Buffer Overflows

CSE 351 Winter 2018

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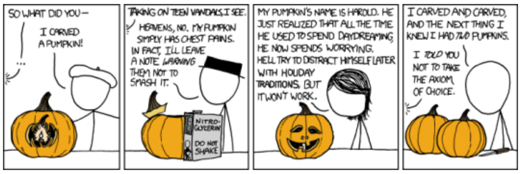

SO WHAT DID YOU—
I CARVED A PUMPKIN!
TAKING ON TEEN VANDALS, I SEE.
HEAVENS, NO. MY PUMPKIN SIMPLY HAS CHEST PAINS. IN FACT, I'LL LEAVE A NOTE ASKING THEM NOT TO SMASH IT.
NITRO-GLYCERIN
DO NOT SHAKE
MY PUMPKIN'S NAME IS HAROLD. HE JUST REALIZED THAT ALL THE TIME HE USED TO SPEND DAYDREAMING HE NOW SPENDS WORRYING. HE'LL TRY TO DISTRACT HIMSELF LATER WITH HOLIDAY TRADITIONS, BUT IT WON'T WORK.
I CARVED AND CARVED, AND THE NEXT THING I KNEW I HAD TWO PUMPKINS.
I TOLD YOU NOT TO TAKE THE AXIOM OF CHOICE.

http://xkcd.com/804/

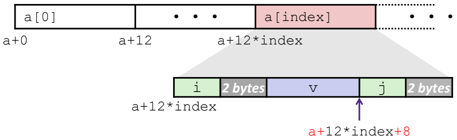
Administrative

- Homework 3 due Friday (2/9)
- Lab 3 due next Friday (2/16)

Accessing Array Elements

- Compute start of array element as: `12*index`
  - `sizeof(S3) = 12`, including alignment padding
- Element `j` is at offset 8 within structure
- Assembler gives offset `a+8`

```
struct S3 {
  short i;
  float v;
  short j;
} a[10];
```



```
short get_j(int index)
{
  return a[index].j;
}
```

```
# %rdi = index
leaq (%rdi,%rdi,2),%rax   # 3*index
movzwl a+8(,%rax,4),%eax
```

Peer Instruction Question

- Minimize the size of the struct by re-ordering the vars

```
struct old {
  int i;

  short s[3];

  char *c;

  float f;
};
```

```
struct new {
  int    i;

  ______ ______;

  ______ ______;

  ______ ______;
};
```

- What are the old and new sizes of the struct?

sizeof(struct old) = _____ sizeof(struct new) = _____

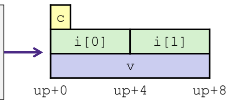
A. 16 bytes
B. 22 bytes
C. 28 bytes
D. 32 bytes
E. We're lost…

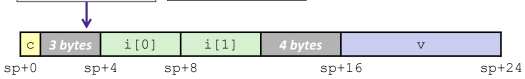
Unions

- Only allocates enough space for the largest element in union
- Can only use one member at a time

```
struct S {
  char c;
  int i[2];
  double v;
} *sp;
```

```
union U {
  char c;
  int i[2];
  double v;
} *up;
```





Summary

- Arrays in C
  - Aligned to satisfy every element's alignment requirement
- Structures
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment
- Unions
  - Provide different views of the same memory location

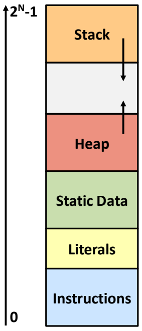
Buffer Overflows

- Address space layout (more details!)
- 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
  - `malloc()`, `calloc()`, `new`, …
- 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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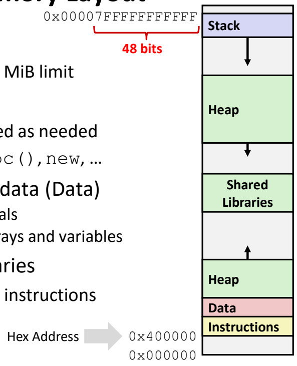
x86-64 Linux Memory Layout

- Stack
  - Runtime stack has 8 MiB limit
- Heap
  - Dynamically allocated as needed
  - `malloc()`, `calloc()`, `new`, …
- Statically allocated data (Data)
  - Read-only: string literals
  - Read/write: global arrays and variables
- Code / Shared Libraries
  - Executable machine instructions
  - Read-only



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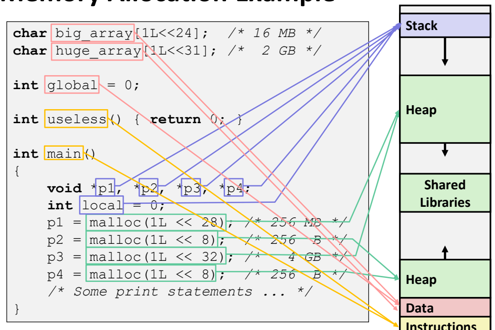
Memory Allocation Example

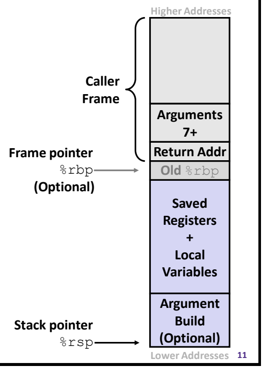


```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

int global = 0;

int useless() { return 0; }

int main()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8);  /* 256  B */
    p3 = malloc(1L << 32); /*   4 GB */
    p4 = malloc(1L << 8);  /* 256  B */
    /* Some print statements ... */
}
```

Where does everything go?

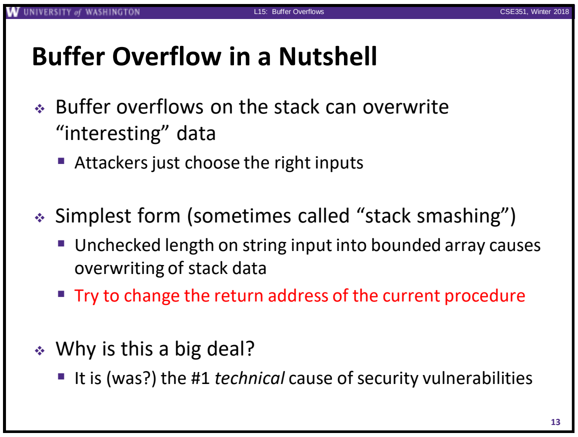
Reminder: x86-64/Linux Stack Frame

- Caller's Stack Frame
  - Arguments (if > 6 args) for this call
  - Return address
    - Pushed by `call` instruction
- Current/ Callee Stack Frame
  - Old frame pointer (optional)
  - Saved register context (when reusing registers)
  - Local variables (if can't be kept in registers)
  - "Argument build" area (If callee needs to call another function -parameters for function about to call, if needed)



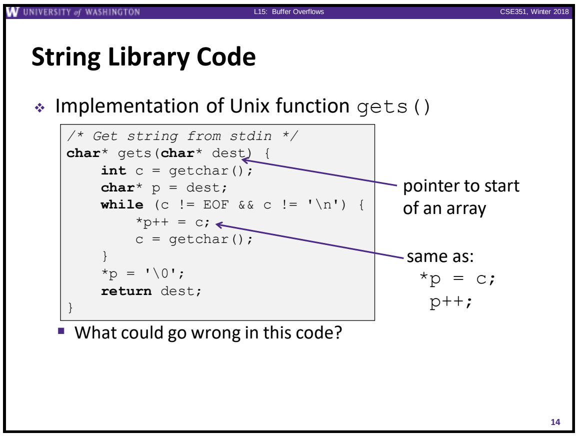
Buffer Overflow in a Nutshell

- Characteristics of the traditional Linux memory layout provide opportunities for malicious programs
  - Data and instructions both stored in the same memory
- 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 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 is (was?) the #1 *technical* cause of security vulnerabilities



String Library Code

- Implementation of Unix function `gets()`

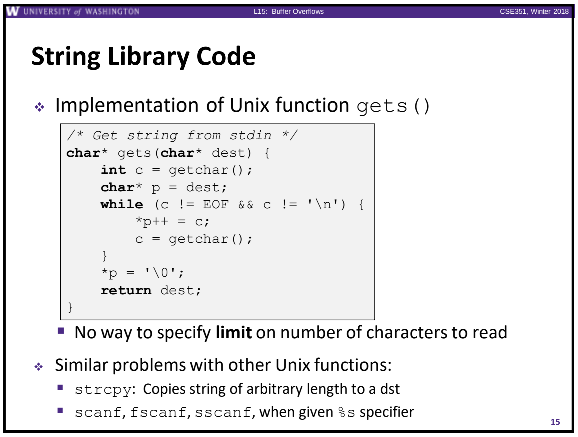
```
/* Get string from stdin */
char* gets(char* dest) {
    int c = getchar();
    char* p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

pointer to start of an array

same as:

```
*p = c;
p++;
```

- What could go wrong in this code?

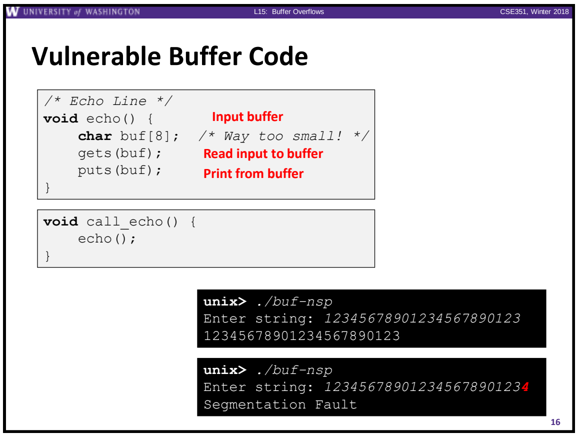


String Library Code

- 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);
}
```

Input buffer

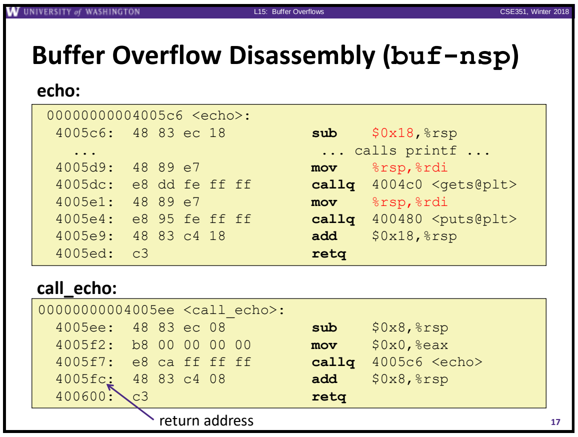
Read input to buffer

Print from buffer

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

```
unix> ./buf-nsp
Enter string: 12345678901234567890123
12345678901234567890123
```

```
unix> ./buf-nsp
Enter string: 123456789012345678901234
Segmentation Fault
```



Buffer Overflow Disassembly (`buf-nsp`)

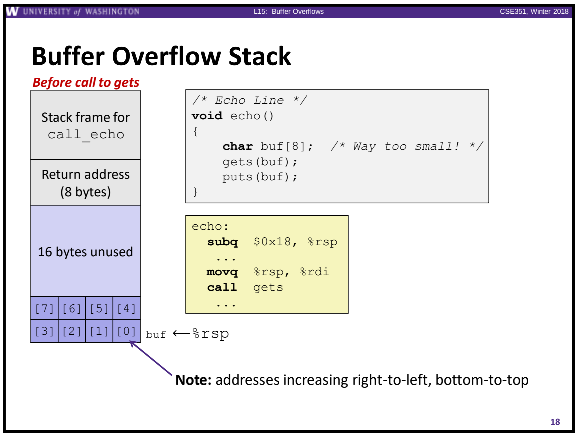
echo:

```
 00000000004005c6 <echo>:
  4005c6:  48 83 ec 18          sub    $0x18,%rsp
   ...                           ... calls printf ...
  4005d9:  48 89 e7             mov    %rsp,%rdi
  4005dc:  e8 dd fe ff ff       callq  4004c0 <gets@plt>
  4005e1:  48 89 e7             mov    %rsp,%rdi
  4005e4:  e8 95 fe ff ff       callq  400480 <puts@plt>
  4005e9:  48 83 c4 18          add    $0x18,%rsp
  4005ed:  c3                   retq
```

call_echo:

```
00000000004005ee <call_echo>:
  4005ee:  48 83 ec 08          sub    $0x8,%rsp
  4005f2:  b8 00 00 00 00       mov    $0x0,%eax
  4005f7:  e8 ca ff ff ff       callq  4005c6 <echo>
  4005fc:  48 83 c4 08          add    $0x8,%rsp
  400600:  c3                   retq
```

return address



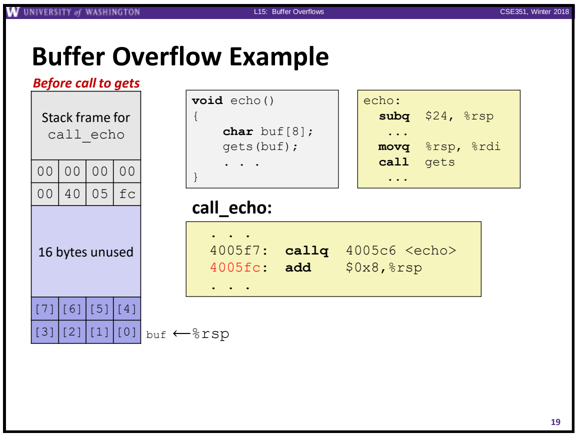
Buffer Overflow Stack

Before call to gets

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

```
echo:
  subq  $0x18, %rsp
   ...
  movq  %rsp, %rdi
  call  gets
   ...
```

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



Buffer Overflow Example

Before call to gets

Stack frame for `call_echo`

00	00	00	00
00	40	05	fc
16 bytes unused			
[7]	[6]	[5]	[4]
[3]	[2]	[1]	[0]

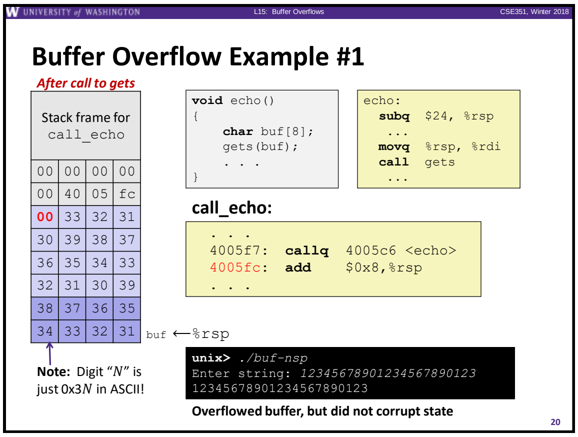
buf ⟵%rsp

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

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

call_echo:

```
  . . .
  4005f7:  callq  4005c6 <echo>
  4005fc:  add    $0x8,%rsp
  . . .
```



Buffer Overflow Example #1

After call to gets

Stack frame for `call_echo`

00	00	00	00
00	40	05	fc
00	33	32	31
30	39	38	37
36	35	34	33
32	31	30	39
38	37	36	35
34	33	32	31

buf ⟵%rsp

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

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

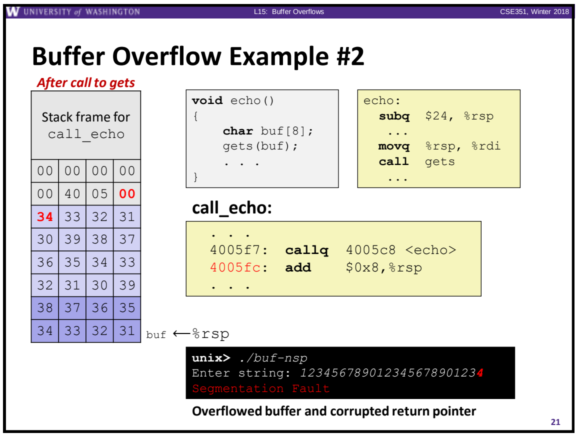
```
echo:
  subq  $24, %rsp
   ...
  movq  %rsp, %rdi
  call  gets
   ...
```

call_echo:

```
  . . .
  4005f7:  callq  4005c6 <echo>
  4005fc:  add    $0x8,%rsp
  . . .
```

```
unix> ./buf-nsp
Enter string: 12345678901234567890123
12345678901234567890123
```

Overflowed buffer, but did not corrupt state



Buffer Overflow Example #2

After call to gets

Stack frame for `call_echo`

00	00	00	00
00	40	05	00
34	33	32	31
30	39	38	37
36	35	34	33
32	31	30	39
38	37	36	35
34	33	32	31

buf ⟵%rsp

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

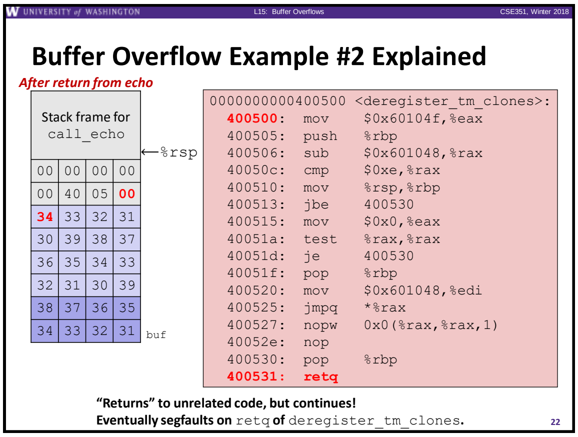
```
echo:
  subq  $24, %rsp
   ...
  movq  %rsp, %rdi
  call  gets
   ...
```

call_echo:

```
  . . .
  4005f7:  callq  4005c8 <echo>
  4005fc:  add    $0x8,%rsp
  . . .
```

```
unix> ./buf-nsp
Enter string: 123456789012345678901234
Segmentation Fault
```

Overflowed buffer and corrupted return pointer



Buffer Overflow Example #2 Explained

After return from echo

Stack frame for `call_echo`

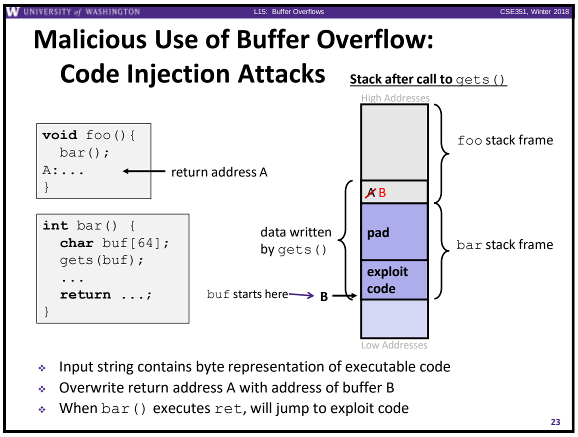
⟵%rsp

00	00	00	00
00	40	05	00
34	33	32	31
30	39	38	37
36	35	34	33
32	31	30	39
38	37	36	35
34	33	32	31

buf

```
0000000000400500 <deregister_tm_clones>:
  400500:  mov    $0x60104f,%eax
  400505:  push   %rbp
  400506:  sub    $0x601048,%rax
  40050c:  cmp    $0xe,%rax
  400510:  mov    %rsp,%rbp
  400513:  jbe    400530
  400515:  mov    $0x0,%eax
  40051a:  test   %rax,%rax
  40051d:  je     400530
  40051f:  pop    %rbp
  400520:  mov    $0x601048,%edi
  400525:  jmpq   *%rax
  400527:  nopw   0x0(%rax,%rax,1)
  40052e:  nop
  400530:  pop    %rbp
  400531:  retq
```

"Returns" to unrelated code, but continues!
Eventually segfaults on `retq` **of** `deregister_tm_clones`.



Malicious Use of Buffer Overflow: Code Injection Attacks

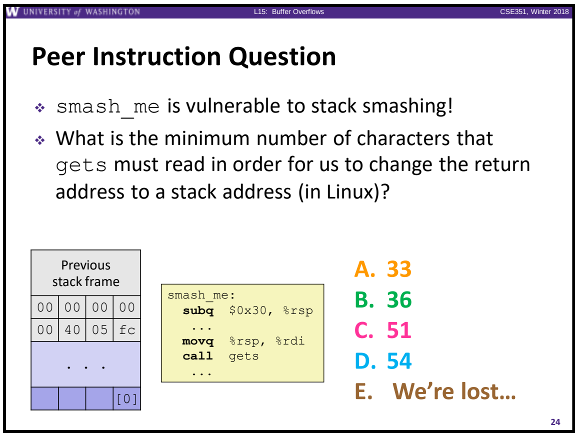
Stack after call to `gets()`

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

return address A

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

- 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



Peer Instruction Question

- `smash_me` 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 (in Linux)?

Previous stack frame

00	00	00	00
00	40	05	fc
. . .			
			[0]

```
smash_me:
  subq  $0x30, %rsp
   ...
  movq  %rsp, %rdi
  call  gets
   ...
```

A. 33
B. 36
C. 51
D. 54
E. We're lost…

Exploits Based on Buffer Overflows

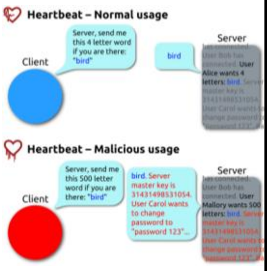
- *Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines*
- Distressingly common in real programs
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- Examples across the decades
  - Original "Internet worm" (1988)
  - *Still happens!!*
    - Heartbleed (2014, affected 17% of servers)
    - Cloudbleed (2017)
  - *Fun:* Nintendo hacks
    - Using glitches to rewrite code: https://www.youtube.com/watch?v=TqK-2jUQBUY
    - FlappyBird in Mario: https://www.youtube.com/watch?v=hB6eY73sLV0

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 TCP 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 young author of the worm was prosecuted…

Heartbleed (2014)

- 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, ...


Heartbeat – Normal usage
Client
Server, send me this 4 letter word if you are there: "bird"
bird
Server
User Bob has connected. User Alice wants 4 letters: bird. Server master key is 31431498531054. User Carol wants to change password to "password 123"...
Heartbeat – Malicious usage
Client
Server, send me this 500 letter word if you are there: "bird"
bird. Server master key is 31431498531054. User Carol wants to change password to "password 123"...
Server
User Bob has connected. User Mallory wants 500 letters: bird. Server master key is 31431498531054. User Carol wants to change password to "password 123"...

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Dealing with buffer overflow attacks

1) Avoid overflow vulnerabilities
2) Employ system-level protections
3) Have compiler use "stack canaries"

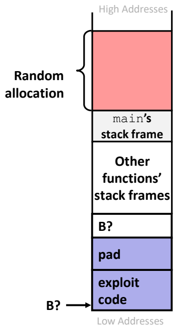
1) Avoid Overflow Vulnerabilities in Code

```
/* 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

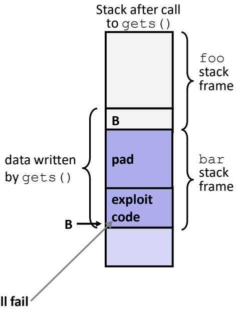
2) System-Level Protections

- **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: Code from Slide 6 executed 5 times; address of variable `local` =
  - `0x7ffd19d3f8ac`
  - `0x7ffe8a462c2c`
  - `0x7ffe927c905c`
  - `0x7ffefd5c27dc`
  - `0x7fffa0175afc`
  - Stack repositioned each time program executes



2) 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



3) Stack Canaries

- Basic Idea: place special value ("canary") on stack just beyond buffer
  - *Secret* value known only to compiler
  - "After" buffer but before return address
  - Check for corruption before exiting function
- GCC implementation (now default)
  - `-fstack-protector`
  - Code back on Slide 14 (`buf-nsp`) compiled with `-fno-stack-protector` flag

```
unix>./buf
Enter string: 12345678
12345678
```

```
unix> ./buf
Enter string: 123456789
*** stack smashing detected ***
```

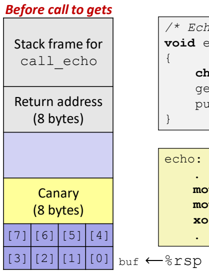
Protected Buffer Disassembly (`buf`)

echo:

```
  400638:  sub    $0x18,%rsp
  40063c:  mov    %fs:0x28,%rax
  400645:  mov    %rax,0x8(%rsp)
  40064a:  xor    %eax,%eax
   ...          ... call printf ...
  400656:  mov    %rsp,%rdi
  400659:  callq  400530 <gets@plt>
  40065e:  mov    %rsp,%rdi
  400661:  callq  4004e0 <puts@plt>
  400666:  mov    0x8(%rsp),%rax
  40066b:  xor    %fs:0x28,%rax
  400674:  je     40067b <echo+0x43>
  400676:  callq  4004f0 <__stack_chk_fail@plt>
  40067b:  add    $0x18,%rsp
  40067f:  retq
```

Setting Up Canary

Before call to gets



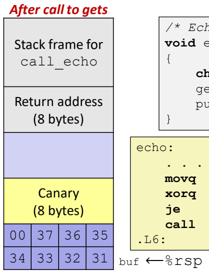
```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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

After call to gets



```
/* 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
    je      .L2                # if same, OK
    call    __stack_chk_fail   # else, FAIL
.L6:        . . .
```

Input: *1234567*

Summary

1) Avoid overflow vulnerabilities
   - Use library routines that limit string lengths

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

3) Have compiler use "stack canaries"