Organisation und Architektur von Rechnern

Lecture 06

Instructor:

Reinhard v. Hanxleden

http://www.informatik.uni-kiel.de/rtsys/teaching/v-sysinf2

These slides are used with kind permission from the Carnegie Mellon University

The 5 Minute Review Session

1. What is the general form of addressing memory for the IA32?
2. What condition codes (CCs) does the IA32 have?
3. How do we set CCs?
4. How do we read CCs?
5. How do we implement `if-then-else` in assembler?

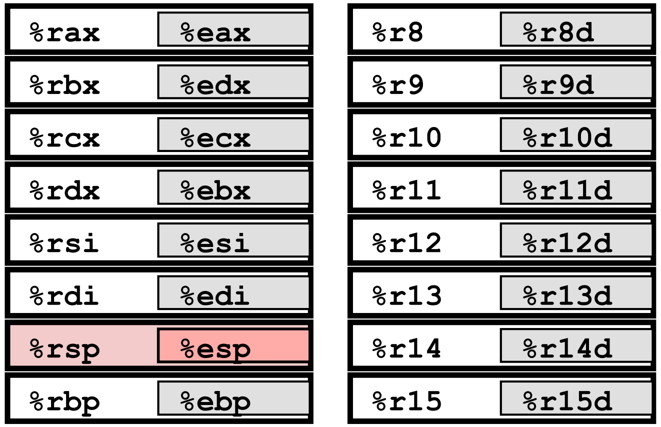
Last Time

- Complete memory addressing mode
  - `(%eax), 17(%eax), 2(%ebx, %ecx, 8), …`

- Arithmetic operations
  - `subl %eax, %ecx           # ecx = ecx + eax`
  - `sall $4,%edx              # edx = edx << 4`
  - `addl 16(%ebp),%ecx        # ecx = ecx + Mem[16+ebp]`
  - `leal 4(%edx,%eax),%eax    # eax = 4 + edx + eax`
  - `imull %ecx,%eax           # eax = eax * ecx`

Last Time

- **x86-64 vs. IA32**
  - Integer registers: **16 x 64-bit** vs. **8 x 32-bit**
  - **`movq, addq,`** … vs. **`movl, addl,`** …
  - Better support for passing function arguments in registers



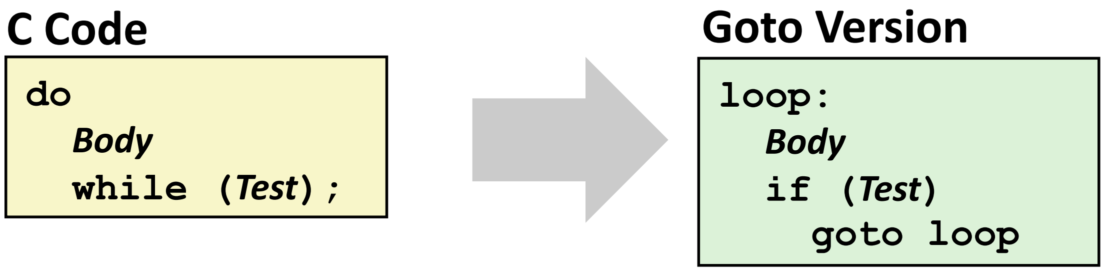
%rax	%eax	%r8	%r8d
%rbx	%edx	%r9	%r9d
%rcx	%ecx	%r10	%r10d
%rdx	%ebx	%r11	%r11d
%rsi	%esi	%r12	%r12d
%rdi	%edi	%r13	%r13d
%rsp	%esp	%r14	%r14d
%rbp	%ebp	%r15	%r15d

- **Control**
  - Condition code registers
  - Set as side effect or by **`cmp, test`**
  - Used:
    - Read out by setx instructions (**`setg, setle`**, …)
    - Or by conditional jumps (**`jle .L4, je .L10,`** …)

CF **ZF** **SF** **OF**

Last Time

- Do-While loop



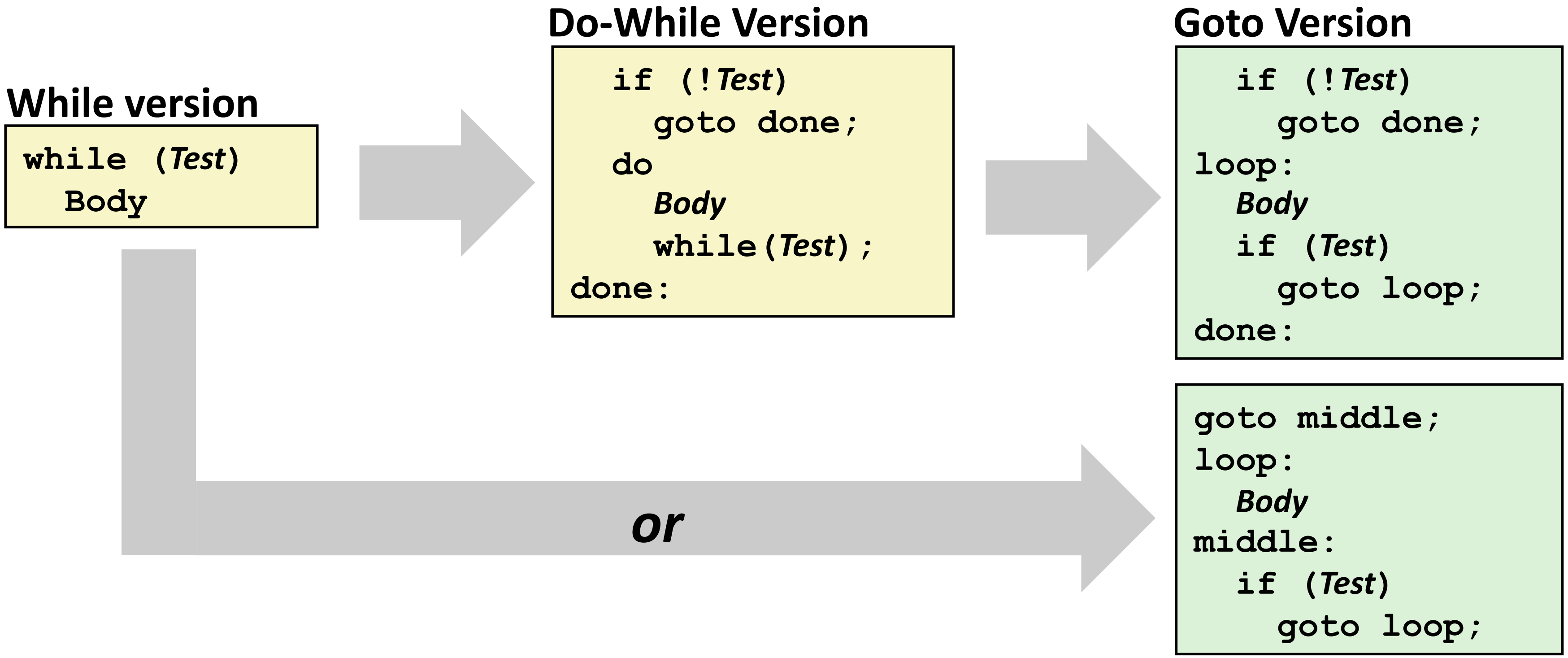
C Code

```
do
  Body
  while (Test);
```

Goto Version

```
loop:
  Body
  if (Test)
    goto loop
```

- While-Do loop



While version

```
while (Test)
  Body
```

Do-While Version

```
  if (!Test)
    goto done;
  do
    Body
    while(Test);
done:
```

Goto Version

```
  if (!Test)
    goto done;
loop:
  Body
  if (Test)
    goto loop;
done:
```

or

```
goto middle;
loop:
  Body
middle:
  if (Test)
    goto loop;
```

Today

- For loops
- Switch statements
- Procedures

“For” Loop Example: Square-and-Multiply

```
/* Compute x raised to nonnegative power p */
int ipwr_for(int x, unsigned p)
{
   int result;
     for (result = 1; p != 0; p = p>>1) {
        if (p & 0x1)
          result *= x;
        x = x*x;
     }
   return result;
}
```

- **Algorithm**
  - Exploit bit representation: $p = p_0 + 2p_1 + 2^2p_2 + \ldots\ 2^{n-1}p_{n-1}$
  - Gives: $x^p = z_0 \cdot z_1^{\;2} \cdot (z_2^{\;2})^{2} \cdot\ \ldots\ \cdot \underbrace{(\ldots((z_{n-1}^{\;2})^{2})\ldots)^{2}}_{n\text{–}1\ \text{times}}$

    $z_i = 1$ when $p_i = 0$

    $z_i = x$ when $p_i = 1$
  - Complexity $O(\log p)$

Example

3^{10} = $3^2 * 3^8$

= $3^2 * ((3^2)^2)^2$

ipwr Computation

```
/* Compute x raised to nonnegative power p */
int ipwr_for(int x, unsigned p)
{
  int result;
    for (result = 1; p != 0; p = p>>1) {
      if (p & 0x1)
        result *= x;
      x = x*x;
    }
  return result;
}
```

before iteration	result	x=3	p=10
1	1	3	10=1010_2
2	1	9	5= 101_2
3	9	81	2= 10_2
4	9	6561	1= 1_2
5	59049	43046721	0

"For" Loop Example

```
int result;
for (result = 1; p != 0; p = p>>1)
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

General Form

```
for  (Init ;  Test ;  Update)
        Body
```

Test

```
p != 0
```

Init

```
result = 1
```

Update

```
p = p >> 1
```

Body

```
 {
   if (p & 0x1)
     result *= x;
   x = x*x;
 }
```

“For”→ “While”→ “Do-While”

For Version

```
for  (Init;  Test;  Update)

     Body
```

While Version

```
Init;
while  (Test)  {
     Body
     Update;
}
```

Do-While Version

```
  Init;
  if  (!Test)
    goto  done;
  do  {
    Body
    Update;
  } while  (Test)
done:
```

Goto Version

```
  Init;
  if  (!Test)
    goto  done;
loop:
  Body
  Update;
  if  (Test)
    goto  loop;
done:
```

For-Loop: Compilation #1

For Version

```
for  (Init;  Test;  Update )

      Body
```

```
for (result = 1; p != 0; p = p>>1)
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

Goto Version

```
   Init;
   if  (!Test)
      goto  done;
loop:
   Body
   Update ;
   if  (Test)
      goto  loop;
done:
```

```
  result = 1;
  if (p == 0)
    goto done;
loop:
  if (p & 0x1)
    result *= x;
  x = x*x;
  p = p >> 1;
  if (p != 0)
    goto loop;
done:
```

“For”→ “While” (Jump-to-Middle)

For Version

```
for  (Init;  Test;  Update )

      Body
```

While Version

```
Init;
while  (Test )  {
      Body
      Update ;
}
```

Goto Version

```
   Init;
   goto middle;
loop:
   Body
   Update ;
middle:
   if  (Test)
      goto loop;
done:
```

For-Loop: Compilation #2

For Version

```
for  (Init;  Test;  Update )

       Body
```

Goto Version

```
   Init;
   goto middle;
loop:
   Body
   Update ;
middle:
   if  (Test)
      goto loop;
done:
```

```
for (result = 1; p != 0; p = p>>1)
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

```
   result = 1;
goto middle;
loop:
   if (p & 0x1)
     result *= x;
   x = x*x;
   p = p >> 1;
middle:
   if (p != 0)
     goto loop;
done:
```

Today

- For loops
- **Switch statements**
- Procedures

Switch Statement Example

```
long switch_eg
   (long x, long y, long z)
{
    long w = 1;
    switch(x) {
    case 1:
        w = y*z;
        break;
    case 2:
        w = y/z;
        /* Fall Through */
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;
    }
    return w;
}
```

- **Multiple case labels**
  - Here: 5, 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

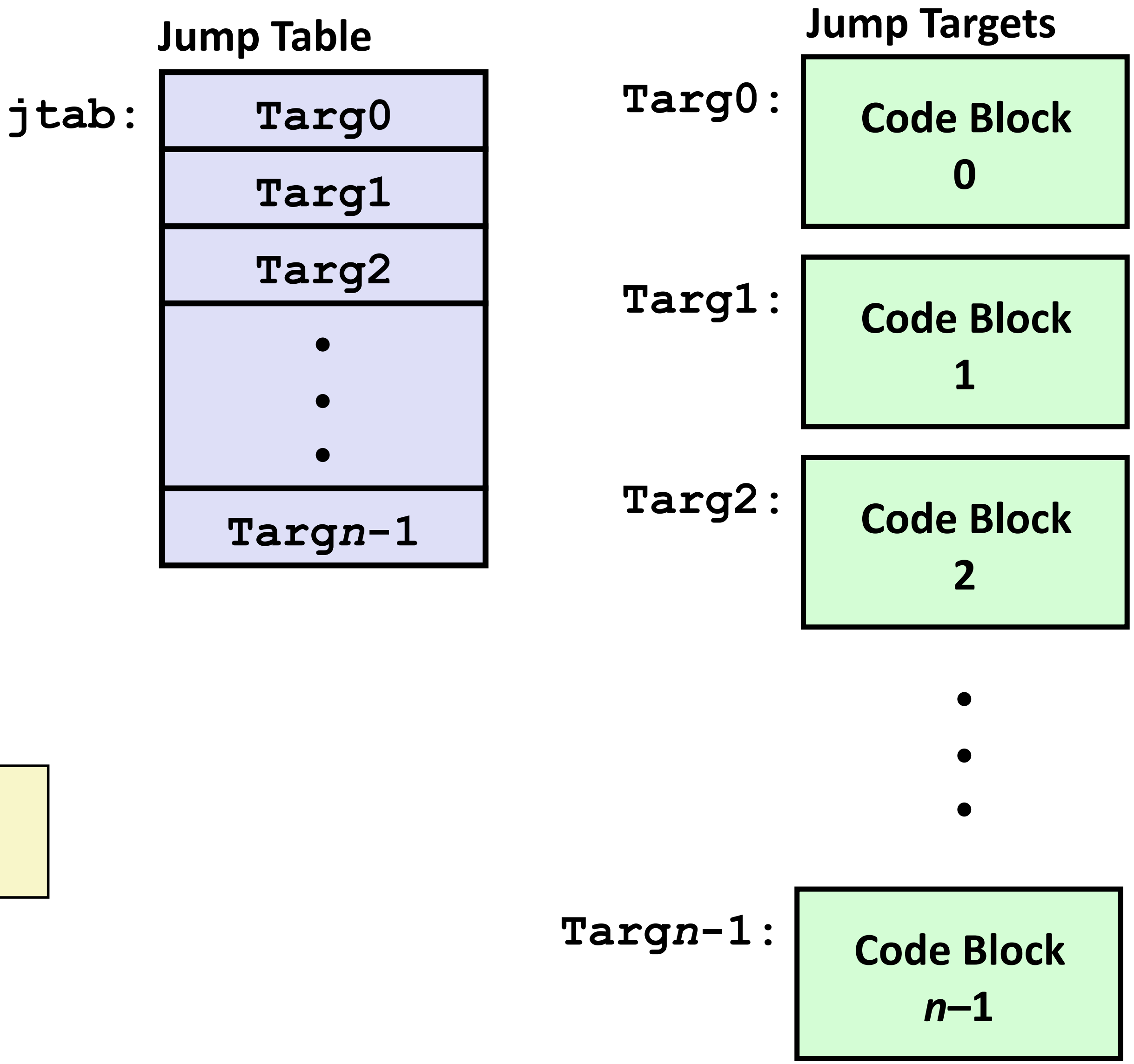
Jump Table Structure

Switch Form

```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1
    • • •
  case val_n-1:
    Block n–1
}
```

Approximate Translation

```
target = JTab[x];
goto *target;
```



Switch Statement Example (IA32)

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

Setup:

```
switch_eg:
   pushl  %ebp              # Setup
   movl   %esp, %ebp        # Setup
   pushl  %ebx              # Setup
   movl   $1, %ebx
   movl   8(%ebp), %edx
   movl   16(%ebp), %ecx
   cmpl   $6, %edx
   ja     .L61
   jmp    *.L62(,%edx,4)
```

Will disappear Blackboard?

Switch Statement Example (IA32)

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

Jump table

```
.section .rodata
   .align 4
.L62:
  .long    .L61   # x = 0
  .long    .L56   # x = 1
  .long    .L57   # x = 2
  .long    .L58   # x = 3
  .long    .L61   # x = 4
  .long    .L60   # x = 5
  .long    .L60   # x = 6
```

Setup:

```
switch_eg:
   pushl  %ebp              # Setup
   movl   %esp, %ebp        # Setup
   pushl  %ebx              # Setup
   movl   $1, %ebx          # w = 1
   movl   8(%ebp), %edx     # edx = x
   movl   16(%ebp), %ecx    # ecx = z
   cmpl   $6, %edx          # x:6
   ja     .L61              # if > goto default
   jmp    *.L62(,%edx,4)    # goto JTab[x]
```

Indirect jump →

Assembly Setup Explanation

- **Table Structure**
  - Each target requires 4 bytes
  - Base address at **`.L62`**

Jump table

```
.section .rodata
    .align 4
.L62:
  .long    .L61   # x = 0
  .long    .L56   # x = 1
  .long    .L57   # x = 2
  .long    .L58   # x = 3
  .long    .L61   # x = 4
  .long    .L60   # x = 5
  .long    .L60   # x = 6
```

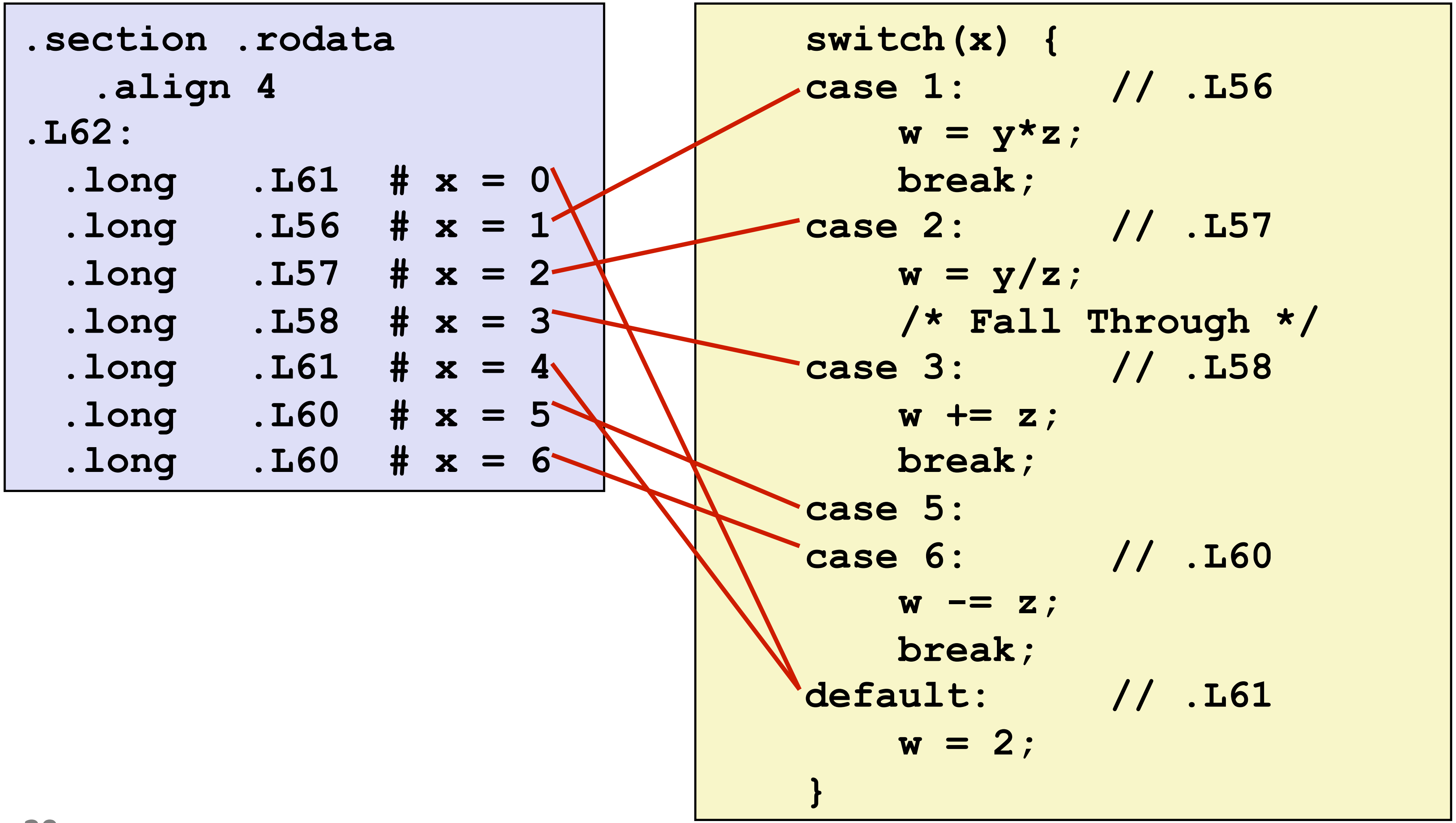
- **Jumping**

  Direct: **`jmp .L61`**
  - Jump target is denoted by label **`.L61`**

  Indirect: **`jmp *.L62(,%edx,4)`**
  - Start of jump table: **`.L62`**
  - Must scale by factor of 4 (labels have 32-bit = 4 Bytes on IA32)
  - Fetch target from effective Address **`.L61 + edx*4`**
    - Only for 0 ≤ **`x`** ≤ 6

Jump Table

Jump table



```
.section .rodata
   .align 4
.L62:
  .long    .L61  # x = 0
  .long    .L56  # x = 1
  .long    .L57  # x = 2
  .long    .L58  # x = 3
  .long    .L61  # x = 4
  .long    .L60  # x = 5
  .long    .L60  # x = 6
```

```
switch(x) {
case 1:       // .L56
    w = y*z;
    break;
case 2:       // .L57
    w = y/z;
    /* Fall Through */
case 3:       // .L58
    w += z;
    break;
case 5:
case 6:       // .L60
    w -= z;
    break;
default:      // .L61
    w = 2;
}
```

Code Blocks (Partial)

```
switch(x) {
  . . .
case 2:       // .L57
    w = y/z;
    /* Fall Through */
case 3:       // .L58
    w += z;
    break;
  . . .
default:      // .L61
    w = 2;
}
```

```
.L61:  // Default case
   movl  $2, %ebx     # w = 2
   movl  %ebx, %eax   # Return w
   popl  %ebx
   leave
   ret
.L57:  // Case 2:
   movl  12(%ebp), %eax   # y
   cltd                  # Div prep
   idivl %ecx            # y/z
   movl  %eax, %ebx # w = y/z
# Fall through
.L58:  // Case 3:
   addl  %ecx, %ebx # w+= z
   movl  %ebx, %eax # Return w
   popl  %ebx
   leave
   ret
```

Code Blocks (Rest)

```
    switch(x) {
    case 1:       // .L56
        w = y*z;
        break;
      . . .
    case 5:
    case 6:       // .L60
        w -= z;
        break;
      . . .
    }
```

```
.L60: // Cases 5&6:
   subl   %ecx, %ebx   # w -= z
   movl   %ebx, %eax   # Return w
   popl   %ebx
   leave
   ret
.L56: // Case 1:
   movl   12(%ebp), %ebx # w = y
   imull  %ecx, %ebx      # w*= z
   movl   %ebx, %eax   # Return w
   popl   %ebx
   leave
   ret
```

x86-64 Switch Implementation

- Same general idea, adapted to 64-bit code
- Table entries 64 bits (pointers)
- Cases use revised code

```
    switch(x) {
    case 1:       // .L50
        w = y*z;
        break;
      . . .
    }
```

```
.L50: // Case 1:
   movq   %rsi, %r8   # w = y
   imulq  %rdx, %r8   # w *= z
   movq   %r8, %rax   # Return w
   ret
```

Jump Table

```
.section .rodata
   .align 8
.L62:
  .quad   .L55  # x = 0
  .quad   .L50  # x = 1
  .quad   .L51  # x = 2
  .quad   .L52  # x = 3
  .quad   .L55  # x = 4
  .quad   .L54  # x = 5
  .quad   .L54  # x = 6
```

IA32 Object Code

- **Setup**
  - Label **`.L61`** becomes address **`0x8048630`**
  - Label **`.L62`** becomes address **`0x80488dc`**

Assembly Code

```
switch_eg:
  . . .
  ja     .L61              # if > goto default
  jmp    *.L62(,%edx,4)  # goto JTab[x]
```

Disassembled Object Code

```
08048610 <switch_eg>:
 . . .
 8048622:   77 0c                    ja     8048630
 8048624:   ff 24 95 dc 88 04 08     jmp    *0x80488dc(,%edx,4)
```

IA32 Object Code (cont.)

- **Jump Table**
  - Doesn’t show up in disassembled code
  - Can inspect using GDB

```
 gdb asm-cntl
(gdb) x/7xw 0x80488dc
```

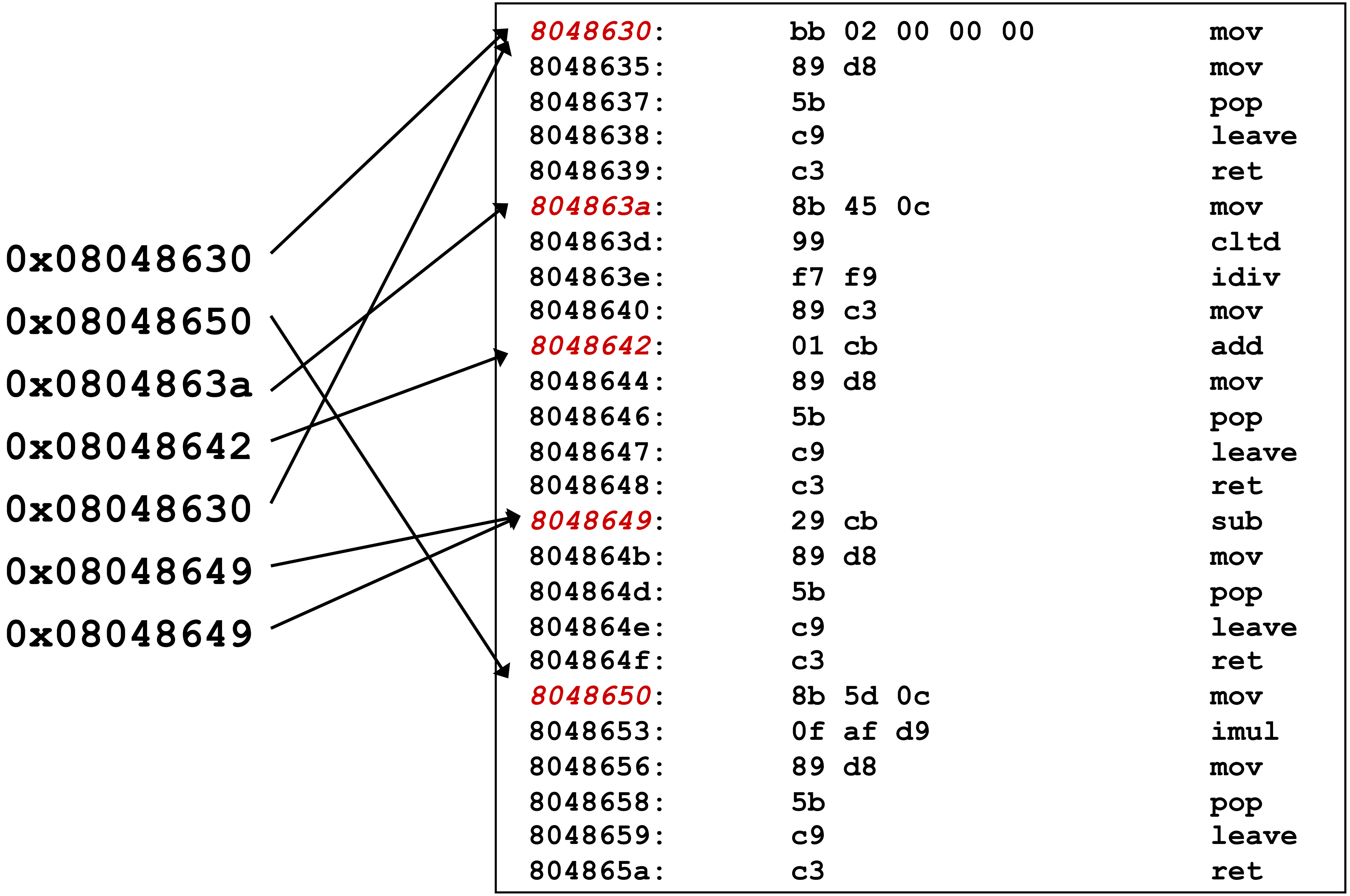
  - Examine 7 hexadecimal format “words” (4-bytes each)
  - Use command “`help x`” to get format documentation

```
0x80488dc:
   0x08048630
   0x08048650
   0x0804863a
   0x08048642
   0x08048630
   0x08048649
   0x08048649
```

Disassembled Targets

```
8048630:        bb 02 00 00 00          mov    $0x2,%ebx
8048635:        89 d8                   mov    %ebx,%eax
8048637:        5b                      pop    %ebx
8048638:        c9                      leave
8048639:        c3                      ret
804863a:        8b 45 0c                mov    0xc(%ebp),%eax
804863d:        99                      cltd
804863e:        f7 f9                   idiv   %ecx
8048640:        89 c3                   mov    %eax,%ebx
8048642:        01 cb                   add    %ecx,%ebx
8048644:        89 d8                   mov    %ebx,%eax
8048646:        5b                      pop    %ebx
8048647:        c9                      leave
8048648:        c3                      ret
8048649:        29 cb                   sub    %ecx,%ebx
804864b:        89 d8                   mov    %ebx,%eax
804864d:        5b                      pop    %ebx
804864e:        c9                      leave
804864f:        c3                      ret
8048650:        8b 5d 0c                mov    0xc(%ebp),%ebx
8048653:        0f af d9                imul   %ecx,%ebx
8048656:        89 d8                   mov    %ebx,%eax
8048658:        5b                      pop    %ebx
8048659:        c9                      leave
804865a:        c3                      ret
```

Matching Disassembled Targets



```
0x08048630
0x08048650
0x0804863a
0x08048642
0x08048630
0x08048649
0x08048649
```

```
8048630:        bb 02 00 00 00          mov
8048635:        89 d8                   mov
8048637:        5b                      pop
8048638:        c9                      leave
8048639:        c3                      ret
804863a:        8b 45 0c                mov
804863d:        99                      cltd
804863e:        f7 f9                   idiv
8048640:        89 c3                   mov
8048642:        01 cb                   add
8048644:        89 d8                   mov
8048646:        5b                      pop
8048647:        c9                      leave
8048648:        c3                      ret
8048649:        29 cb                   sub
804864b:        89 d8                   mov
804864d:        5b                      pop
804864e:        c9                      leave
804864f:        c3                      ret
8048650:        8b 5d 0c                mov
8048653:        0f af d9                imul
8048656:        89 d8                   mov
8048658:        5b                      pop
8048659:        c9                      leave
804865a:        c3                      ret
```

x86-64 Object Code

- **Setup**
  - Label **`.L61`** becomes address **`0x0000000000400716`**
  - Label **`.L62`** becomes address **`0x0000000000400990`**

Assembly Code

```
switch_eg:
  . . .
  ja    .L55            # if > goto default
  jmp   *.L56(,%rdi,8)  # goto JTab[x]
```

Disassembled Object Code

```
0000000000400700 <switch_eg>:
 . . .
  40070d:  77 07                ja     400716
  40070f:  ff 24 fd 90 09 40 00 jmpq   *0x400990(,%rdi,8)
```

x86-64 Object Code (cont.)

- **Jump Table**
  - Can inspect using GDB

```
 gdb asm-cntl
(gdb) x/7xg 0x400990
```

  - Examine 7 hexadecimal format “giant words” (8-bytes each)
  - Use command “`help x`” to get format documentation

```
0x400990:
   0x0000000000400716
   0x0000000000400739
   0x0000000000400720
   0x000000000040072b
   0x0000000000400716
   0x0000000000400732
   0x0000000000400732
```

Sparse Switch Example

```
/* Return x/111 if x is multiple
   && <= 999.  -1 otherwise */
int div111(int x)
{
  switch(x) {
  case   0: return 0;
  case 111: return 1;
  case 222: return 2;
  case 333: return 3;
  case 444: return 4;
  case 555: return 5;
  case 666: return 6;
  case 777: return 7;
  case 888: return 8;
  case 999: return 9;
  default: return -1;
  }
}
```

- Not practical to use jump table
  - Would require 1000 entries
- Obvious translation into if-then-else would have max. of 9 tests

Sparse Switch Code (IA32)

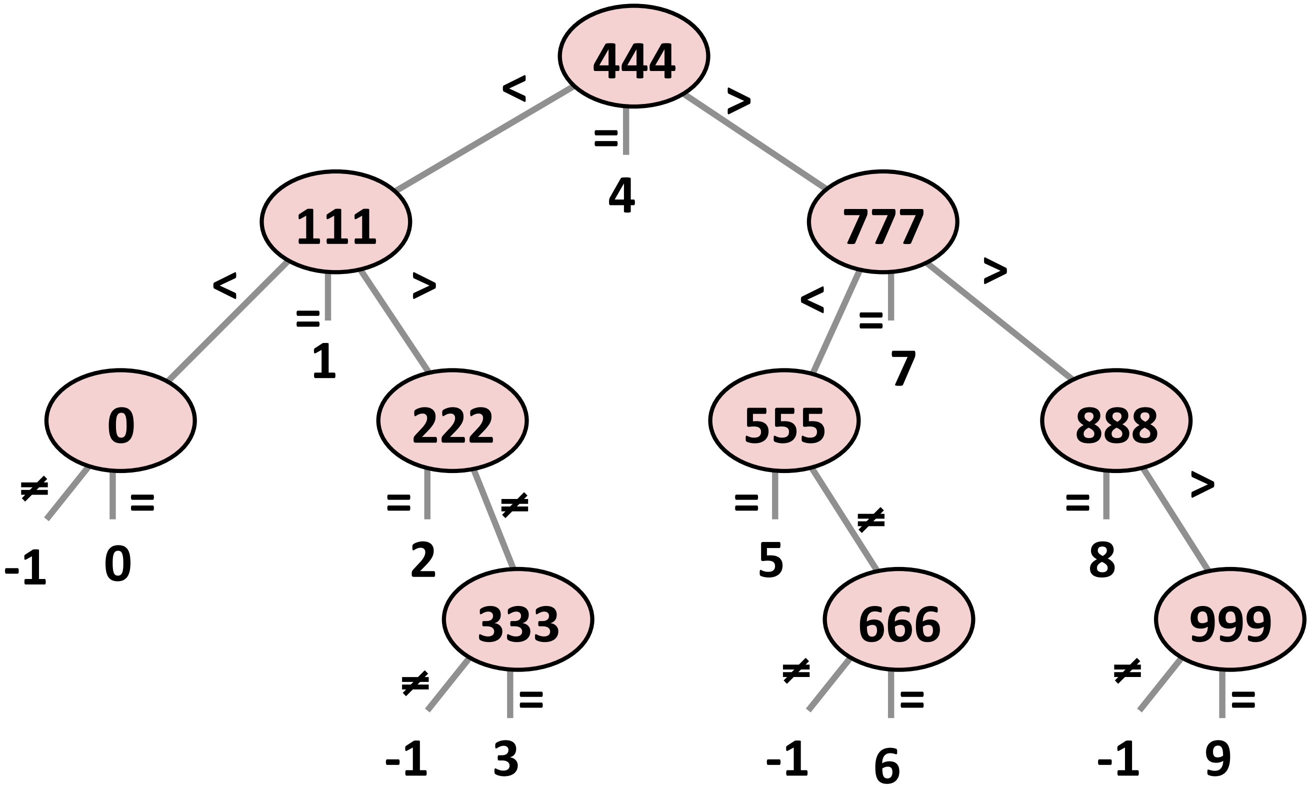
```
    movl 8(%ebp),%eax  # get x
    cmpl $444,%eax     # x:444
    je L8
    jg L16
    cmpl $111,%eax     # x:111
    je L5
    jg L17
    testl %eax,%eax    # x:0
    je L4
    jmp L14

    . . .
```

- Compares x to possible case values
- Jumps different places depending on outcomes

```
       . . .
L5:
       movl $1,%eax
       jmp L19
L6:
       movl $2,%eax
       jmp L19
L7:
       movl $3,%eax
       jmp L19
L8:
       movl $4,%eax
       jmp L19
       . . .
```

Sparse Switch Code Structure



- Organizes cases as binary tree
- Logarithmic performance

Summarizing

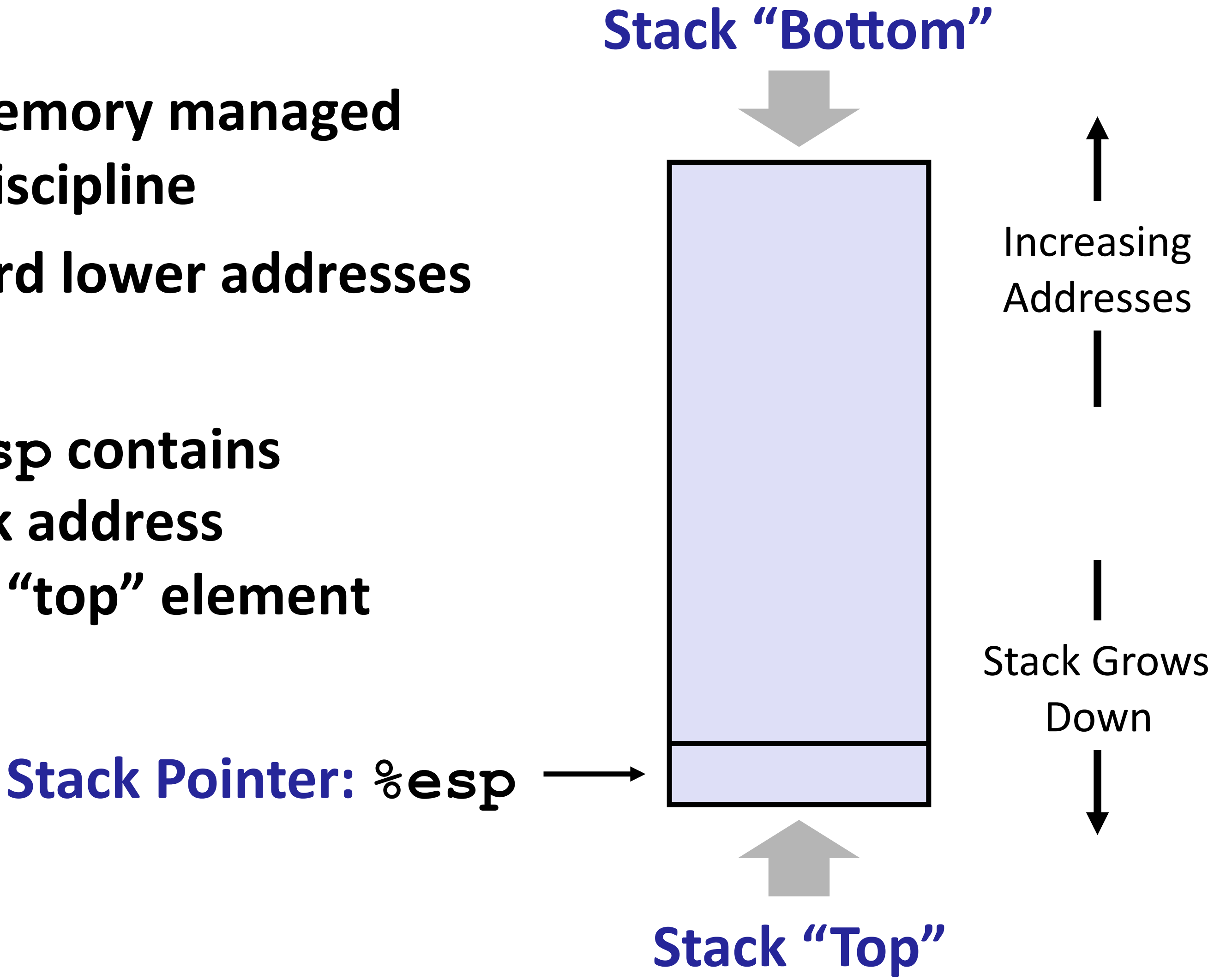
- **C Control**
  - if-then-else
  - do-while
  - while, for
  - switch
- **Assembler Control**
  - Conditional jump
  - Conditional move
  - Indirect jump
  - Compiler
  - Must generate assembly code to implement more complex control
- **Standard Techniques**
  - IA32 loops converted to do-while form
  - x86-64 loops use jump-to-middle
  - Large switch statements use jump tables
  - Sparse switch statements may use decision trees (not shown)
- **Conditions in CISC**
  - CISC machines generally have condition code registers

Today

- For loops
- Switch statements
- **Procedures**

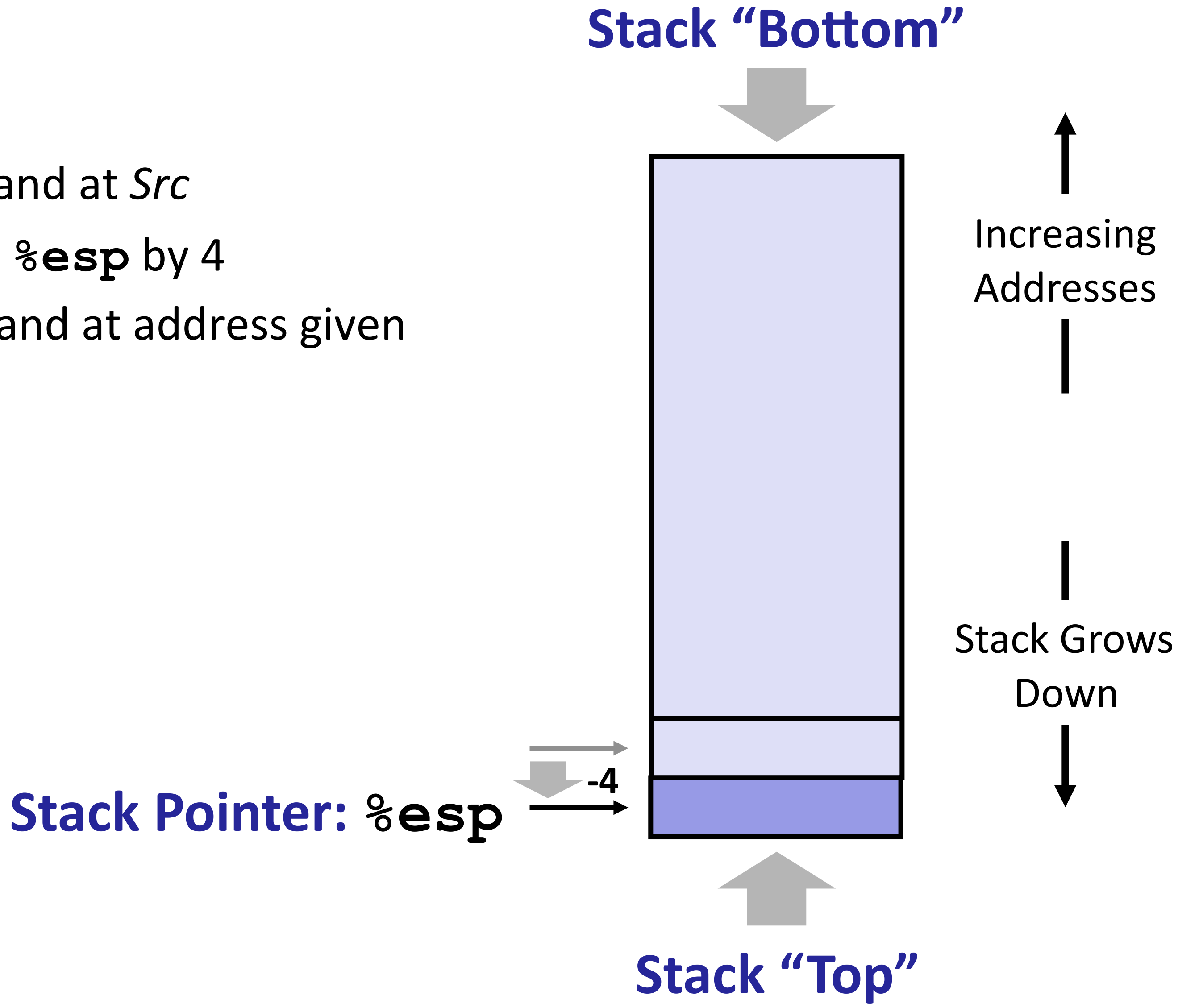
IA32 Stack

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



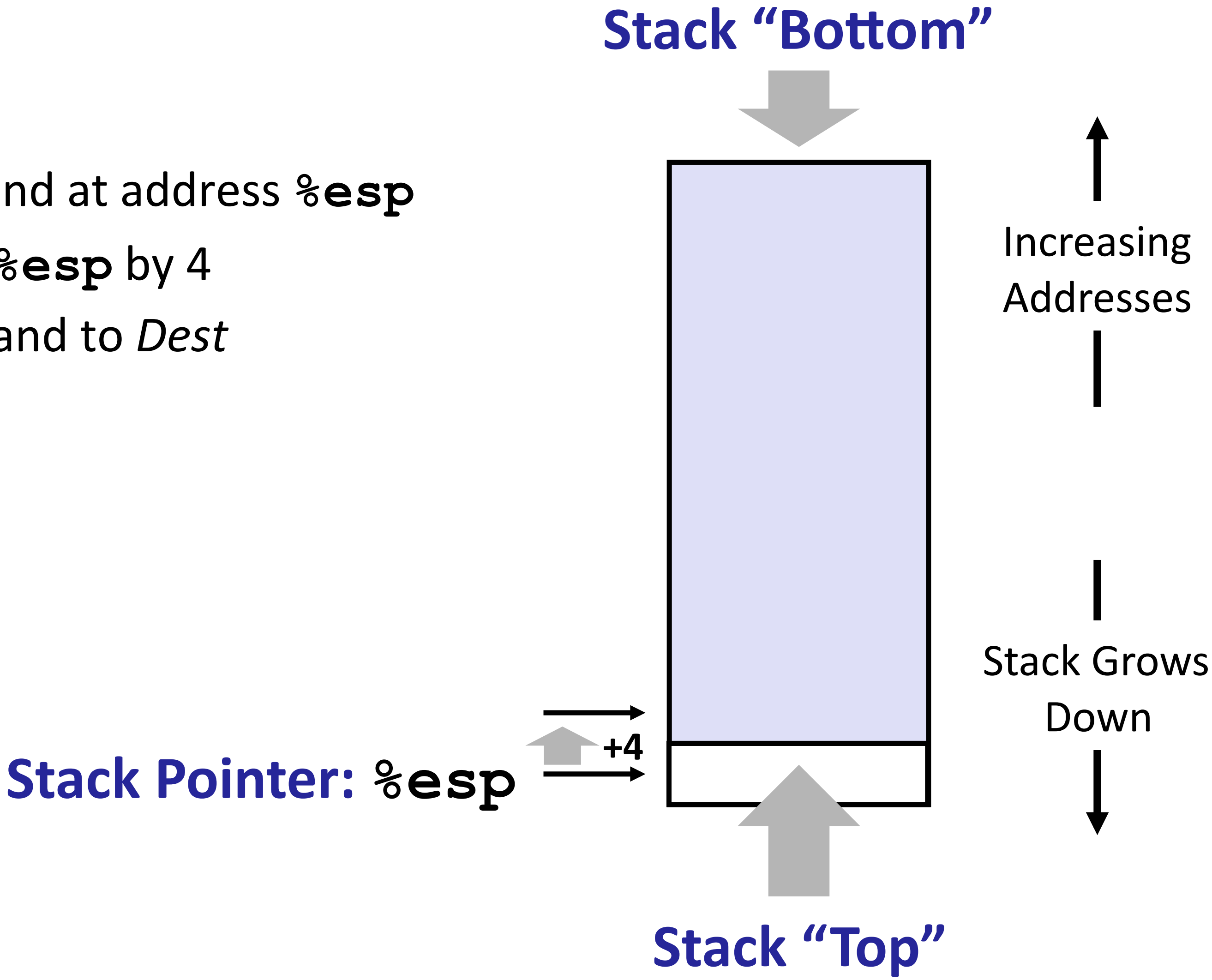
IA32 Stack: Push

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



IA32 Stack: Pop

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



Procedure Control Flow

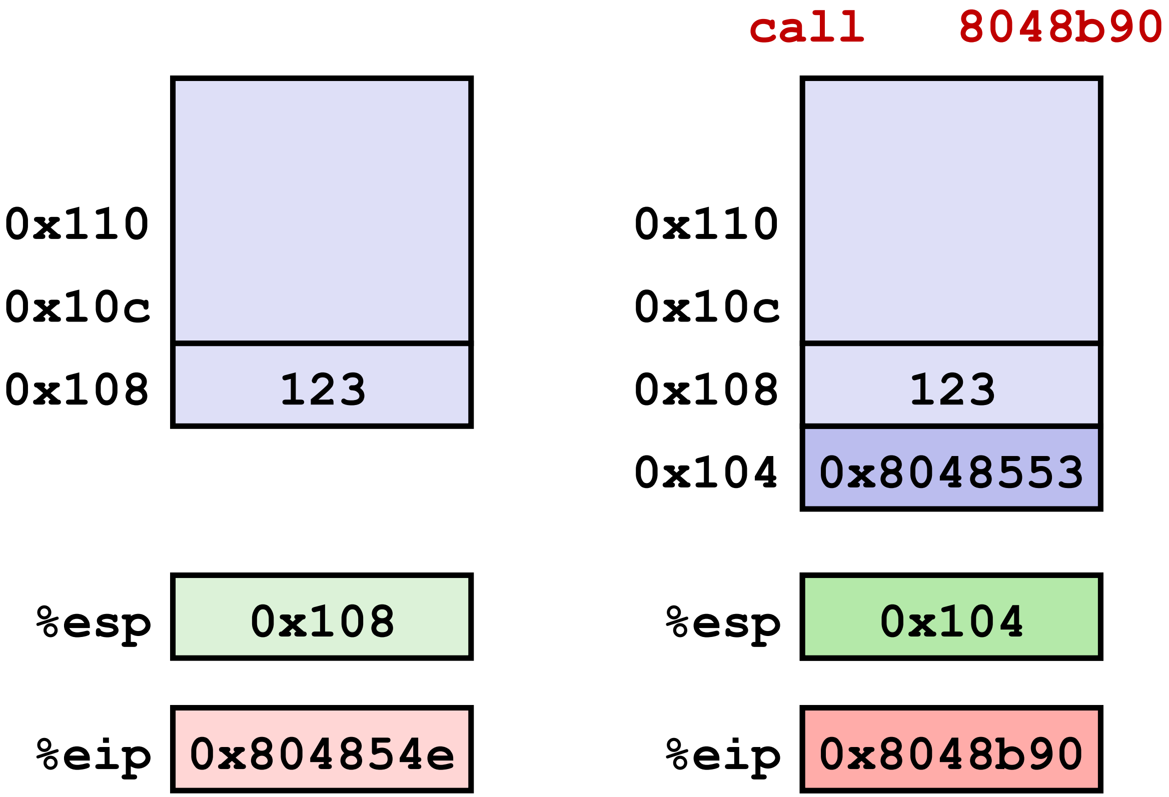
- **Use stack to support procedure call and return**
- **Procedure call: `call` *`label`***
  - Push return address on stack
  - Jump to *`label`*
- **Return address:**
  - Address of instruction beyond `call`
  - Example from disassembly

```
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

0x110

0x10c

0x108 123

0x104 0x8048553

%esp 0x108

%eip 0x804854e

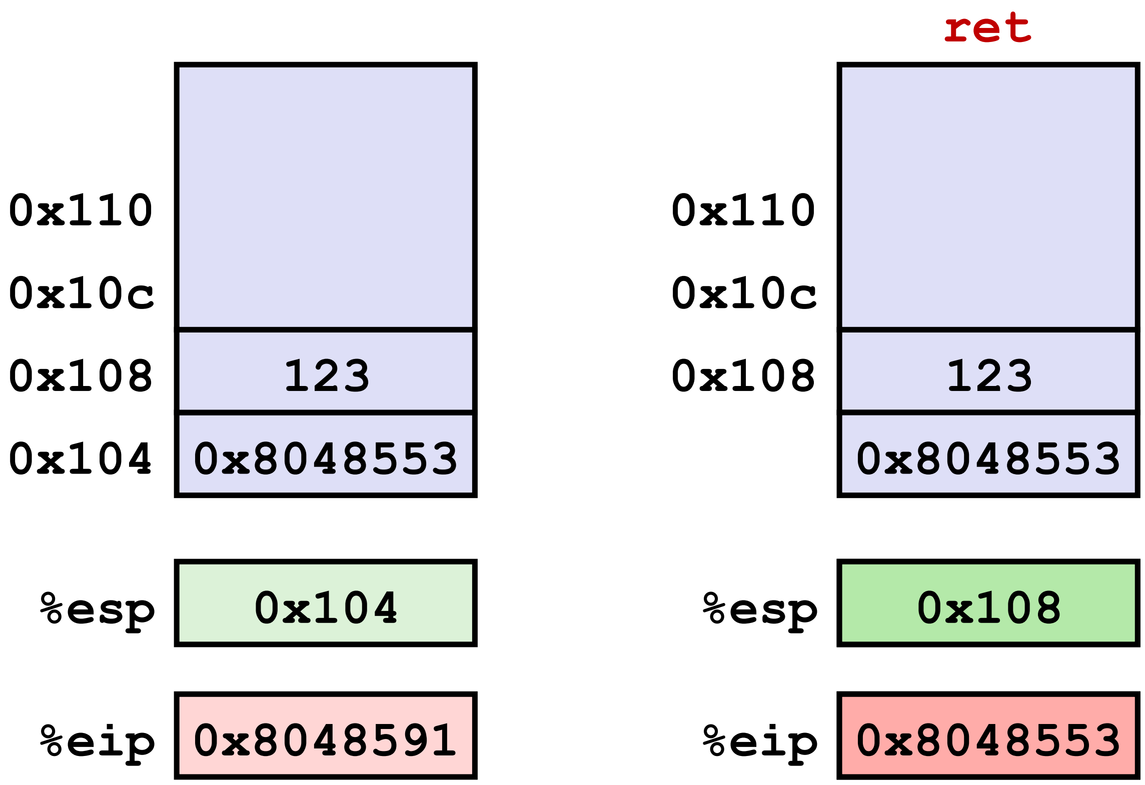
%esp 0x104

%eip 0x8048b90

%eip: 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: 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

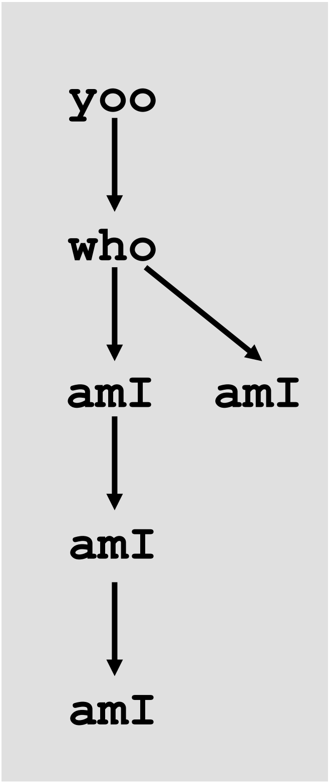
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

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

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

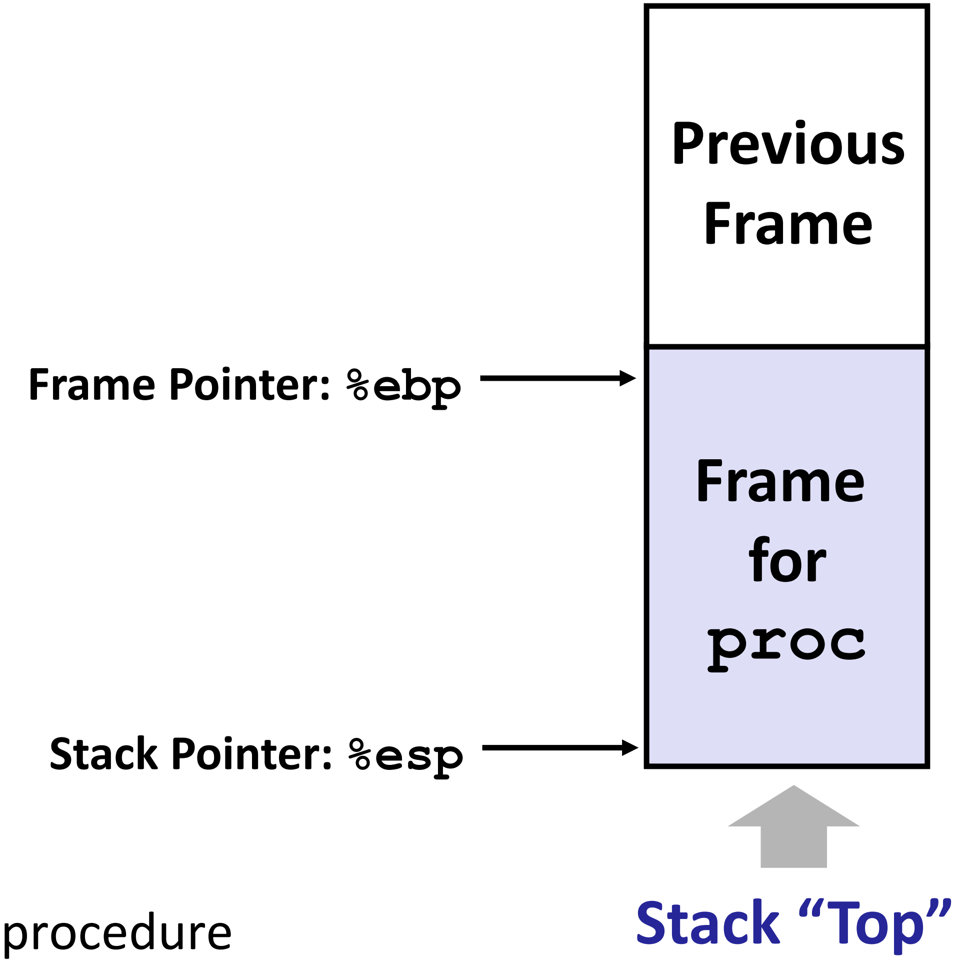
Procedure amI is recursive

Example
Call Chain



Stack Frames

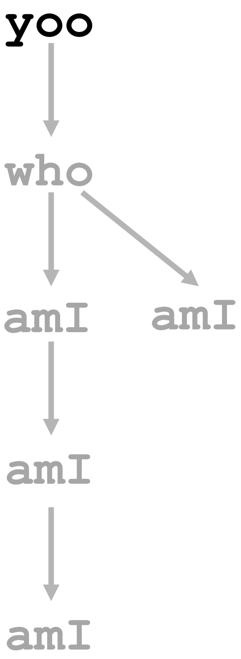
- **Contents**
  - Local variables
  - Return information
  - Temporary space

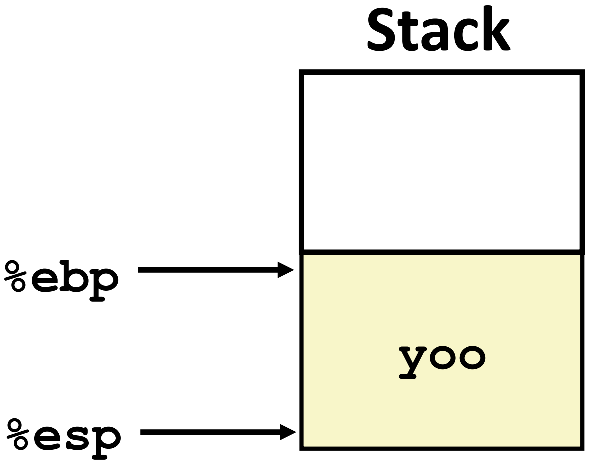


- **Management**
  - Space allocated when enter procedure
    - "Set-up" code
  - Deallocated when return
    - "Finish" code

Example

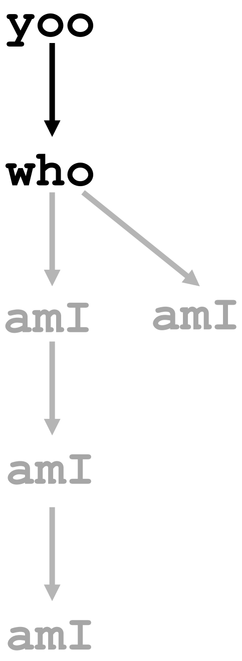
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

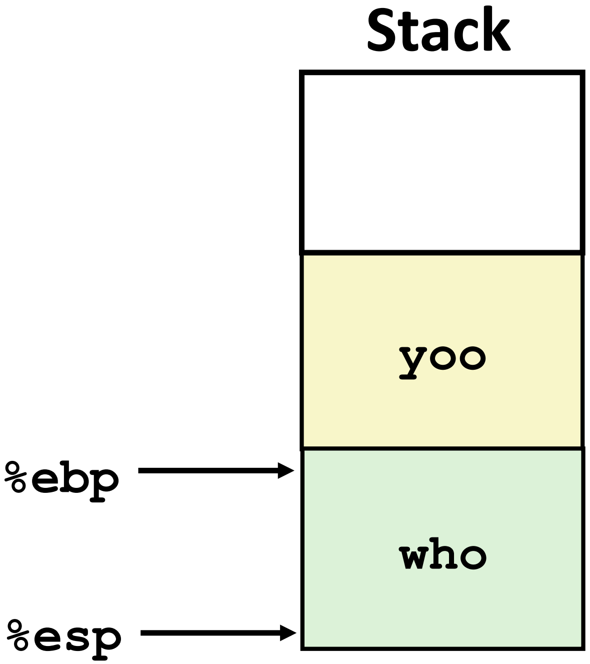




Example

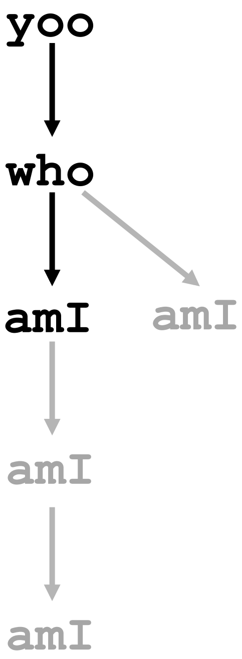
```
who(…)
{
  • • •
  amI();
  • • •
  amI();
  • • •
}
```

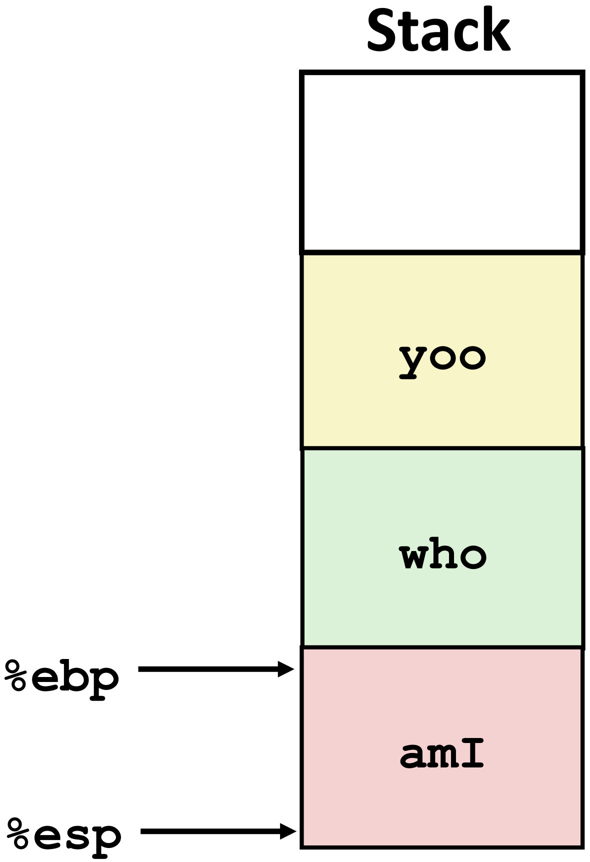




Example

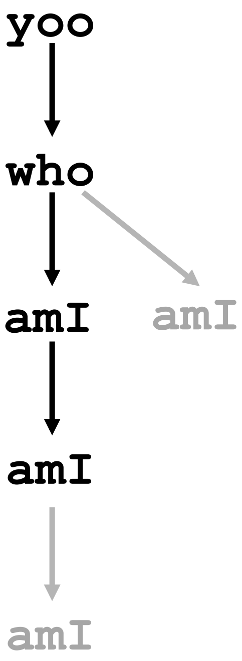
```
amI(…)
{
    •
    •
    amI();
    •
    •
}
```

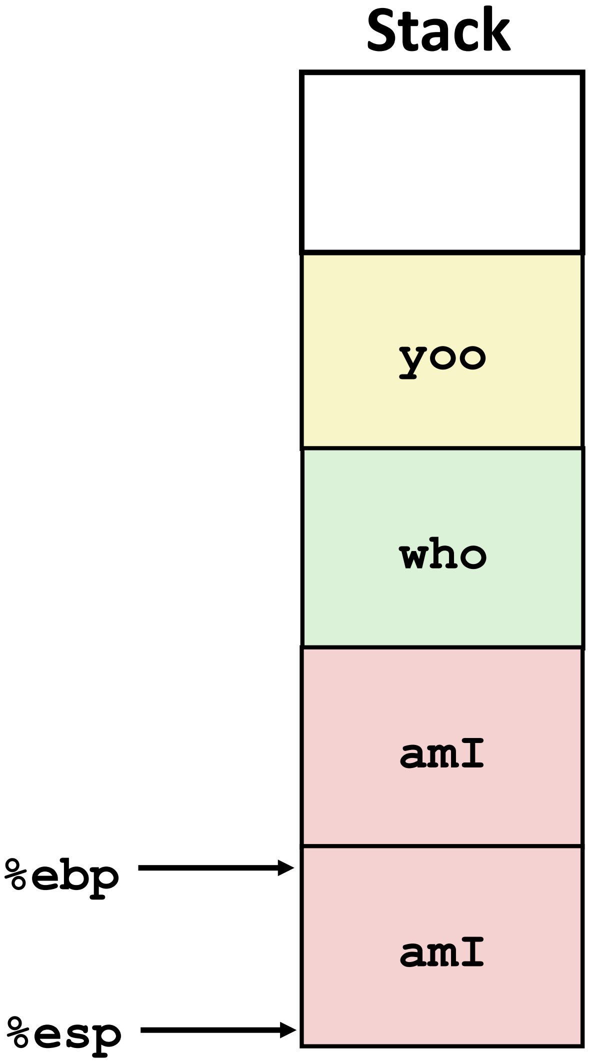




Example

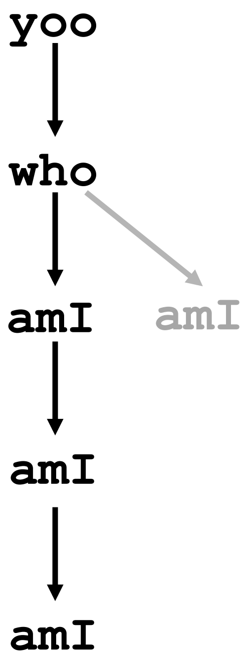
```
amI(…)
{
    •
    •
    amI();
    •
    •
}
```

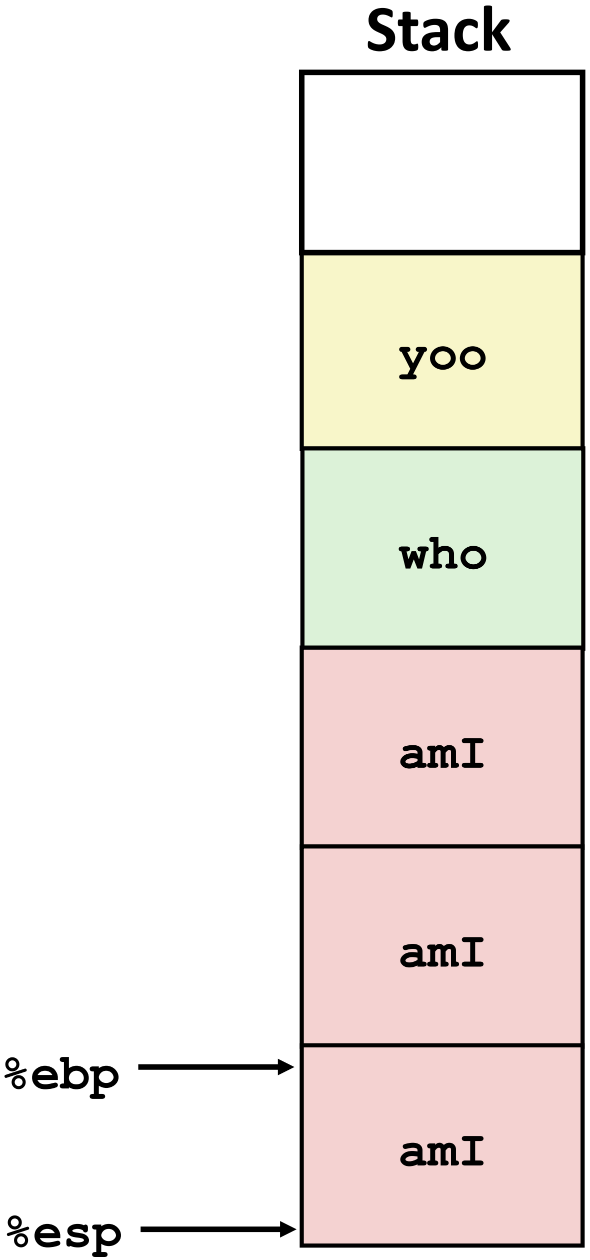




Example

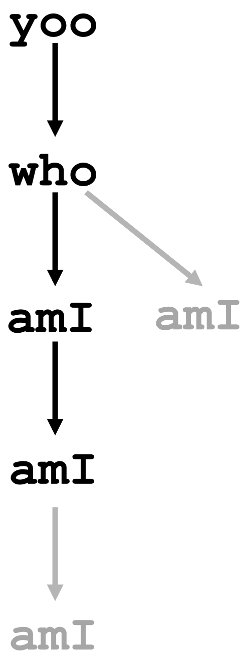
```
amI(…)
{
    •
    •
    amI();
    •
    •
}
```

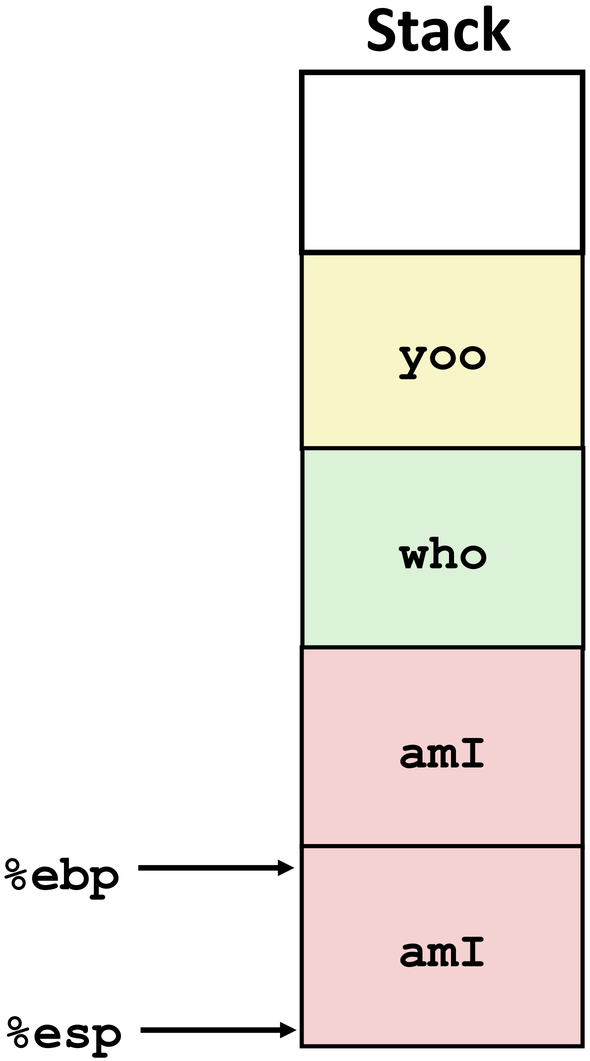




Example

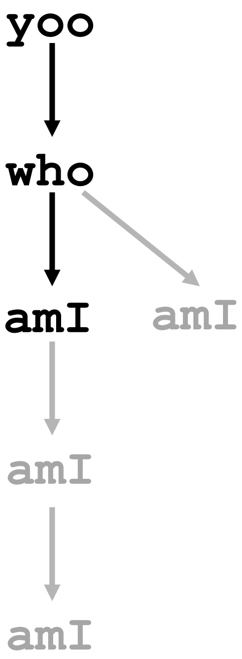
```
amI(…)
{
    •
    •
    amI();
    •
    •
}
```

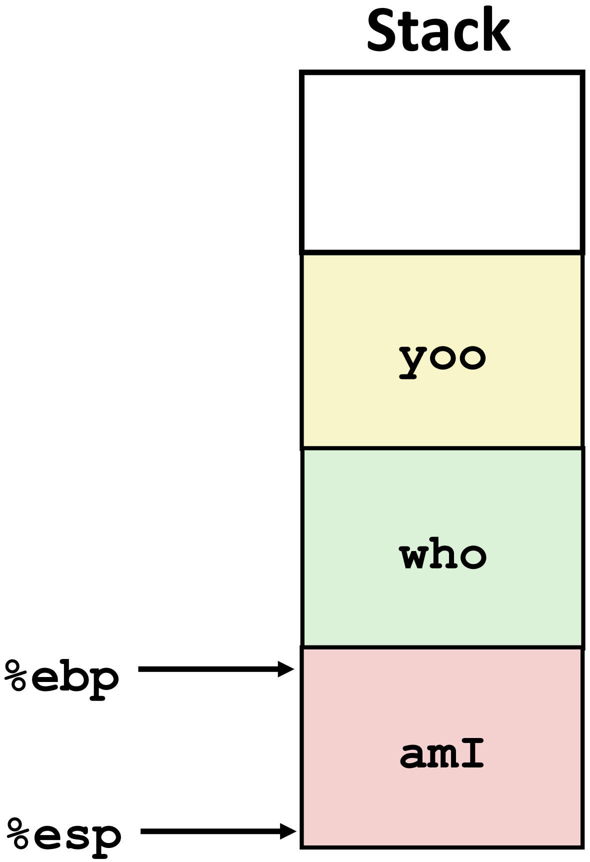




Example

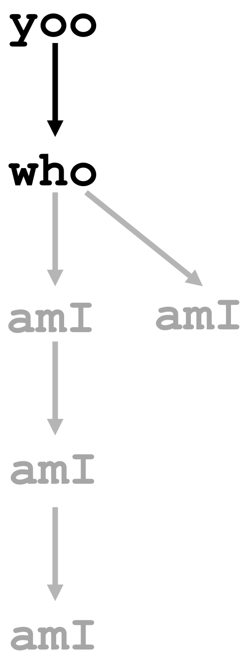
```
amI(…)
{
      •
      •
      amI();
      •
      •
}
```

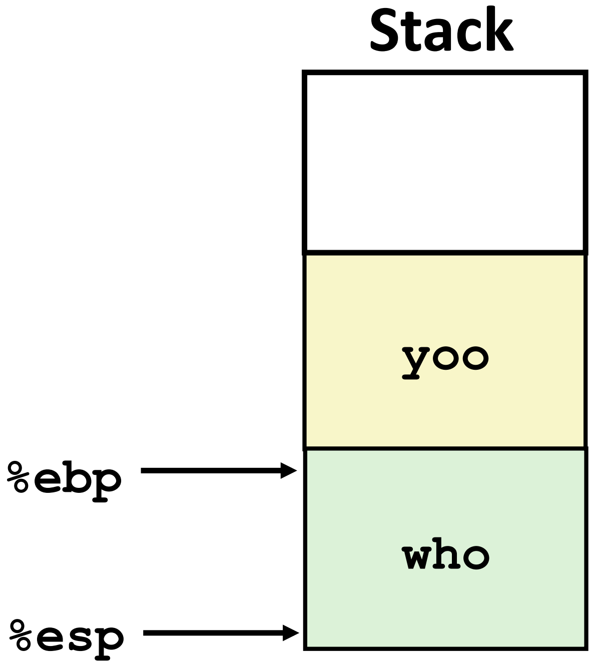




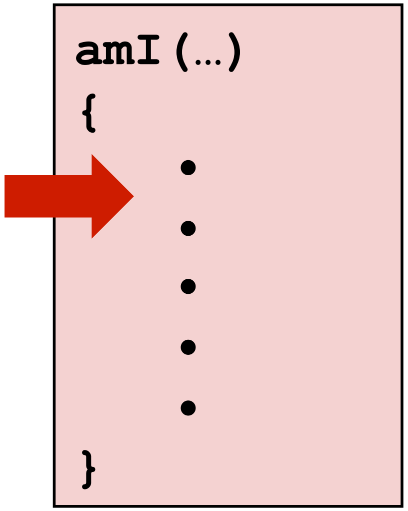
Example

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

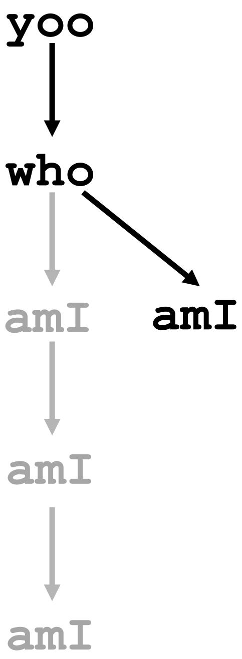


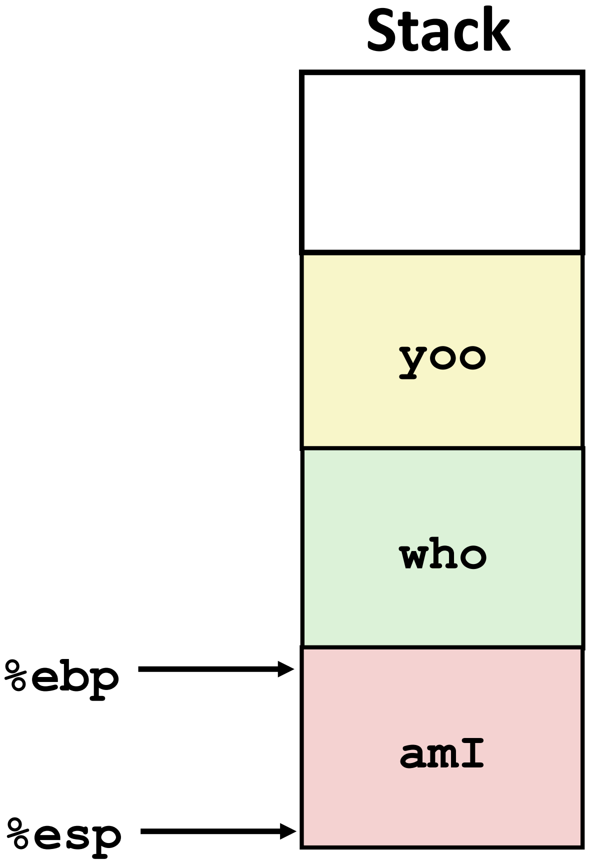


Example



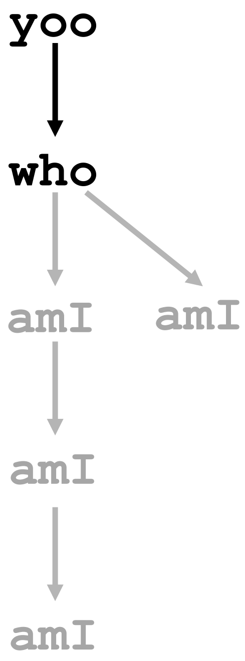
```
amI (…)
{
    •
    •
    •
    •
    •
}
```

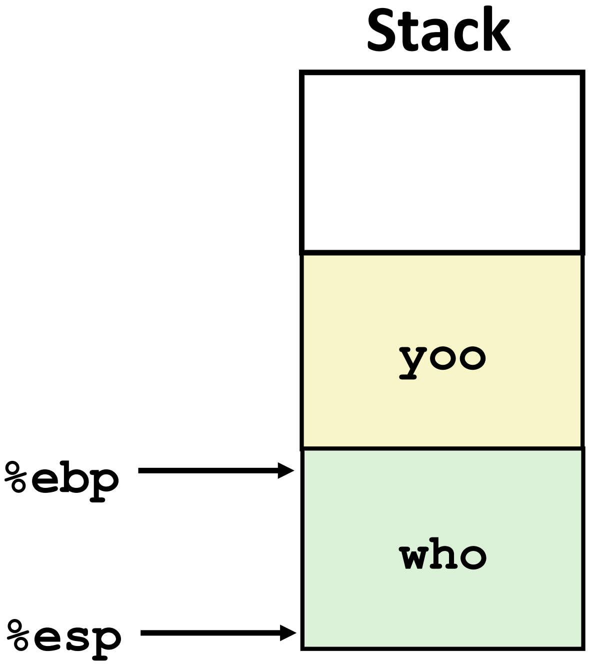




Example

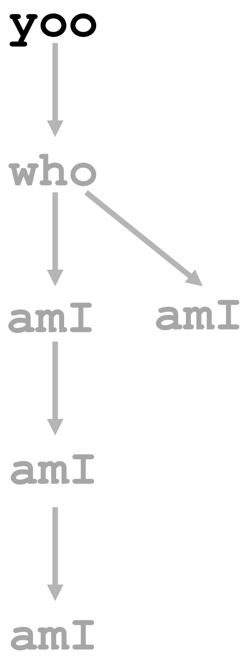
```
who(…)
{
   • • •
   amI();
   • • •
   amI();
   • • •
}
```

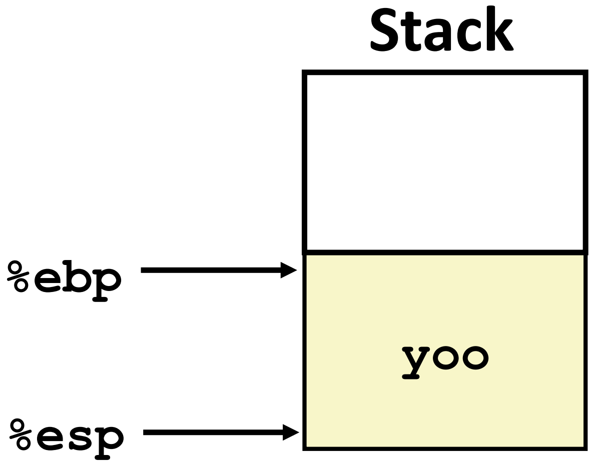




Example

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

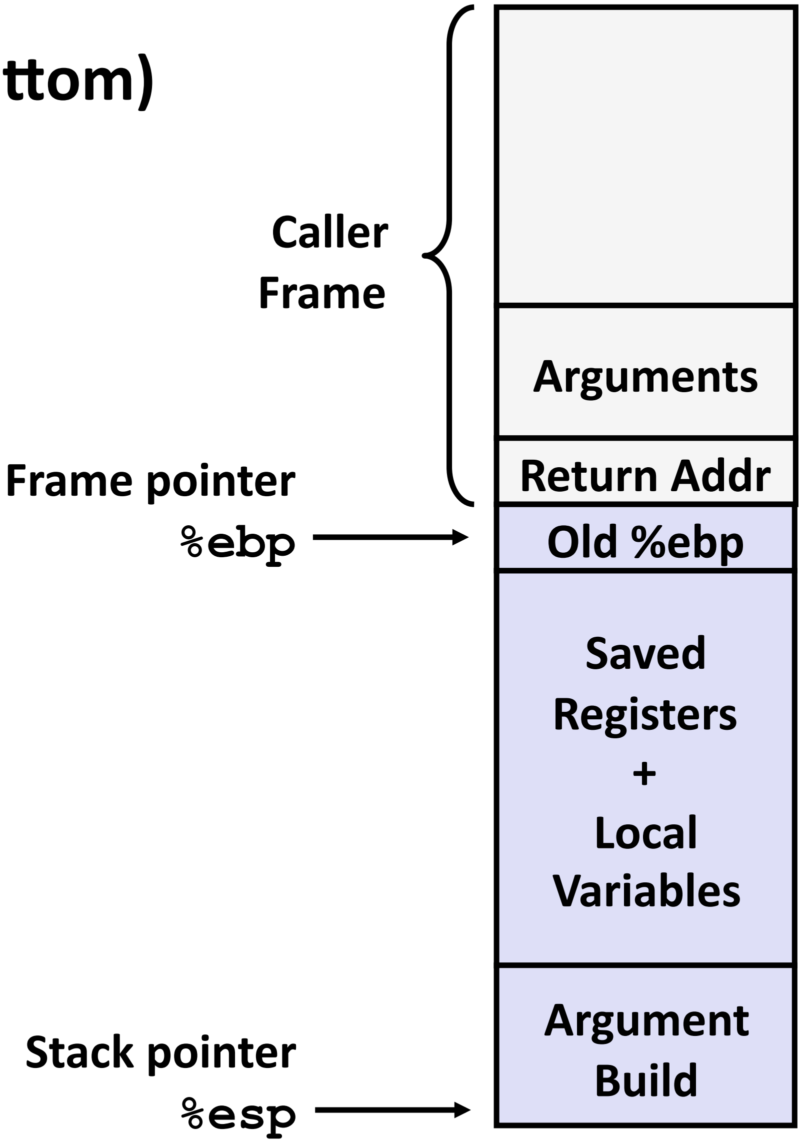




IA32/Linux Stack Frame

- **Current Stack Frame ("Top" to Bottom)**
  - "Argument build:"
    Parameters for function about to call
  - 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

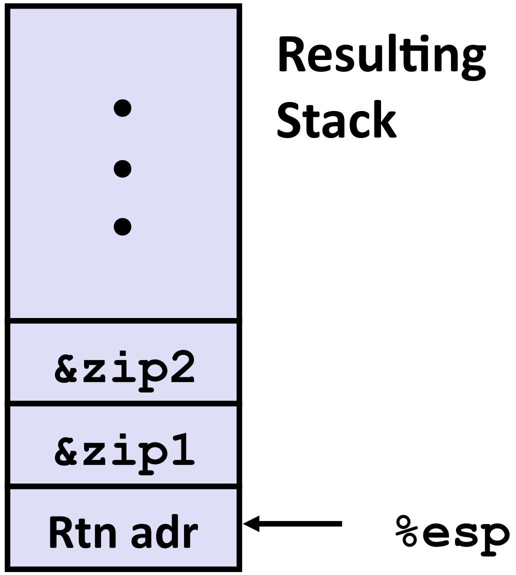
```
int zip1 = 15213;
int zip2 = 91125;

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
```

Set
Up

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

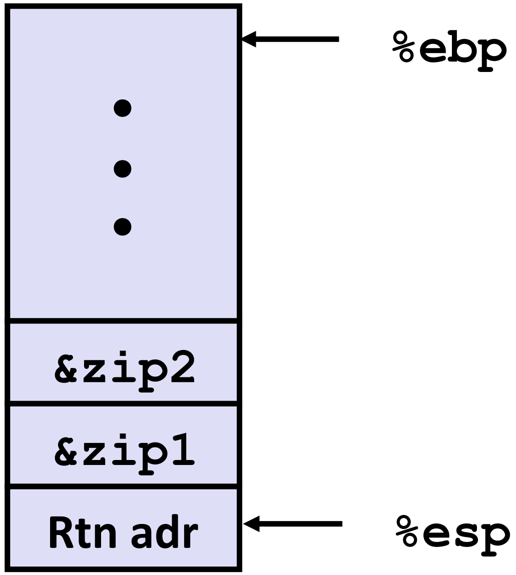
Body

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

Finish

swap Setup #1

Entering Stack



•
•
•

&zip2

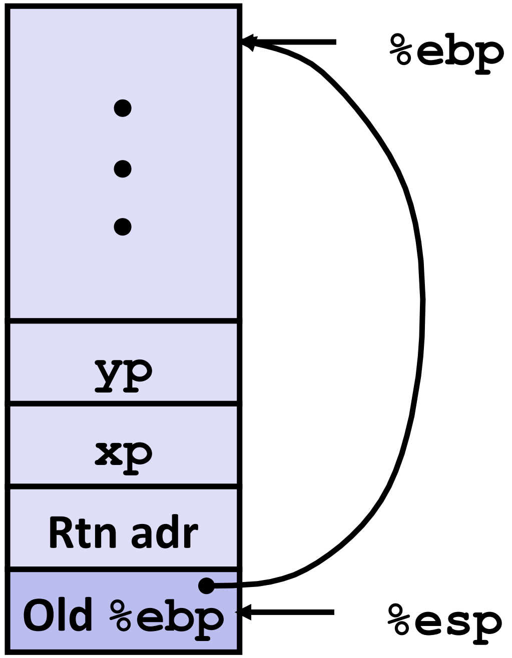
&zip1

Rtn adr

%ebp

%esp

Resulting Stack



•
•
•

yp

xp

Rtn adr

Old %ebp

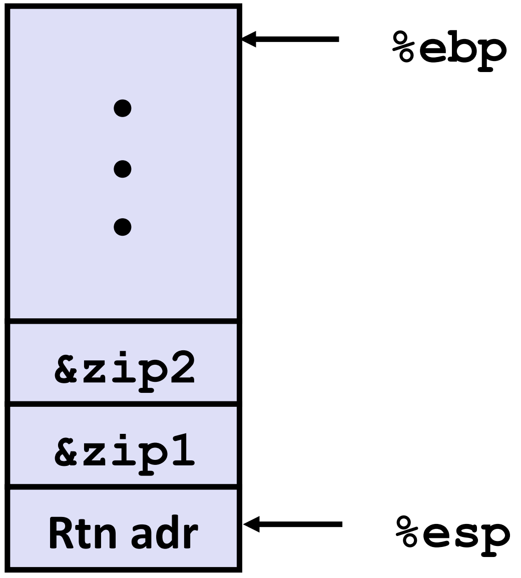
%ebp

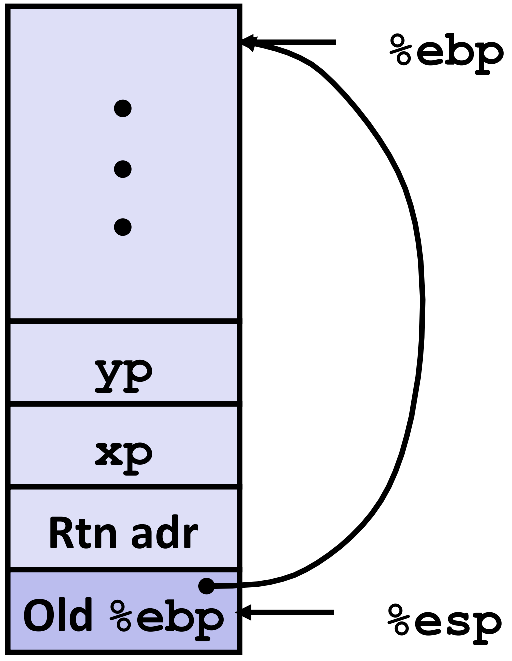
%esp

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

swap Setup #1

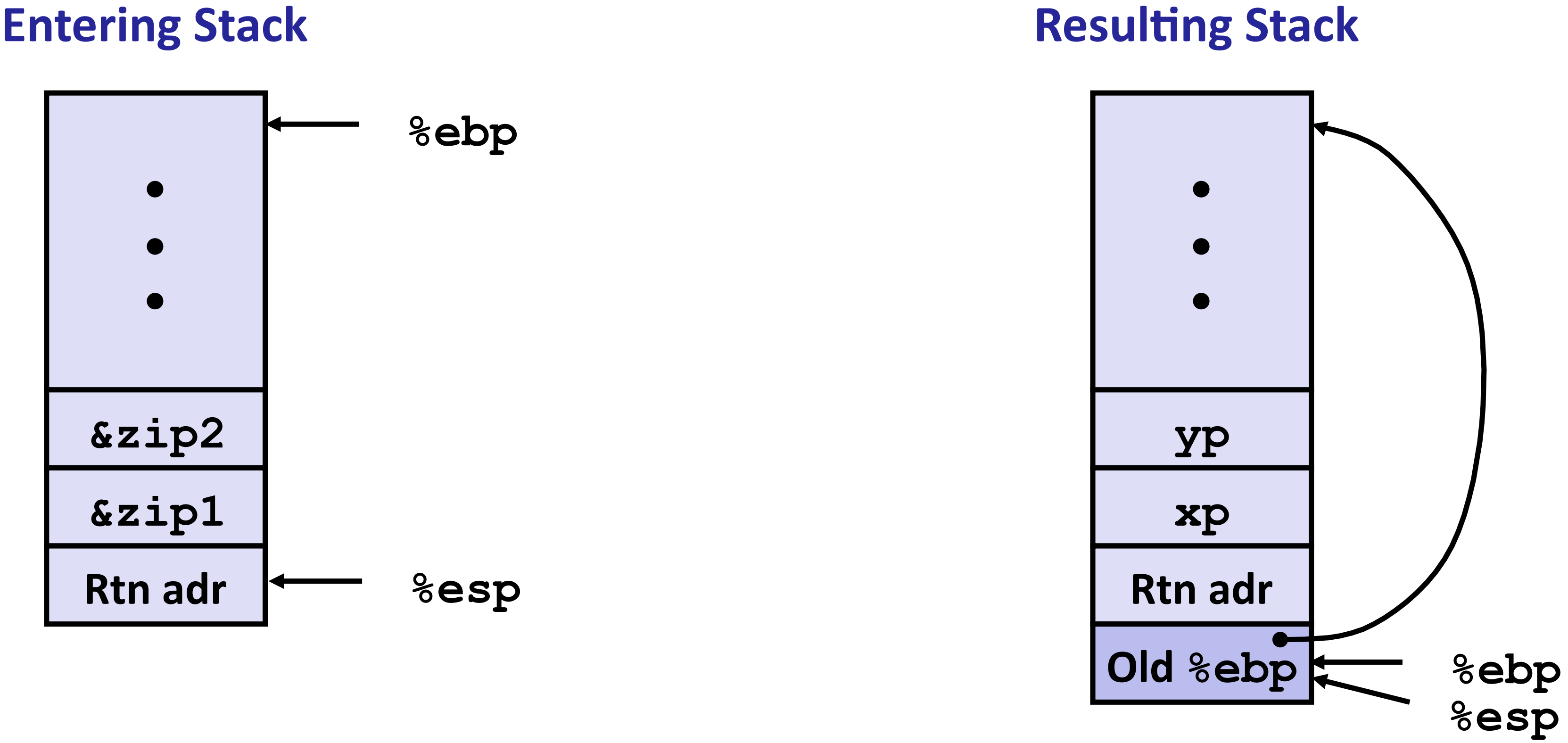
Entering Stack





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

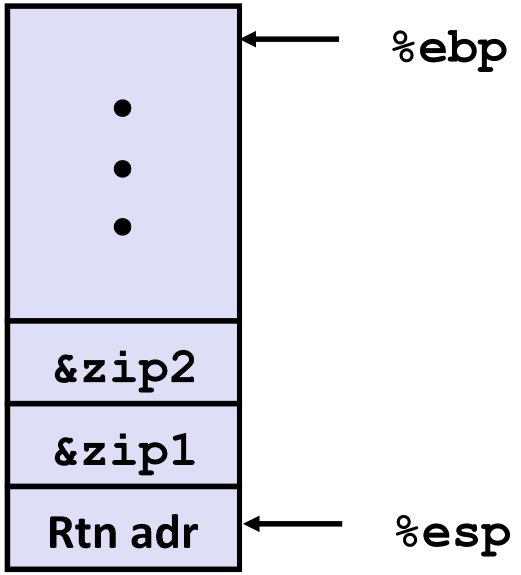
swap Setup #1

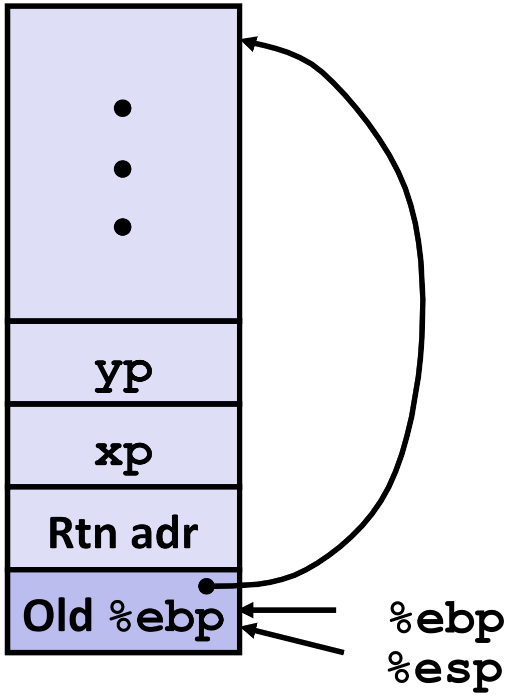


```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

swap Setup #1

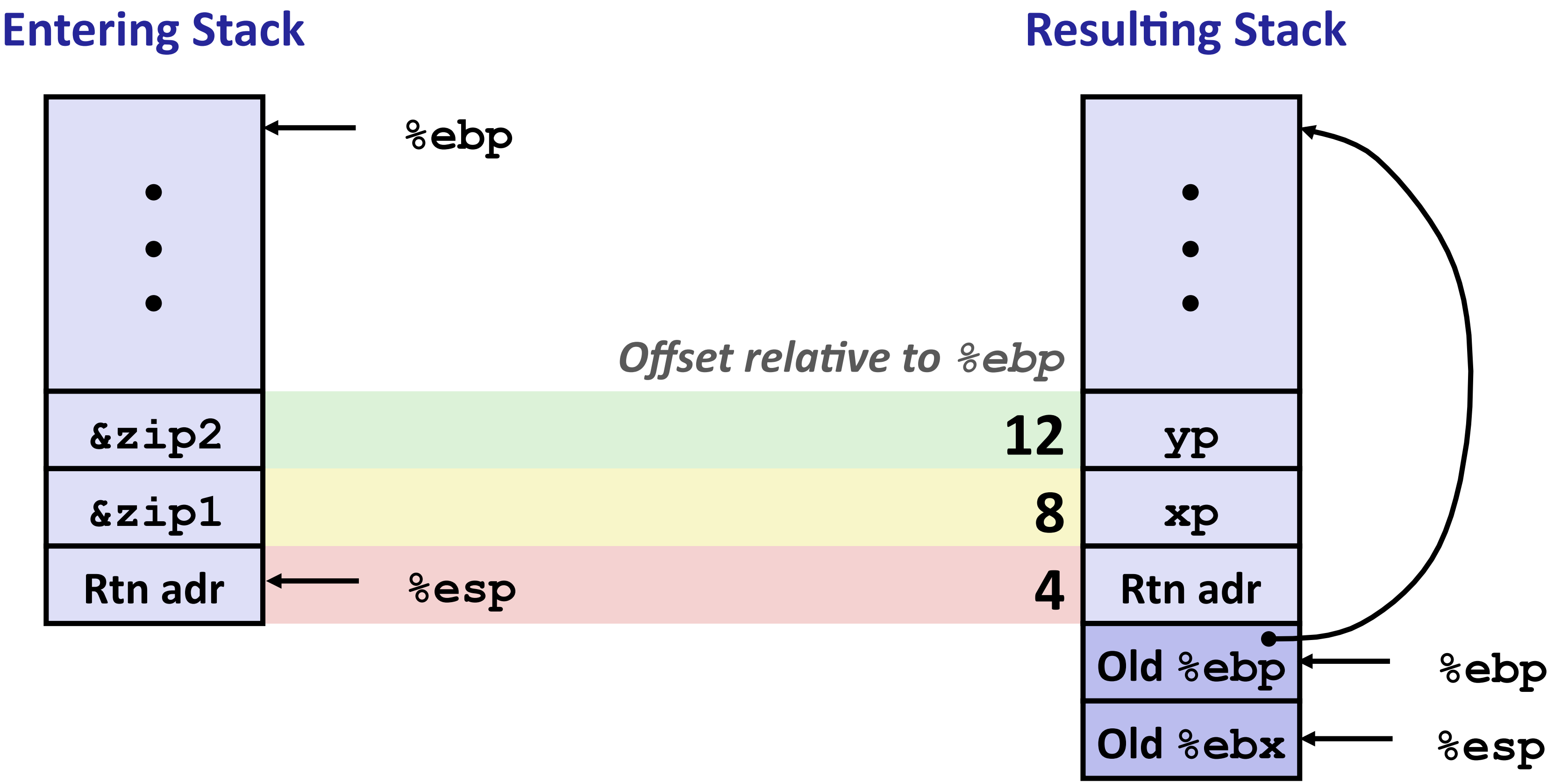
Entering Stack





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

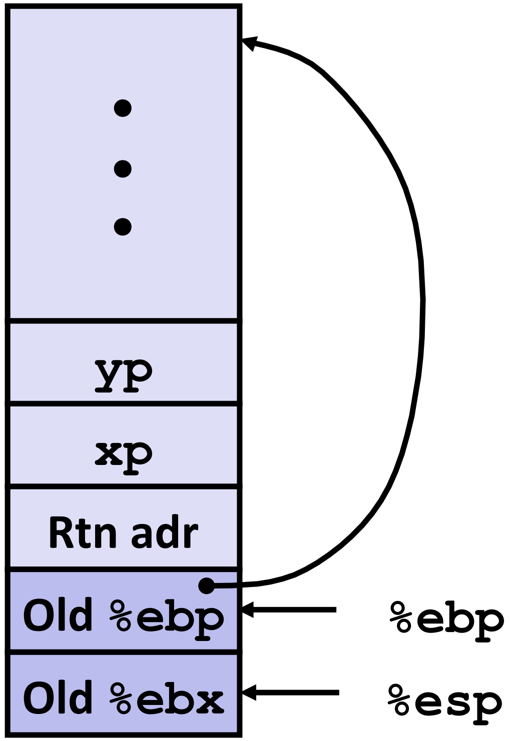
swap Setup #1



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

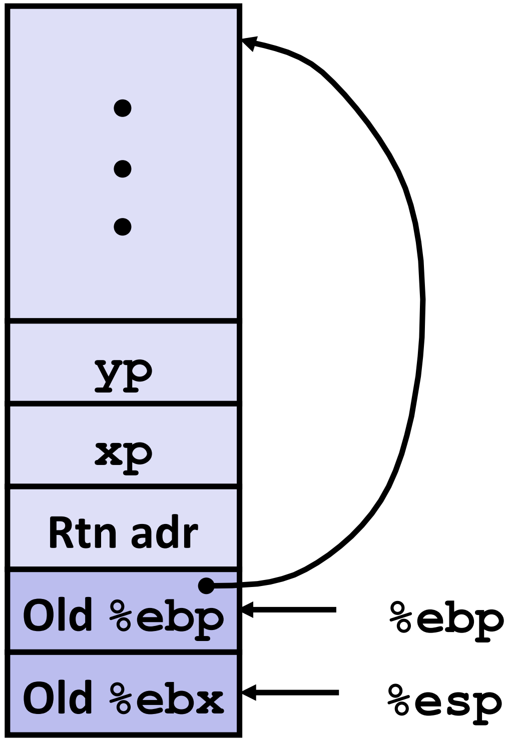
swap Finish #1

swap’s Stack



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

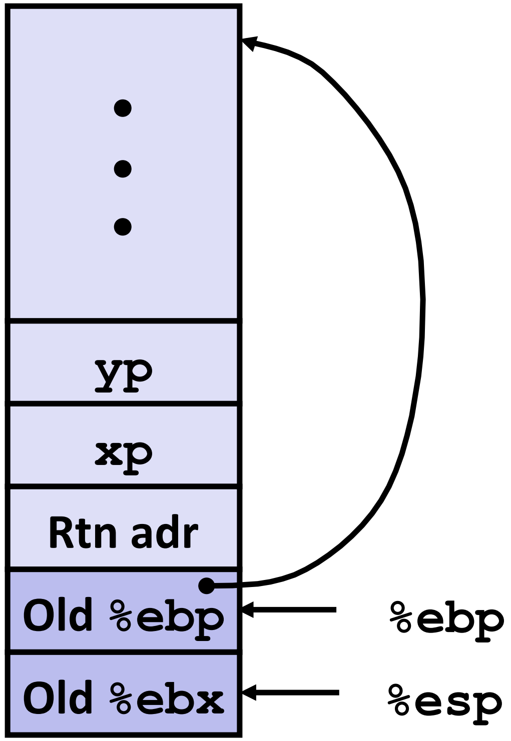
Resulting Stack

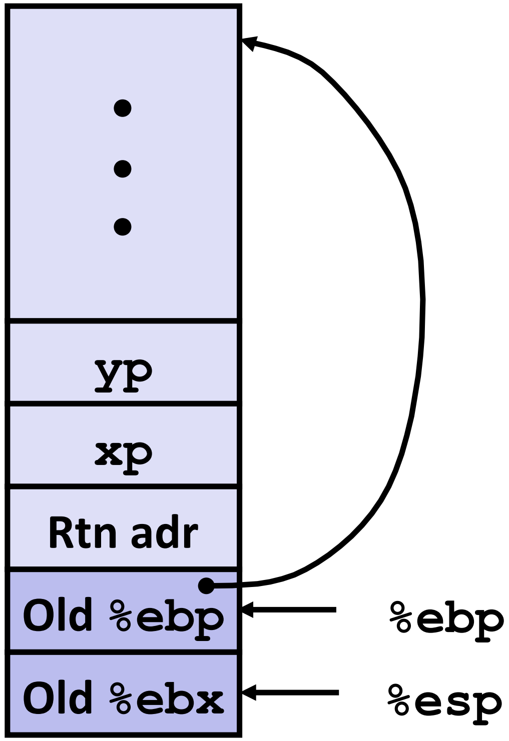


Observation: Saved and restored register %ebx

swap Finish #2

swap's Stack

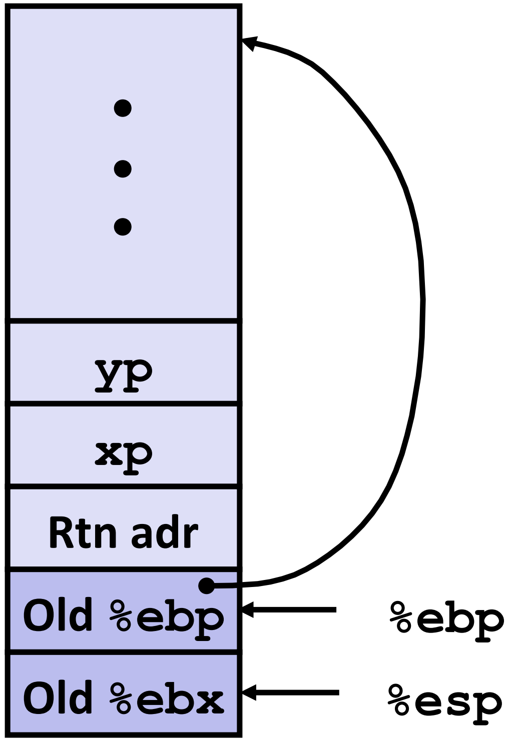




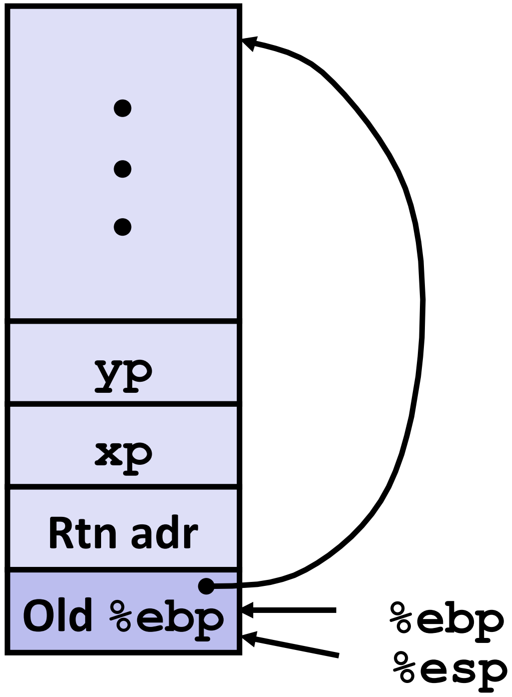
```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

swap Finish #2

swap' s Stack

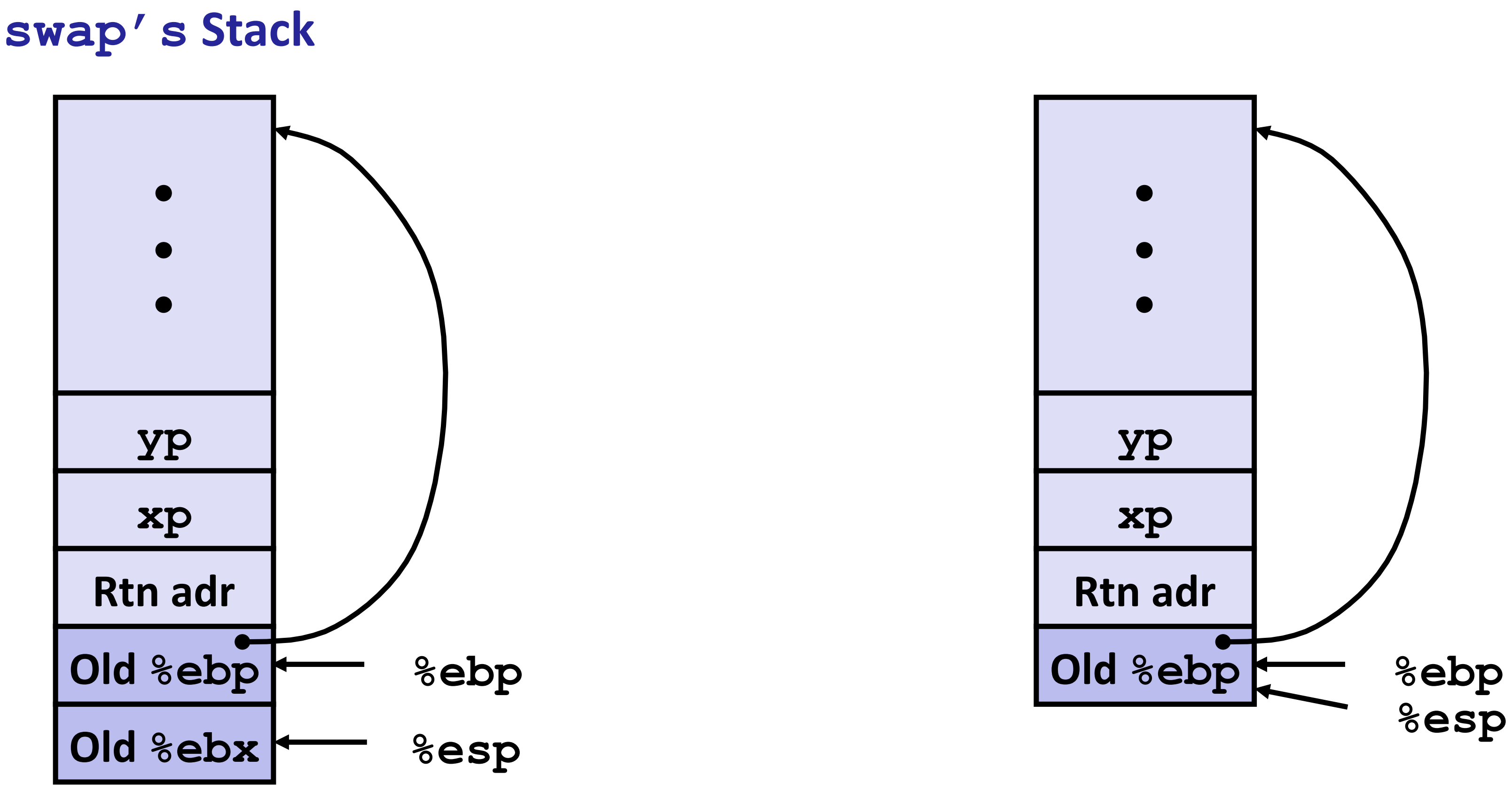


Resulting Stack



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

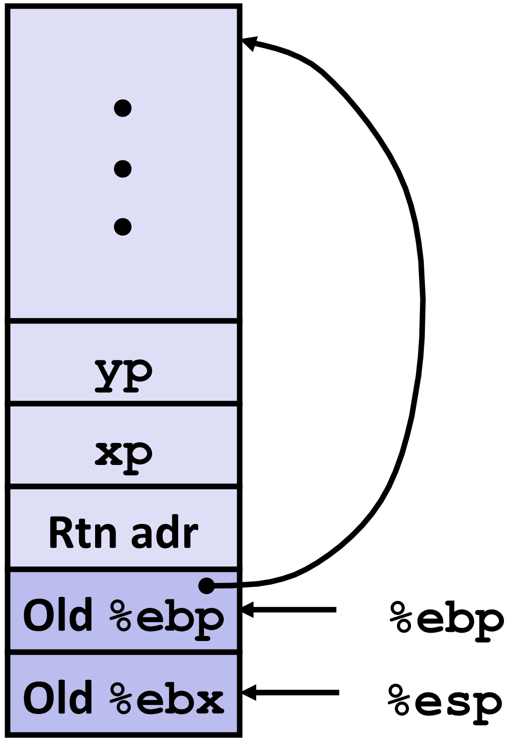
swap Finish #2



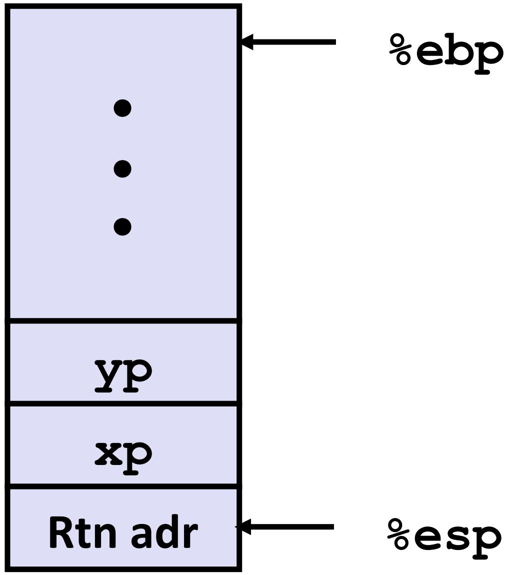
```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

swap Finish #3

swap's Stack



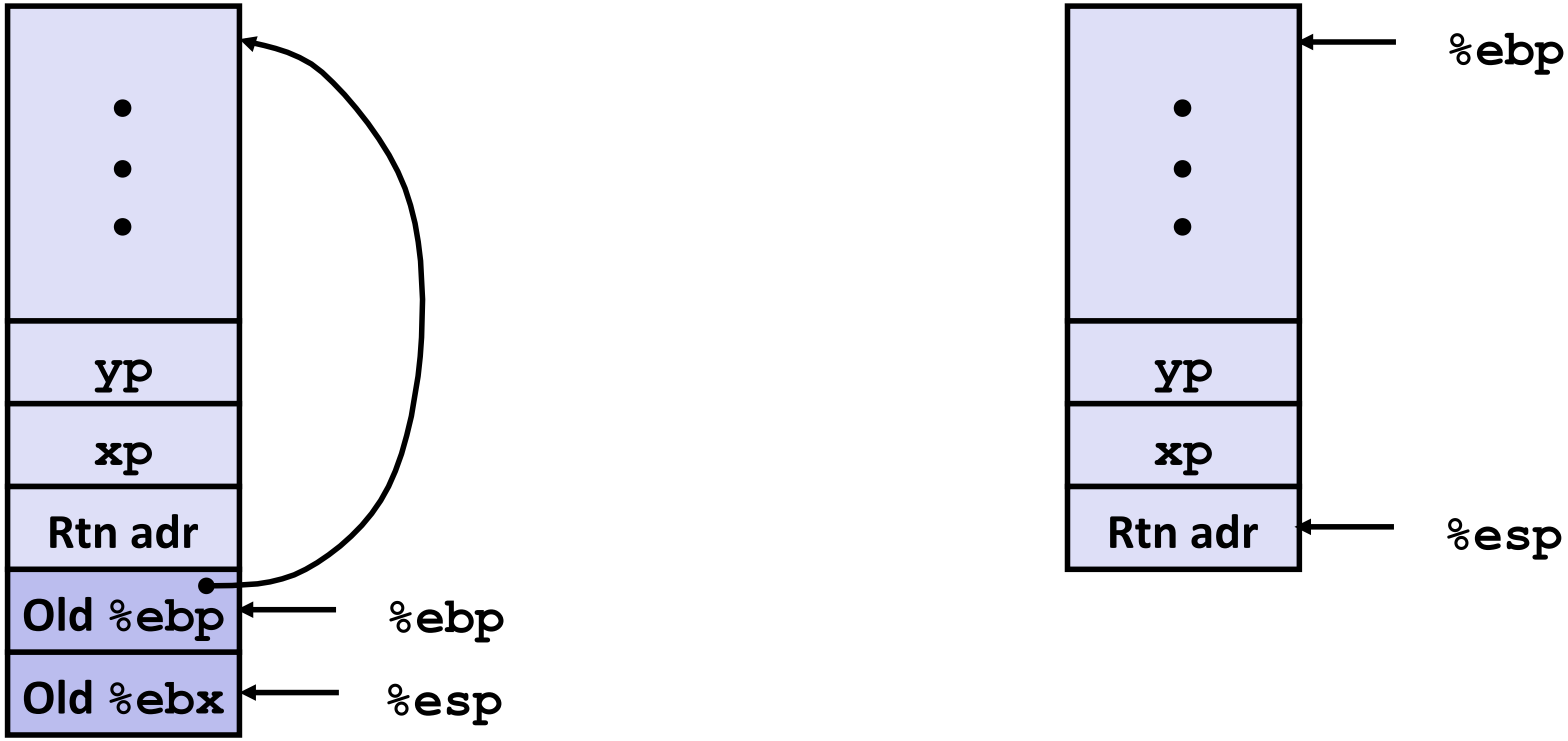
Resulting Stack



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

swap Finish #4

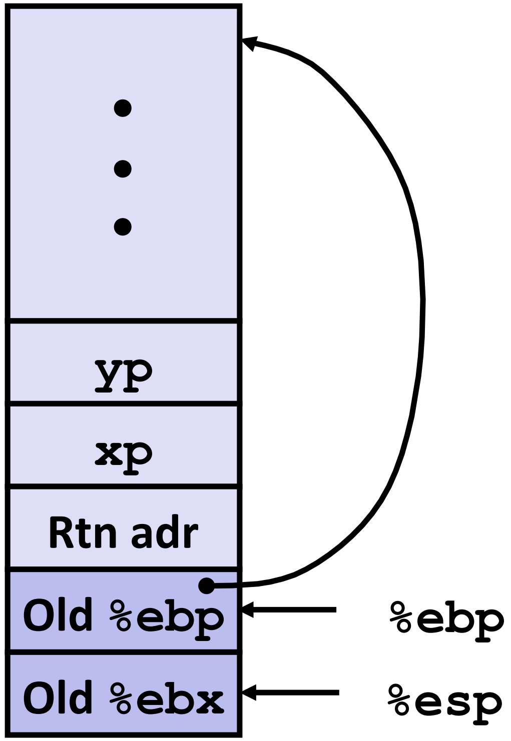
swap' s Stack



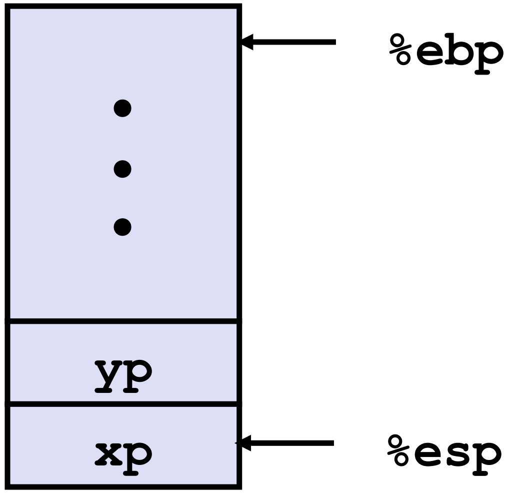
```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

swap Finish #4

swap' s Stack



Resulting Stack



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

- **Observation**
  - Saved & restored register **%ebx**
  - Didn't do so for **%eax, %ecx**, or **%edx**

Disassembled swap

```
080483a4 <swap>:
 80483a4:    55          push   %ebp
 80483a5:    89 e5       mov    %esp,%ebp
 80483a7:    53          push   %ebx
 80483a8:    8b 55 08    mov    0x8(%ebp),%edx
 80483ab:    8b 4d 0c    mov    0xc(%ebp),%ecx
 80483ae:    8b 1a       mov    (%edx),%ebx
 80483b0:    8b 01       mov    (%ecx),%eax
 80483b2:    89 02       mov    %eax,(%edx)
 80483b4:    89 19       mov    %ebx,(%ecx)
 80483b6:    5b          pop    %ebx
 80483b7:    c9          leave
 80483b8:    c3          ret
```

Calling Code

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

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`

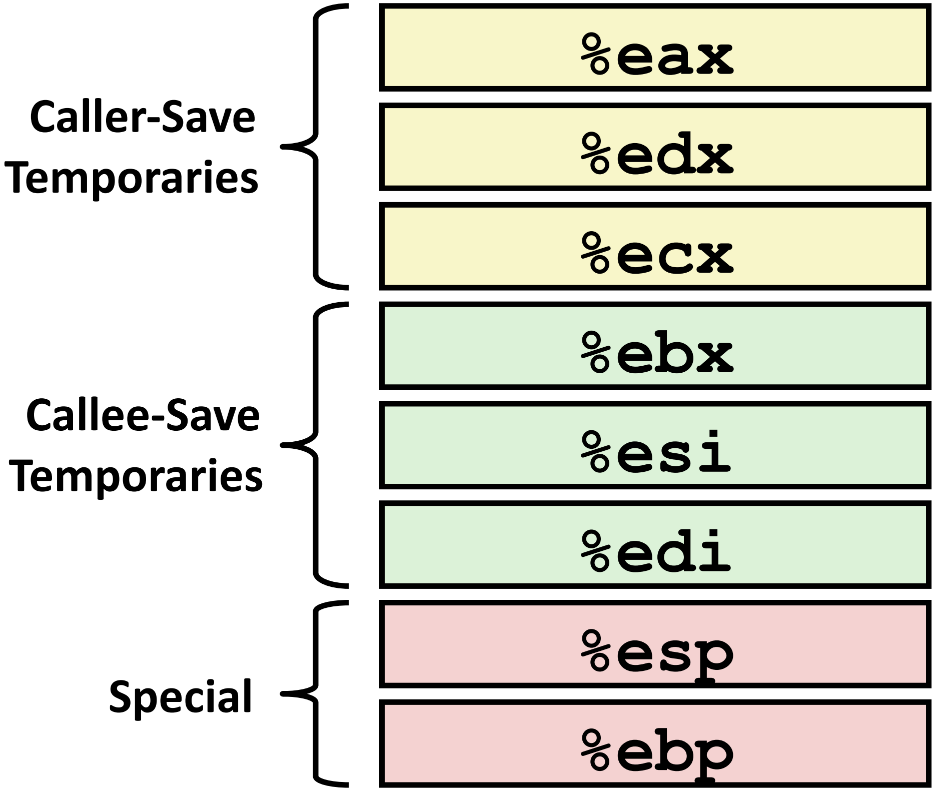
Register Saving Conventions

- **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

- `%eax, %edx, %ecx`
  - Caller saves prior to call if values are used later
- `%eax`
  - also used to return integer value
- `%ebx, %esi, %edi`
  - Callee saves if wants to use them
- `%esp, %ebp`
  - special



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 saved 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
```

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

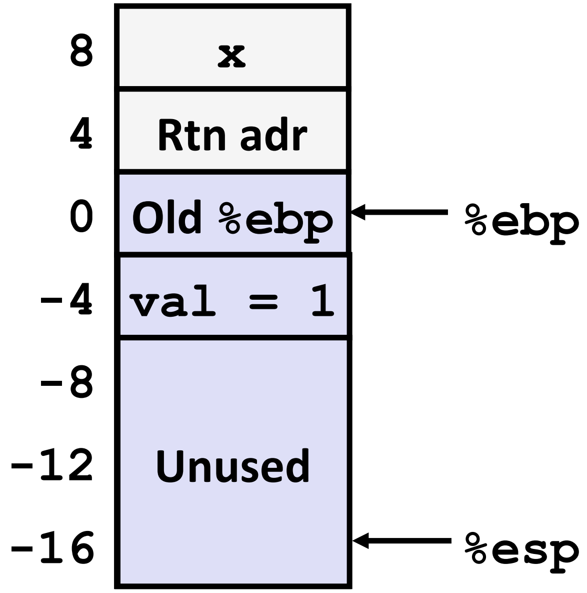
```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- Pass pointer to update location

Creating & Initializing Pointer

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

- Compute pointer to `val` as `-4(%ebp)`
- Push on stack as second argument



Initial part of `sfact`

```
_sfact:
   pushl %ebp
   movl  %esp,%ebp
   subl  $16,%esp
   movl  8(%ebp),%edx
   movl  $1,-4(%ebp)
```

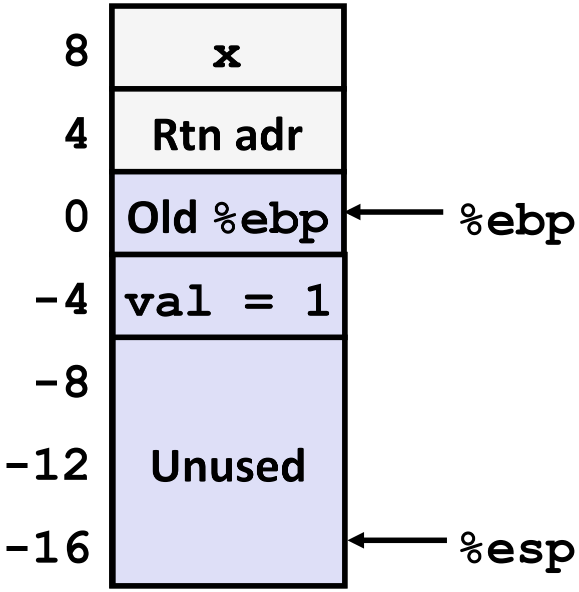
Creating & Initializing Pointer

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

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

Initial part of `sfact`

```
_sfact:
  pushl %ebp              # Save %ebp
  movl %esp,%ebp          # Set %ebp
  subl $16,%esp           # Add 16 bytes
  movl 8(%ebp),%edx       # edx = x
  movl $1,-4(%ebp)        # val = 1
```



8 x

4 Rtn adr

0 Old %ebp ← %ebp

-4 val = 1

-8

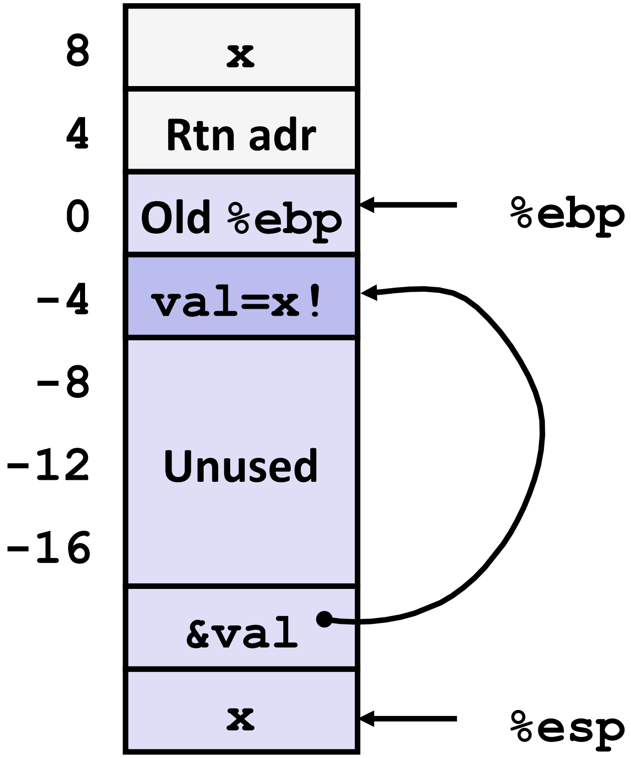
-12 Unused

-16 ← %esp

Passing Pointer

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

Stack at time of call



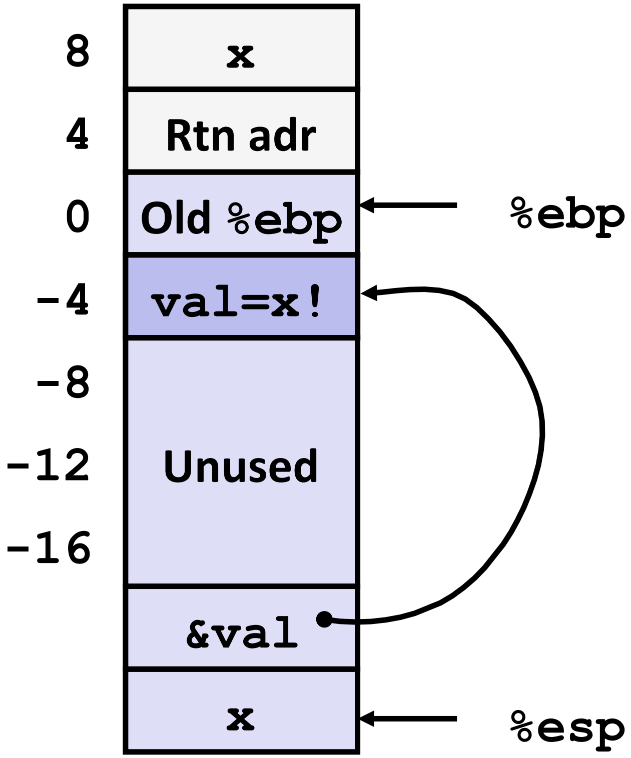
Calling s_helper from sfact

```
   leal -4(%ebp),%eax
   pushl %eax
   pushl %edx
   call s_helper
   movl -4(%ebp),%eax
   • • •
```

Passing Pointer

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

Stack at time of call

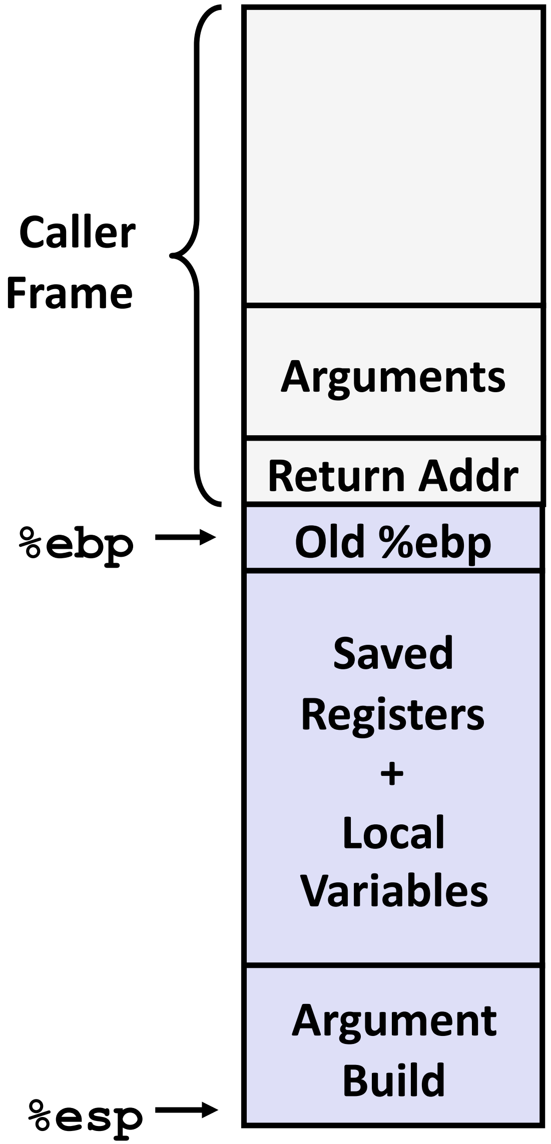


Calling s_helper from sfact

```
   leal -4(%ebp),%eax # Compute &val
   pushl %eax         # Push on stack
   pushl %edx         # Push x
   call s_helper      # call
   movl -4(%ebp),%eax # Return val
   • • •              # Finish
```

IA 32 Procedure Summary

- **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
  - 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


Caller Frame
Arguments
Return Addr
%ebp
Old %ebp
Saved Registers + Local Variables
Argument Build
%esp