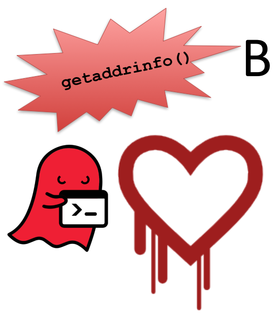
CS 240
Foundations of Computer Systems

WELLESLEY




# Buffer Overflows

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

Big picture: buggy C can
let attackers control your code!




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

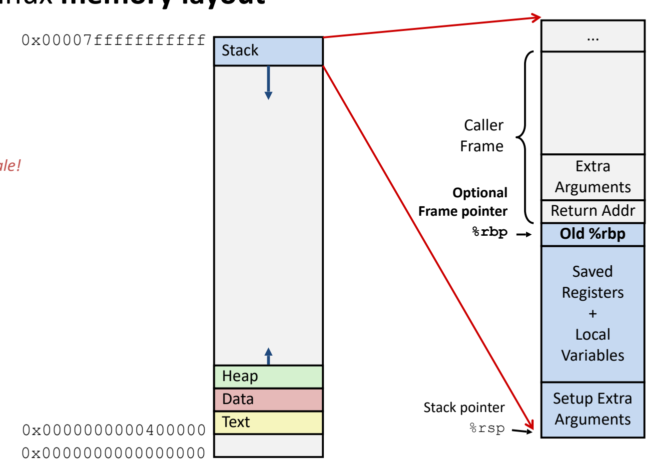
*Goal*: how the stack + lack of bounds checking make C program vulnerable to a certain (serious!) type of **security vulnerability**

- Understanding buffer overflows
  - Refresher on memory layout
  - C ibrary 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**

*Not drawn to scale!*



# 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)**



# 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: 0123456789012345678901234
Segmentation Fault
```

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

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Stack frame for `call_echo` | | | | | | | | |
| 00 | 00 | 00 | 00 | 00 | 40 | 06 | f6 | Return Address |
| 20 bytes unused | | | | | | | | |
| | | | | [3] | [2] | [1] | [0] | buf ⟵%rsp |
| +7 | +6 | +5 | +4 | +3 | +2 | +1 | +0 | |

```
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

*After call to gets*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Stack frame for `call_echo` | | | | | | | | |
| 00 | 00 | 00 | 00 | 00 | 40 | 06 | f6 | Return Address |
| **00** | 32 | 31 | 30 | 39 | 38 | 37 | 36 | |
| 35 | 34 | 33 | 32 | 31 | 30 | 39 | 38 | |
| 37 | 36 | 35 | 34 | 33 | 32 | 31 | 30 | buf ⟵%rsp |
| +7 | +6 | +5 | +4 | +3 | +2 | +1 | +0 | |

Null Terminator

```
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: 01234567890123456789012
01234567890123456789012
```

Overflowed buffer, but did not corrupt state



## Buffer overflow example: input #2

*After call to gets*

Null Terminator

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Stack frame for `call_echo` | | | | | | | | |
| 00 | 00 | 00 | 00 | 00 | 40 | **00** | **34** | Return Address |
| **33** | 32 | 31 | 30 | 39 | 38 | 37 | 36 | |
| 35 | 34 | 33 | 32 | 31 | 30 | 39 | 38 | |
| 37 | 36 | 35 | 34 | 33 | 32 | 31 | 30 | buf ⟵%rsp |
| +7 | +6 | +5 | +4 | +3 | +2 | +1 | +0 | |

```
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: 0123456789012345678901234
Segmentation Fault
```

Overflowed buffer and corrupted return pointer

# Buffer overflow example: input #3

*After call to gets*

Null Terminator

| Stack frame for call_echo | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 00 | 00 | 00 | 00 | 00 | 40 | 06 | **00** | Return Address |
| **33** | 32 | 31 | 30 | 39 | 38 | 37 | 36 | |
| 35 | 34 | 33 | 32 | 31 | 30 | 39 | 38 | |
| 37 | 36 | 35 | 34 | 33 | 32 | 31 | 30 | buf ⟵%rsp |

```
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
012345678901234567890123
```

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



# Buffer overflow example: input #3

*After call to gets*

Null Terminator

| Stack frame for call_echo | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 00 | 00 | 00 | 00 | 00 | 40 | 06 | **00** | Return Address |
| **33** | 32 | 31 | 30 | 39 | 38 | 37 | 36 | |
| 35 | 34 | 33 | 32 | 31 | 30 | 39 | 38 | |
| 37 | 36 | 35 | 34 | 33 | 32 | 31 | 30 | buf ⟵%rsp |

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)

```
#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
```

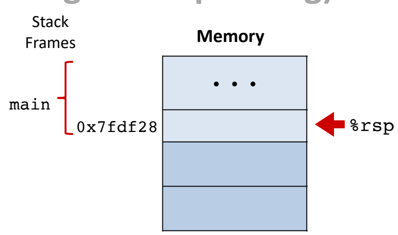


# Simplified exploit example (no alignment padding)

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

%rdi

%rsp

%rip

## Simplified exploit example (no alignment padding)

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

```
delete_all_files:
40003e: call    evil
        …
```

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

Stack Frames

Memory

. . .

main

0x7fdf28 0x40004d ← %rsp

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

%rdi

%rsp 0x7fdf28

%rip 0x401126



## Simplified exploit example (no alignment padding)

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

```
delete_all_files:
40003e: call    evil
        …
```

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

Stack Frames

Memory

. . .

main

0x7fdf28 0x40004d

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

%rdi

%rsp

%rip



## Simplified exploit example (no alignment padding)

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

```
delete_all_files:
40003e: call    evil
        …
```

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

Stack Frames

Memory

. . .

main

0x7fdf28 0x40004d

read_input

0x7fdf20 ← %rsp

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

%rdi 0x7fdf20

%rsp 0x7fdf20

%rip 0x40112f



## Simplified exploit example (no alignment padding)

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

```
delete_all_files:
40003e: call    evil
        …
```

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

Stack Frames

Memory

. . .

main

0x7fdf28 0x40004d

read_input

0x7fdf20 ← %rsp

**Discuss: what address would we want to appear, and where, to have our exploit delete all files? (Recall: *little endian*)**

%rdi 0x7fdf20 arg to `gets` is 0x7fdf20

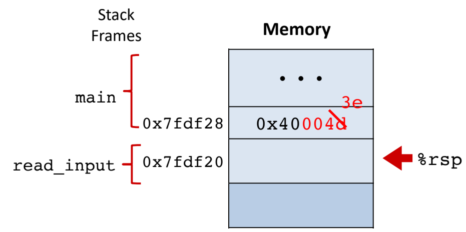
**Draw out the bytes (in hex) of the exploit string.**

## Simplified exploit example (no alignment padding)

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

```
delete_all_files:
40003e: call   evil
        …
```

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




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

9 bytes, since we only need to overwrite part of the address

input:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| any | any | any | any | any | any | any | any | 3e |

we could also write 16 bytes (2 words) to go to any address!



**Warmup for the buffer assignment: given an executable, how could an attacker tell how long their input string needs to be?** 0

- 16 bytes, since the return address is one word above the input buffer. **(A)**
- Dump the x86, see how the stack frame is set up **(B)**
- Trace with gdb, see where the return from the previous function is placed on t… **(C)**
- It's impossible to determine the length of the input string ahead of time, so g… **(D)**
- None of the above **(E)**

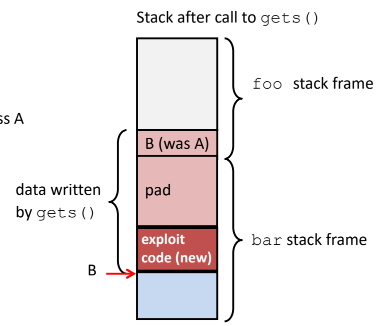


## Exploiting buffer overflows: arbitrary code

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

return address A

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



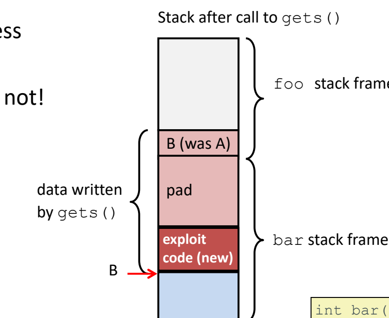



## Exploiting buffer overflows: when is this a problem?

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




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

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

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

# Exploits in the wild

optional

*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!*

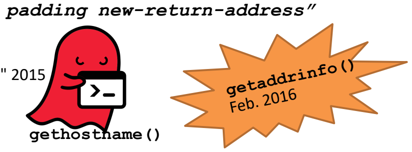
Attack by sending phony argument:

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

...

Still happening

"Ghost:" 2015

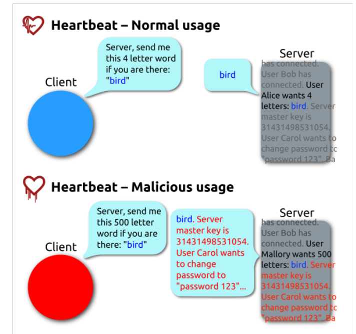





# Heartbleed (2014)

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, ...

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# 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

optional

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*