MACHINE-LEVEL PROGRAMMING III: SWITCH STATEMENTS AND IA32 PROCEDURES

Today

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

Switch Statement Example

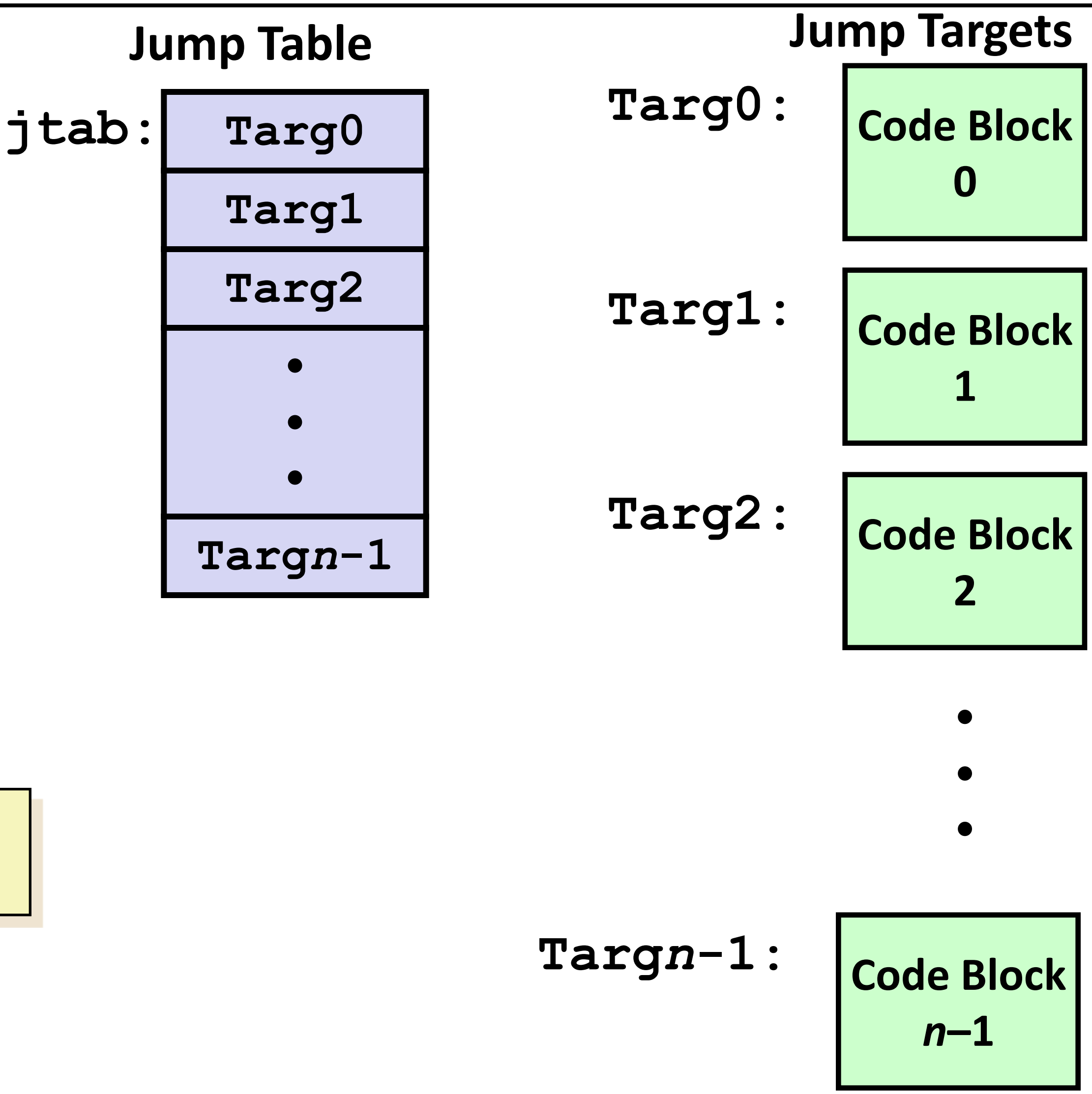
```
long switch_eg
   (long x, long y, long z)
{
    long w = 1;
    switch(x) {
    case 1:
        w = y*z;
        break;
    case 2:
        w = y/z;
        /* Fall Through */
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w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

- 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

Assembly Setup Explanation

- Table Structure
  - Each target requires 4 bytes
  - Base address at **.L7**

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
```

- 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 $0 \leq \mathbf{x} \leq 6$

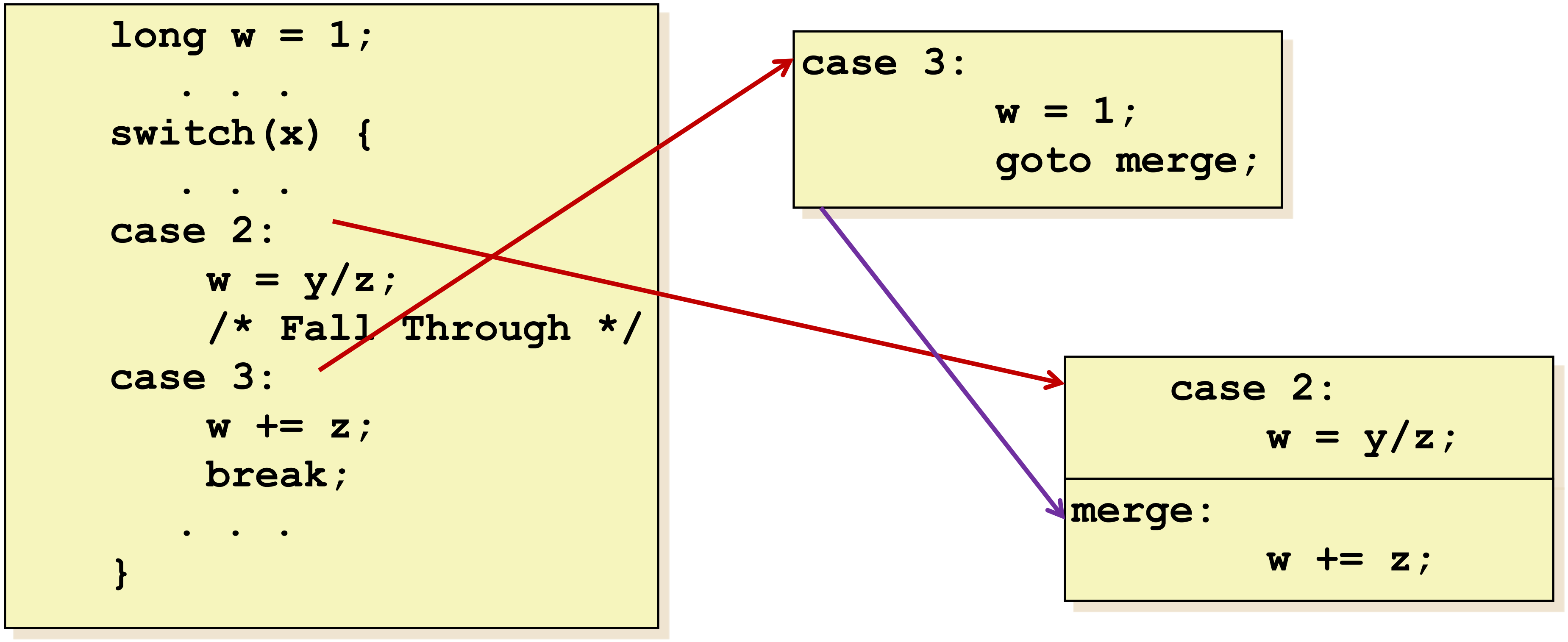
Jump Table

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
```

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`**
    - E<u>x</u>amine <u>7</u> he<u>x</u>adecimal format “<u>w</u>ords” (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
```

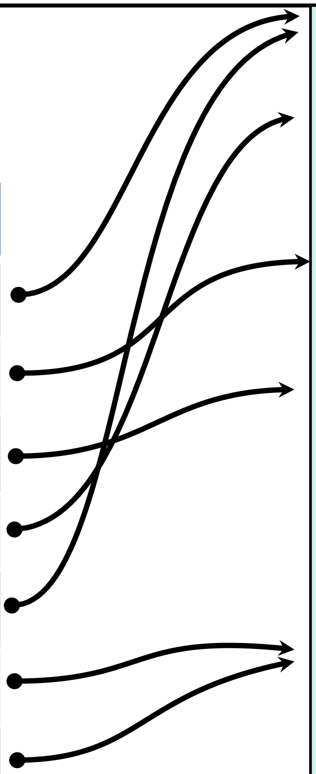
Address	Value	x
0x8048660	0x8048422	0
0x8048664	0x8048432	1
0x8048668	0x804843b	2
0x804866c	0x8048429	3
0x8048670	0x8048422	4
0x8048674	0x804844b	5
0x8048678	0x804844b	6

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

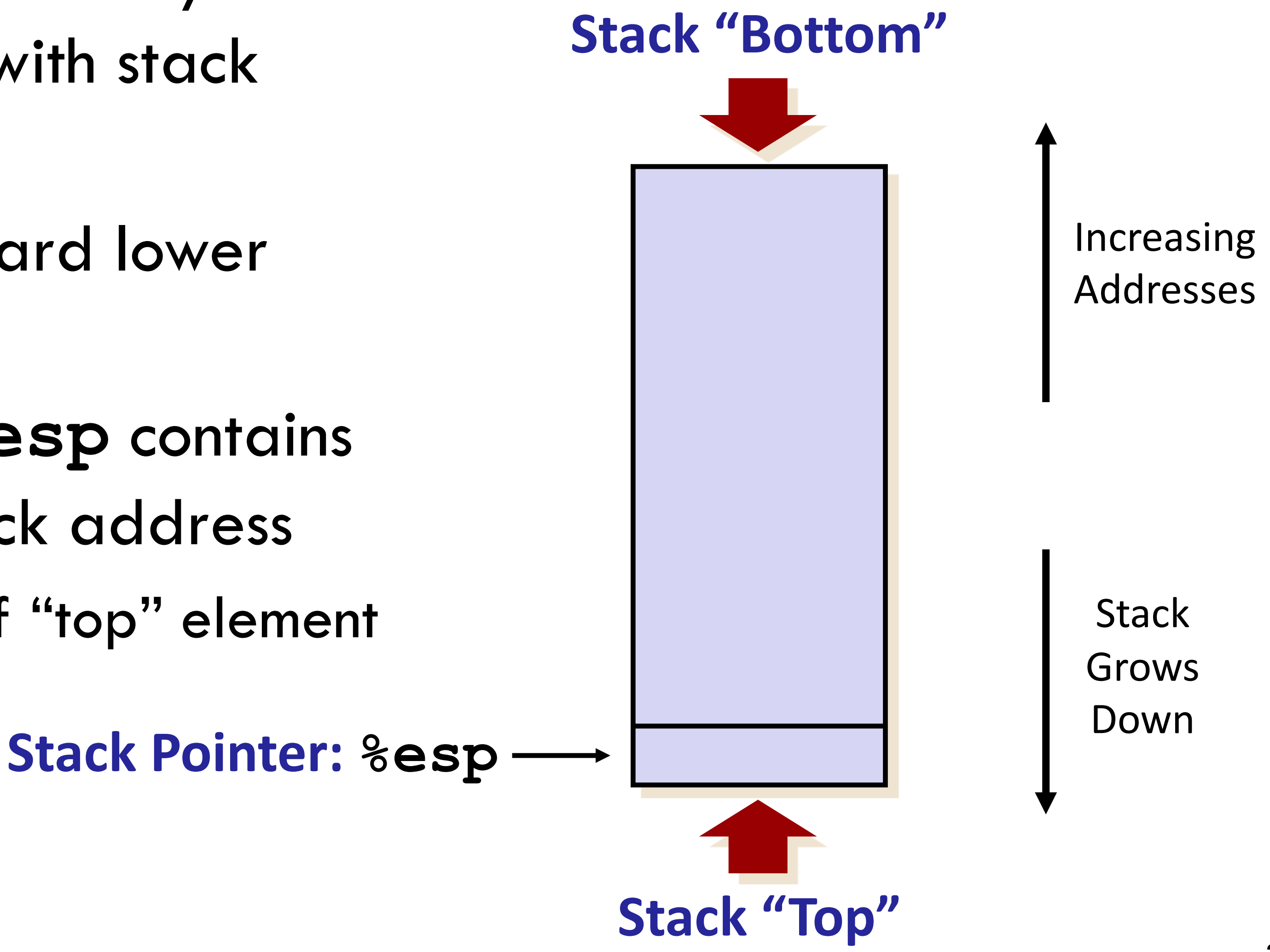
- C Control
  - if-then-else
  - do-while
  - while, for
  - switch
- Assembler Control
  - Conditional jump
  - Conditional move
  - Indirect jump
  - Compiler generates code sequence to implement more complex control
- Standard Techniques
  - Loops converted to do-while form
  - Large switch statements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

Today

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

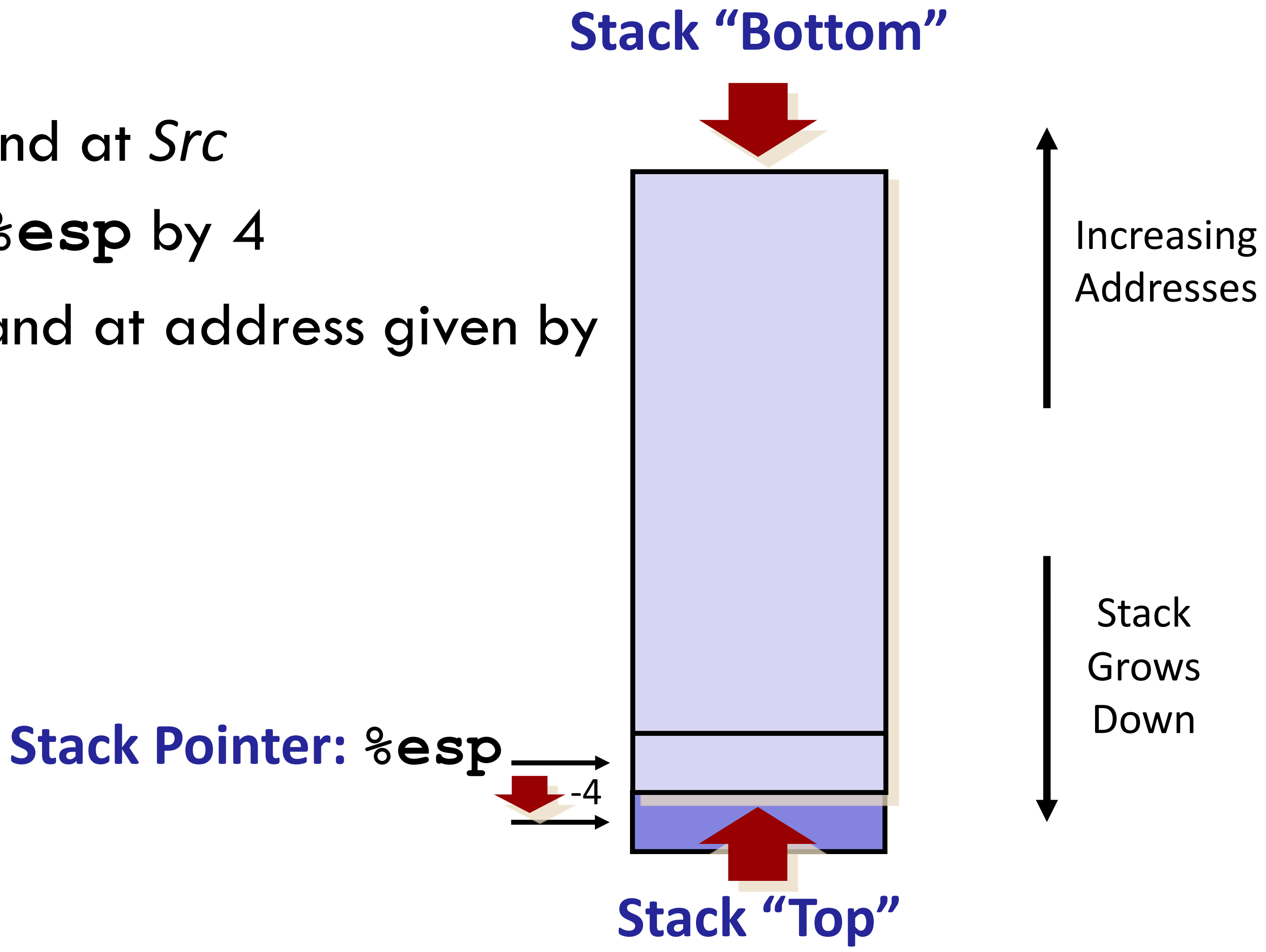
IA32 Stack

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

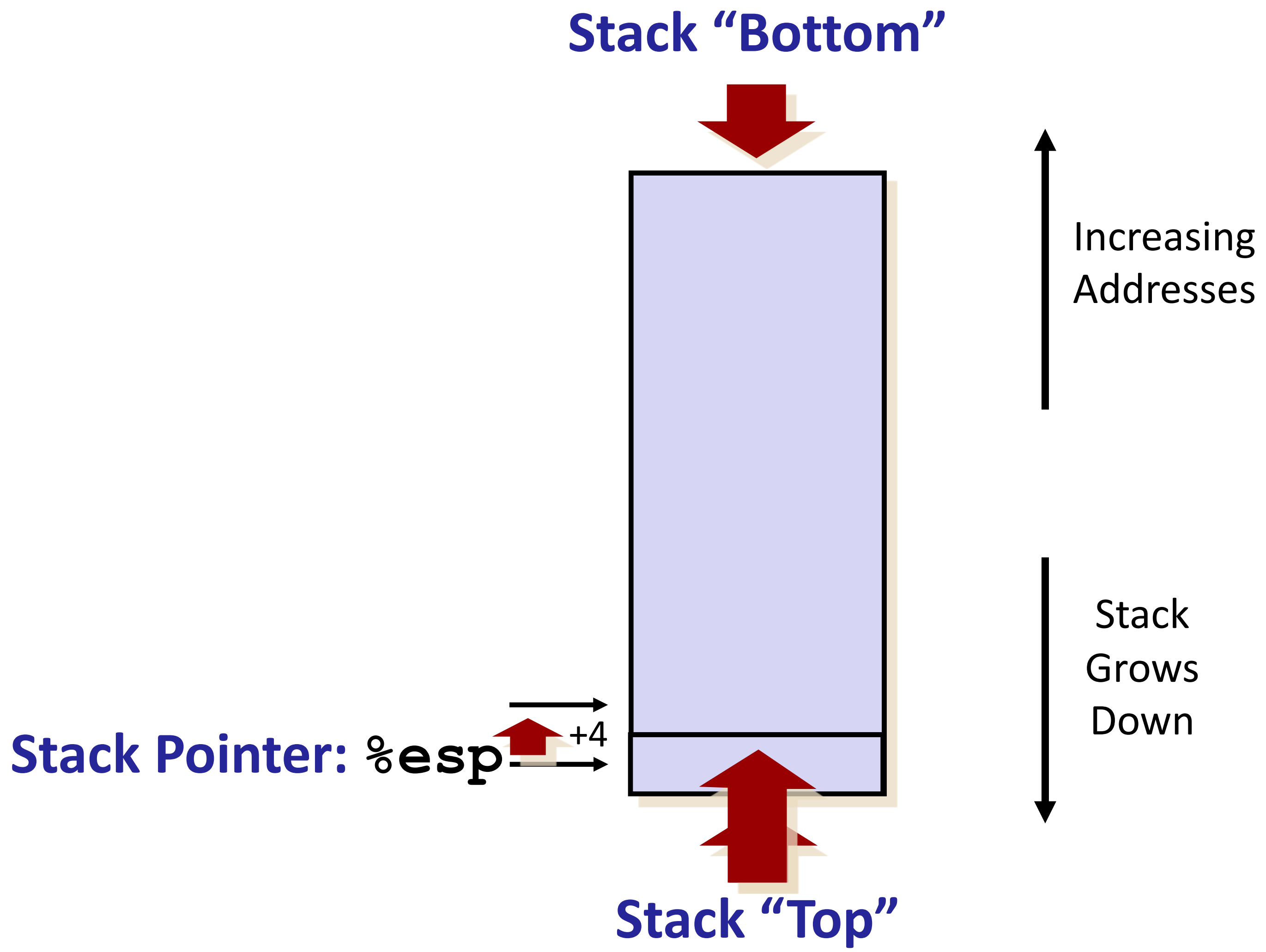


IA32 Stack: Push

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



IA32 Stack: Pop



Procedure Control Flow

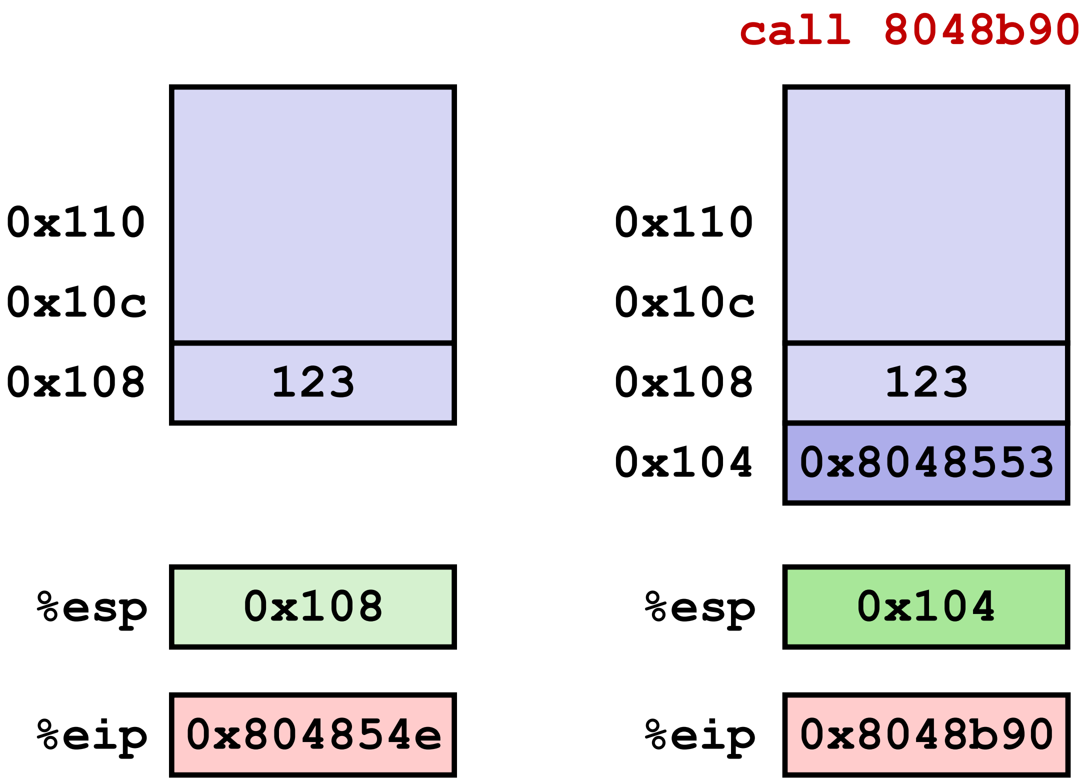
- Use stack to support procedure call and return
- Procedure call: **`call label`**
  - Push return address on stack
  - Jump to ***label***
- Return address:
  - Address of the next instruction right after call
  - Example from disassembly

```
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

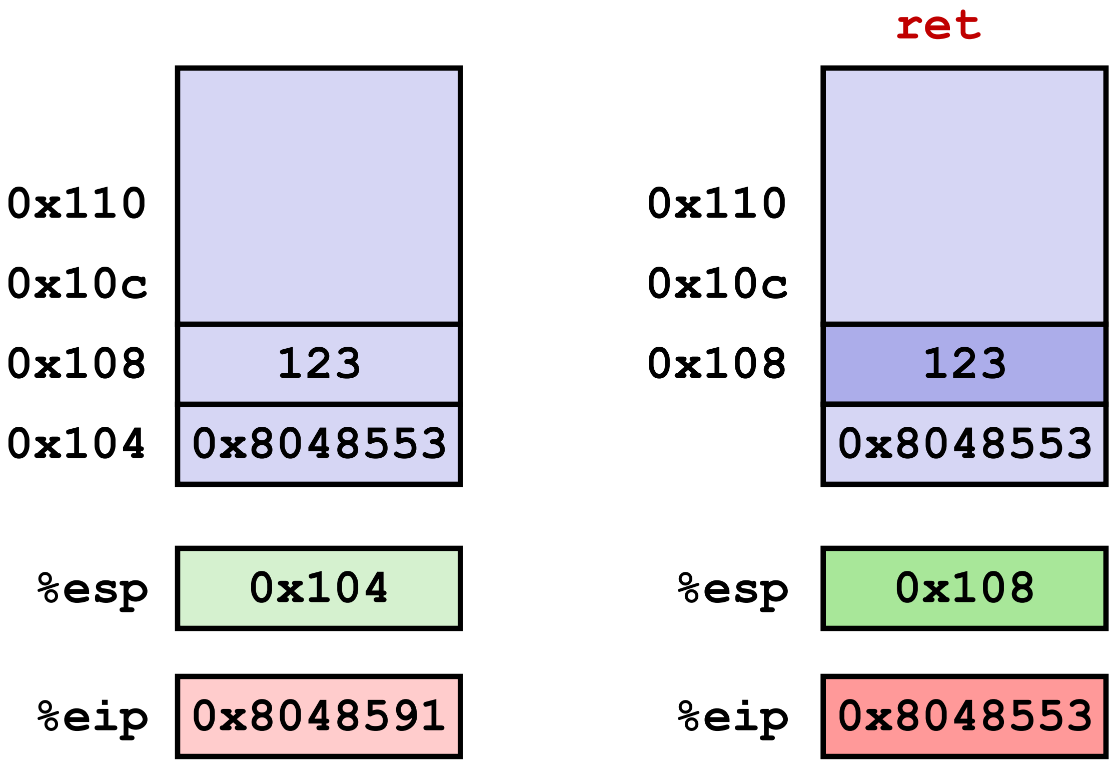
```
804854e:      e8 3d 06 00 00        call    8048b90 <main>
8048553:      50                    pushl   %eax
```



`%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();
   •
   •
}
```

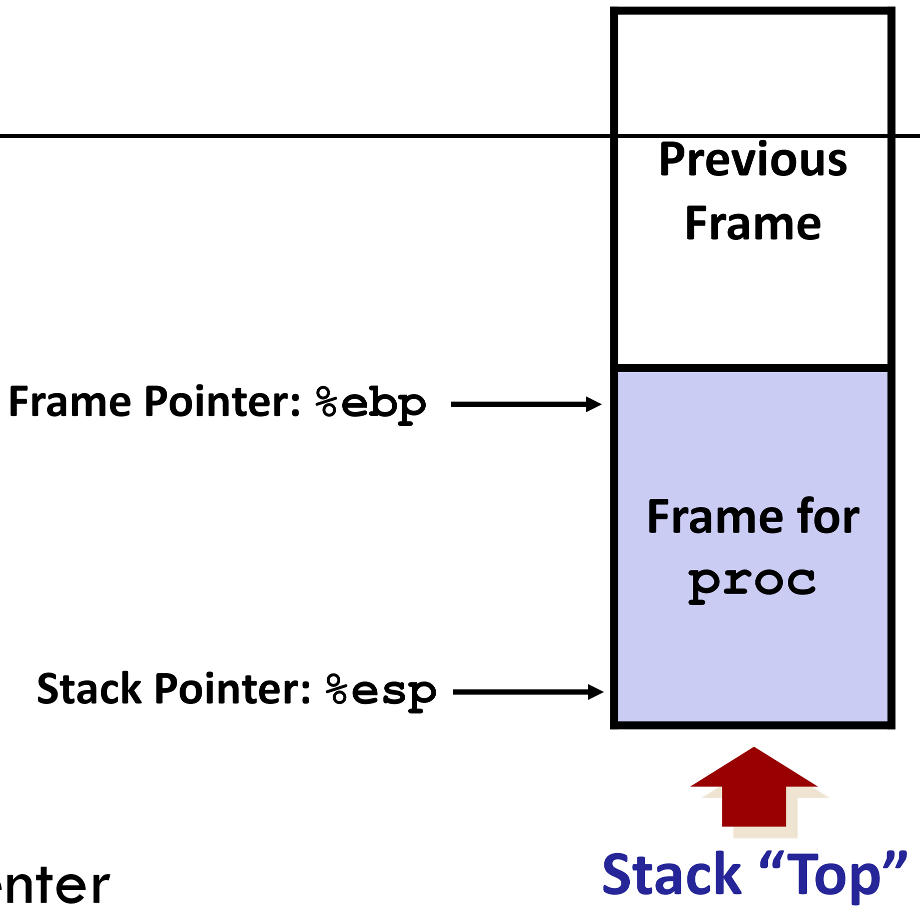
Example Call Chain

$$\begin{tikzcd}
\texttt{yoo} \arrow[d] & \\
\texttt{who} \arrow[d] \arrow[dr] & \\
\texttt{amI} \arrow[d] & \texttt{amI} \\
\texttt{amI} \arrow[d] & \\
\texttt{amI} &
\end{tikzcd}$$

Procedure `amI()` is recursive

Stack Frames

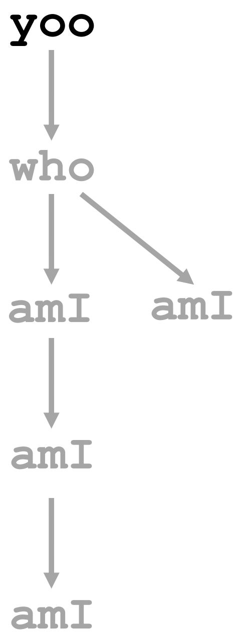
- Contents
  - Local variables
  - Return information
  - Temporary space

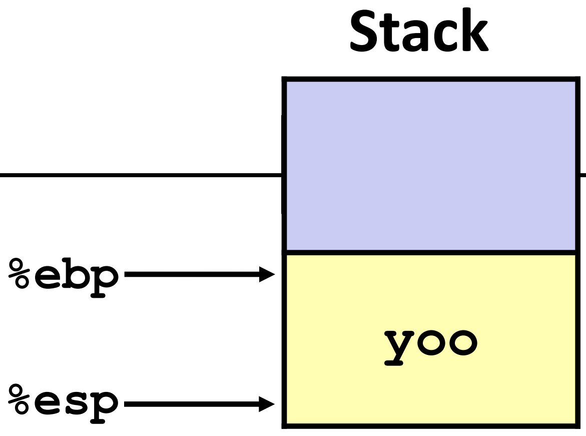


- Management
  - Space allocated when enter procedure
    - "Set-up" code
  - Deallocated when return
    - "Finish" code

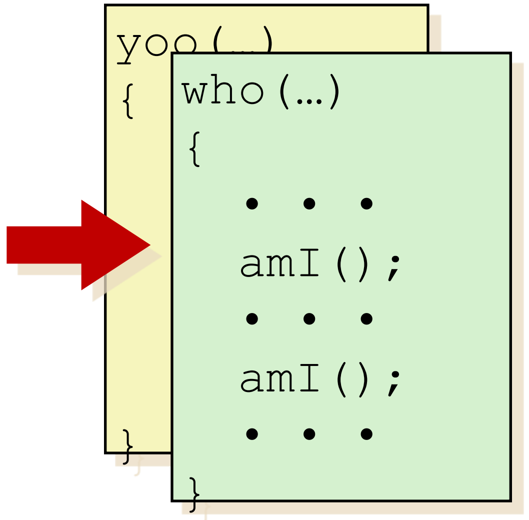
Example

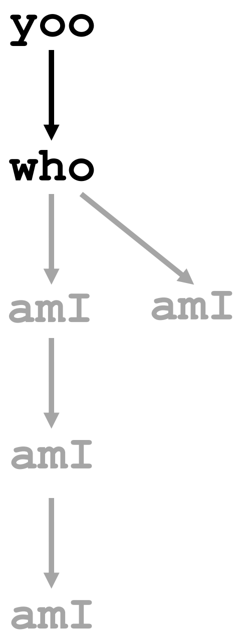
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

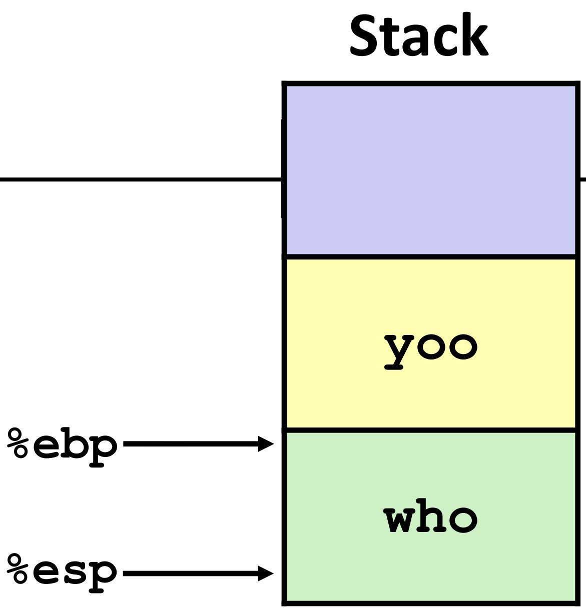




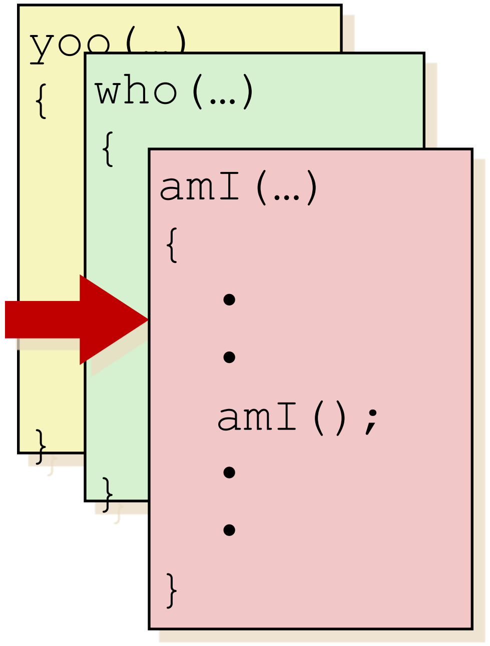
Example

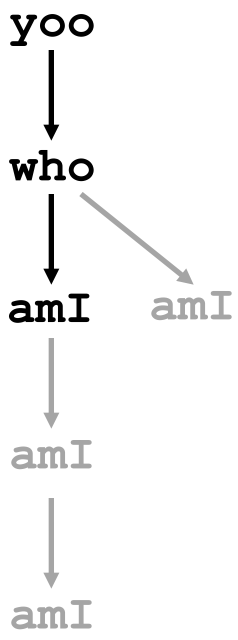


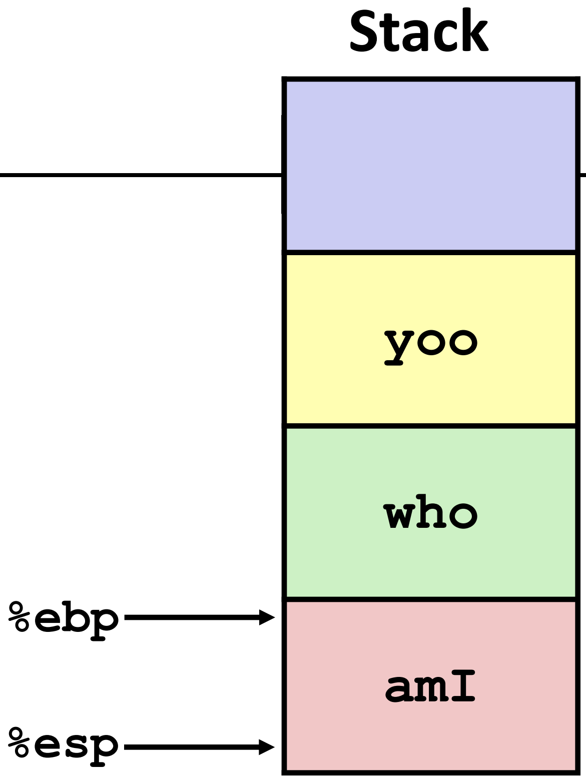




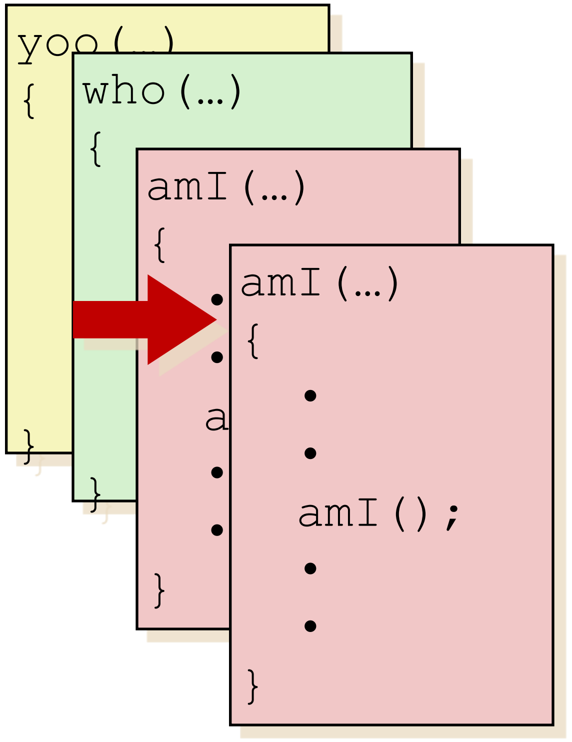
Example

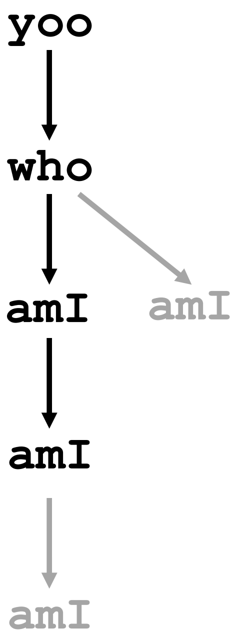

yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
amI();
•
•
}

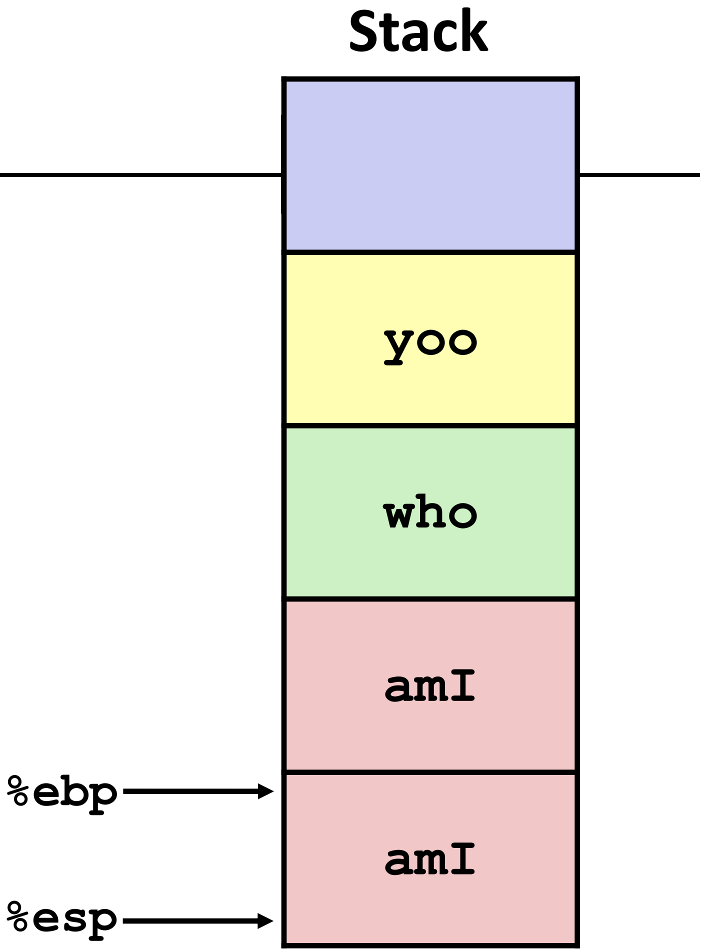

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
%ebp
%esp

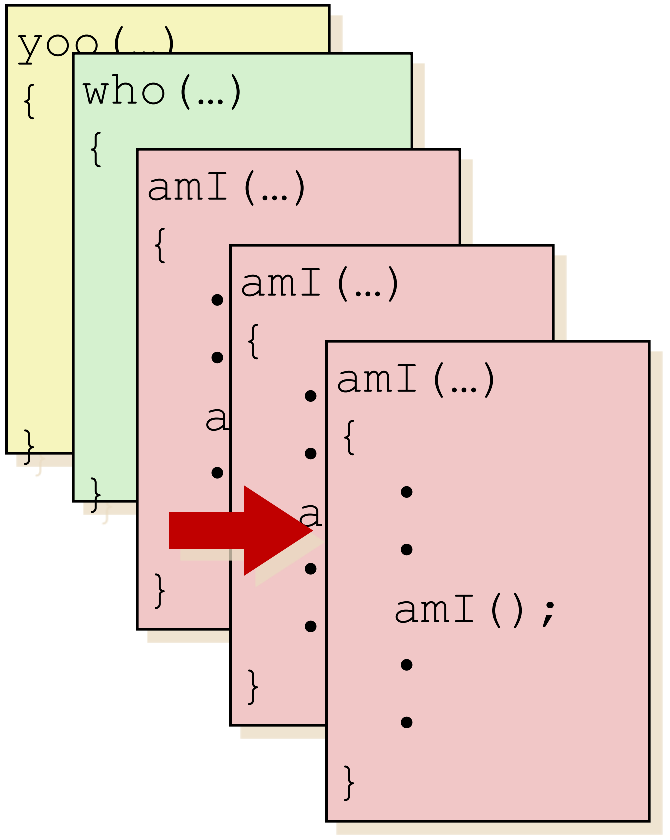
Example

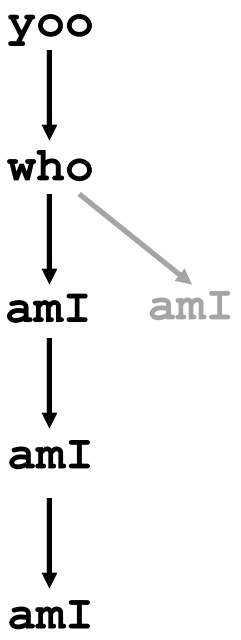

yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
a
•
•
}
amI(…)
{
•
•
amI();
•
•
}

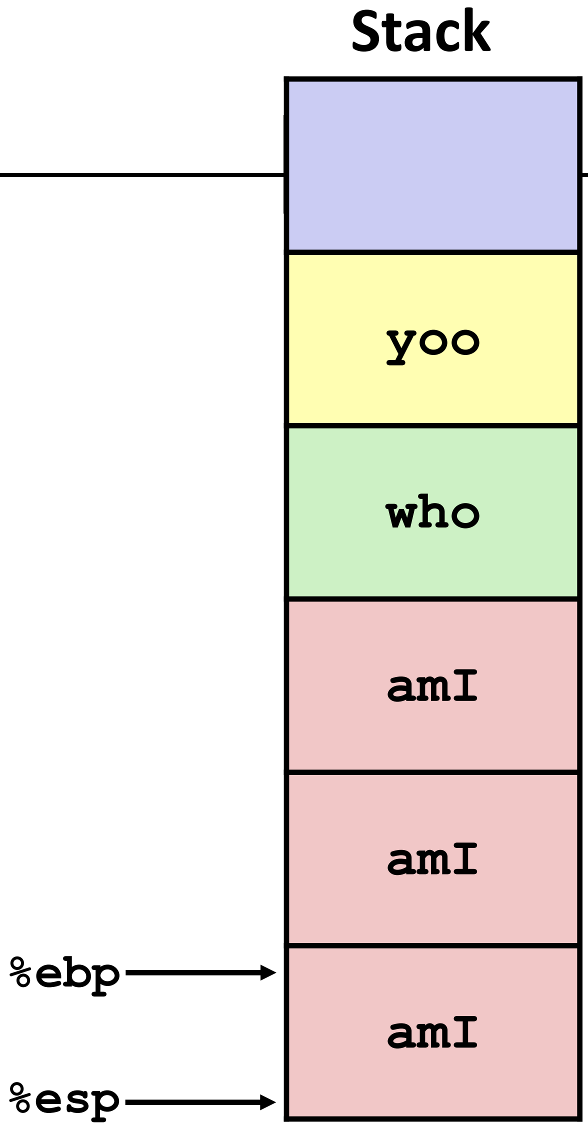

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
%ebp
%esp

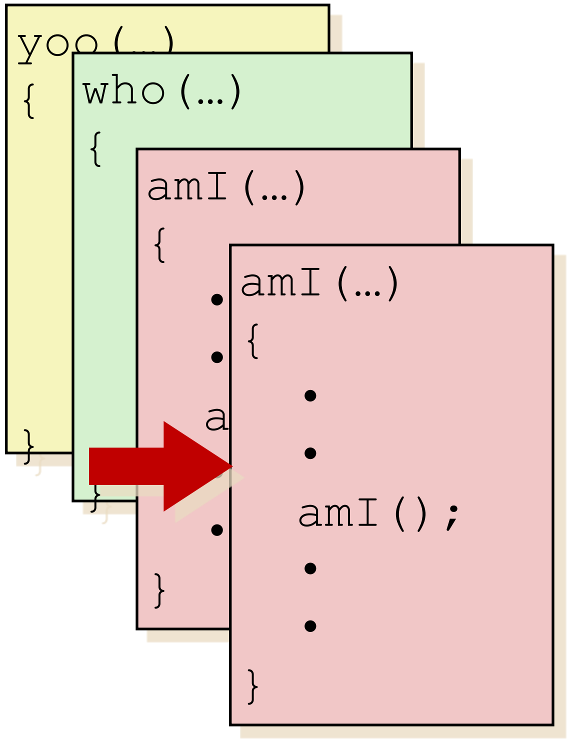
Example


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


yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
amI
%ebp
%esp

Example


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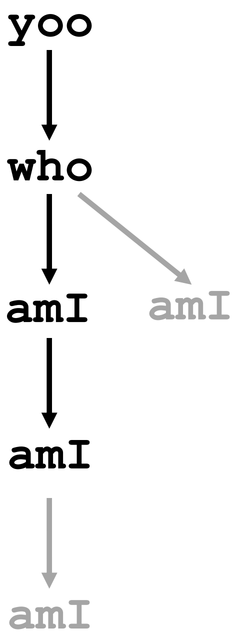
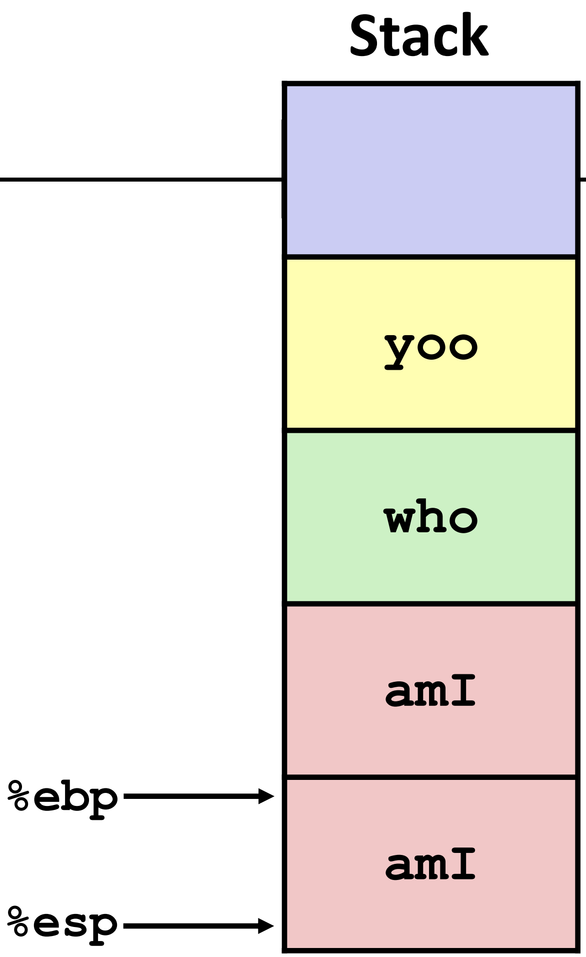
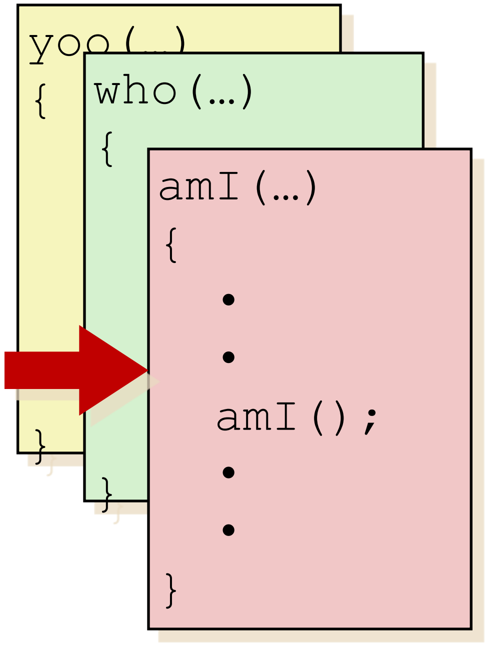
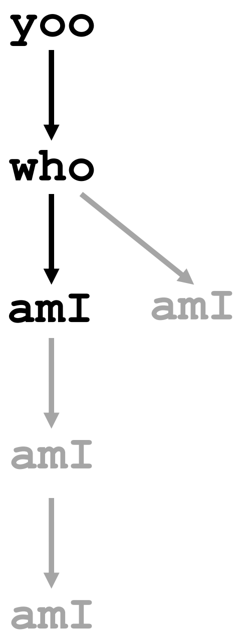
amI(…)
{
•
•
amI();
•
•
}

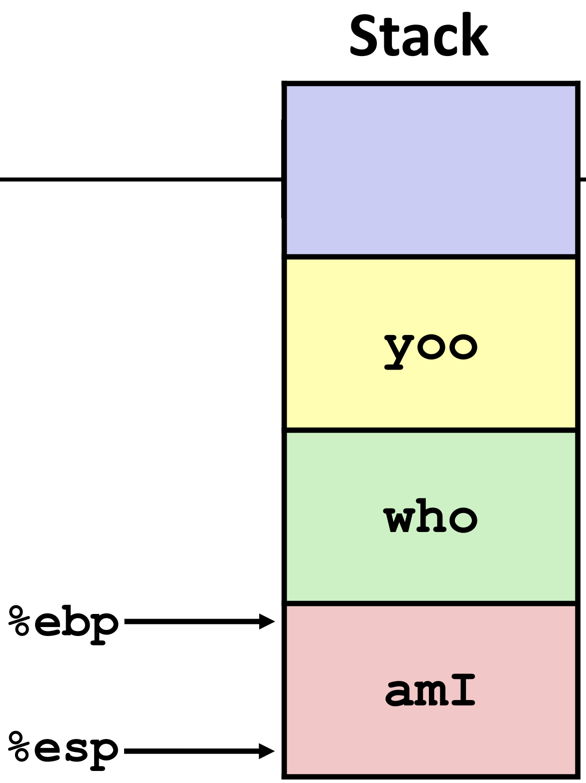

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
%ebp
%esp

Example

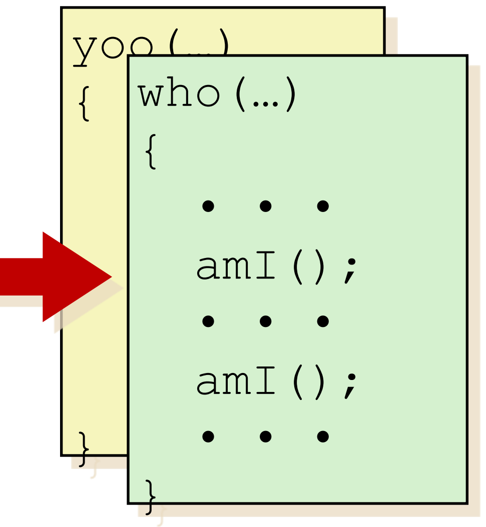

yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
amI();
•
•
}

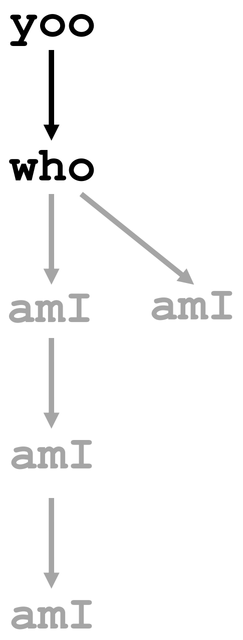

yoo
who
amI
amI
amI
amI

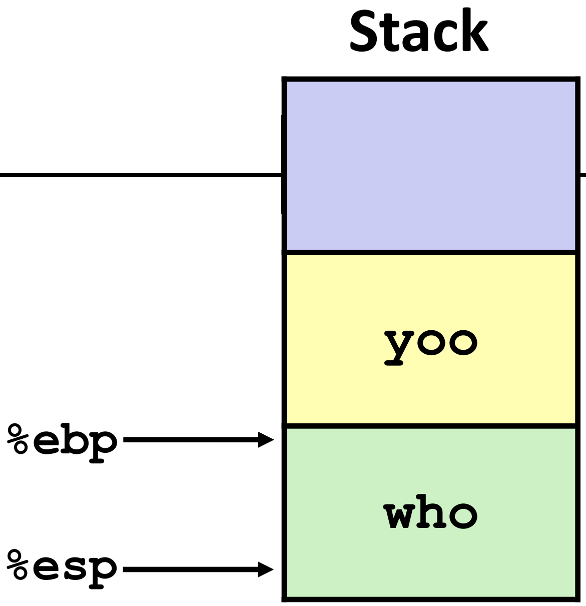

Stack
yoo
who
amI
%ebp
%esp

Example

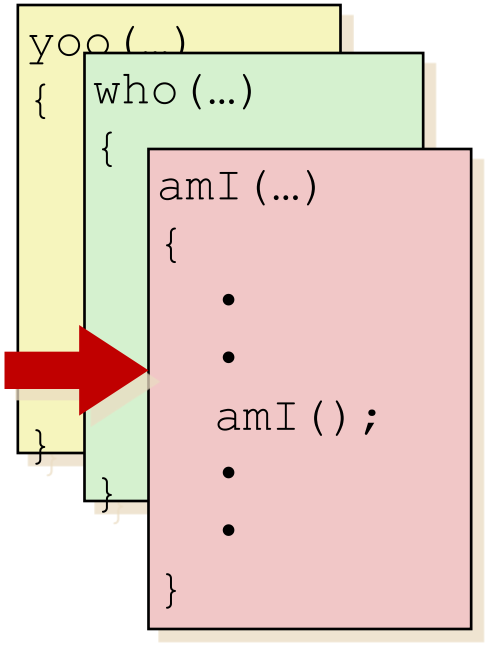
```
yoo(…)
{
  who(…)
  {
    • • •
    amI();
    • • •
    amI();
    • • •
  }
}
```

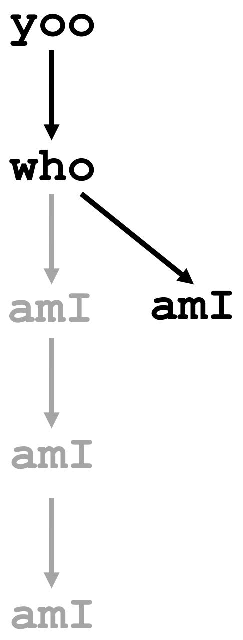


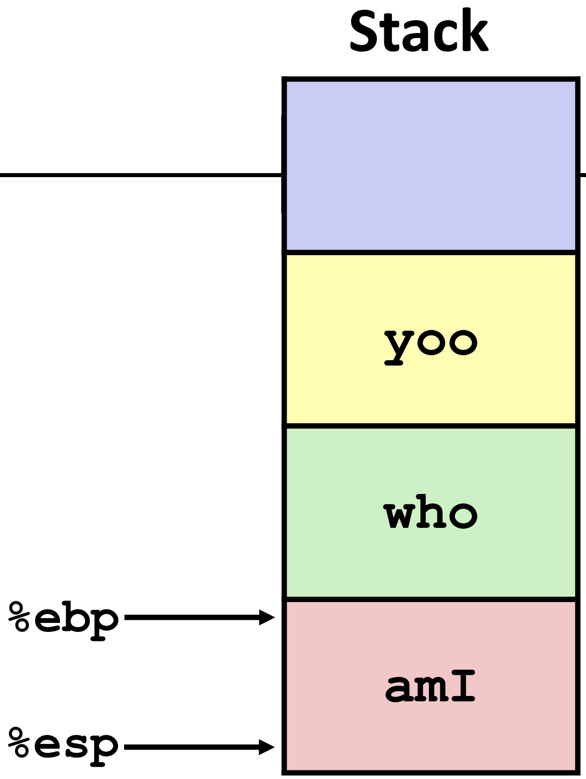




Example


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


yoo
who
amI
amI
amI
amI
amI

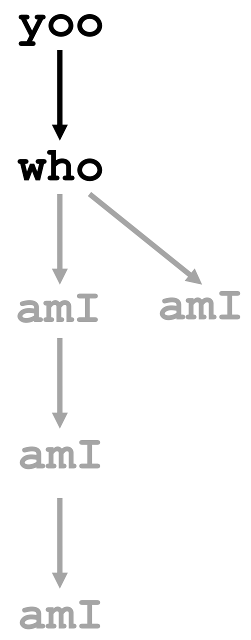

Stack
yoo
who
amI
%ebp
%esp

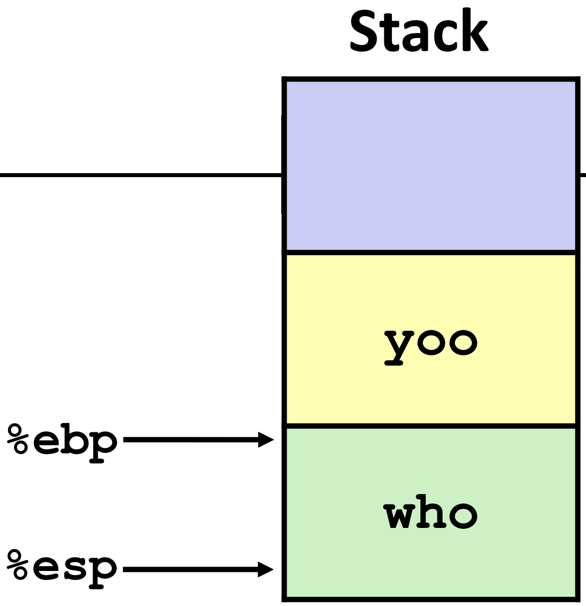
Example

```
yoo(…)
{
```

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

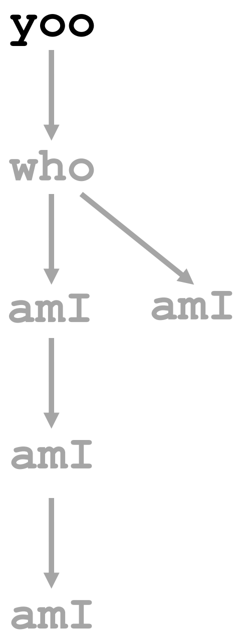
```
}
```

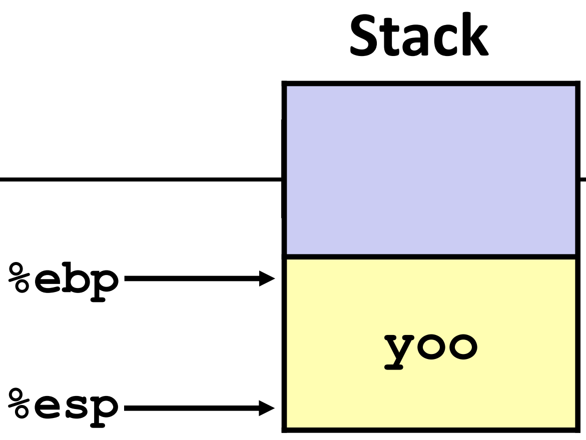




Example

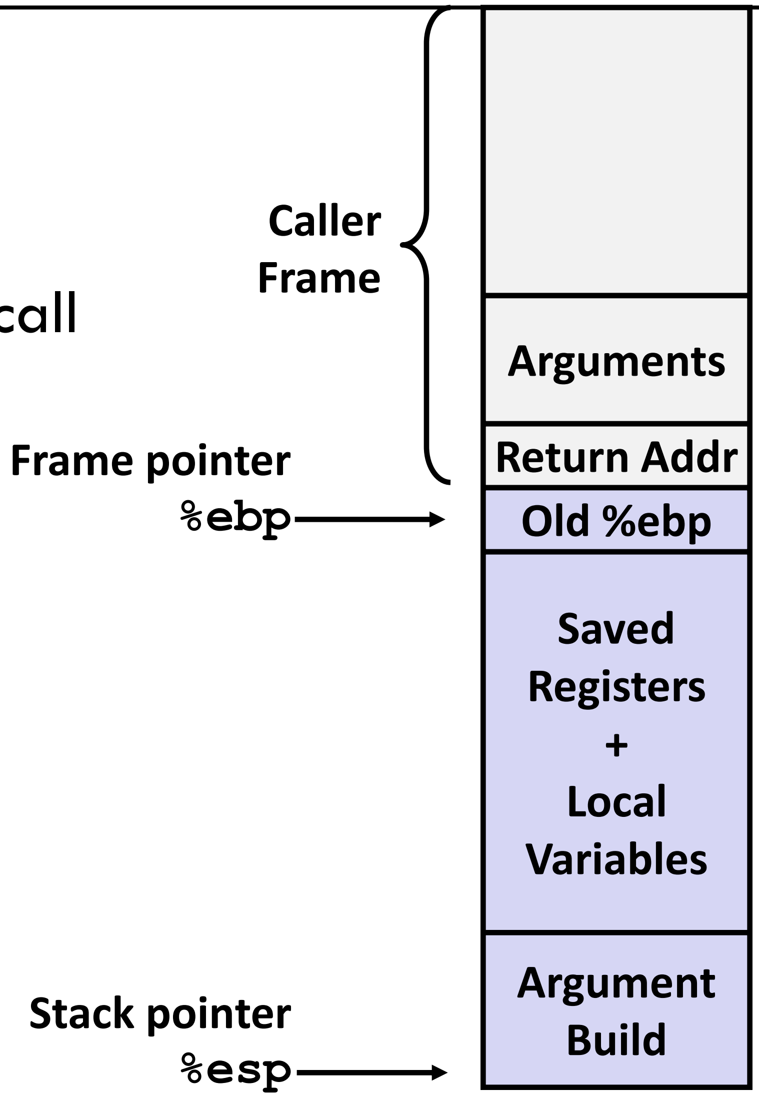
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```





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



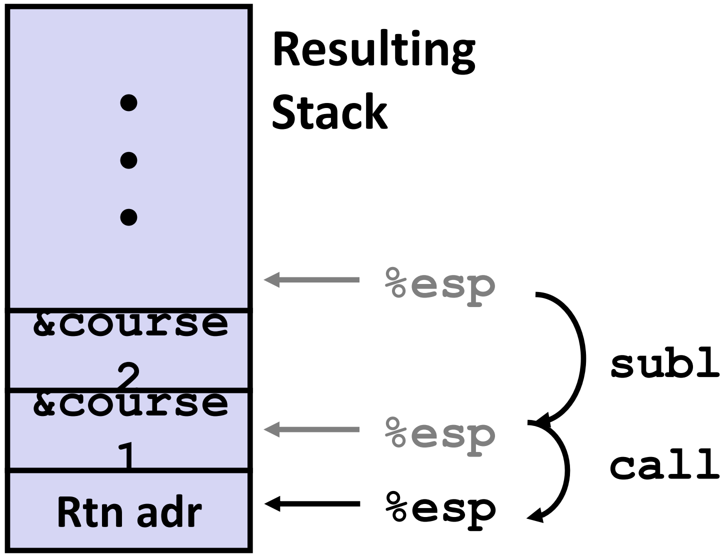
Revisiting swap

```
int course1 = 15213;
int course2 = 18243;

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

Calling swap from call_swap

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

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



Revisiting swap

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

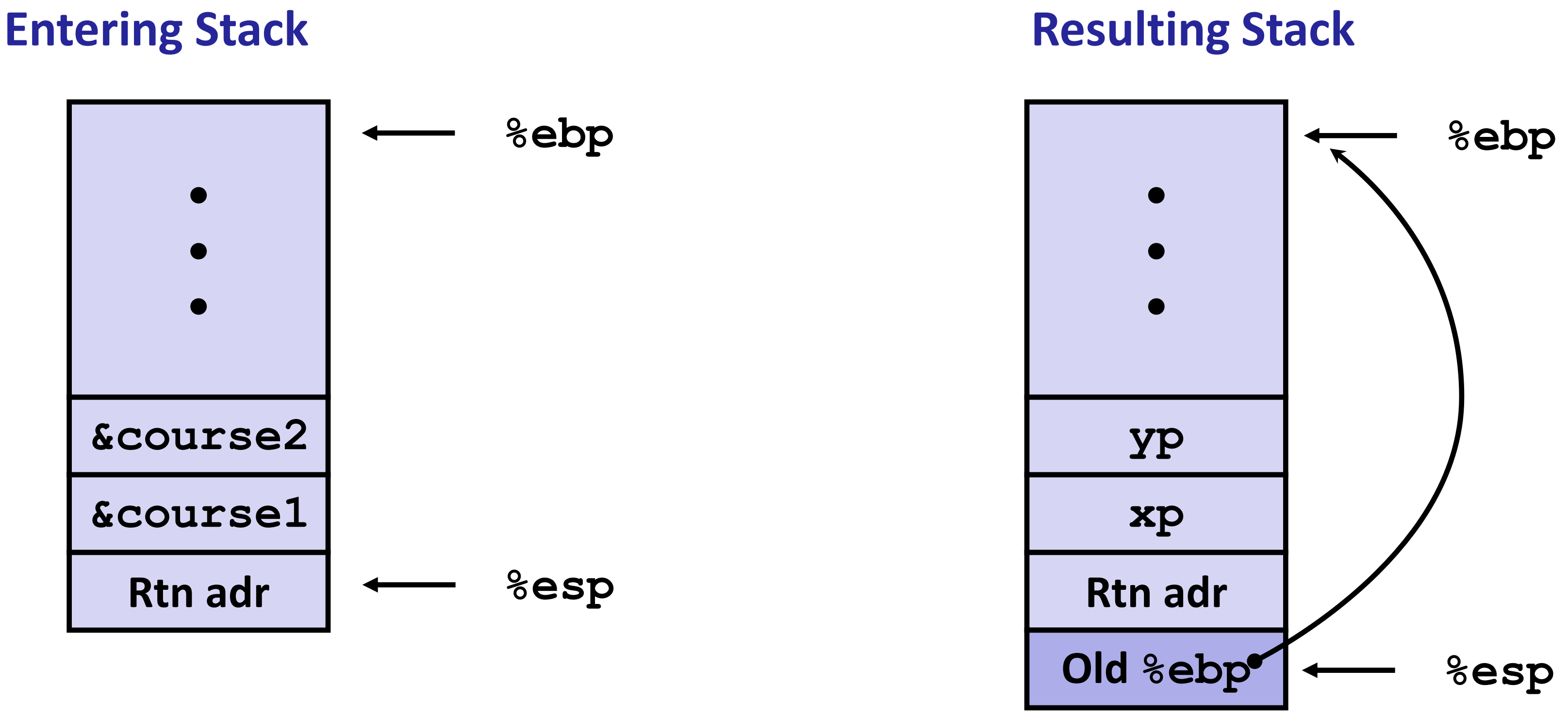
```
swap:
    pushl %ebp
    movl  %esp, %ebp
    pushl %ebx

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

    popl  %ebx
    popl  %ebp
    ret
```

$\left.\begin{array}{l}\texttt{pushl \%ebp}\\ \texttt{movl \%esp, \%ebp}\\ \texttt{pushl \%ebx}\end{array}\right\}$ **Set Up**

$\left.\begin{array}{l}\texttt{movl 8(\%ebp), \%edx}\\ \texttt{...}\\ \texttt{movl \%ebx, (\%ecx)}\end{array}\right\}$ **Body**

$\left.\begin{array}{l}\texttt{popl \%ebx}\\ \texttt{popl \%ebp}\\ \texttt{ret}\end{array}\right\}$ **Finish**

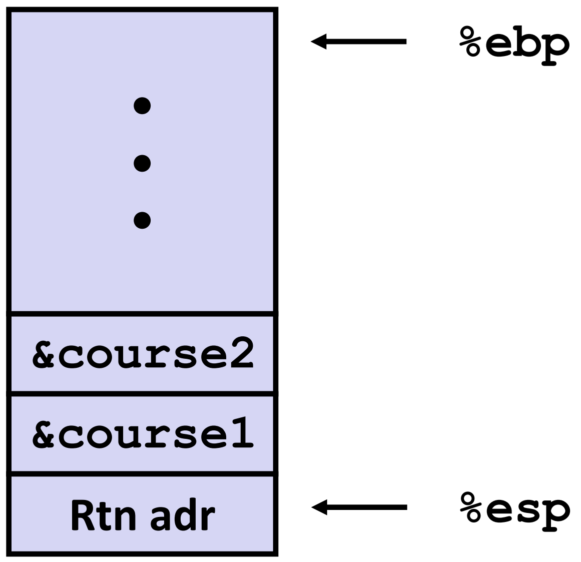
swap Setup #1



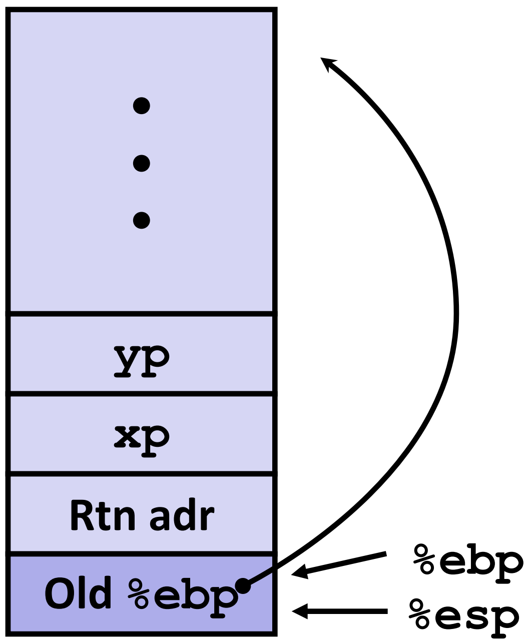
```
swap:
    pushl  %ebp
    movl  %esp,%ebp
    pushl  %ebx
```

swap Setup #2

Entering Stack

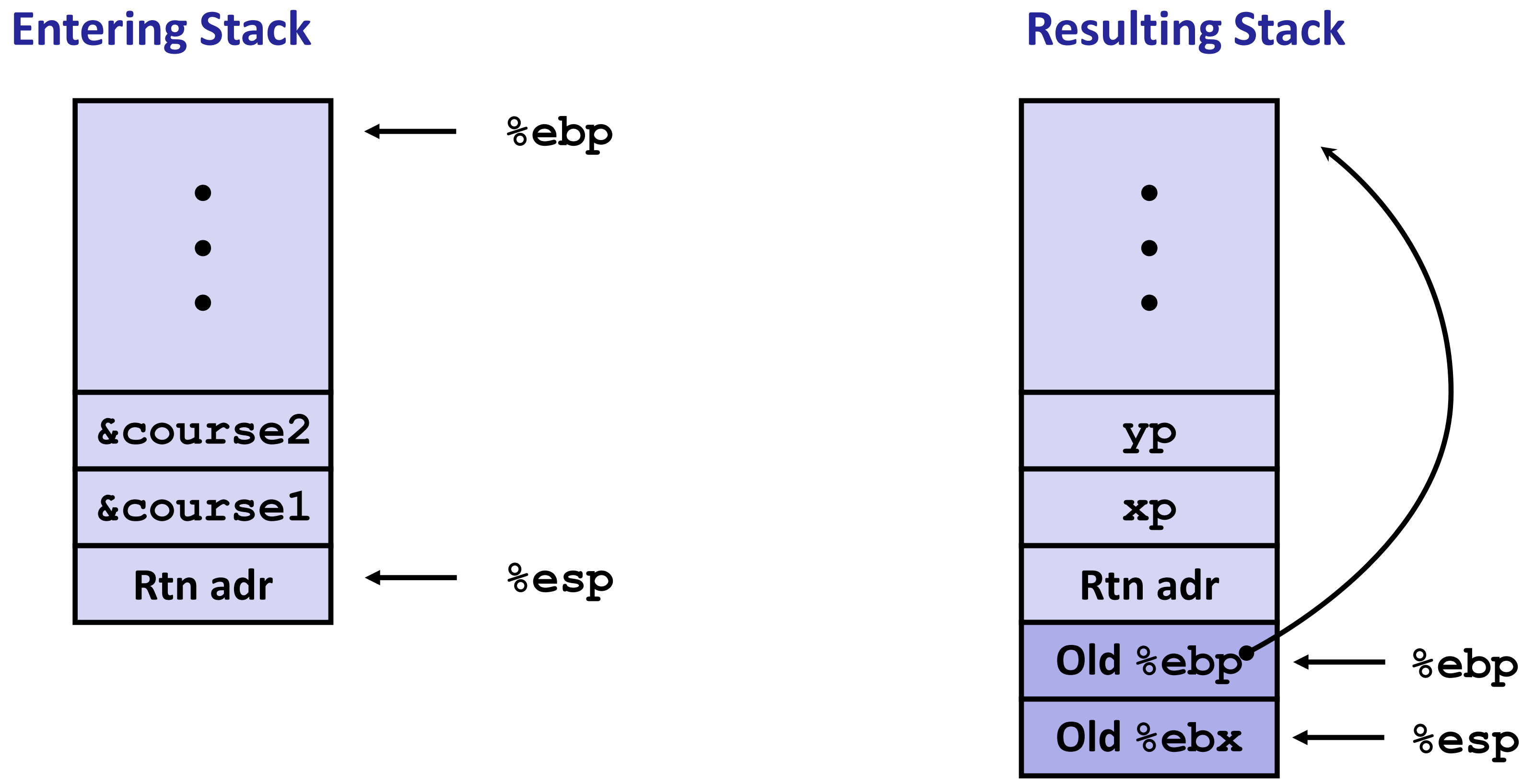


Resulting Stack



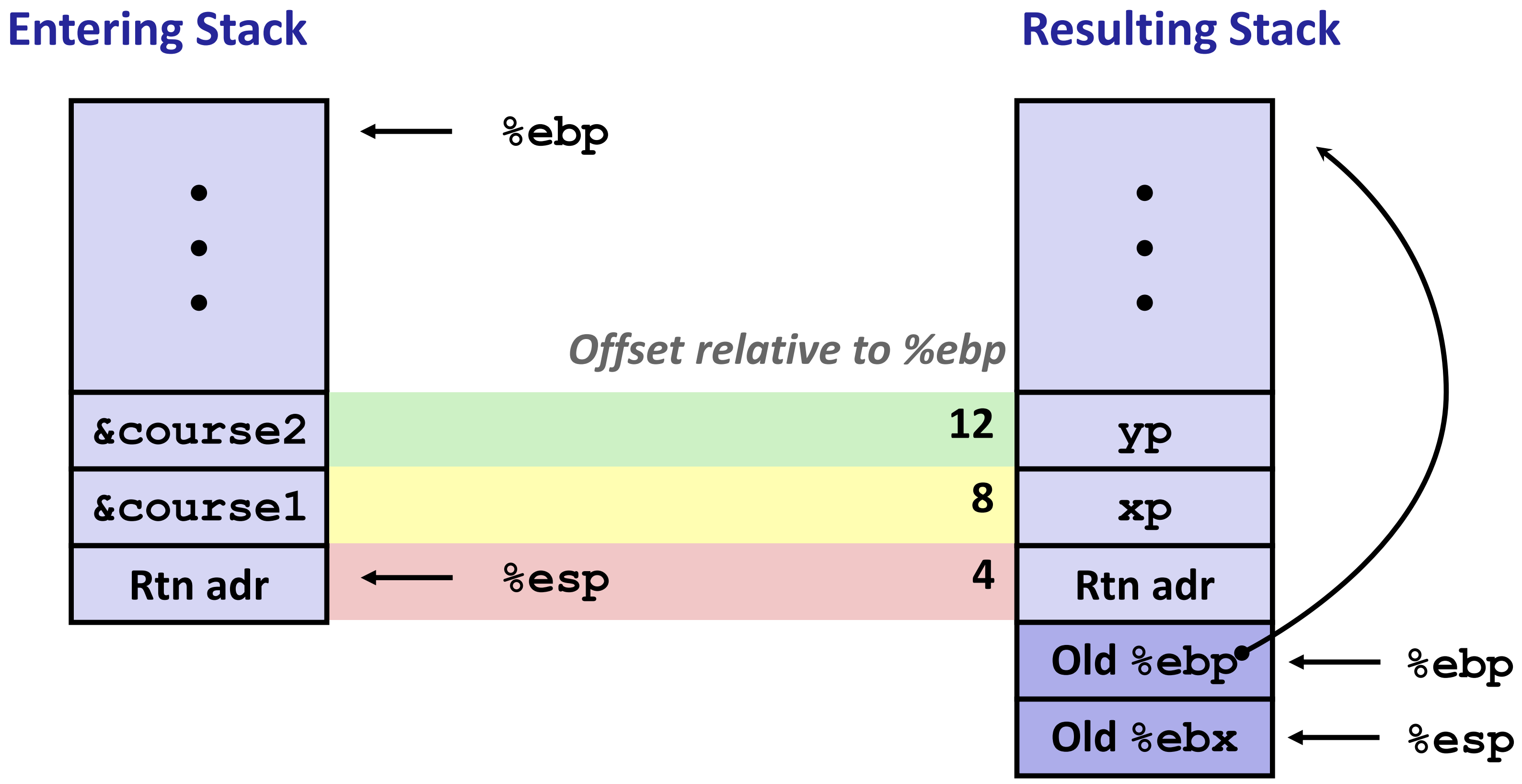
```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

swap Setup #3



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

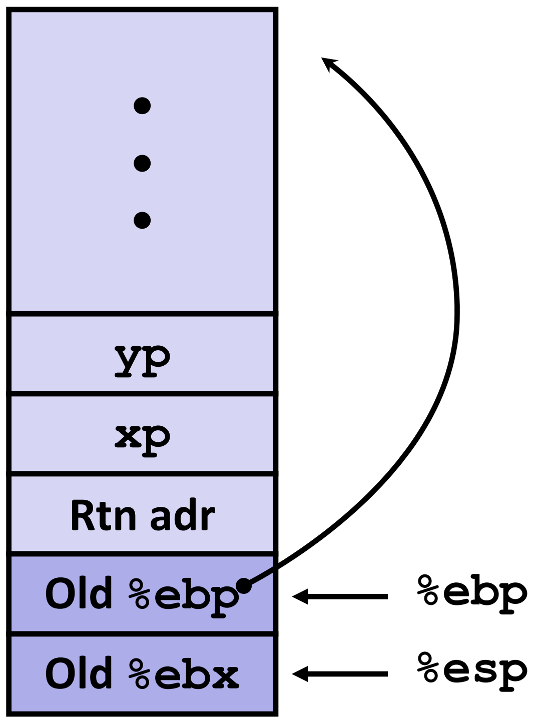
`swap` Body



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

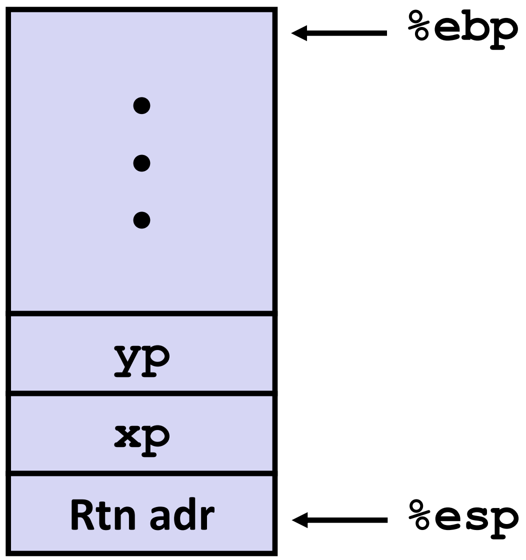
`swap` Finish

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
```

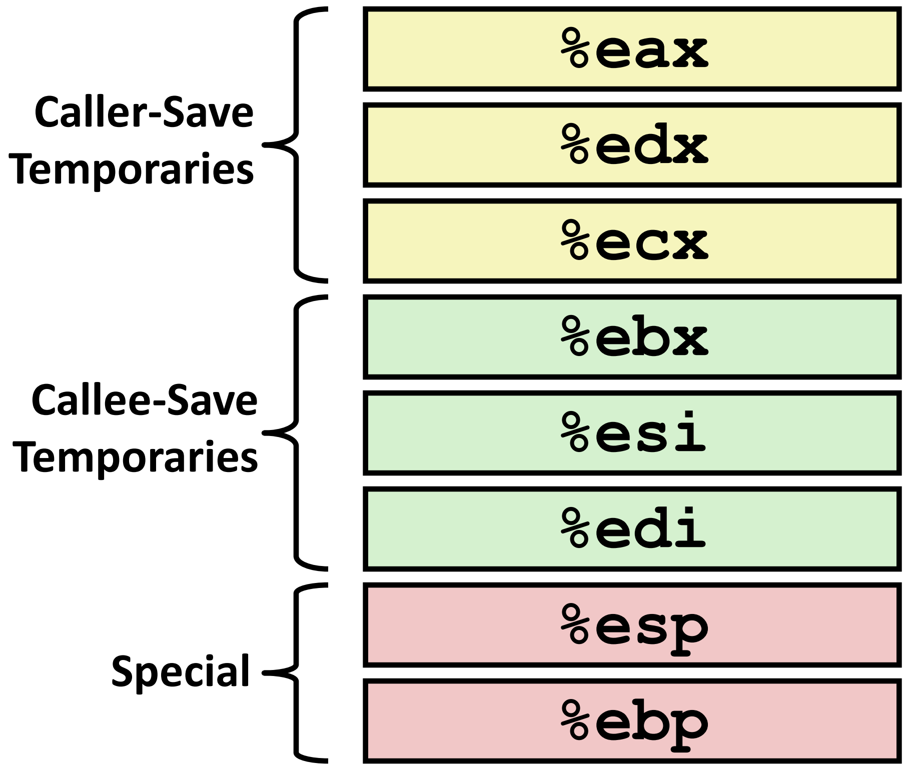
  - Contents of register **`%edx`** overwritten by **`who`**
  - This could be trouble ➙ something should be done!
    - Need some coordination

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

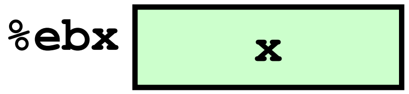
```
pcount_r:
    pushl  %ebp
    movl   %esp, %ebp
    pushl  %ebx
    subl   $4, %esp
    movl   8(%ebp), %ebx
    movl   $0, %eax
    testl  %ebx, %ebx
    je     .L3
    movl   %ebx, %eax
    shrl   %eax
    movl   %eax, (%esp)
    call   pcount_r
    movl   %ebx, %edx
    andl   $1, %edx
    leal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

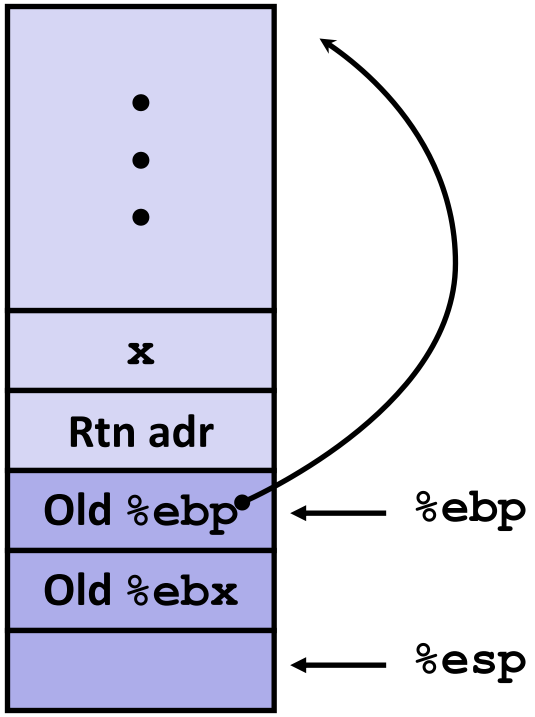
Recursive Call #1

```
/* 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`



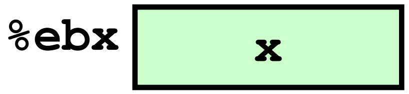


Recursive Call #2

```
/* 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

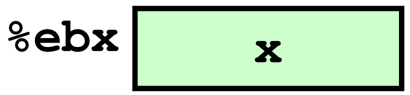


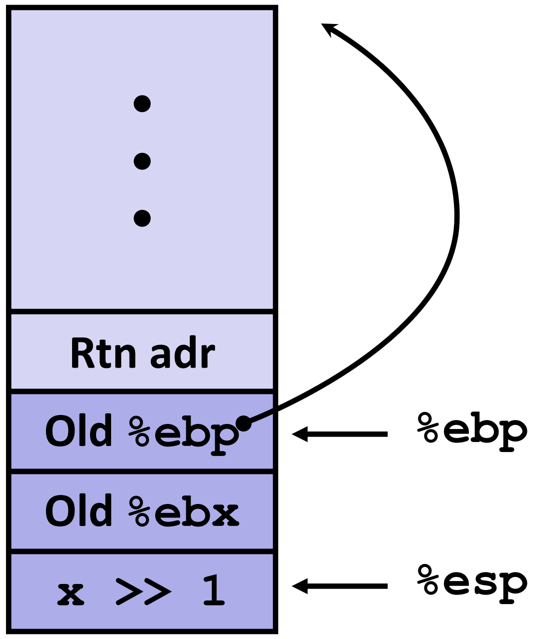
Recursive Call #3

```
/* 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



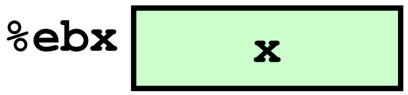


Recursive Call #4

```
/* 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

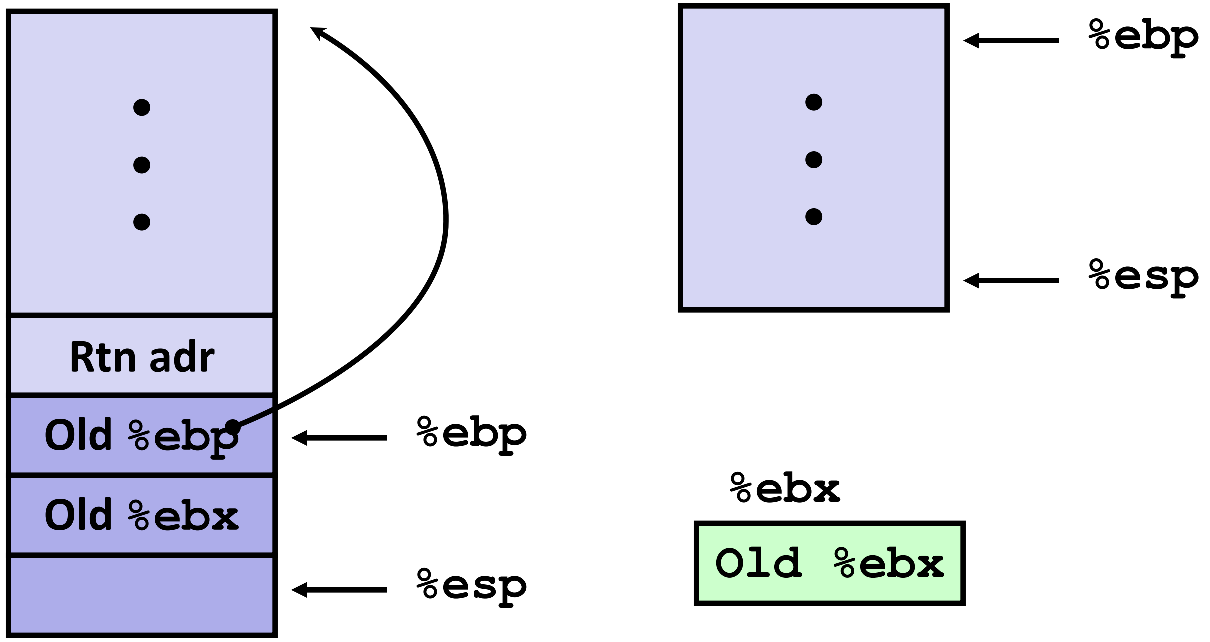


Recursive Call #5

```
/* 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`

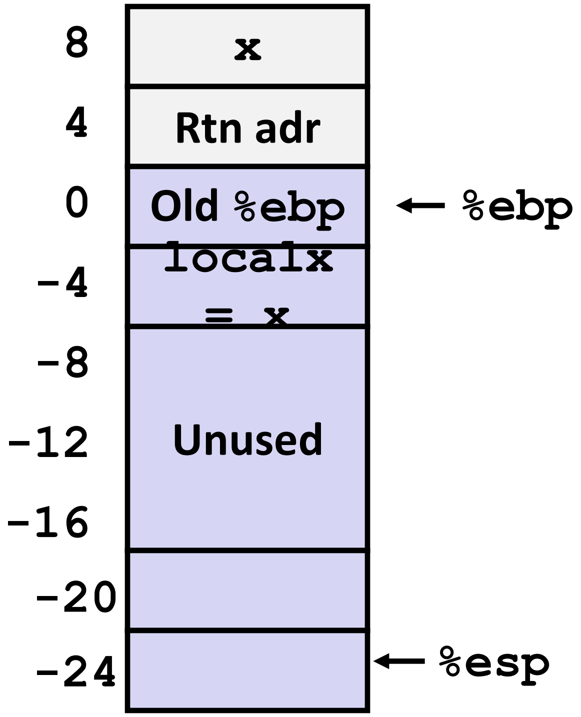
Creating and Initializing Local Variable

```
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
```



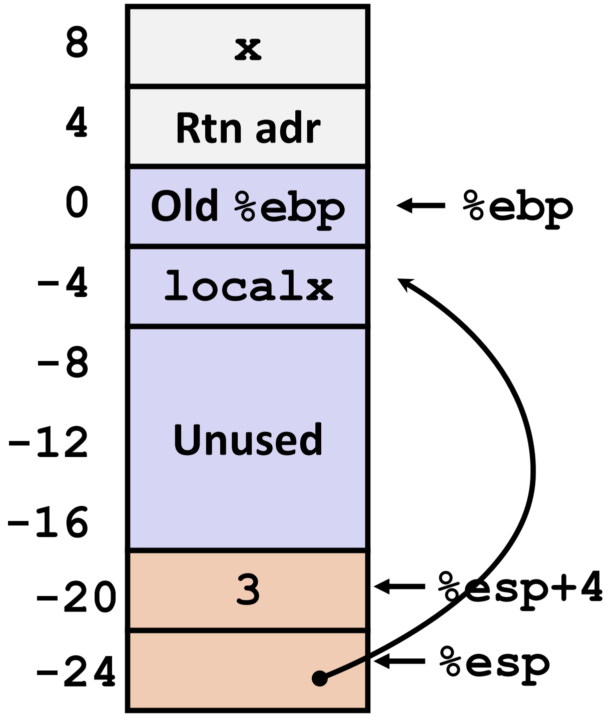
Creating Pointer as Argument

```
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
```



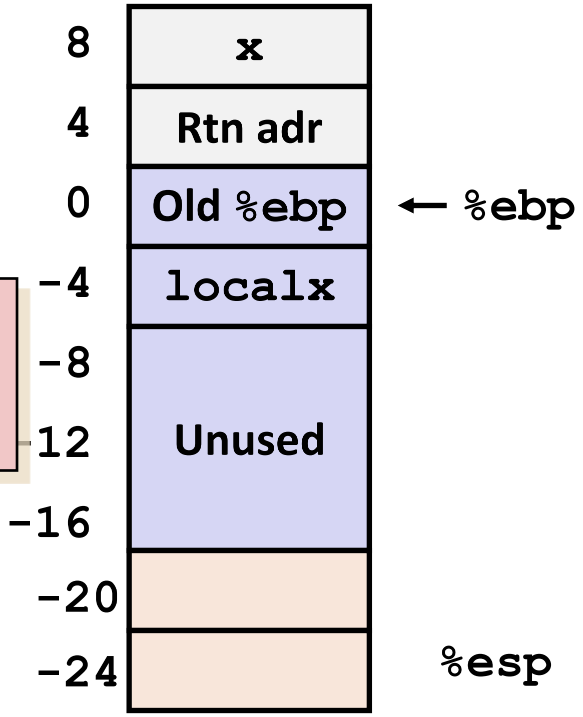
Retrieving local variable

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

- Retrieve localx from stack as return value

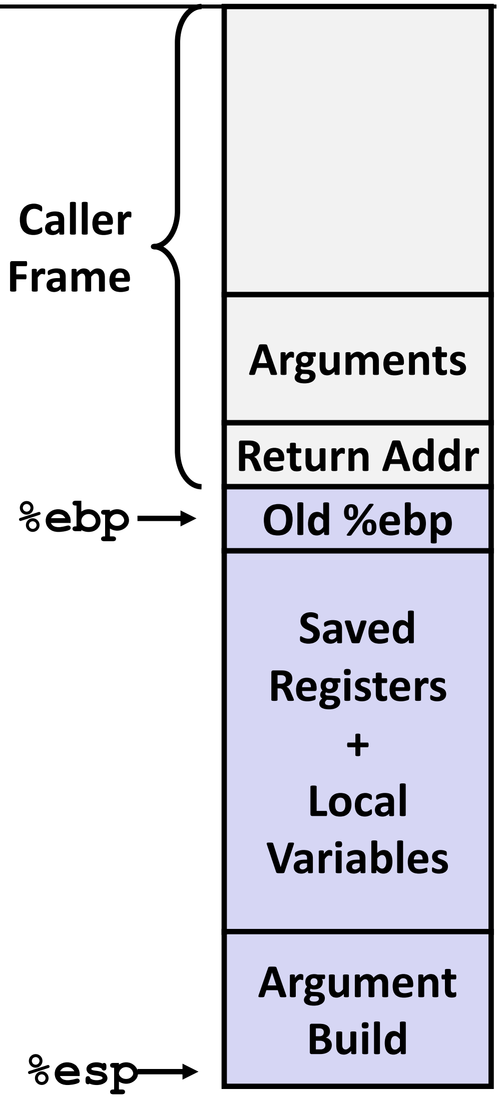
Final part of add3

```
  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`


Caller Frame
Arguments
Return Addr
%ebp
Old %ebp
Saved Registers + Local Variables
Argument Build
%esp