Machine-Level Programming III - Procedures

Today

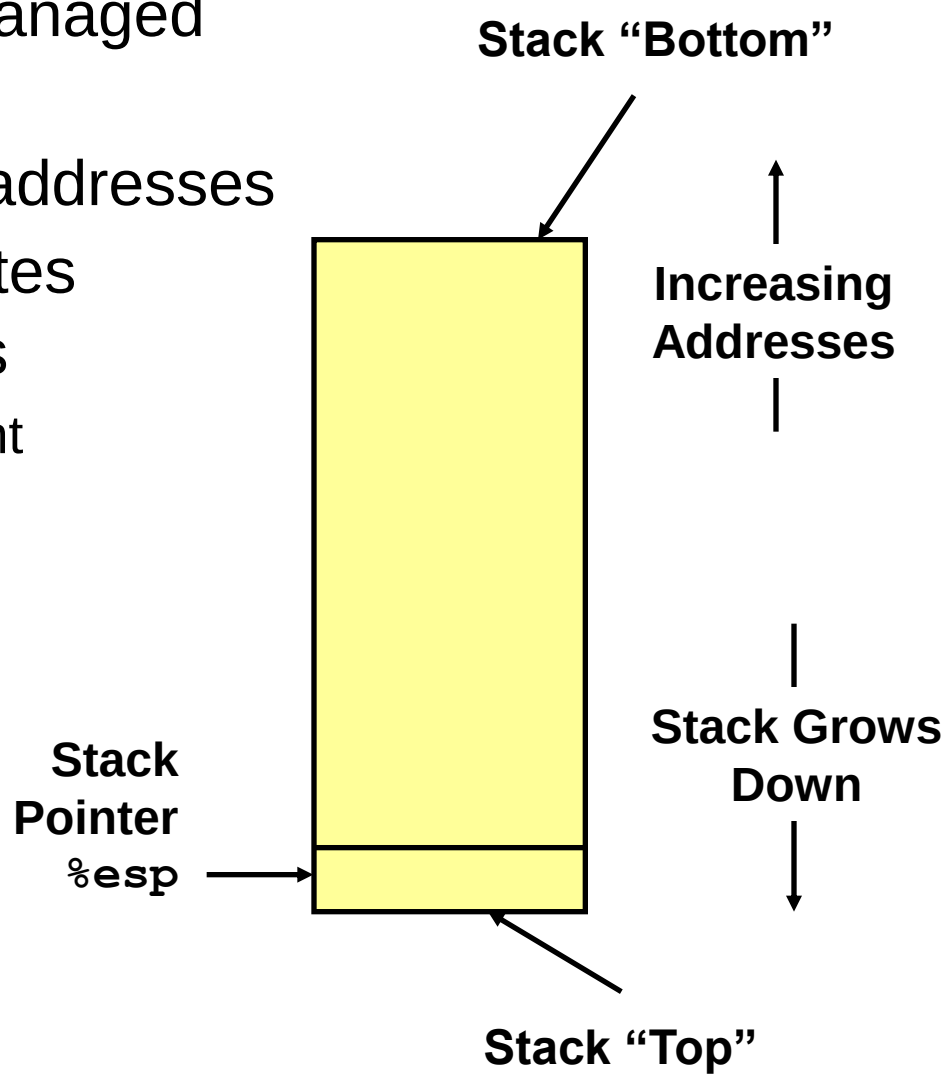
- IA32 stack discipline
- Register saving conventions
- Creating pointers to local variables

Next time

- Structured data

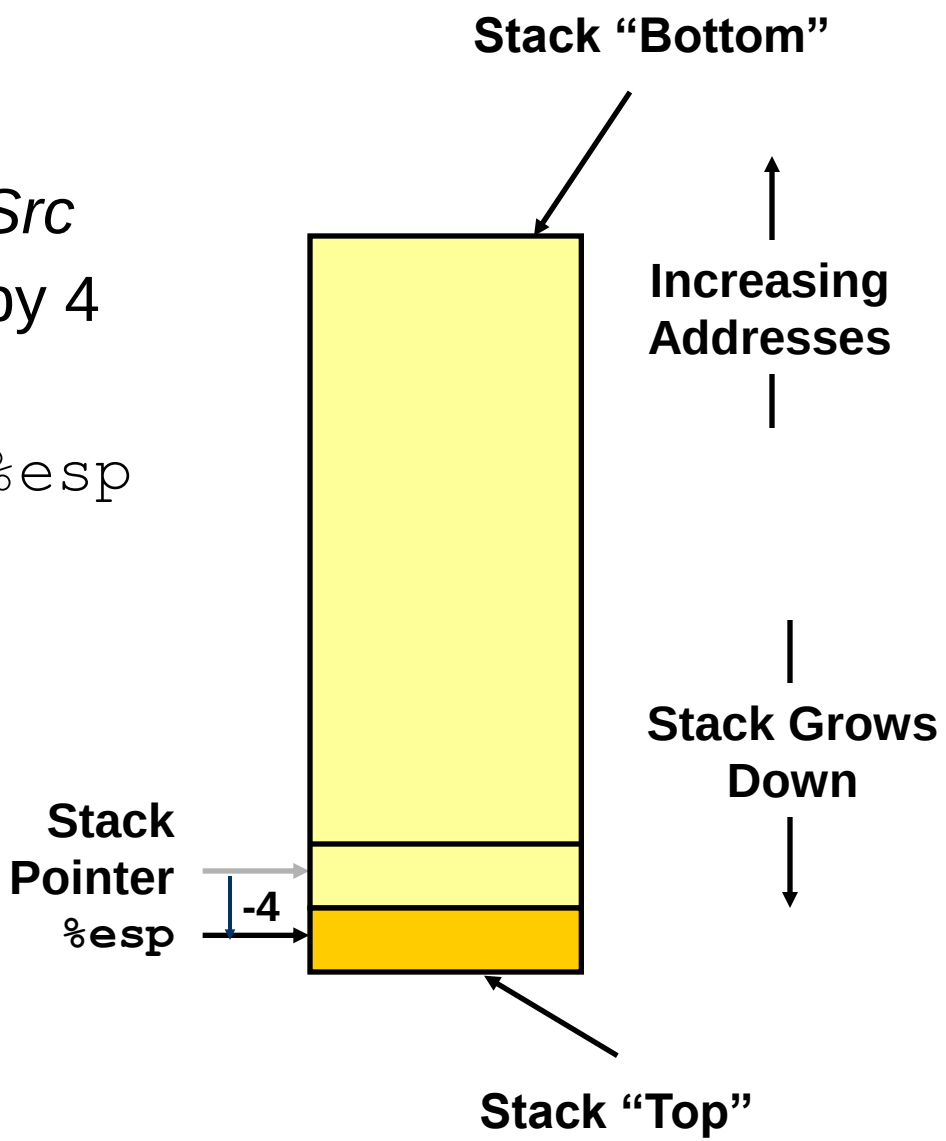
IA32 Stack

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



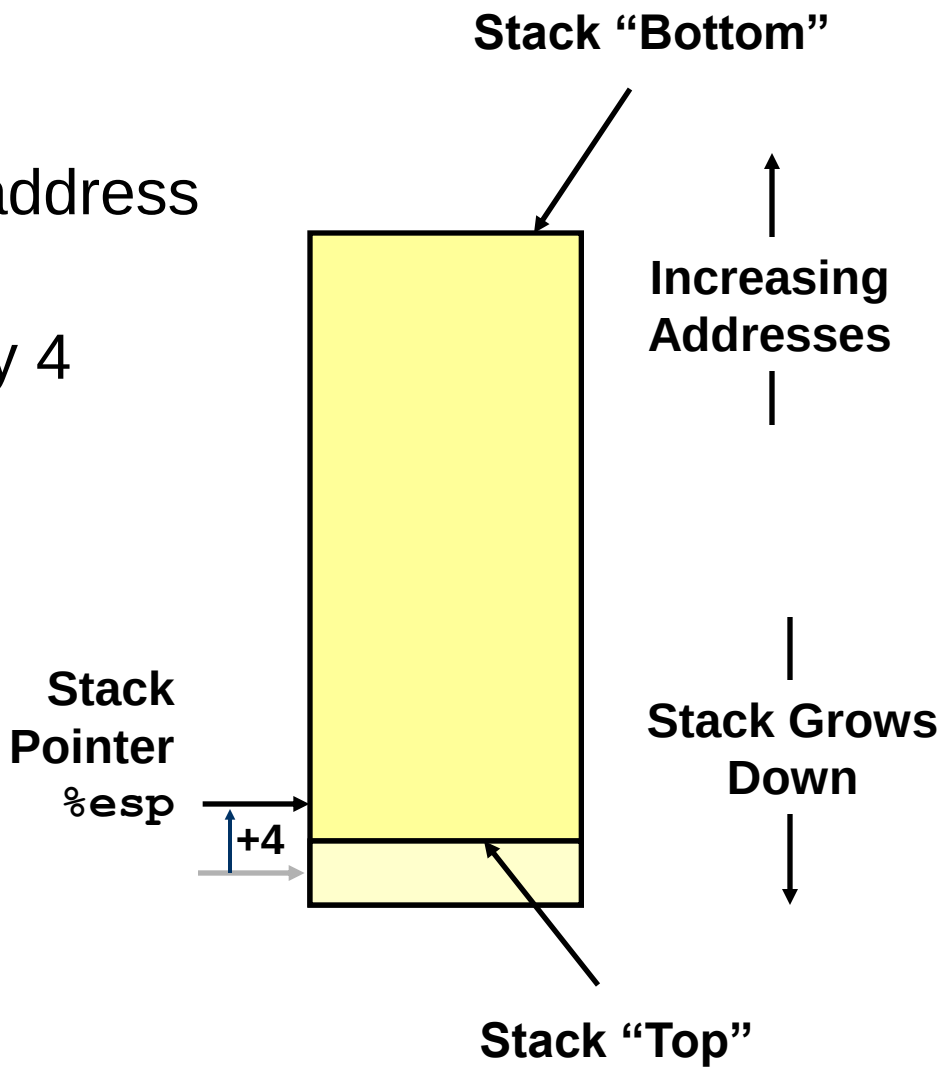
IA32 Stack pushing

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

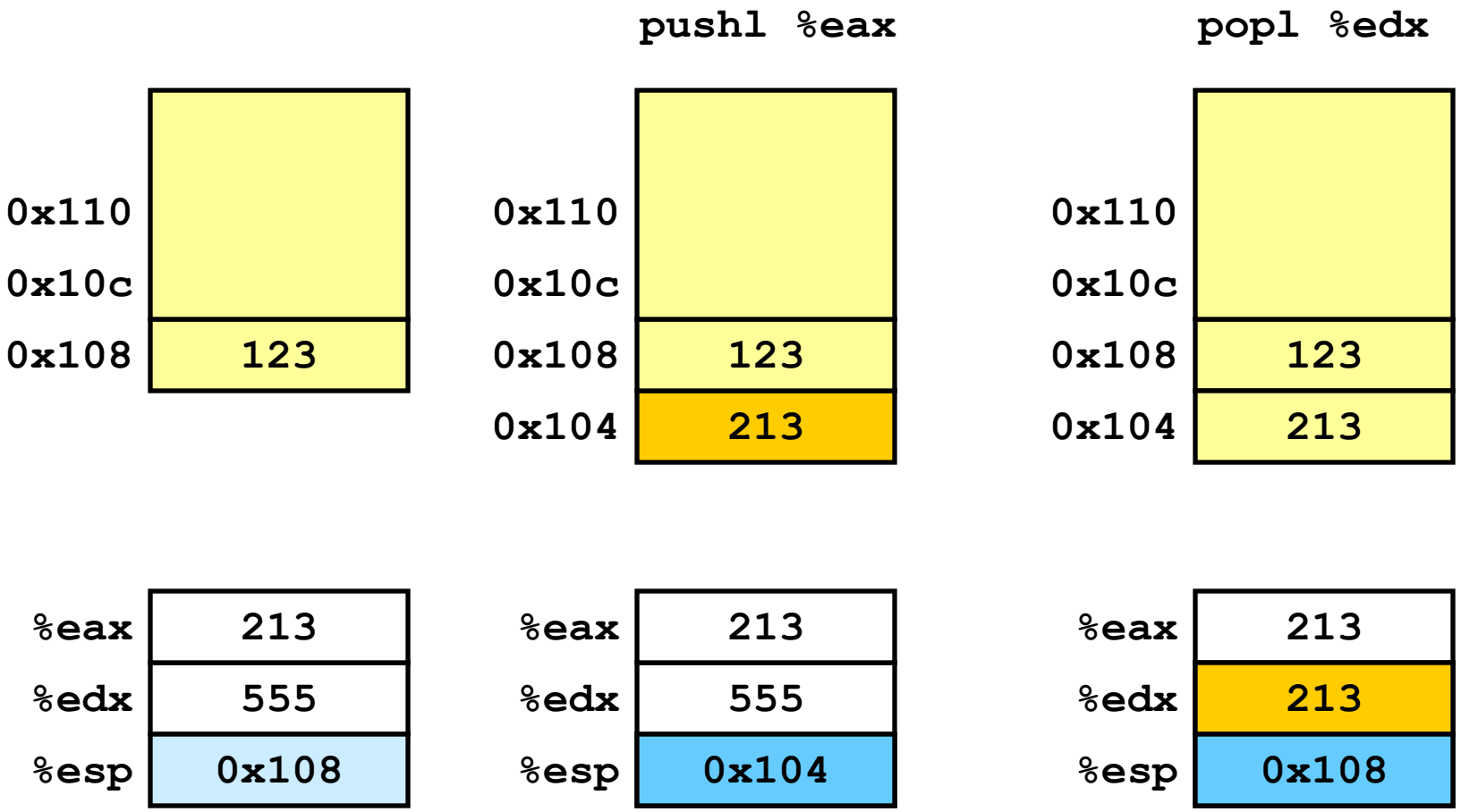


IA32 Stack popping

- Popping
  - `popl` *Dest*
  - Read operand at address given by `%esp`
  - Increment `%esp` by 4
  - Write to *Dest*



Stack operation examples



Procedure control flow

- Use stack to support procedure call and return
- Procedure call

  `call` *`label`* Push return address on stack; jump to *`label`*

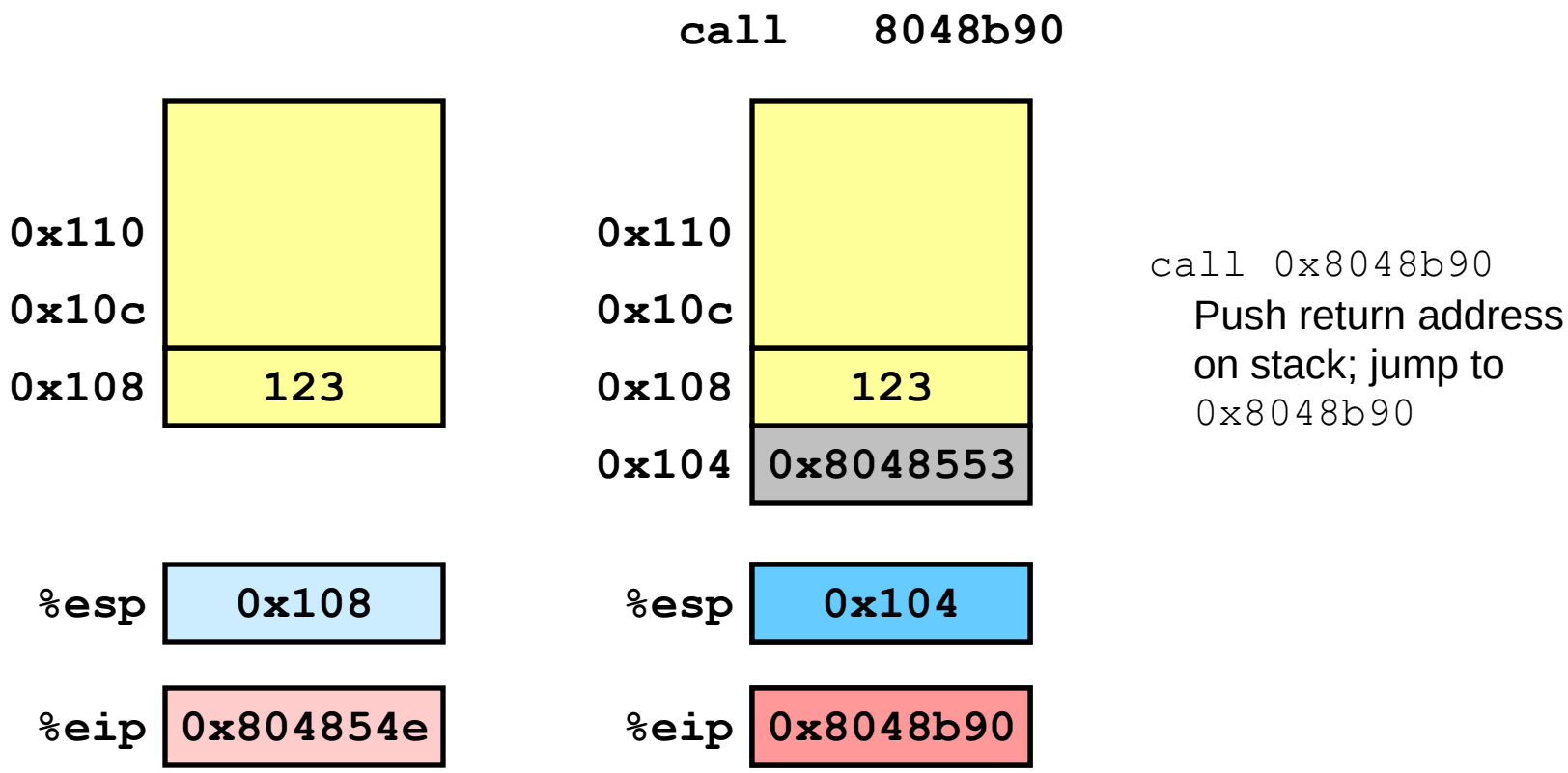
  `call` *`*Operand`* Similar, but indirect
- Return address value
  - Address of instruction immediately following `call`
  - Example from disassembly

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

    - Return address = `0x8048553`
- Procedure return
  - `leave` Prepare stack for return
  - `ret` Pop address from stack; jump to address (stack should be ready)

Procedure call example

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

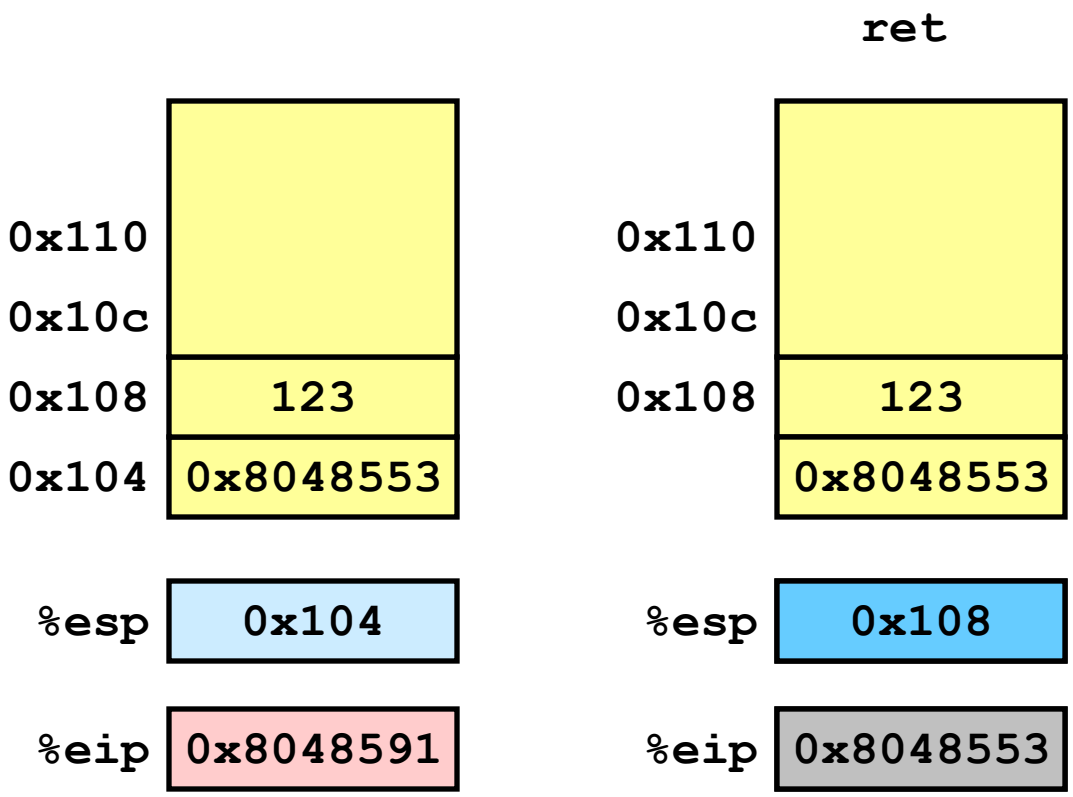


`call 0x8048b90`
Push return address on stack; jump to `0x8048b90`

`%eip` is program counter

Procedure return example

```
8048591:   c3                    ret
```



`ret` Pop address from stack; jump to address

`%eip` is 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

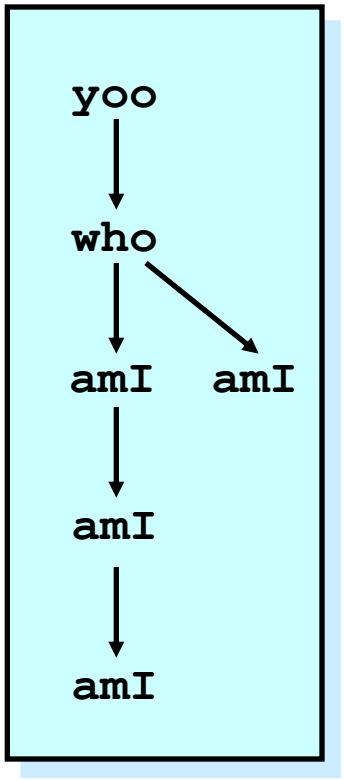
Code structure

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

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

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

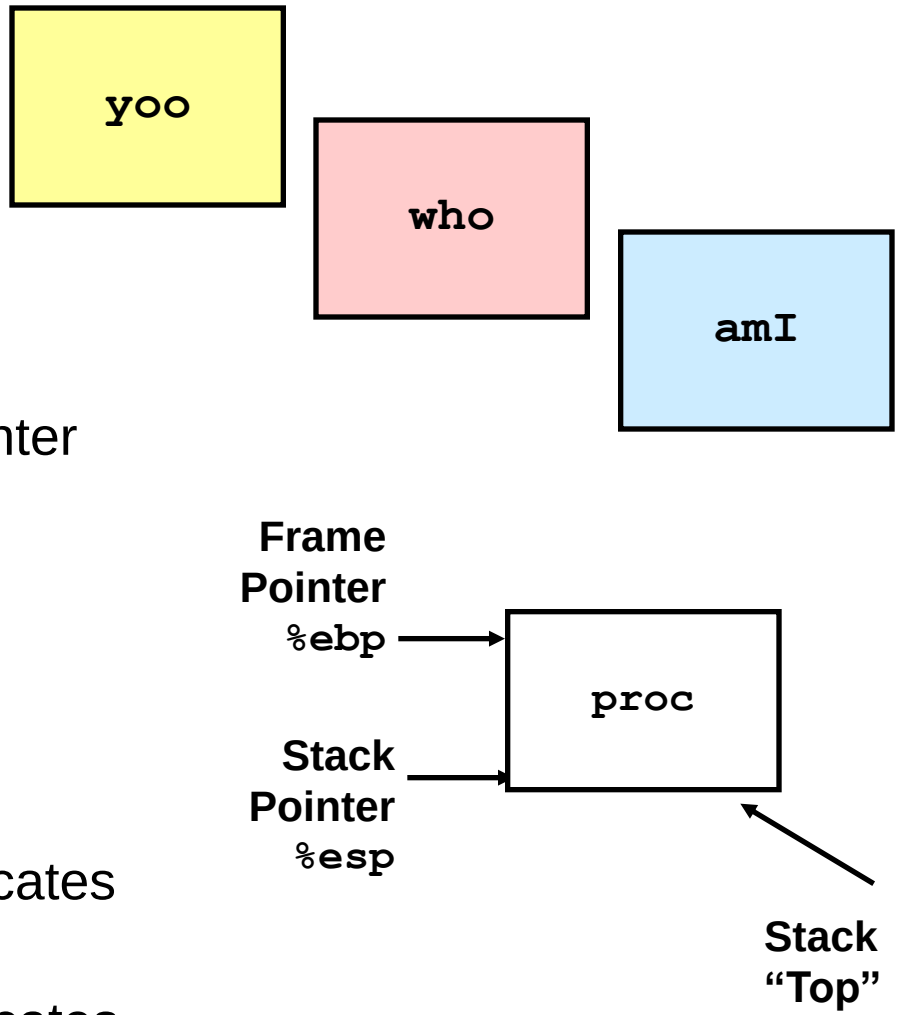
Call Chain



Procedure `amI` recursive

Stack frames

- Contents
  - Local variables
  - Return information
  - Temporary space
- Management
  - Space allocated when enter procedure
    - "Set-up" code
  - Deallocated when return
    - "Finish" code
- Pointers
  - Stack pointer `%esp` indicates stack top
  - Frame pointer `%ebp` indicates start of current frame

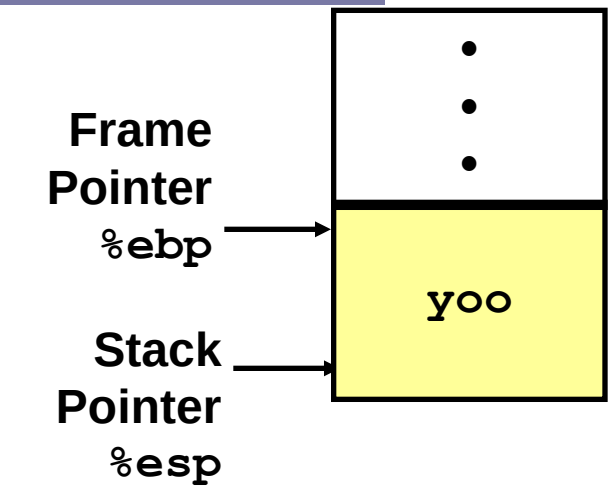


Stack operation

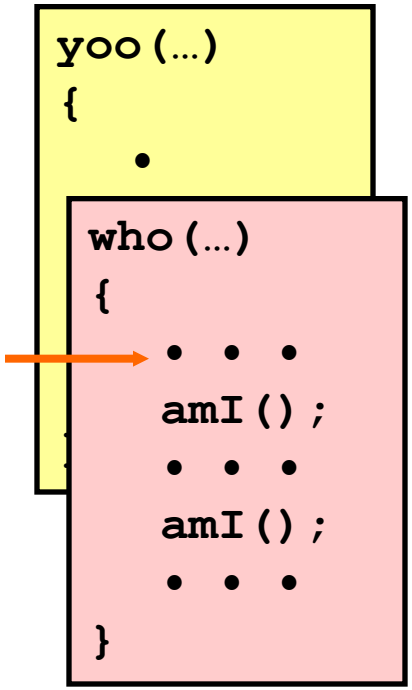
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

Call Chain

yoo



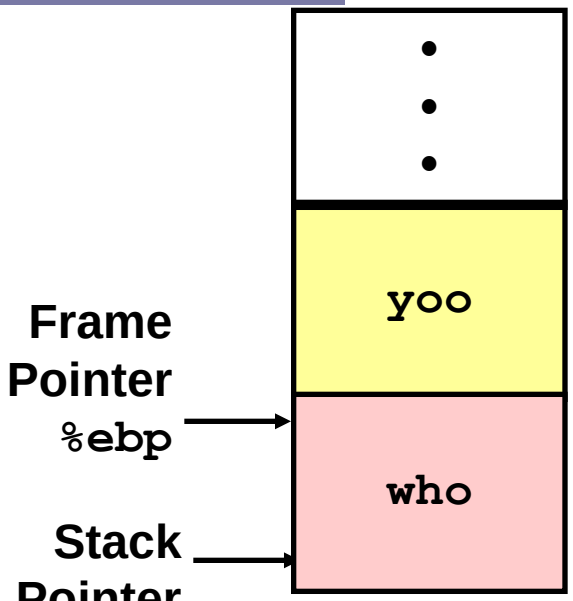
Stack operation



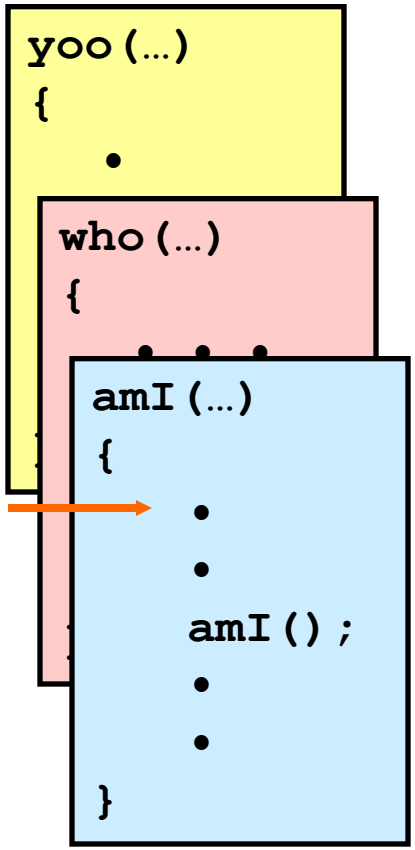
Call Chain

yoo

who

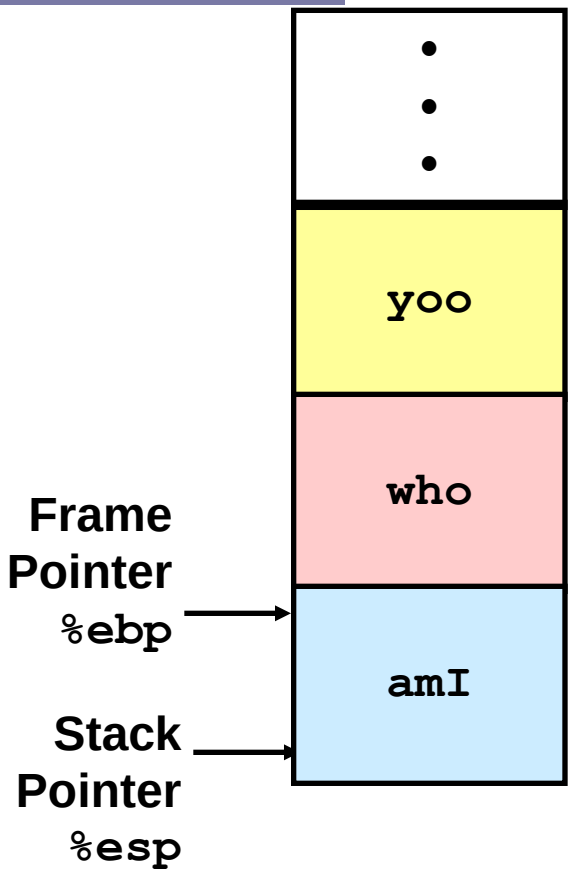


Stack operation

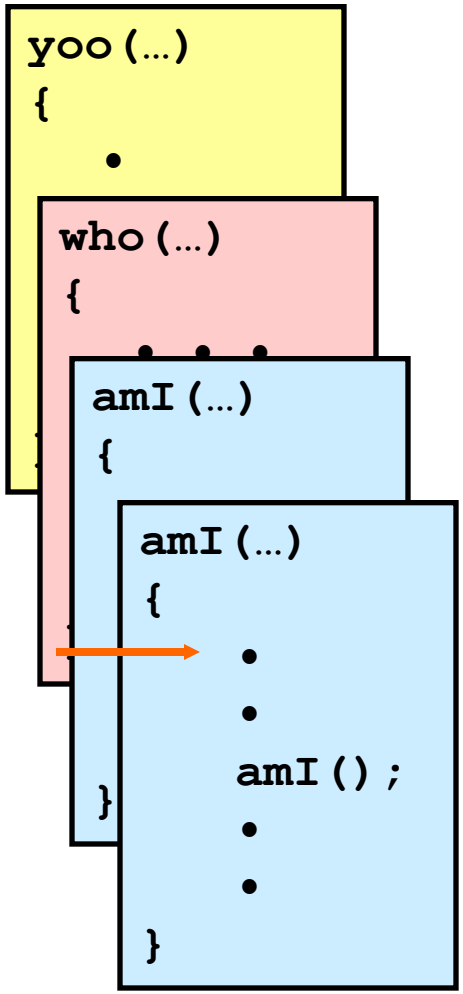


Call Chain

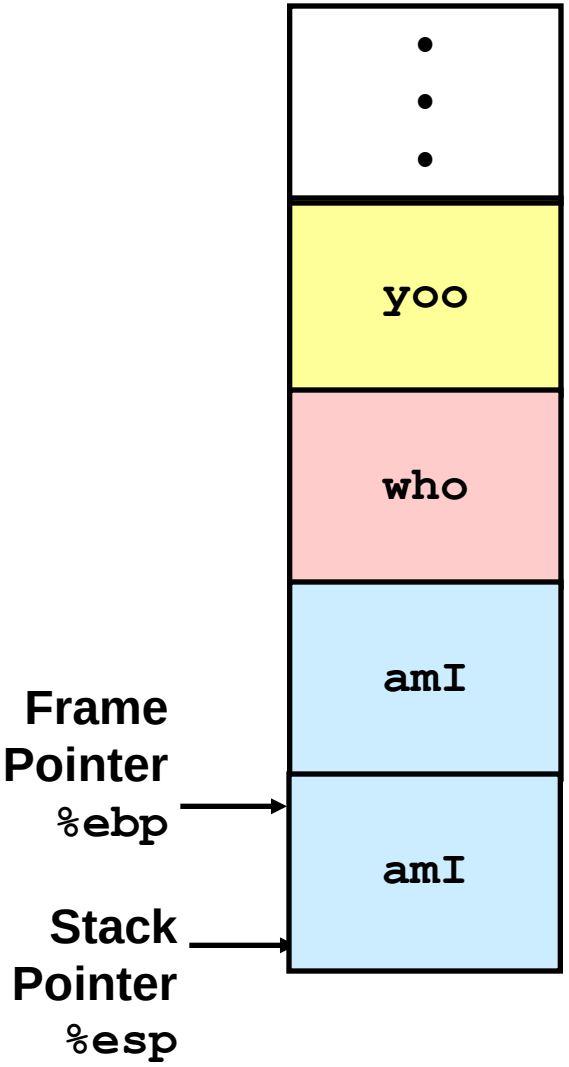
yoo
who
amI



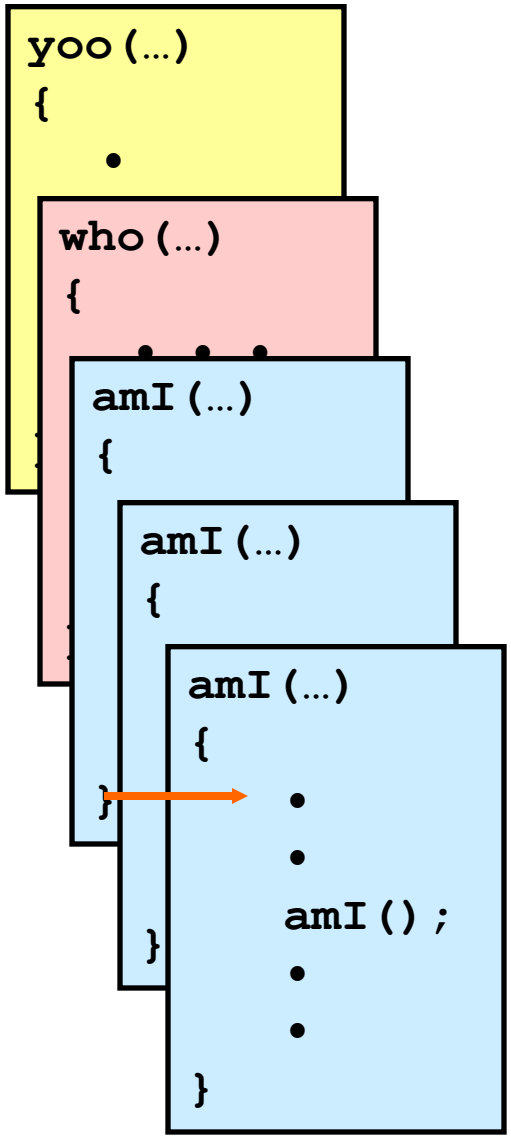
Stack operation



Call Chain

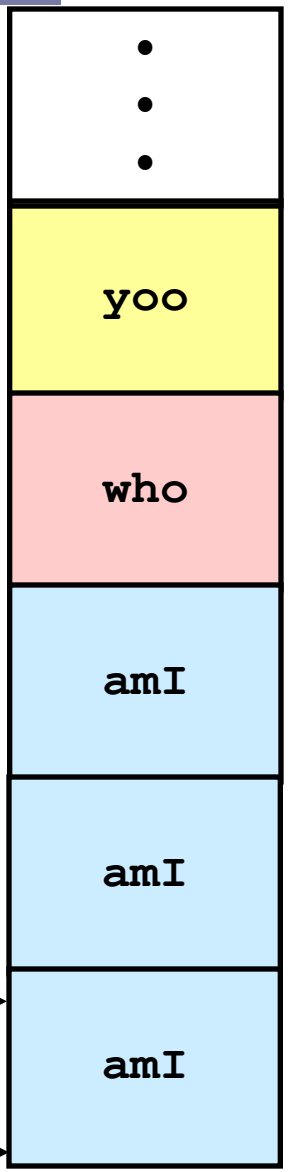


Stack operation



Call Chain

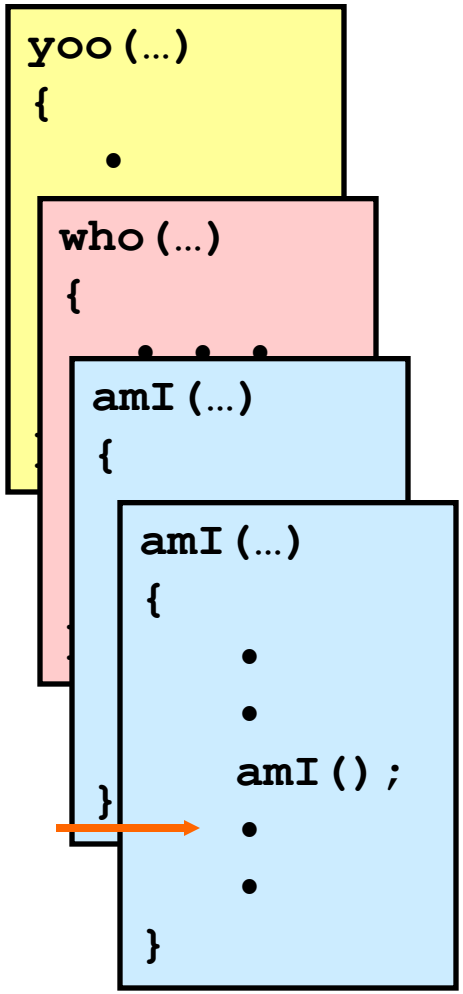
yoo
who
amI
amI
amI



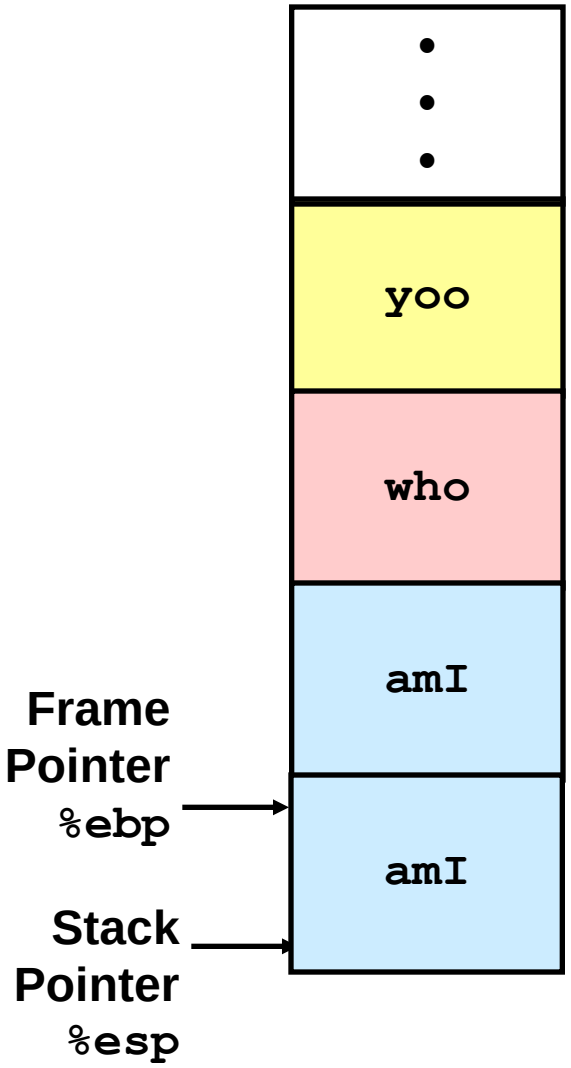
Frame Pointer `%ebp`

Stack Pointer `%esp`

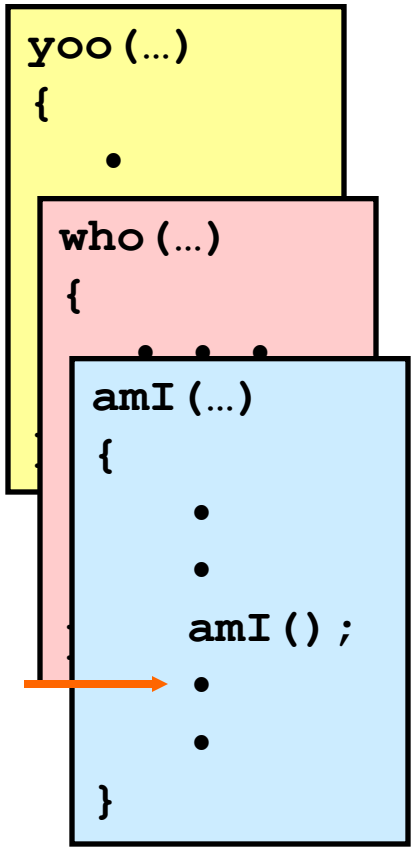
Stack operation



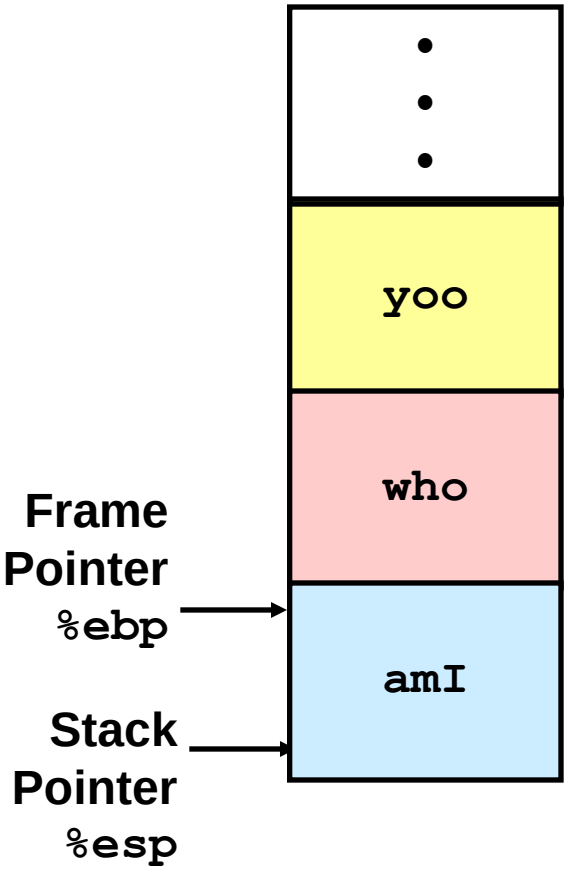
Call Chain



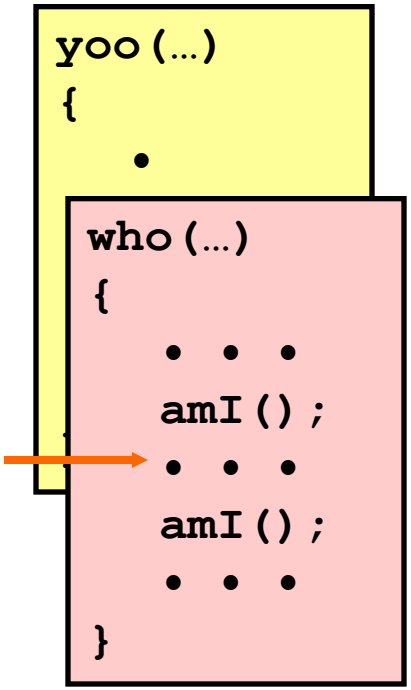
Stack operation



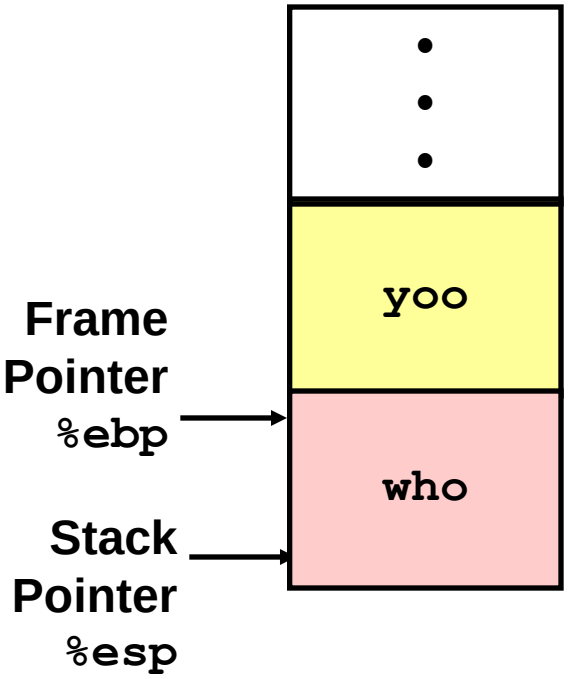
Call Chain



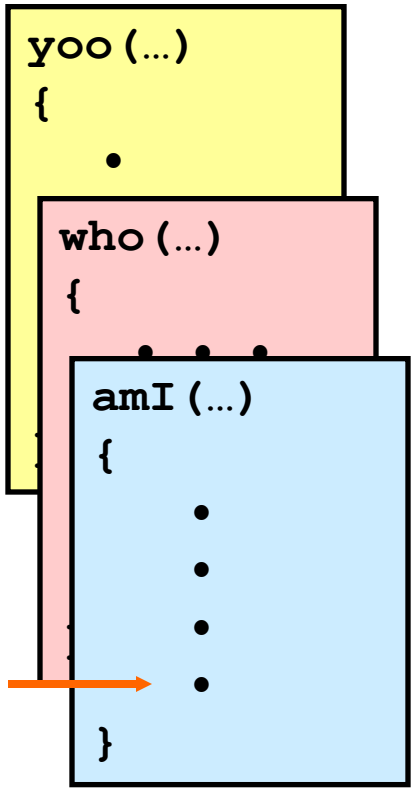
Stack operation



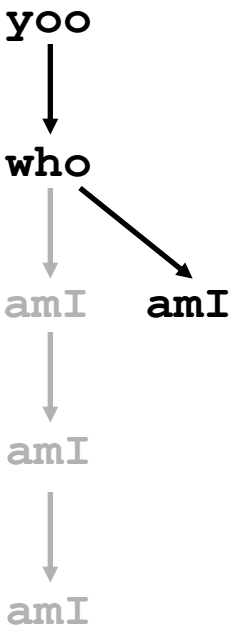
Call Chain

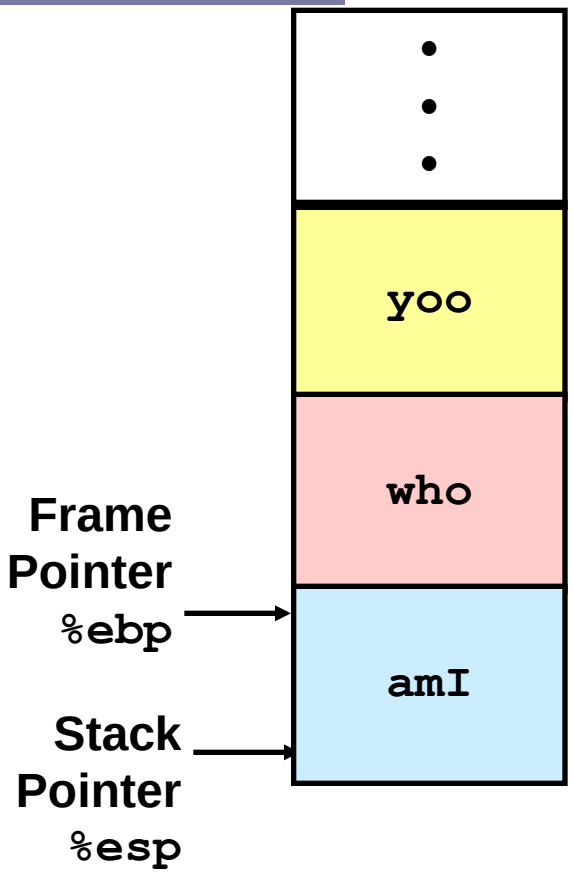


Stack operation

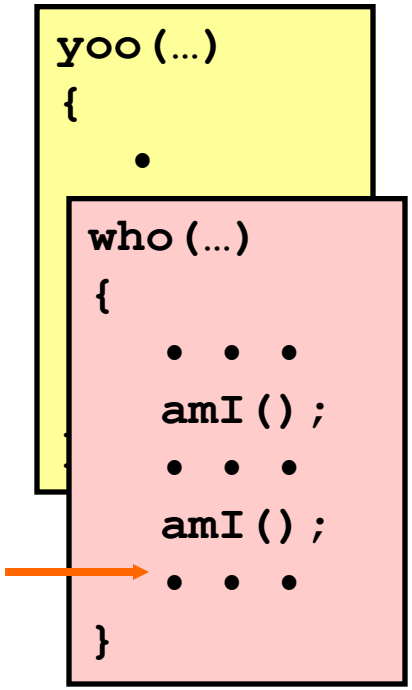


Call Chain

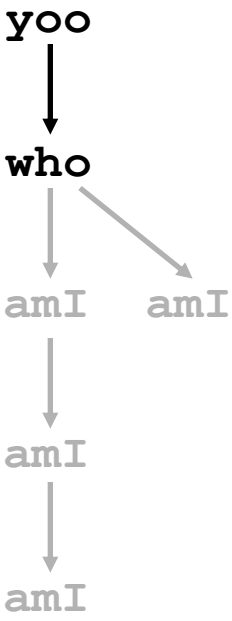


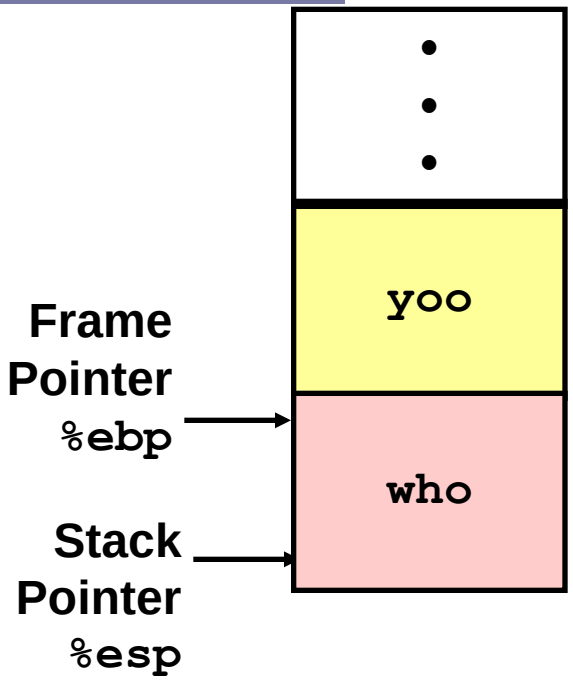


Stack operation



Call Chain

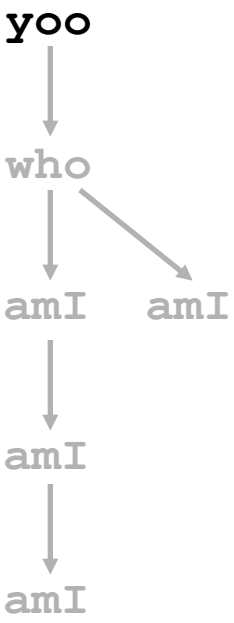


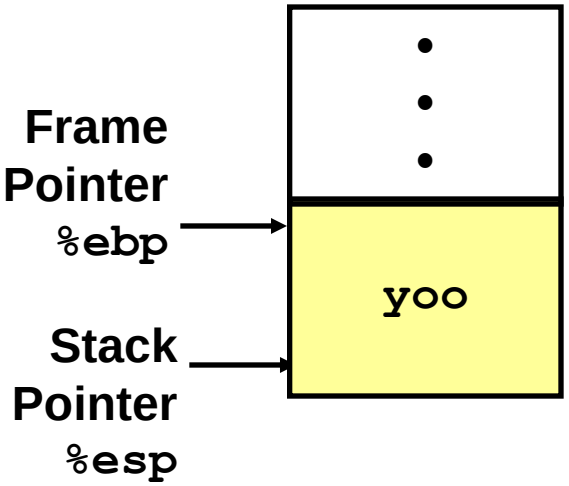


Stack operation

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

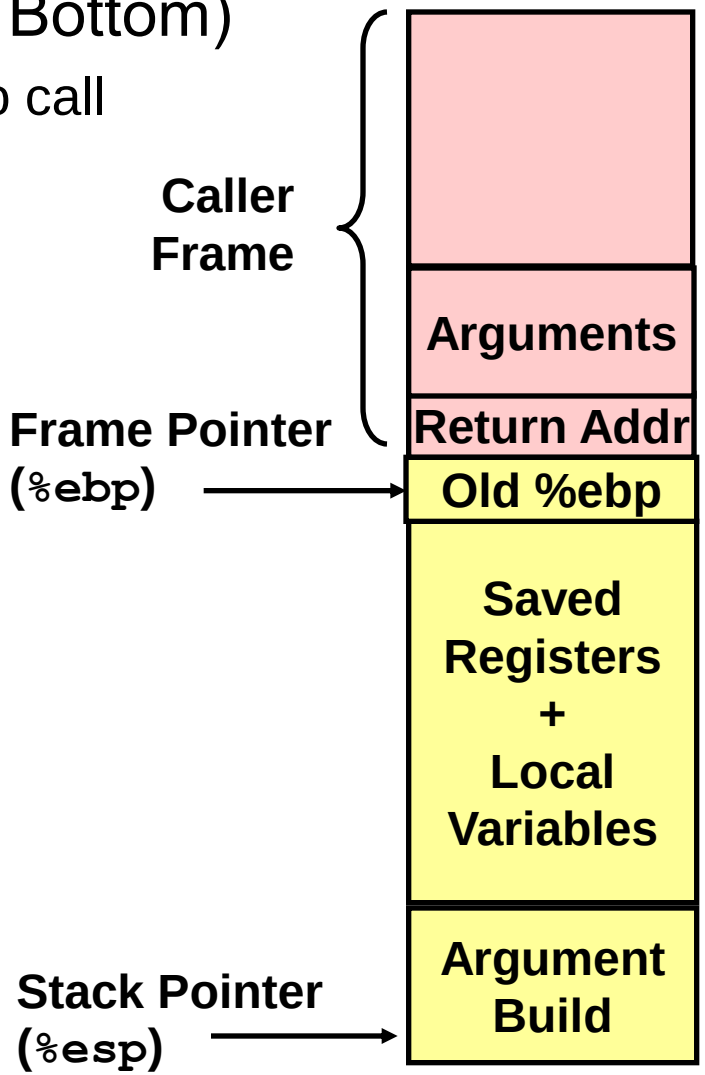
Call Chain





IA32/Linux stack frame

- Current stack frame ("Top" to Bottom)
  - Parameters for function about to call
    - "Argument build"
  - 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

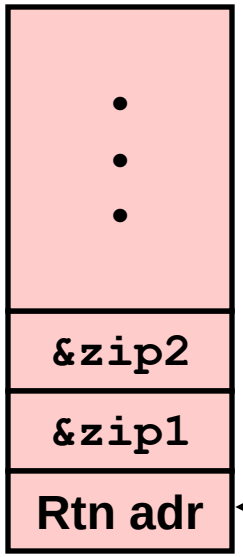
```
int zip1 = 15213;
int zip2 = 91125;

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

Calling `swap` from `call_swap`

```
call_swap:
    pushl   %ebp
    movl    %esp, %ebp
    subl    $16, %esp
    pushl   $zip2  # Global Var
    pushl   $zip1  # Global Var
    call    swap
    . . .
```

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



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

    pop %ebx
    leave
    ret
```

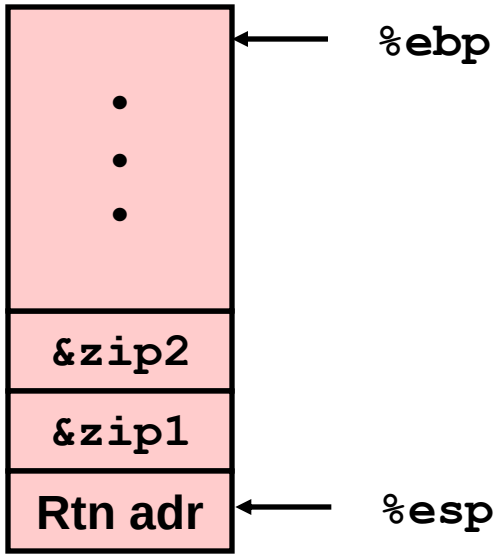
Set Up

Body

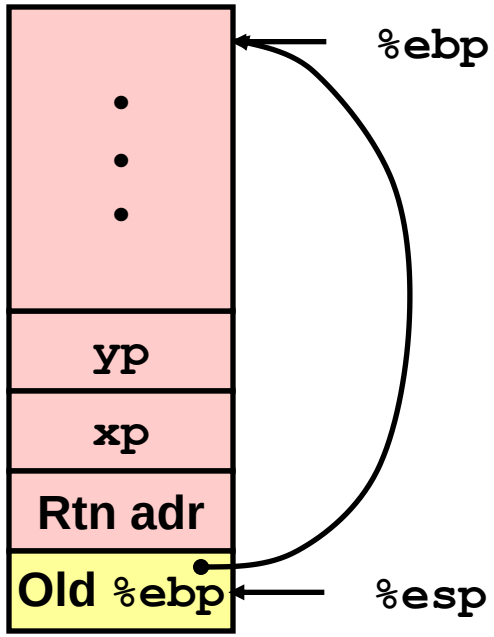
Finish

swap Setup #1

Entering Stack



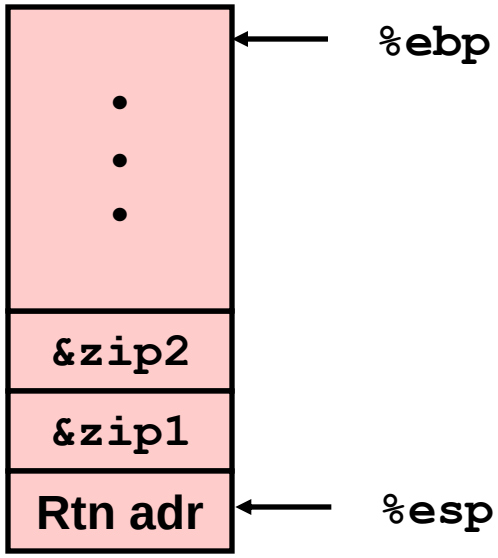
Resulting Stack



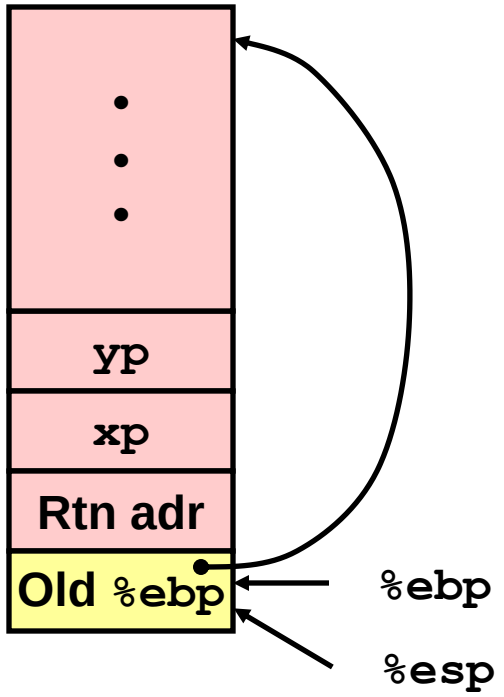

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #2

Entering Stack



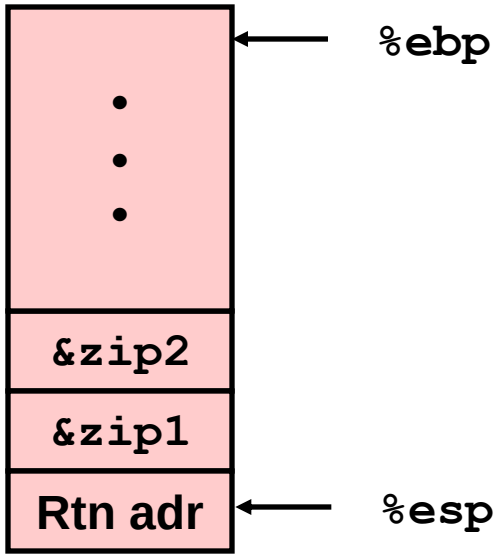
Resulting Stack



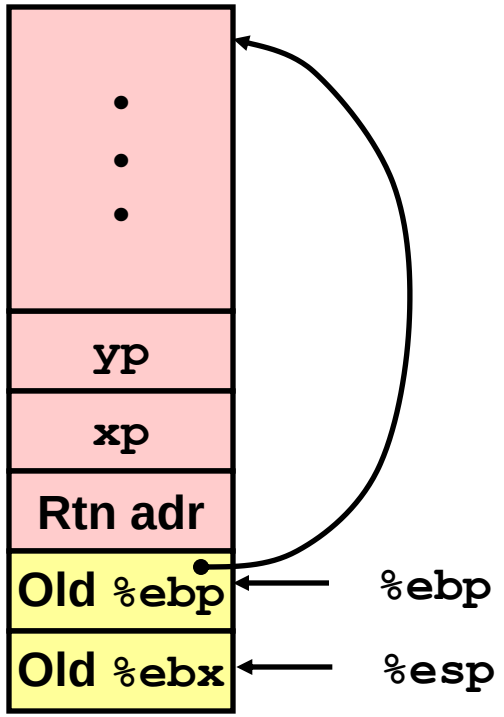

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #3

Entering Stack

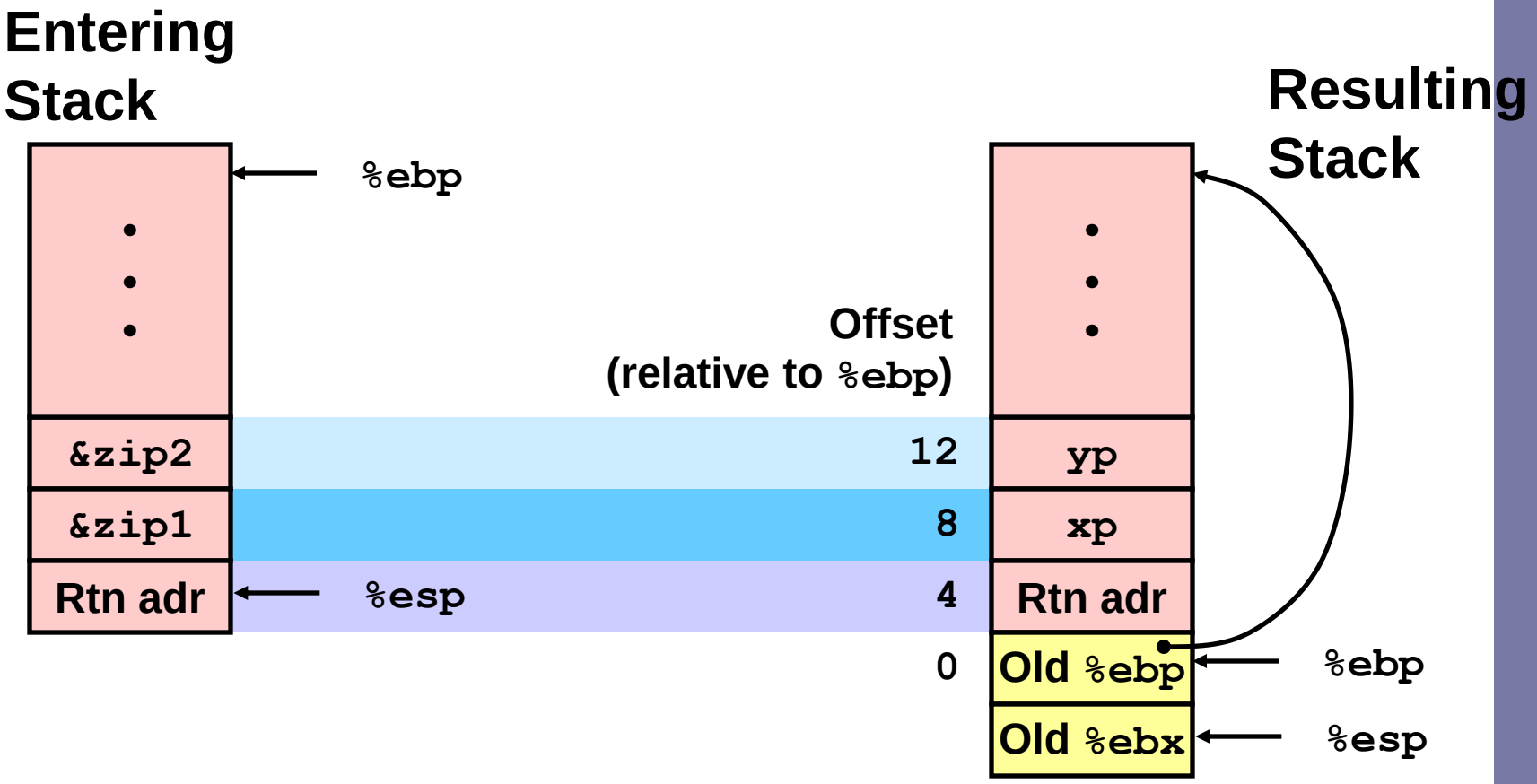


Resulting Stack




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

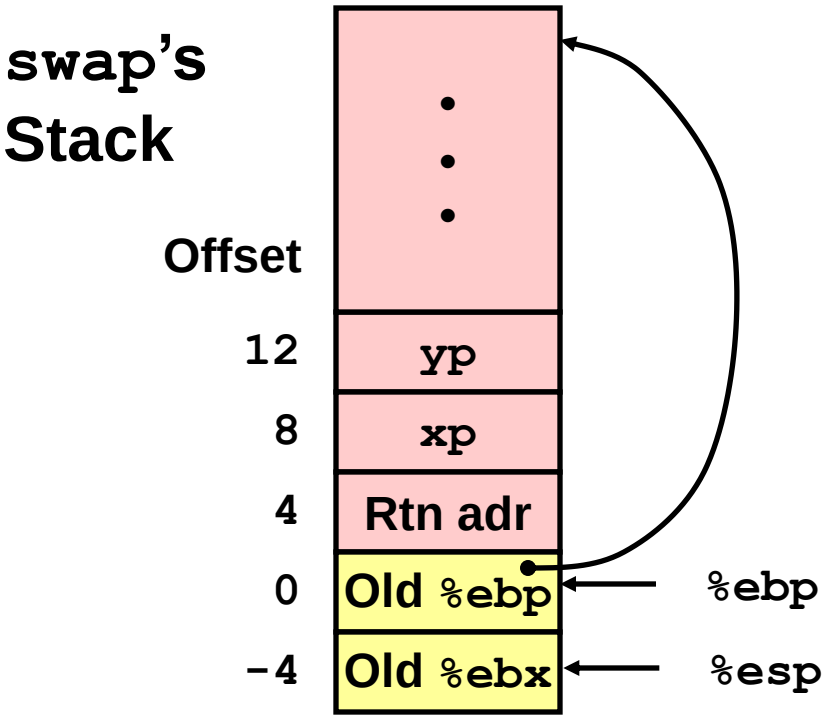
Effect of swap setup

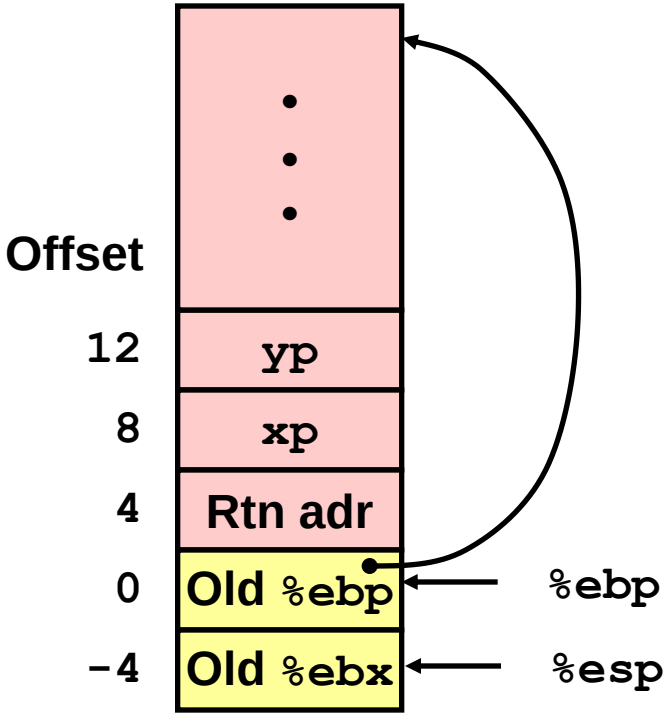



```
movl 12(%ebp),%ecx # get yp
movl 8(%ebp),%edx  # get xp
. . .
```

} Body

swap Finish #1

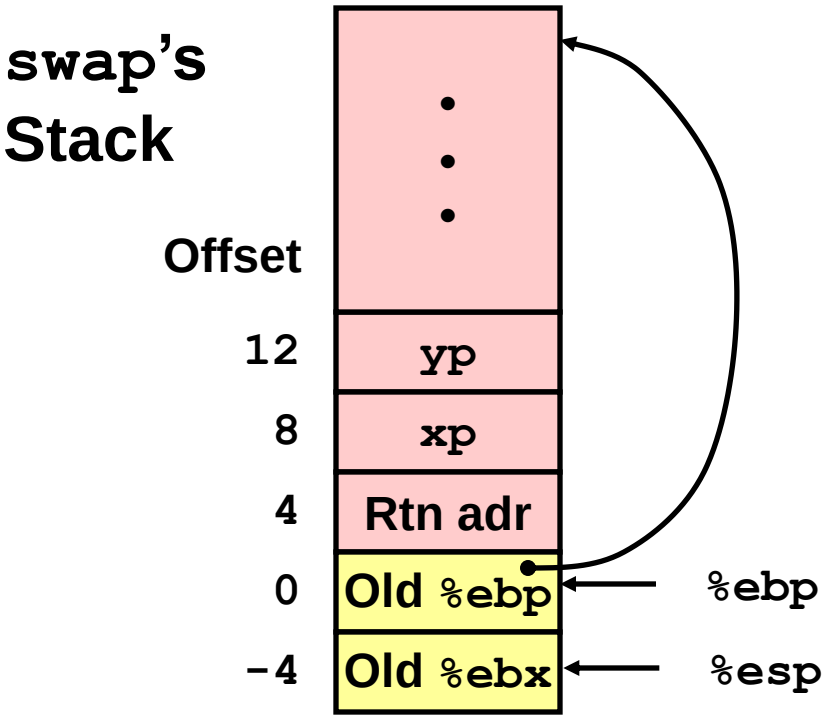


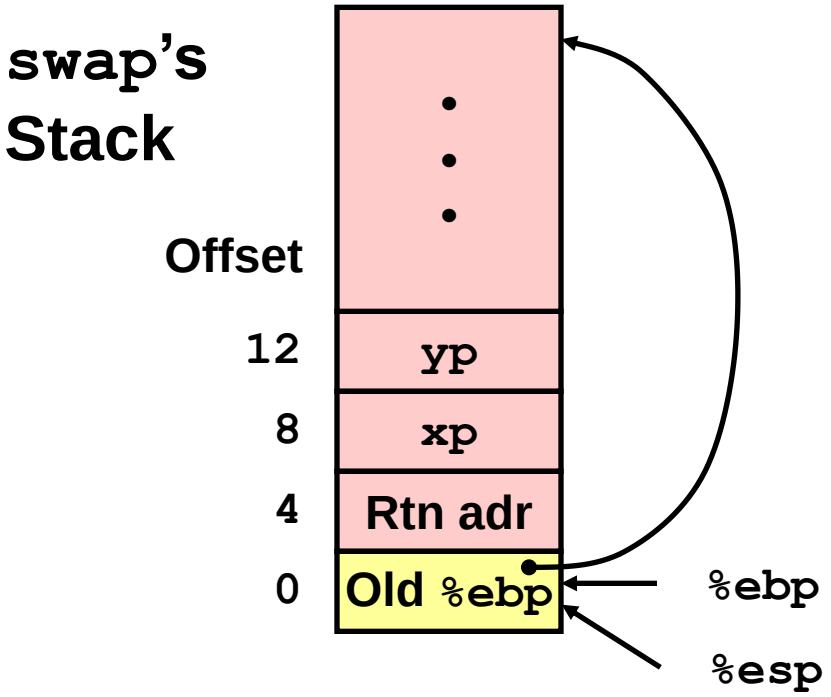



```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

- Observation
  - Saved & restored register `%ebx`

swap Finish #2

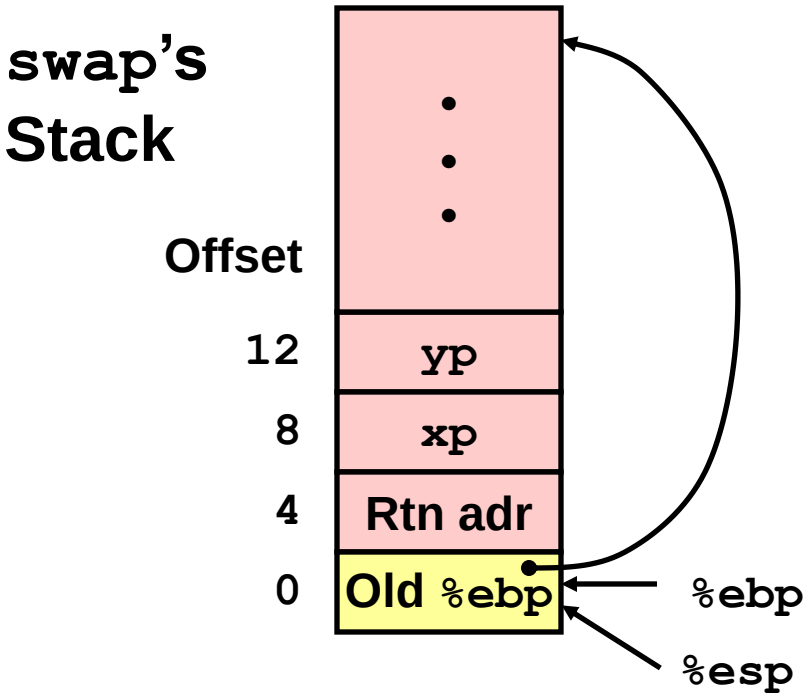


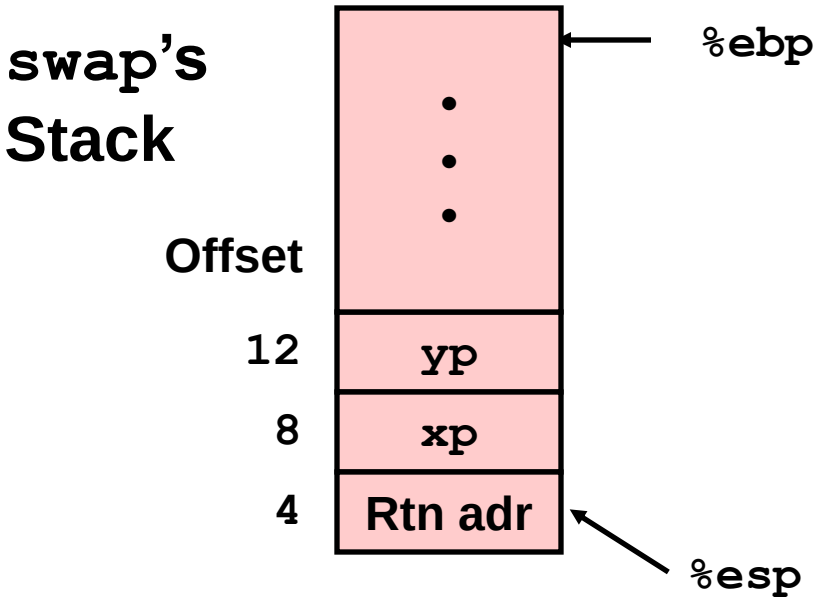


- Save stack pointer to beginning of frame

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

swap Finish #3



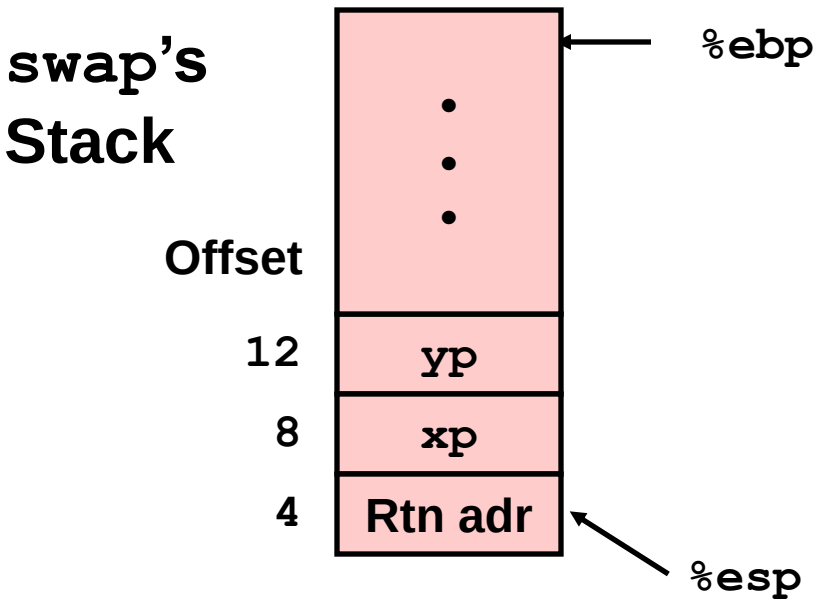


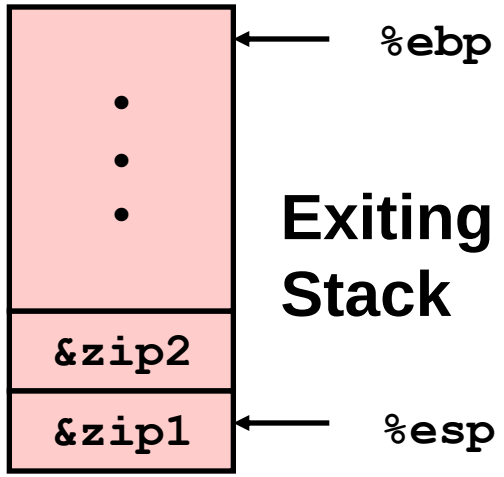
- Restore saved `%ebp` and set stack ptr to end of caller's frame

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

Pop address from stack & jump there

swap Finish #4






```
leave   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 register be used for temporary storage?

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

```
who:
    • • •
    movl 8(%ebp), %edx
    addl $91125, %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 register be used for temporary storage?
- Conventions
  - "Caller Save"
    - Caller saves temporary in its frame before calling
  - "Callee Save"
    - Callee saves temporary in its frame before using

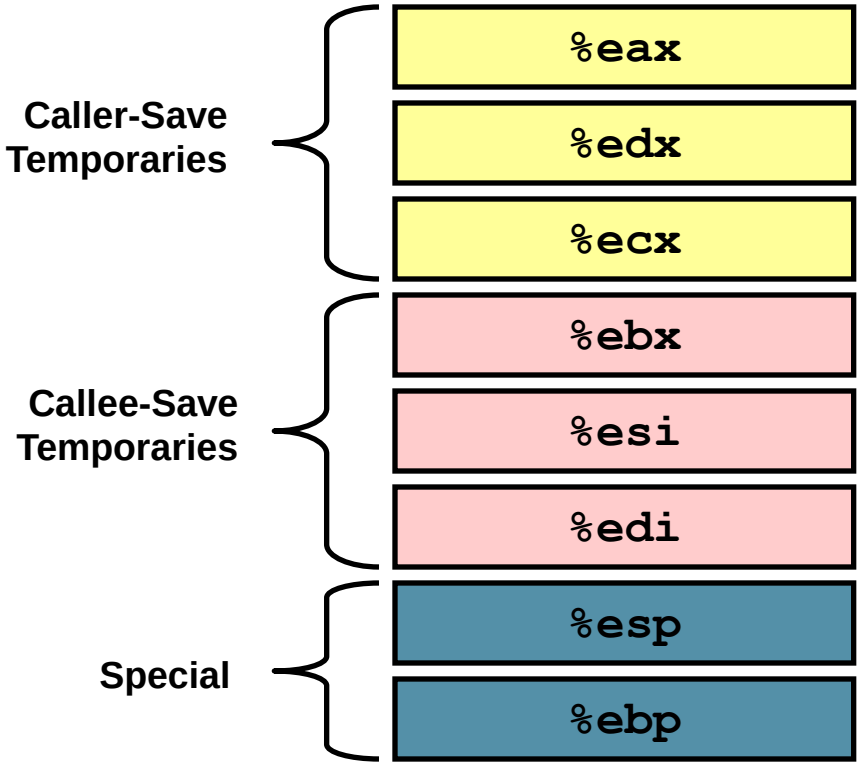
IA32/Linux register usage

- Integer registers
  - Two have special uses

    `%ebp`, `%esp`
  - Three managed as callee-save

    `%ebx`, `%esi`, `%edi`
    - Old values saved on stack prior to using
  - Three managed as caller-save

    `%eax`, `%edx`, `%ecx`
    - Do what you please, but expect any callee to do so, as well
  - Register `%eax` also stores returned value



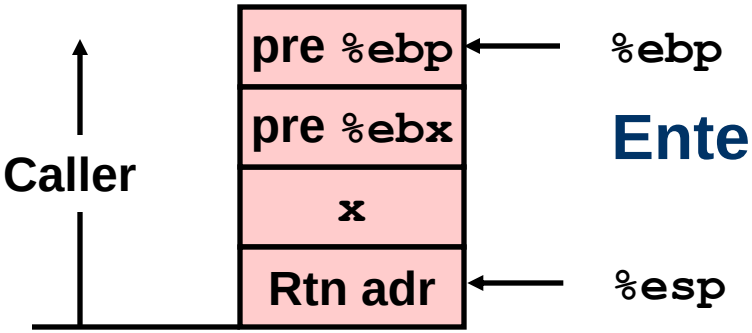
Recursive factorial

```
int rfact(int x)
{
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

- Registers
  - `%eax` used without first saving
  - `%ebx` used, but save at beginning & restore at end

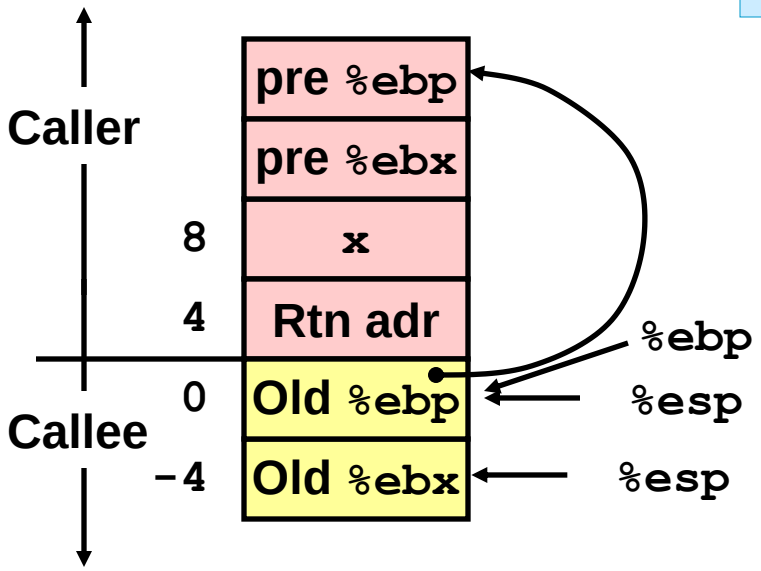
```
.globl rfact
     .type  rfact,@function
rfact:
     pushl %ebp
     movl %esp,%ebp
     pushl %ebx
     movl 8(%ebp),%ebx
     cmpl $1,%ebx
     jle .L78
     leal -1(%ebx),%eax
     pushl %eax
     call rfact
     imull %ebx,%eax
     jmp .L79
     .align 4
.L78:
     movl $1,%eax
.L79:
     movl -4(%ebp),%ebx
     movl %ebp,%esp
     popl %ebp
     ret
```

Rfact stack setup



Entering Stack

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



Rfact body

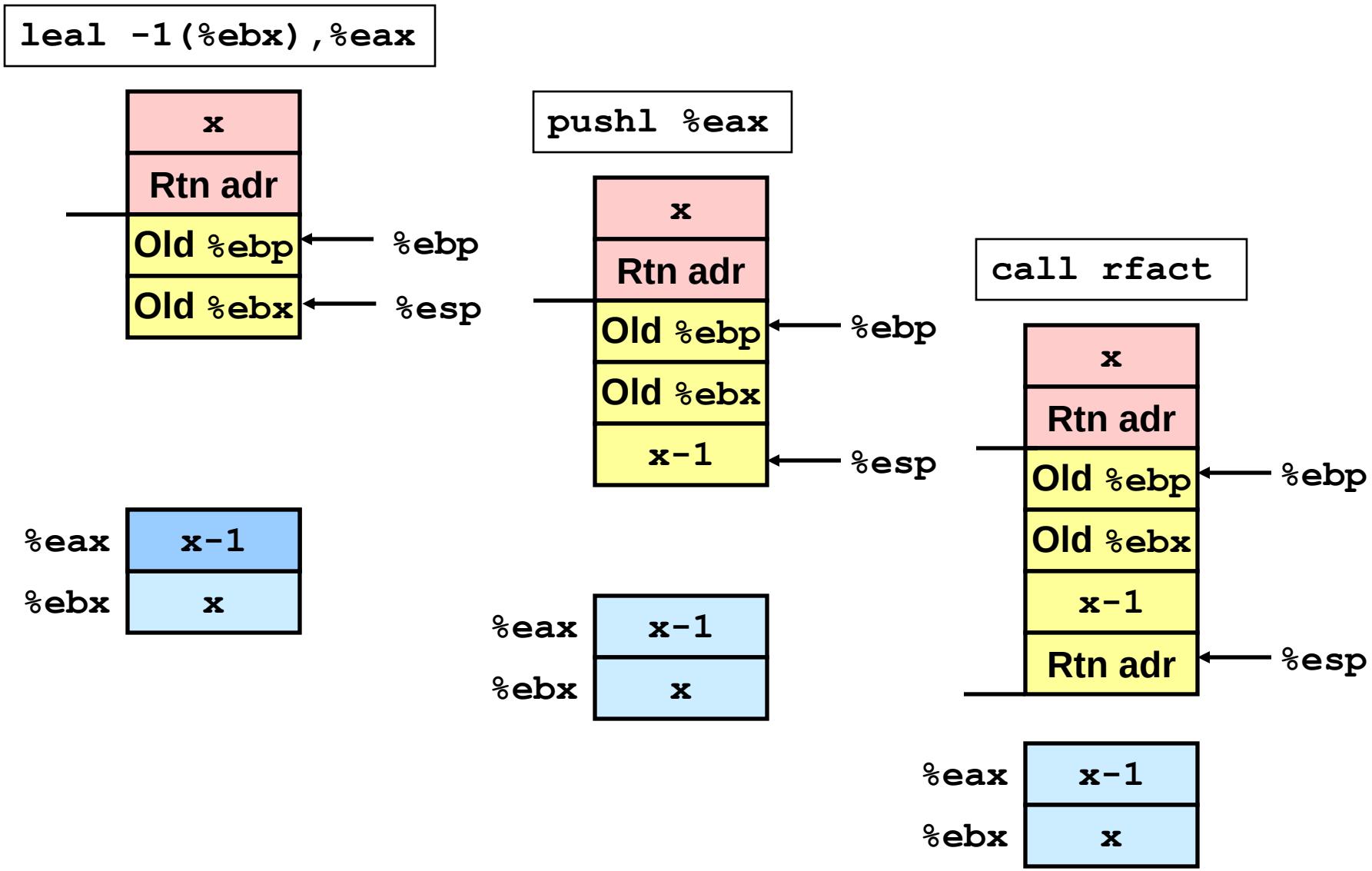
Recursion

```
  movl 8(%ebp),%ebx     # ebx = x
  cmpl $1,%ebx          # Compare x : 1
  jle .L78              # If <= goto Term
  leal -1(%ebx),%eax    # eax = x-1
  pushl %eax            # Push x-1
  call rfact            # rfact(x-1)
  imull %ebx,%eax       # rval * x
  jmp .L79              # Goto done
.L78:                   # Term:
  movl $1,%eax          # return val = 1
.L79:                   # Done:
```

```
int rfact(int x)
{
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1) ;
  return rval * x;
}
```

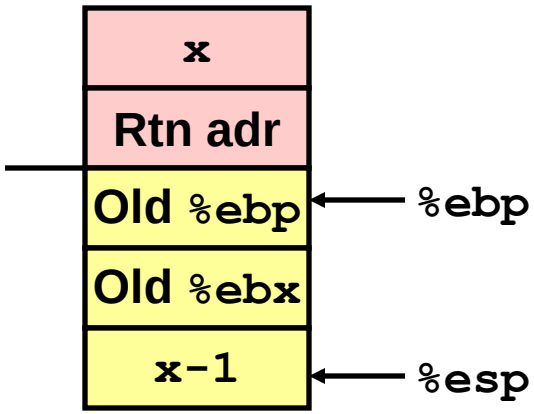
- Registers
  - `%ebx` Stored value of x
  - `%eax`
    - Temporary value of `x-1`
    - Returned value from `rfact(x-1)`
    - Returned value from this call

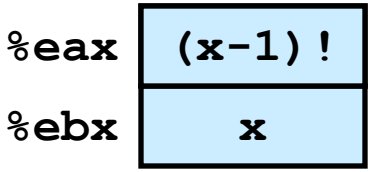
Rfact recursion



Rfact result

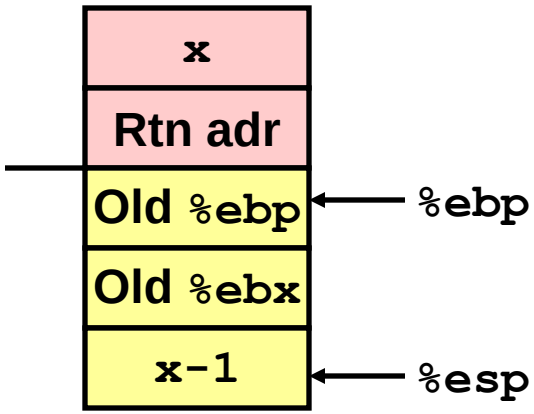
Return from Call

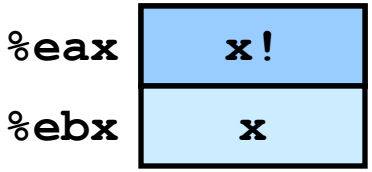




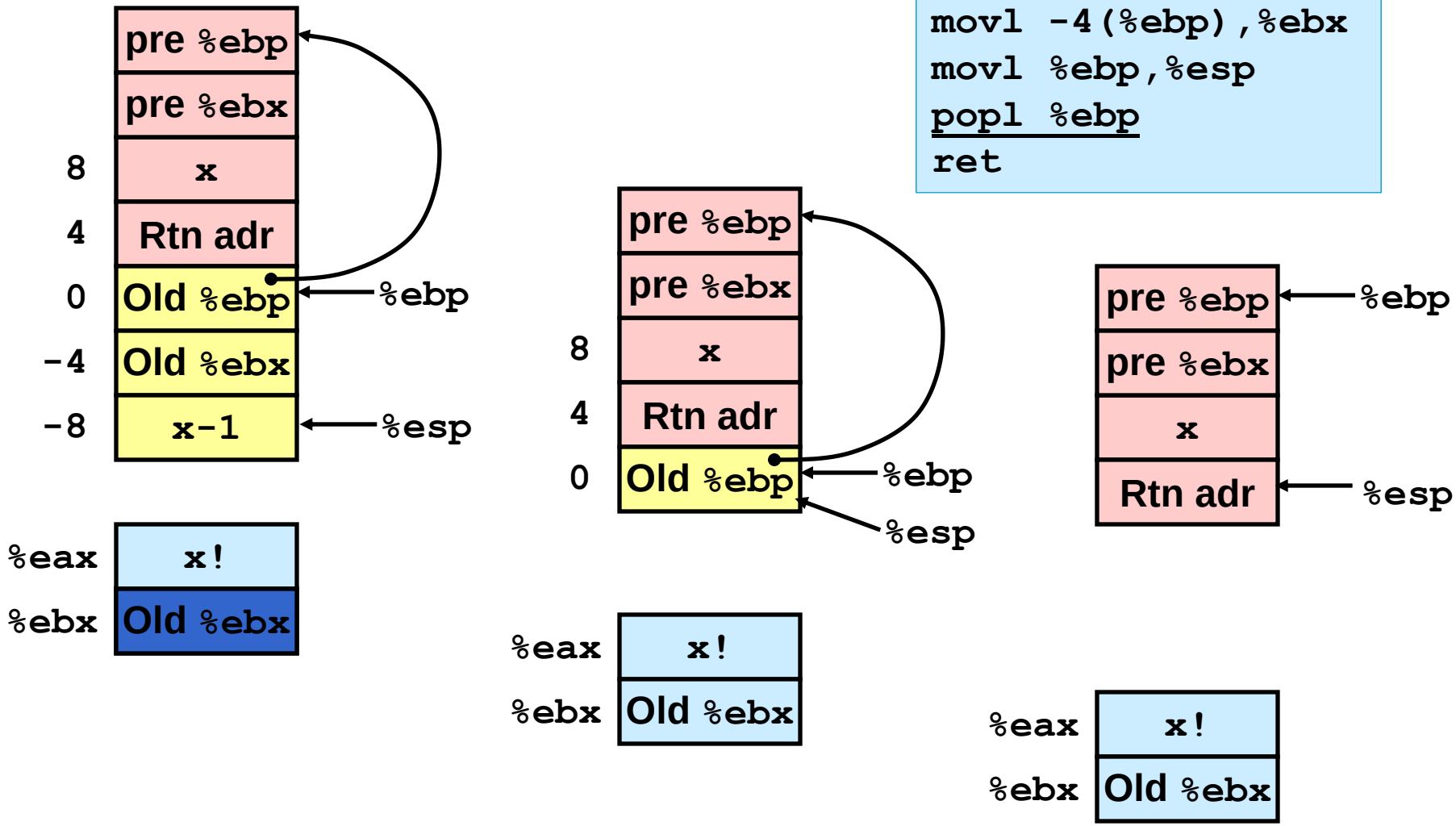
Assume that `rfact(x-1)` returns `(x-1)!` in register `%eax`

```
imull %ebx,%eax
```





Rfact completion



Summary

- The stack makes recursion work
  - Private storage for each instance of procedure call
    - Instantiations don't clobber each other
    - Addressing of locals + arguments can be relative to stack positions
  - Can be managed by stack discipline
    - Procedures return in inverse order of calls
- IA32 Procedures combination of instructions + conventions
  - Call / Ret instructions
  - Register usage conventions
    - Caller / Callee save
    - %ebp and %esp
  - Stack frame organization conventions