Machine-Level Programming III: Switch Statements and IA32 Procedures

15-213/18-213/15-513: Introduction to Computer Systems

7th Lecture, 5 June 2013

Instructors:

Gregory Kesden

Today

- **Switch statements**
- **IA 32 Procedures**
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

```
long switch_eg
   (long x, long y, long z)
{
    long w = 1;
    switch(x) {
    case 1:
        w = y*z;
        break;
    case 2:
        w = y/z;
        /* Fall Through */
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;
    }
    return w;
}
```

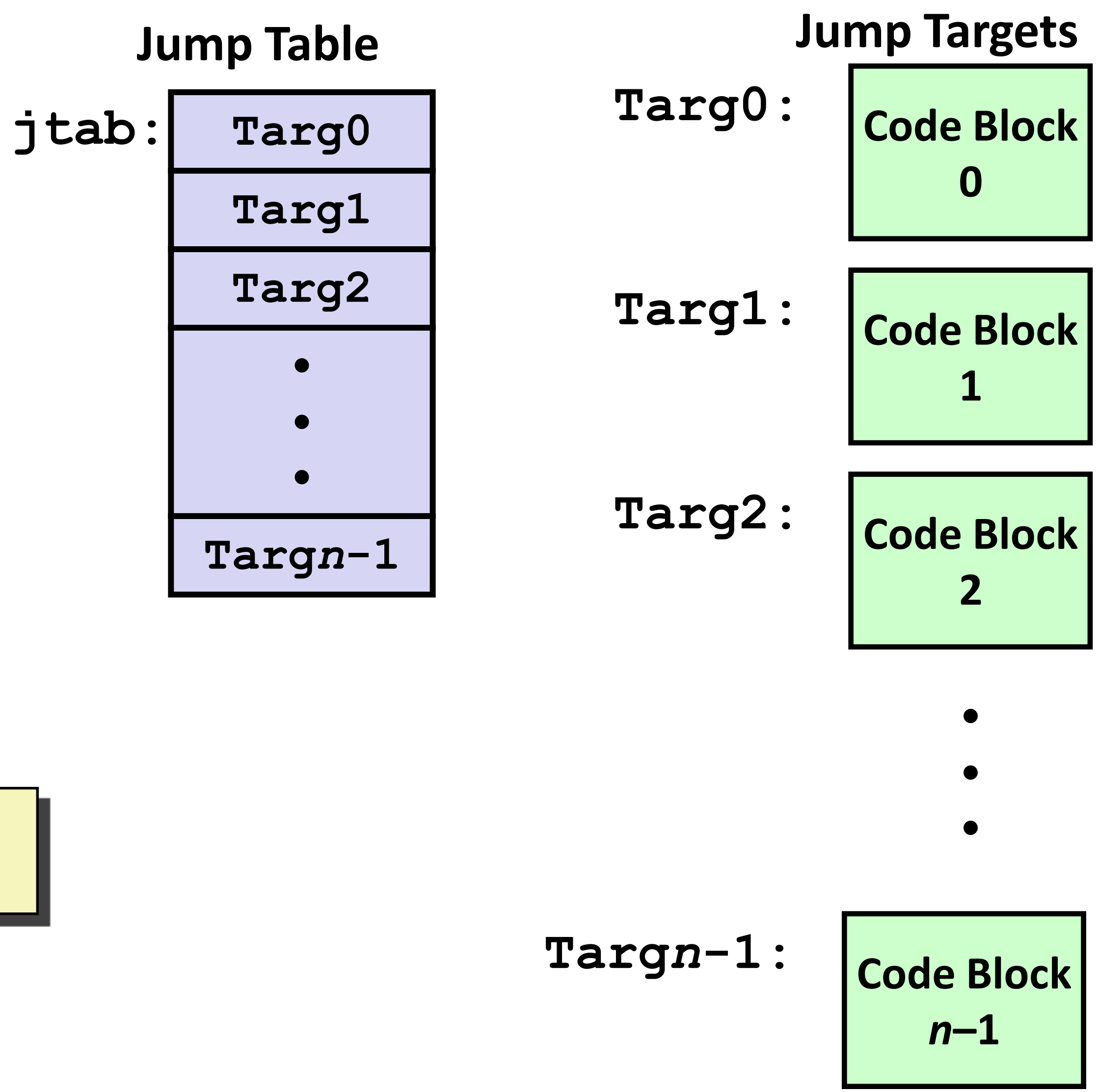
Switch Statement Example

- **Multiple case labels**
  - Here: 5 & 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

Jump Table Structure

Switch Form

```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1
    • • •
  case val_n-1:
    Block n–1
}
```



Approximate Translation

```
target = JTab[x];
goto *target;
```

Switch Statement Example (IA32)

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

What range of values takes default?

Setup:

```
 switch_eg:
   pushl  %ebp           # Setup
   movl   %esp, %ebp     # Setup
   movl   8(%ebp), %eax  # %eax = x
   cmpl   $6, %eax       # Compare x:6
   ja     .L2            # If unsigned > goto default
   jmp    *.L7(,%eax,4)  # Goto *JTab[x]
```

Note that **w** not initialized here

Switch Statement Example (IA32)

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

Jump table

```
.section    .rodata
  .align 4
.L7:
  .long       .L2  # x = 0
  .long       .L3  # x = 1
  .long       .L4  # x = 2
  .long       .L5  # x = 3
  .long       .L2  # x = 4
  .long       .L6  # x = 5
  .long       .L6  # x = 6
```

Setup:

```
switch_eg:
   pushl   %ebp            # Setup
   movl    %esp, %ebp      # Setup
   movl    8(%ebp), %eax   # eax = x
   cmpl    $6, %eax        # Compare x:6
   ja      .L2             # If unsigned > goto default
   jmp     *.L7(,%eax,4)   # Goto *JTab[x]
```

Indirect jump → `jmp *.L7(,%eax,4)`

Assembly Setup Explanation

- **Table Structure**
  - Each target requires 4 bytes
  - Base address at `.L7`
- **Jumping**
  - **Direct:** `jmp .L2`
  - Jump target is denoted by label `.L2`
  - **Indirect:** `jmp *.L7(,%eax,4)`
  - Start of jump table: `.L7`
  - Must scale by factor of 4 (labels have 32-bits = 4 Bytes on IA32)
  - Fetch target from effective Address `.L7 + eax*4`
    - Only for $0 \le$ **x** ≤ 6

Jump table

```
.section    .rodata
  .align 4
.L7:
  .long     .L2 # x = 0
  .long     .L3 # x = 1
  .long     .L4 # x = 2
  .long     .L5 # x = 3
  .long     .L2 # x = 4
  .long     .L6 # x = 5
  .long     .L6 # x = 6
```

Jump Table

Jump table

```
.section   .rodata
  .align 4
.L7:
  .long     .L2 # x = 0
  .long     .L3 # x = 1
  .long     .L4 # x = 2
  .long     .L5 # x = 3
  .long     .L2 # x = 4
  .long     .L6 # x = 5
  .long     .L6 # x = 6
```

```
switch(x) {
case 1:         // .L3
    w = y*z;
    break;
case 2:         // .L4
    w = y/z;
    /* Fall Through */
case 3:         // .L5
    w += z;
    break;
case 5:
case 6:         // .L6
    w -= z;
    break;
default:        // .L2
    w = 2;
}
```

Handling Fall-Through

```
long w = 1;
   . . .
switch(x) {
   . . .
case 2:
    w = y/z;
    /* Fall Through */
case 3:
    w += z;
    break;
   . . .
}
```

```
case 3:
        w = 1;
        goto merge;
```

```
    case 2:
        w = y/z;

merge:
        w += z;
```

Code Blocks (Partial)

```
switch(x) {
case 1:         // .L3
      w = y*z;
      break;
 . . .
case 3:        // .L5
    w += z;
    break;
  . . .
default:       // .L2
    w = 2;
}
```

```
.L2:                    # Default
   movl  $2, %eax       # w = 2
   jmp   .L8            # Goto done

.L5:                    # x == 3
   movl  $1, %eax       # w = 1
   jmp   .L9            # Goto merge

.L3:                    # x == 1
   movl  16(%ebp), %eax   # z
   imull 12(%ebp), %eax   # w = y*z
   jmp   .L8             # Goto done
```

Code Blocks (Rest)

```
switch(x) {
  . . .
  case 2:  // .L4
      w = y/z;
      /* Fall Through */
  merge:    // .L9
      w += z;
      break;
  case 5:
  case 6:  // .L6
      w -= z;
      break;
}
```

```
.L4:                # x == 2
   movl  12(%ebp), %edx
   movl  %edx, %eax
   sarl  $31, %edx
   idivl 16(%ebp)   # w = y/z

.L9:                # merge:
   addl  16(%ebp), %eax # w += z
   jmp   .L8        # goto done

.L6:                # x == 5, 6
   movl  $1, %eax       # w = 1
   subl  16(%ebp), %eax # w = 1-z
```

Switch Code (Finish)

```
return w;
```

```
.L8:                # done:
   popl  %ebp
   ret
```

- **Noteworthy Features**
  - Jump table avoids sequencing through cases
    - Constant time, rather than linear
  - Use jump table to handle holes and duplicate tags
  - Use program sequencing to handle fall-through
  - Don’t initialize w = 1 unless really need it

x86-64 Switch Implementation

- Same general idea, adapted to 64-bit code
- Table entries 64 bits (pointers)
- Cases use revised code

```
    switch(x) {
    case 1:       // .L3
        w = y*z;
        break;
      . . .
    }
```

```
.L3:
   movq    %rdx, %rax
   imulq   %rsi, %rax
   ret
```

Jump Table

```
  .section  .rodata
  .align 8
.L7:
  .quad     .L2     # x = 0
  .quad     .L3     # x = 1
  .quad     .L4     # x = 2
  .quad     .L5     # x = 3
  .quad     .L2     # x = 4
  .quad     .L6     # X = 5
  .quad     .L6     # x = 6
```

IA32 Object Code

- **Setup**
  - Label `.L2` becomes address `0x8048422`
  - Label `.L7` becomes address `0x8048660`

Assembly Code

```
switch_eg:
  . . .
  ja    .L2              # If unsigned > goto default
  jmp   *.L7(,%eax,4)    # Goto *JTab[x]
```

Disassembled Object Code

```
08048410 <switch_eg>:
 . . .
 8048419:77 07                   ja     8048422 <switch_eg+0x12>
 804841b:ff 24 85 60 86 04 08    jmp    *0x8048660(,%eax,4)
```

IA32 Object Code (cont.)

- **Jump Table**
  - Doesn't show up in disassembled code
  - Can inspect using GDB
  - **`gdb switch`**
  - **`(gdb) x/7xw 0x8048660`**
    - Examine 7 hexadecimal format "words" (4-bytes each)
    - Use command "**`help x`**" to get format documentation

```
0x8048660:    0x08048422    0x08048432    0x0804843b    0x08048429
0x8048670:    0x08048422    0x0804844b    0x0804844b
```

IA32 Object Code (cont.)

- Deciphering Jump Table

```
0x8048660:    0x08048422    0x08048432    0x0804843b    0x08048429
0x8048670:    0x08048422    0x0804844b    0x0804844b
```

Address	Value	x
0x8048660	0x8048422	0
0x8048664	0x8048432	1
0x8048668	0x804843b	2
0x804866c	0x8048429	3
0x8048670	0x8048422	4
0x8048674	0x804844b	5
0x8048678	0x804844b	6

Disassembled Targets

```
8048422:   b8 02 00 00 00        mov    $0x2,%eax
8048427:   eb 2a                 jmp    8048453 <switch_eg+0x43>
8048429:   b8 01 00 00 00        mov    $0x1,%eax
804842e:   66 90                 xchg   %ax,%ax # noop
8048430:   eb 14                 jmp    8048446 <switch_eg+0x36>
8048432:   8b 45 10              mov    0x10(%ebp),%eax
8048435:   0f af 45 0c           imul   0xc(%ebp),%eax
8048439:   eb 18                 jmp    8048453 <switch_eg+0x43>
804843b:   8b 55 0c              mov    0xc(%ebp),%edx
804843e:   89 d0                 mov    %edx,%eax
8048440:   c1 fa 1f              sar    $0x1f,%edx
8048443:   f7 7d 10              idivl  0x10(%ebp)
8048446:   03 45 10              add    0x10(%ebp),%eax
8048449:   eb 08                 jmp    8048453 <switch_eg+0x43>
804844b:   b8 01 00 00 00        mov    $0x1,%eax
8048450:   2b 45 10              sub    0x10(%ebp),%eax
8048453:   5d                    pop    %ebp
8048454:   c3                    ret
```

Matching Disassembled Targets

Value
0x8048422
0x8048432
0x804843b
0x8048429
0x8048422
0x804844b
0x804844b

```
8048422:    mov    $0x2,%eax
8048427:    jmp    8048453 <switch_eg+0x43>
8048429:    mov    $0x1,%eax
804842e:    xchg   %ax,%ax
8048430:    jmp    8048446 <switch_eg+0x36>
8048432:    mov    0x10(%ebp),%eax
8048435:    imul   0xc(%ebp),%eax
8048439:    jmp    8048453 <switch_eg+0x43>
804843b:    mov    0xc(%ebp),%edx
804843e:    mov    %edx,%eax
8048440:    sar    $0x1f,%edx
8048443:    idivl  0x10(%ebp)
8048446:    add    0x10(%ebp),%eax
8048449:    jmp    8048453 <switch_eg+0x43>
804844b:    mov    $0x1,%eax
8048450:    sub    0x10(%ebp),%eax
8048453:    pop    %ebp
8048454:    ret
```

Summarizing

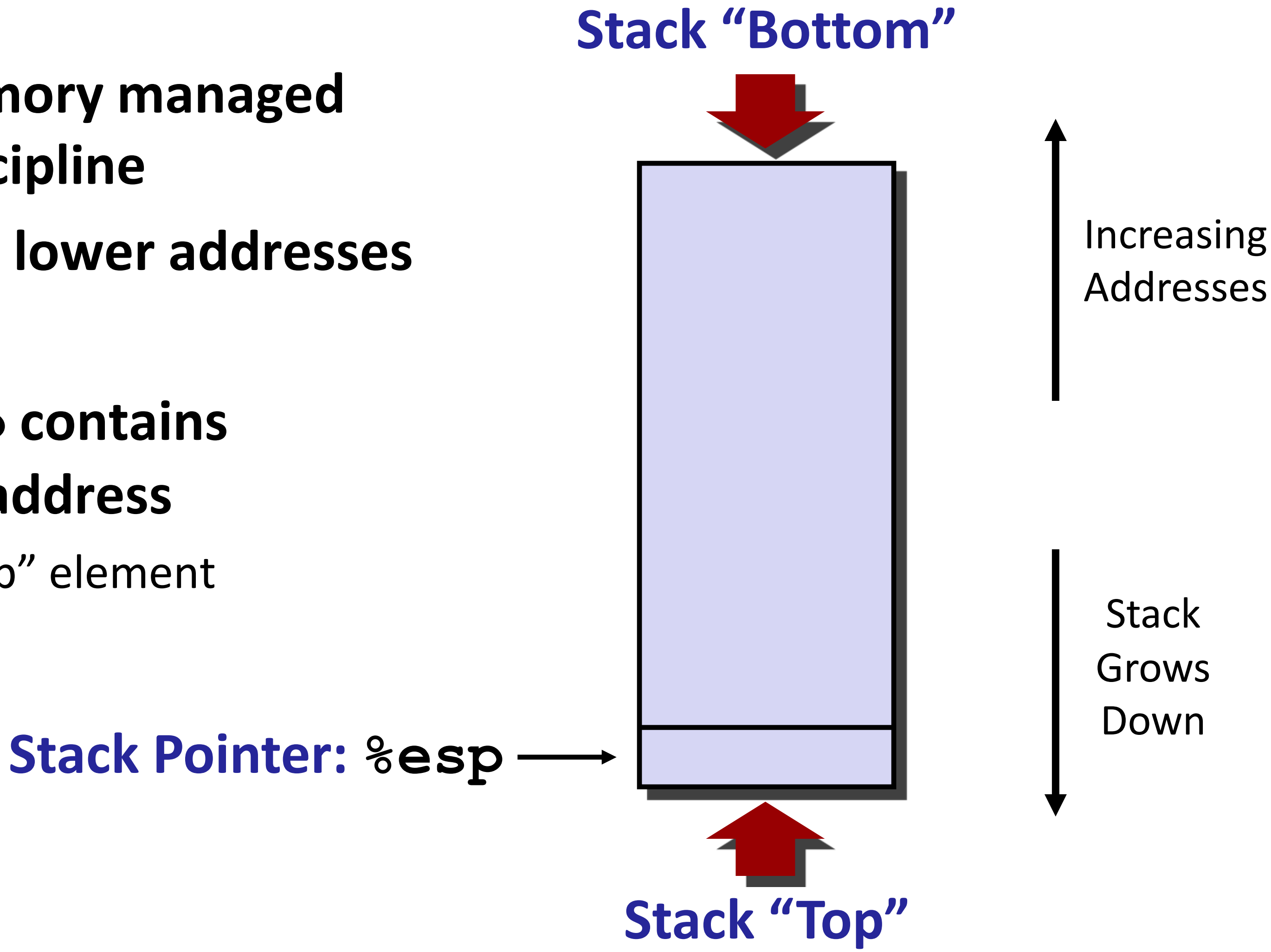
- **C Control**
  - if-then-else
  - do-while
  - while, for
  - switch
- **Assembler Control**
  - Conditional jump
  - Conditional move
  - Indirect jump
  - Compiler generates code sequence to implement more complex control
- **Standard Techniques**
  - Loops converted to do-while form
  - Large switch statements use jump tables
  - Sparse switch statements may use decision trees

Today

- **Switch statements**
- **IA 32 Procedures**
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

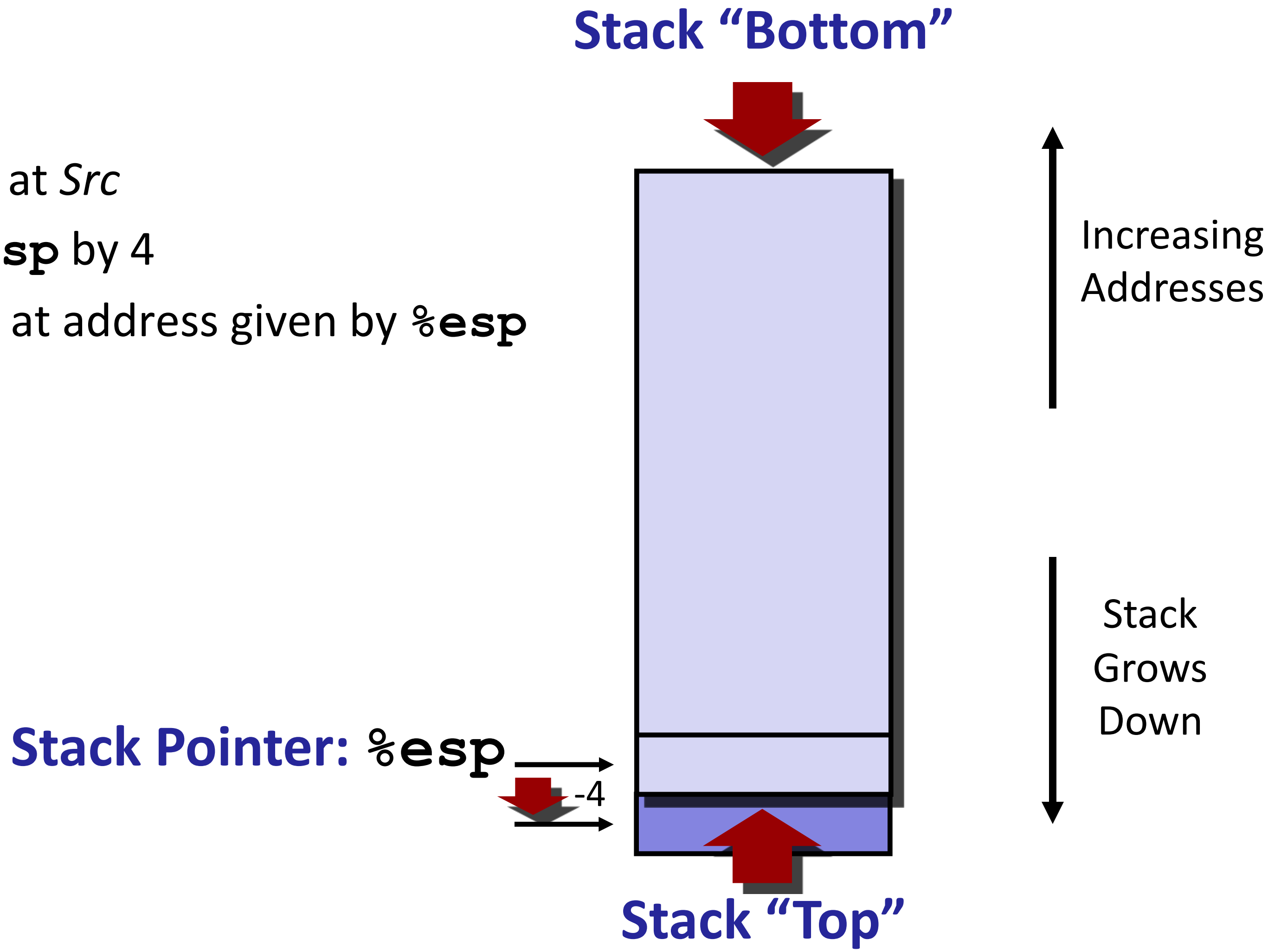
IA32 Stack

- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register `%esp` contains lowest stack address
  - address of "top" element



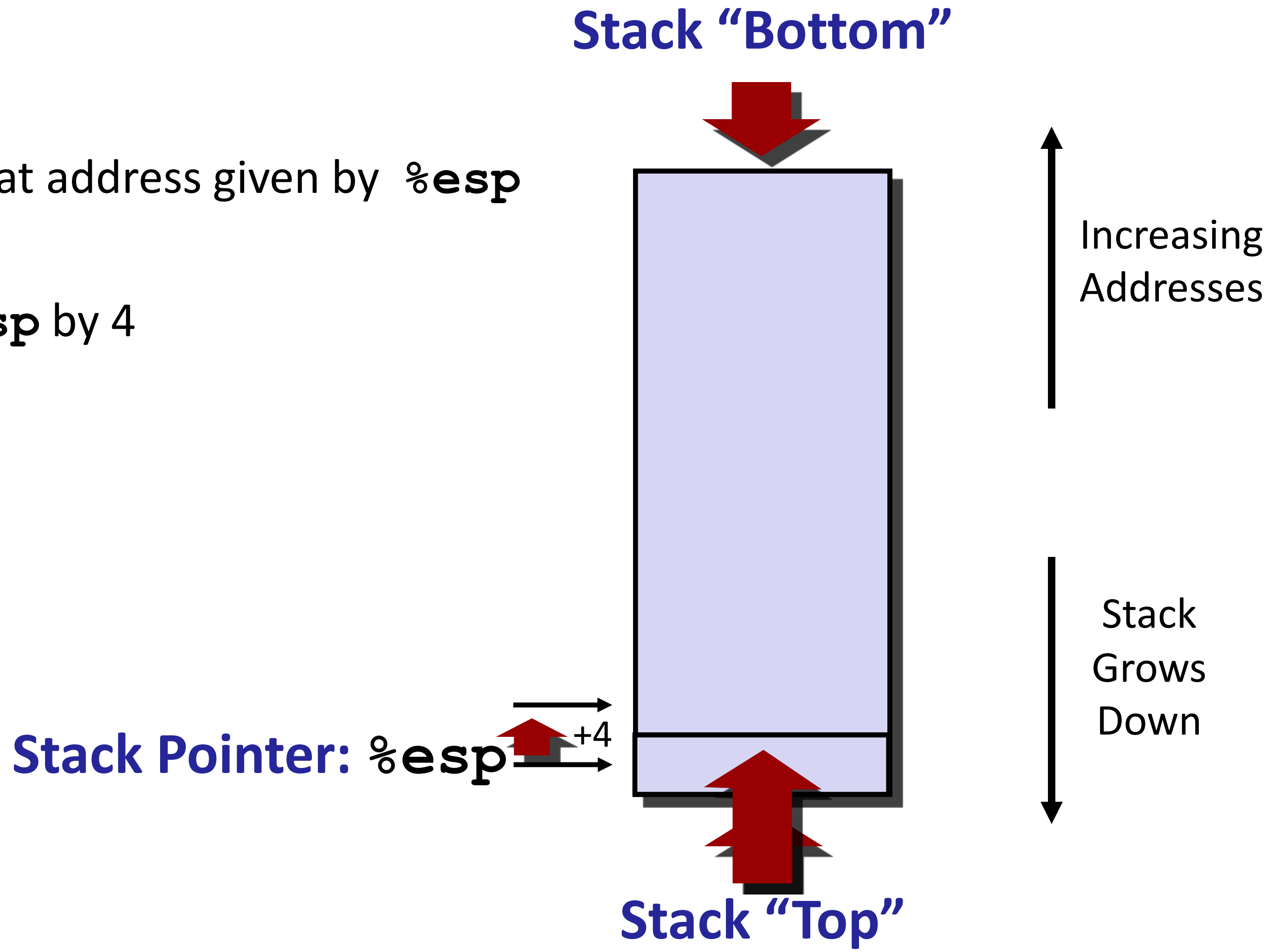
IA32 Stack: Push

- **`pushl`** ***Src***
  - Fetch operand at *Src*
  - Decrement **`%esp`** by 4
  - Write operand at address given by **`%esp`**



IA32 Stack: Pop

- **`Popl`** ***Dst***
  - Read operand at address given by **`%esp`**
  - Put into Dst
  - Increment **`%esp`** by 4



Procedure Control Flow

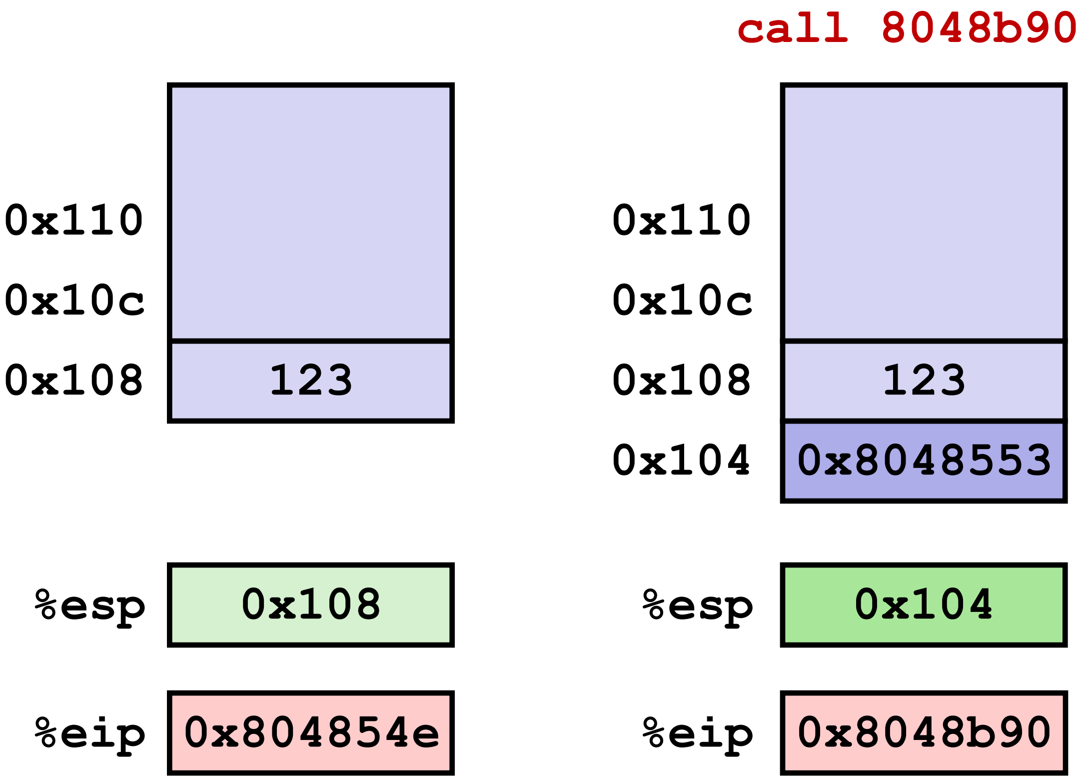
- **Use stack to support procedure call and return**
- **Procedure call:** **`call label`**
  - Push return address on stack
  - Jump to ***label***
- **Return address:**
  - Address of the next instruction right after call
  - Example from disassembly

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

  - Return address = **`0x8048553`**
- **Procedure return:** **`ret`**
  - Pop address from stack
  - Jump to address

Procedure Call Example

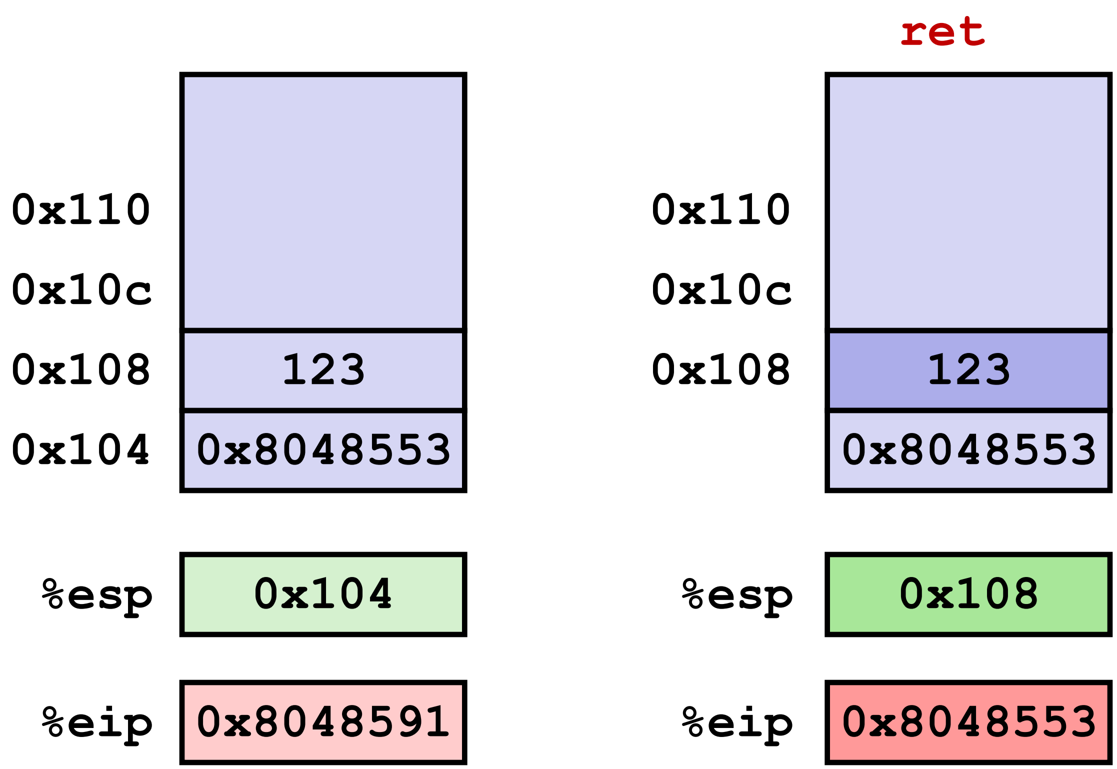
```
804854e:      e8 3d 06 00 00         call    8048b90 <main>
8048553:      50                     pushl   %eax
```



***%eip*: program counter**

Procedure Return Example

```
8048591:     c3                         ret
```



%eip: program counter

Stack-Based Languages

- **Languages that support recursion**
  - e.g., C, Pascal, Java
  - Code must be "*Reentrant*"
    - Multiple simultaneous instantiations of single procedure
  - Need some place to store state of each instantiation
    - Arguments
    - Local variables
    - Return pointer
- **Stack discipline**
  - State for given procedure needed for limited time
    - From when called to when return
  - Callee returns before caller does
- **Stack allocated in *Frames***
  - state for single procedure instantiation

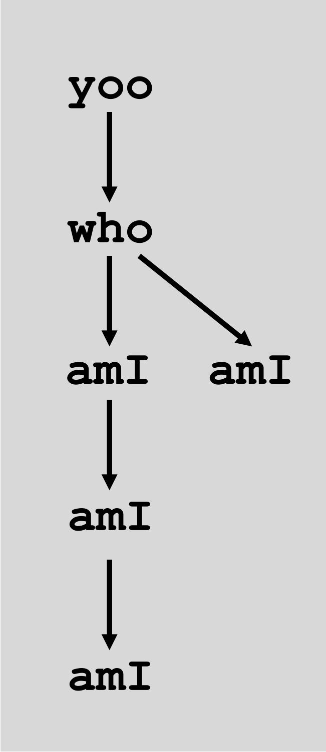
Call Chain Example

```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

```
who(…)
{
   • • •
   amI();
   • • •
   amI();
   • • •
}
```

```
amI(…)
{
   •
   •
   amI();
   •
   •
}
```

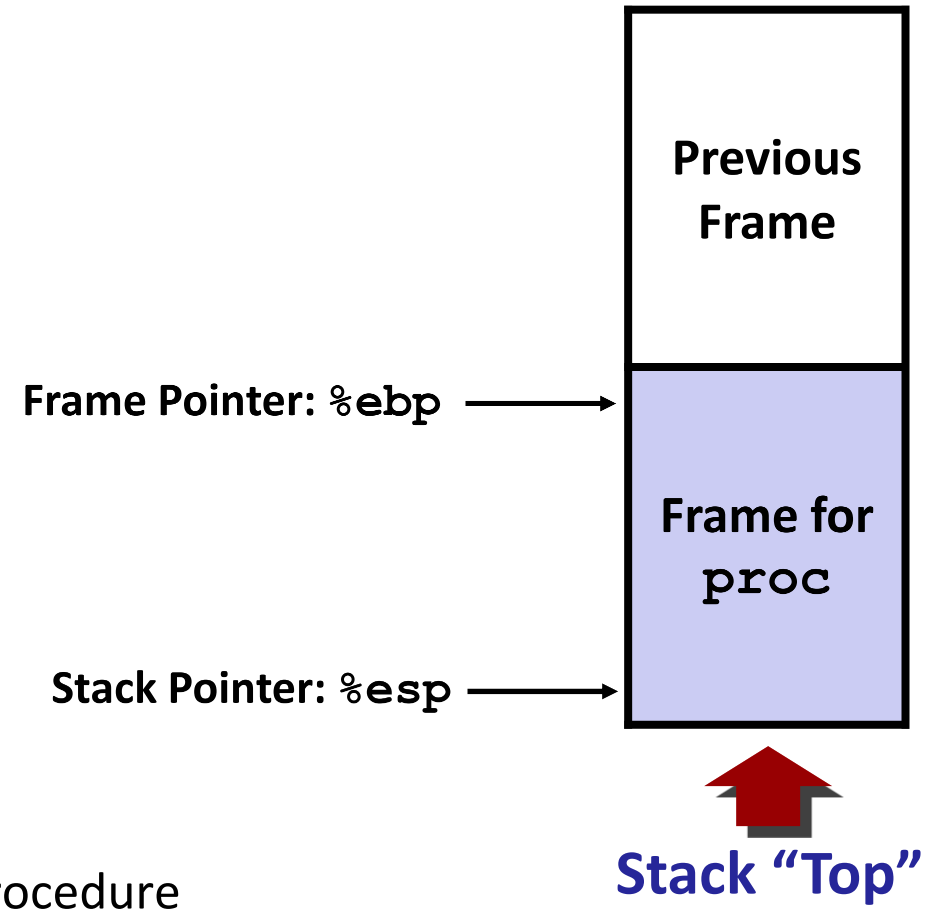
Example Call Chain



Procedure `amI()` is recursive

Stack Frames

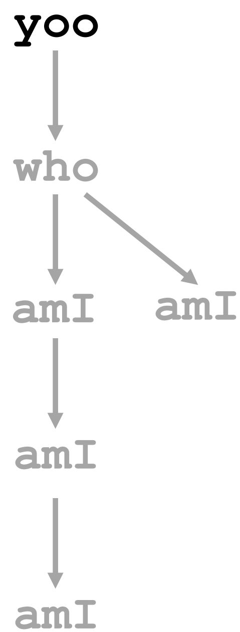
- **Contents**
  - Local variables
  - Return information
  - Temporary space

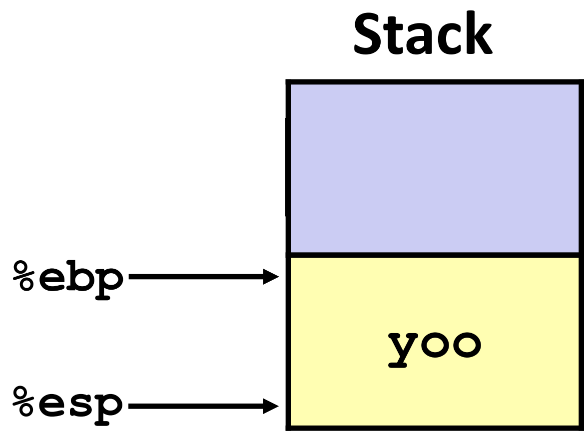


- **Management**
  - Space allocated when enter procedure
    - "Set-up" code
  - Deallocated when return
    - "Finish" code

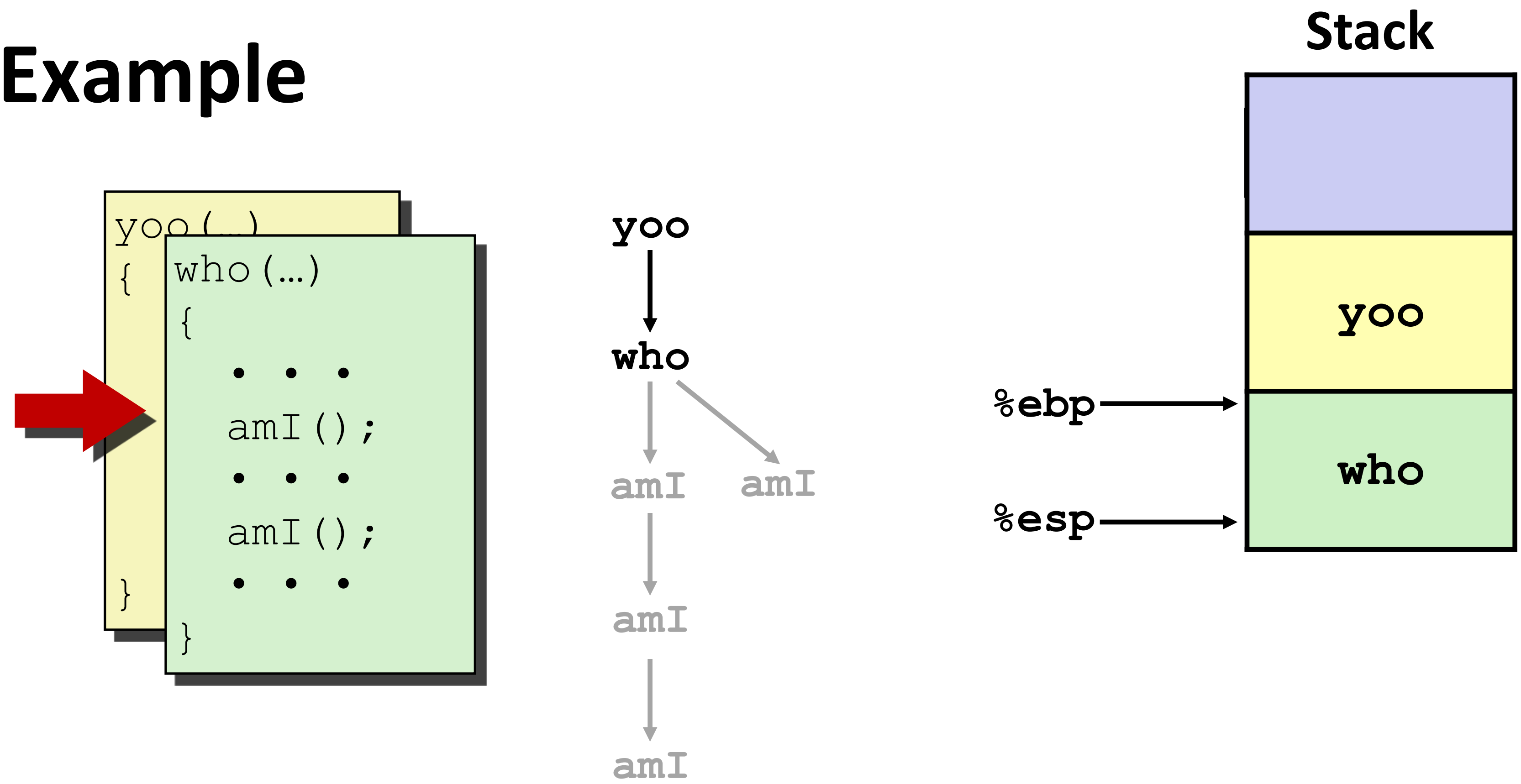
Example

```
yoo(…)
{
  •
  •
  who();
  •
  •
}
```

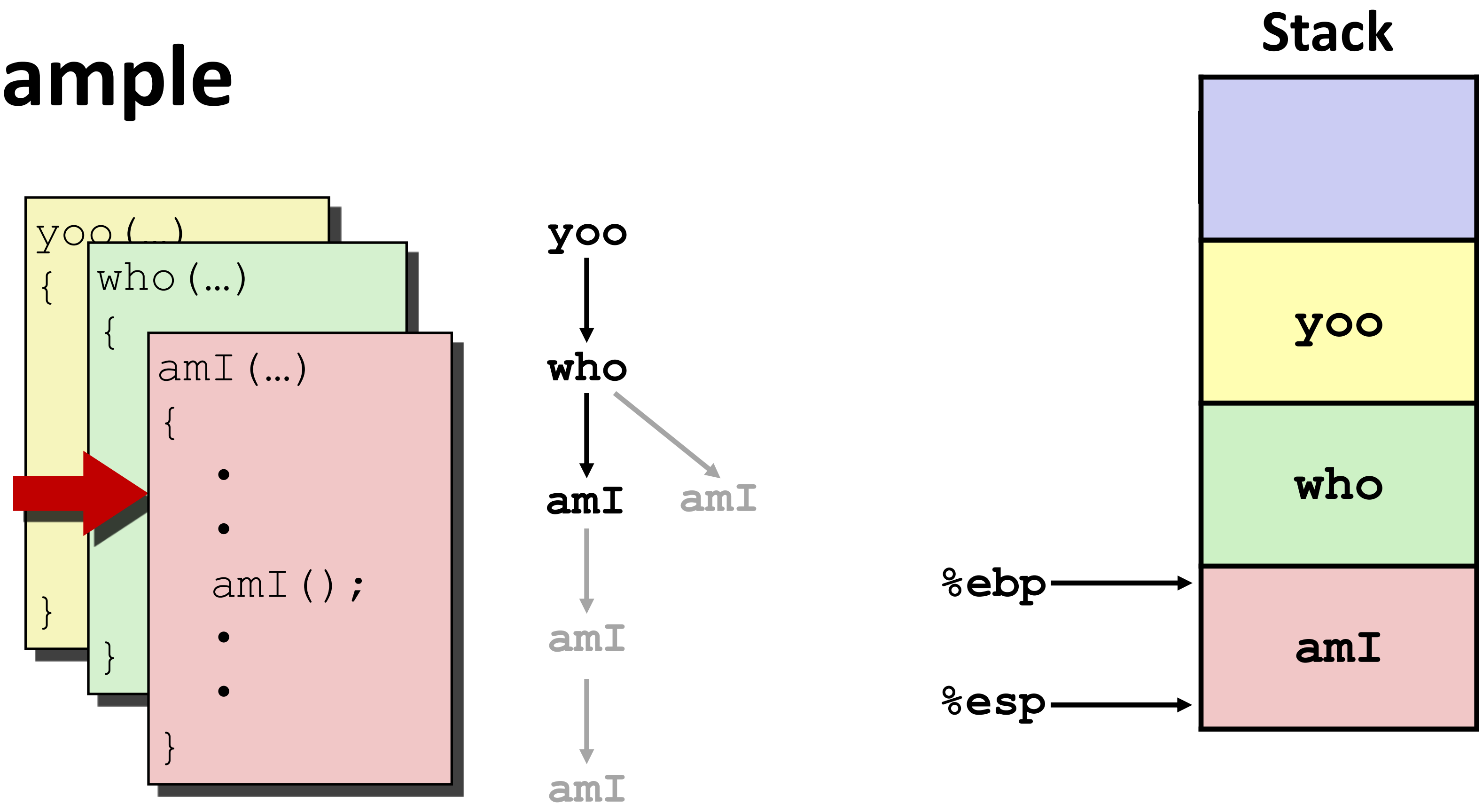




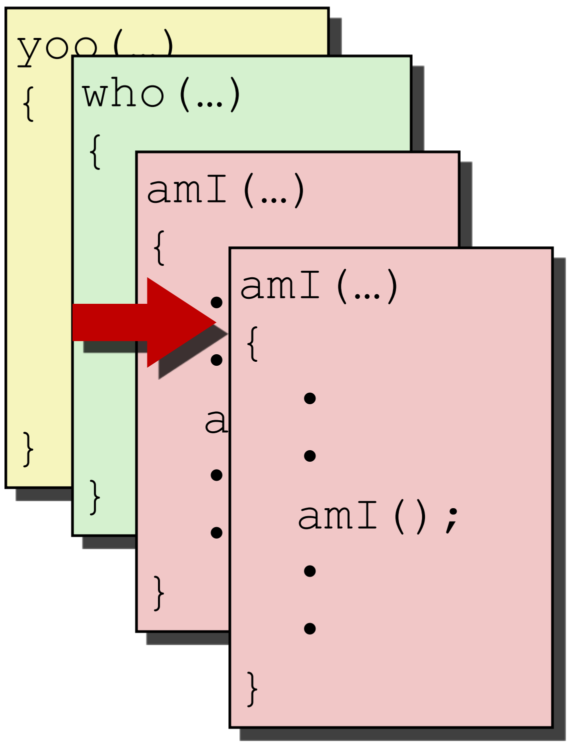
Example

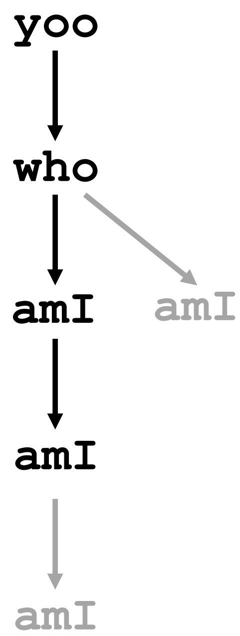


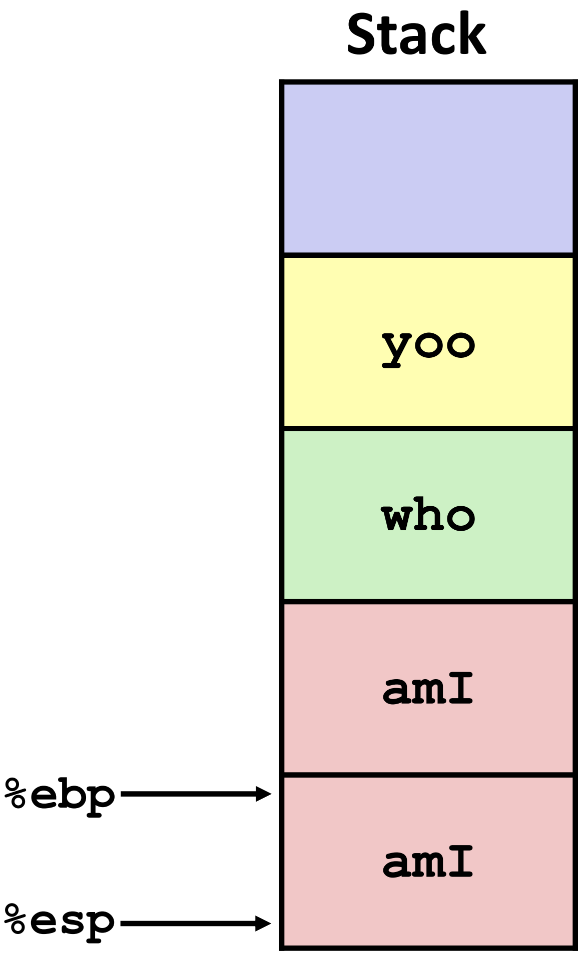
Example


yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
amI();
•
•
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
%ebp
%esp

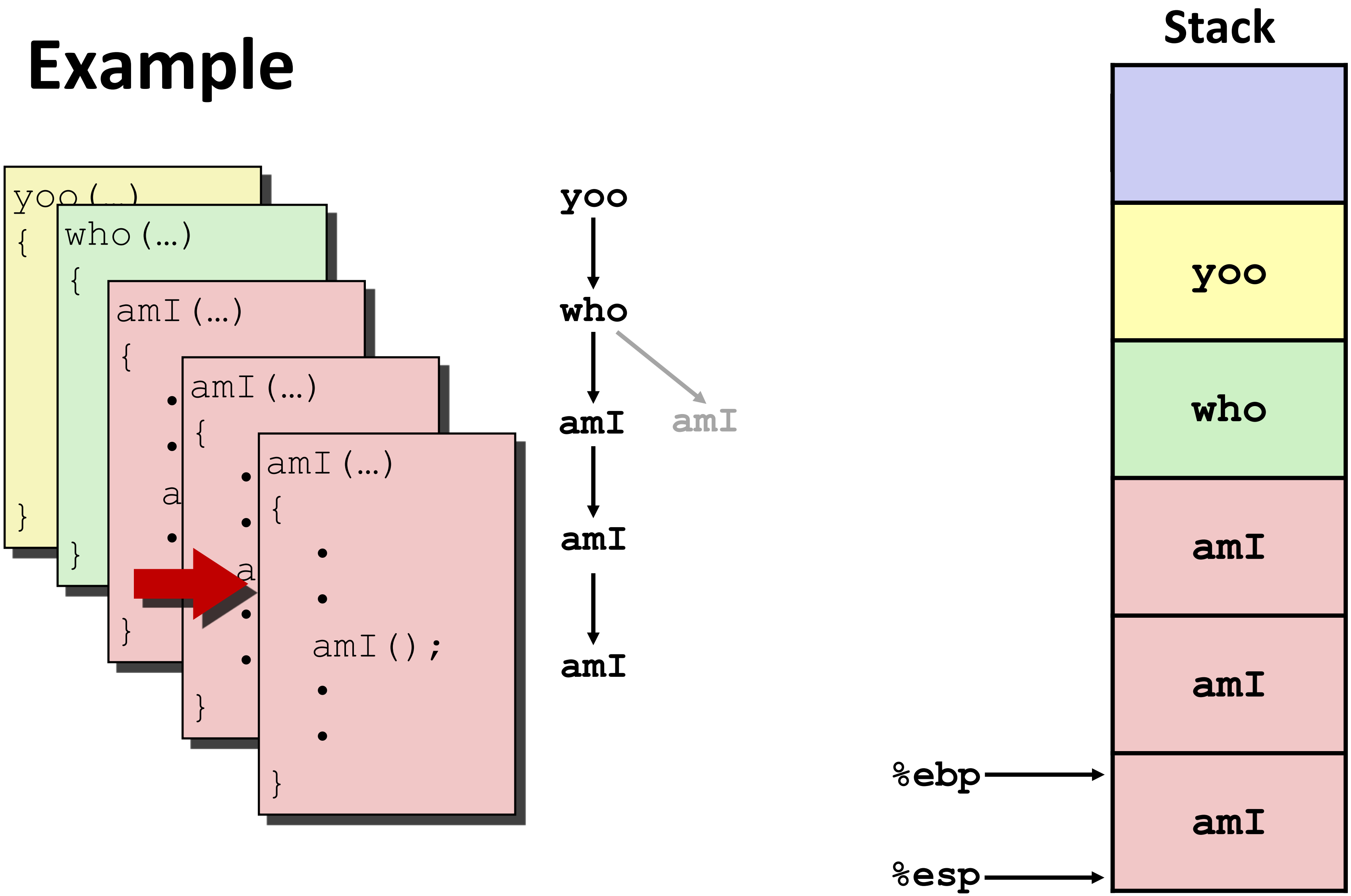
Example


yoo(…)
{
}
who(…)
{
}
amI(…)
{
}
amI(…)
{
amI();
}

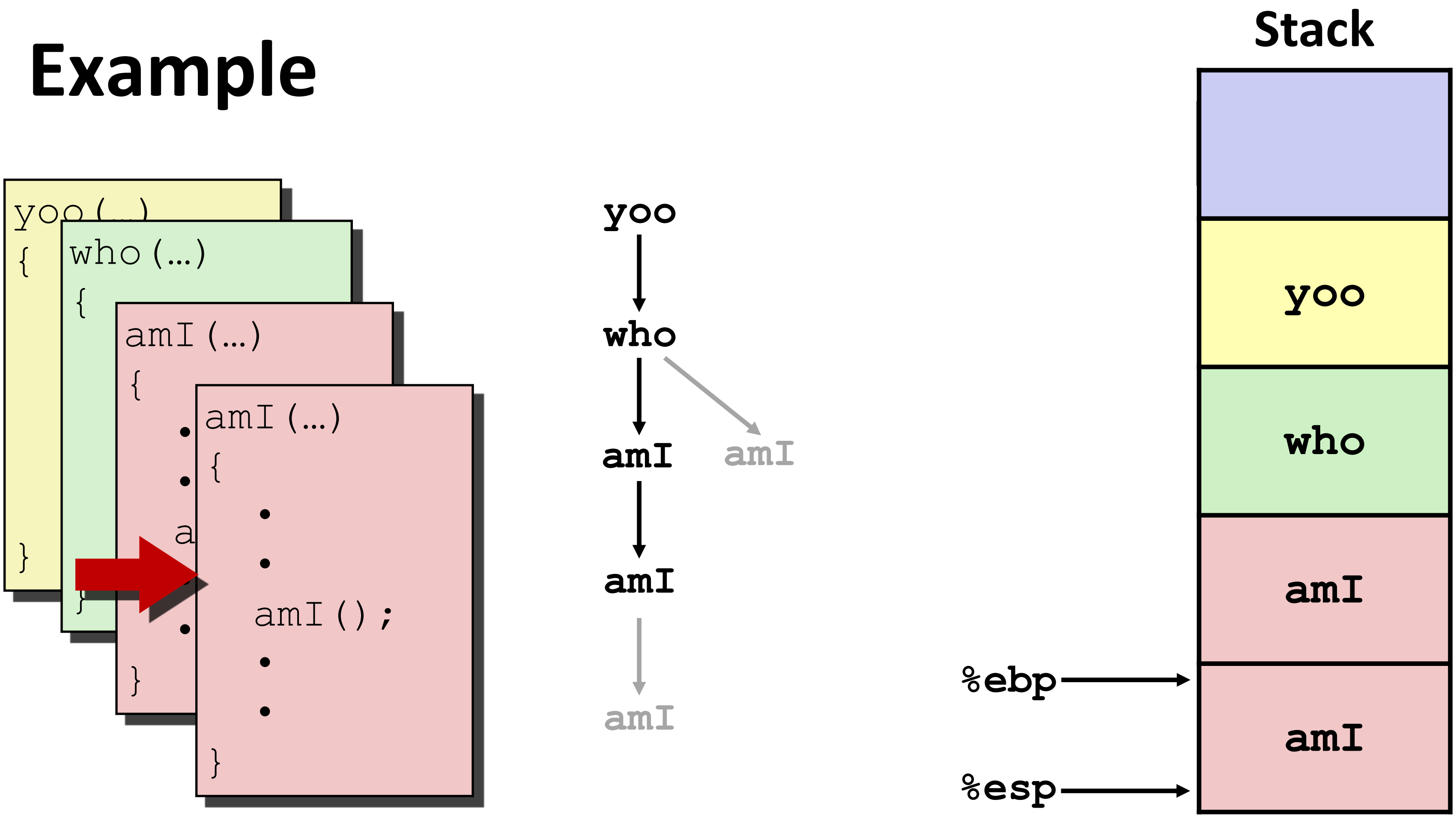

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
%ebp
%esp

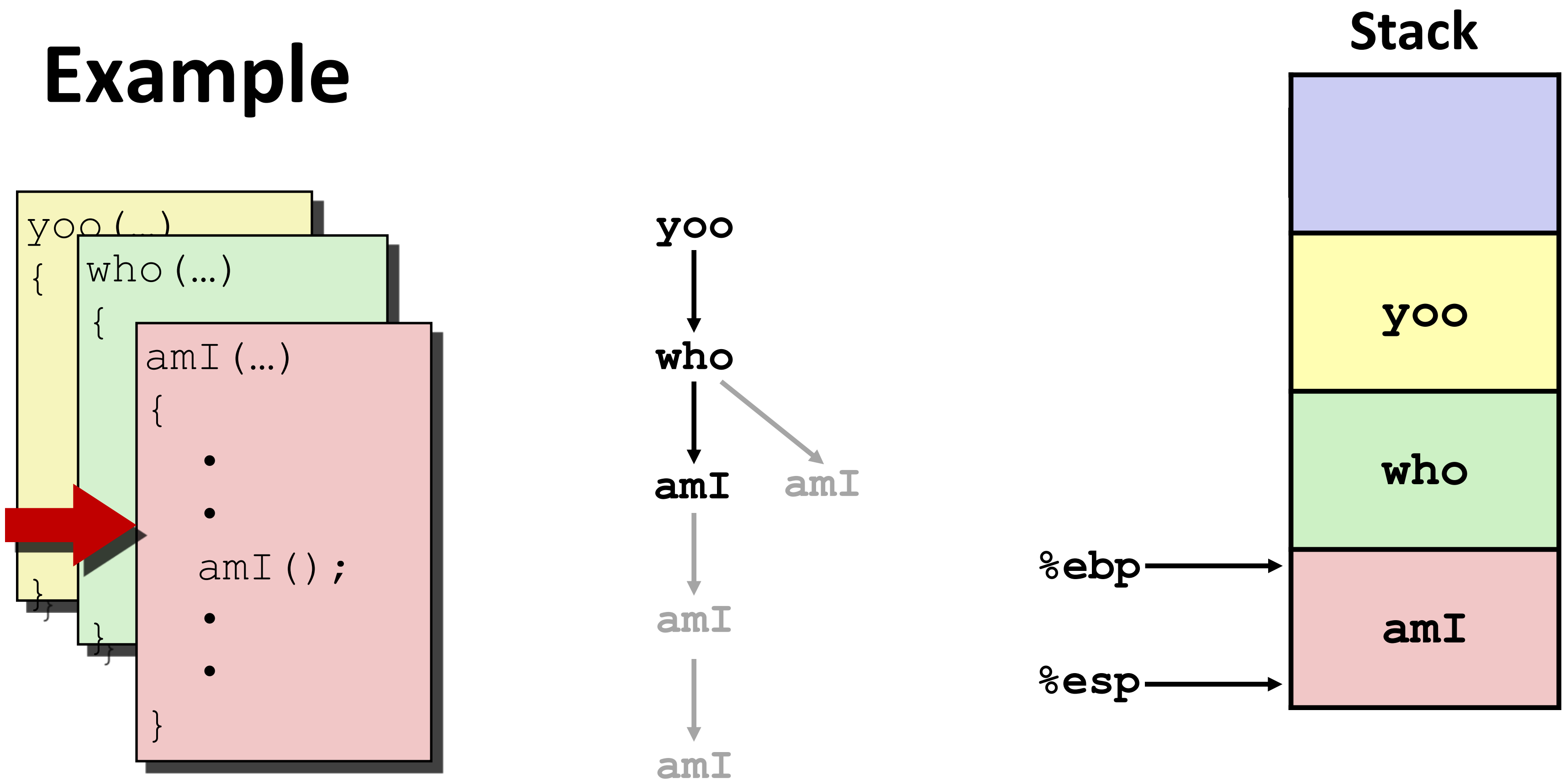
Example


yoo(…)
{
}
who(…)
{
}
amI(…)
{
}
amI(…)
{
}
amI(…)
{
amI();
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
amI
amI
%ebp
%esp

Example

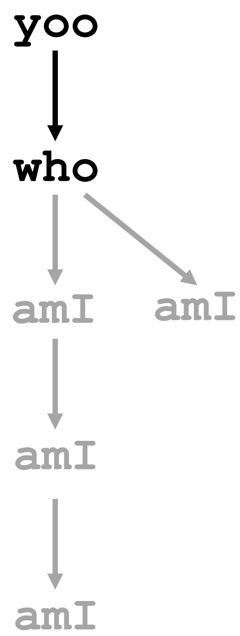

yoo(…)
{
}
who(…)
{
}
amI(…)
{
}
amI(…)
{
amI();
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
amI
%ebp
%esp

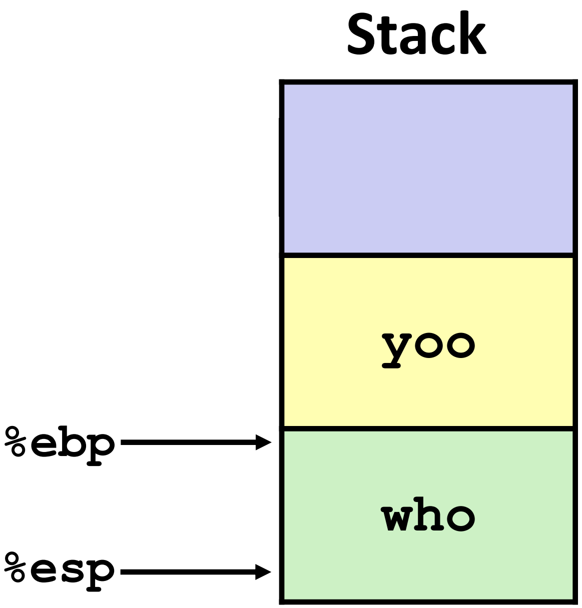
Example


yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
amI();
•
•
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
%ebp
%esp

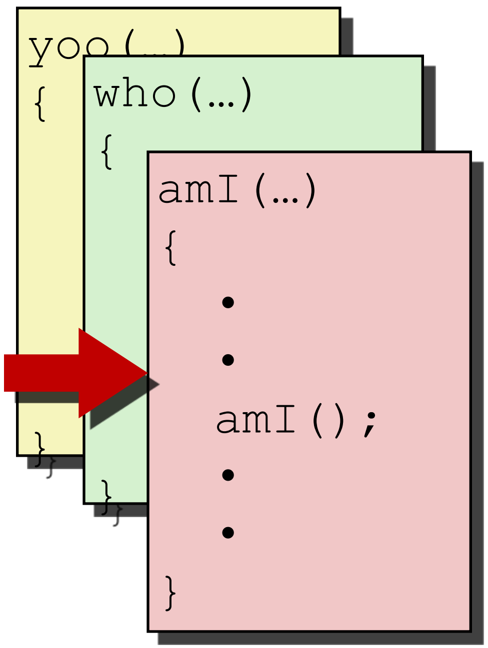
Example

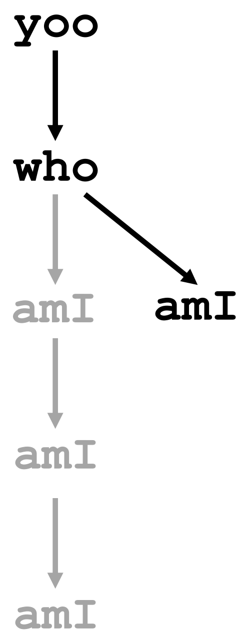
```
yoo(…)
{
    who(…)
    {
        • • •
        amI();
        • • •
        amI();
        • • •
    }
}
```

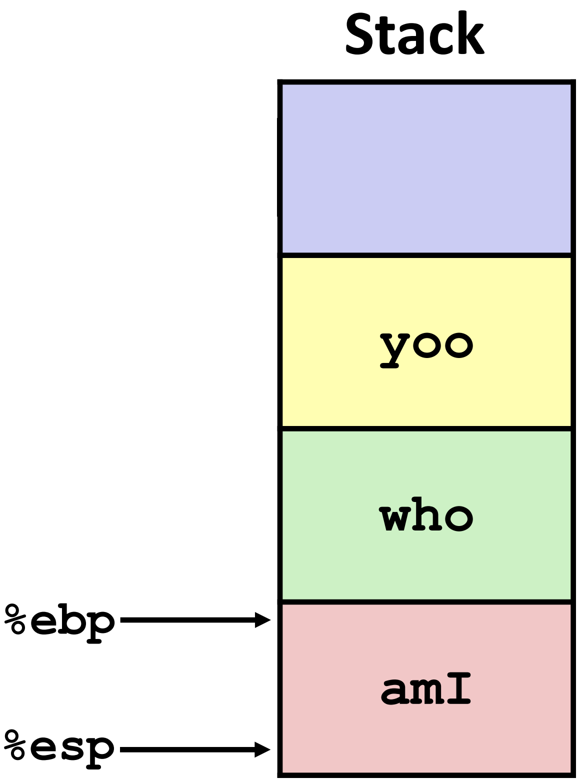




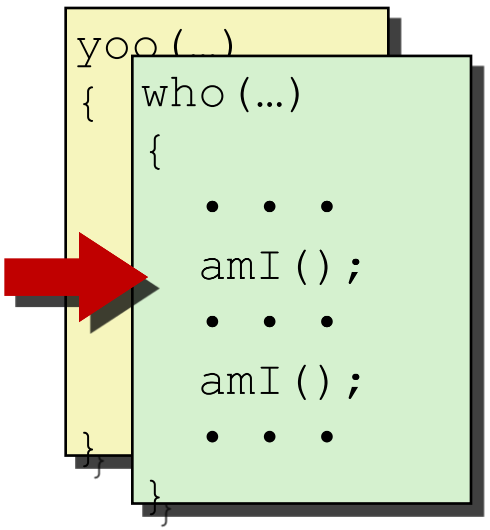
Example

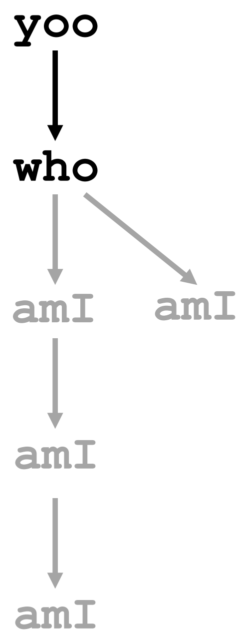

yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
amI();
•
•
}

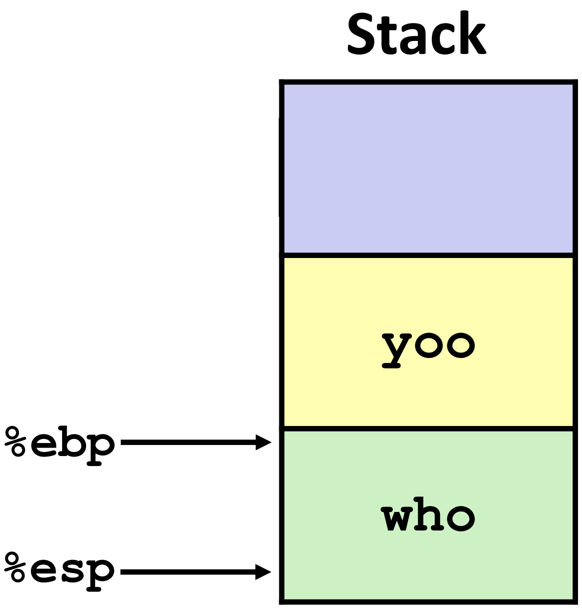

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
%ebp
%esp

Example

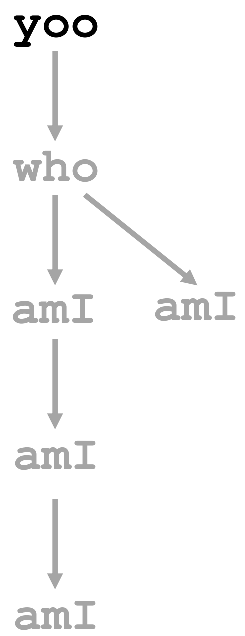


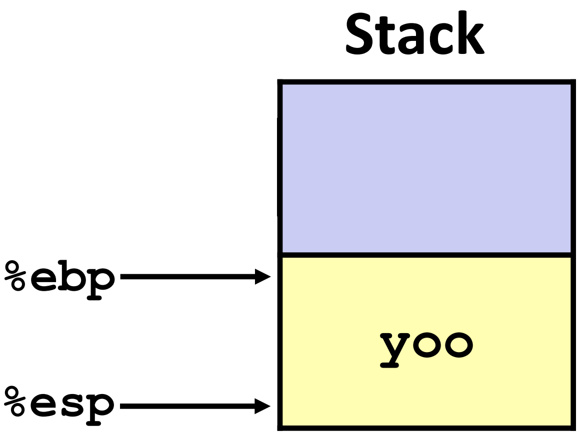




Example

```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

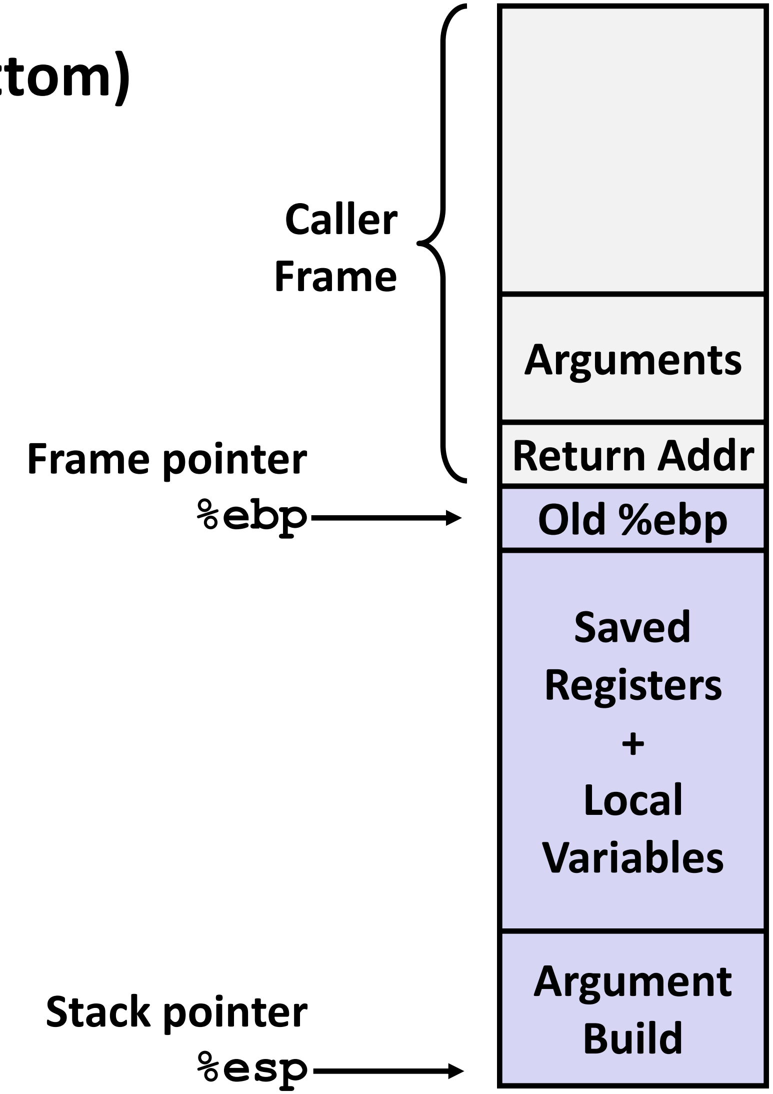




IA32/Linux Stack Frame

- **Current Stack Frame ("Top" to Bottom)**
  - "Argument build:"
    Parameters for function about to call
  - Local variables
    If can't keep in registers
  - Saved register context
  - Old frame pointer

- **Caller Stack Frame**
  - Return address
    - Pushed by `call` instruction
  - Arguments for this call



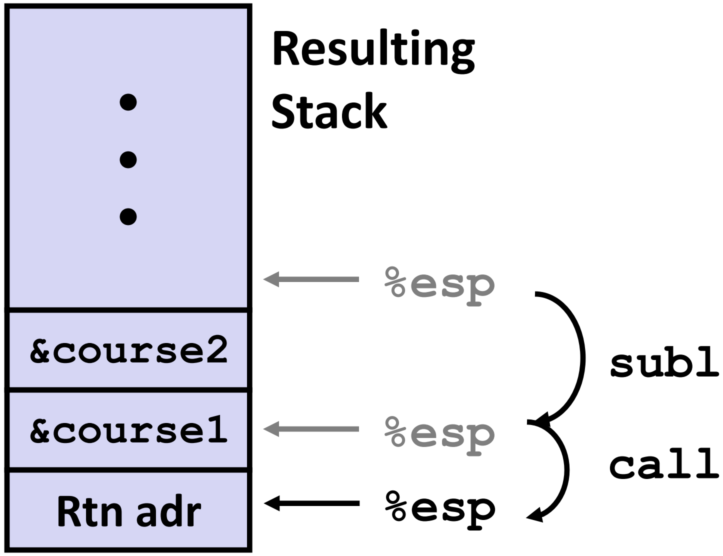
Revisiting swap

```
int course1 = 15213;
int course2 = 18213;

void call_swap() {
  swap(&course1, &course2);
}
```

```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

Calling swap from call_swap

```
call_swap:
    • • •
    subl    $8, %esp
    movl    $course2, 4(%esp)
    movl    $course1, (%esp)
    call    swap
    • • •
```



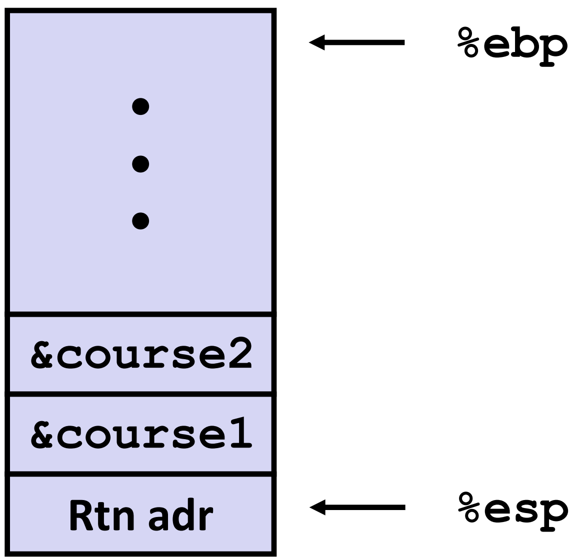
Revisiting swap

```c
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

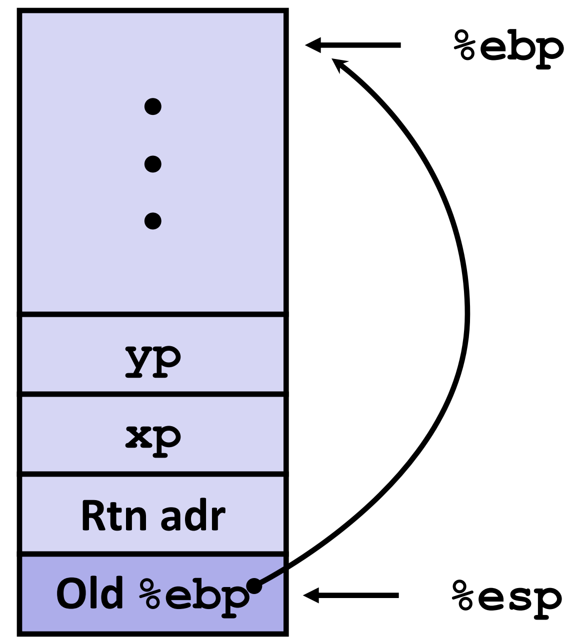
```
swap:
    pushl %ebp              
    movl  %esp, %ebp         Set Up
    pushl %ebx

    movl  8(%ebp), %edx
    movl  12(%ebp), %ecx
    movl  (%edx), %ebx       Body
    movl  (%ecx), %eax
    movl  %eax, (%edx)
    movl  %ebx, (%ecx)

    popl  %ebx
    popl  %ebp               Finish
    ret
```

swap Setup #1

Entering Stack

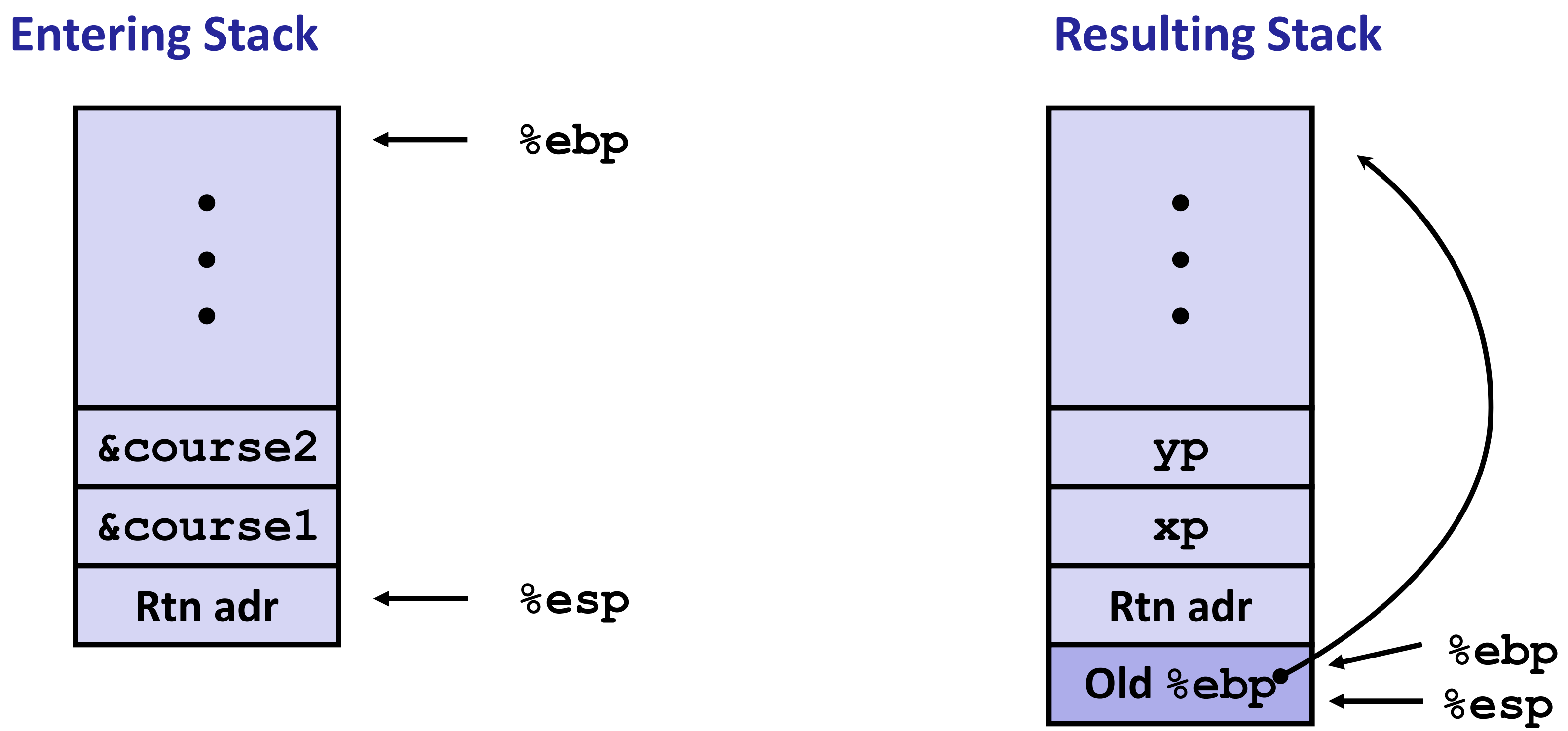


Resulting Stack




```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

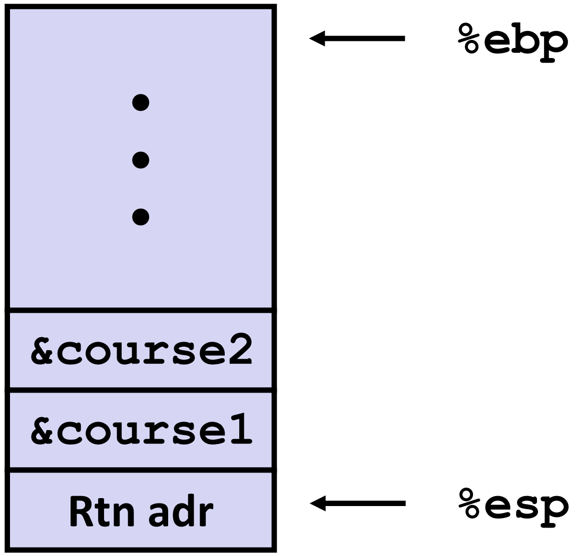
swap Setup #2



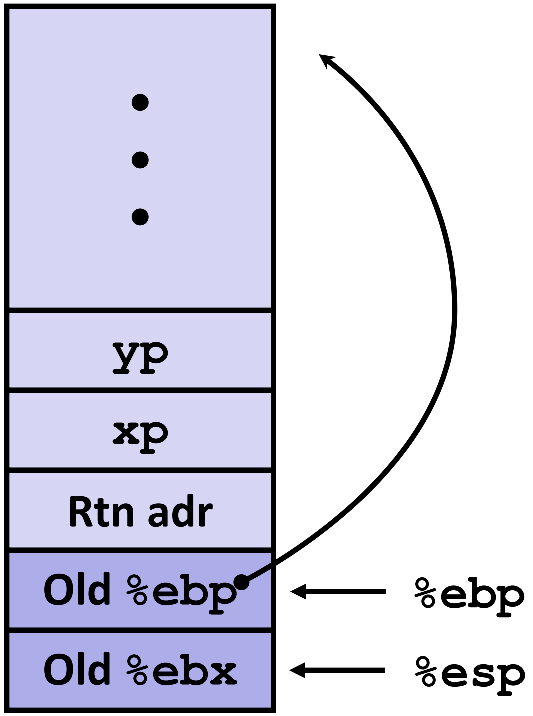

```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

`swap` Setup #3

Entering Stack

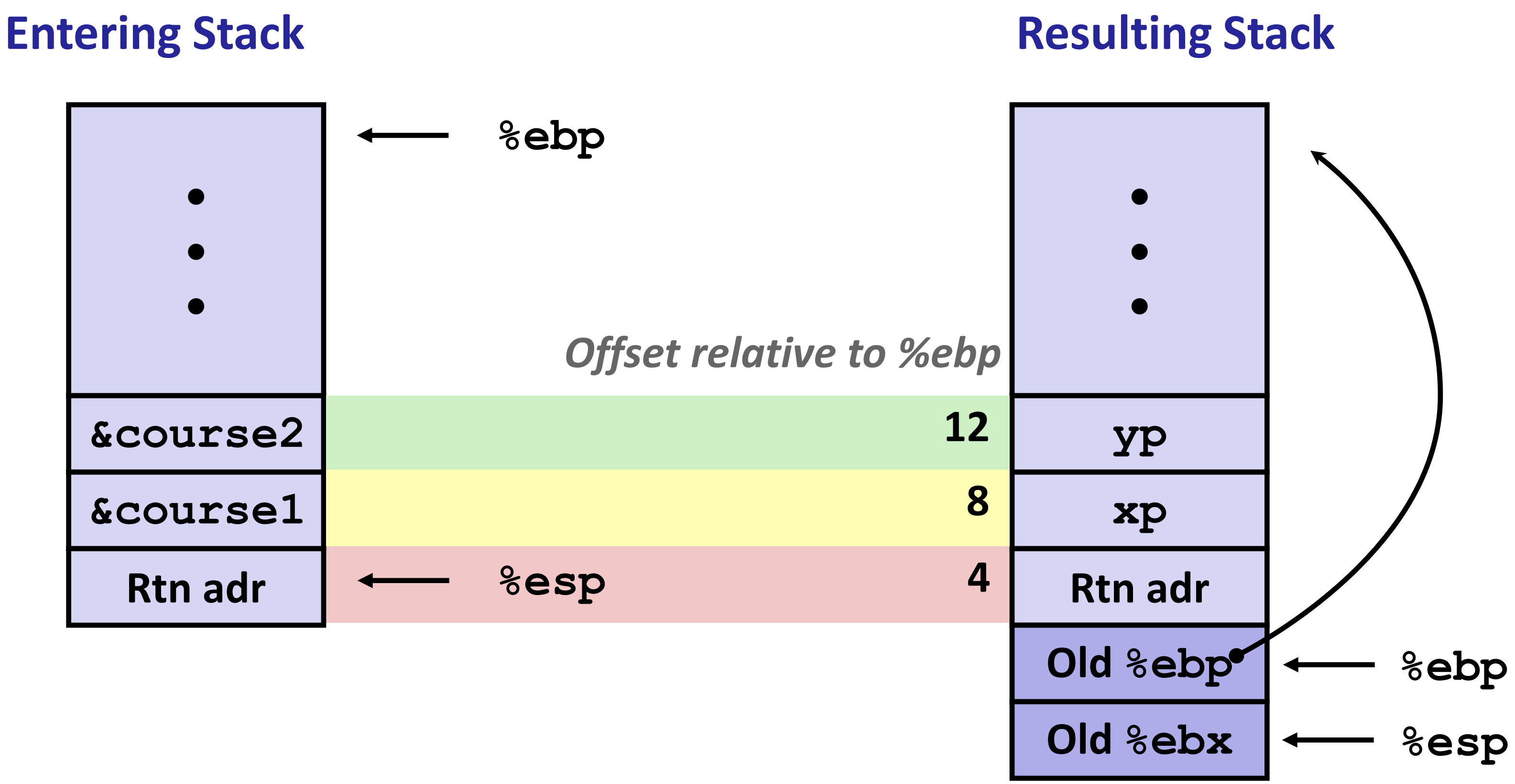


Resulting Stack




```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

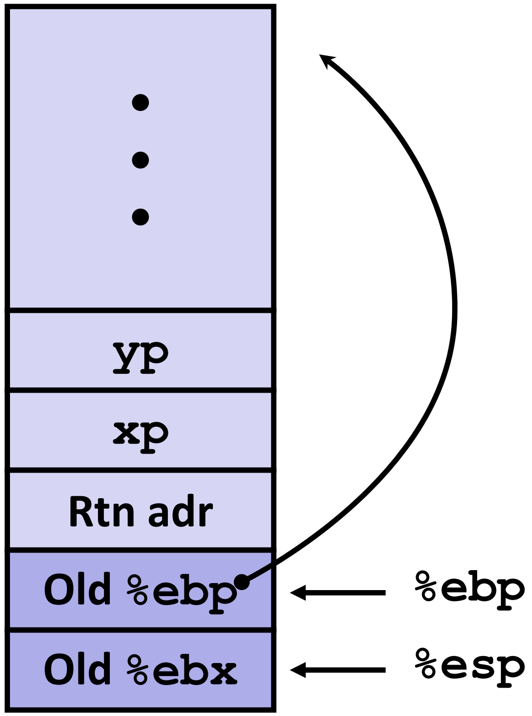
swap Body




```
movl 8(%ebp),%edx    # get xp
movl 12(%ebp),%ecx   # get yp
. . .
```

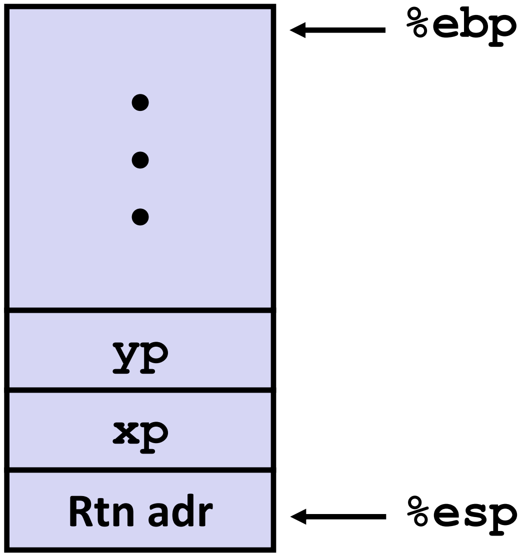
swap Finish

Stack Before Finish




```
popl    %ebx
popl    %ebp
```

Resulting Stack



- **Observation**
  - Saved and restored register **%ebx**
  - Not so for **%eax**, **%ecx**, **%edx**

Disassembled swap

```
08048384 <swap>:
 8048384:   55                      push   %ebp
 8048385:   89 e5                   mov    %esp,%ebp
 8048387:   53                      push   %ebx
 8048388:   8b 55 08                mov    0x8(%ebp),%edx
 804838b:   8b 4d 0c                mov    0xc(%ebp),%ecx
 804838e:   8b 1a                   mov    (%edx),%ebx
 8048390:   8b 01                   mov    (%ecx),%eax
 8048392:   89 02                   mov    %eax,(%edx)
 8048394:   89 19                   mov    %ebx,(%ecx)
 8048396:   5b                      pop    %ebx
 8048397:   5d                      pop    %ebp
 8048398:   c3                      ret
```

Calling Code

```
 80483b4:  movl   $0x8049658,0x4(%esp) # Copy &course2
 80483bc:  movl   $0x8049654,(%esp)    # Copy &course1
 80483c3:  call   8048384 <swap>       # Call swap
 80483c8:  leave                       # Prepare to return
 80483c9:  ret                         # Return
```

Today

- Switch statements
- IA 32 Procedures
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

Register Saving Conventions

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

```
yoo:
    • • •
    movl $15213, %edx
    call who
    addl %edx, %eax
    • • •
    ret
```

```
who:
    • • •
    movl 8(%ebp), %edx
    addl $18243, %edx
    • • •
    ret
```

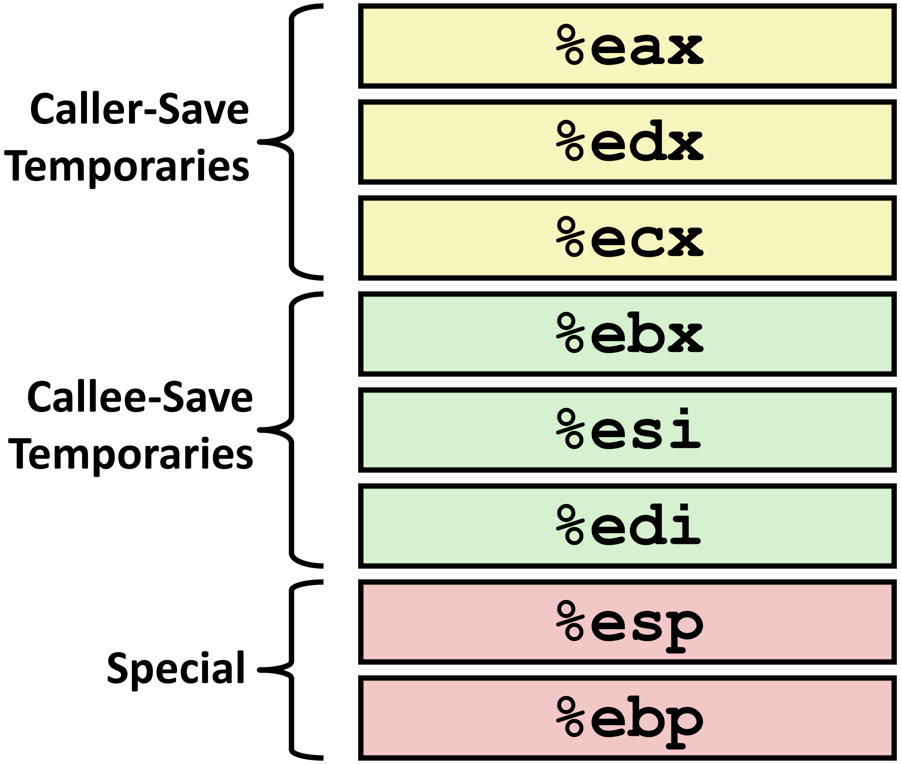
  - Contents of register `%edx` overwritten by `who`
  - This could be trouble ➞ something should be done!
    - Need some coordination

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 in its frame before the call
  - ***"Callee Save"***
    - Callee saves temporary values in its frame before using

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



Today

- Switch statements
- IA 32 Procedures
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

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

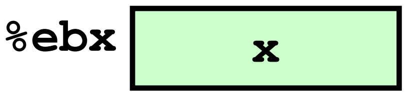
```
pcount_r:
    pushl  %ebp
    movl   %esp, %ebp
    pushl  %ebx
    subl   $4, %esp
    movl   8(%ebp), %ebx
    movl   $0, %eax
    testl  %ebx, %ebx
    je   .L3
    movl   %ebx, %eax
    shrl   %eax
    movl   %eax, (%esp)
    call   pcount_r
    movl   %ebx, %edx
    andl   $1, %edx
    leal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

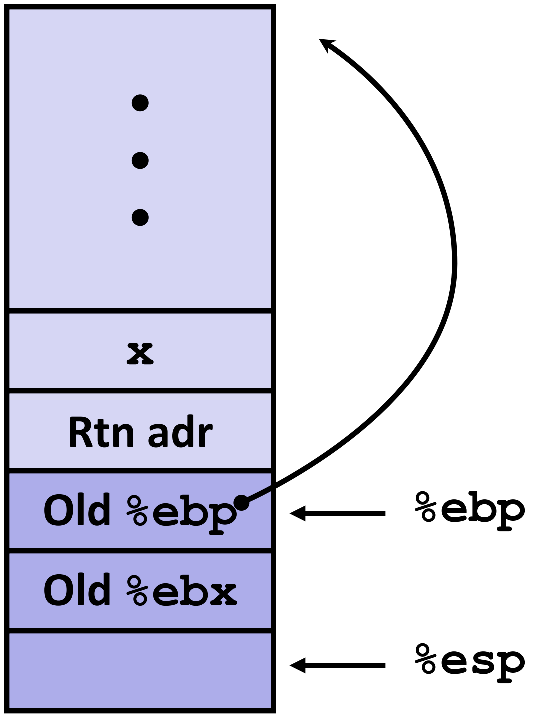
Recursive Call #1

```
/* 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`





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

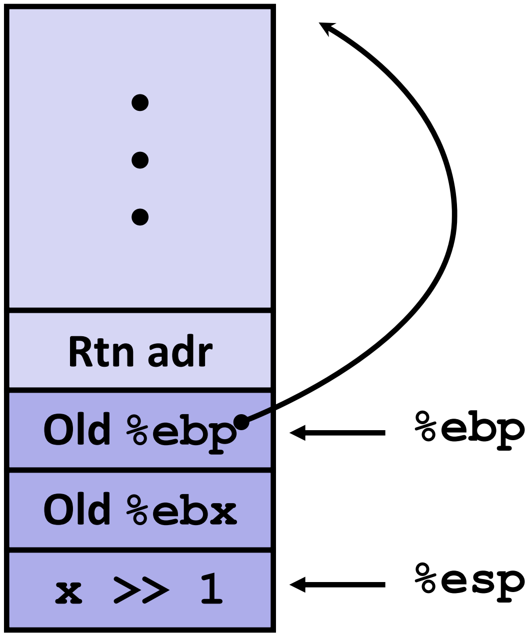
`%ebx`	`x`

Recursive Call #3

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

```
  • • •
movl   %ebx, %eax
shrl   %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



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

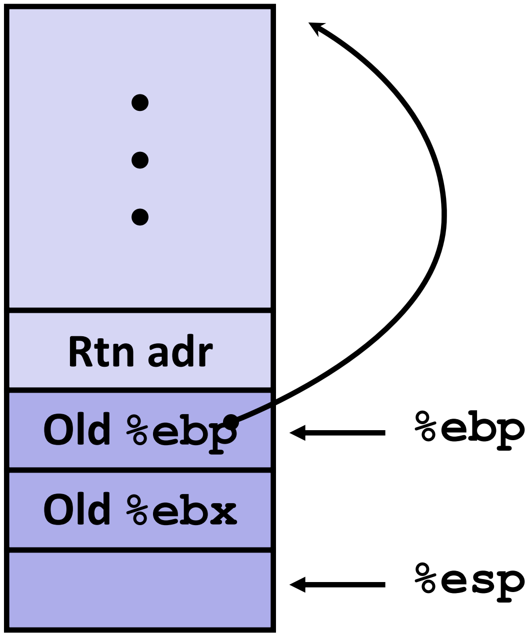
%ebx	x

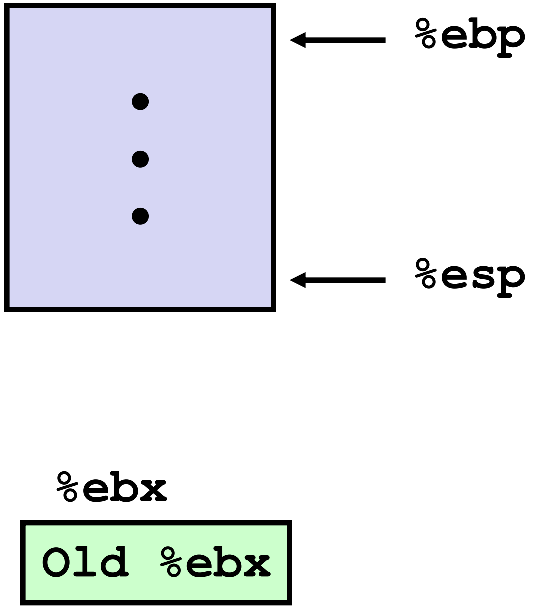
Recursive Call #5

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

```
      • • •
L3:
     addl $4, %esp
     popl %ebx
     popl %ebp
     ret
```

- **Actions**
  - Restore values of %ebx and %ebp
  - Restore %esp





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

Pointer Code

Generating Pointer

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

Referencing Pointer

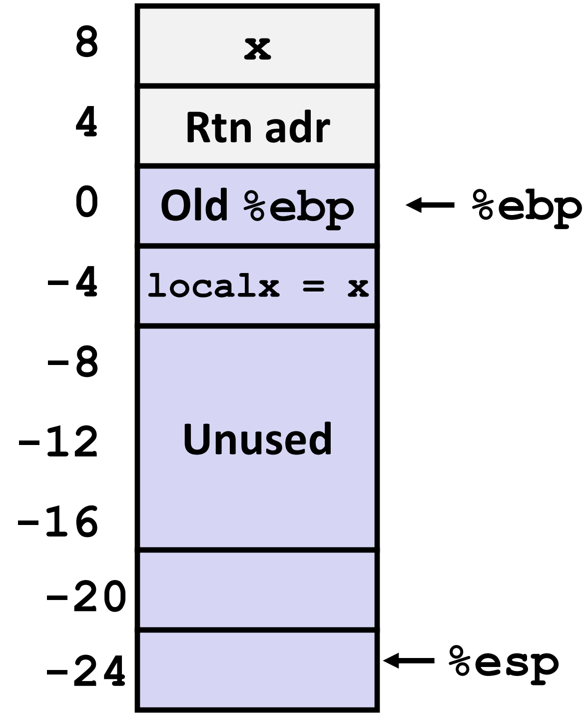
```
/* Increment value by k */
void incrk(int *ip, int k) {
  *ip += k;
}
```

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

Creating and Initializing Local Variable

```
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
```

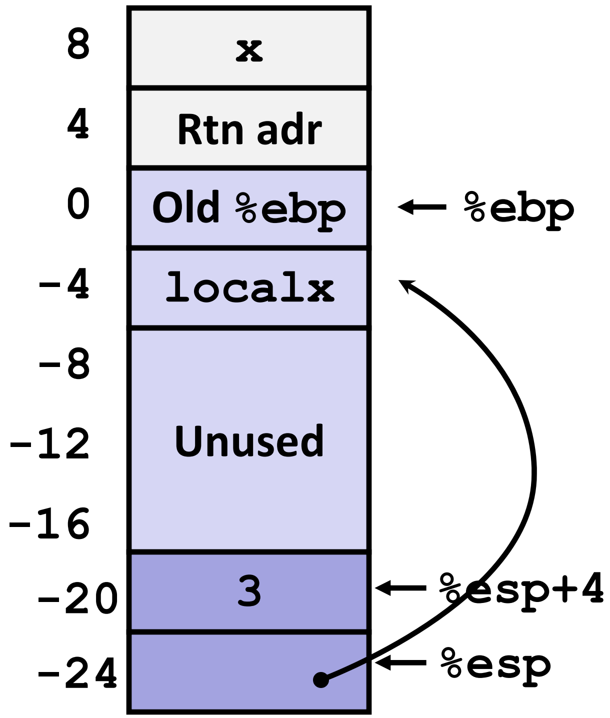
Creating Pointer as Argument

```
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
```



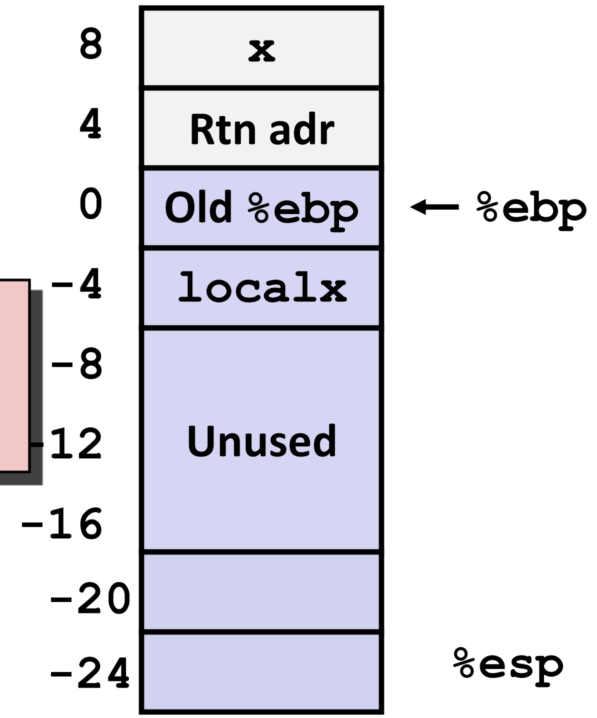
Retrieving local variable

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

- Retrieve localx from stack as return value

Final part of add3

```
movl -4(%ebp), %eax # Return val= localx
leave
ret
```



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**