Machine-Level Programming III: (Switch Statements) and IA32 Procedures

Lecture 4, March 10, 2011

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Credits to Randy Bryant & Dave O'Hallaron from Carnegie Mellon

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;
}
```

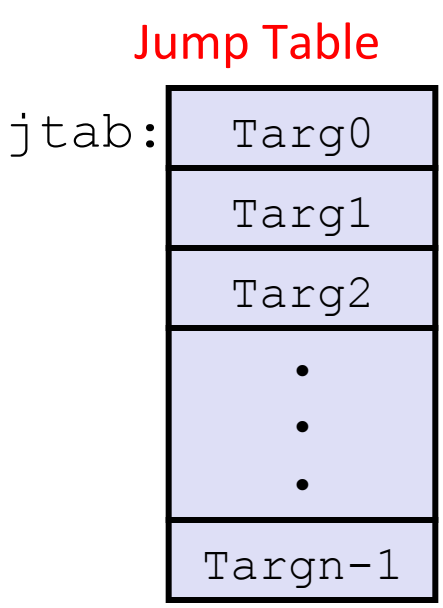
Switch Statement Example

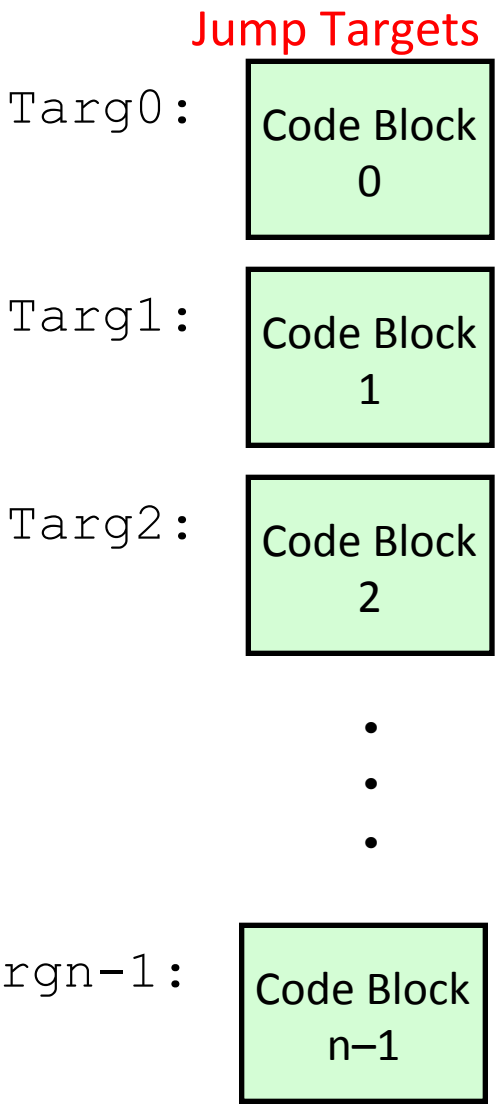
- **Multiple case labels**
  - Here: 5 & 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

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

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 $0 \le x \le 6$

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

Try it yourself!

- **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.)

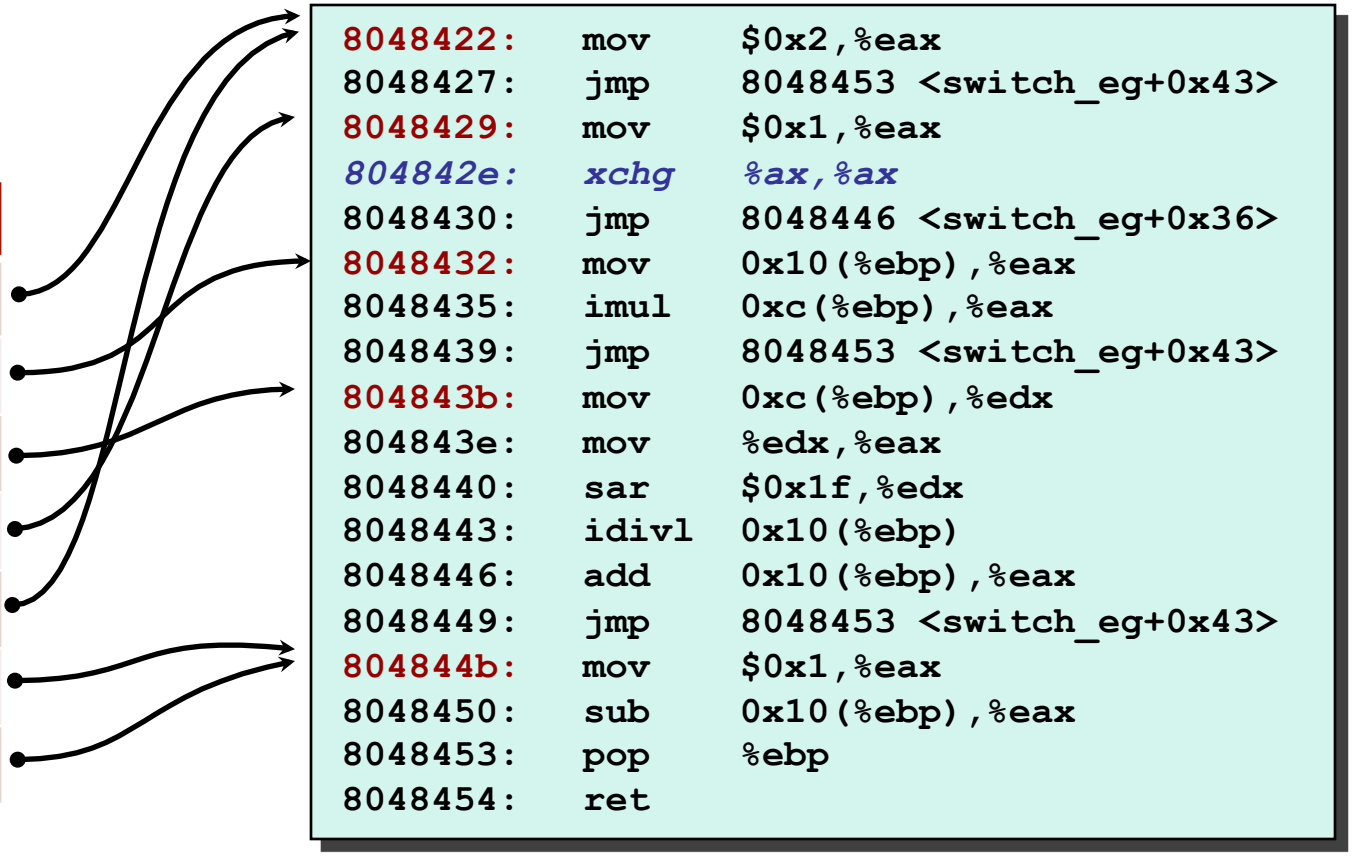
- **Jump Table**
  - Doesn't show up in disassembled code
  - Does show up with gcc -S
  - Can inspect using GDB
  - `gdb switch`
  - `(gdb) x/7xw 0x8048660`
    - Examine 7 hexadecimal format "words" (4-bytes each)
    - Use command "`help x`" to get format documentation

PP3.29

Matching Disassembled Targets

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

Jump table



```
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

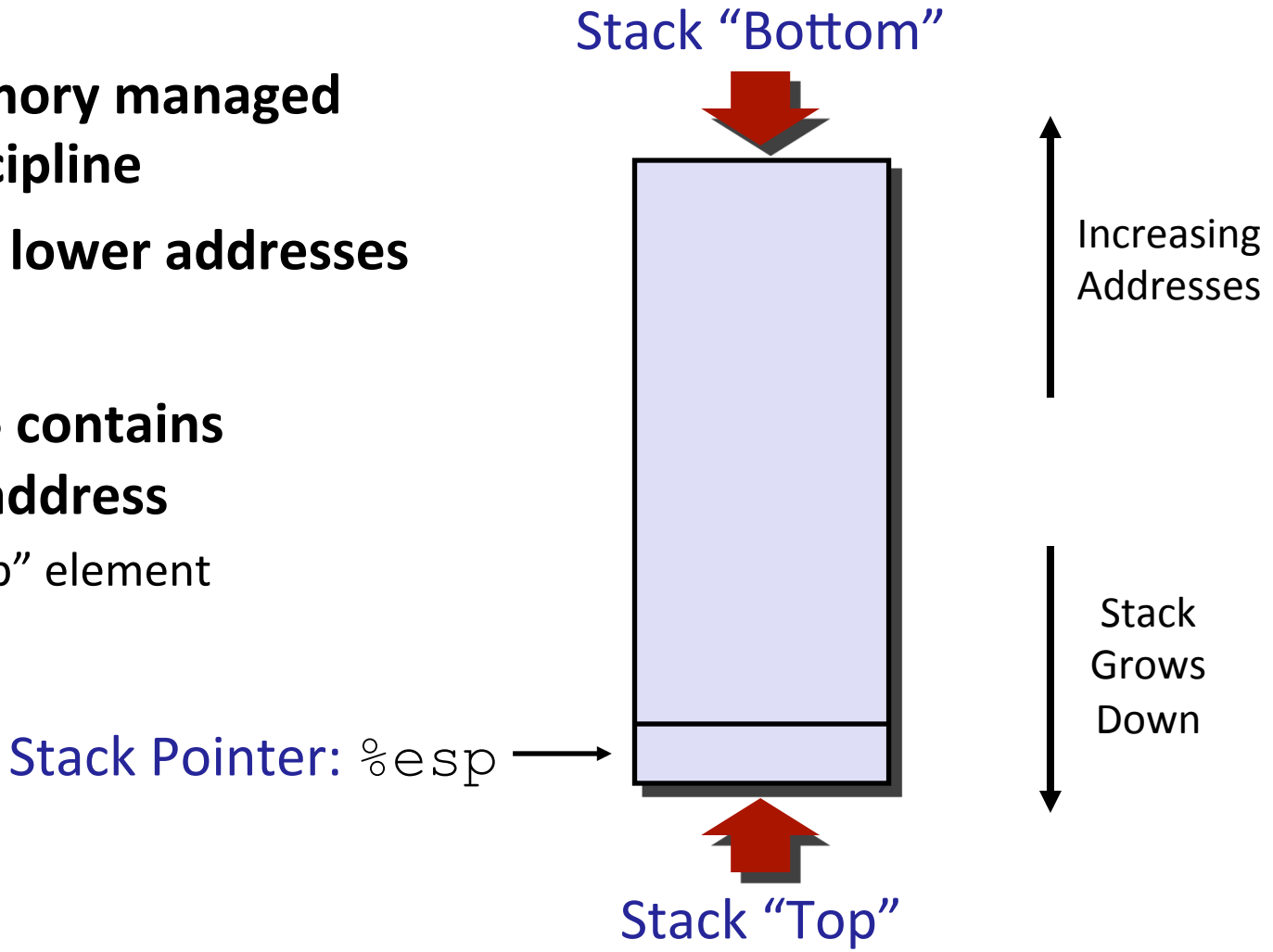
Today

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

IA32 Stack

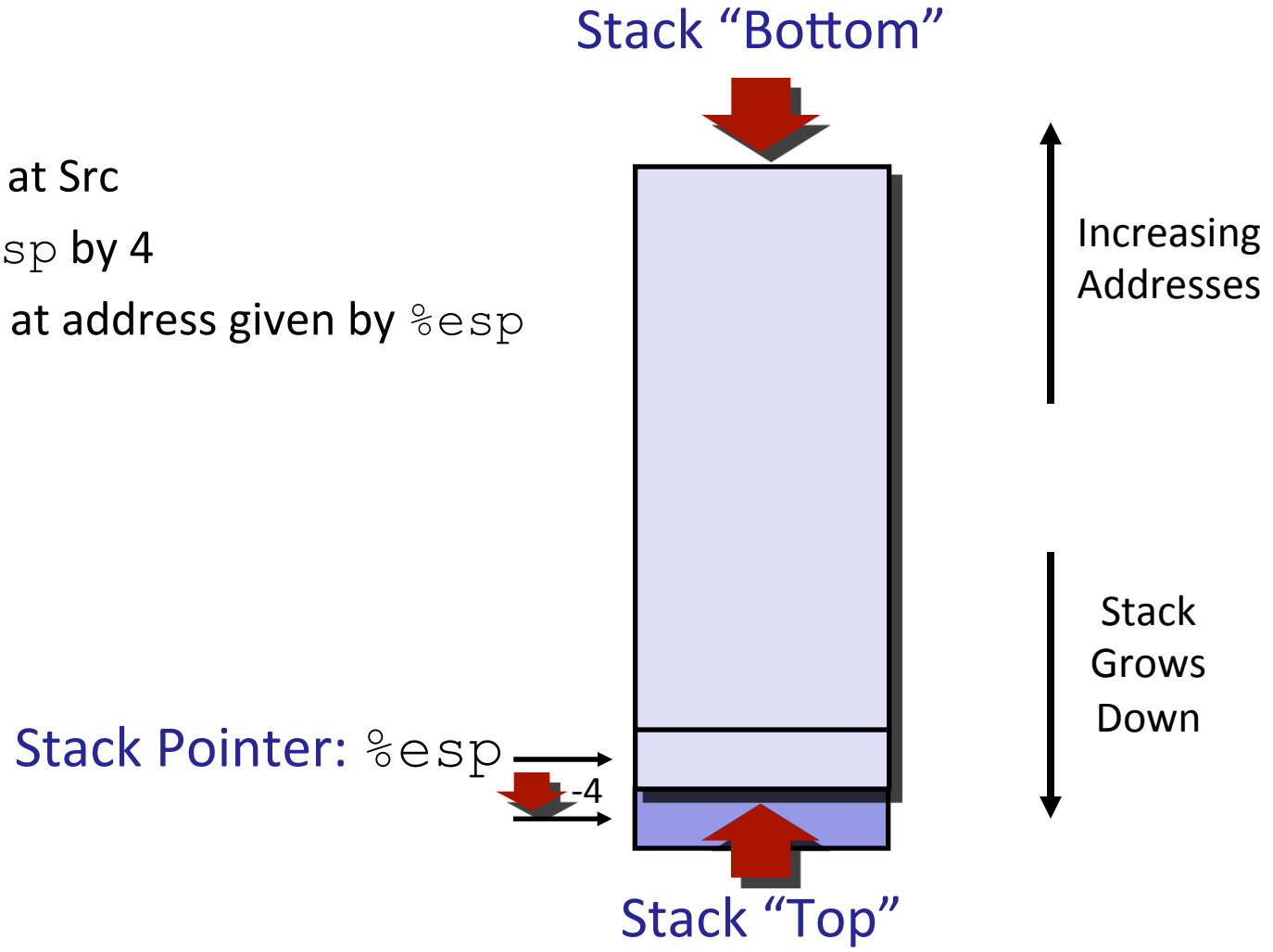
- **Region of memory managed with stack discipline**
- **Grows toward lower addresses**

- **Register `%esp` contains lowest stack address**
  - address of "top" element

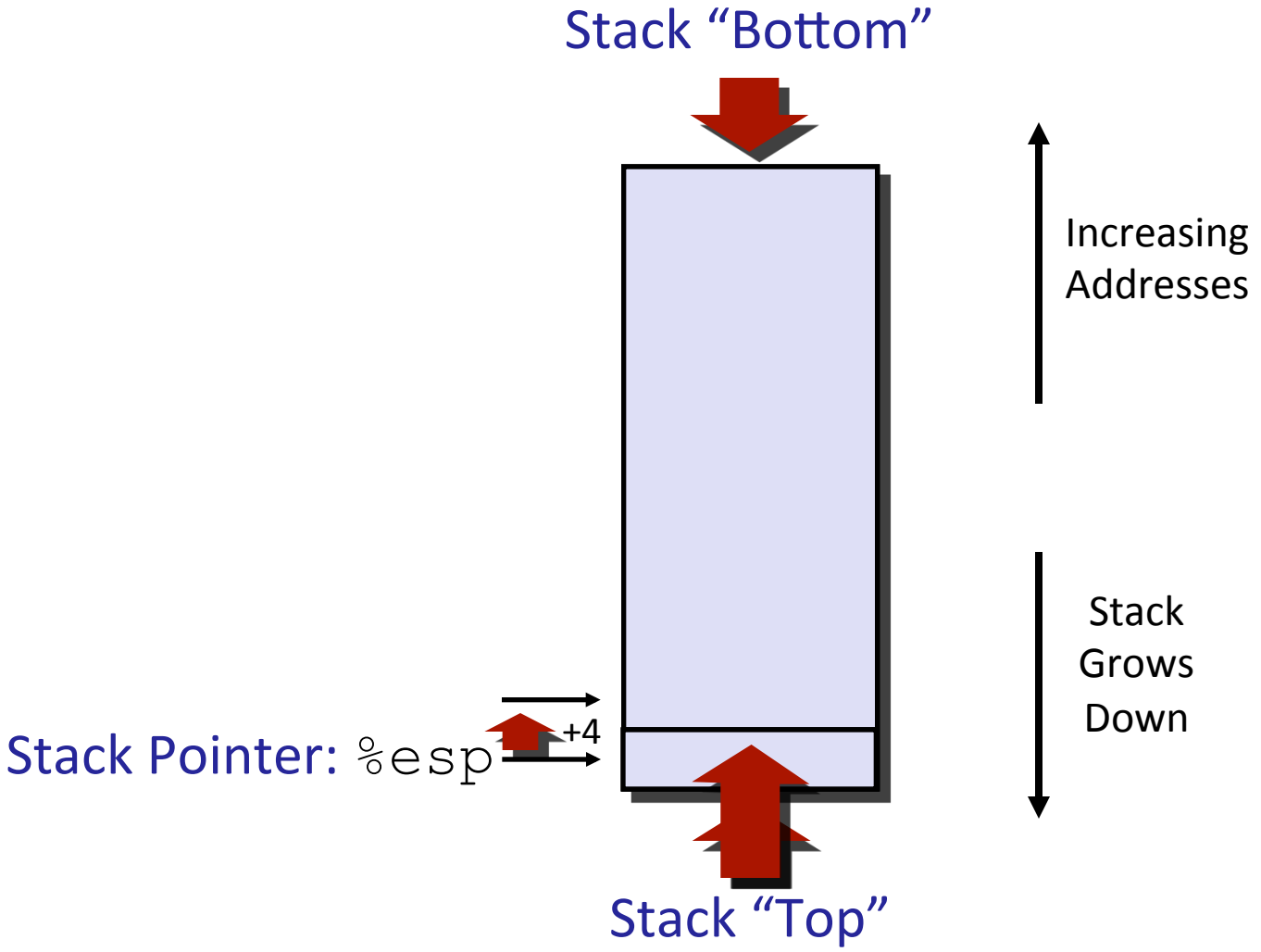


IA32 Stack: Push

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



IA32 Stack: Pop



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Procedure Control Flow

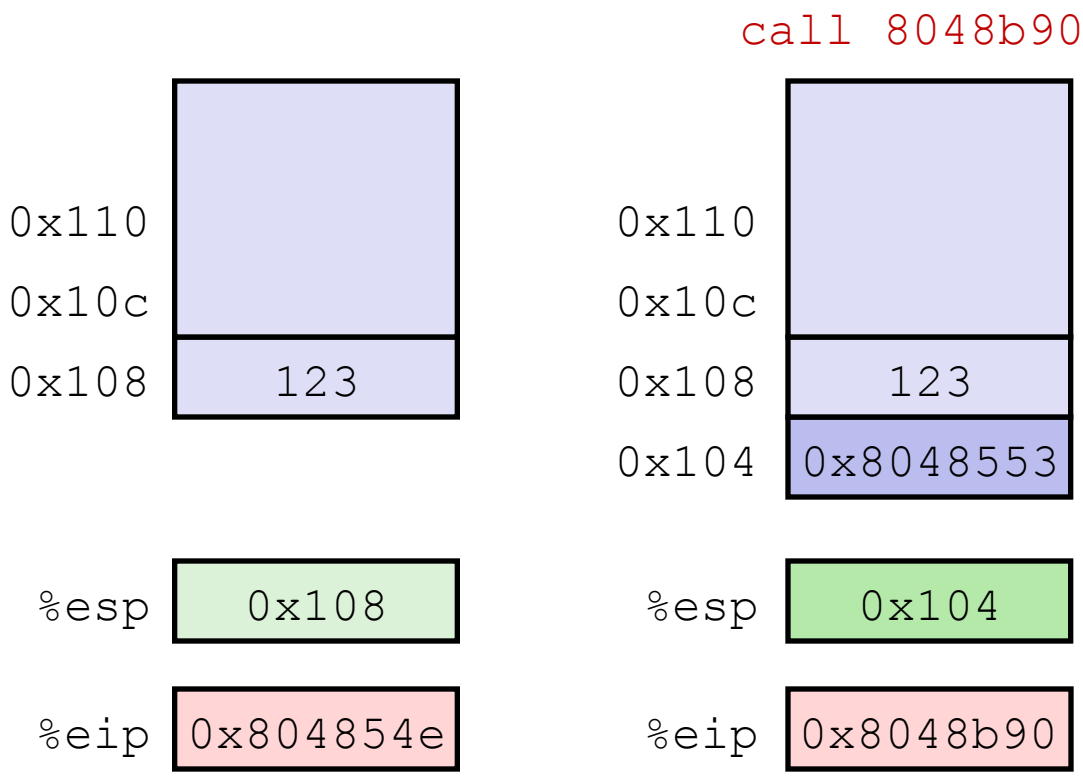
- **Use stack to support procedure call and return**
- **Procedure call: `call label`**
  - Push return address on stack
  - Jump to label
- **Return address:**
  - Address of the next instruction right after call
  - Example from disassembly

```
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

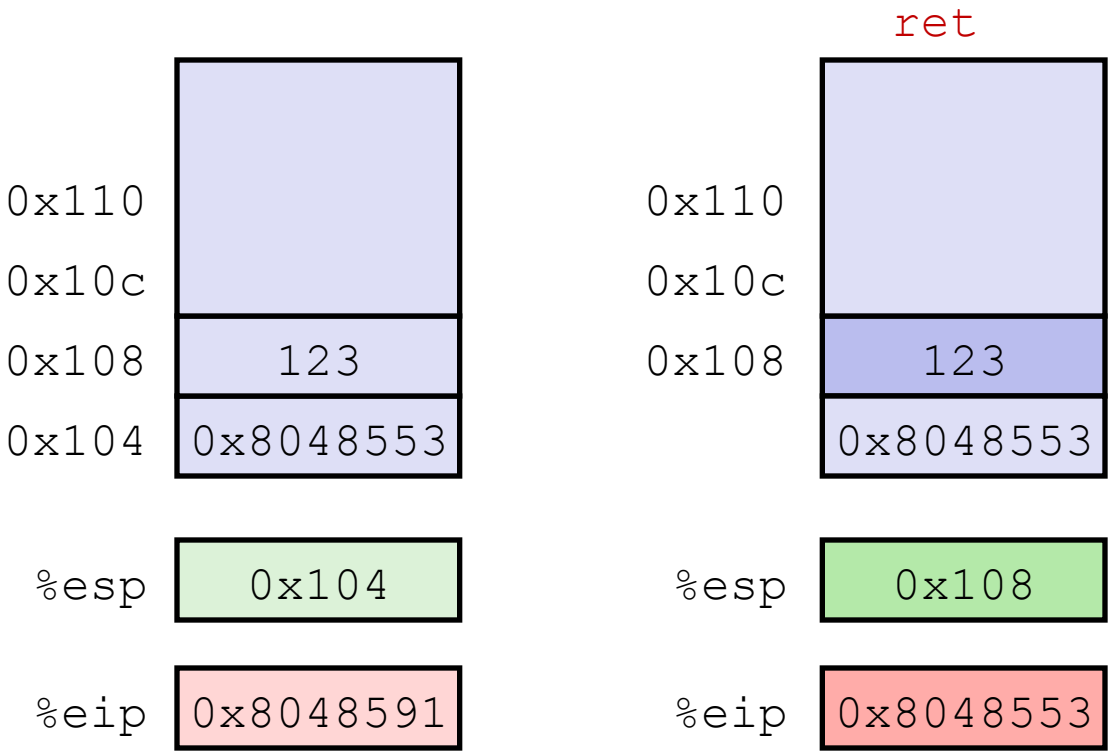
```
804854e:    e8 3d 06 00 00       call   8048b90 <main>
8048553:    50                   pushl  %eax
```



%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

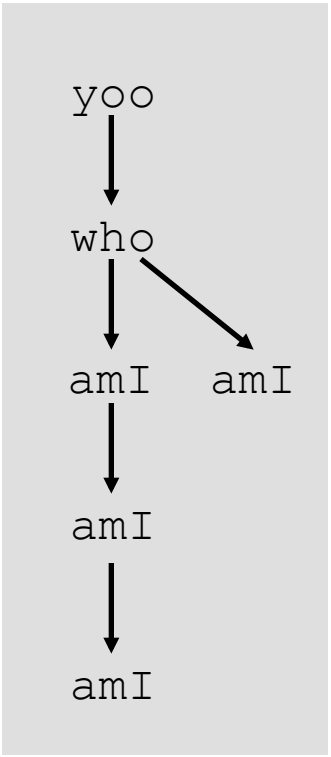
Call Chain Example

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

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

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

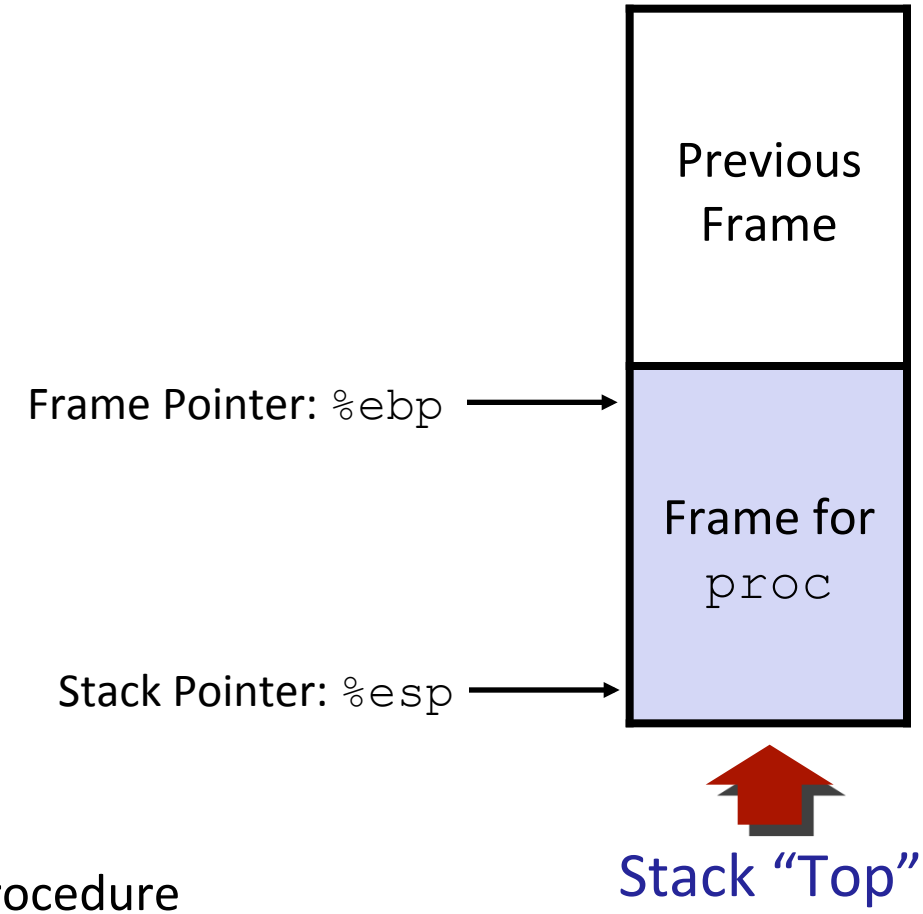
Example
Call Chain



Procedure `amI()` is recursive

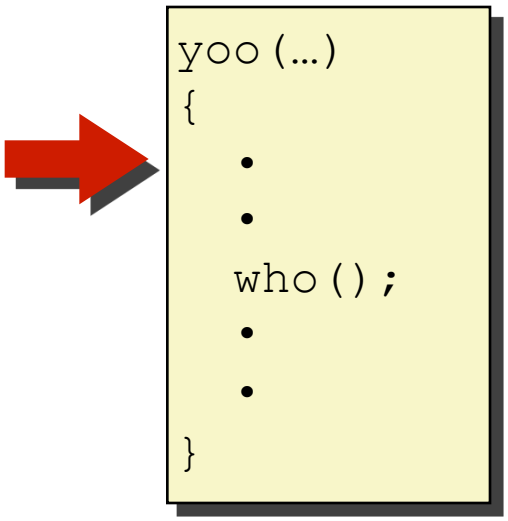
Stack Frames

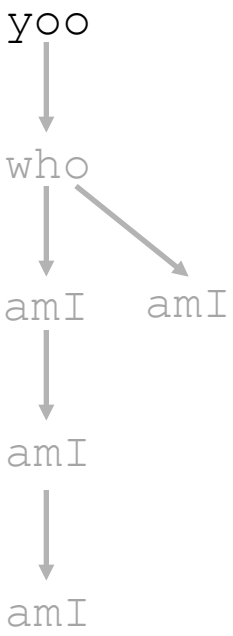
- **Contents**
  - Local variables
  - Return information
  - Temporary space

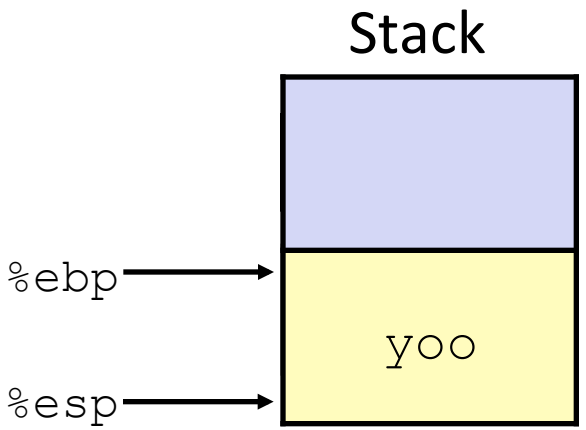


- **Management**
  - Space allocated when enter procedure
    - "Set-up" code
  - Deallocated when return
    - "Finish" code

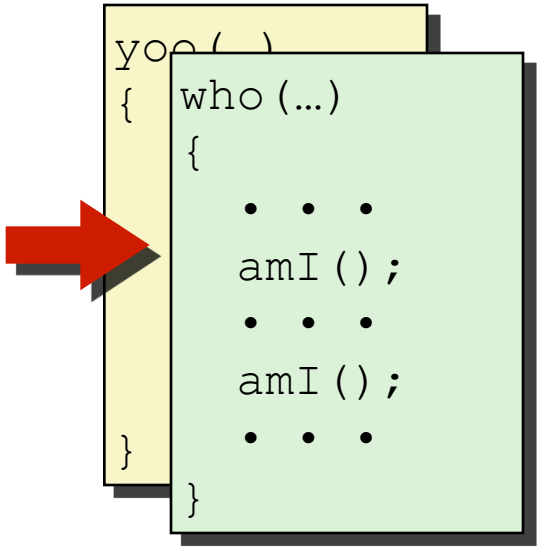
Example

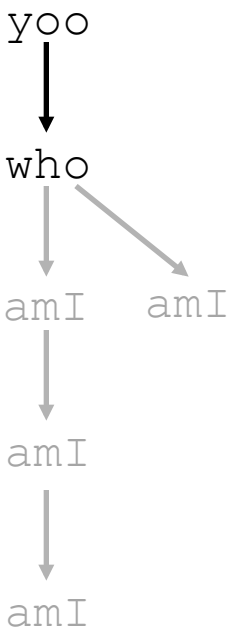


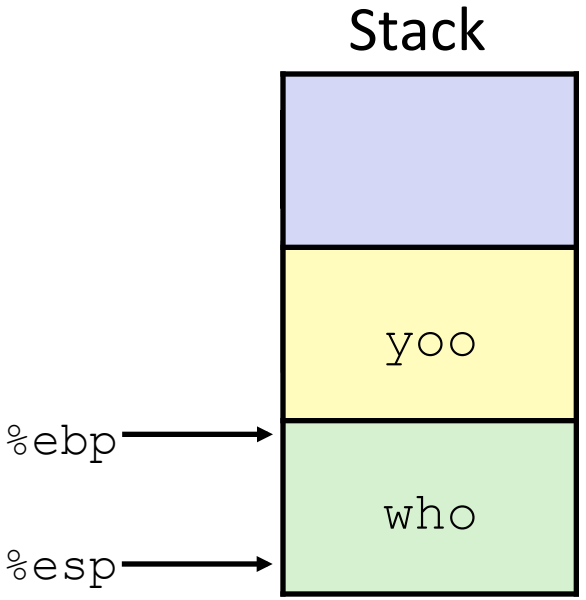




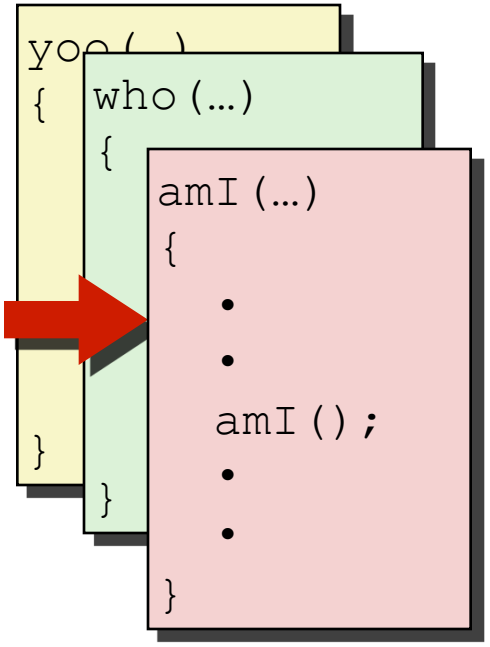
Example

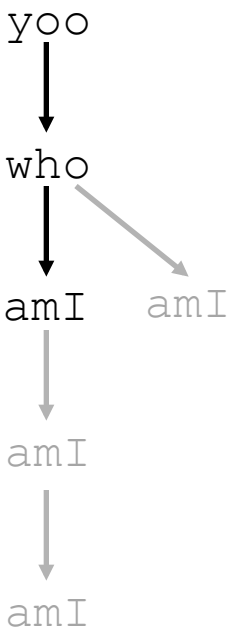


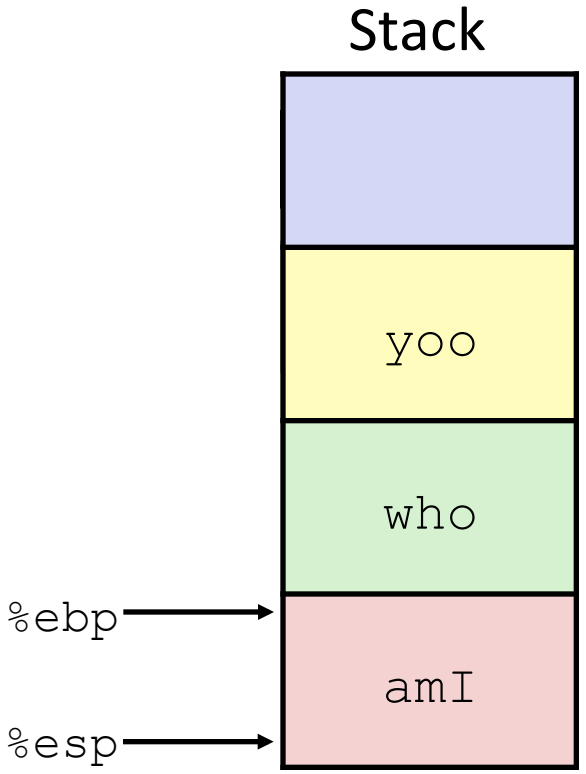




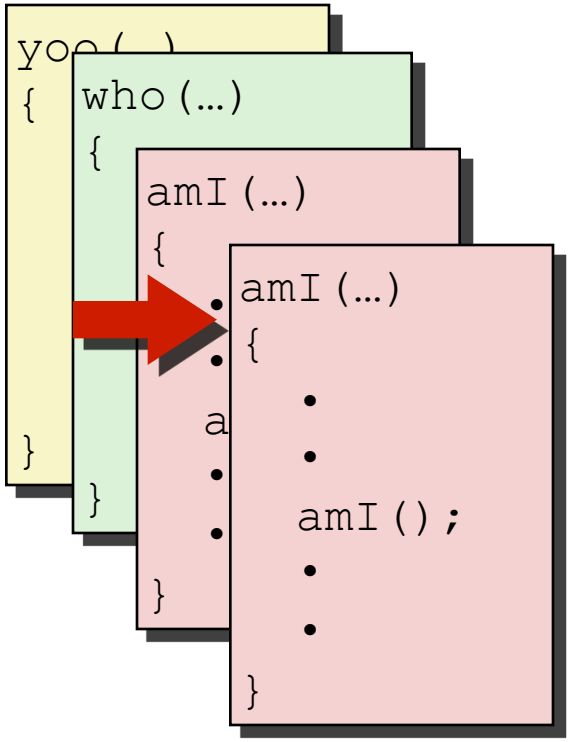
Example

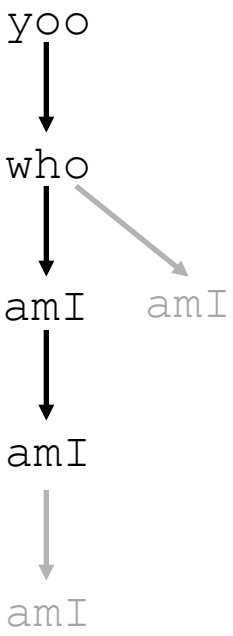

yoo( )
{
who(…)
{
amI(…)
{
•
•
amI();
•
•
}
}
}

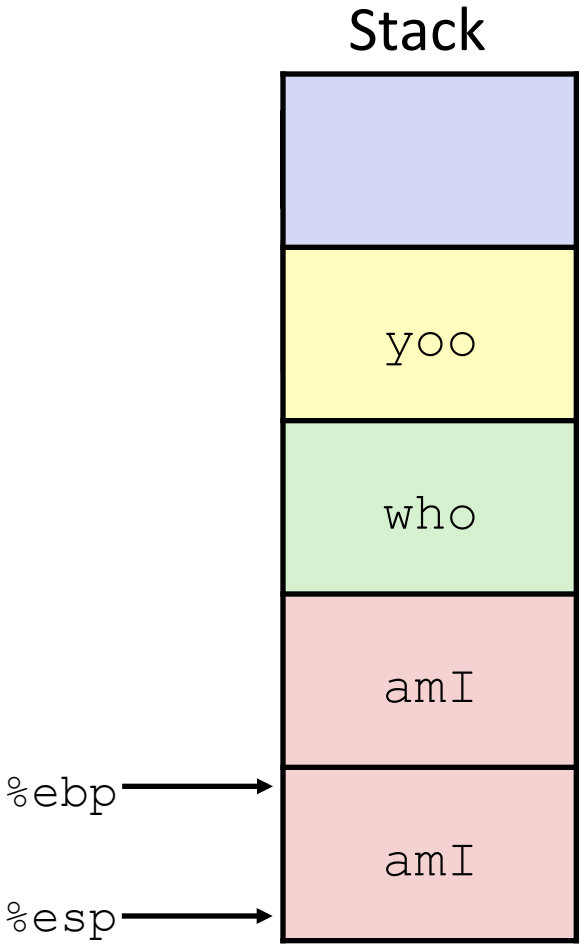

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
%ebp
%esp

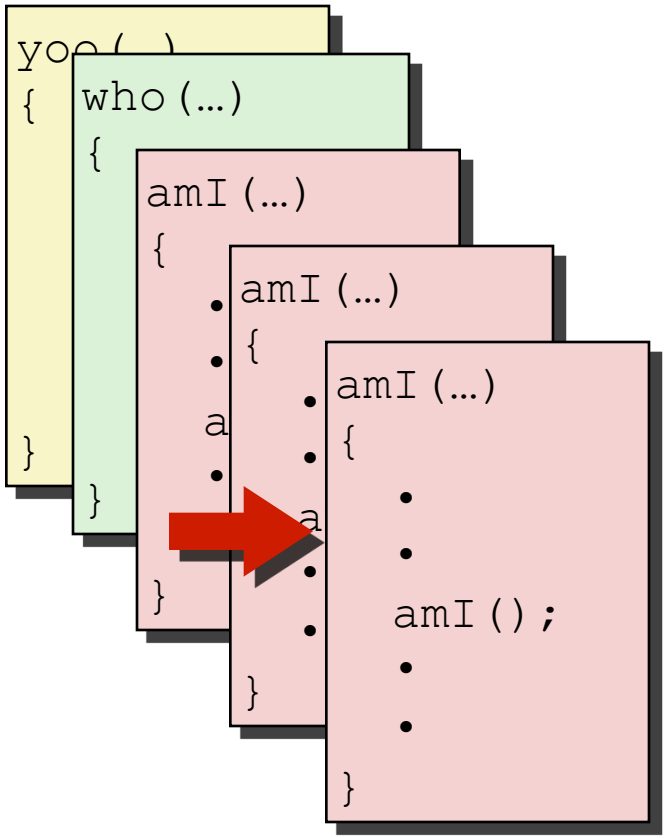
Example

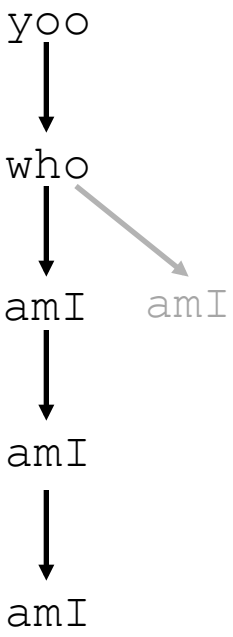

yoo( )
{
who(…)
{
amI(…)
{
amI(…)
{
amI();
}
}
}
}

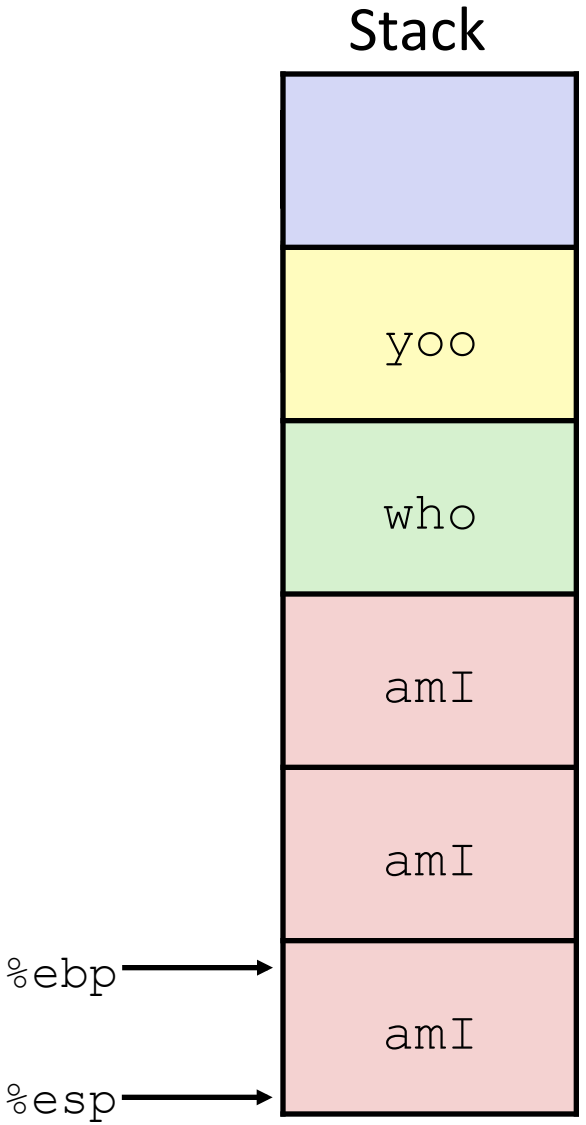

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
%ebp
%esp

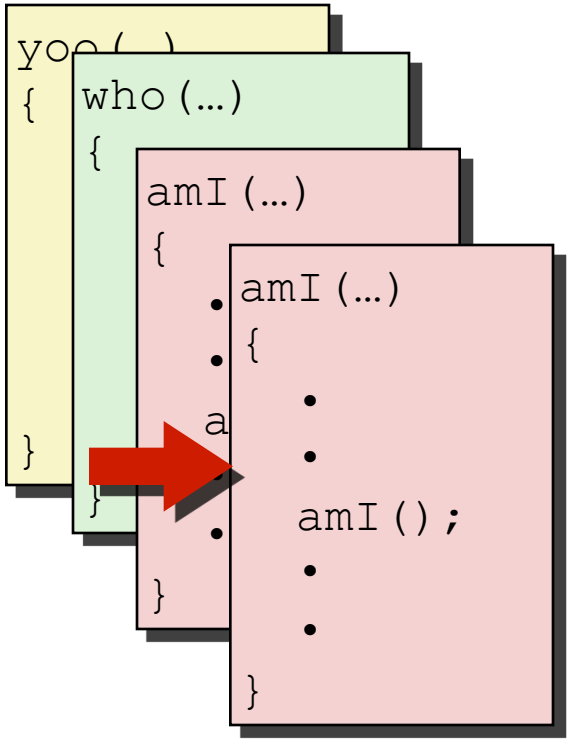
Example


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


yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
amI
%ebp
%esp

Example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}
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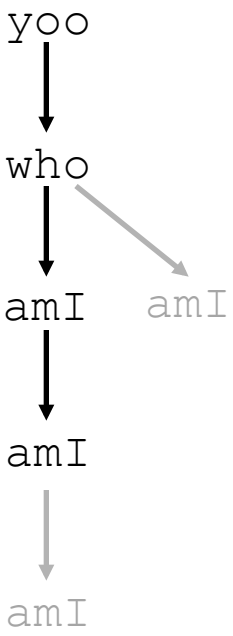
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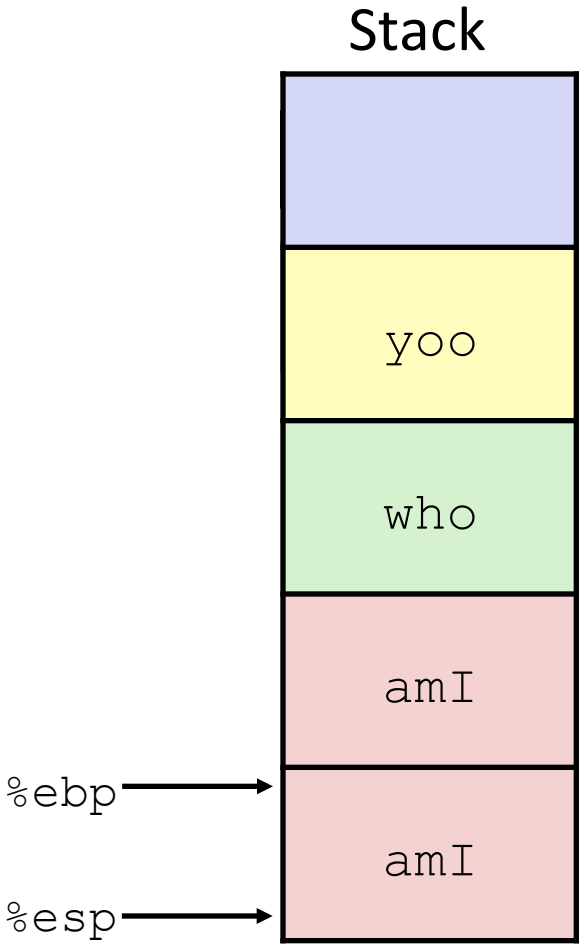
Stack
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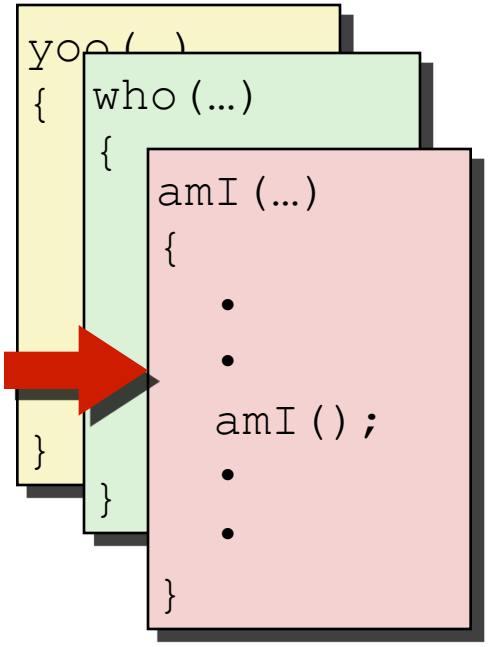
Example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{
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amI(…)
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•
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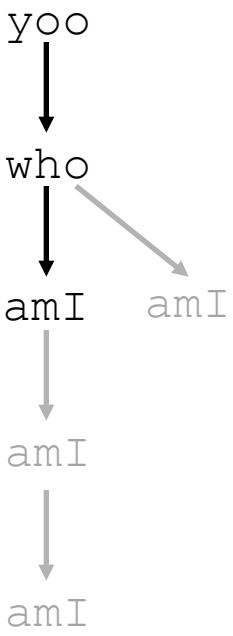
•
•
}
}
}


yoo
who
amI
amI
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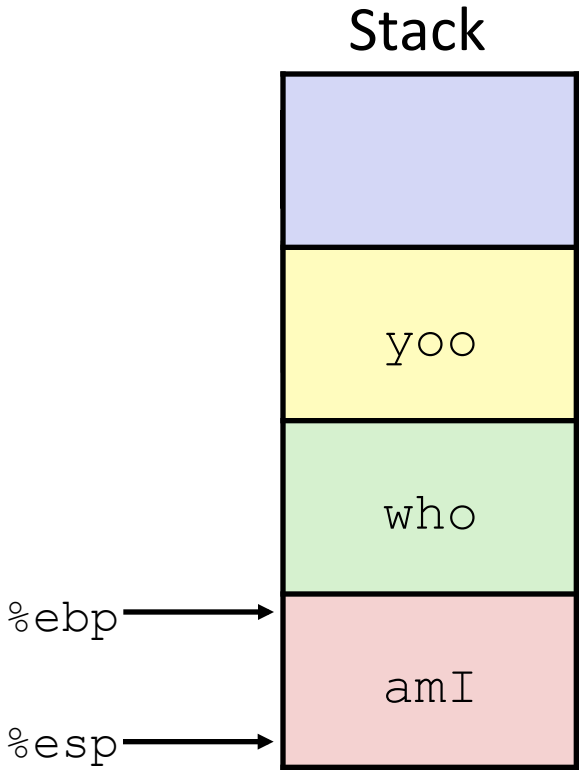
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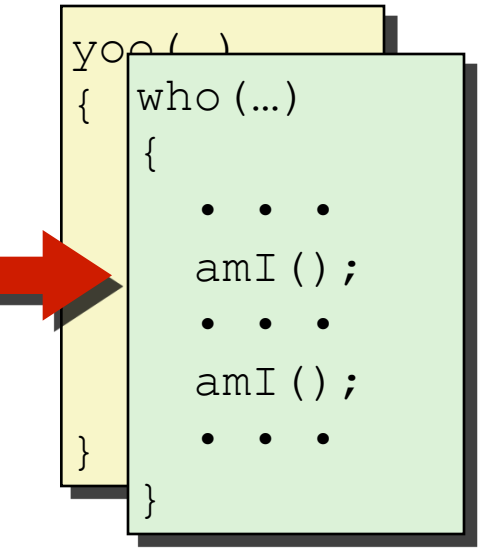
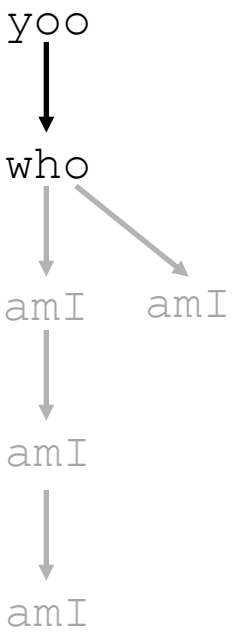
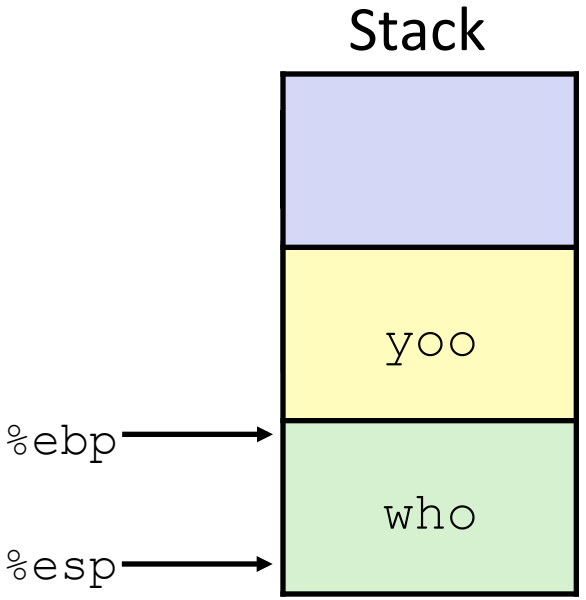
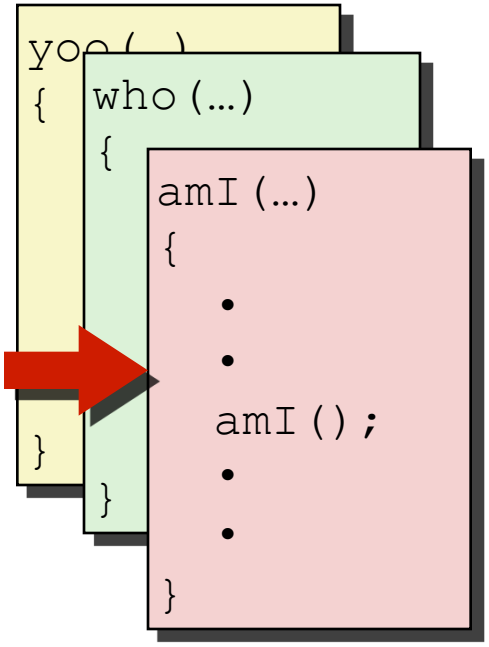
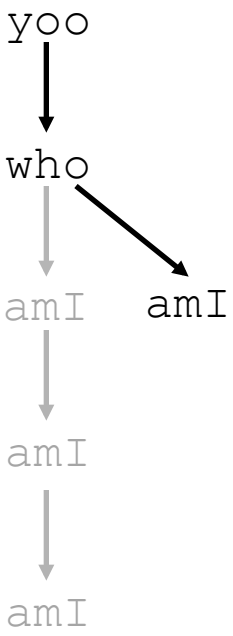


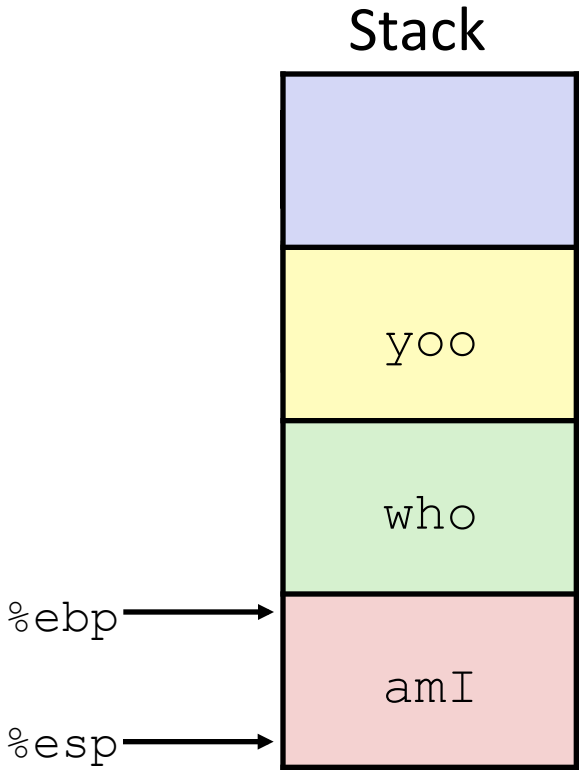




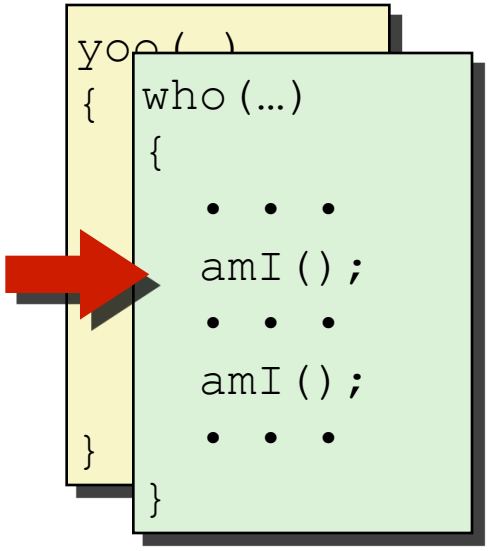
Example

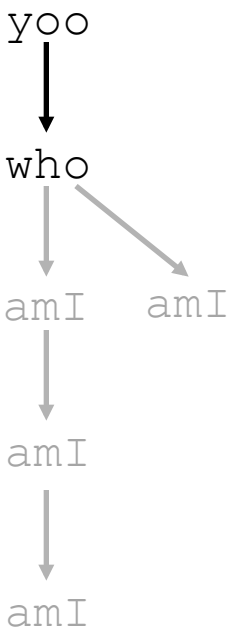

yoo( )
{
who(…)
{
amI(…)
{
•
•
amI();
•
•
}
}
}

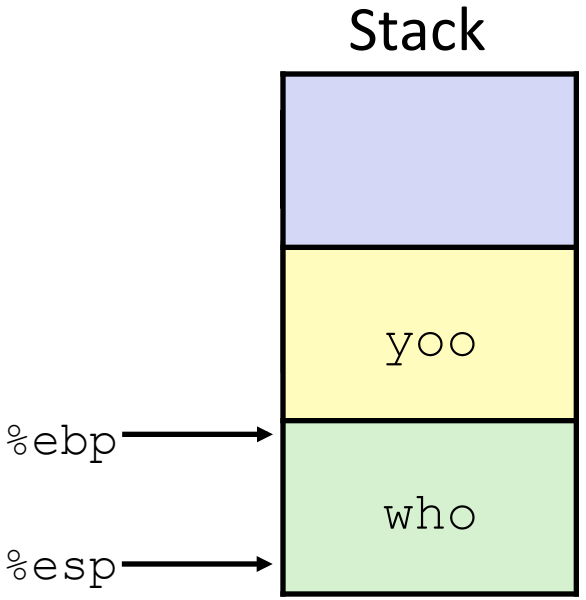

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
%ebp
%esp

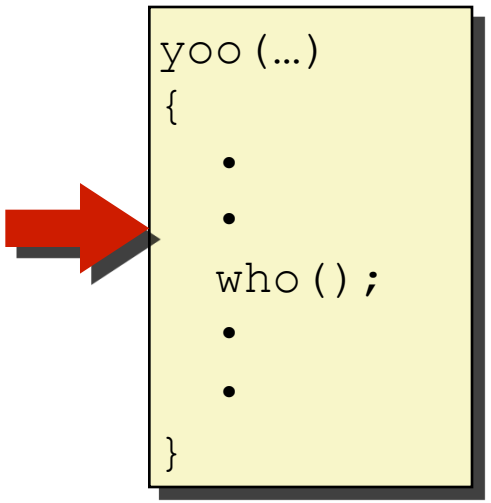
Example

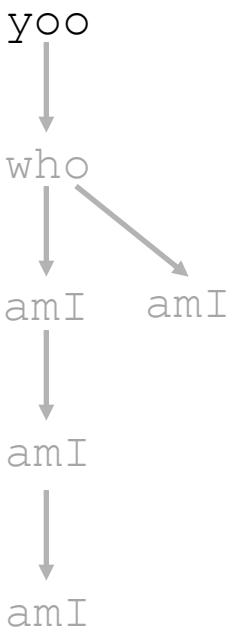


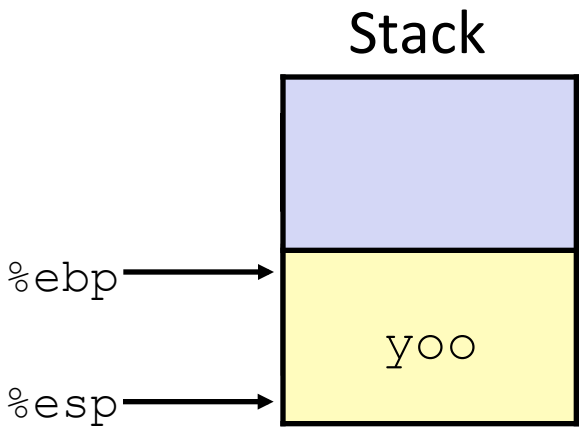




Example



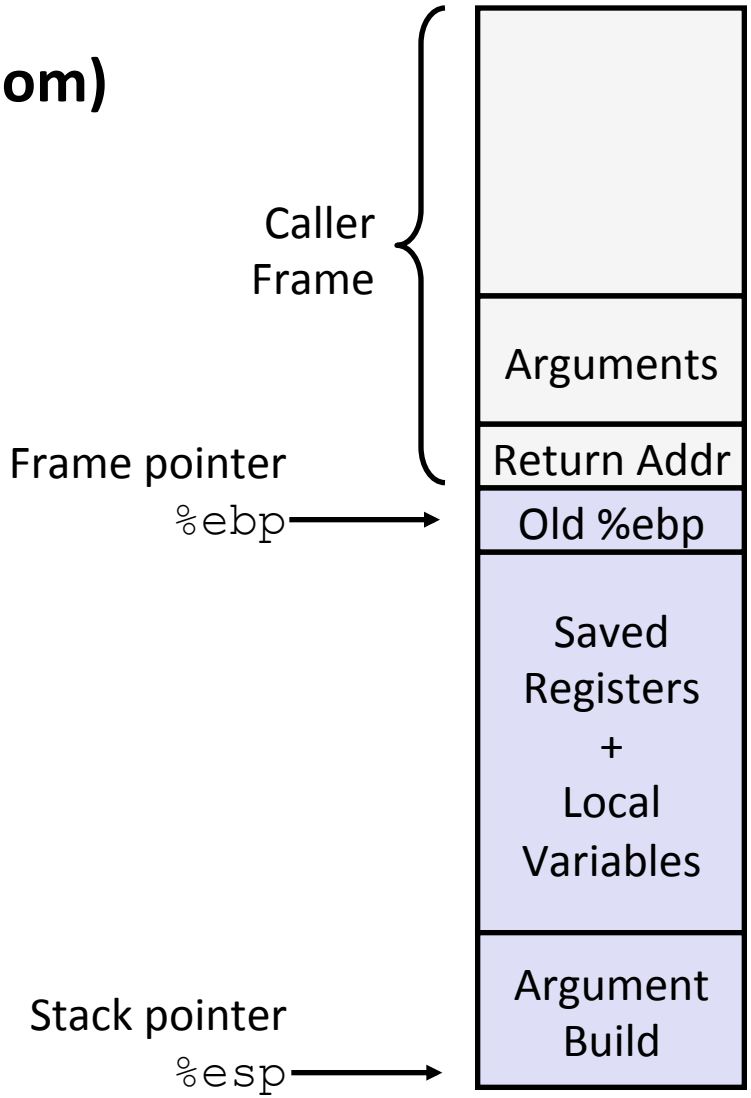




IA32/Linux Stack Frame

- **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

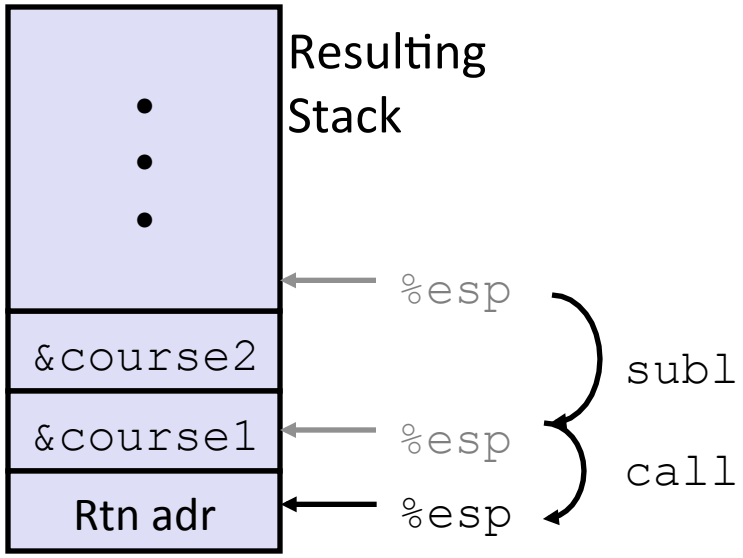
```
int course1 = 15213;
int course2 = 18243;

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
```

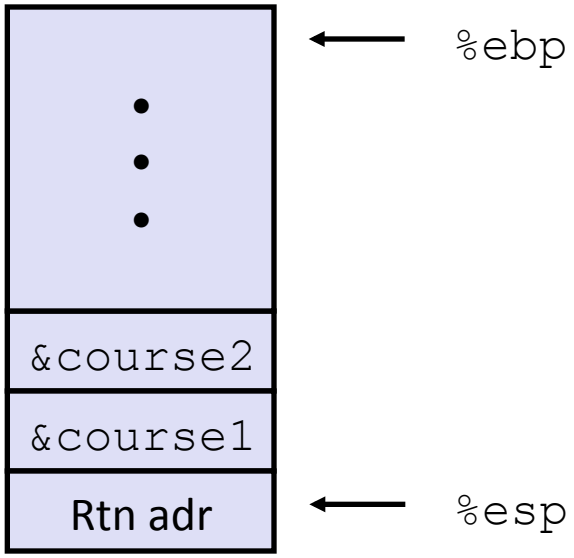
Set Up

Body

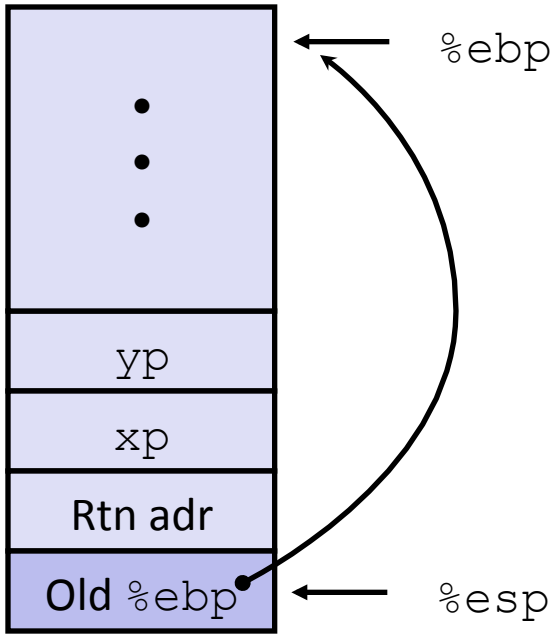
Finish

swap Setup #1

Entering Stack



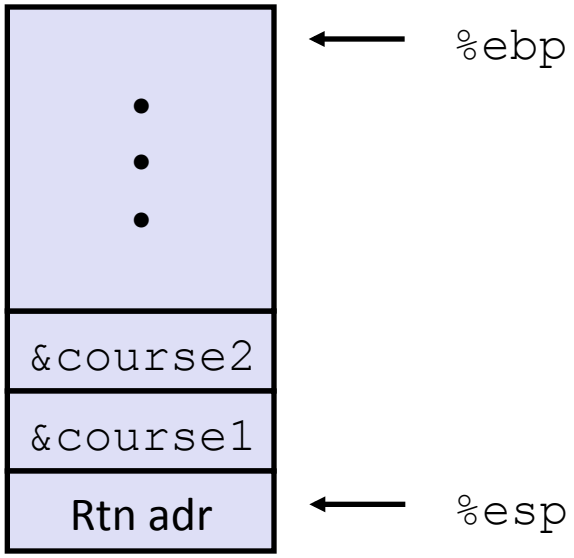
Resulting Stack



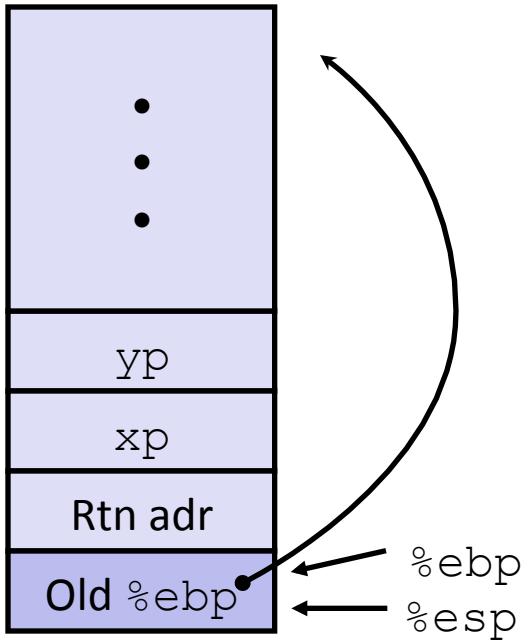

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #2

Entering Stack



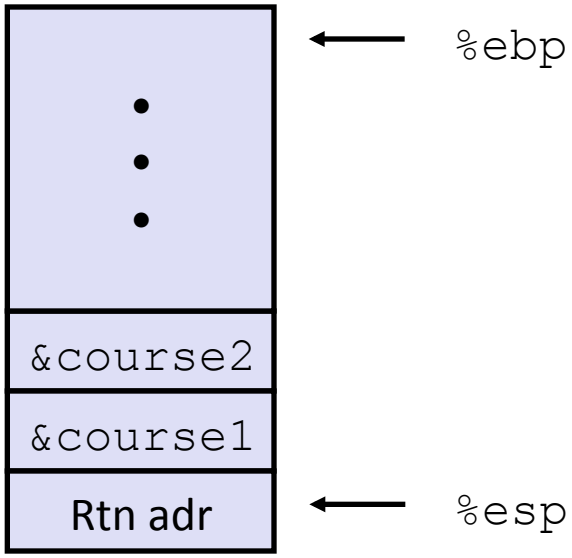
Resulting Stack



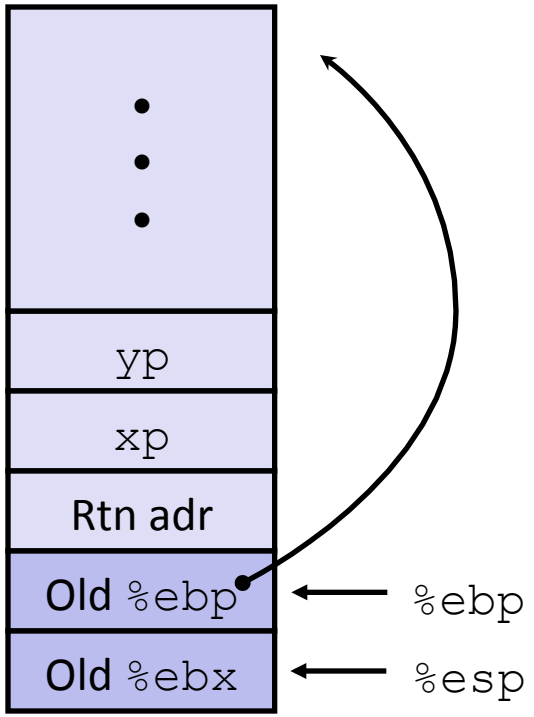

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #3

Entering Stack

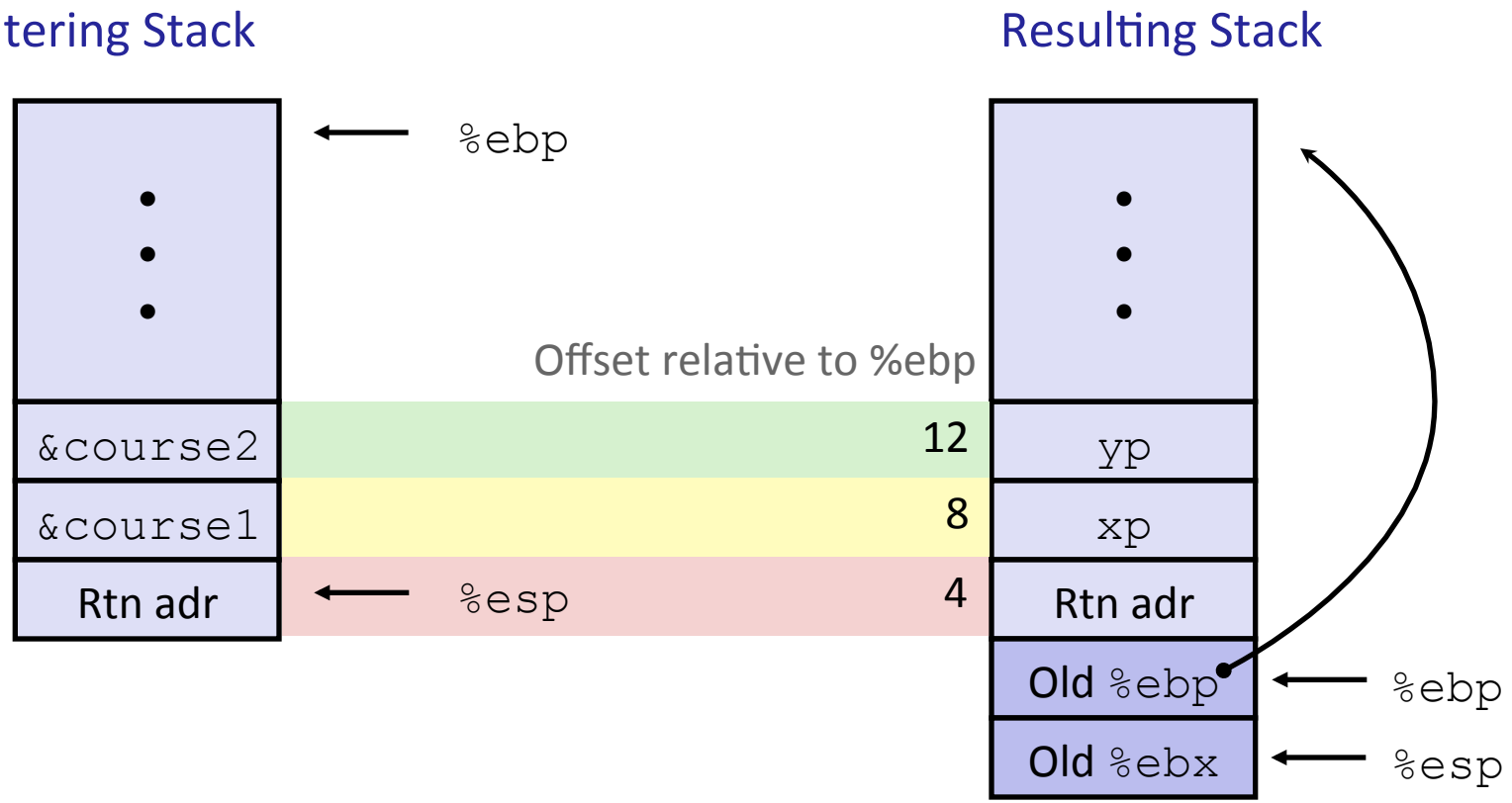


Resulting Stack




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

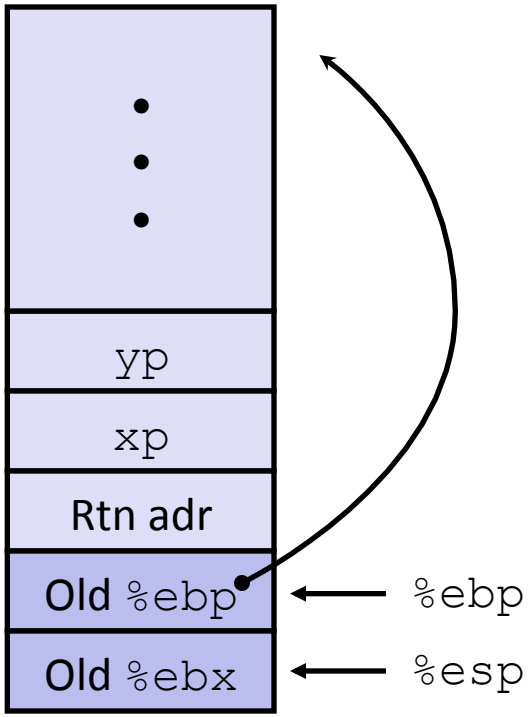
swap Body




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

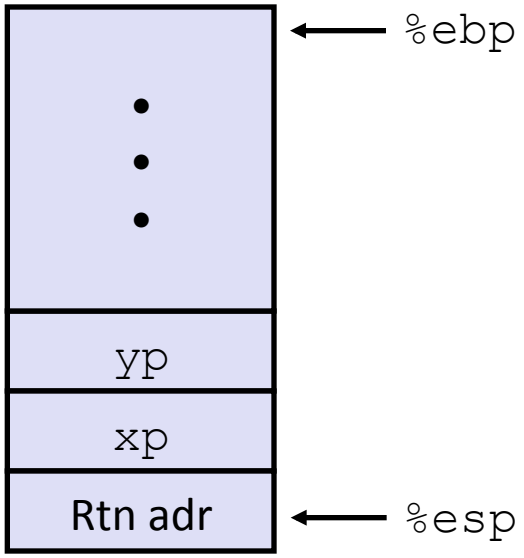
swap Finish

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
```

Pointer Code

Generating Pointer

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

Referencing Pointer

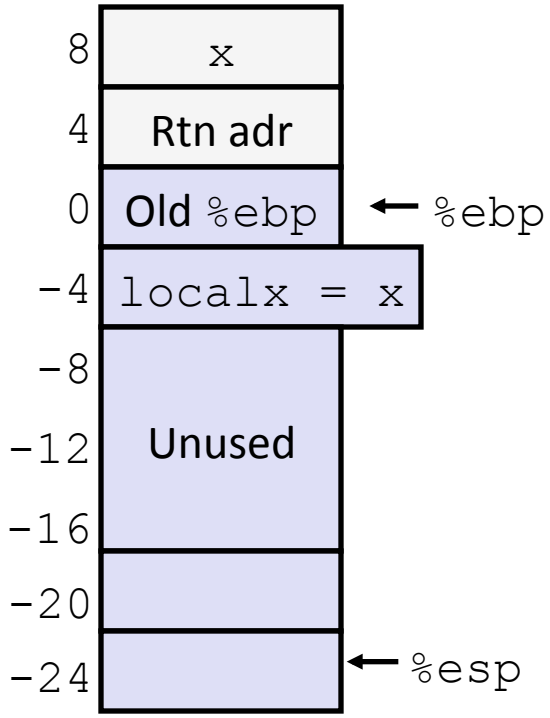
```
/* Increment value by k */
void incrk(int *ip, int k) {
  *ip += k;
}
```

- **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
```

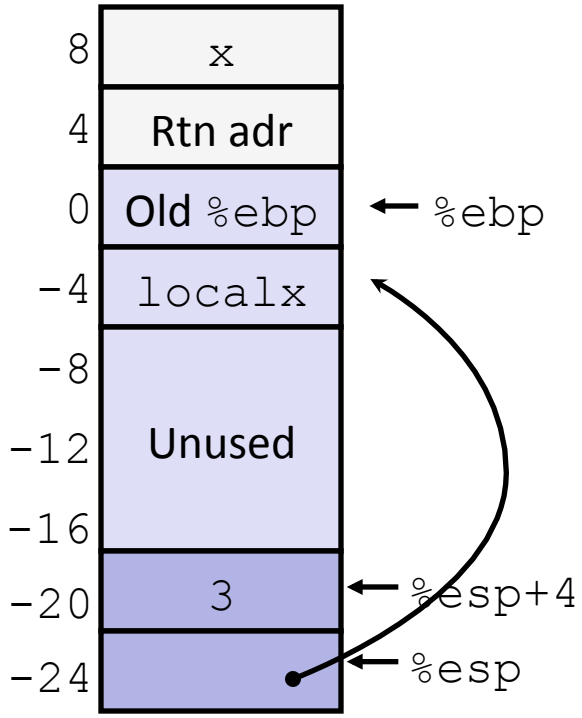
Creating Pointer as Argument

```
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
```



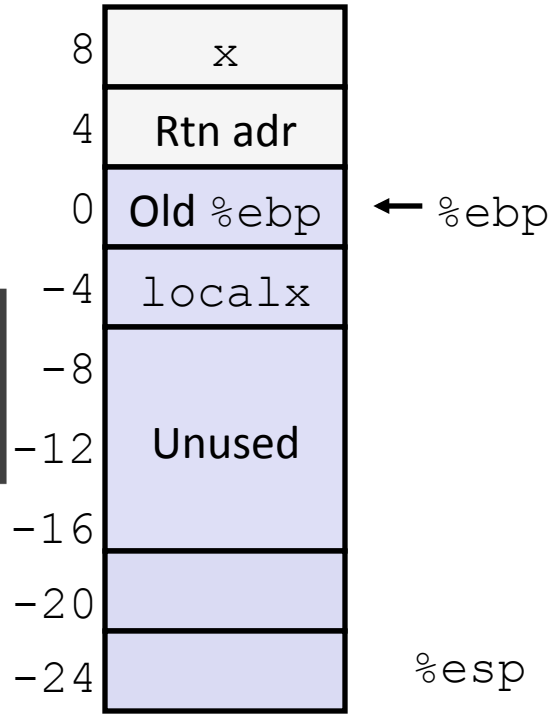
Retrieving local variable

```
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`