complex forms include **code injection**
  - Attacker can cause a program to run their own code!
- Why is this a big deal?
  - One of the most common *technical* causes of security vulnerabilities
    - Social engineering is more common than any technical cause

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;
}
```

What could go wrong with this code?

String Library Code (pt 2)

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;
}
```

- What if the function reads in more data than we have space for in `dest`?
- Similar problem in other standard library functions
  - `strcpy()`
  - `scanf()`, if given a `%s` specifier

Vulnerable Buffer Code

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

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

- `gets()` writes from stdin to `buf`
- `puts()` writes from `buf` to stdout
- What happens if `gets()` writes past the end of `buf`?

```
unix:~$ ./run_echo
Enter string: 123456789012345
123456789012345
```

```
unix:~$ ./run_echo
Enter string: 1234567890123456
Segmentation fault (core dumped)
```

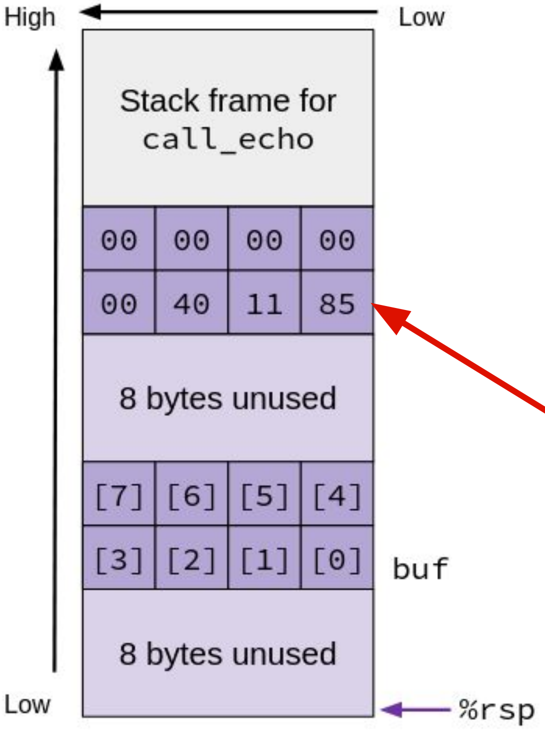
Vulnerable Buffer Code Disassembly

```
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
```

```
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

Vulnerable Code Stack (before gets())

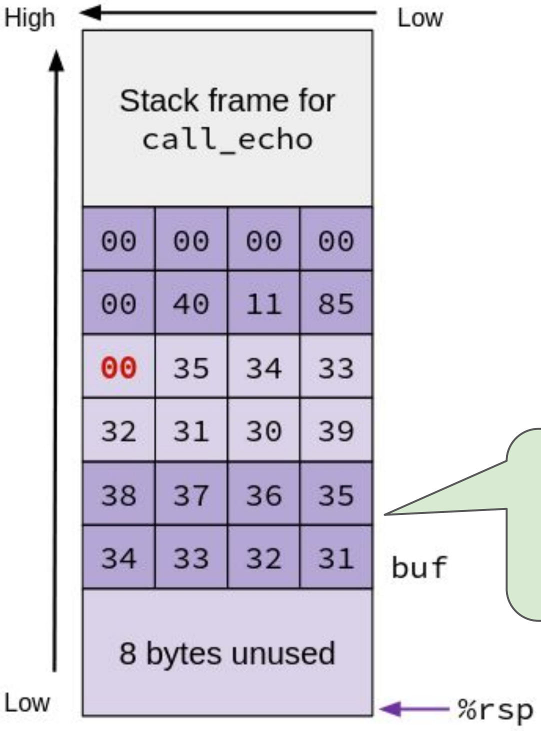



```c
void echo() {
     char buf[8];
     . . .
     gets(buf);
     . . .
}
```

```
echo:
   subq $0x18,%rsp
   ...
   leaq 0x8(%rsp),%rdi
   ...
   call gets
   ...
   addq $0x18,%rsp
   retq
```

```
call_echo:
   ...
   401180: call echo
   401185: addq $0x8,%rsp
   ...
```

Example #1 (after `gets()`)



Every digit *N* has the ASCII `0x3`*N*

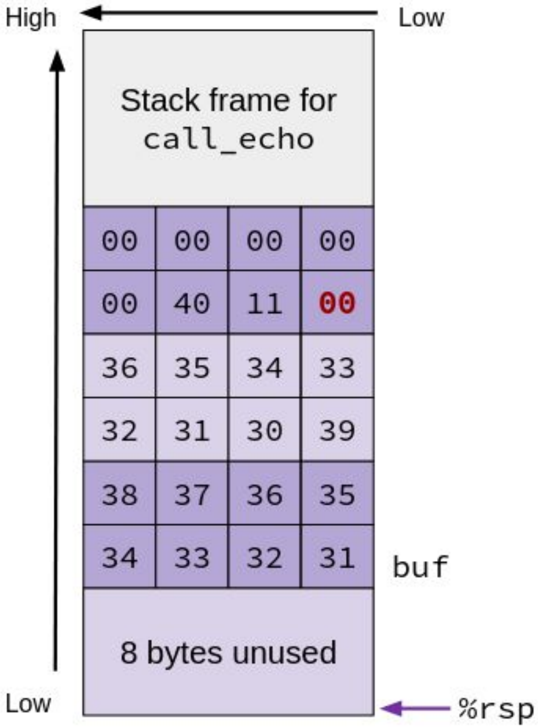
```
void echo() {
    char buf[8];
    . . .
    gets(buf);
    . . .
}
```

```
echo:
   subq $0x18,%rsp
   ...
   leaq 0x8(%rsp),%rdi
   ...
   call gets
   ...
   addq $0x18,%rsp
   retq
```

```
unix:~$ ./run_echo
Enter string: 123456789012345
123456789012345
```

Overflowed buffer, but didn't corrupt important data

Example #2 (after gets())

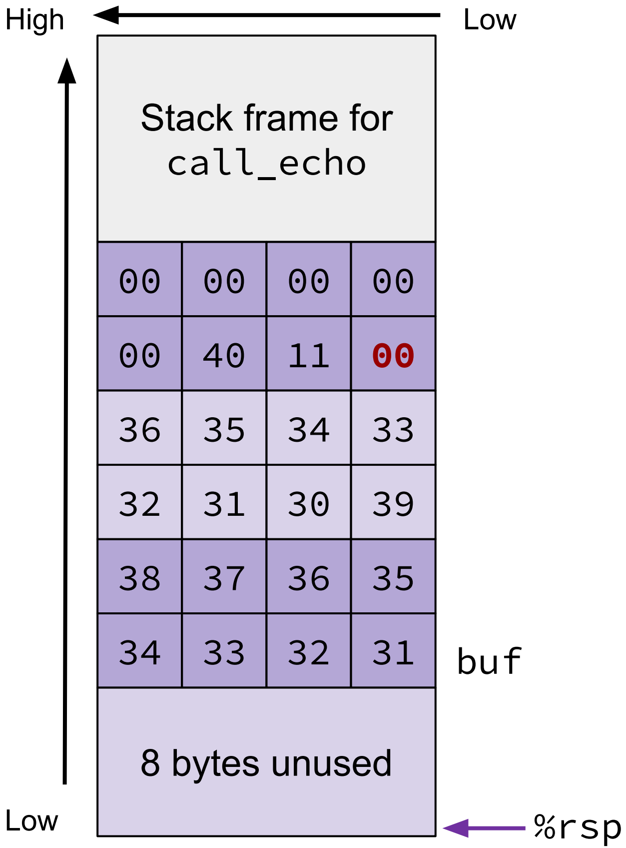



```c
void echo() {
    char buf[8];
    . . .
    gets(buf);
    . . .
}
```

```
echo:
   subq $0x18,%rsp
   ...
   leaq 0x8(%rsp),%rdi
   ...
   call gets
   ...
   addq $0x18,%rsp
   retq
```

```
unix:~$ ./run_echo
Enter string: 1234567890123456
Segmentation fault (core dumped)
```

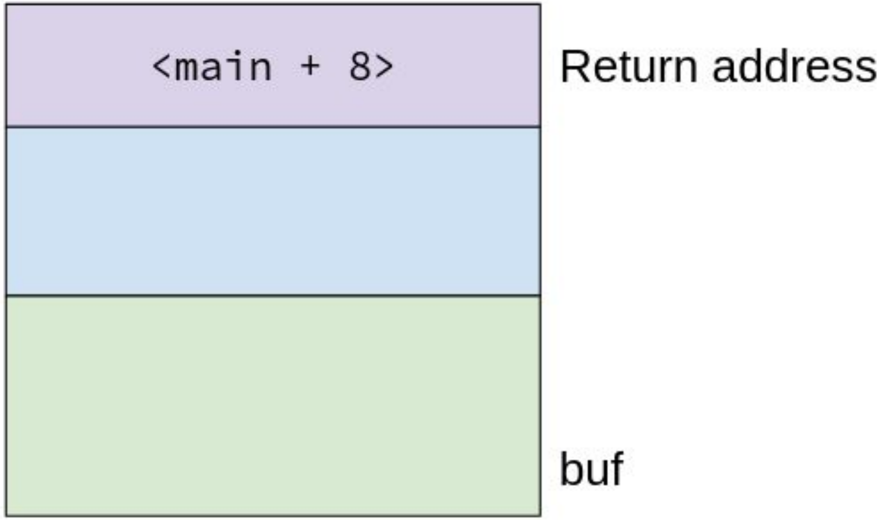
Overwrote the return address!


High
Low
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
Low
%rsp

Attack Time

Buffer Overflow Attacks: Stack Smashing

- Simpler attack
  - Overwrite the return address
- Usually execute another function in instruction memory



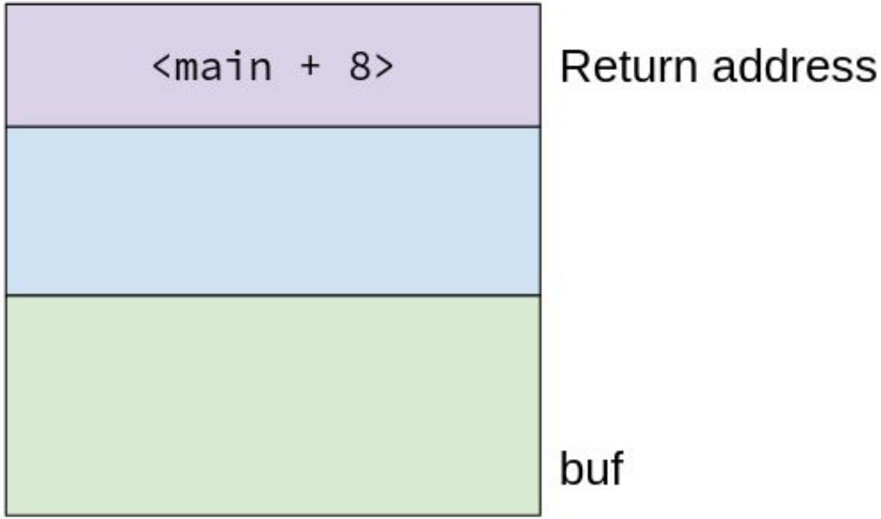
Buffer Overflow Attacks: Stack Smashing (pt 2)

- Simplest common attack
  - Overwrite the return address
- Usually execute another function in instruction memory

```
Enter string: <padding><foo>
```

Buffer Overflow Attacks: Code Injection

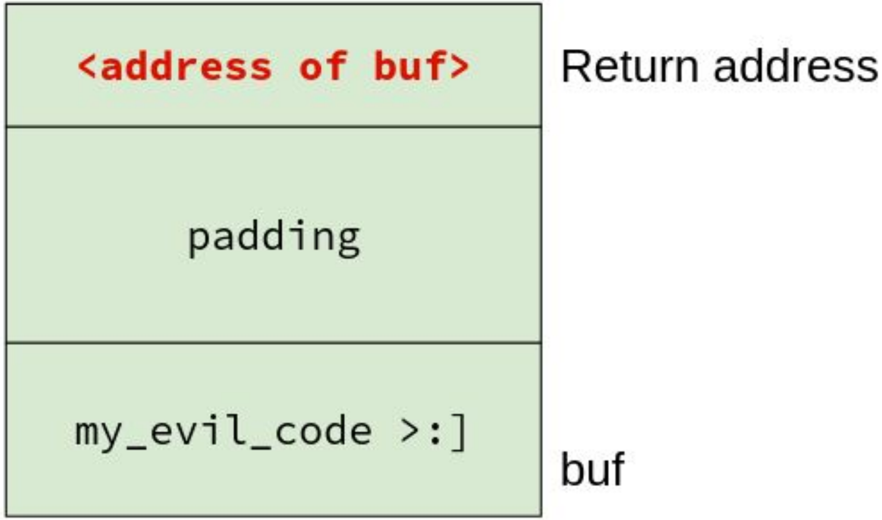
- Allows attacker to execute **arbitrary code** on victim machine!
- Write byte code into the buffer, then overwrite the return address to point to that code

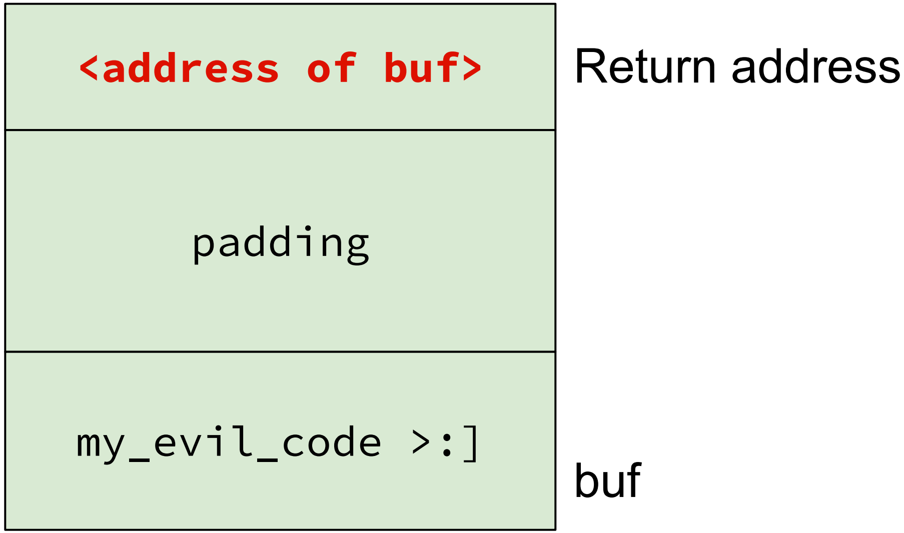


Buffer Overflow Attacks: Code Injection (pt 2)

- Allows attacker to execute **arbitrary code** on victim machine!
- Write byte code into the buffer, then overwrite the return address to point to that code
  - When current function returns, it will execute the code you put in the buffer!

```
Enter string: <evil_code><padding>
<address of buf>
```




<address of buf>
padding
my_evil_code >:]
Return address
buf

Practice Question

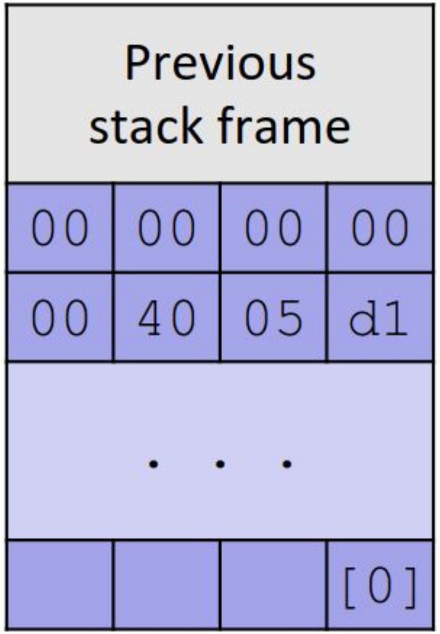
`buggy` is vulnerable to stack smashing!

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)

A) 27
B) 20
C) 51
D) 54

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



Lecture Topics

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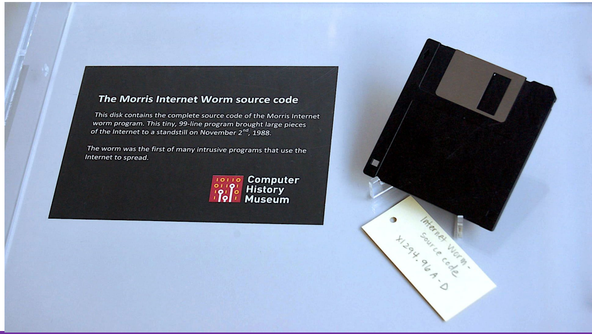
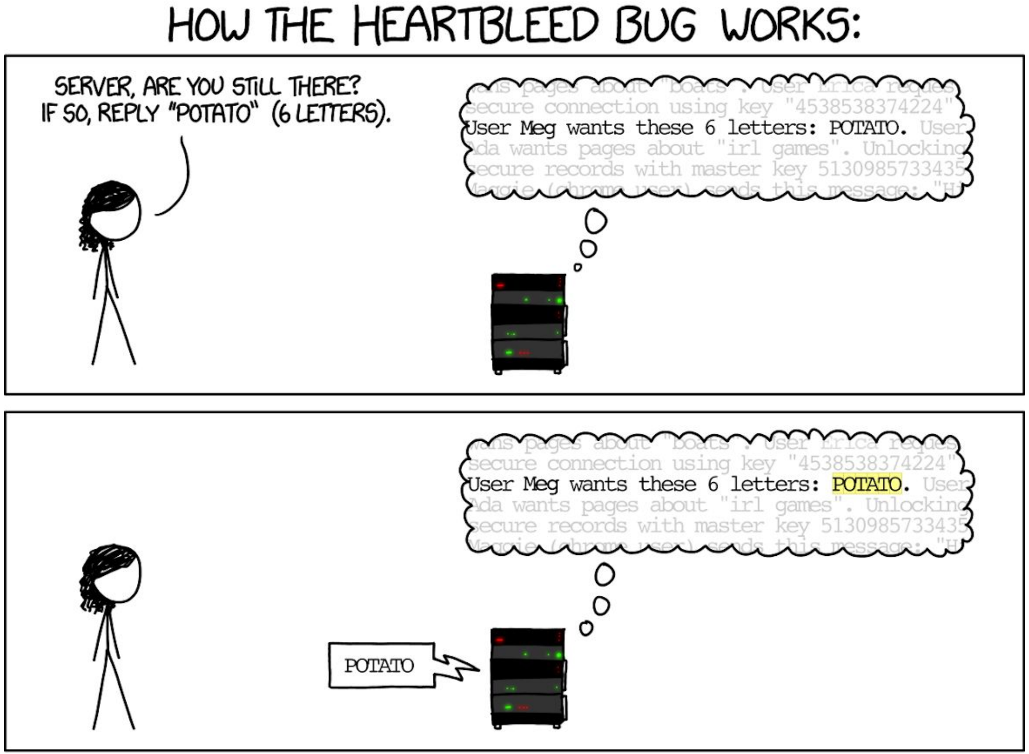
- **Exploits Based on Buffer Overflows**
- Defenses against buffer overflow
- Societal Impact

Morris Worm (1988)

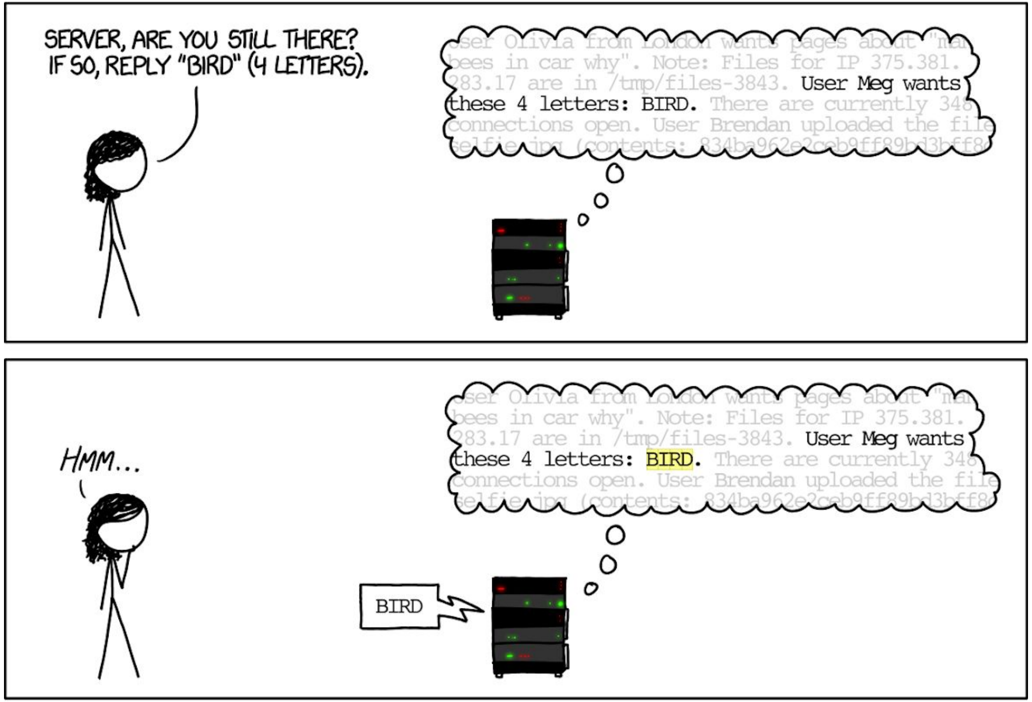
- First ever internet worm
- Exploited finger server (`fingerd`), used gets to read the argument sent by the client
  - Attacked `fingerd` server with phony argument:
    - Ex: `finger "exploit-code padding new-return-addr"`
- Invaded ~6000 computers in hours (10% of the internet)
- The author, Robert Morris, was prosecuted
  - First conviction under 1986 Computer Fraud and Abuse Act
  - Now an MIT professor…



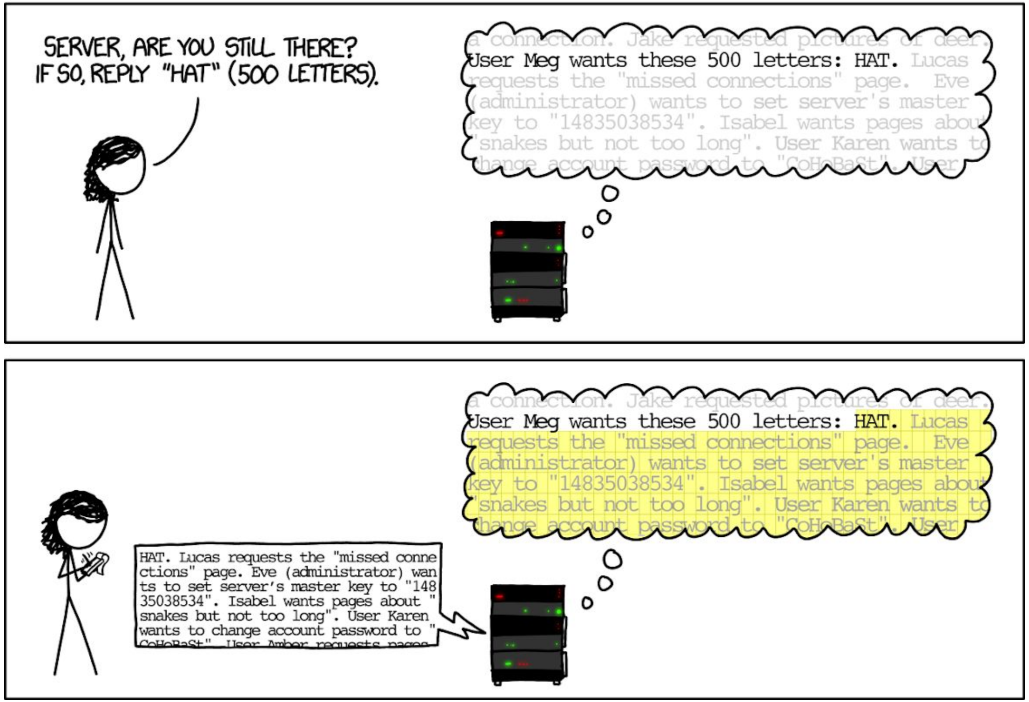
Heardbleed (2014)



Heardbleed (2014) (pt 2)

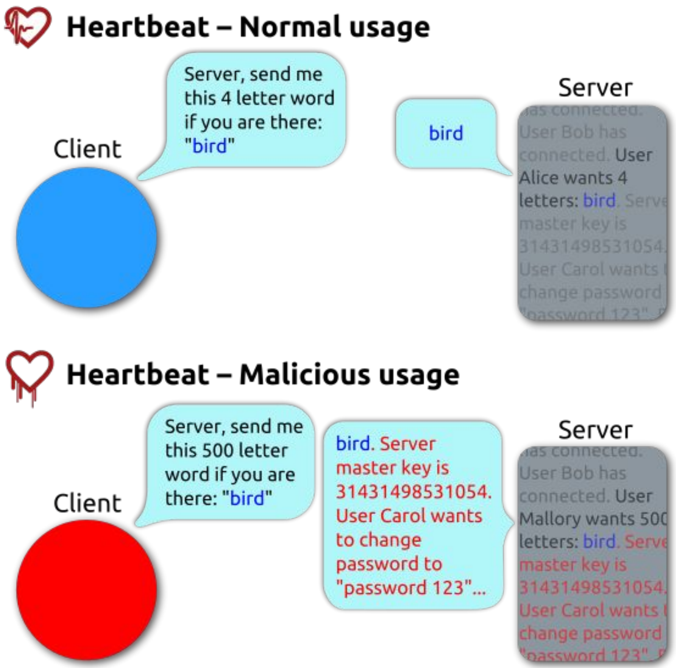


Heardbleed (2014) (pt 3)



Heartbleed Explained

- Exploited vulnerability in OpenSSL
  - Open-source security library
- “Heartbeat” packet: message and length
  - Server echos message back
  - Trusted the given length!
    - Allowed attackers to read contents of memory
- ~17% of the internet affected
  - GitHub, Yahoo, Amazon Web Services, etc.



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

Lecture Topics

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- Buffer overflow
  - Input buffers on the stack
  - Overflow attacks and code injection
- Exploits Based on Buffer Overflows
- **Defenses against buffer overflow**
- Societal Impact

System-Level Protections

- **Non-executable memory segments**
  - In traditional x86, only “read” and “write” permissions, could execute anything
  - x86-64 added “execute” permissions
    - Only instruction memory marked executable
    - Attempting to execute non-executable memory will cause a segfault
- **Randomized stack offsets**
  - At start of program, allocate a random amount of stack space
    - Shifts addresses for the rest of the program
    - Addresses will be different every time it’s run
- **Pros**: automatic (programmer doesn’t have to do anything)
- **Cons**: requires hardware support, doesn’t stop all attacks (*e.g.*, return to libc)

Compiler-Level Protections

- **Stack canaries**
  - Place special value ("canary") in the stack just beyond the buffer
    - Check value for corruptio before exiting function
  - GCC implementation: `-fstack-protector`
  - **Pros**:
    - Easy to implement
  - **Cons**:
    - Only detects errors, doesn't stop them
    - *Slow*

```
unix:~$ ./run_echo
Enter string: 12345678
12345678
```

```
unix:~$ ./run_echo
Enter string: 123456789
*** stack smashing detected ***
```

Programmer-Level Protections

- Avoid using unsafe standard library functions
  - `gets()`, `strcpy()`, etc.
    - No way to pass in array size!
  - Most have been replaced with safer alternatives (`fgets()`, `strncpy()`, etc.)
- Don't use `scanf()` with a `%s` conversion specifier
  - Use `fgets()` to read the string
  - Use `%ns` (where `n` is the max size you can read in not including the null-terminator)
- Keep track of array bounds
  - Define macros for array sizes
  - Watch out for off-by-1 errors and integer overflow

Programmer-Level Protections (pt 2)

- Alternatively, use another language that does array index bounds check
  - Most modern languages check at runtime
- What if I need a low-level systems language?
  - **Rust** is a systems language designed with security in mind
    - Does compile-time array bounds checking
- Not always possible, some projects are better suited for C

Lecture Topics

- Memory Layout Review
- Buffer overflow
  - Input buffers on the stack
  - Overflow attacks and code injection
- Exploits Based on Buffer Overflows
- Defenses against buffer overflow
- **Societal Impact**

Discussion

Take a few minutes to think about the question, and then share your thoughts with the class.

- Although it's not as common as it once was, C is still the default language in certain areas of the industry (operating systems, embedded systems, etc.).
- Why do we still use C if it's so insecure?
  - What benefits are there to using C?
  - What kinds of things does C allow us to do that we can't do in other languages?
  - What might dissuade developers from using another language?

Security vs. Functionality

- Not always mutually exclusive, but often in tension
  - “The only system which is truly secure is one which is switched off and unplugged locked in a titanium lined safe, buried in a concrete bunker, and is surrounded by nerve gas and very highly paid armed guards. Even then, I wouldn't stake my life on it.” *-Gene Stafford*
- Many things we do in systems programming use C features like pointer casting etc.
  - Even Rust has “unsafe”!
- Security checks incur overhead

Two Narratives in C

1. “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.”
   a. Emphasis on the **individual**
2. “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.”
   a. Emphasis on **structures**

Accessibility and Computer Science

- Is C accessible?
  - “C is good for two things: being beautiful and creating catastrophic day-0s in memory management.”
- Is *programming* accessible?
  - A notoriously difficult task to do correctly (even for experts!)
  - Ideological foundations tend to over-emphasize individuals

- **You** know how to program. What now?

```
/*
 * 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

Discussion (pt 2)

Discuss the following questions in groups of 2-4. Then we'll share as a class.

- What do you think of when you hear the word "hacker"? Where did your beliefs about hacking come from?
- What are some of the possible consequences & objectives of hacking (i.e., to what ends might someone engage in hacking)?

What is a "hacker"?

- Very different from what you see in the movies!
    - Real hacking is much more tedious
- Stereotype is a single (usually male) person
    - Emphasizes "rugged individualism"
    - Plays into dominant narratives about who programmers are
    - Romanticizes crime (though "ethical hacking" does exist)
- *Where do these stereotypes come from?*

Some history

- Programming used to be thought of as “women’s work”
  - Played into gender stereotypes: tedious, detail-oriented work
- So what changed?
  - Between the 1960s-80s, computing culture shifted
    - Focus on individualism
    - Competition (think hackathons, etc.)
    - Higher barriers to entry (specialized CS degrees)
  - These stereotypes were pushed to turn programing into a “legitimate” science
- The “hacker” stereotype was a part of this cultural shift!

Think this is cool?

- You’ll love Lab 3 :)
- Take CSE 484 (Security)
  - 1st lab is a more in-depth version of Lab 3
- More examples in bonus slides
  - Talk to Tadayoshi Kohno or Franzi Roesner if you want to know more about these
- Optional readings on Ed
- Nintendo fun!
  - Flappy bird in Mario: https://www.youtube.com/watch?v=hB6eY73sLV0

BONUS SLIDES

You won’t be tested on this material, but it’s interesting nonetheless :)

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

- DNA Sequencer reads in DNA, encodes in binary, stores in a buffer
  - 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/

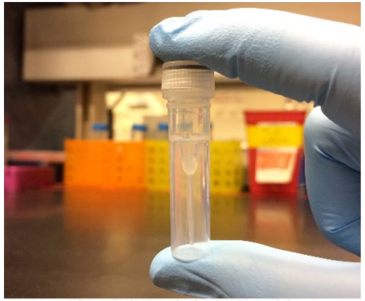
Figure 1: Our synthesized DNA exploit