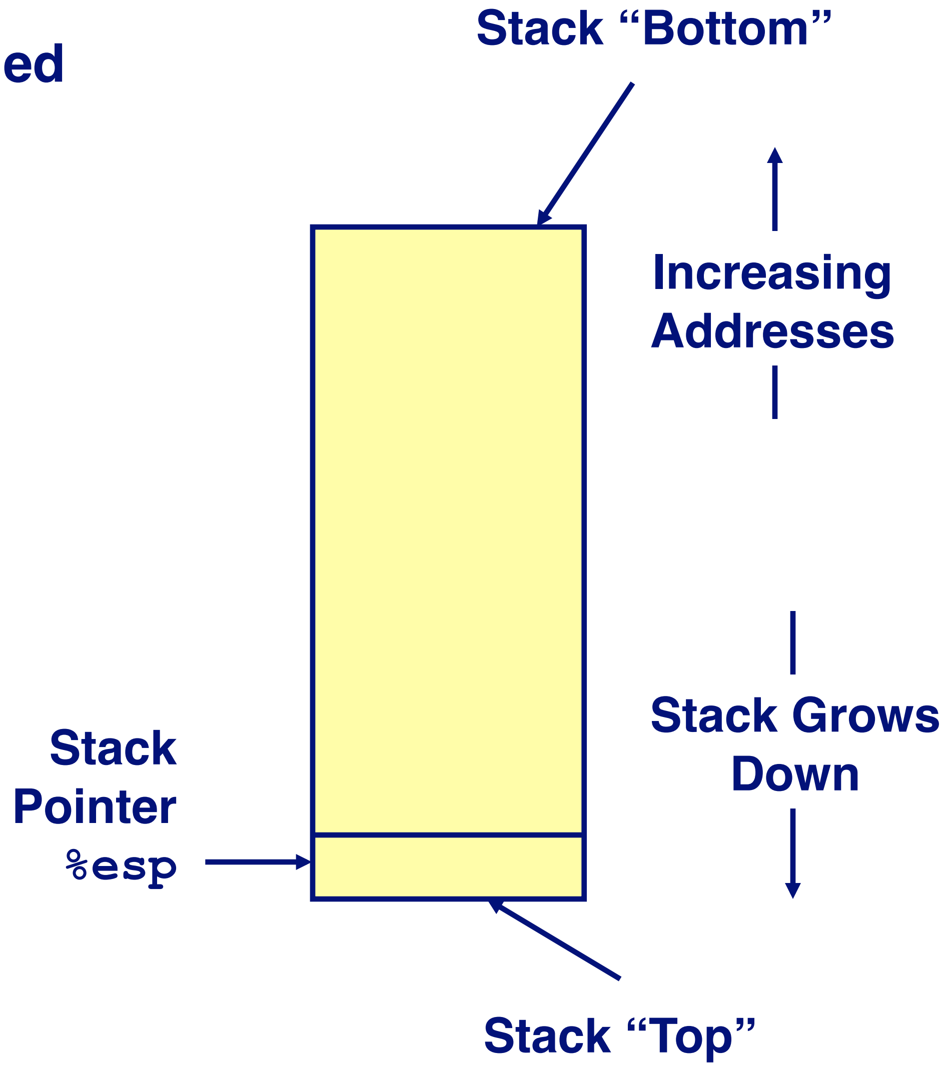
Machine-Level Programming III: Procedures

Topics

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

IA32 Stack

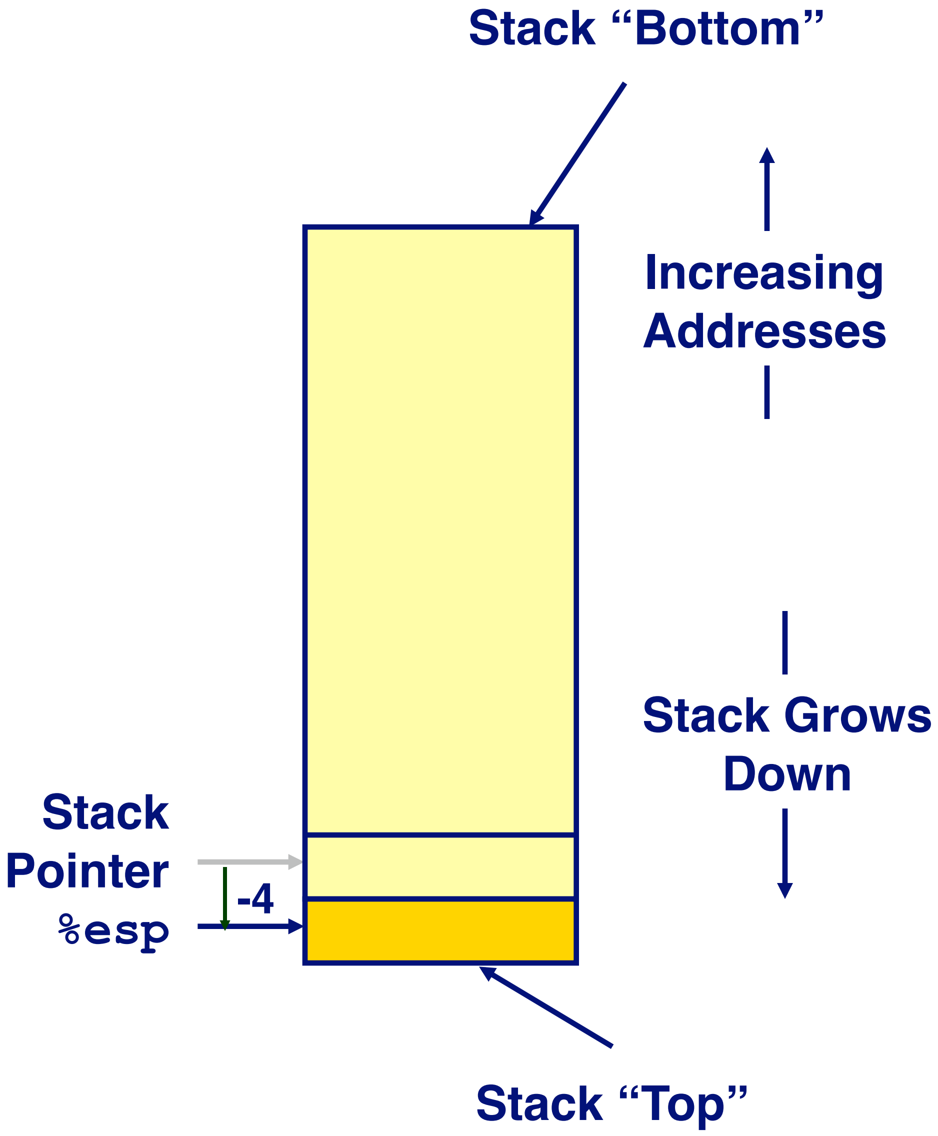
- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register `%esp` indicates lowest stack address
  - address of top element



IA32 Stack Pushing

Pushing

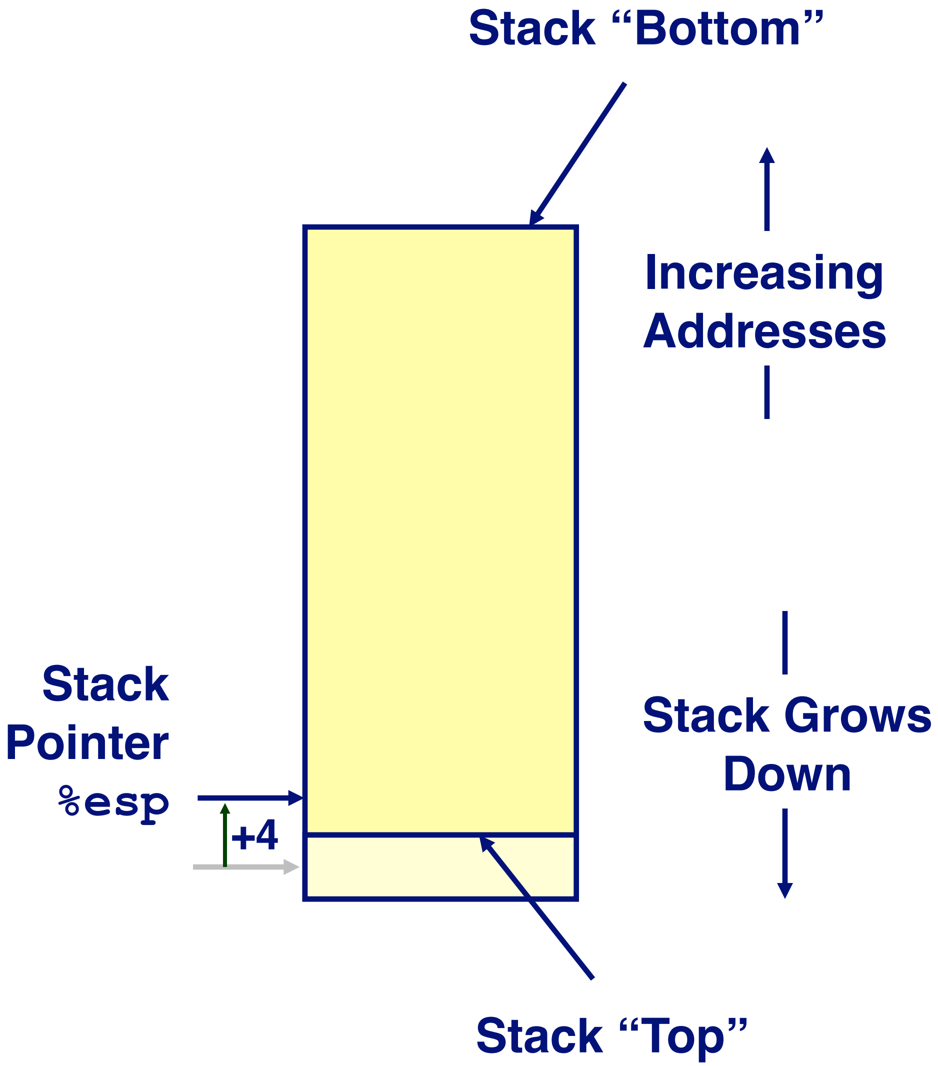
- `pushl` *Src*
- Fetch operand at *Src*
- Decrement `%esp` by 4
- Write operand at address given by `%esp`



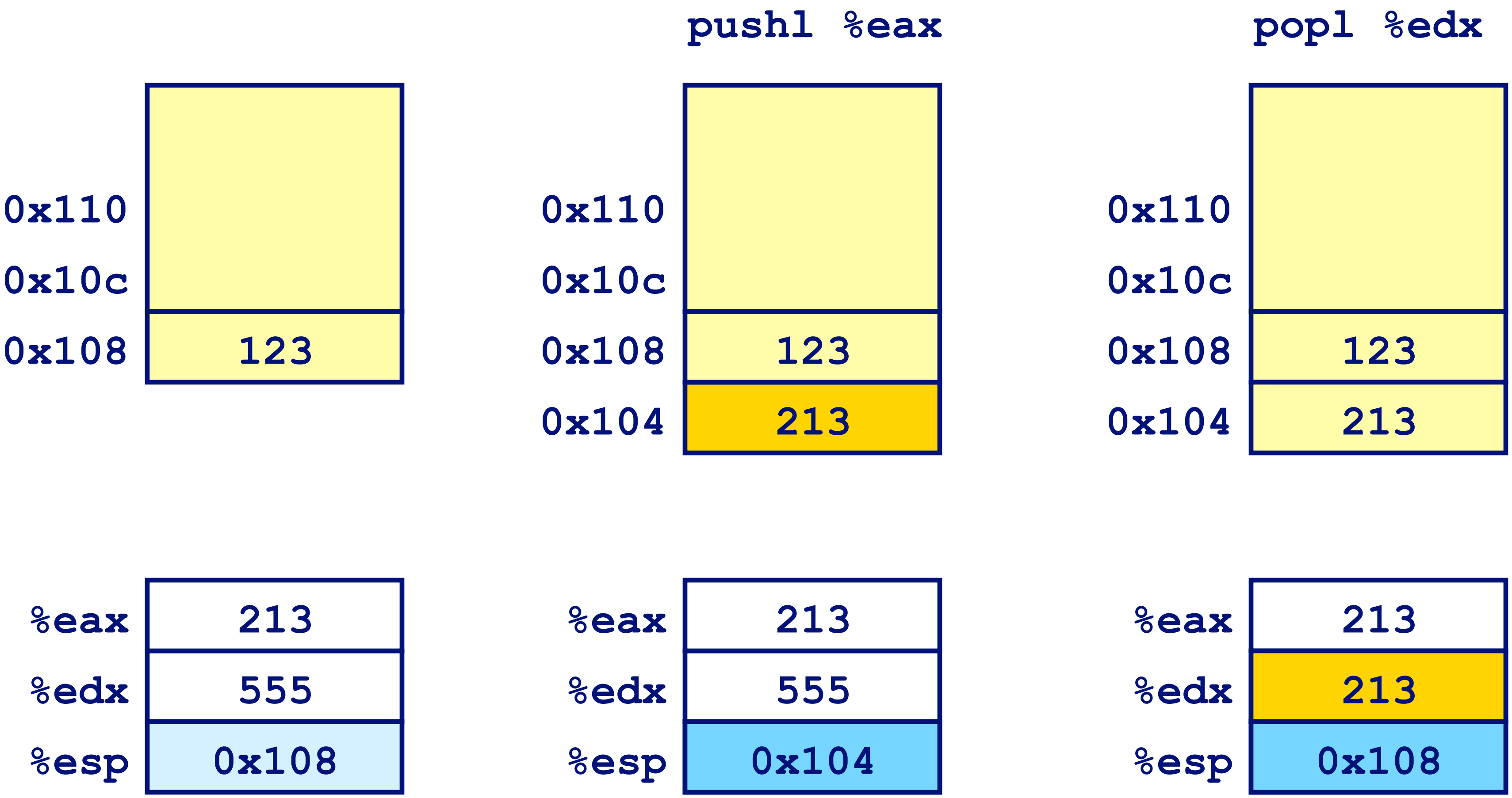
IA32 Stack Popping

Popping

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



Stack Operation Examples



0x110	
0x10c	
0x108	123

%eax	213
%edx	555
%esp	0x108

`pushl %eax`

0x110	
0x10c	
0x108	123
0x104	213

%eax	213
%edx	555
%esp	0x104

`popl %edx`

0x110	
0x10c	
0x108	123
0x104	213

%eax	213
%edx	213
%esp	0x108

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
```

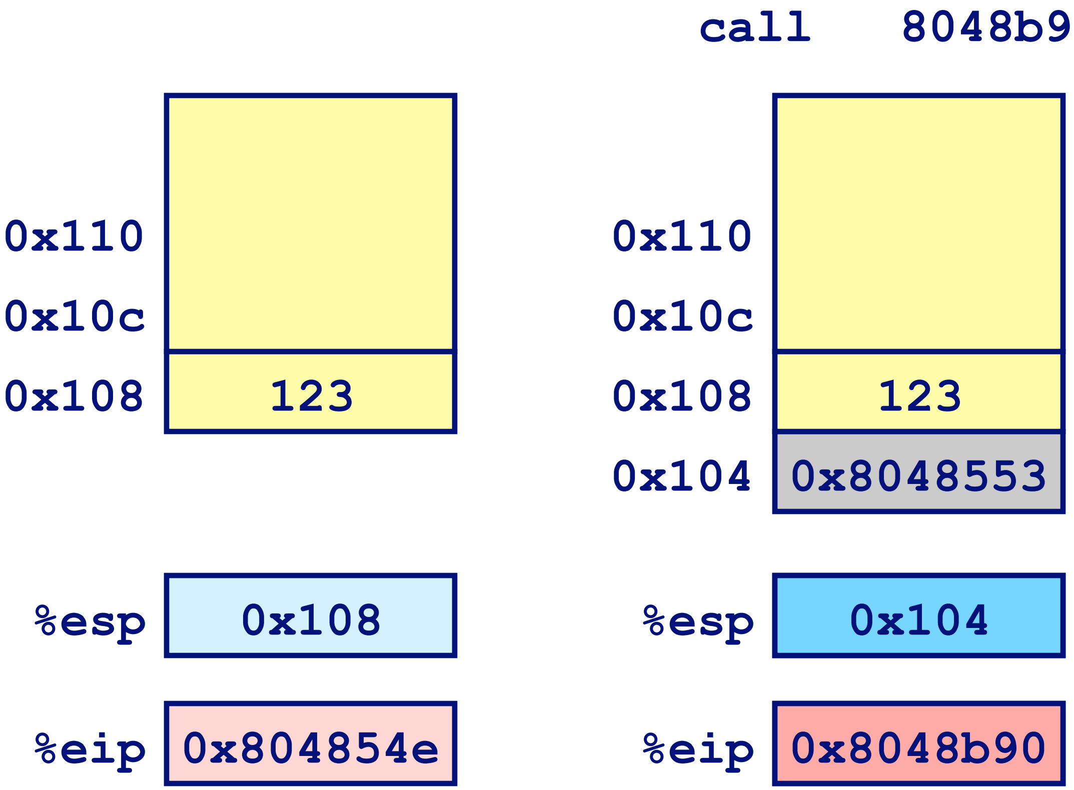
  - Return address = `0x8048553`

Procedure return:

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

Procedure Call Example

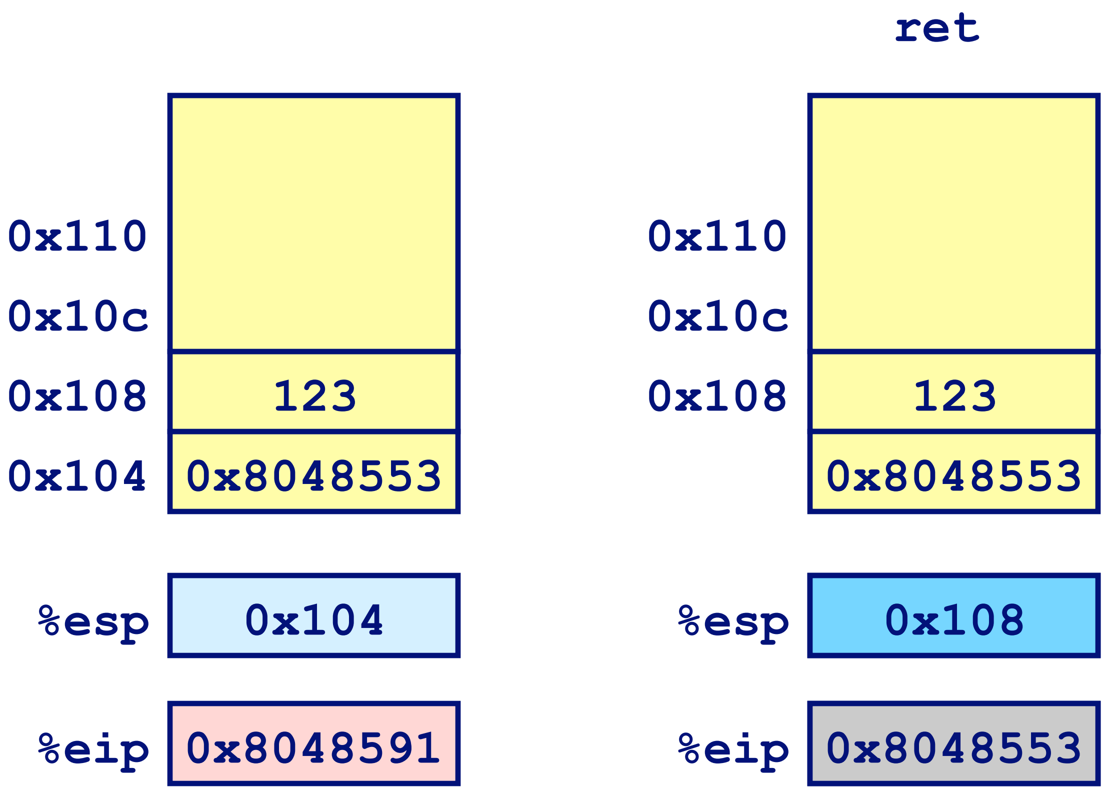
```
804854e:   e8 3d 06 00 00       call    8048b90 <main>
8048553:   50                   pushl   %eax
```



`%eip` **is 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` 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

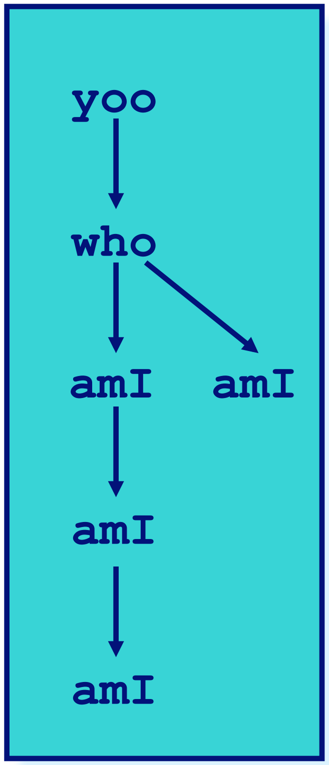
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

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

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

- Procedure `amI` recursive

Call Chain



Stack Frames

Contents

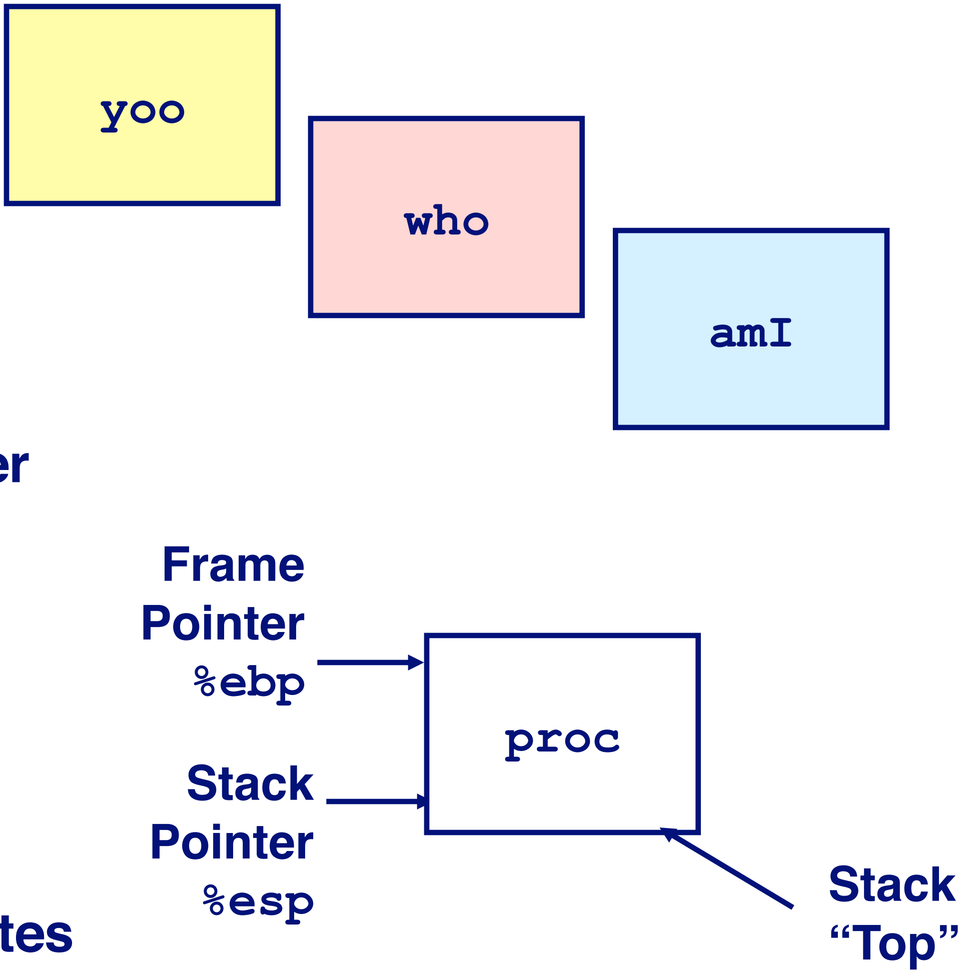
- Local variables
- Return information
- Temporary space

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

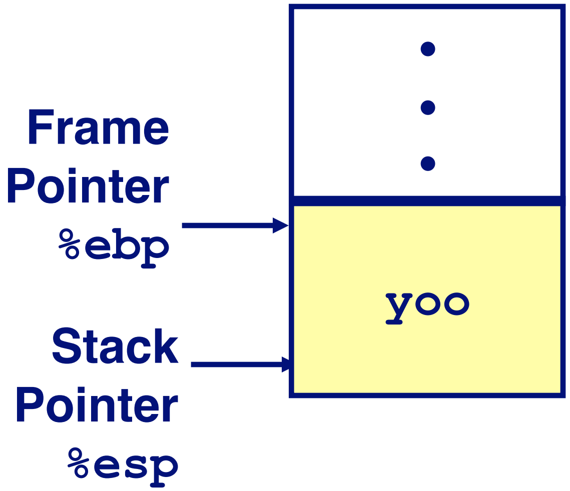


Stack Operation

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

Call Chain

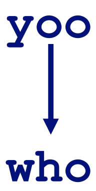
yoo

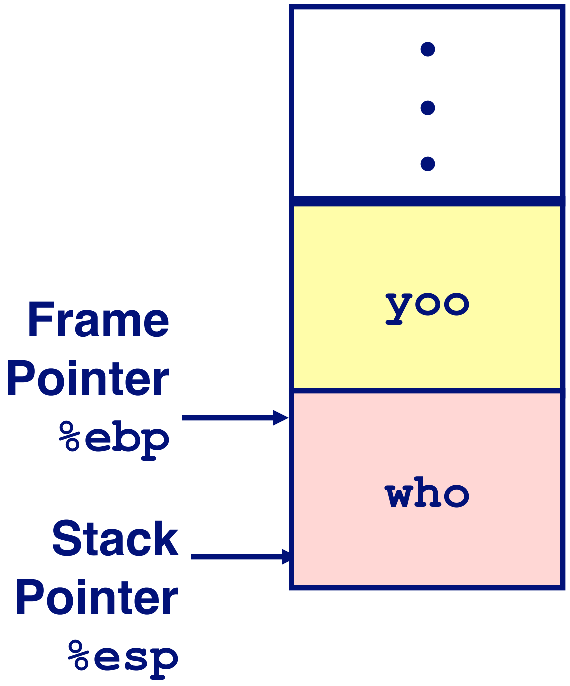


Stack Operation

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

Call Chain

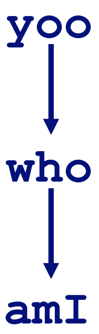


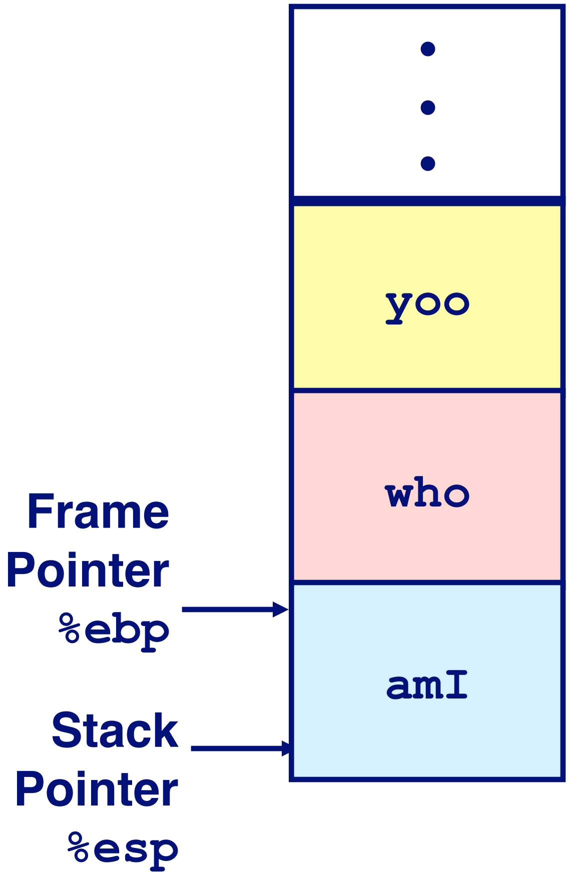


Stack Operation

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

Call Chain

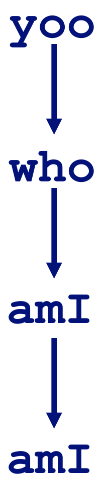


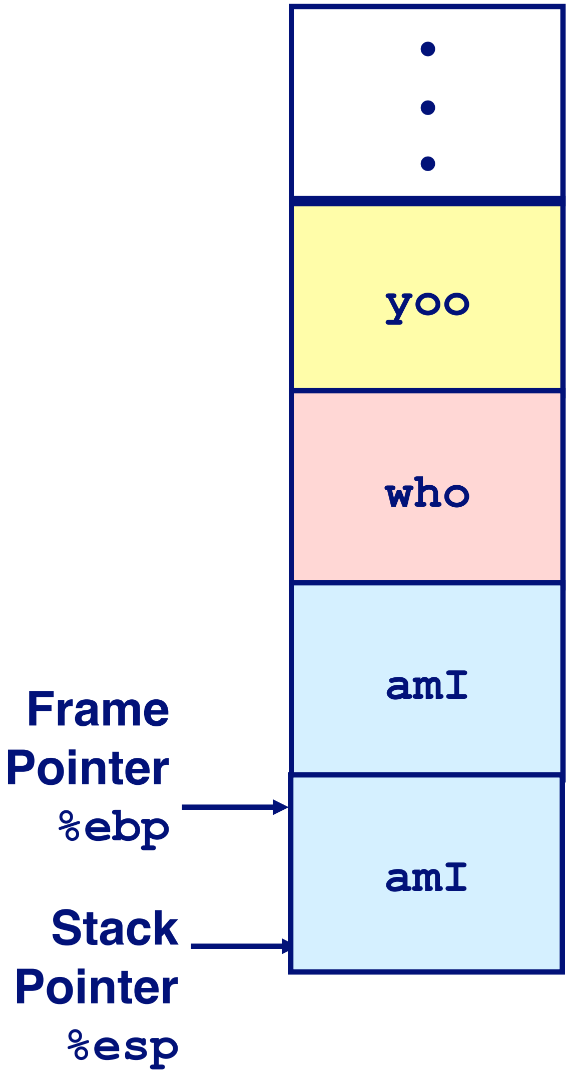


Stack Operation

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

Call Chain

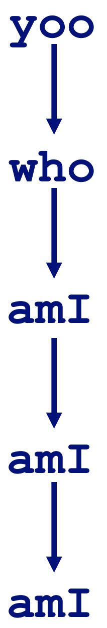


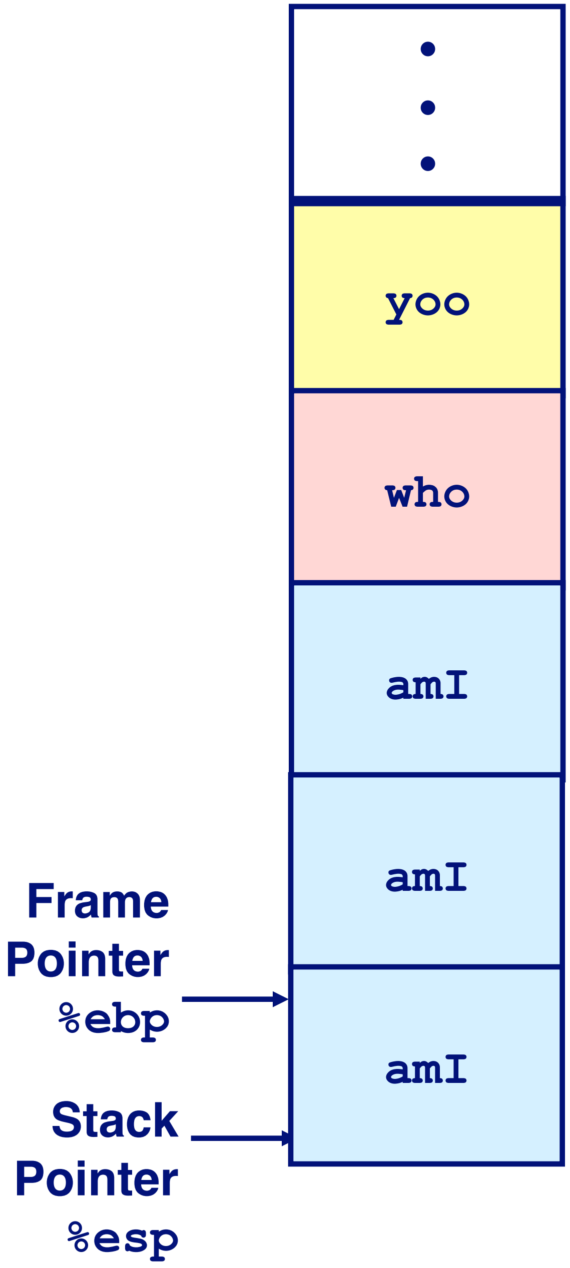


Stack Operation

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

Call Chain

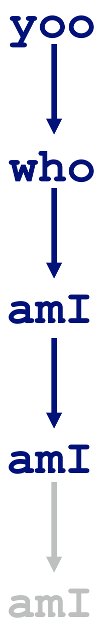


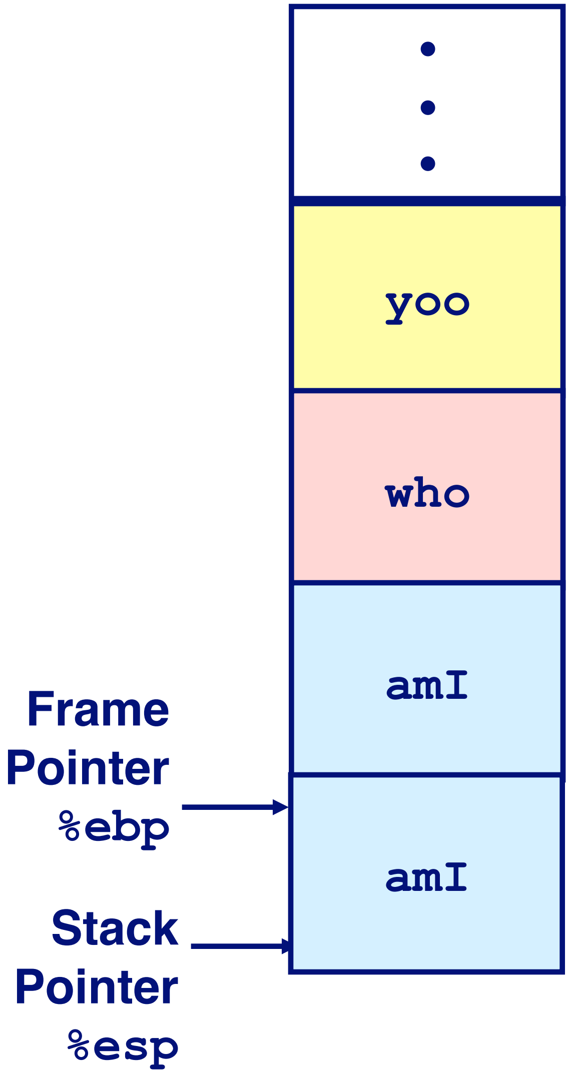


Stack Operation

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

Call Chain

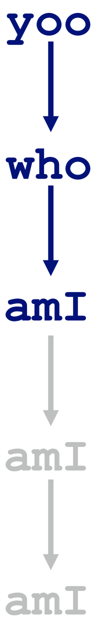




Stack Operation

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

Call Chain



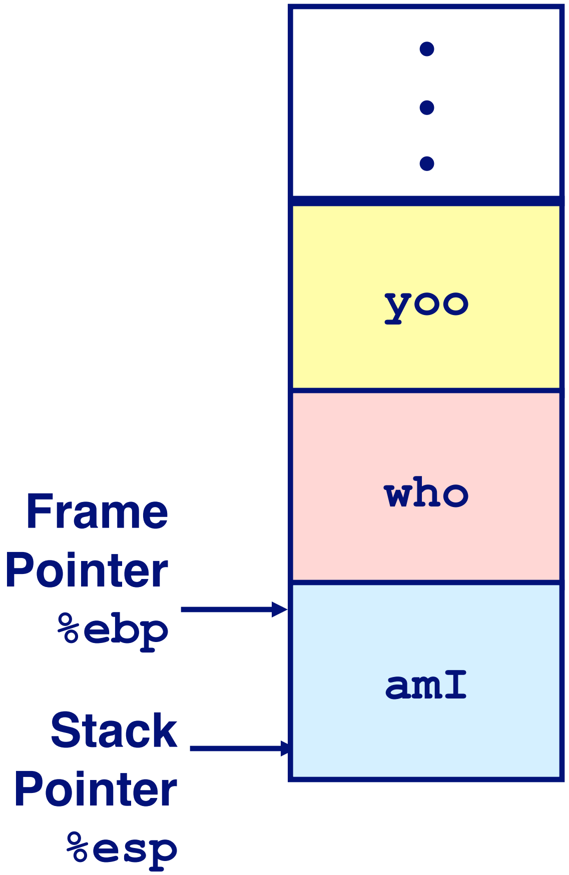
yoo

who

amI

amI

amI



•
•
•

yoo

who

amI

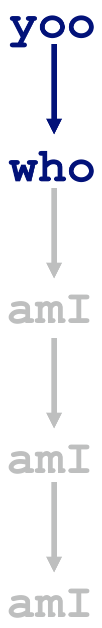
Frame Pointer %ebp

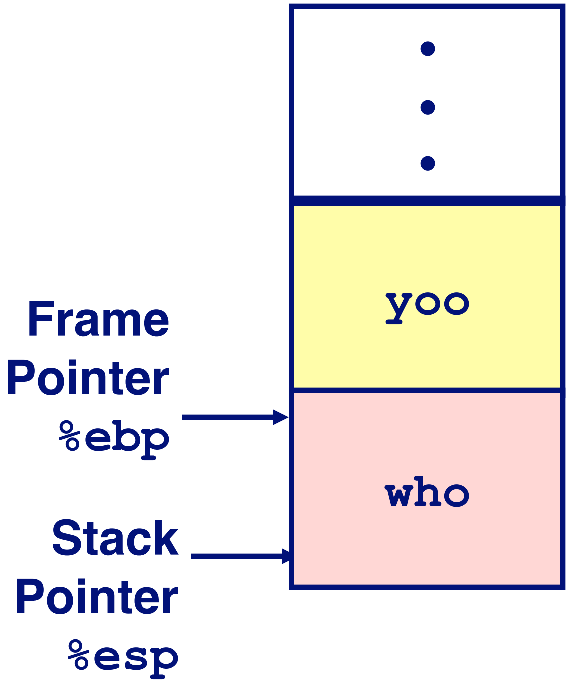
Stack Pointer %esp

Stack Operation

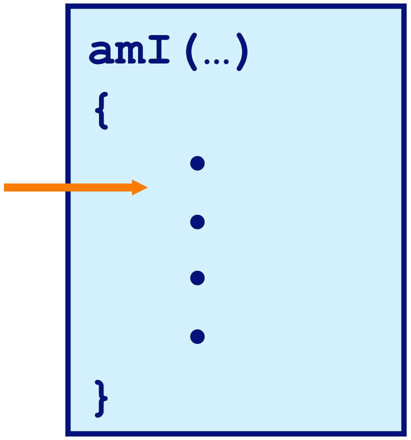
```
who(…)
{
    • • •
    amI();
    • • •
    amI();
    • • •
}
```

Call Chain

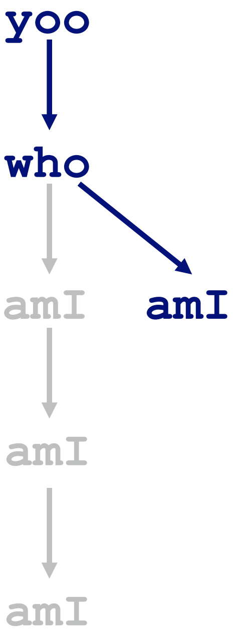


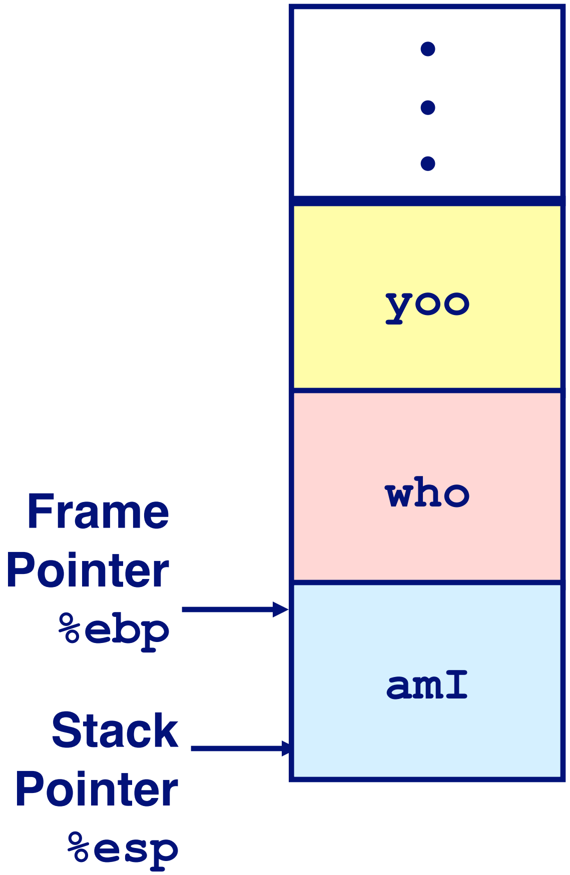


Stack Operation



Call Chain

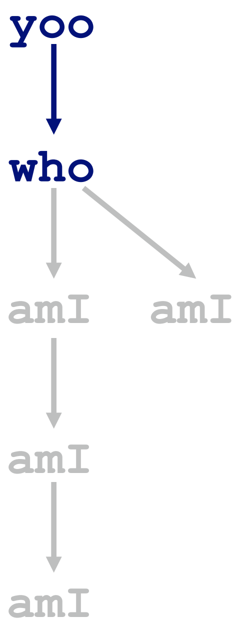


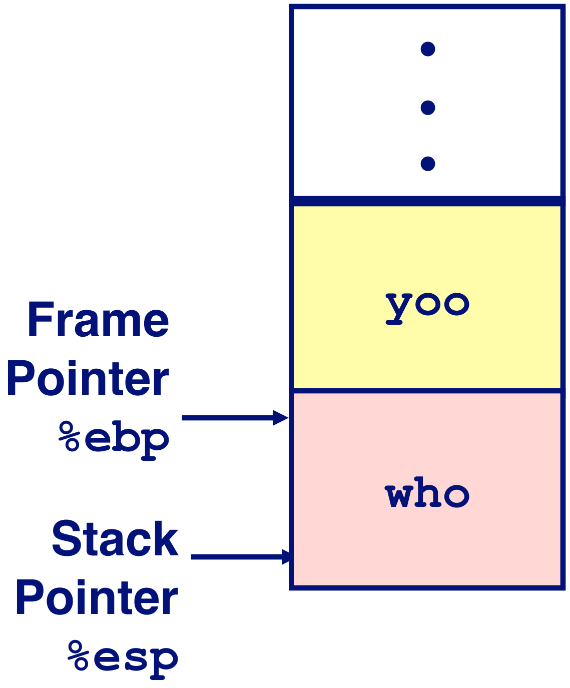


Stack Operation

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

Call Chain

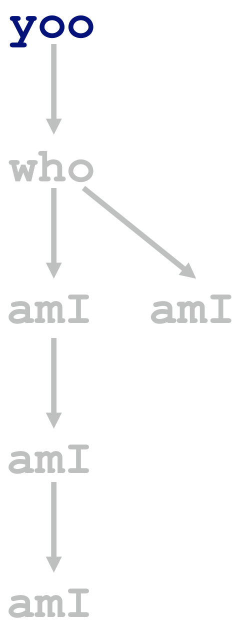


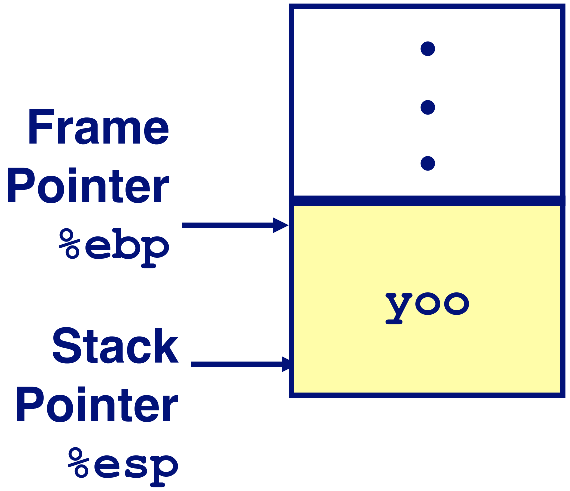


Stack Operation

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

Call Chain





Frame Pointer %ebp

Stack Pointer %esp

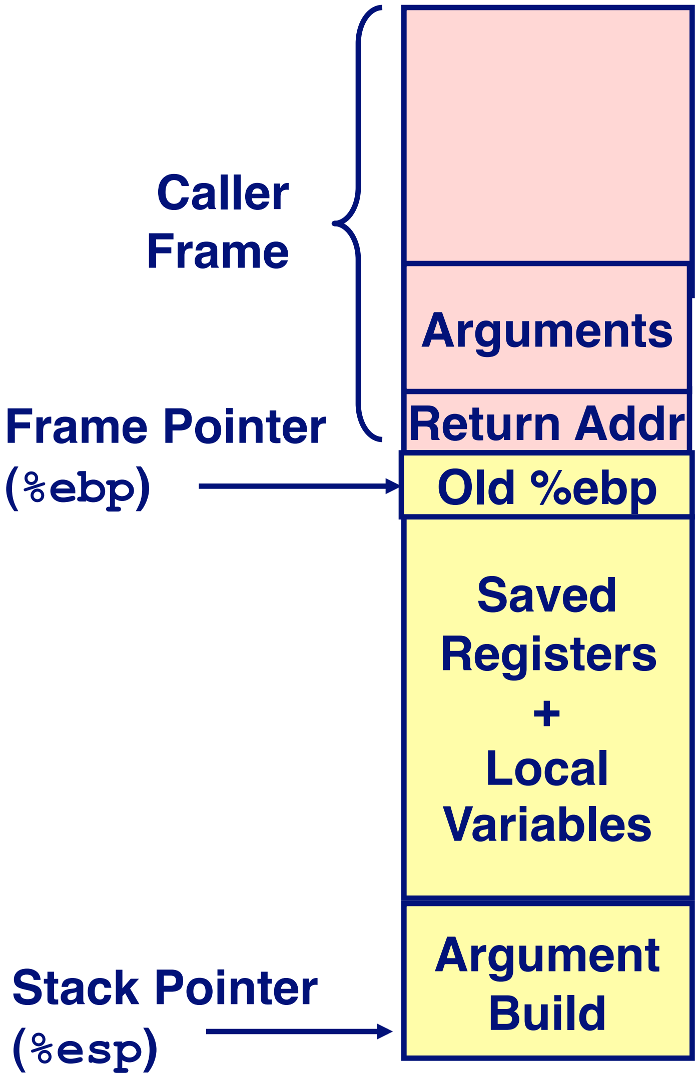
IA32/Linux Stack Frame

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

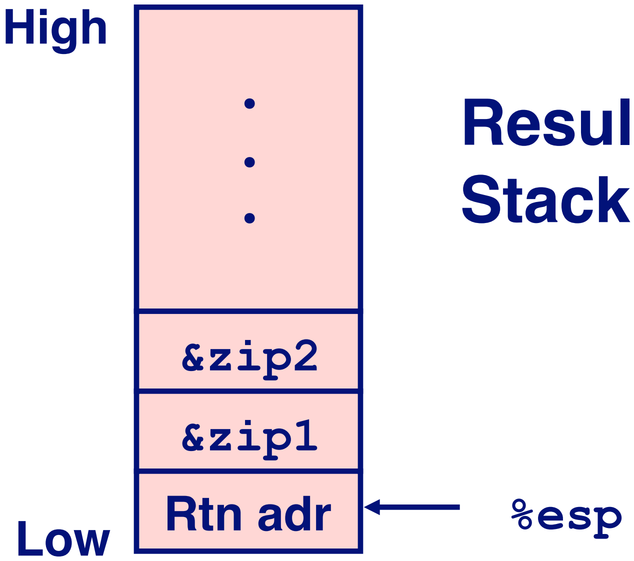
```
int zip1 = 15213;
int zip2 = 91125;

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
    • • •
```



High

•
•
•

&zip2

&zip1

Rtn adr

%esp

Low

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
```

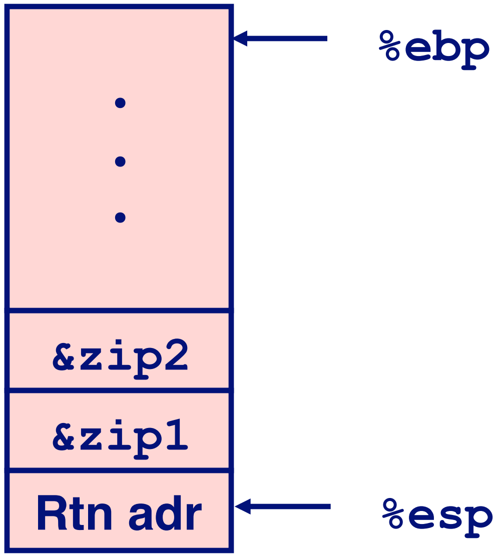
Set Up

Body

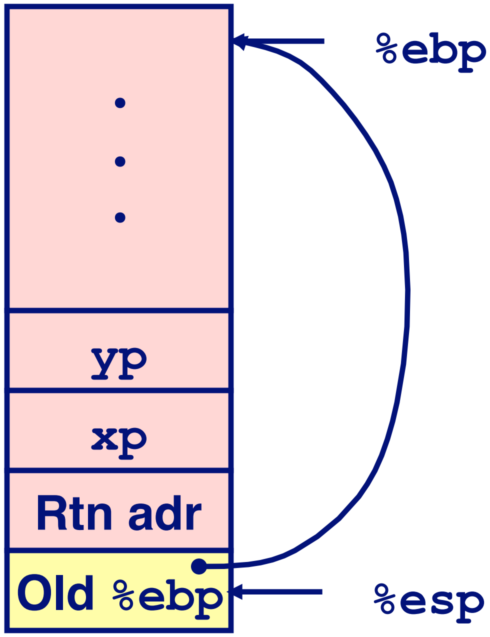
Finish

swap Setup #1

Entering Stack



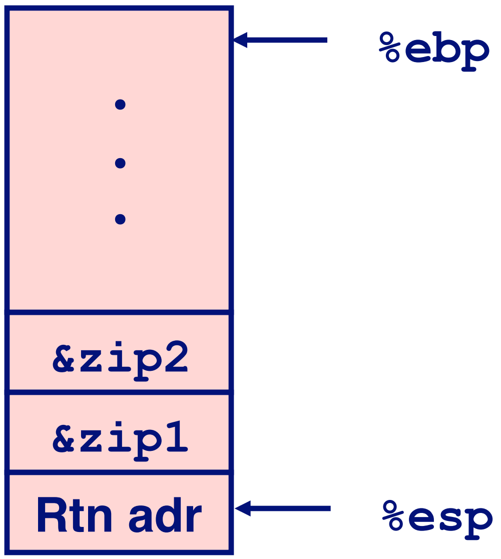
Resulting Stack



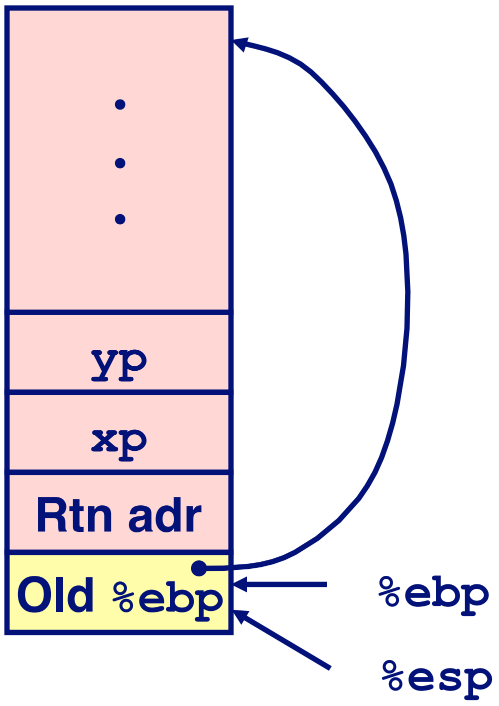
```
swap:
    pushl  %ebp
    movl  %esp,%ebp
    pushl  %ebx
```

swap Setup #2

Entering Stack

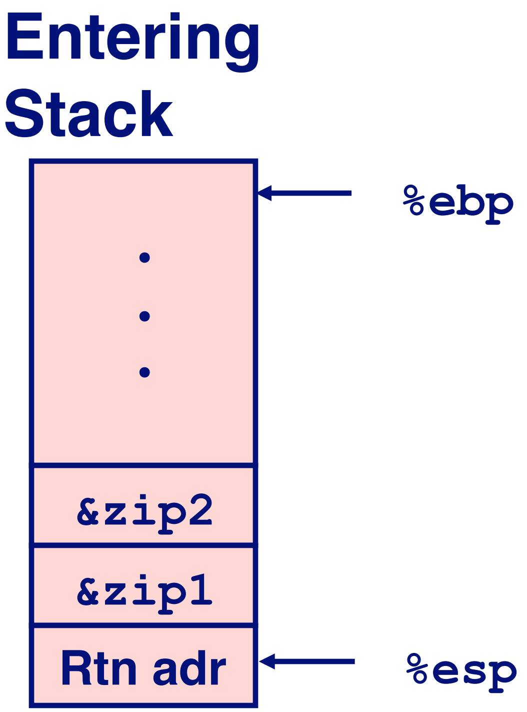


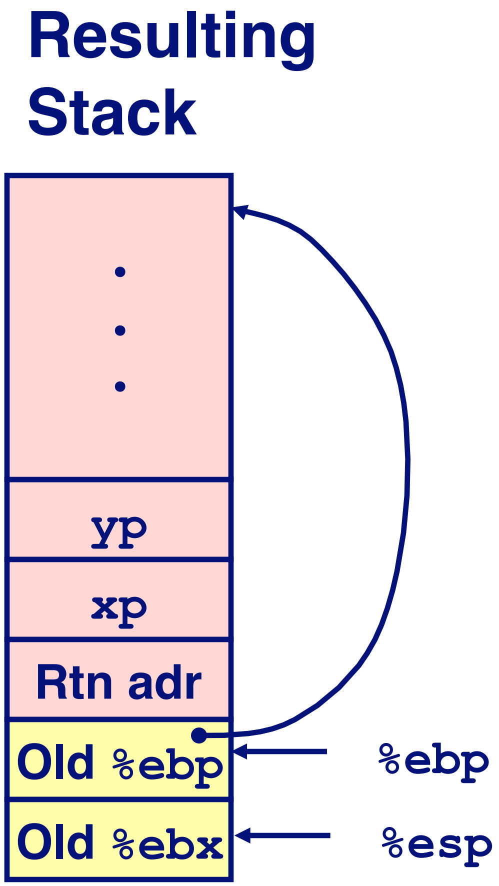
Resulting Stack



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

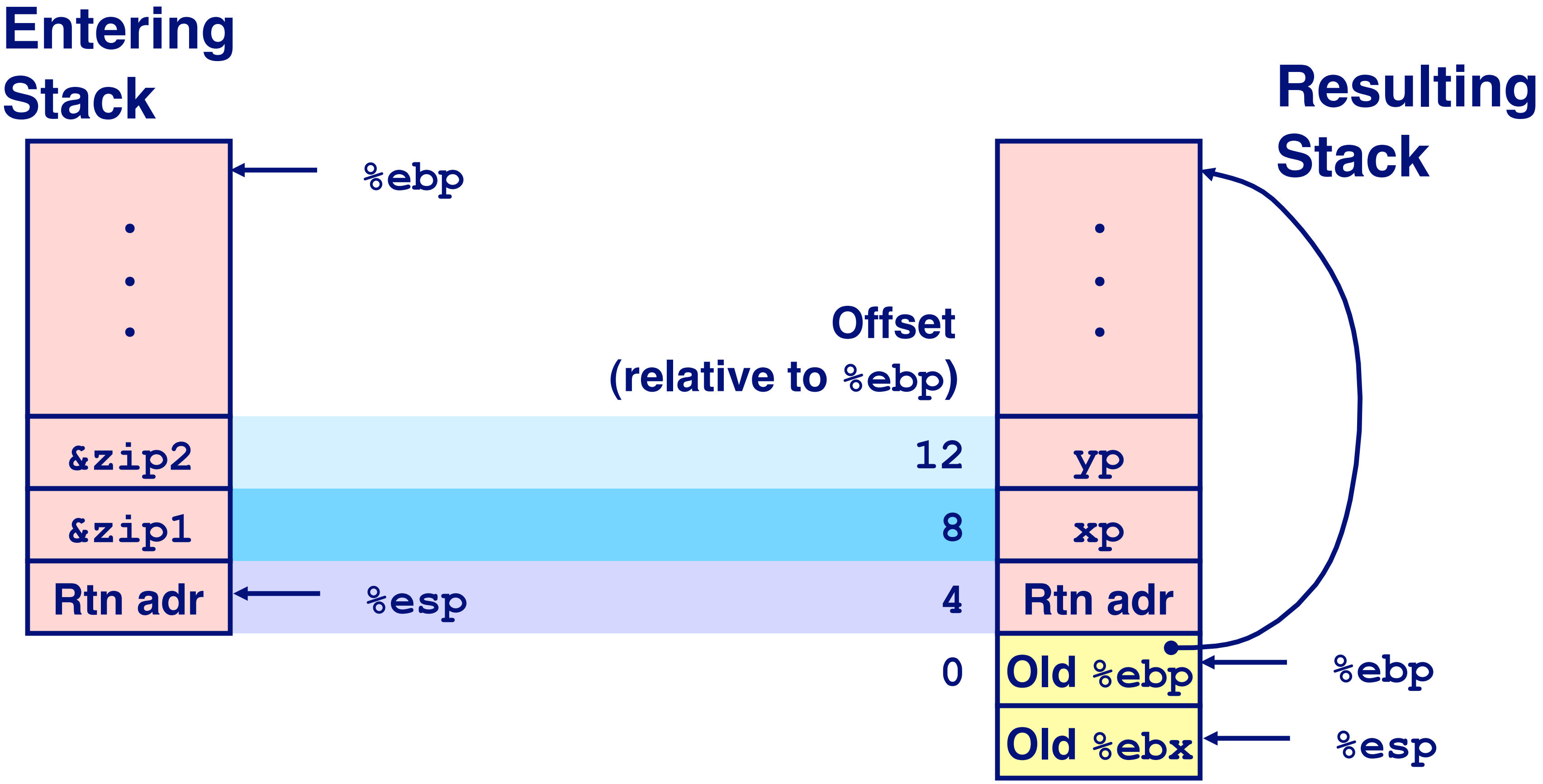
swap Setup #3





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

Effect of swap Setup

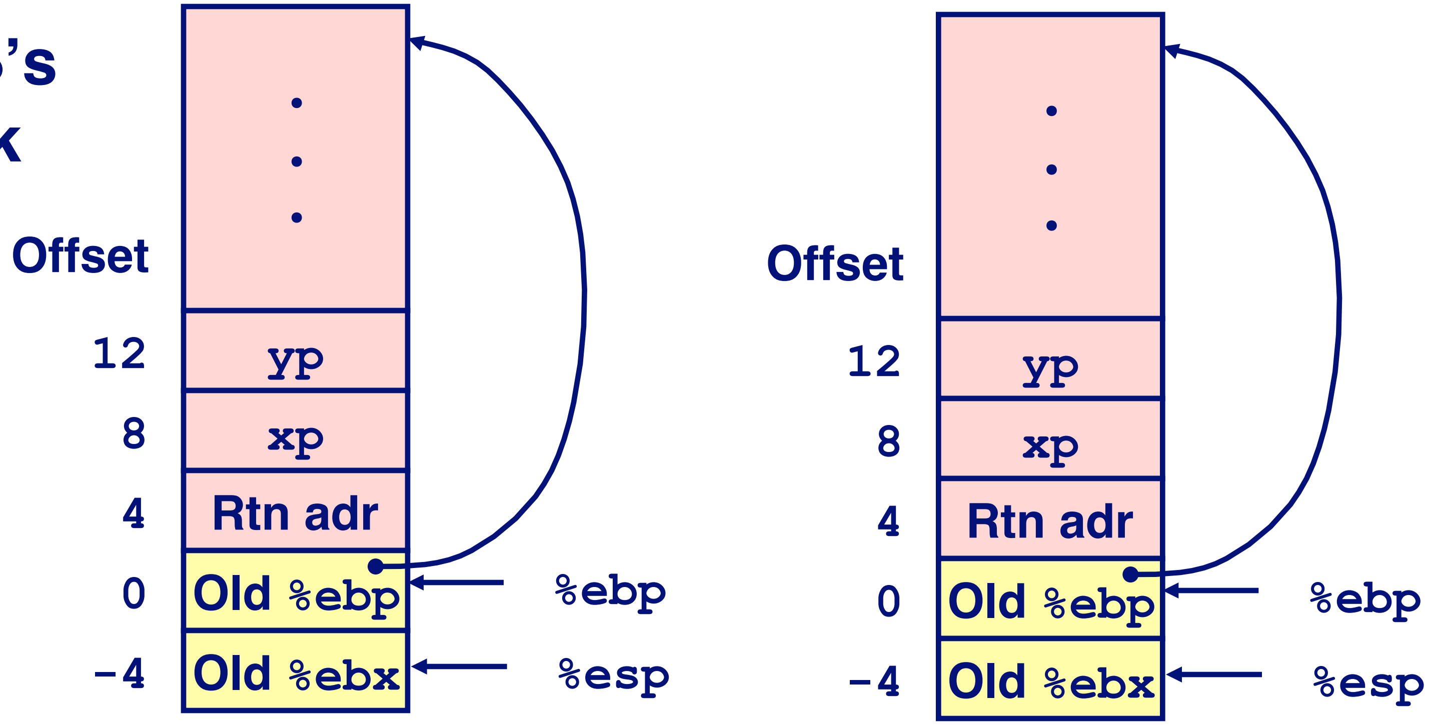


```
movl 12(%ebp),%ecx # get yp
movl 8(%ebp),%edx  # get xp
. . .
```

Body

swap Finish #1

swap's
Stack

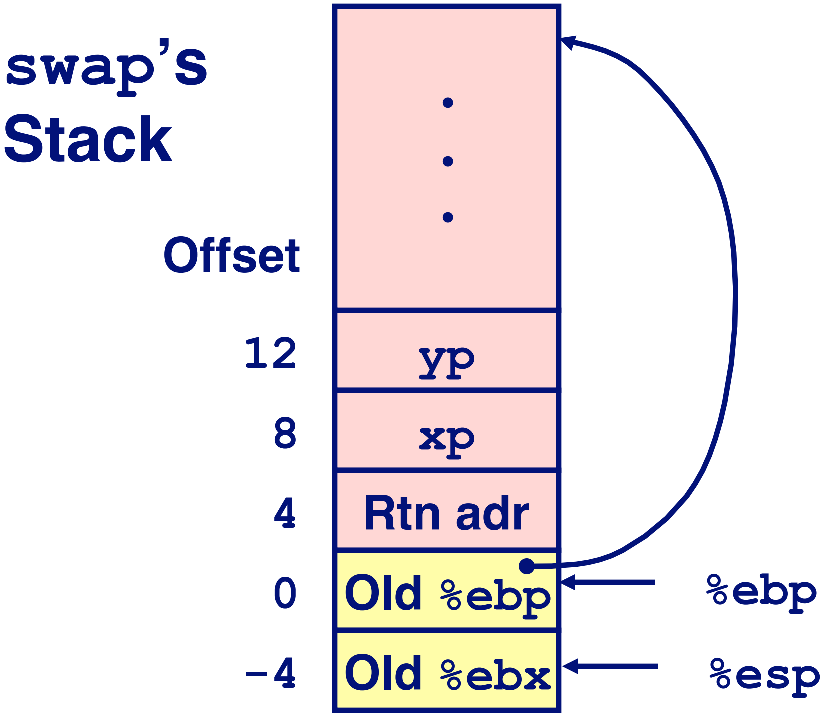


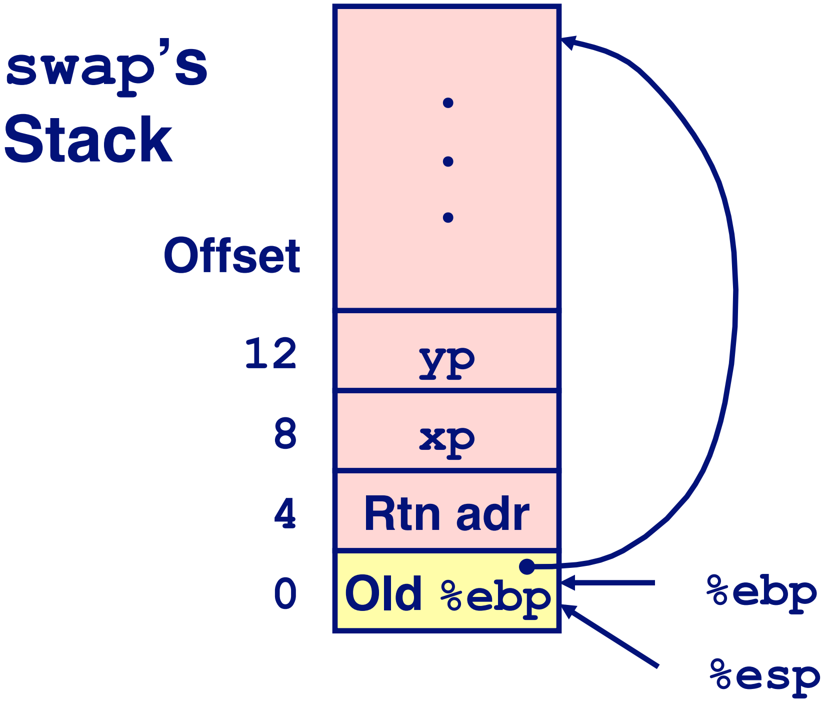
```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Observation

- Saved & restored register %ebx

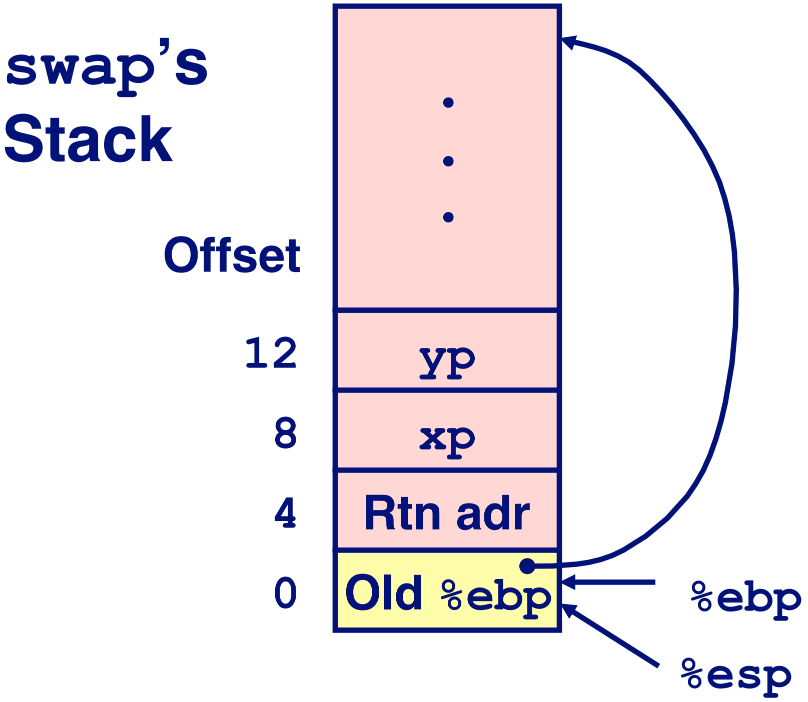
swap Finish #2

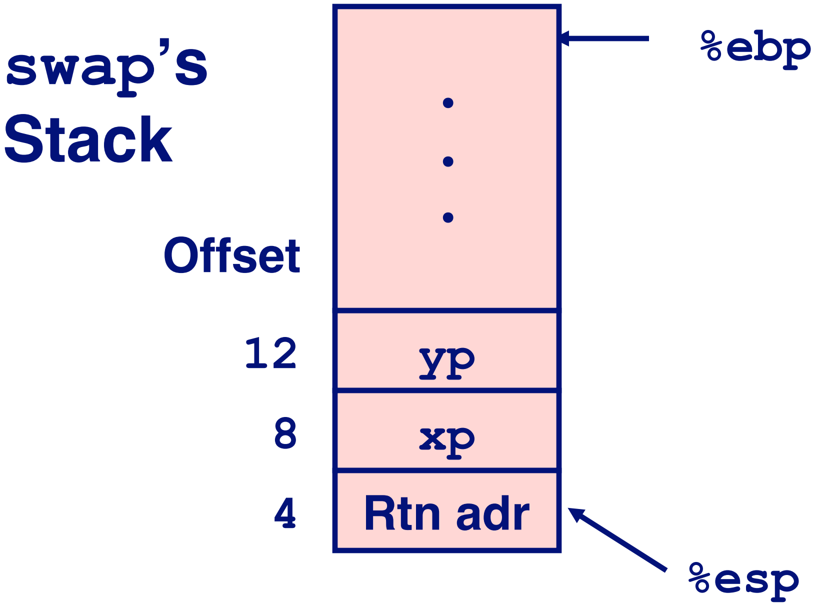




```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

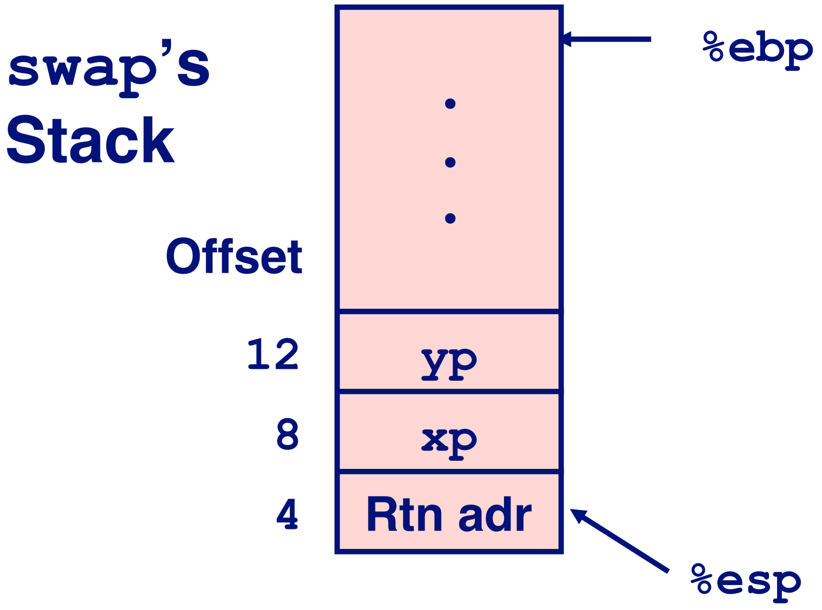
swap Finish #3

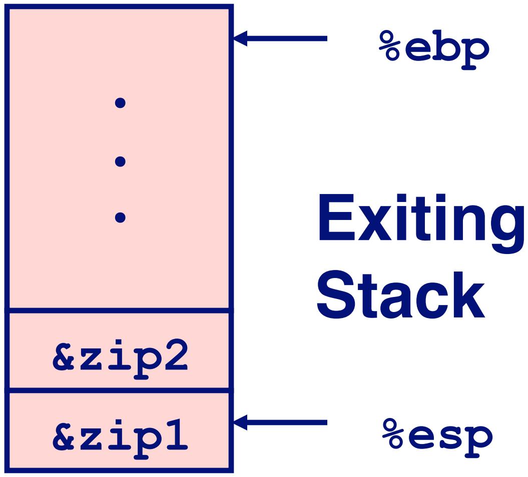




```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

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`

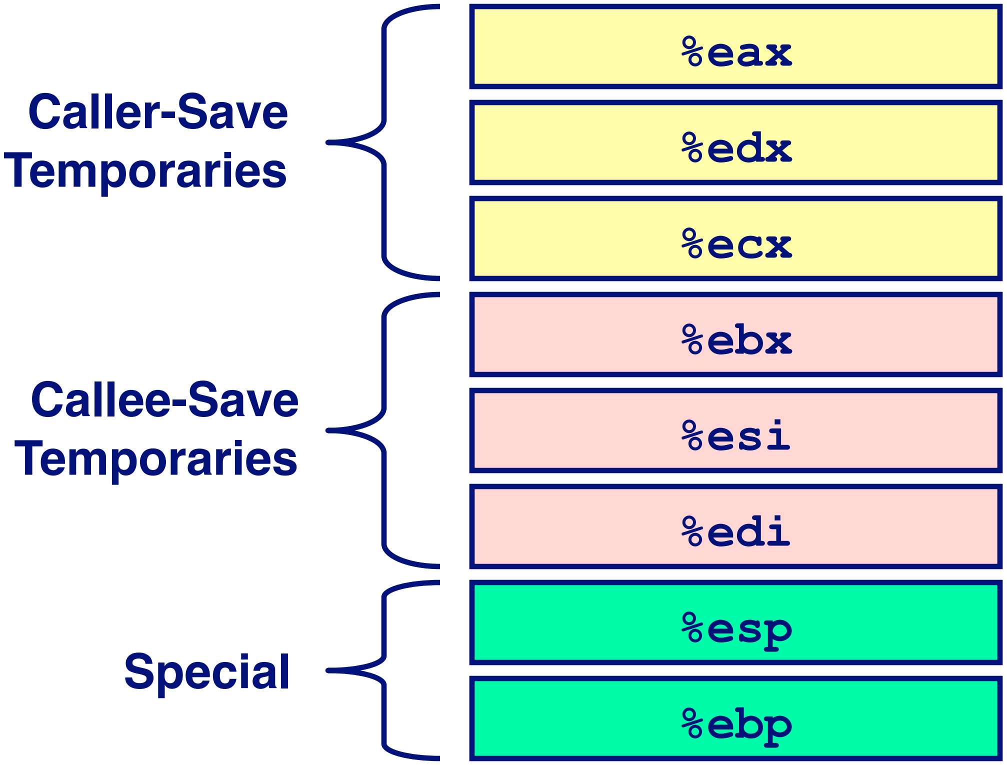
  - Old values saved on stack prior to using

- 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



Caller-Save Temporaries

Callee-Save Temporaries

Special

Recursive Factorial

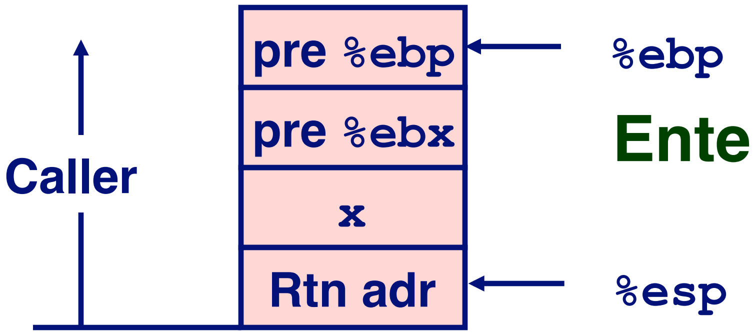
```
int rfact(int x)
{
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

Registers

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

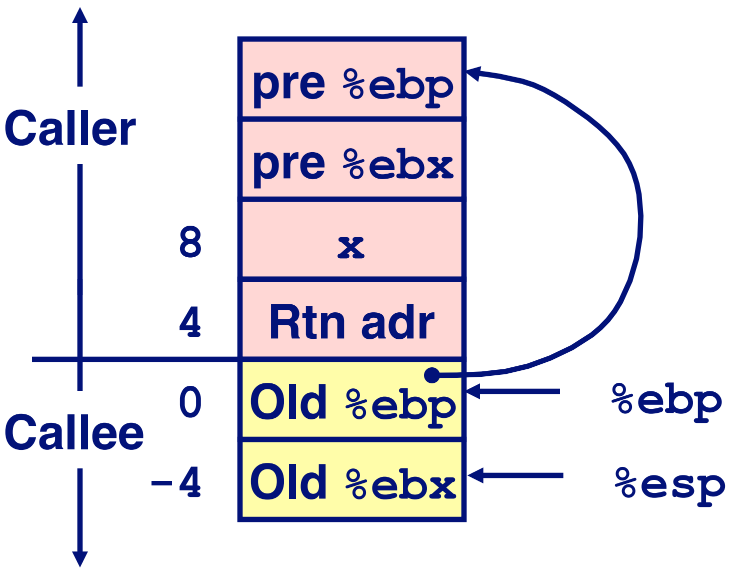
```
.globl rfact
    .type
rfact,@function
rfact:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
    movl 8(%ebp),%ebx
    cmpl $1,%ebx
    jle .L78
    leal -1(%ebx),%eax
    pushl %eax
    call rfact
    imull %ebx,%eax
    jmp .L79
    .align 4
.L78:
    movl $1,%eax
.L79:
    movl -4(%ebp),%ebx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

Rfact Stack Setup



Entering Stack

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



Rfact Body

```
  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:
```

Recursion

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

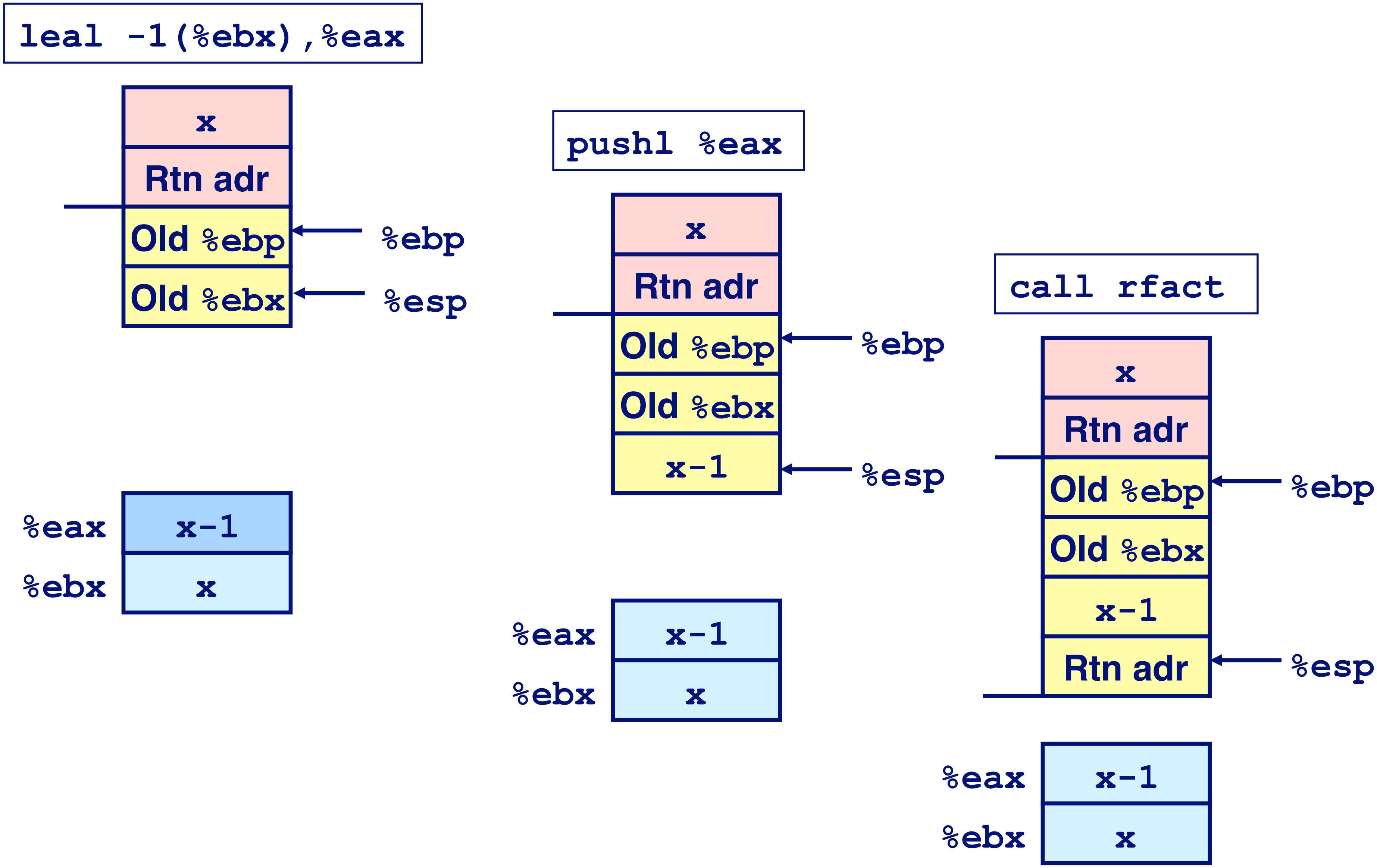
Registers

`%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
```

x

Rtn adr

Old %ebp ← %ebp

Old %ebx ← %esp

%eax x-1

%ebx x

```
pushl %eax
```

x

Rtn adr

Old %ebp ← %ebp

Old %ebx

x-1 ← %esp

%eax x-1

%ebx x

```
call rfact
```

x

Rtn adr

Old %ebp ← %ebp

Old %ebx

x-1

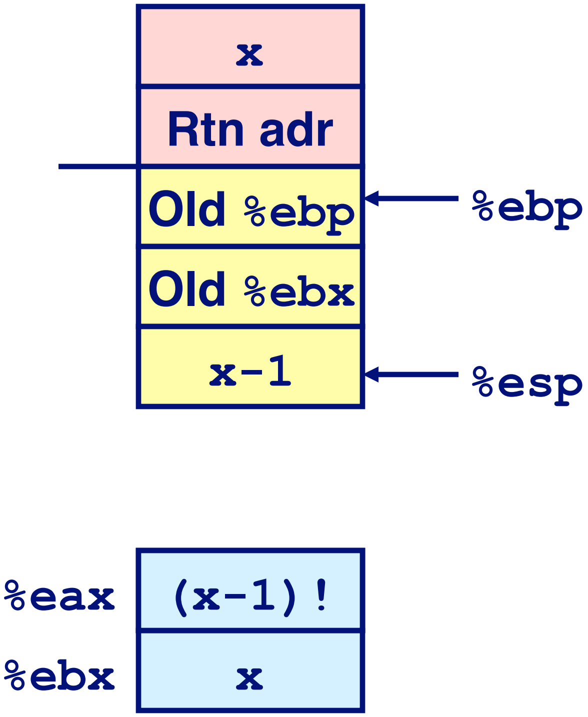
Rtn adr ← %esp

%eax x-1

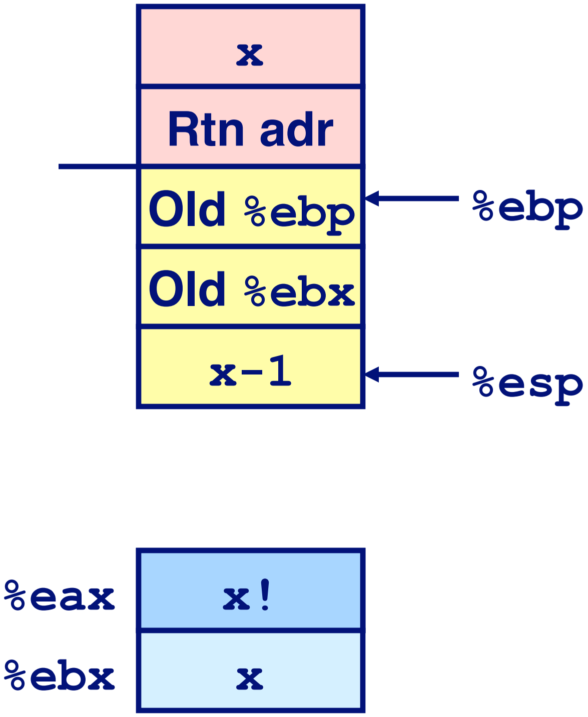
%ebx x

Rfact Result

Return from Call



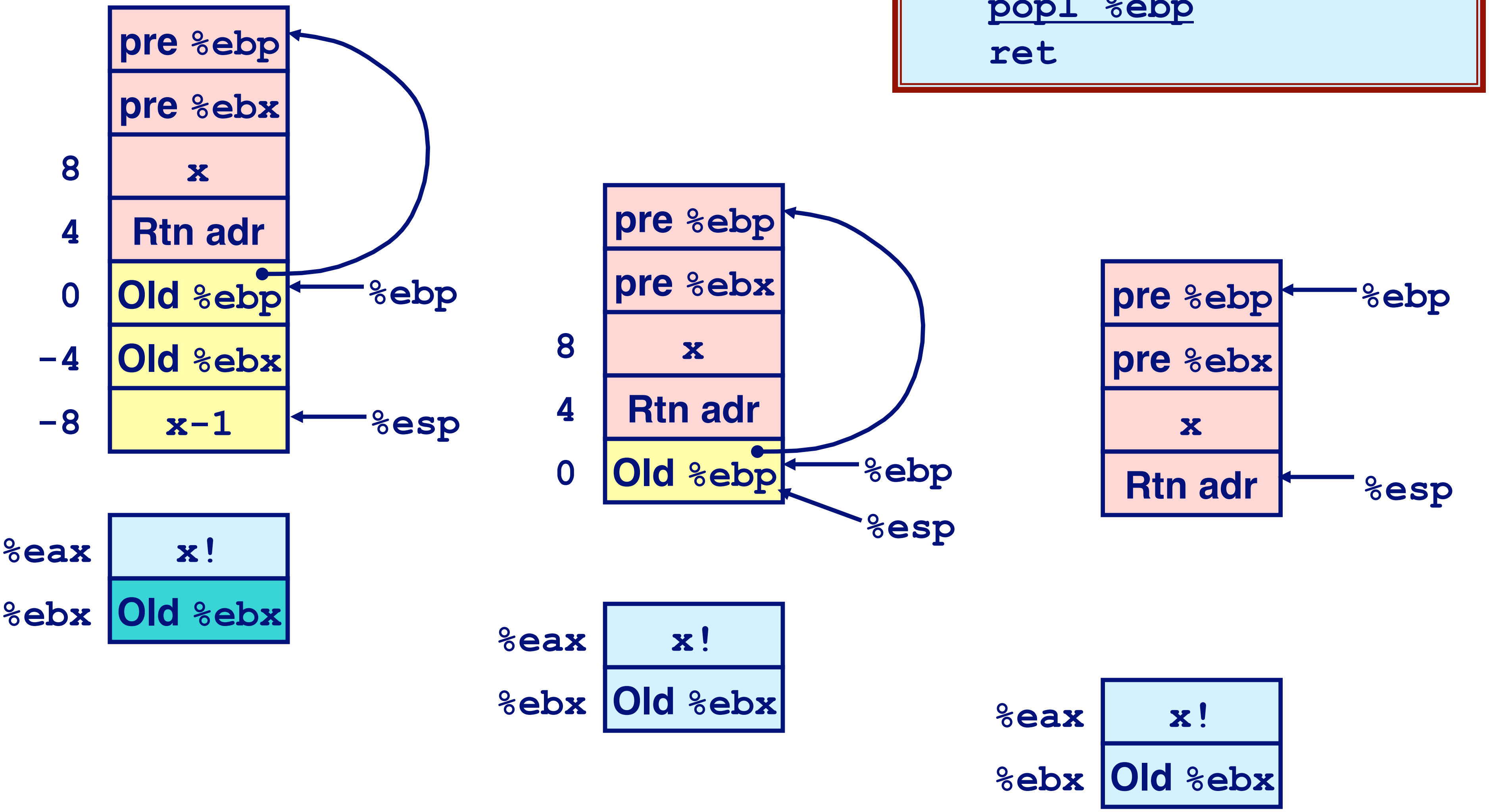
```
imull %ebx,%eax
```



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

Rfact Completion

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



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