Assembly Language: Function Calls

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Goals of this Lecture

- Function call problems:
  - Calling and returning
  - Passing parameters
  - Storing local variables
  - Handling registers without interference
  - Returning values
- IA-32 solutions to those problems
  - Pertinent instructions and conventions

Recall from Last Lecture

Examples of Operands

- Immediate Operand
  - movl $5, …
    - CPU uses 5 as source operand
  - movl $i, …
    - CPU uses address denoted by i as source operand
- Register Operand
  - movl %eax, …
    - CPU uses contents of EAX register as source operand

Recall from Last Lecture (cont.)

- Memory Operand: Direct Addressing
  - movl i, …
    - CPU fetches source operand from memory at address i
- Memory Operand: Indirect Addressing
  - movl (%eax), …
    - CPU considers contents of EAX to be an address
    - Fetches source operand from memory at that address
- Memory Operand: Base+Displacement Addressing
  - movl 8(%eax), …
    - CPU computes address as 8 + [contents of EAX]
    - Fetches source operand from memory at that address

Recall from Last Lecture (cont.)

- Memory Operand: Indexed Addressing
  - movl 8(%eax, %ecx), …
    - Computes address as 8 + [contents of EAX] + [contents of ECX]
    - Fetches source operand from memory at that address
- Memory Operand: Scaled Indexed Addressing
  - movl 8(%eax, %ecx, 4), …
    - Computes address as 8 + [contents of EAX] + ([contents of ECX] * 4)
    - Fetches source operand from memory at that address
- Same for destination operand, except…
- Destination operand cannot be immediate

Function Call Problems

1. Calling and returning
   - How does caller function *jump* to callee function?
   - How does callee function *jump back* to the right place in caller function?
2. Passing parameters
   - How does caller function pass *parameters* to callee function?
3. Storing local variables
   - Where does callee function store its *local variables?*
4. Handling registers
   - How do caller and callee functions use *same registers* without interference?
5. Returning a value
   - How does callee function send *return value* back to caller function?

Problem 1: Calling and Returning

How does caller function *jump* to callee function?

- I.e., Jump to the address of the callee's first instruction

How does the callee function *jump back* to the right place in caller function?

- I.e., Jump to the instruction immediately following the most-recently-executed call instruction

Attempted Solution: Use Jmp Instruction

- Attempted solution: caller and callee use jmp instruction

```
P:                # Function P

   …

   jmp R          # Call R

Rtn_point1:

   …
```

```
R:                # Function R

   …

   jmp Rtn_point1   # Return
```

Attempted Solution: Use Jmp Instruction

- Problem: callee may be called by multiple callers

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

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

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

Attempted Solution: Use Register

- Attempted solution 2: Store return address in register

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

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

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

Special form of jmp instruction; we will not use

Attempted Solution: Use Register

- Problem: Cannot handle nested function calls

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

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

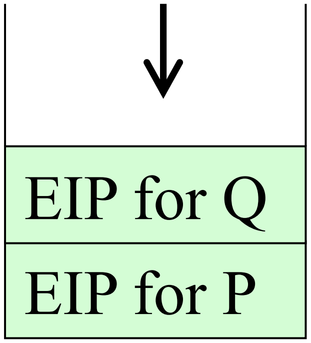
```
Q:                # Function Q
   movl $Rtn_point2, %eax
   jmp R          # Call R
Rtn_point2:
   …
   jmp %eax       # Return
```

Problem if P calls Q, and Q calls R

Return address for P to Q call is lost

IA-32 Solution: Use the Stack

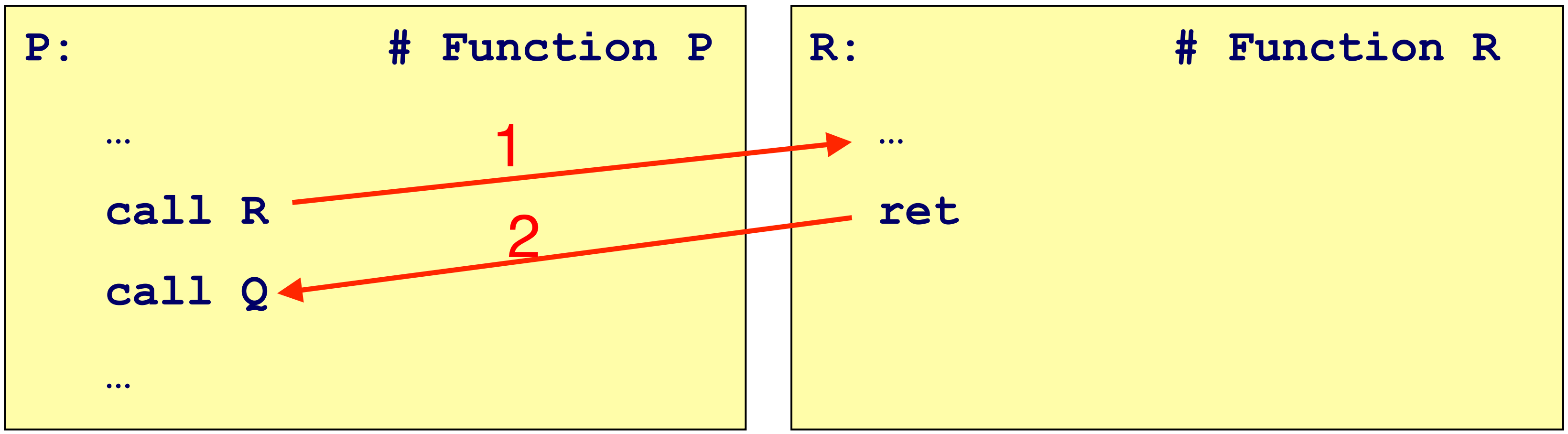
- May need to store many return addresses
  - The number of nested functions is not known in advance
  - A return address must be saved for as long as the function invocation continues, and discarded thereafter
- Addresses used in reverse order
  - E.g., function P calls Q, which then calls R
  - Then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



- Last-in-first-out data structure (stack)
  - Caller pushes return address on the stack
  - … and callee pops return address off the stack
- IA 32 solution: Use the stack via call and ret

IA-32 Call and Ret Instructions

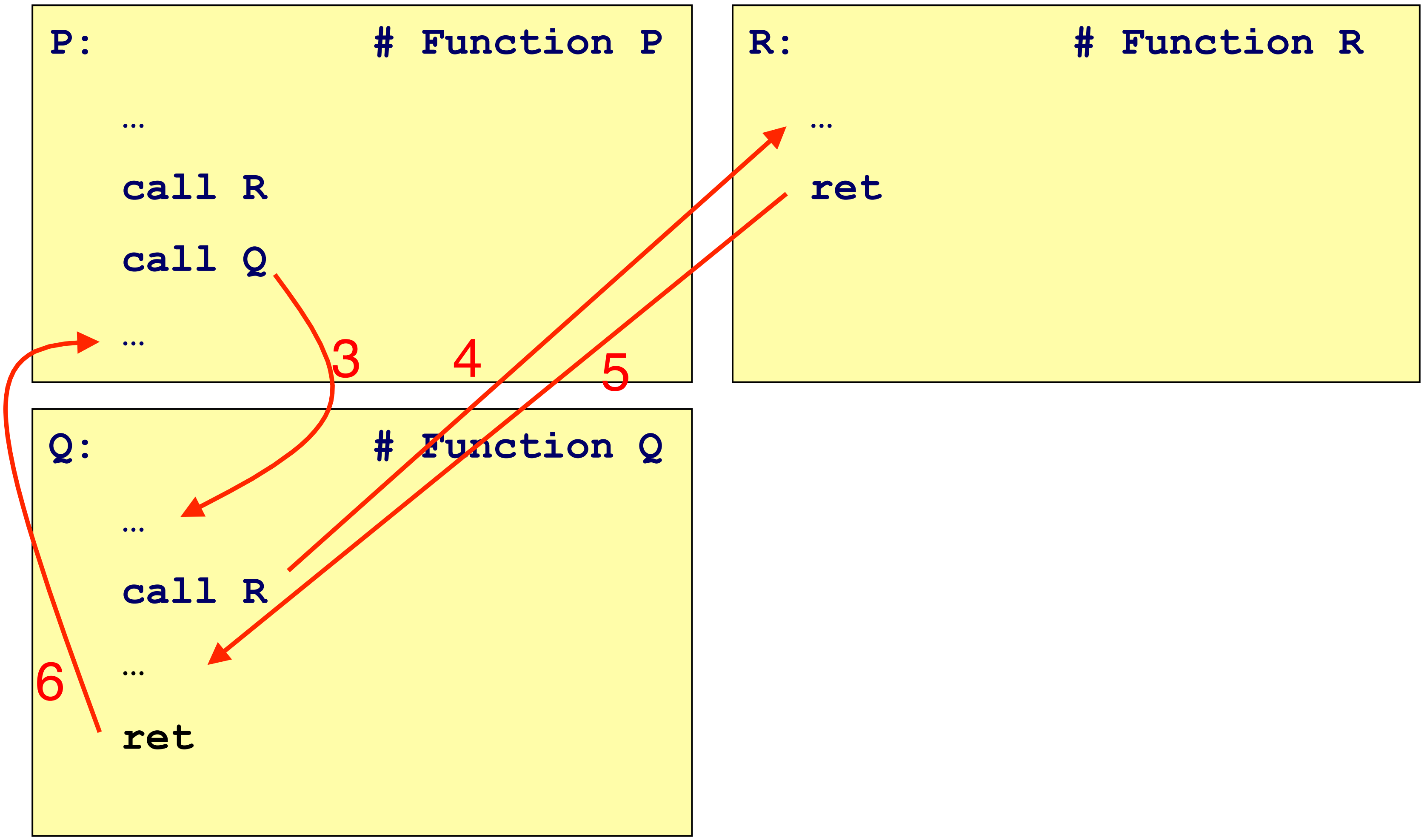
- Ret instruction “knows” the return address




```
Q:                  # Function Q

    …

    call R

    …

    ret
```

IA-32 Call and Ret Instructions

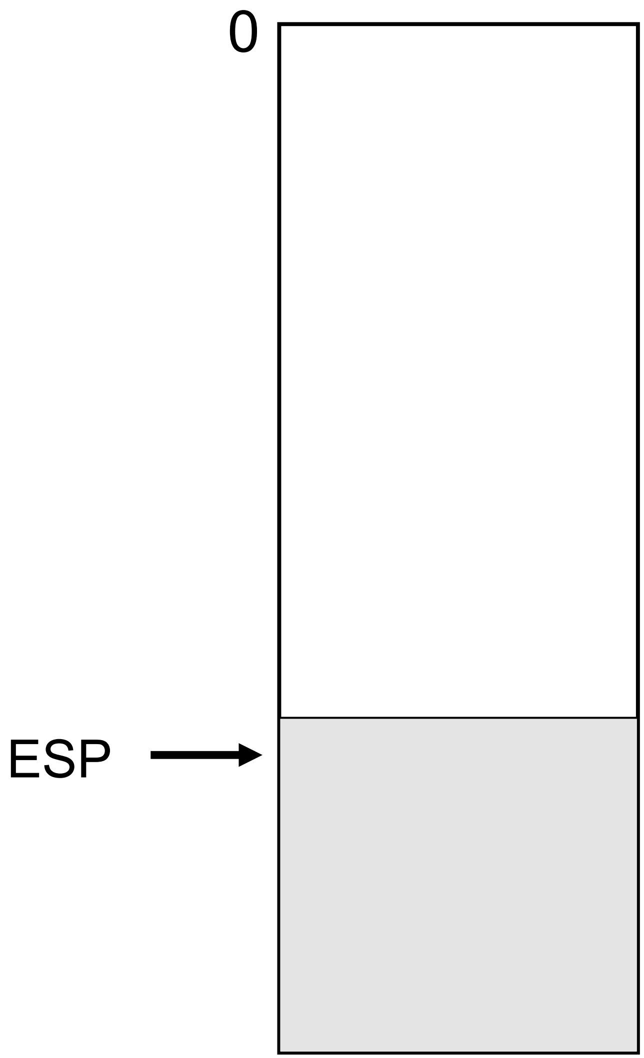
- Ret instruction "knows" the return address



Implementation of Call

- ESP (stack pointer register) points to top of stack

Instruction	Effective Operations
`pushl src`	`subl $4, %esp` `movl src, (%esp)`
`popl dest`	`movl (%esp), dest` `addl $4, %esp`

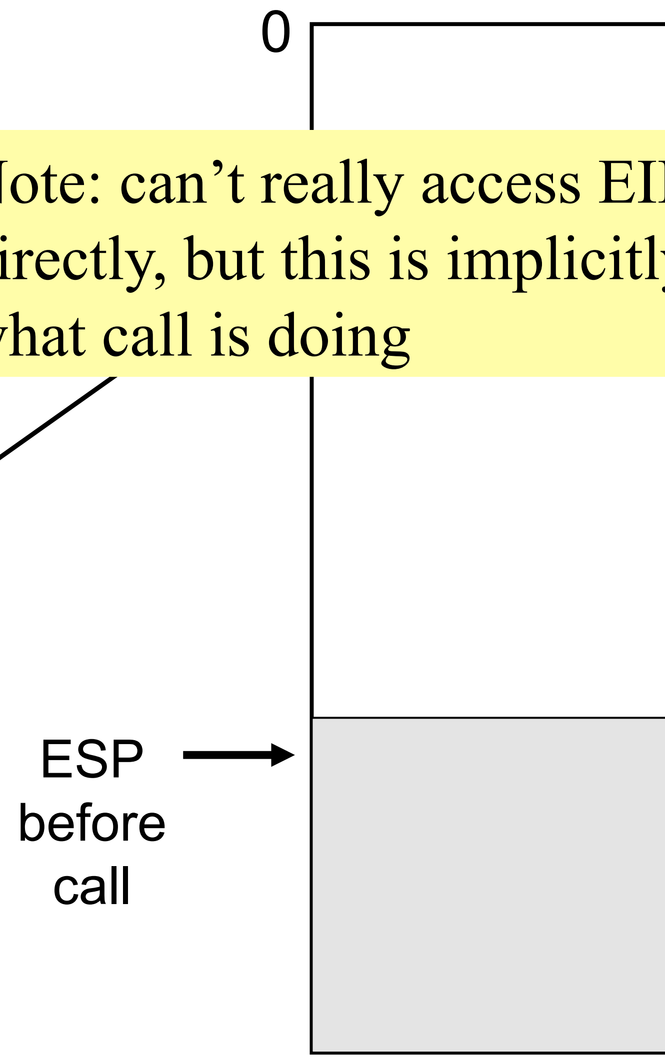


Implementation of Call

- EIP (instruction pointer register) points to next instruction to be executed

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`

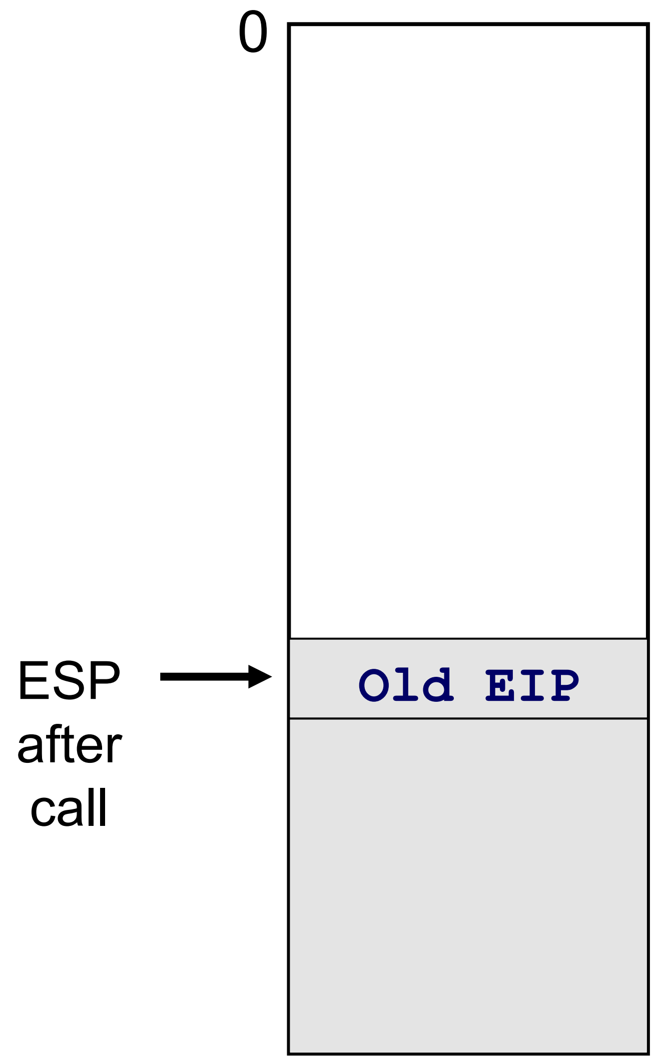
Note: can’t really access EIP directly, but this is implicitly what call is doing



Call instruction pushes return address (old EIP) onto stack

Implementation of Call

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`

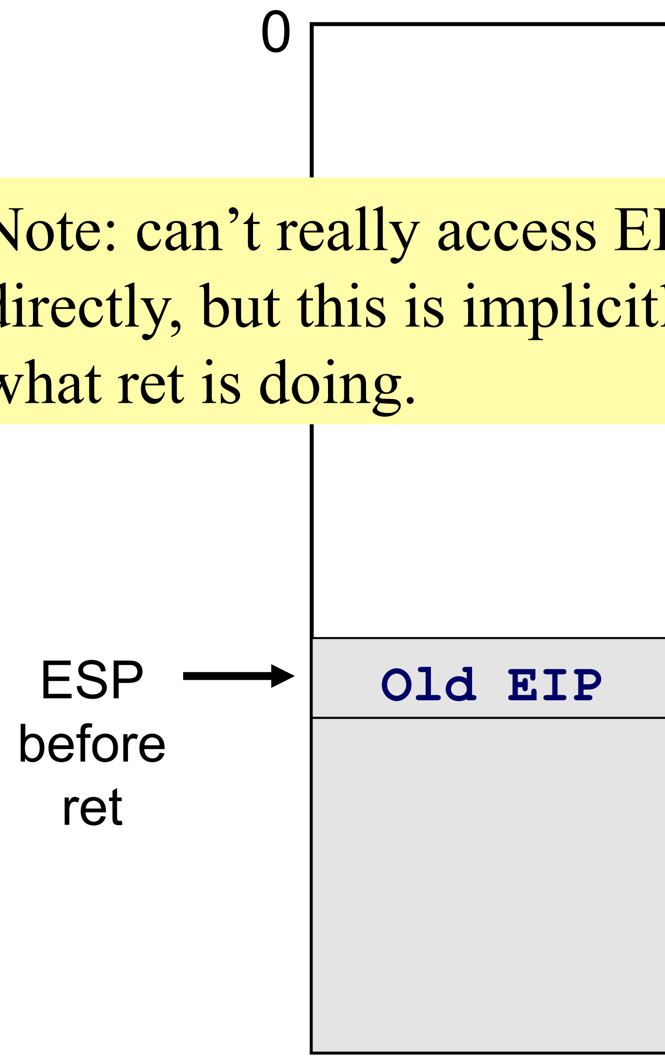


Implementation of Ret

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`

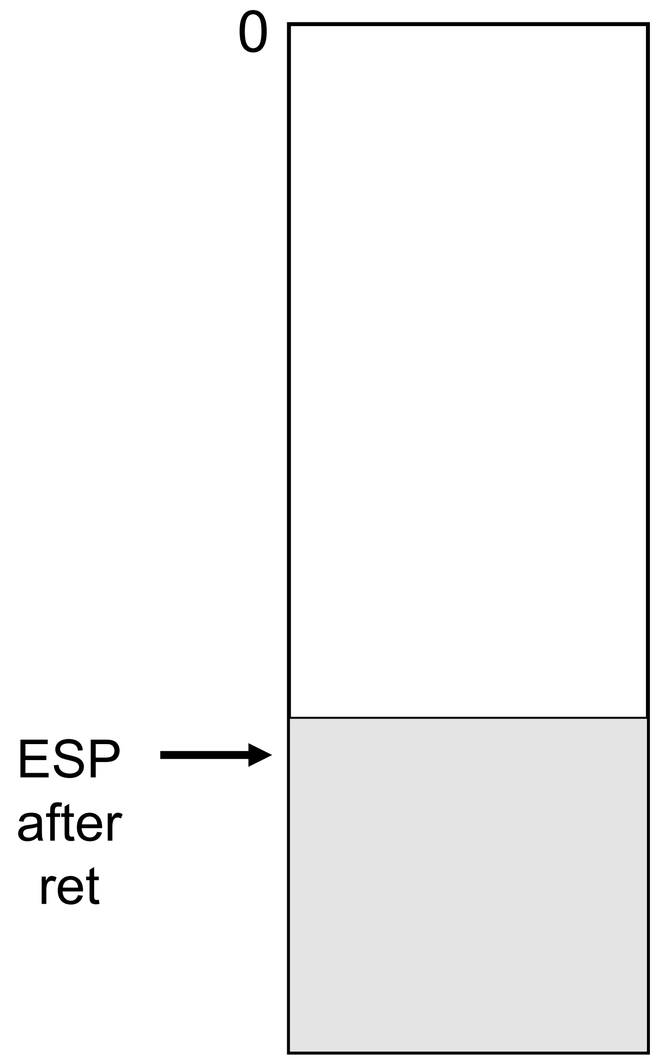
Note: can’t really access EIP directly, but this is implicitly what ret is doing.

Ret instruction pops stack, thus placing return address (old EIP) into EIP



Implementation of Ret

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`



Problem 2: Passing Parameters

- Problem: How does caller function pass *parameters* to callee function?

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

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

Attempted Solution: Use Registers

- Attempted solution: Pass parameters in registers

```
f:
   movl $3, %eax
   movl $4, %ebx
   movl $5, %ecx
   call add3
   …
```

```
add3:
   …
   # Use EAX, EBX, ECX
   …
   ret
```

Attempted Solution: Use Registers

- Problem: Cannot handle nested function calls

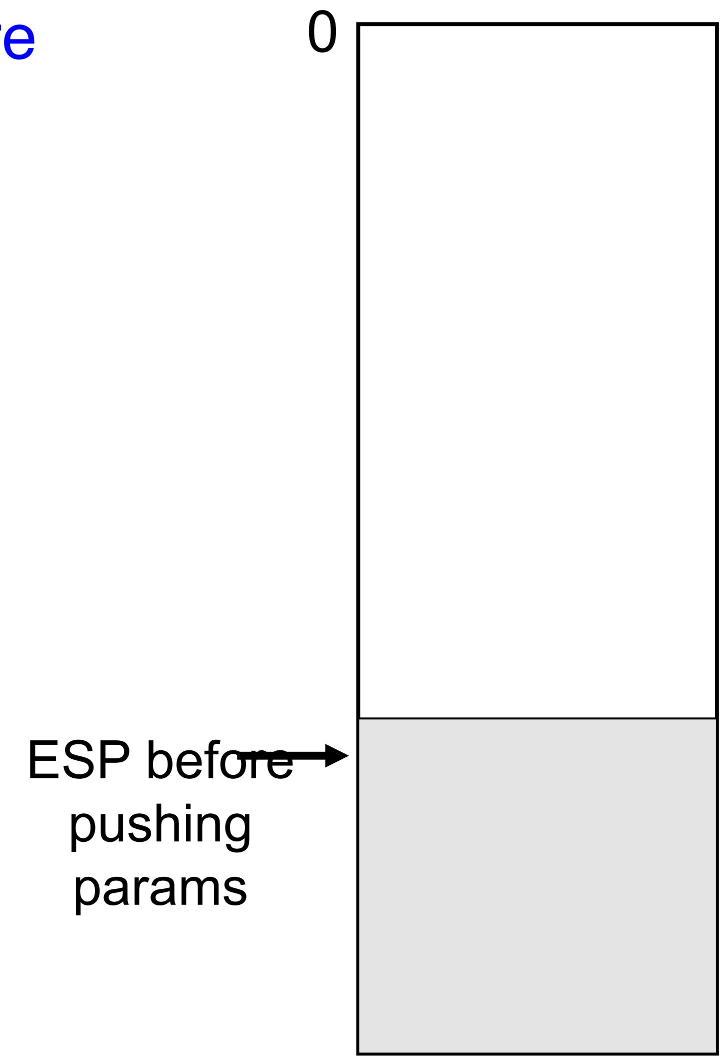
```
f:
    movl $3, %eax
    movl $4, %ebx
    movl $5, %ecx
    call add3
    …
```

```
add3:
    …
    movl $6, %eax
    call g
    # Use EAX, EBX, ECX
    # But EAX is corrupted!
    …
    ret
```

- Also: How to pass parameters that are longer than 4 bytes?

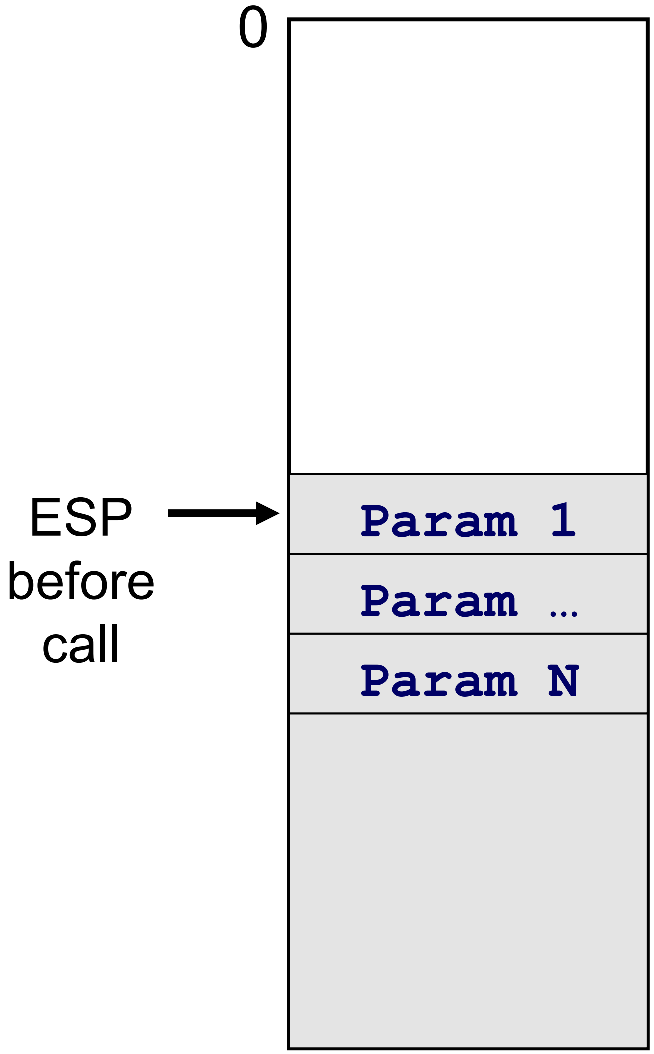
IA-32 Solution: Use the Stack

- Caller pushes parameters before executing the call instruction



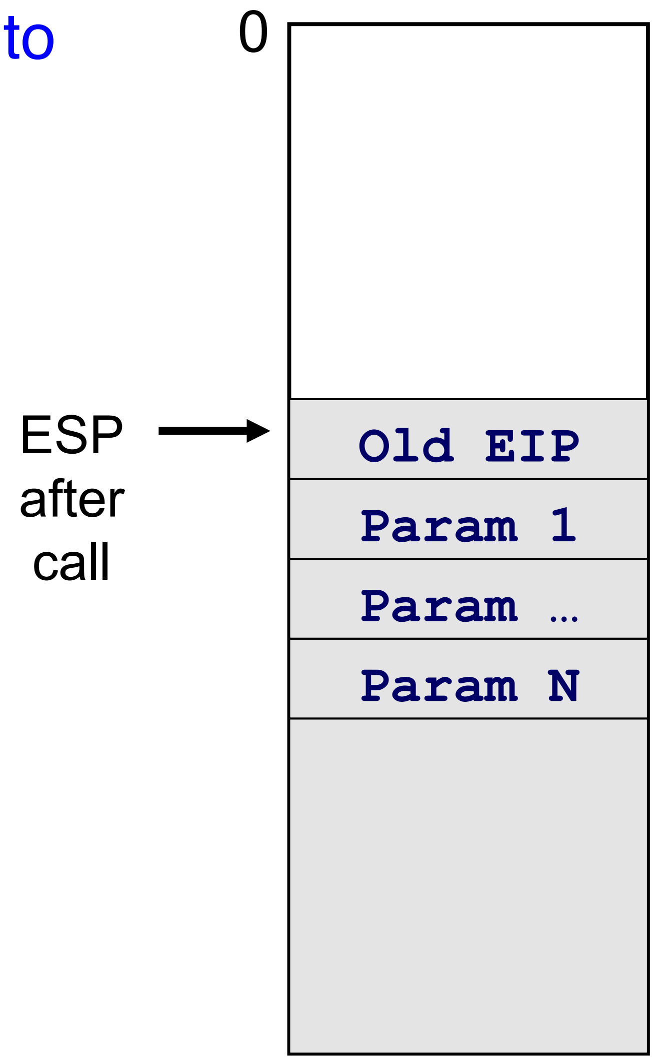
IA-32 Parameter Passing

- Caller pushes parameters in the reverse order
  - Push N^{th} param first
  - Push 1^{st} param last
  - So first param is at top of the stack at the time of the Call



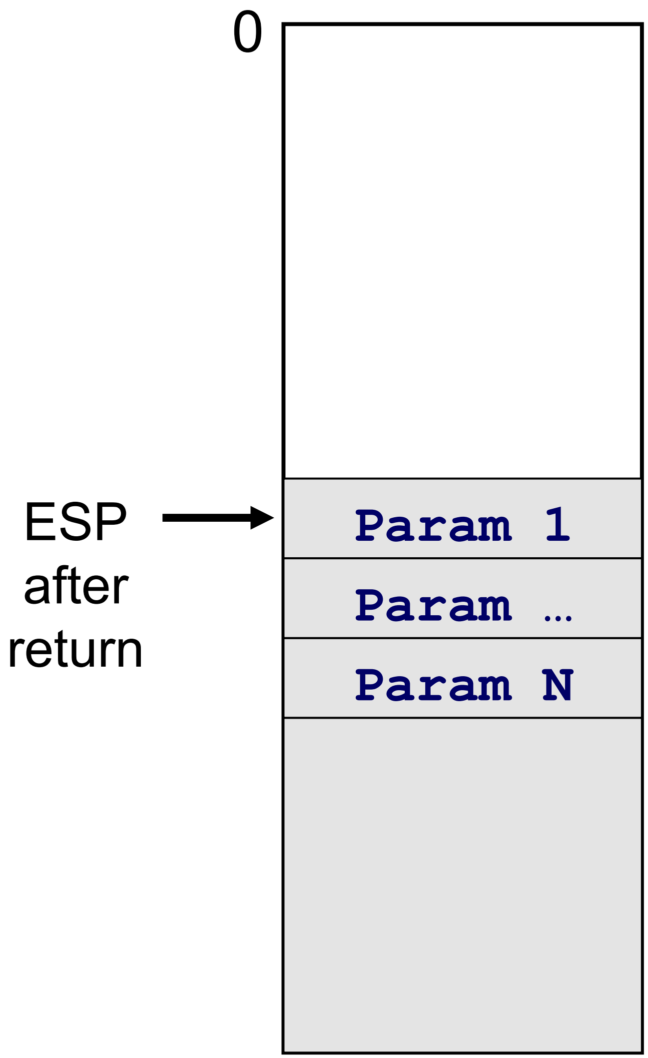
IA-32 Parameter Passing

- Callee addresses params relative to ESP: Param 1 as 4(%esp)



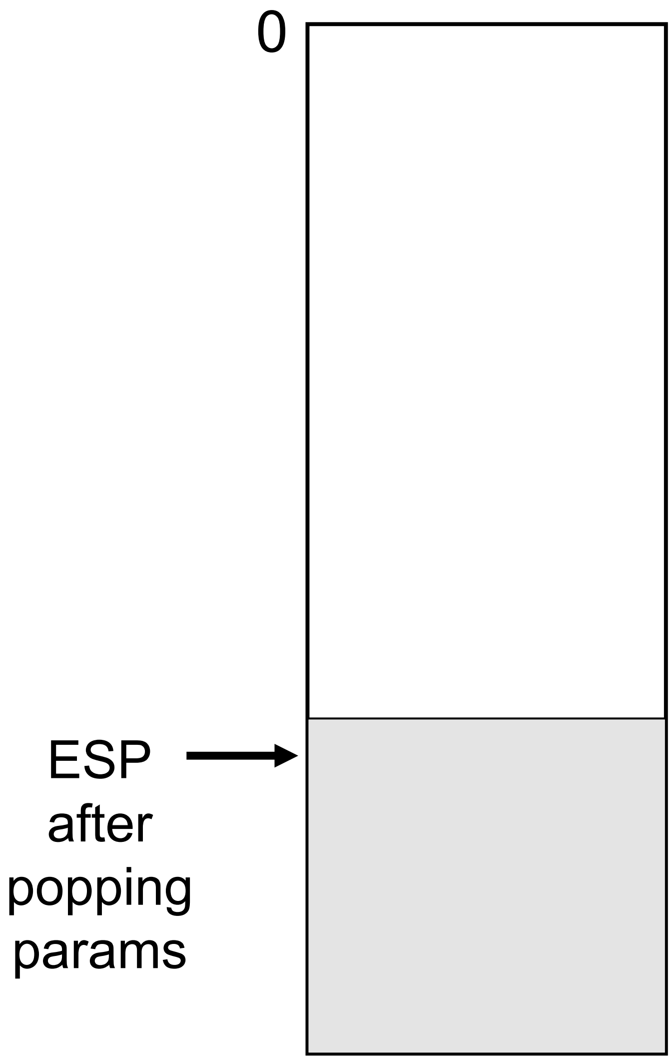
IA-32 Parameter Passing

- After returning to the caller…



IA-32 Parameter Passing

- … the caller pops the parameters from the stack



IA-32 Parameter Passing

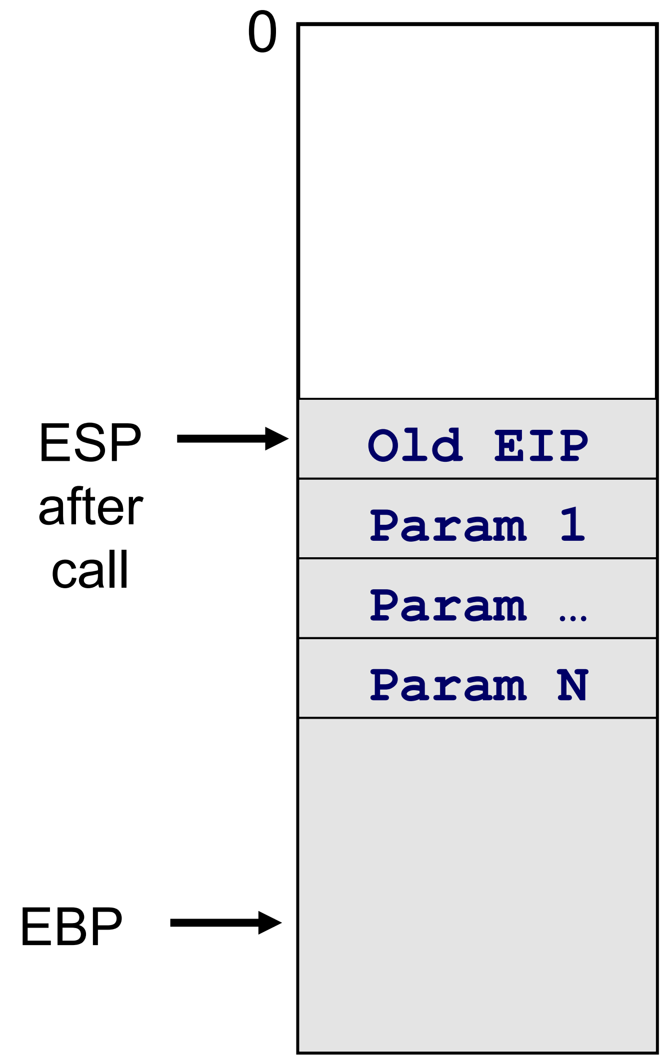
For example:

```
f:
    …
    # Push parameters
    pushl $5
    pushl $4
    pushl $3
    call add3
    # Pop parameters
    addl $12, %esp
```

```
add3:
    …
    movl 4(%esp), wherever
    movl 8(%esp), wherever
    movl 12(%esp), wherever
    …
    ret
```

Base Pointer Register: EBP

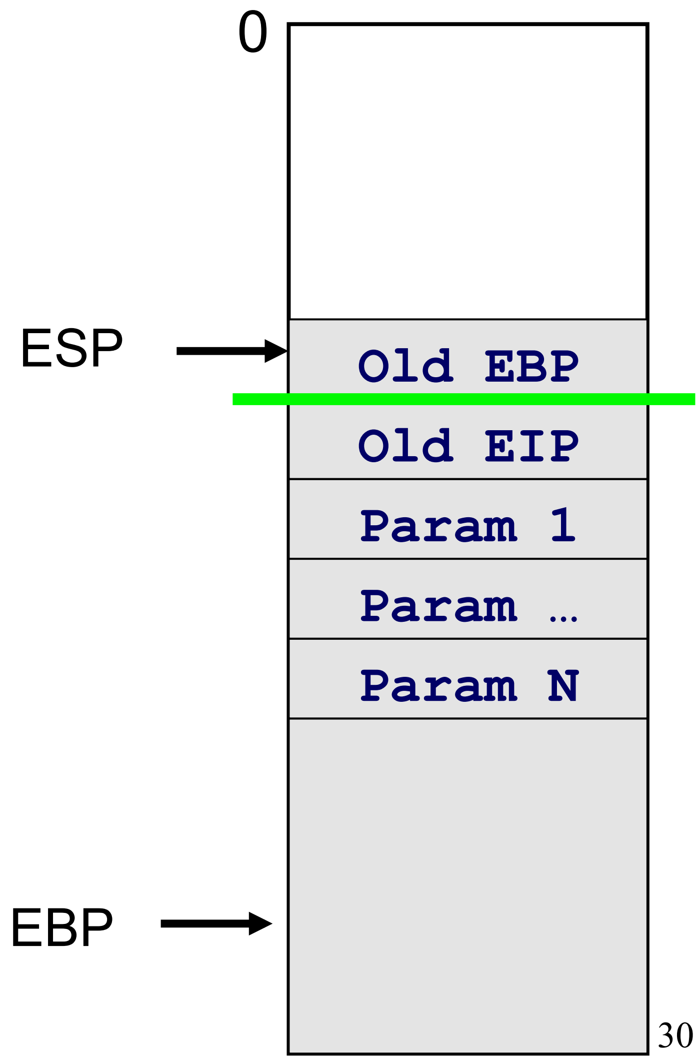
- Problem:
  - As callee executes, ESP may change
    - E.g., preparing to call another function
  - Error-prone for callee to reference params as offsets relative to ESP
- Solution:
  - Use EBP as fixed reference point to access params



Using EBP

- Need to save old value of EBP
  - Before overwriting EBP register
- Callee executes "prolog"

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

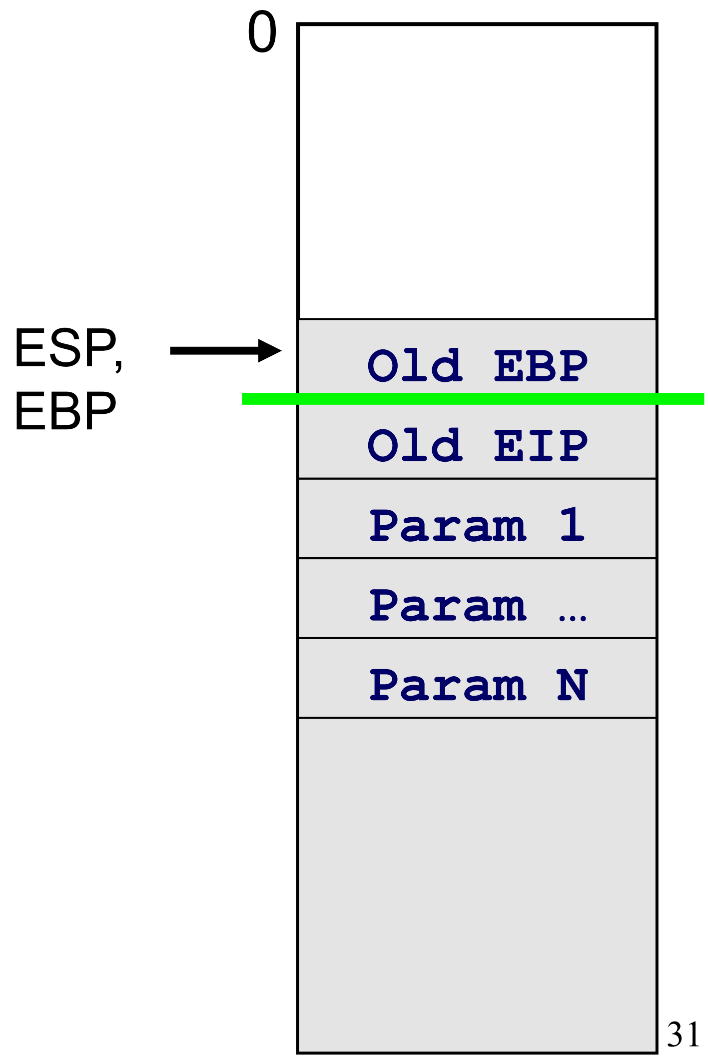


Base Pointer Register: EBP

- Callee executes "prolog"

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

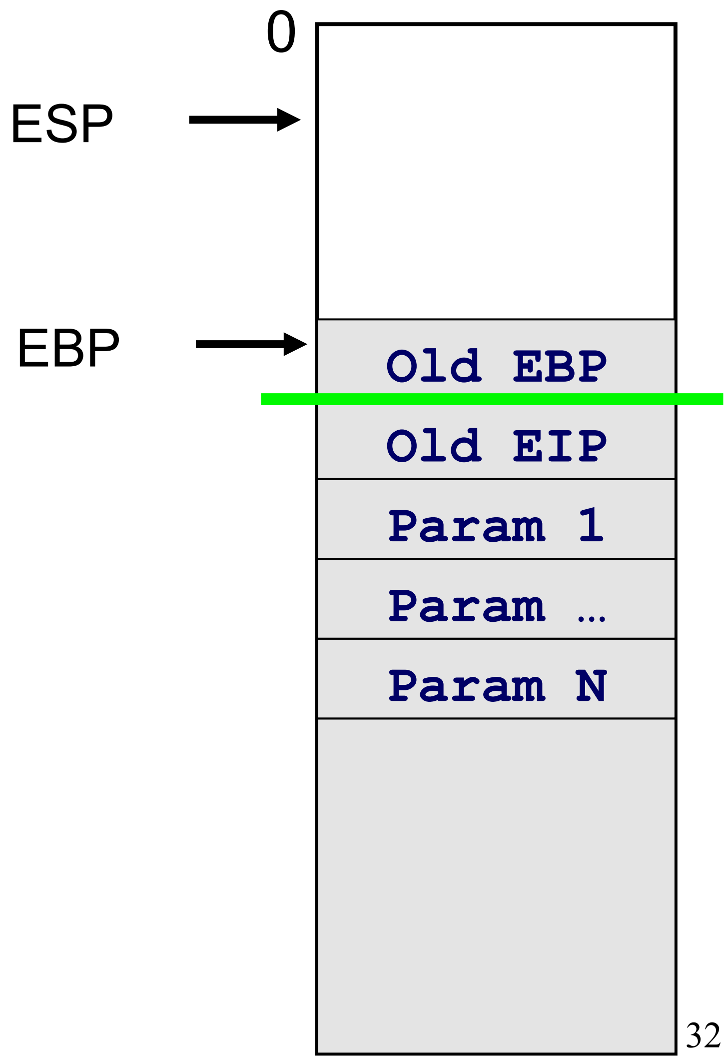
- Regardless of ESP, callee can reference param 1 as 8(%ebp), param 2 as 12(%ebp), etc.



Base Pointer Register: EBP

- Before returning, callee must restore ESP and EBP to their old values
- Callee executes "epilog"

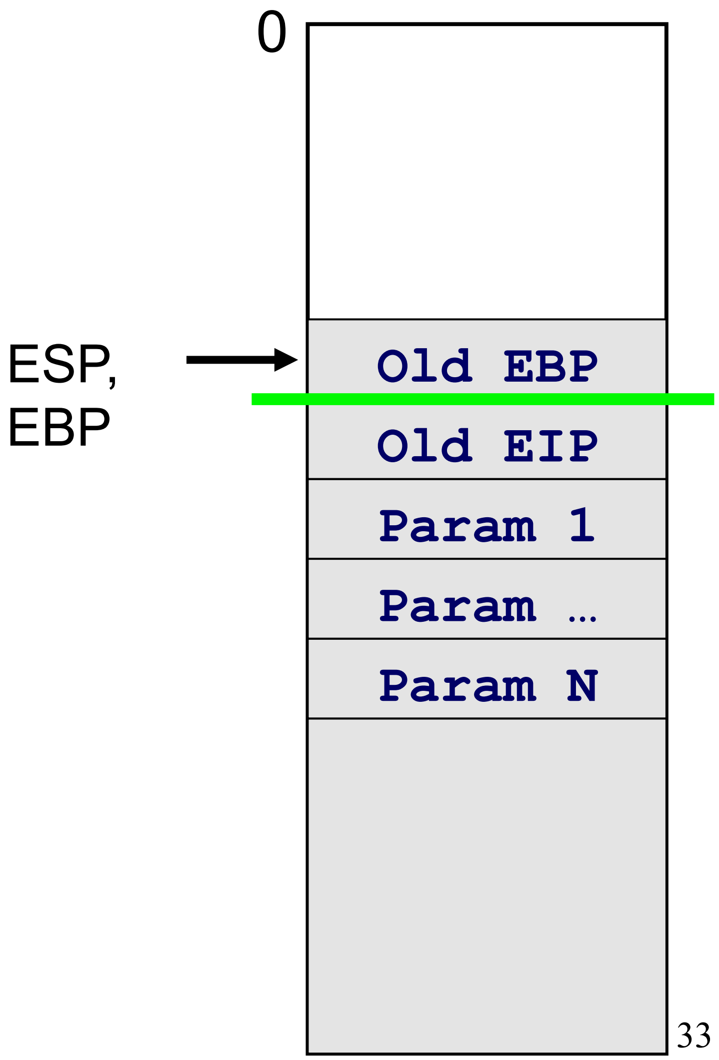
```
movl %ebp, %esp
popl %ebp
ret
```



Base Pointer Register: EBP

- Callee executes "epilog"

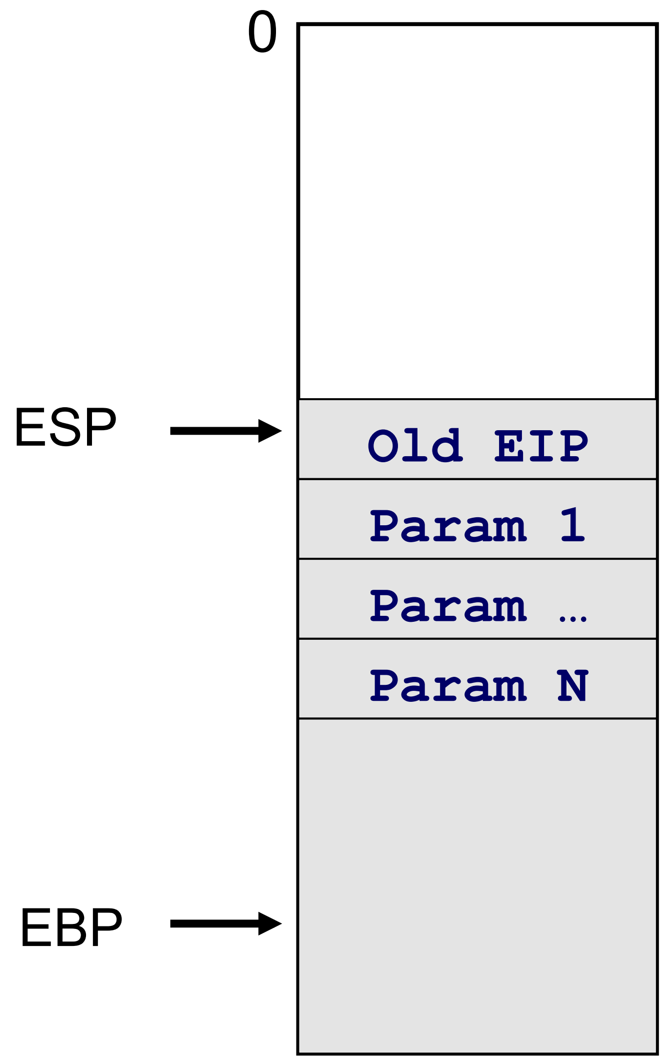
```
movl %ebp, %esp
popl %ebp
ret
```



Base Pointer Register: EBP

- Callee executes “epilog”

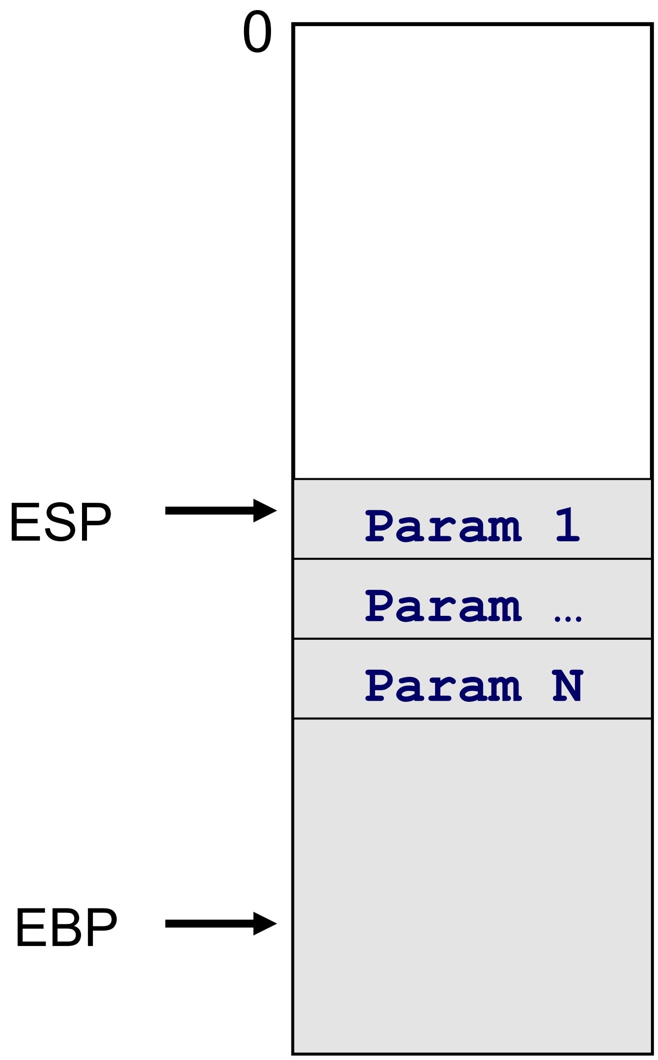
```
movl %ebp, %esp
popl %ebp
ret
```



Base Pointer Register: EBP

- Callee executes “epilog”

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



Problem 3: Storing Local Variables

- Where does callee function store its *local variables?*

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

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

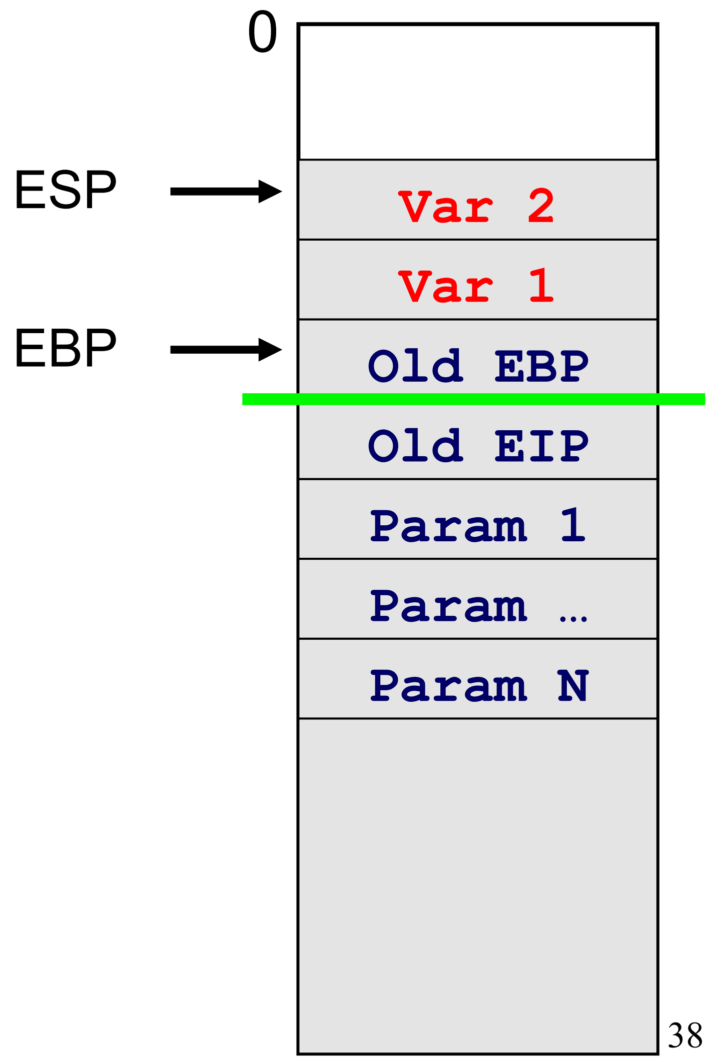
IA-32 Solution: Use the Stack

- 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);
}
```

IA-32 Local Variables

- Local variables of the callee are allocated on the stack
- Allocation done by moving the stack pointer
- Example: allocate memory for two integers
  - subl $4, %esp
  - subl $4, %esp
  - (or equivalently, subl $8, %esp)
- Reference local variables as negative offsets relative to EBP
  - -4(%ebp)
  - -8(%ebp)



IA-32 Local Variables

For example:

```
add3:
    …
    # Allocate space for d
    subl $4, %esp
    …
    # Access d
    movl whatever, -4(%ebp)
    …
    ret
```

Problem 4: Handling Registers

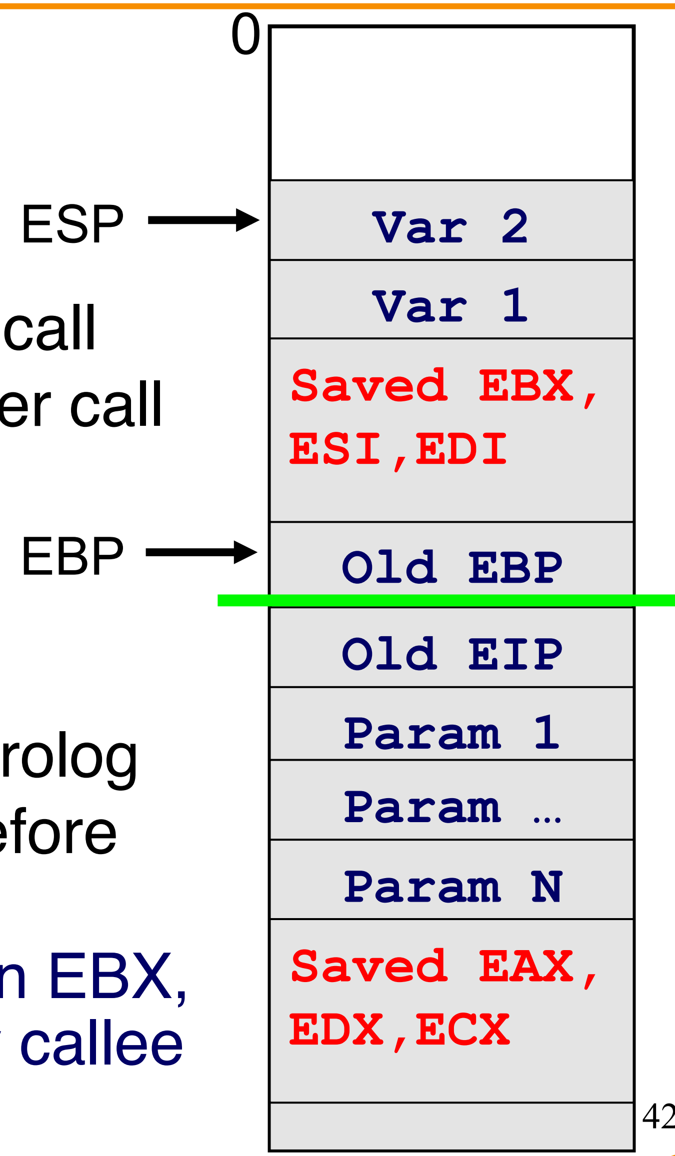
- Problem: How do caller and callee functions use *same registers* without interference?
- Registers are a finite resource!
  - In principle: Each function should have its own set of registers
  - In reality: All functions must use the same small set of registers
- Callee may use a register that the caller also is using
  - When callee returns control to caller, old register contents may be lost
  - Caller function cannot continue where it left off

IA-32 Solution: Define a Convention

- IA-32 solution: save the registers on the stack
  - Someone must save old register contents
  - Someone must later restore the register contents
- Define a convention for who saves and restores which registers

IA-32 Register Handling

- Caller-save registers
  - **EAX, EDX, ECX**
  - If necessary…
    - Caller saves on stack before call
    - Caller restores from stack after call
- Callee-save registers
  - **EBX, ESI, EDI**
  - If necessary…
    - Callee saves on stack after prolog
    - Callee restores from stack before epilog
  - Caller can assume that values in EBX, ESI, EDI will not be changed by callee



Problem 5: Return Values

- Problem: How does callee function send return value back to caller function?
- In principle:
  - Store return value in stack frame of caller
- Or, for efficiency:
  - Known small size => store return value in register
  - Other => store return value in 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);
}
```

IA-32 Return Values

IA-32 Convention:

- Integral type or pointer:
  - Store return value in EAX
  - char, short, int, long, pointer
- Floating-point type:
  - Store return value in floating-point register
  - (Beyond scope of course)
- Structure:
  - Store return value on stack
  - (Beyond scope of course)

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

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

Stack Frames

Summary of IA-32 function handling:

- Stack has one **stack frame** per active function invocation
- ESP points to top (low memory) of current stack frame
- EBP points to bottom (high memory) of current stack frame
- Stack frame contains:
  - Return address (Old EIP)
  - Old EBP
  - Saved register values
  - Local variables
  - Parameters to be passed to callee function

A Simple Example

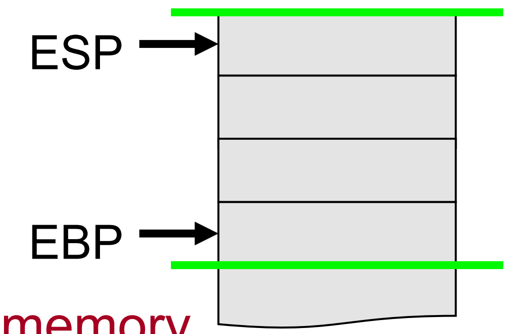
```
int add3(int a, int b, int c)
{
  int d;
  d = a + b + c;
  return d;
}
```

```
/* In some calling function */

  …
  x = add3(3, 4, 5);
  …
```

Trace of a Simple Example 1

```
x = add3(3, 4, 5);
```

Low memory

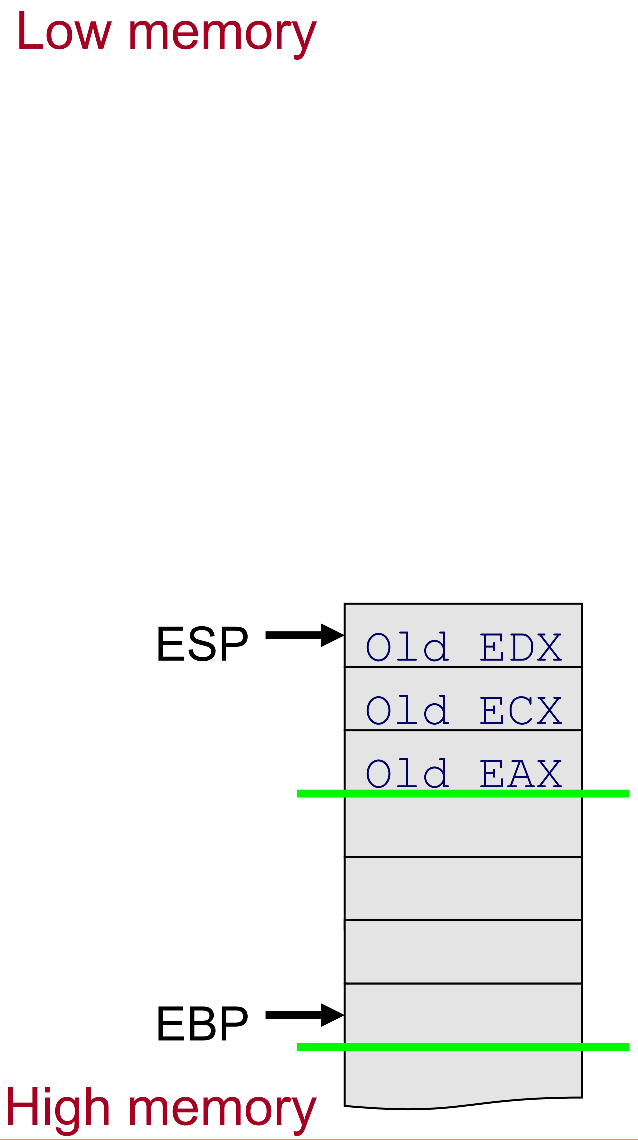


High memory

Trace of a Simple Example 2

```
x = add3(3, 4, 5);
```

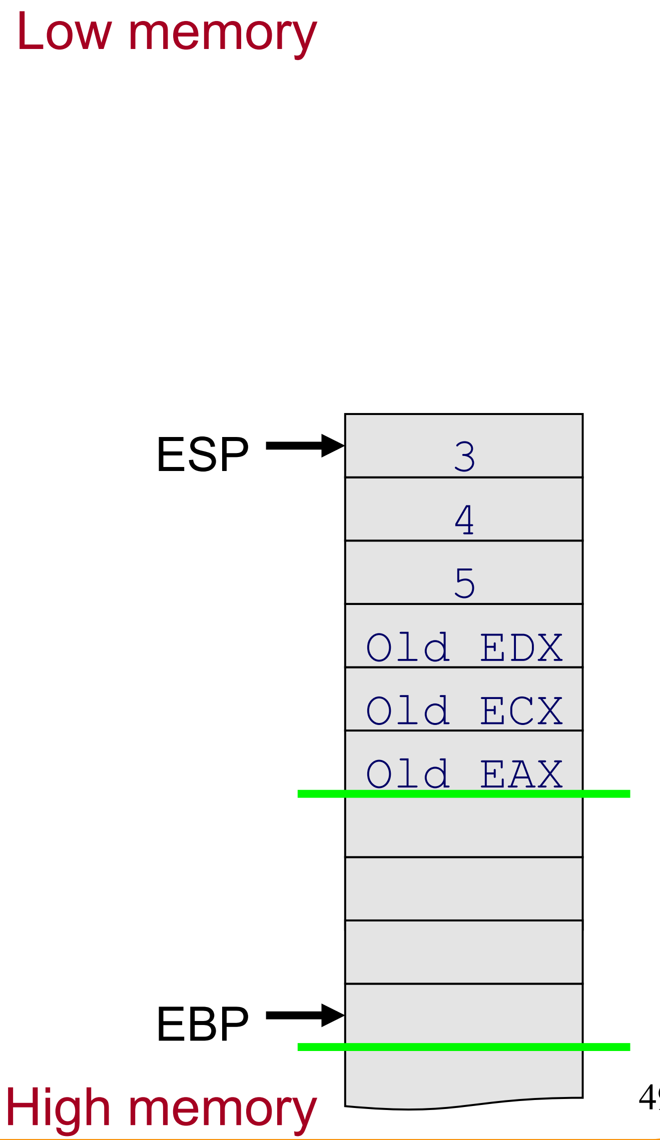
 # Save caller-save registers if necessary
pushl %eax
pushl %ecx
pushl %edx



Trace of a Simple Example 3

```
x = add3(3, 4, 5);
```

```
# Save caller-save registers if necessary
pushl %eax
pushl %ecx
pushl %edx
# Push parameters
pushl $5
pushl $4
pushl $3
```

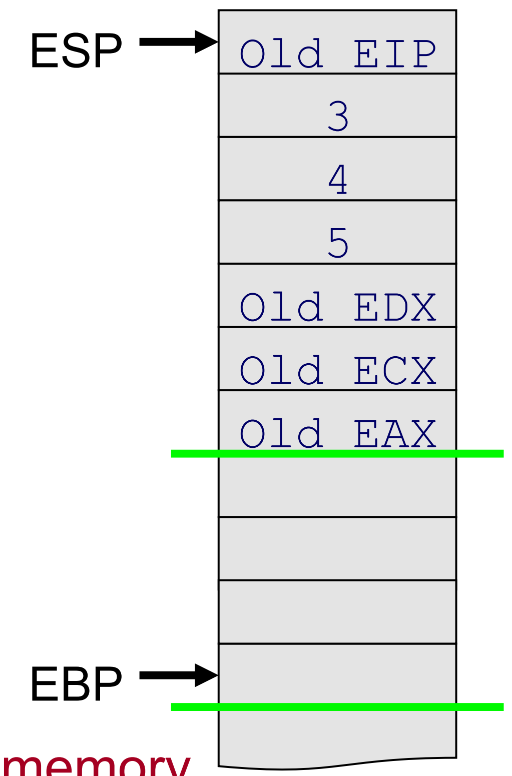


Trace of a Simple Example 4

```
x = add3(3, 4, 5);
```

Low memory

```
# Save caller-save registers if necessary
pushl %eax
pushl %ecx
pushl %edx
# Push parameters
pushl $5
pushl $4
pushl $3
# Call add3
call add3
```



High memory

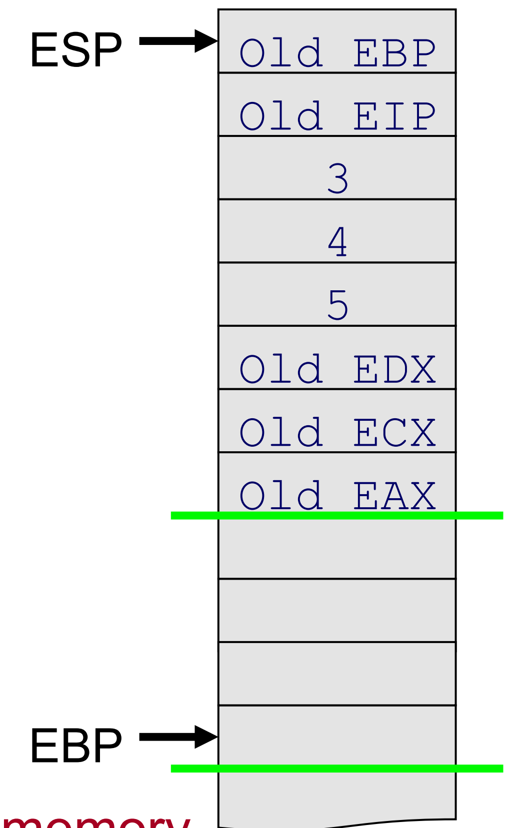
Trace of a Simple Example 5

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

Low memory

 # Save old EBP
pushl %ebp

Prolog



High memory

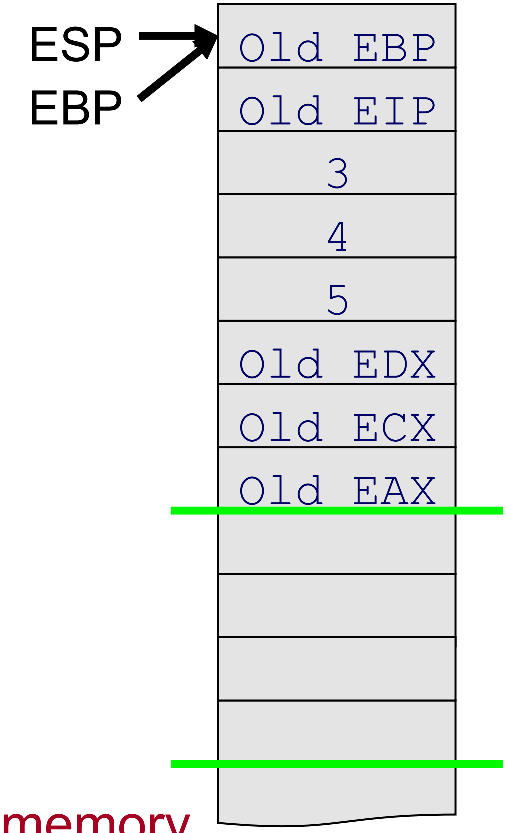
Trace of a Simple Example 6

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

```
# Save old EBP
pushl %ebp
# Change EBP
movl %esp, %ebp
```

Prolog

Low memory



High memory

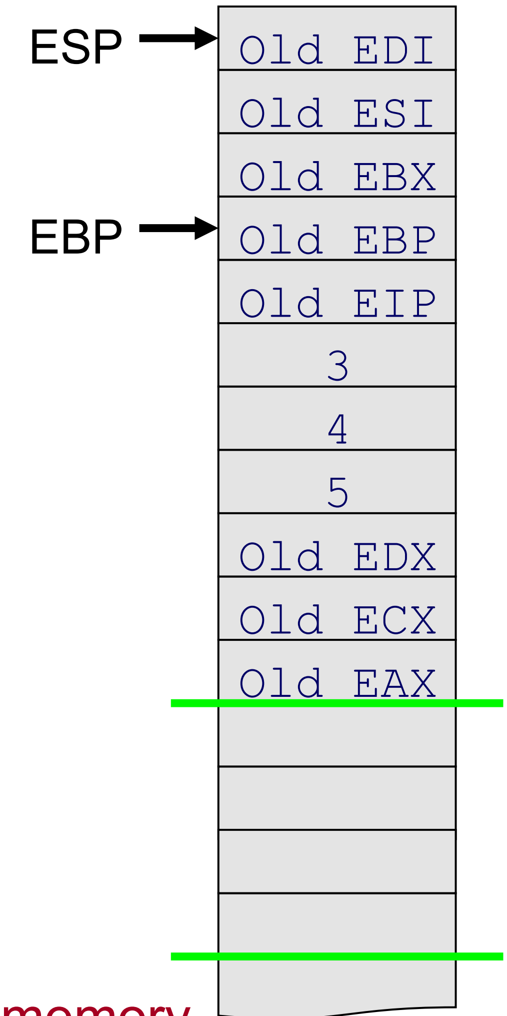
Trace of a Simple Example 7

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

```
# Save old EBP
pushl %ebp
# Change EBP
movl %esp, %ebp
# Save caller-save registers if necessary
pushl %ebx
pushl %esi
pushl %edi
```

Unnecessary here; add3 will not change the values in these registers

Low memory

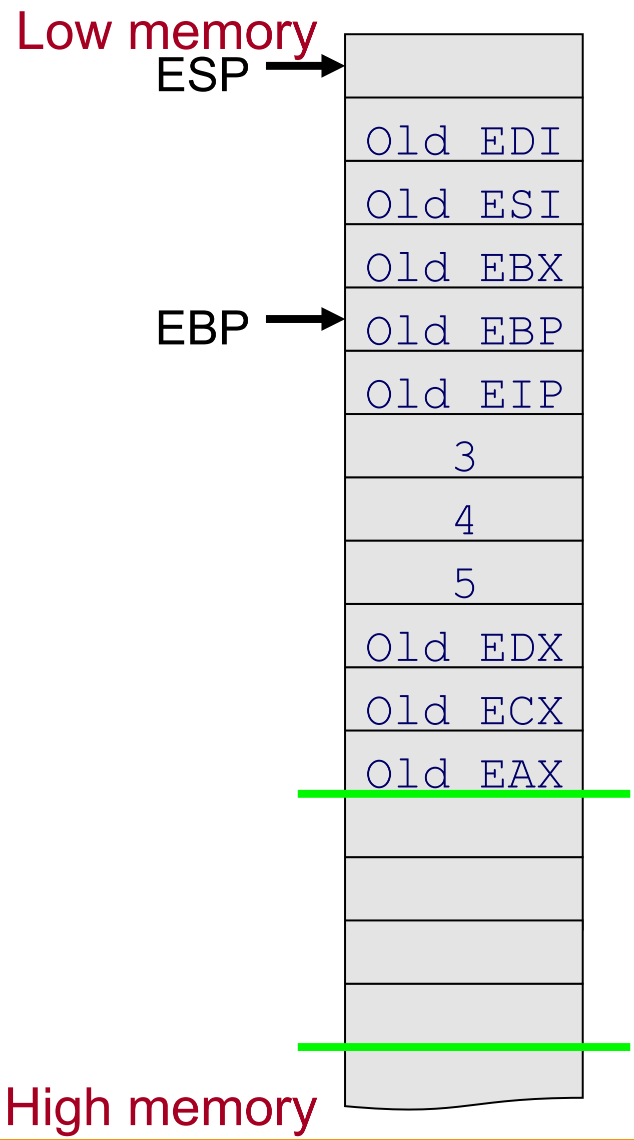


High memory

Trace of a Simple Example 8

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

```
# Save old EBP
pushl %ebp
# Change EBP
movl %esp, %ebp
# Save caller-save registers if necessary
pushl %ebx
pushl %esi
pushl %edi
# Allocate space for local variable
subl $4, %esp
```



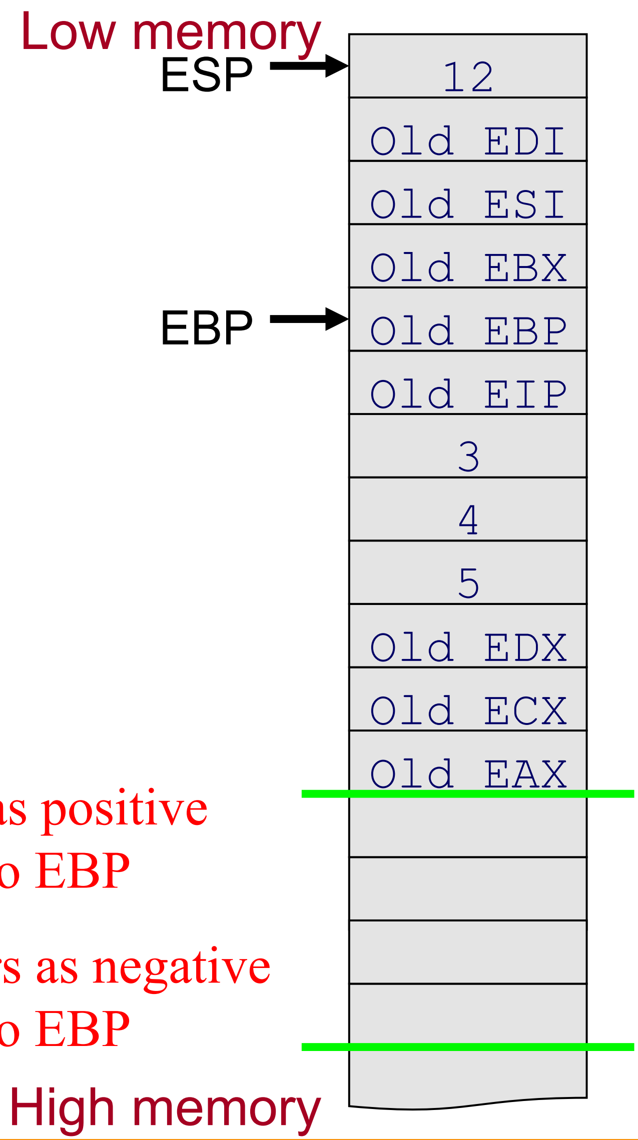
Trace of a Simple Example 9

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

```
# Save old EBP
pushl %ebp
# Change EBP
movl %esp, %ebp
# Save caller-save registers if necessary
pushl %ebx
pushl %esi
pushl %edi
# Allocate space for local variable
subl $4, %esp
# Perform the addition
movl 8(%ebp), %eax
addl 12(%ebp), %eax
addl 16(%ebp), %eax
movl %eax, -16(%ebp)
```

Access params as positive offsets relative to EBP

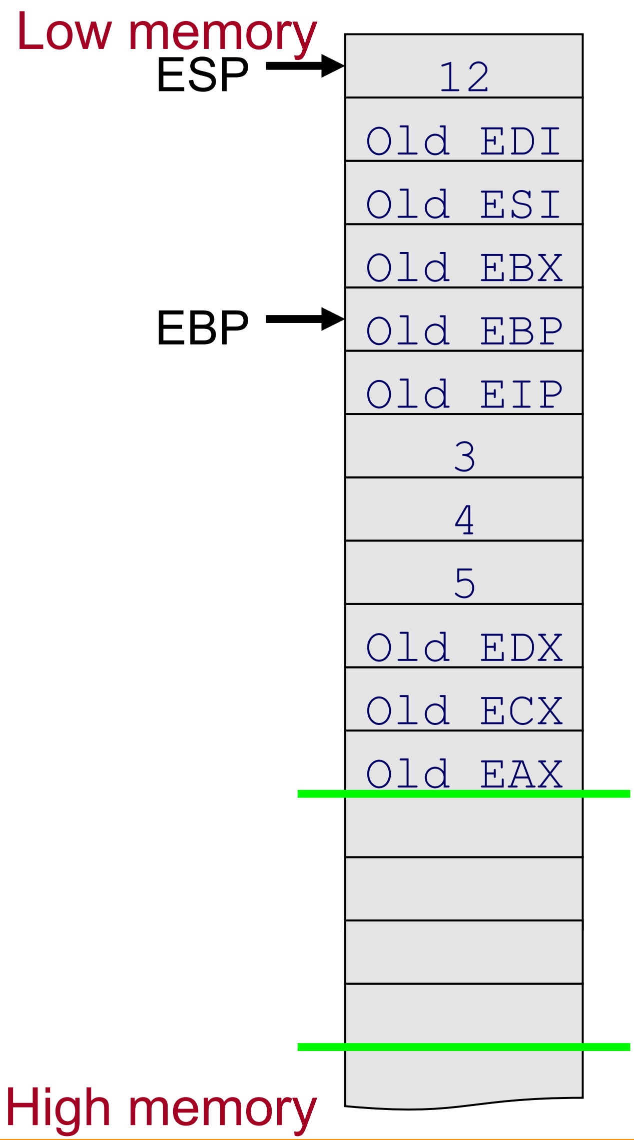
Access local vars as negative offsets relative to EBP



Trace of a Simple Example 10

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

```
# Copy the return value to EAX
movl -16(%ebp), %eax
# Restore callee-save registers if necessary
movl -12(%ebp), %edi
movl -8(%ebp), %esi
movl -4(%ebp), %ebx
```

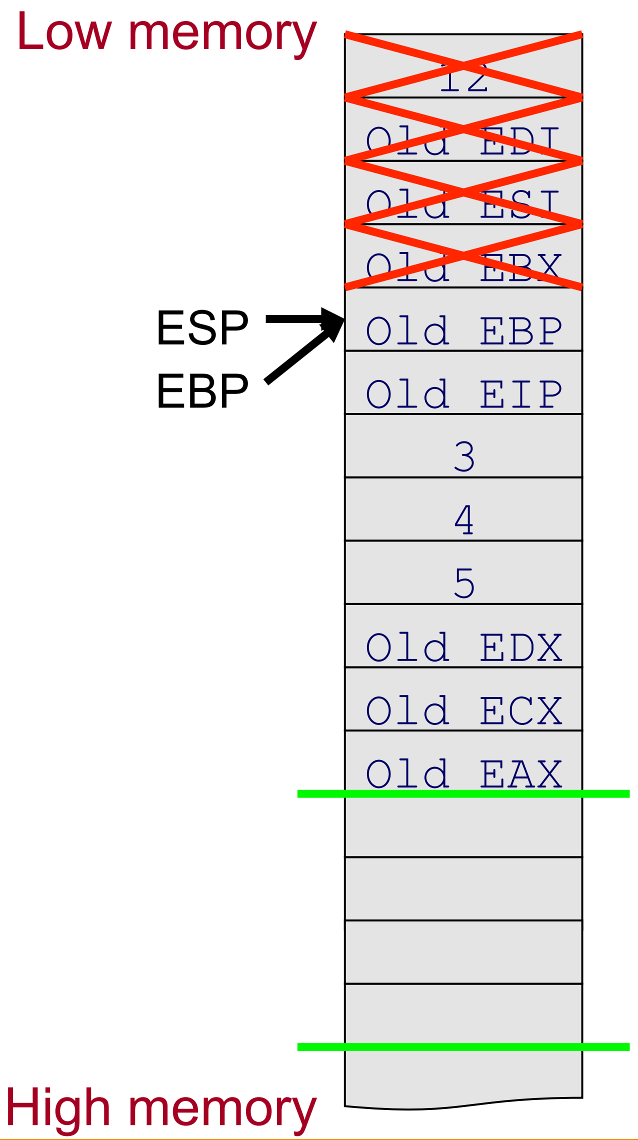


Trace of a Simple Example 11

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

```
# Copy the return value to EAX
movl -16(%ebp), %eax
# Restore callee-save registers if necessary
movl -12(%ebp), %edi
movl -8(%ebp), %esi
movl -4(%ebp), %ebx
# Restore ESP
movl %ebp, %esp
```

Epilog

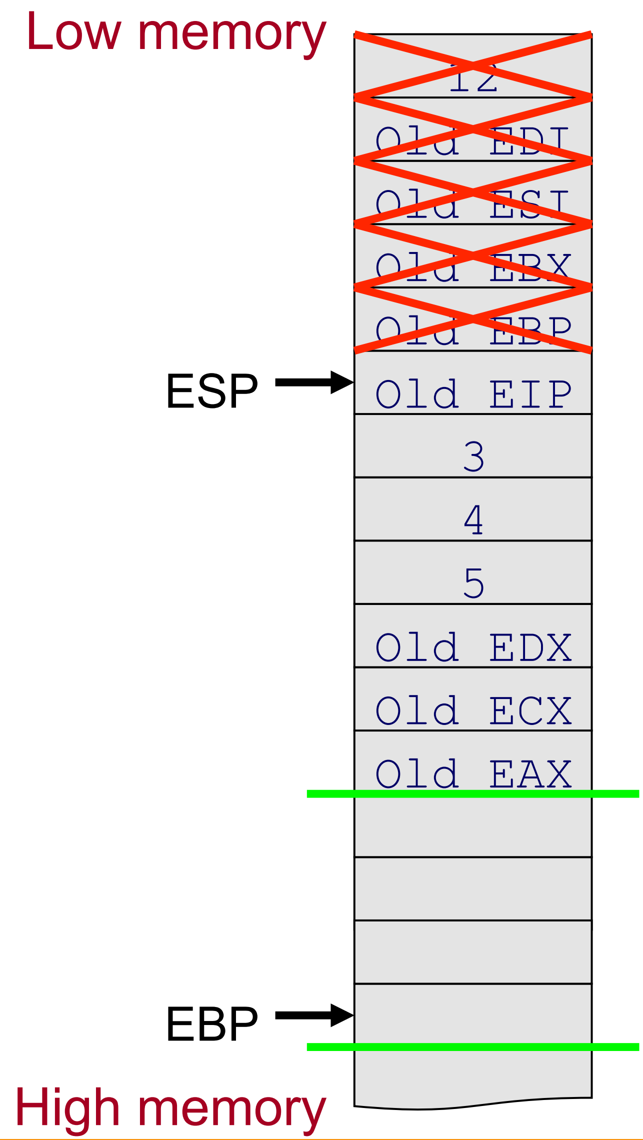


Trace of a Simple Example 12

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

```
# Copy the return value to EAX
movl -16(%ebp), %eax
# Restore callee-save registers if necessary
movl -12(%ebp), %edi
movl -8(%ebp), %esi
movl -4(%ebp), %ebx
# Restore ESP
movl %ebp, %esp
# Restore EBP
popl %ebp
```

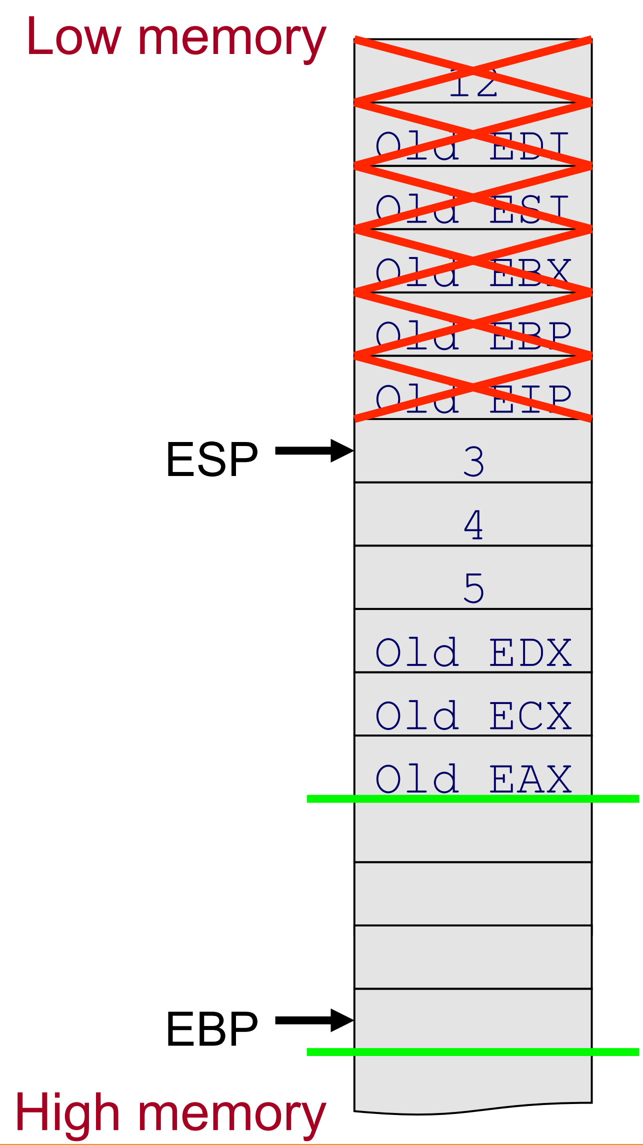
Epilog



Trace of a Simple Example 13

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

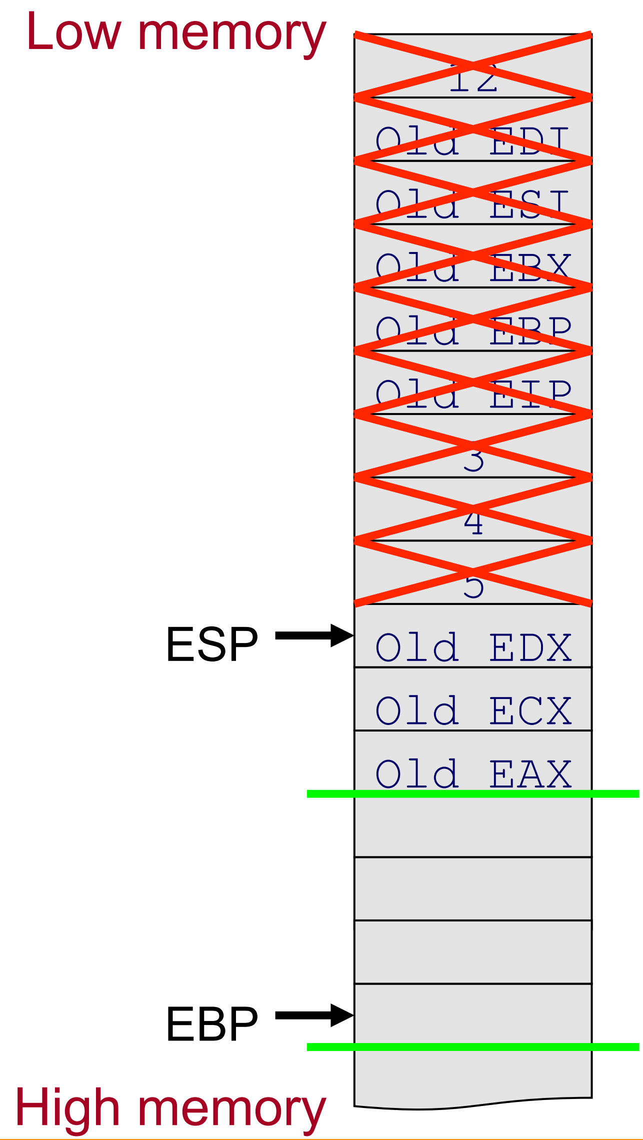
```
# Copy the return value to EAX
movl -16(%ebp), %eax
# Restore callee-save registers if necessary
movl -12(%ebp), %edi
movl -8(%ebp), %esi
movl -4(%ebp), %ebx
# Restore ESP
movl %ebp, %esp
# Restore EBP
popl %ebp
# Return to calling function
ret
```



Trace of a Simple Example 14

```
x = add3(3, 4, 5);
```

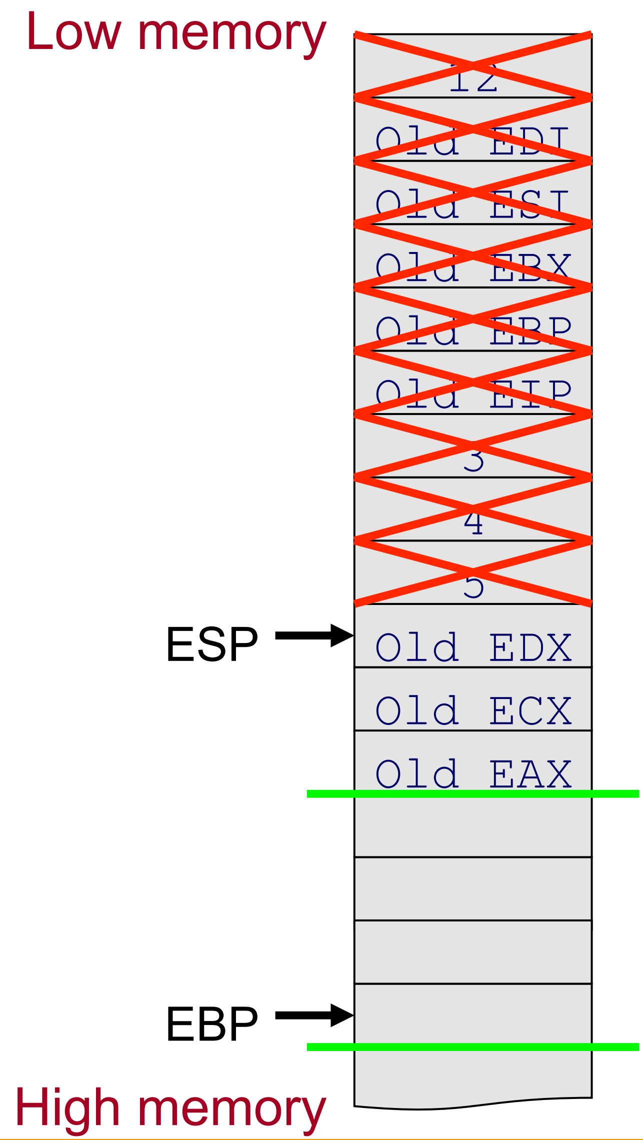
```
# Save caller-save registers if necessary
pushl %eax
pushl %ecx
pushl %edx
# Push parameters
pushl $5
pushl $4
pushl $3
# Call add3
call add3
# Pop parameters
addl $12, %esp
```



Trace of a Simple Example 15

```
x = add3(3, 4, 5);
```

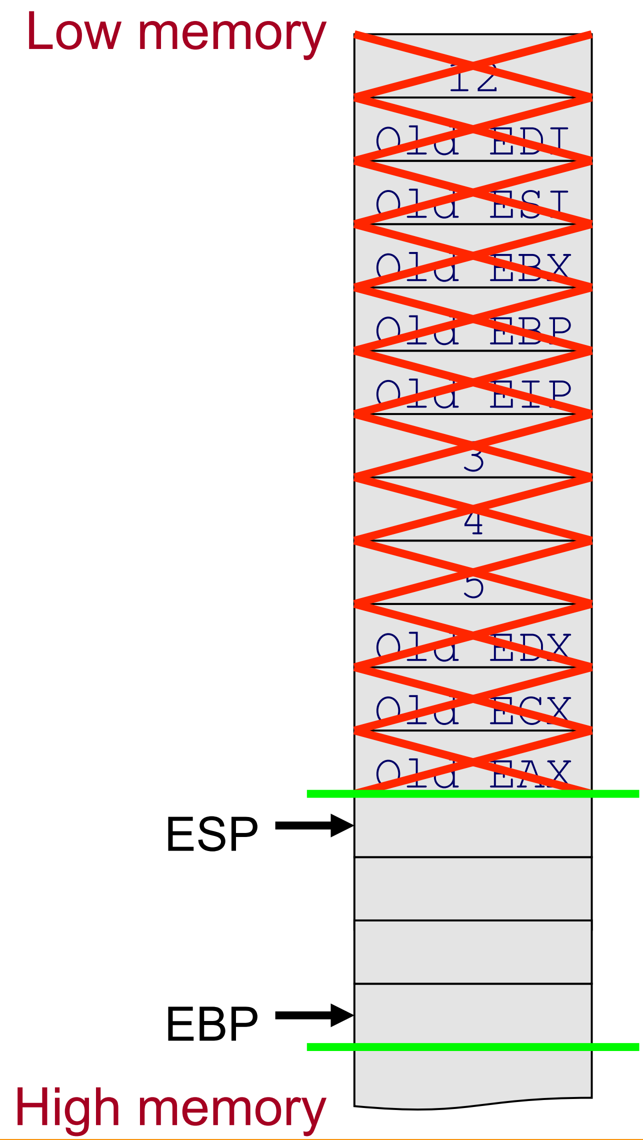
```
# Save caller-save registers if necessary
pushl %eax
pushl %ecx
pushl %edx
# Push parameters
pushl $5
pushl $4
pushl $3
# Call add3
call add3
# Pop parameters
addl %12, %esp
# Save return value
movl %eax, wherever
```



Trace of a Simple Example 16

```
x = add3(3, 4, 5);
```

Save caller-save registers if necessary
pushl %eax
pushl %ecx
pushl %edx
Push parameters
pushl $5
pushl $4
pushl $3
Call add3
call add3
# Pop parameters
addl %12, %esp
# Save return value
movl %eax, *wherever*
 # Restore caller-save registers if necessary
popl %edx
popl %ecx
popl %eax

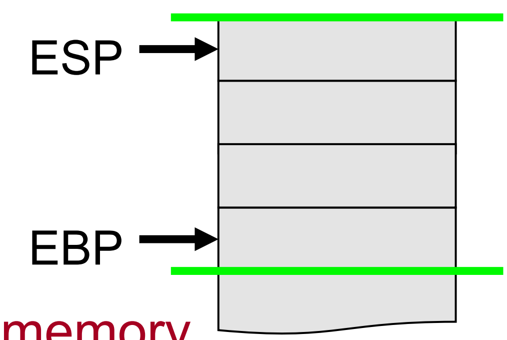


Trace of a Simple Example 17

```
x = add3(3, 4, 5);
```

```
# Save caller-save registers if necessary
pushl %eax
pushl %ecx
pushl %edx
# Push parameters
pushl $5
pushl $4
pushl $3
# Call add3
call add3
# Pop parameters
addl %12, %esp
# Save return value
movl %eax, wherever
# Restore caller-save registers if necessary
popl %edx
popl %ecx
popl %eax
# Proceed!
…
```

Low memory



High memory

Summary

- Calling and returning
  - Call instruction: push EIP onto stack and jump
  - Ret instruction: pop stack to EIP
- Passing parameters
  - Caller pushes onto stack
  - Callee accesses as positive offsets from EBP
  - Caller pops from stack

Summary (cont.)

- Storing local variables
  - Callee pushes on stack
  - Callee accesses as negative offsets from EBP
  - Callee pops from stack
- Handling registers
  - Caller saves and restores EAX, ECX, EDX if necessary
  - Callee saves and restores EBX, ESI, EDI if necessary
- Returning values
  - Callee returns data of integral types and pointers in EAX