



Assembly Language: Function Calls

1



Goals of this Lecture

- **Help you learn:**
 - **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

2

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

3

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

4

Recall from Last Lecture (cont.)



- **Memory Operand: Indexed Addressing**
 - `movl 8(%eax, %ecx), ...`
 - CPU computes address as $8 + [\text{contents of EAX}] + [\text{contents of ECX}]$; fetches source operand from memory at that address
- **Memory Operand: Scaled Indexed Addressing**
 - `movl 8(%eax, %ecx, 4), ...`
 - CPU computes address as $8 + [\text{contents of EAX}] + ([\text{contents of ECX}] * 4)$; fetches source operand from memory at that address
- **Same for destination operand, except...**
 - Destination operand cannot be immediate

5

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?

6

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

7

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
```

8

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:
...
```

9

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:
...
```

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

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

Special form of jmp instruction; we will not use

10

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

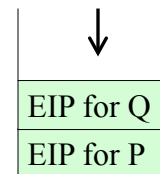
Return address for P to Q call is lost

11

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

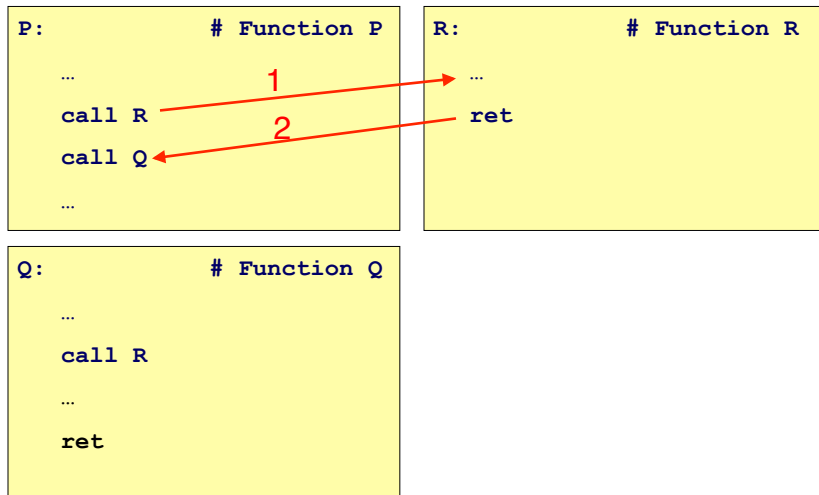


12

IA-32 Call and Ret Instructions



- Ret instruction “knows” the return address

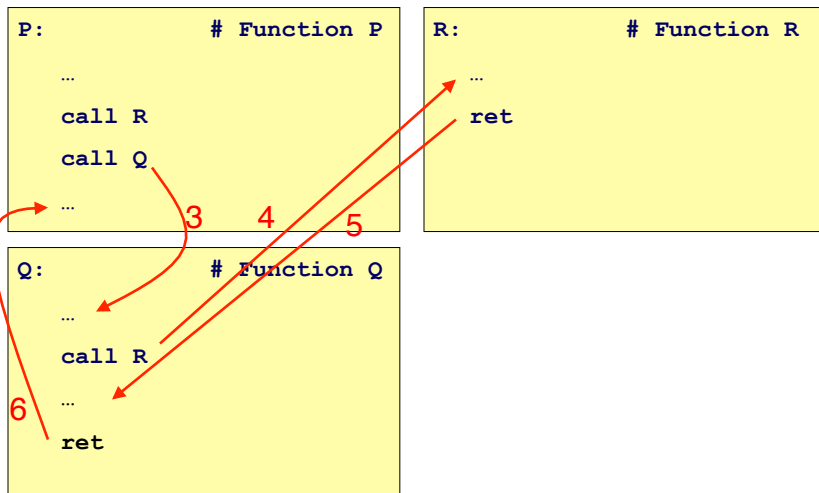


13

IA-32 Call and Ret Instructions



- Ret instruction “knows” the return address



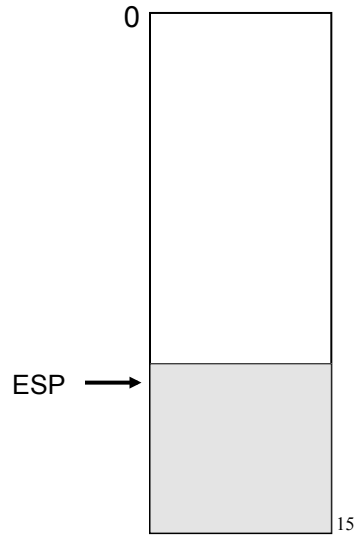
14

Implementation of Call



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

Instruction	Effective Operations
<code>pushl src</code>	<code>subl \$4, %esp</code> <code>movl src, (%esp)</code>
<code>popl dest</code>	<code>movl (%esp), dest</code> <code>addl \$4, %esp</code>



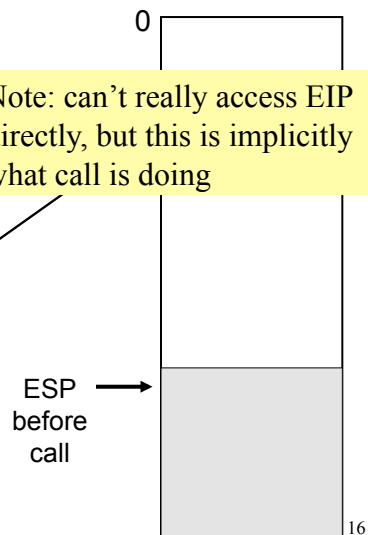
Implementation of Call



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

Instruction	Effective Operations
<code>pushl src</code>	<code>subl \$4, %esp</code> <code>movl src, (%esp)</code>
<code>popl dest</code>	<code>movl (%esp), dest</code> <code>addl \$4, %esp</code>
<code>call addr</code>	<code>pushl %eip</code> <code>jmp addr</code>

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

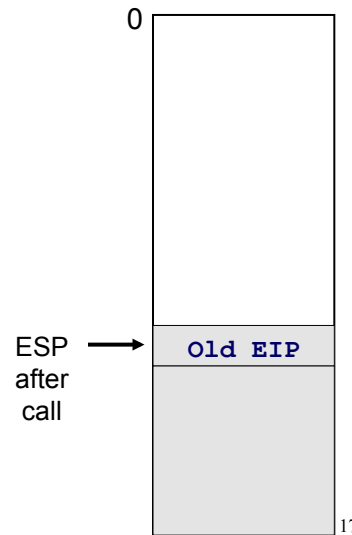


Call instruction pushes return address (old EIP) onto stack

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

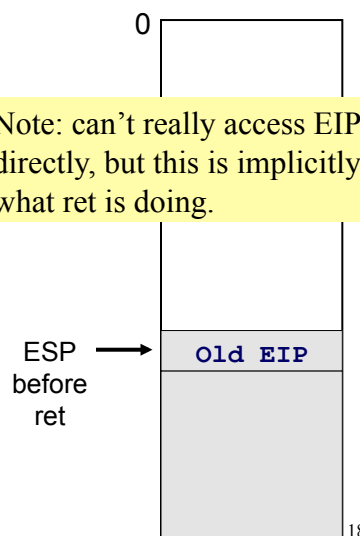


Implementation of Ret



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.

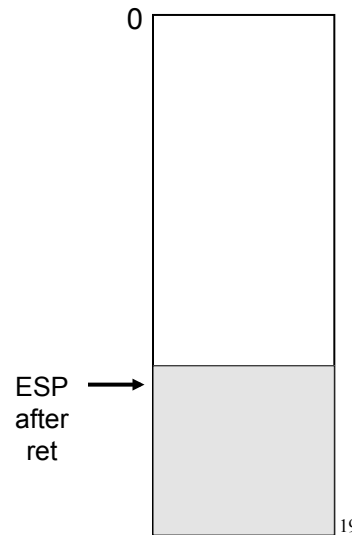


Ret instruction pops stack, thus placing return address (old EIP) into EIP

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
```

21

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
```

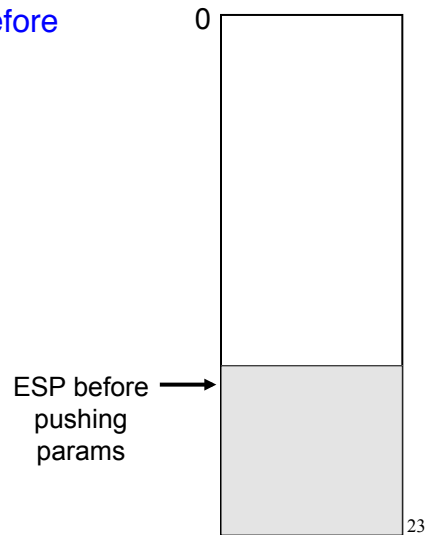
- Also: How to pass parameters that are longer than 4 bytes?

22

IA-32 Solution: Use the Stack



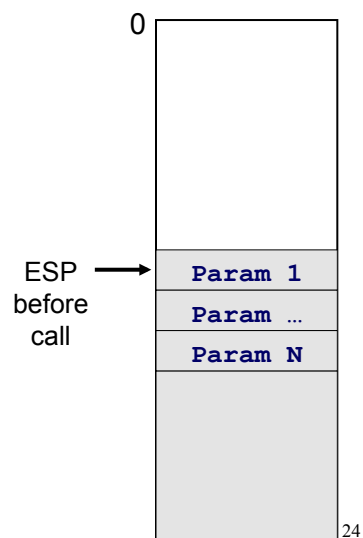
- Caller pushes parameters before executing the call instruction



IA-32 Parameter Passing



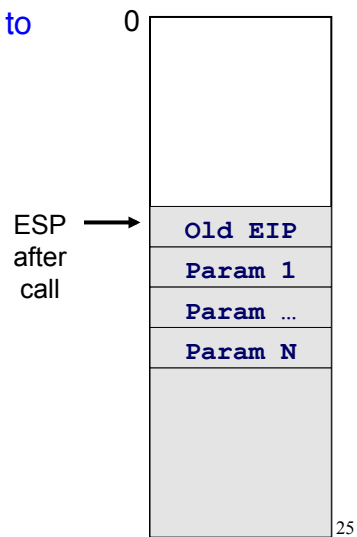
- Caller pushes parameters in the reverse order
 - Push Nth param first
 - Push 1st param last
 - So first param is at top of the stack at the time of the Call



IA-32 Parameter Passing



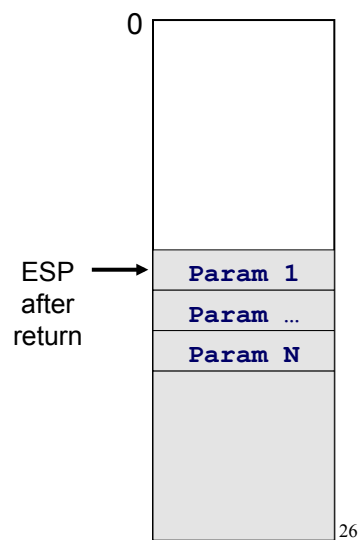
- Callee addresses params relative to ESP: Param 1 as 4(%esp)



IA-32 Parameter Passing



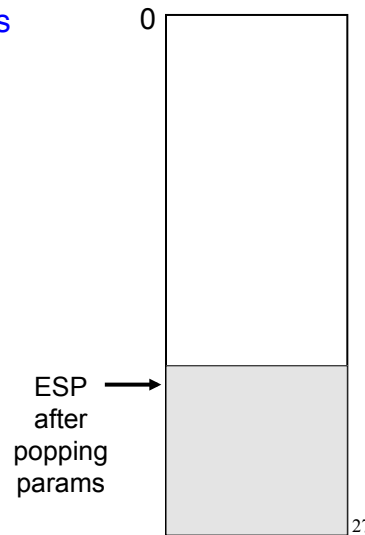
- After returning to the caller...



IA-32 Parameter Passing



- ... the caller pops the parameters from the stack



27

IA-32 Parameter Passing



For example:

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

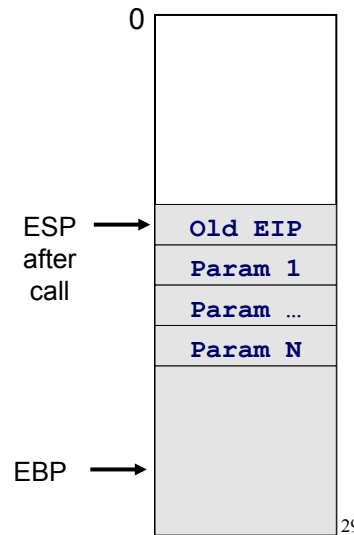
```
add3:
...
movl 4(%esp), wherever
movl 8(%esp), wherever
movl 12(%esp), wherever
...
ret
```

28

Base Pointer Register: EBP



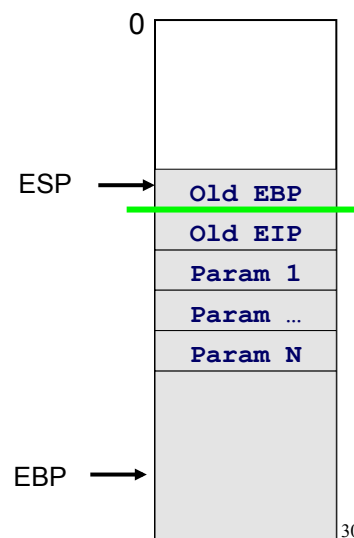
- **Problem:**
 - As callee executes, ESP may change
 - E.g., preparing to call another function
 - Error-prone for callee to reference params as offsets relative to ESP
- **Solution:**
 - Use EBP as fixed reference point to access params



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

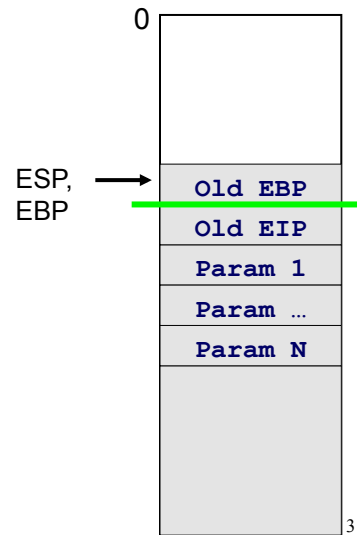


- Callee executes “prolog”

```
pushl %ebp
```

```
→ movl %esp, %ebp
```

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



31

Base Pointer Register: EBP



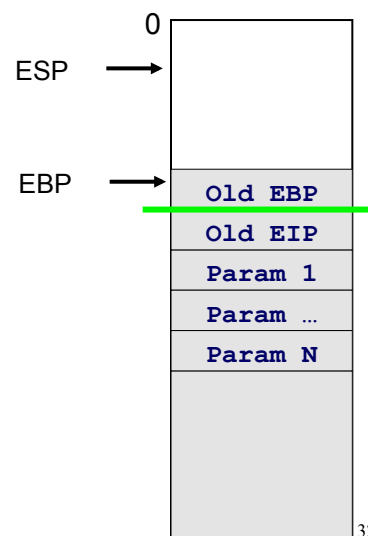
- Before returning, callee must restore ESP and EBP to their old values

- Callee executes “epilog”

```
→ movl %ebp, %esp
```

```
popl %ebp
```

```
ret
```



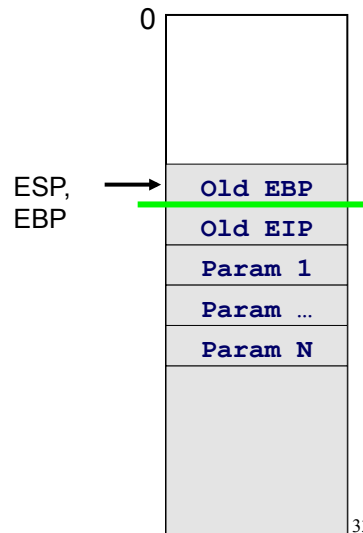
32

Base Pointer Register: EBP



- Callee executes “epilog”

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



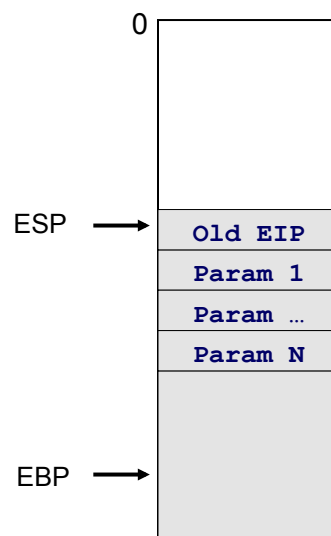
33

Base Pointer Register: EBP



- Callee executes “epilog”

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



34

Base Pointer Register: EBP

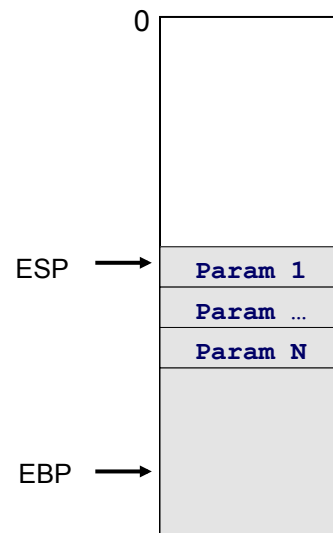


- Callee executes “epilog”

```
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);
}
```

36

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;
}

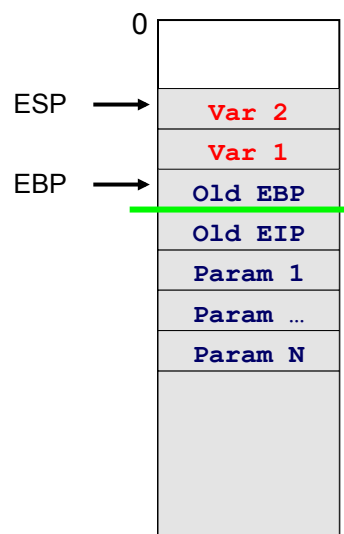
int foo(void)
{
    return add3(3, 4, 5);
}
```

37

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)`



38

IA-32 Local Variables



For example:

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

39

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

40

IA-32 Solution: Define a Convention



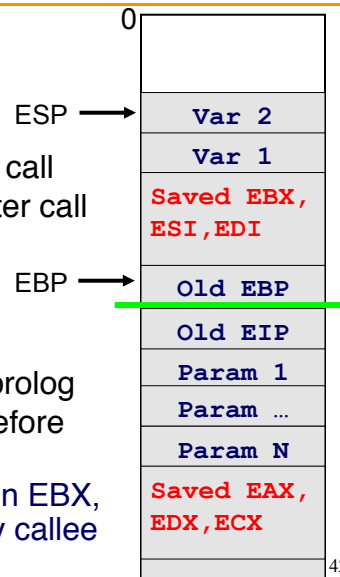
- IA-32 solution: save the registers on the stack
 - Someone must save old register contents
 - Someone must later restore the register contents
- Define a convention for who saves and restores which registers

41

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



42

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);
}
```

43

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);
}
```

44

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

45

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);
...
```

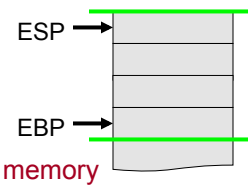
46

Trace of a Simple Example 1



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

Low memory



47

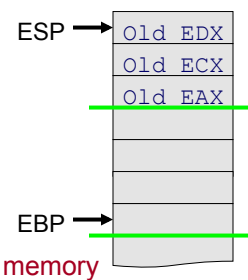
Trace of a Simple Example 2



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

Low memory

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



48

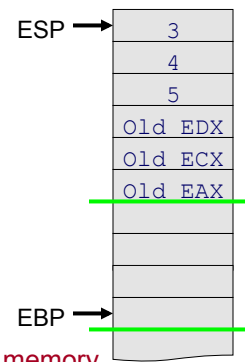
Trace of a Simple Example 3



```
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
```



High memory

49

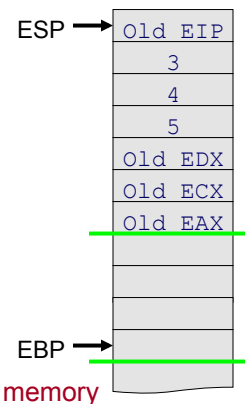
Trace of a Simple Example 4



```
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

50

Trace of a Simple Example 5

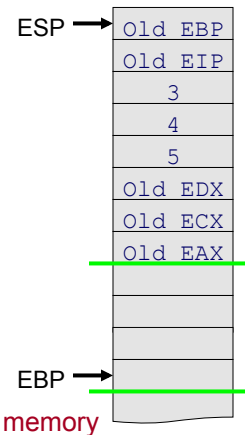


```
int add3(int a, int b, int c) {
    int d;
    d = a + b + c;
    return d;
}
```

```
# Save old EBP
pushl %ebp
```

} Prolog

Low memory



51

Trace of a Simple Example 6

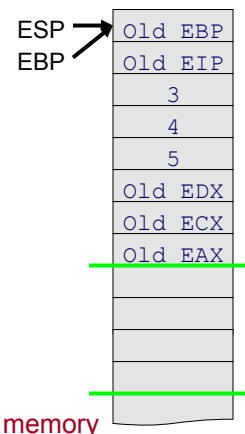


```
int add3(int a, int b, int c) {
    int d;
    d = a + b + c;
    return d;
}
```

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

} Prolog

Low memory



52

Trace of a Simple Example 7

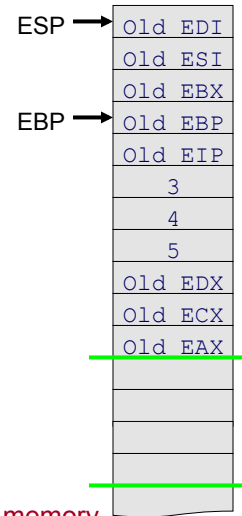


```
int add3(int a, int b, int c) {
    int d;
    d = a + b + c;
    return d;
}
```

```
# 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



53

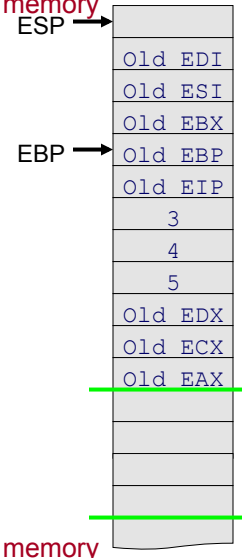
Trace of a Simple Example 8



```
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
```

Low memory



54

Trace of a Simple Example 9

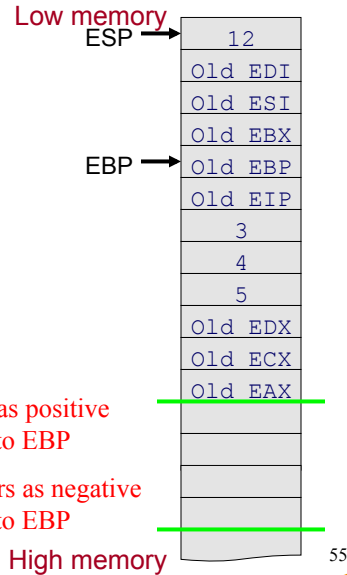


```
int add3(int a, int b, int c) {
    int d;
    d = a + b + c;
    return d;
}
```

```
# 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

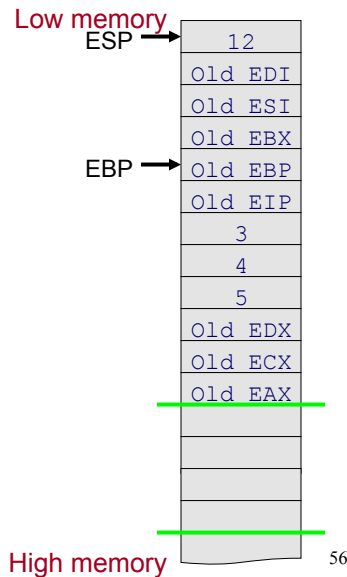


Trace of a Simple Example 10



```
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

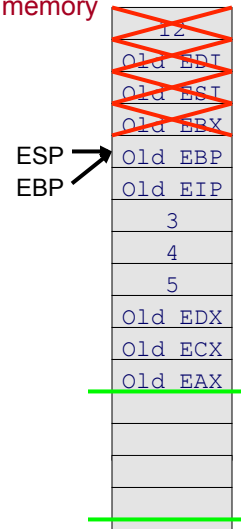


```
int add3(int a, int b, int c) {
    int d;
    d = a + b + c;
    return d;
}
```

```
# 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

Low memory



High memory

57

Trace of a Simple Example 12

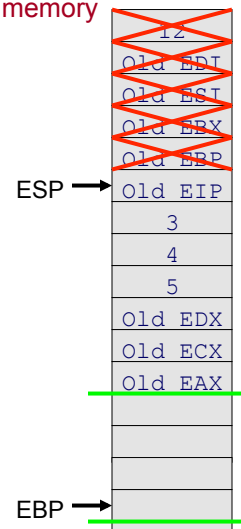


```
int add3(int a, int b, int c) {
    int d;
    d = a + b + c;
    return d;
}
```

```
# 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

Low memory



High memory

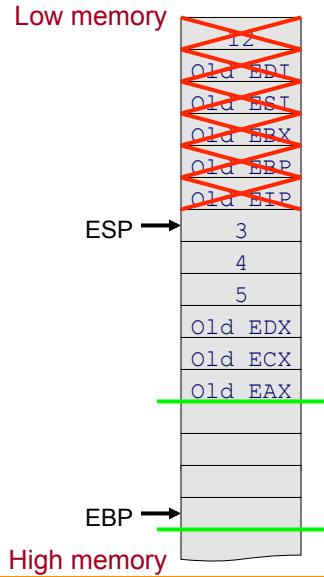
58

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
```

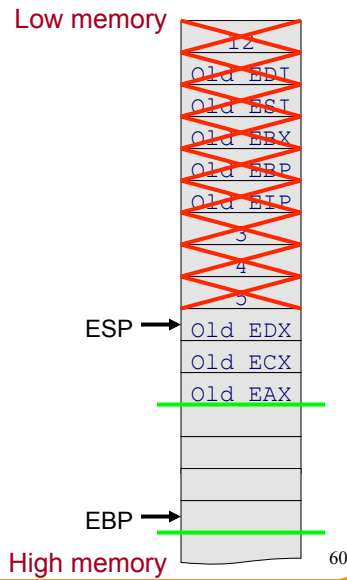


Trace of a Simple Example 14



```
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
```



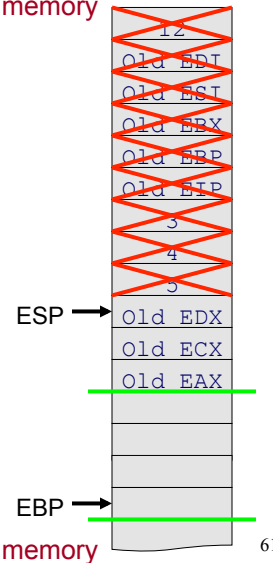
Trace of a Simple Example 15



```
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
```

Low memory



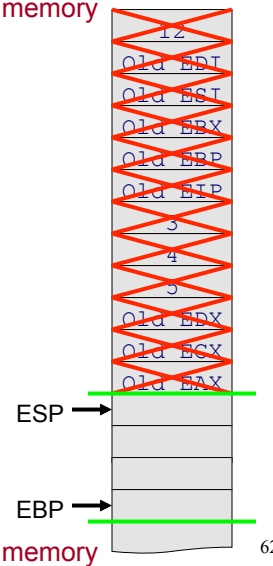
Trace of a Simple Example 16



```
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
```

Low memory



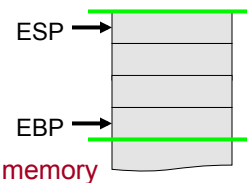
Trace of a Simple Example 17



```
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
# Pop parameters
addl %12, %esp
# Save return value
movl %eax, wherever
# Restore caller-save registers if necessary
popl %edx
popl %ecx
popl %eax
# Proceed!
...
```



63

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

64

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