15-213

"The course that gives CMU its Zip!"

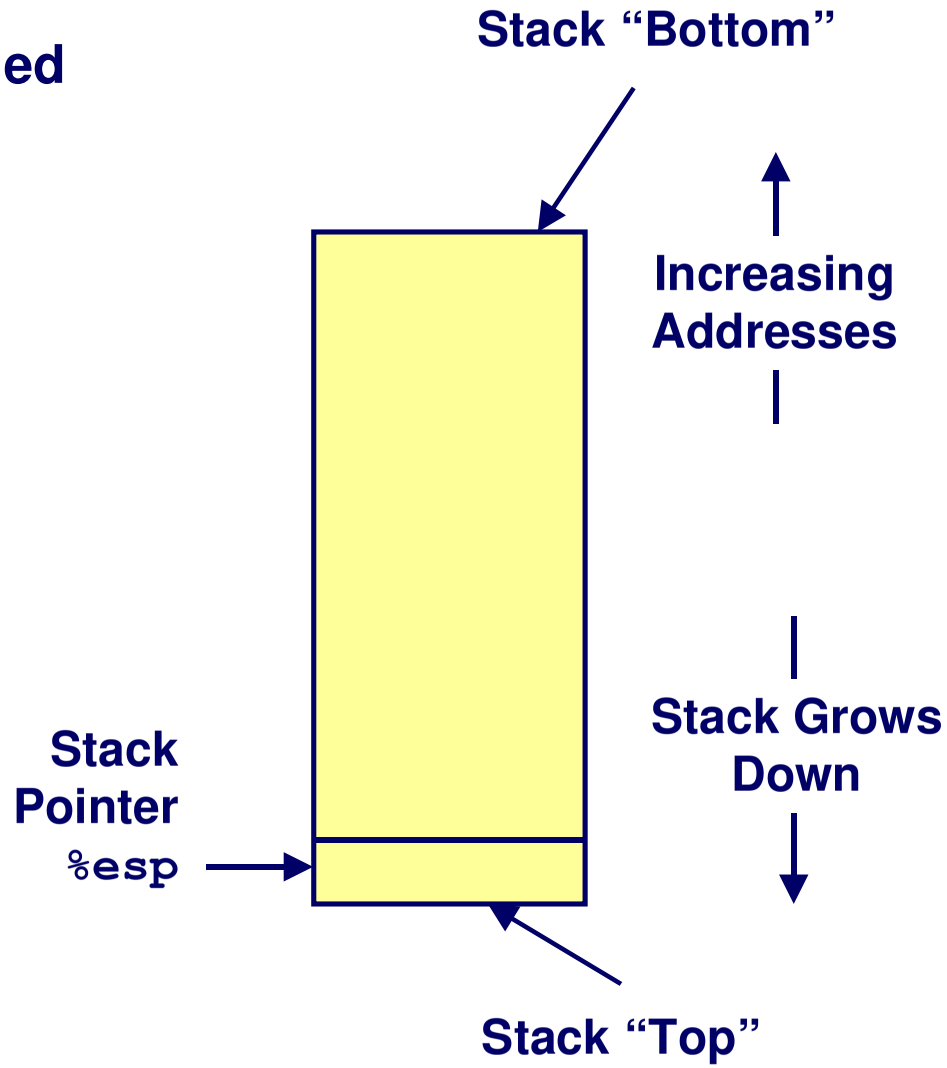
Machine-Level Programming III: Procedures Sept. 17, 2002

Topics

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

IA32 Stack

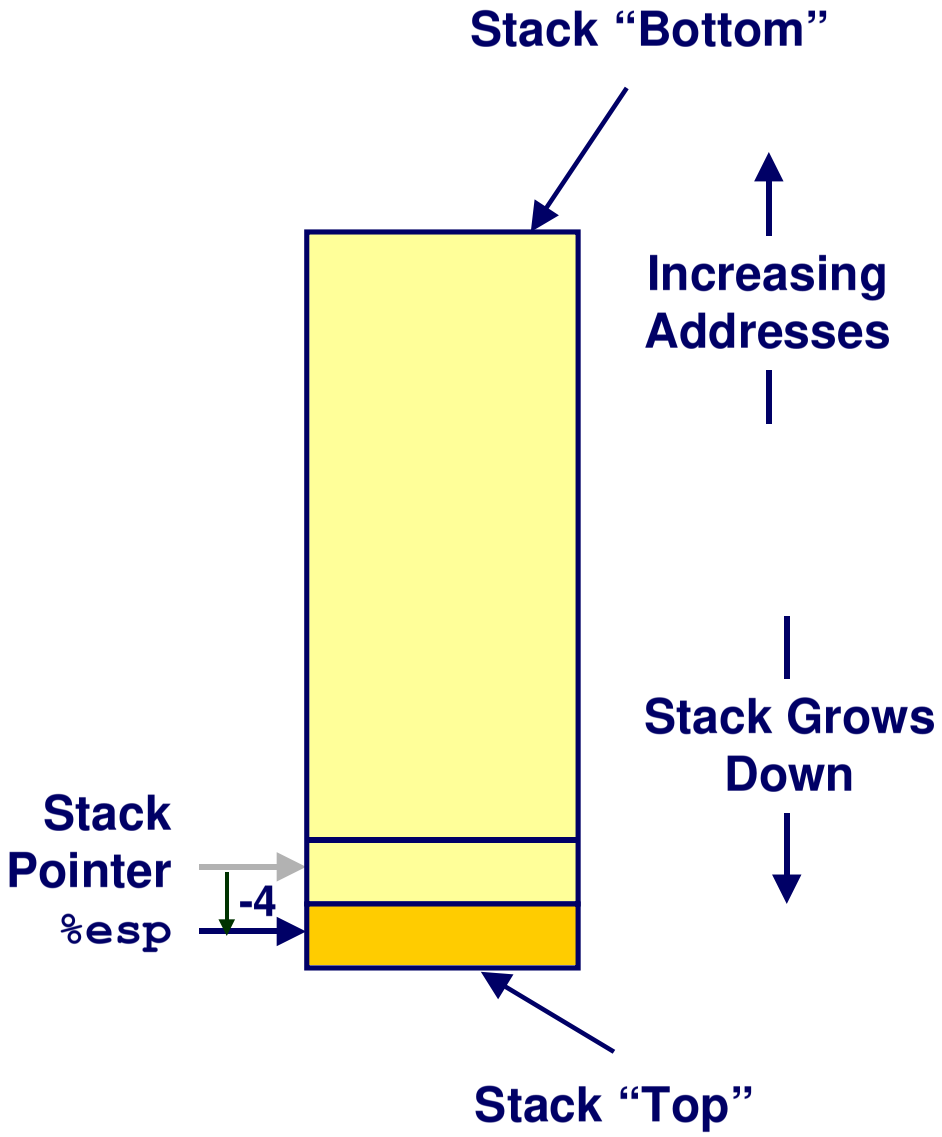
- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register `%esp` indicates lowest stack address
  - address of top element



IA32 Stack Pushing

Pushing

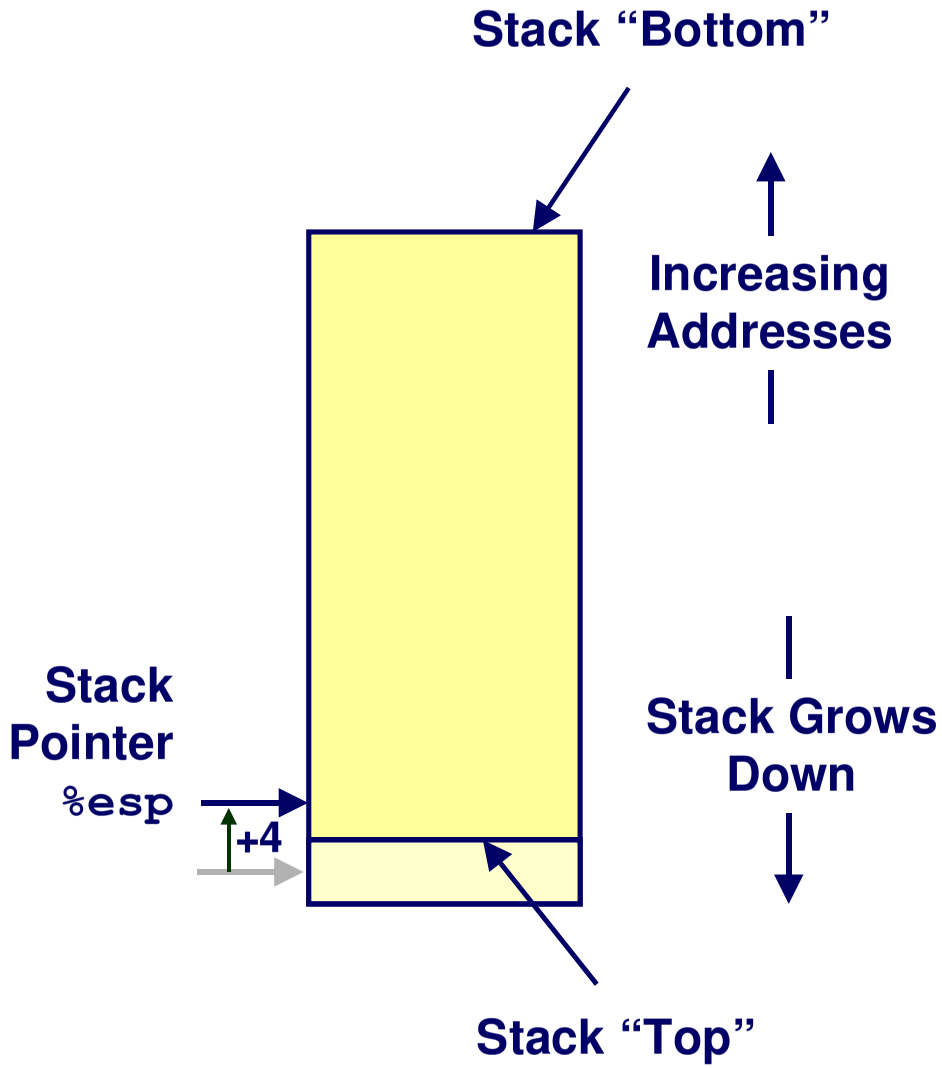
- `pushl` *Src*
- Fetch operand at *Src*
- Decrement `%esp` by 4
- Write operand at address given by `%esp`



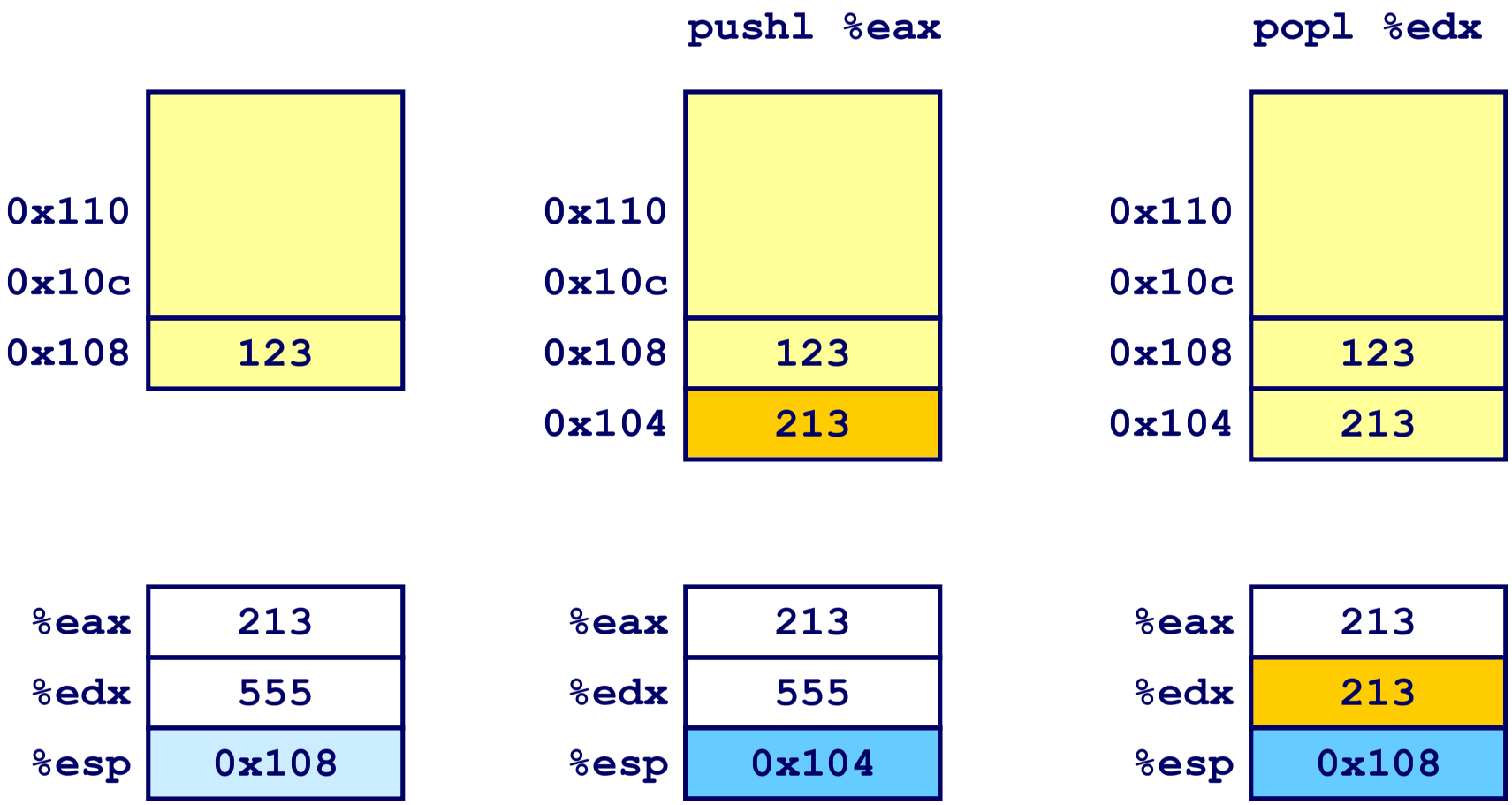
IA32 Stack Popping

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`*

Return address value

- Address of instruction beyond `call`
- Example from disassembly

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

  - Return address = `0x8048553`

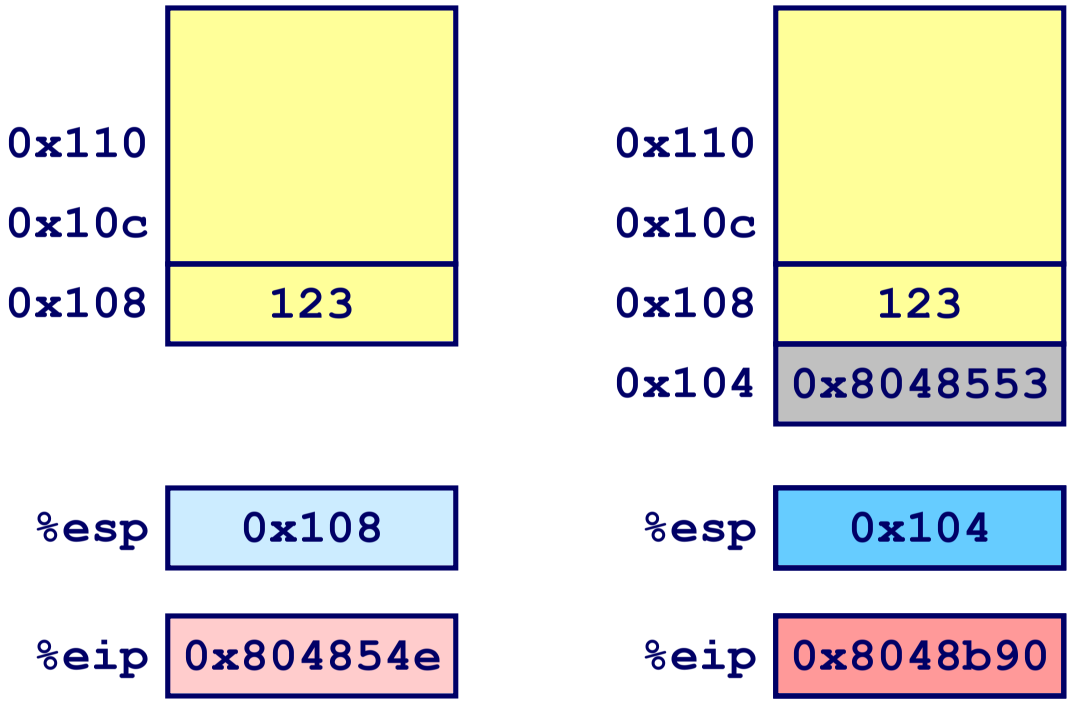
Procedure return:

- `ret` Pop address from stack; Jump to address

Procedure Call Example

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

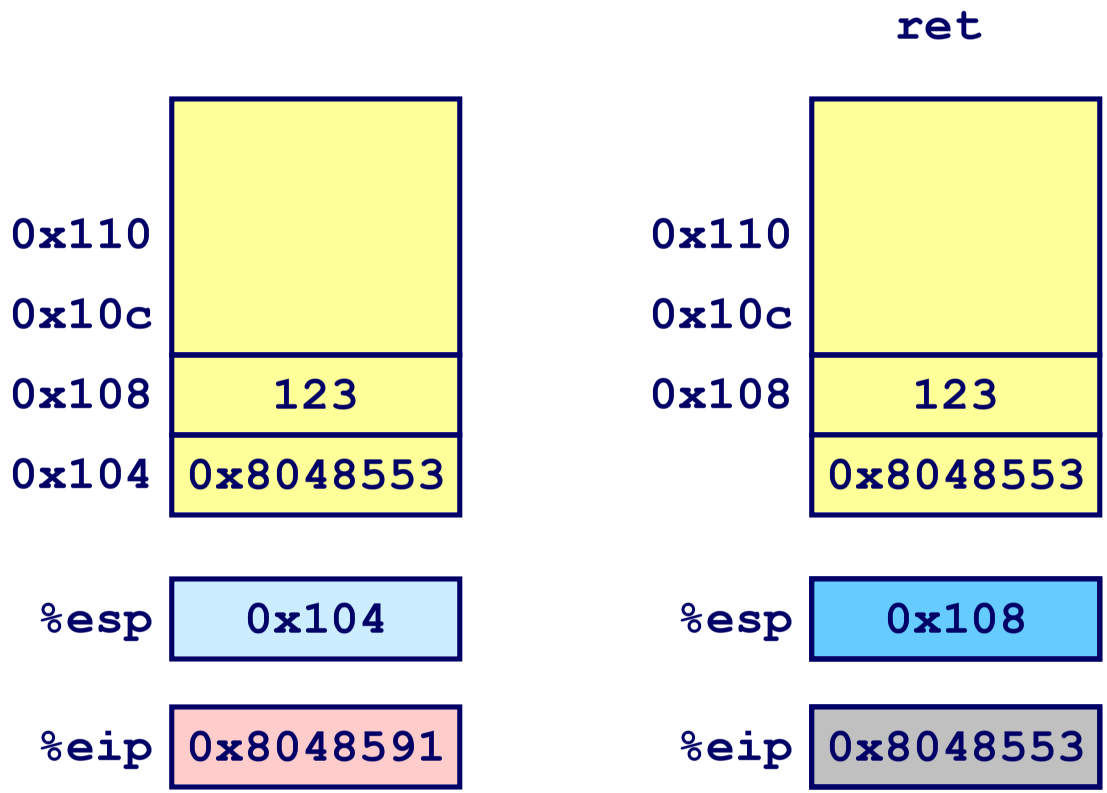
`call 8048b90`



`%eip` is program counter

Procedure Return Example

```
8048591:   c3                    ret
```



`%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

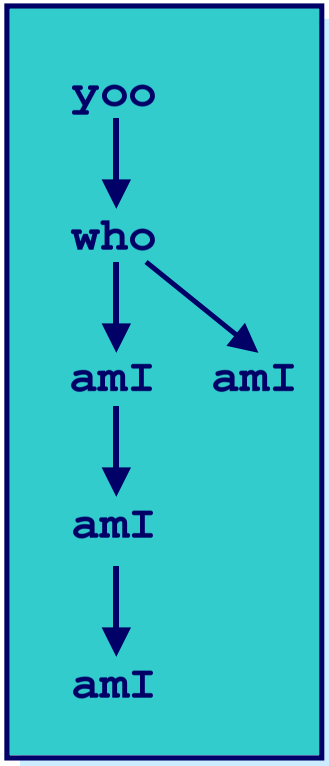
Code Structure

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

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

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

Call Chain



- Procedure `amI` recursive

Stack Frames

Contents

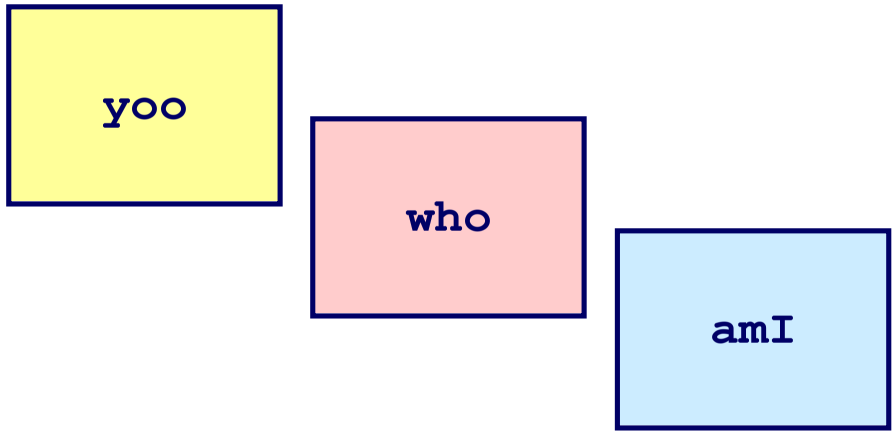
- Local variables
- Return information
- Temporary space

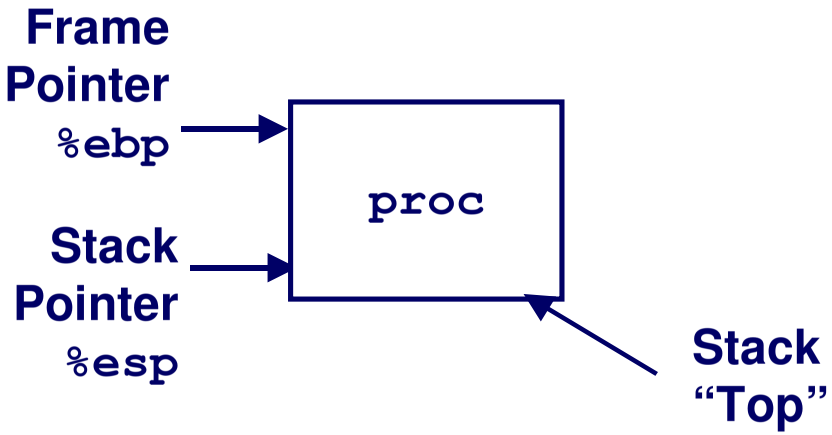
Management

- 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



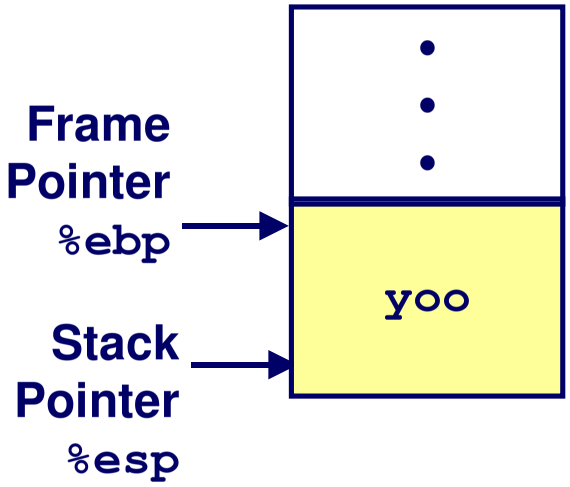


Stack Operation

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

Call Chain

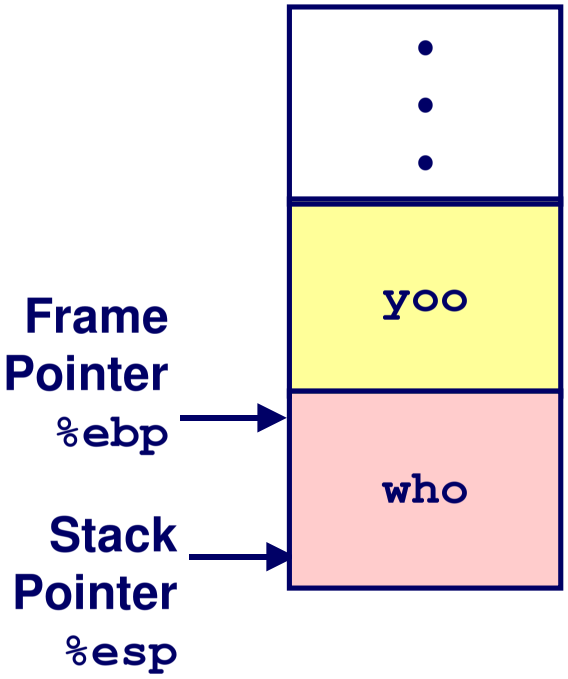
yoo



Stack Operation

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

Call Chain

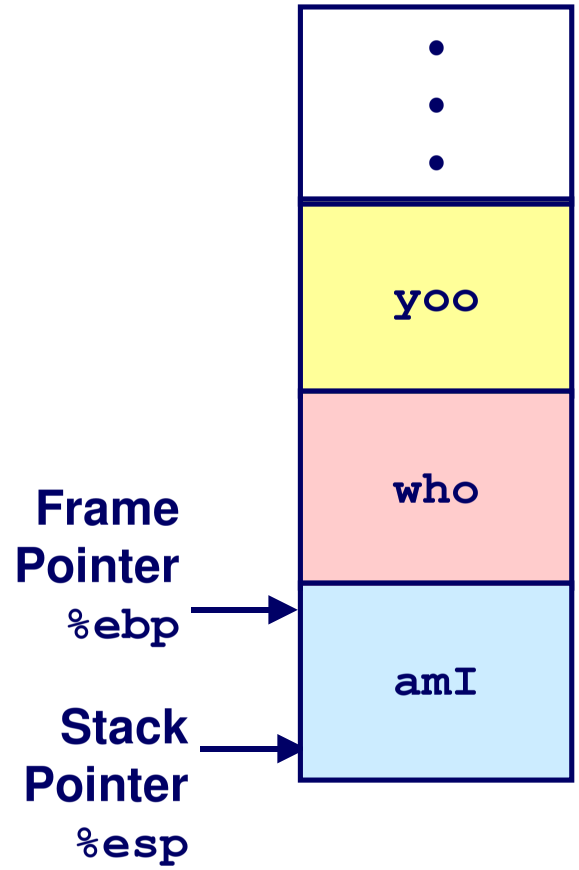


Stack Operation

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

Call Chain

yoo
↓
who
↓
amI



Stack Operation

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

Call Chain

yoo
↓
who
↓
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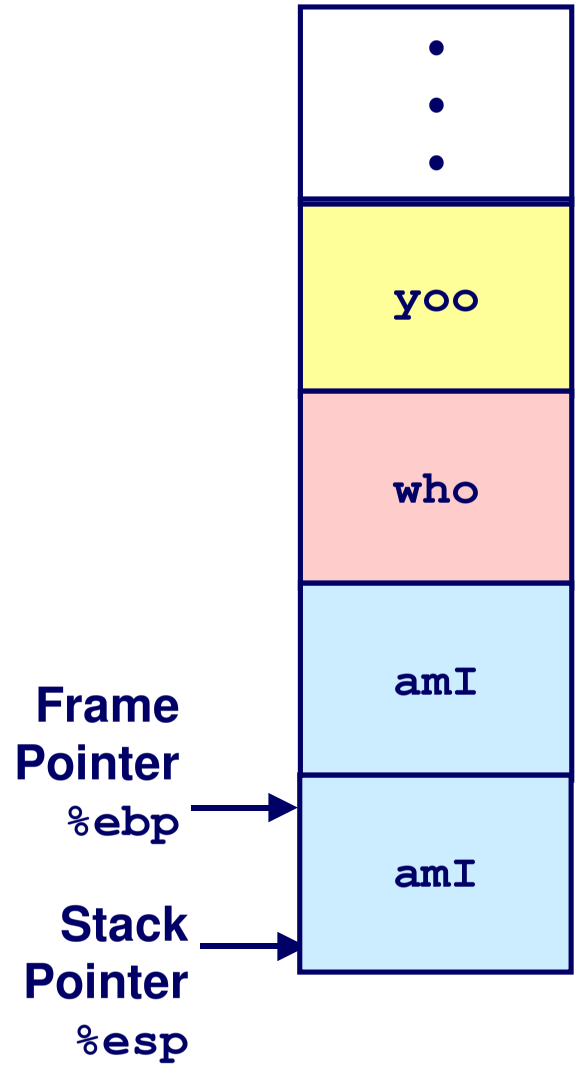
↓
amI



Stack Operation

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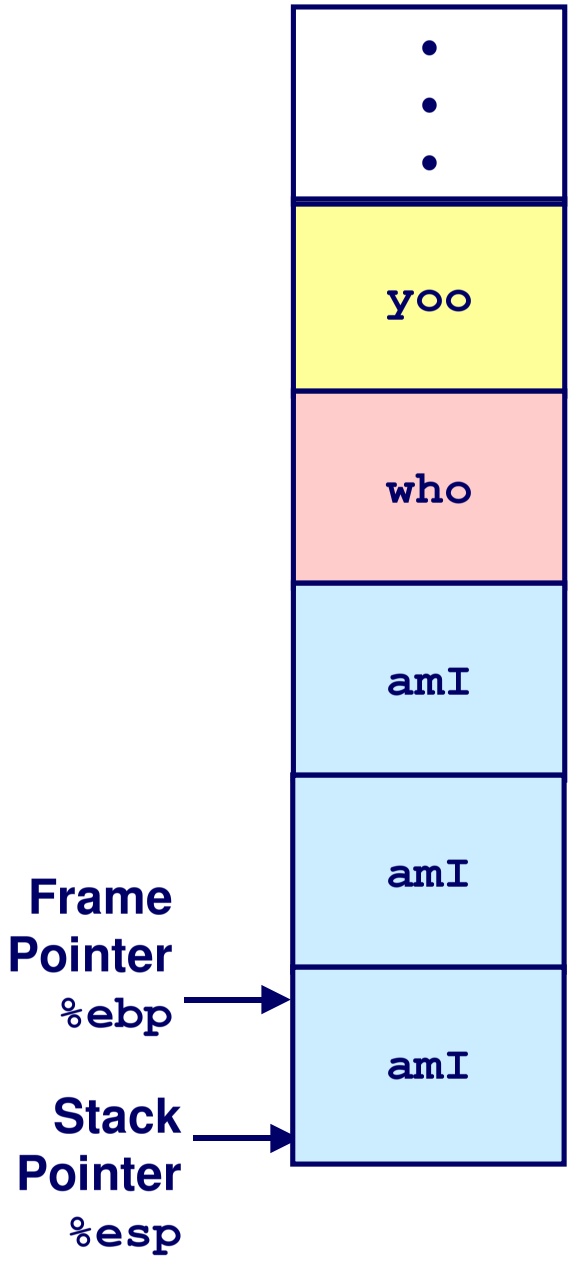
{
    •
    •
    amI();
    •
    •
}
```

Call Chain



Stack Operation

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    •
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```
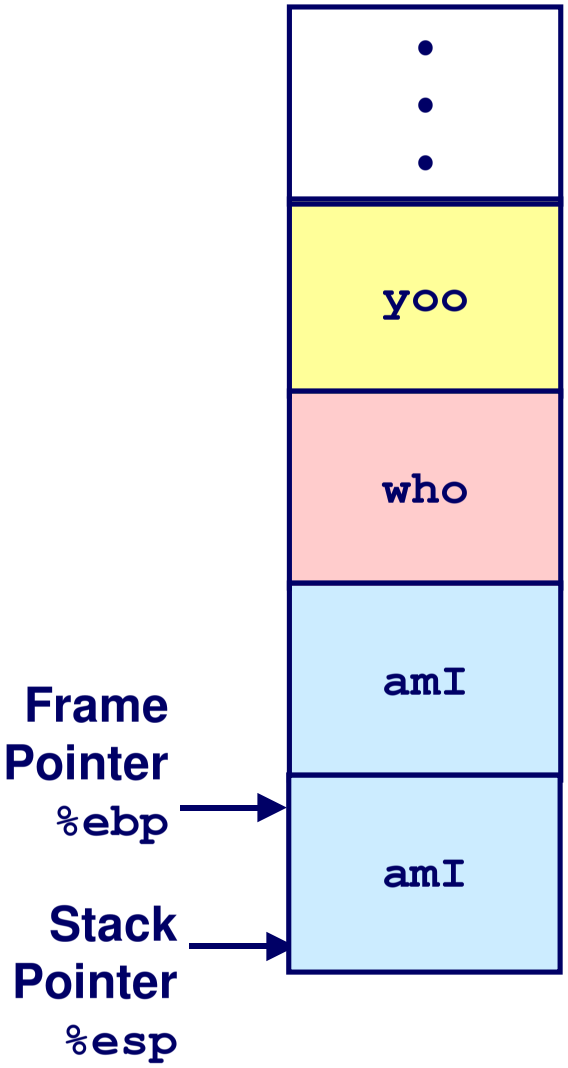

Call Chain



Stack Operation

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{
    •
    •
    amI();
    •
    •
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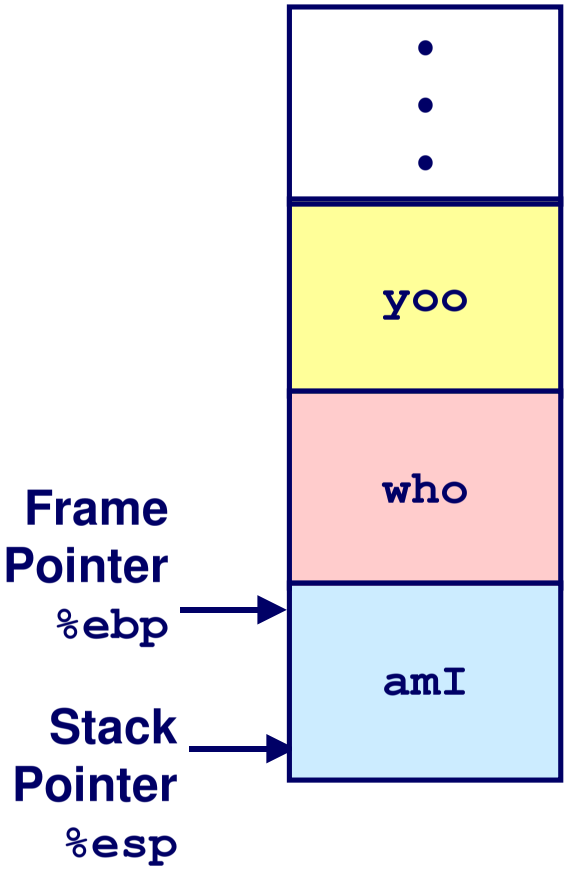
```

Call Chain



Stack Operation

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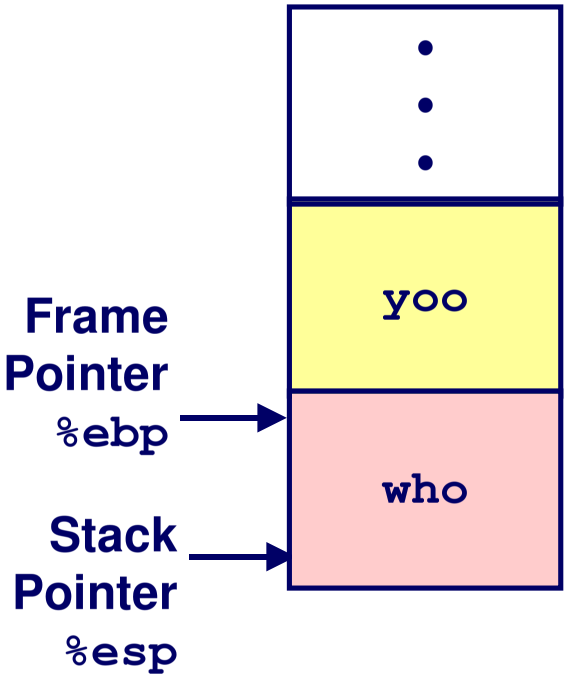
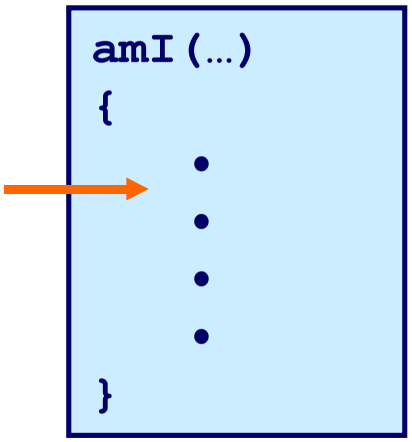
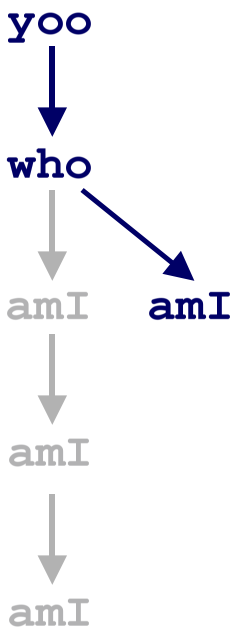

Call Chain

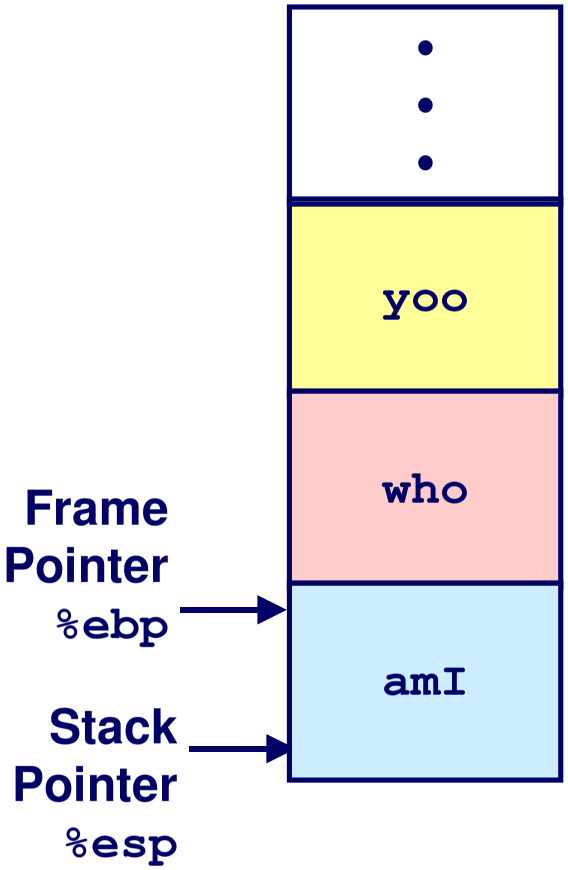


Stack Operation



Call Chain

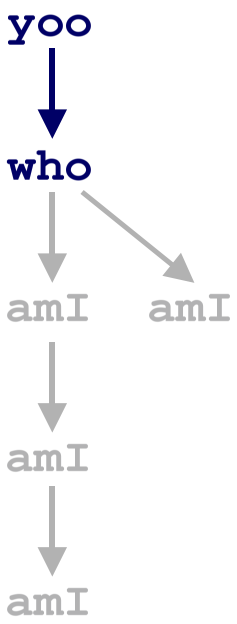


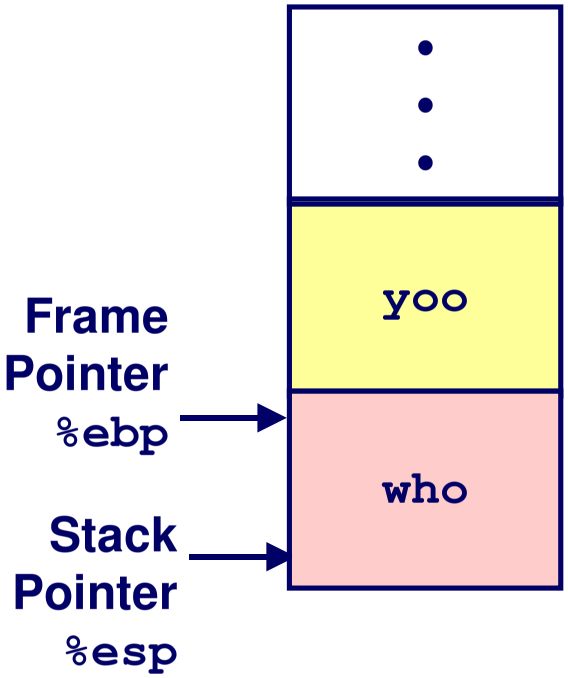


Stack Operation

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

Call Chain

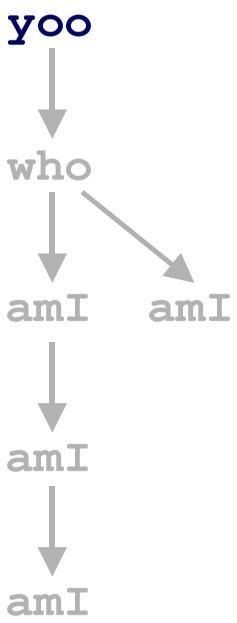


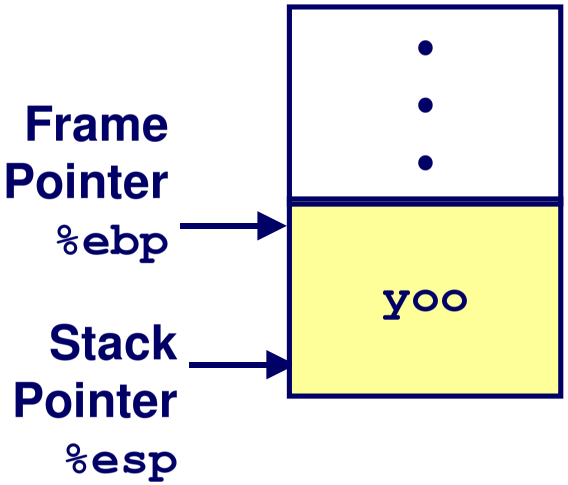


Stack Operation

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

Call Chain





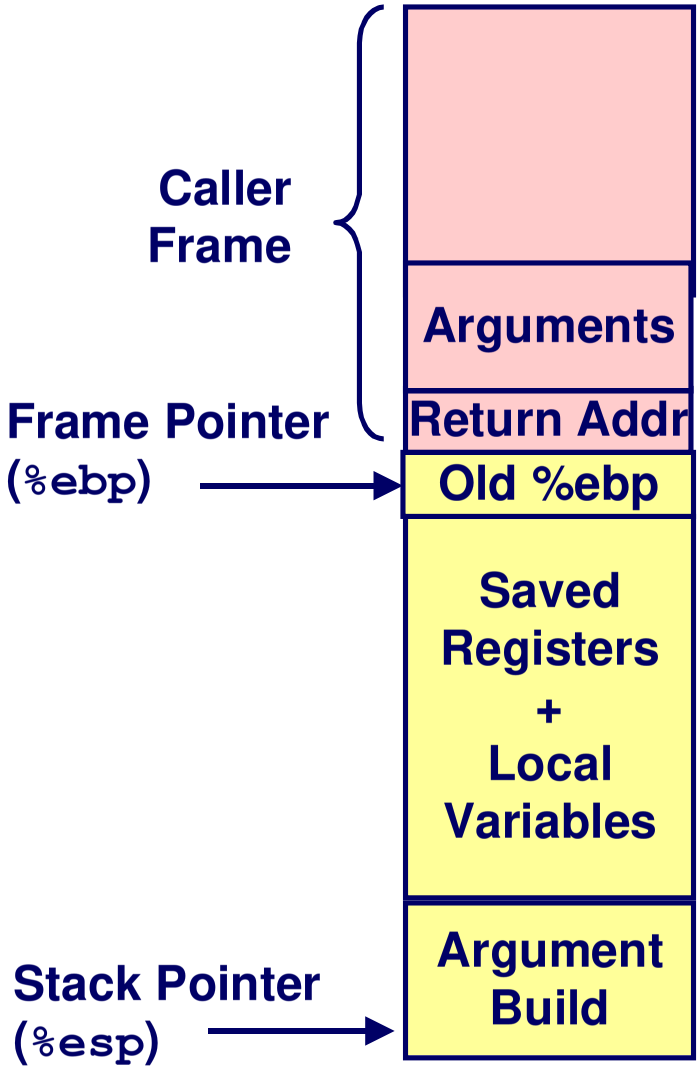
IA32/Linux Stack Frame

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



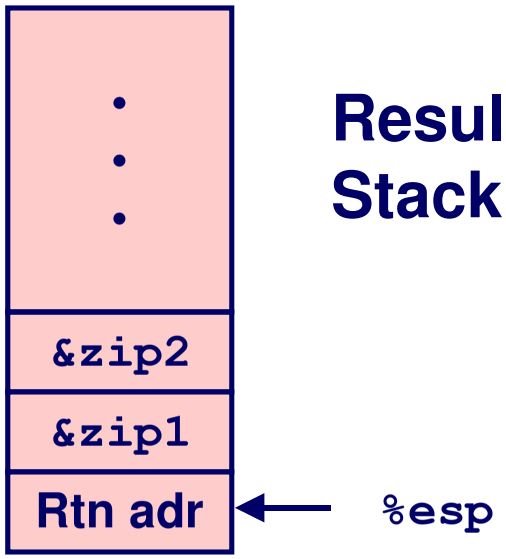
Revisiting swap

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

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

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

Calling `swap` from `call_swap`

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



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
```

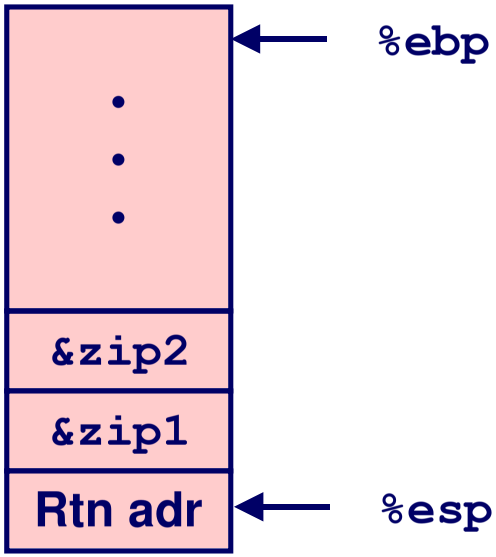
Set Up

Body

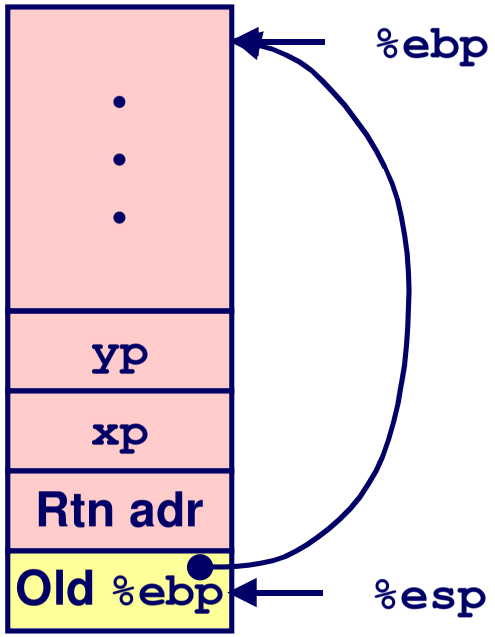
Finish

swap Setup #1

Entering Stack



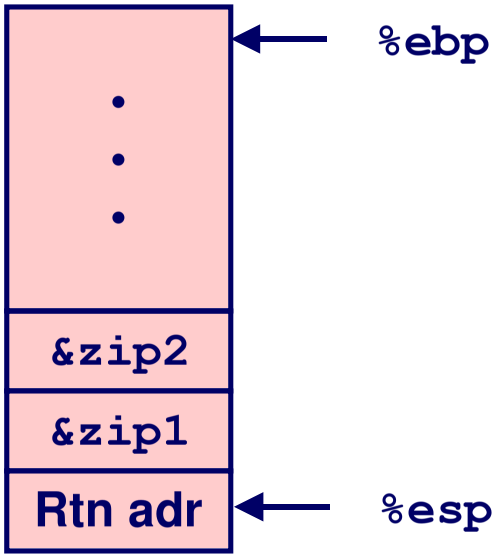
Resulting Stack



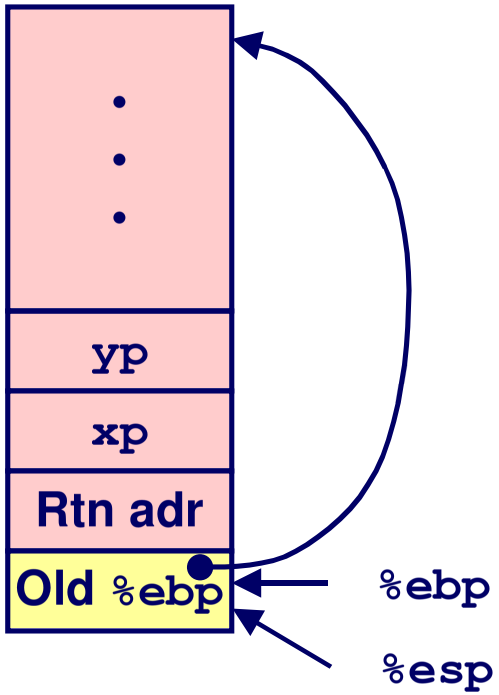

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #2

Entering Stack



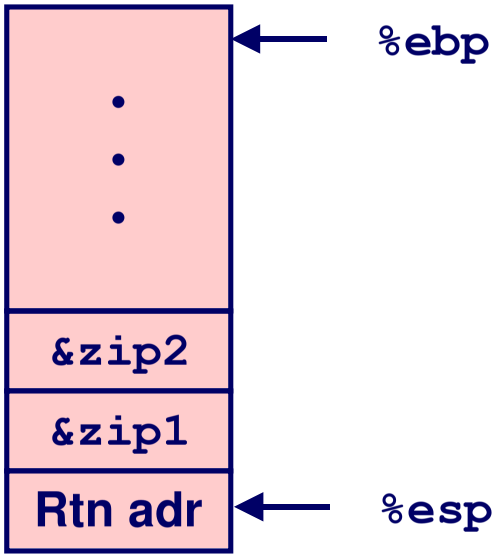
Resulting Stack



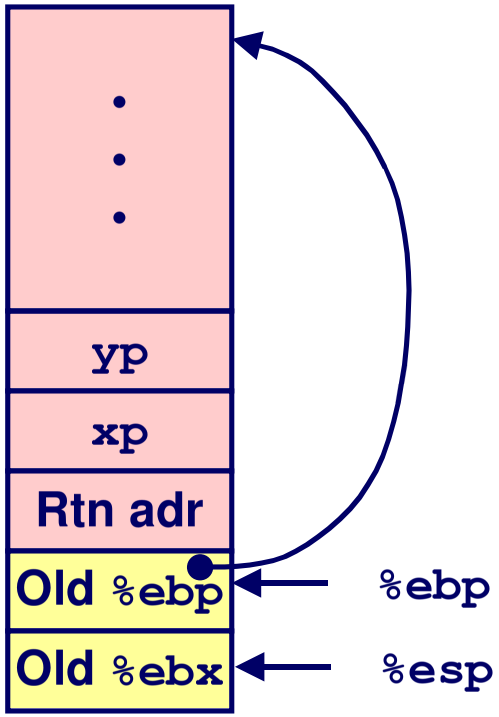

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #3

Entering Stack

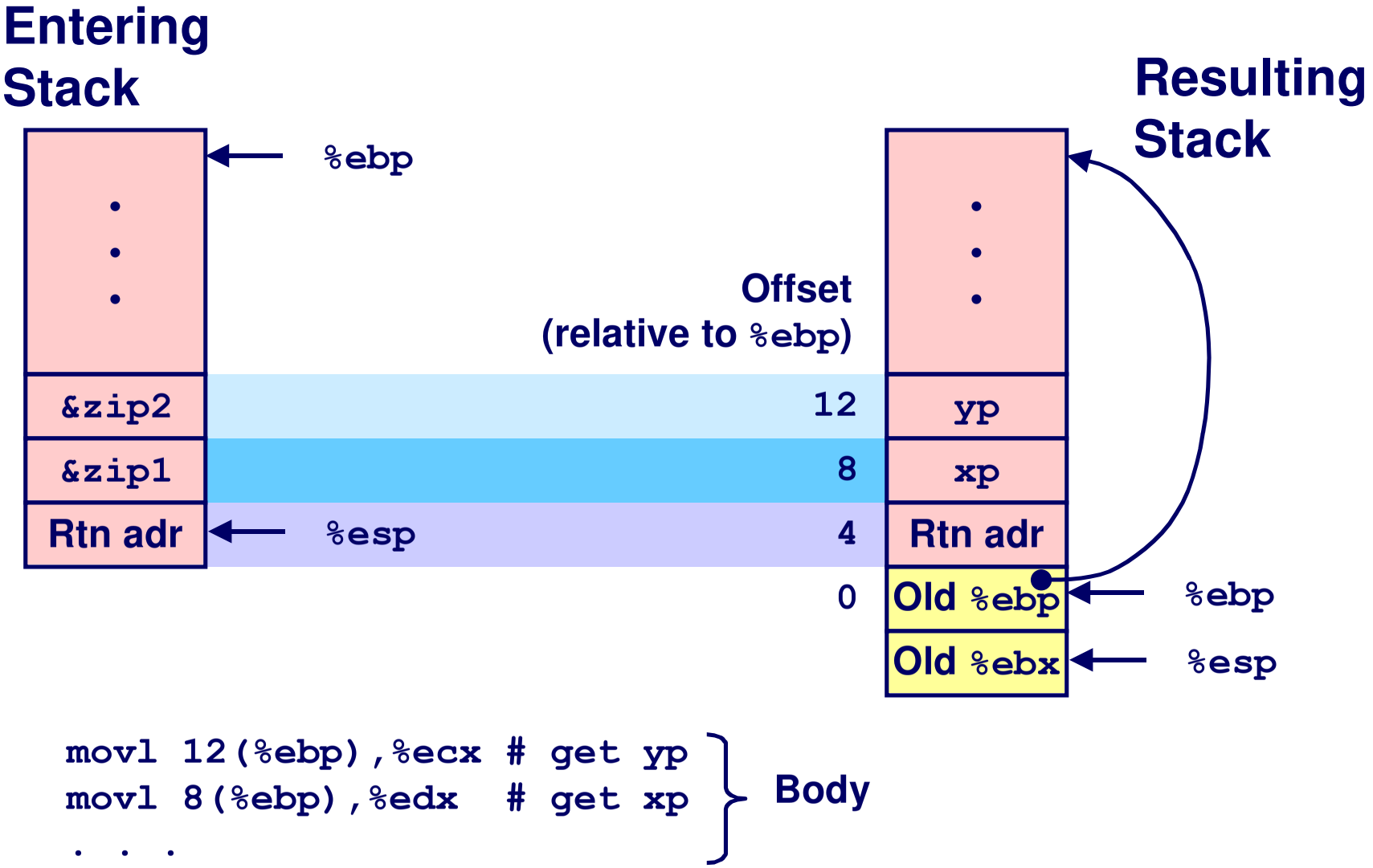


Resulting Stack




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

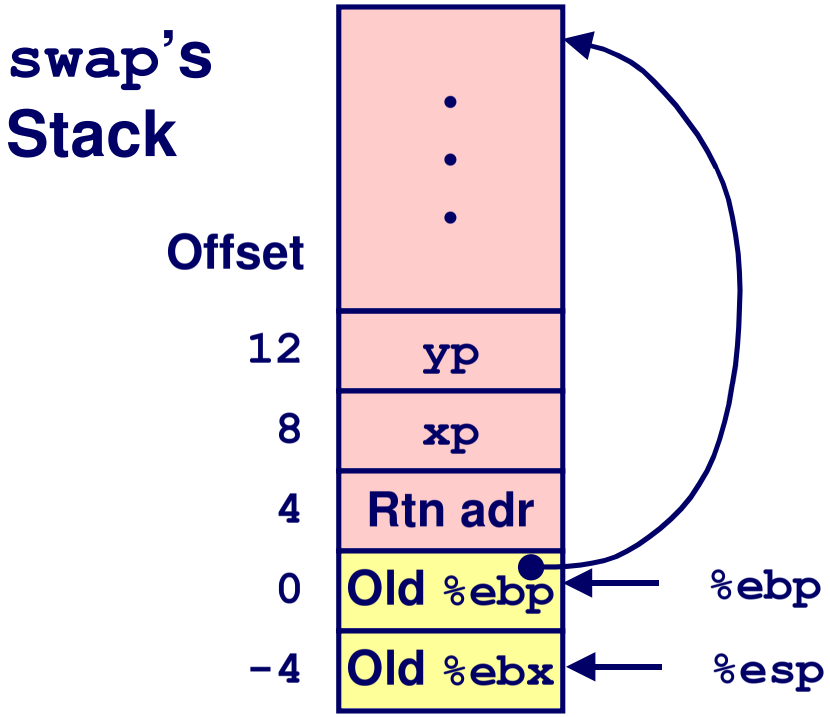
Effect of swap Setup

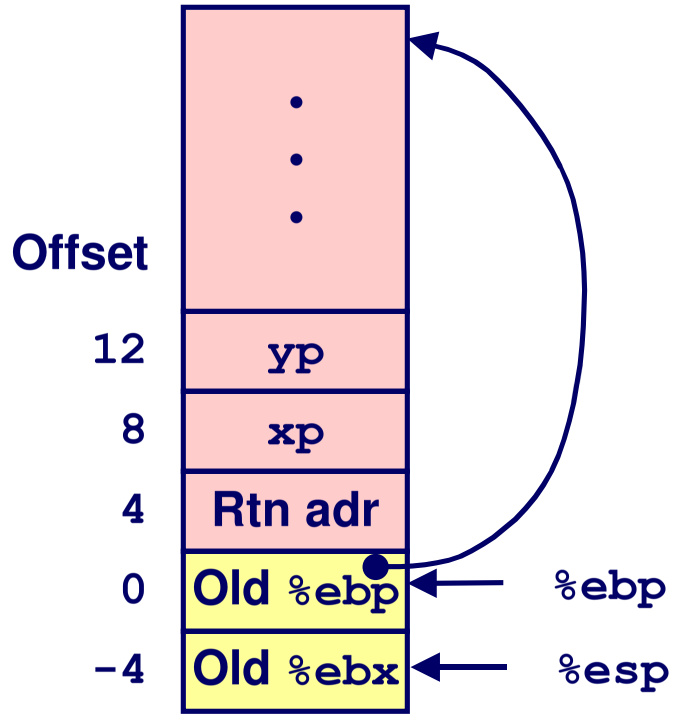



```
movl 12(%ebp),%ecx # get yp
movl 8(%ebp),%edx  # get xp
. . .
```

} Body

swap Finish #1



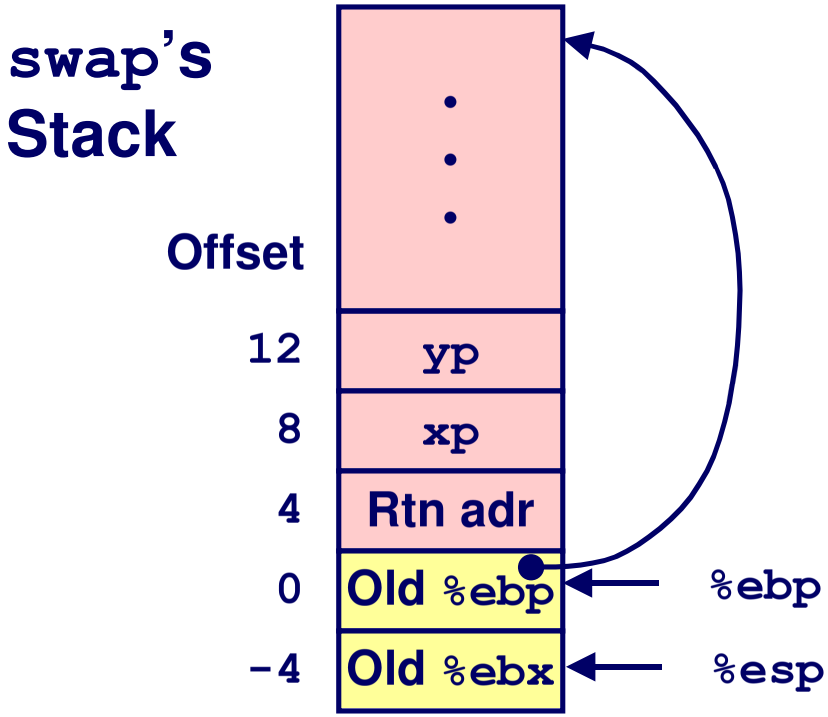


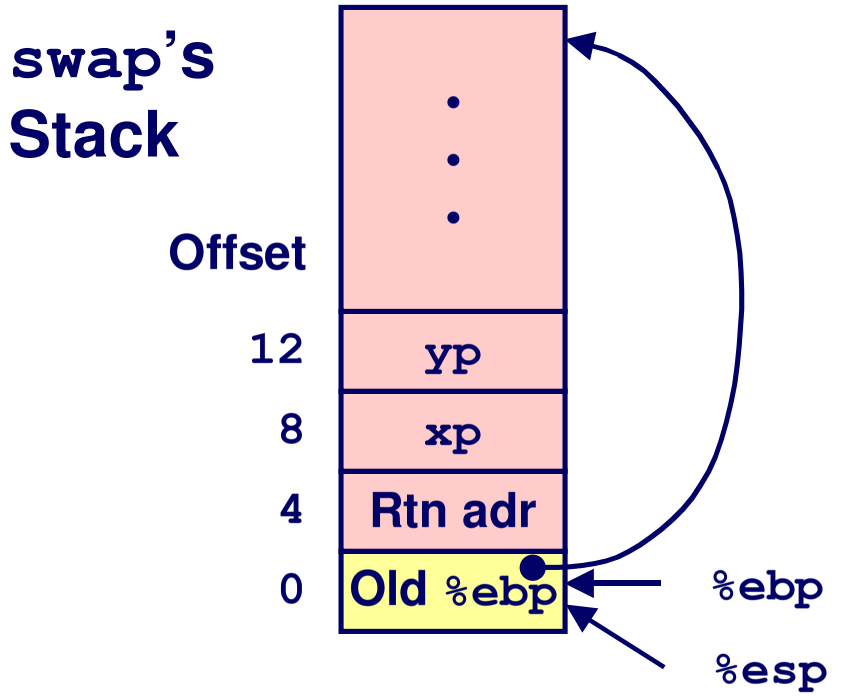

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Observation

- Saved & restored register `%ebx`

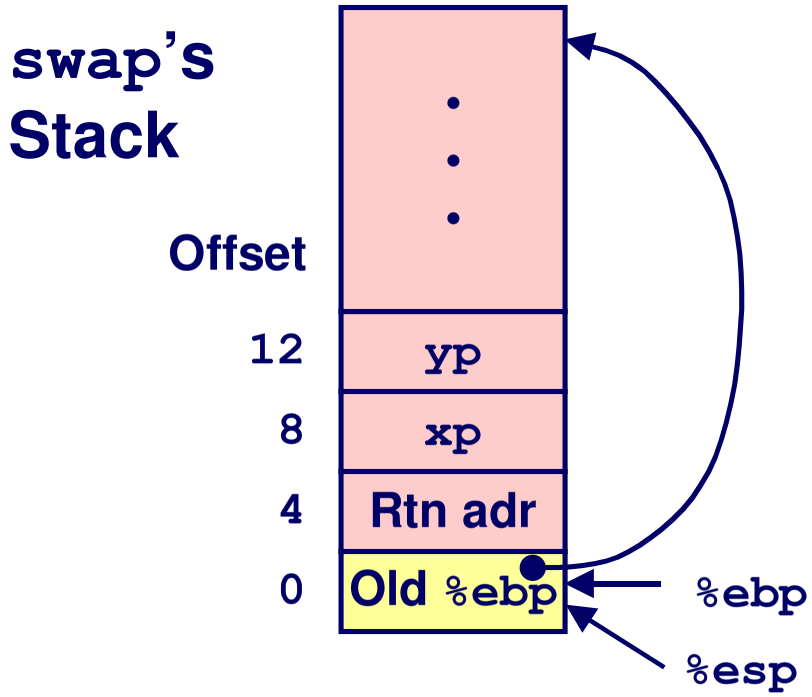
swap Finish #2

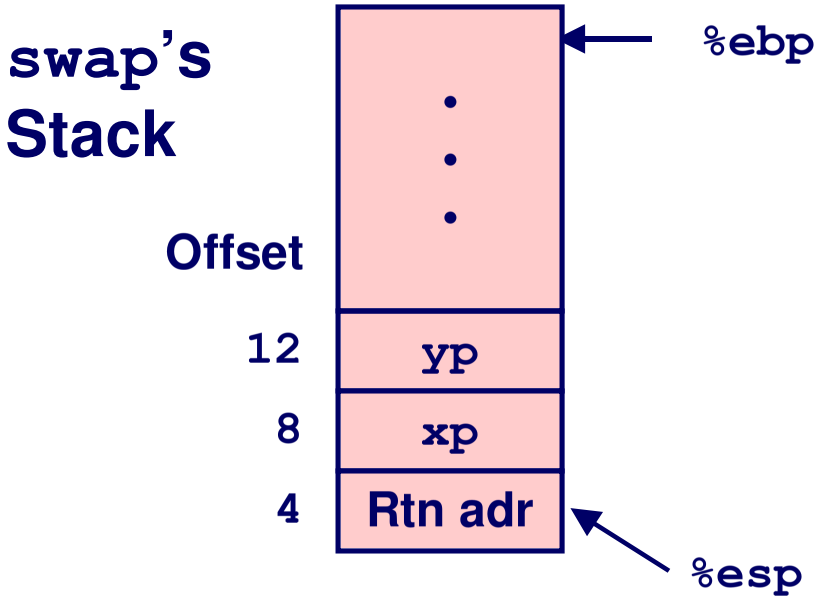





```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

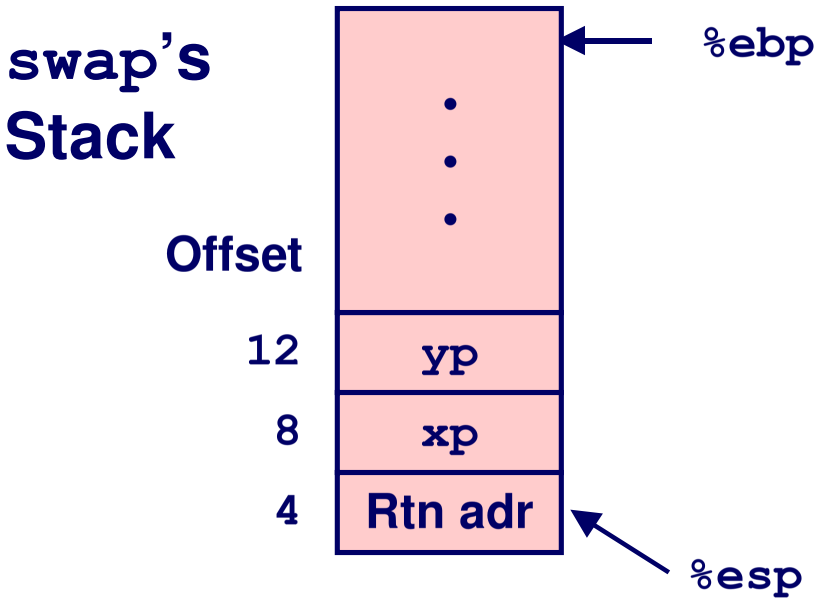
swap Finish #3

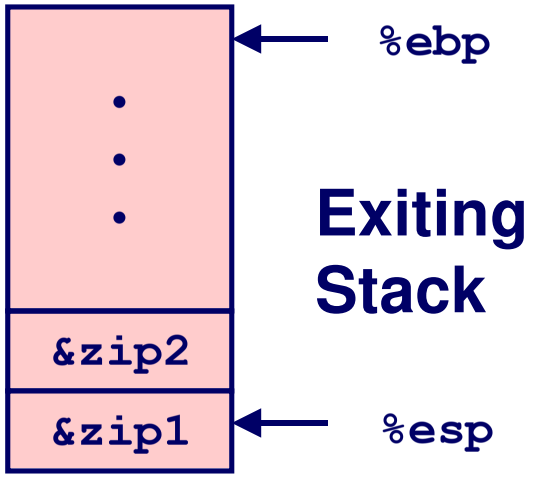





```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

swap Finish #4






```
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?

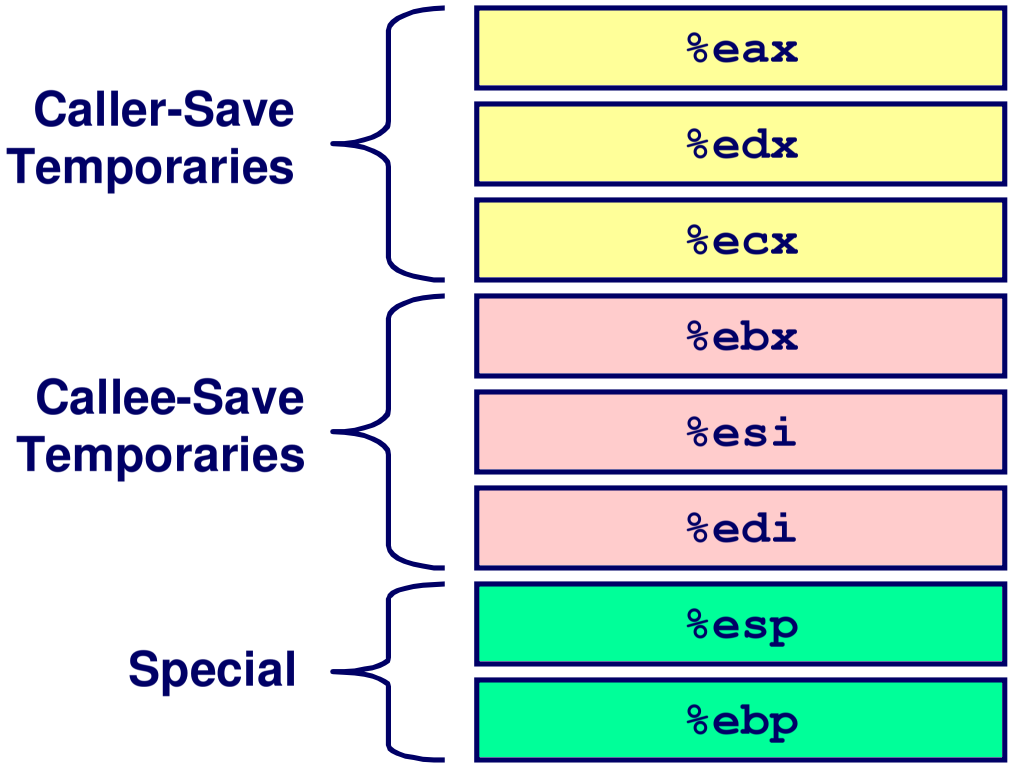
Conventions

- "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

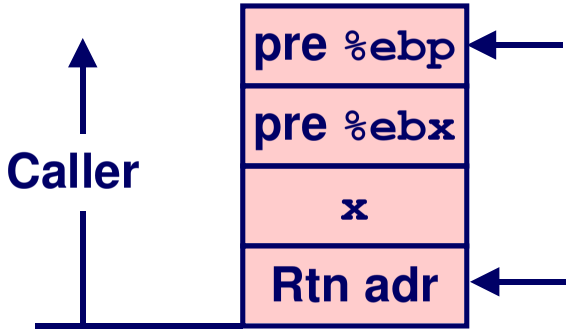
```
int rfact(int x)
{
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

Registers

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

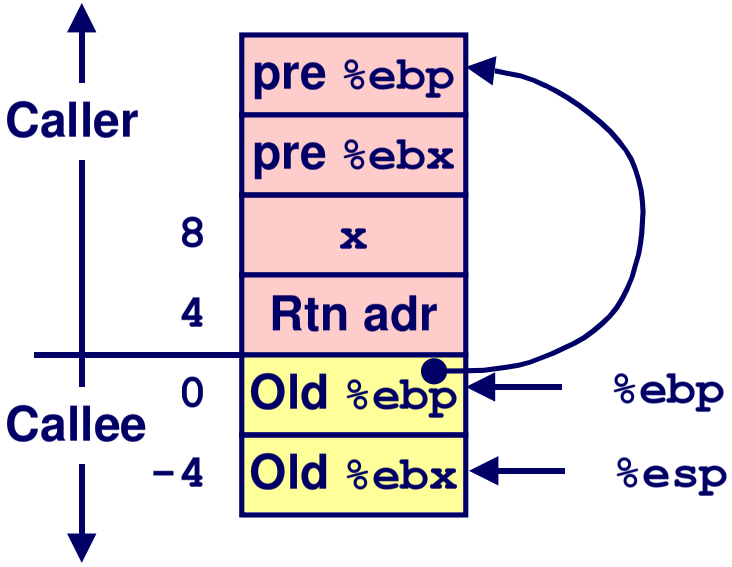
```
.globl rfact
    .type
rfact,@function
rfact:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
    movl 8(%ebp),%ebx
    cmpl $1,%ebx
    jle .L78
    leal -1(%ebx),%eax
    pushl %eax
    call rfact
    imull %ebx,%eax
    jmp .L79
    .align 4
.L78:
    movl $1,%eax
.L79:
    movl -4(%ebp),%ebx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

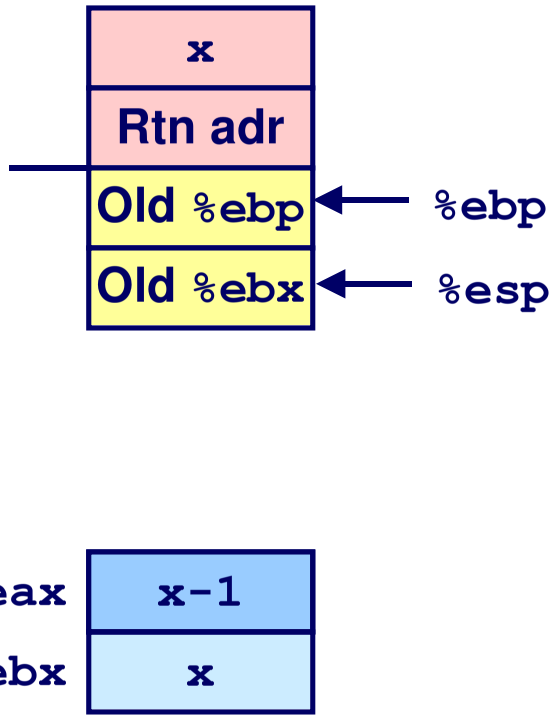
`%ebx` Stored value of x

`%eax`

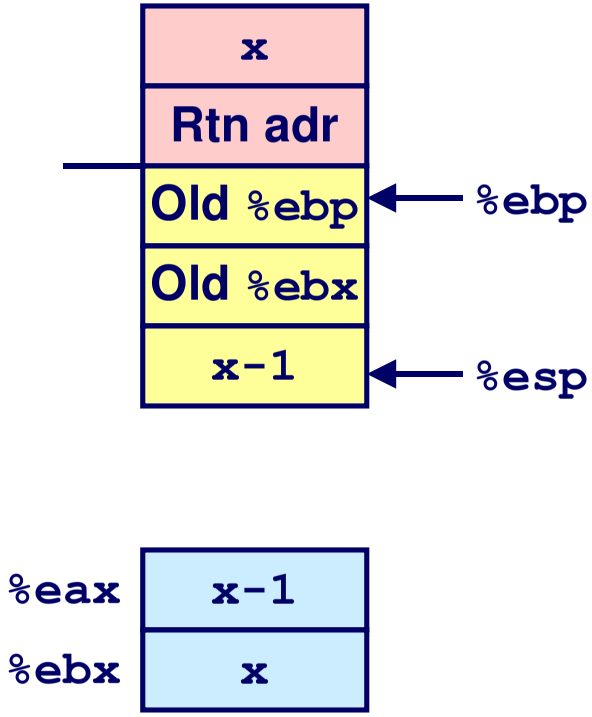
- Temporary value of `x-1`
- Returned value from `rfact(x-1)`
- Returned value from this call

Rfact Recursion

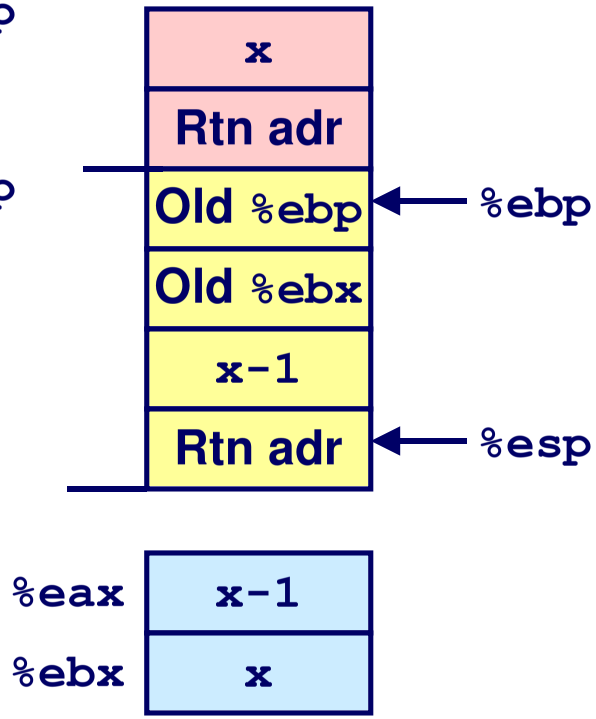
```
leal -1(%ebx),%eax
```




```
pushl %eax
```

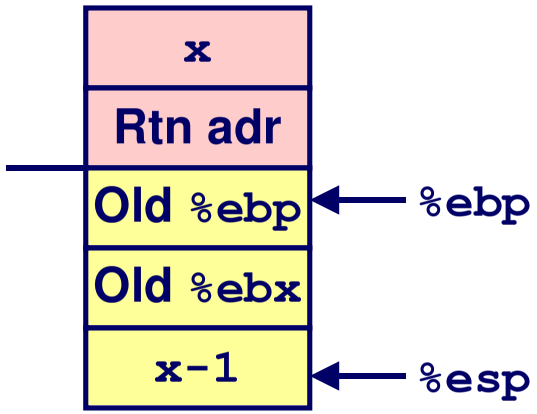


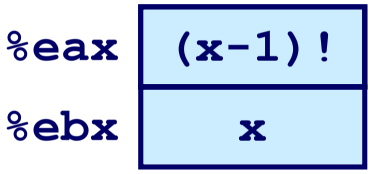

```
call rfact
```



Rfact Result

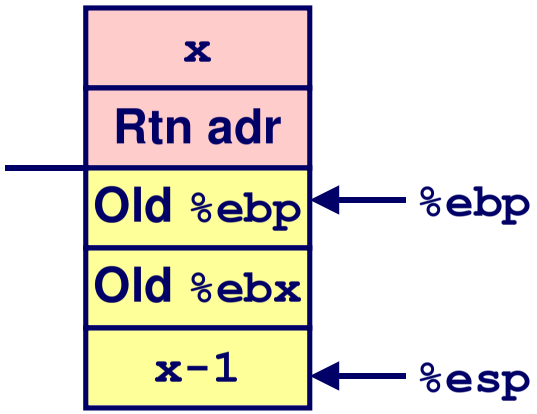
Return from Call

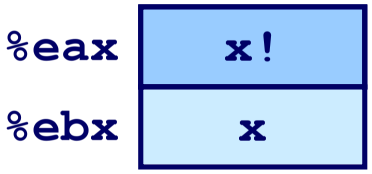




Assume that `rfact(x-1)` returns `(x-1)!` in register `%eax`

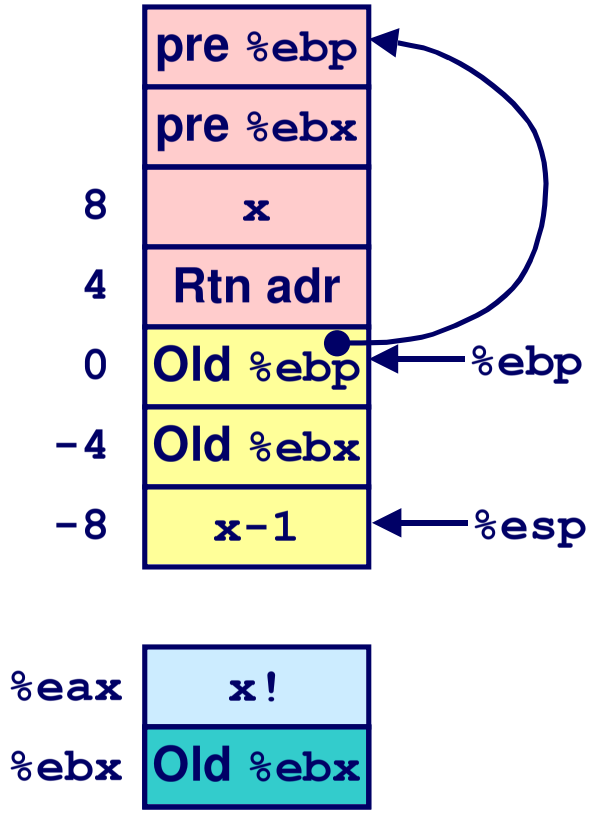
```
imull %ebx,%eax
```

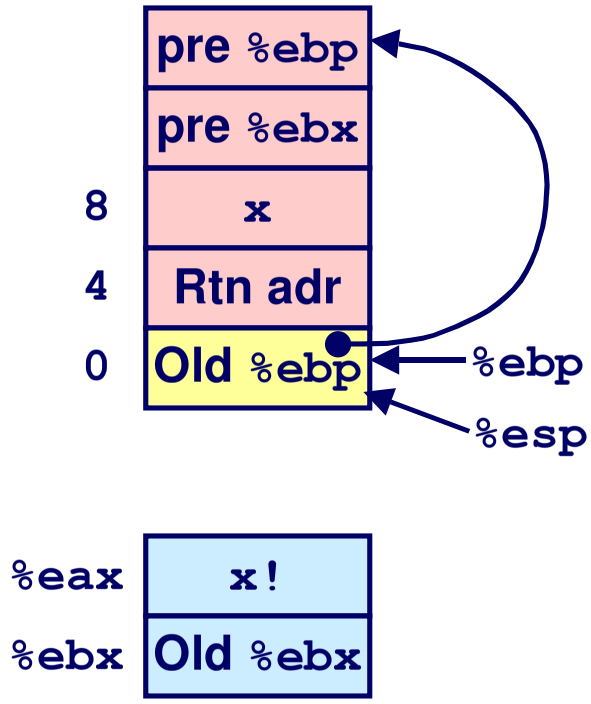


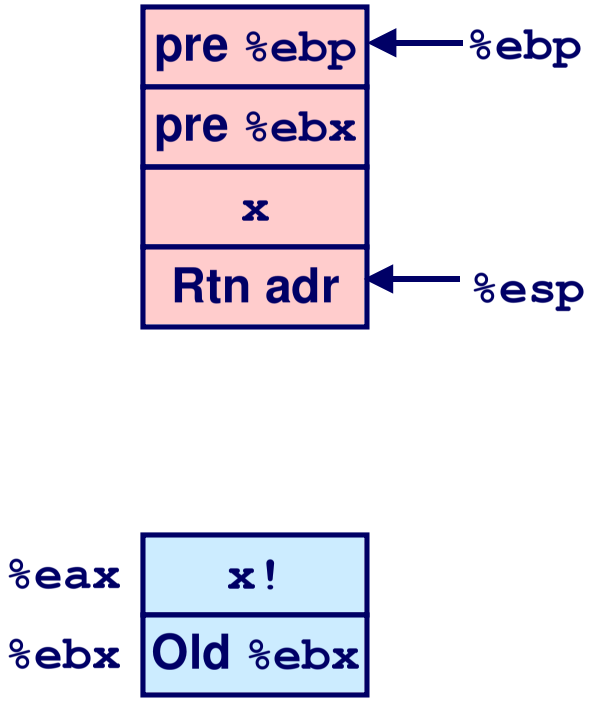


Rfact Completion

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







Pointer Code

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

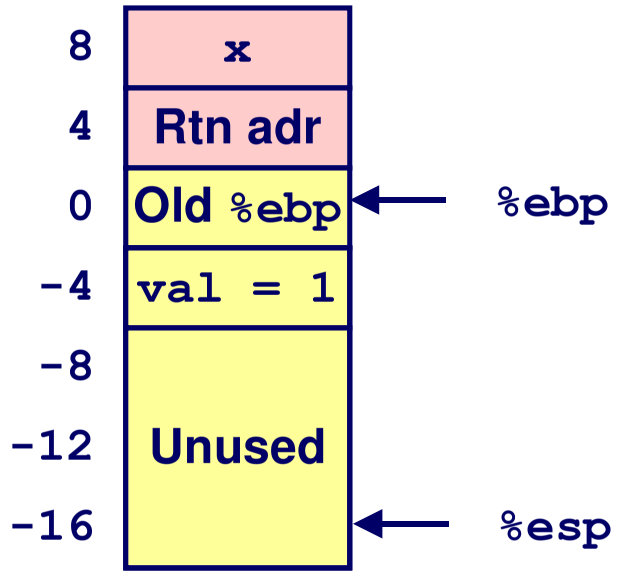
```
int sfact(int x)
{
   int val = 1;
   s_helper(x, &val);
   return val;
}
```

- Pass pointer to update location

Creating & Initializing Pointer

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
```



Using Stack for Local Variable

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

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

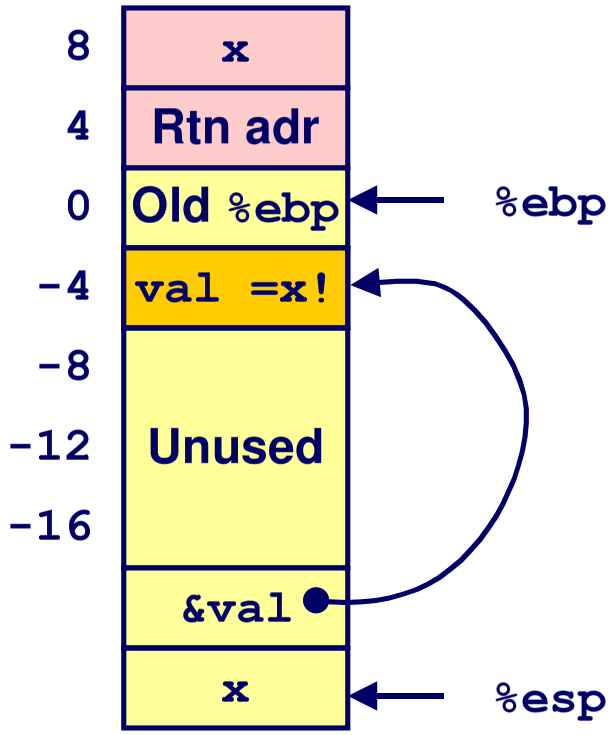
Passing Pointer

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
```

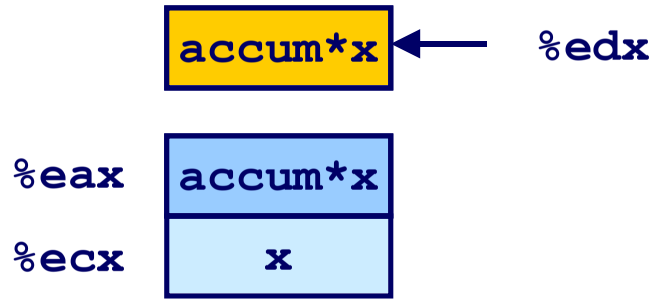
```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

Stack at time of call



Using Pointer

```
void s_helper
   (int x, int *accum)
{
   • • •
     int z = *accum * x;
     *accum = z;
   • • •
}
```




```
   • • •
movl %ecx,%eax     # z = x
imull (%edx),%eax  # z *= *accum
movl %eax,(%edx)   # *accum = z
   • • •
```

- Register `%ecx` holds `x`
- Register `%edx` holds pointer to `accum`
  - Use access `(%edx)` to reference memory

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