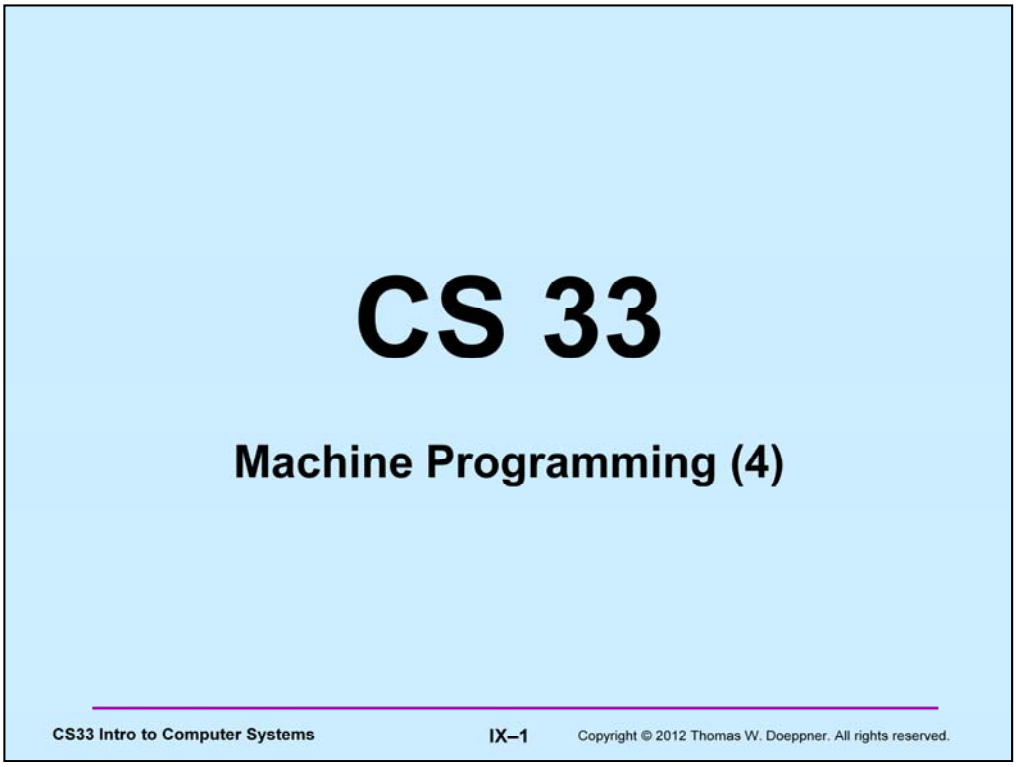
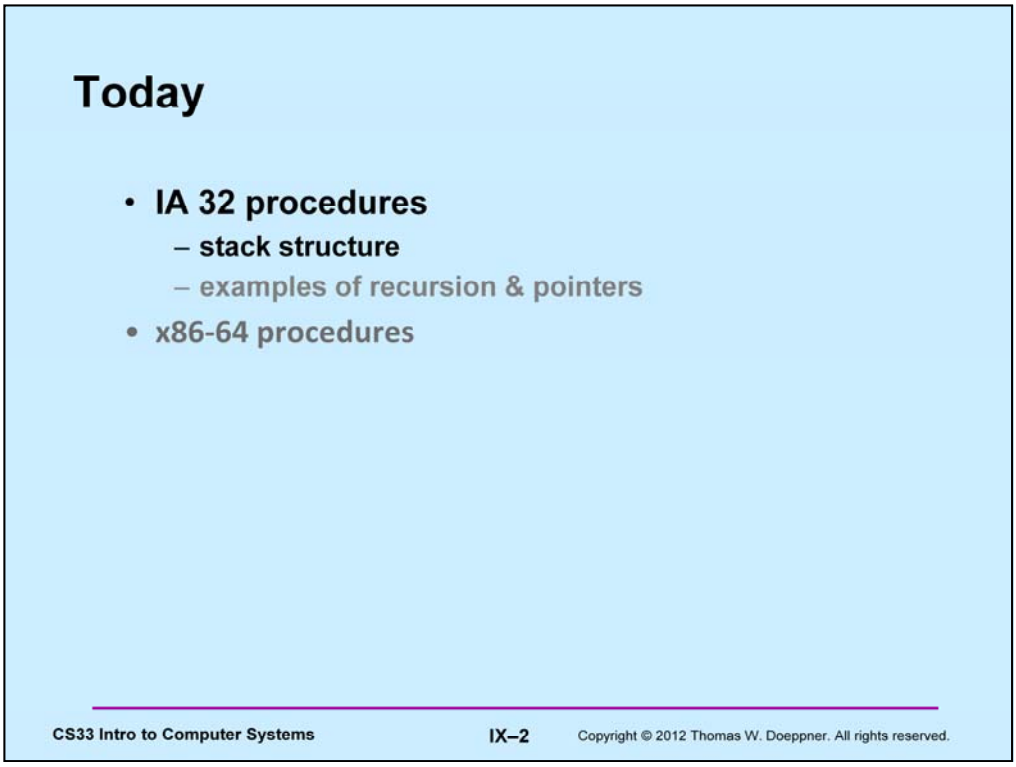


Many of the slides in this lecture are either from or adapted from slides provided by the authors of the textbook "Computer Systems: A Programmer's Perspective," 2nd Edition and are provided from the website of Carnegie-Mellon University, course 15-213, taught by Randy Bryant and David O'Hallaron in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



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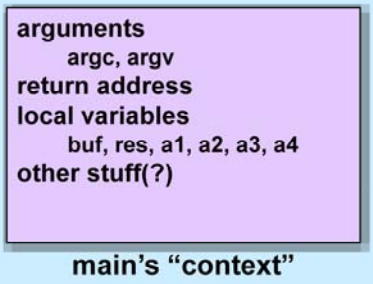
Stacks and Procedures (1)

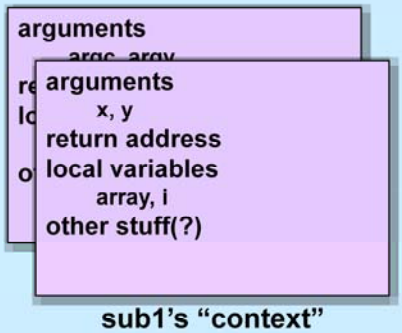
```
int main(int argc, char *argv[]) {
  char buf[1024];
  int res, a1, a2, a3, a4;

  ...

  res = sub1(a1, a2);
  a3 = res +1;

  ...

  res = sub2(a2, a3, a4);
  res += 6;

  ...

  return 0;
}
```



main's "context"

Stacks and Procedures (2)

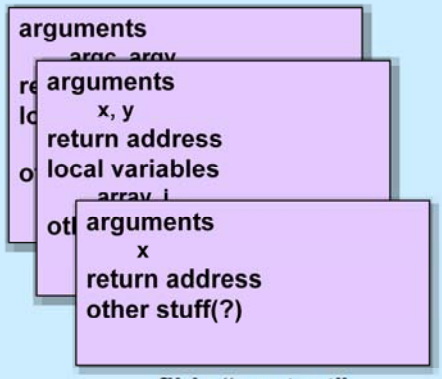
```
int sub1(int x, int y) {
  int array[24];
  int i;

  ...

  for (i=0; i<24; i++)
    array[i] = fib[i];

  ...

  return sub10(24, array);
}
```



sub1's "context"

Stacks and Procedures (3)

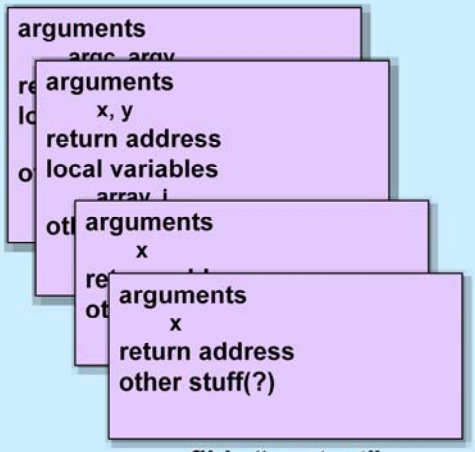
```
int fib(int x) {
  if (x < 2)
    return x;
  else
    return fib(x-1)+fib(x-2);
}
```



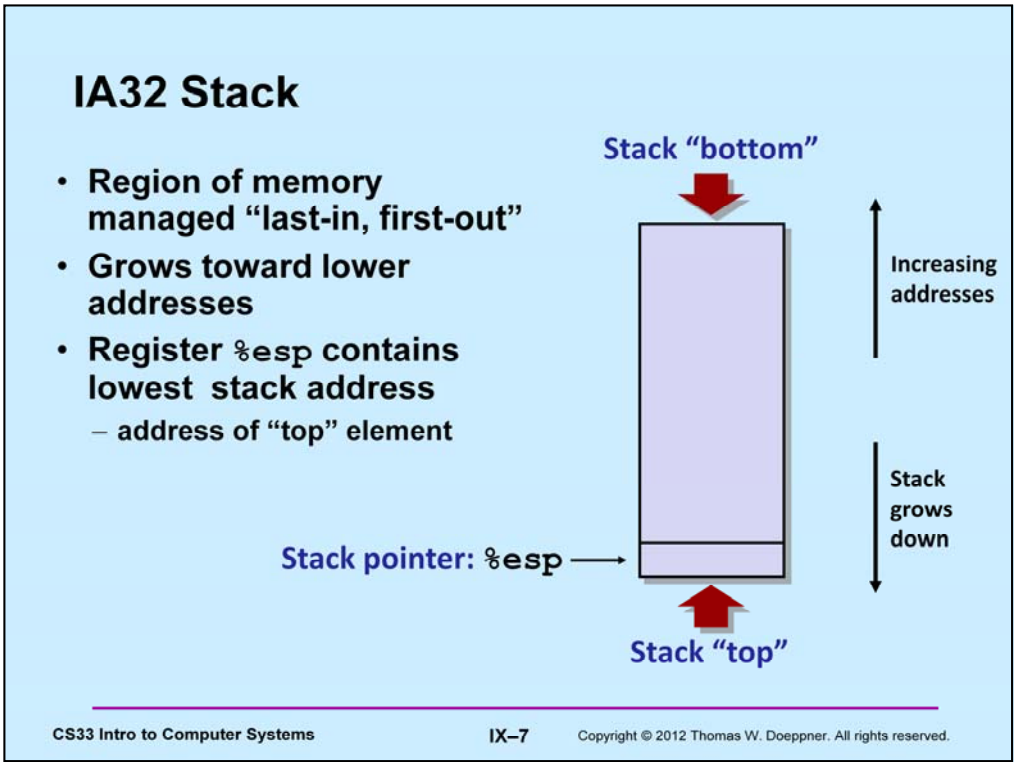
fib's "context"

Stacks and Procedures (4)

```
int fib(int x) {
  if (x < 2)
    return x;
  else
    return fib(x-1)+fib(x-2);
}
```



fib's "context"



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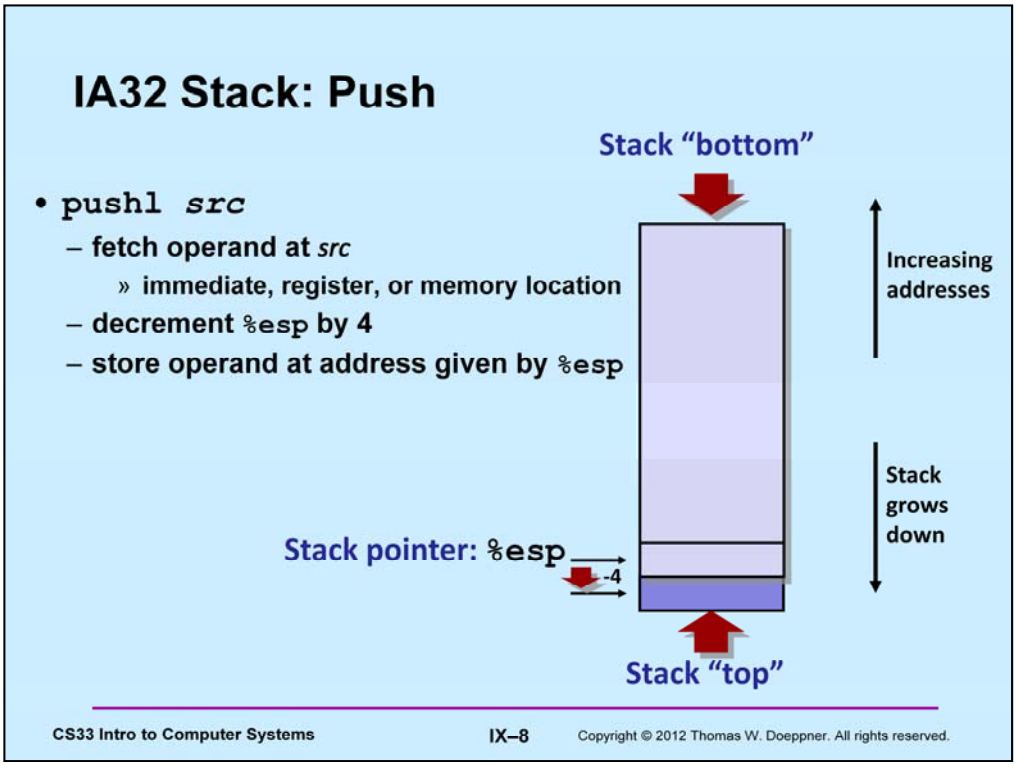

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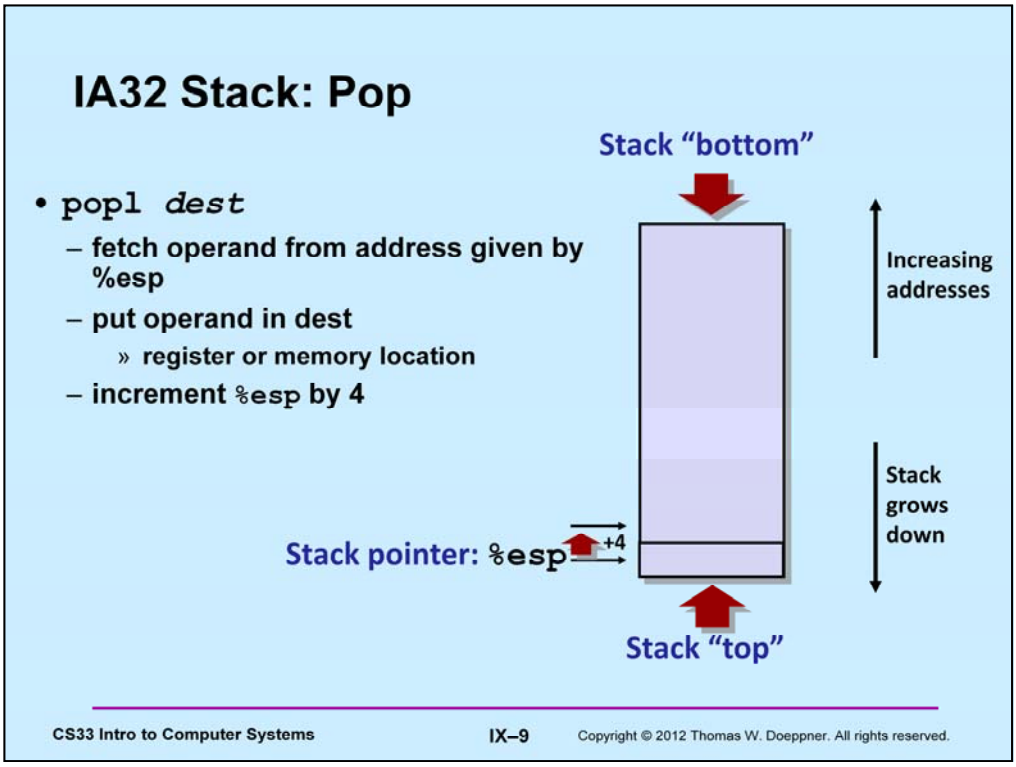

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Procedure Control Flow

- 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 right 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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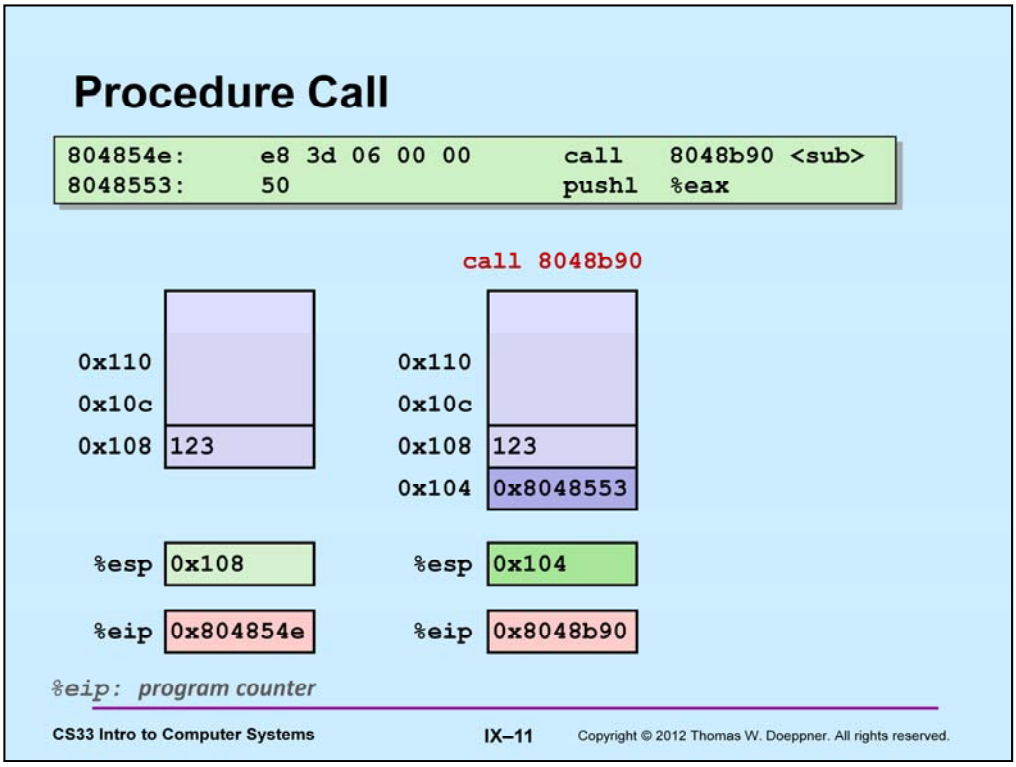

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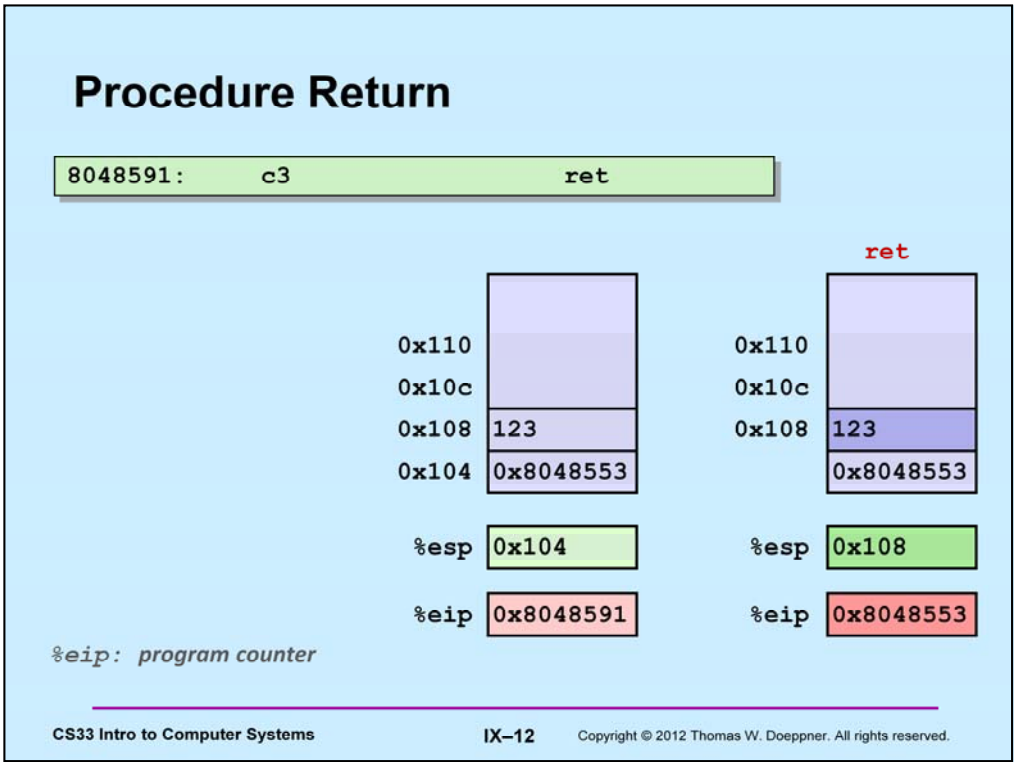

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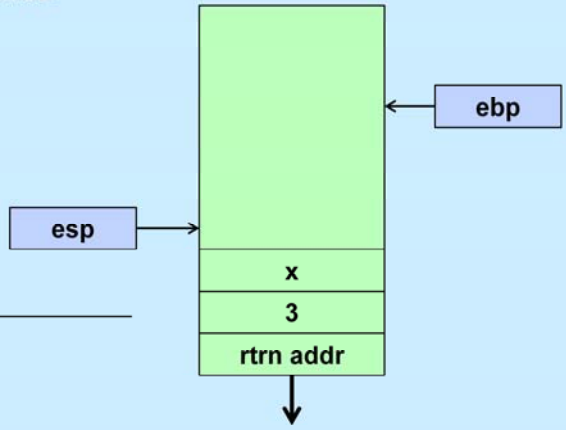
Passing Arguments

```
int x;
int res;
int main() {
  ...
  res = subr(3, x);
  ...
}
```

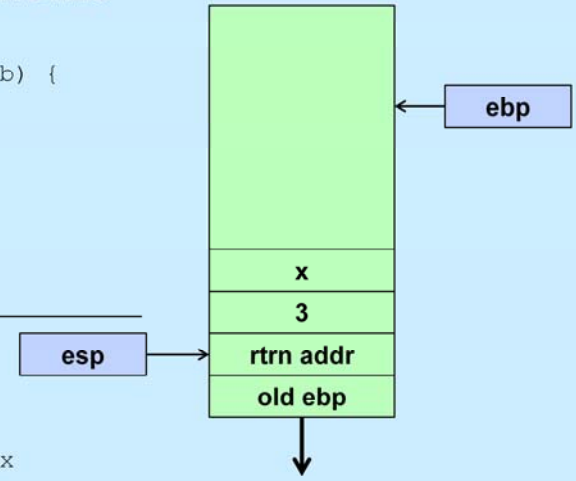
```
main:
  ...
  pushl x
  pushl $3
  call subr
  movl %eax,res
  ...
```



Retrieving Arguments

```
int subr(int a, int b) {
  return a + b;
}
```

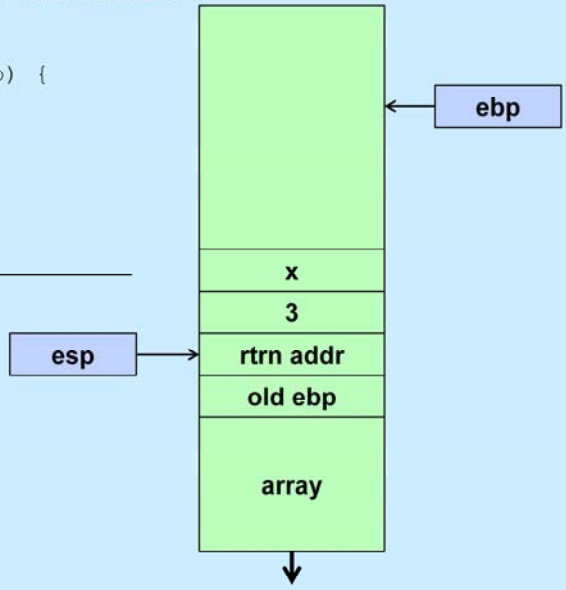
```
subr:
  pushl %ebp
  movl %esp, %ebp
  movl 12(%ebp), %eax
  addl 8(%ebp), %eax
  popl %ebp
  ret
```

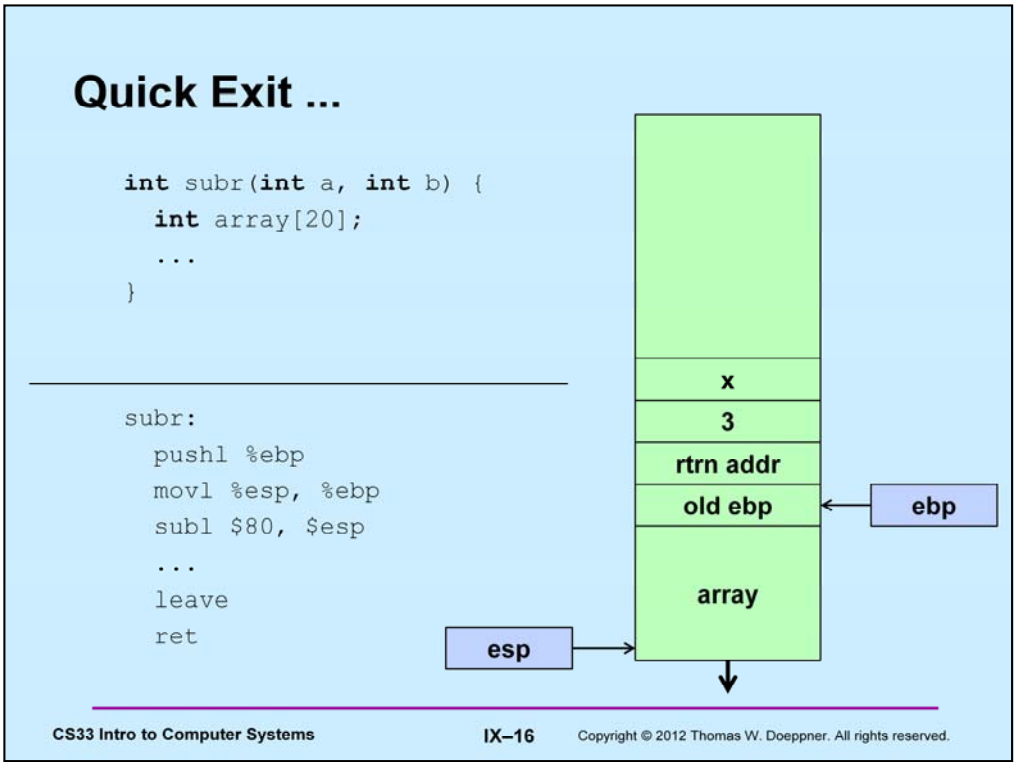


Space for Local Variables

```
int subr(int a, int b) {
  int array[20];
  ...
}
```

```
subr:
  pushl %ebp
  movl %esp, %ebp
  subl $80, $esp
  ...
  addl $80, $esp
  popl %ebp
  ret
```





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 register be used for temporary storage?
- Conventions
  - *"caller save"*
    - » caller saves temporary values on stack before the call
    - » restores them after call
  - *"callee save"*
    - » callee saves temporary values on stack before using
    - » restores them before returning

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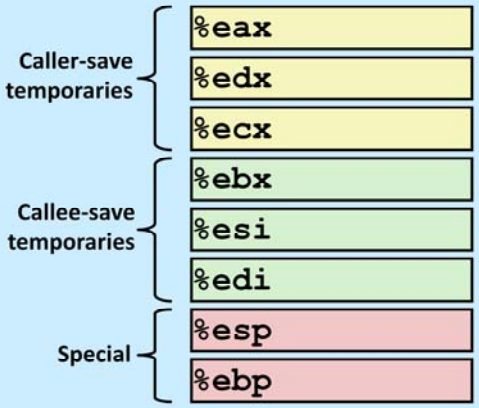
IA32/Linux+Windows Register Usage

- %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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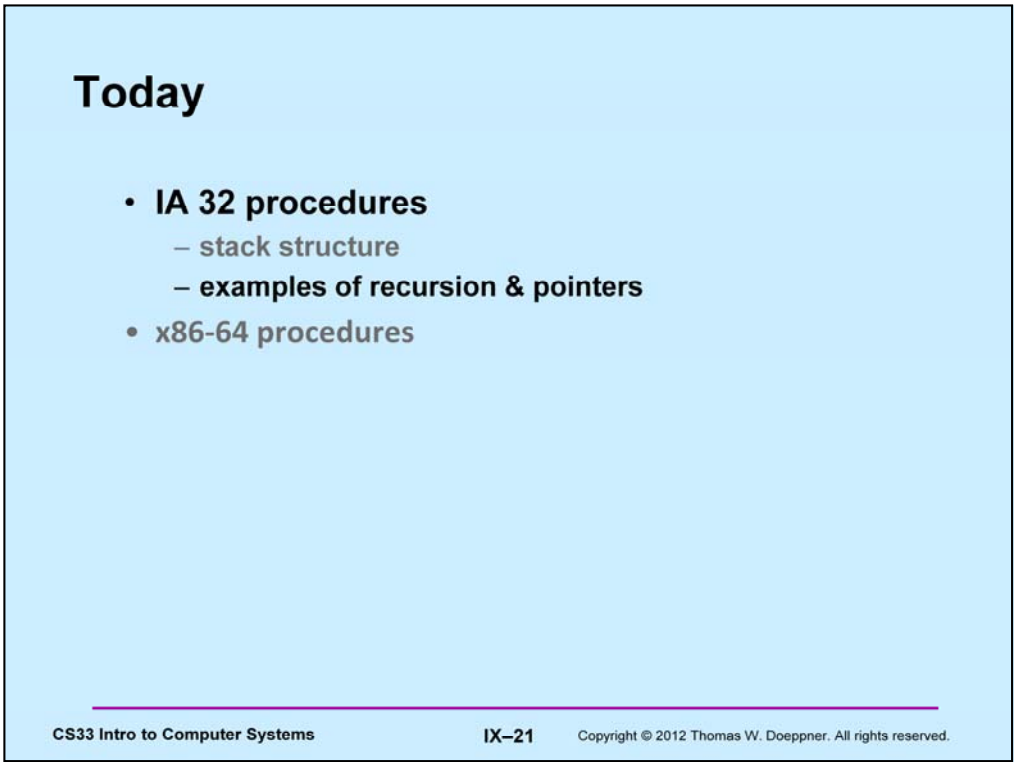

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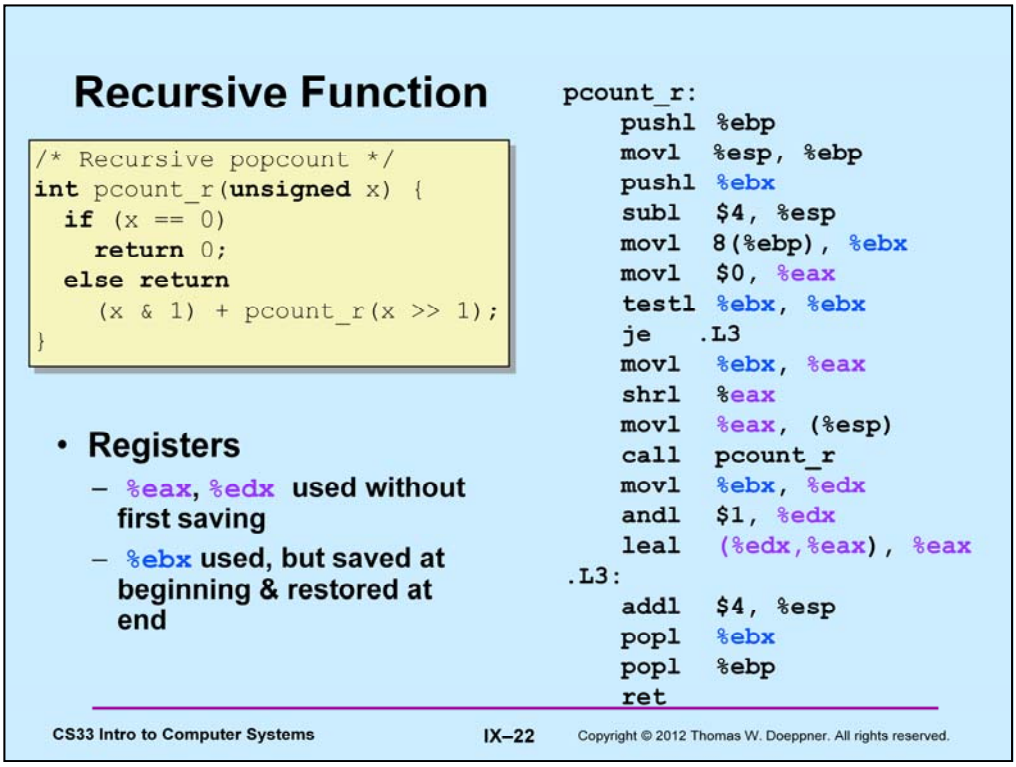

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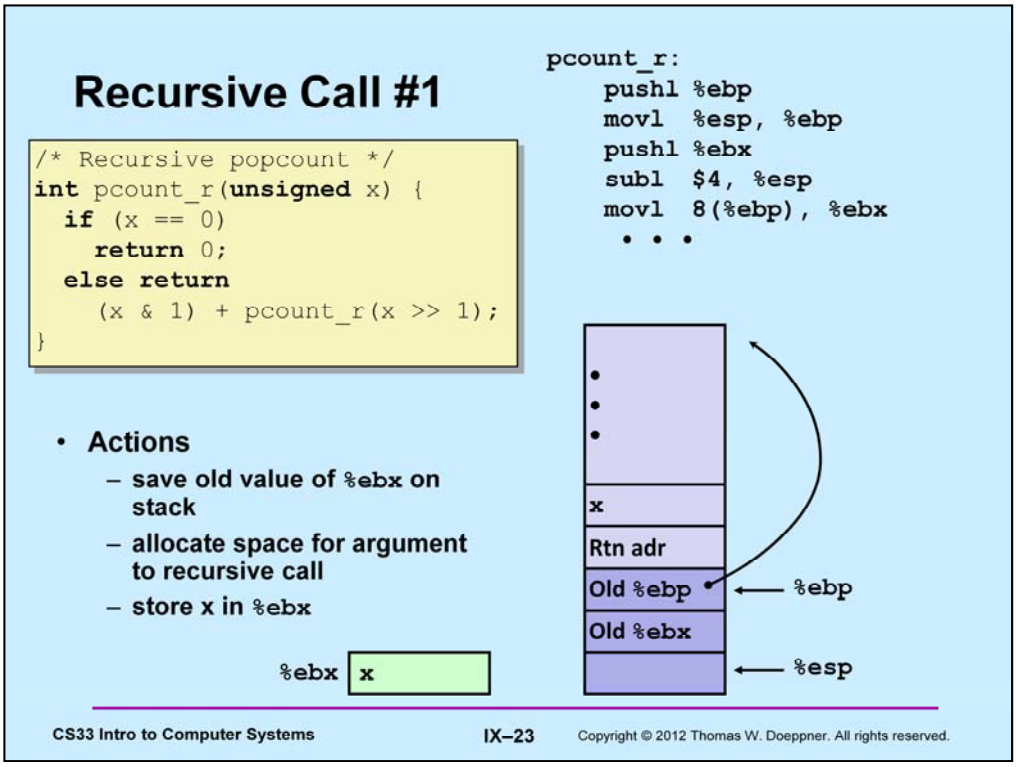

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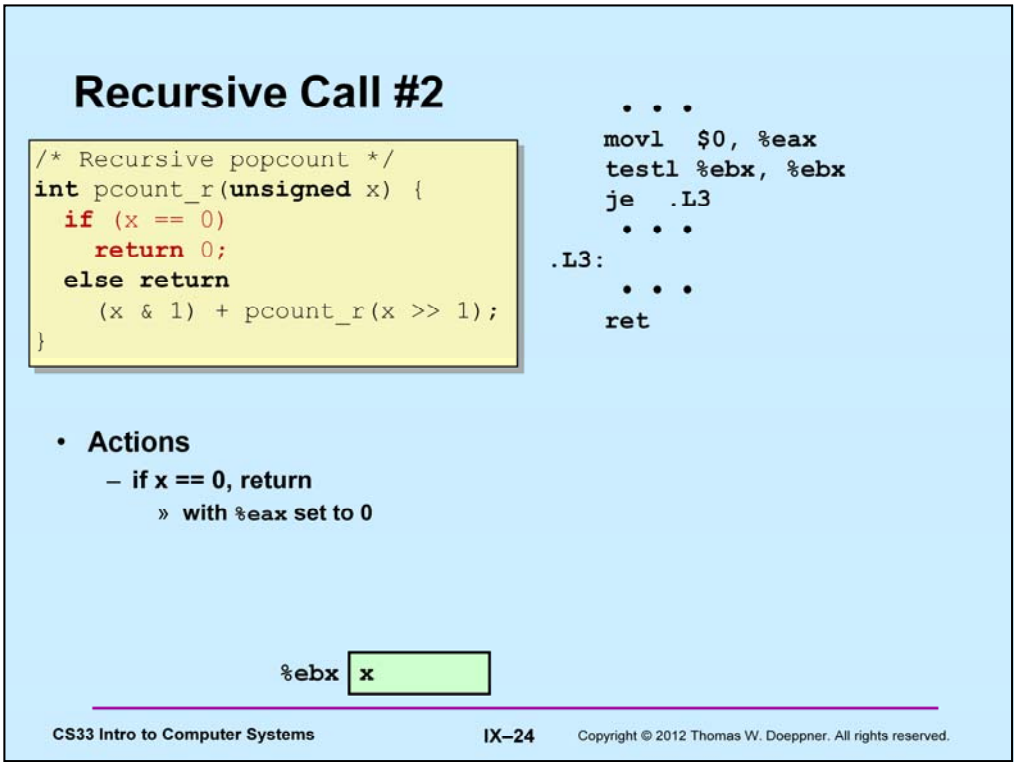

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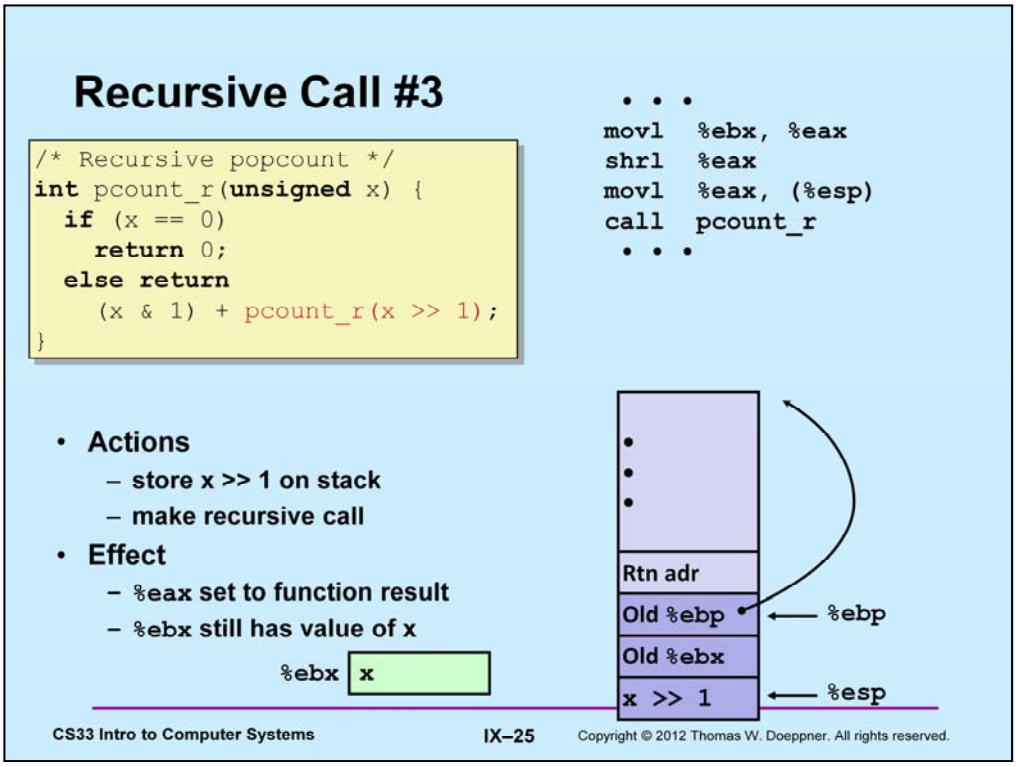

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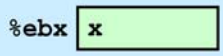
Recursive Call #4

```
/* 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



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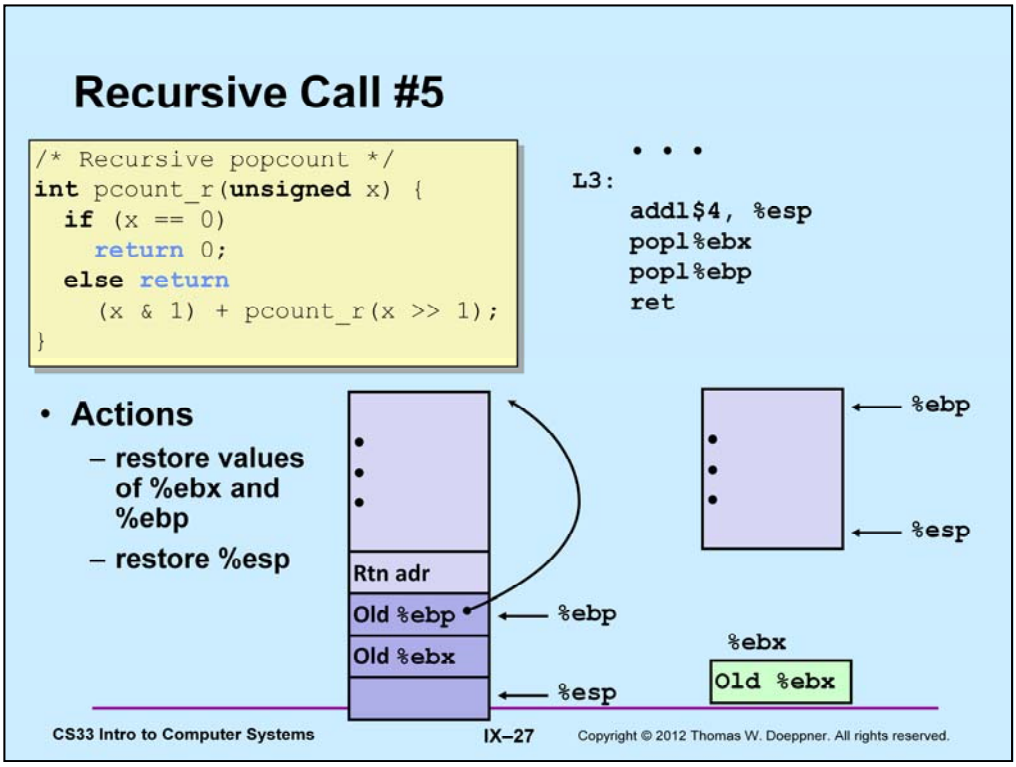

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Observations About Recursion

- 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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Pointer Code

Generating Pointer

```
/* Compute x + 3 */
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

Referencing Pointer

```
/* Increment value by k */
void incrk(int *ip, int k) {
  *ip += k;
}
```

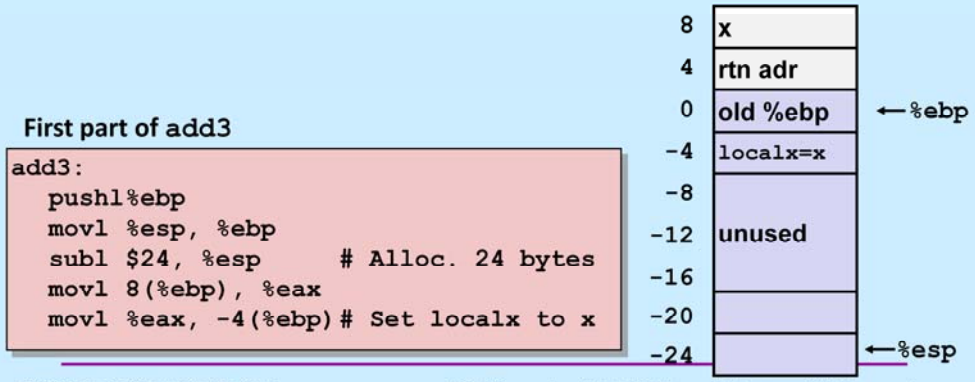
- **add3 creates pointer and passes it to `incrk`**

Supplied by CMU.

Creating and Initializing Local Variables

```
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

- Variable localx must be stored on stack
  - because: need to create pointer to it
- Compute pointer as -4(%ebp)



First part of add3

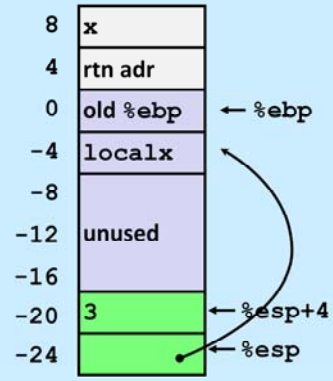
```
add3:
   pushl%ebp
   movl %esp, %ebp
   subl $24, %esp      # Alloc. 24 bytes
   movl 8(%ebp), %eax
   movl %eax, -4(%ebp)# Set localx to x
```


Supplied by CMU.

Creating Pointer as Argument

```
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

- Use leal instruction to compute address of localx



Middle part of add3

```
  movl $3, 4(%esp)    # 2nd arg = 3
  leal -4(%ebp), %eax# &localx
  movl %eax, (%esp)   # 1st arg = &localx
  call incrk
```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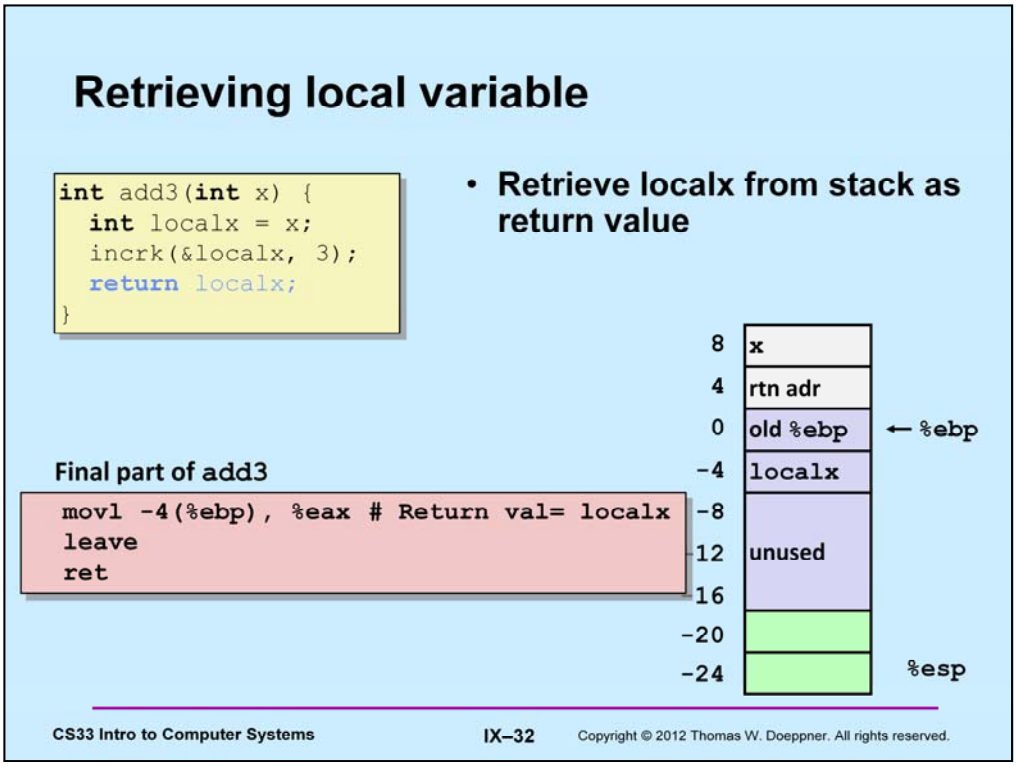

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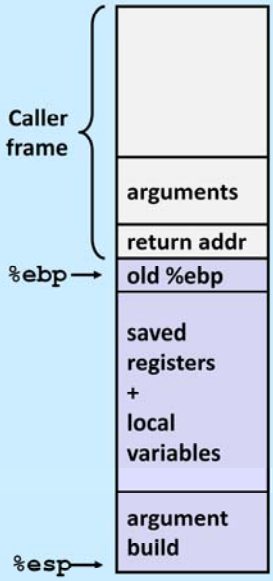
IA 32 Procedure Summary

- Important Points
  - stack is the right data structure for procedure call / return
    - » if P calls Q, then Q returns before P
- Recursion (& mutual recursion) handled by normal calling conventions
  - can safely store values in local stack frame and in callee-saved registers
  - put function arguments at top of stack
  - result return in `%eax`
- Pointers are addresses of values
  - on stack or global



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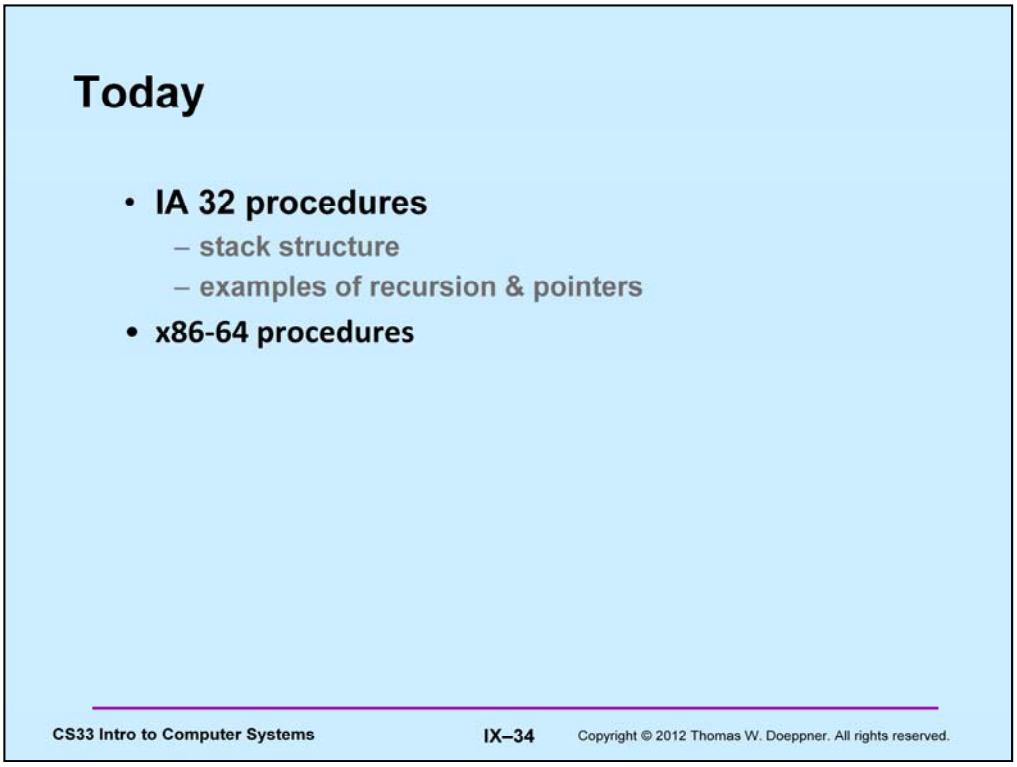

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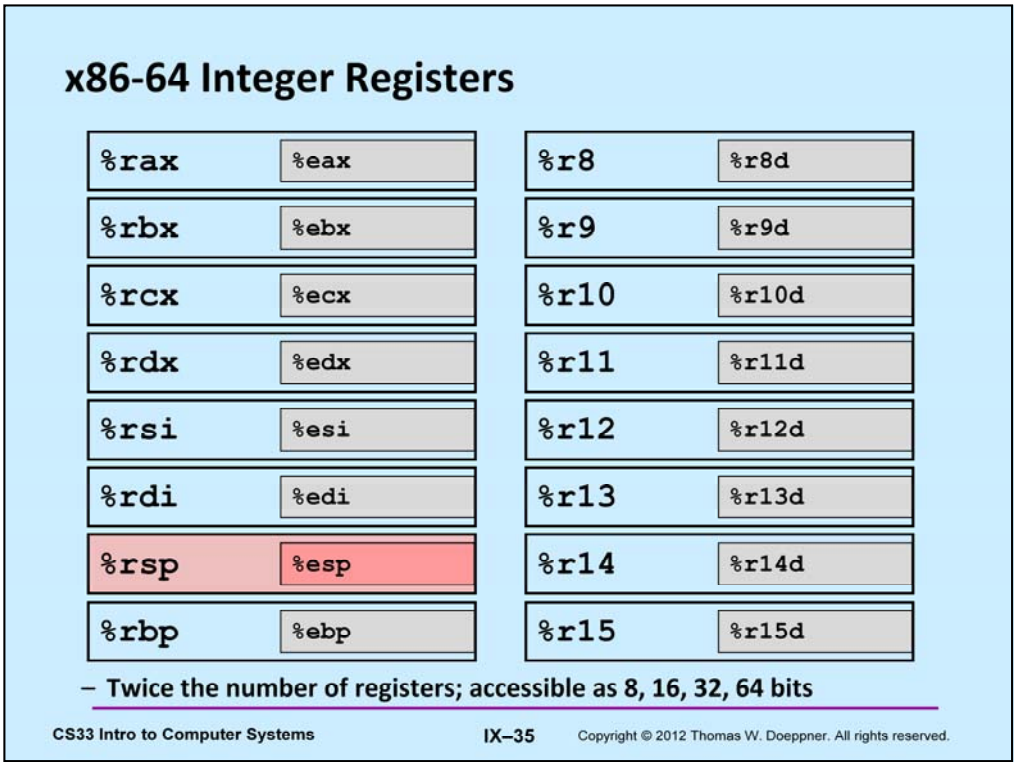

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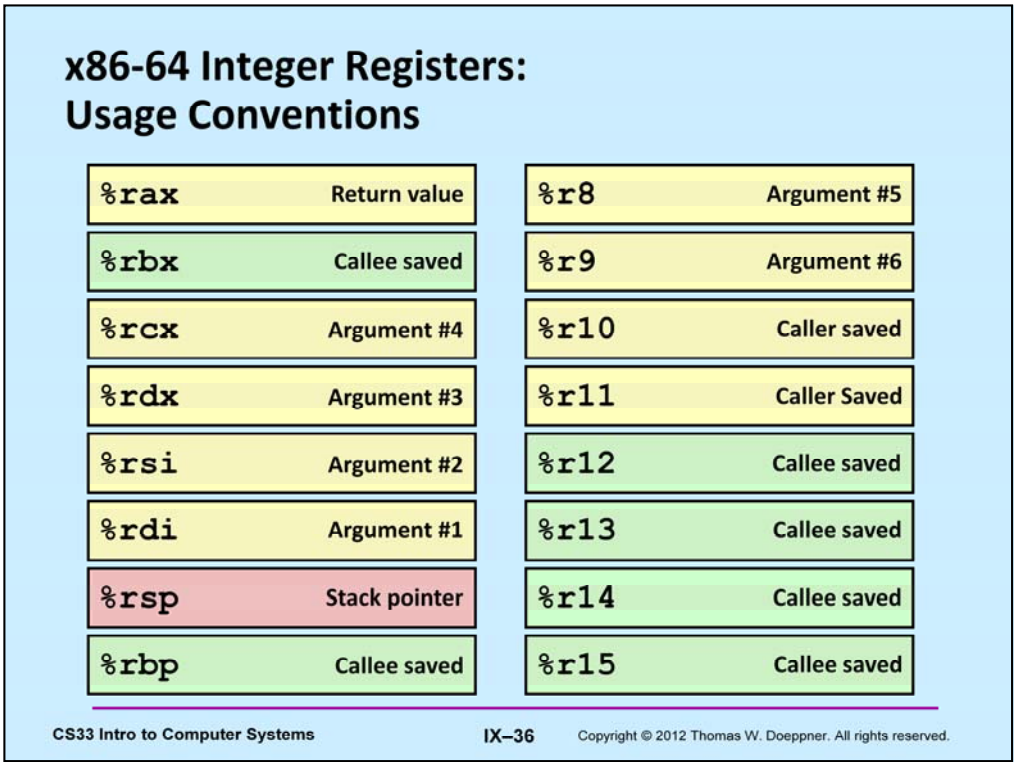

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x86-64 Registers

- Arguments passed to functions via registers
  - if more than 6 integral parameters, then pass rest on stack
  - these registers can be used as caller-saved as well
- All references to stack frame via stack pointer
  - eliminates need to update `%ebp/%rbp`
- Other registers
  - 6 callee-saved
  - 2 caller-saved
  - 1 return value (also usable as caller-saved)
  - 1 special (stack pointer)

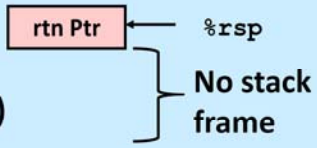
Supplied by CMU.

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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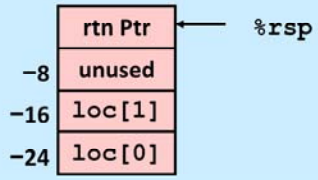
x86-64 Locals in the Red Zone

```
/* 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**



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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
```


Supplied by CMU.

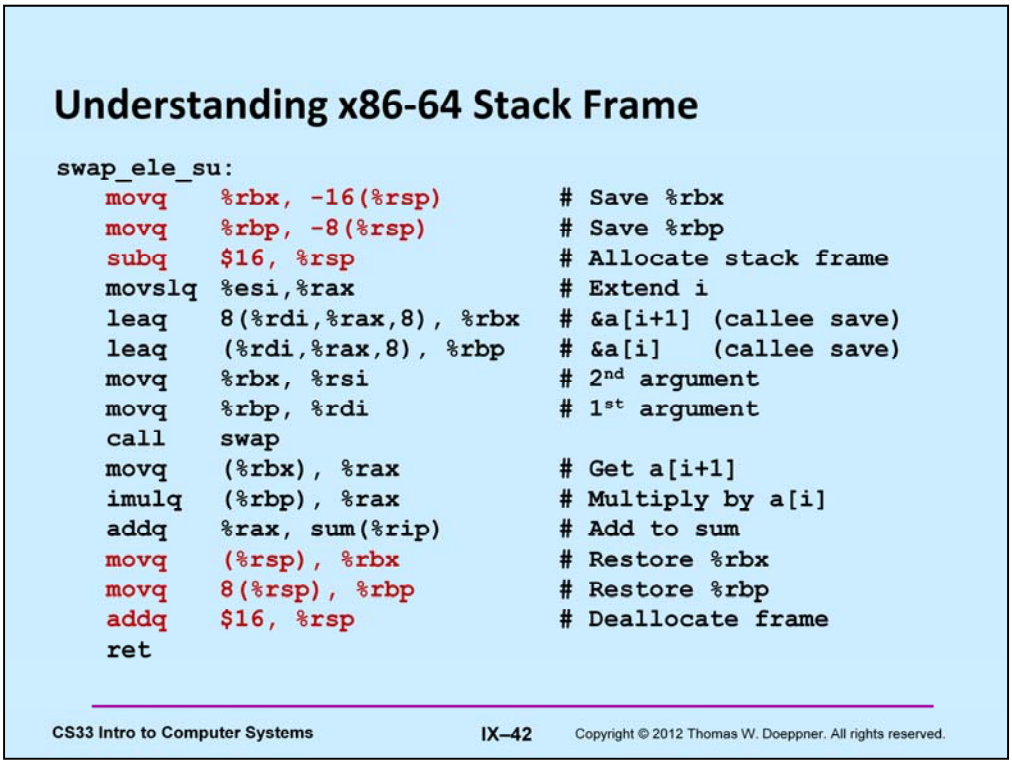
x86-64 Stack Frame Example

```
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
- Must set up stack frame to save these registers

```
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
```

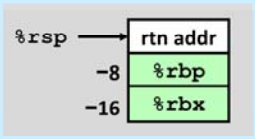

Supplied by CMU.



Supplied by CMU.

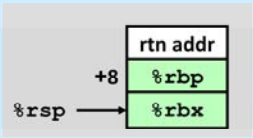
Understanding x86-64 Stack Frame

```
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
```


Supplied by CMU.

Interesting Features of Stack Frame

- Allocate entire frame at once
  - all stack accesses can be relative to `%rsp`
  - do by decrementing stack pointer
  - can delay allocation, since safe to temporarily use red zone
- Simple deallocation
  - increment stack pointer
  - no base/frame pointer needed

Supplied by CMU.

x86-64 Procedure Summary

- Heavy use of registers
  - parameter passing
  - more temporaries since more registers
- Minimal use of stack
  - sometimes none
  - allocate/deallocate entire block
- Many tricky optimizations
  - what kind of stack frame to use
  - various allocation techniques

Supplied by CMU.