CS 240
Foundations of Computer Systems

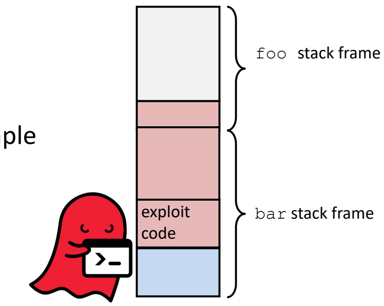
Buffer Overflows

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

Outline

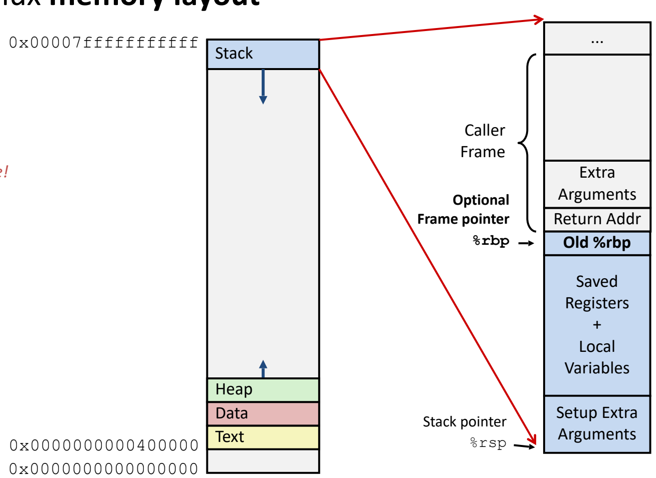
Goal: how the stack + lack of bounds checking make C program vulnerable to a certain (serious!) type of security vulnerability

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



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?

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: 01234567890123456789901234
Segmentation Fault
```

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


Vulnerable buffer code using `gets` : disassembled x86

echo code

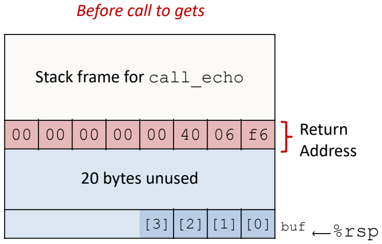
```
00000000004006cf <echo>:
 4006cf:  48 83 ec 18          sub    $24,%rsp
 4006d3:  48 89 e7             mov    %rsp,%rdi
 4006d6:  e8 a5 ff ff ff       callq  400680 <gets>
 4006db:  48 89 e7             mov    %rsp,%rdi
 4006de:  e8 3d fe ff ff       callq  400520 <puts@plt>
 4006e3:  48 83 c4 18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




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

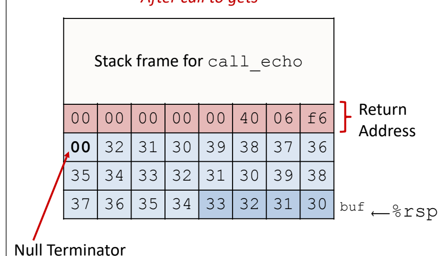
```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

call_echo:

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


Buffer overflow example: input #1

After call to gets




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

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

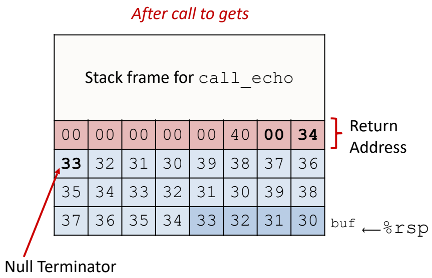
call_echo:

```
 . . .
 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




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

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

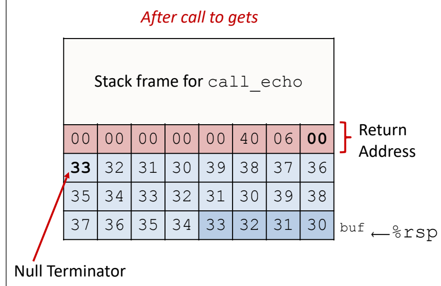
call_echo:

```
 . . .
 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




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

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

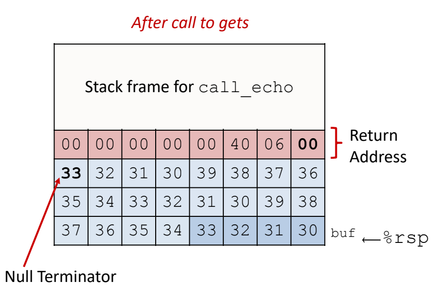
call_echo:

```
 . . .
 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



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
```

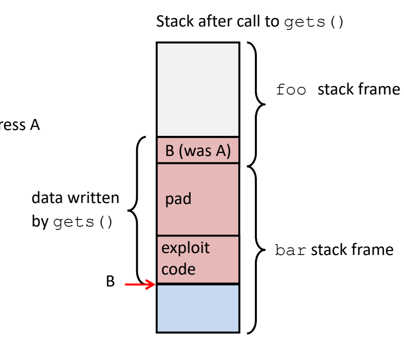
Works because: "Returns" to unrelated code, despite what the C code had!
Lots of things happen, without modifying critical state
Eventually executes `retq` back to `main`

Exploiting buffer overflows

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

return address A

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



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
        …
```

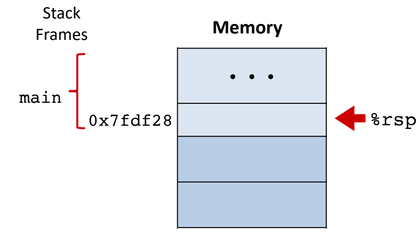
```
main:
        …       …
400048: call    read_input
40004d: addq    $8, %rsp
400051: ret
```


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

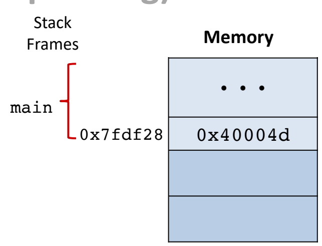
%rsp %rip

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

%rsp %rip

Simplified exploit example (no padding)

```
read_input:
401126: subq    $8, %rsp
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40113d: ret
```
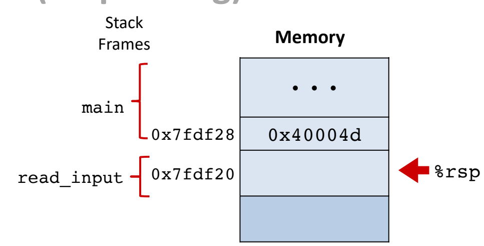

```
delete_all_files:
40003e: call    evil
        …
```

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



Discuss: how long would the user input on standard in need for a buffer overflow attack? What address would we want to appear, and where, to delete all files?

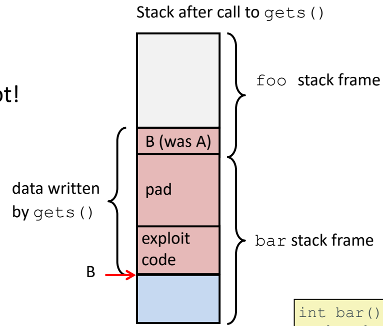
%rsp %rip

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

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

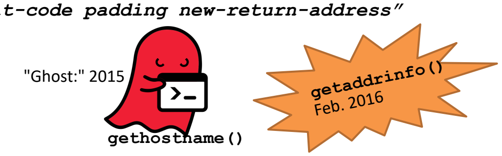
commandline facebook of the 80s!

Attack by sending phony argument:

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

…

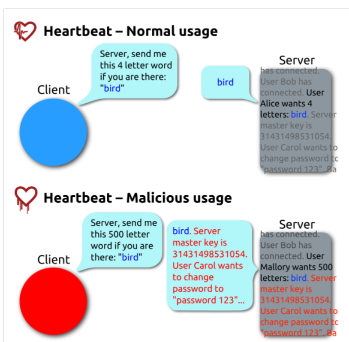
Still happening



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

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

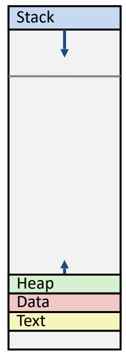
1. Randomize stack base, maybe frame padding

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



Conclusion of unit: Hardware-Software Interface (ISA)

Lectures
- (building on everything from HW)
- Programming with Memory
- x86 Basics
- x86 Control Flow
- x86 Procedures, Call Stack
- Representing Data Structures
- Buffer Overflows

Labs
- (building on everything from HW)
- 7: Pointers in C
- 8: x86 Assembly
- 9: x86 Stack
- 10: Data structures in memory
- 11: Buffer overflows (less)

Topics
- C programming: pointers, dereferencing, arrays, cursor-style programming, using malloc
- x86: instruction set architecture, machine code, assembly language, reading/writing x86, basic program translation
- Procedures and the call stack, data layout, security implication

Assignments
- Pointers
- x86
- Buffer (less)

Mid-semester exam 2: ISA
November 16
(1 week from today)