The Hardware/Software Interface

CSE351 Spring 2013

Procedures and Stacks I

Roadmap

Data & addressing
Integers & floats
Machine code & C
x86 assembly programming
Procedures & stacks
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

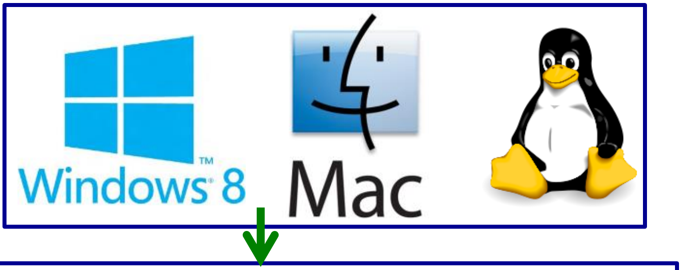
Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

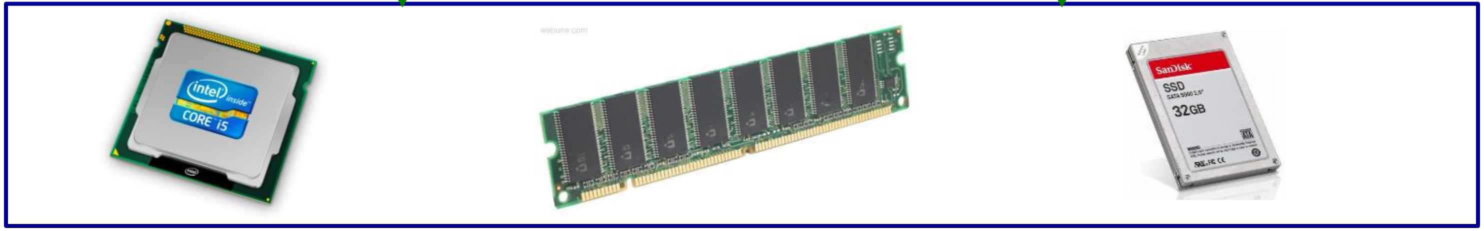
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:



Computer system:

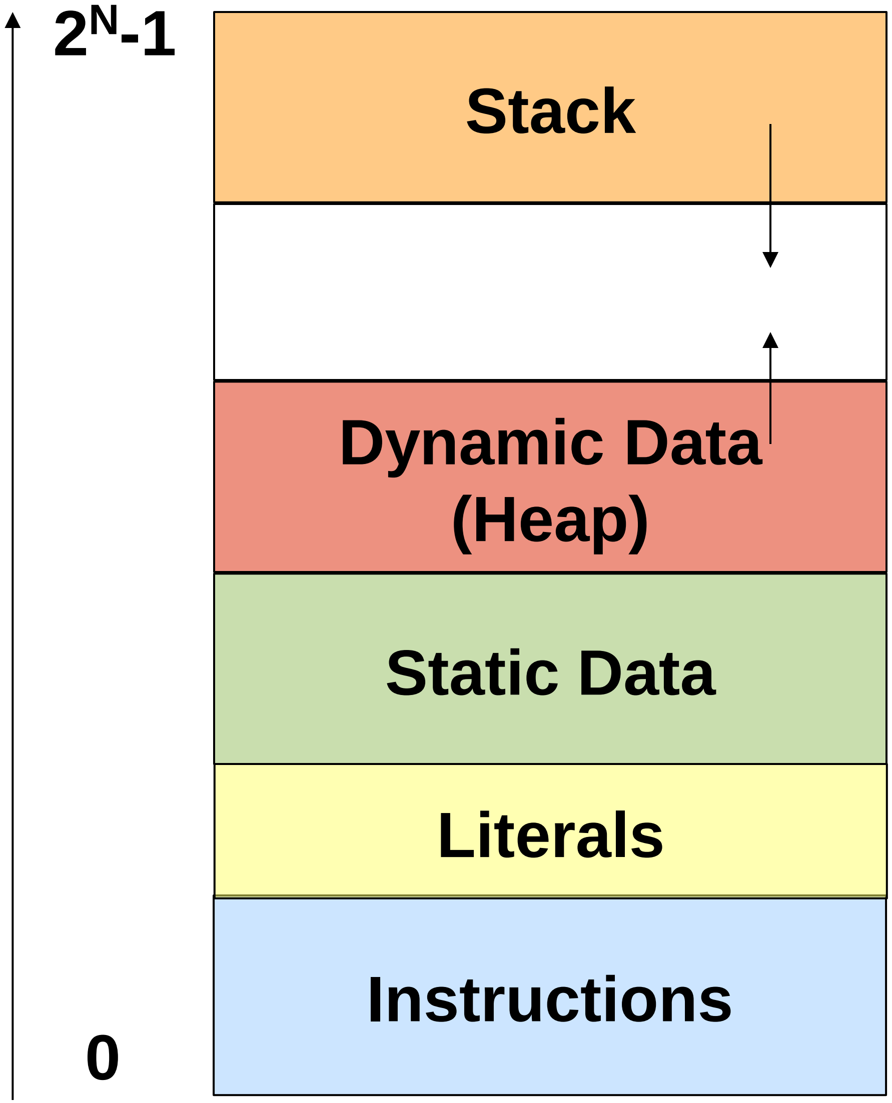


Procedures and Call Stacks

- How do I pass arguments to a procedure?
- How do I get a return value from a procedure?
- Where do I put local variables?
- When a function returns, how does it know where to return to?

- To answer these questions, we need a *call stack* …

Memory Layout



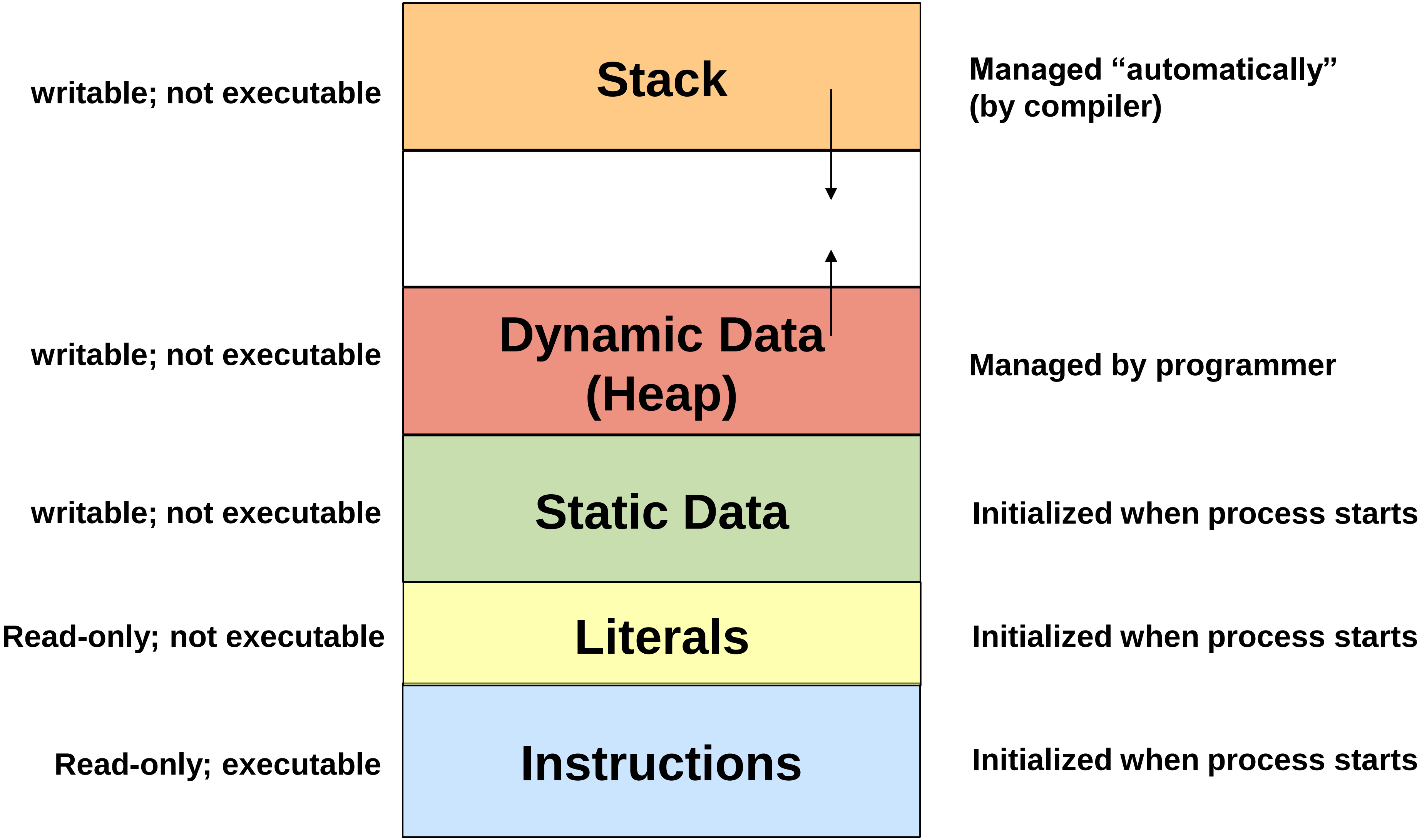
local variables;
procedure context

variables allocated with
new or *malloc*

static variables
(including global variables (C))

literals (e.g., “example”)

Memory Layout



writable; not executable | Stack | Managed "automatically" (by compiler)

writable; not executable | Dynamic Data (Heap) | Managed by programmer

writable; not executable | Static Data | Initialized when process starts

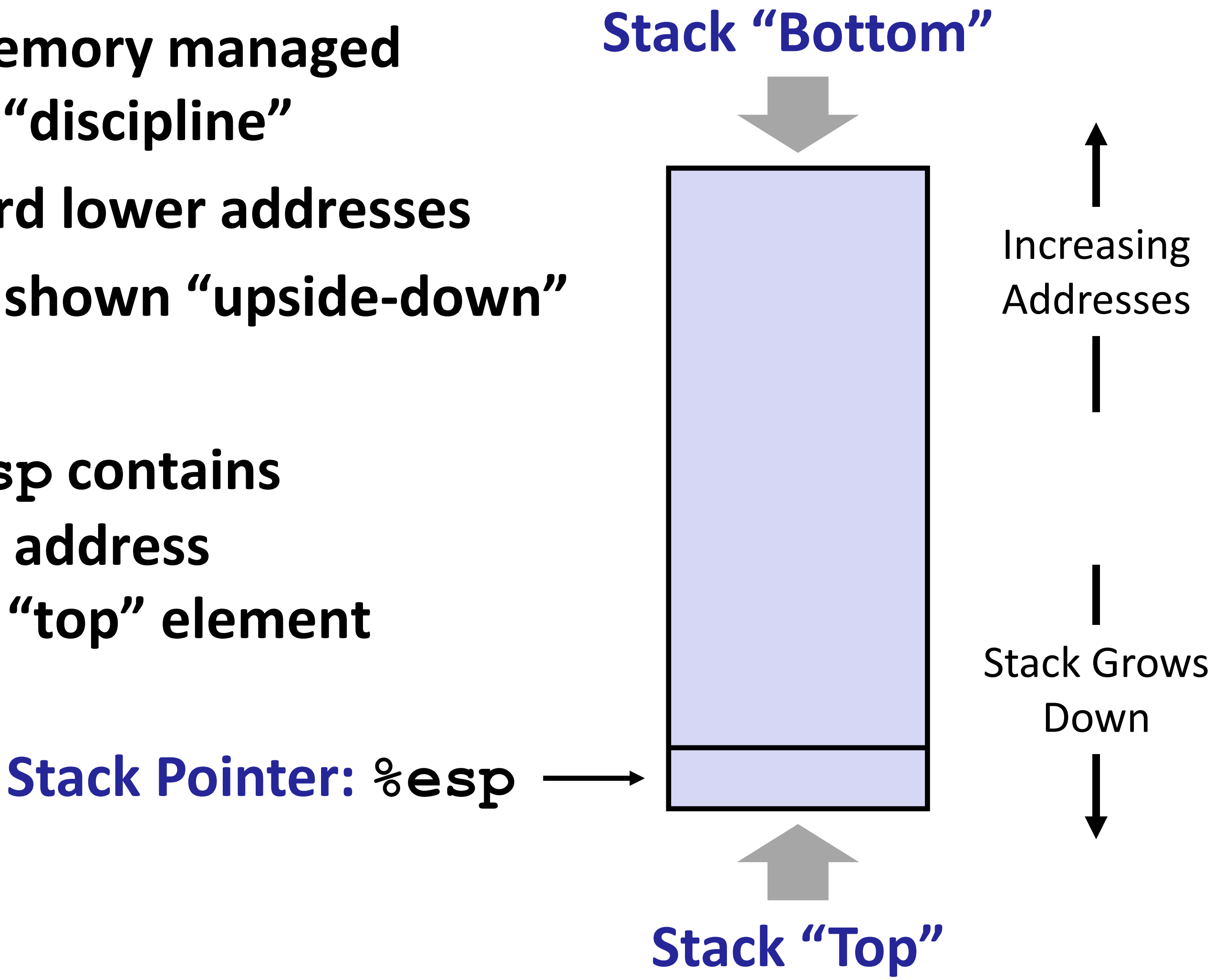
Read-only; not executable | Literals | Initialized when process starts

Read-only; executable | Instructions | Initialized when process starts

IA32 Call Stack

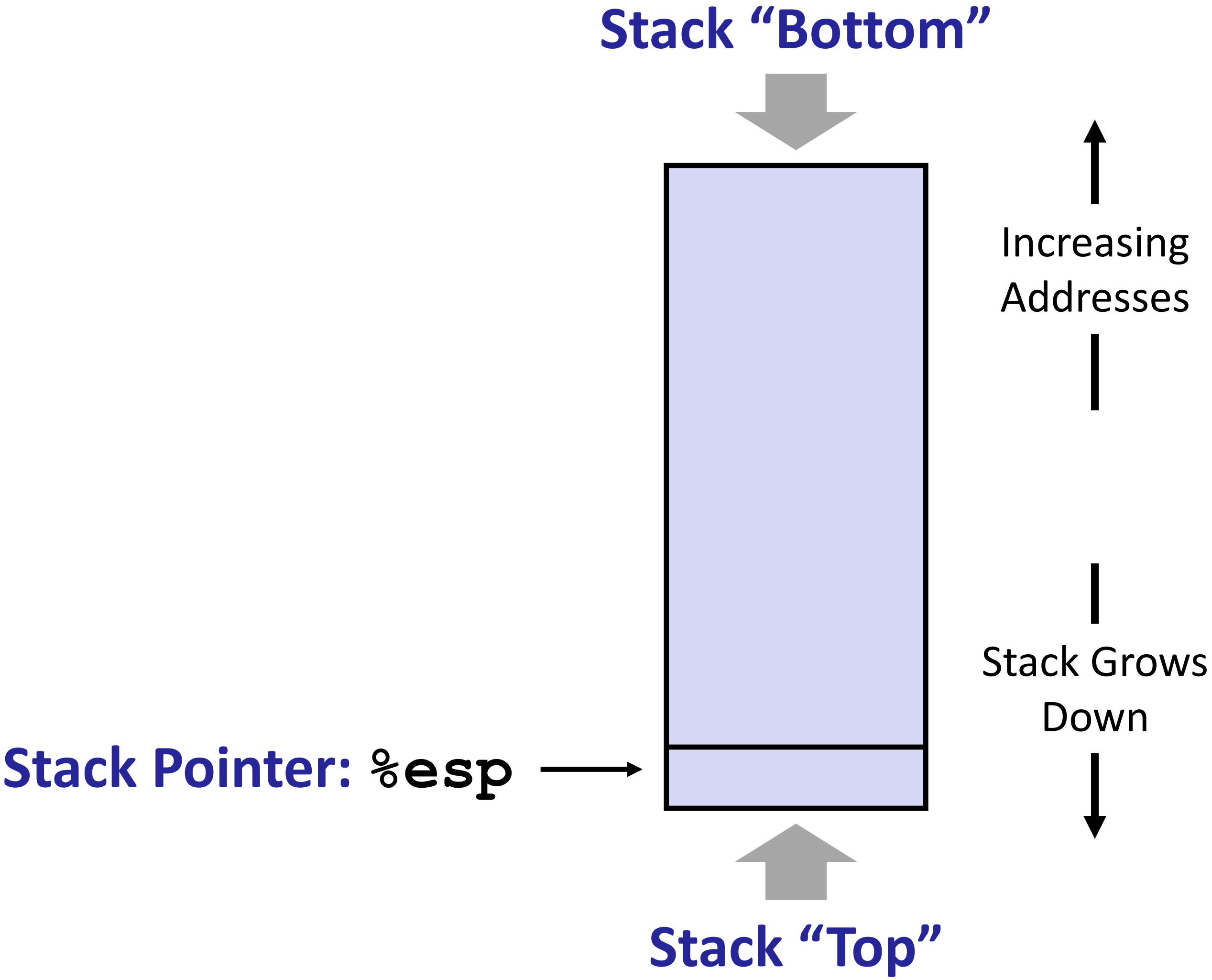
- Region of memory managed with a stack “discipline”
- Grows toward lower addresses
- Customarily shown “upside-down”

- Register `%esp` contains lowest stack address = address of “top” element



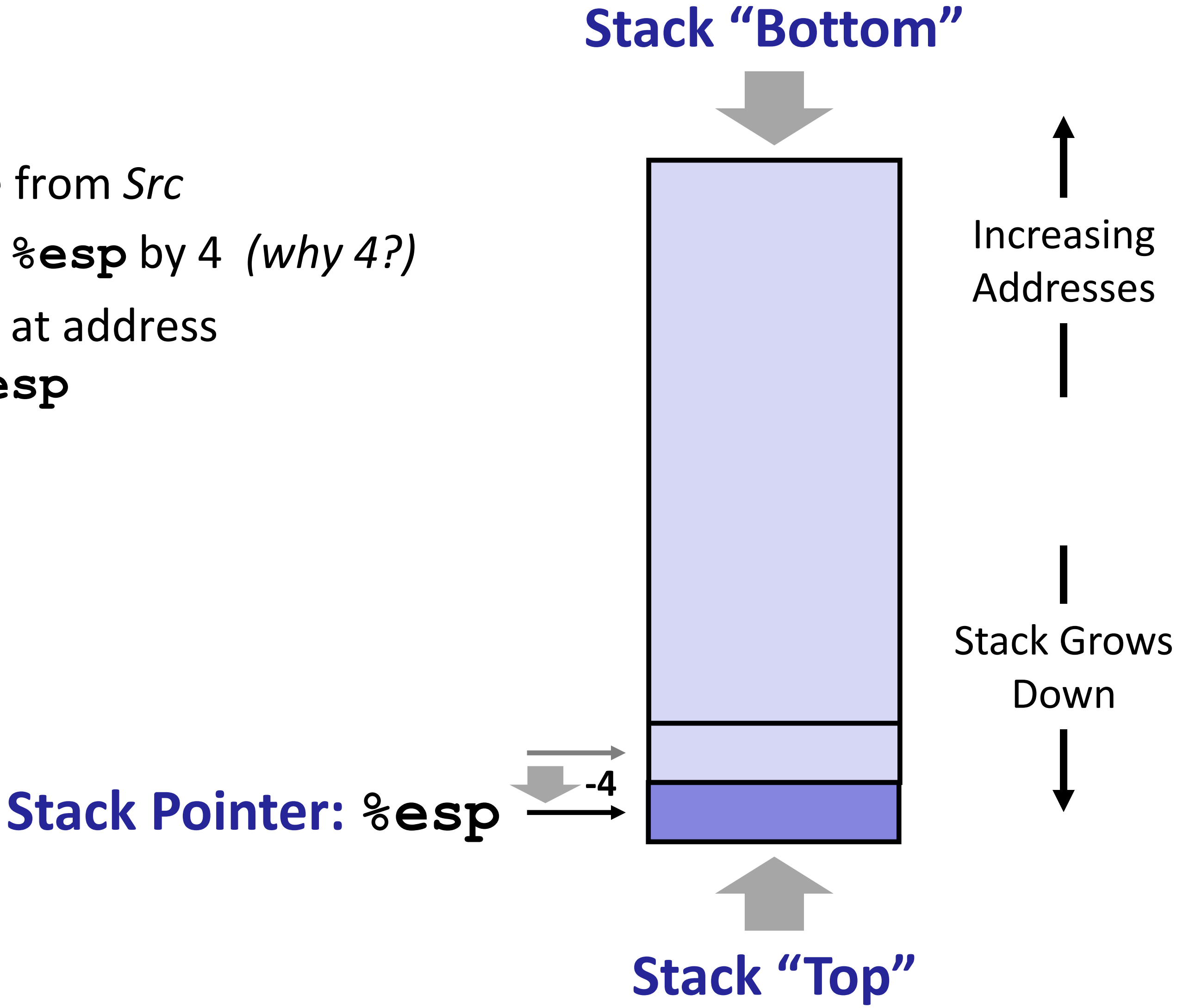
IA32 Call Stack: Push

- `pushl` *Src*



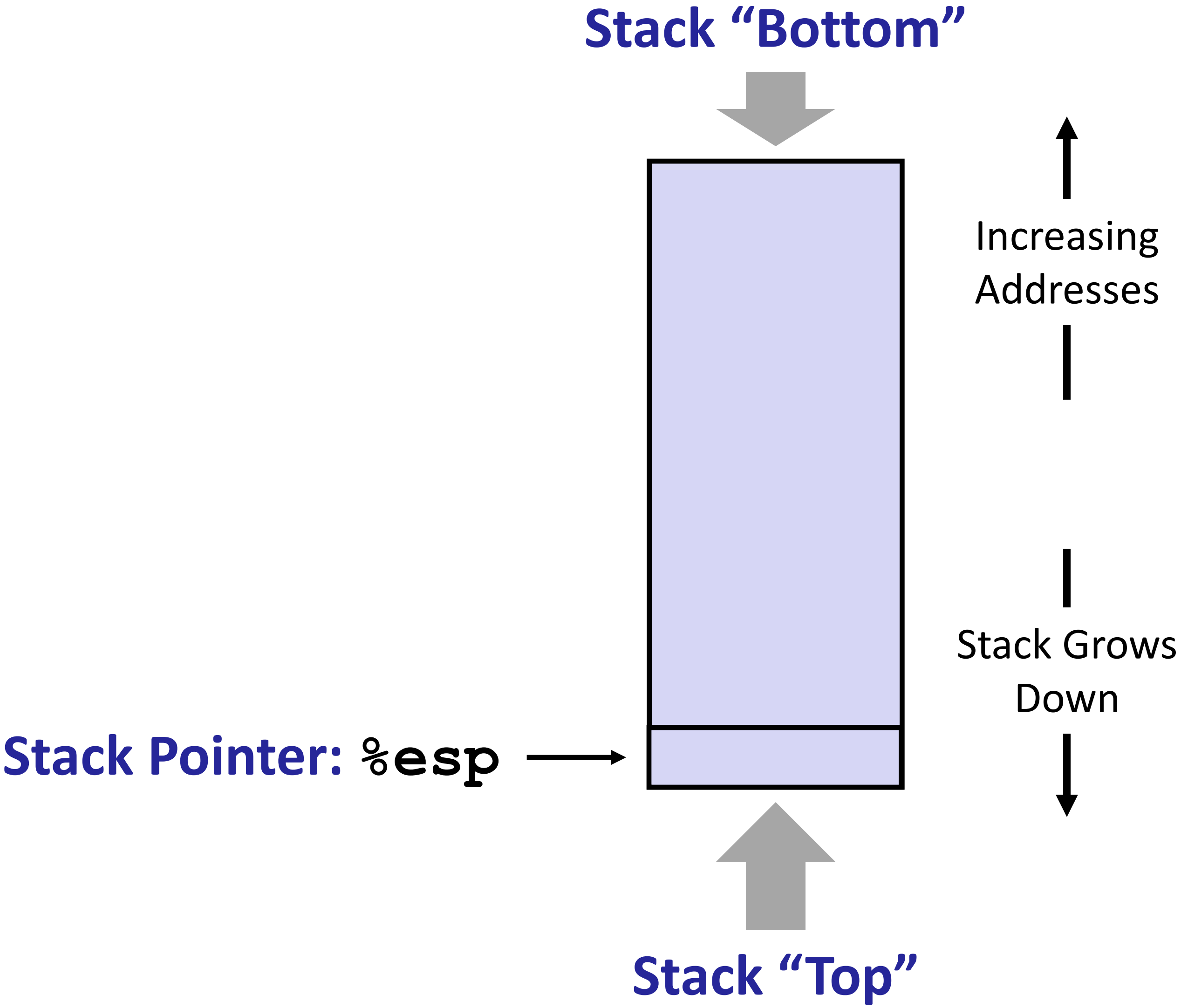
IA32 Call Stack: Push

- `pushl` *Src*
  - Fetch value from *Src*
  - Decrement `%esp` by 4 *(why 4?)*
  - Store value at address given by `%esp`



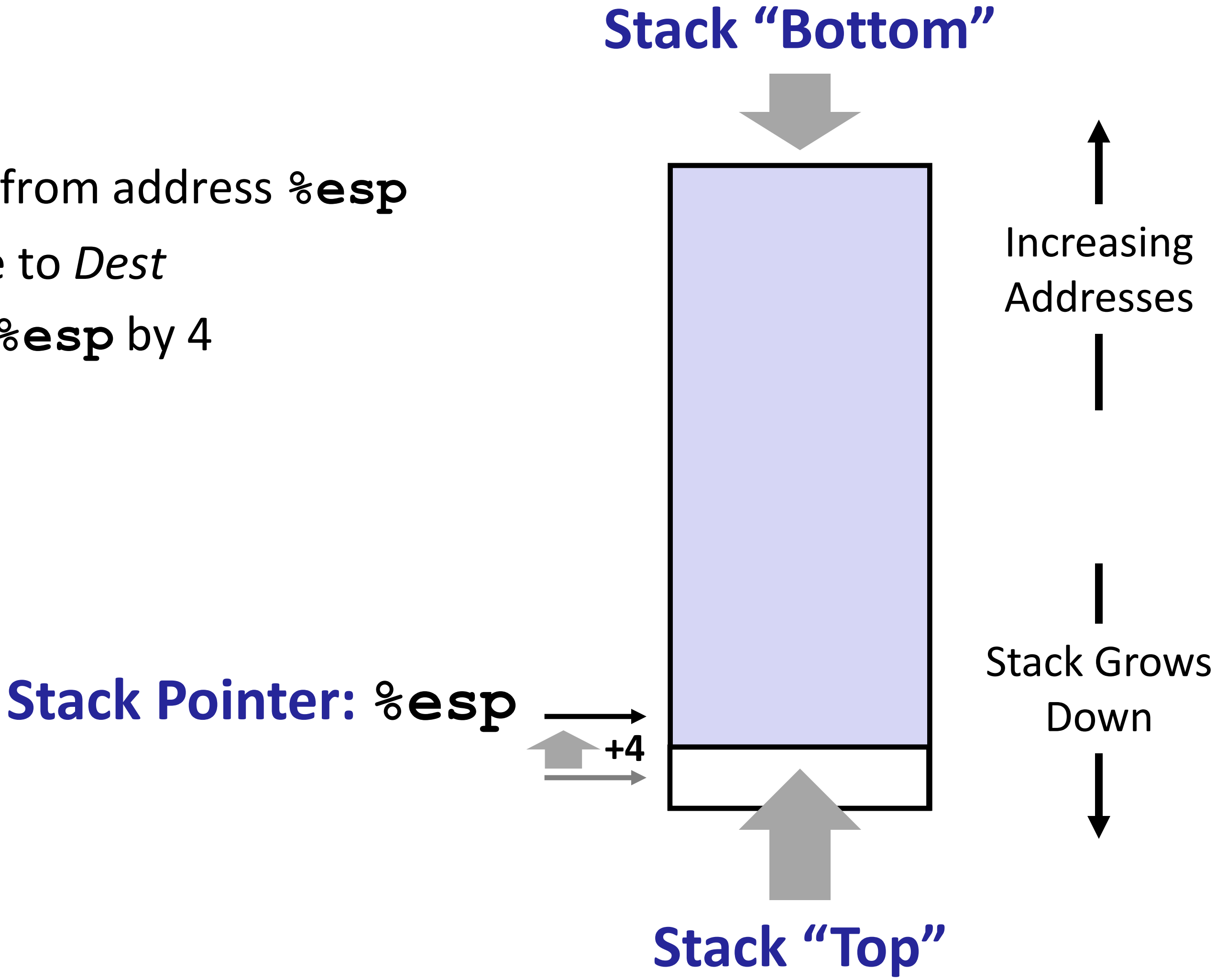
IA32 Call Stack: Pop

- `popl` *Dest*

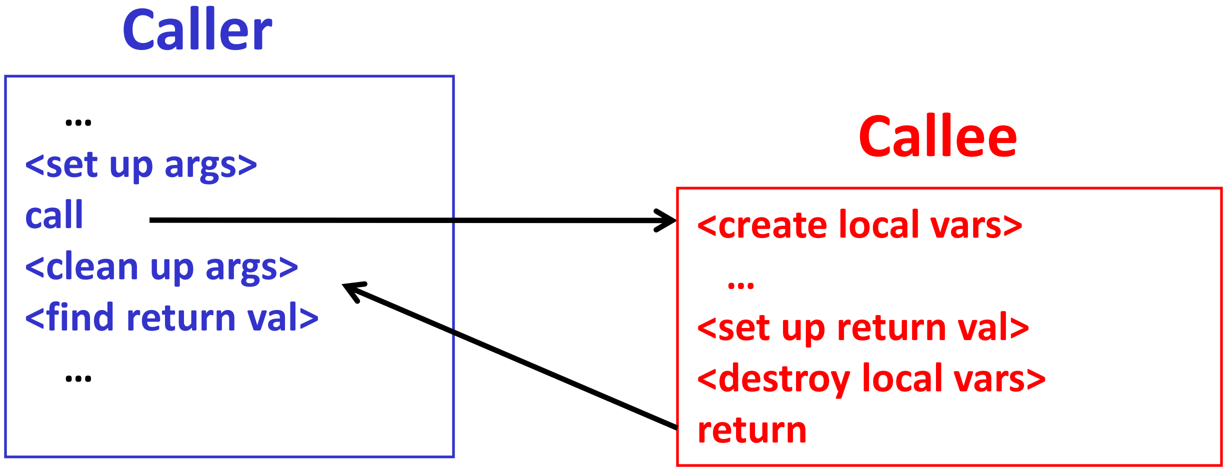


IA32 Call Stack: Pop

- `popl` *Dest*
  - Load value from address **`%esp`**
  - Write value to *Dest*
  - Increment **`%esp`** by 4

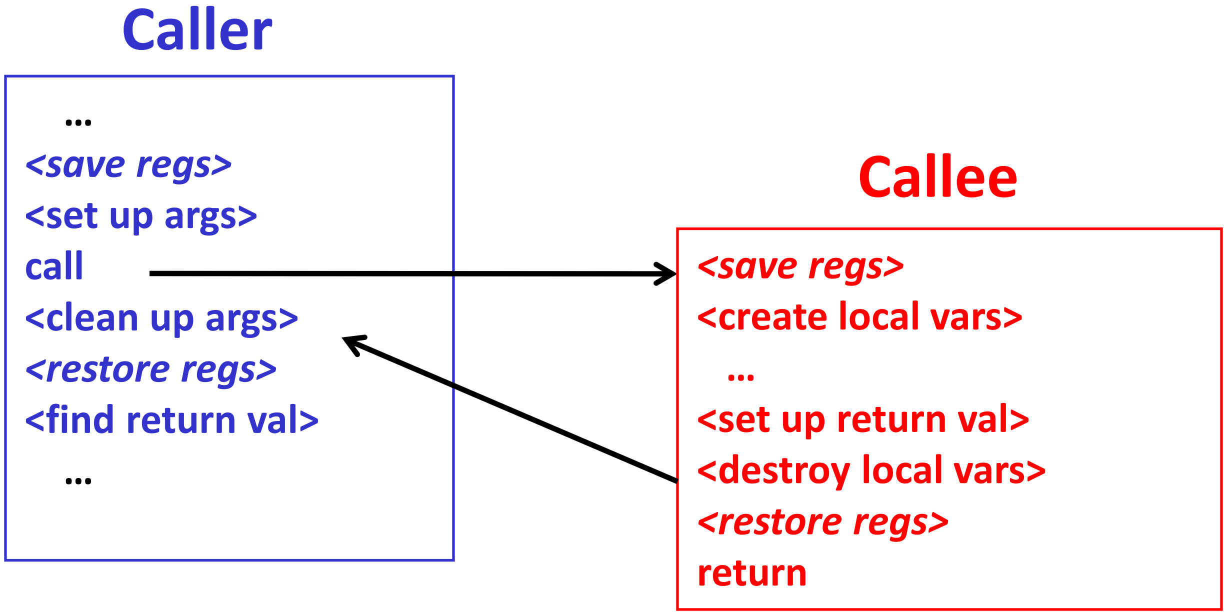


Procedure Call Overview



- **Callee must know where to find args**
- **Callee must know where to find "return address"**
- **Caller must know where to find return val**
- **Caller and Callee run on same CPU → use the same registers**
  - Caller might need to save registers that Callee might use
  - Callee might need to save registers that Caller has used

Procedure Call Overview



Caller

…

<save regs>

<set up args>

call

<clean up args>

<restore regs>

<find return val>

…

Callee

<save regs>

<create local vars>

…

<set up return val>

<destroy local vars>

<restore regs>

return

- **The convention of where to leave/find things is called the procedure call linkage**
  - Details vary between systems
  - We will see the convention for IA32/Linux in detail
  - What could happen if our program didn’t follow these conventions?

Procedure Control Flow

- **Use stack to support procedure call and return**
- **Procedure call:** `call` ***`label`***
  - Push return address on stack
  - Jump to ***`label`***

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 instruction after **`call`**
  - Example from disassembly:

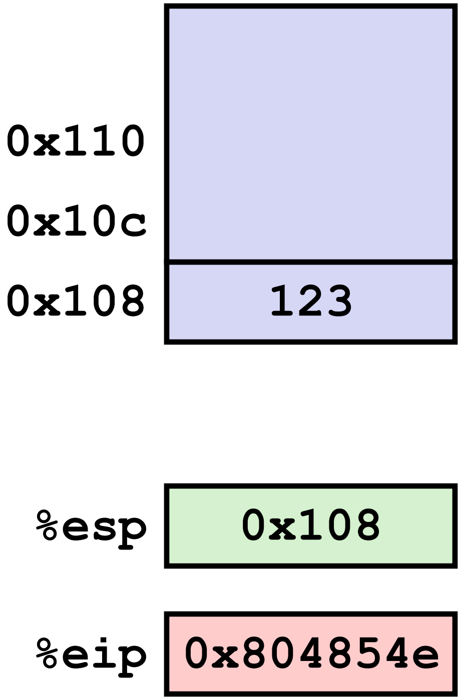
```
804854e:   e8 3d 06 00 00      call    8048b90 <main>
8048553:   50                  pushl   %eax
```

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

Procedure Call Example

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

call   8048b90



%eip: program counter

Procedure Call Example

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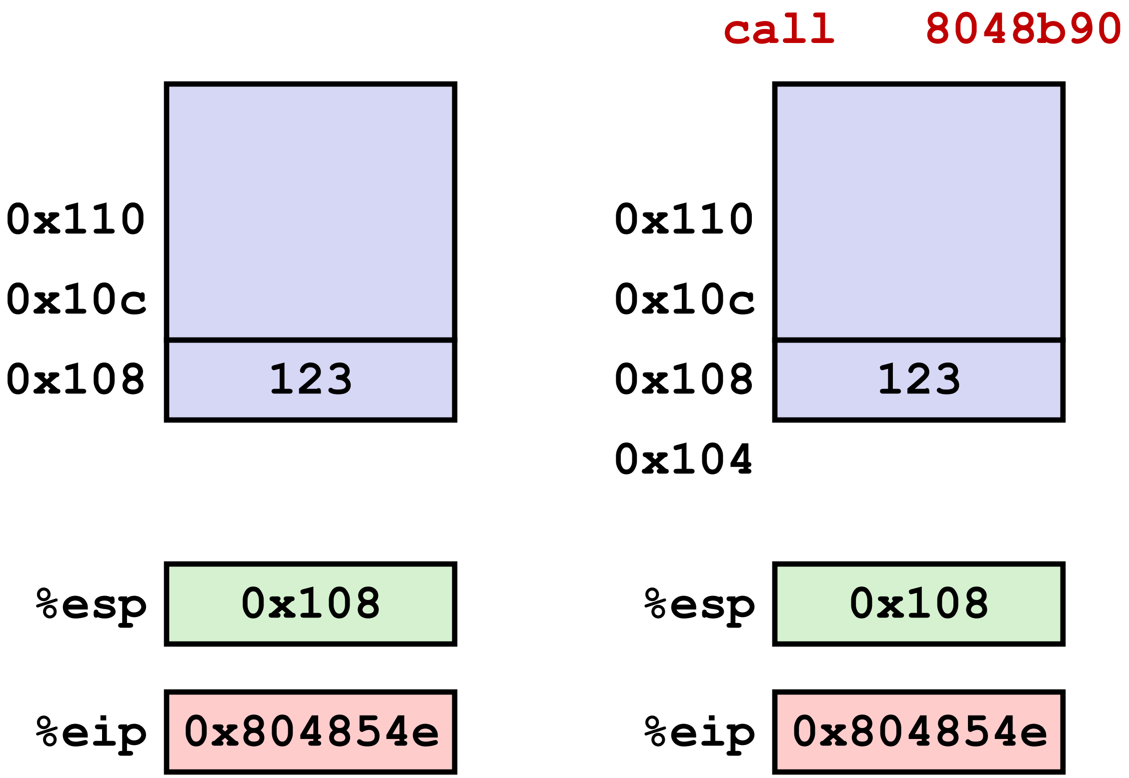
```



call 8048b90

0x110

0x10c

0x108 123

0x104

%esp 0x108

%eip 0x804854e

0x110

0x10c

0x108 123

%esp 0x108

%eip 0x804854e

`%eip:` program counter

Procedure Call Example

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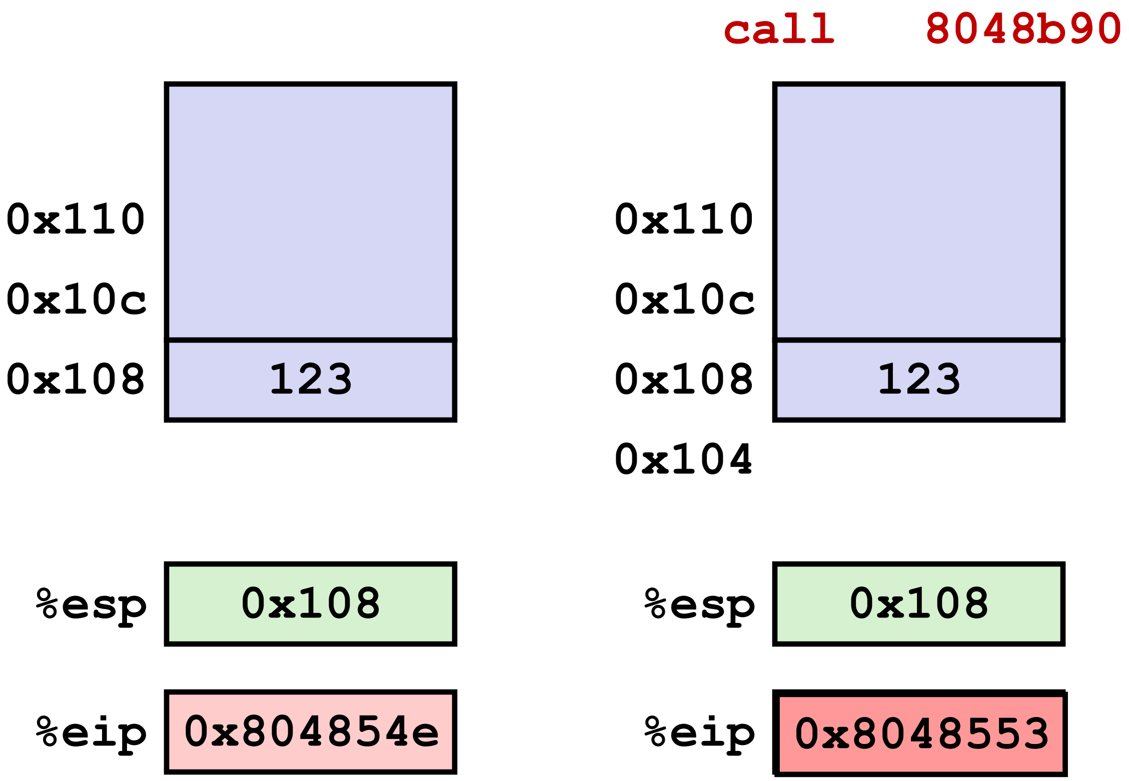

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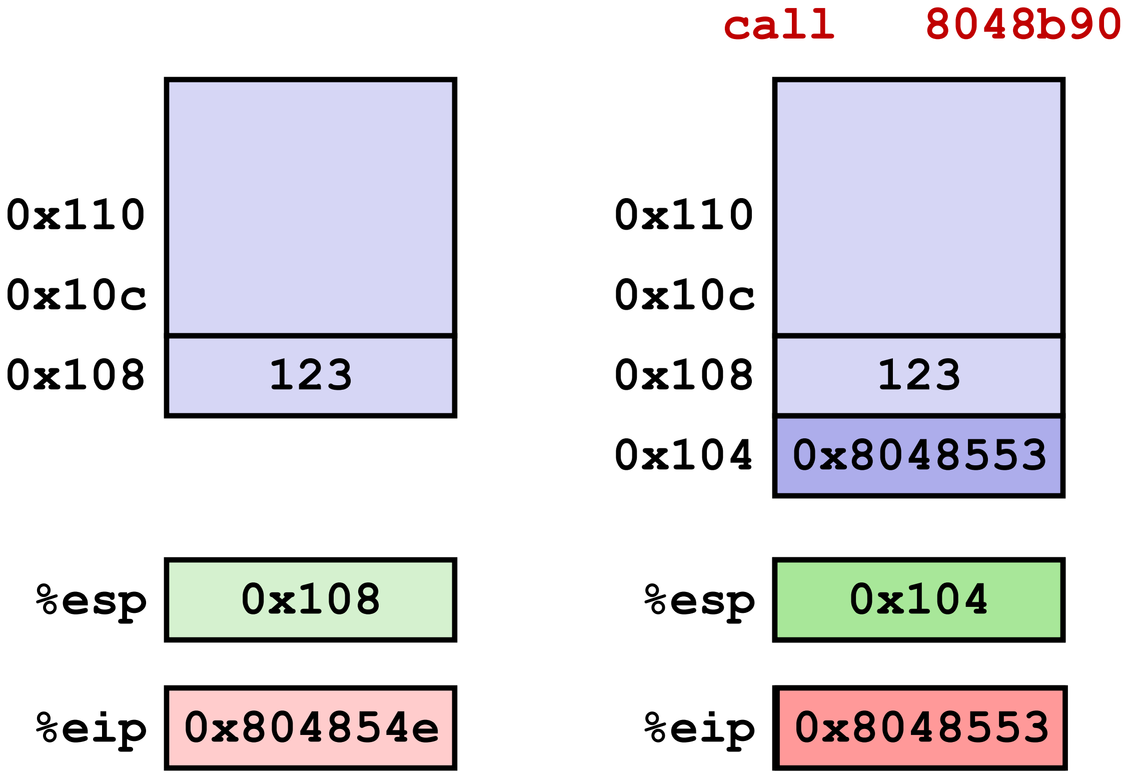

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Procedure Call Example

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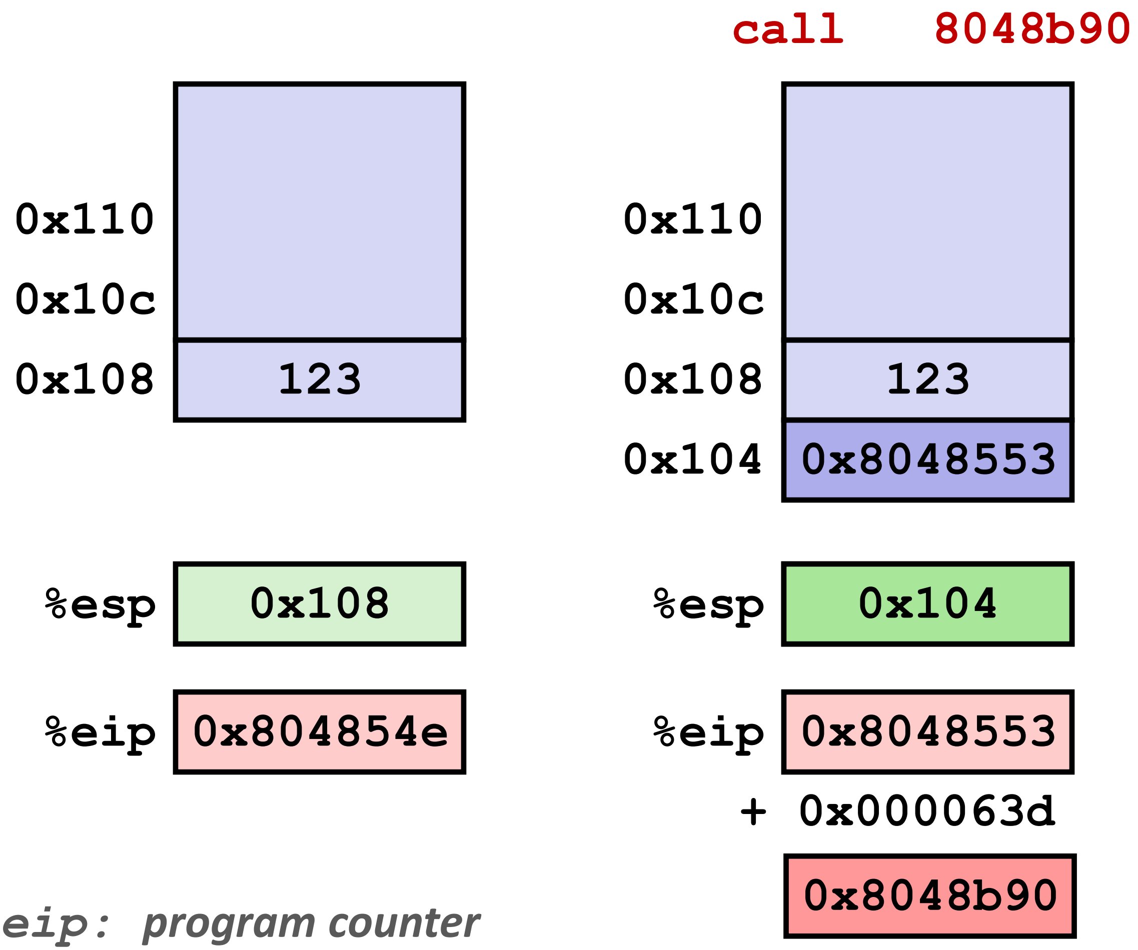
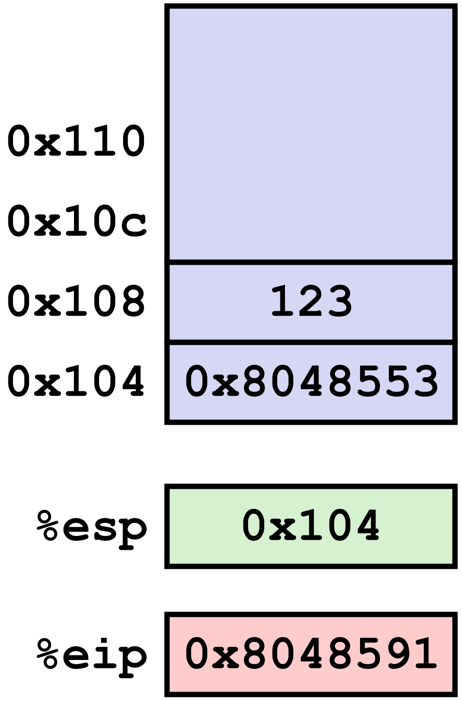


%eip: program counter

Procedure Return Example

```
8048591:      c3                    ret
```

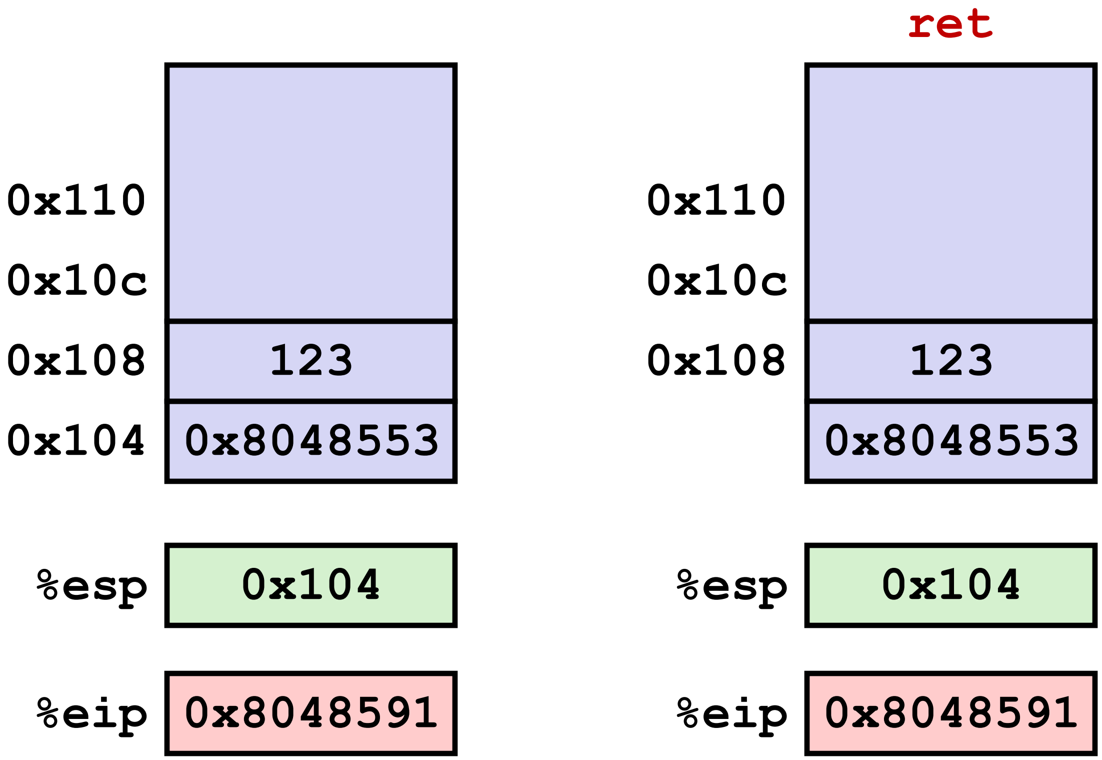
ret



`%eip`: program counter

Procedure Return Example

```
8048591:      c3                    ret
```



`%eip:` program counter

Procedure Return Example

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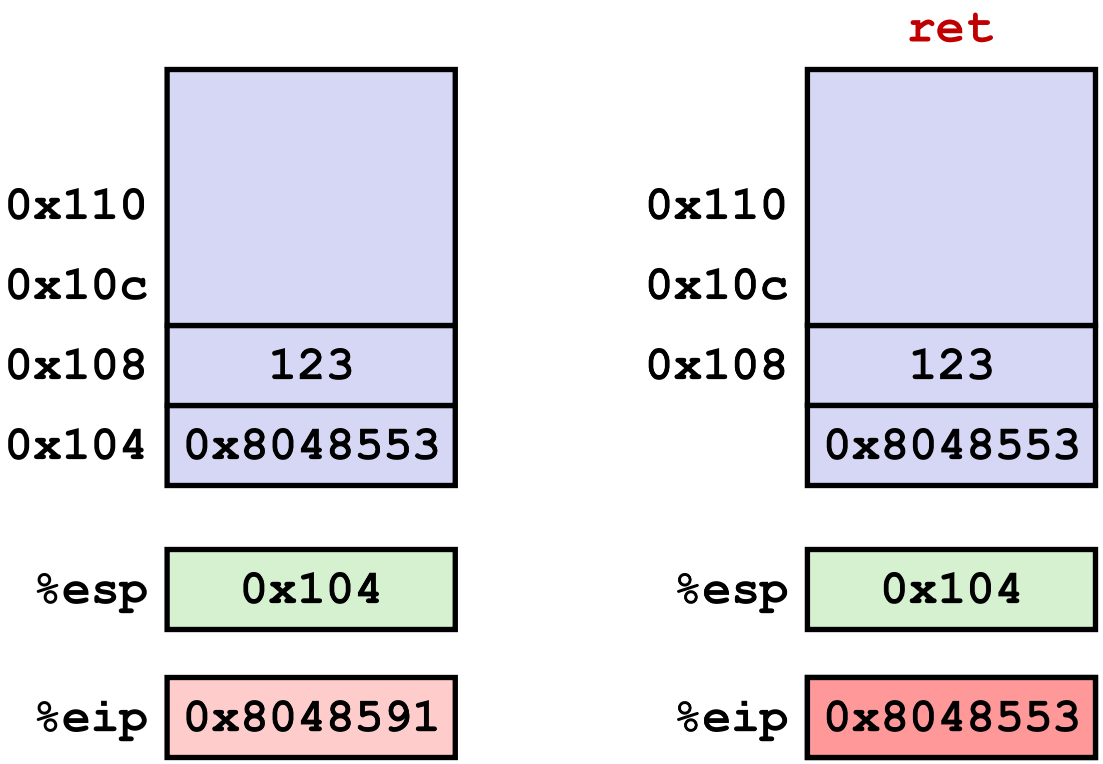
```



ret

0x110
0x10c
0x108 123
0x104 0x8048553

%esp 0x104

%eip 0x8048591

0x110
0x10c
0x108 123
0x8048553

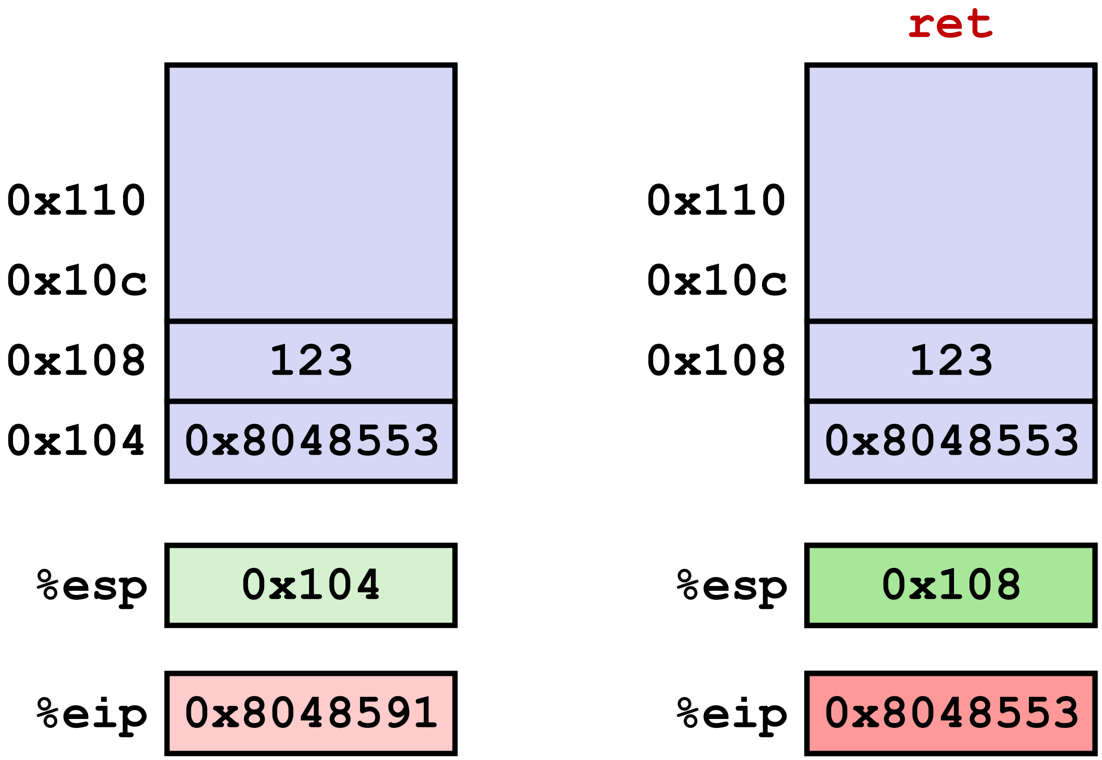
%esp 0x104

%eip 0x8048553

`%eip`: program counter

Procedure Return Example

```
8048591:      c3                    ret
```



ret

0x110
0x10c
0x108 123
0x104 0x8048553

%esp 0x104

%eip 0x8048591

0x110
0x10c
0x108 123
0x8048553

%esp 0x108

%eip 0x8048553

%eip: program counter

Stack-Based Languages

- **Languages that support recursion**
  - e.g., C, Pascal, Java
  - Code must be *re-entrant*
    - Multiple simultaneous instantiations of single procedure
  - Need some place to store state of each instantiation
    - Arguments
    - Local variables
    - Return pointer
- **Stack discipline**
  - State for a given procedure needed for a limited time
    - Starting from when it is called to when it returns
  - Callee always returns before caller does
- **Stack allocated in *frames***
  - State for a single procedure instantiation

Call Chain Example

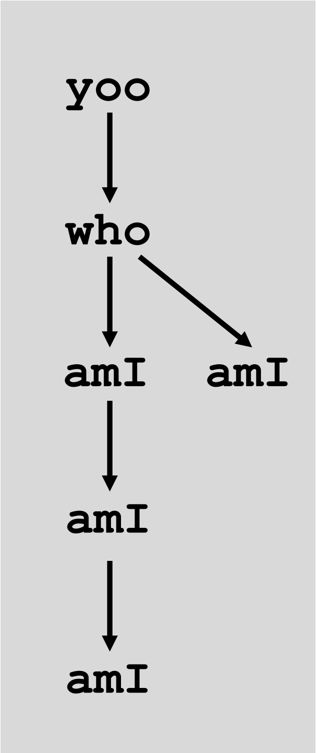
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

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

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

Procedure amI is recursive (calls itself)

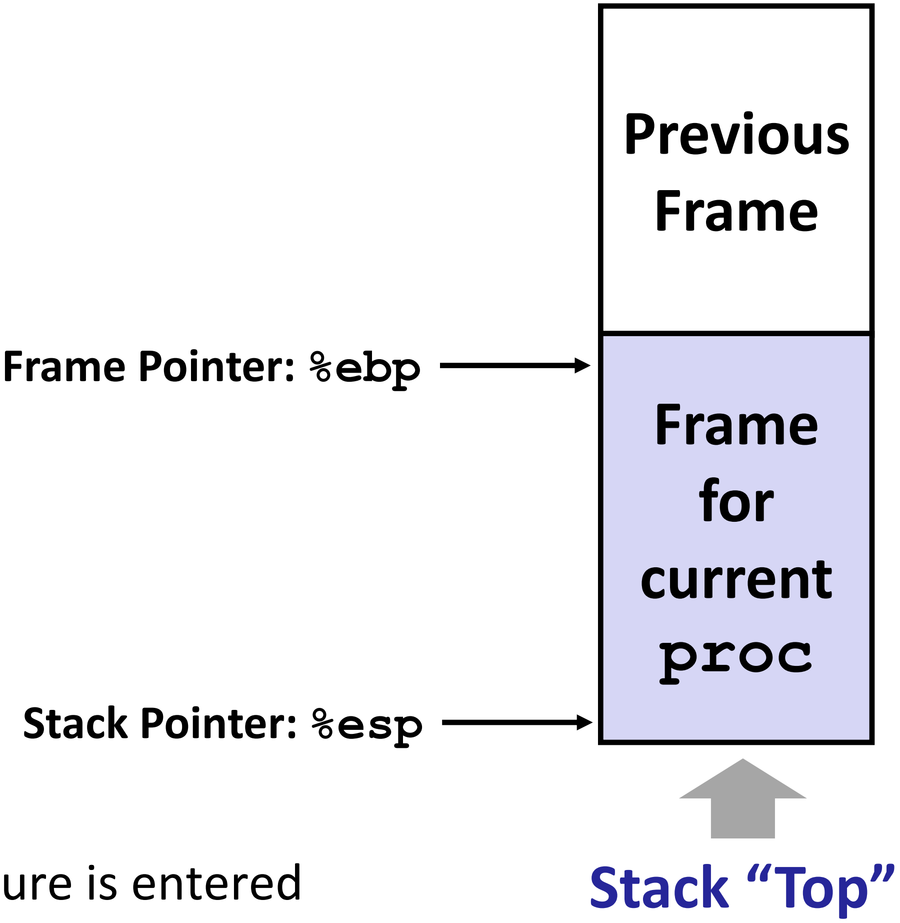
Example Call Chain



yoo
who
amI
amI
amI
amI

Stack Frames

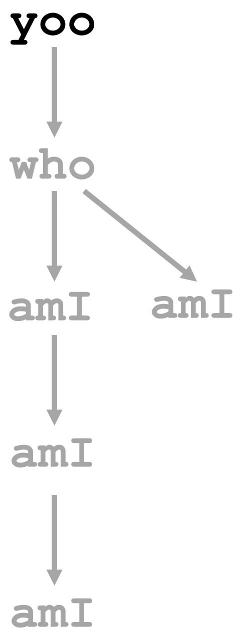
- **Contents**
  - Local variables
  - Function arguments
  - Return information
  - Temporary space

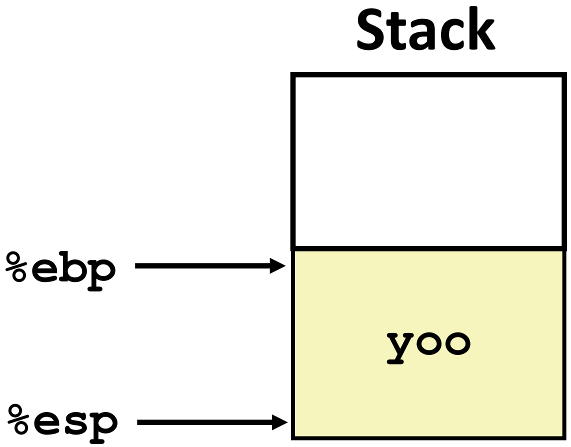


- **Management**
  - Space allocated when procedure is entered
    - "Set-up" code
  - Space deallocated upon return
    - "Finish" code

Example

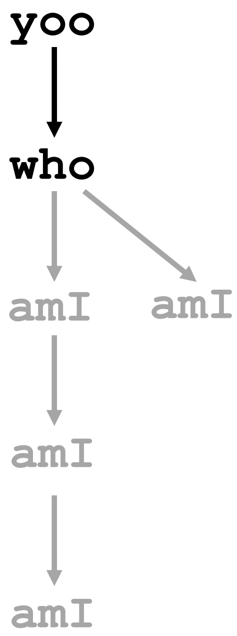
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

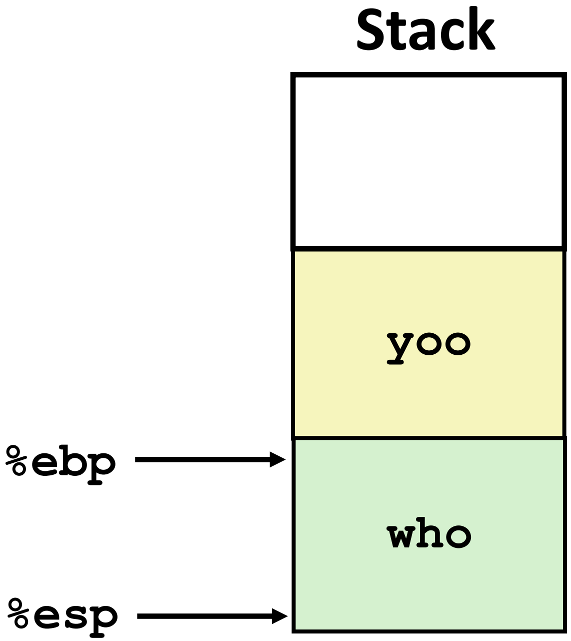




Example

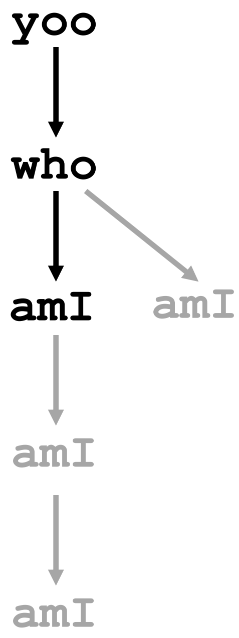
```
who(…)
{
   • • •
   amI();
   • • •
   amI();
   • • •
}
```

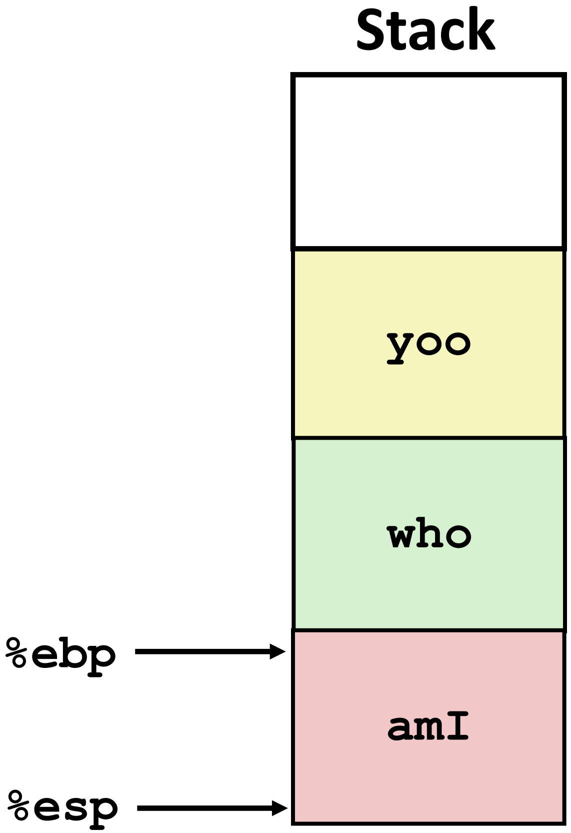




Example

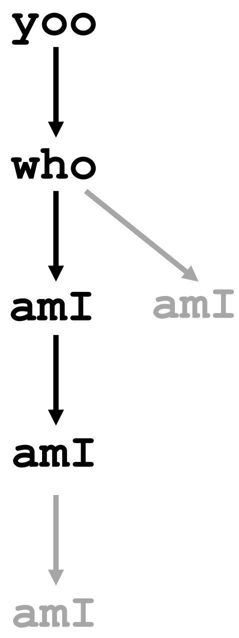
```
amI(…)
{
      •
      •
      amI();
      •
      •
}
```

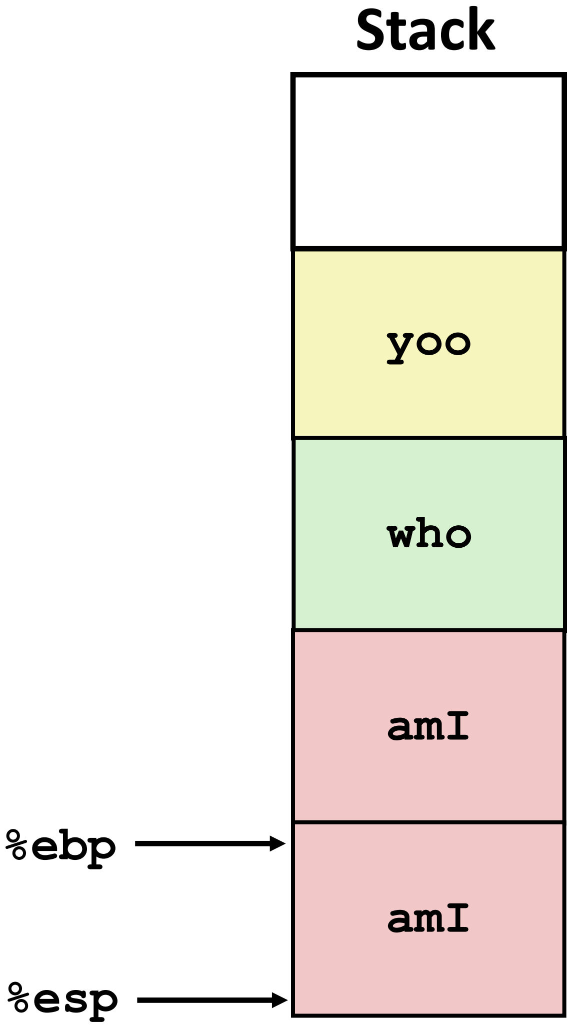




Example

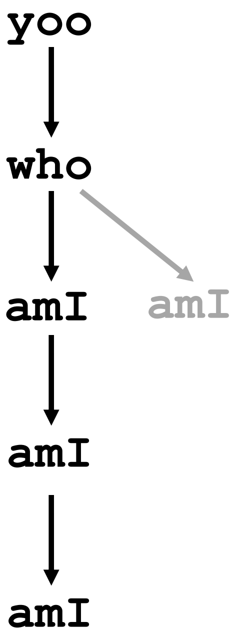
```
amI(…)
{
      •
      •
      amI();
      •
      •
}
```

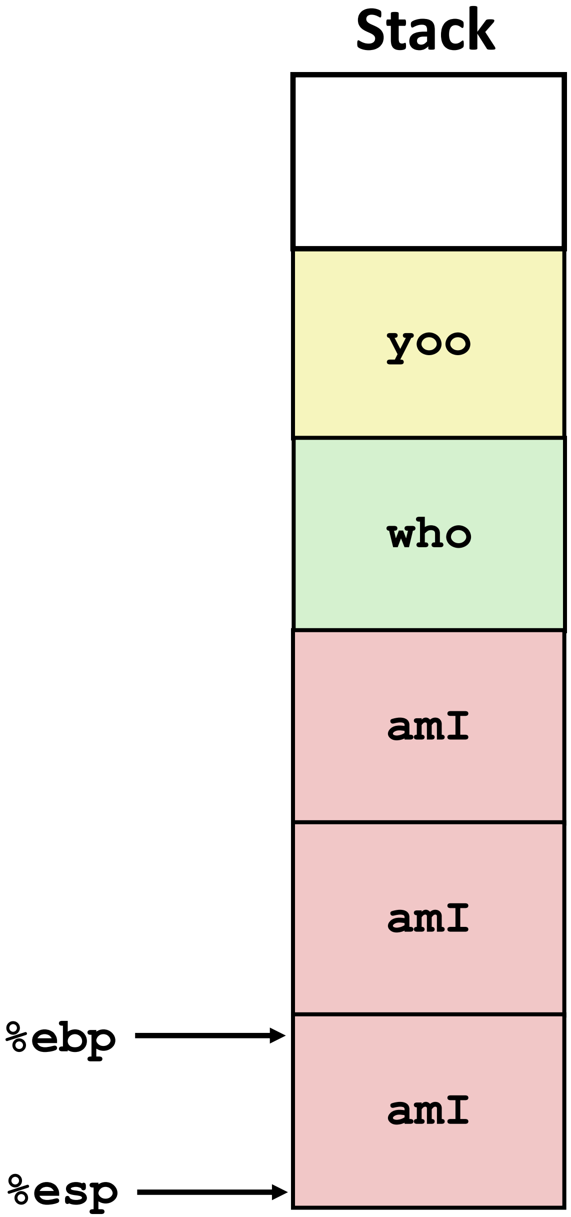




Example

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





Example

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     •
}
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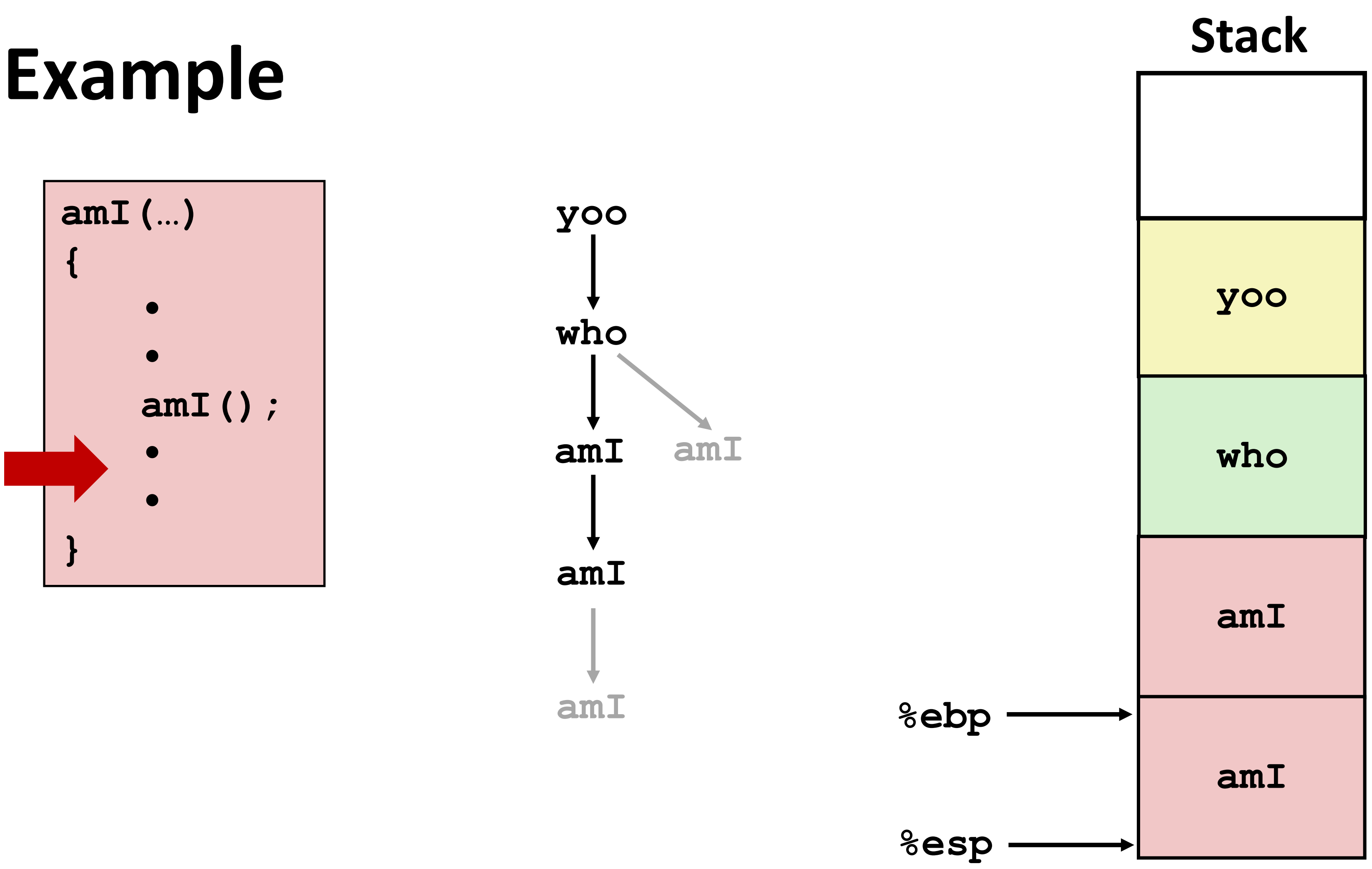

Example

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      •
      •
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      •
      •
}
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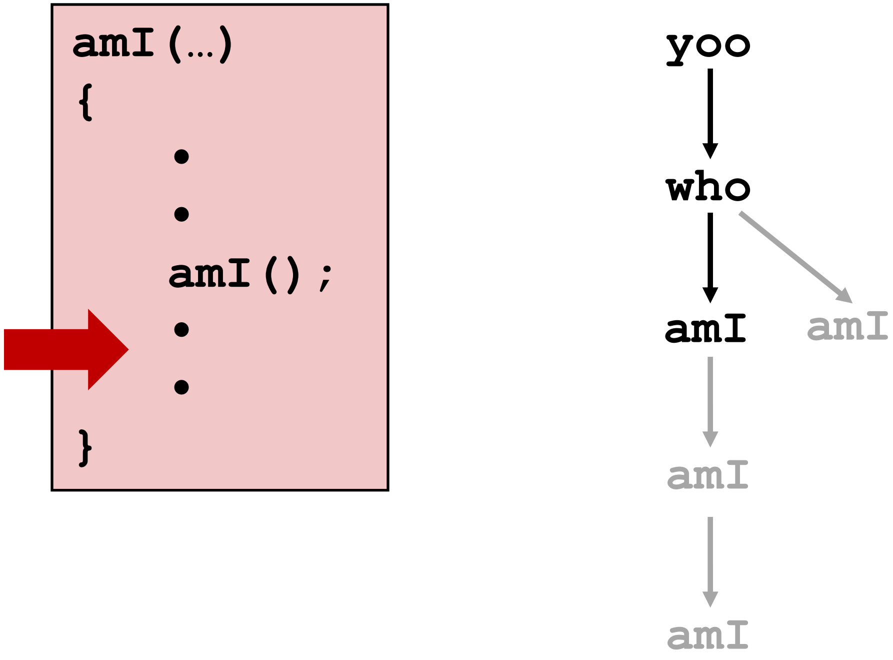
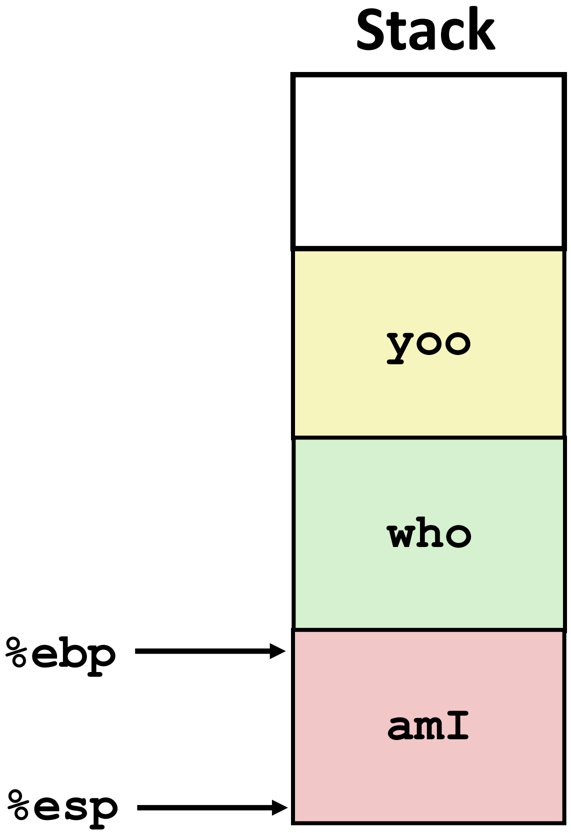
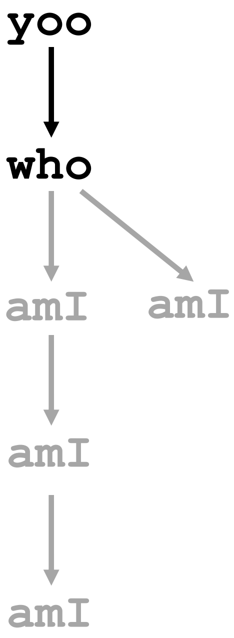
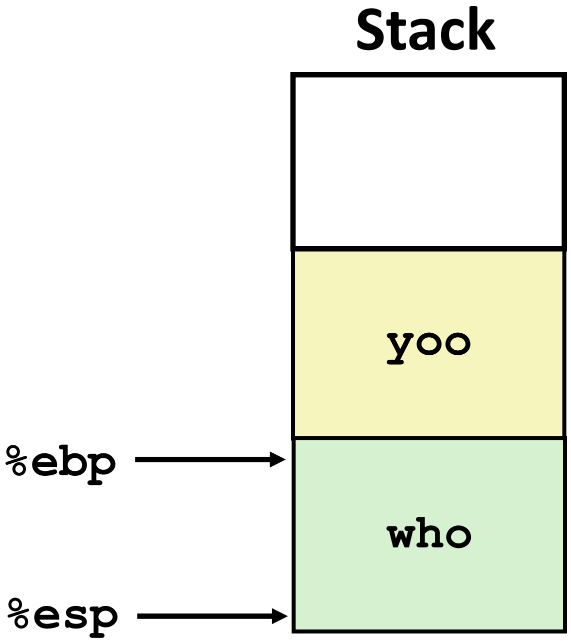




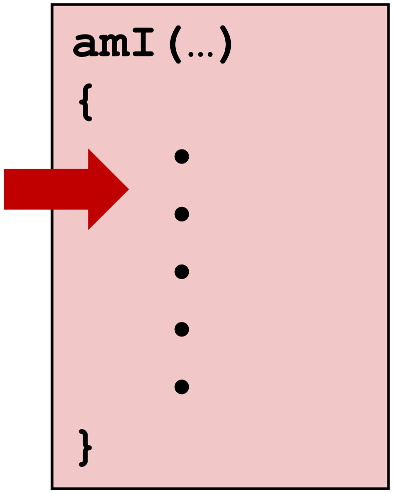
Example

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

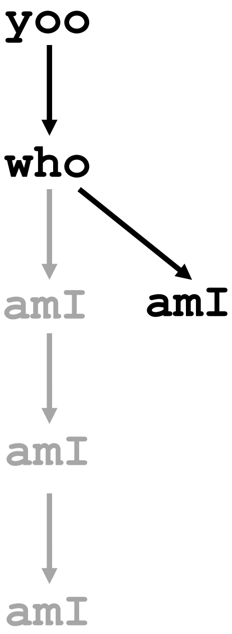




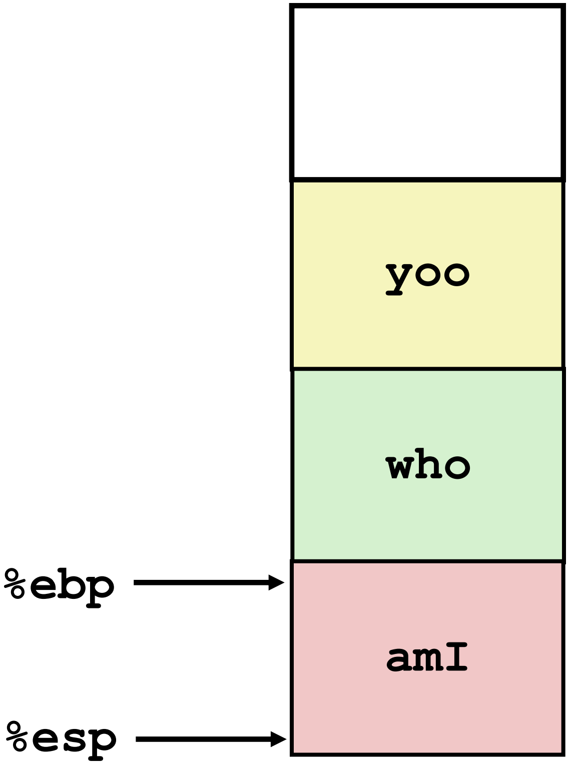
Example



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



Stack



Example

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    • • •
    amI();
    • • •
}
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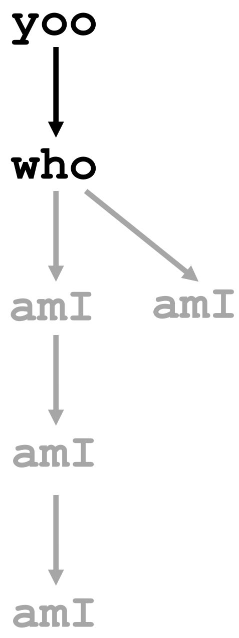
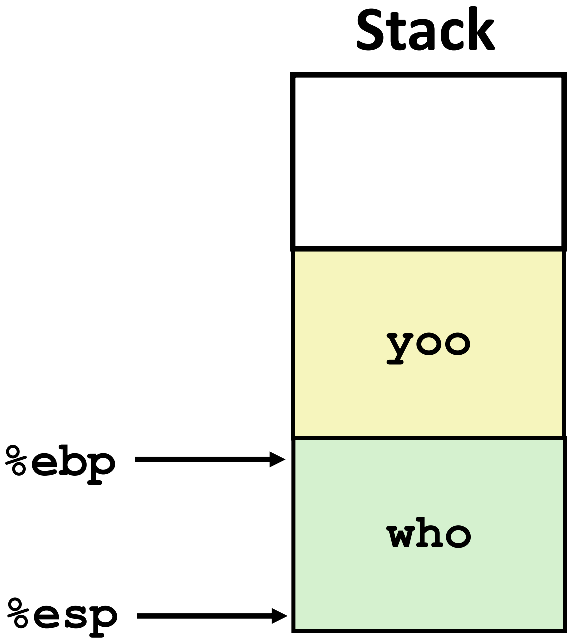
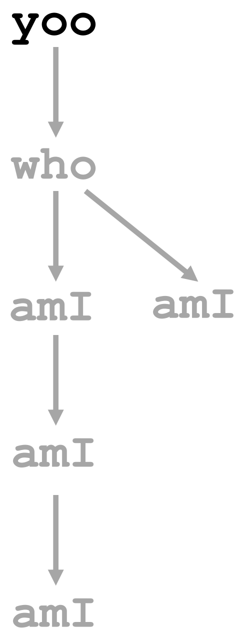
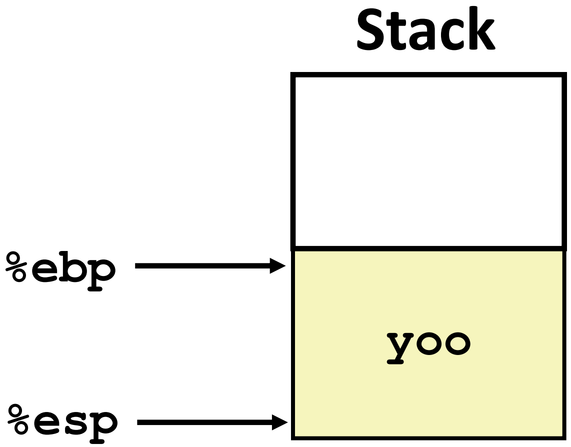




Example

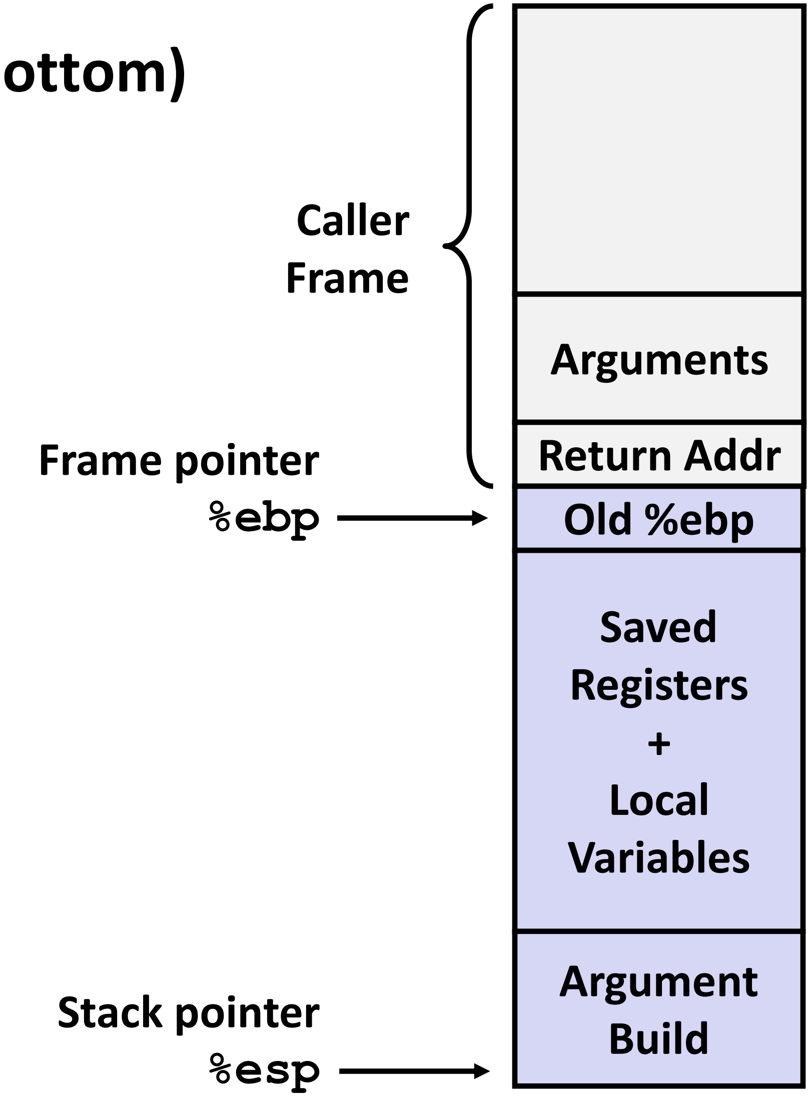
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```





IA32/Linux Stack Frame

- **Current Stack Frame ("Top" to Bottom)**
  - "Argument build" area (parameters for function about to be called)
  - Local variables (if can't be kept in registers)
  - Saved register context (when reusing registers)
  - Old frame pointer (for caller)
- **Caller's Stack Frame**
  - Return address
    - Pushed by `call` instruction
  - Arguments for this call



Revisiting swap

```
int zip1 = 15213;
int zip2 = 98195;

void call_swap()
{
  swap(&zip1, &zip2);
}
```

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

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void call_swap()
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}
```

Calling swap from call_swap

```
call_swap:
    • • •
    pushl $zip2    # Global Var
    pushl $zip1    # Global Var
    call swap
    • • •
```

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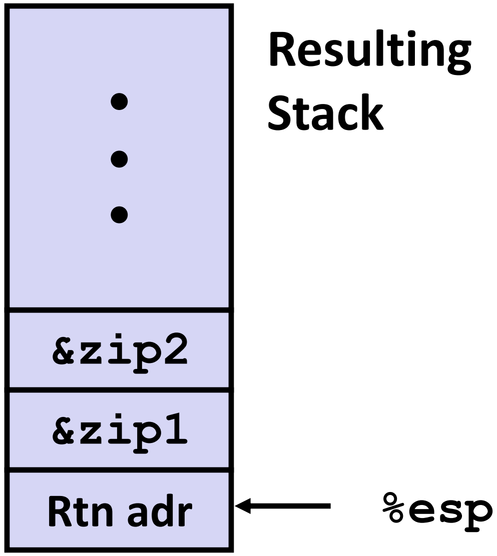
    • • •
```



Resulting Stack

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
```

Set Up

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

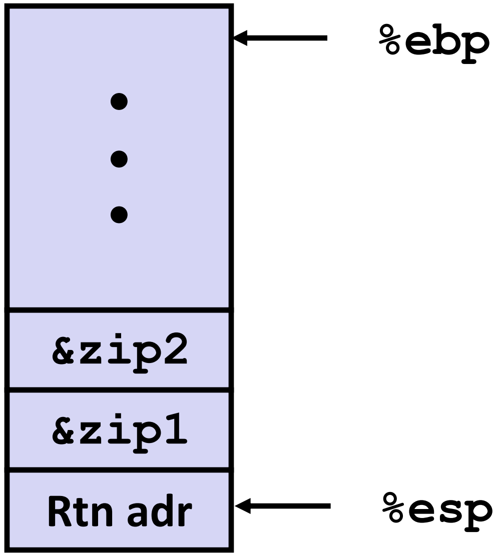
Body

```
    movl -4(%ebp),%ebx
    movl %ebp,%esp
    popl %ebp
    ret
```

Finish

swap Setup #1

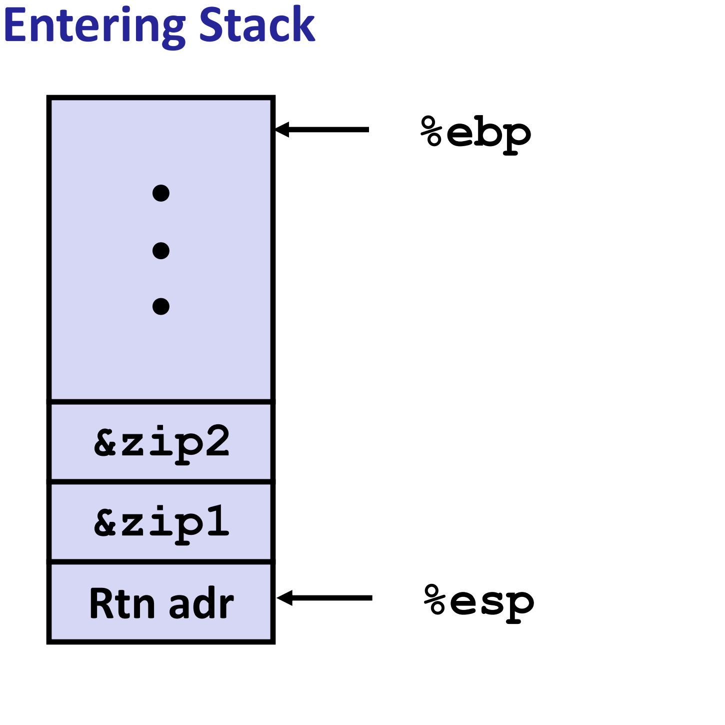
Entering Stack

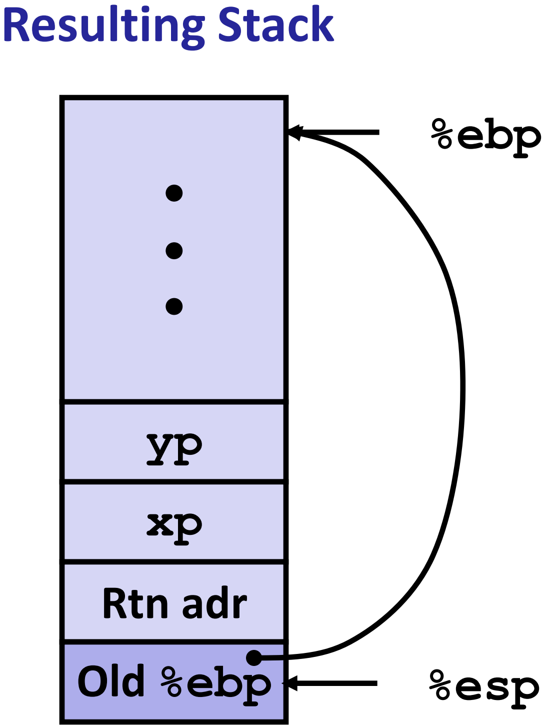


Resulting Stack?

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

swap Setup #1

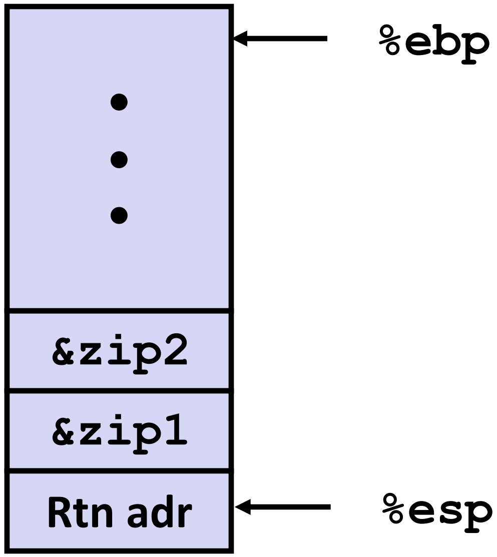




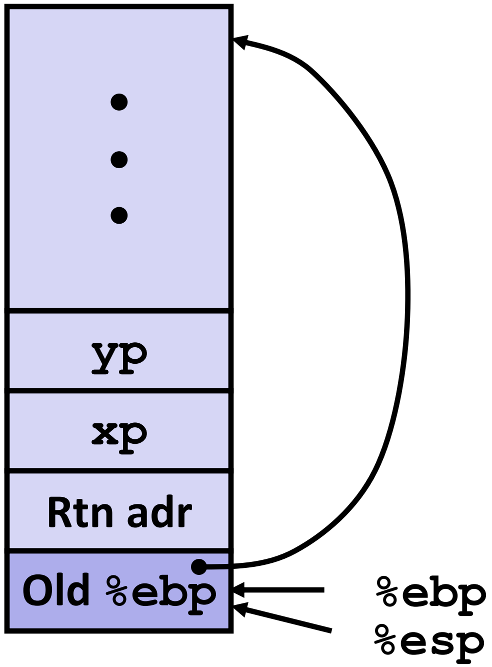
```
swap:
    pushl  %ebp
    movl  %esp,%ebp
    pushl  %ebx
```

swap Setup #2

Entering Stack

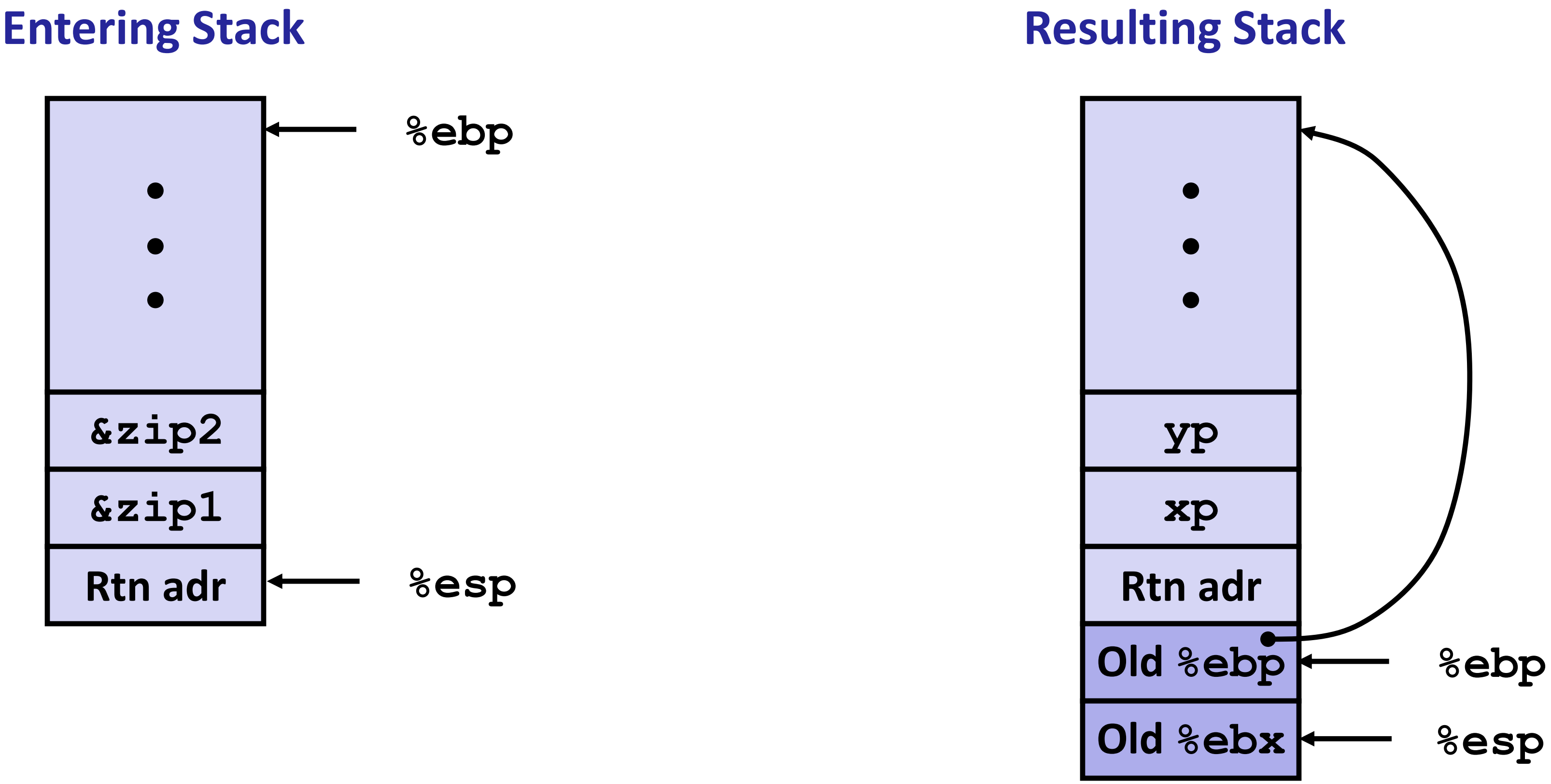


Resulting Stack



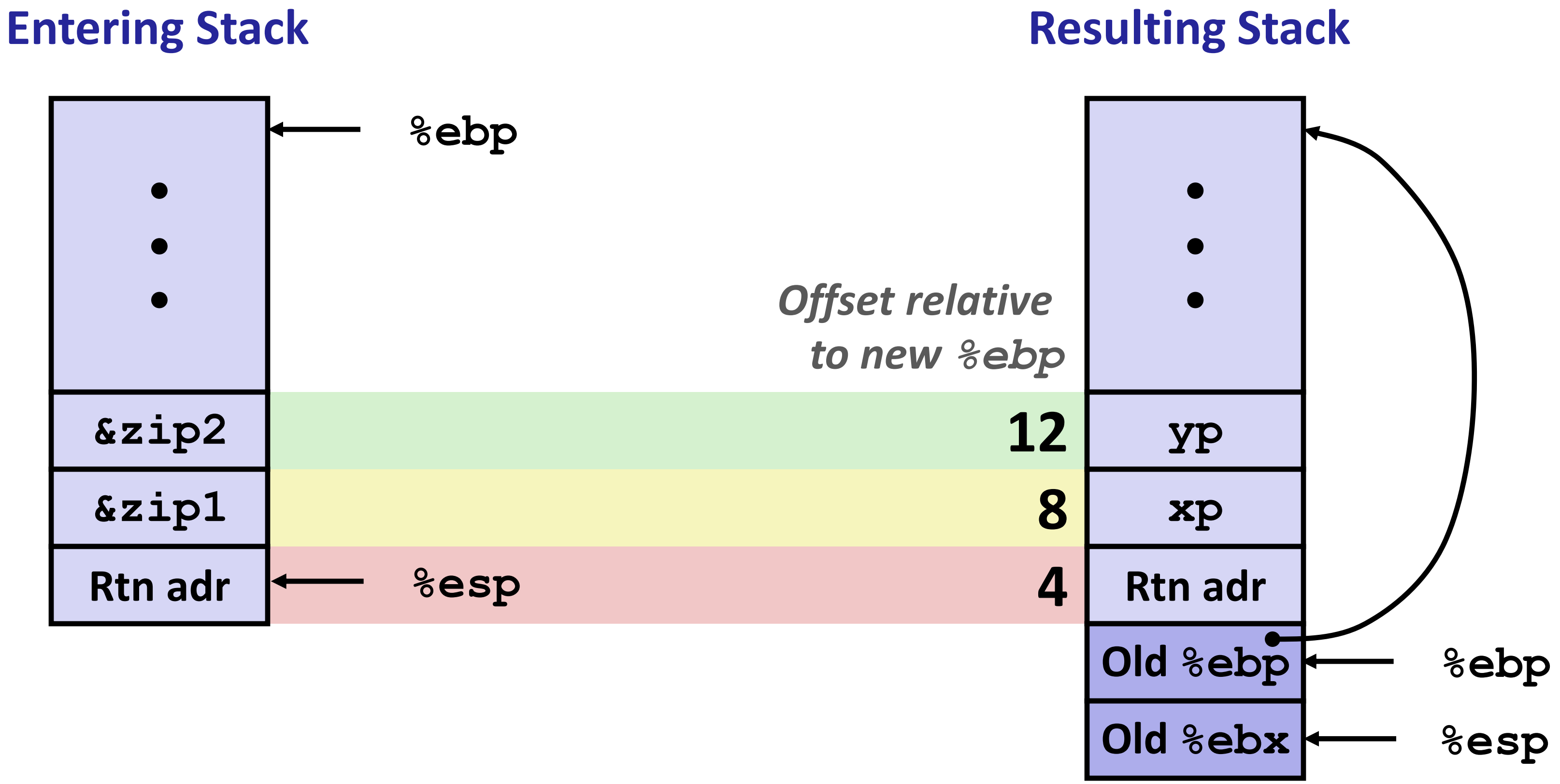
```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

swap Setup #3



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

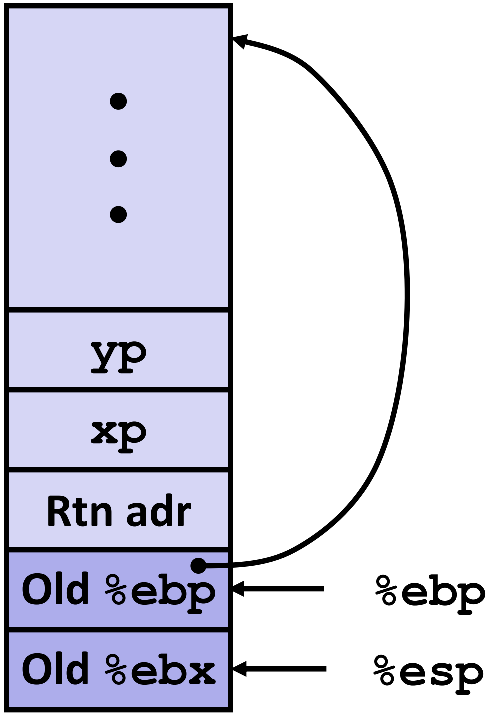
swap Body



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

swap Finish #1

swap’ s Stack

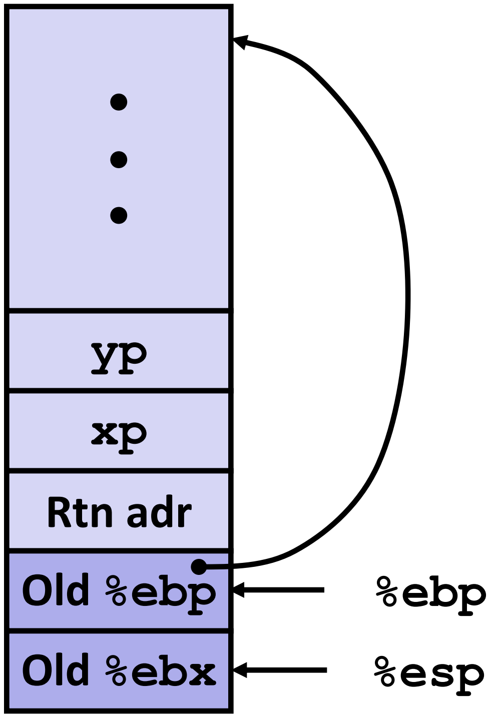


Resulting Stack?

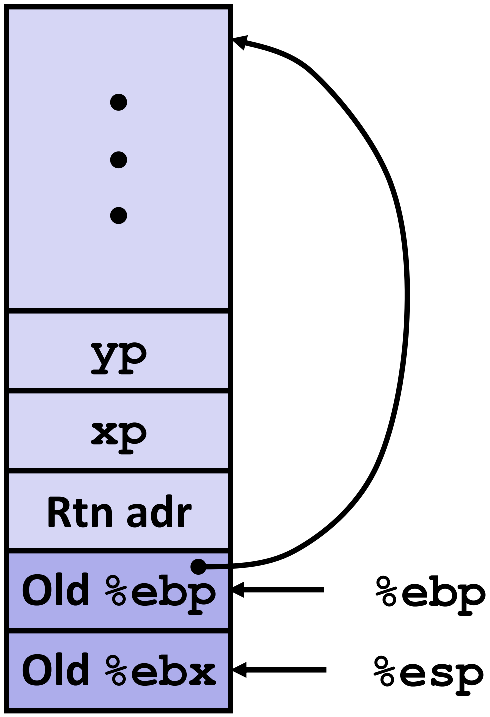
```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

swap Finish #1

swap's Stack



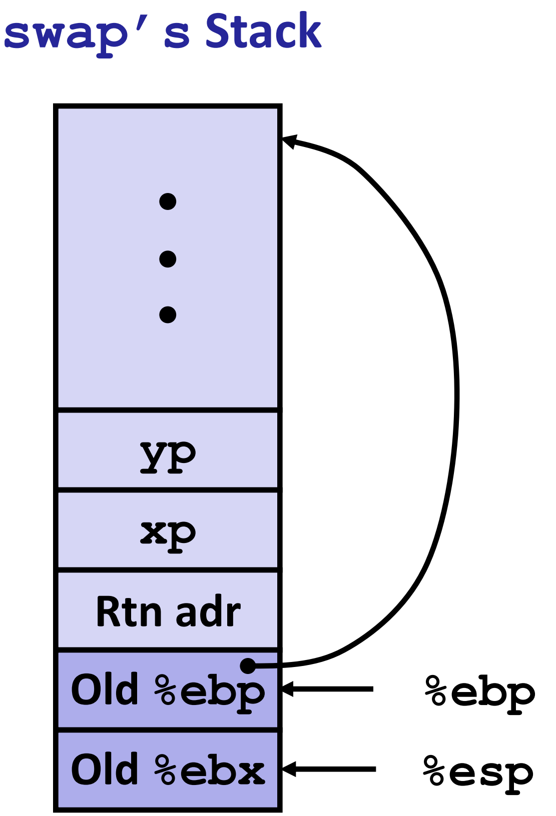
Resulting Stack

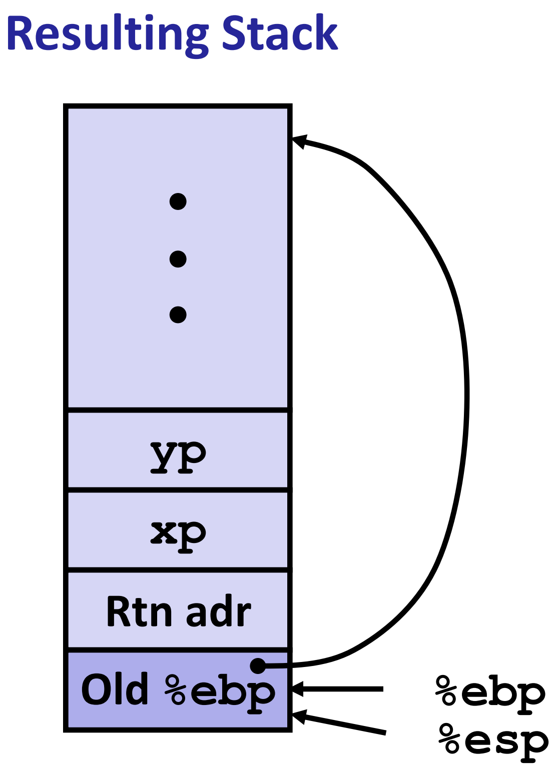


```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Observation: Saved and restored register %ebx

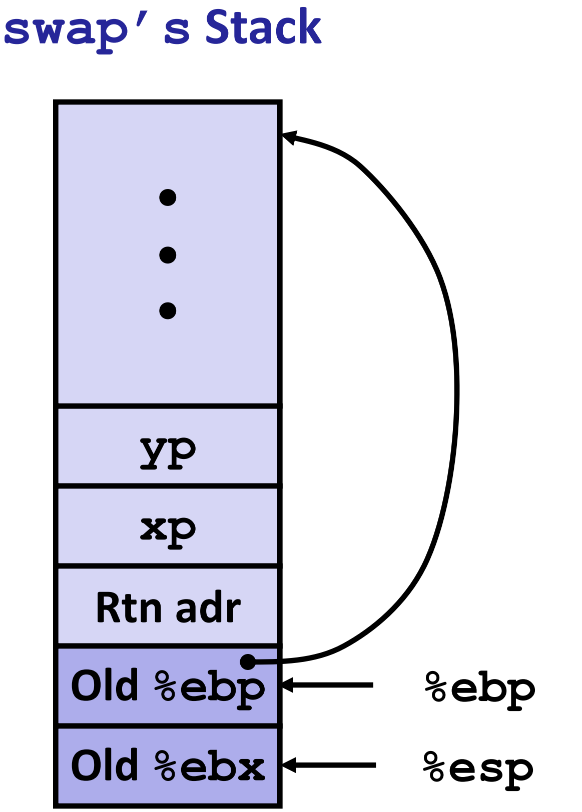
swap Finish #2

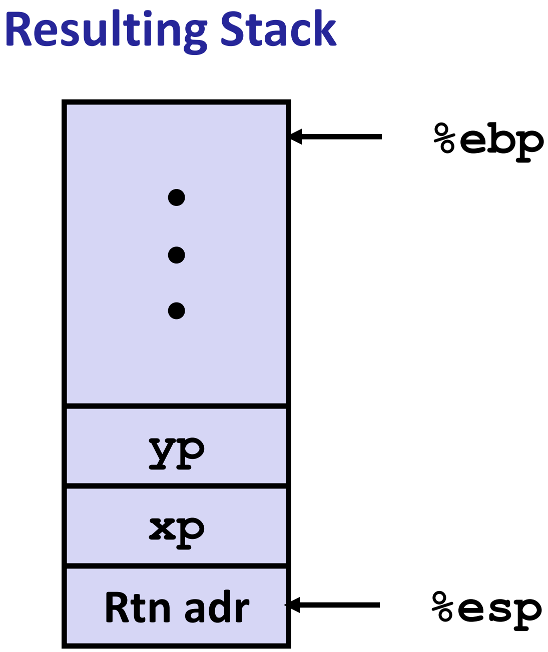




```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

swap Finish #3

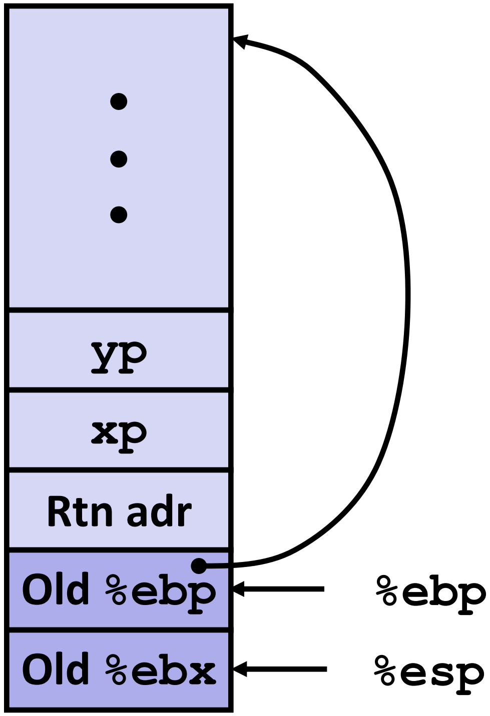




```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl  %ebp
ret
```

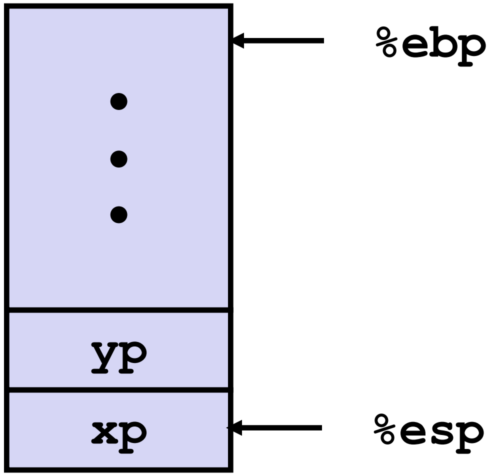
swap Finish #4

swap’ s Stack



```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Resulting Stack



Disassembled swap

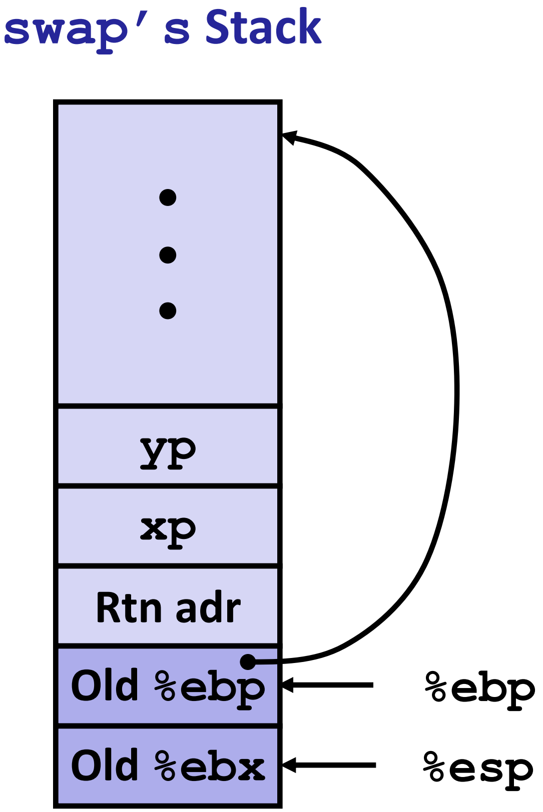
```
080483a4 <swap>:
 80483a4:    55              push    %ebp
 80483a5:    89 e5           mov     %esp,%ebp
 80483a7:    53              push    %ebx
 80483a8:    8b 55 08        mov     0x8(%ebp),%edx
 80483ab:    8b 4d 0c        mov     0xc(%ebp),%ecx
 80483ae:    8b 1a           mov     (%edx),%ebx
 80483b0:    8b 01           mov     (%ecx),%eax
 80483b2:    89 02           mov     %eax,(%edx)
 80483b4:    89 19           mov     %ebx,(%ecx)
 80483b6:    5b              pop     %ebx
 80483b7:    c9              leave
 80483b8:    c3              ret
```

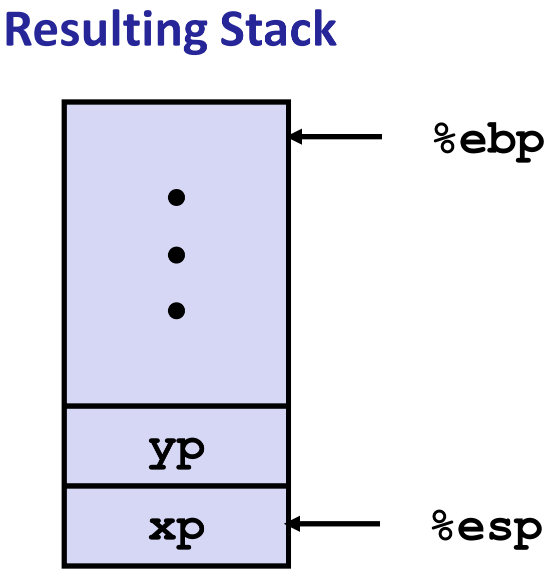
```
mov     %ebp,%esp
pop     %ebp
```

Calling Code

```
8048409:    e8 96 ff ff ff    call  80483a4 <swap>
804840e:    8b 45 f8          mov   0xfffffff8(%ebp),%eax
```

swap Finish #4





```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

- **Observation**
  - Saved & restored register **%ebx**
  - Didn't do so for **%eax, %ecx**, or **%edx**

Register Saving Conventions

- When procedure `yoo` calls `who`:
  - `yoo` is the *caller*
  - `who` is the *callee*

- Can a register be used for temporary storage?

```
yoo:
    • • •
    movl $12345, %edx
    call who
    addl %edx, %eax
    • • •
    ret
```

```
who:
    • • •
    movl 8(%ebp), %edx
    addl $98195, %edx
    • • •
    ret
```

  - Contents of register `%edx` overwritten by `who`

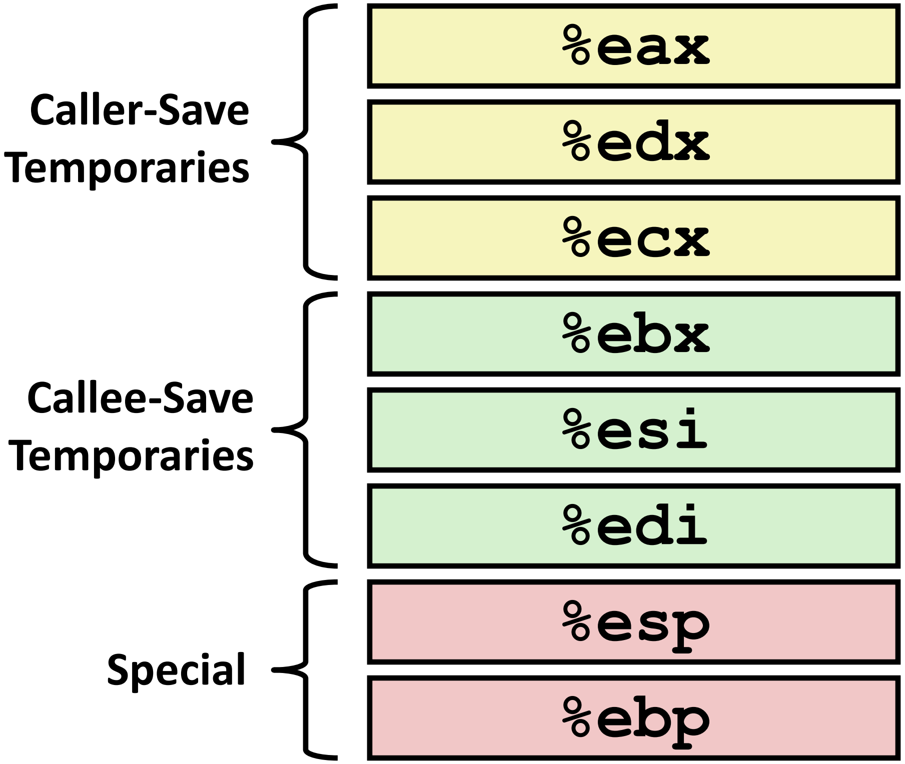
Register Saving Conventions

- **When procedure `yoo` calls `who`:**
  - `yoo` is the ***caller***
  - `who` is the ***callee***

- **Can a register be used for temporary storage?**
- **Conventions**
  - ***"Caller Save"***
    - Caller saves temporary values in its frame before calling
  - ***"Callee Save"***
    - Callee saves temporary values in its frame before using

IA32/Linux 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



Example: Pointers to Local Variables

Recursive Procedure

```
void s_helper
  (int x, int *accum)
{
  if (x <= 1)
    return;
  else {
    int z = *accum * x;
    *accum = z;
    s_helper (x-1,accum);
  }
}
```

Top-Level Call

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- Pass pointer to update location

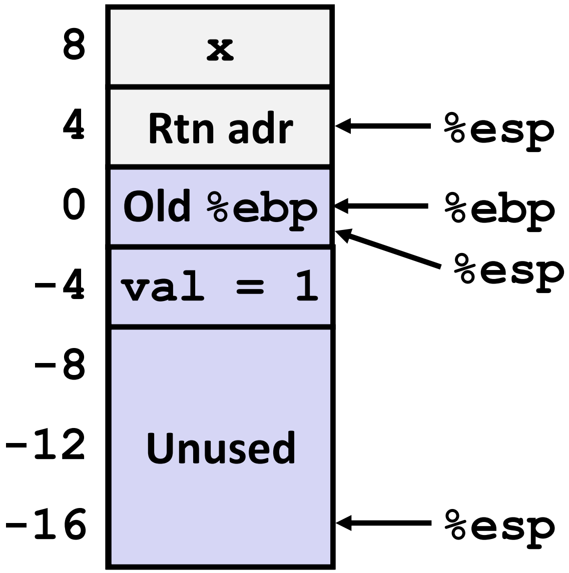
Creating & Initializing Pointer

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- **Variable `val` must be stored on stack**
  - Because: Need to create pointer to it
- **Compute pointer as `-4(%ebp)`**
- **Push on stack as second argument**

Initial part of `sfact`

```
_sfact:
   pushl %ebp          # Save %ebp
   movl %esp,%ebp      # Set %ebp
   subl $16,%esp       # Add 16 bytes
   movl 8(%ebp),%edx   # edx = x
   movl $1,-4(%ebp)    # val = 1
```



8 x

4 Rtn adr ← %esp

0 Old %ebp ← %ebp

← %esp

-4 val = 1

-8

-12 Unused

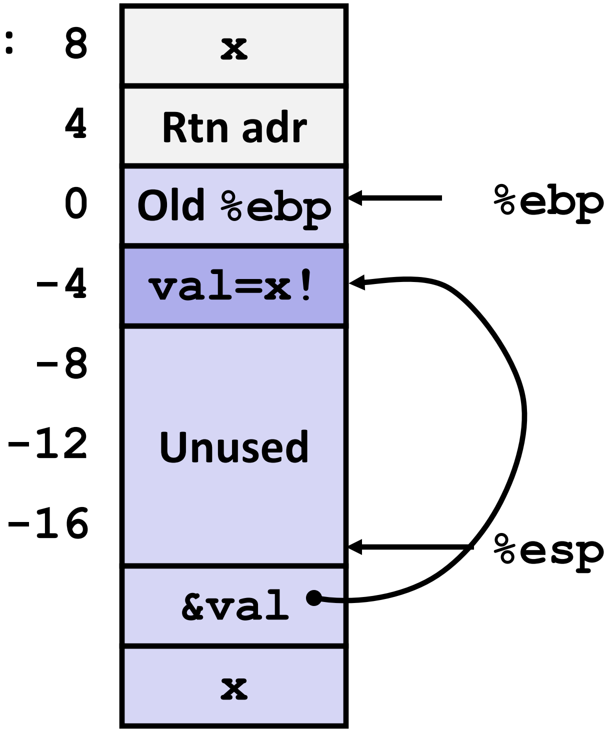
-16 ← %esp

Passing Pointer

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- **Variable `val` must be stored on stack**
  - Because: Need to create pointer to it
- **Compute pointer as `-4(%ebp)`**
- **Push on stack as second argument**

Stack at time of call:



8 x

4 Rtn adr

0 Old %ebp ← %ebp

-4 val=x!

-8

-12 Unused

-16 ← %esp

&val

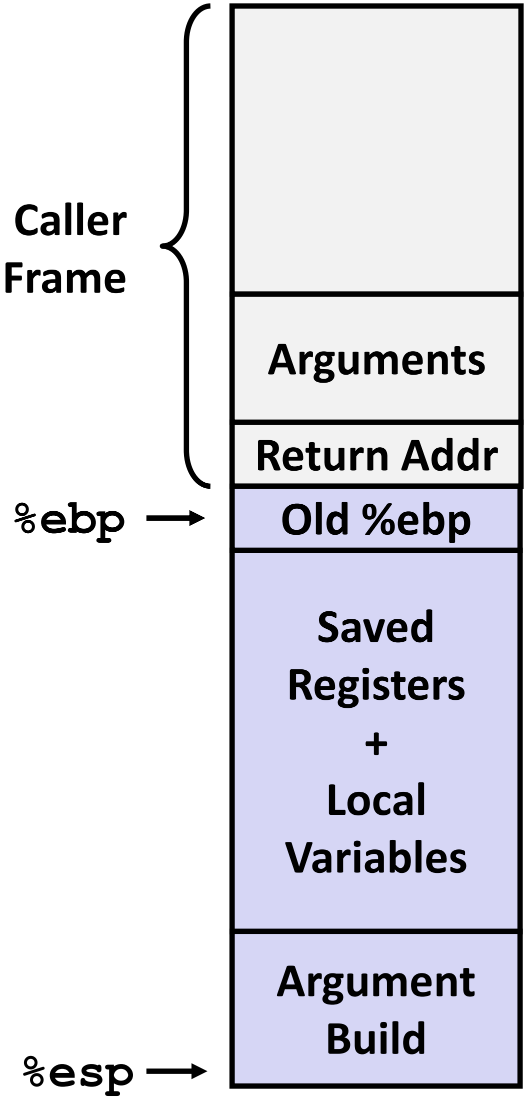
x

Calling `s_helper` from `sfact`

```
  leal -4(%ebp),%eax  # Compute &val
  pushl %eax          # Push on stack
  pushl %edx          # Push x
  call s_helper       # call
  movl -4(%ebp),%eax  # Return val
  • • •               # Finish
```

IA 32 Procedure Summary

- **Important points:**
  - IA32 procedures are a combination of *instructions* and *conventions*
    - Conventions prevent functions from disrupting each other
  - Stack is the right data structure for procedure call / return
    - If P calls Q, then Q returns before P
- **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 returned in **`%eax`**


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