The Hardware/Software Interface

CSE351 Winter 2013

Procedures and Stacks I

Roadmap

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
```

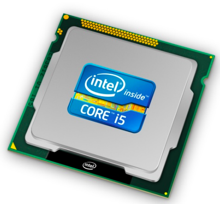
Machine code:

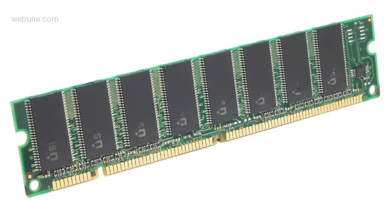
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 8 Mac

Computer system:





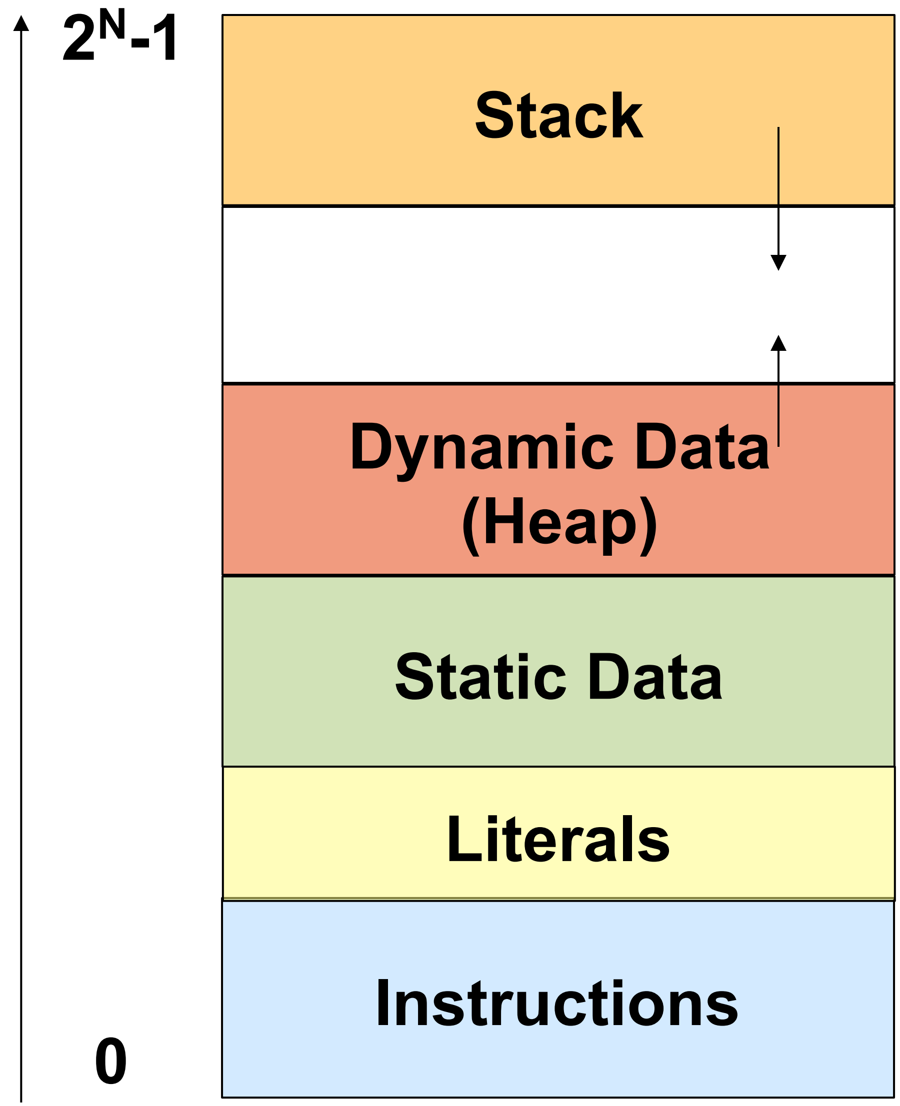
- Data & addressing
- Integers & floats
- Machine code & C
- x86 assembly programming
- **Procedures & stacks**
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

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



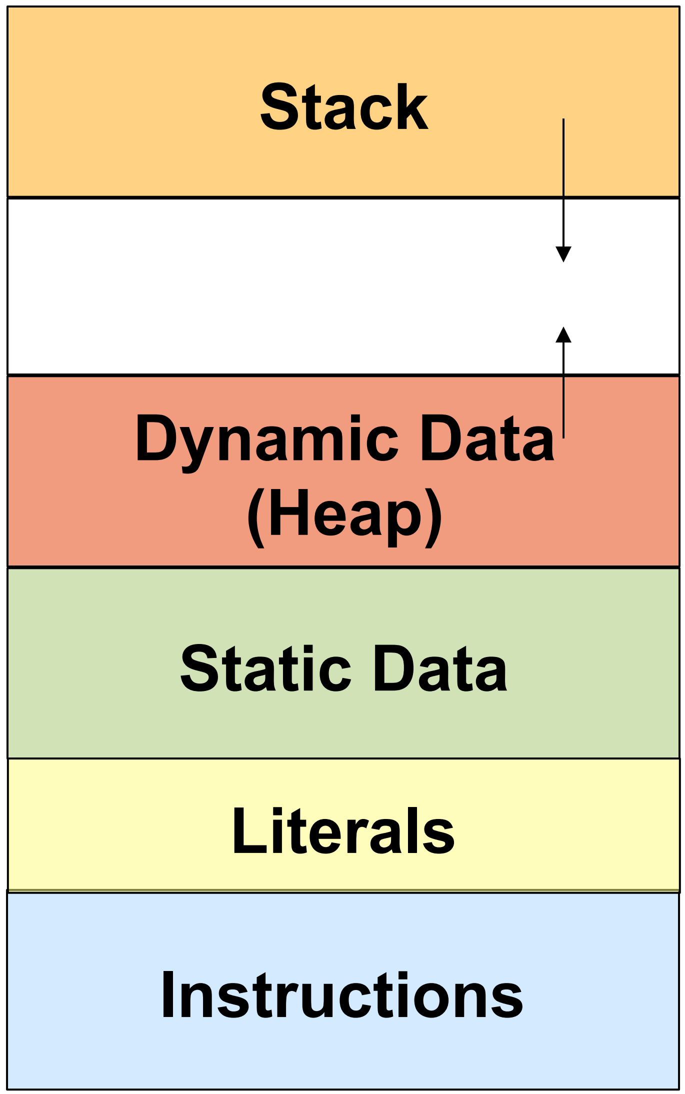
local variables;
procedure context

variables allocated with
new or *malloc*

static variables
(including global variables (C))

literals (e.g., "example")

Memory Layout

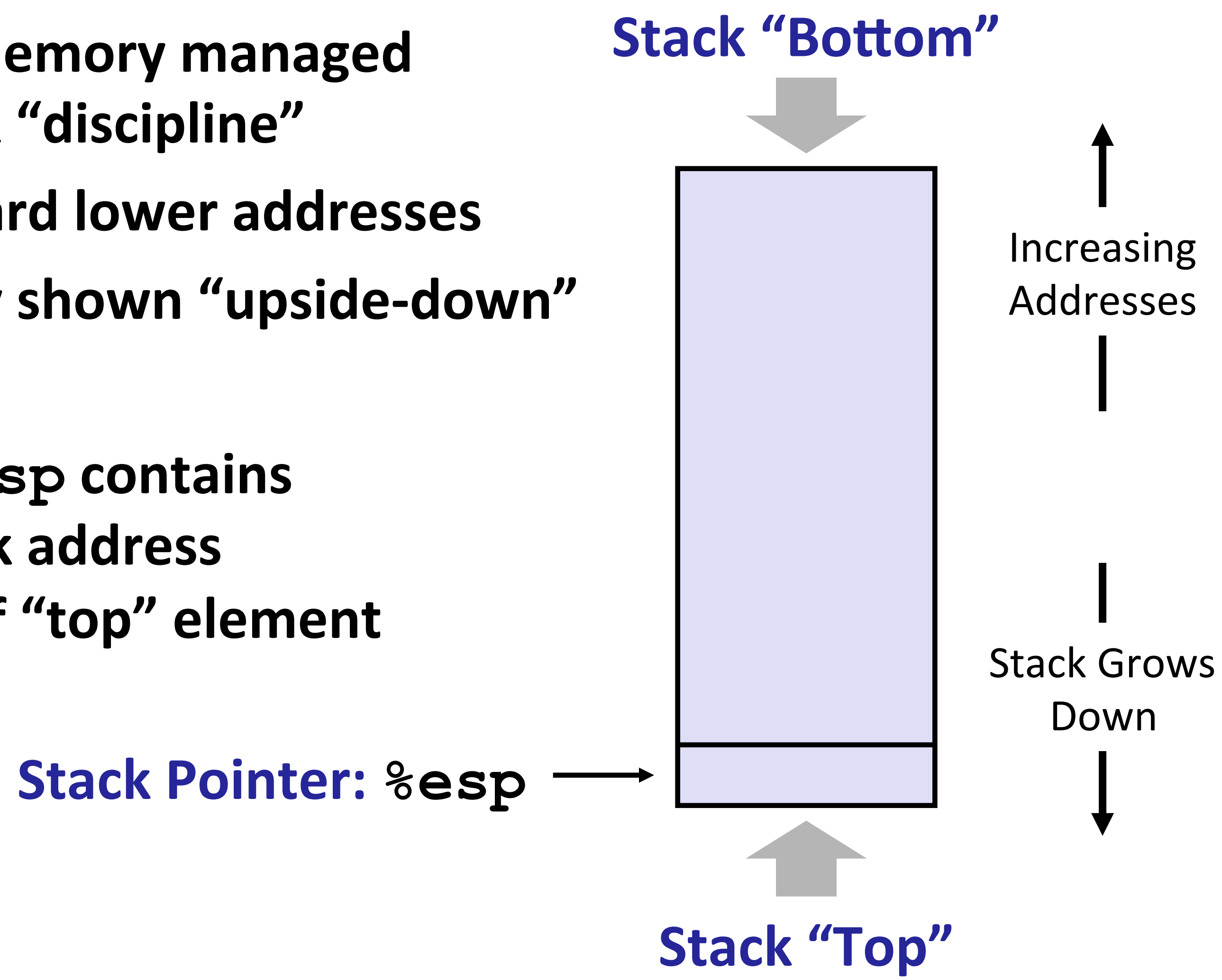


writable; not executable	Managed "automatically" (by compiler)
writable; not executable	Managed by programmer
writable; not executable	Initialized when process starts
Read-only; not executable	Initialized when process starts
Read-only; executable	Initialized when process starts

IA32 Call Stack

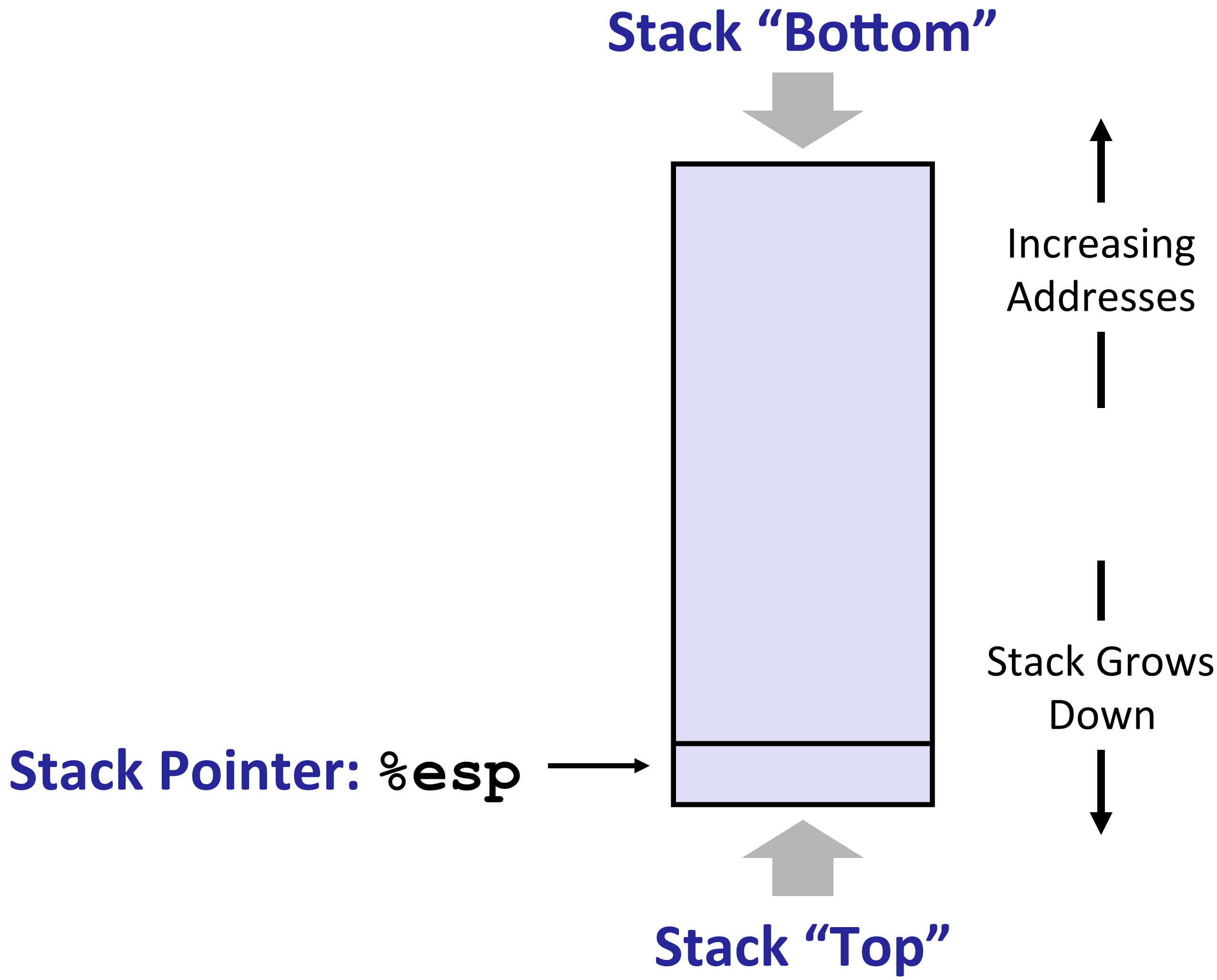
- Region of memory managed with a stack "discipline"
- Grows toward lower addresses
- Customarily shown "upside-down"

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



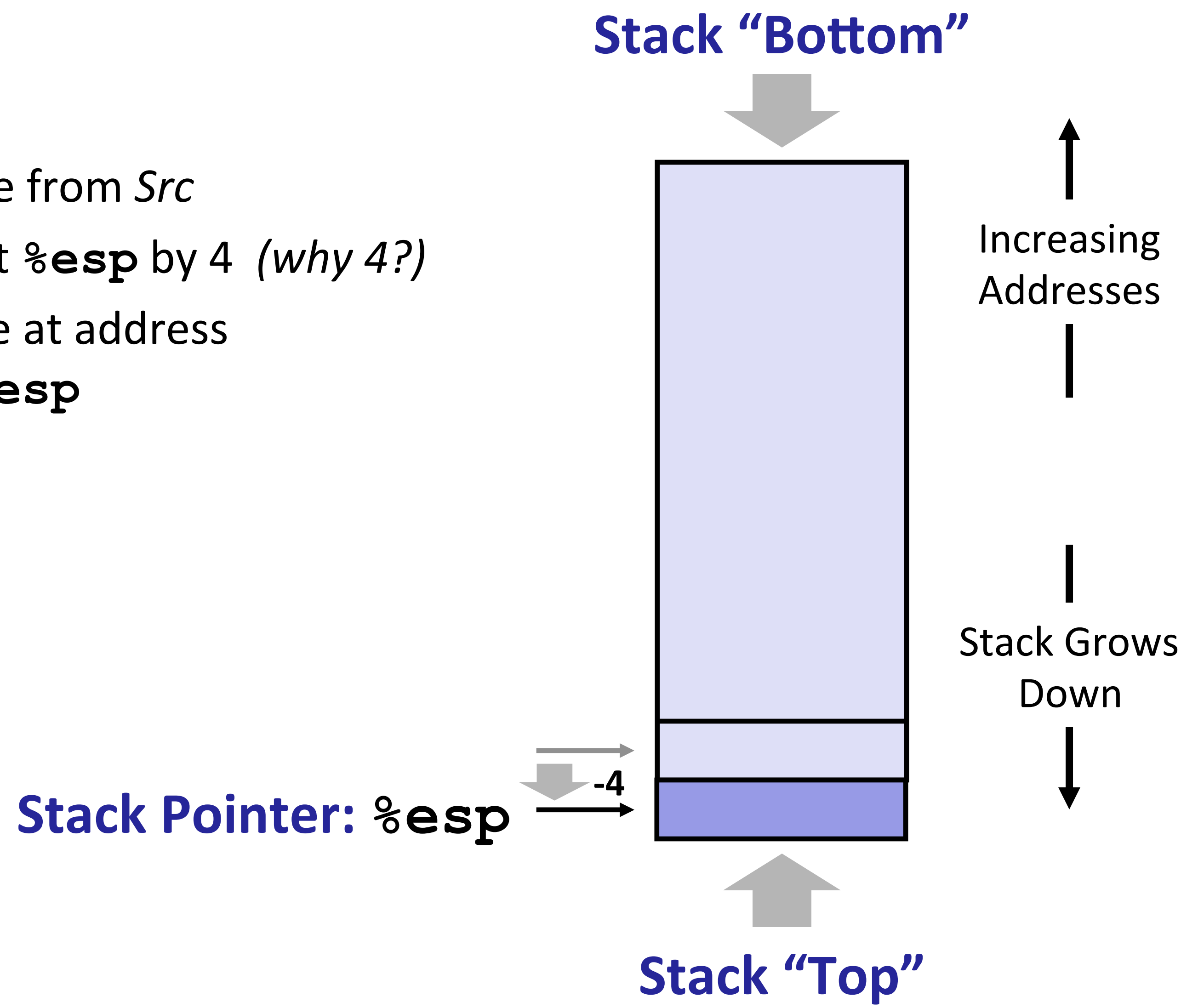
IA32 Call Stack: Push

- `pushl` *Src*



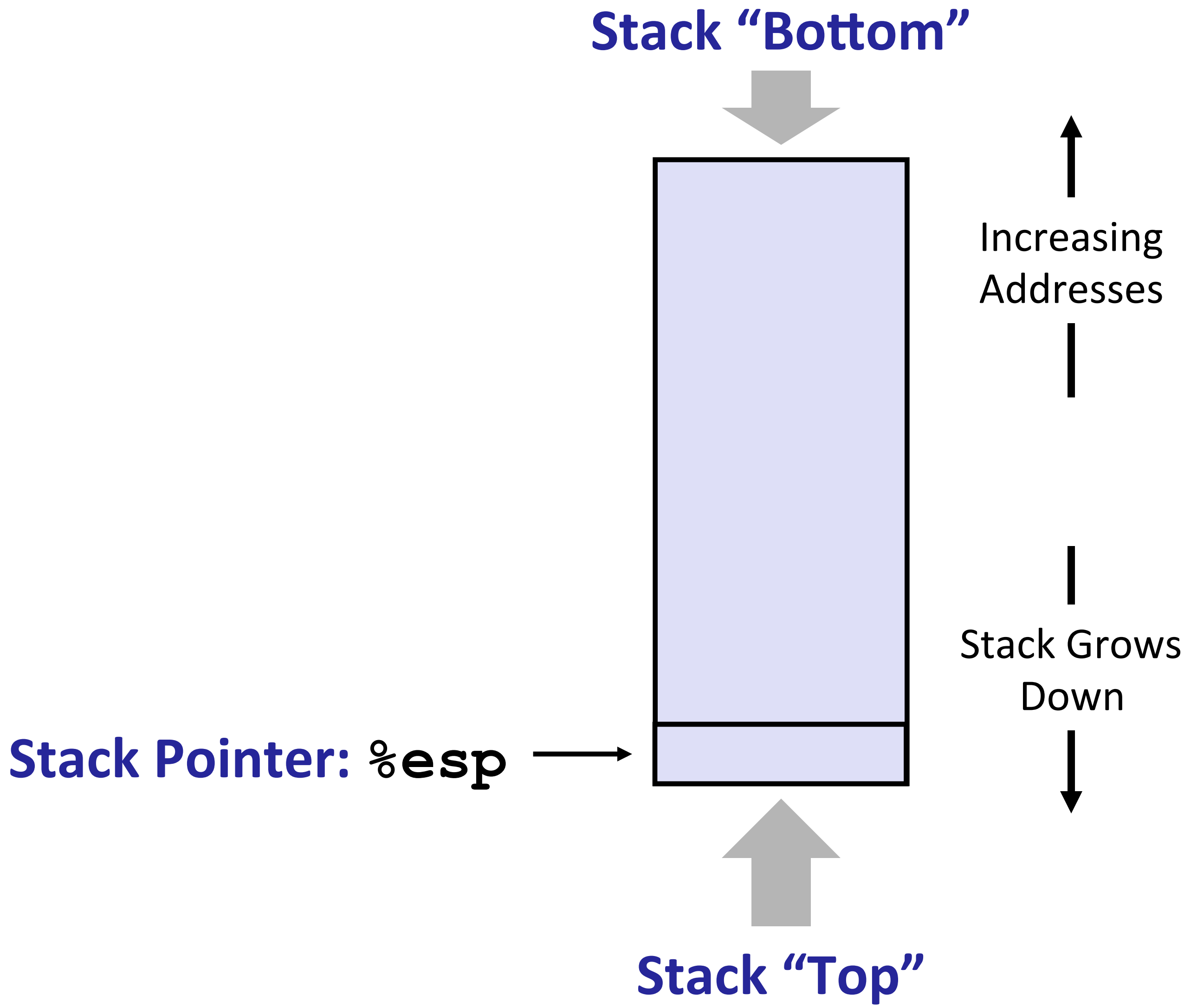
IA32 Call Stack: Push

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



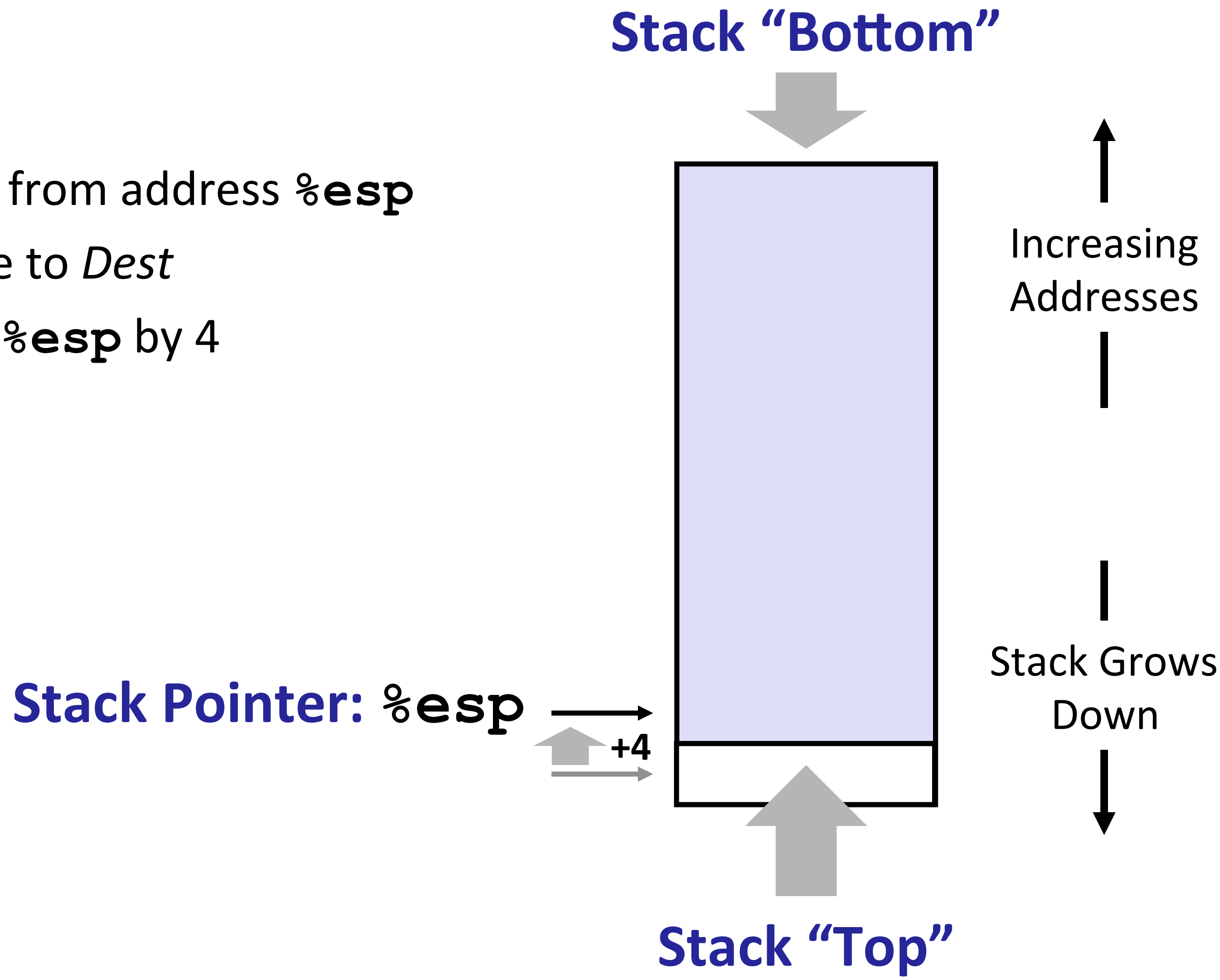
IA32 Call Stack: Pop

- **`popl`** ***Dest***

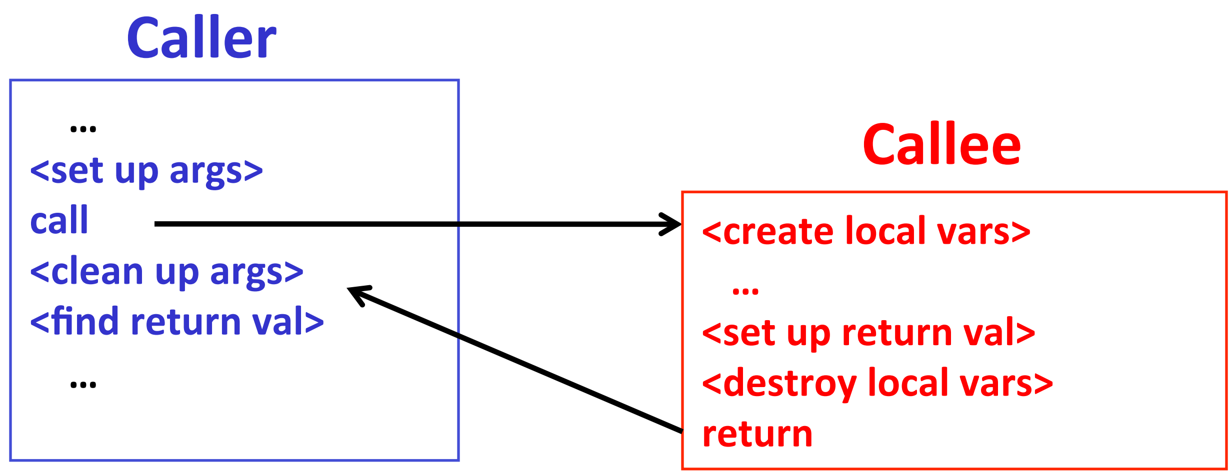


IA32 Call Stack: Pop

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

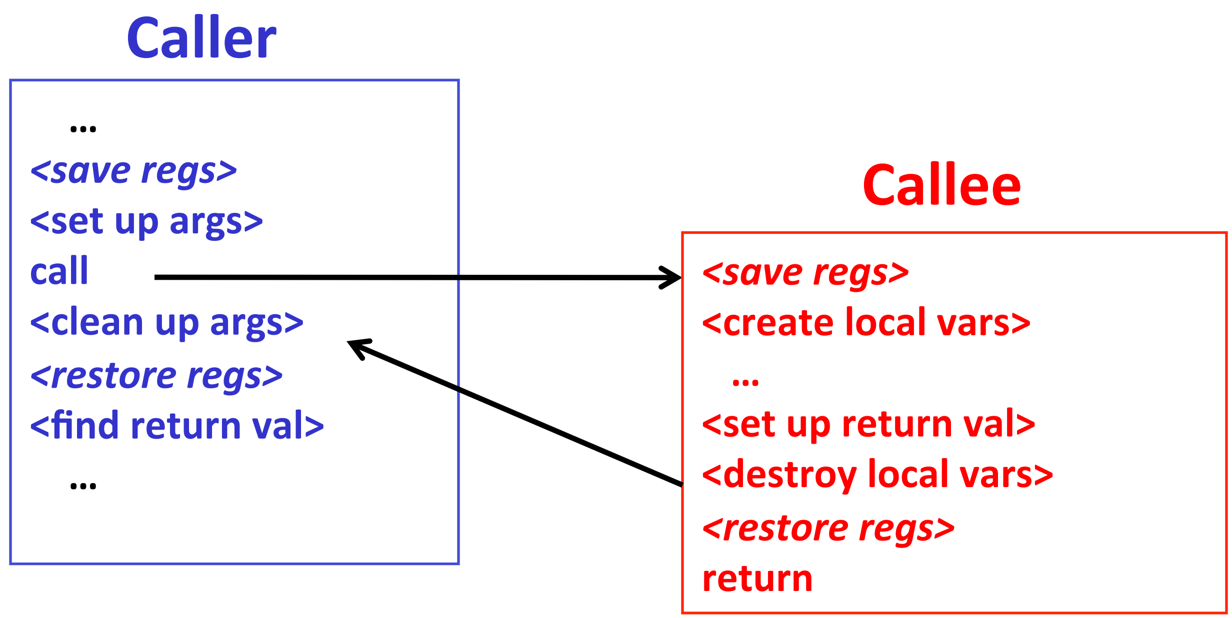


Procedure Call Overview



- **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



- **The <u>convention</u> of where to leave/find things is called the <u>procedure call linkage</u>**
  - Details vary between systems
  - We will see the convention for <u>IA32/Linux</u> 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:

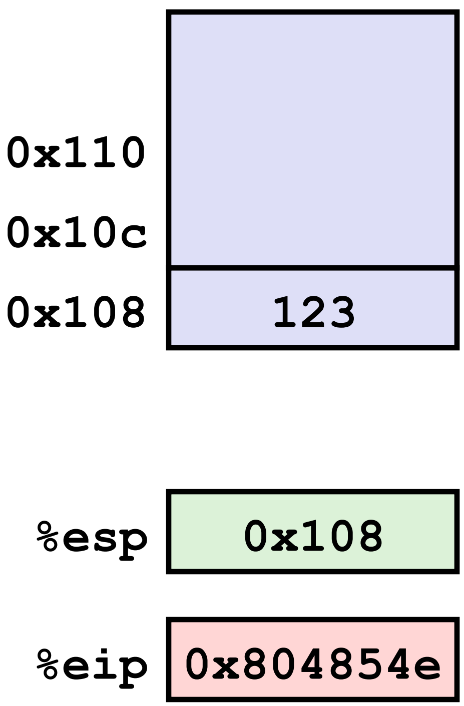
```
804854e:   e8 3d 06 00 00     call    8048b90 <main>
8048553:   50                 pushl   %eax
```

  - 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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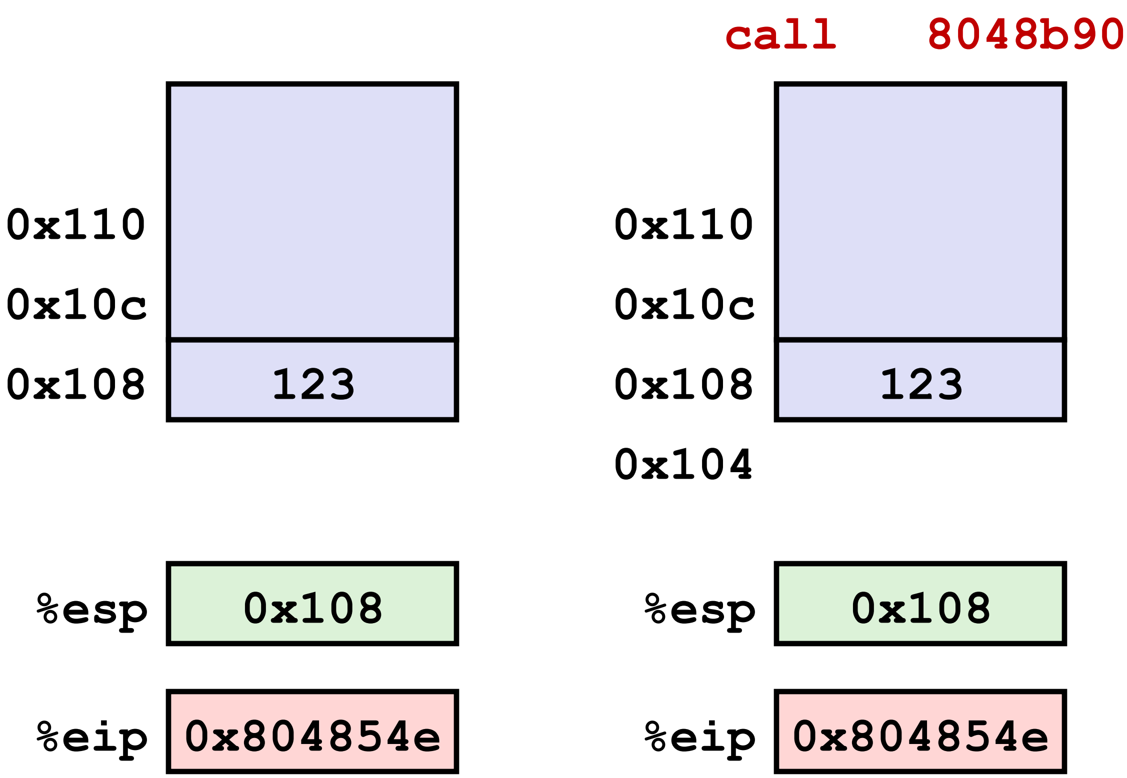

`%eip`: program counter

Procedure Call Example

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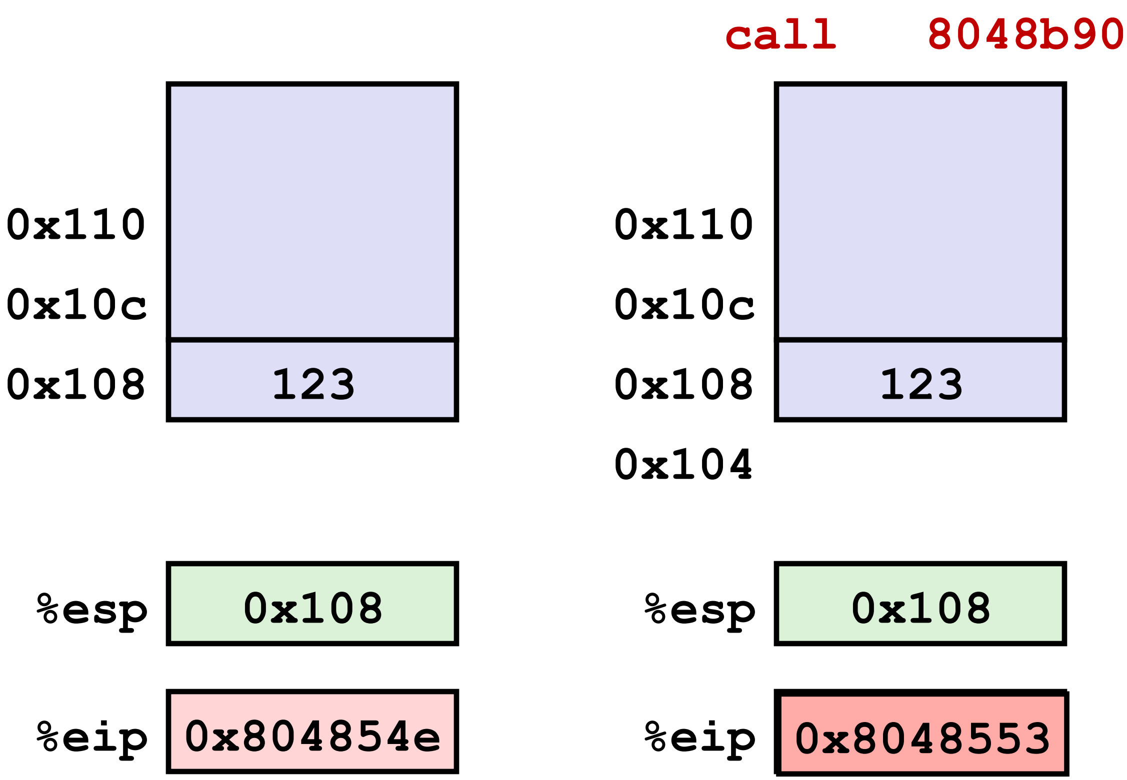

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Procedure Call Example

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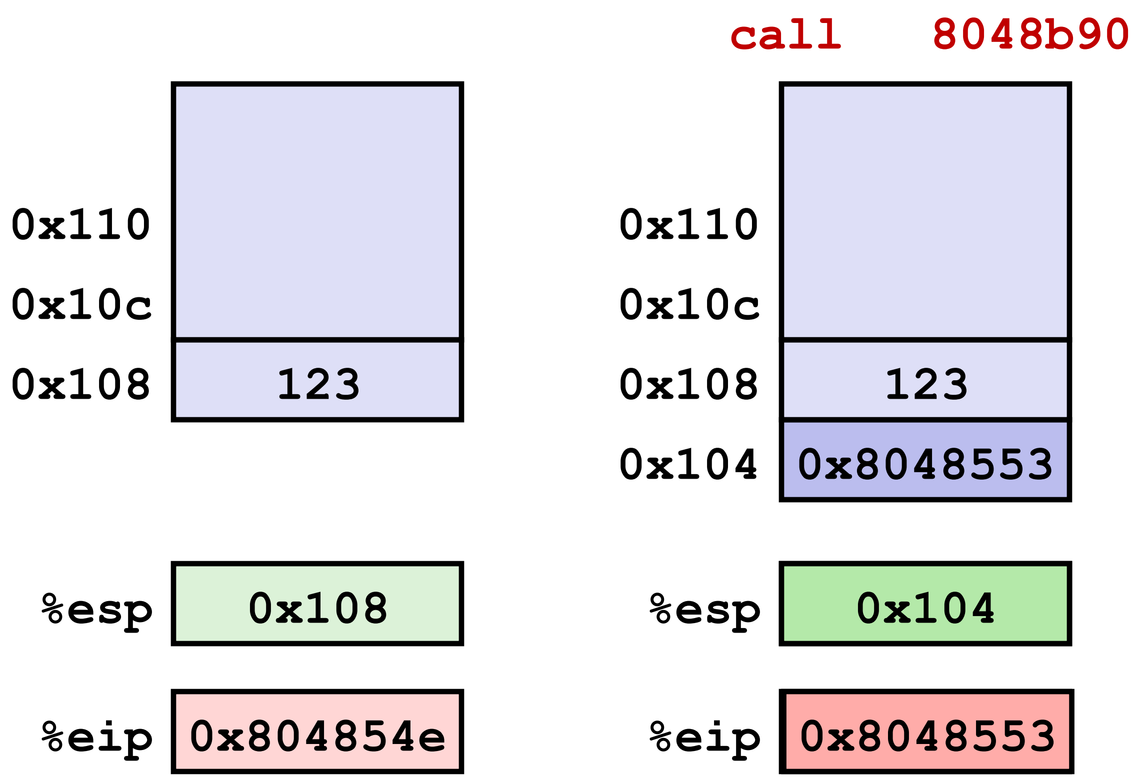

`%eip`: program counter

Procedure Call Example

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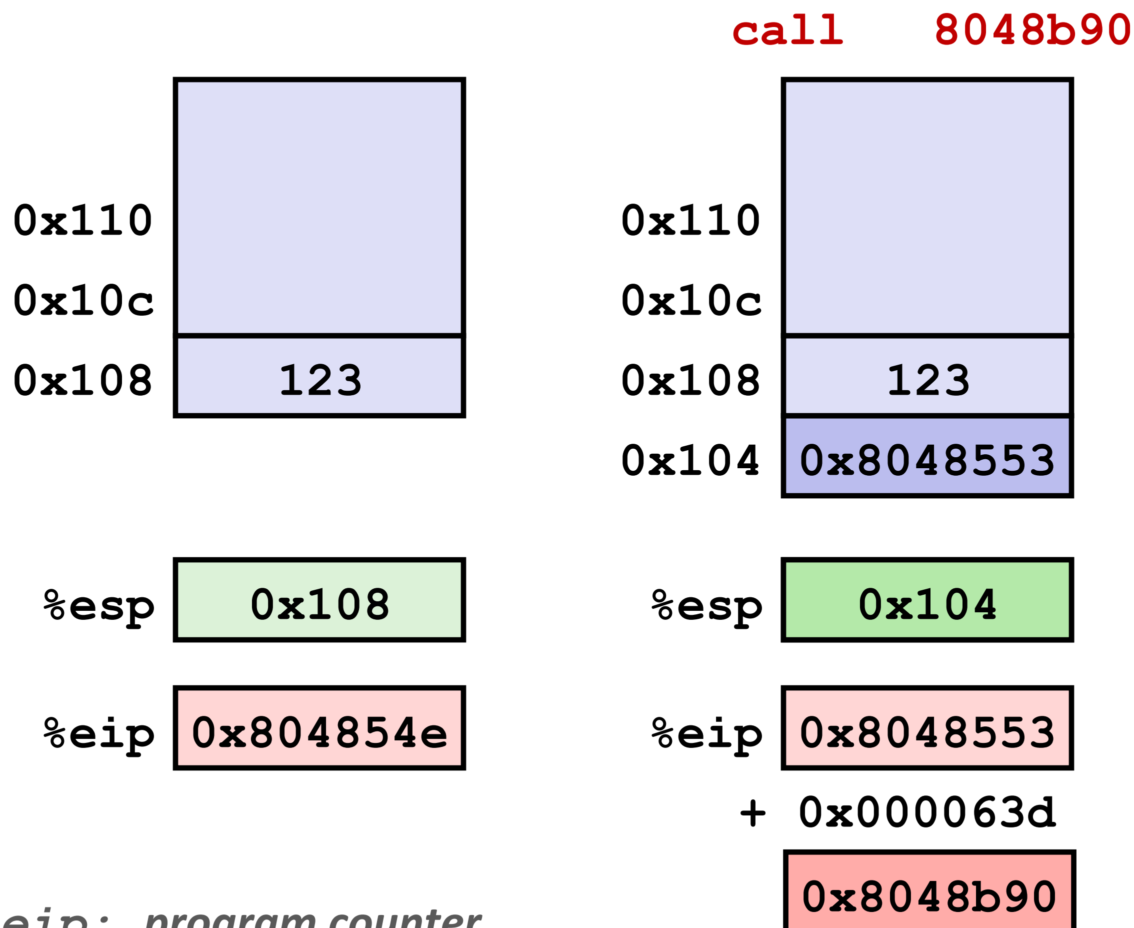


%eip: program counter

Procedure Return Example

```
8048591:      c3                    ret
```

ret

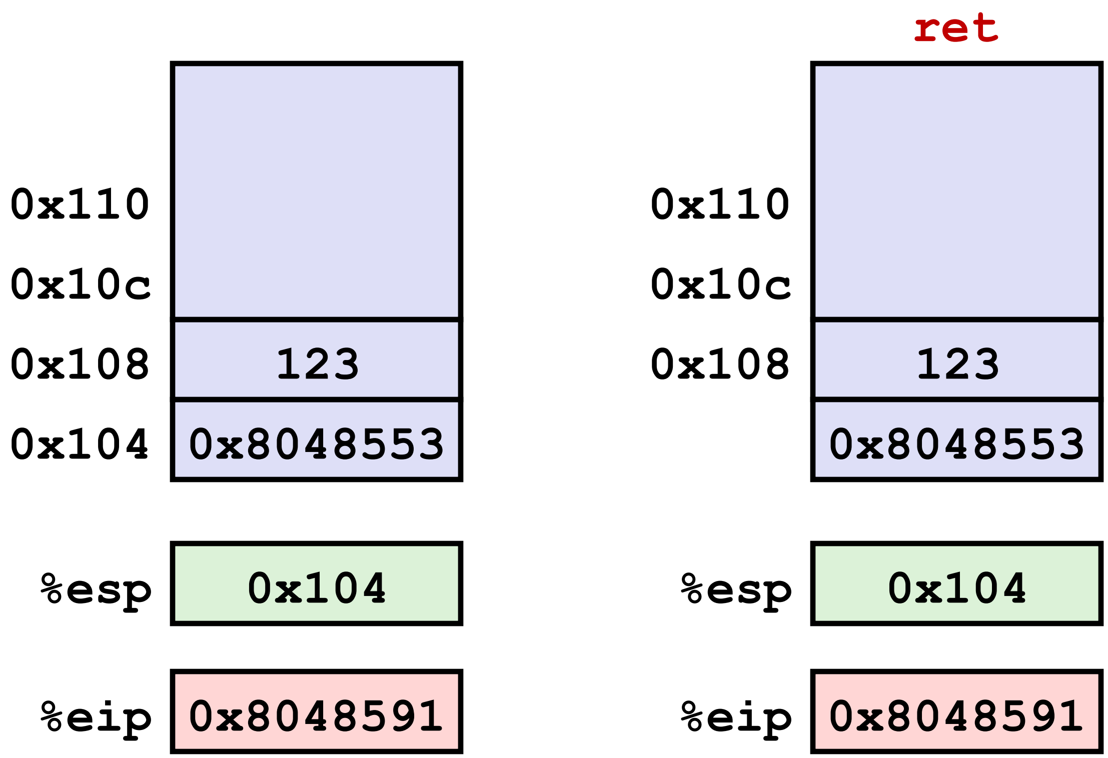
0x110	
0x10c	
0x108	123
0x104	0x8048553

%esp	0x104
%eip	0x8048591

`%eip:` program counter

Procedure Return Example

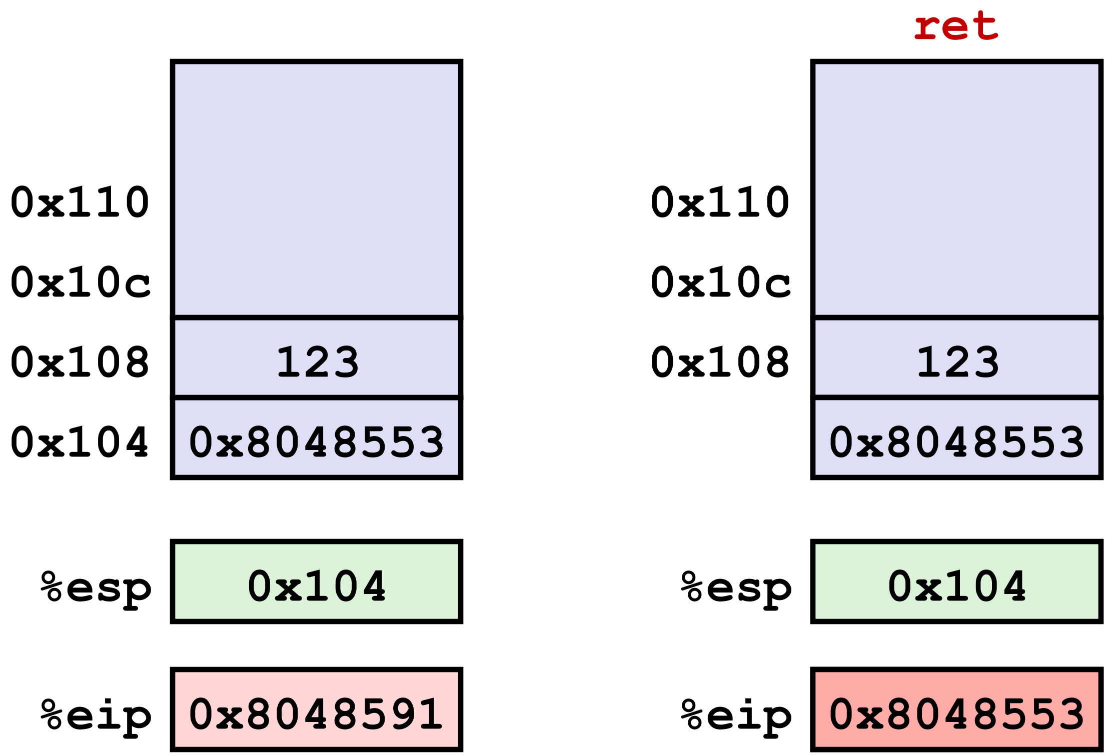
```
8048591:      c3                ret
```



`%eip`: program counter

Procedure Return Example

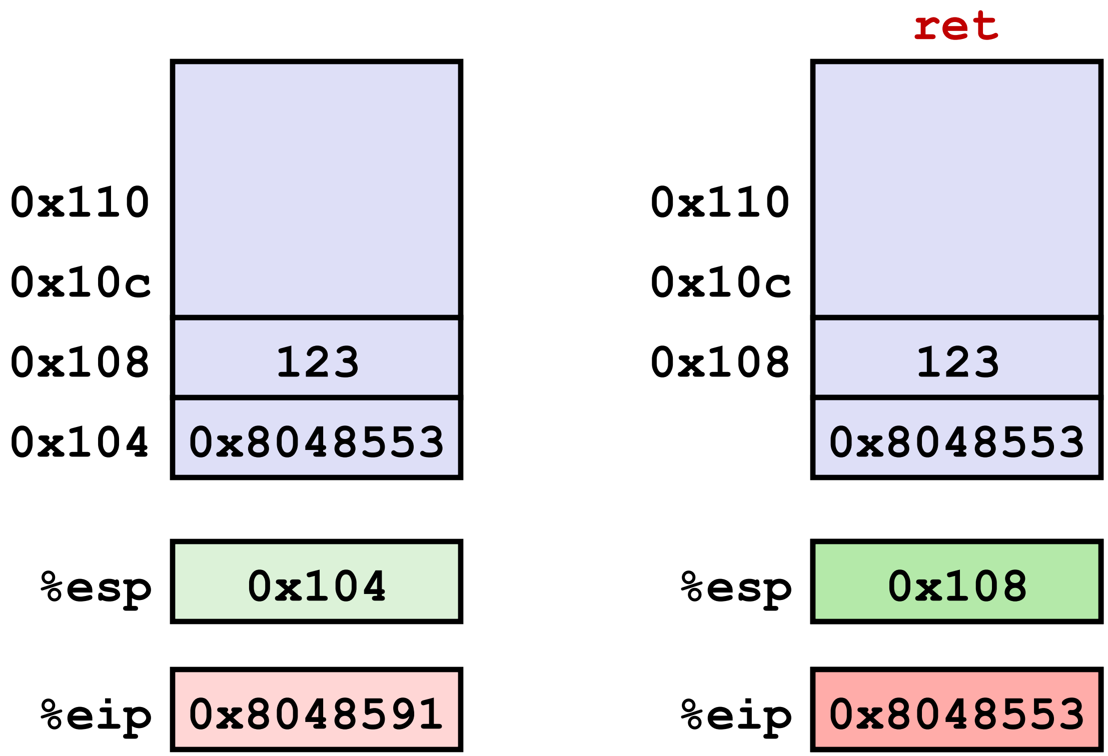
```
8048591:     c3                    ret
```



`%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 ***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

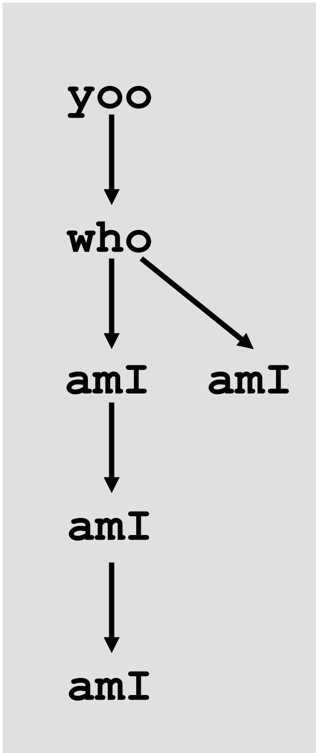
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

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

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

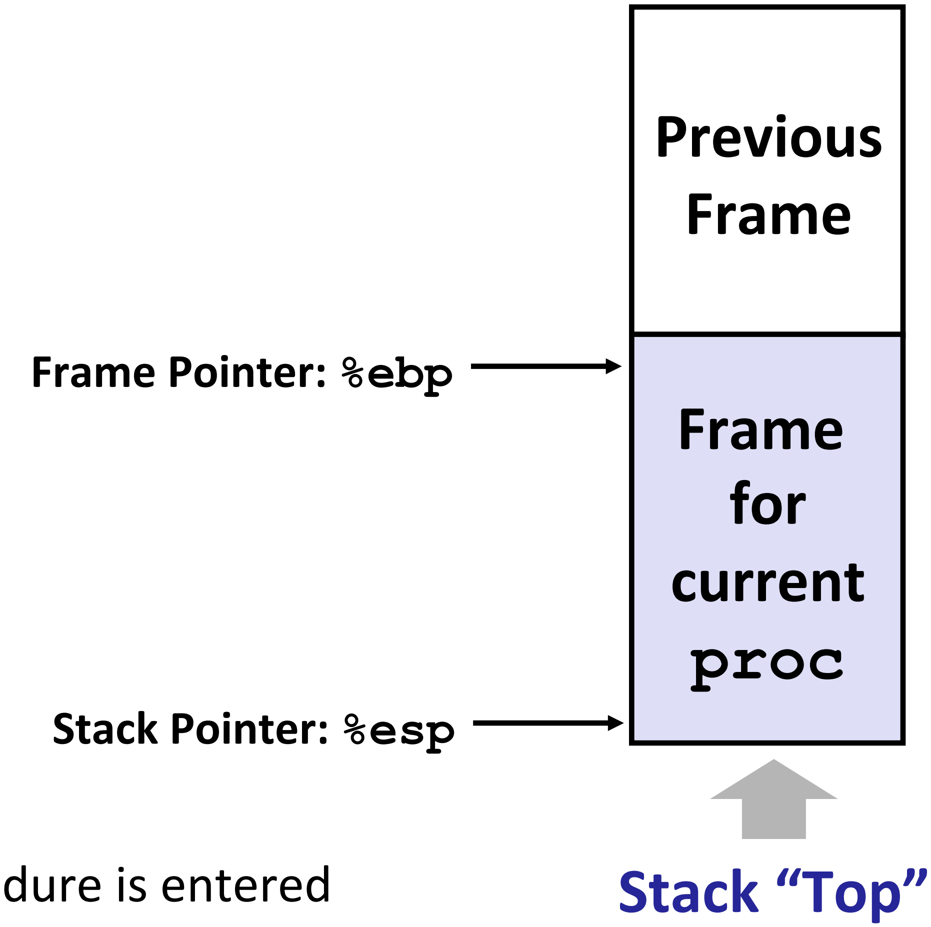
Procedure `amI` is recursive (calls itself)

Example Call Chain



Stack Frames

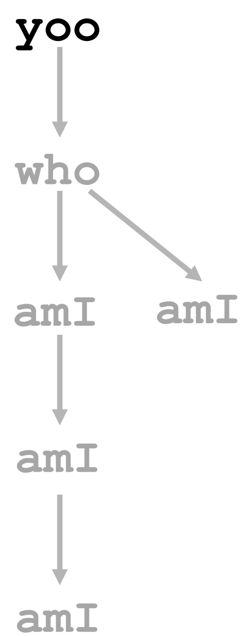
- **Contents**
  - Local variables
  - Function arguments
  - Return information
  - Temporary space

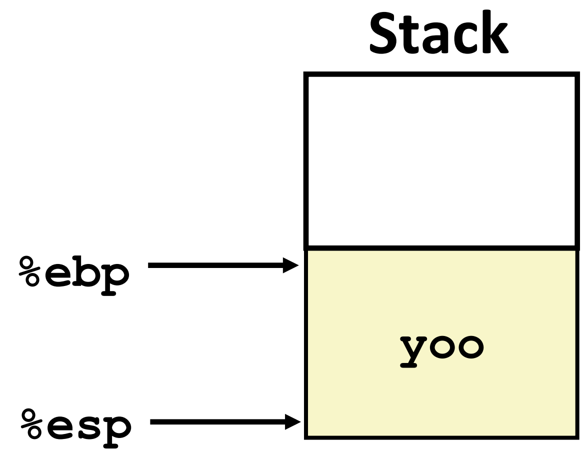


- **Management**
  - Space allocated when procedure is entered
    - "Set-up" code
  - Space deallocated upon return
    - "Finish" code

Example

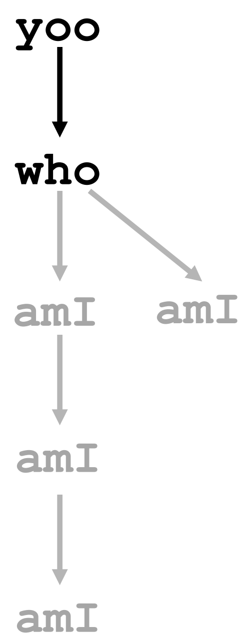
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

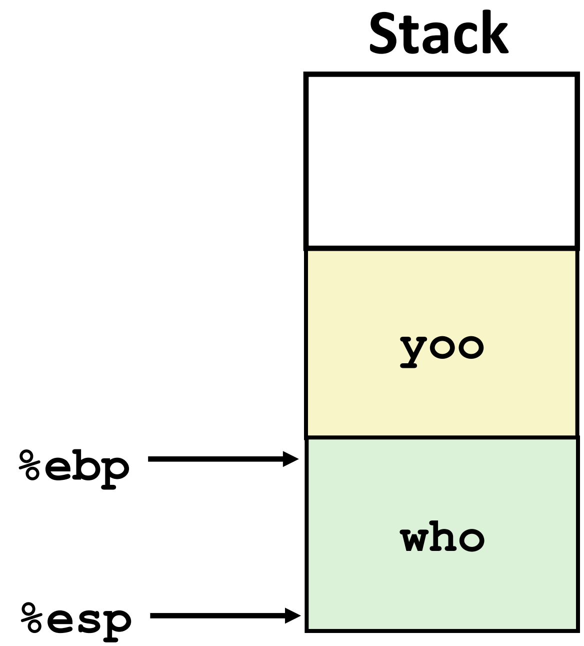




Example

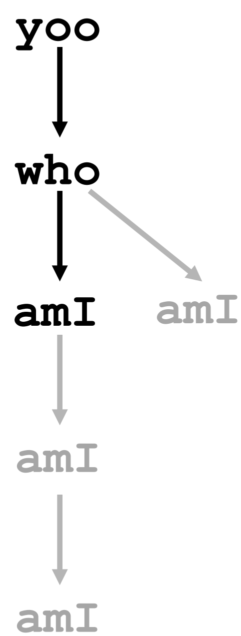
```
who(…)
{
    • • •
    amI();
    • • •
    amI();
    • • •
}
```

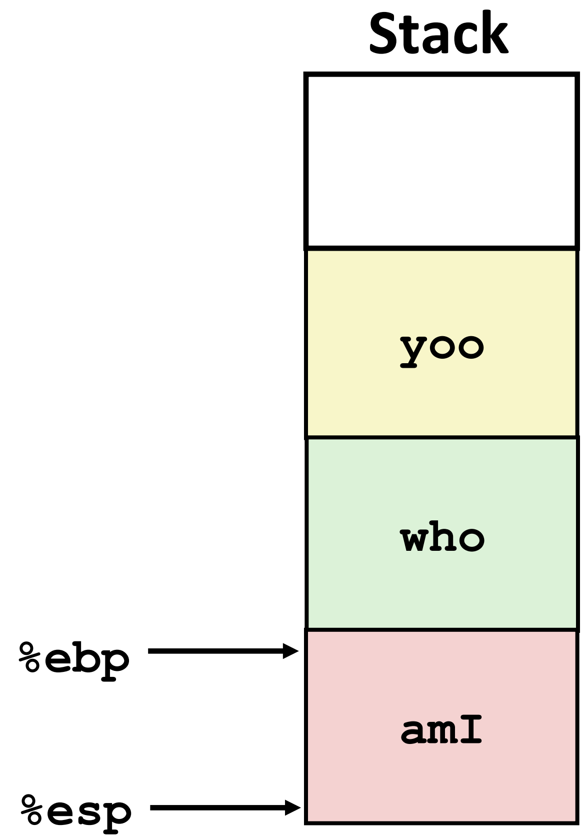




Example

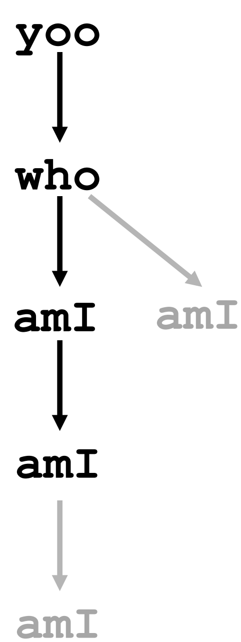
```
amI(…)
{
    •
    •
    amI();
    •
    •
}
```



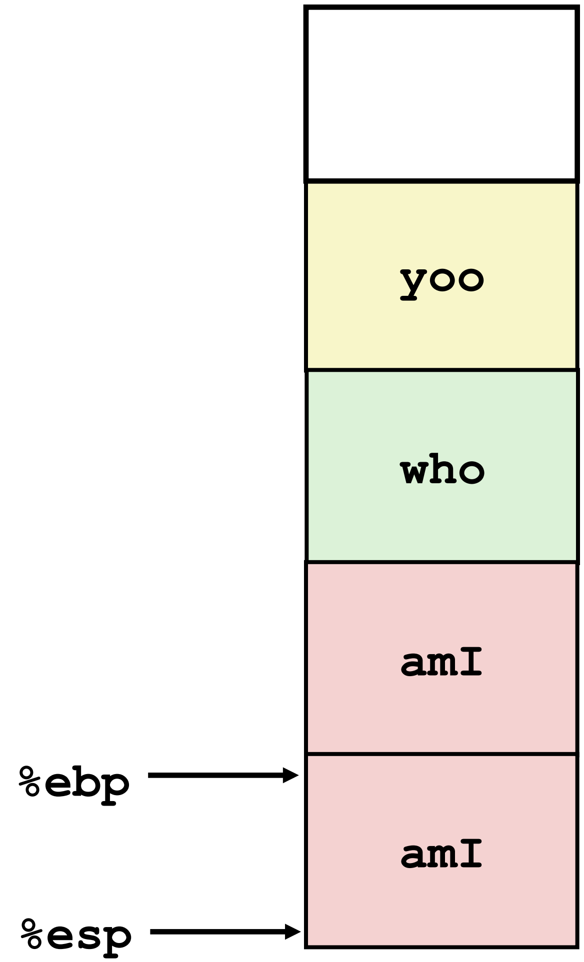


Example

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

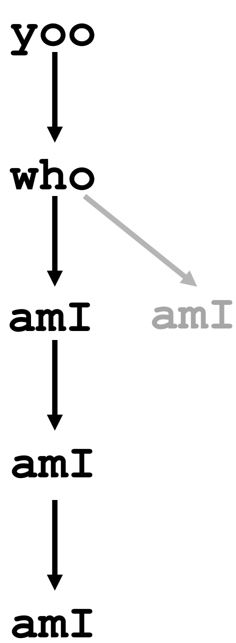


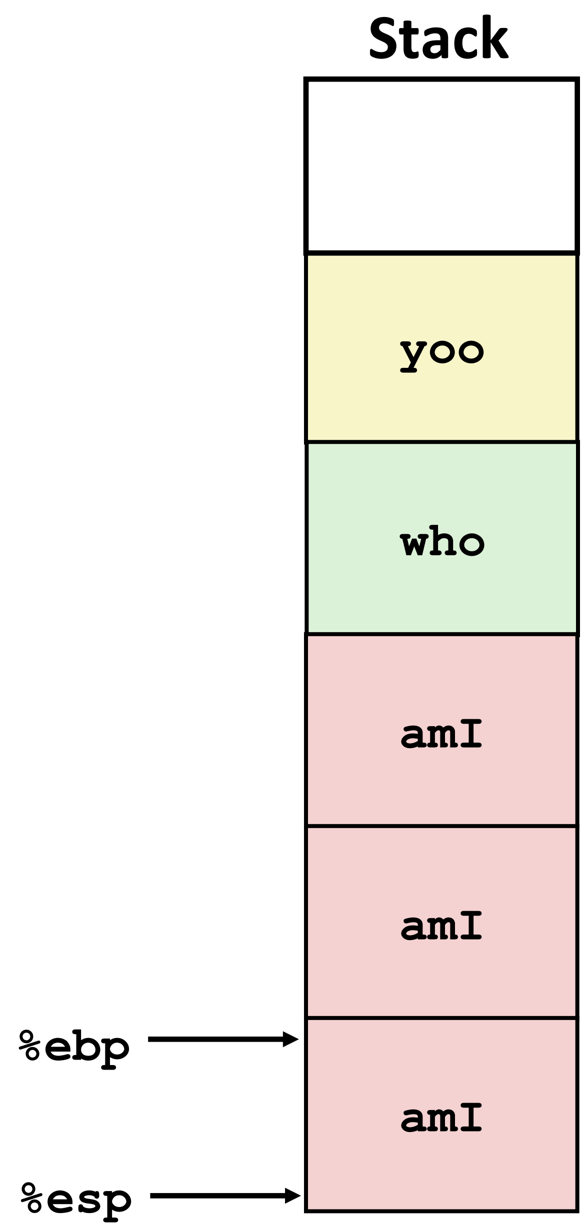
Stack



Example

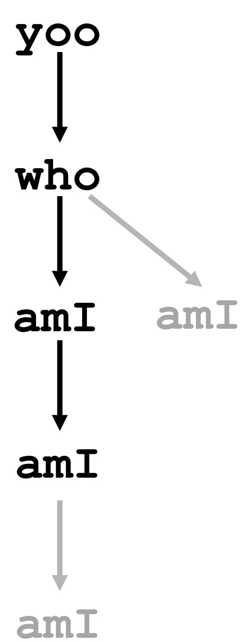
```
amI(…)
{
    •
    •
    amI();
    •
    •
}
```

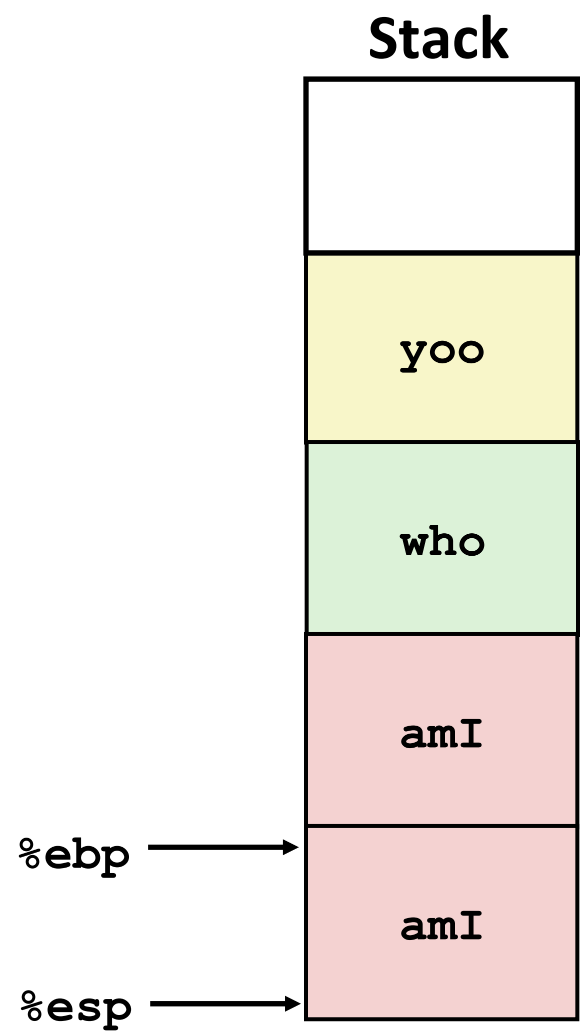




Example

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





Example

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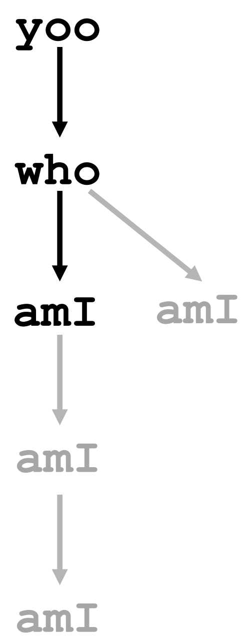
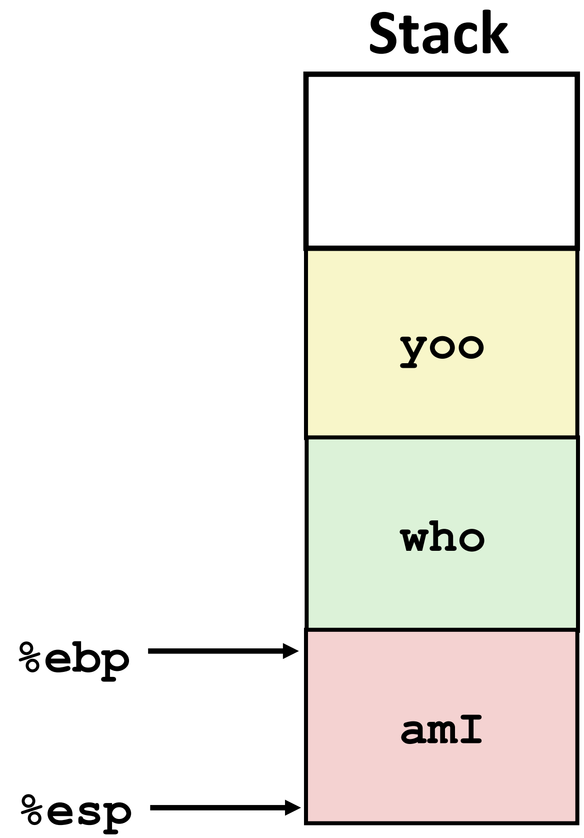
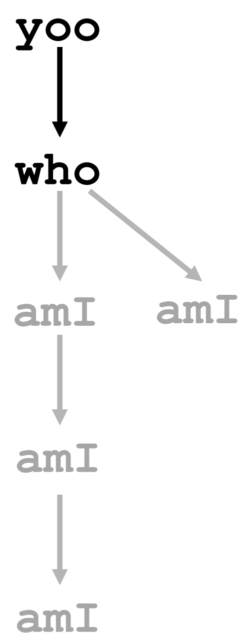
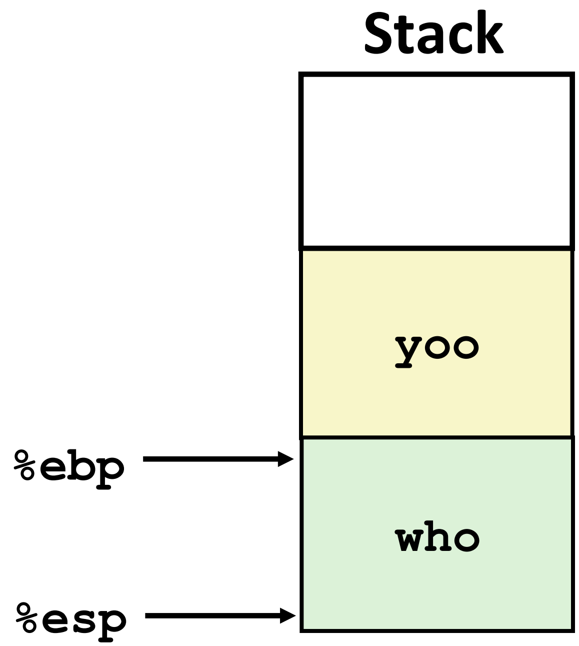




Example

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





Example

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{
    •
    •
    •
    •
    •
}
```

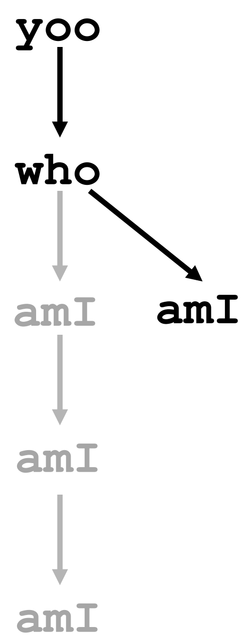

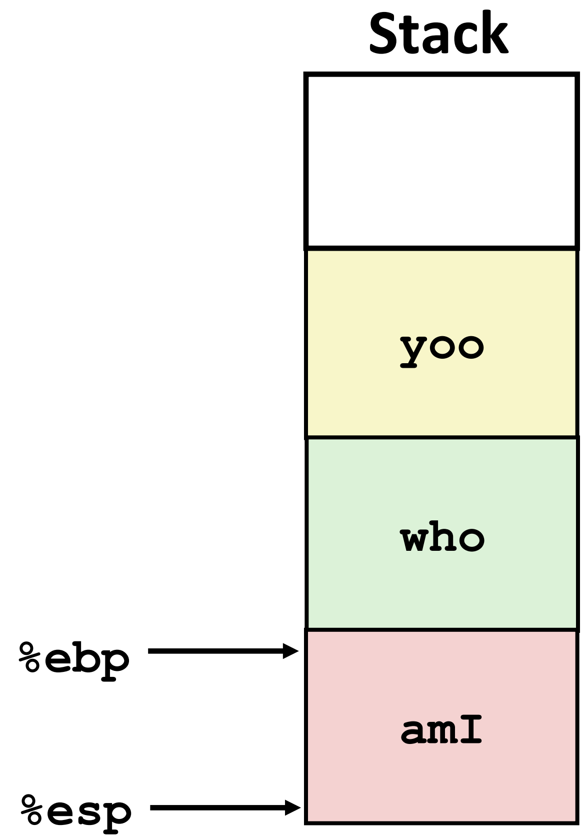

Example

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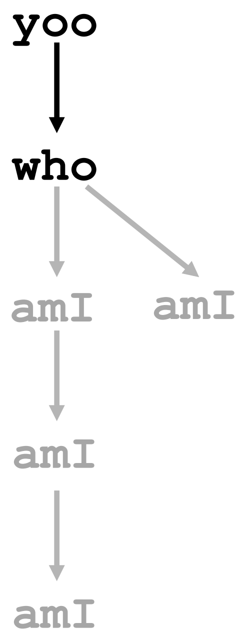
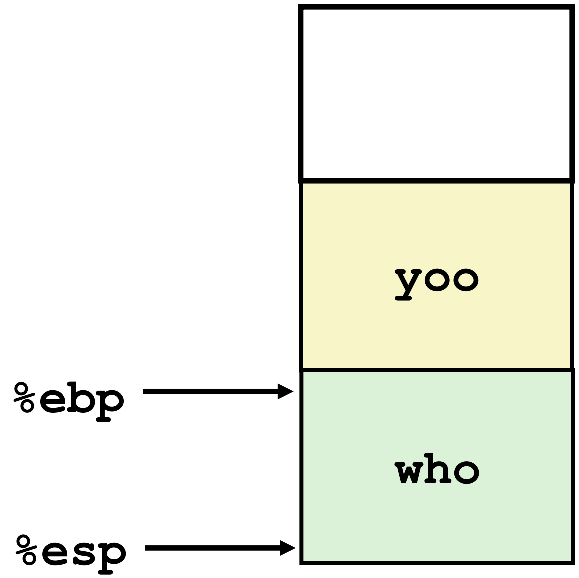
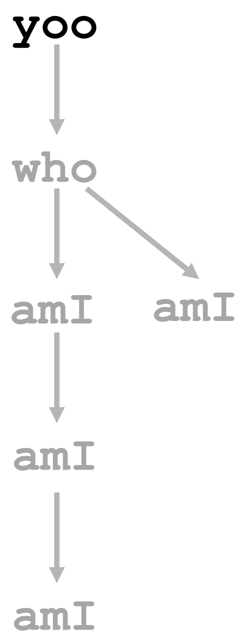


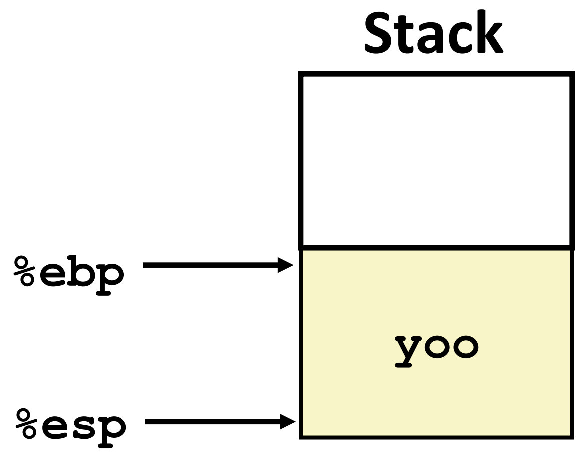
Stack



Example

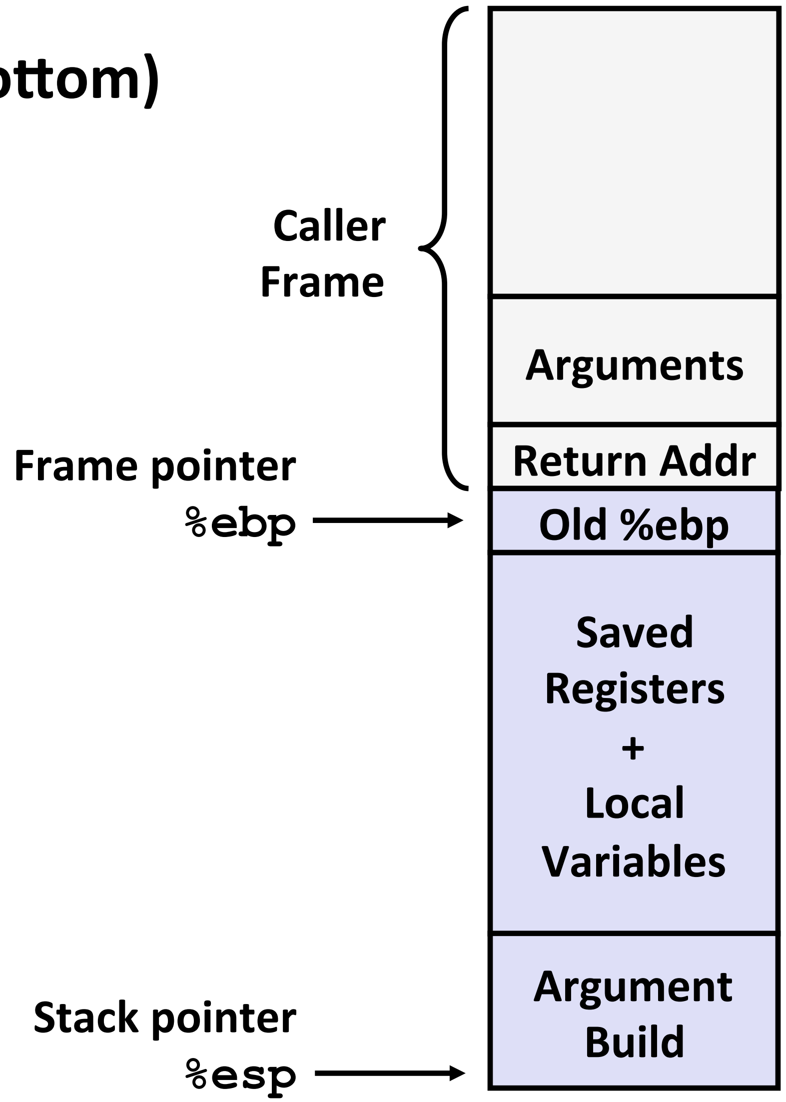
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```





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;
}
```

Revisiting swap

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

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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```

Calling swap from `call_swap`

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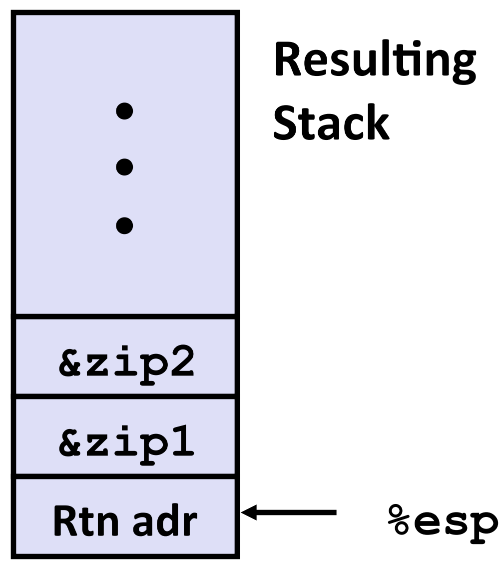


Resulting Stack

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

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

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

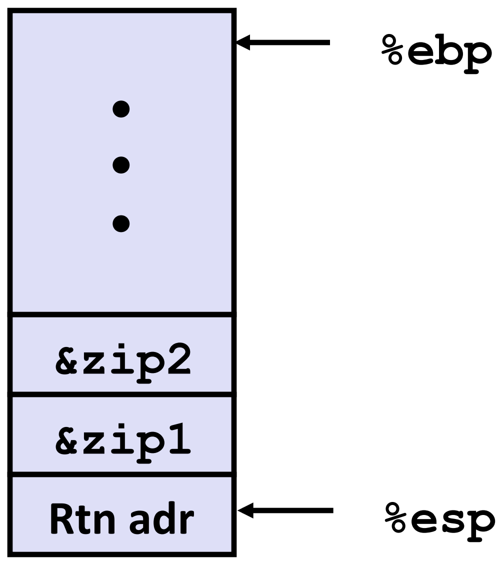
Set Up

Body

Finish

swap Setup #1

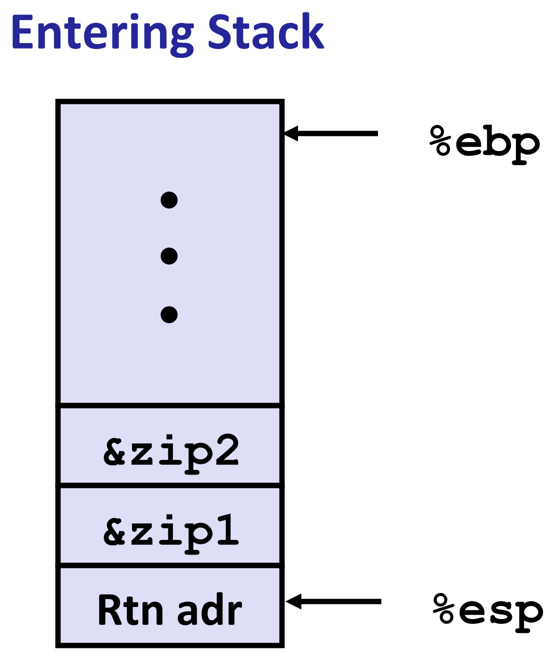
Entering Stack

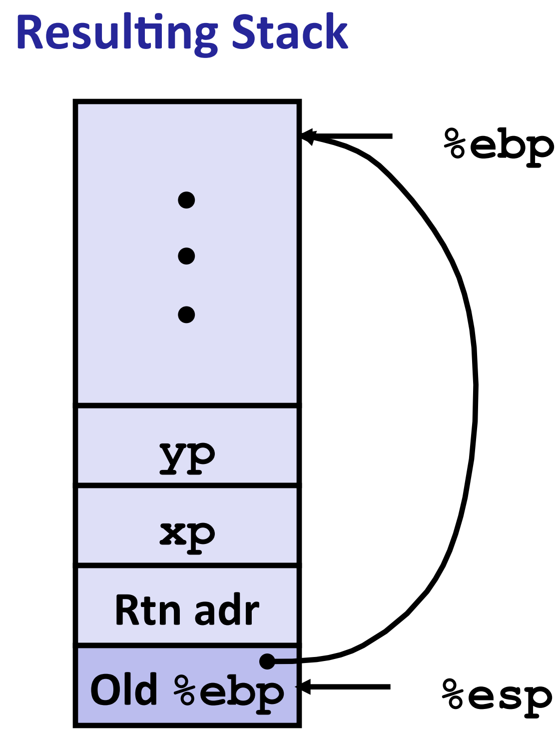


Resulting Stack?

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

swap Setup #1

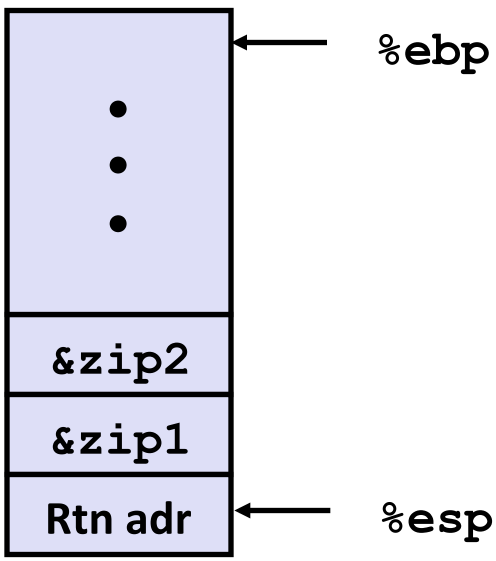




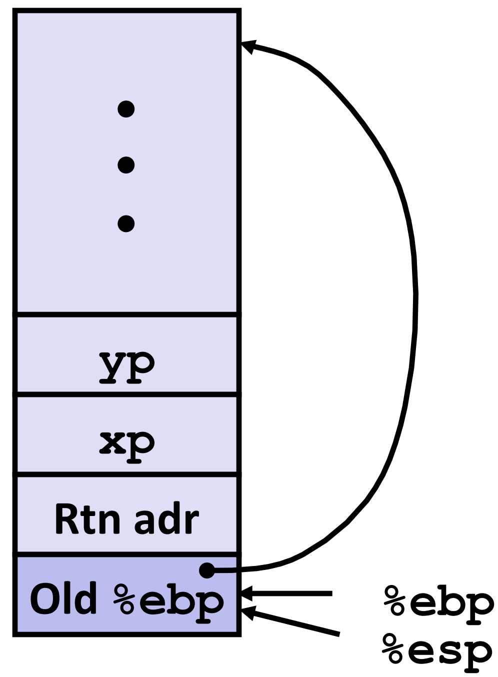

```
swap:
    pushl  %ebp
    movl  %esp,%ebp
    pushl  %ebx
```

swap Setup #2

Entering Stack



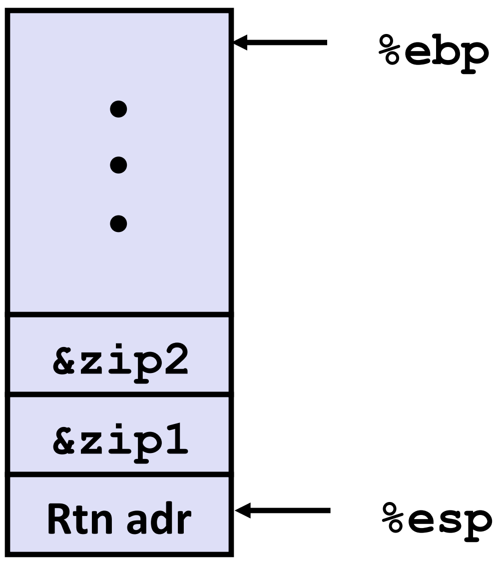
Resulting Stack



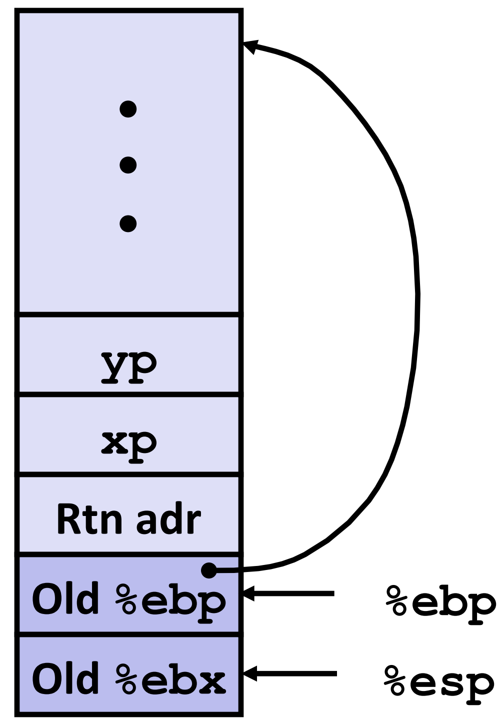

```
swap:
    pushl  %ebp
    movl  %esp,%ebp
    pushl  %ebx
```

swap Setup #3

Entering Stack

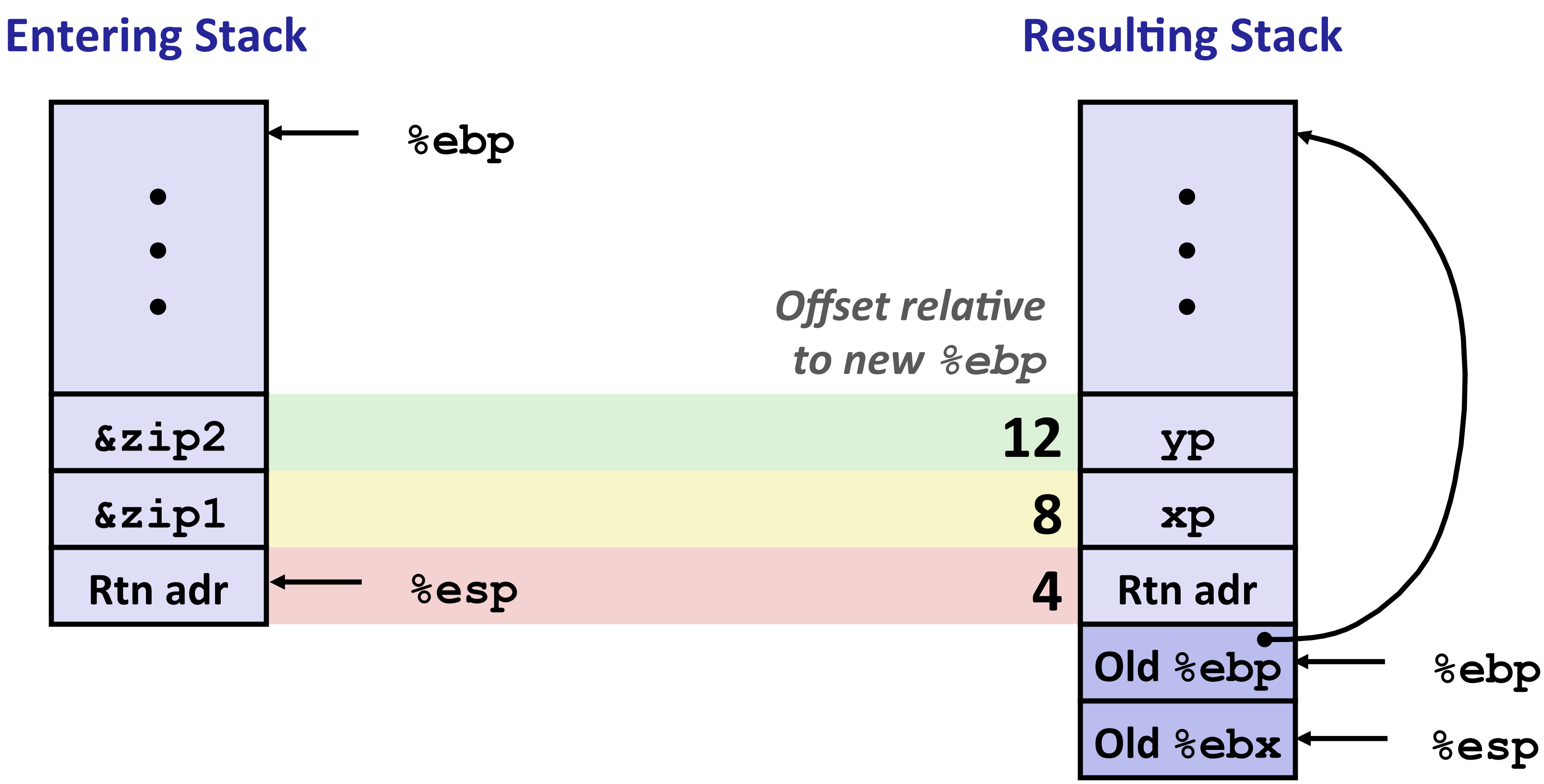


Resulting Stack




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

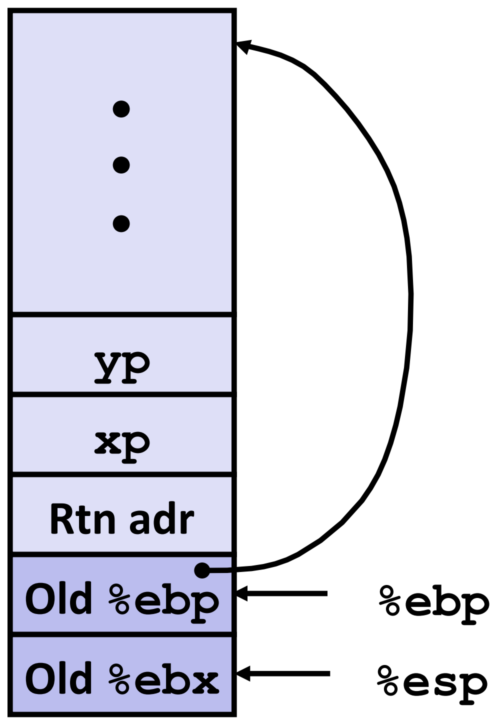
swap Body




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

swap Finish #1

swap's Stack

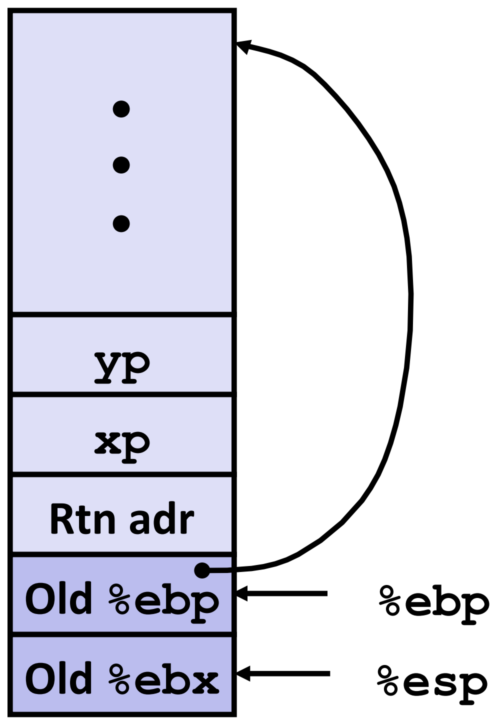



```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Resulting Stack?

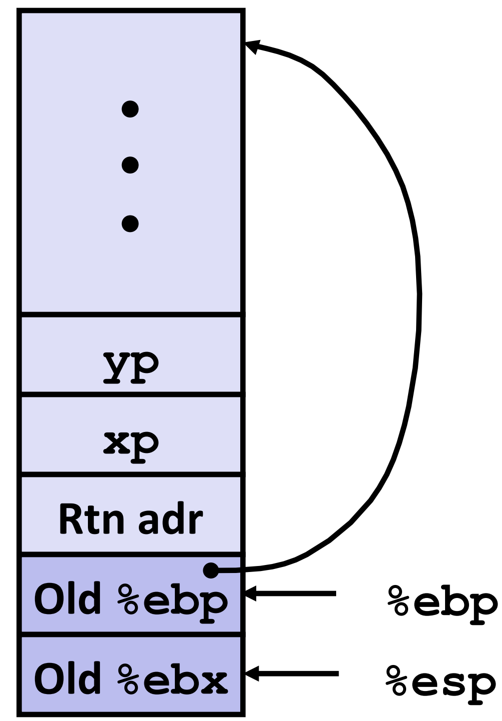
swap Finish #1

swap's Stack




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

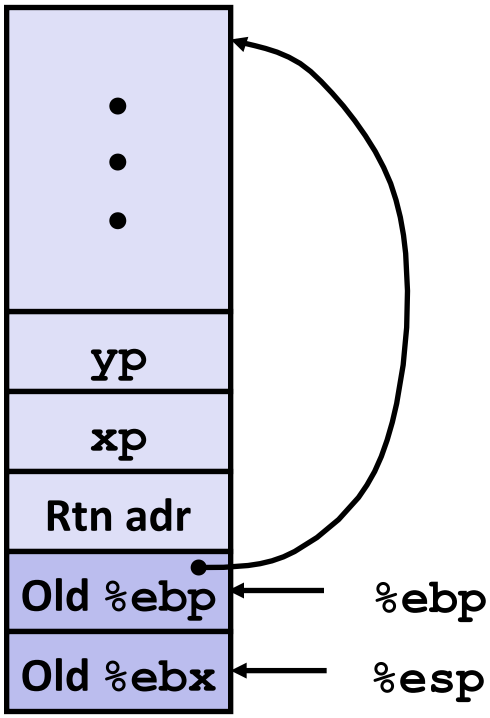
Resulting Stack



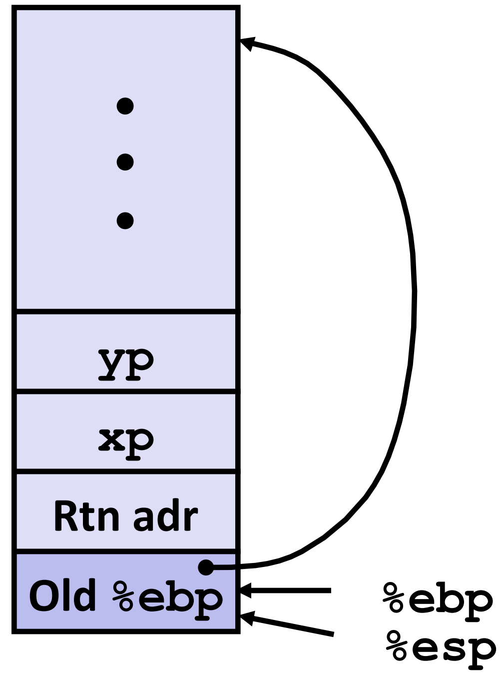
Observation: Saved and restored register %ebx

swap Finish #2

swap's Stack

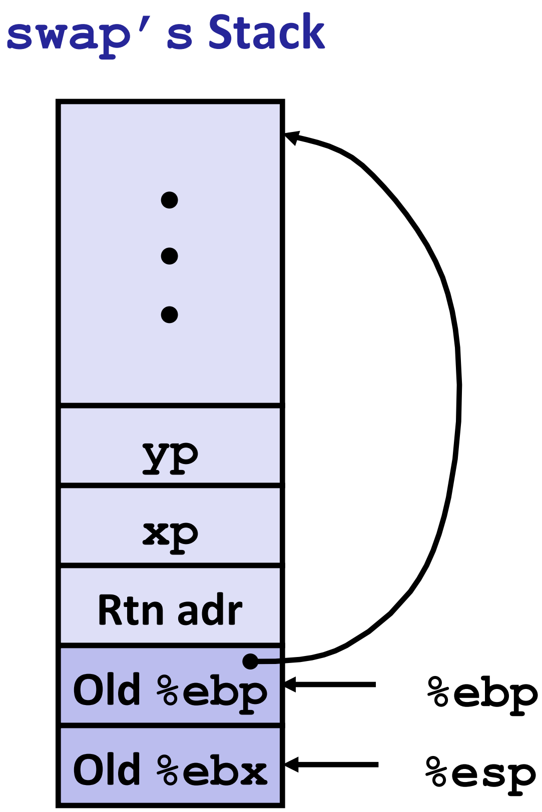


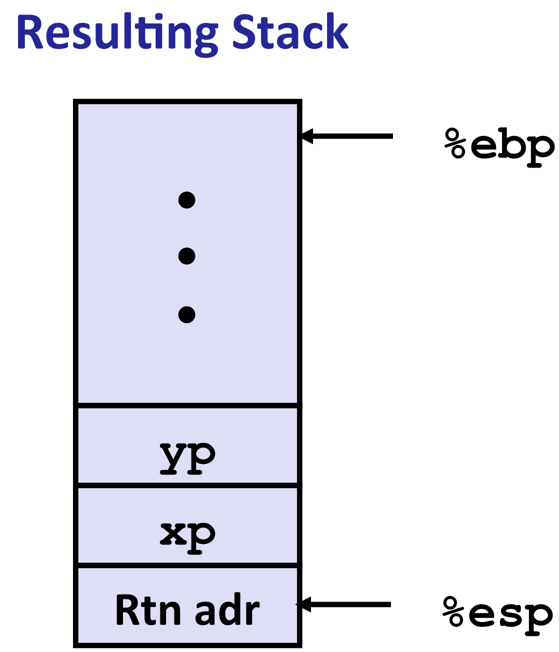
Resulting Stack




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

swap Finish #3

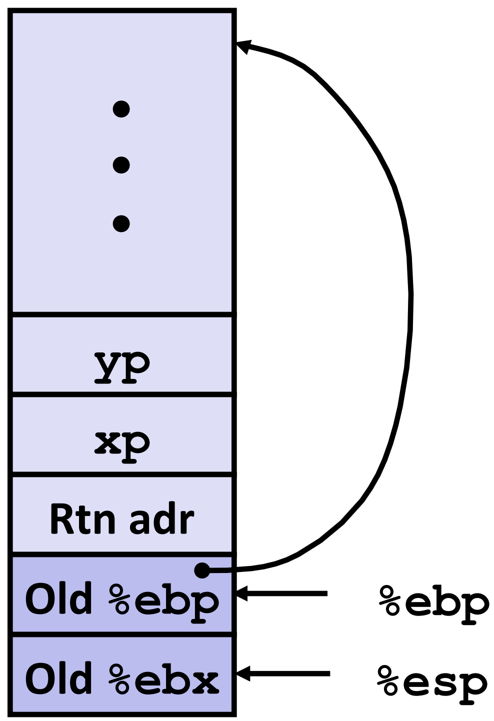




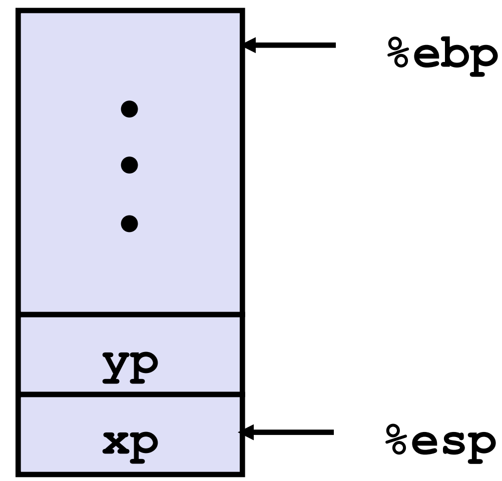

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

swap Finish #4

swap's Stack



Resulting Stack




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

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
```

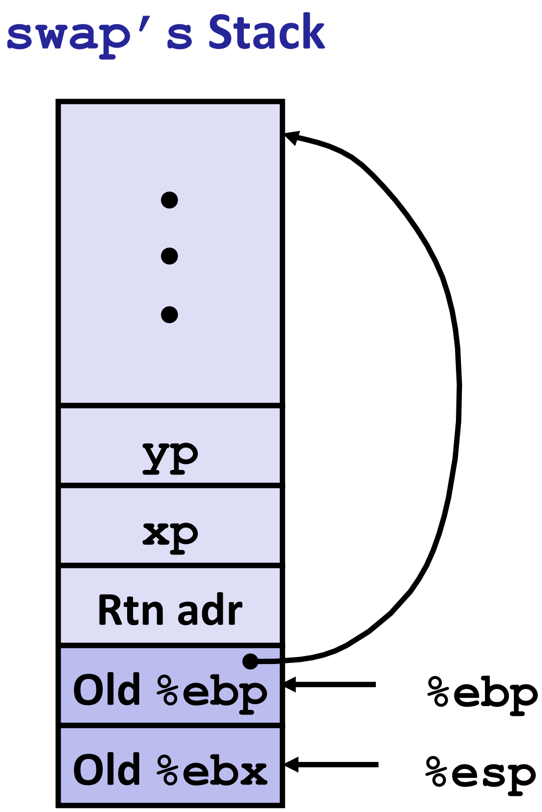
```
mov    %ebp,%esp
pop    %ebp
```

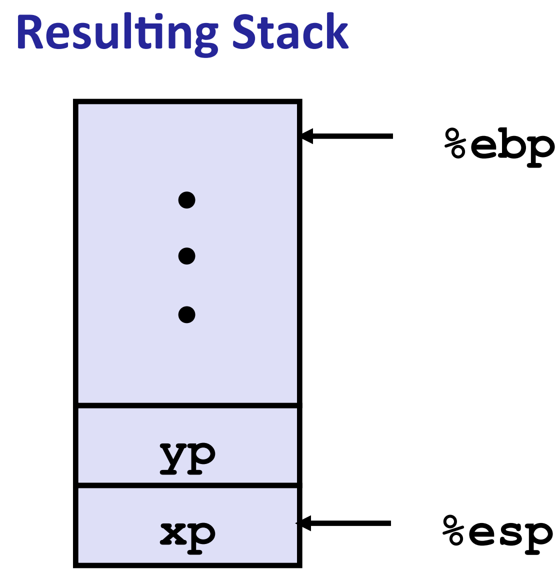
Calling Code

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

```
0x0804840e + 0xffffff96 = 0x080483a4
```

`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`**

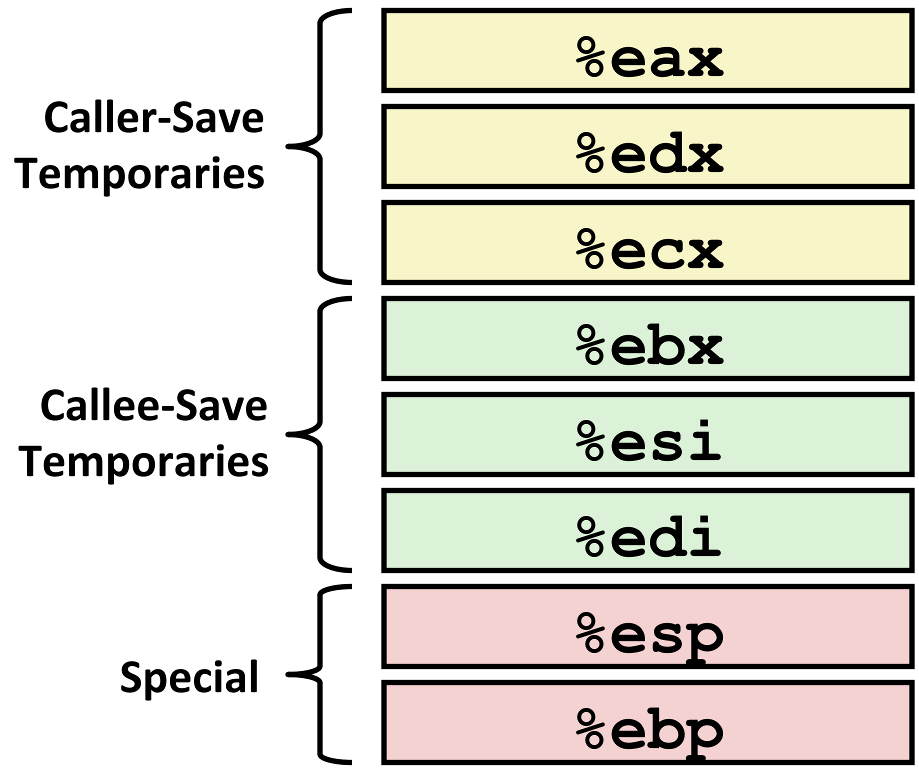
Register Saving Conventions

- **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

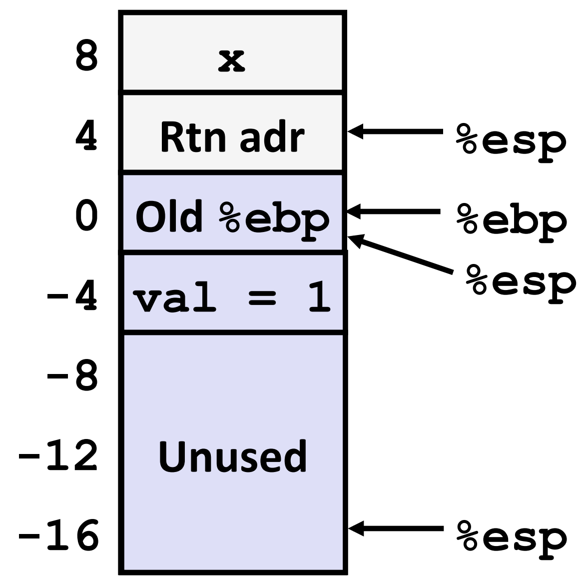
Creating & Initializing Pointer

```
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
```

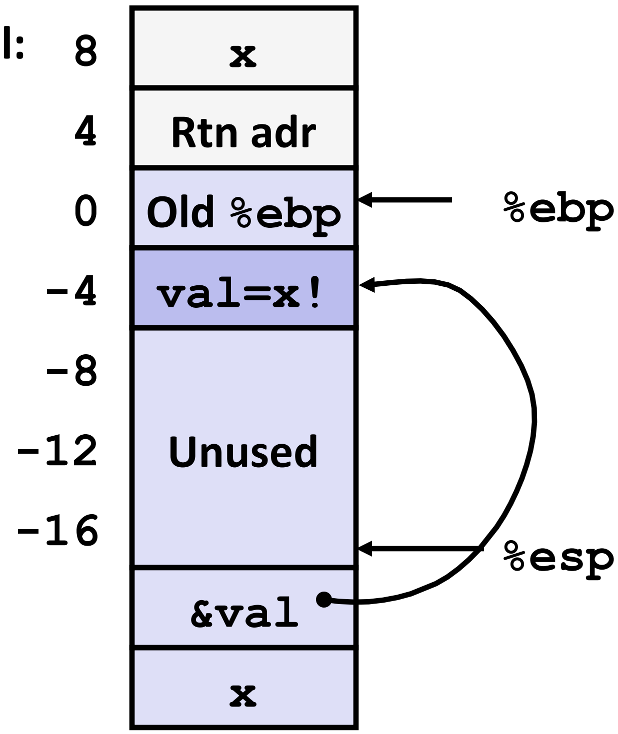


Passing Pointer

```
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:



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`**