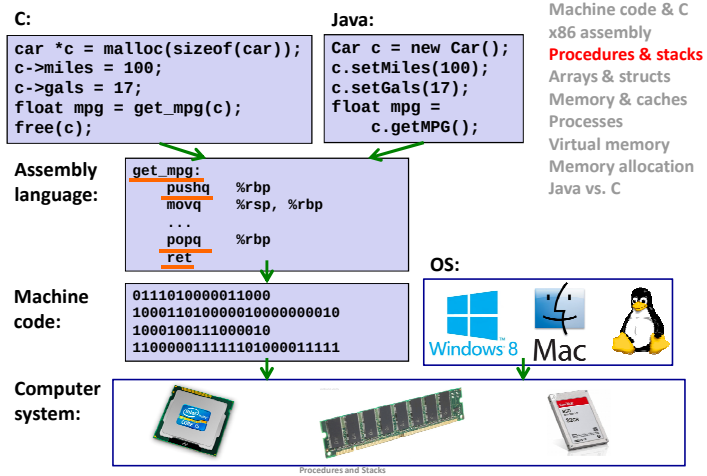
Roadmap

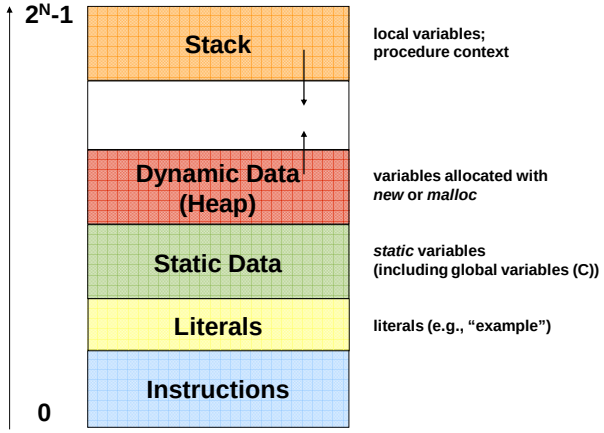


Memory & data
Integers & floats
Machine code & C
x86 assembly
Procedures & stacks
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

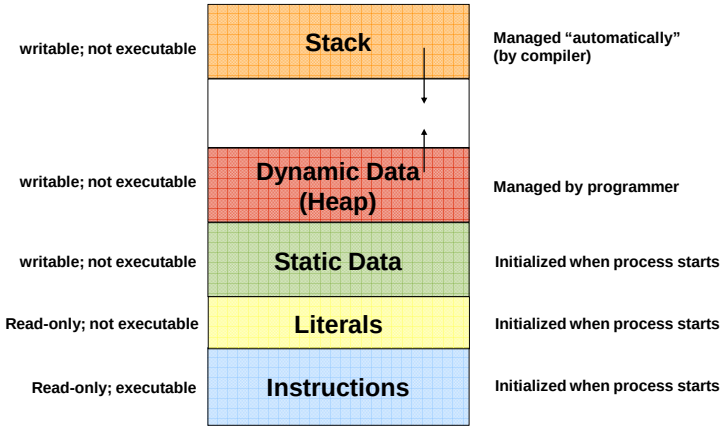
Section 5: Procedures & Stacks

- Stacks in memory and stack operations
- The stack used to keep track of procedure calls
- Return addresses and return values
- Stack-based languages
- The Linux stack frame
- Passing arguments on the stack
- Allocating local variables on the stack
- Register-saving conventions
- Procedures and stacks on x64 architecture

Memory Layout



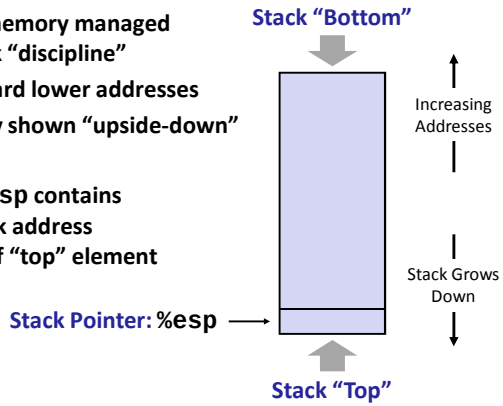
Memory Layout



IA32 Call Stack

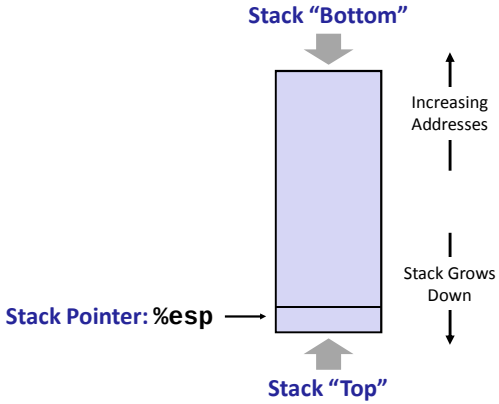
- Region of memory managed with a stack "discipline"
- Grows toward lower addresses
- Customarily shown "upside-down"

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



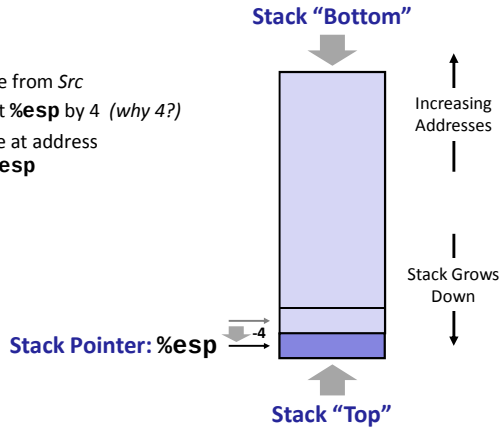
IA32 Call Stack: Push

- `pushl` *Src*



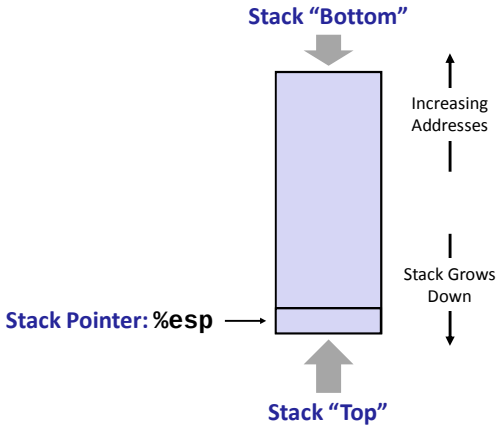
IA32 Call Stack: Push

- `pushl` *Src*
  - Fetch value from *Src*
  - Decrement %esp by 4 *(why 4?)*
  - Store value at address given by %esp



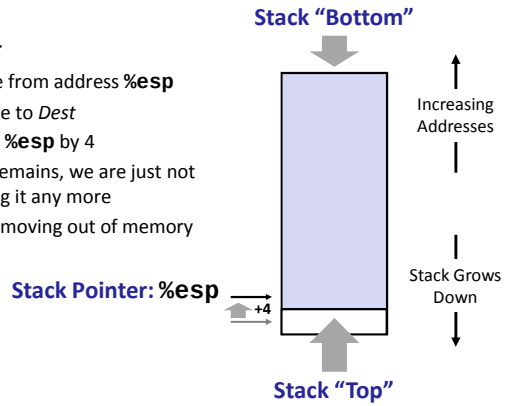
IA32 Call Stack: Pop

- `popl` *Dest*



IA32 Call Stack: Pop

- **`popl` *Dest***
  - Load value from address **%esp**
  - Write value to *Dest*
  - Increment **%esp** by 4
  - Item still remains, we are just not referencing it any more
  - Not really moving out of memory



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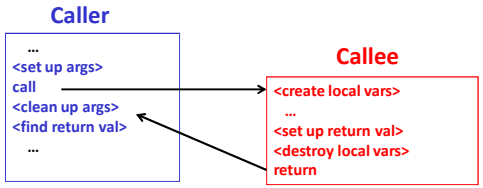
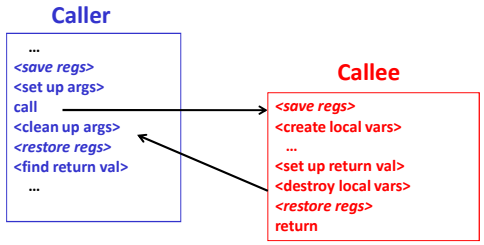
Procedure Call Overview



- **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**
  - Caller might need to save registers that Callee might use
  - Callee might need to save registers that Caller has used

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
  - What could happen if our program didn't follow these conventions?

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

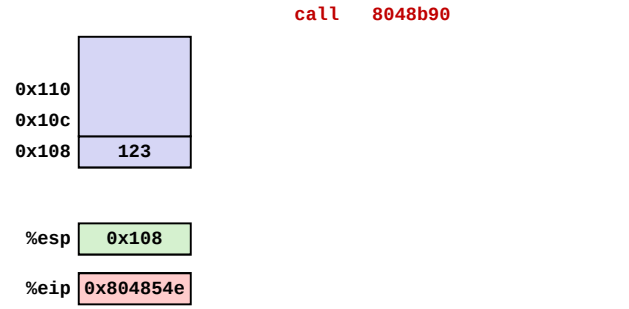
- **Use stack to support procedure call and return**
- **Procedure call: `call label`**
  - Push return address on stack
  - Jump to ***`label`***
- **Return address:**
  - Address of instruction after `call`
  - Example from disassembly:

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

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

Procedure Call Example

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



`%eip`: program counter

Procedure Call Example

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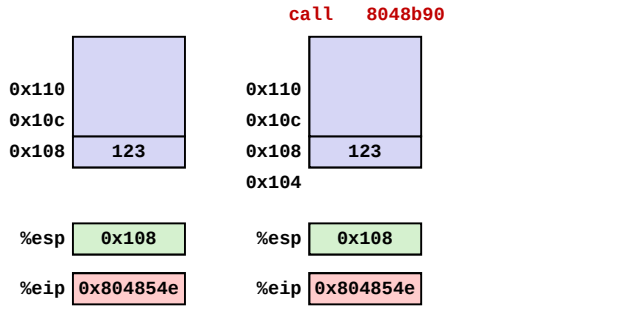

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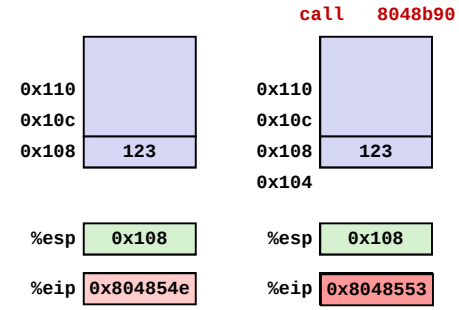

%eip: program counter

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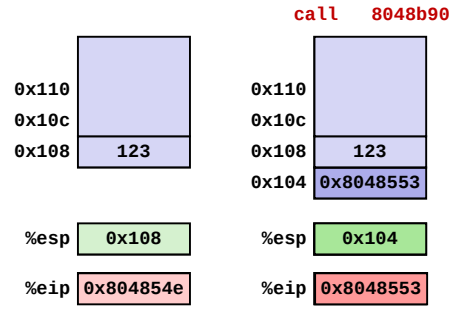

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Procedure Call Example

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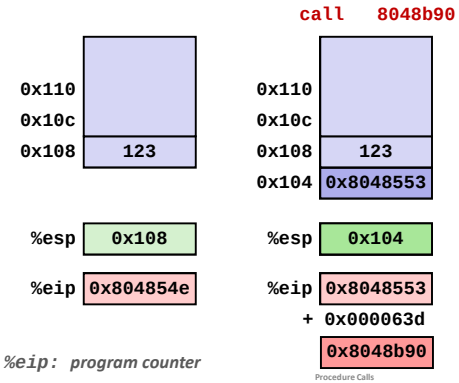
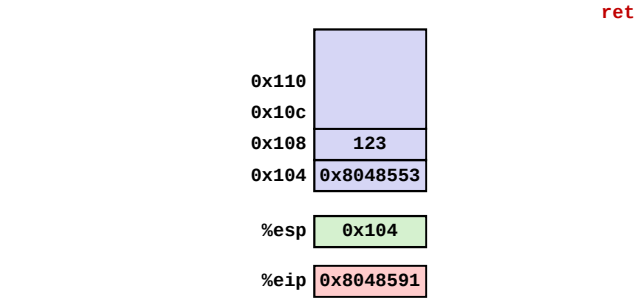


%eip: program counter

Procedure Return Example

```
8048591:    c3                  ret
```



%eip: program counter

Procedure Return Example

```
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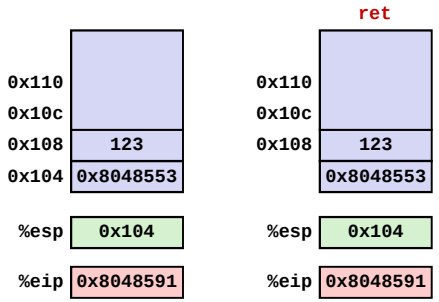

%eip: program counter

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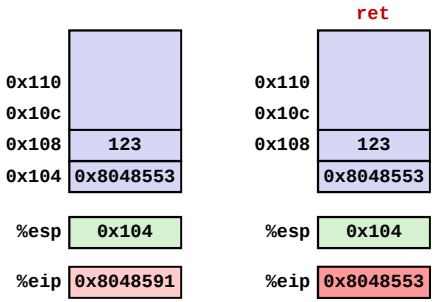

%eip: program counter

Procedure Return Example

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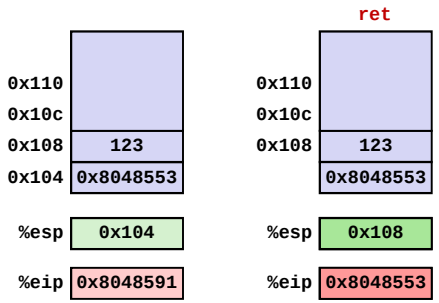

%eip: program counter

Return Values

- **By convention, values returned by procedures are placed in the %eax register**
  - Choice of %eax is arbitrary, could have easily been a different register
- **Caller must make sure to save that register before calling a callee that returns a value**
  - Part of register-saving convention we'll see later
- **Callee placed return value (any type that can fit in 4 bytes – integer, float, pointer, etc.) into the %eax register**
  - For return values greater than 4 bytes, best to return a pointer to them
- **Upon return, caller finds the return value in the %eax register**

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Stack-Based Languages

- **Languages that support recursion**
  - e.g., C, Pascal, Java
  - Code must be *re-entrant*
    - Multiple simultaneous instantiations of single procedure
  - 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

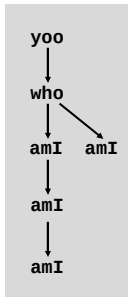
Call Chain Example

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

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

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

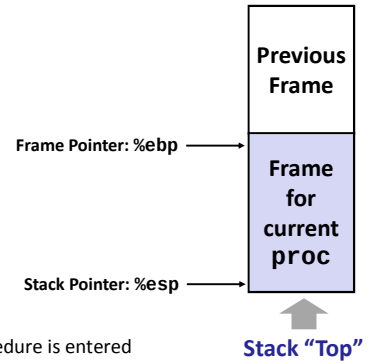
Example Call Chain



Procedure `amI` is recursive (calls itself)

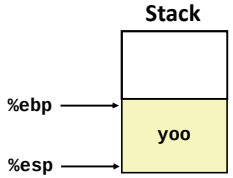
Stack Frames

- **Contents**
  - Local variables
  - Function arguments
  - Return information
  - Temporary space
- **Management**
  - Space allocated when procedure is entered
    - "Set-up" code
  - Space deallocated upon return
    - "Finish" code



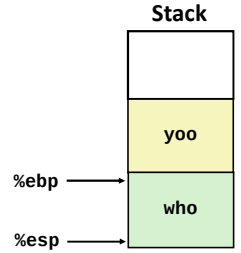
Example

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



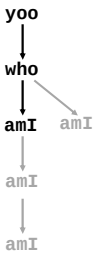
Example

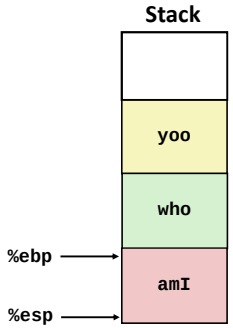
```
who(…)
{
  • • •
  amI();
  • • •
  amI();
  • • •
}
```



Example

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





Example

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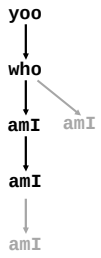

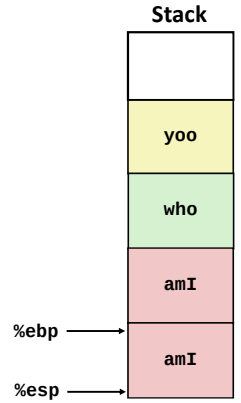

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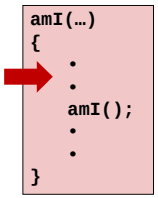

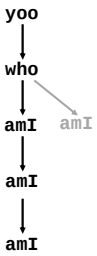

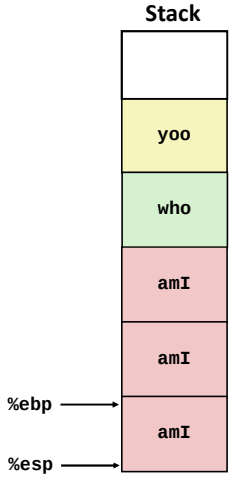

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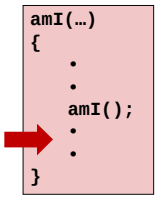

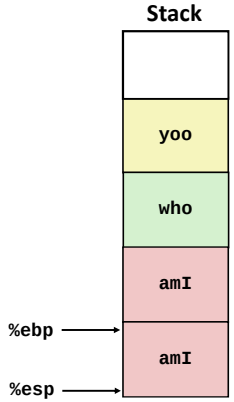

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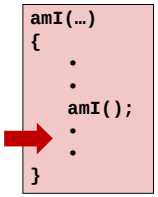

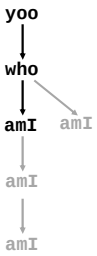

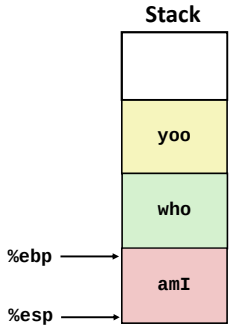

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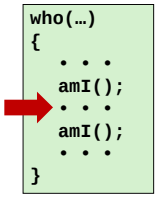

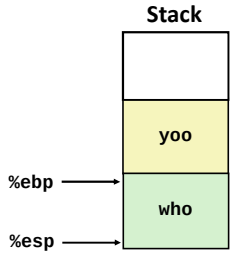

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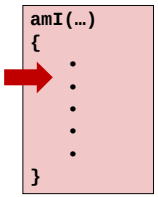

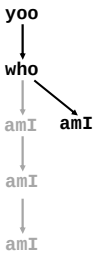

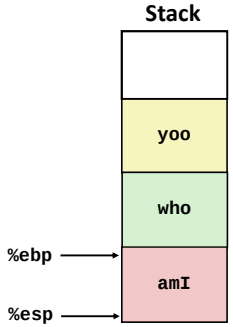

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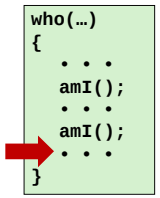
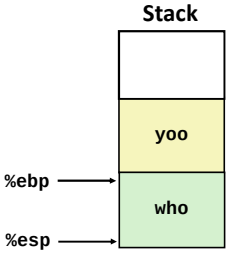
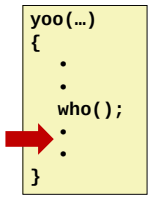
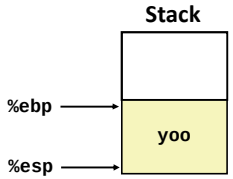




Example





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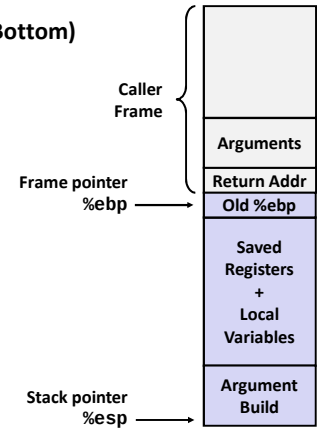
IA32/Linux Stack Frame

- **Current Stack Frame ("Top" to Bottom)**
  - "Argument build" area (parameters for function about to be called)
  - Local variables (if can't be kept in registers)
  - Saved register context (when reusing registers)
  - Old frame pointer (for caller)
- **Caller's 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;
}
```


Revisiting swap

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

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

Calling swap from `call_swap`

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

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


Revisiting swap

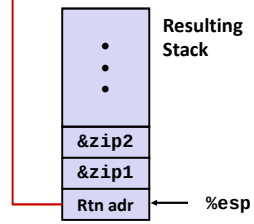
```
int zip1 = 15213;
int zip2 = 98195;

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

Calling swap from `call_swap`

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

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



Revisiting swap

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

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

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

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

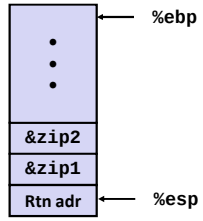
Set Up

Body

Finish

swap Setup #1

Entering Stack

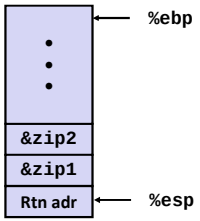


Resulting Stack?

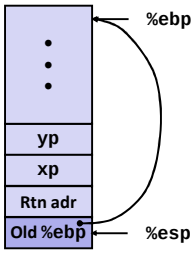
```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```


swap Setup #1

Entering Stack



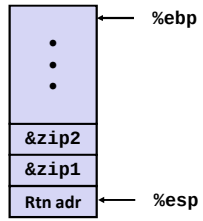
Resulting Stack



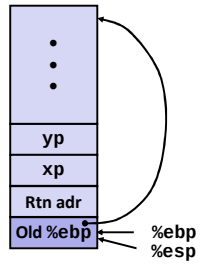

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```


swap Setup #2

Entering Stack



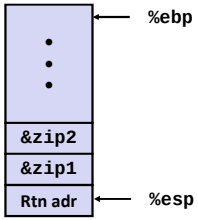
Resulting Stack



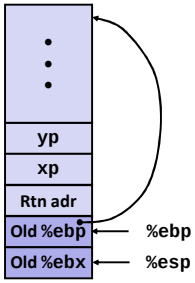

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #3

Entering Stack



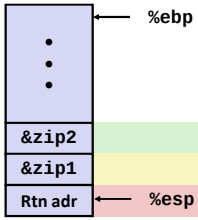
Resulting Stack



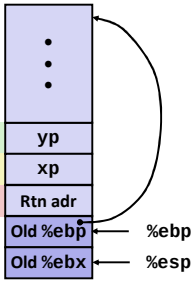

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```


swap Body

Entering Stack



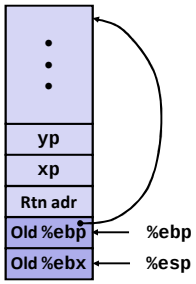
Resulting Stack




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


swap Finish #1

swap's Stack

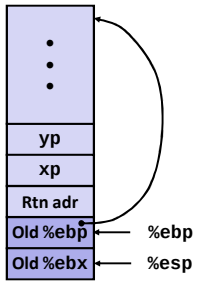


Resulting Stack?

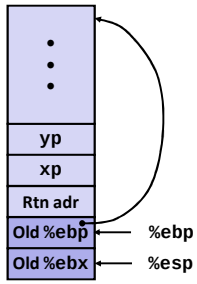
```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```


swap Finish #1

swap's Stack



Resulting Stack

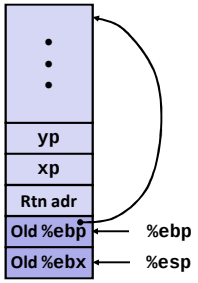



```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

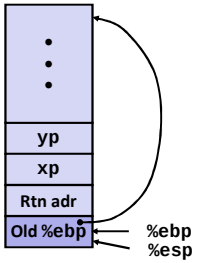
Observation: Saved and restored register %ebx

swap Finish #2

swap's Stack



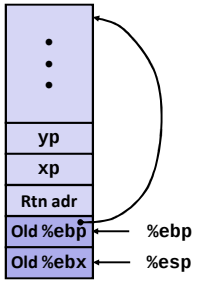
Resulting Stack



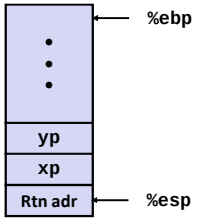

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```


swap Finish #3

swap's Stack



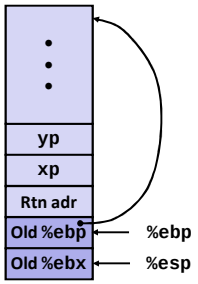
Resulting Stack



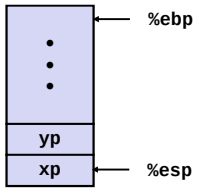

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```


swap Finish #4

swap's Stack



Resulting Stack




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


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
```

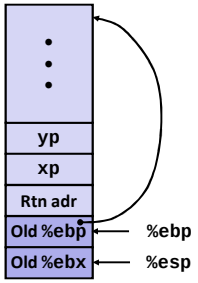
```
mov    %ebp,%esp
pop    %ebp
```

Calling Code

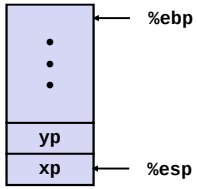
```
 8048409:   e8 96 ff ff ff   call 80483a4 <swap>
 804840e:   8b 45 f8         mov  0xfffffff8(%ebp),%eax
```

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**

Section 5: Procedures & Stacks

- Stacks in memory and stack operations
- The stack used to keep track of procedure calls
- Return addresses and return values
- Stack-based languages
- The Linux stack frame
- Passing arguments on the stack
- Allocating local variables on the stack
- Register-saving conventions
- Procedures and stacks on x64 architecture

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**

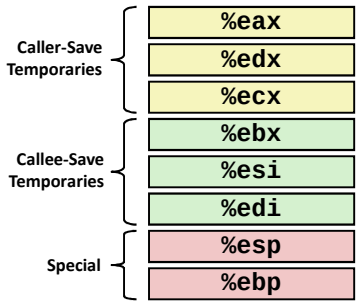
Register Saving Conventions

- When procedure **yoo** calls **who**:
  - **yoo** is the *caller*
  - **who** is the *callee*

- Can a register be used for temporary storage?
- Conventions
  - *"Caller Save"*
    - Caller saves temporary values in its frame before calling
  - *"Callee Save"*
    - Callee saves temporary values 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 form of callee save – restored to original values upon exit from procedure



Example: Pointers to Local Variables

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

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

- **Pass pointer to update location**

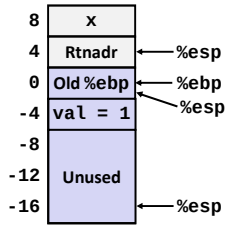
Creating & Initializing Pointer

```
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
```



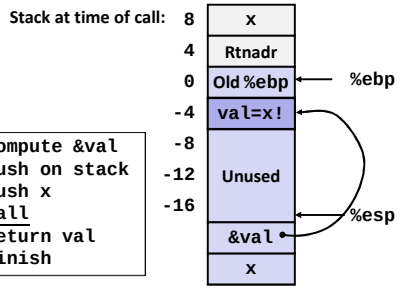
Passing Pointer

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

- **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**

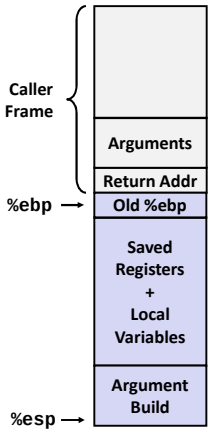
Calling `s_helper` from `sfact`

```
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

- **Important points:**
  - IA32 procedures are a combination of *instructions* and *conventions*
    - Conventions prevent functions from disrupting each other
  - Stack is the right data structure for procedure call / return
    - If P calls Q, then Q returns before P
- **Recursion handled by normal calling conventions**
  - Can safely store values in local stack frame and in callee-saved registers
  - Put function arguments at top of stack
  - Result returned in **%eax**



Section 5: Procedures & Stacks

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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

%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, IA32 vs. x86-64 versions

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

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

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

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

- **Arguments 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
- **Local variables also in registers (if there is room)**
- **`callq` instruction stores 64-bit return address on stack**
  - Address pushed onto stack, decrementing %rsp by 8
- **No frame pointer**
  - All references to stack frame made relative to %rsp; eliminates need to update %ebp/%rbp, which is now available for general-purpose use
- **Functions can access memory up to 128 bytes beyond %rsp: the "red zone"**
  - Can store some temps on stack without altering %rsp
- **Registers still designated "caller-saved" or "callee-saved"**

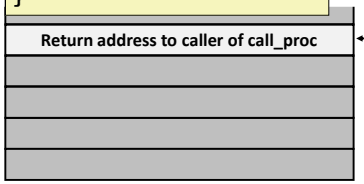
x86-64 Stack Frames

- **Often (ideally), x86-64 functions need no stack frame at all**
  - Just a return address is pushed onto the stack when a function call is made
- **A function *does* need a stack frame when it:**
  - Has too many local variables to hold in registers
  - Has local variables that are arrays or structs
  - Uses the address-of operator (&) to compute the address of a local variable
  - Calls another function that takes more than six arguments
  - Needs to save the state of callee-save registers before modifying them

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)
  • • •
```

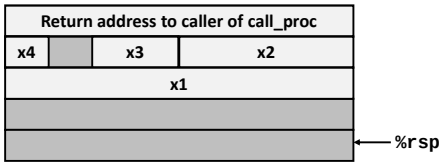


NB: Details may vary depending on compiler.

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);
}
```

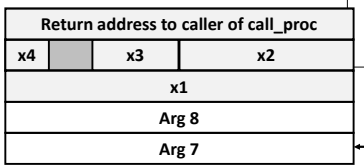
```
call_proc:
  subq  $32,%rsp
  movq  $1,16(%rsp)
  movl  $2,24(%rsp)
  movw  $3,28(%rsp)
  movb  $4,31(%rsp)
  • • •
```



Example

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

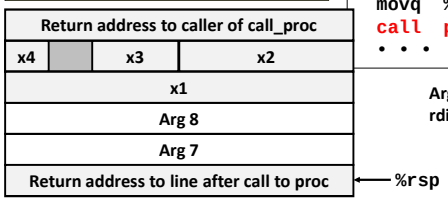


Arguments passed in (in order):
rdi, rsi, rdx, rcx, r8, r9, then stack

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



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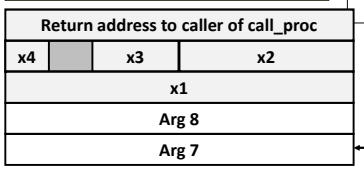
```
call_proc:
  • • •
  movswl 28(%rsp),%eax
  movsbl 31(%rsp),%edx
  subl   %edx,%eax
  cltq
  movslq 24(%rsp),%rdx
  addq   16(%rsp),%rdx
  imulq  %rdx,%rax
  addq   $32,%rsp
  ret
```



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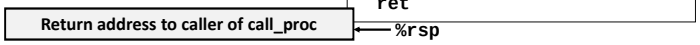

x86-64 Procedure Summary

- **Heavy use of registers (faster than using stack in memory)**
  - Parameter passing
  - More temporaries since more registers
- **Minimal use of stack**
  - Sometimes none
  - When needed, allocate/deallocate entire frame at once
  - No more frame pointer: address relative to stack pointer
- **More room for compiler optimizations**
  - Prefer to store data in registers rather than memory
  - Minimize modifications to stack pointer