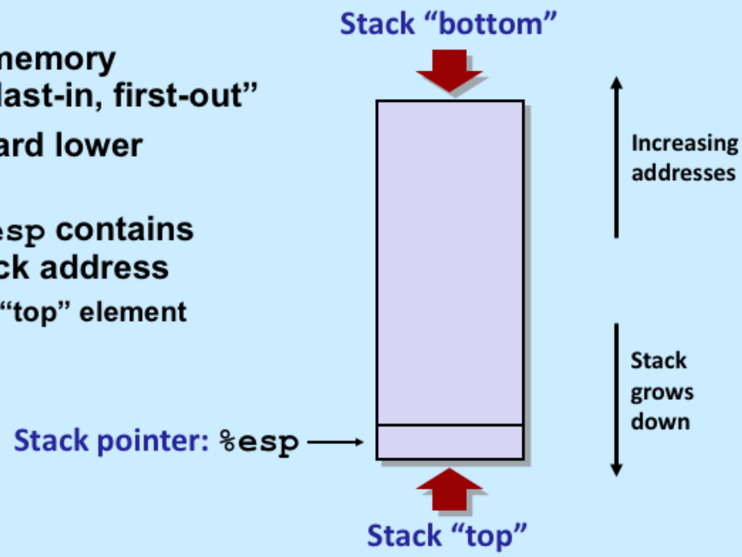
CS 33

Machine Programming (3)

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.

IA32 Stack

- Region of memory managed "last-in, first-out"
- Grows toward lower addresses
- Register `%esp` contains lowest stack address
  - address of "top" element



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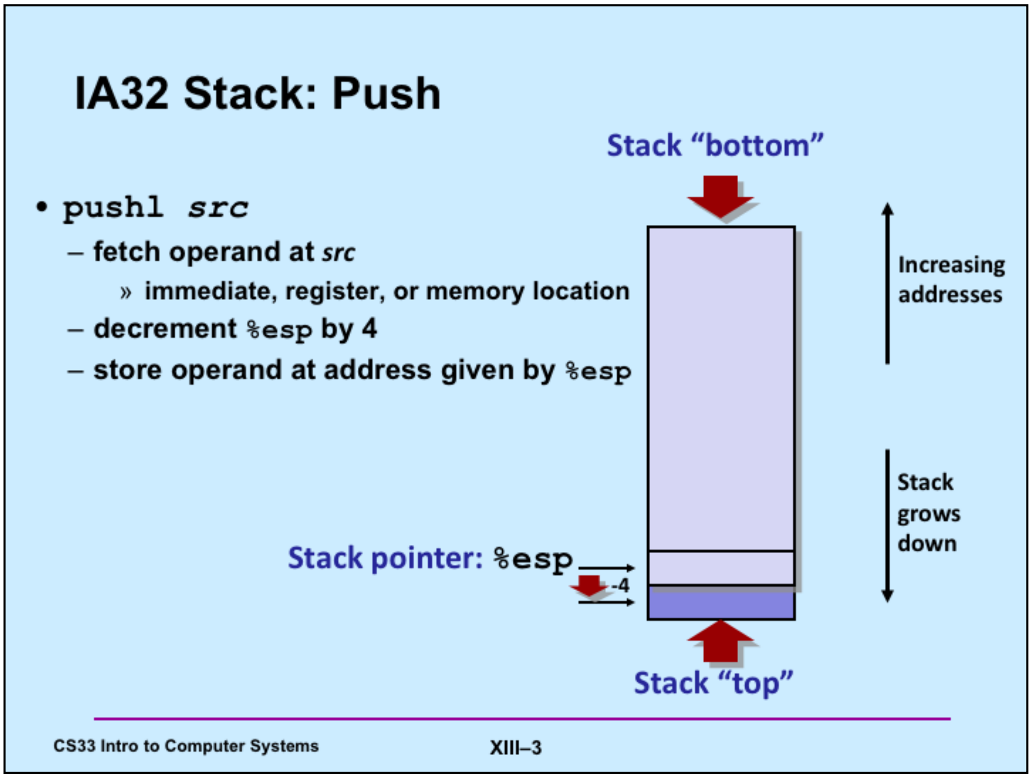

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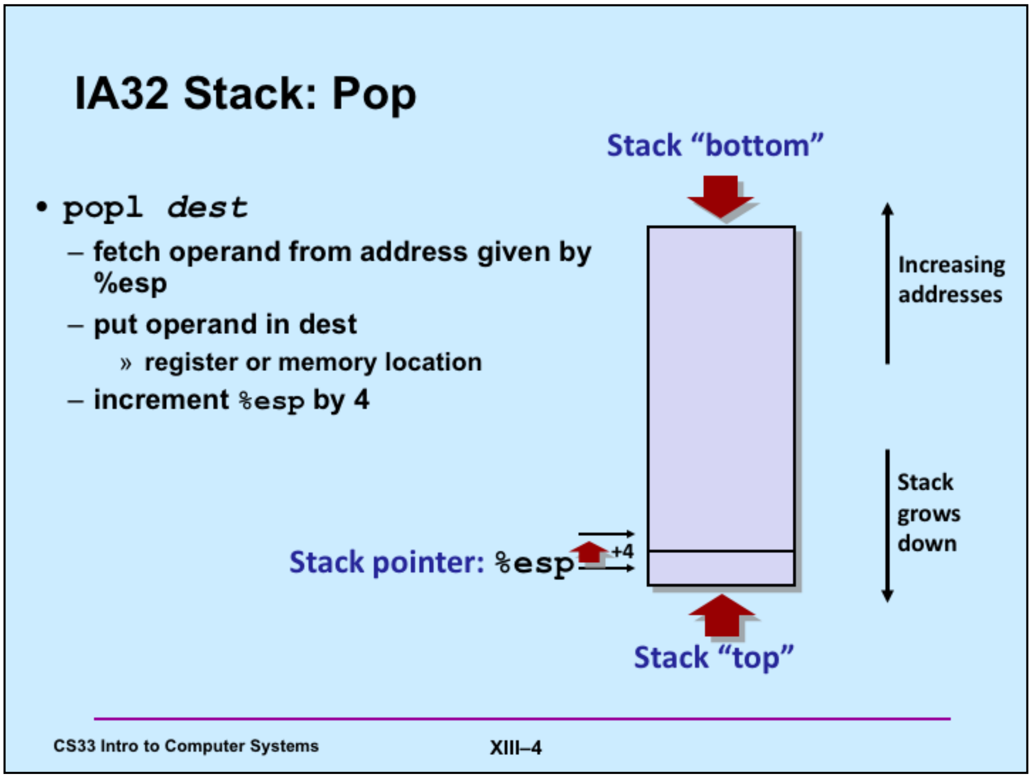

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Procedure Control Flow

- Use stack to support procedure call and return
- Procedure call: `call sub`
  - push return address on stack
  - jump to *sub*
- Return address:
  - address of the next instruction after call
  - example from disassembly

```
804854e:  e8 3d 06 00 00     call   8048b90 <sub>
8048553:  50                 pushl  %eax
```

  - return address = `0x8048553`
- Procedure return: `ret`
  - pop address from stack
  - jump to address

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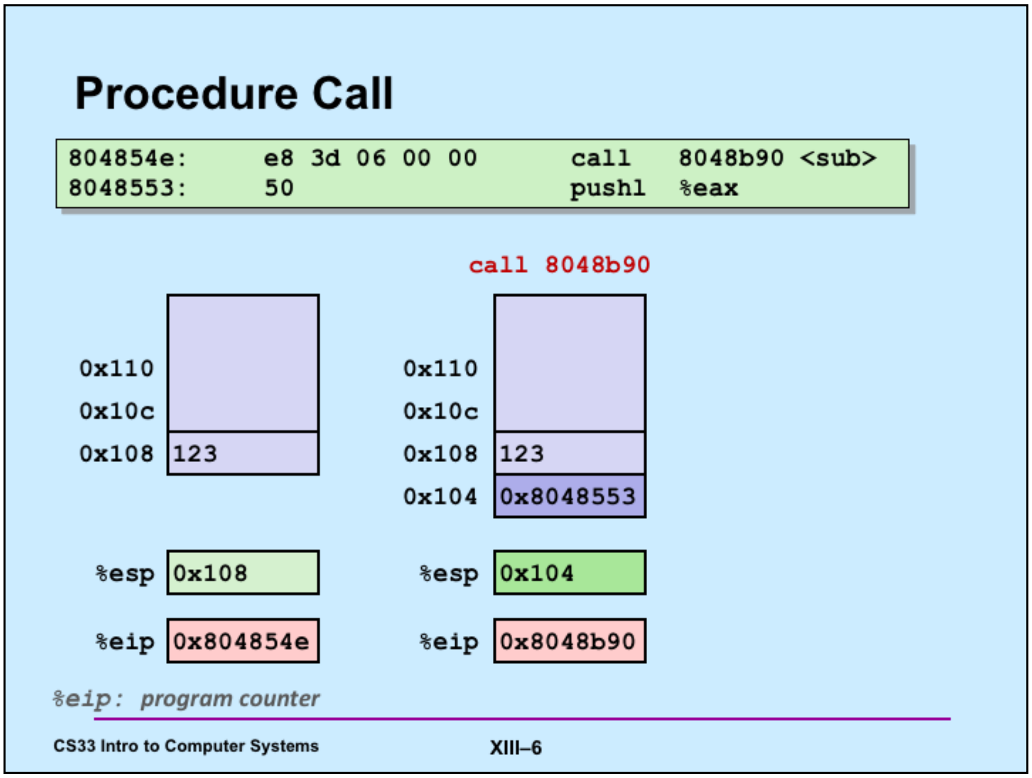

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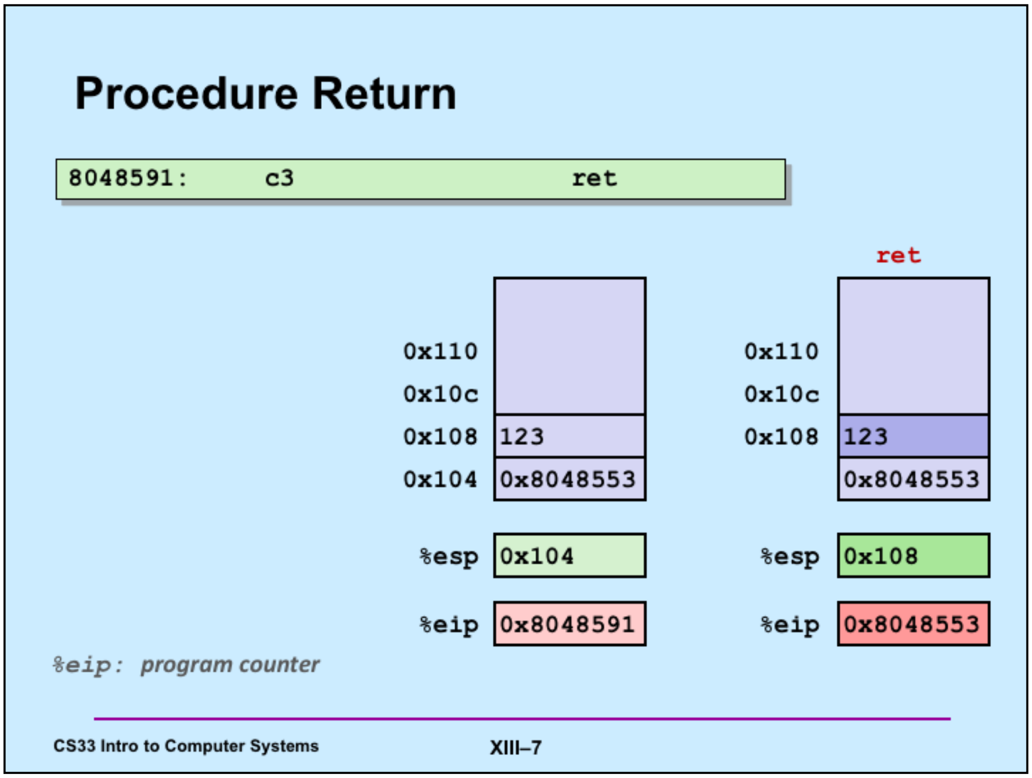

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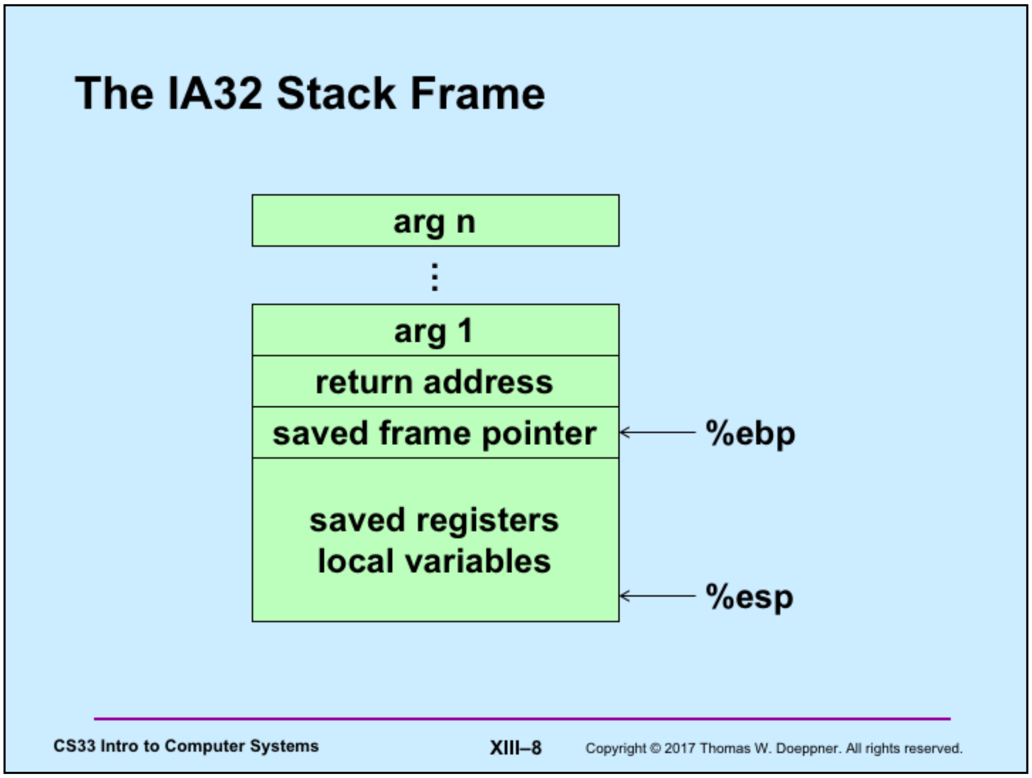
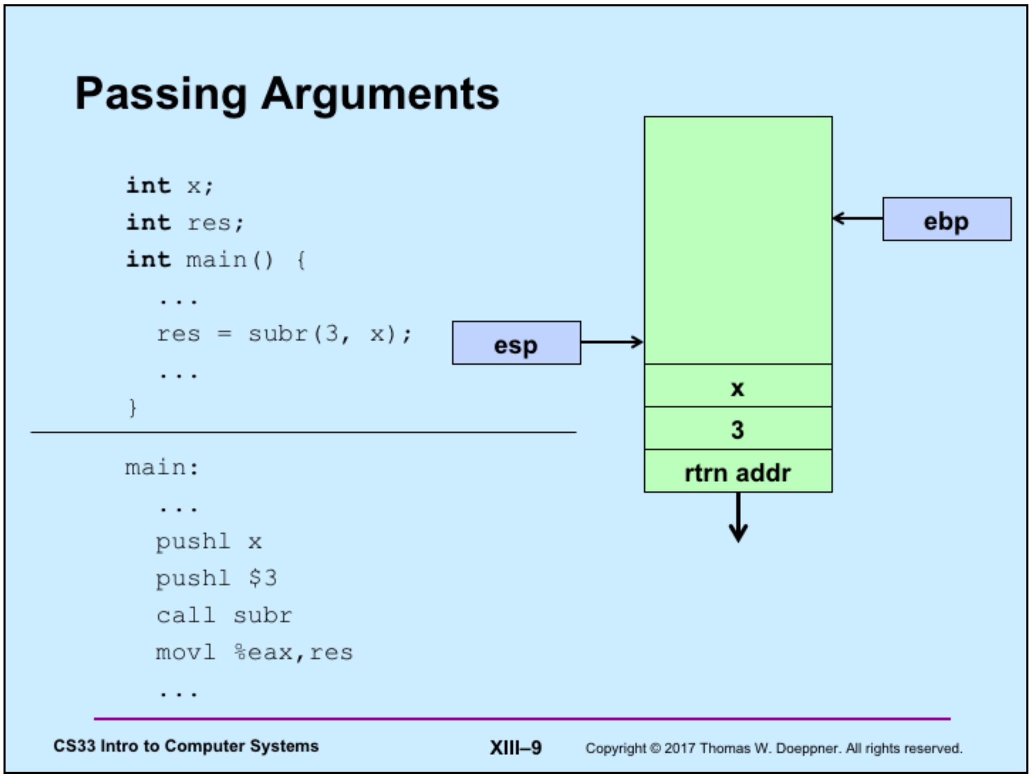
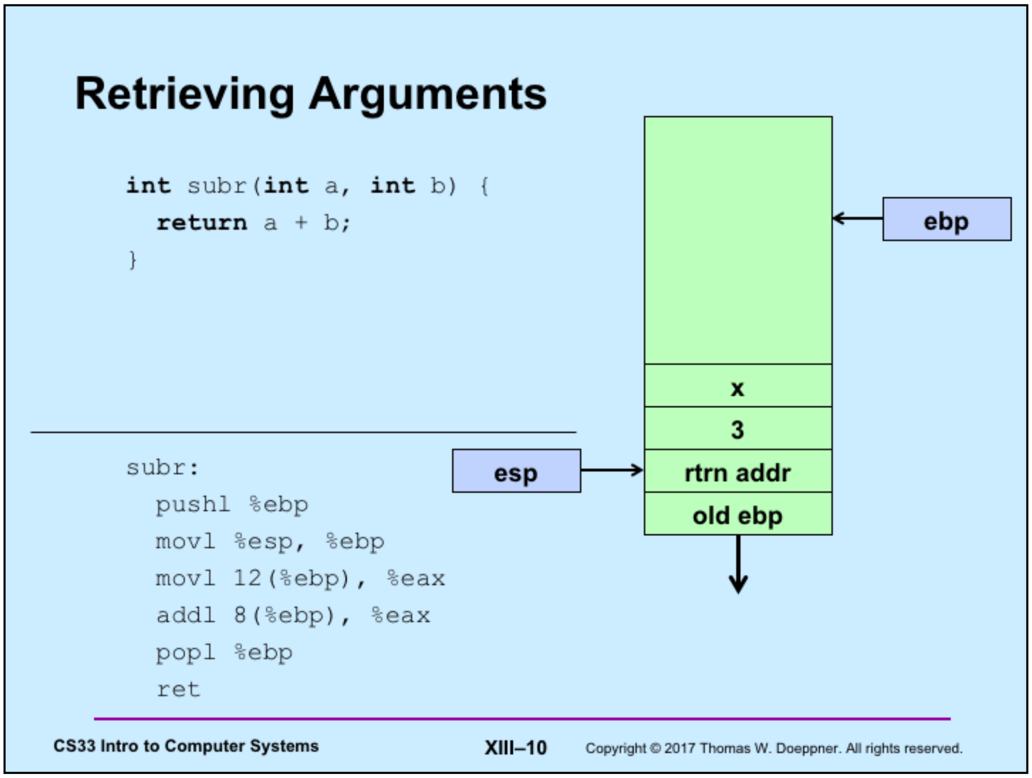


For the IA32 architecture, each function's stack frame is organized as in the slide. %ebp, sometimes called the base pointer, but more generically the frame pointer, points to a standard offset within stack frame. It's used to refer to the arguments pushed into the caller's stack frame as well as to local variables, etc., pushed into the function's stack frame.

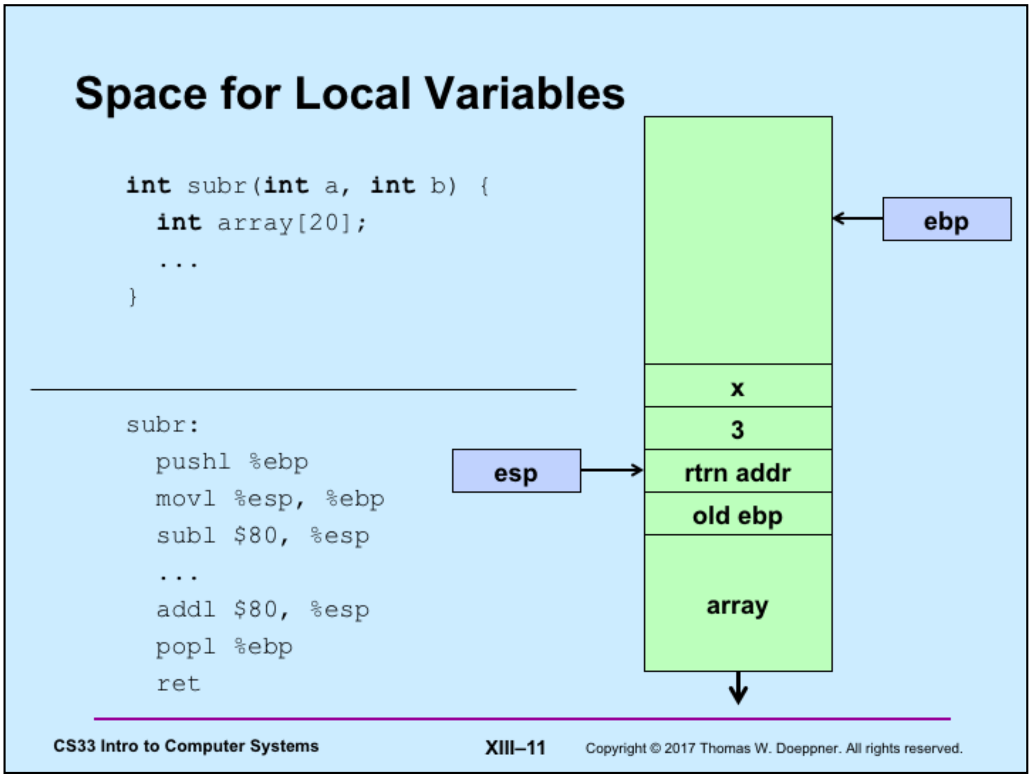


The convention for the IA32 architecture is for the caller of a function to push its arguments on the stack in reverse order. It then calls the function, which has the effect of pushing the return address (the address of the instruction following the call) onto the stack.

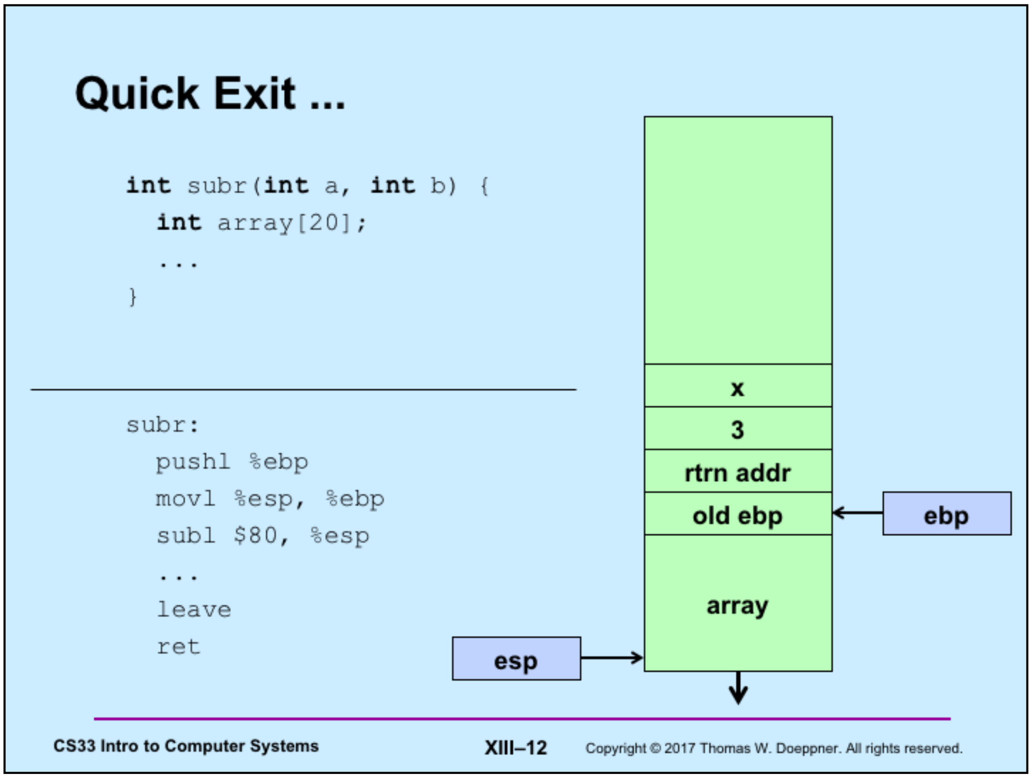


Again, following the IA32 convention, the first think a function does is to push the contents of %ebp onto the stack, thus saving the pointer to the caller's stack frame. It then copies the current stack pointer (%esp) into %ebp, so that %ebp now refers to the current stack frame. Having done this, the function can now refer to its arguments via offsets from %ebp.

When the function is ready to return to its caller, it first pops off the stack the copy of the caller's %ebp that was pushed onto the stack, replacing the current contents of %ebp with this saved value. This has the effect of making the caller's stack frame the current frame. Next the function calls *ret*, which pops the return address off the stack and sets %eip (the instruction pointer) to that value, causing control to return to the caller at the instruction following the call instruction.



If the function has local variables, these are allocated on the stack by decrementing the stack pointer to account for the space needed, and then popped of the stack when the function returns by adding the space occupied back to the stack pointer.



The *leave* instruction causes the contents of ebp to be copied into esp, thereby removing everything from the stack that had been pushed into the frame. It then pops the current stack top (the old ebp) into the ebp register. The effect of *leave* is thus to return to the caller's stack frame.

There is an *enter* instruction that has the same effect as that of the first three instructions of subr combined (it has an operand that indicates how much space for local variables to allocate). However, it's not used by gcc, apparently because it's slower than doing it as shown in the slide.

Register-Saving Conventions

- When procedure `yoo` calls `who`:
  - `yoo` is the *caller*
  - `who` is the *callee*
- Can registers be used for temporary storage?

```
yoo:
    • • •
    movl $33, %edx
    call who
    addl %edx, %eax
    • • •
    ret
```

```
who:
    • • •
    movl 8(%ebp), %edx
    addl $32, %edx
    • • •
    ret
```

  - contents of register `%edx` overwritten by `who`
  - this could be trouble: something should be done!
    - » need some coordination

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Register-Saving Conventions

- **When procedure `yoo` calls `who`:**
  - `yoo` is the *caller*
  - `who` is the *callee*
- **Can registers be used for temporary storage?**
- **Conventions**
  - *"caller save"*
    - » caller saves registers containing temporary values on stack before the call
    - » restores them after call
  - *"callee save"*
    - » callee saves registers on stack before using
    - » restores them before returning

Supplied by CMU.

IA32/Linux+Windows Register Usage

- `%eax`, `%edx`, `%ecx`
  - caller saves prior to call if values are used later
- `%eax`
  - also used to return integer value
- `%ebx`, `%esi`, `%edi`
  - callee saves if wants to use them
- `%esp`, `%ebp`
  - special form of callee-save
  - restored to original values upon exit from procedure

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Register-Saving Example

```
yoo:
   . . .
   movl $33, %edx
   pushl %edx
   call who
   popl %edx
   addl %edx, %eax
   . . .
   ret
```

```
who:
   . . .
   pushl %ebx
   . . .
   movl 4(%ebp), %ebx
   addl %53, %ebx
   movl 8(%ebp), %edx
   addl $32, %edx
   . . .
   popl %ebx
   . . .
   ret
```


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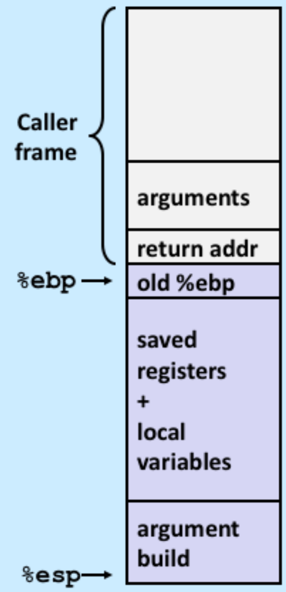
Quiz 1

- **The leave instruction copies the current value of %ebp into %esp. It's followed by a ret instruction. Does this approach for returning from a procedure work if there are saved registers in the stack frame?**
  a) always
  b) usually
  c) never



Recursive Function

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

- **Registers**
  - %eax, %edx used without first saving
  - %ebx used, but saved at beginning & restored at end

```
pcount_r:
    pushl  %ebp
    movl   %esp, %ebp
    pushl  %ebx
    subl   $4, %esp
    movl   8(%ebp), %ebx
    movl   $0, %eax
    testl  %ebx, %ebx
    je     .L3
    movl   %ebx, %eax
    shrl   $1, %eax
    movl   %eax, (%esp)
    call   pcount_r
    movl   %ebx, %edx
    andl   $1, %edx
    leal   (%edx,%eax), %eax
.L3:
    addl   $4, %esp
    popl   %ebx
    popl   %ebp
    ret
```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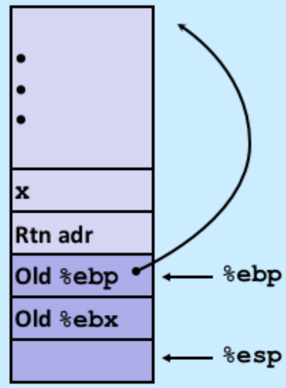
Recursive Call #1

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
pcount_r:
    pushl %ebp
    movl %esp, %ebp
    pushl %ebx
    subl $4, %esp
    movl 8(%ebp), %ebx
     • • •
```

- Actions
  - save old value of `%ebx` on stack
  - allocate space for argument to recursive call
  - store x in `%ebx`



`%ebx` x

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Recursive Call #2

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
     • • •
    movl   $0, %eax
    testl %ebx, %ebx
    je   .L3
     • • •
.L3:
     • • •
    ret
```

- **Actions**
  - if x == 0, return
    - » with `%eax` set to 0

`%ebx` | x

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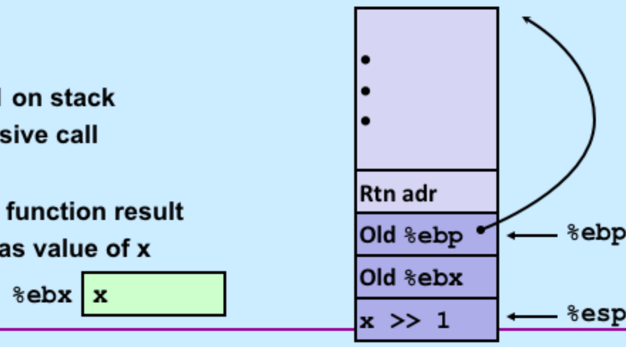
Recursive Call #3

```c
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
 • • •
movl   %ebx, %eax
shrl   $1, %eax
movl   %eax, (%esp)
call   pcount_r
 • • •
```

- Actions
  - store x >> 1 on stack
  - make recursive call
- Effect
  - %eax set to function result
  - %ebx still has value of x



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Recursive Call #4

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
  • • •
movl    %ebx, %edx
andl    $1, %edx
leal   (%edx,%eax), %eax
  • • •
```

- **Assume**
  - `%eax` holds value from recursive call
  - `%ebx` holds x
- **Actions**
  - compute (x & 1) + computed value
- **Effect**
  - `%eax` set to function result

%ebx	x

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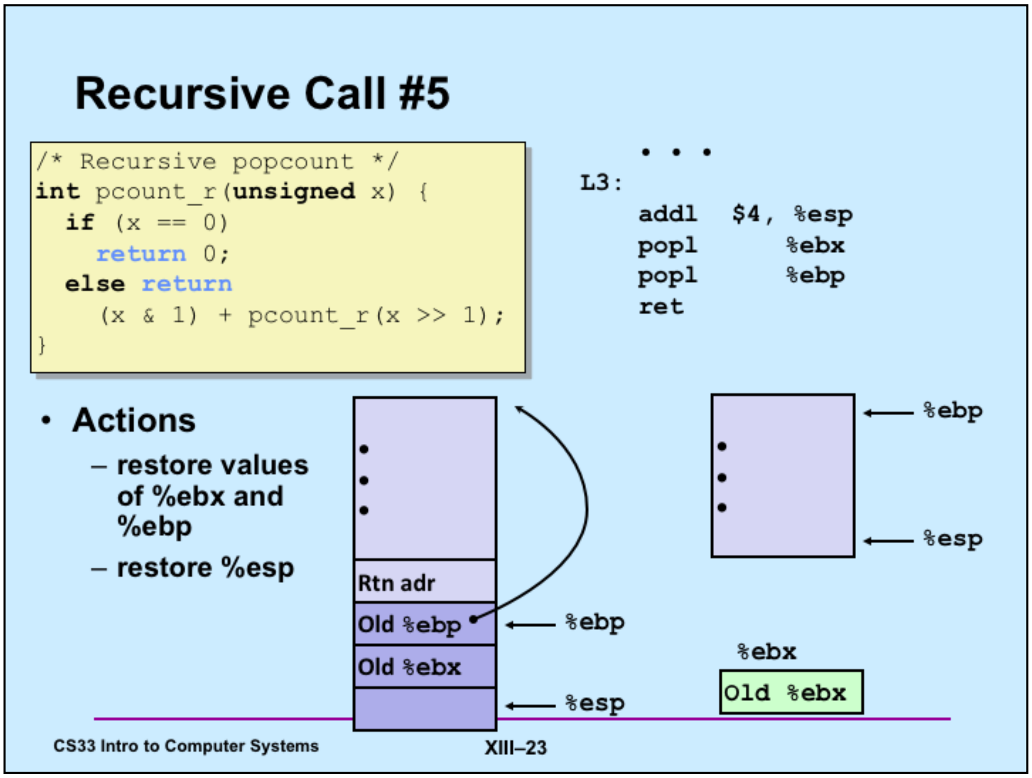

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Observations About Recursion

- Handled without special consideration
  - stack frames mean that each function call has private storage
    - saved registers & local variables
    - saved return pointer
  - register-saving conventions prevent one function call from corrupting another's data
  - stack discipline follows call / return pattern
    - if P calls Q, then Q returns before P
    - last-in, first-out
- Also works for mutual recursion
  - P calls Q; Q calls P

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Why Bother with a Frame Pointer?

- It 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 frame pointer is superfluous
  - it can be used as a general-purpose register

Note that "frame pointer" is synonymous with "base pointer".

x86-64 General-Purpose Registers: 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

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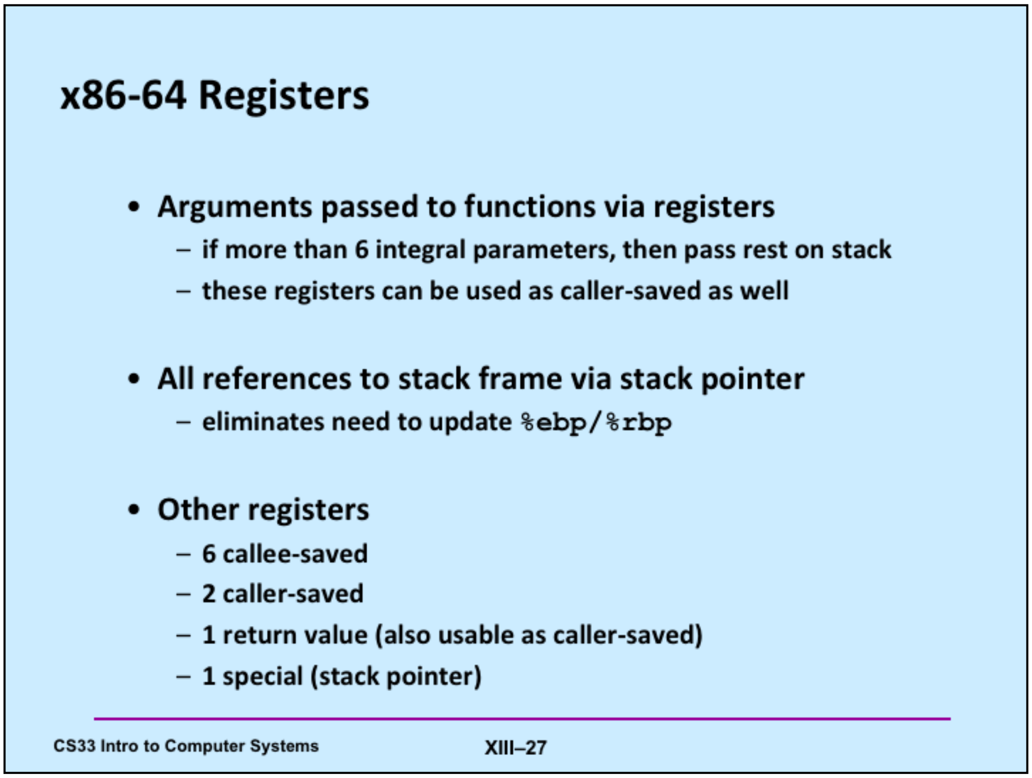

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Note that the *leave* instruction is no longer relevant, since %rbp does not contain the address of the stack frame.

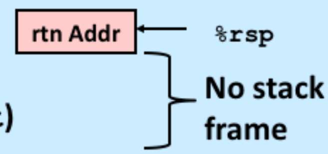
Also note that the conventions shown in the slide are those adopted by gcc on Linux; they aren't necessarily used by other compilers or on other operating systems. Even gcc doesn't use these conventions if optimization is completely turned off (in which case arguments are passed on the stack, just as for IA32).

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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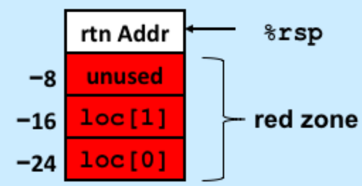
Note that *swap_l* is a *leaf* function, meaning that it does not call other functions.

x86-64 Locals in the Red Zone

```
/* Swap, using local array */
void swap_a(long *xp, long *yp)
{
    volatile long loc[2];
    loc[0] = *xp;
    loc[1] = *yp;
    *xp = loc[1];
    *yp = loc[0];
}
```

```
swap_a:
  movq  (%rdi), %rax
  movq  %rax, -24(%rsp)
  movq  (%rsi), %rax
  movq  %rax, -16(%rsp)
  movq  -16(%rsp), %rax
  movq  %rax, (%rdi)
  movq  -24(%rsp), %rax
  movq  %rax, (%rsi)
  ret
```

- **Avoiding stack-pointer change**
  - can hold all information within small window beyond stack pointer
    - » 128 bytes
    - » “red zone”



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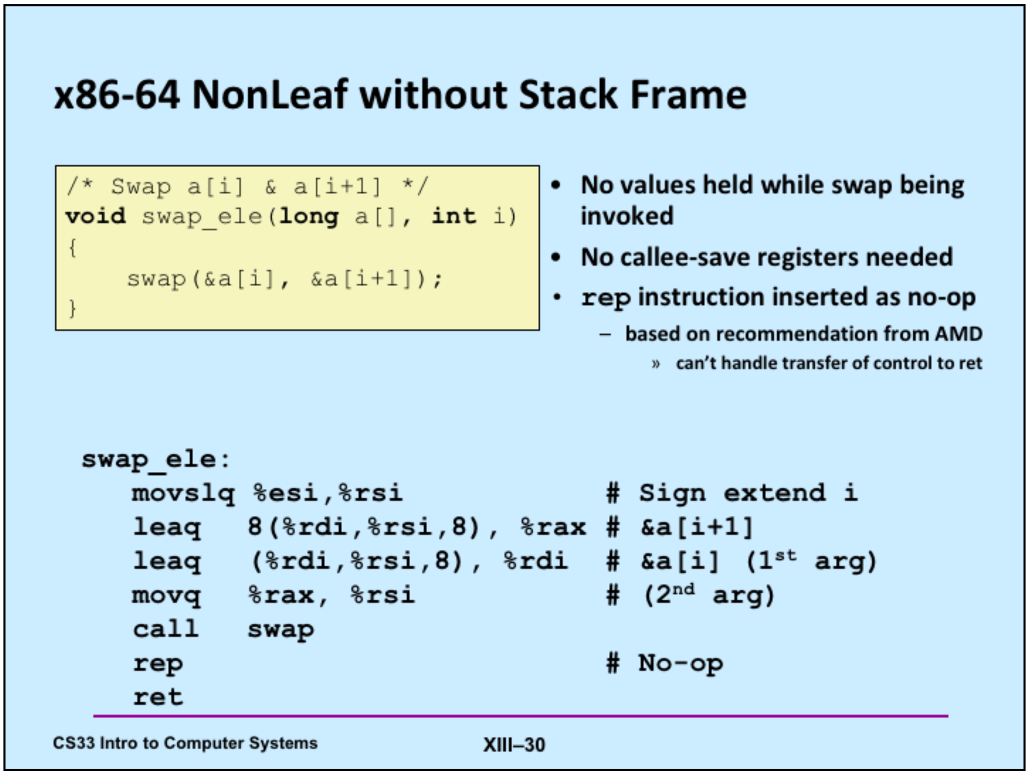
The *volatile* keyword tells the compiler that it may not perform optimizations on the associated variable such as storing it strictly in registers and not in memory. It’s used primarily in cases where the variable might be modified via other routines that aren’t apparent when the current code is being 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.



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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 0x0000000008888888. 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]);
}
```

```
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
```

- **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

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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
```


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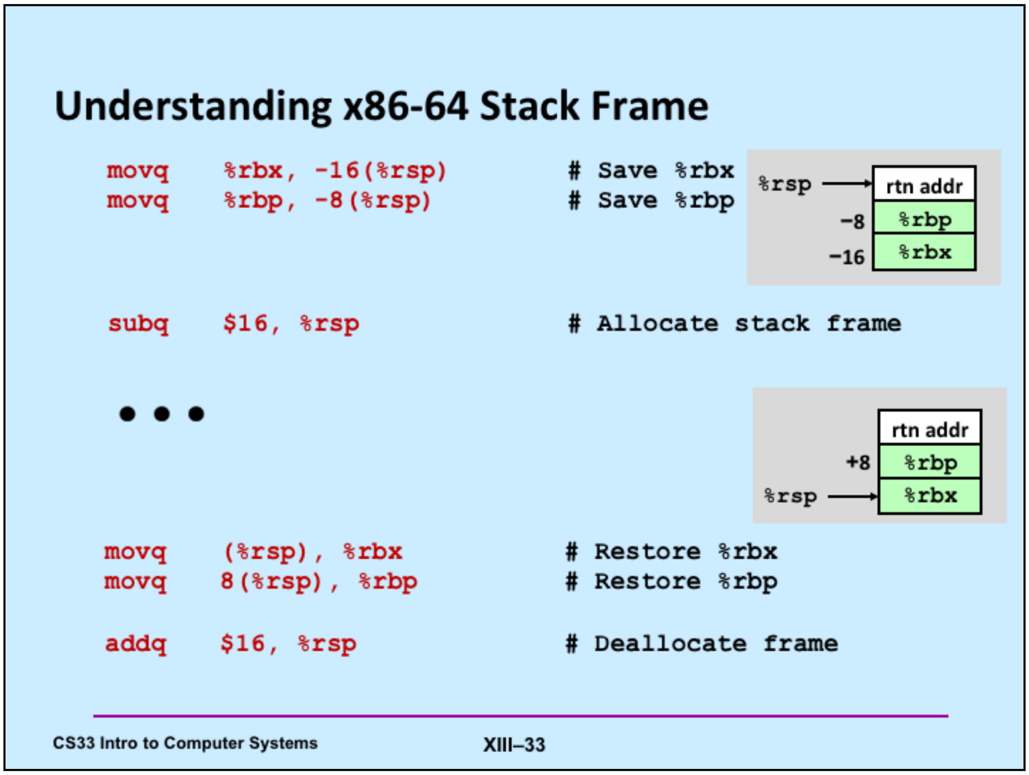

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Quiz 2

```
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);
}
```

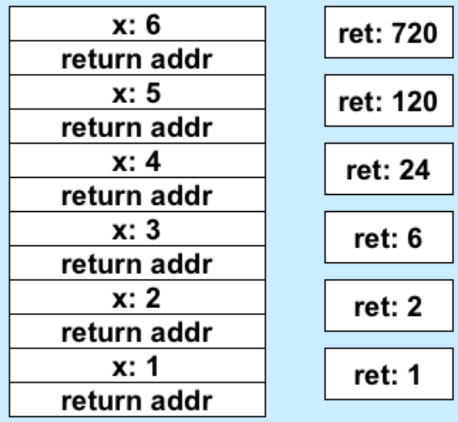

The slide shows two implementations of the factorial function. Both use recursion. In the version on the left, the result of each recursive call is used within the invocation that issued the call. In the second, the result of each recursive call is simply returned. This is known as *tail recursion*.

No Tail Recursion (1)

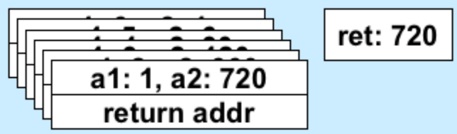
x: 6
return addr
x: 5
return addr
x: 4
return addr
x: 3
return addr
x: 2
return addr
x: 1
return addr

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.

Code: gcc –O2

```
f2:
        cmpl    $1, %edi
        movl    %esi, %eax
        je      .L8
.L12:
        imull   %edi, %eax
        subl    $1, %edi
        cmpl    $1, %edi
        jne     .L12
.L8:
        rep
        ret
```

loop!

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.