Procedure Calls

CS 217

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Procedure Calls

- Procedure: a piece of code with a well-defined interface, and well-defined entry and exit points
- **Call:** jump to the beginning of an arbitrary procedure
- **Return:** jump back to the caller
- The jump address in the return operation is dynamically determined
  - Jump to the instruction immediately following the Call instruction in the Caller

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Implementing Procedure Calls

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

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

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

What should the return instruction in R jump to?

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Implementing Procedure 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 Procedure Calls

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

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

```
Q:          # Proc 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

Need to use a Stack

- P calls Q, Q calls R, R calls S, S calls P again
- A return address needs to be saved for as long as the procedure invocation continues
- Return addresses are used in Last-In-First-Out order
- Stack is a natural solution

Stack Frames

- Use stack for all temporary data related to each active procedure invocation
- Return address
- Procedure arguments
- Local variables of procedures
- Saving registers across invocations

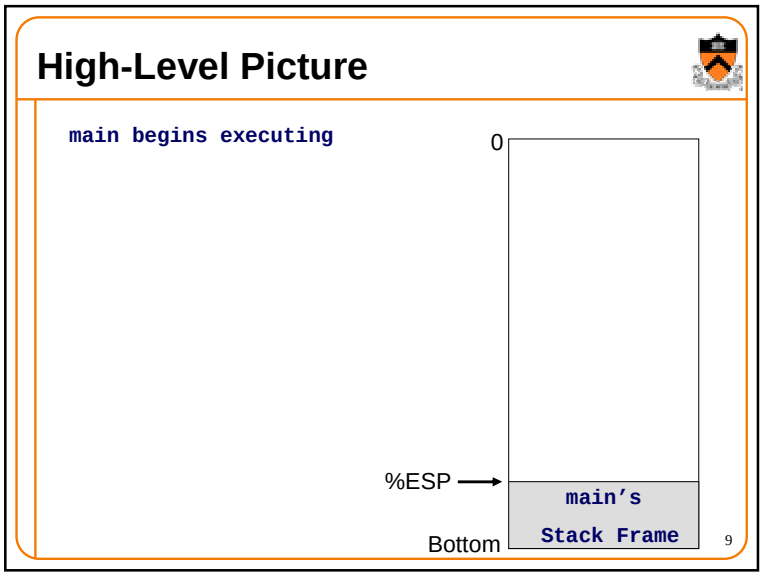
Stack Frame

- Stack has one Stack Frame for each active procedure 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
```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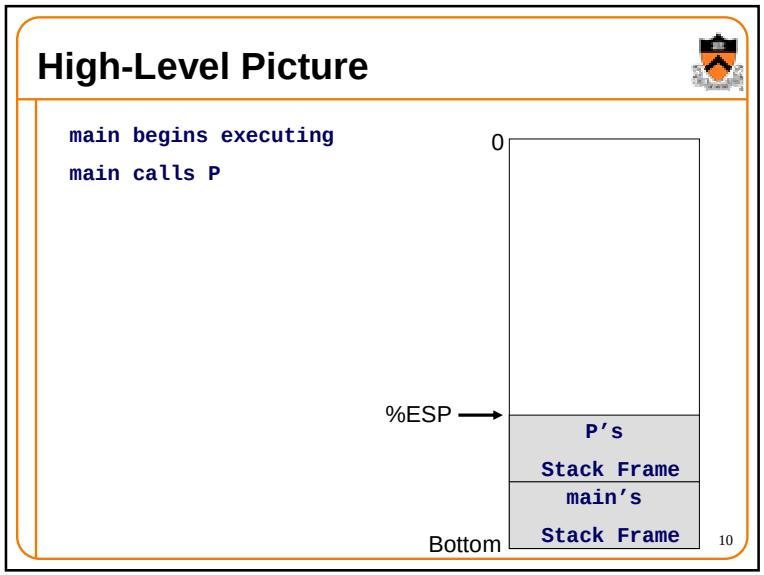
High-Level Picture



```
main begins executing
main calls P
```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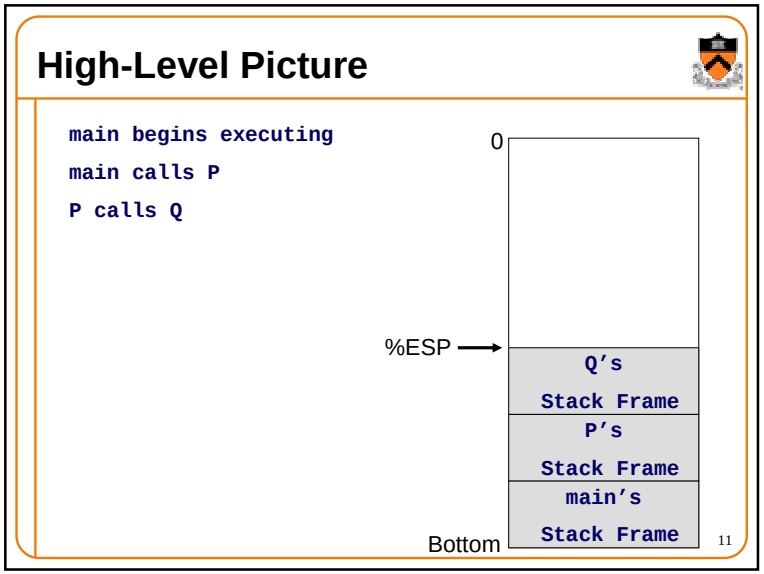
High-Level Picture



```
main begins executing
main calls P
P calls Q
```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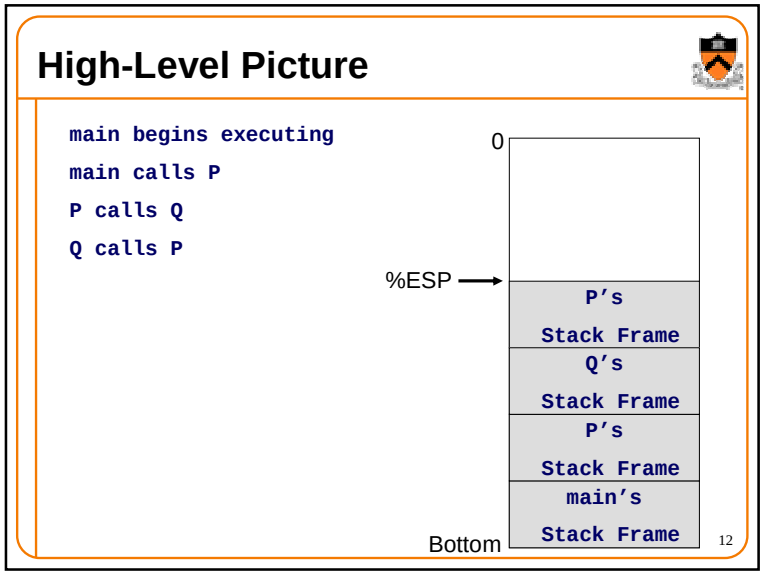
High-Level Picture



```
main begins executing
main calls P
P calls Q
Q calls P
```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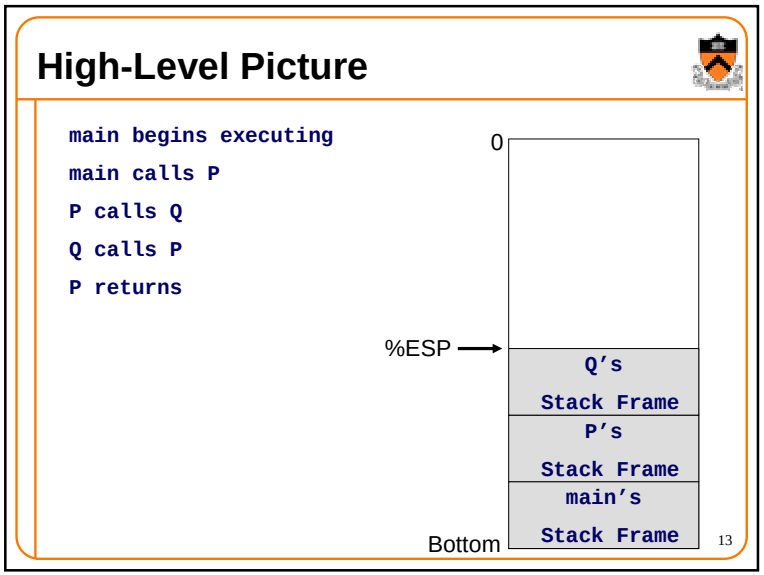
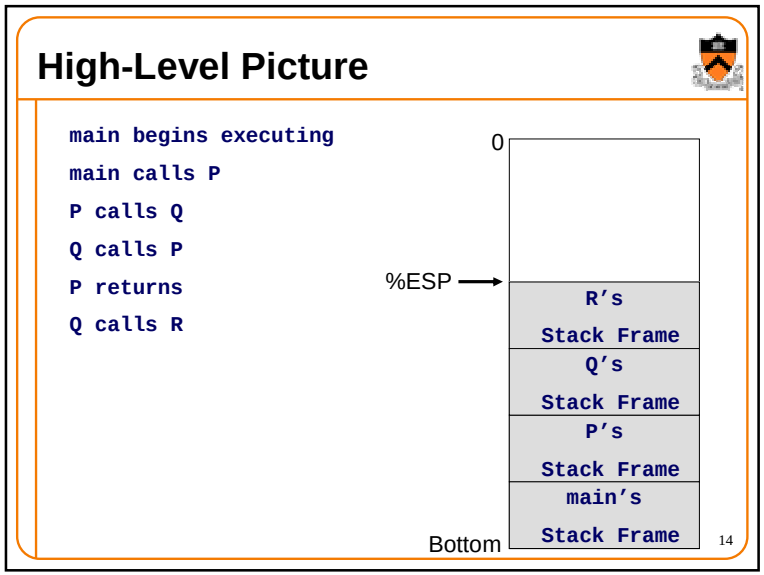
High-Level Picture



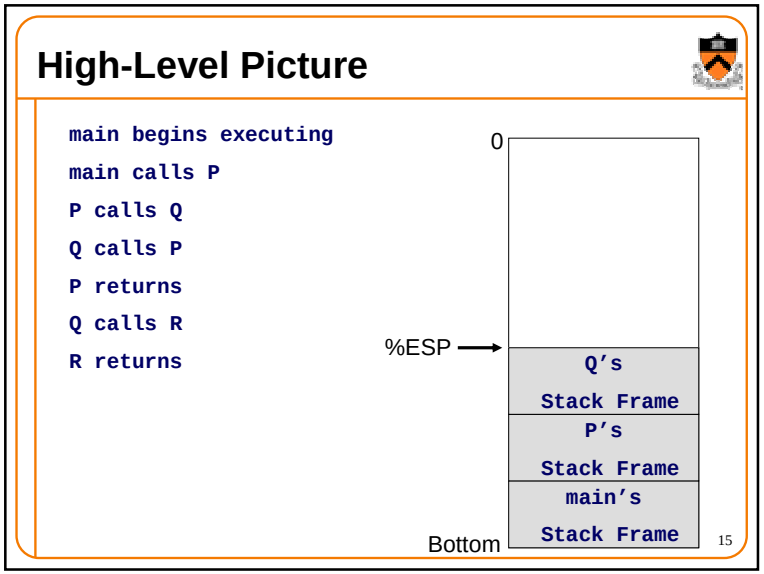
```
main begins executing
main calls P
P calls Q
Q calls P
P returns
```


High-Level Picture



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


High-Level Picture



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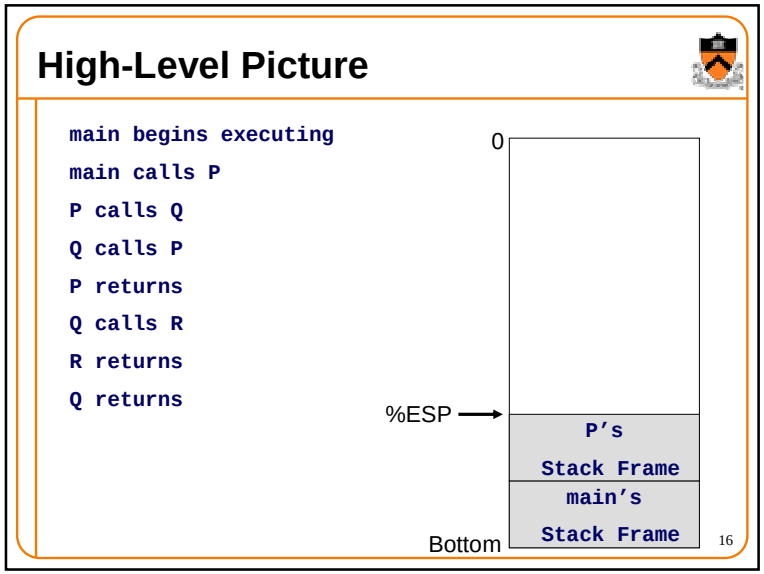
High-Level Picture



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High-Level Picture

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P calls Q
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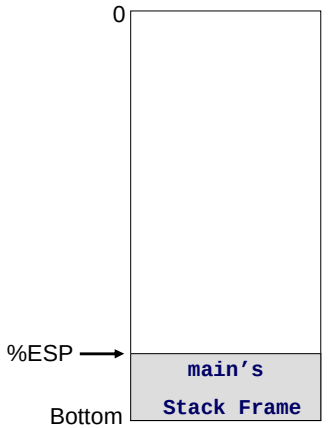

High-Level Picture

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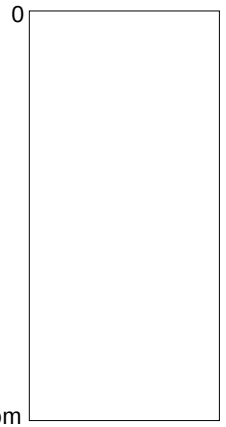
main begins executing
main calls P
P calls Q
Q calls P
P returns
Q calls R
R returns
Q returns
P returns
main returns
```

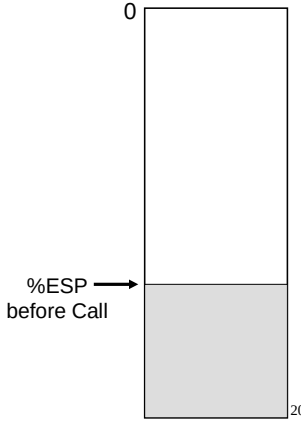


Procedure Call Details

- Call and Return instructions
- Argument passing between procedures
- Base pointer management (EBP)
- Local variables
- Register saving conventions

Call and Return Instructions

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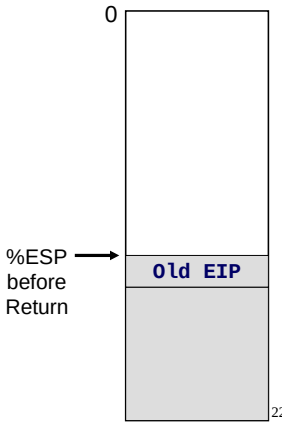
Return instruction assumes that the return address is at the top of the stack



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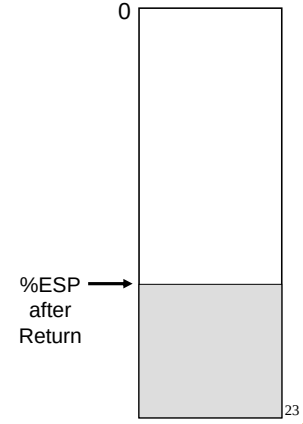

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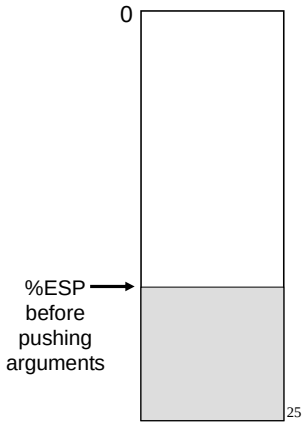
Input Parameters

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



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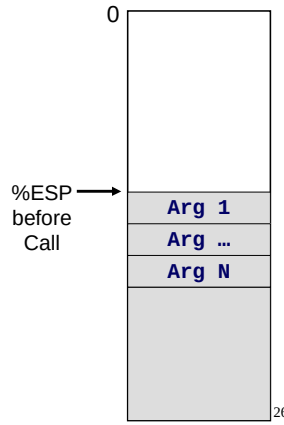

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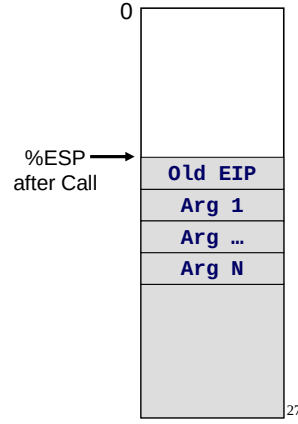
Callee can address arguments relative to ESP: Arg 1 as 4(%esp)



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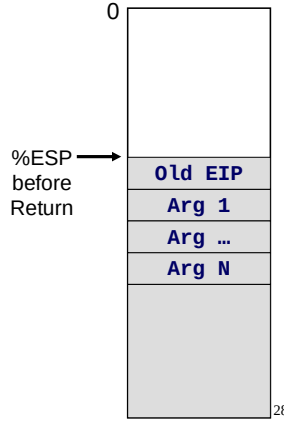

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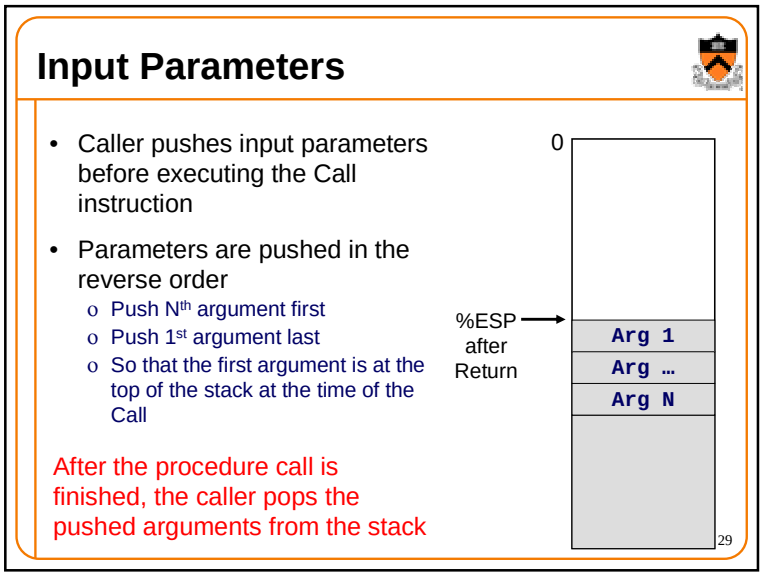
Input Parameters



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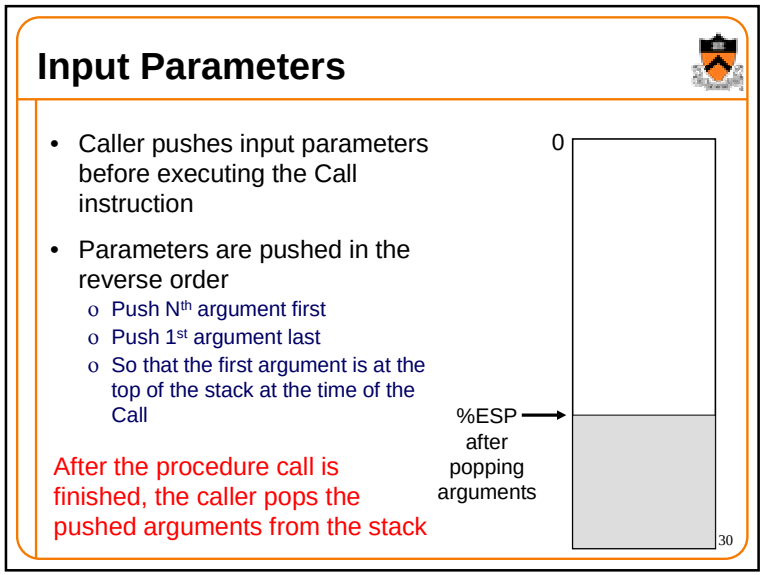
After the procedure call is finished, the caller pops the pushed arguments from the stack

Input Parameters



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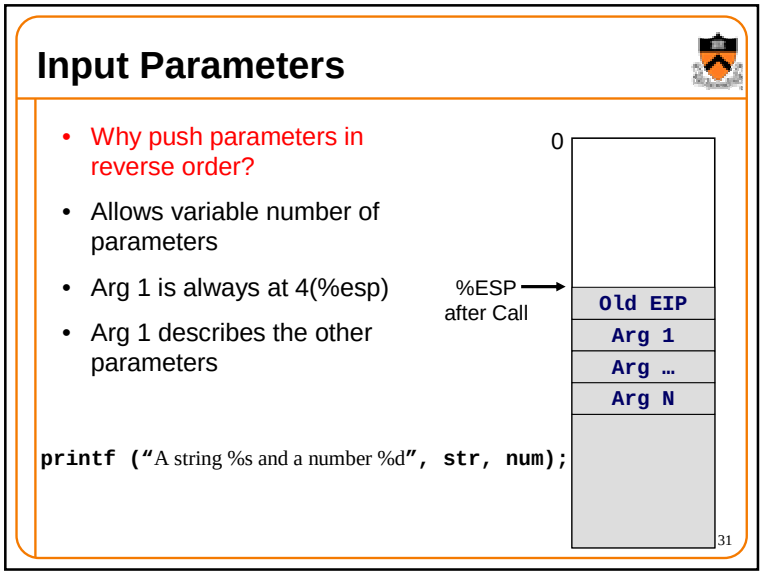
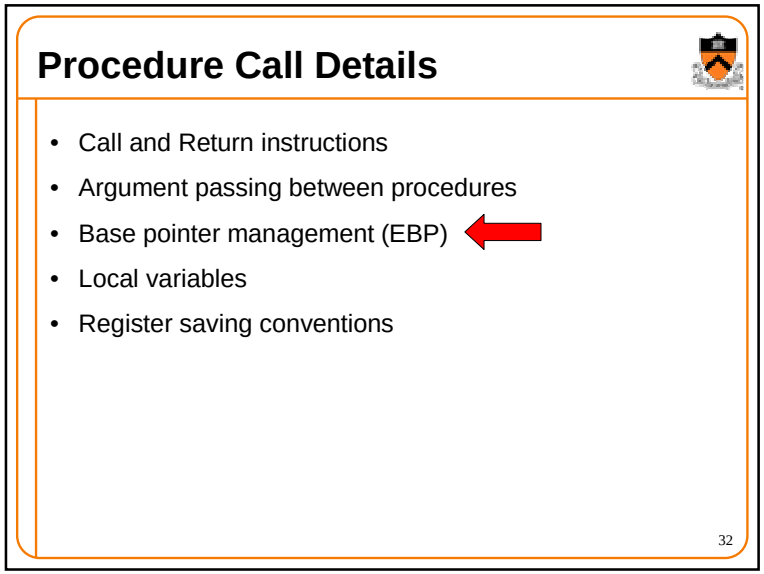


- Why push parameters in reverse order?
- Allows variable number of parameters
- Arg 1 is always at 4(%esp)
- Arg 1 describes the other parameters

```
printf ("A string %s and a number %d", str, num);
```


Procedure Call Details

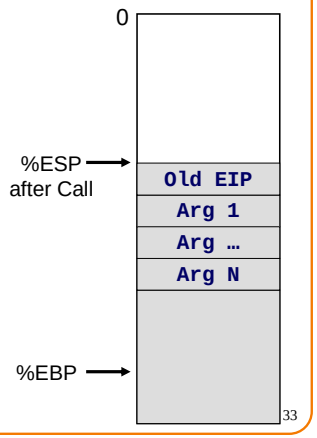


- Call and Return instructions
- Argument passing between procedures
- Base pointer management (EBP)
- Local variables
- Register saving conventions

Base Pointer: EBP

- As Callee executes, ESP may change
- Use EBP as a fixed reference point to access arguments and 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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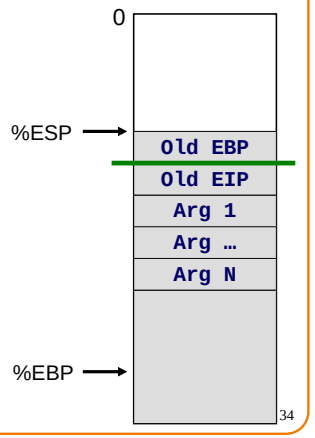
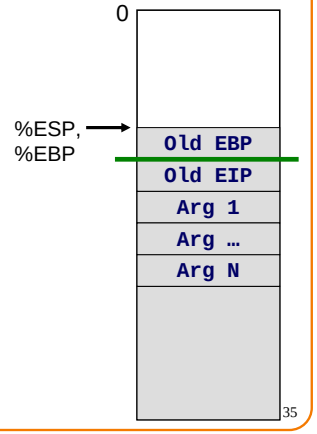


Base Pointer: EBP

- 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
```

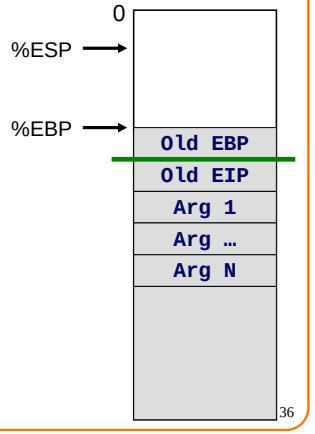
- Regardless of ESP, Callee can address Arg 1 as 8(%ebp)



Base Pointer: EBP

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

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



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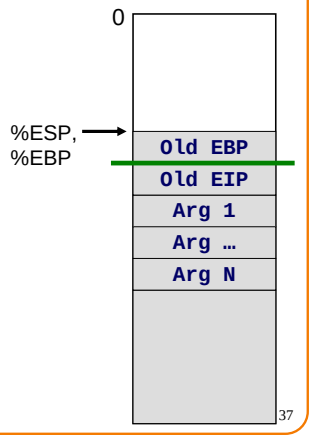

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Base Pointer: EBP

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```

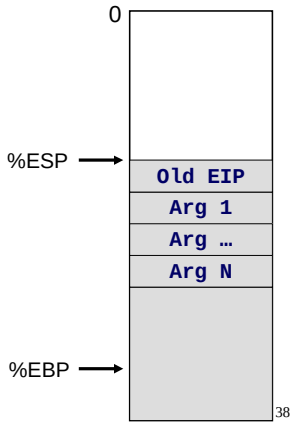

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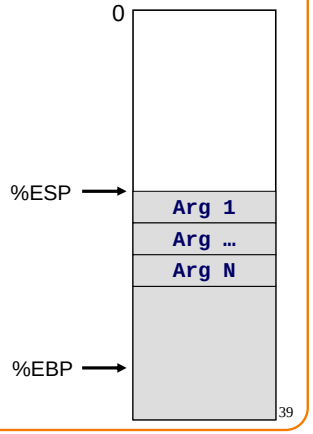

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Procedure Call Details

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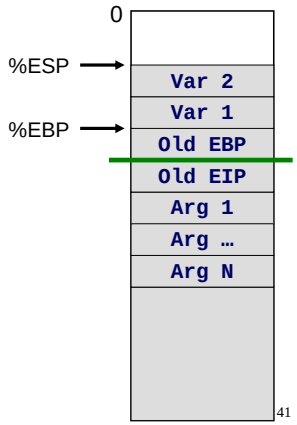
Allocation for Local Variables

- 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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Procedure Call Details

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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. BAD!
  - Someone must save old register contents and later restore
- Need a convention for who saves and restores which registers

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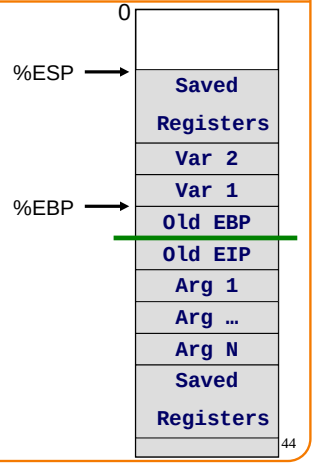
GCC/Linux Convention

- Caller-save registers
  - **%eax, %edx, %ecx**
  - Save on stack prior to calling
  - Restore after return
- Callee-save registers
  - **%ebx, %esi, %edi**
  - Old values saved on stack prior to using
  - Restore after using
- %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 );
}
```


A Simple Example

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

  d = a + b + c;

  return d;
}
```

```
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 and
# 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
```


System Calls

```
.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
int $0x80
```

Summary

- Temporary data related to procedure invocations is stored on the stack
- Stack Frame for a procedure invocation includes return address, procedure arguments, local variables and saved registers
- Call and Ret instructions implement procedure calls
- Base pointer EBP is used as a fixed reference point in the Stack Frame
- Arguments and local variables are addressed relative to the base pointer

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