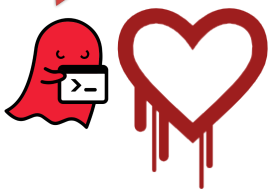
CS 240
Foundations of Computer Systems

WELLESLEY

Buffer Overflows



Address space layout,
the stack discipline,
+ C's lack of bounds-checking
= HUGE PROBLEM

https://cs.wellesley.edu/~cs240/

THE WHITE HOUSE

MENU

FEBRUARY 26, 2024

Statements of Support for Software Measurability and Memory Safety

ONCD › BRIEFING ROOM › PRESS RELEASE

Read the full report here

Read the fact sheet here

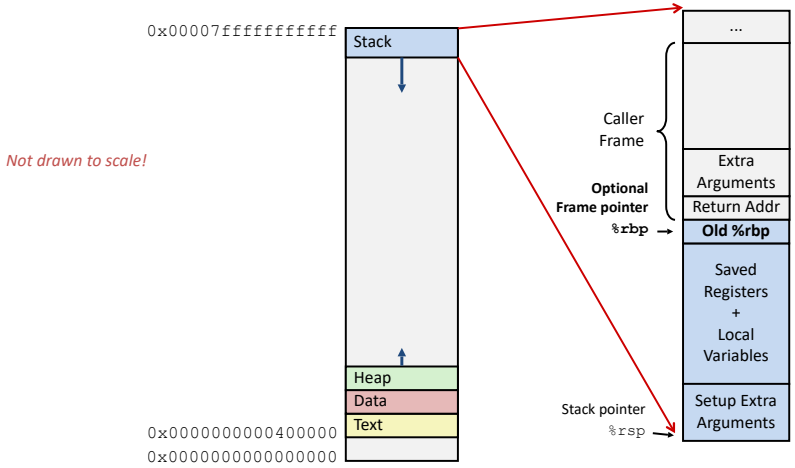
Today, the Office of the National Cyber Director released a new Technical Report titled *"Back to the Building Blocks: A Path Toward Secure and Measurable Software."* This report builds upon the President's National Cybersecurity Strategy, addressing the technical community to tackle undiscovered vulnerabilities that malicious actors can exploit.

Outline

Goal: how the stack + lack of bounds checking make C program vulnerable to a certain (serious!) type of **security vulnerability**

- Understanding buffer overflows
  - Refresher on memory layout
  - C library function: `gets`
  - `gets + echo` buffer overflow example
  - You: simplified security exploit example
- Buffer overflows in the wild
  - When this is a problem
  - Real-world implications

x86-64 Linux **memory layout**



C: String library code

C standard library 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 = p + 1;
```

What could go wrong when using this code?

What will happen if the input string from stdin is longer than the space allocated at dest?

0

```
/* 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;
}
```

- The C code will not compile. **(A)**
- An out-of-bounds exception. **(B)**
- It will only get the part of the input. **(C)**
- It depends on the memory layout. **(D)**
- None of the above **(E)**

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

What will happen if the input string from stdin is longer than the space allocated at dest?

0

```
/* 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;
}
```

- (A) The C code will not compile. 0%
- (B) An out-of-bounds exception. 0%
- (C) It will only get the part of the input. 0%
- (D) It depends on the memory layout. 0%
- (E) None of the above 0%

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

What will happen if the input string from stdin is longer than the space allocated at dest?

0

```
/* 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;
}
```

- (A) The C code will not compile. 0%
- (B) An out-of-bounds exception. 0%
- (C) It will only get the part of the input. 0%
- (D) It depends on the memory layout. 0%
- (E) None of the above 0%

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

C: String library code

C standard library 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 = p + 1;
```

What could go wrong when using this code?

Same problem in many C library functions:

strcpy: Copies string of arbitrary length

scanf, fscanf, sscanf, when given **%s** conversion specification

C: Vulnerable buffer code using gets (…)

```
/* Echo Line */
void echo() {
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

These two lines of code introduce a vulnerability!

```
int main() {
    printf("Type a string:");
    echo();
    return 0;
}
```

```
$ ./bufdemo
Type a string:123
123
```

```
$ ./bufdemo
Type a string: 012345678901234567890123
Segmentation Fault
```

```
$ ./bufdemo
Type a string: 01234567890123456789012
012345678901234567890123
```


Vulnerable buffer code using gets : disassembled x86

echo code

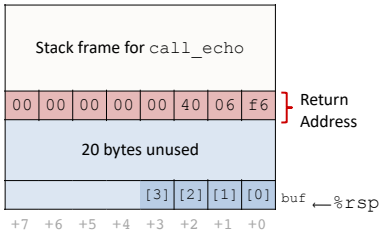
```
00000000004006cf <echo>:
 4006cf:  48 83 ec 18           sub    $24,%rsp
 4006d3:  48 89 e7              mov    %rsp,%rdi
 4006d6:  e8 a5 ff ff ff        callq  400680 <gets>
 4006db:  48 89 e7              mov    %rsp,%rdi
 4006de:  e8 3d fe ff ff        callq  400520 <puts@plt>
 4006e3:  48 83 c4 18           add    $24,%rsp
 4006e7:  c3                    retq
```

caller code

```
4006e8:   48 83 ec 08          sub    $0x8,%rsp
 4006ec:  b8 00 00 00 00        mov    $0x0,%eax
 4006f1:  e8 d9 ff ff ff        callq  4006cf <echo>
 4006f6:  48 83 c4 08           add    $0x8,%rsp
 4006fa:  c3                    retq
```


Buffer overflow example: before input

Before call to gets



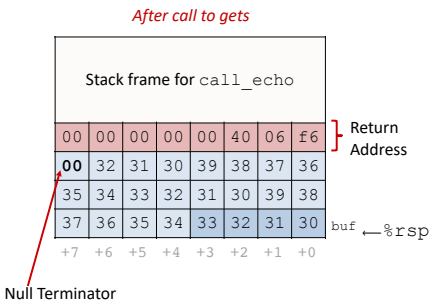

```
void echo() {
    char buf[4];
    gets(buf);
    ...
}
```

```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

call_echo:

```
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $0x8,%rsp
  . . .
```

Buffer overflow example: input #1




```
void echo() {
    char buf[4];
    gets(buf);
    ...
}
```

```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

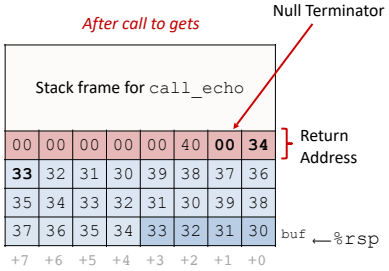
call_echo:

```
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $0x8,%rsp
  . . .
```

```
$ ./bufdemo
Type a string: 012345678901234567890123456789012
012345678901234567890123456789012
```

Overflowed buffer, but did not corrupt state

Buffer overflow example: input #2




```
void echo() {
    char buf[4];
    gets(buf);
    ...
}
```

```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

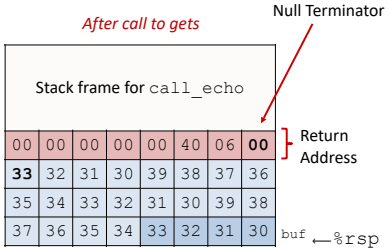
call_echo:

```
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $0x8,%rsp
  . . .
```

```
unix> ./bufdemo
Type a string: 012345678901234567890123456789012345
Segmentation Fault
```

Overflowed buffer and corrupted return pointer

Buffer overflow example: input #3




```
void echo() {
    char buf[4];
    gets(buf);
    ...
}
```

```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

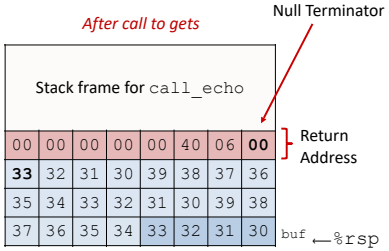
call_echo:

```
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $0x8,%rsp
  . . .
```

```
unix> ./bufdemo-nsp
Type a string: 012345678901234567890123
0123456789012345678901230
```

Overflowed buffer, corrupted return pointer, but program seems to work?!

Buffer overflow example: input #3



Some other place in .text

```
  . . .
  400600:  mov    %rsp,%rbp
  400603:  mov    %rax,%rdx
  400606:  shr    $0x3f,%rdx
  40060a:  add    %rdx,%rax
  40060d:  sar    %rax
  400610:  jne    400614
  400612:  pop    %rbp
  400613:  retq
```

Works because: “Returns” to unrelated code, despite what the C code had!
Lots of things happen, without modifying critical state
Eventually executes `retq` back to `main`

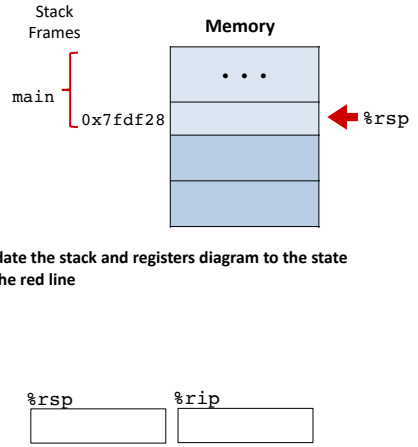
Simplified exploit example (no padding)

```c
#include <stdio.h>

void delete_all_files() {
    // … users shouldn't be able to call this
}

void read_input() {
    char buf[8];
    gets(buf);
}

int main() {
    read_input();
}
```

```
read_input:
401126: subq    $8, %rsp
40112a: leaq    (%rsp), %rdi
40112f: movl    $0, %eax
401134: call    gets
401139: addq    $24, %rsp
40113d: ret

delete_all_files:
40003e: call    evil
        …

main:
            …   …
400048: call    read_input
40004d: addq    $8, %rsp
400051: ret
```


Simplified exploit example (no padding)

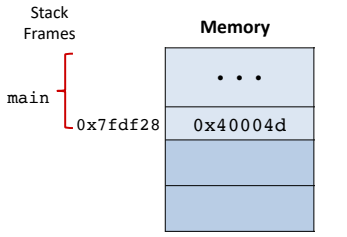
```
read_input:
401126: subq    $8, %rsp
40112a: leaq    (%rsp), %rdi
40112f: movl    $0, %eax
401134: call    gets
401139: addq    $24, %rsp
40113d: ret

delete_all_files:
40003e: call    evil
        …

main:
            …   …
400048: call    read_input
40004d: addq    $8, %rsp
400051: ret
```



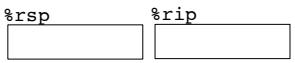
Update the stack and registers diagram to the state at the red line

Simplified exploit example (no padding)

```
read_input:
401126: subq    $8, %rsp
40112a: leaq    (%rsp), %rdi
40112f: movl    $0, %eax
401134: call    gets
401139: addq    $24, %rsp
40113d: ret

delete_all_files:
40003e: call    evil
        …

main:
            …   …
400048: call    read_input
40004d: addq    $8, %rsp
400051: ret
```

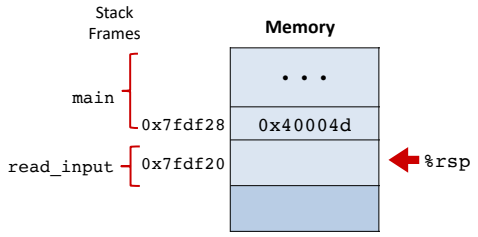


Update the stack and registers diagram to the state at the red line



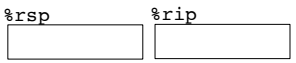
Simplified exploit example (no padding)

```
read_input:
401126: subq    $8, %rsp
40112a: leaq    (%rsp), %rdi
40112f: movl    $0, %eax
401134: call    gets
401139: addq    $24, %rsp
40113d: ret

delete_all_files:
40003e: call    evil
        …

main:
            …   …
400048: call    read_input
40004d: addq    $8, %rsp
400051: ret
```

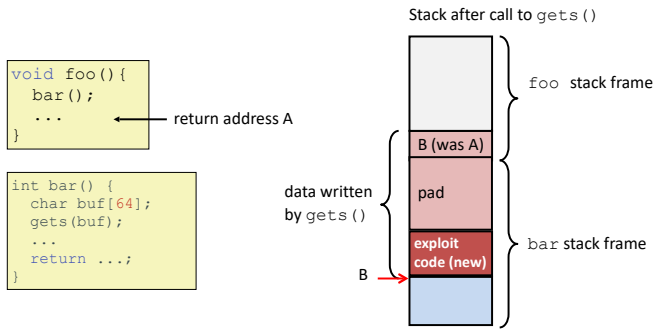


Discuss: what address would we want to appear, and where, to have our exploit delete all files?

Draw out the bytes (in hex) of the exploit string.



Exploiting buffer overflows: arbitrary code



Exploiting buffer overflows: when is this a problem?

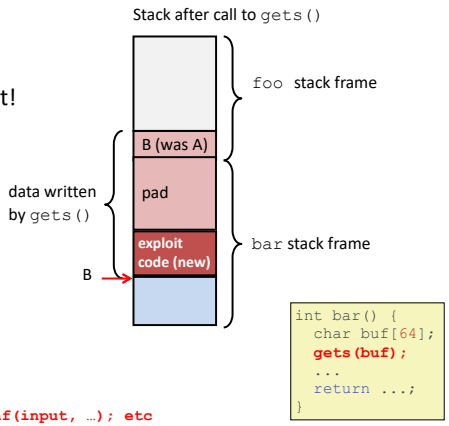
We could construct x86 code to mess up our own programs call stack

But, we trust our own code to not!

The problem: allowing user input (untrusted source) to potentially corrupt the stack

Combination of: untrusted input, code that does not enforce bounds

`gets(input); strcpy(input, …); scanf(input, …); etc`



Exploits in the wild

Buffer overflow bugs allow remote attackers to execute arbitrary code on machines running vulnerable software.

1988: Internet worm

Early versions of the finger server daemon (fingerd) used **`gets()`** to read the argument sent by the client:

```
finger somebody@cs.wellesley.edu
```

commandline facebook of the 80s!

Attack by sending phony argument:

```
finger "exploit-code padding new-return-address"
```

…

Still happening

"Ghost:" 2015

Heartbleed (2014)

optional

Buffer over-read in OpenSSL

Widely used encryption library (https)

"Heartbeat" packet

Specifies length of message

Server echoes that much back

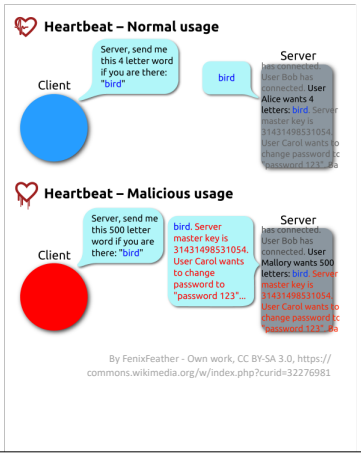
Library just "trusted" this length

Allowed attackers to read contents of memory anywhere they wanted

~17% of Internet affected

"Catastrophic"

Github, Yahoo,
Stack Overflow, Amazon AWS, ...



Avoiding overrun vulnerabilities

1. Use a memory-safe language (not C)!

2. If you have to use C, use library functions that limit string lengths.
   `fgets` instead of **`gets`**

```
/* Echo Line */
void echo() {
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

   `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

Other ideas?

System-level protections

Available in modern OSs/compilers/hardware
(We disabled these for buffer assignment.)

1. Randomize stack base, maybe frame padding

2. Detect stack corruption
   save and check stack "canary" values

3. Non-executable memory segments
   stack, heap, data, … everything except text
   hardware support

Helpful, not foolproof!
   Return-oriented programming, over-reads, etc.

not drawn to scale