Function Calls

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COS 217

Reading: Chapter 4 of “Programming From the Ground Up”

(available online from the course Web site)

Goals of Today’s Lecture

- Finishing introduction to assembly language
  - EFLAGS register and conditional jumps
  - Addressing modes
- Memory layout of the UNIX process
  - Data, BSS, roData, Text
  - Stack frames, and the stack pointer ESP
- Calling functions
  - Call and ret commands
  - Placing arguments on the stack
  - Using the base pointer EBP

Detailed Example

```
n      %edx
count  %ecx
```

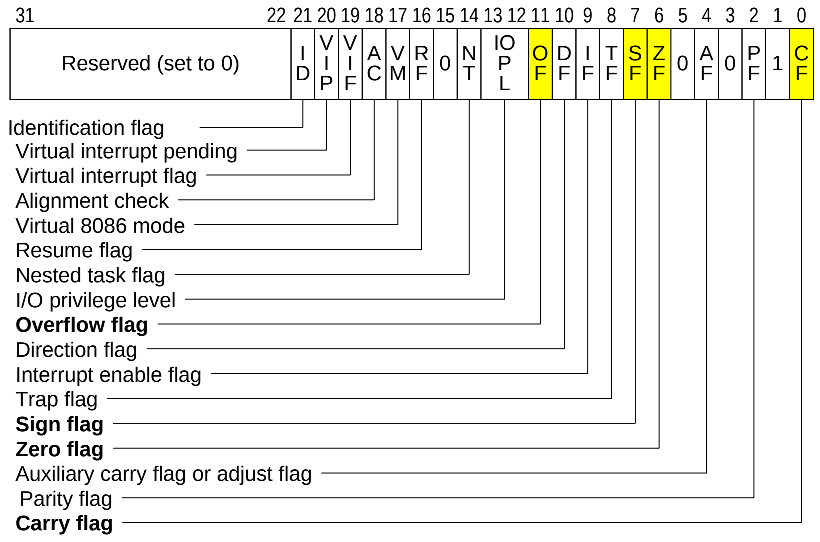
```
count=0;
while (n>1) {
  count++;
  if (n&1)
    n = n*3+1;
  else
    n = n/2;
}
```

```
        movl   $0, %ecx
.loop:
        cmpl   $1, %edx
        jle    .endloop
        addl   $1, %ecx
        movl   %edx, %eax
        andl   $1, %eax
        je     .else
        movl   %edx, %eax
        addl   %eax, %edx
        addl   %eax, %edx
        addl   $1, %edx
        jmp    .endif
.else:
        sarl   $1, %edx
.endif:
        jmp    .loop
.endloop:
```

Setting the EFLAGS Register

- Comparison **`cmpl`** compares two integers
  - Done by subtracting the first number from the second
    - Discarding the results, but setting the eflags register
  - Example:
    - **`cmpl $1, %edx`** (computes %edx – 1)
    - **`jle .endloop`** (looks at the sign flag and the zero flag)
- Logical operation **`andl`** compares two integers
  - Example:
    - **`andl $1, %eax`** (bit-wise AND of %eax with 1)
    - **`je .else`** (looks at the zero flag)
- Unconditional branch **`jmp`**
  - Example:
    - **`jmp .endif`** and **`jmp .loop`**

EFLAGS Register & Condition Codes



A Simple Assembly Program

```
.section .data
# pre-initialized
# variables go here

.section .bss
# zero-initialized
# variables go here

.section .rodata
# pre-initialized
# constants go here
```

```
.section .text
.globl _start
_start:
# Program starts executing
# here

# Body of the program goes
# here

# Program ends with an
# “exit()” system call
# to the operating system
movl $1, %eax
movl $0, %ebx
int $0x80
```

Main Parts of the Program

- Break program into sections (**`.section`**)
  - Data, BSS, RoData, and Text
- Starting the program
  - Making _start a global (**`.global _start`**)
    - Tells the assembler to remember the symbol **`_start`**
    - … because the linker will need it
  - Identifying the start of the program (**`_start`**)
    - Defines the value of the label **`_start`**
- Exiting the program
  - Specifying the exit() system call (**`movl $1, %eax`**)
    - Linux expects the system call number in EAX register
  - Specifying the status code (**`movl $0, %ebx`**)
    - Linux expects the status code in EBX register
  - Interrupting the operating system (**`int $0x80`**)

Function Calls

- Function
  - A piece of code with well-defined entry and exit points, and a well-defined interface
- "Call" and "Return" abstractions
  - **Call:** jump to the beginning of an arbitrary procedure
  - **Return:** jump to the instruction immediately following the "most-recently-executed" Call instruction
- The jump address in the return operation is dynamically determined

Implementing Function Calls

```
P:          # Function P
  …
  jmp R     # Call R
Rtn_point1:
  …
```

```
R:          # Function R
  …
  jmp ???   # Return
```

```
Q:          # Function Q
  …
  jmp R     # Call R
Rtn_point2:
  …
```

What should the return instruction in R jump to?

Implementing Function Calls

```
P:           # Proc P
   movl $Rtn_point1, %eax
   jmp R     # Call R
Rtn_point1:
   …
```

```
R:           # Proc R
   …
   jmp %eax  # Return
```

```
Q:           # Proc Q
   movl $Rtn_point2, %eax
   jmp R     # Call R
Rtn_point2:
   …
```

Convention: At Call time, store return address in EAX

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Problem: Nested Function Calls

```
P:           # Function P
   movl $Rtn_point1, %eax
   jmp Q     # Call Q
Rtn_point1:
   …
```

```
R:           # Function R
   …
   jmp %eax  # Return
```

```
Q:           # Function Q
   movl $Rtn_point2, %eax
   jmp R     # Call R
Rtn_point2:
   …
   jmp %eax  # Return
```

- Problem if P calls Q, and Q calls R
- Return address for P to Q call is lost

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Need to Use a Stack

- A return address needs to be saved for as long as the function invocation continues
- Return addresses are used in the reverse order that they are generated: Last-In-First-Out
- The number of return addresses that may need to be saved is not statically known
- Saving return addresses on a Stack is the most natural solution

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Stack Frames

- Use stack for all temporary data related to each active function invocation

  - Return address
  - Input parameters
  - Local variables of function
  - Saving registers across invocations

  $\left.\right\}$ **Stack Frame**

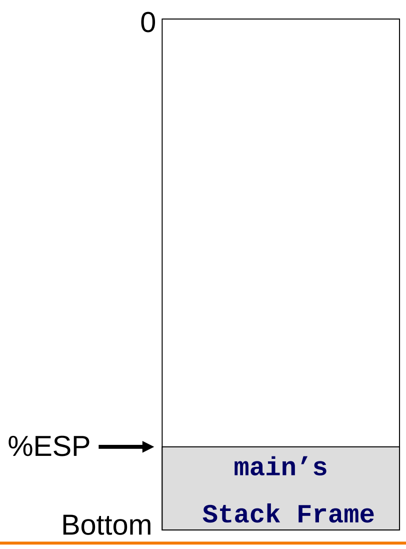
- Stack has one Stack Frame per active function invocation

High-Level Picture

- At Call time, push a new Stack Frame on top of the stack
- At Return time, pop the top-most Stack Frame

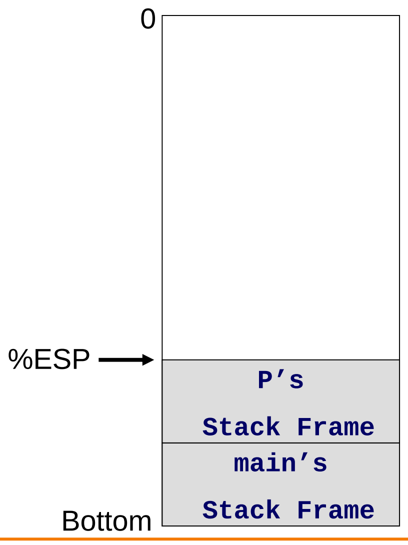
High-Level Picture

`main begins executing`



High-Level Picture

```
main begins executing
main calls P
```



High-Level Picture

```
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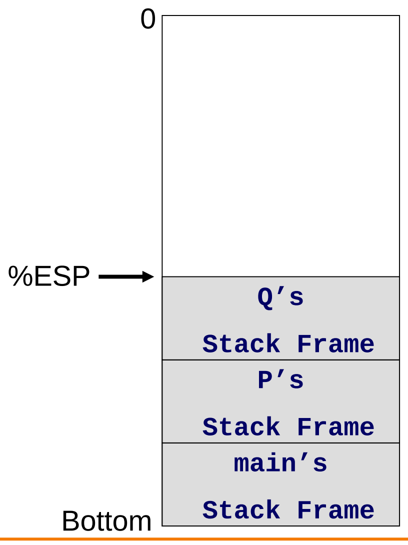
P calls Q
```



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P calls Q
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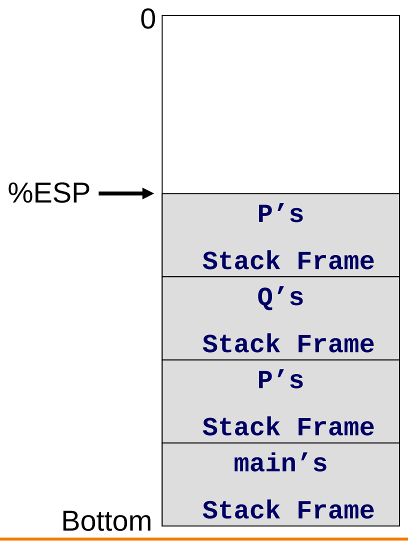
```



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```
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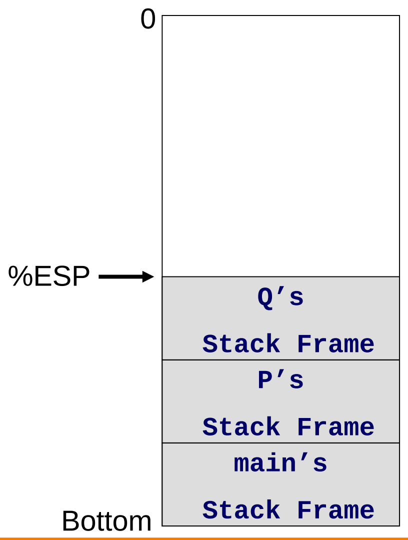
main calls P
P calls Q
Q calls P
P returns
```



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main calls P
P calls Q
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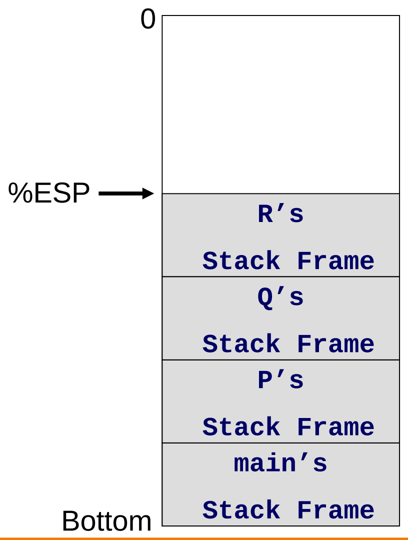
P returns
Q calls R
```



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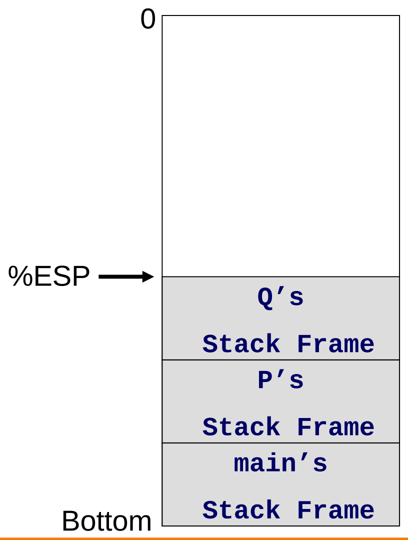

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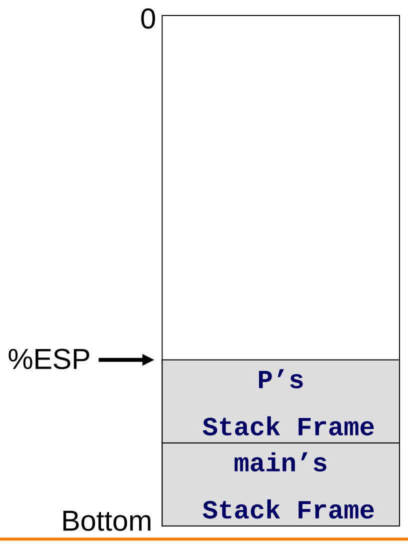

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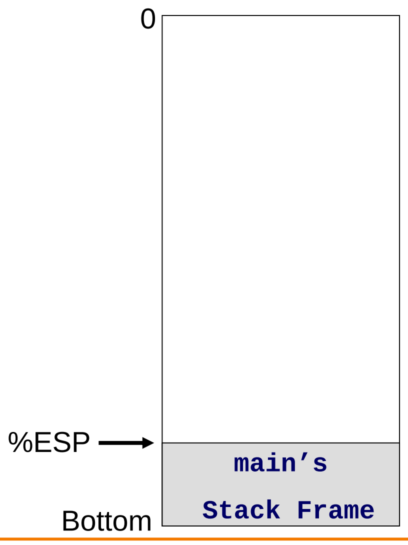

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Q returns
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main returns
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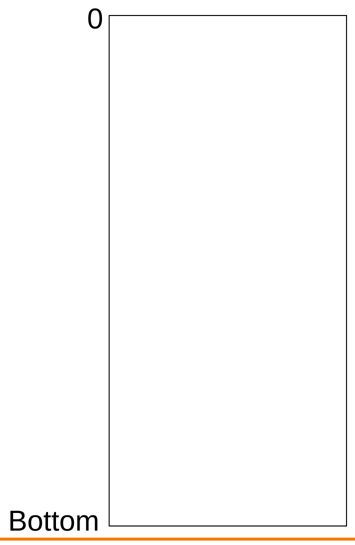


Function Call Details

- Call and Return instructions
- Argument passing between procedures
- Local variables
- Register saving conventions

Call and Return Instructions

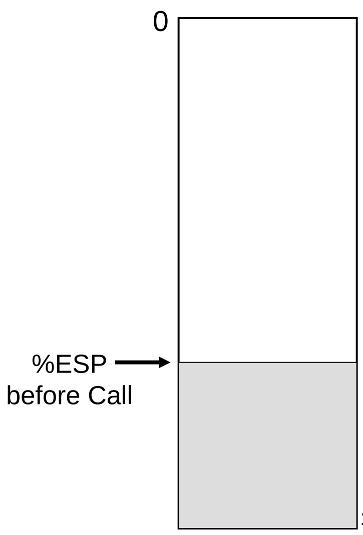
Instruction	Function

`pushl src`	`subl $4, %esp`
	`movl src, (%esp)`

`popl dest`	`movl (%esp), dest`
	`addl $4, %esp`

`call addr`	`pushl %eip`
	`jmp addr`

`ret`	`pop %eip`



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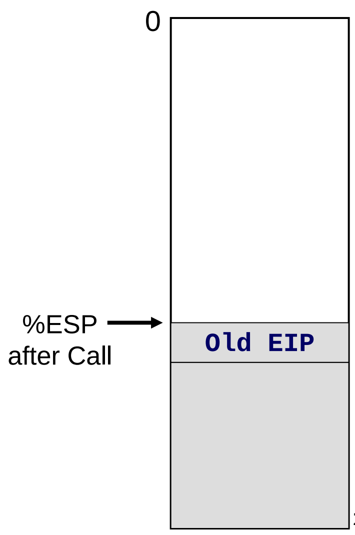

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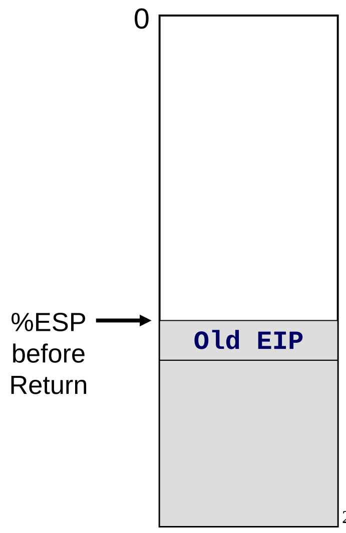
Return instruction assumes that the return address is at the top of the stack



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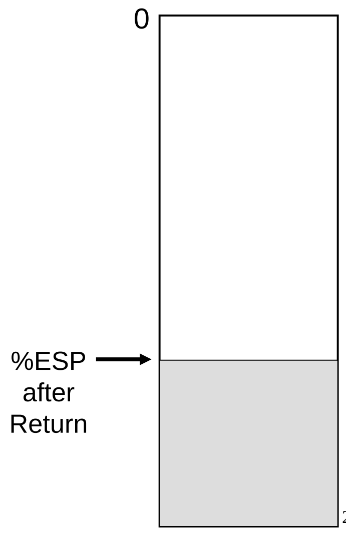
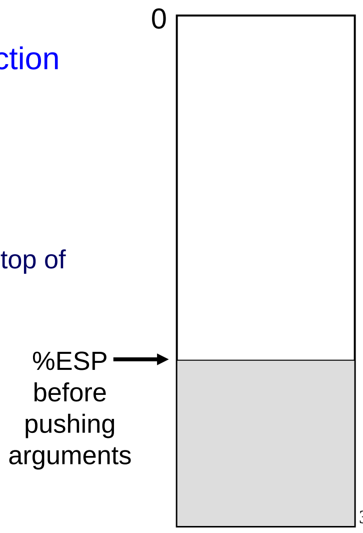


Input Parameters

- Caller pushes input parameters before executing the Call instruction
- Parameters are pushed in the reverse order
  - Push N^th argument first
  - Push 1^st argument last
  - So that the first argument is at the top of the stack at the time of the Call



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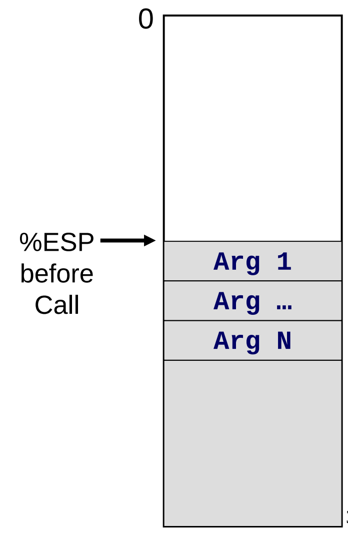

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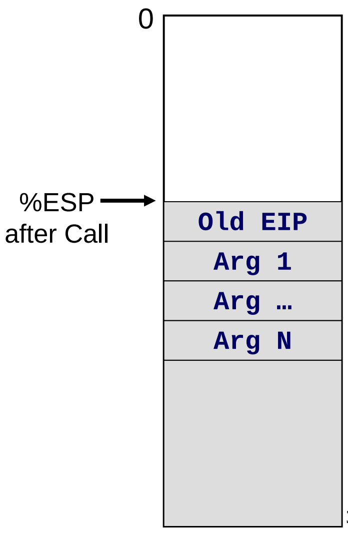
Callee can address arguments relative to ESP: Arg 1 as 4(%esp)



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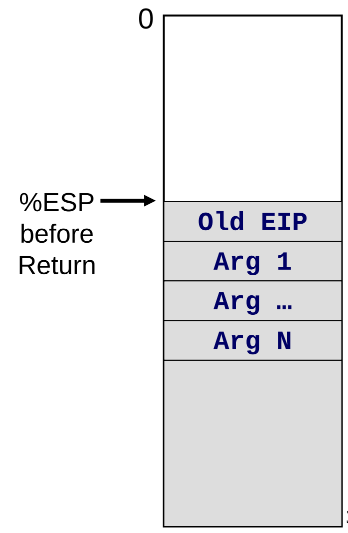

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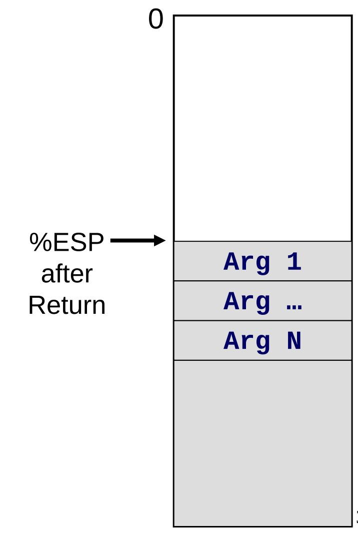
After the function call is finished, the caller pops the pushed arguments from the stack



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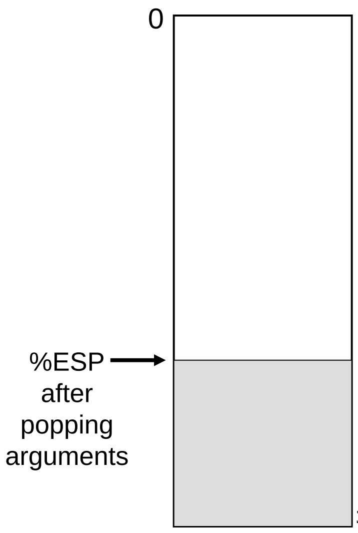
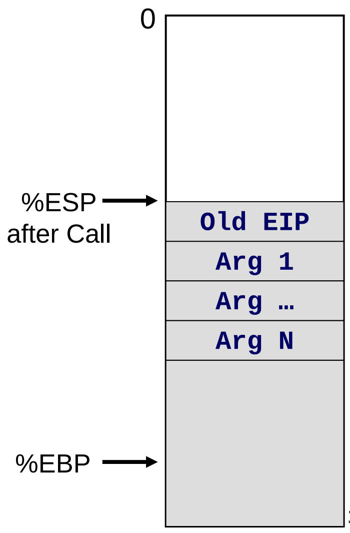


Base Pointer: EBP

- As Callee executes, ESP may change
- Use EBP as a fixed reference point to access arguments and other local variables
- Need to save old value of EBP before using EBP
- Callee begins by executing

```
pushl %ebp
movl %esp, %ebp
```



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```
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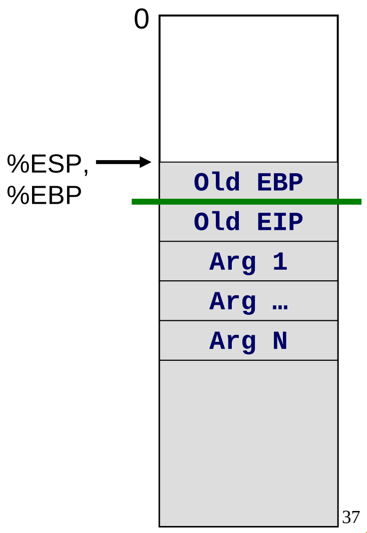
```

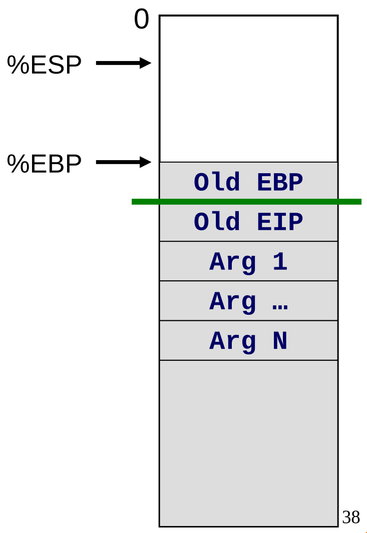
- Regardless of ESP, Callee can address Arg 1 as 8(%ebp)



Base Pointer: EBP

- Before returning, Callee must restore EBP to its old value
- Executes

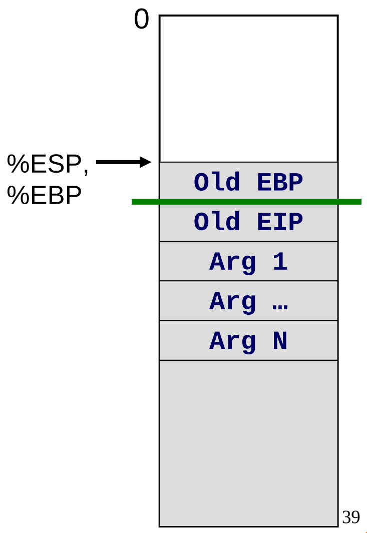
```
→ movl %ebp, %esp
  popl %ebp
  ret
```



Base Pointer: EBP

- Before returning, Callee must restore EBP to its old value
- Executes

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



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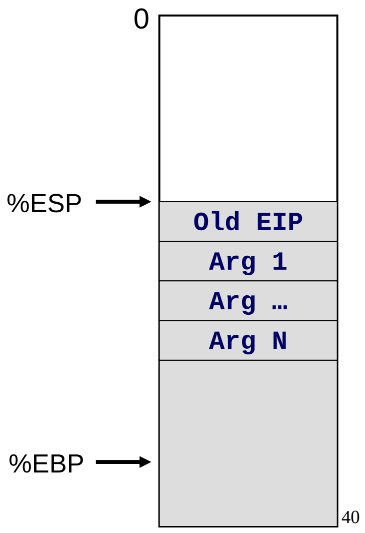

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- Executes

```
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ret
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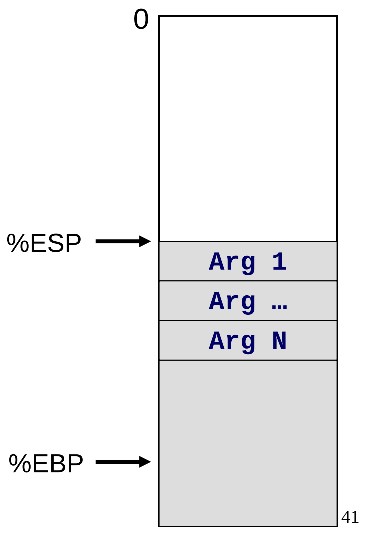
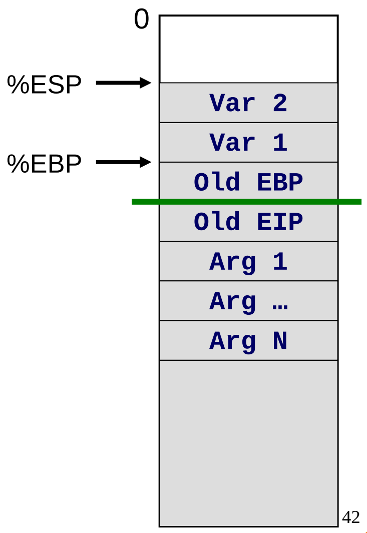


Allocation for Local Variables

- Local variables of the Callee are also allocated on the stack
- Allocation done by moving the stack pointer
- Example: allocate two integers
  - subl $4, %esp
  - subl $4, %esp
  - (or equivalently, subl $8, %esp)
- Reference local variables using the base pointer
  - -4(%ebp)
  - -8(%ebp)

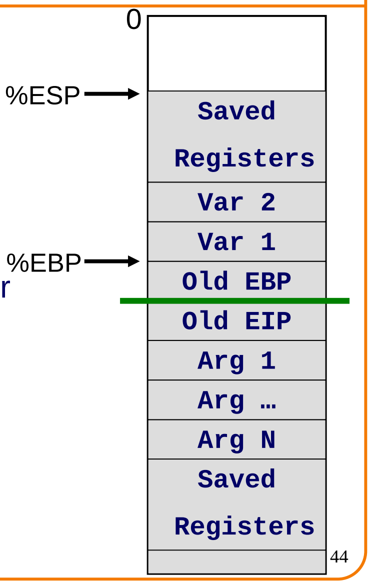


Use of Registers

- Problem: Callee may use a register that the caller is also using
  - When callee returns control to caller, old register contents may be lost
  - Someone must save old register contents and later restore
- Need a convention for who saves and restores which registers

GCC/Linux Convention

- Caller-save registers
  - **`%eax, %edx, %ecx`**
  - Save on stack prior to calling
- Callee-save registers
  - **`%ebx, %esi, %edi`**
  - Old values saved on stack prior to using
- %esp, %ebp handled as described earlier
- Return value is passed from Callee to Caller in %eax



A Simple Example

```
int add3(int a, int b, int c)
{
  int d;

  d = a + b + c;

  return d;
}
```

```
int foo(void)
{
  return add3( 3, 4, 5 );
}
```

A Simple Example

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int add3(int a, int b, int c){
  int d;
  d = a + b + c;
  return d;
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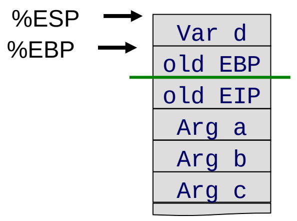


```
add3:
 # Save old ebp and set up new ebp
  pushl %ebp
  movl %esp, %ebp

 # Allocate space for d
  subl $4, $esp
```

```
#  In general, one may need to push
# callee-save registers onto the stack

 # Add the three arguments
 movl 8(%ebp), %eax
 addl 12(%ebp), %eax
 addl 16(%ebp), %eax

 # Put the sum into d
 movl %eax, -4(%ebp)

 # Return value is already in eax

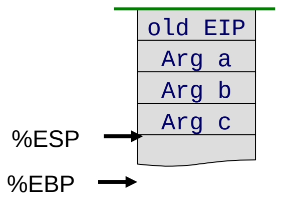
 # In general, one may need to pop
 # callee-save registers

# Restore old ebp, discard stack frame
 movl %ebp, %esp
 popl %ebp

# Return
 ret
```

A Simple Example

```
int foo(void) {
  return add3( 3, 4, 5 );
}
```



```
foo:
 # Save old ebp, and set-up
 # new ebp
  pushl %ebp
  movl %esp, %ebp

 # No local variables

 # No need to save callee-save
 # registers as we
 # don't use any registers
```

```
# No need to save caller-
# save registers either

# Push arguments in reverse order
 pushl $5
 pushl $4
 pushl $3

 call add3

# Return value is already in eax

# Restore old ebp and
# discard stack frame
 movl %ebp, %esp
 popl %ebp

# Return
 ret
```

Conclusion

- Invoking a function
  - Call: call the function
  - Ret: return from the instruction
- Stack Frame for a function invocation includes
  - Return address,
  - Procedure arguments,
  - Local variables, and
  - Saved registers
- Base pointer EBP
  - Fixed reference point in the Stack Frame
  - Useful for referencing arguments and local variables