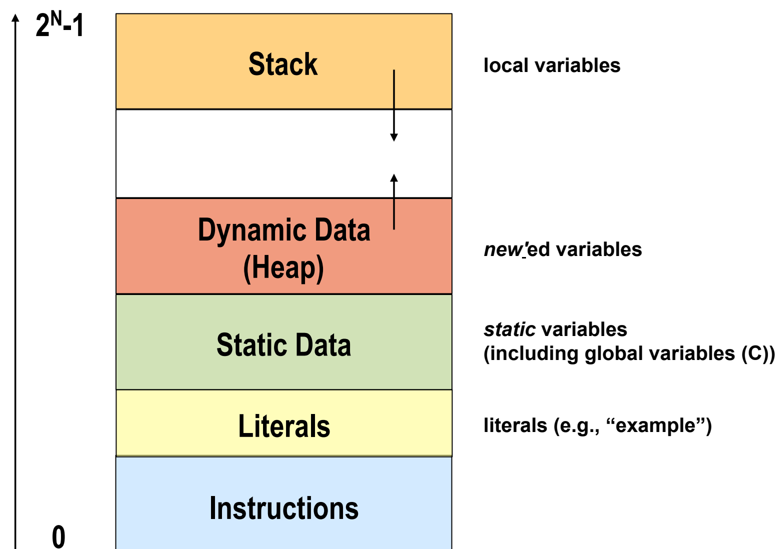
Procedures and Call Stacks

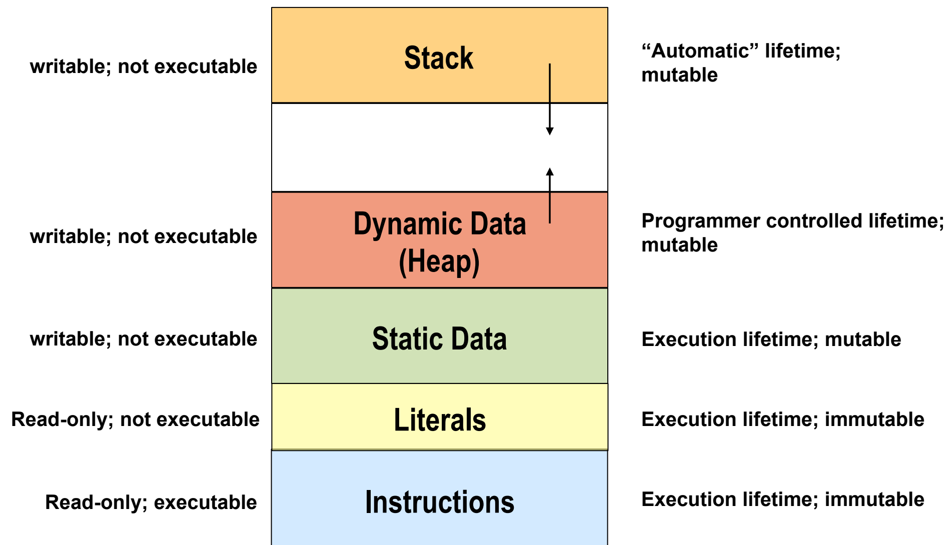
- How do I pass arguments to a procedure?
- How do I get a return value from a procedure?
- Where do I put local variables?
- When a function returns, how does it know where to return to?

- To answer these questions, we need a *call stack* …

Memory Layout



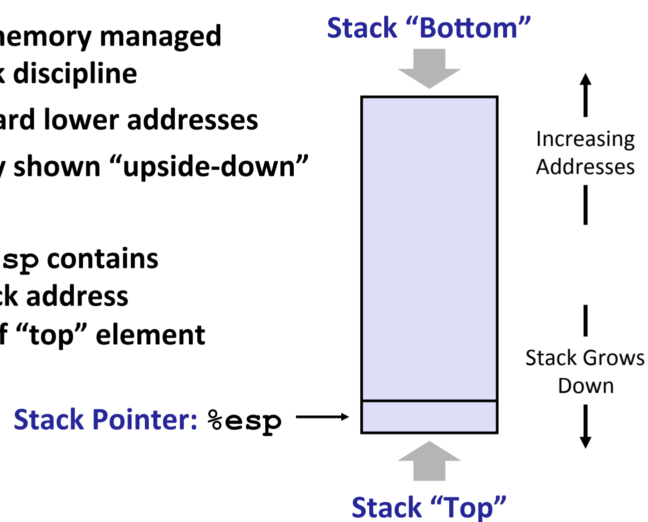
Memory Layout



IA32 Stack

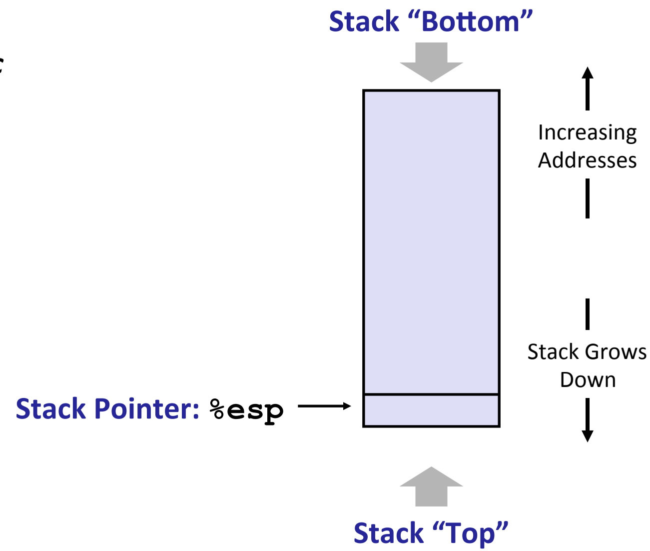
- Region of memory managed with a stack discipline
- Grows toward lower addresses
- Customarily shown "upside-down"

- Register `%esp` contains lowest stack address = address of "top" element



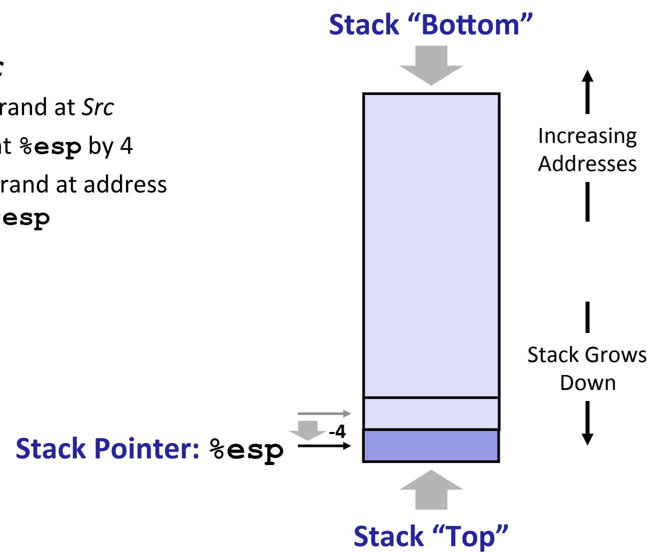
IA32 Stack: Push

- **pushl** *Src*



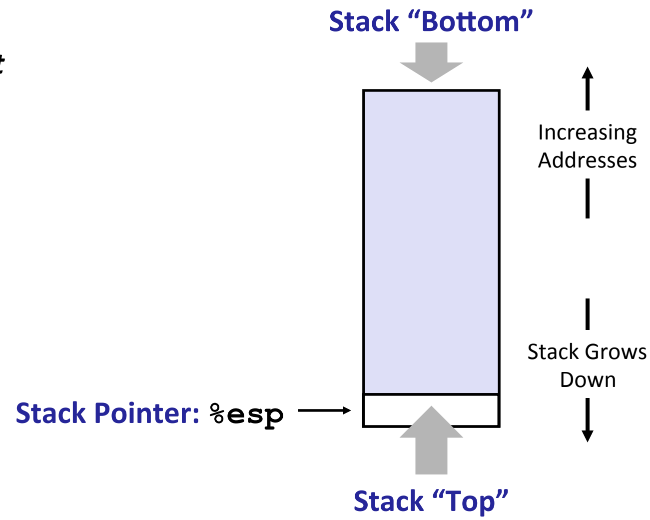
IA32 Stack: Push

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



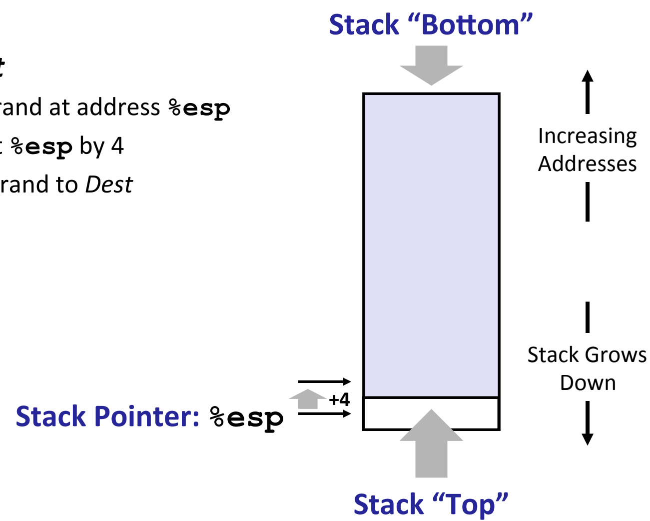
IA32 Stack: Pop

- `popl` ***Dest***

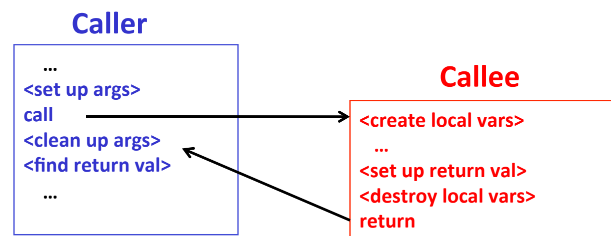


IA32 Stack: Pop

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

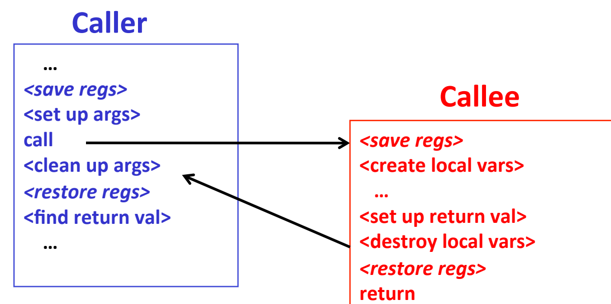


Procedure Call Overview



- **Callee must know where to find args**
- **Callee must know where to find "return address"**
- **Caller must know where to find return val**
- **Caller and Callee run on same cpu → use the same registers**
  - Might need to *save* registers used by Callee

Procedure Call Overview



- **The convention of where to leave/find things is called the procedure call linkage**
  - Details vary between systems
  - We will see the convention for IA32/Linux in detail

Procedure Control Flow

- **Use stack to support procedure call and return**
- **Procedure call: `call label`**
  - Push return address on stack
  - Jump to ***label***

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
```

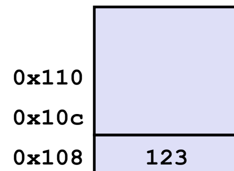
  - Return address = **`0x8048553`**
- **Procedure return: `ret`**
  - Pop address from stack
  - Jump to address

Procedure Call Example

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

call 8048b90

0x110
0x10c
0x108



%esp 0x108

%eip 0x804854e

%eip: program counter

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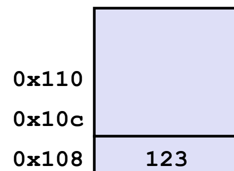
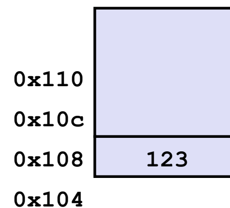


%esp 0x108

%eip 0x804854e

0x110
0x10c
0x108
0x104



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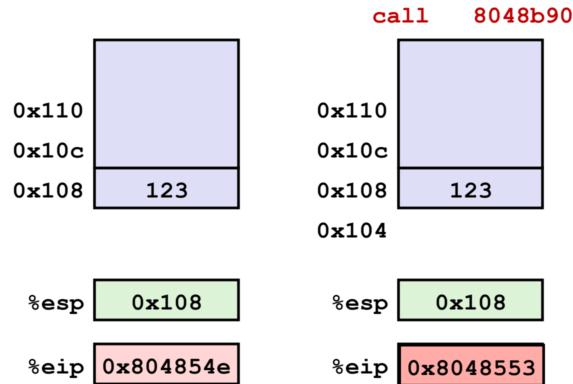

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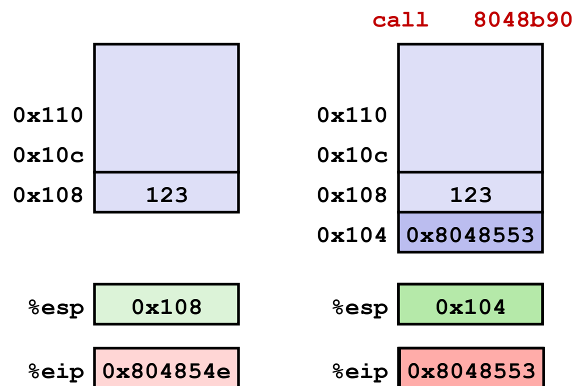

%eip: program counter

Procedure Call Example

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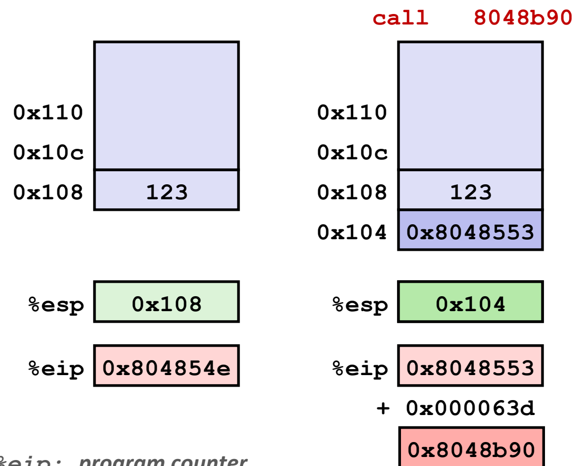
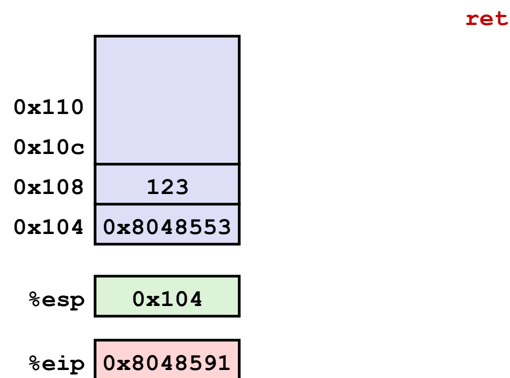


%eip: *program counter*

Procedure Return Example

```
8048591:      c3                    ret
```



%eip: *program counter*

Procedure Return Example

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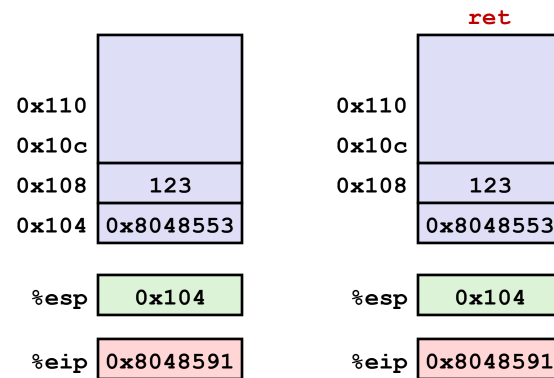

%eip: program counter

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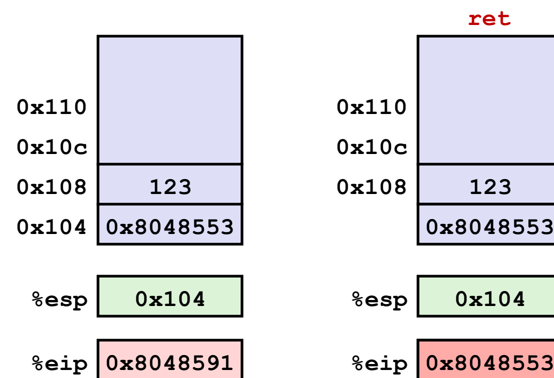

%eip: program counter

Procedure Return Example

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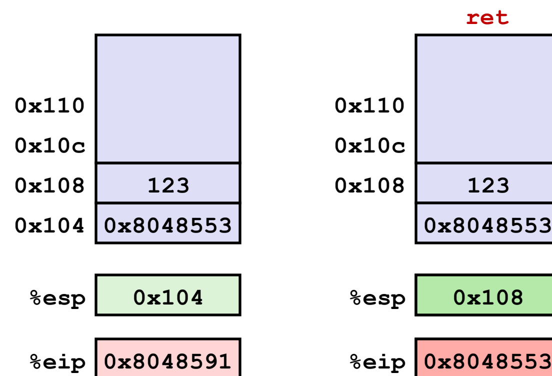


`%eip`: *program counter*

Stack-Based Languages

- **Languages that support recursion**
  - e.g., C, Pascal, Java
  - Code must be *re-entrant*
    - Multiple simultaneous instantiations of single procedure
      - What would happen if code could not be reentrant?
  - Need some place to store state of each instantiation
    - Arguments
    - Local variables
    - Return pointer
- **Stack discipline**
  - State for a given procedure needed for a limited time
    - Starting from when it is called to when it returns
  - Callee always returns before caller does
- **Stack allocated in *frames***
  - State for a single procedure instantiation

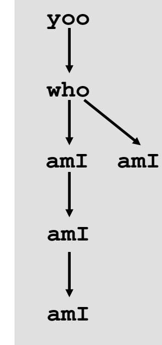
Call Chain Example

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

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

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

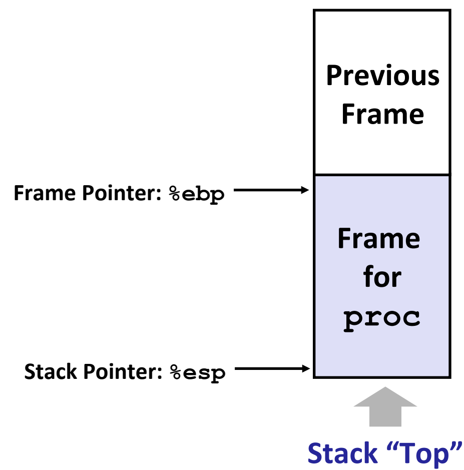
Example
Call Chain



Procedure `amI` is recursive
(calls itself)

Stack Frames

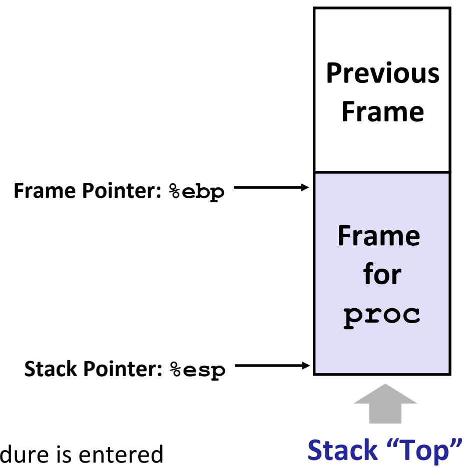
- **Contents**
  - Local variables
  - Return information
  - Temporary space



- **Management?**

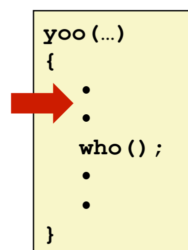
Stack Frames

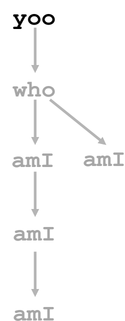
- **Contents**
  - Local variables
  - Return information
  - Temporary space

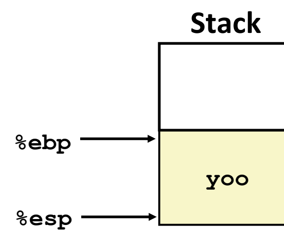


- **Management**
  - Space allocated when procedure is entered
    - "Set-up" code
  - Space deallocated upon return
    - "Finish" code

Example

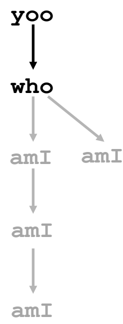


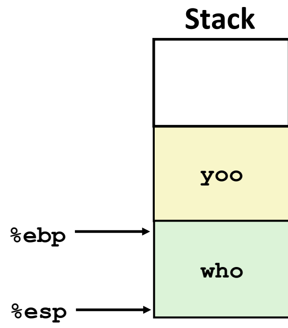




Example

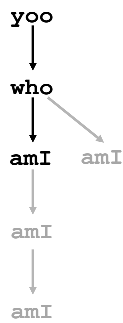
```
who(…)
{
   • • •
   amI();
   • • •
   amI();
   • • •
}
```

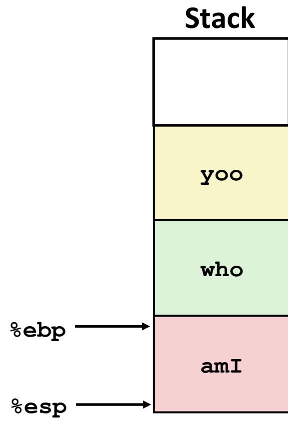




Example

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





Example

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    •
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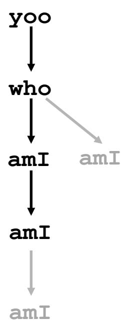

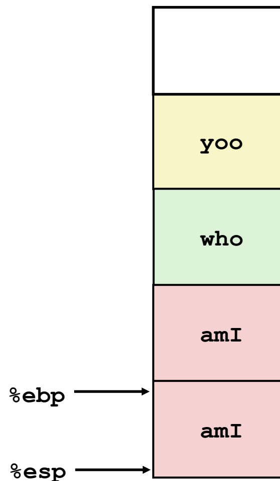

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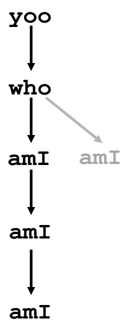

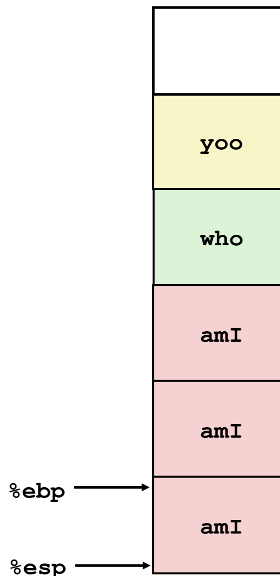

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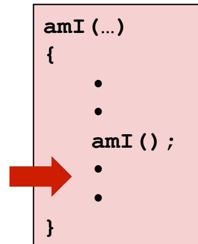
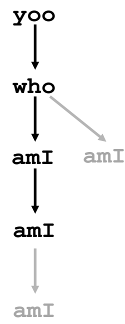
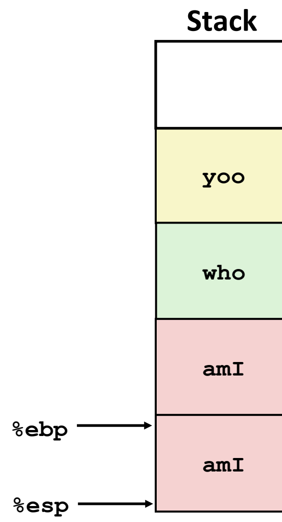




Stack



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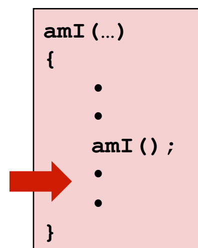
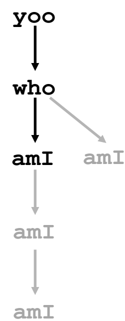
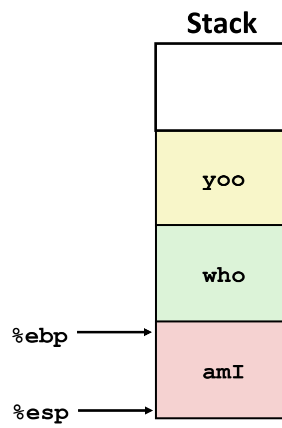
Example





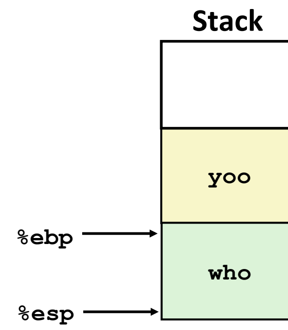
Stack



Example

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

```
yoo
 ↓
who
 ↓    ↘
amI   amI
 ↓
amI
 ↓
amI
```



Example

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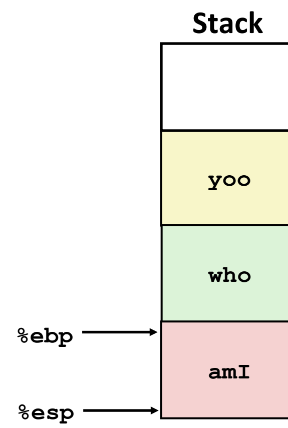

Example

```
who(…)
{
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   • • •
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```
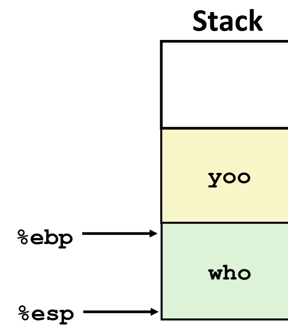

yoo → who → amI, amI; amI → amI → amI



Example

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yoo(…)
{
   •
   •
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   •
   •
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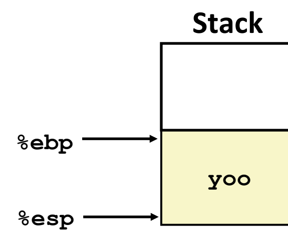
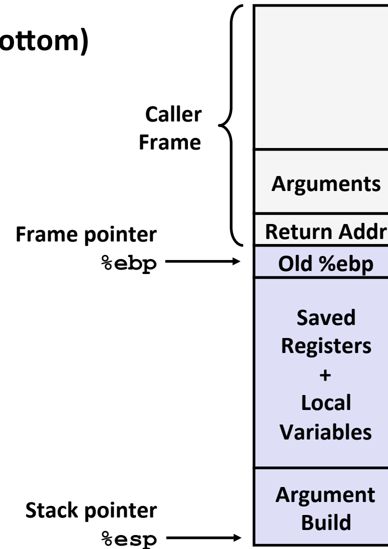
```

yoo → who → amI, amI; amI → amI → amI



IA32/Linux Stack Frame

- **Current Stack Frame ("Top" to Bottom)**
  - Old frame pointer
  - Local variables
    If can't be just kept in registers
  - Saved register context
    When reusing registers
  - "Argument build area"
    Parameters for function
    about to be called
- **Caller Stack Frame**
  - Return address
    Pushed by `call` instruction
  - Arguments for this call



Revisiting swap

```
int zip1 = 15213;
int zip2 = 98195;

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

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

Calling swap from `call_swap`

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


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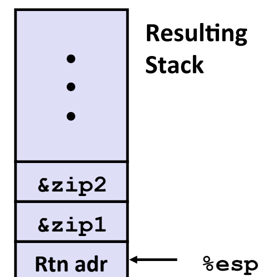

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  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

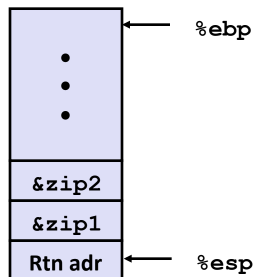
```
swap:
    pushl %ebp              } Set
    movl %esp,%ebp          } Up
    pushl %ebx

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

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


swap Setup #1

Entering Stack

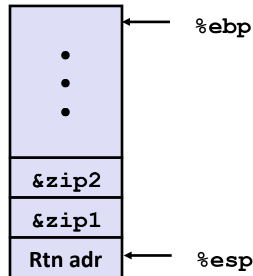


Resulting Stack?

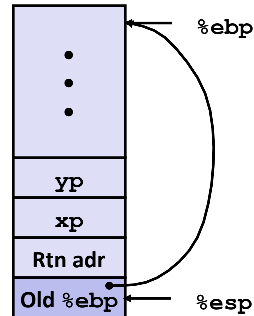
```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #1

Entering Stack



Resulting Stack

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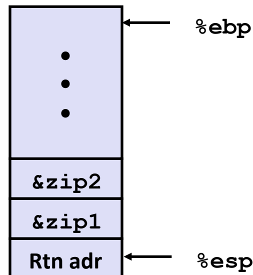
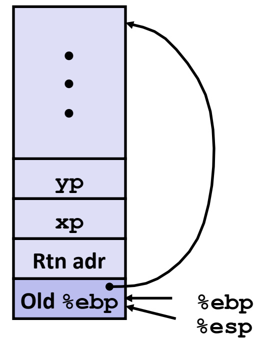
swap Setup #1

Entering Stack



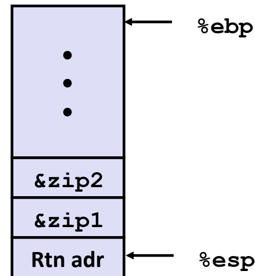
Resulting Stack



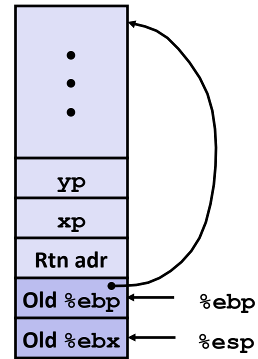

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #1

Entering Stack



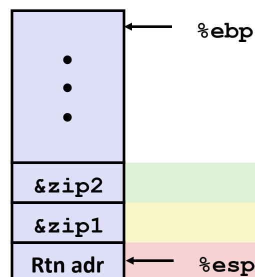
Resulting Stack




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


swap Setup #1

Entering Stack



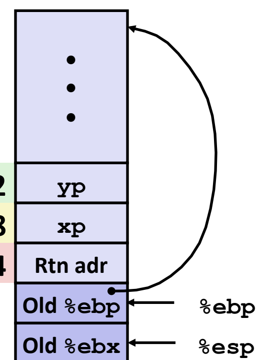
Offset relative to new %ebp

12

8

4

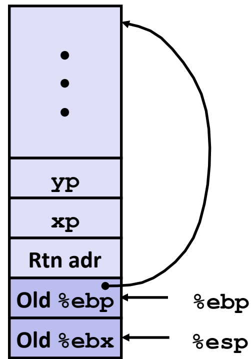
Resulting Stack




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

swap Finish #1

swap's Stack

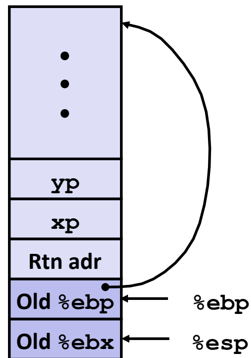


Resulting Stack?

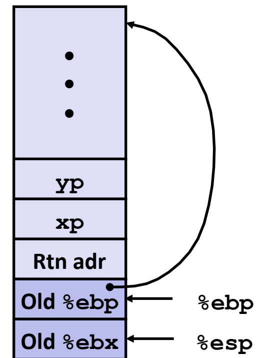
```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```


swap Finish #1

swap's Stack



Resulting Stack

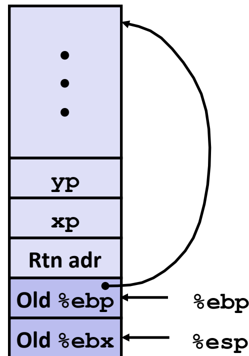



```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

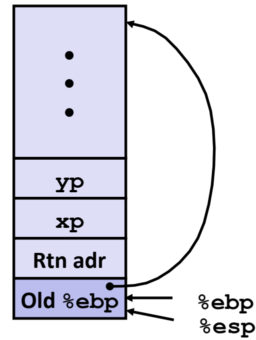
Observation: Saved and restored register %ebx

swap Finish #2

swap' s Stack



Resulting Stack

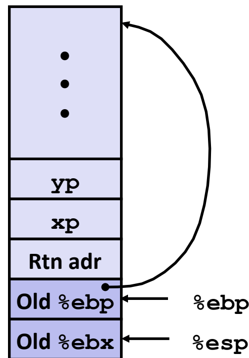



```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

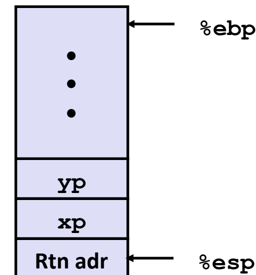
same as popl %ebx
but only because %esp = %ebp - 4

swap Finish #3

swap' s Stack



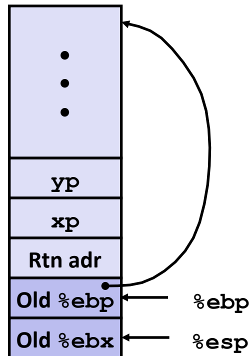
Resulting Stack



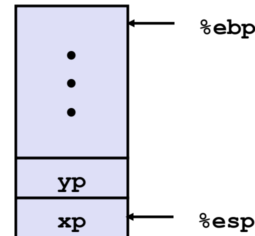

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

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
```

```
mov    %ebp,%esp
pop    %ebp
```

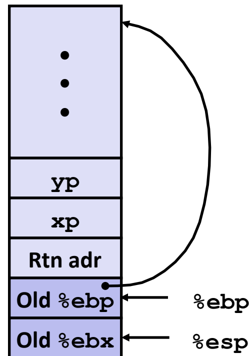
Calling Code

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

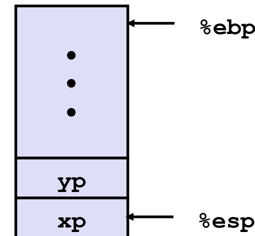
`0x0804840e + 0xffffff96 = 0x080483a4`

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**

Register Saving Conventions

- **When procedure yoo calls who:**
  - **yoo** is the *caller*
  - **who** is the *callee*
- **Can a register be used for temporary storage?**

```
yoo:
   • • •
   movl $12345, %edx
   call who
   addl %edx, %eax
   • • •
   ret
```

```
who:
   • • •
   movl 8(%ebp), %edx
   addl $98195, %edx
   • • •
   ret
```

  - Contents of register **%edx** overwritten by **who**

Saving registers

- **When should you save them?**

- **When should you not save them?**
  - Why not save all of them?

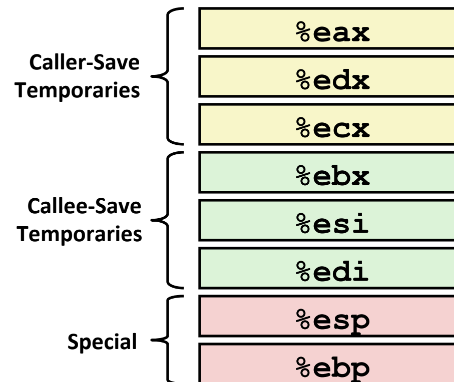
Register Saving Conventions

- **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
- **Why do we have these conventions?**

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;
}
```

```
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
```

Recursive Factorial

```
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
```

- **Registers**
  - `%ebx` used, but saved at beginning & restored at end
  - `%eax` used without first saving
    - expect caller to save
    - pushed onto stack as parameter for next call
    - used for return value

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**

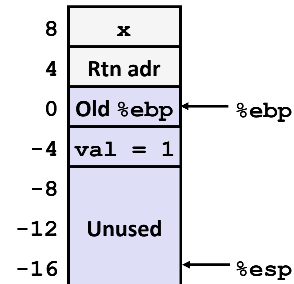
Creating & Initializing Pointer

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

- **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`

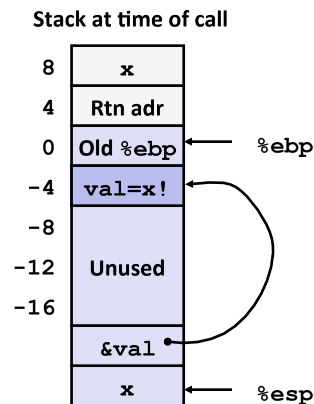
```
_sfact:
   pushl %ebp          # Save %ebp
   movl %esp,%ebp      # Set %ebp
   subl $16,%esp       # Add 16 bytes
   movl 8(%ebp),%edx   # edx = x
   movl $1,-4(%ebp)    # val = 1
```



Passing Pointer

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

Stack at time of call

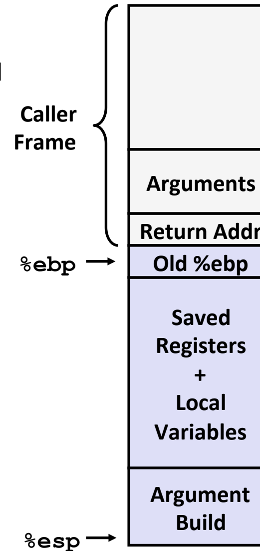


Calling `s_helper` from `sfact`

```
   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

- **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



x86-64 Procedure Calling Convention

- **Doubling of registers makes us less dependent on stack**
  - Store argument in registers
  - Store temporary variables in registers

- **What do we do if we have too many arguments or too many temporary variables?**

x86-64 64-bit Registers: Usage Conventions

Register	Usage	Register	Usage
%rax	Return value	%r8	Argument #5
%rbx	Callee saved	%r9	Argument #6
%rcx	Argument #4	%r10	Caller saved
%rdx	Argument #3	%r11	Caller Saved
%rsi	Argument #2	%r12	Callee saved
%rdi	Argument #1	%r13	Callee saved
%rsp	Stack pointer	%r14	Callee saved
%rbp	Callee saved	%r15	Callee saved

Revisiting swap, again

```
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 (pushl %ebp … pushl %ebx); Body (movl 12(%ebp),%ecx … movl %ebx,(%ecx)); Finish (movl -4(%ebp),%ebx … ret)

Revisiting swap, IA32 vs. x86-64 versions

```
swap:
    pushl %ebp              } Set
    movl %esp,%ebp          } Up
    pushl %ebx

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

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

```
swap (64-bit long ints):
    movq    (%rdi), %rdx
    movq    (%rsi), %rax
    movq    %rax, (%rdi)
    movq    %rdx, (%rsi)
    ret
```

- **Operands passed in registers**
  - First (**`xp`**) in **`%rdi`**, second (**`yp`**) in **`%rsi`**
  - 64-bit pointers
- **No stack operations required (except `ret`)**
- **Avoiding stack**
  - Can hold all local information in registers

X86-64 procedure call highlights

- **Arguments (up to first 6) in registers**
  - Faster to get these values from registers than from stack in memory
- **Callq instructions stores 64-bit address on stack**
  - Address pushed onto stack decrementing rsp by 8
- **Local variables also in registers (if there is room)**
  - Eliminates stack accesses and need to allocate stack space
- **Functions can access storage on stack up to 128 beyond rsp**
  - Can store some temps on stack without altering rsp
- **No frame pointer**
  - All references to stack made relative to rsp, no need to restore base ptr
- **Some registers designated "callee-saved"**
  - Must to restored by callee before ret

Passing differently sized arguments

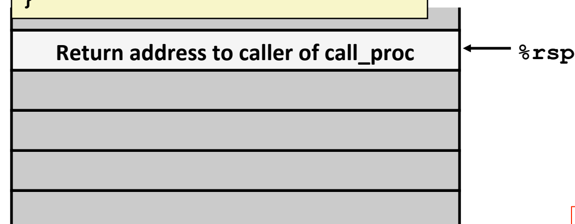
- Use registers %edi, %esi, %edx, … for 32-bit arguments
- Use registers %di, %si, %dx, … for 16-bit arguments
- Use registers %dil, %sil, %dl, … for 8-bit arguments

- Useful instructions:
  - movzbl: move byte to low-end of long zero-filled
  - movslq: move long to low-end of quad sign-extended

Example

```
long int call_proc()
{
  long  x1 = 1;
  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```

```
call_proc:
  subq  $32,%rsp
  movq  $1,16(%rsp)
  movl  $2,24(%rsp)
  movw  $3,28(%rsp)
  movb  $4,31(%rsp)
  • • •
```

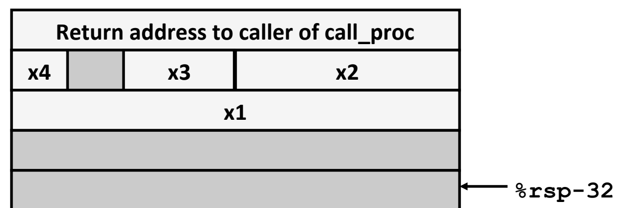


NB: Details may vary depending on compiler.

Example

```
long int call_proc()
{
  long  x1 = 1;
  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```

```
call_proc:
  subq  $32,%rsp
  movq  $1,16(%rsp)
  movl  $2,24(%rsp)
  movw  $3,28(%rsp)
  movb  $4,31(%rsp)
  • • •
```



Example

```
long int call_proc()
{
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  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```
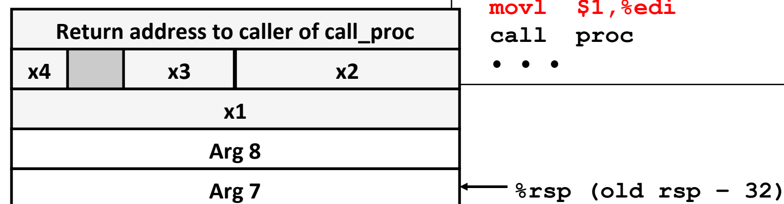
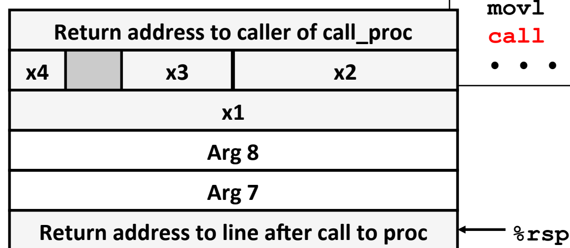

```
call_proc:
  • • •
  leaq  24(%rsp),%rcx
  leaq  16(%rsp),%rsi
  leaq  31(%rsp),%rax
  movq  %rax,8(%rsp)
  movl  $4,(%rsp)
  leaq  28(%rsp),%r9
  movl  $3,%r8d
  movl  $2,%edx
  movl  $1,%edi
  call  proc
  • • •
```



Example

```
long int call_proc()
{
  long  x1 = 1;
  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```

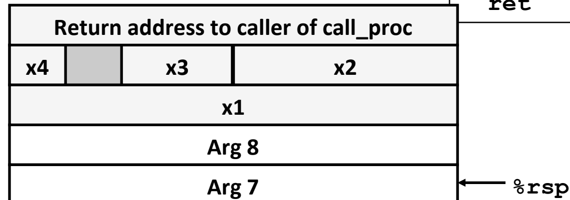
```
call_proc:
  • • •
  leaq  24(%rsp),%rcx
  leaq  16(%rsp),%rsi
  leaq  31(%rsp),%rax
  movq  %rax,8(%rsp)
  movl  $4,(%rsp)
  leaq  28(%rsp),%r9
  movl  $3,%r8d
  movl  $2,%edx
  movl  $1,%edi
  call  proc
  • • •
```



Example

```
long int call_proc()
{
  long  x1 = 1;
  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```

```
call_proc:
  • • •
  movswl 28(%rsp),%eax
  movsbl 31(%rsp),%edx
  subl   %edx,%eax
  cltq
  movslq 24(%rsp),%rdx
  addq   16(%rsp),%rdx
  imulq  %rdx,%rax
  addq   $32,%rsp
  ret
```



Example

```
long int call_proc()
{
  long  x1 = 1;
  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```

```
call_proc:
  • • •
  movswl 28(%rsp),%eax
  movsbl 31(%rsp),%edx
  subl   %edx,%eax
  cltq
  movslq 24(%rsp),%rdx
  addq   16(%rsp),%rdx
  imulq  %rdx,%rax
  addq   $32,%rsp
  ret
```

Return address to caller of call_proc ← %rsp

x86-64 Procedure Summary

- **Heavy use of registers (faster than using stack in memory)**
  - Parameter passing
  - More temporaries since more registers
- **Minimal use of stack**
  - Sometimes none (best case, less memory references)
  - Address relative to stack pointer when necessary
  - No more base pointer
  - Allocate/deallocate entire block
- **Many optimizations**
  - What kind of stack frame to use
  - Various allocation techniques