CS 31: Intro to Systems
Functions and the Stack

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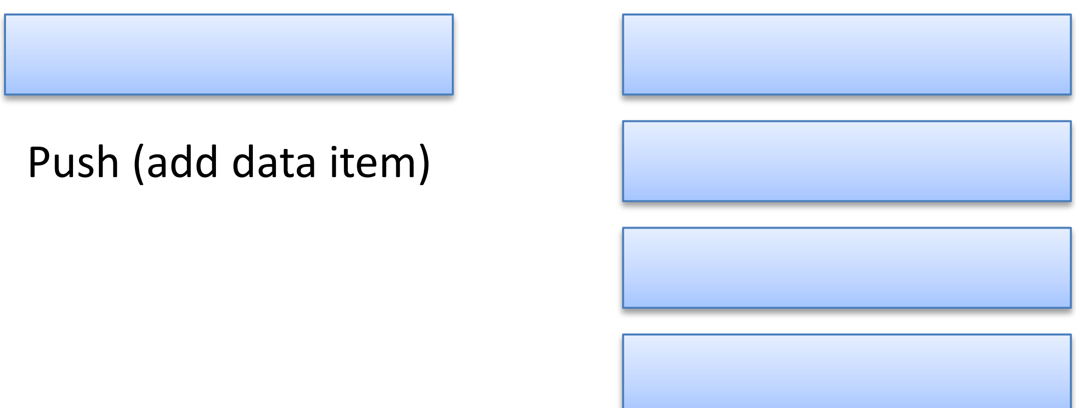
Reading Quiz

Overview

- Stack data structure, applied to memory
- Behavior of function calls
- Storage of function data, at IA32 level

"A" Stack

- A stack is a basic data structure
  - Last in, first out behavior (LIFO)
  - Two operations
    - Push (add item to top of stack)
    - Pop (remove item from top of stack)

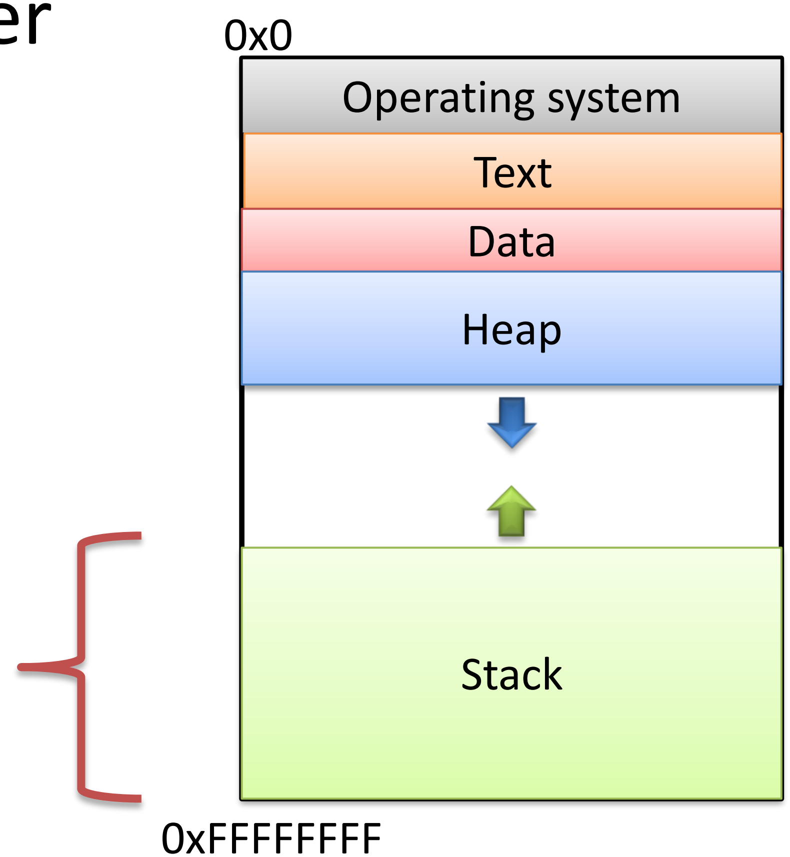


“The” Stack

- Apply stack data structure to memory
  - Store local (automatic) variables
  - Maintain state for functions (e.g., where to return)
- Organized into units called *frames*
  - One frame represents all of the information for one function.
  - Sometimes called *activation records*

Memory Model

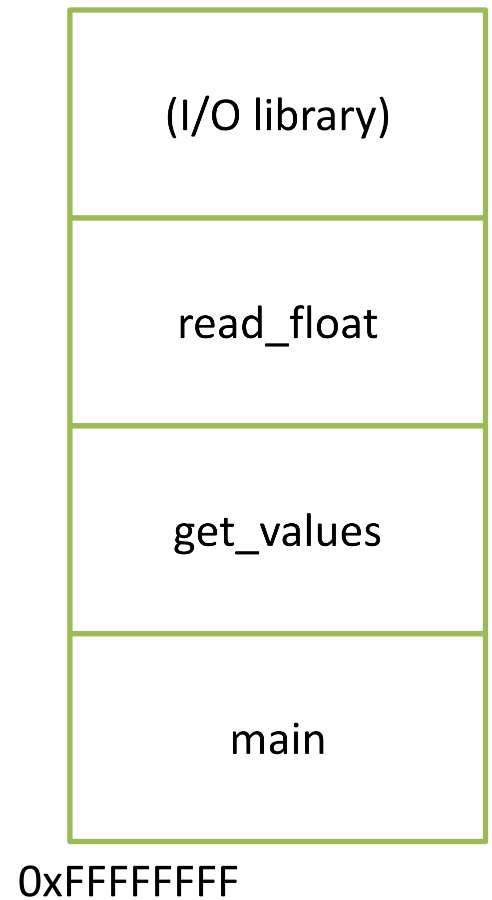
- Starts at the highest memory addresses, grows into lower addresses.



Stack Frames

- As functions get called, new frames added to stack.

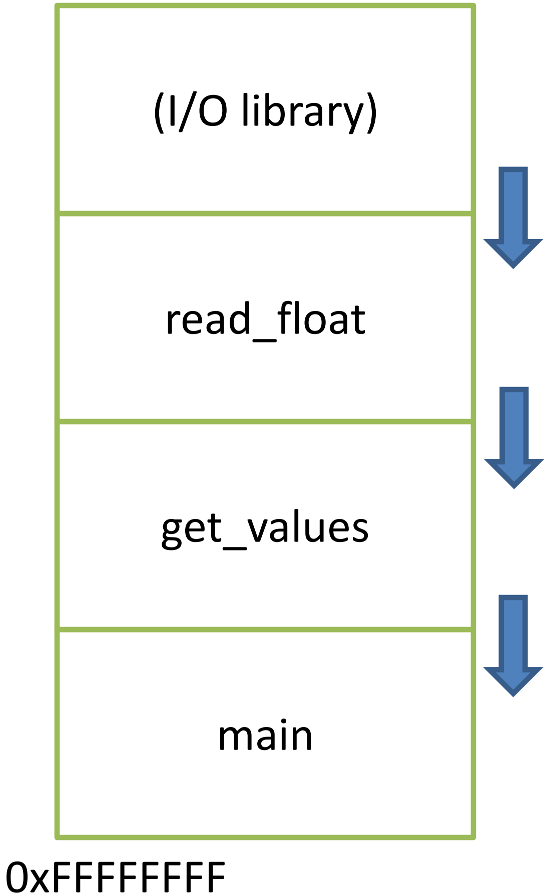
- Example: Lab 4
  - main calls get_values()
  - get_values calls read_float()
  - read_float calls I/O library



Stack Frames

- As functions return,
  frames removed from stack.

- Example: Lab 4
  - I/O library returns to read_float
  - read_float returns to get_values
  - get_values returns to main



All of this stack growing/shrinking happens automatically (from the programmer's perspective).

What is responsible for creating and removing stack frames?

A. The user

B. The compiler

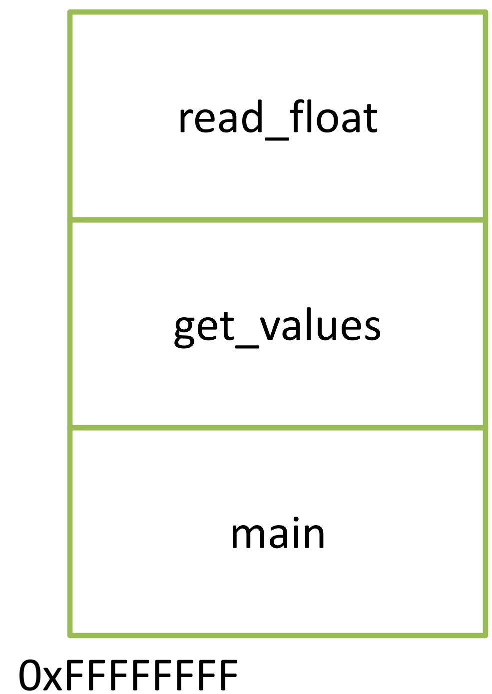
C. C library code

D. The operating system

E. Something / someone else

Stack Frame Contents

- What needs to be stored in a stack frame?
  - Alternatively: What *must* a function know / access?
  - Hint: At least 5 things



Stack Frame Contents

- What needs to be stored in a stack frame?
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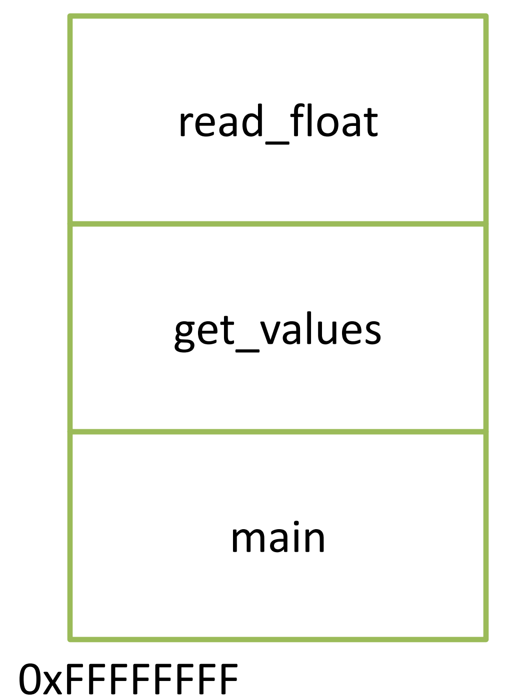
- Local variables



Local Variables

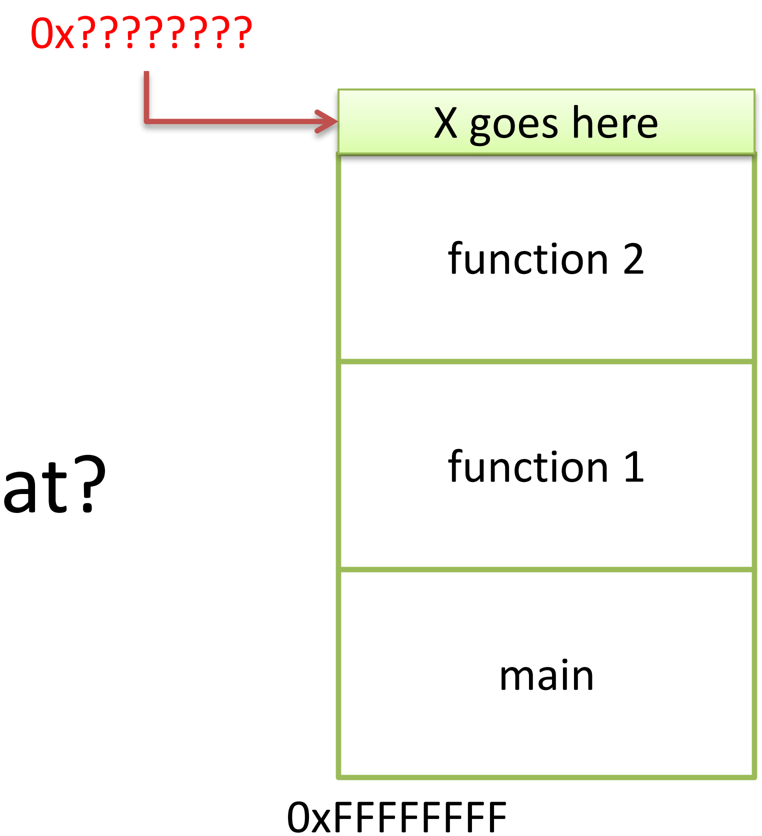
If the programmer says:

```
int x = 0;
```

Where should x be stored?

(Recall basic stack data structure)

Which memory address is that?



How should we determine the address to use for storing a new local variable?

A. The programmer specifies the variable location.

B. The CPU stores the location of the current stack frame.

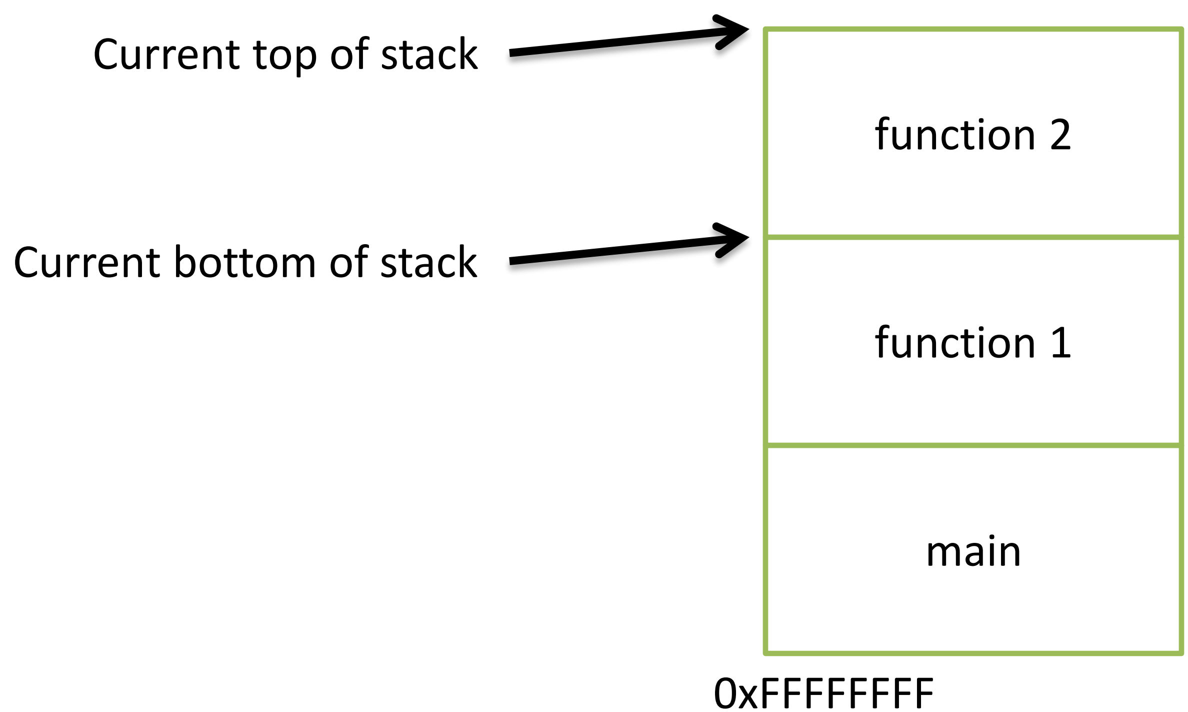
C. The operating system keeps track of the top of the stack.

D. The compiler knows / determines where the local data for each function will be as it generates code.

E. The address is determined some other way.

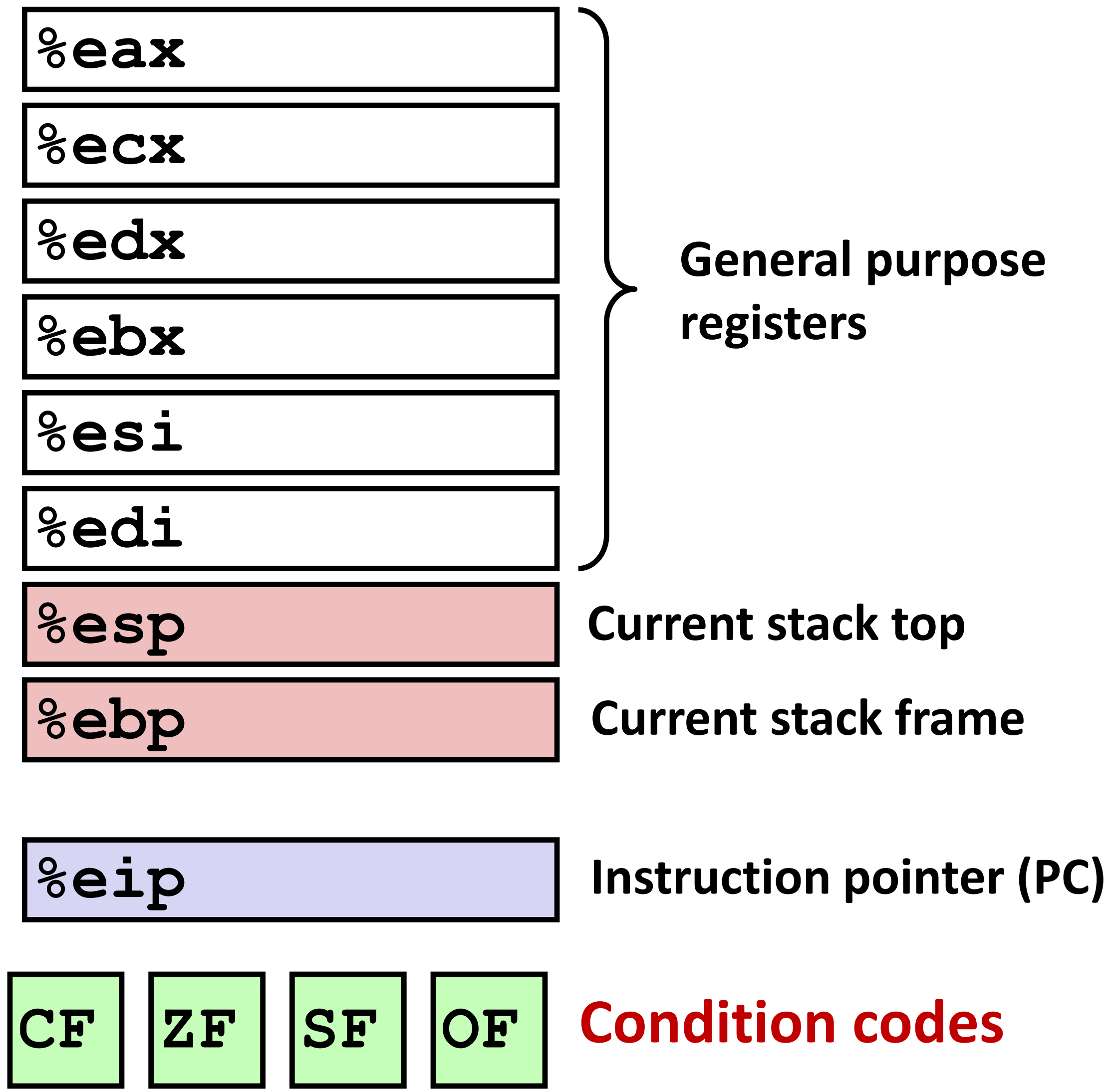
Stack Frame Location

- Where in memory is the current stack frame?



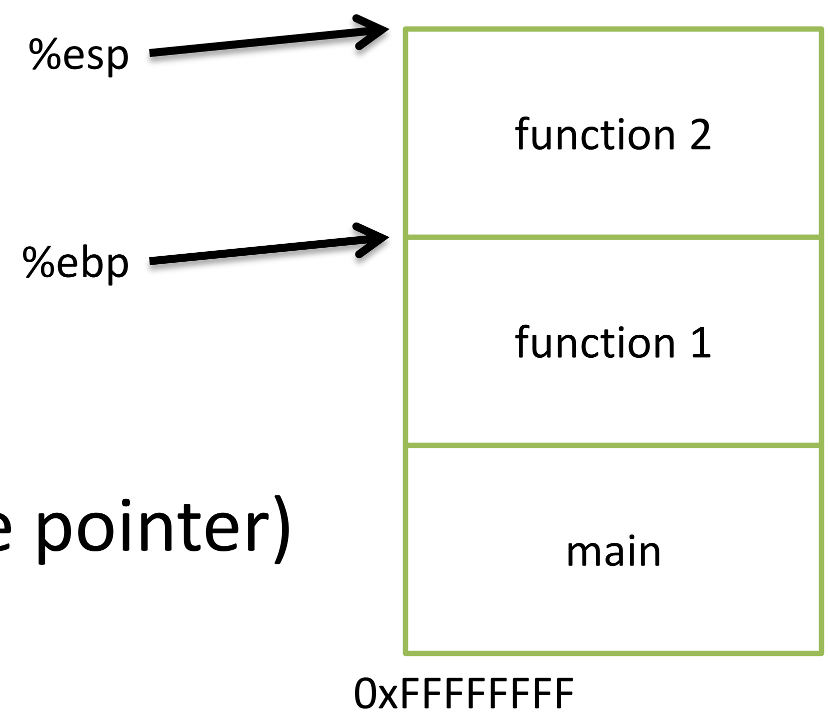
Recall: IA32 Registers

- Information about currently executing program



Stack Frame Location

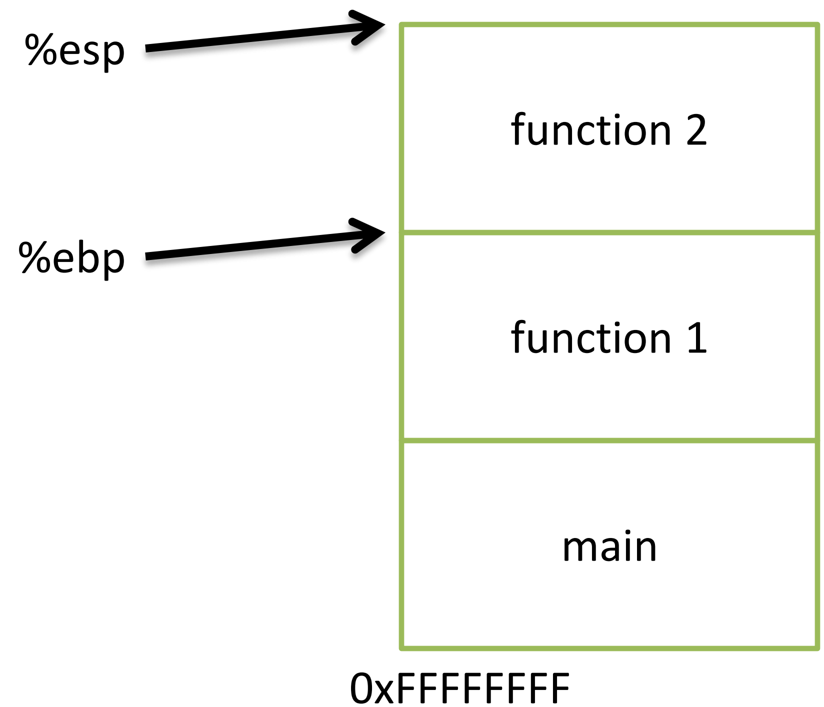
- Where in memory is the current stack frame?
- Maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp
- %esp: stack pointer
- %ebp: frame pointer (base pointer)



Stack Frame Location

- Compiler ensures that this invariant holds.
  - We'll see how a bit later.

- This is why all local variables we've seen in IA32 are relative to %ebp or %esp!



How would we implement pushing x to the top of the stack in IA32?

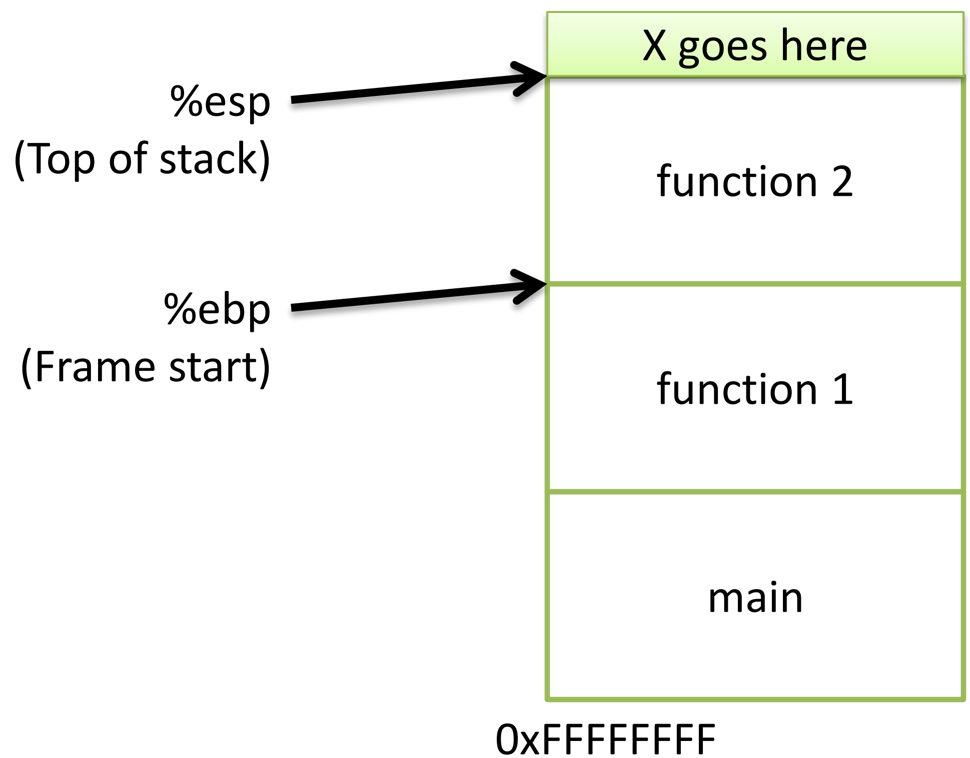
A. Increment %esp
   Store x at (%esp)

B. Store x at (%esp)
   Increment %esp

C. Decrement %esp
   Store x at (%esp)

D. Store x at (%esp)
   Decrement %esp

E. Copy %esp to %ebp
   Store x at (%ebp)



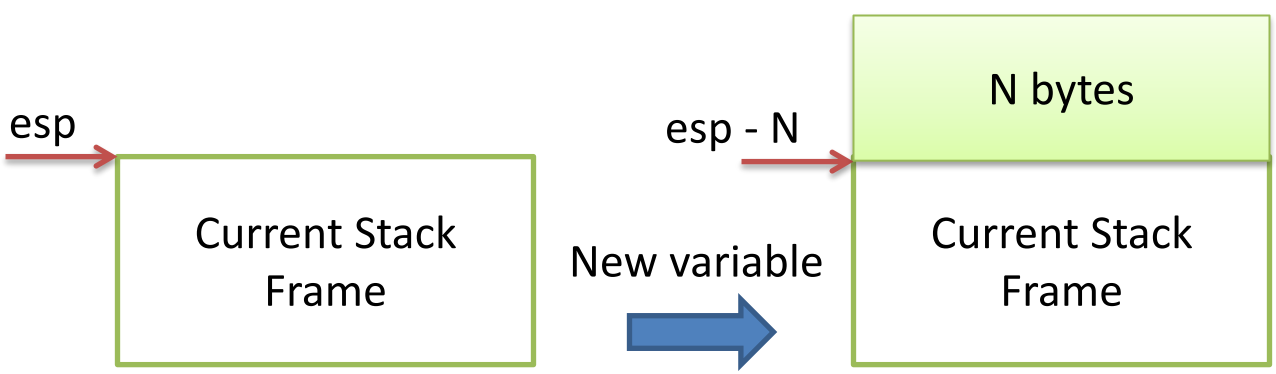
Push & Pop

- IA32 provides convenient instructions:
  - `pushl src`
    - Move stack pointer up by 4 bytes `subl $4, %esp`
    - Copy 'src' to current top of stack `movl src, (%esp)`
  - `popl dst`
    - Copy current top of stack to 'dst' `movl (%esp), dst`
    - Move stack pointer down 4 bytes `addl $4, %esp`

- src and dst are the contents of any register

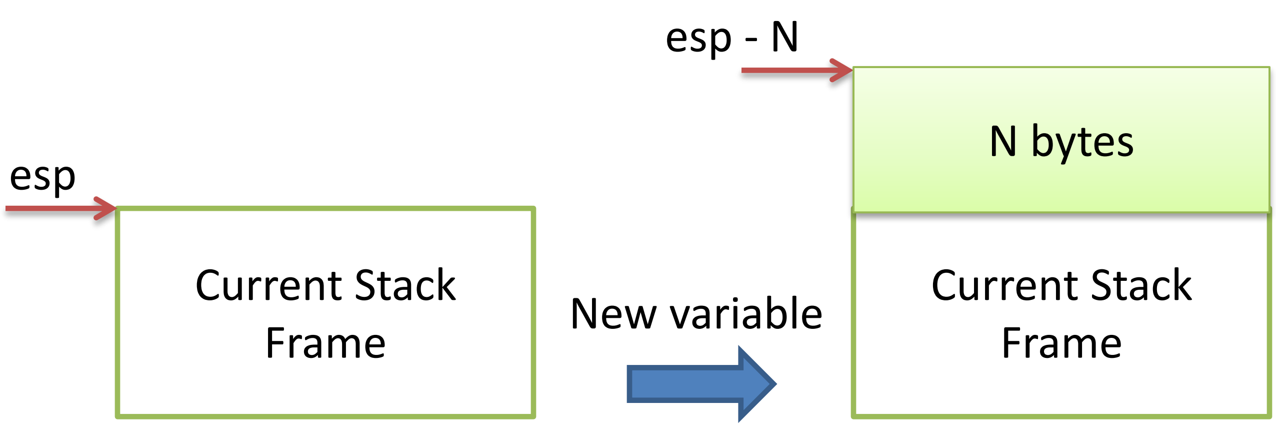
Local Variables

- More generally, we can make space on the stack for N bytes by subtracting N from %esp



Local Variables

- More generally, we can make space on the stack for N bytes by subtracting N from %esp
- When we're done, free the space by adding N back to %esp

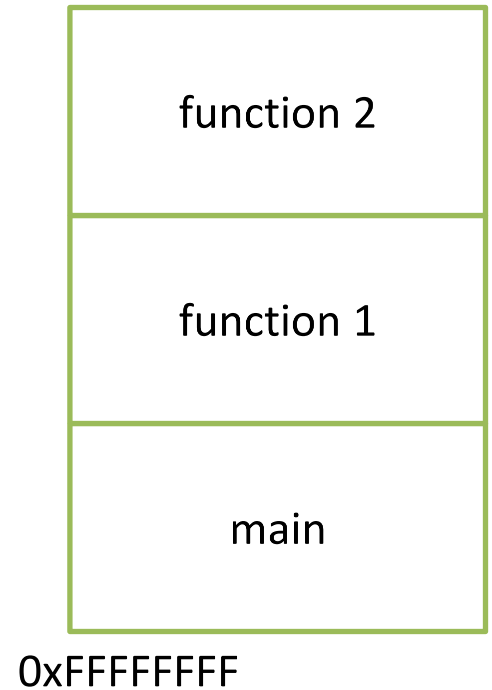


Stack Frame Contents

- What needs to be stored in a stack frame?
  - Alternatively: What *must* a function know?

- Local variables
- Previous stack frame base address
- Function arguments
- Return value
- Return address

- Saved registers
- Spilled temporaries



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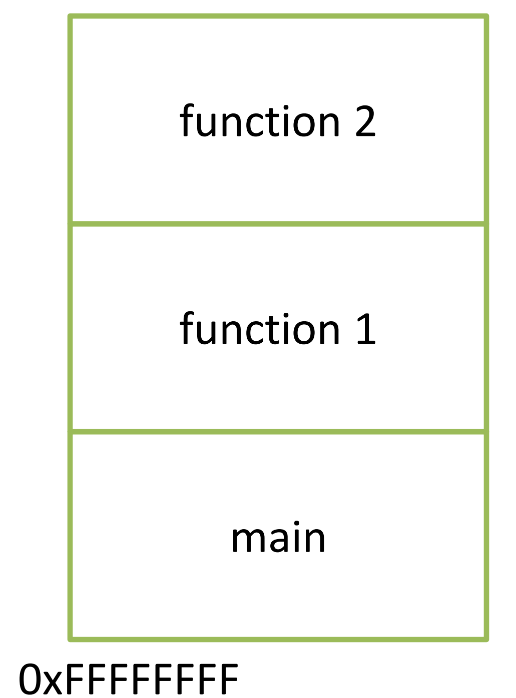
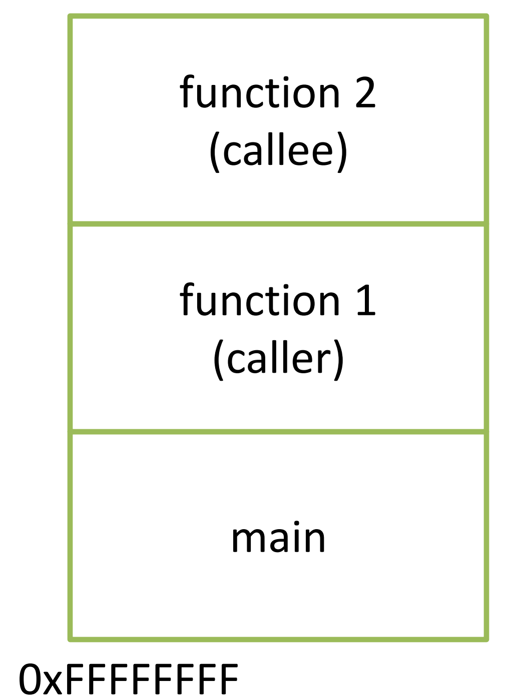


Stack Frame Relationships

- If function 1 calls function 2:
  - function 1 is the caller
  - function 2 is the callee

- With respect to main:
  - main is the caller
  - function 1 is the callee



Reading Quiz

Stack Frame Relationships

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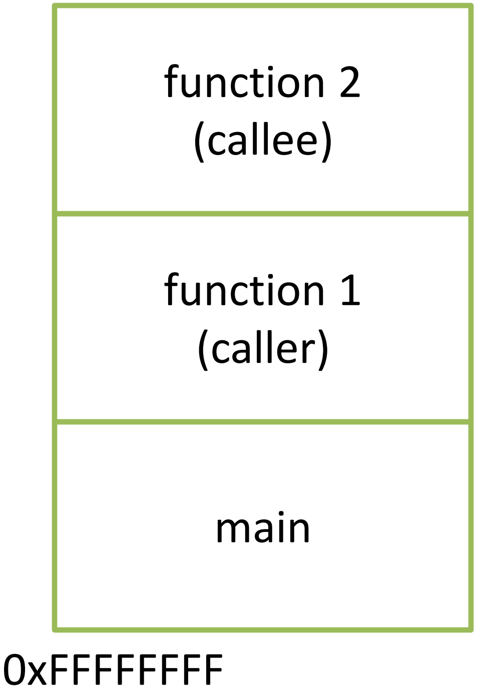

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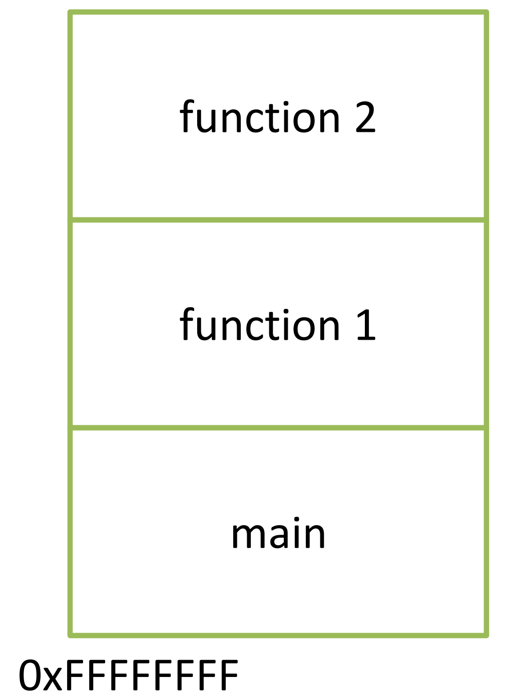

What is responsible for creating and removing stack frames?

A. The user

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How should we determine the address to use for storing a new local variable?

A. The programmer specifies the variable location.

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Important Distinction

- Q: What is responsible for creating and removing stack frames?
  - A: Compiler
  - Intuition: Every stack frame is the same, regardless of where in memory it lives.

- How should we determine the address to use for storing a new local variable on the stack?
  - A: Keep track of where the stack is via CPU regs
  - Intuition: The compiler does NOT know which functions will be executed at runtime (depends on input)

Program Characteristics

- Compile time (static)
  - Information that is known by analyzing your program
  - Independent of the machine and inputs
- Run time (dynamic)
  - Information that isn’t known until program is running
  - Depends on machine characteristics and user input

The Compiler Can…

- Perform type checking.
- Determine how much space you need on the stack to store local variables.
- Insert IA32 instructions for you to set up the stack for function calls.
  - Create stack frames on function call
  - Restore stack to previous state on function return

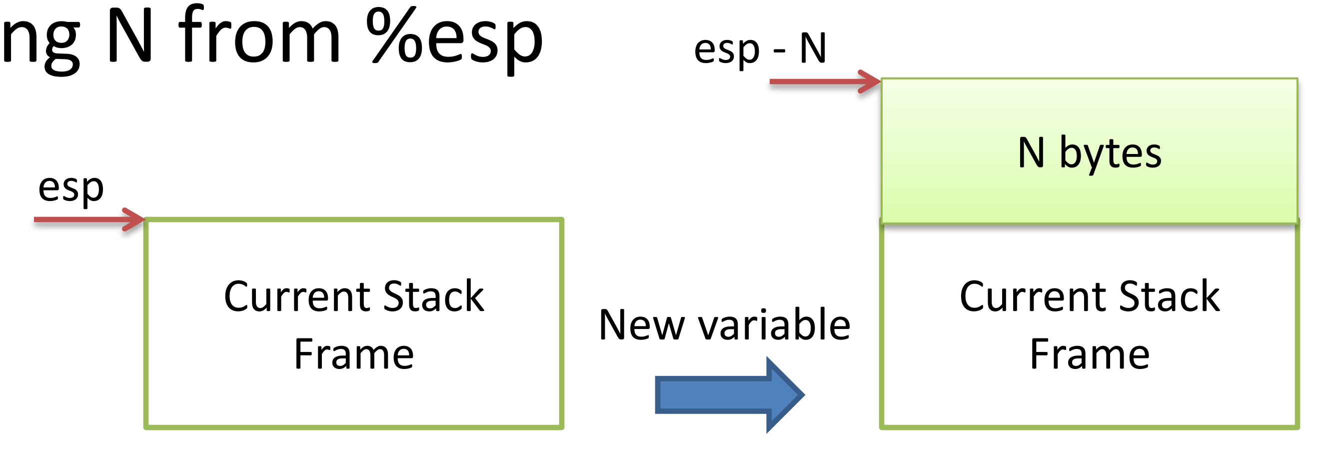
Local Variables

- ISA provides convenience instructions:
  - `pushl src`

    ```
    subl $4, %esp
    movl src, (%esp)
    ```
  - `popl dst`

    ```
    movl (%esp), dst
    addl $4, %esp
    ```

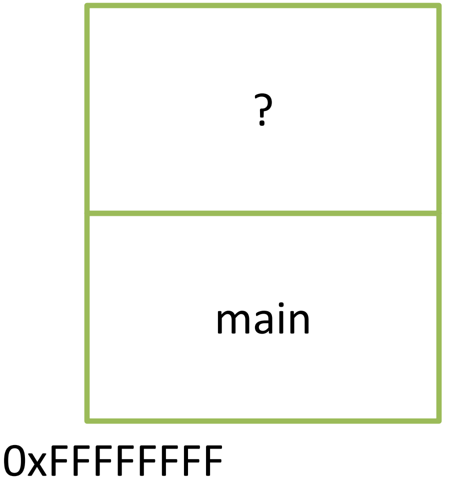
- Compiler can allocate N bytes on the stack by subtracting N from %esp



The Compiler Can't…

- Predict user input.

```
int main() {
  int decision = [read user input];
  if (x > 5) {
    funcA(x);
  } else {
    funcB();
  }
}
```



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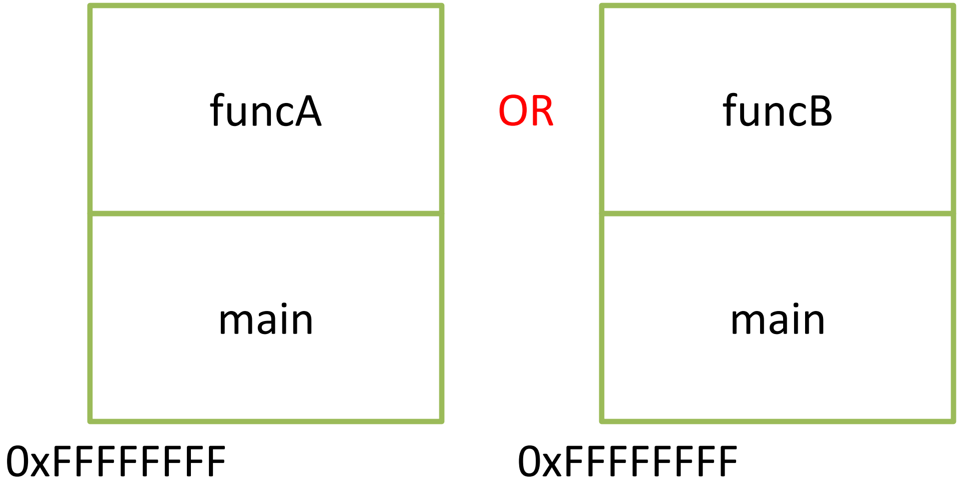
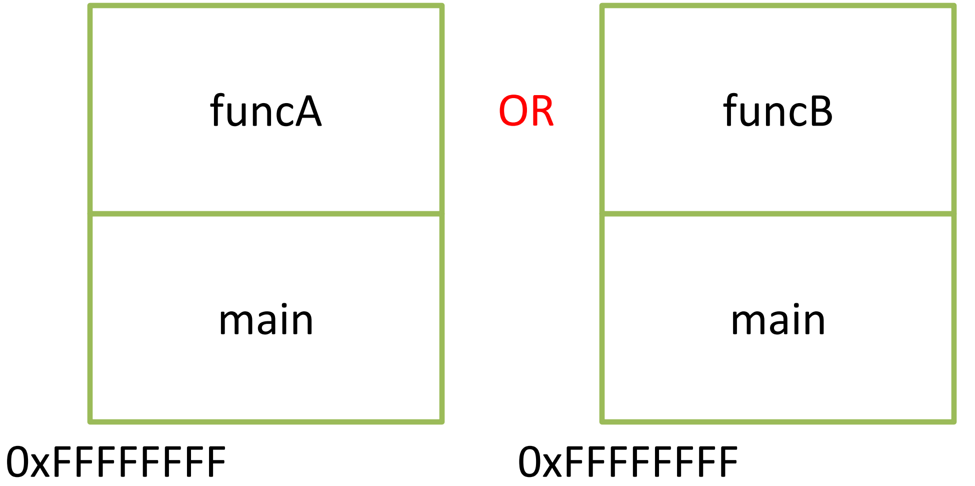


The Compiler Can't…

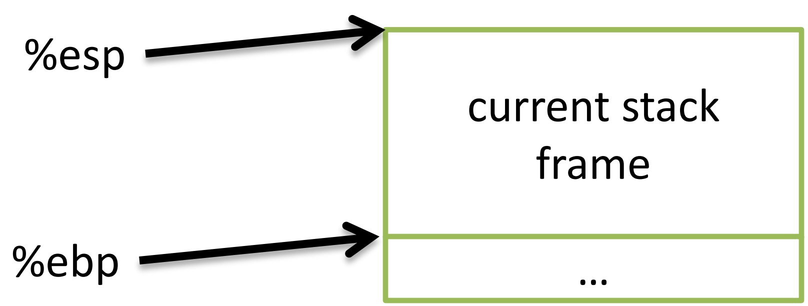
- Predict user input.
- Can't assume a function will always be at a certain address on the stack.

Alternative: create stack frames relative to the current (dynamic) state of the stack.



Dynamic Stack Accounting

- Dedicate CPU registers for stack bookkeeping
  - %esp (stack pointer): Top of current stack frame
  - %ebp (frame pointer): Base of current stack frame
- Compiler maintains these pointers by inserting instructions on function call/return.
  - It doesn't know (or care about) the exact addresses they point to.



Stack Frame Contents

- What needs to be stored in a stack frame?
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- Local variables
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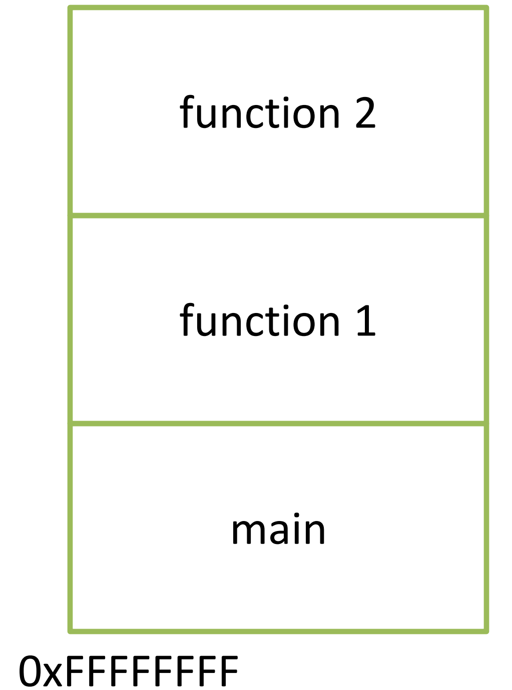

Where should we store all this stuff?

Previous stack frame base address
Function arguments
Return value
Return address

A. In registers
B. On the heap
C. In the caller’s stack frame
D. In the callee’s stack frame
E. Somewhere else

Calling Convention

- You could store this stuff wherever you want!
  - The hardware does NOT care.
  - What matters: everyone agrees on where to find the necessary data.

- Calling convention: agreed upon system for exchanging data between caller and callee

IA32 Calling Convention (gcc)

- In register %eax:
  - The return value
- In the callee's stack frame:
  - The caller's %ebp value (previous frame pointer)
- In the caller's frame (shared with callee):
  - Function arguments
  - Return address (saved PC value)

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Return Value

- If the callee function produces a result, the caller can find it in %eax
- We saw this when we wrote our while loop:
  - Copy the result to %eax before we finished up

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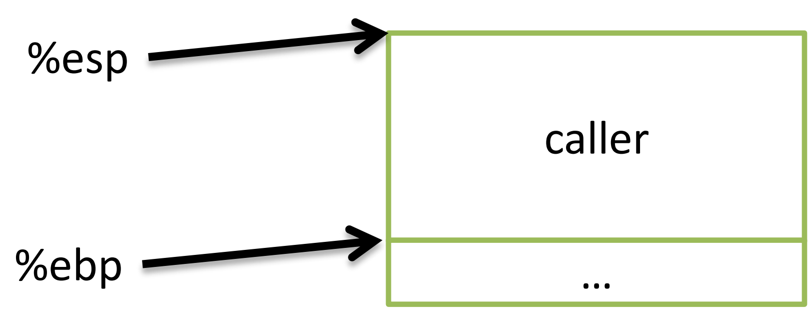
Frame Pointer

- Must maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp

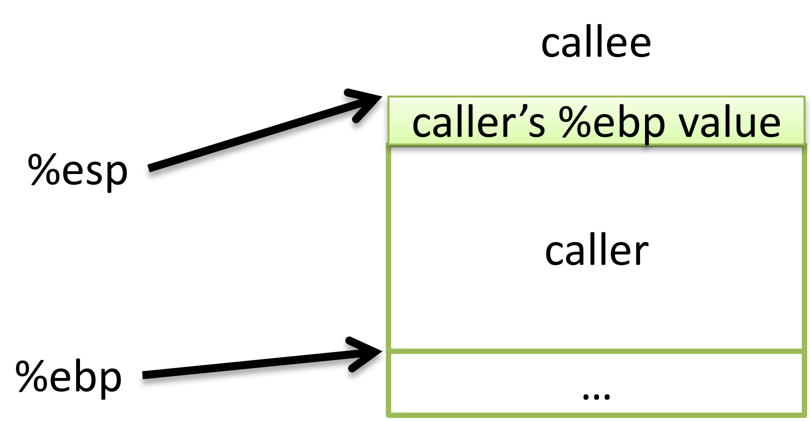
- Must adjust %esp, %ebp on call / return.



Frame Pointer

- Must maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp

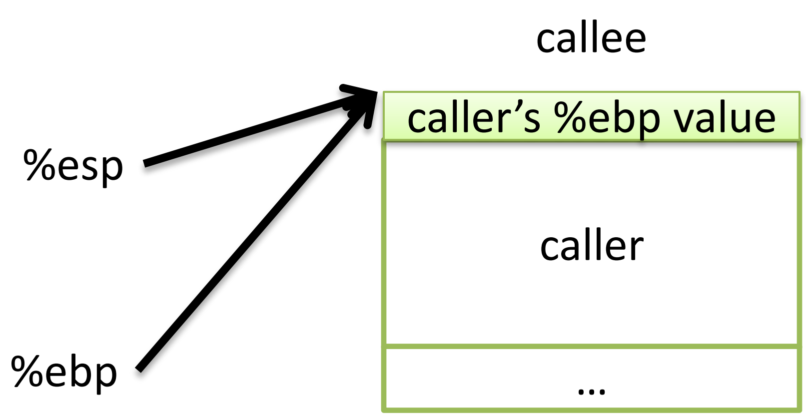
- Immediately upon calling a function:
  1. pushl %ebp



Frame Pointer

- Must maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp

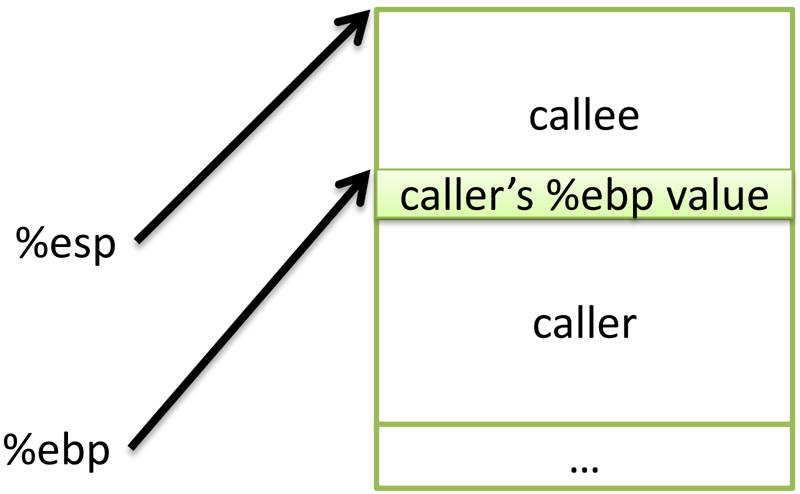
- Immediately upon calling a function:
  1. pushl %ebp
  2. Set %ebp = %esp



Frame Pointer

- Must maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp

- Immediately upon calling a function:
  1. pushl %ebp
  2. Set %ebp = %esp
  3. Subtract N from %esp



Callee can now execute.

Frame Pointer

- Must maintain invariant:
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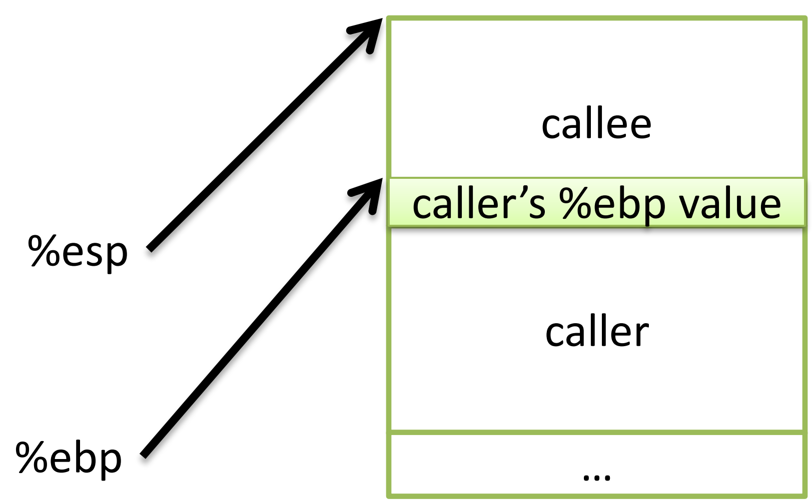
- To return, reverse this:



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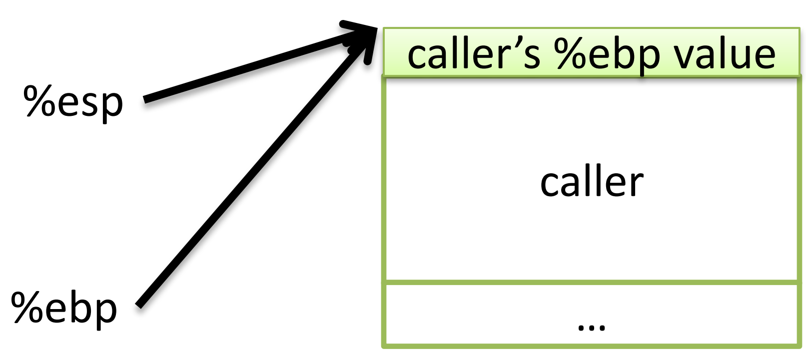

Frame Pointer

- Must maintain invariant:
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  1. set %esp = %ebp
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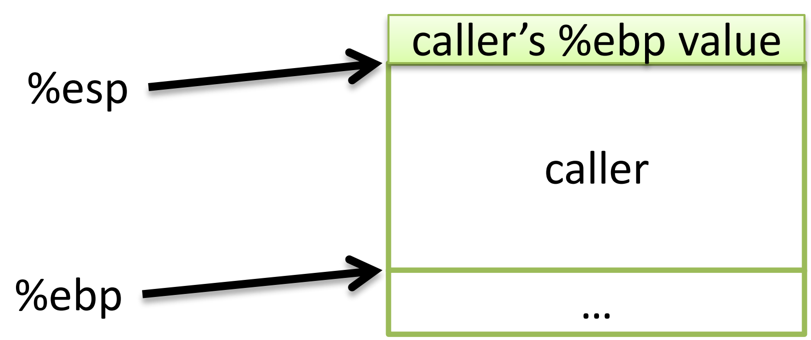
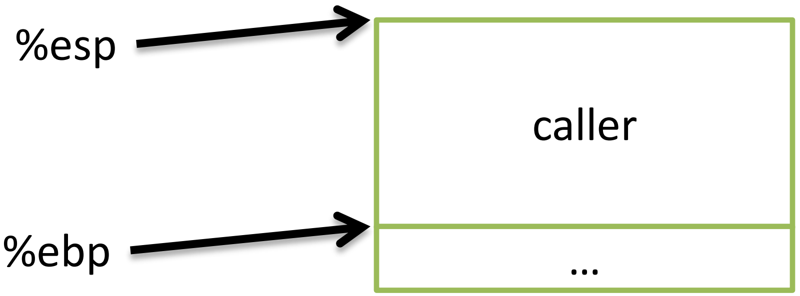


Frame Pointer

- Must maintain invariant:
  – The current function's stack frame is always between the addresses stored in %esp and %ebp

- To return, reverse this:
  1. set %esp = %ebp
  2. popl %ebp

IA32 has another convenience instruction for this: leave



Back to where we started.

Recall: Assembly While Loop

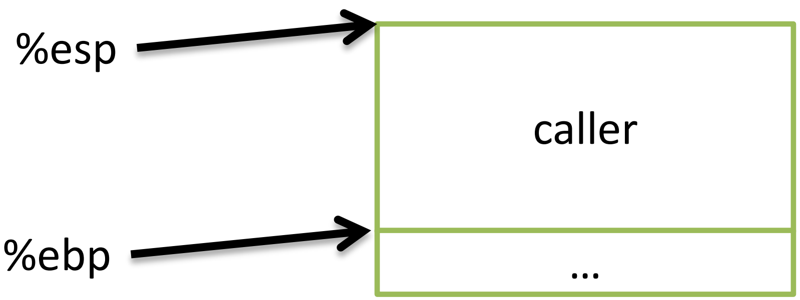
```
sum_function:
    pushl %ebp
    movl %esp, %ebp

    # Your code here

    movl $10, %eax
    leave
    ret
```

Set up the stack frame for this function. (pushl %ebp, movl %esp, %ebp)

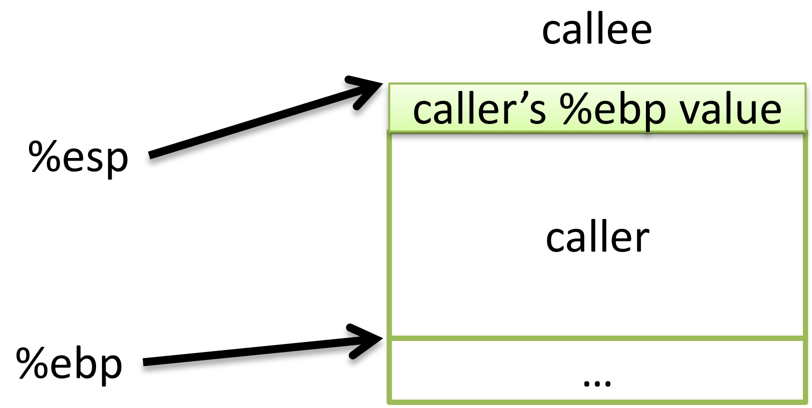
Store return value in %eax. (movl $10, %eax)

Restore caller's %esp, %ebp. (leave)

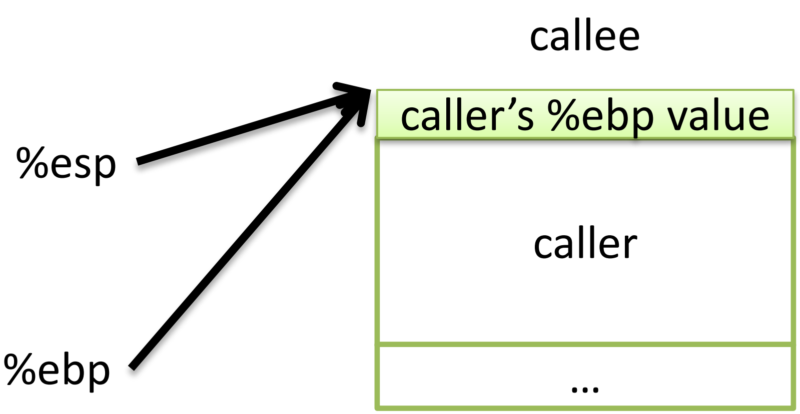
Frame Pointer: Function Call



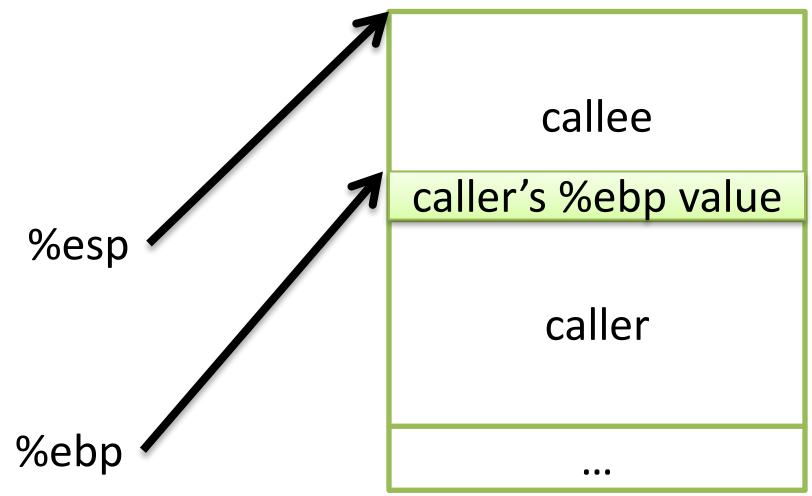
Initial state



pushl %ebp (store caller's frame pointer)

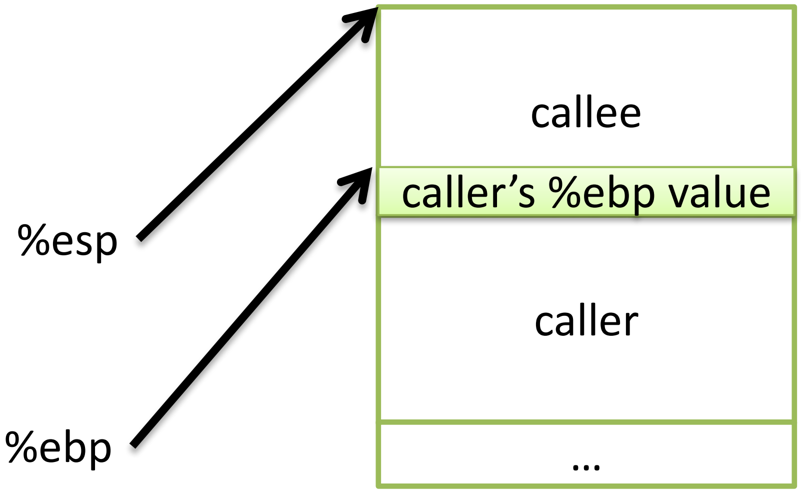


movl %esp, %ebp
(establish callee's frame pointer)

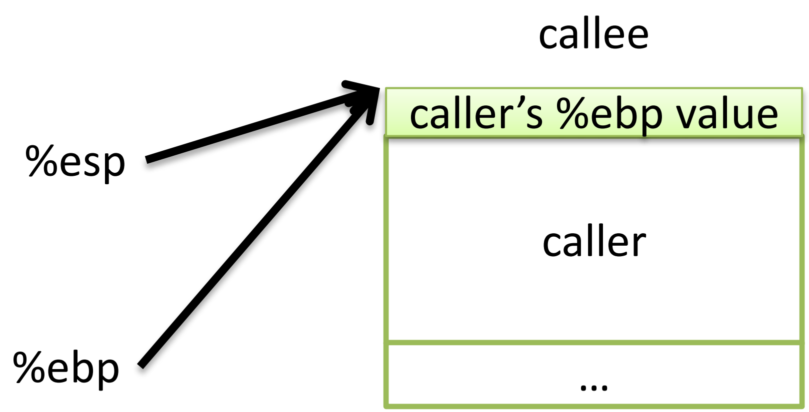


subl $SIZE, %esp
(allocate space for callee's locals)

Frame Pointer: Function Return

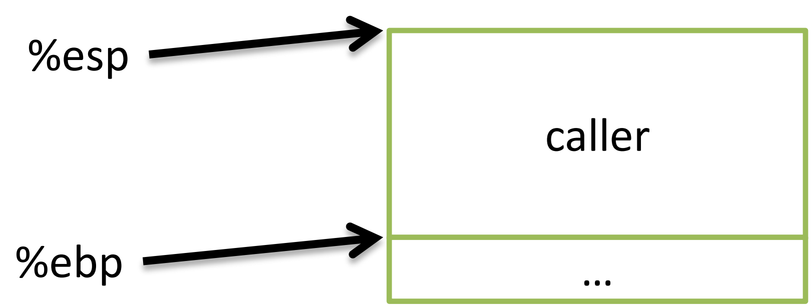


Want to restore caller's frame.



movl %ebp, %esp
(restore caller's stack pointer)

IA32 provides a convenience instruction that does all of this: `leave`



popl %ebp (restore caller's frame pointer)

Lab 4: swap.s

```
swap:
    pushl %ebp
    movl %esp, %ebp
    subl $16, %esp

    # Your code here

    leave
    ret
```

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- In the caller's frame (shared with callee):
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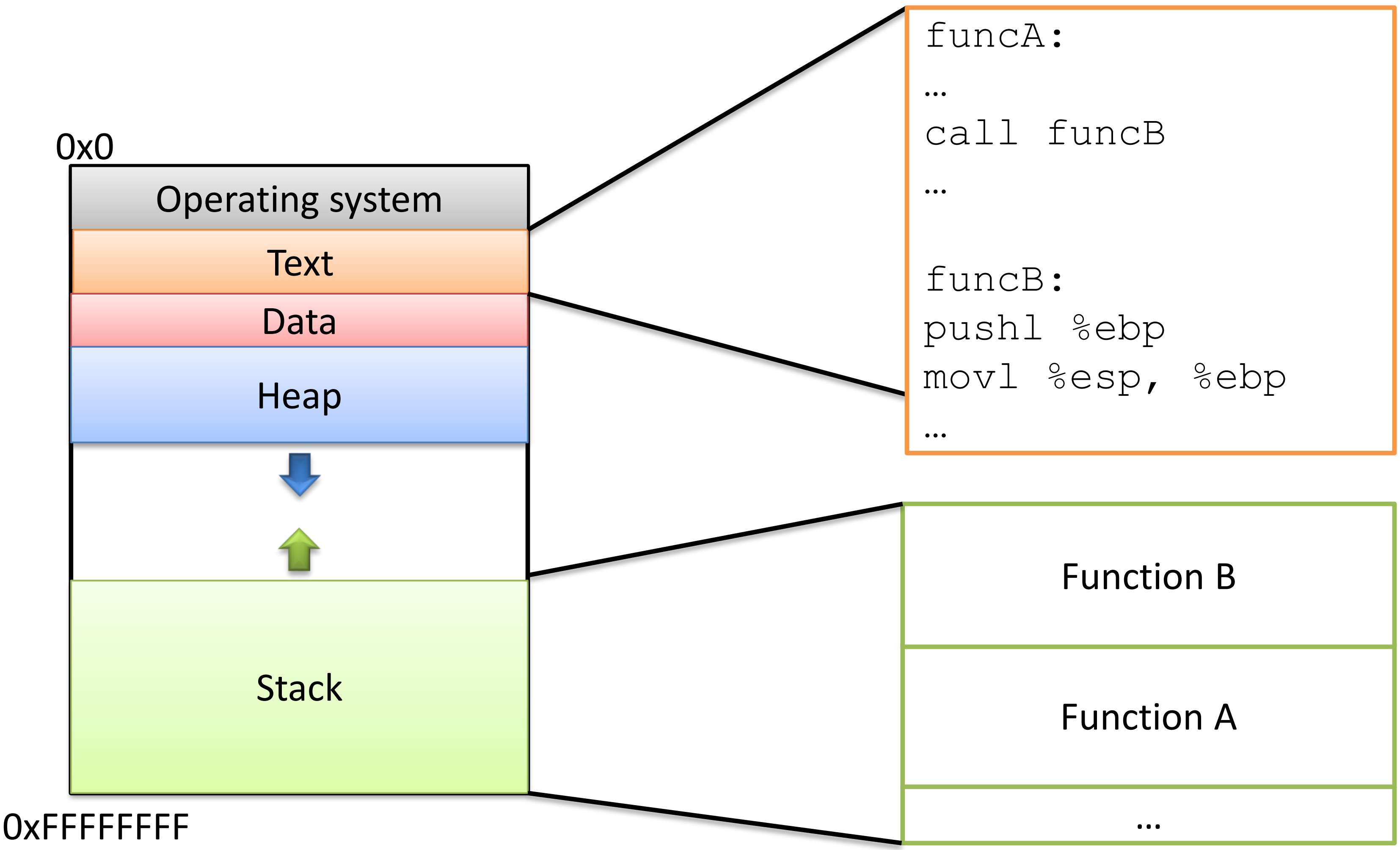
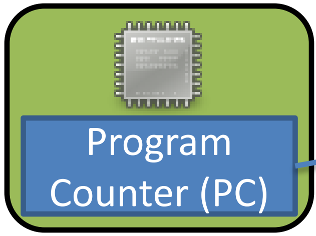
Instructions in Memory



Program Counter

Recall: PC stores the address of the next instruction.
(A pointer to the next instruction.)



What do we do now?

Follow PC, fetch instruction:

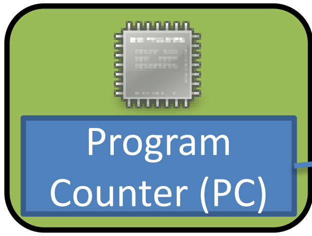
```
addl $5, %ecx
```

Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Program Counter

Recall: PC stores the address of the next instruction.
(A pointer to the next instruction.)



Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

What do we do now?

Follow PC, fetch instruction:

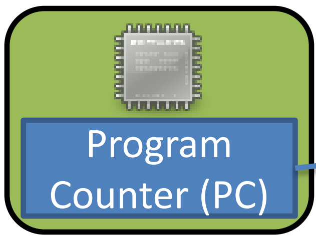
`addl $5, %ecx`

Update PC to next instruction.

Execute the `addl`.

Program Counter

Recall: PC stores the address of the next instruction.
(A pointer to the next instruction.)



What do we do now?

Follow PC, fetch instruction:

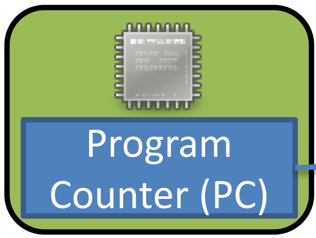
```
movl $ecx, -4(%ebp)
```

Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Program Counter

Recall: PC stores the address of the next instruction.
(A pointer to the next instruction.)



Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

What do we do now?

Follow PC, fetch instruction:

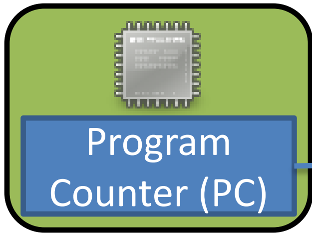
`movl $ecx, -4(%ebp)`

Update PC to next instruction.

Execute the `movl`.

Program Counter

Recall: PC stores the address of the next instruction.
(A pointer to the next instruction.)



Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

What do we do now?

Keep executing in a straight line downwards like this until:

We hit a jump instruction.
We call a function.

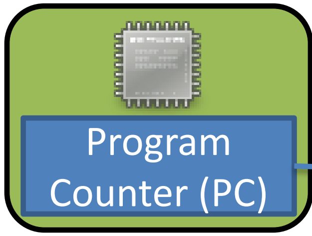
Changing the PC: Jump

- On a jump:
  - Check condition codes
  - Set PC to execute elsewhere (not next instruction)

- Do we ever need to go back to the instruction after the jump?

Maybe (and if so, we'd have a label to jump back to), but usually not.

Changing the PC: Functions

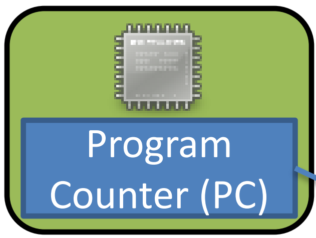


What we'd like this to do:

Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Changing the PC: Functions



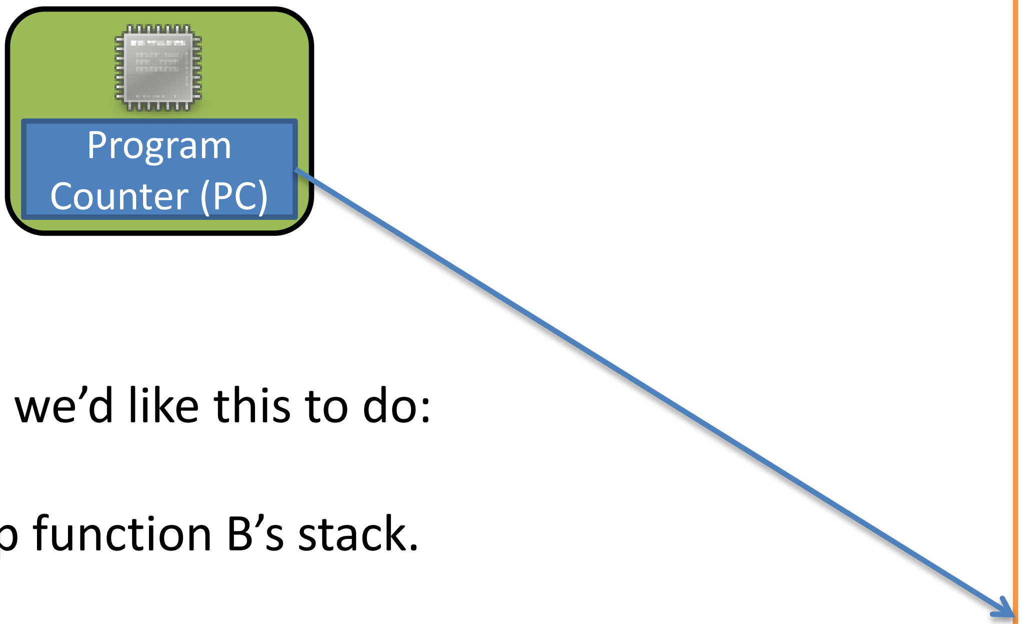
Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

What we'd like this to do:

Set up function B's stack.

Changing the PC: Functions



Text Memory Region

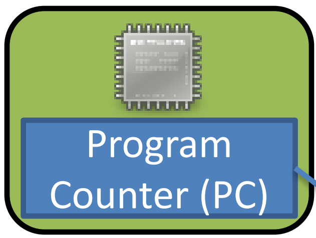
```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

What we'd like this to do:

Set up function B's stack.

Execute the body of B, produce result (stored in %eax).

Changing the PC: Functions



Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

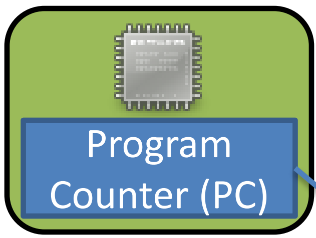
What we'd like this to do:

Set up function B's stack.

Execute the body of B, produce result (stored in %eax).

Restore function A's stack.

Changing the PC: Functions



Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

What we'd like this to do:

Return:
Go back to what we were doing before funcB started.

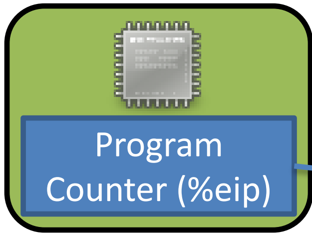
Unlike jumping, we intend to go back!

Like `push`, `pop`, and `leave`, `call` and `ret` are convenience instructions.
What should they do to support the PC-changing behavior we need? (The PC is %eip.)

call	ret
In words:	In words:
In instructions:	In instructions:

Functions and the Stack

Executing instruction:
`call funcB`



PC points to next instruction

Text Memory Region

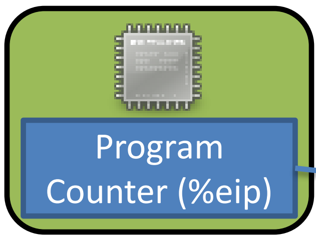
```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Stack Memory Region

Function A
…

Functions and the Stack

1. pushl %eip



Text Memory Region

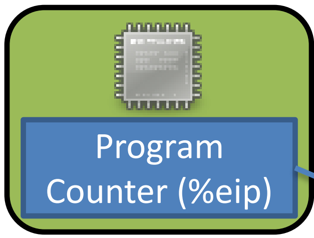
```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Stack Memory Region

Stored PC in funcA
Function A
…

Functions and the Stack

1. pushl %eip
2. jump funcB
3. (execute funcB)



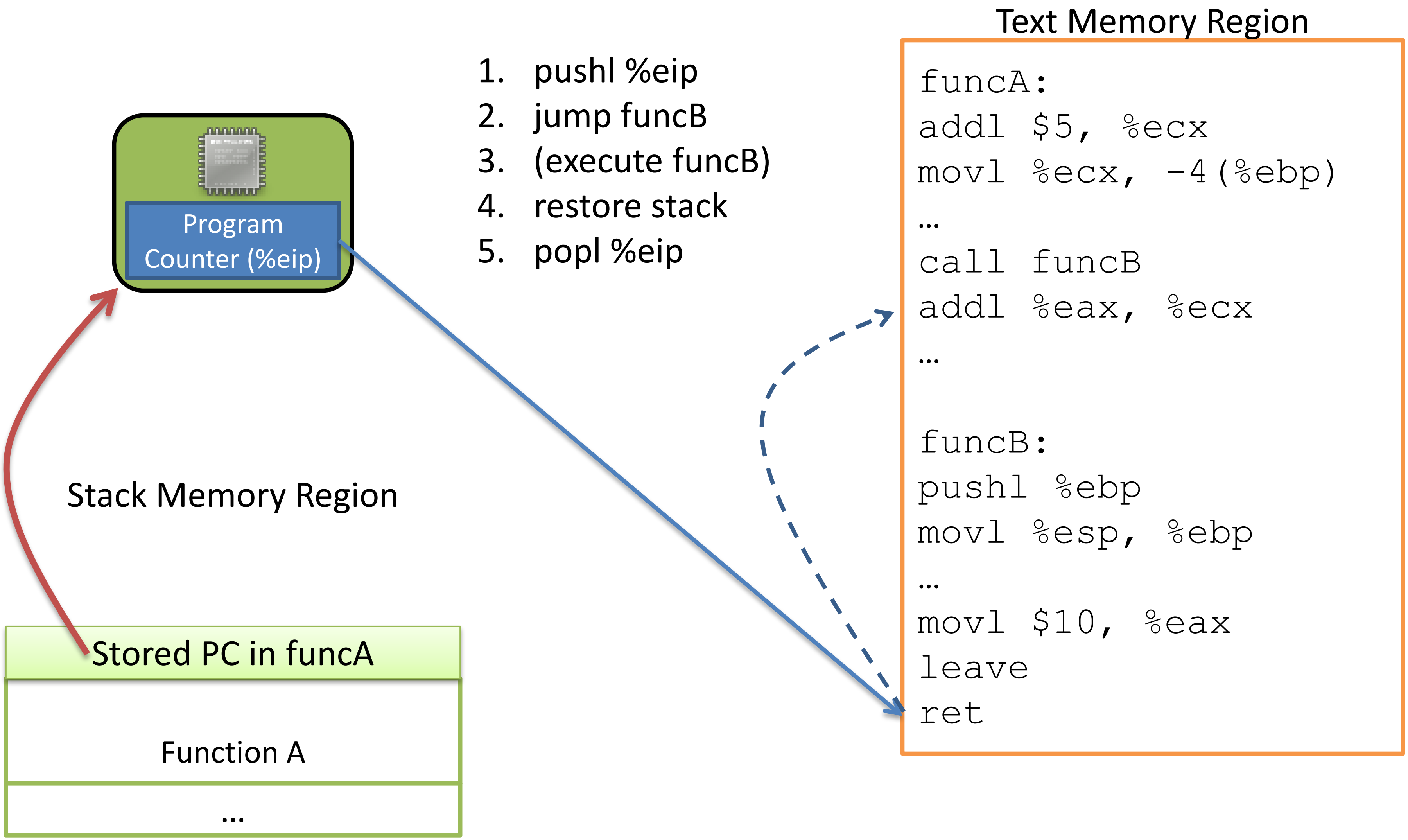
Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Stack Memory Region

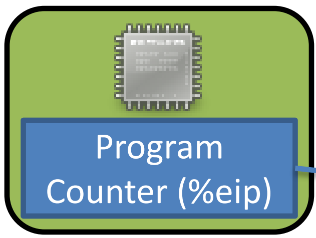
Function B
Stored PC in funcA
Function A
…

Functions and the Stack



Functions and the Stack

6. (resume funcA)



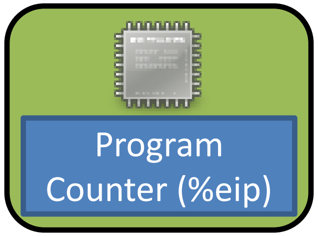
Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Stack Memory Region

Function A
…

Functions and the Stack



1. pushl %eip
2. jump funcB
3. (execute funcB)
4. restore stack
5. popl %eip
6. (resume funcA)

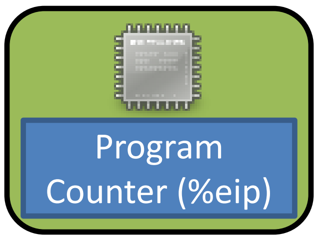
Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Stack Memory Region

Stored PC in funcA
Function A
…

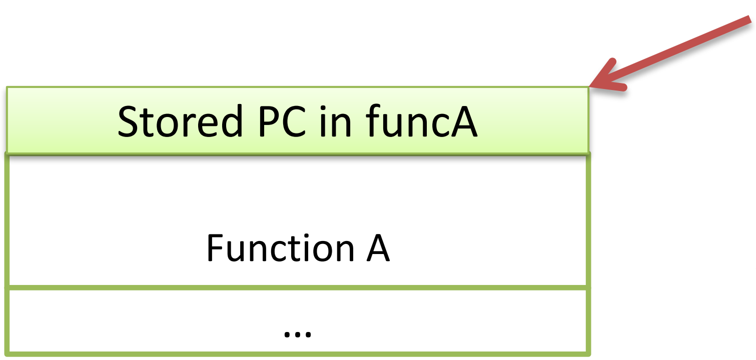
Functions and the Stack



1. pushl %eip
2. jump funcB
3. (execute funcB)
4. restore stack
5. popl %eip
6. (resume funcA)

Steps 1–2: call
Step 4: leave
Step 5: ret

Stack Memory Region



Return address:

Address of the instruction we should jump back to when we finish (return from) the currently executing function.

IA32 Stack / Function Call Instructions

`pushl`	Create space on the stack and place the source there.	`subl $4, %esp` `movl src, (%esp)`
`popl`	Remove the top item off the stack and store it at the destination.	`movl (%esp), dst` `addl $4, %esp`
`call`	1. Push return address on stack 2. Jump to start of function	`push %eip` `jmp target`
`leave`	Prepare the stack for return (restoring caller's stack frame)	`movl %ebp, %esp` `popl %ebp`
`ret`	Return to the caller, PC ← saved PC (pop return address off the stack into PC (eip))	`popl %eip`

IA32 Calling Convention (gcc)

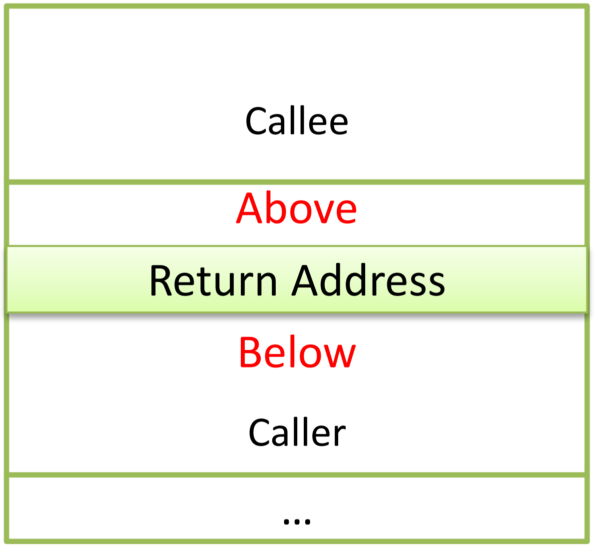
- In register %eax:
  - The return value
- In the callee's stack frame:
  - The caller's %ebp value (previous frame pointer)
- In the caller's frame (shared with callee):
  - Function arguments
  - Return address (saved PC value)

We know we're going to place arguments on the stack, in the caller's frame. Should they go above or below the return address?

A. Above

B. Below

C. Somewhere else



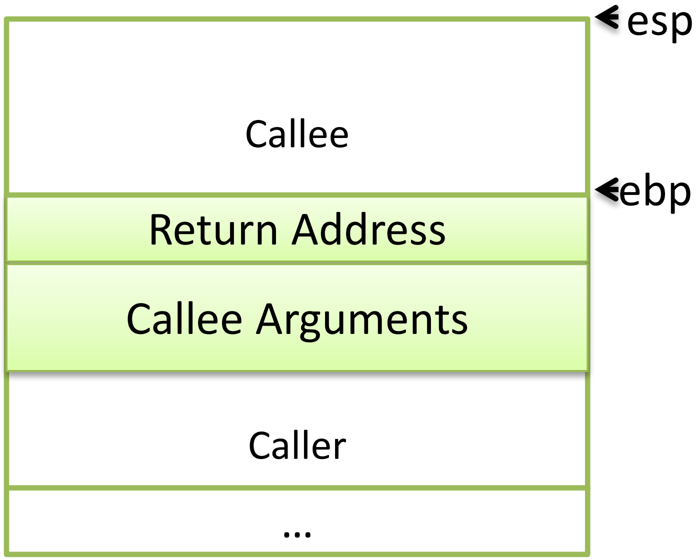
IA32 Stack / Function Call Instructions

`pushl`	Create space on the stack and place the source there.	`subl $4, %esp` `movl src, (%esp)`
`popl`	Remove the top item off the stack and store it at the destination.	`movl (%esp), dst` `addl $4, %esp`
`call`	1. Push return address on stack 2. Jump to start of function	`push %eip` `jmp target`
`leave`	Prepare the stack for return (restoring caller's stack frame)	`movl %ebp, %esp` `popl %ebp`
`ret`	Return to the caller, PC ← saved PC (pop return address off the stack into PC (eip))	`popl %eip`

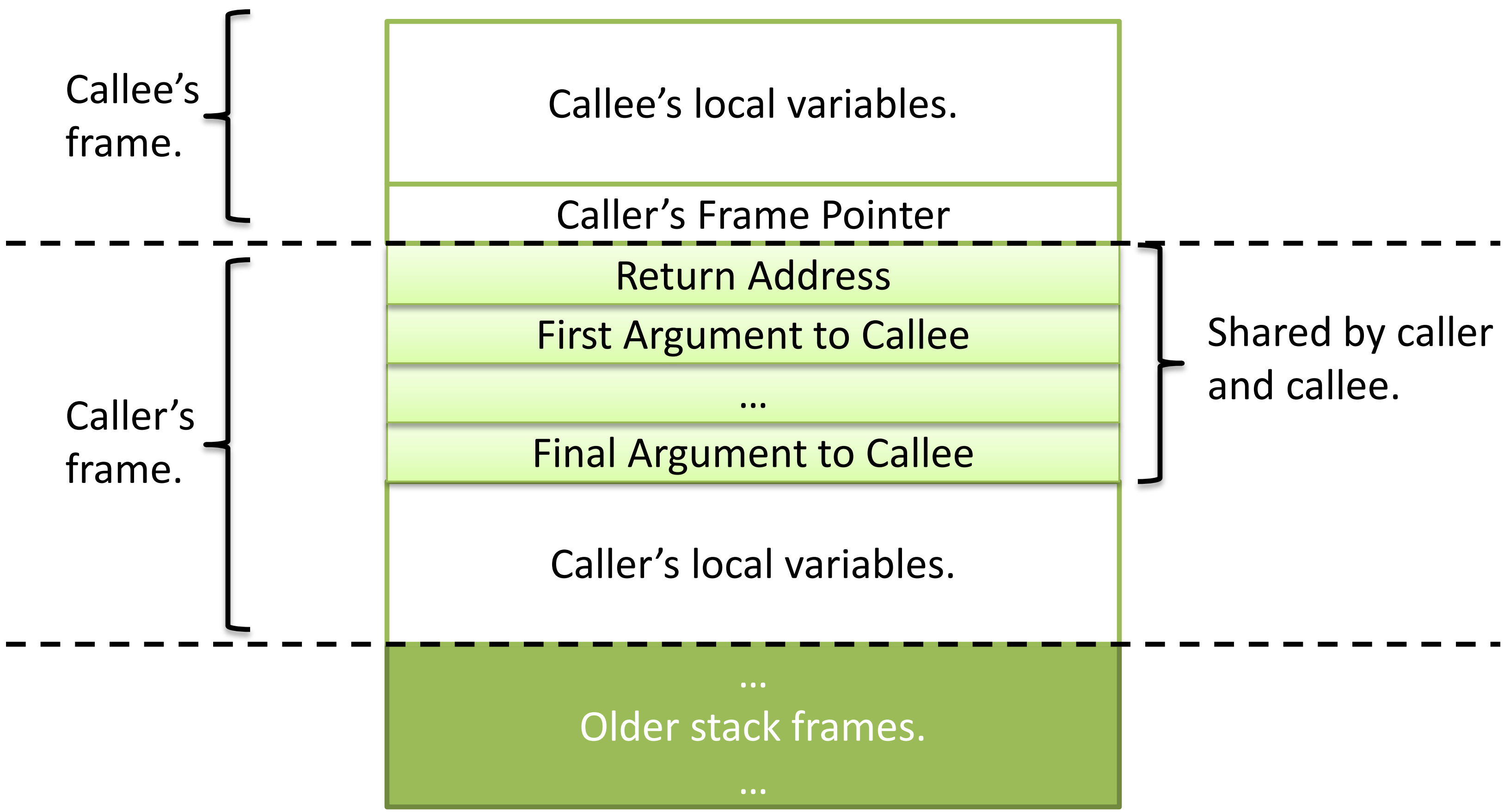
Arguments

- Arguments to the callee are stored just underneath the return address.
- Does it matter what order we store the arguments in?
- Not really, as long as we're consistent (follow conventions).

This is why arguments can be found at positive offsets relative to %ebp.



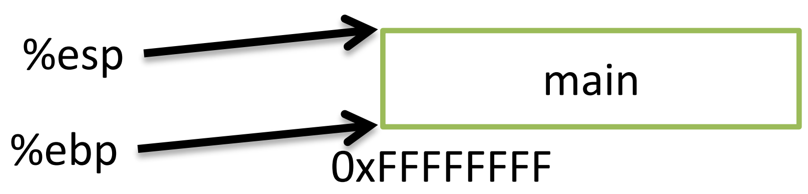
Putting it all together…



How would we translate this to IA32? What should be on the stack?

```
int func(int a, int b, int c) {
  return b+c;
}

int main() {
  func(1, 2, 3);
}
```

Assume the stack initially looks like:



How would we translate this to IA32? What should be on the stack?

main:

func:

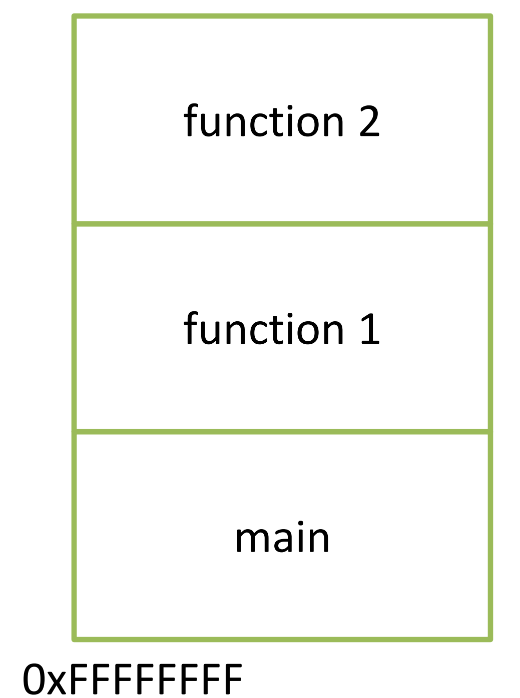
Stack

Stack Frame Contents

- What needs to be stored in a stack frame?
  - Alternatively: What *must* a function know?

- Local variables
- Previous stack frame base address
- Function arguments
- Return value
- Return address

- Saved registers
- Spilled temporaries



Saving Registers

- Registers are a scarce resource, but they're fast to access. Memory is plentiful, but slower to access.

- Should the caller save its registers to free them up for the callee to use?
- Should the callee save the registers in case the caller was using them?
- Who needs more registers for temporary calculations, the caller or callee?

- Clearly the answers depend on what the functions do…

Splitting the difference…

- We can’t know the answers to those questions in advance…

- We have six general-purpose registers, let’s divide them into two groups:
  - Caller-saved: %eax, %ecx, %edx
  - Callee-saved: %ebx, %esi, %edi

Register Convention

This is why I've told you to only use these three registers.

- Caller-saved: %eax, %ecx, %edx
  - If the caller wants to preserve these registers, it must save them prior to calling callee
  - callee free to trash these, caller will restore if needed

- Callee-saved: %ebx, %esi, %edi
  - If the callee wants to use these registers, it must save them first, and restore them before returning
  - caller can assume these will be preserved

Running Out of Registers

- Some computations require more than six registers to store temporary values.

- *Register spilling*: The compiler will move some temporary values to memory, if necessary.
  - Values pushed onto stack, popped off later
  - No explicit variable declared by user

Midterm

- The midterm will cover material up to here.

- The exam will be in class on Thursday, March 5