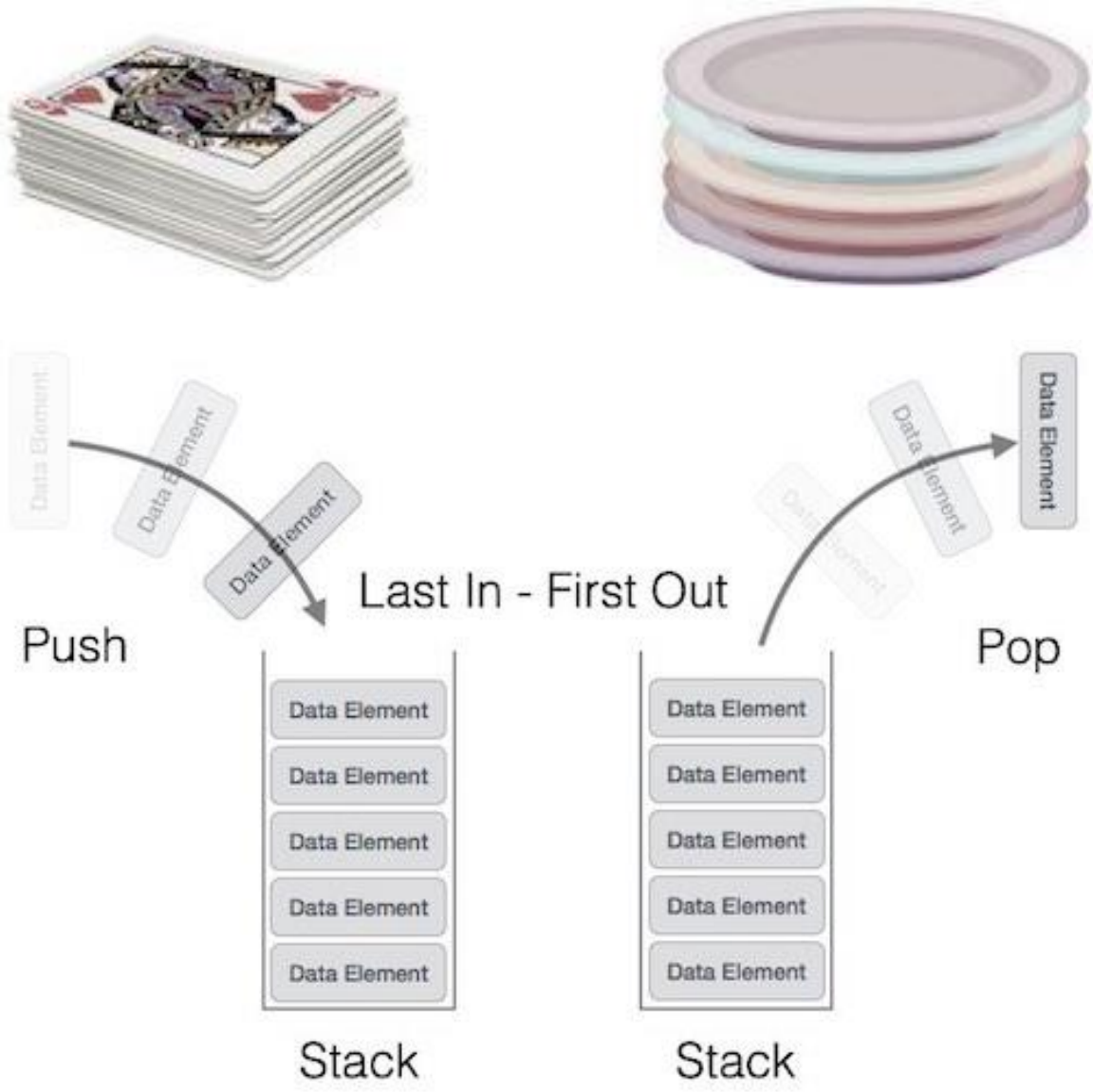
Assembly III: Procedures

Jo, Heeseung

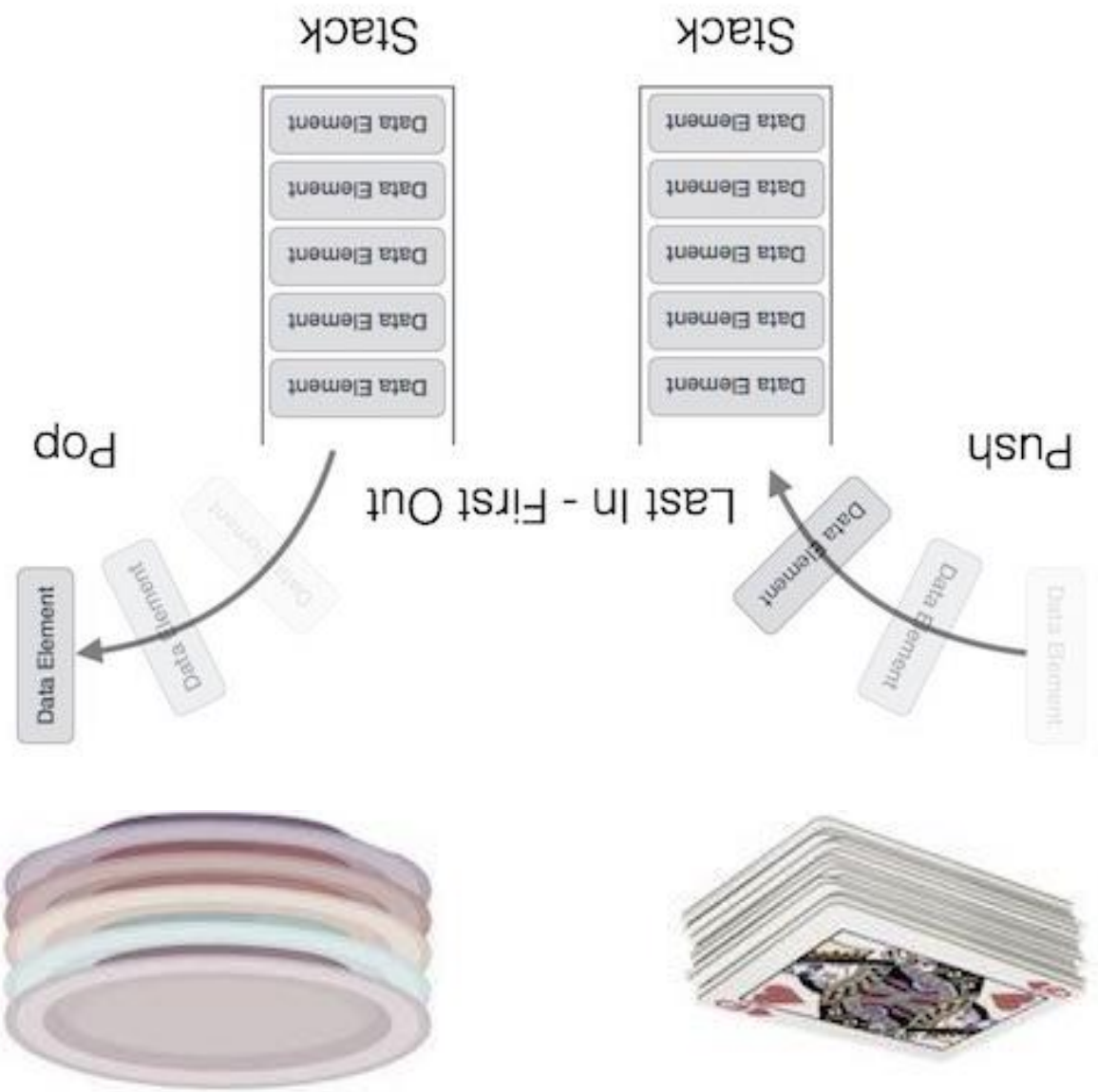
Stack structure

Stack



Stack structure

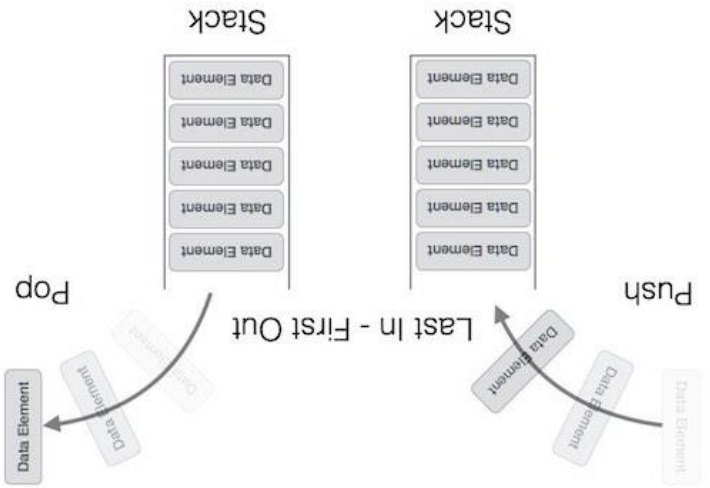
Stack

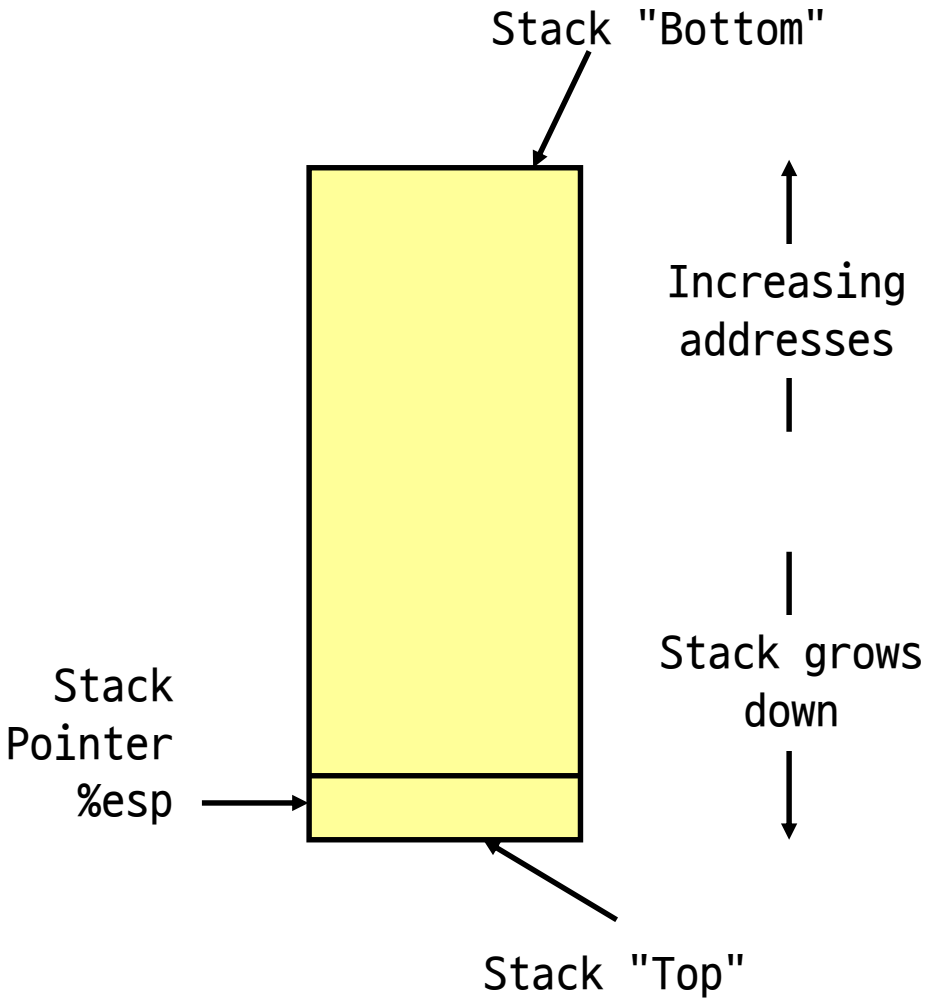


IA-32 Stack (1)

Characteristics

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

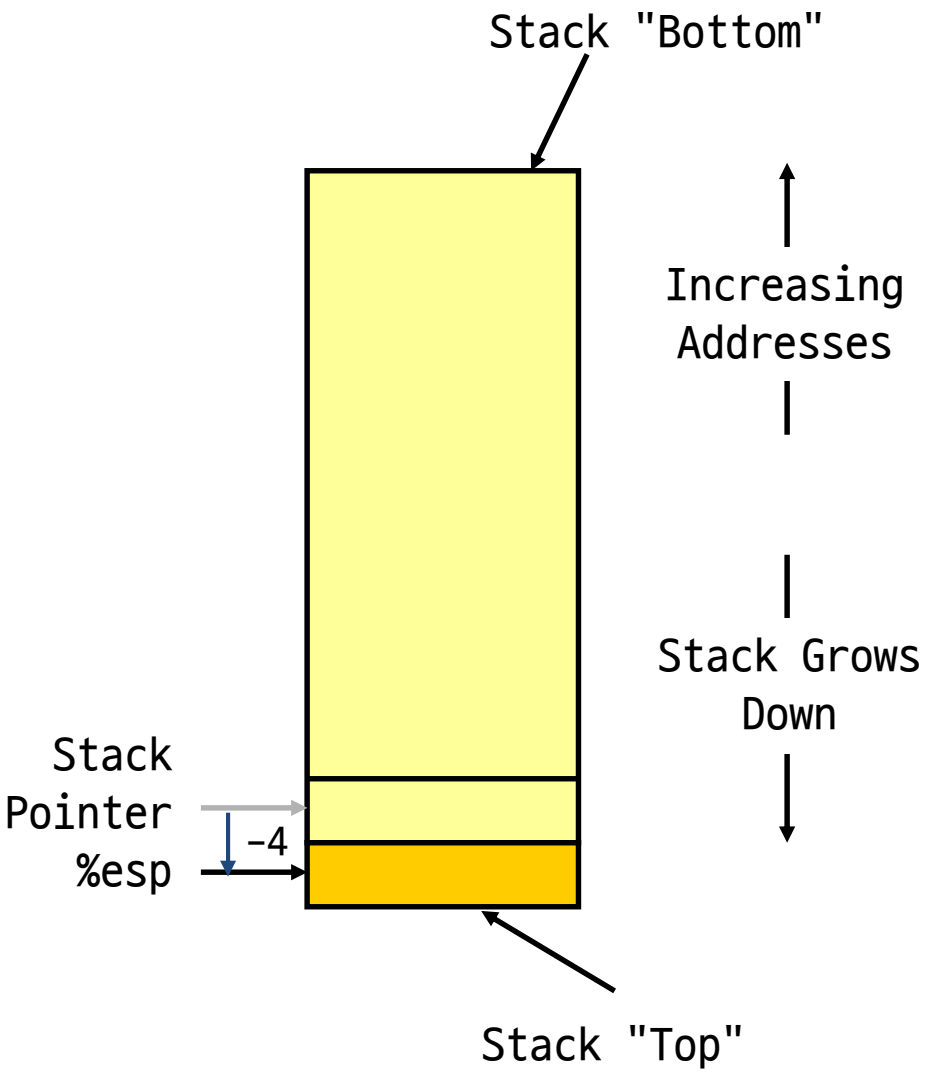




IA-32 Stack (2)

Pushing

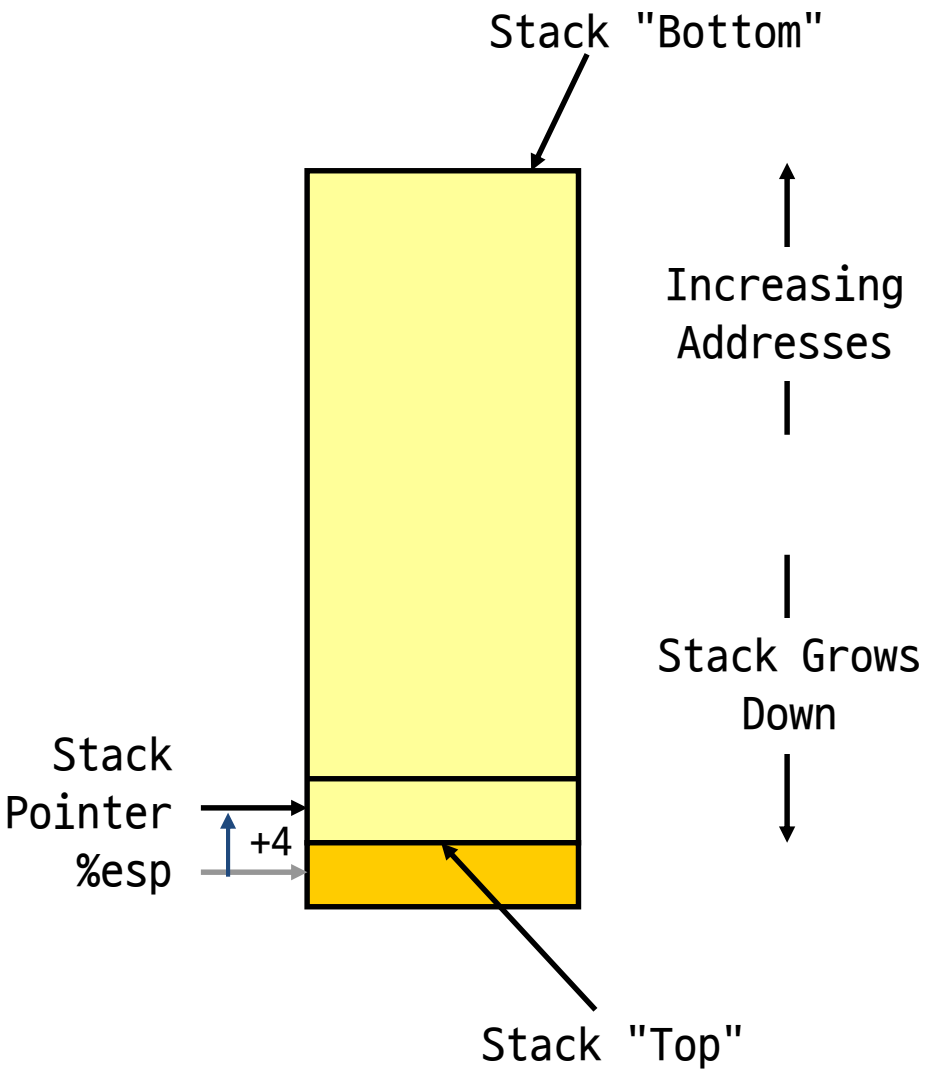
- **pushl Src**
- Fetch operand at Src
- Decrement **%esp** by 4
- Write operand at address given by **%esp**



IA-32 Stack (3)

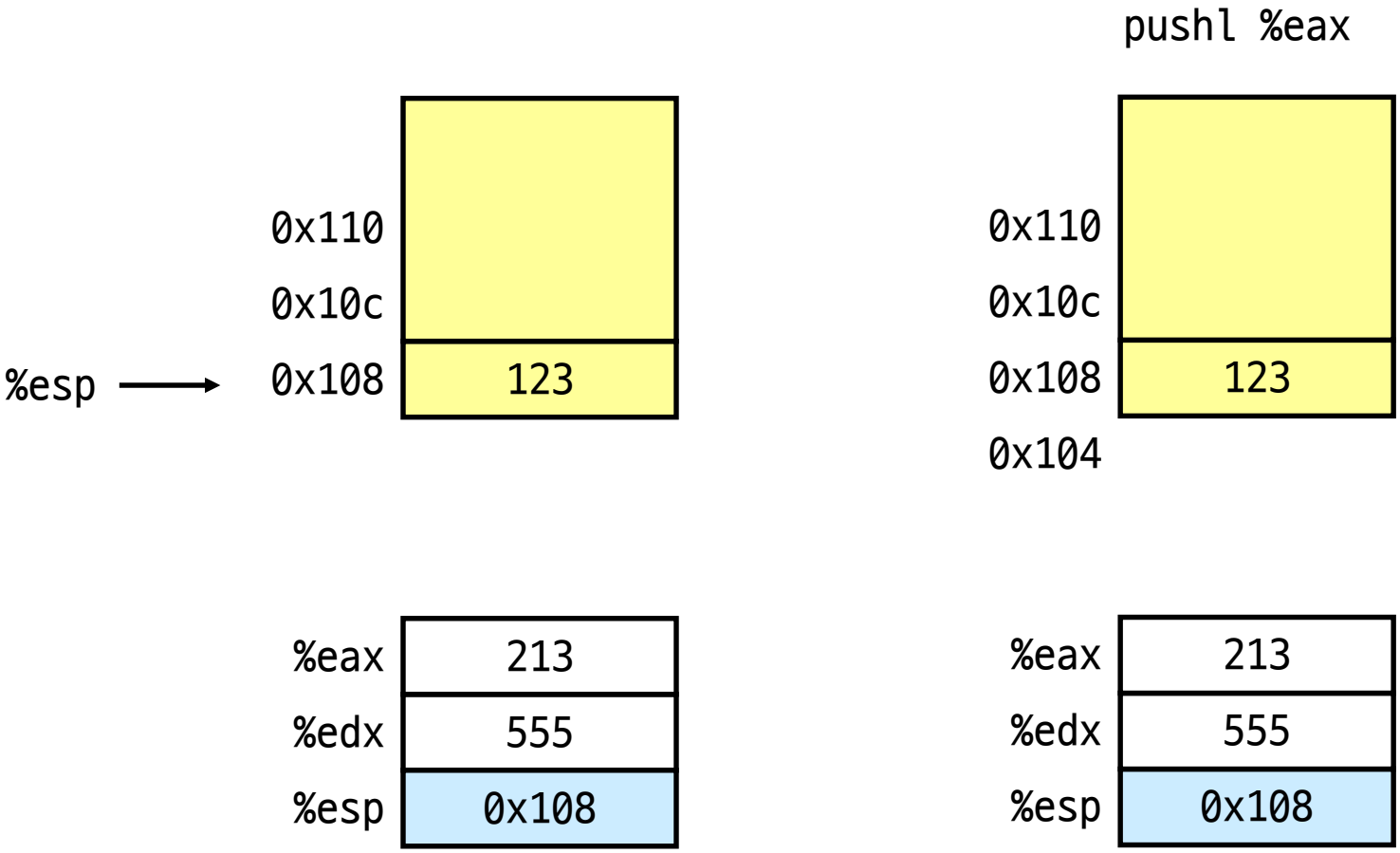
Popping

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



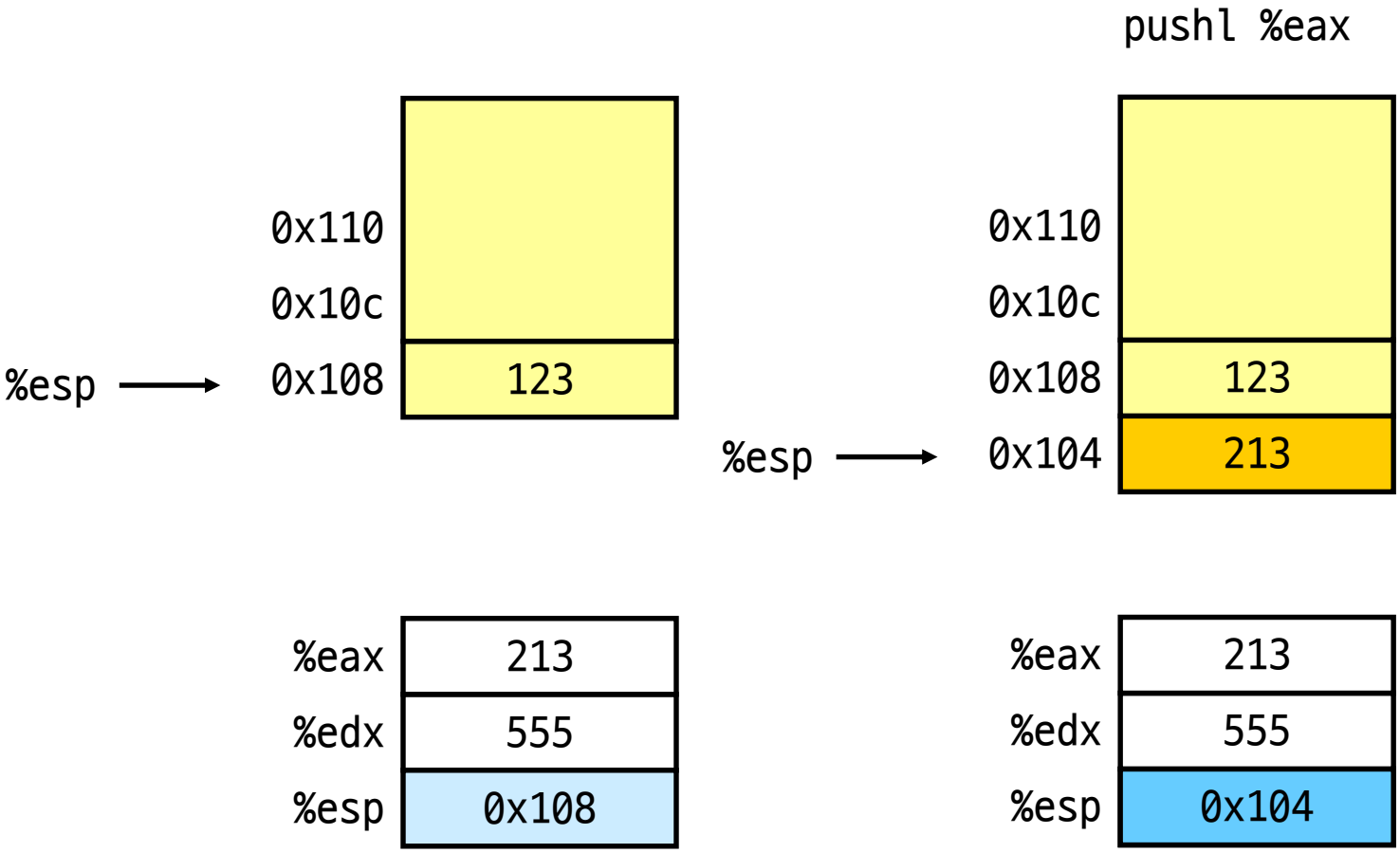
IA-32 Stack (4)

Stack operation examples



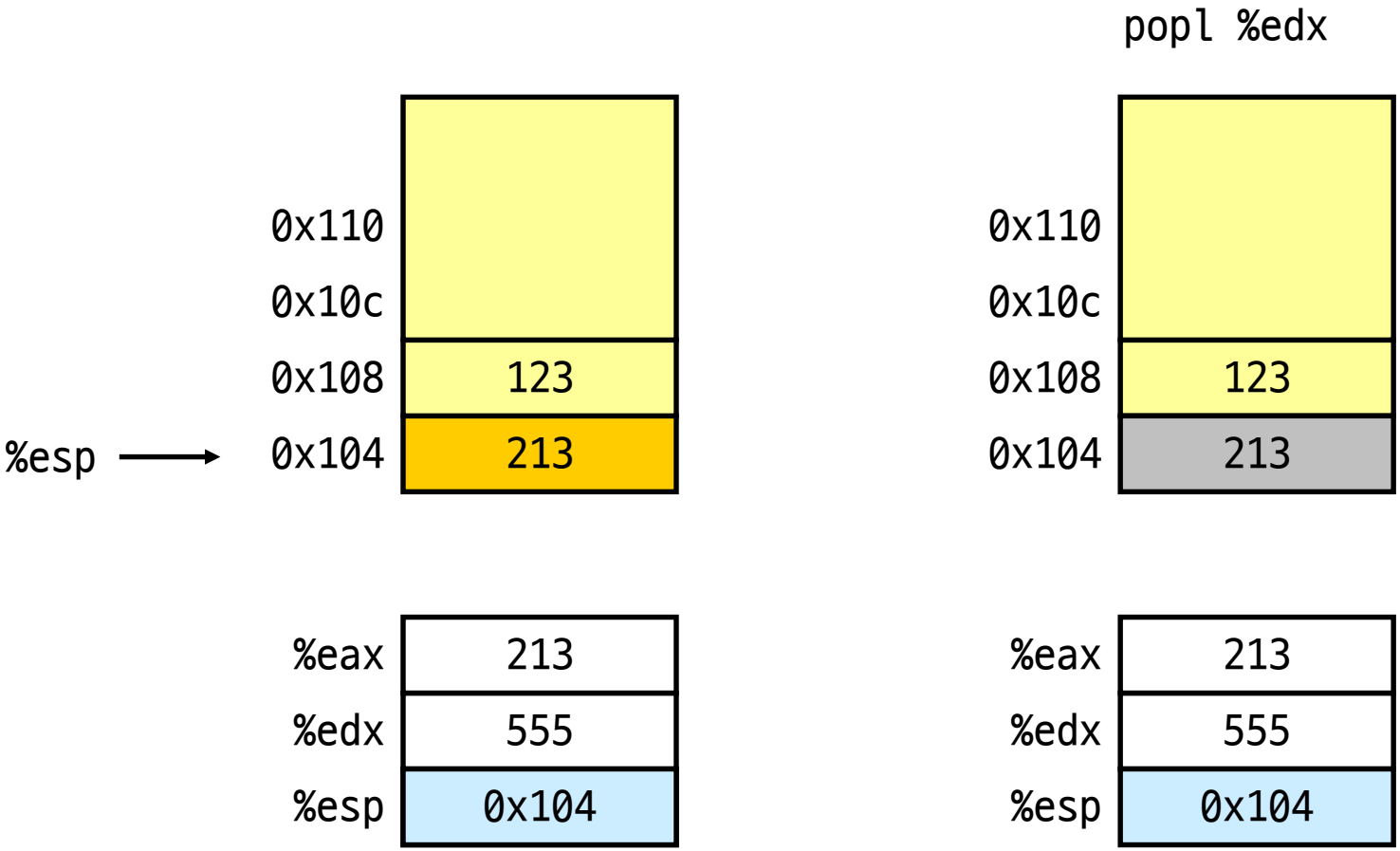
IA-32 Stack (4)

Stack operation examples



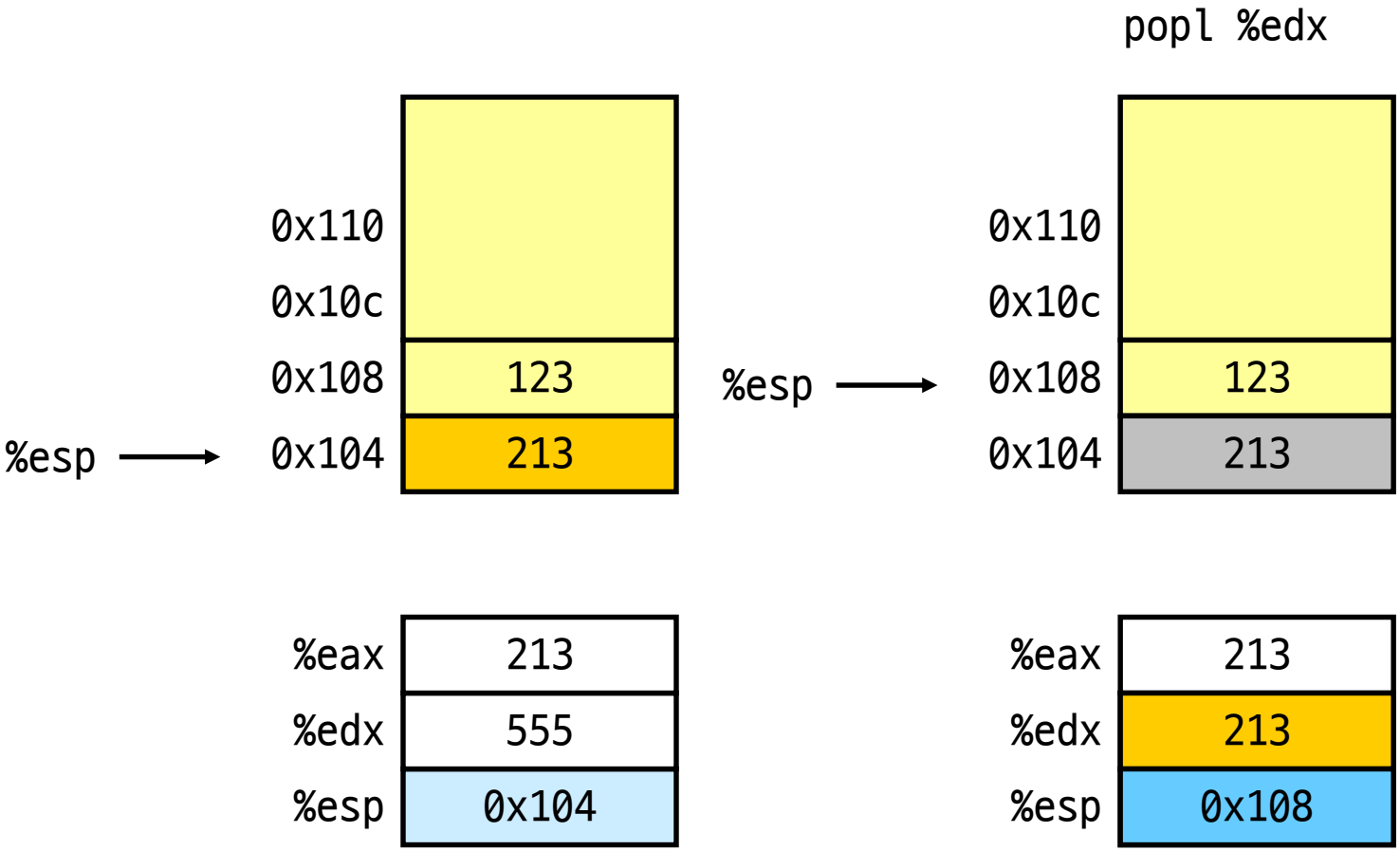
IA-32 Stack (4)

Stack operation examples



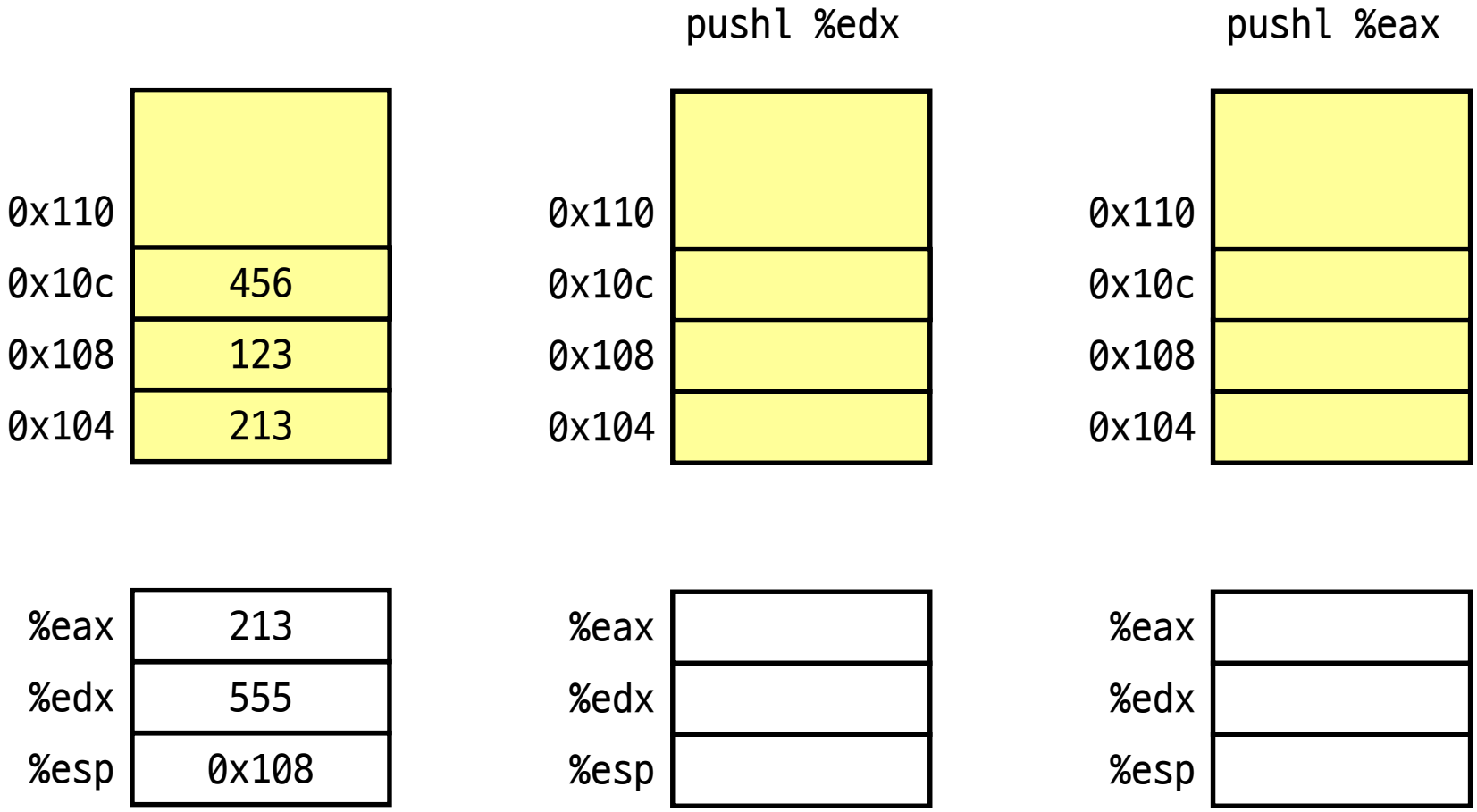
IA-32 Stack (4)

Stack operation examples



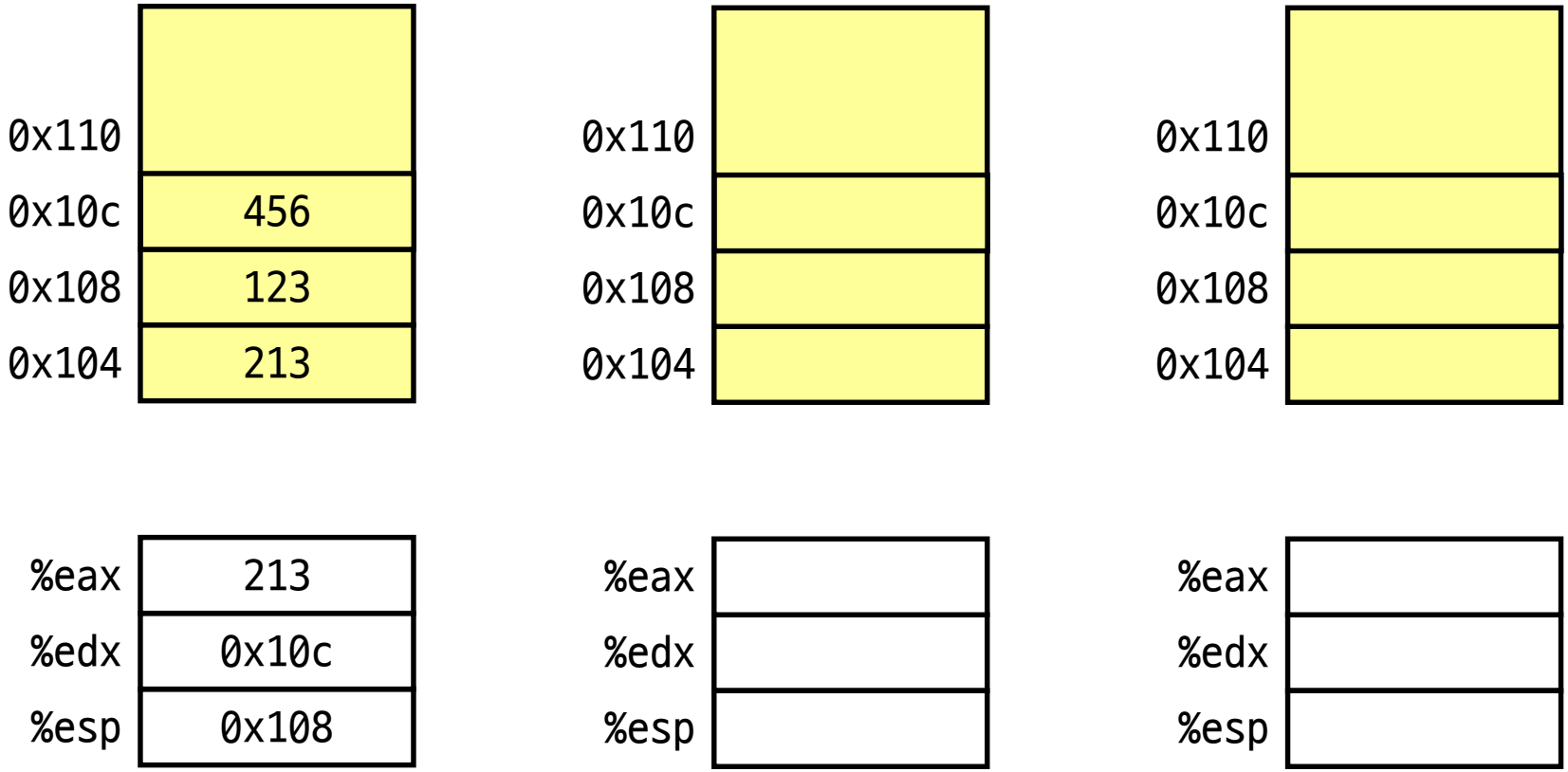
IA-32 Stack (5)

Exercise



IA-32 Stack (6)

Exercise



Procedure Control Flow

Use stack to support procedure call and return

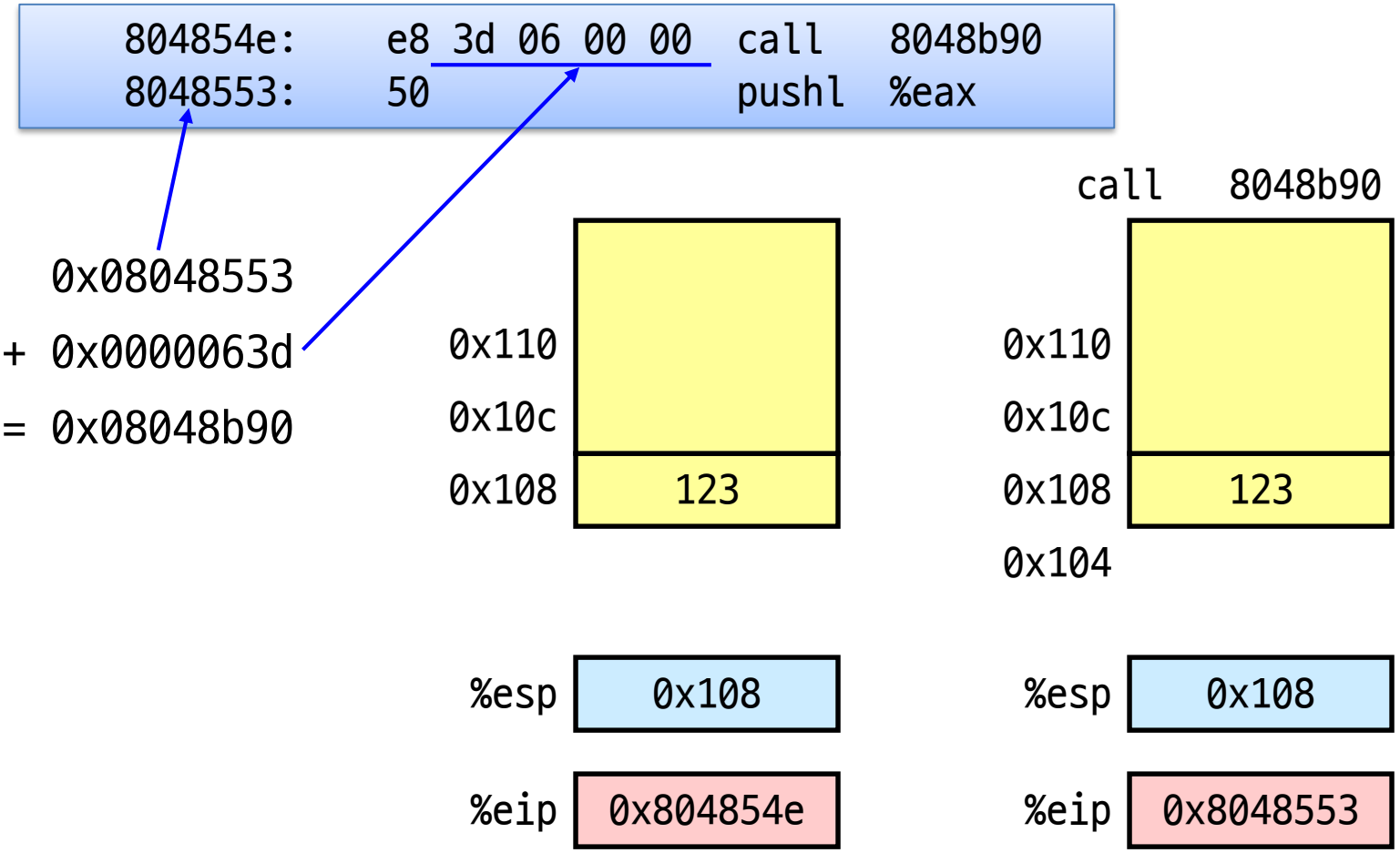
Procedure call

- **call** *label*
  1. Push return address (current EIP register value) on stack
  2. Jump to *label*
- Return address value
  - Address of instruction beyond call

Procedure return

- **ret**
  1. Pop return address from stack
  2. Jump to address

Procedure Call Example



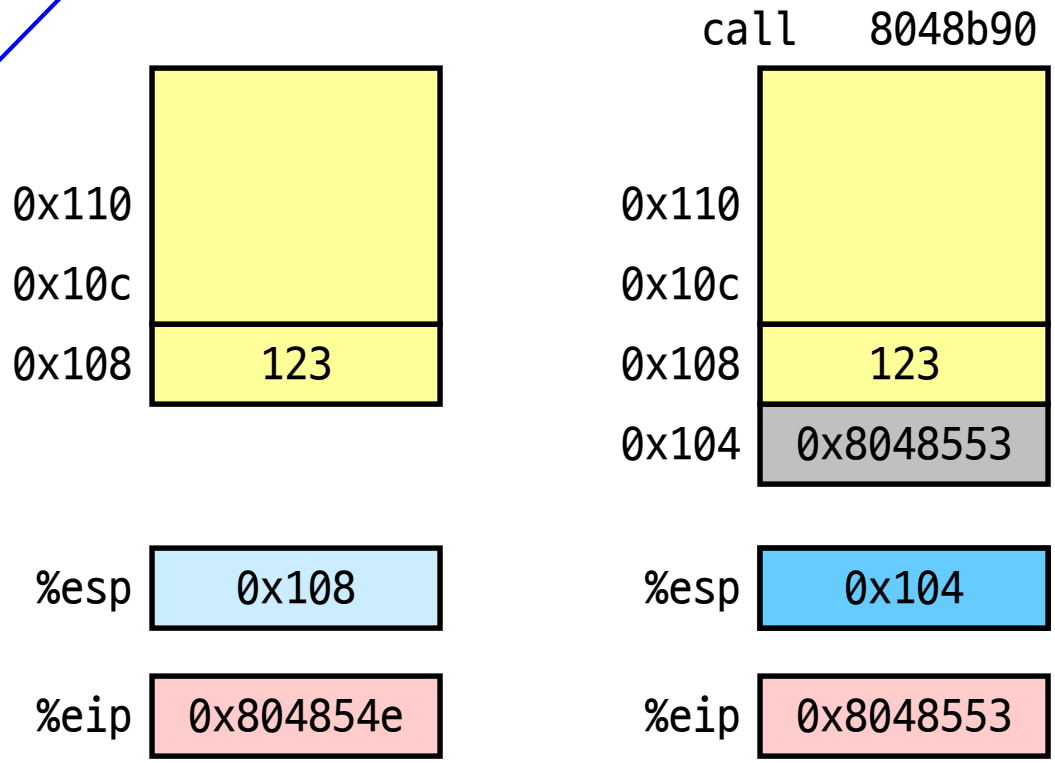
call label

1. Push return address (current EIP register value) on stack
2. Jump to *label*

Procedure Call Example

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

0x08048553
+ 0x0000063d
= 0x08048b90



%eip is program counter

call label

1. Push return address (current EIP regstger value) on stack
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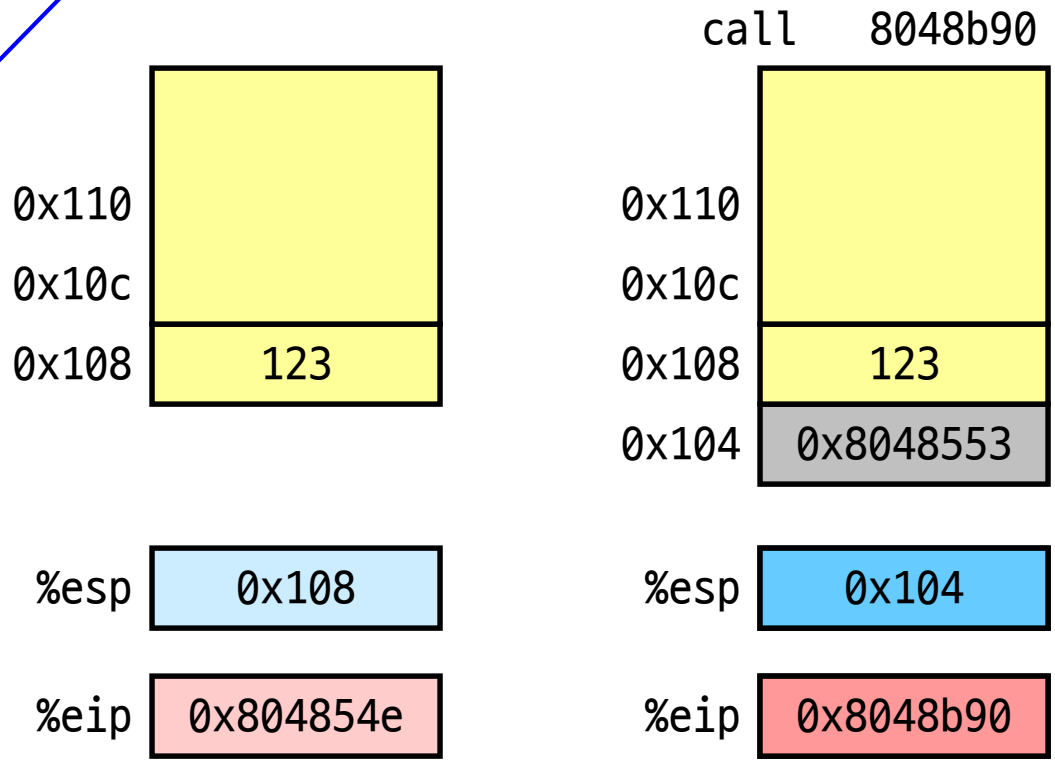
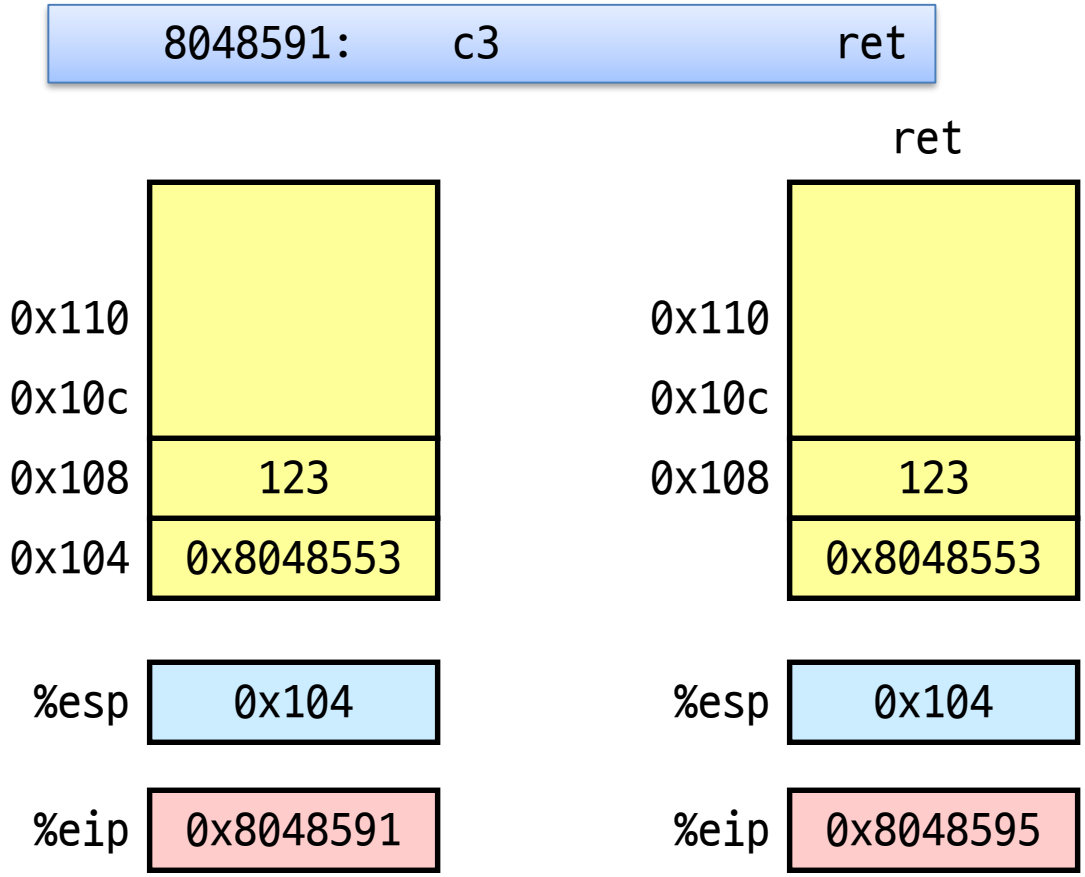


%eip is program counter

call label

1. Push return address (current EIP regstger value) on stack
2. Jump to *label*

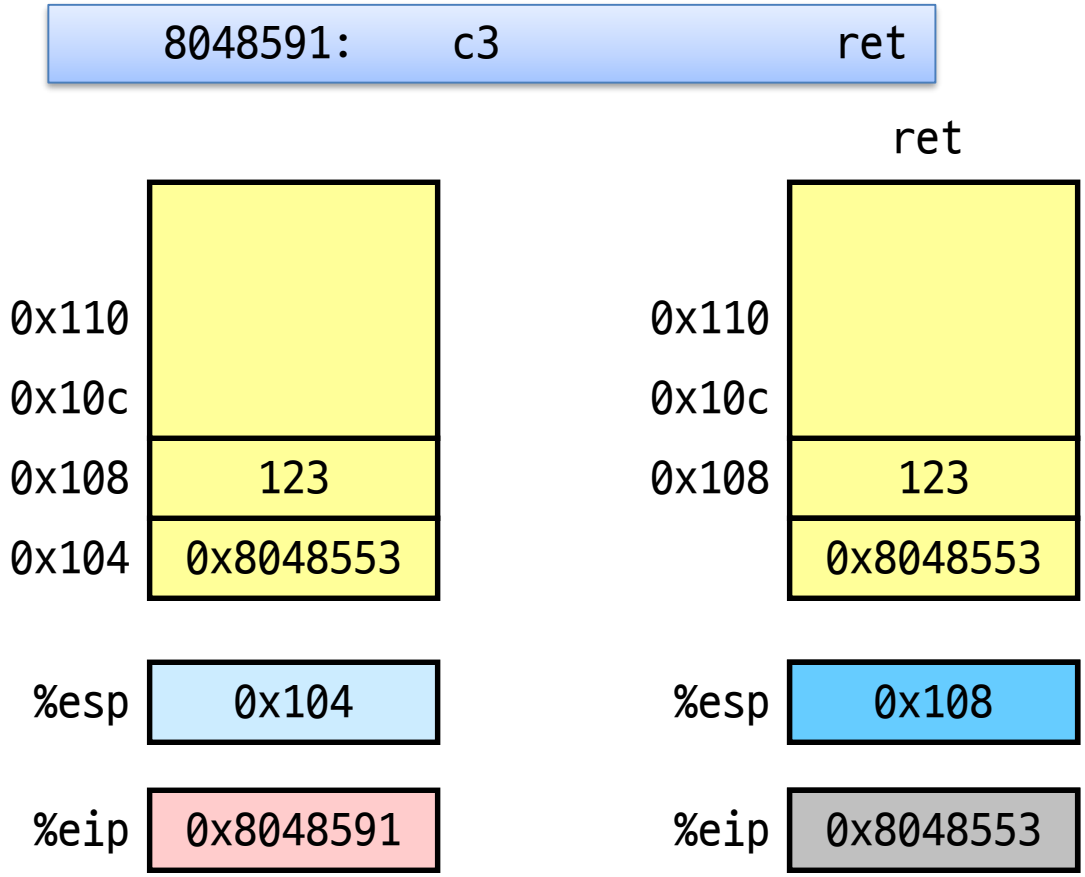
Procedure Return Example



%eip is program counter

ret
1. Pop return address from stack
2. Jump to address

Procedure Return Example



%eip is program counter

ret
1. Pop return address from stack
2. Jump to address

Return Value (1)

How does callee function send return value back to caller function?

In principle

- Store return value in stack frame of caller

Or, for efficiency

- Known small size => store return value in register
- Other => store return value in stack

Return Value (2)

IA-32 Convention

Integral type or pointer

- Store return value in EAX register
- char, short, int, long, pointer

Floating-point type

- Store return value in floating point register
- Beyond scope of course

Structure

- Store return value on stack
- Beyond scope of course

Recursive vs. Iteration

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

```
int whilefact(int x)
{
  int rval = 1;
  while (x > 1) {
    rval = rval * x;
    x = x - 1;
  }
  return rval;
}
```

Stack-based Languages (1)

Languages that support recursion

- e.g., C, Pascal, Java, etc.
- Code must be "Reentrant"
  - Multiple simultaneous instantiations of single procedure
- Need some place to store state of each instantiation
  - Arguments, local variables, return pointer

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

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

Stack-based Languages (2)

Stack discipline

- State for given procedure needed for limited time
  - From when called to when return
- Callee returns before caller does

Stack frame

- State for single procedure instantiation

Stack Frames (1)

Code Structure

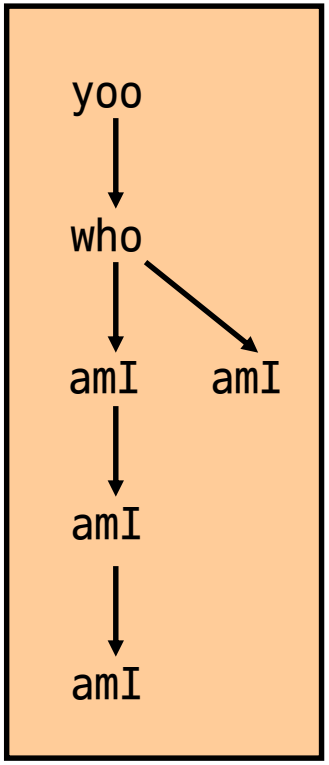
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

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

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

Procedure amI recursive

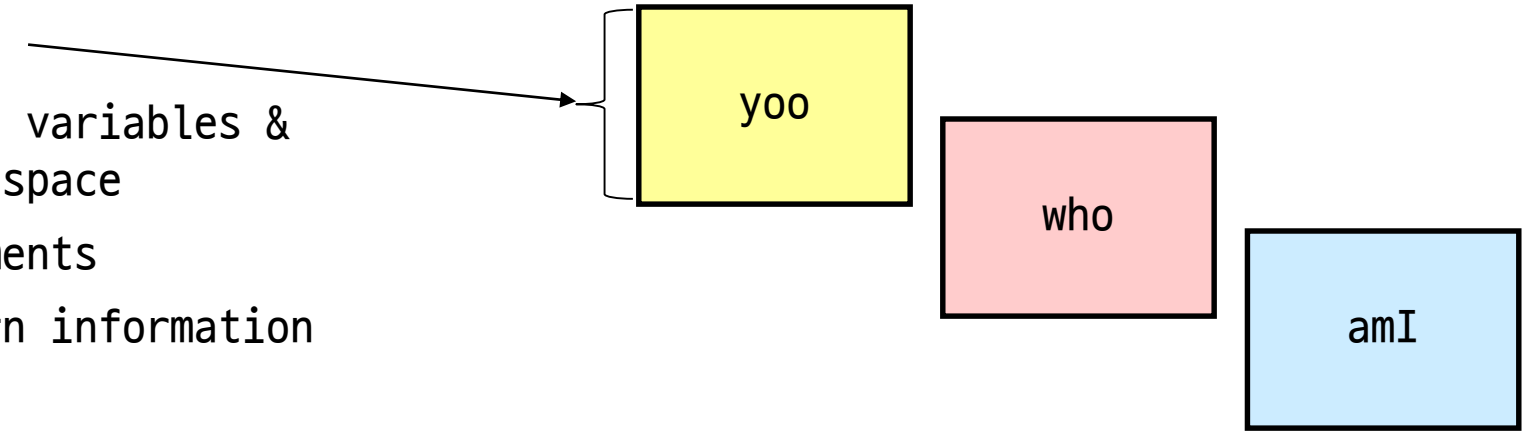
Call Chain



Stack Frames (2)

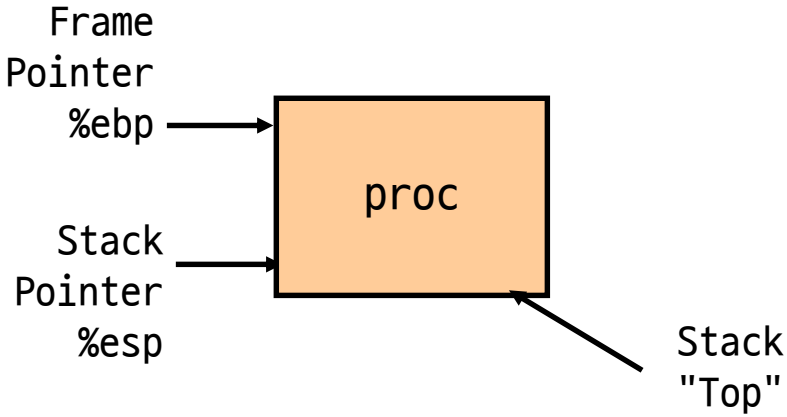
Contents

- Local variables & temp space
- Arguments
- Return information



Management

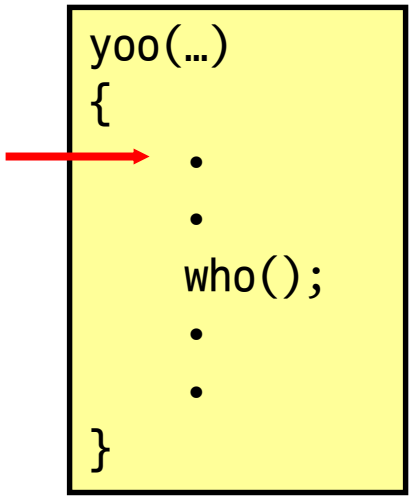
- Space allocated when enter procedure
  - "set-up" code
- Deallocated when return
  - "finish" code



Pointers

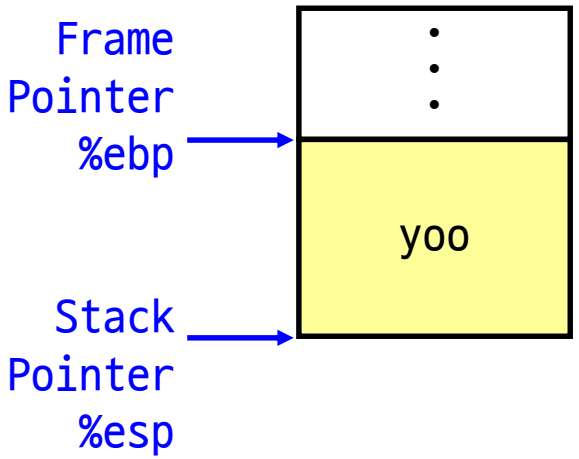
- Stack pointer %esp indicates stack top
- Frame pointer %ebp indicates start of current frame

Stack Frames (3)

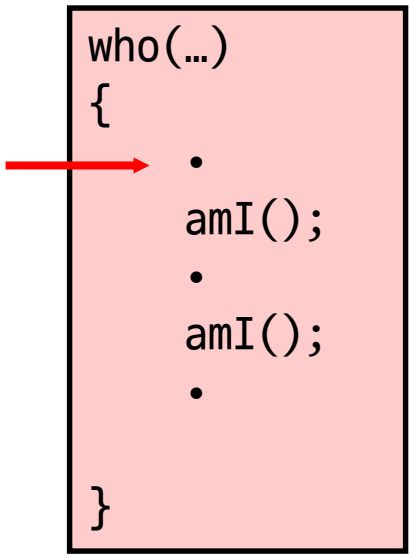


Call Chain

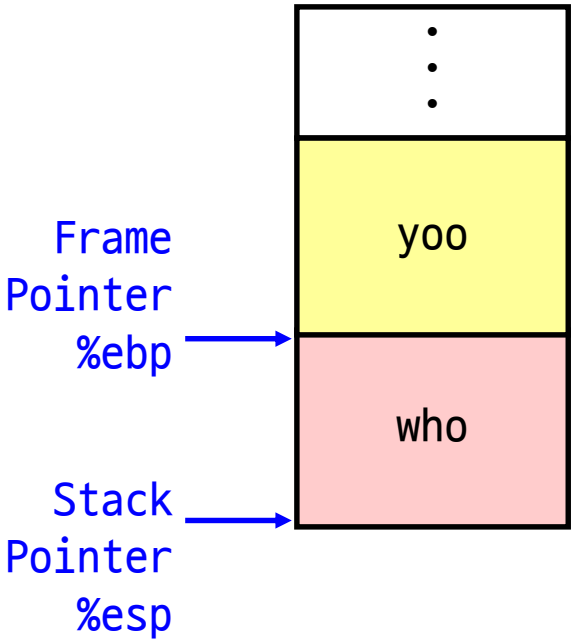
yoo



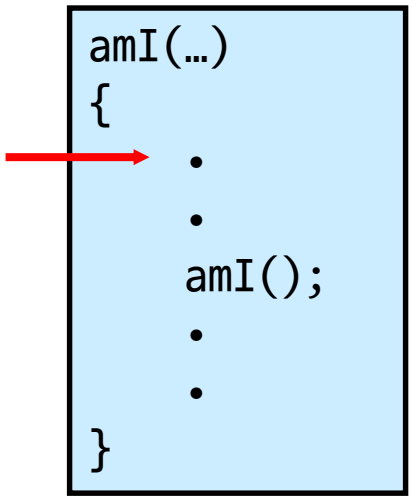
Stack Frames (4)



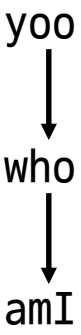
Call Chain

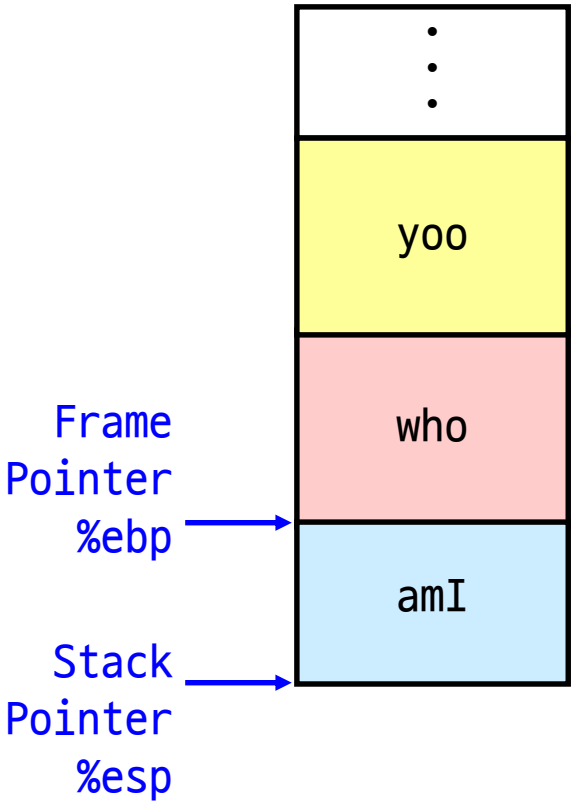


Stack Frames (5)

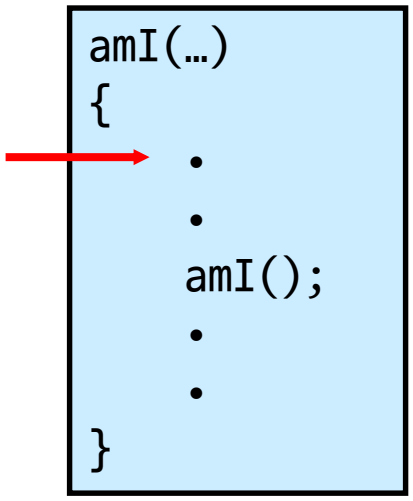


Call Chain

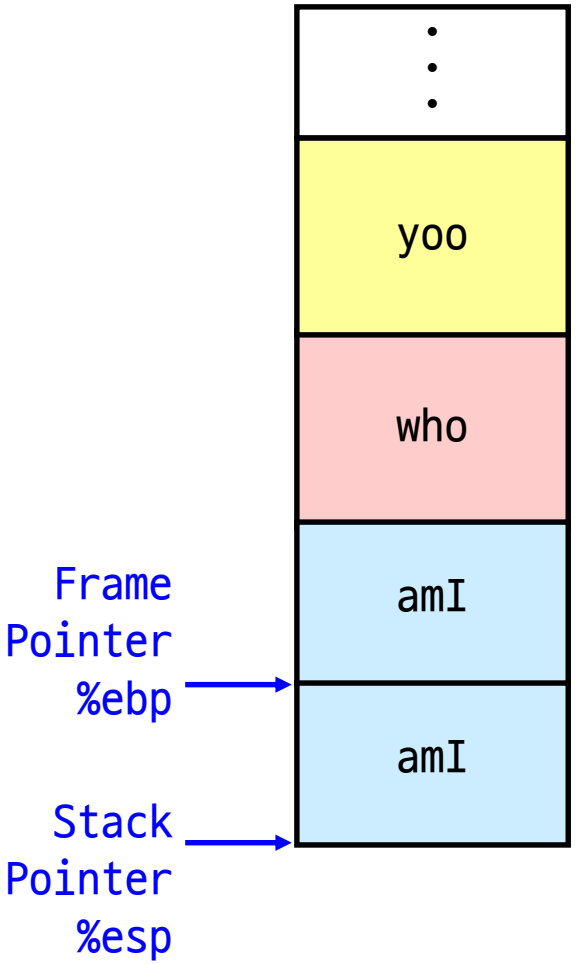




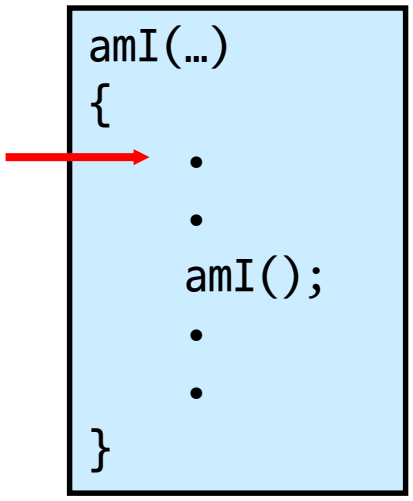
Stack Frames (6)



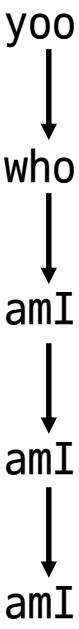
Call Chain

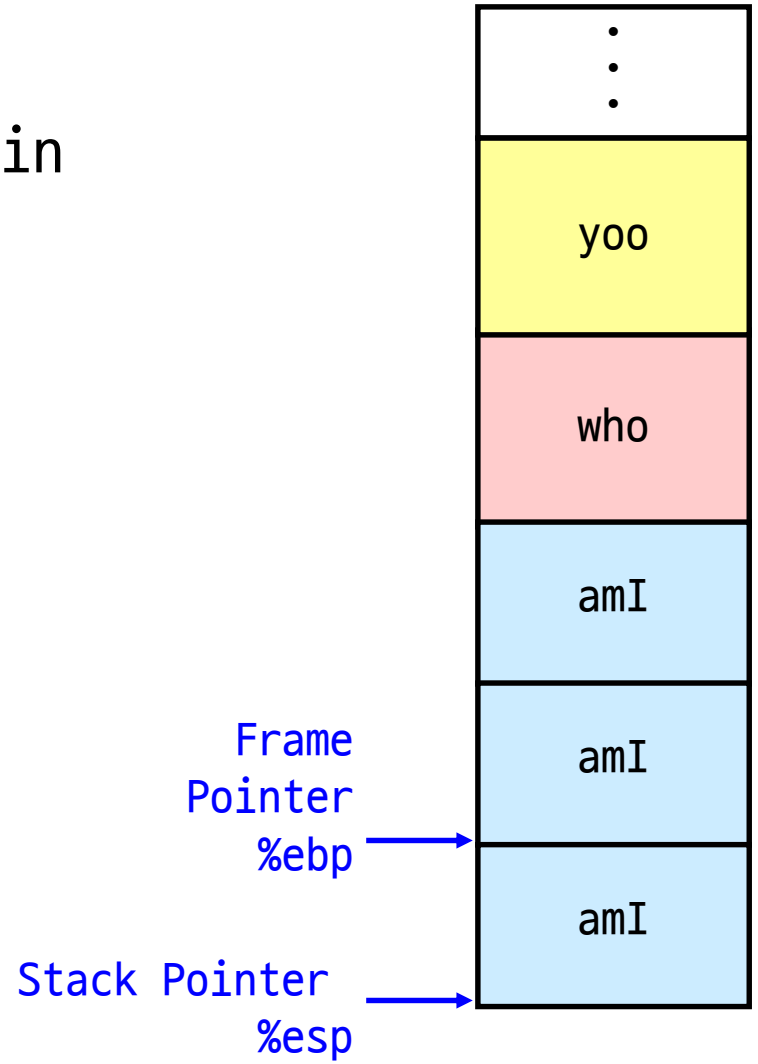


Stack Frames (7)

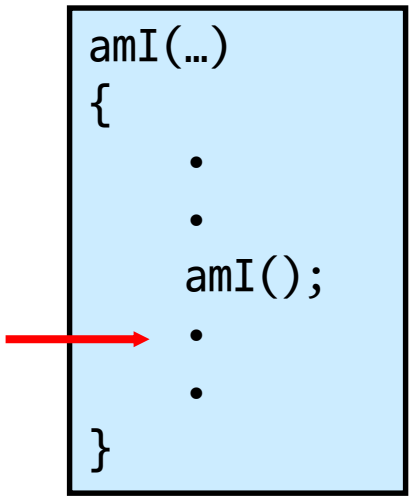


Call Chain

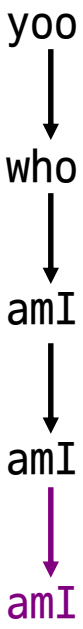


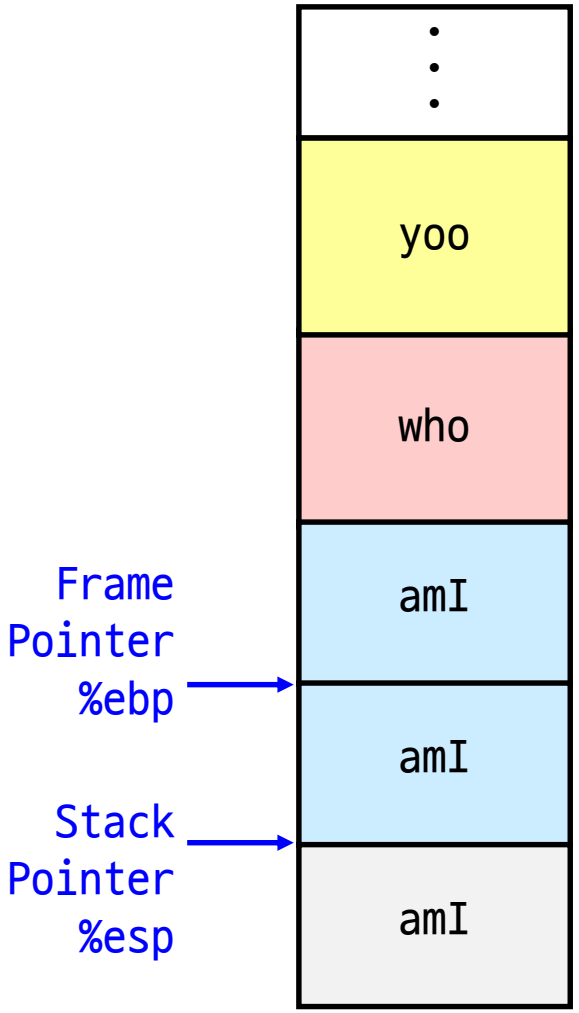


Stack Frames (8)

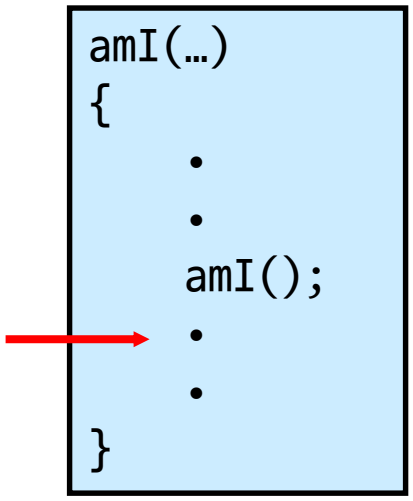


Call Chain

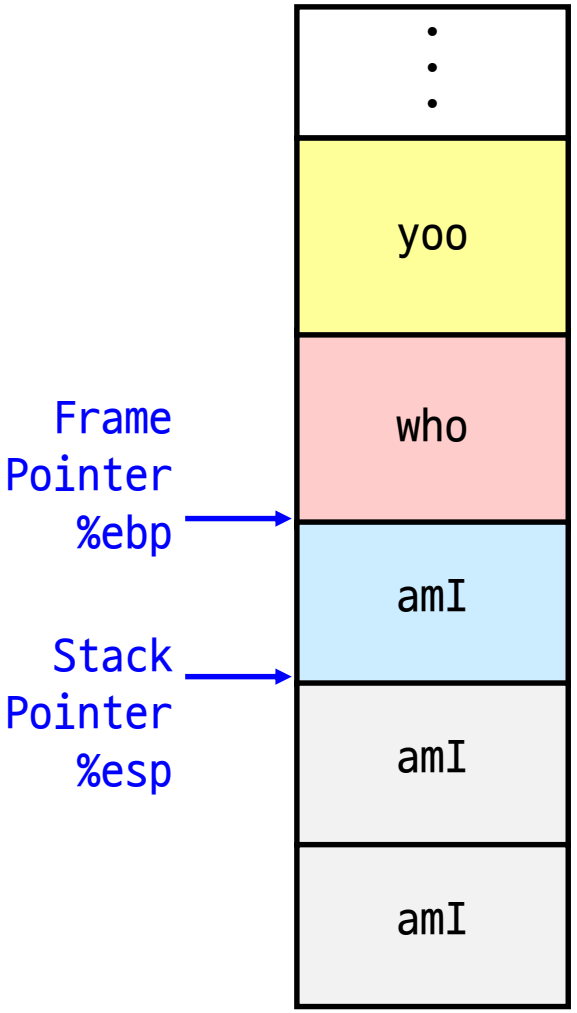




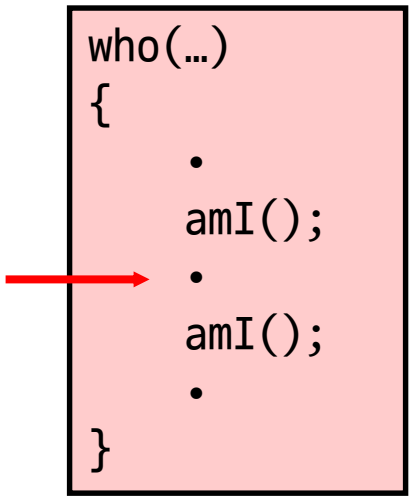
Stack Frames (9)



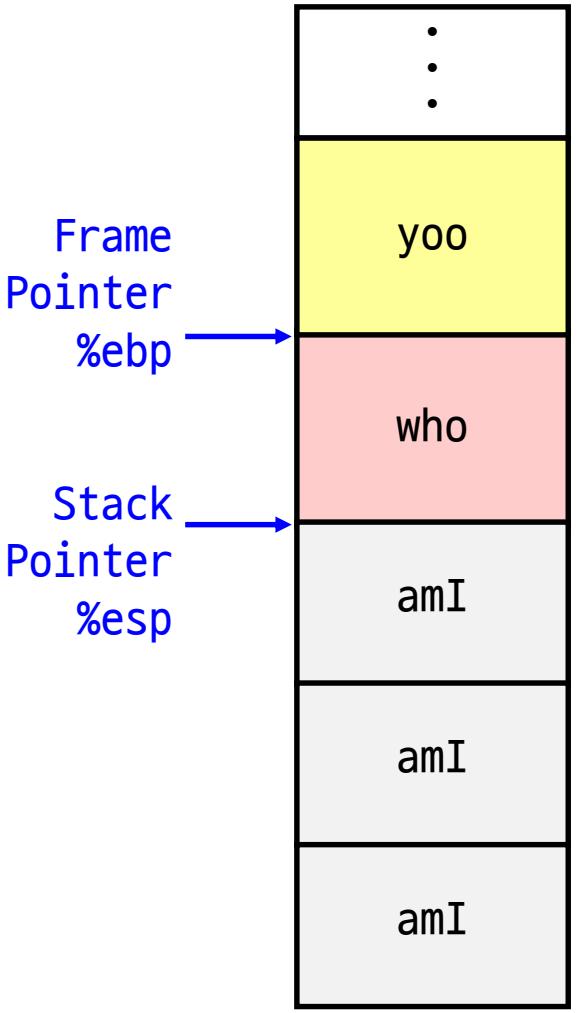
Call Chain



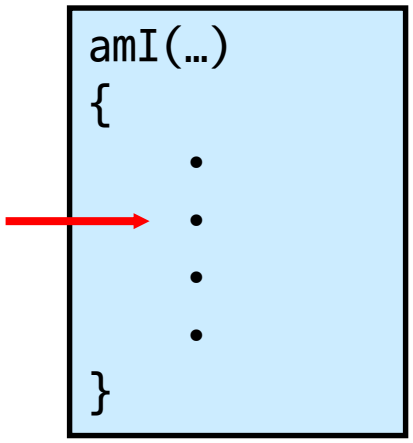
Stack Frames (10)



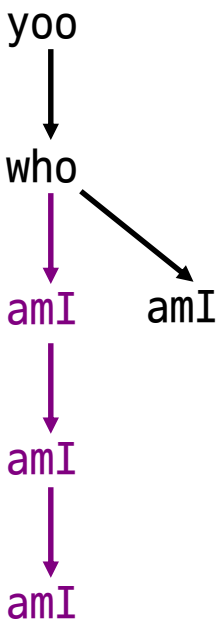
Call Chain

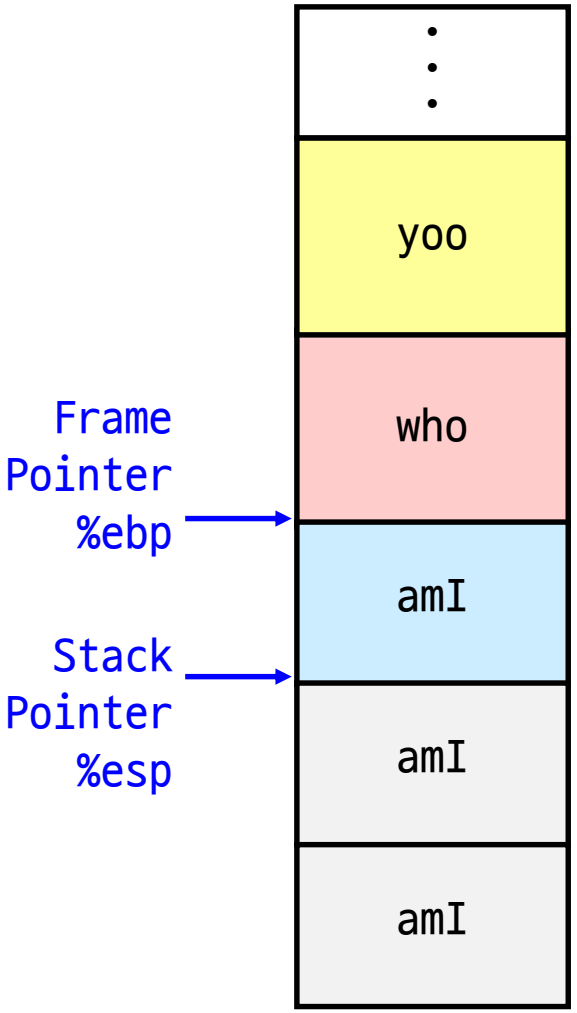


Stack Frames (11)

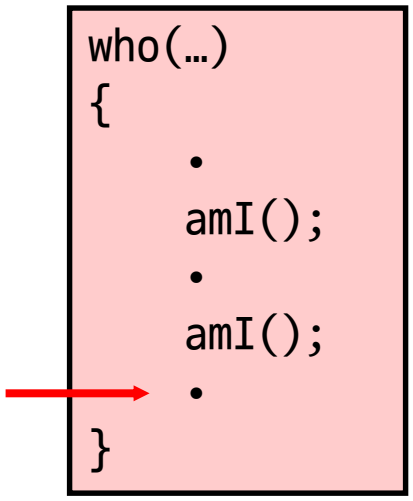


Call Chain

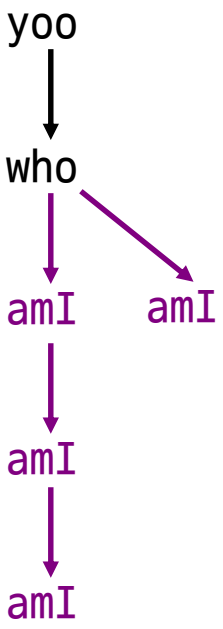


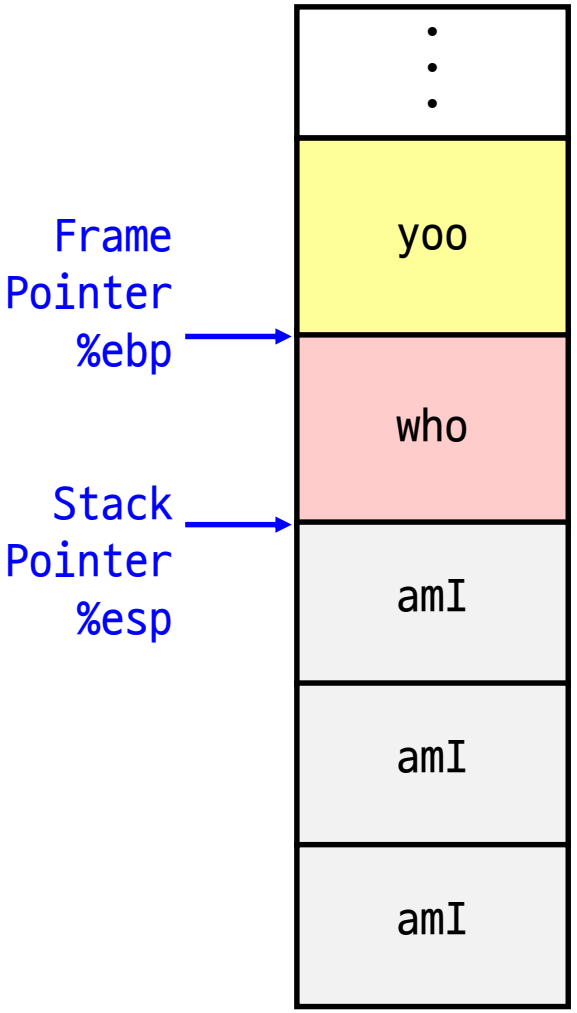


Stack Frames (12)

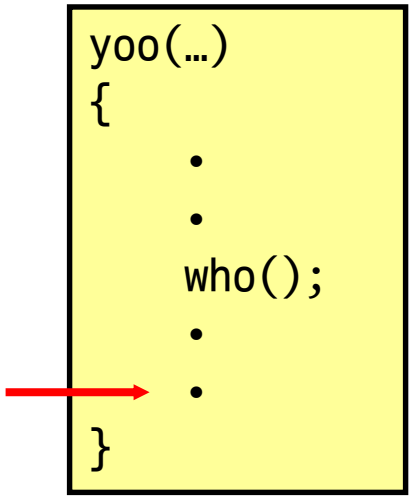


Call Chain

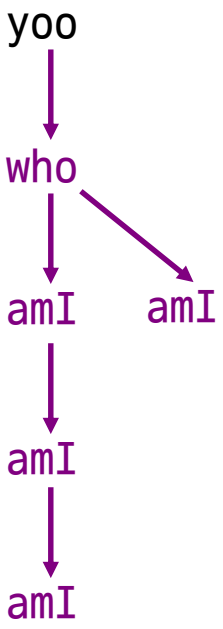


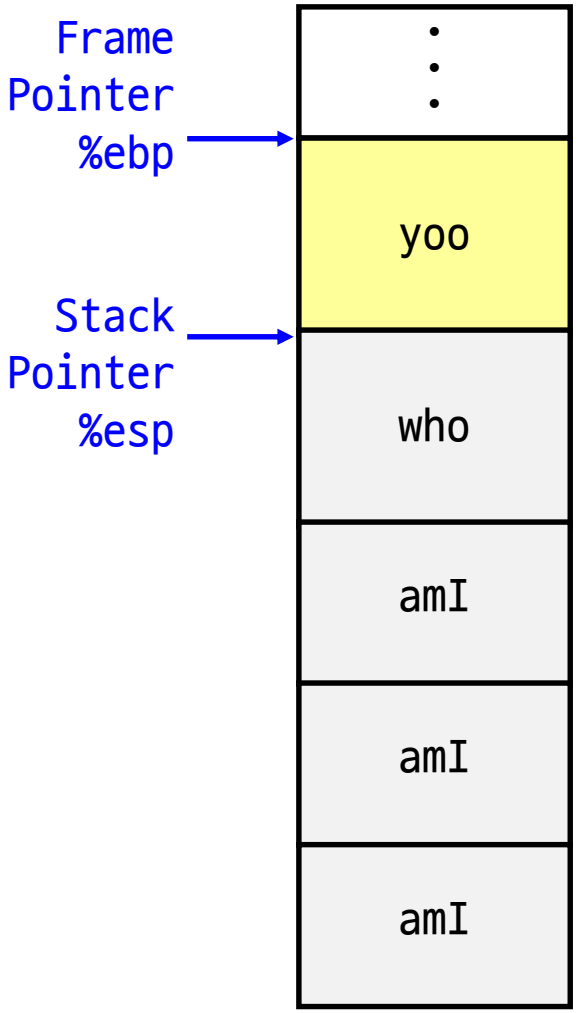


Stack Frames (13)



Call Chain





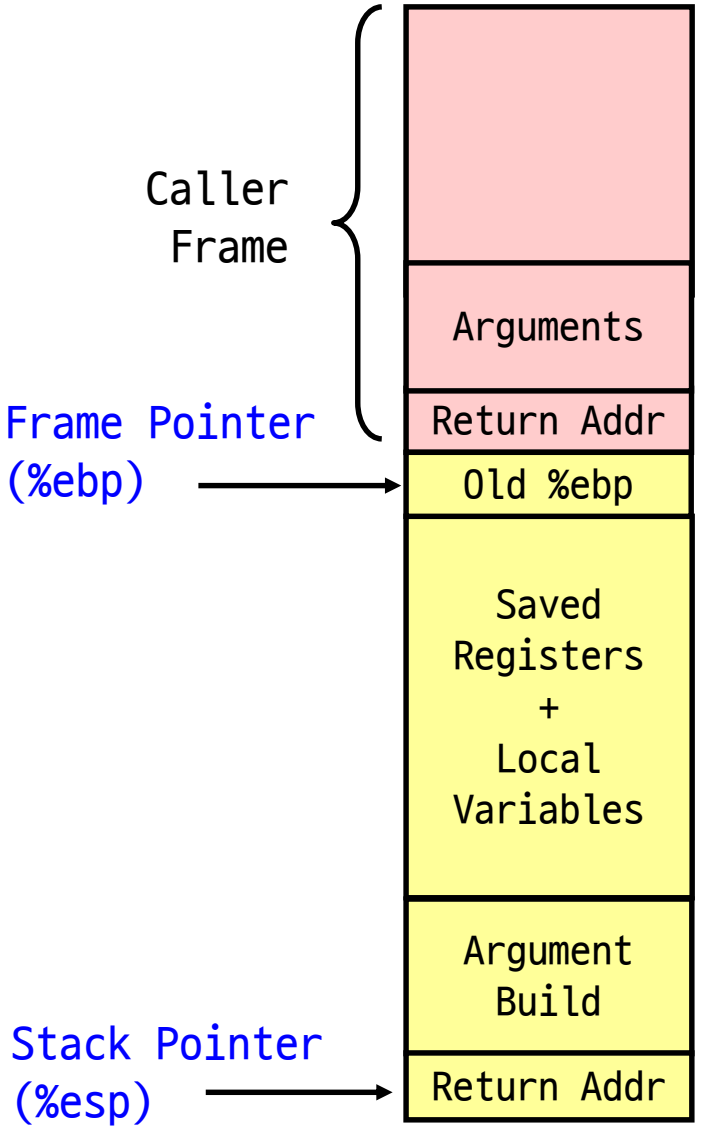
IA-32/Linux Stack Frame

Caller stack frame

- Arguments to call
- Return address
  - Pushed by call instruction

Current stack frame ("Top" to Bottom)

- Old frame pointer
- Saved register context
  - %ebx, %esi, %edi (callee-save)
- Local variables
  - If can't keep in registers
- If call another function,
- Parameters for function about to call
  - "Argument build"
- Return address



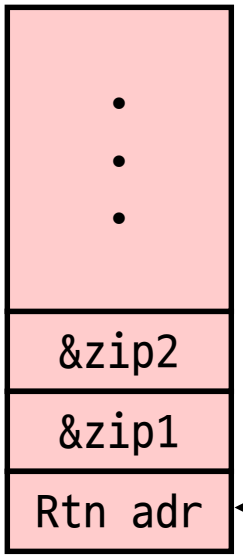
Revisiting swap (1)

```
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 (2)

```
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
```

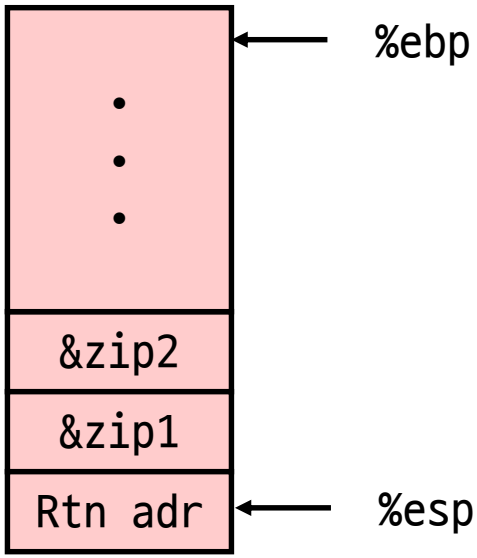
Setup

Body

Finish

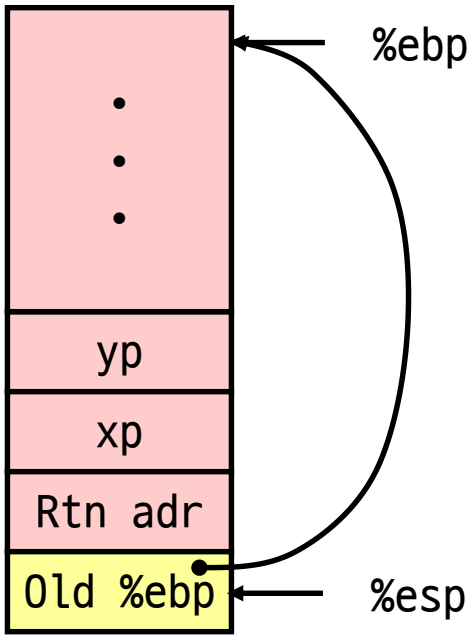
Swap Setup (1)

Entering Stack



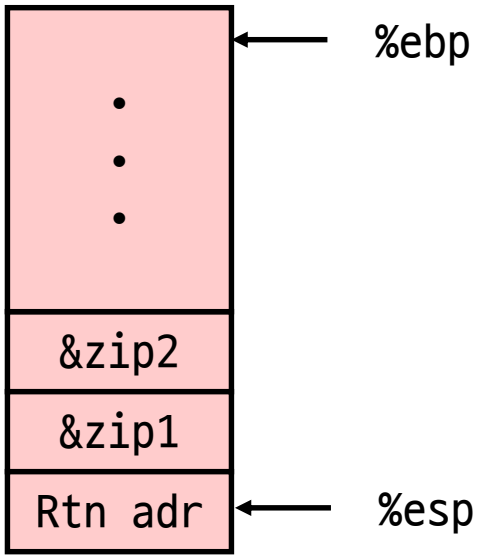

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

Resulting Stack



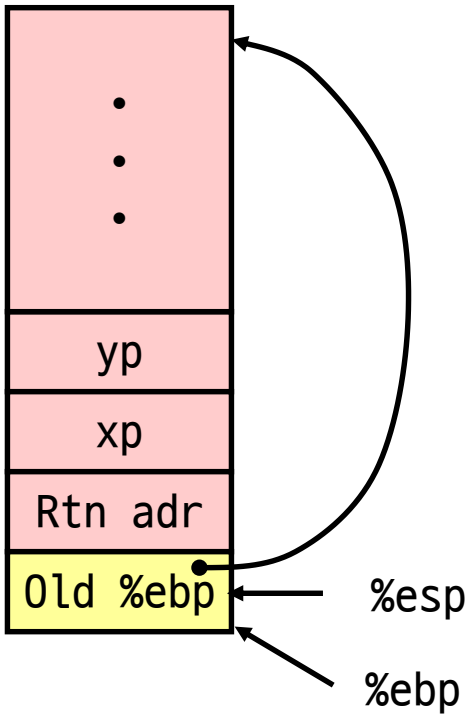
Swap Setup (2)

Entering Stack



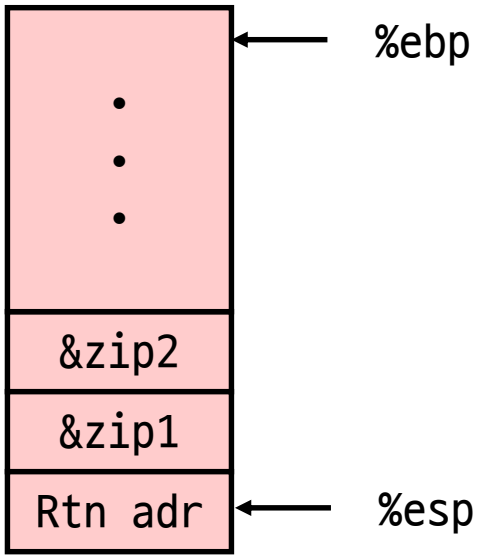

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

Resulting Stack

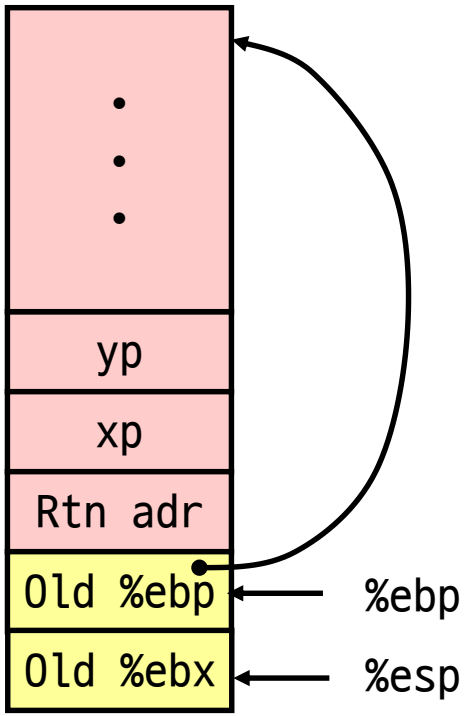


Swap Setup (3)

Entering Stack



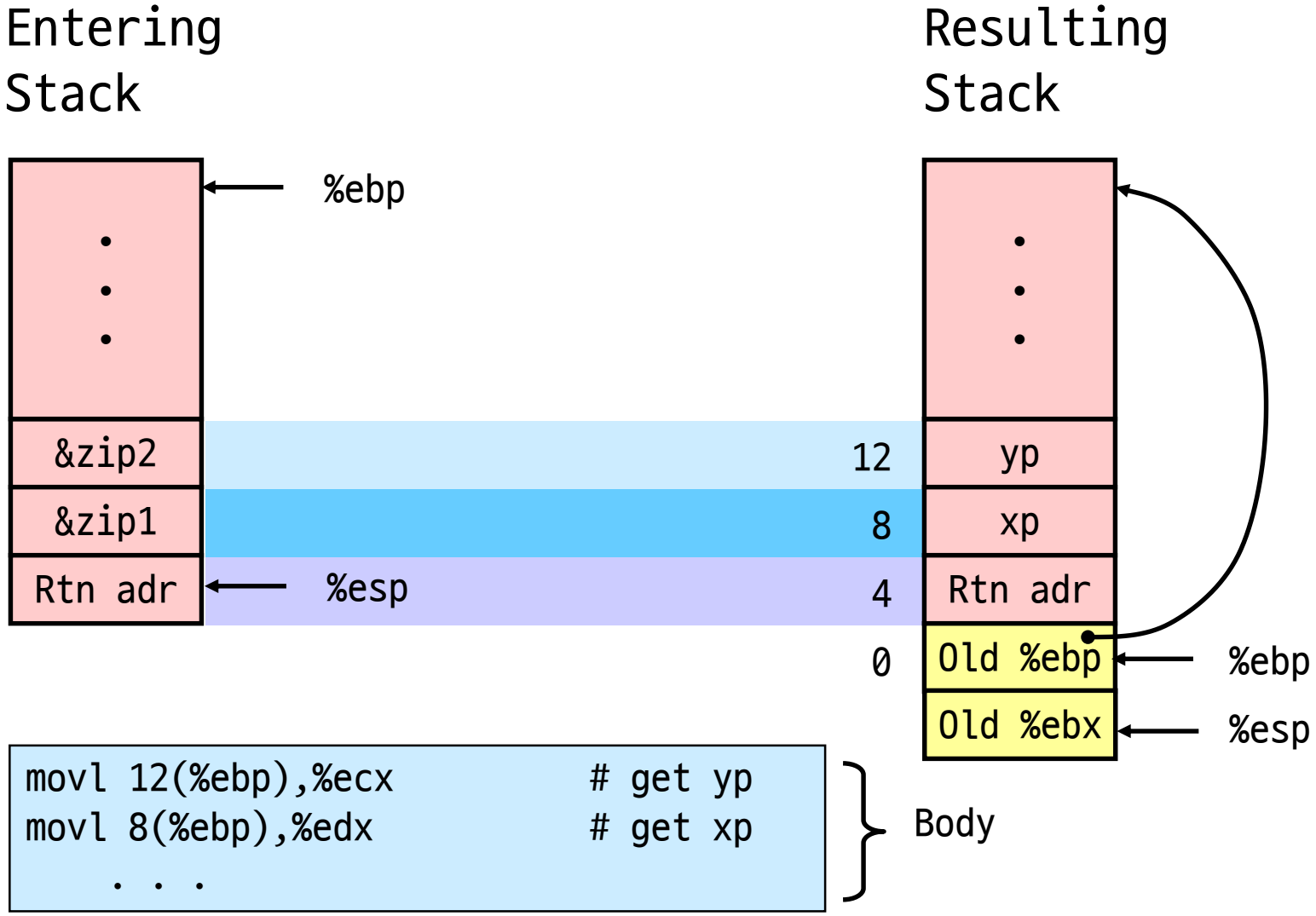
Resulting Stack



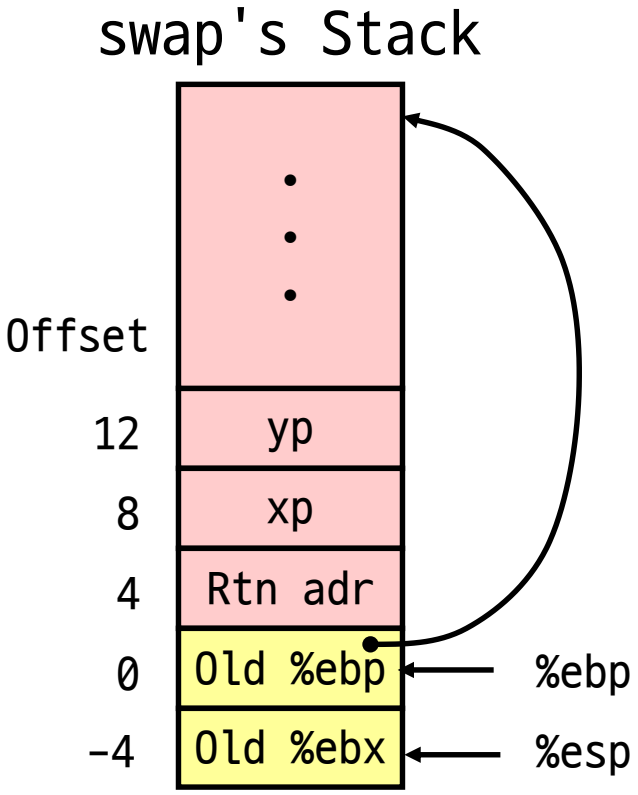

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

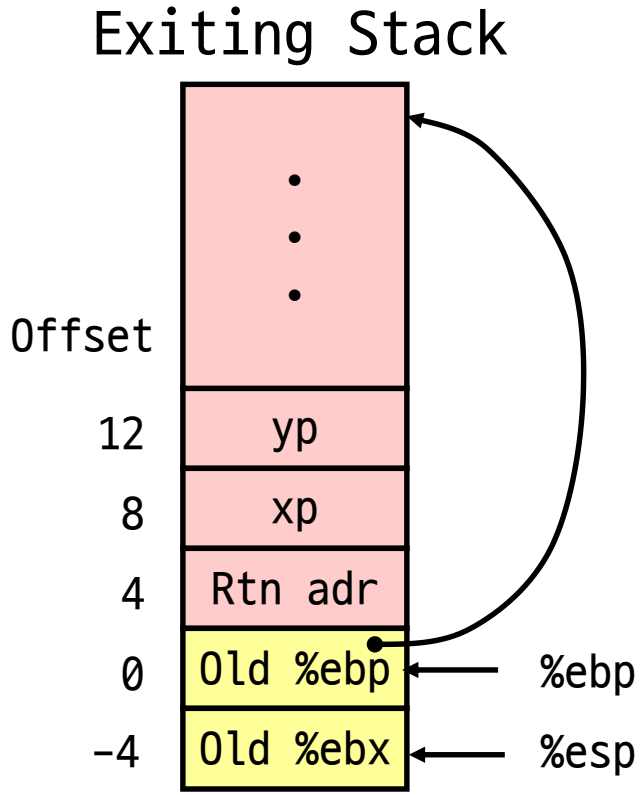
Why ?

Effect of swap Setup



swap Finish (1)



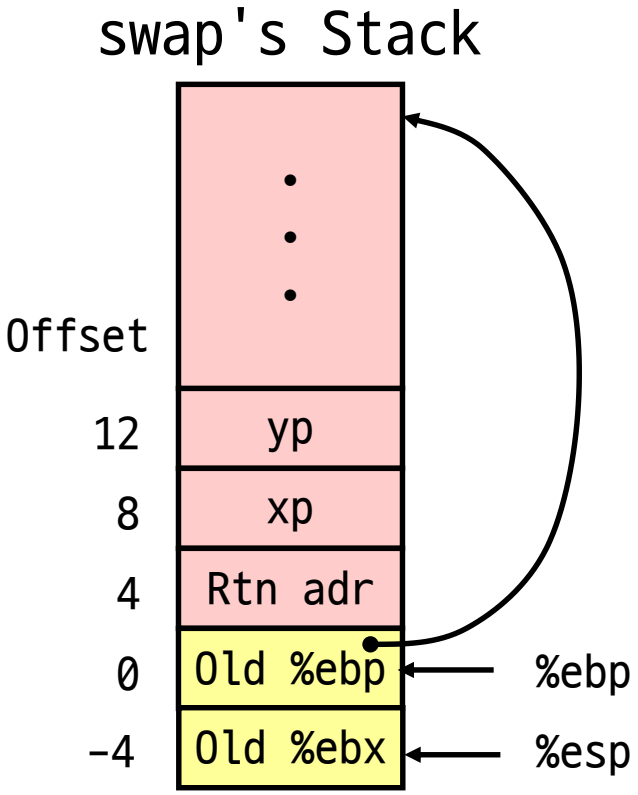


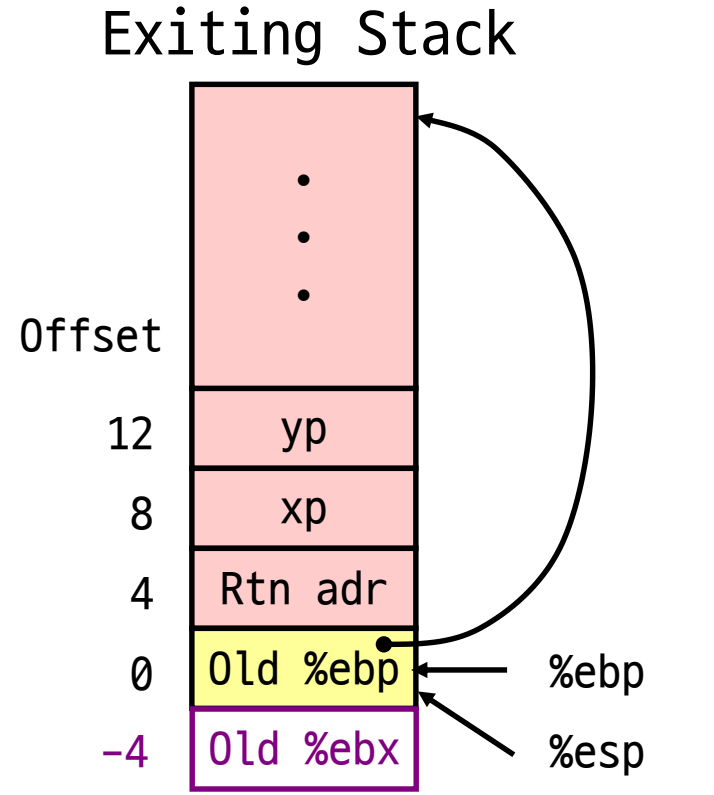

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Observation

- Saved & restored register %ebx

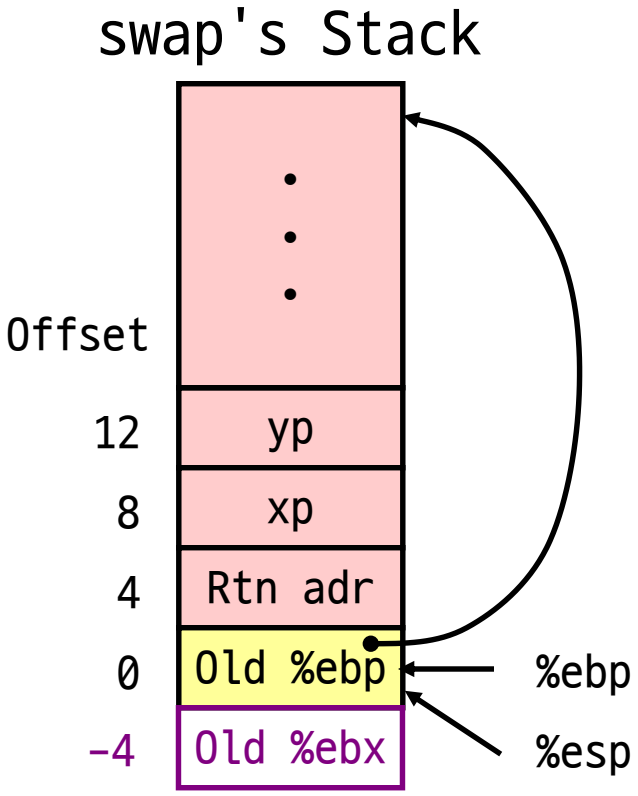
swap Finish (2)

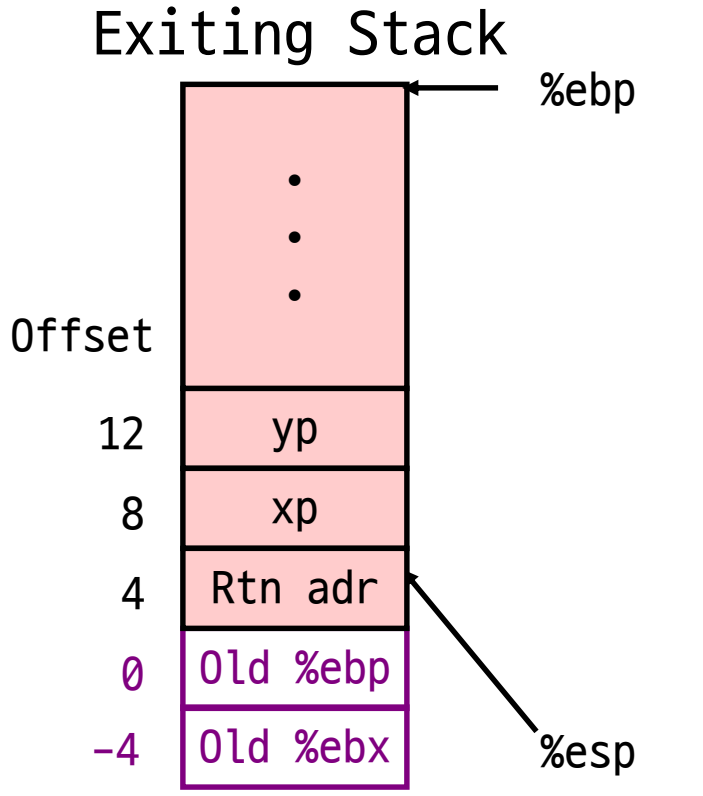





```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

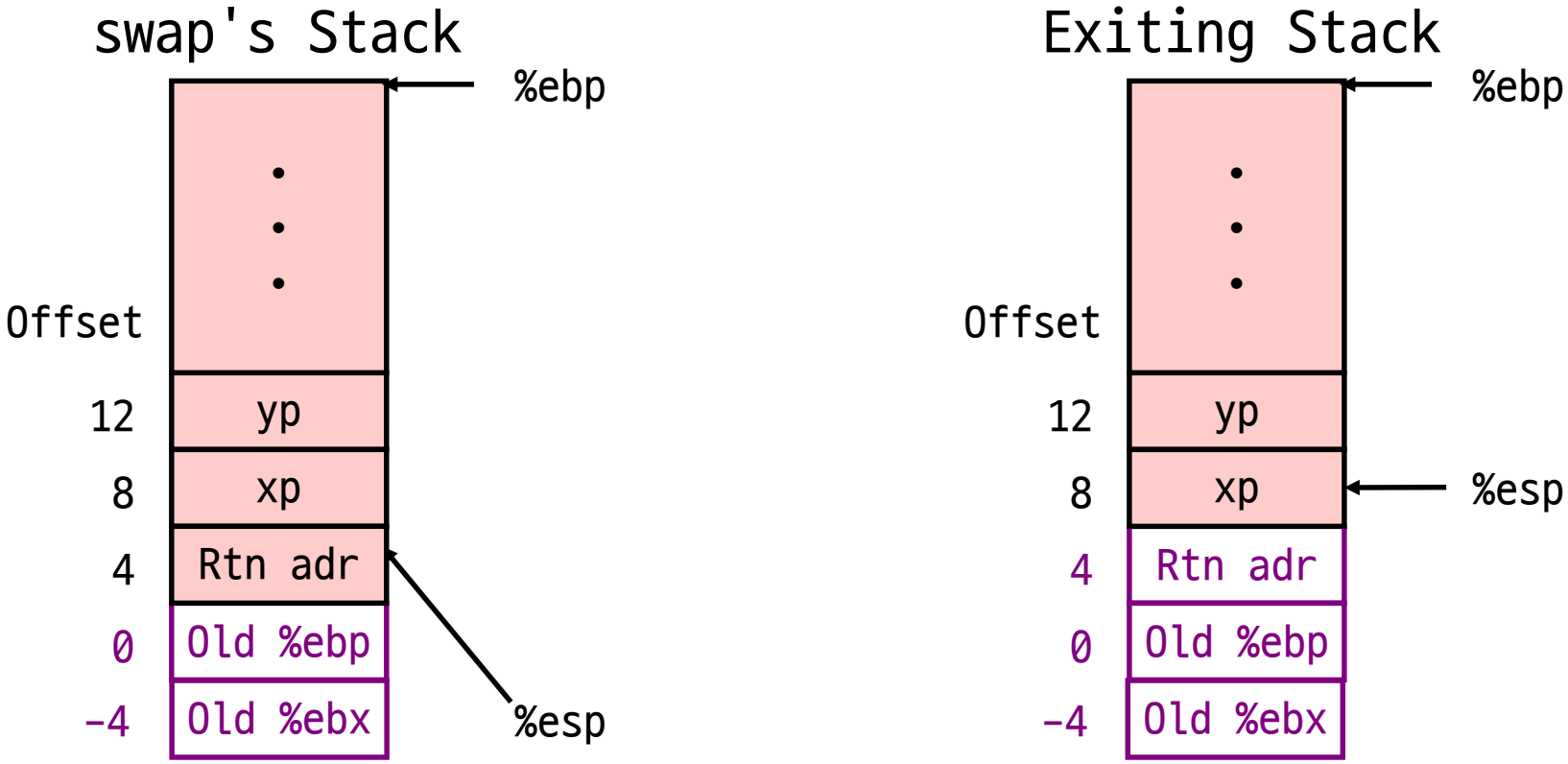
swap Finish (3)






```
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, %edx

Register Saving Conventions (1)

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 (2)

Conventions

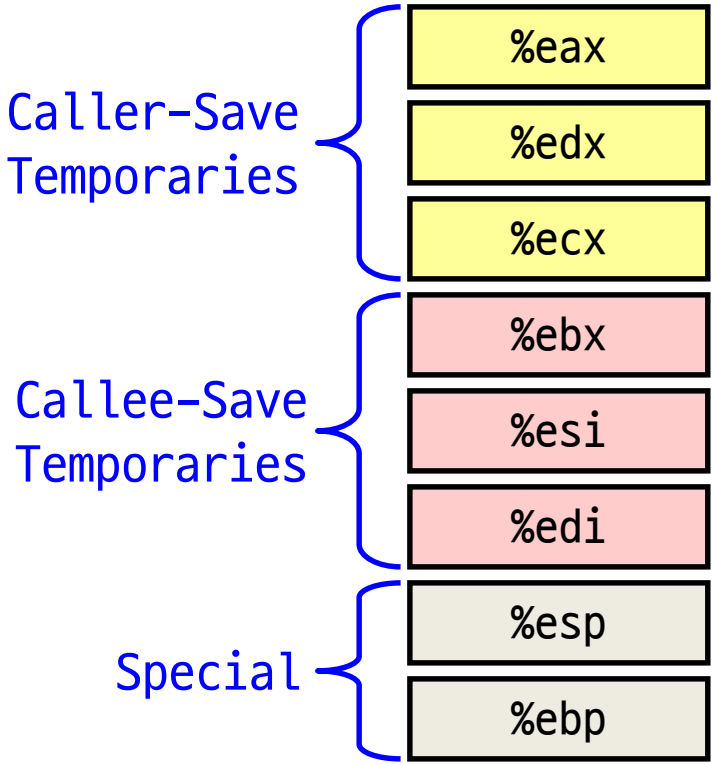
- Caller save
  - Caller saves temporary in its frame before calling
- Callee save
  - Callee saves temporary in its frame before using

- IA-32 ?

IA-32/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



Revisiting arith

```
int arith (int x, int y, int z)
{
  int t1 = x + y;
  int t2 = z + t1;
  int t3 = x + 4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;

  return rval;
}
```

```
arith:
    pushl %ebp
    movl %esp,%ebp

    movl 8(%ebp),%eax
    movl 12(%ebp),%edx
    leal (%edx,%eax),%ecx
    leal (%edx,%edx,2),%edx
    sall $4,%edx
    addl 16(%ebp),%ecx
    leal 4(%edx,%eax),%eax
    imull %ecx,%eax

    movl %ebp,%esp
    popl %ebp
    ret
```

Set Up

Body

Finish

Revisiting max

```
int max(int x, int y)
{
  if (x > y)
    return x;
  else
    return y;
}
```

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

        movl 8(%ebp),%ebx
        movl 12(%ebp),%eax
        cmpl %eax,%ebx
        jle L9
        movl %ebx,%eax
L9:

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

Set Up

Body

Finish

Revisiting Do-While

Goto Version

```
int fact_goto (int x)
{
  int result = 1;
loop:
  result *= x;
  x = x - 1;
  if (x > 1)
    goto loop;
  return result;
}
```

Assembly

```
_fact_goto:
   pushl %ebp              # Setup
   movl %esp,%ebp          # Setup

   movl $1,%eax            # eax = 1
   movl 8(%ebp),%edx       # edx = x
L11:
   imull %edx,%eax         # result *= x
   decl %edx               # x--
   cmpl $1,%edx            # Compare x : 1
   jg L11                  # if > goto loop

   movl %ebp,%esp          # Finish
   popl %ebp               # Finish
   ret                     # Finish
```

Recursive Factorial: rfact

Registers

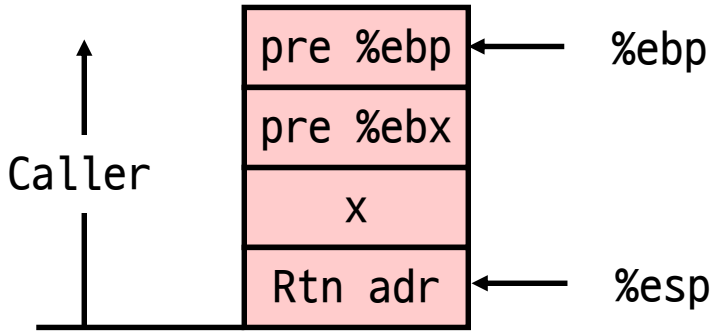
- **%eax** used without first saving
- **%ebx** used, but save at beginning & restore at end

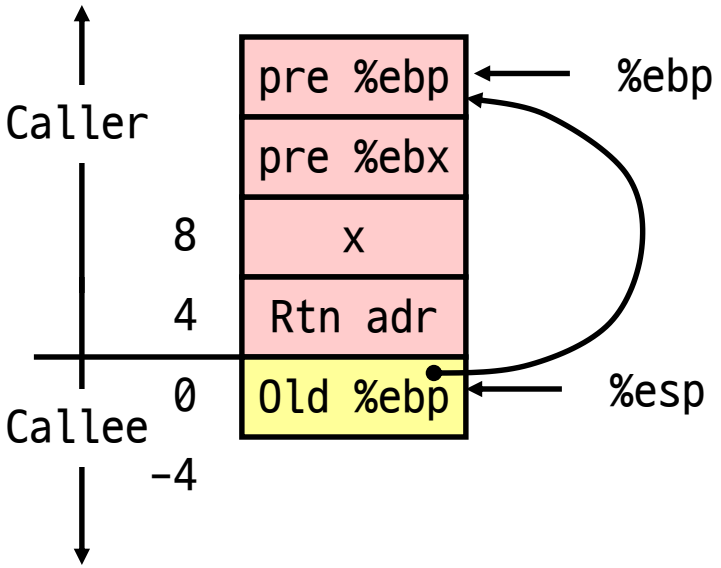
```
int rfact(int x)
{
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

```
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

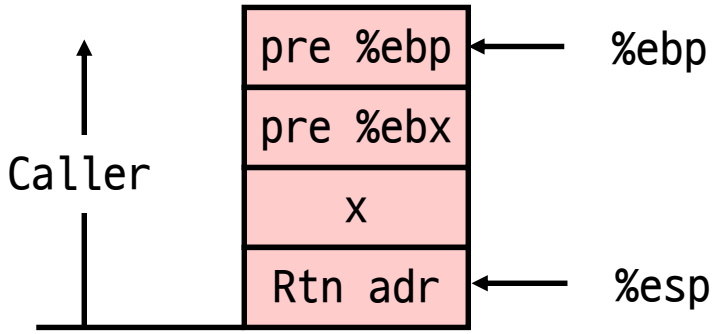


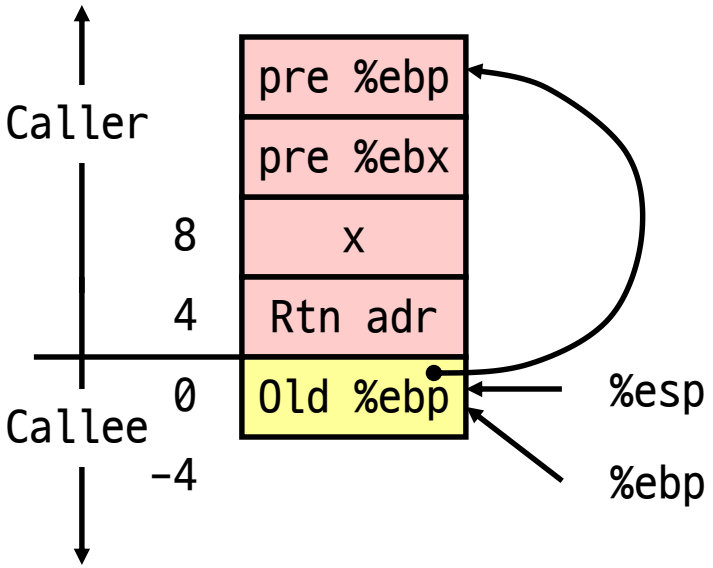



```
rfact:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

rfact Stack Setup

Entering Stack

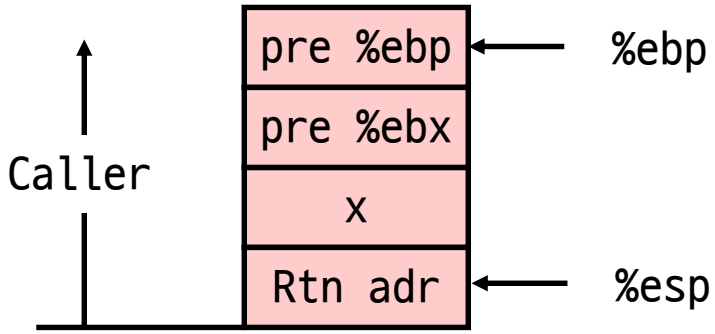


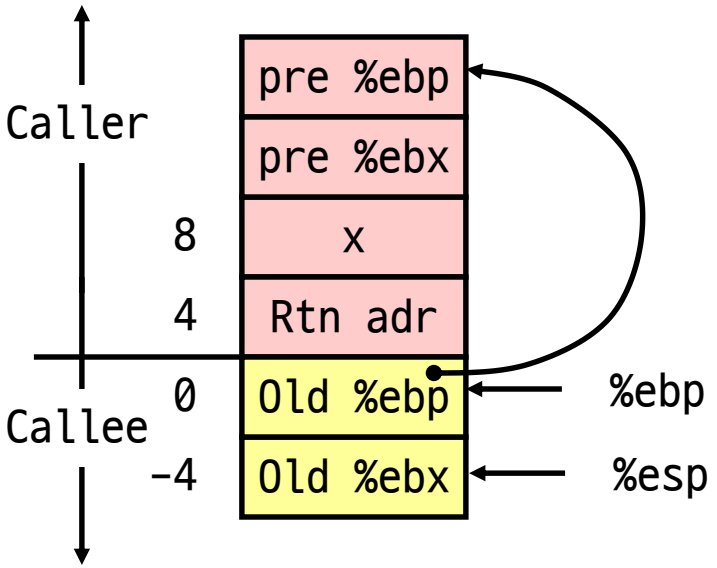



```
rfact:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

rfact Stack Setup

Entering Stack






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

rfact Body

Registers

- **%ebx**: stored value of **x**
- **%eax**
  - Temporary value of **x-1**
  - Returned value from **rfact(x-1)**
  - Returned value from this call

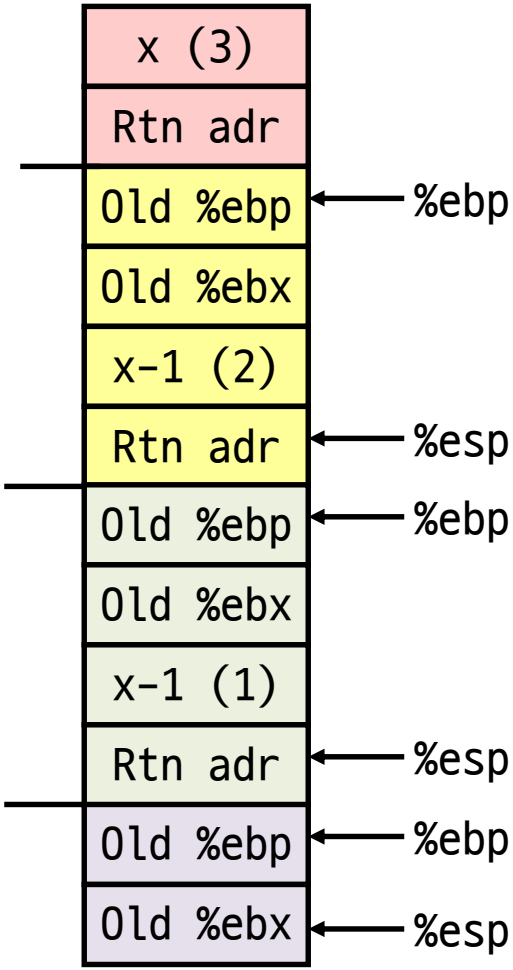
```
int rfact(int x)
{
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

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:
```

rfact Body

rfact(3)




```
   movl  8(%ebp), %ebx          # ebx = x (3)
   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:
```

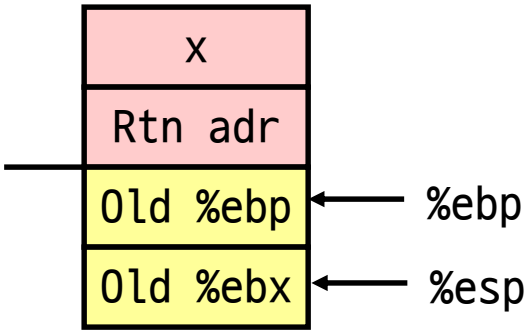
```
   movl  8(%ebp), %ebx          # ebx = x (2)
   cmpl  $1,%ebx                # Compare x : 1
   jle   .L78                   # If <= goto Term
   leal  -1(%ebx), %eax         # eax = x-1
   pushl %eax                   # Push x-1
   call  rfact                  # rfact(x-1)
   imull %ebx, %eax             # rval * x
   jmp   .L79                   # Goto done
.L78:                           # Term:
   movl  $1, %eax               # return val = 1
.L79:                           # Done:
```

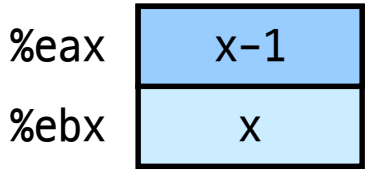
```
   movl  8(%ebp), %ebx          # ebx = x (1)
   cmpl  $1,%ebx                # Compare x : 1
   jle   .L78                   # If <= goto Term
   leal  -1(%ebx), %eax         # eax = x-1
   pushl %eax                   # Push x-1
   call  rfact                  # rfact(x-1)
   imull %ebx, %eax 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

rfact Recursion

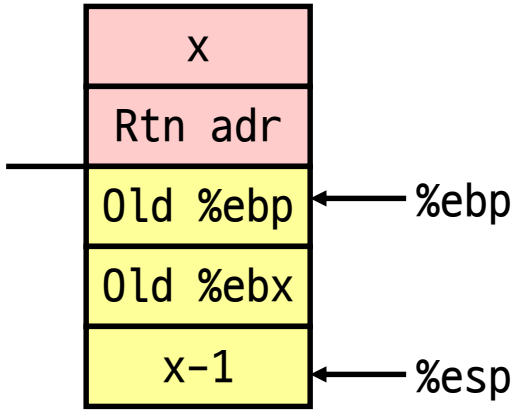
```
movl   8(%ebp),%ebx          # ebx = x
cmpl   $1,%ebx               # Compare x : 1
jle    .L78                  # If <= goto Term
leal   -1(%ebx),%eax         # eax = x-1
pushl %eax                   # Push x-1
call   rfact                 # rfact(x-1)
... ...
```

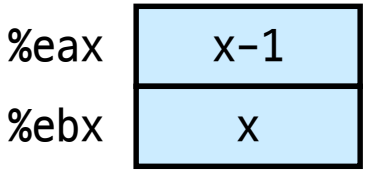
leal -1(%ebx), %eax



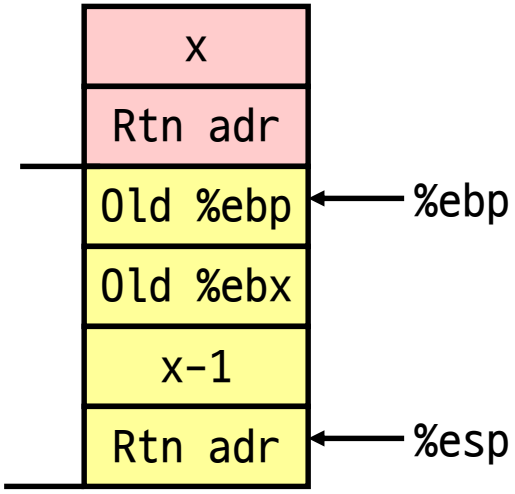


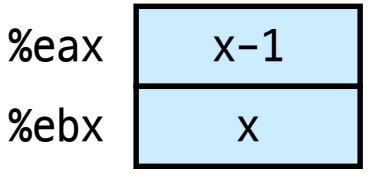
pushl %eax





call rfact

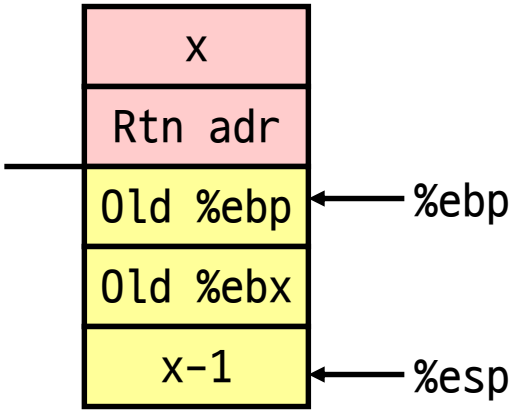


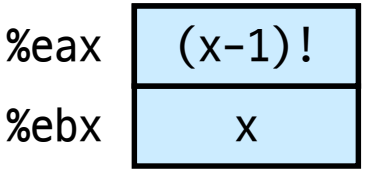


rfact Result

```
   ... ...
   call  rfact                  # rfact(x-1)
   imull %ebx,%eax              # rval * x
   jmp   .L79                   # Goto done
.L78:                           # Term:
   movl  $1,%eax                # return val = 1
.L79:                           # Done:
```

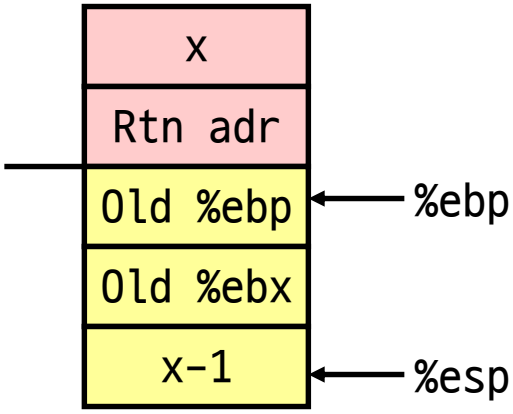
Return from Call

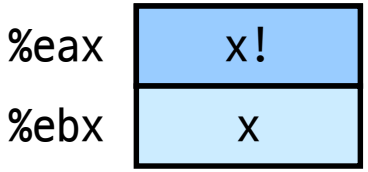




Assume that rfact(x-1) returns (x-1)! in register %eax

imull %ebx, %eax

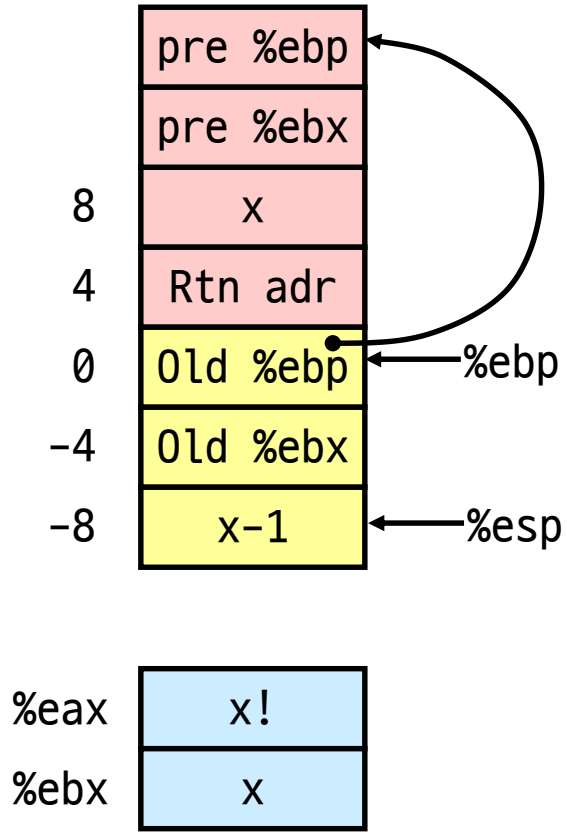




rfact Completion

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

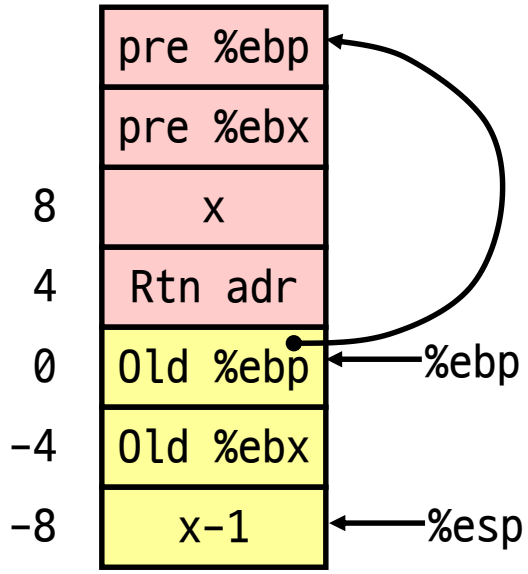
```
movl -4(%ebp), %ebx
```

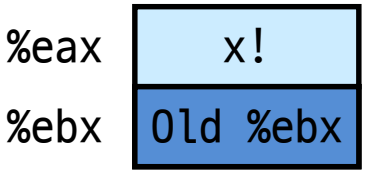


rfact Completion

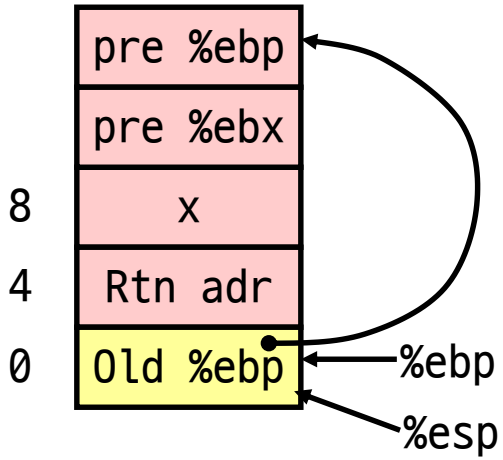
```
movl  -4(%ebp),%ebx
movl  %ebp,%esp
popl  %ebp
ret
```

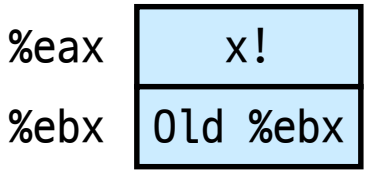
movl -4(%ebp), %ebx



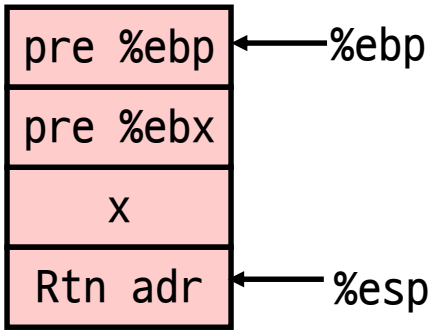


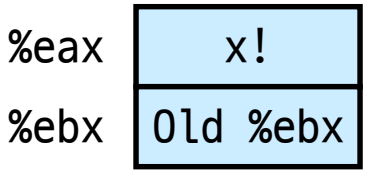
movl %ebp, %esp





popl %ebp





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

Procedures = Instructions + Conventions

- Call / Ret instructions
- Register usage conventions
  - Caller save (%eax, %ecx, %edx) / Callee save (%ebx, %esi, %edi)
  - **%ebp** and **%esp**
- Stack frame organization conventions