Assembly Language: Function Calls

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Goals of Today's Lecture

- Challenges of supporting functions
  - Providing information for the called function
    - Function arguments and local variables
  - Allowing the calling function to continue where it left off
    - Return address and contents of registers
- Stack: last-in-first-out data structure
  - Stack frame: args, local vars, return address, registers
  - Stack pointer: pointing to the current top of the stack
- Calling functions
  - Call and ret instructions, to call and return from functions
  - Pushing and popping the stack frame
  - Using the base pointer EBP as a reference point

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Challenges of Supporting Functions

- Code with a well-defined entry and exit points
  - Call: How does the CPU *go to* that entry point?
  - Return: How does the CPU *go back* to the right place, when "right place" depends on who called the function?
- With arguments and local variables
  - How are the *arguments* passed from the caller?
  - Where should the *local variables* be stored?
- Providing a return value
  - How is the *return value* returned to the calling function?
- Without changing variables in other functions
  - How are the values stored in registers protected?

Call and Return Abstractions

- Call a function
  - Jump to the beginning of an arbitrary procedure
  - I.e., jump to the address of the function's first instruction
- Return from a function
  - Jump to the instruction immediately following the "most-recently-executed" Call instruction
  - But, the same function may be called from many places!

```
P:              # Function P

  …

  jmp R         # Call R

Rtn_point1:

  …
```

```
R:              # Function R

  …

  jmp Rtn_point1   # Return
```

Challenge: Where to Return?

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

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

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

What should the return instruction in R jump to???

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Store Return Address in Register?

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

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

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

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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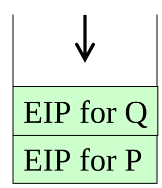
Solution: Put Return Address on a Stack

- May need to store many return addresses
  - The number of nested functions is not known in advance
  - A return address must be saved for as long as the function invocation continues
- Addresses used in reverse order
  - E.g., function P calls Q, which then calls R
  - Then R returns to Q which then returns to P



- Last-in-first-out data structure (stack)
  - Calling function pushes return address on the stack
  - … and called function pops return address off the stack

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Arguments to the Function

- Calling function needs to pass arguments
  - Cannot simply put arguments in a specific register
  - Because function calls may be nested
- So, put the arguments on the stack, too!
  - Calling function pushes arguments on the stack
  - Called function loads/stores- them on the stack

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

  d = a + b + c;

  return d;
}
```

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

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Local Variables

- Local variables: called function has local variables
  - Short-lived, so don't need a permanent location in memory
  - Size known in advance, so don't need to allocate on the heap
- So, the function just uses the top of the stack
  - Store local variables on the top of the stack
  - The local variables disappear after the function returns

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

  d = a + b + c;

  return d;
}


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

Registers

- Registers
  - Small, fast memory (e.g., directly on the CPU chip)
  - Used as temporary storage for computations
- Cannot have separate registers per function
  - Could have arbitrary number of nested functions
  - Want to allow each function to use all the registers
- Could write all registers out to memory
  - E.g., save values corresponding to program variables
    - Possible, but a bit of a pain…
  - E.g., find someplace to stash intermediate results
    - Where would we put them?
- Instead, save the registers on the stack, too

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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

  } **Stack Frame**

- Stack has one Stack Frame per active function invocation

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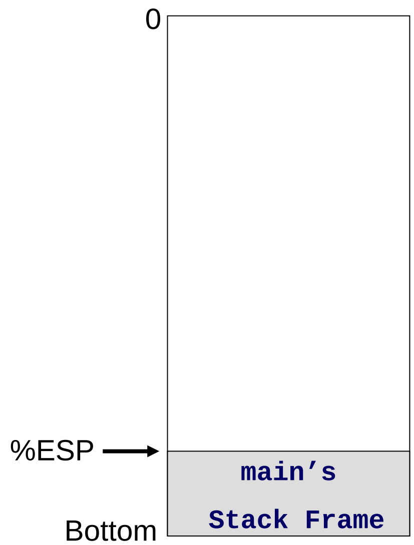
High-Level Picture

main begins executing



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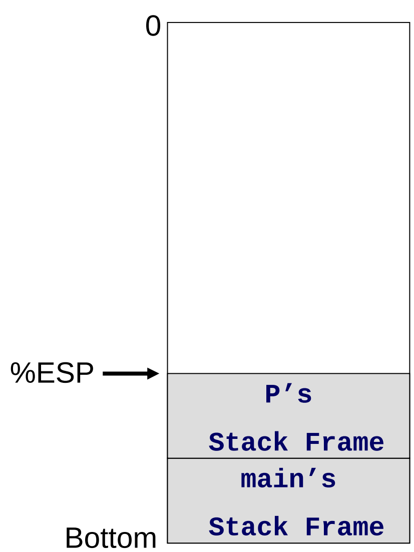
High-Level Picture

main begins executing

main calls P



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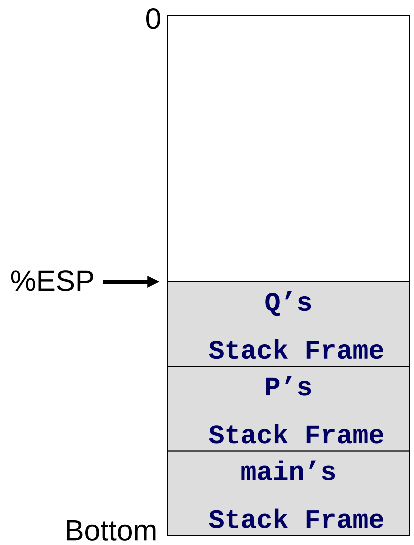
High-Level Picture

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



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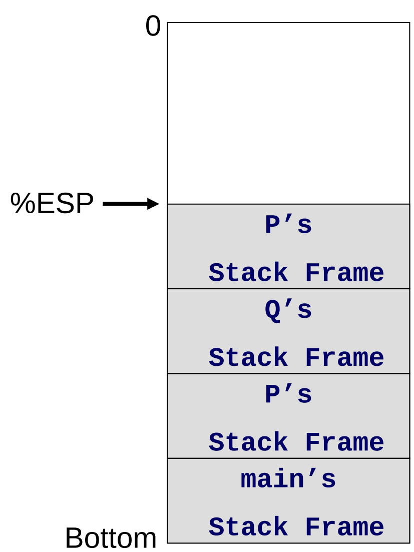
High-Level Picture

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



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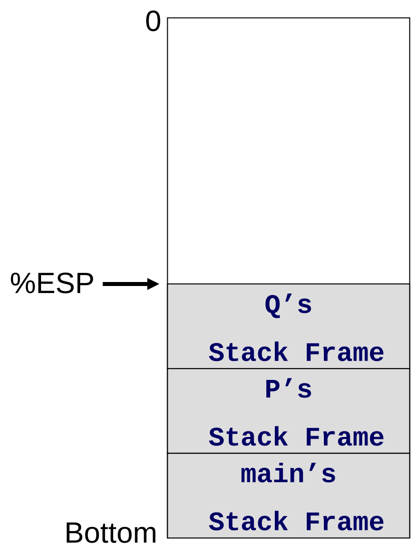
High-Level Picture

```
main begins executing
main calls P
P calls Q
Q calls P
P returns
```



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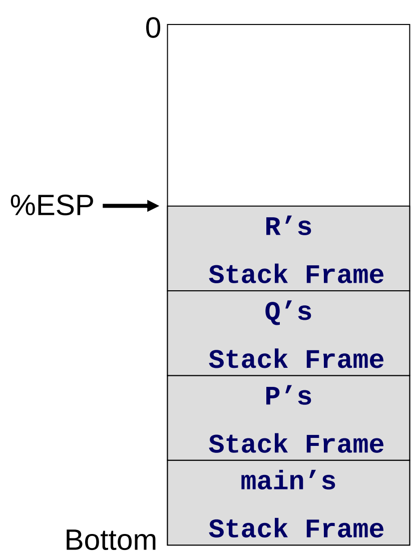
High-Level Picture

```
main begins executing
main calls P
P calls Q
Q calls P
P returns
Q calls R
```



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High-Level Picture

```
main begins executing
main calls P
P calls Q
Q calls P
P returns
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R returns
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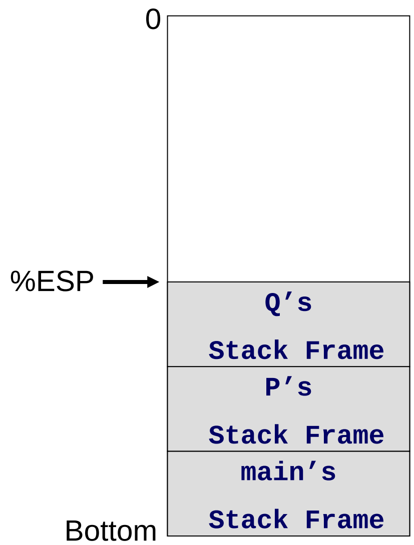

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High-Level Picture

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P returns
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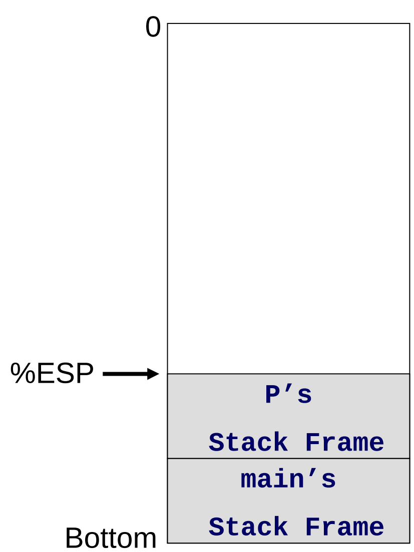
Q returns
```



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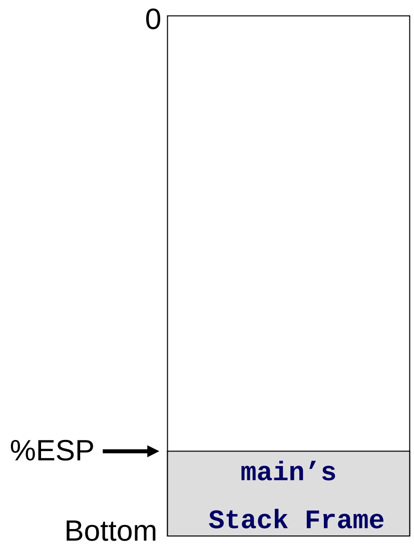
High-Level Picture

```
main begins executing
main calls P
P calls Q
Q calls P
P returns
Q calls R
R returns
Q returns
P returns
```



High-Level Picture

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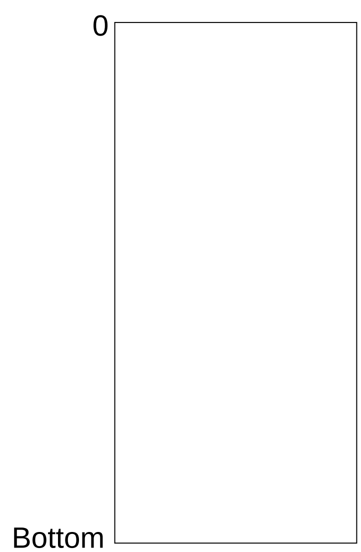

Function Call Details

- Call and Return instructions
  - Call: push EIP on the stack, and jump to function
  - Return: pop the stack into the EIP to go back
- Argument passing between procedures
  - Calling function pushes arguments on to the stack
  - Called function reads/writes on the stack
- Local variables
  - Called function creates and manipulates on the stack
- Register saving conventions
  - Either calling or called function saves all of the registers before use

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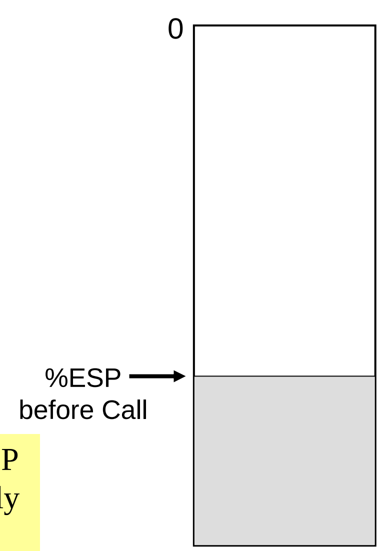
Call and Return Instructions

Instruction	Effective Operations
`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`

Note: can't really access EIP directly, but this is implicitly what call and ret are doing.



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Call and Return Instructions

Instruction	Operation
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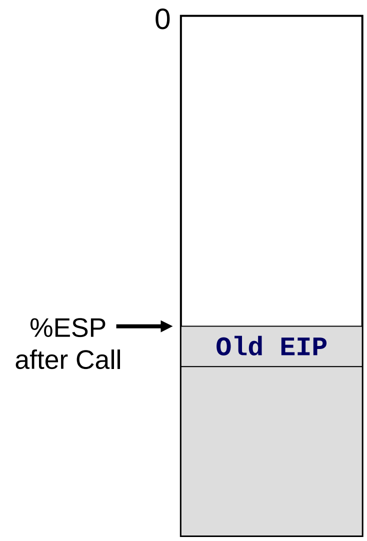

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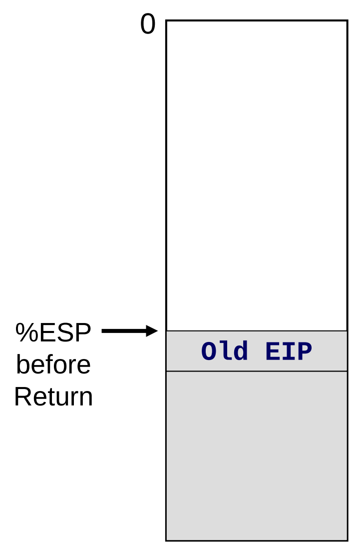
`ret`	`pop %eip`

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



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Call and Return Instructions

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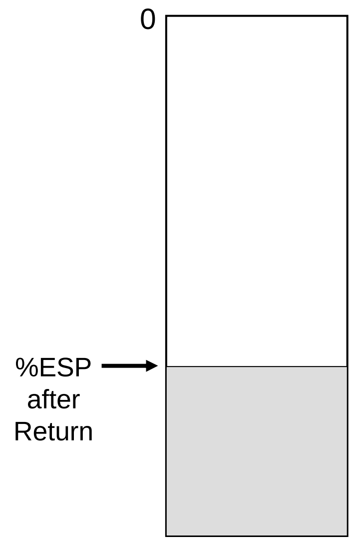
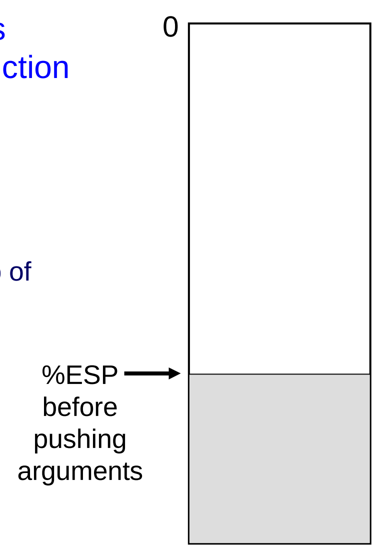


Input Parameters

- 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 first argument is at the top of the stack at the time of the Call



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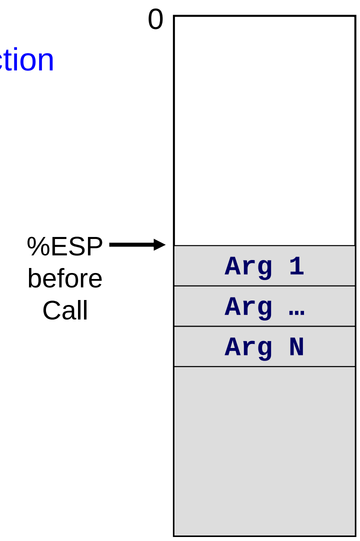

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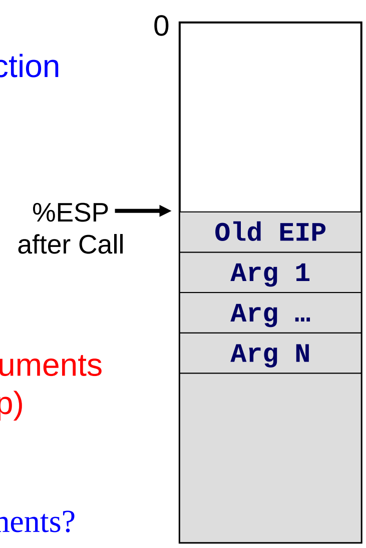
Called function can address arguments relative to ESP: Arg 1 as 4(%esp)



Why is the EIP put on *after* the arguments?

Input Parameters

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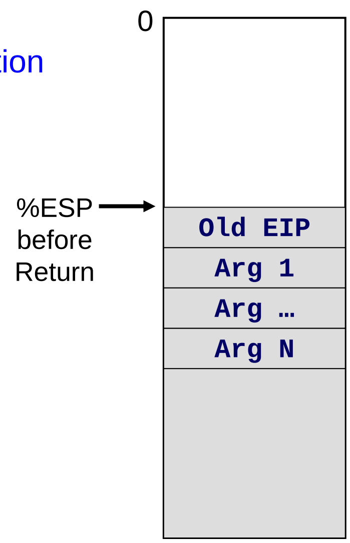

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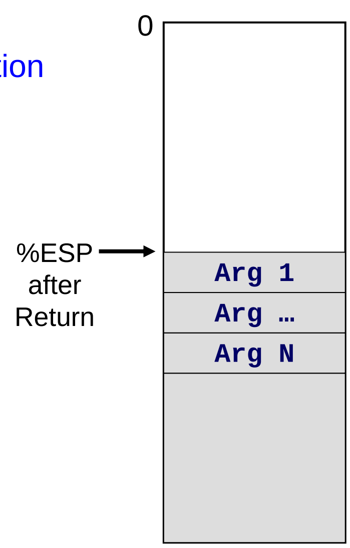
After the function call is finished, the caller pops the pushed arguments from the stack



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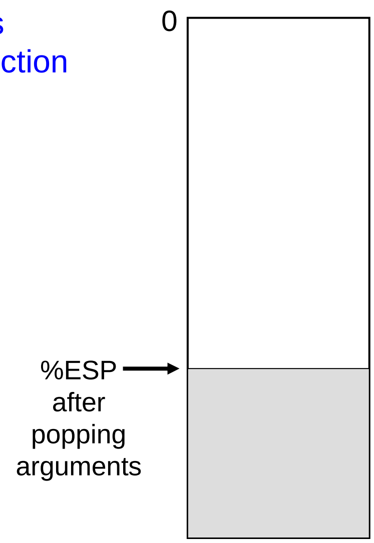
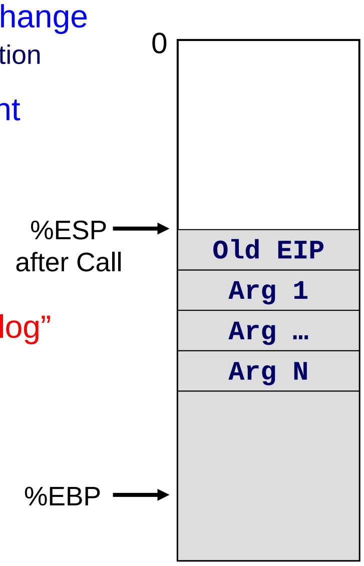


Base Pointer: EBP

- As Callee executes, ESP may change
  - E.g., preparing to call another function
- Use EBP as fixed reference point
  - E.g., to access arguments and other local variables
- Need to save old value of EBP
  - Before overwriting EBP register
- Callee begins by executing "prolog"

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



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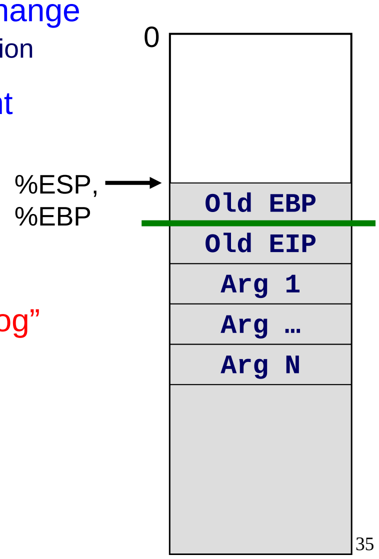
  - E.g., preparing to call another function
- Use EBP as fixed reference point
  - E.g., to access arguments and other local variables
- Need to save old value of EBP
  - Before overwriting EBP register
- Callee begins by executing "epilog"

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

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



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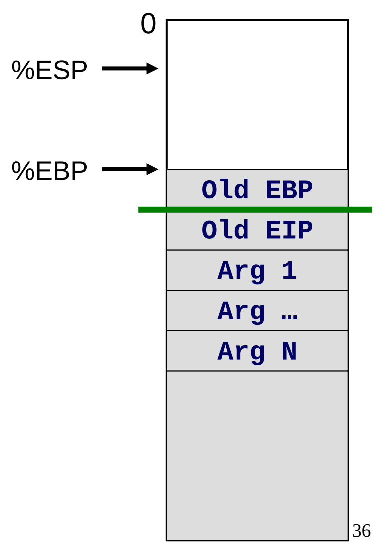
Base Pointer: EBP

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

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



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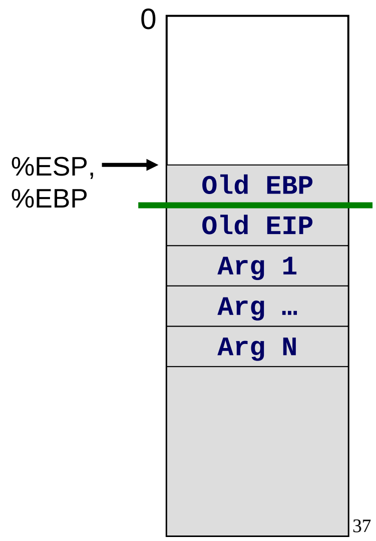
Base Pointer: EBP

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

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



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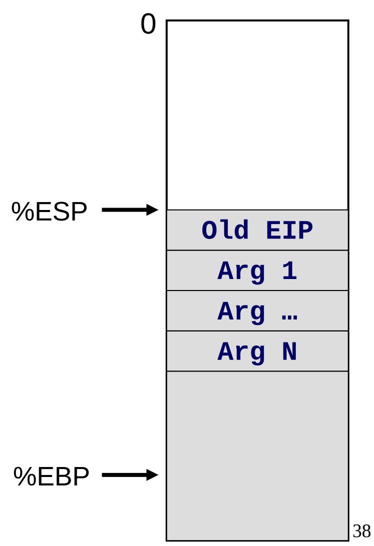
Base Pointer: EBP

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

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



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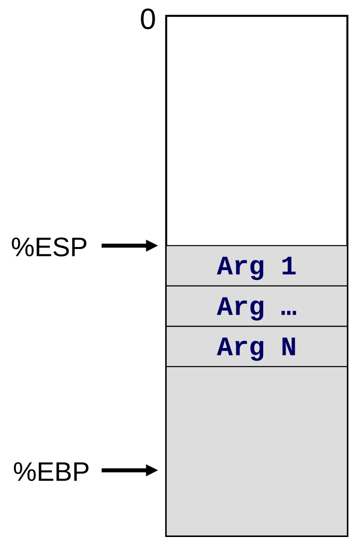
Base Pointer: EBP

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

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



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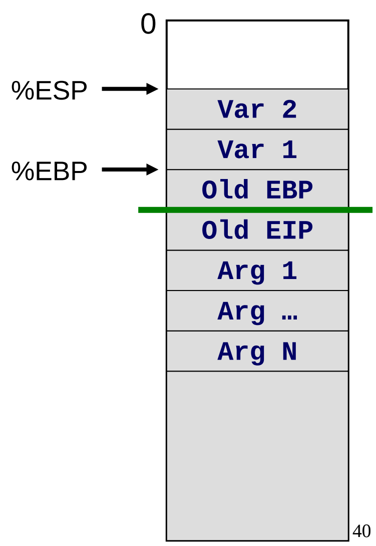
Allocation for Local Variables

- 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)



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Use of Registers

- Problem: Called function may use a register that the calling function is also using
  - When called function returns control to calling function, old register contents may be lost
  - Calling function cannot continue where it left off
- Solution: save the registers on the stack
  - Someone must save old register contents
  - Someone must later restore the register contents
- Need a convention for who saves and restores which registers

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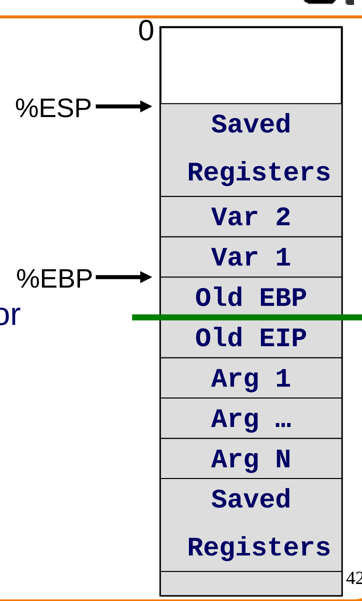
GCC/Linux Convention

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



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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 );
}
```

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A Simple Example

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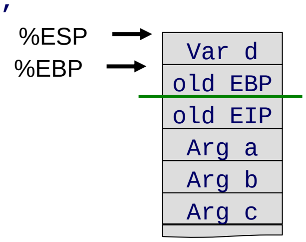
```




```
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
```

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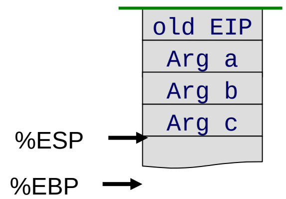
A Simple Example

```
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

# Pop arguments from the stack
 addl $12, %esp

# Return value is already in eax

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

# Return
 ret
```

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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

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