CS 31: Introduction to Computer Systems

11-12: Functions and the Stack

February 26 - March 5

SWARTHMORE COLLEGE

Reading Quiz

Today

- 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)

Pop (remove and return item)

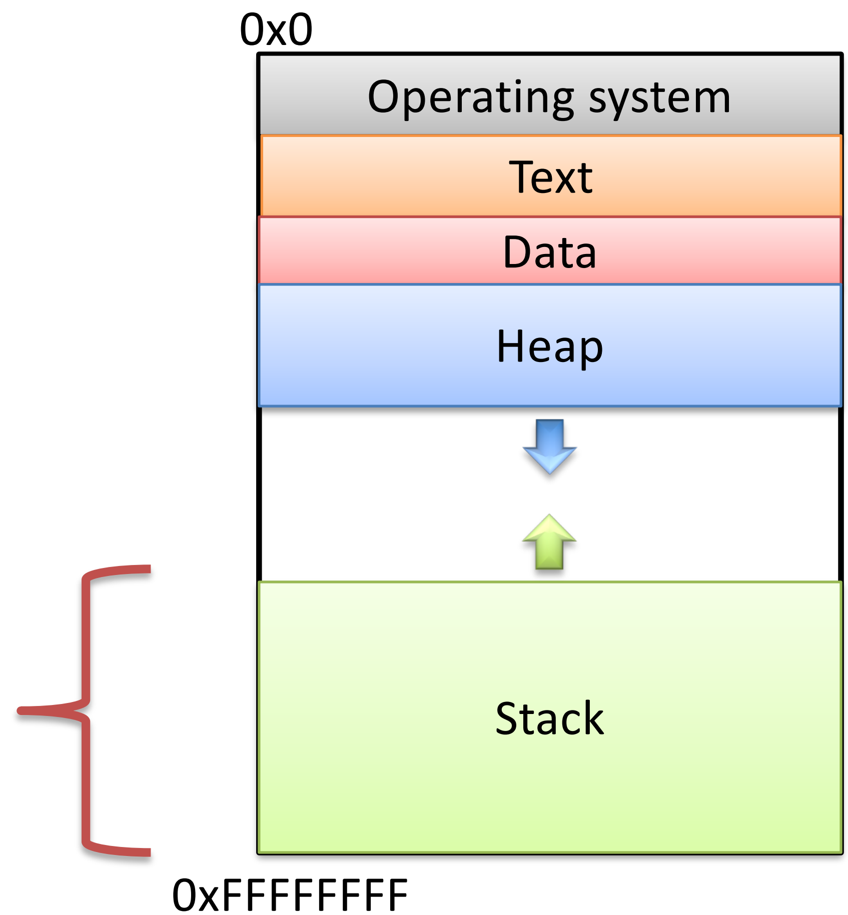
“The” Stack

- 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.

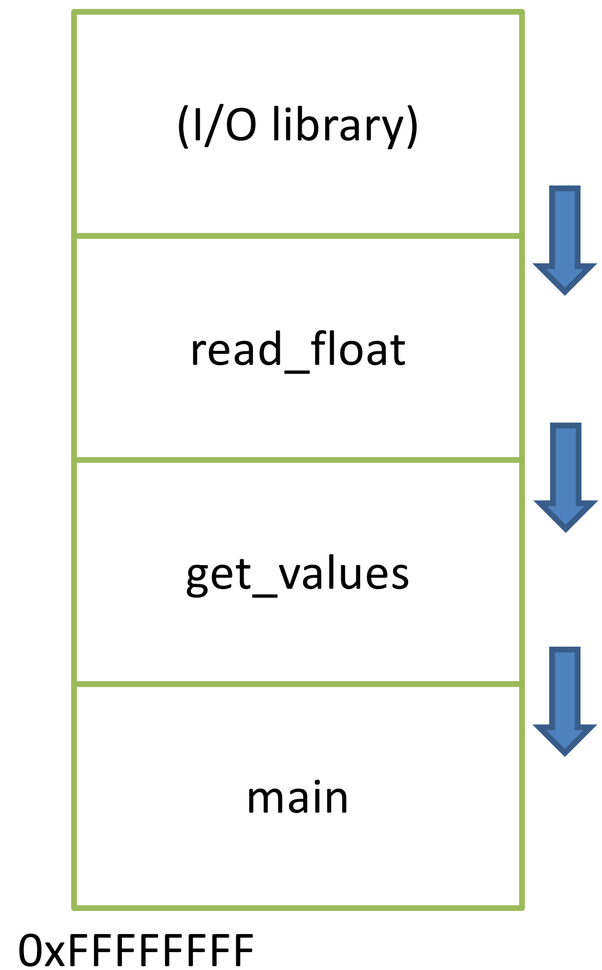
- Example: Lab 4
  - main calls get_values()
  - get_values calls read_float()
  - read_float calls I/O library

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

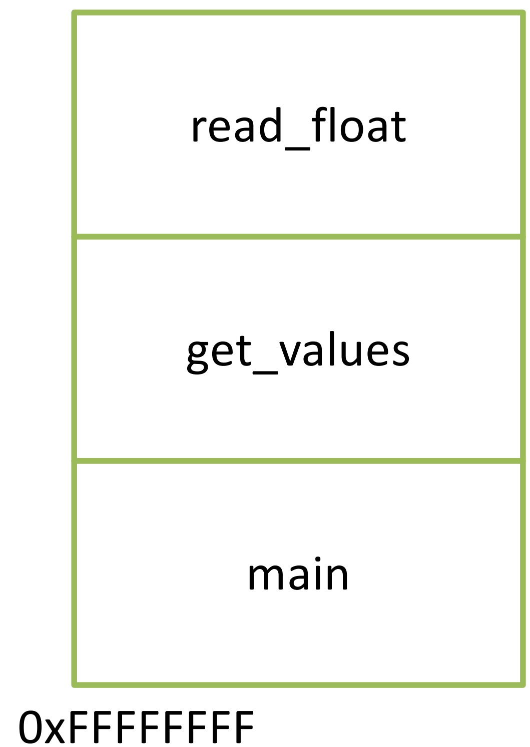
D. The operating system

E. Something / someone else

Insight: EVERY function needs a stack frame. Creating / destroying a stack frame is a (mostly) generic procedure.

Stack Frame Contents

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



Local Variables

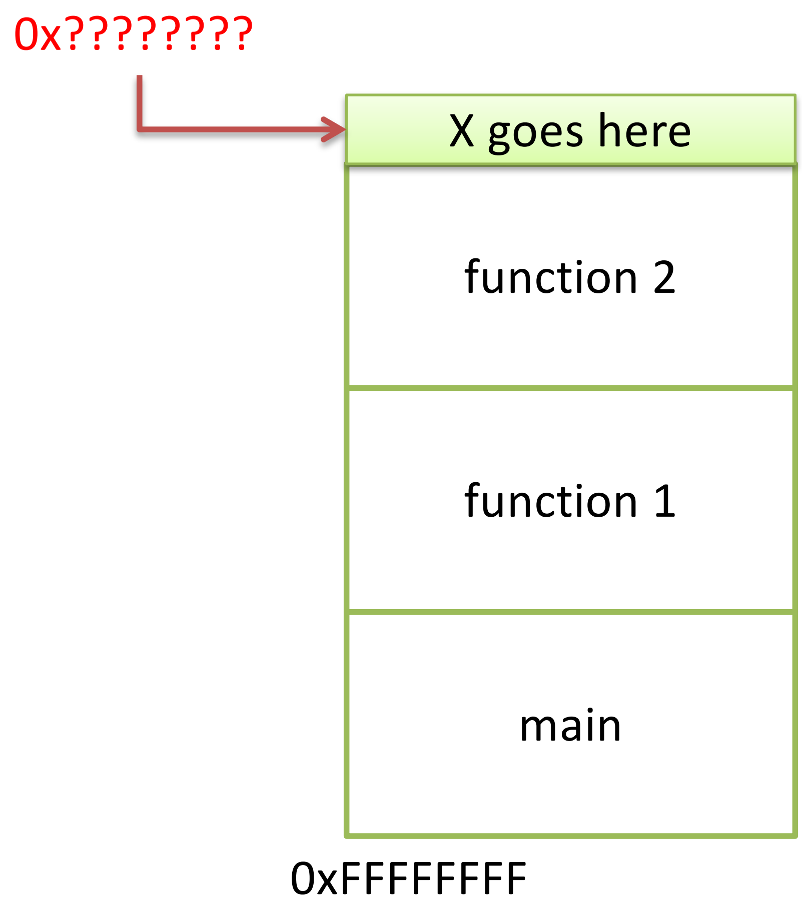
If the programmer says:

```
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.

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…

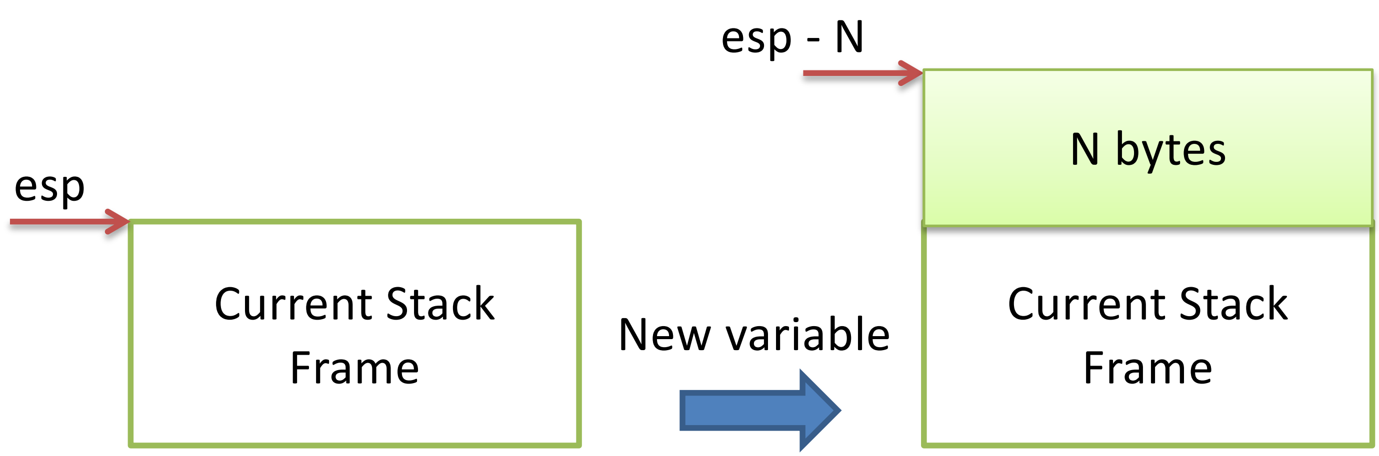
- Perform type checking.

- 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

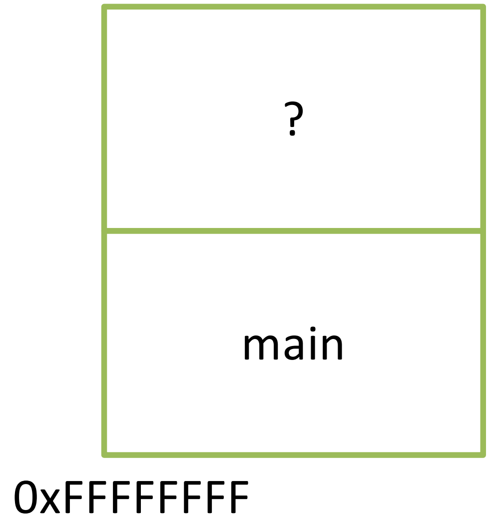
- Compiler can allocate N bytes on the stack by subtracting N from the “stack pointer”: %esp



The Compiler Can't…

- Predict user input.

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



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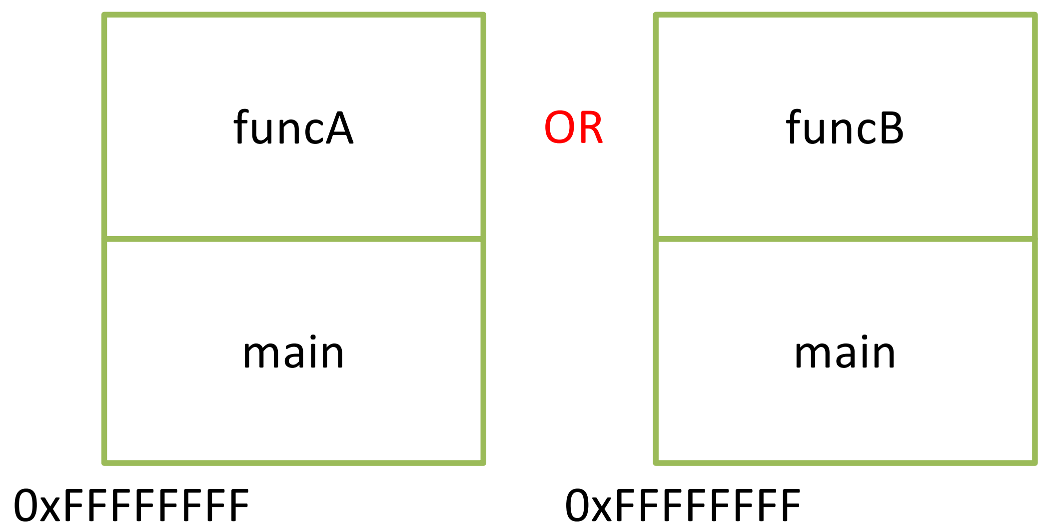
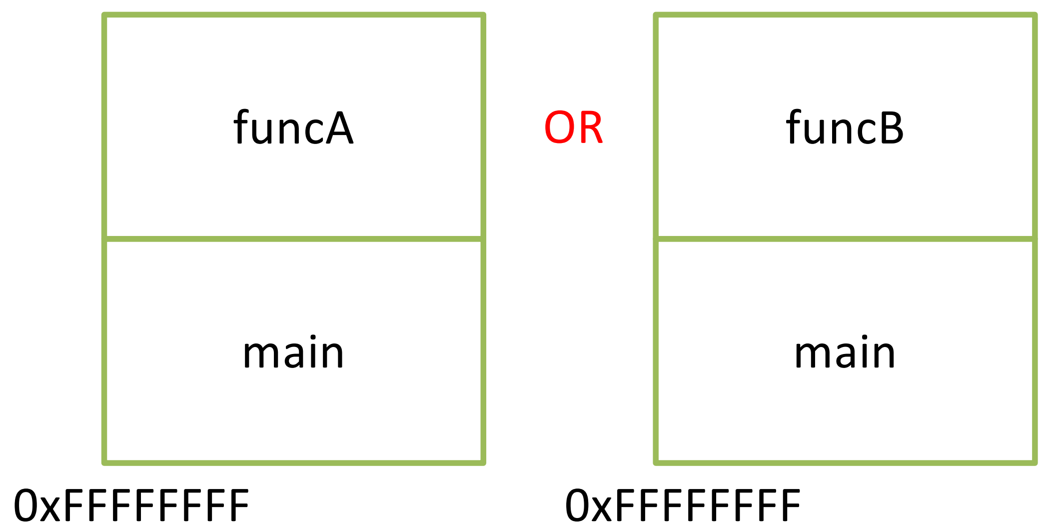


The Compiler Can't…

- Predict user input.

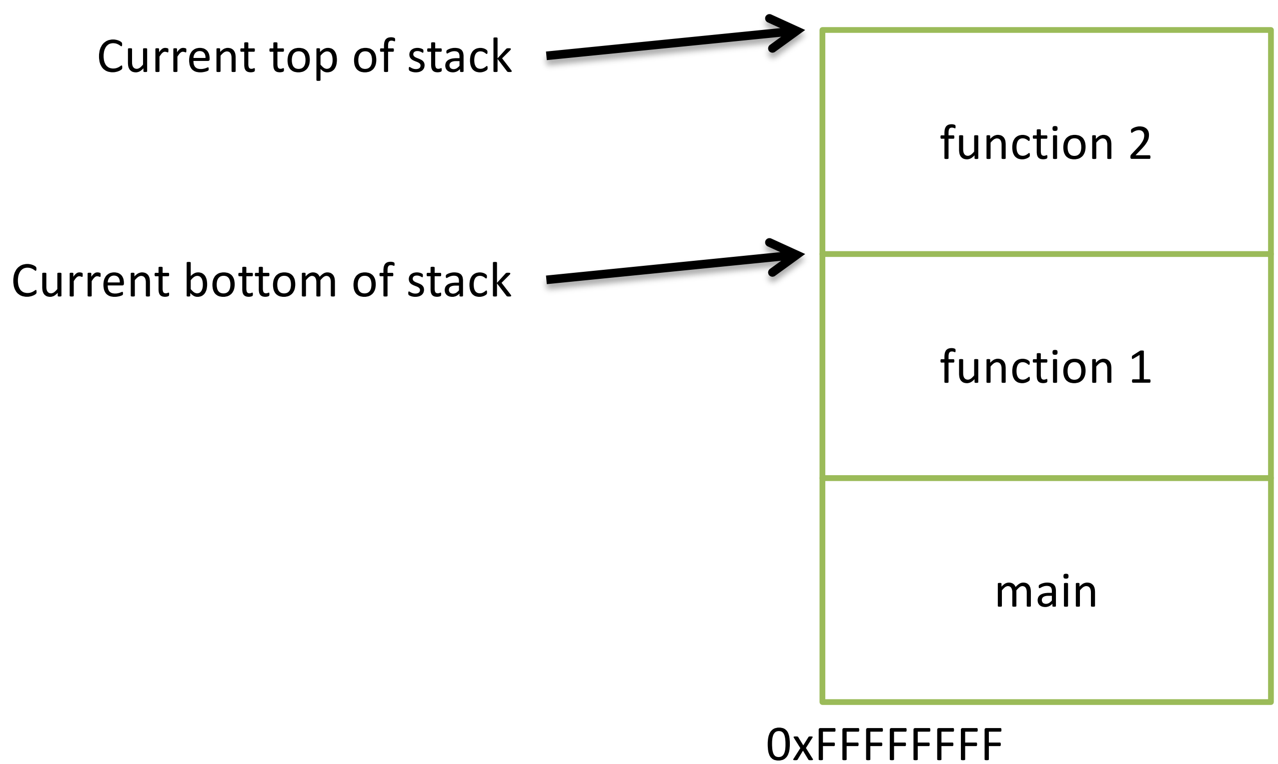
- Can't assume a function will always be at a certain address on the stack.

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



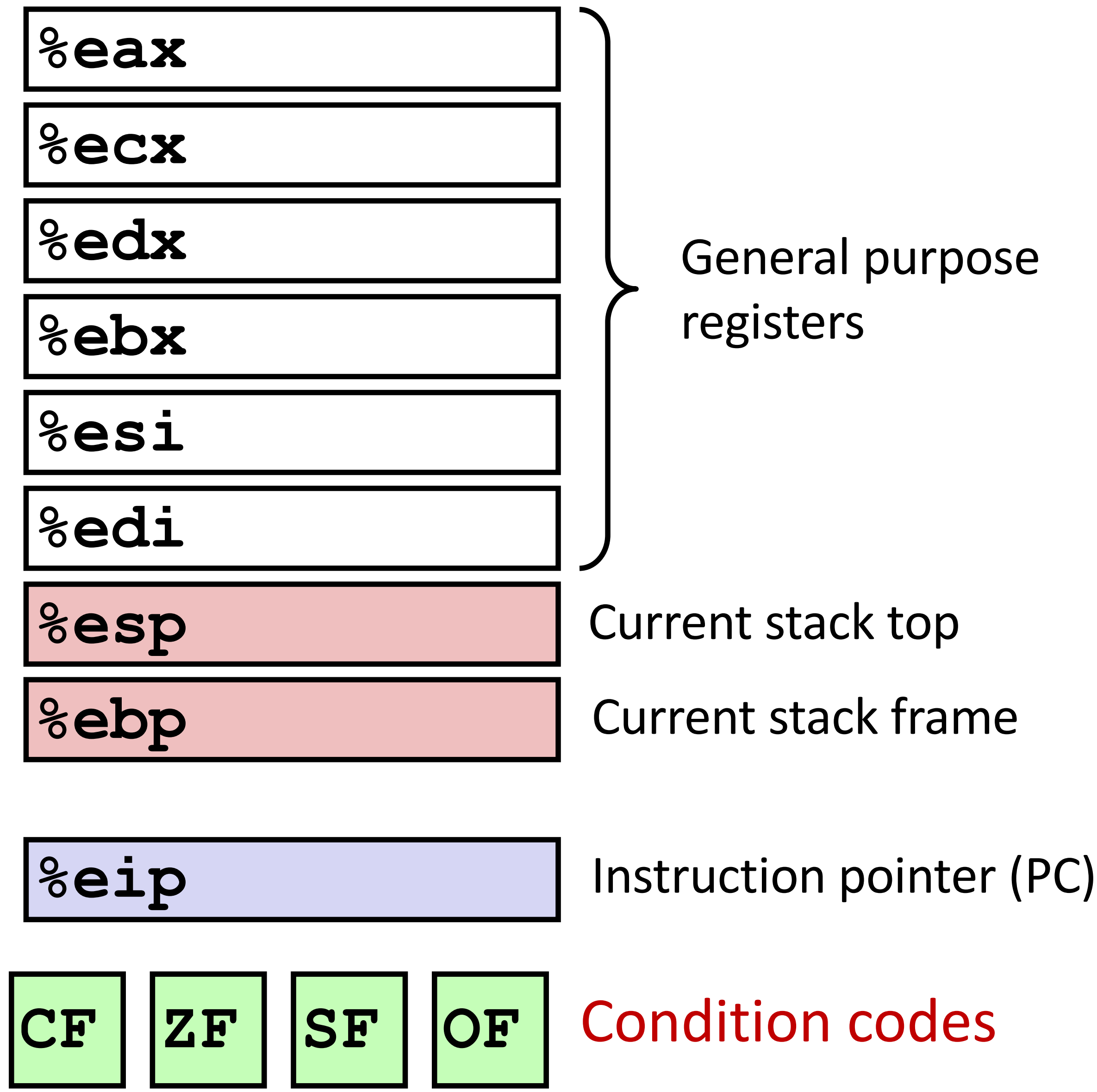
Stack Frame Location

- Where in memory is the current stack frame?



Recall: IA32 Registers

- Information about currently executing program

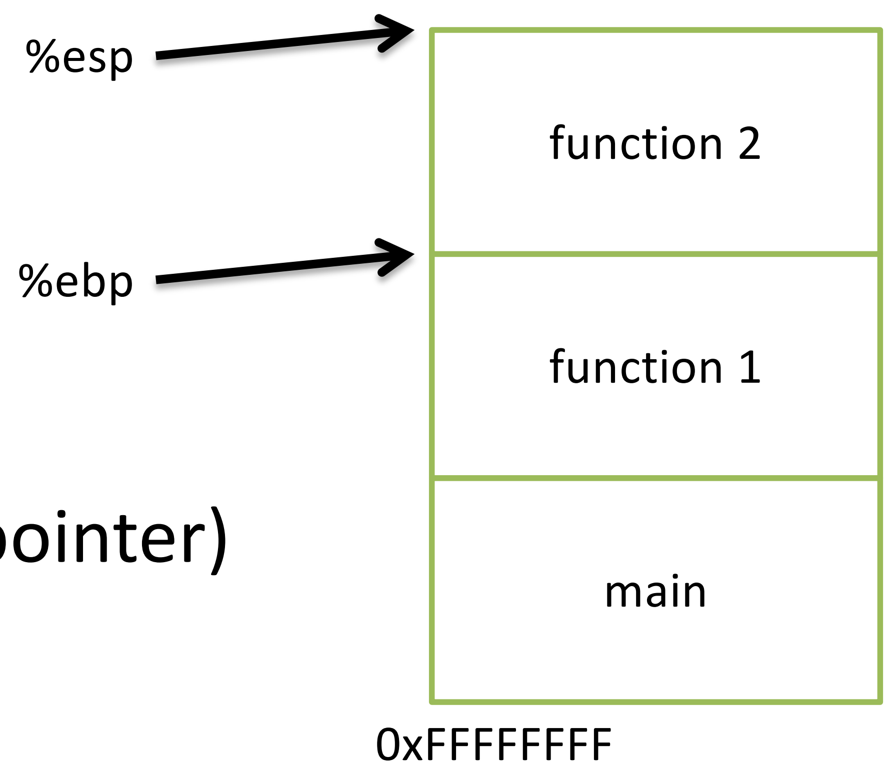


Stack Frame Location

- 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

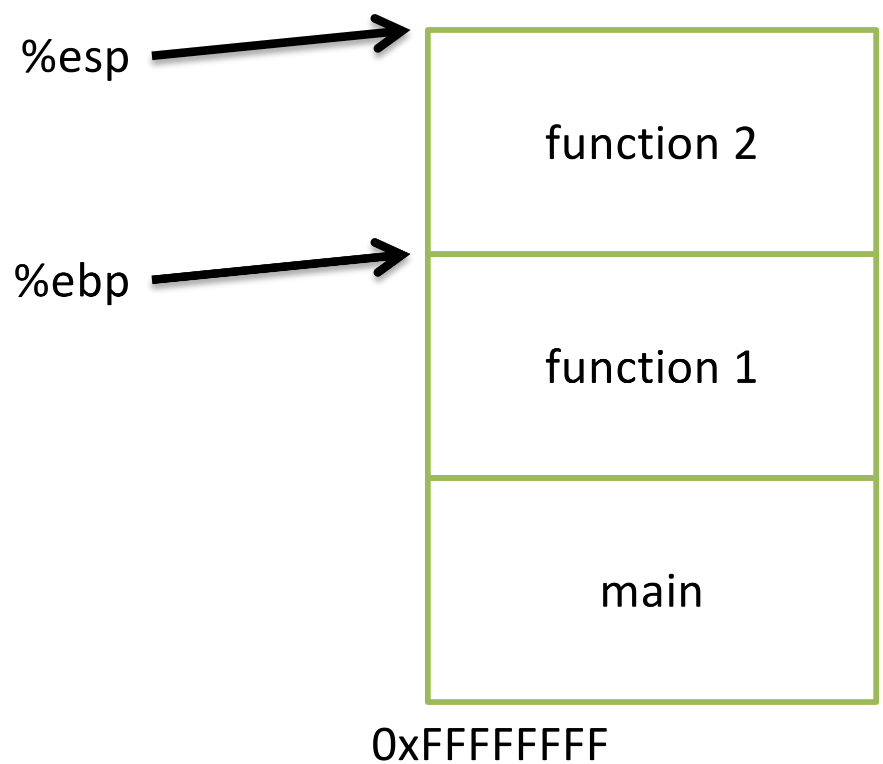
- %esp: stack pointer
- %ebp: frame pointer (base pointer)



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?

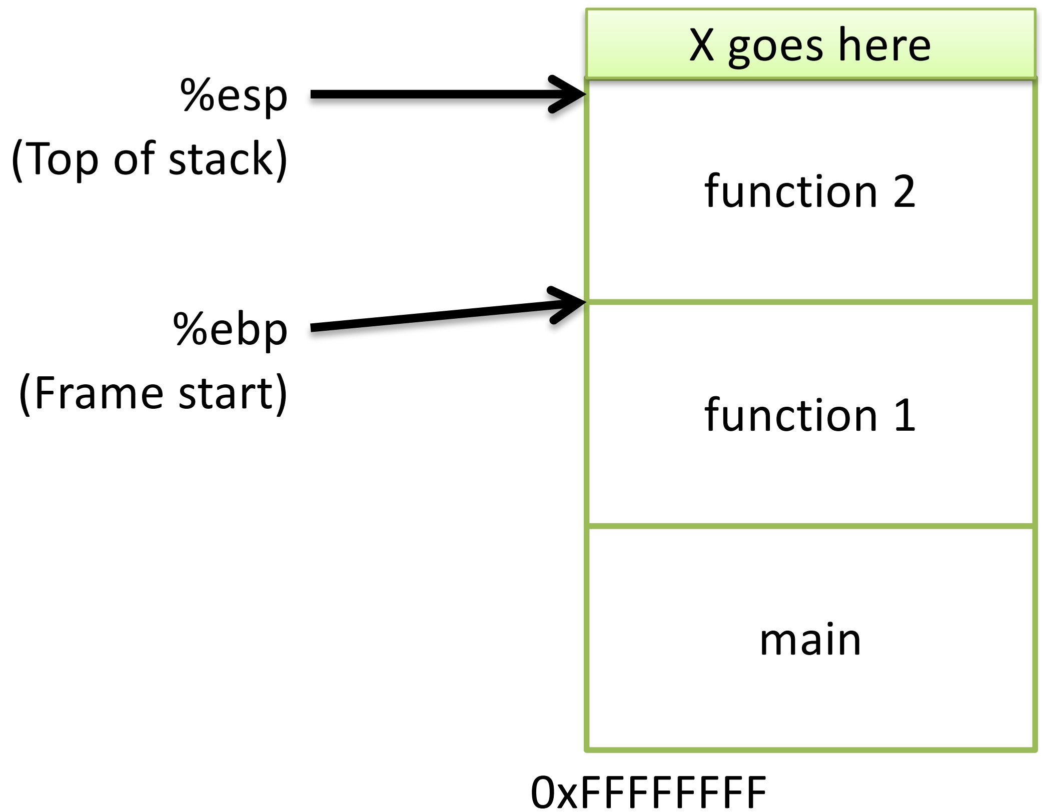
A. Increment %esp
   Store x at (%esp)

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)



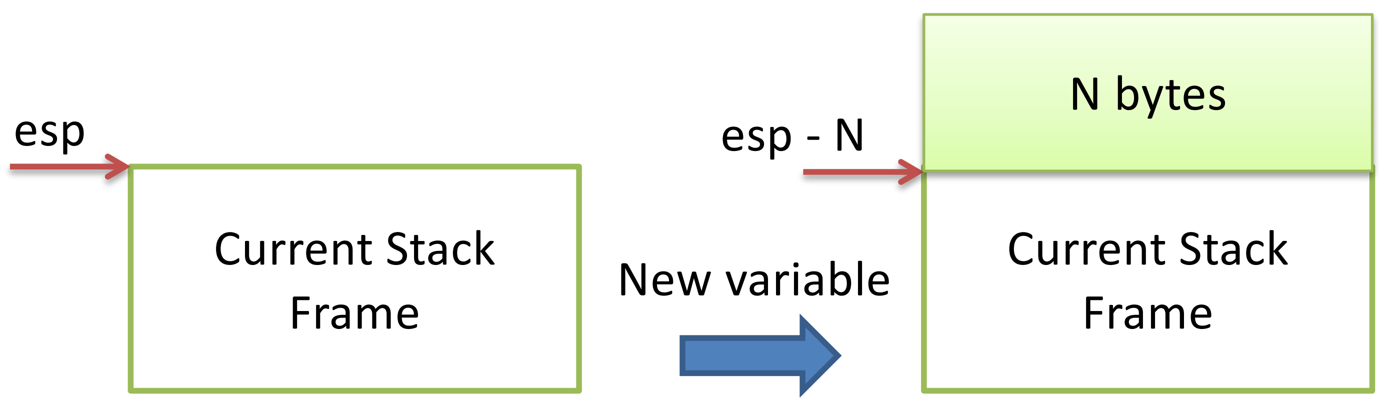
Push & Pop

- 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

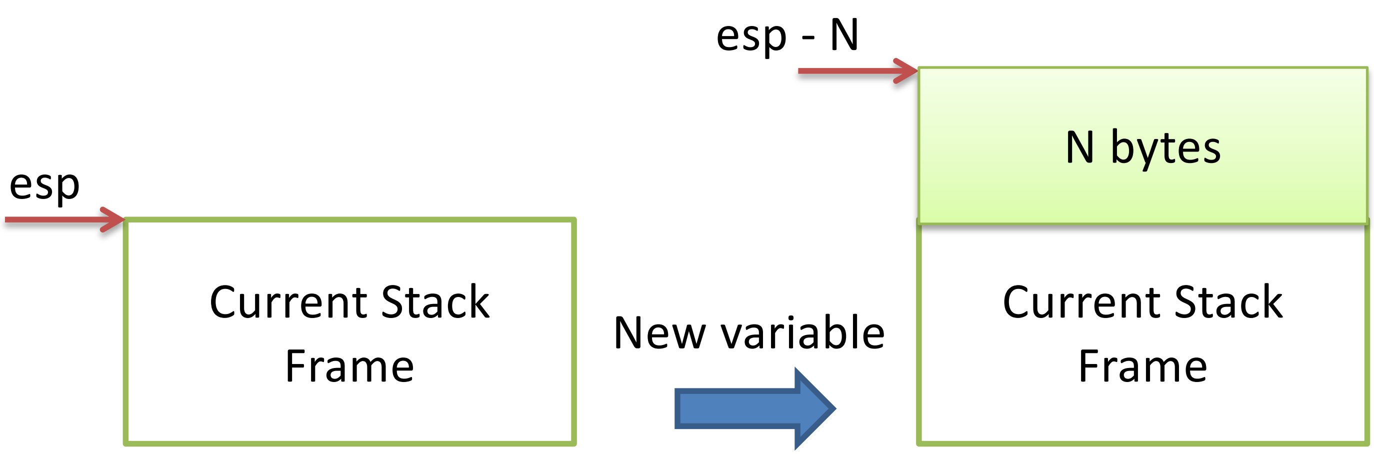
Local Variables

- 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

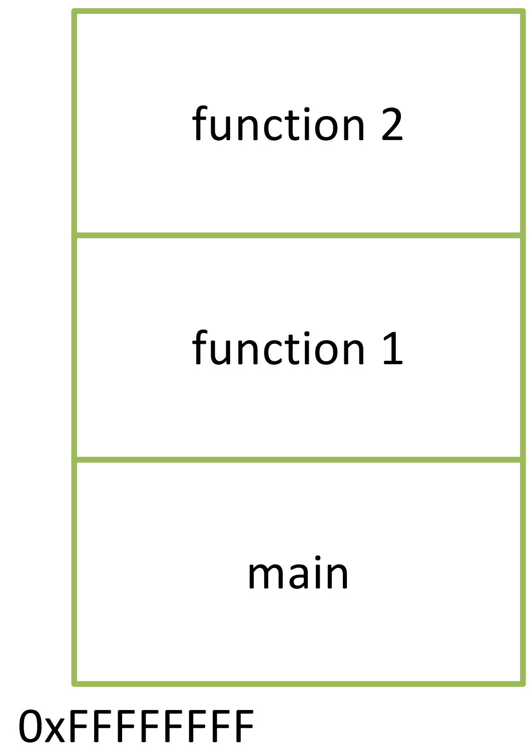


Stack Frame Contents

- 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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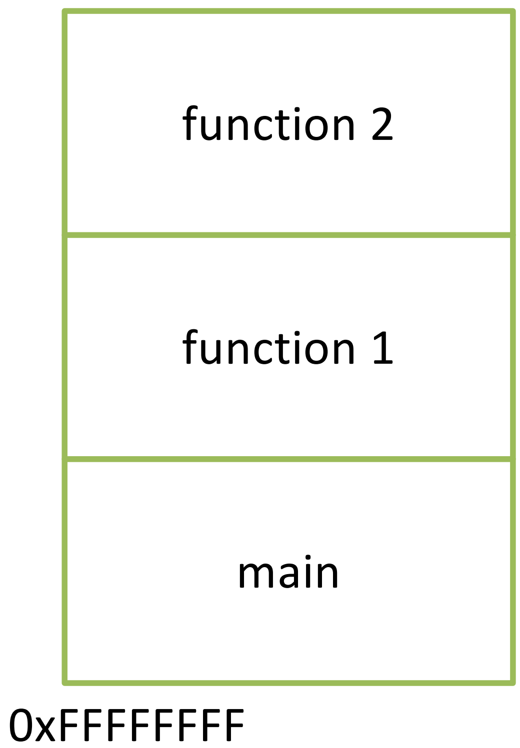
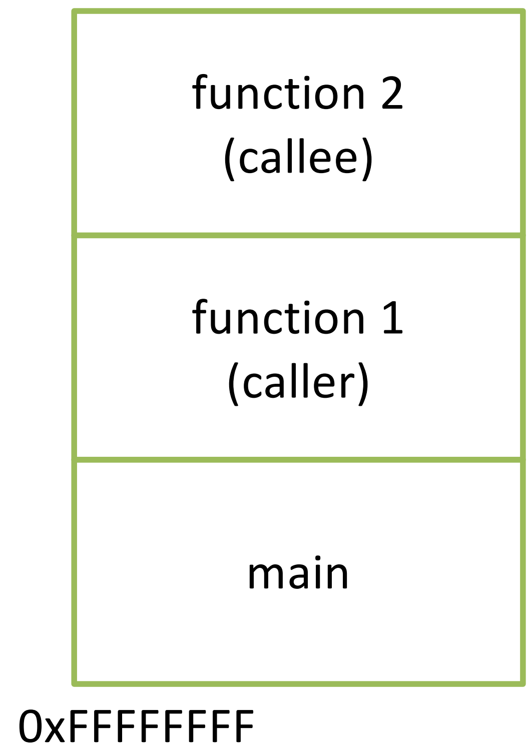


Stack Frame Relationships

- 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



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

Program Characteristics

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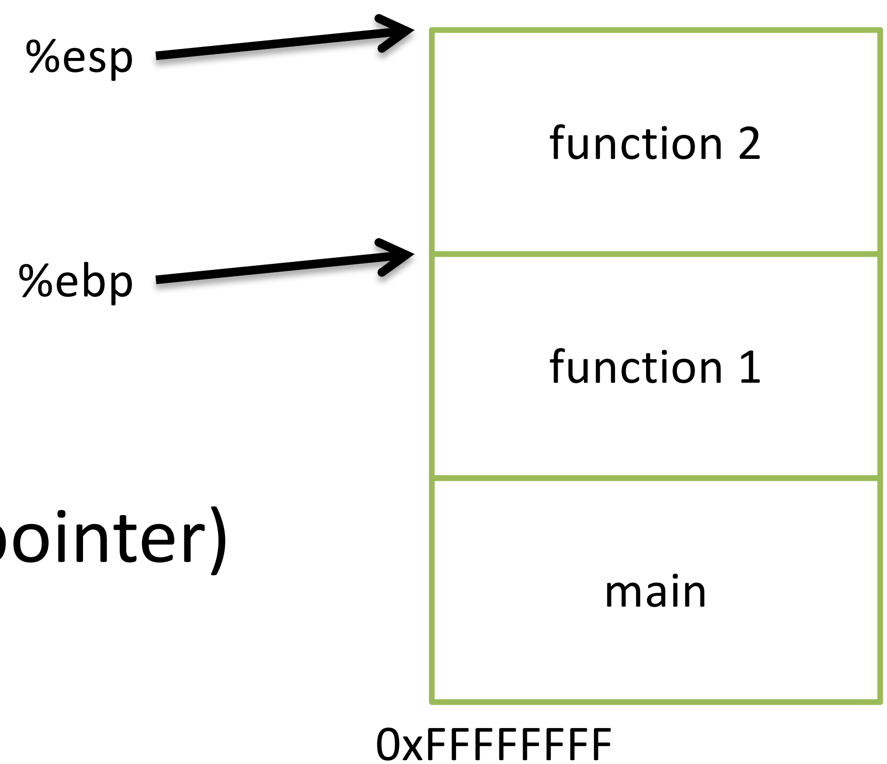

- %esp: stack pointer
- %ebp: frame pointer (base pointer)

Push & Pop

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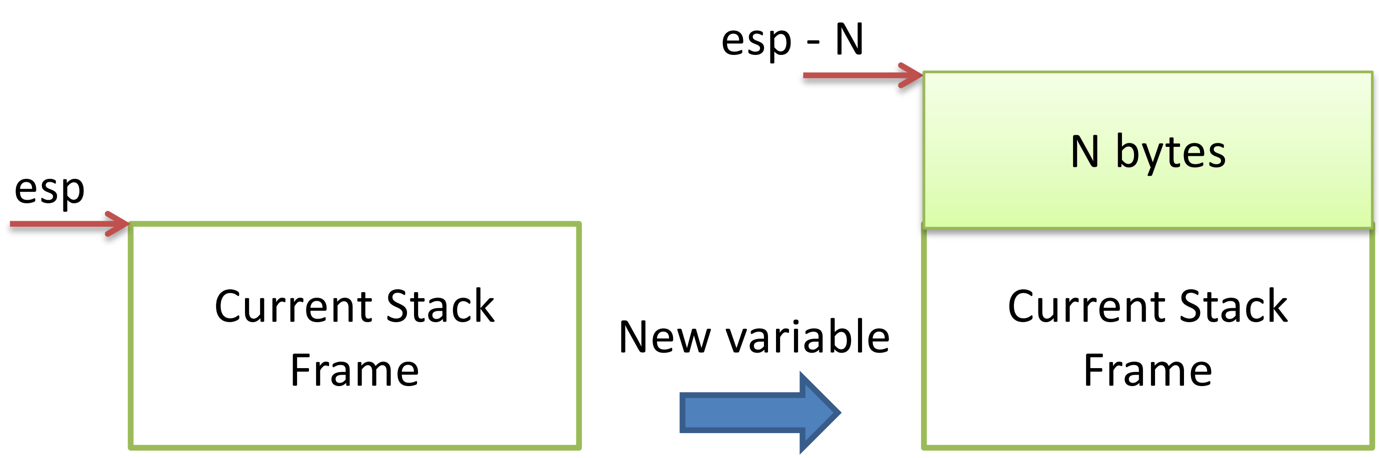

Stack Frame Contents

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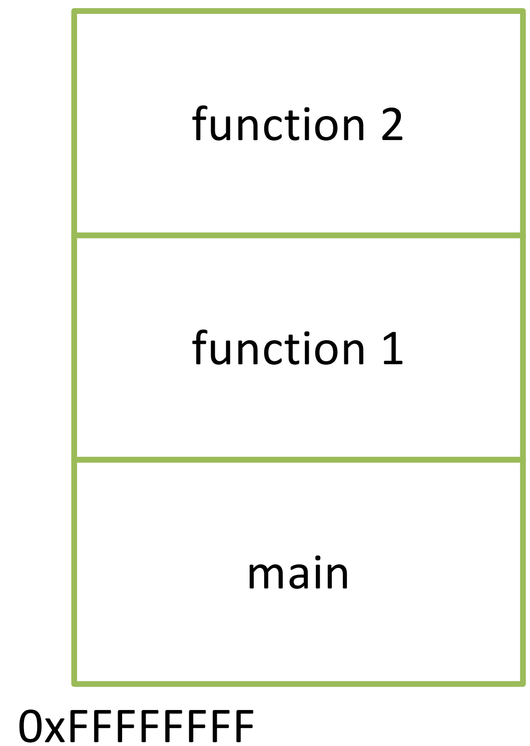

Where should we store all this stuff?

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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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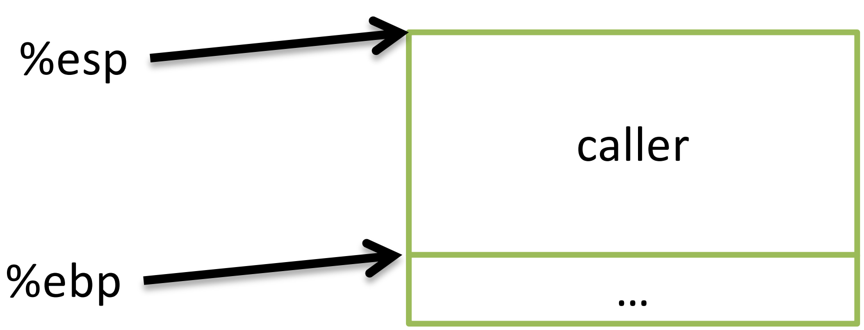
Frame Pointer

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

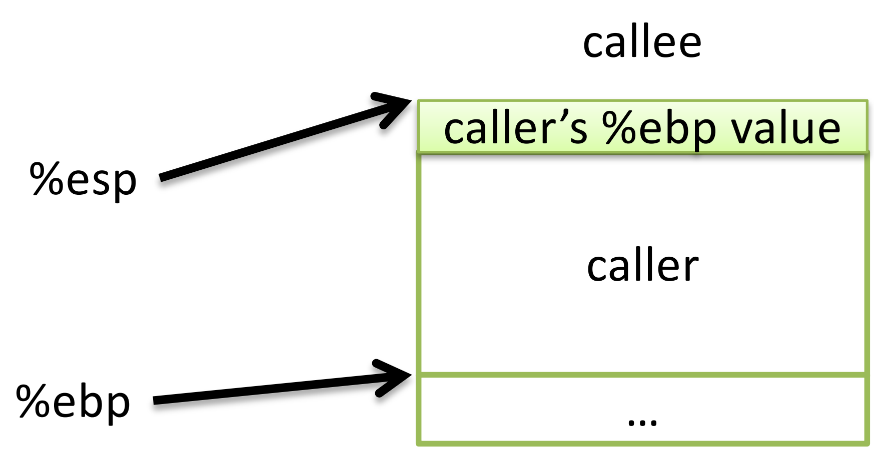
- Must adjust %esp, %ebp on call / return.



Frame Pointer

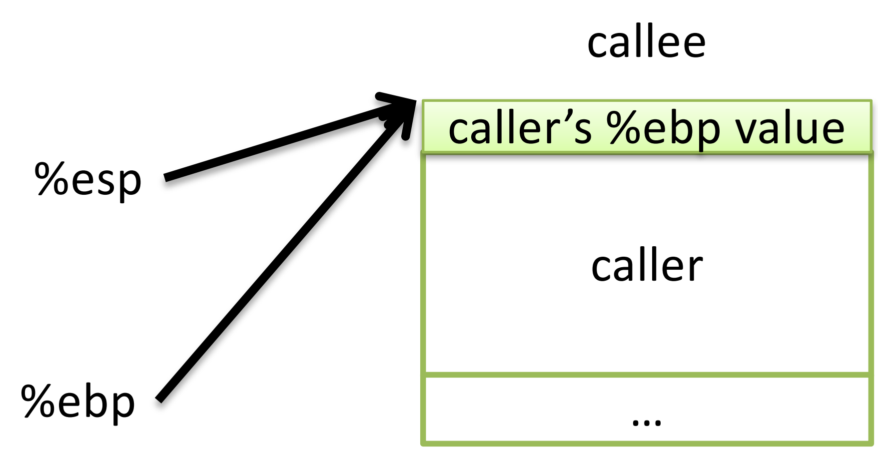
- Must maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp

- 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

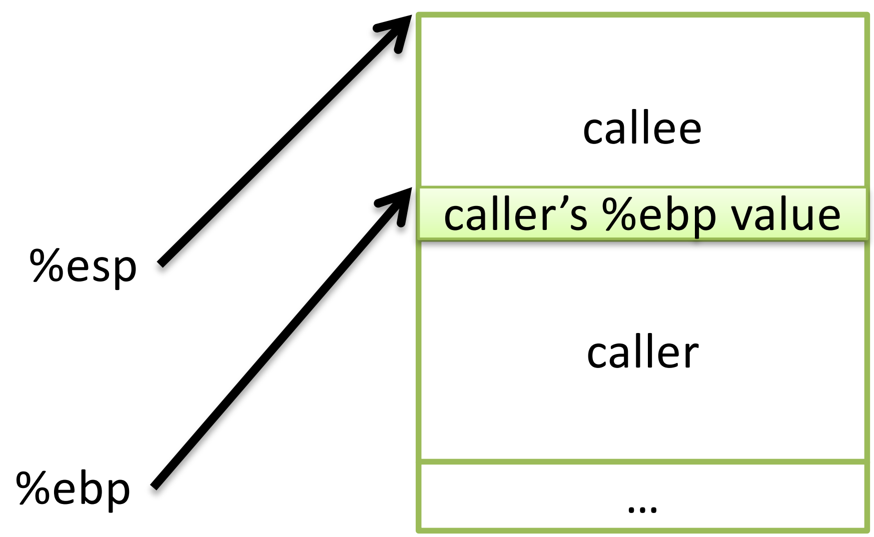


Frame Pointer

- 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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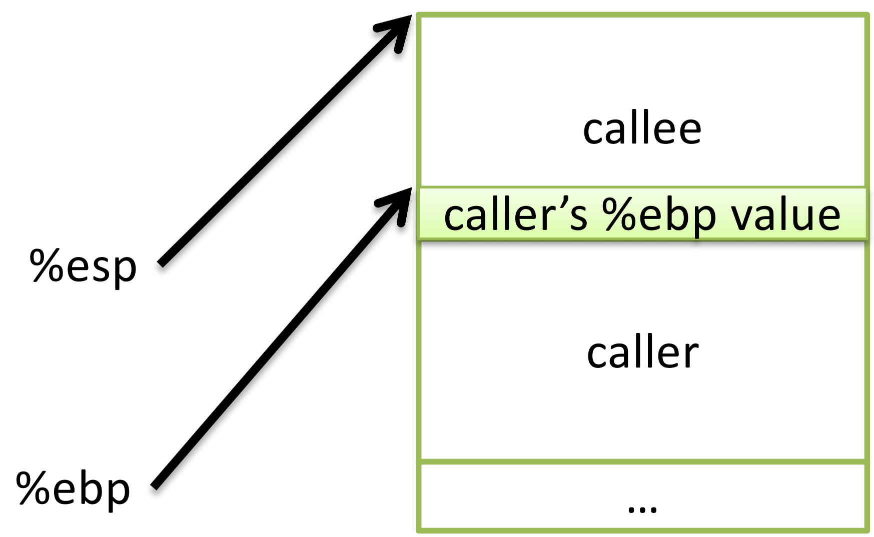
- To return, reverse this:



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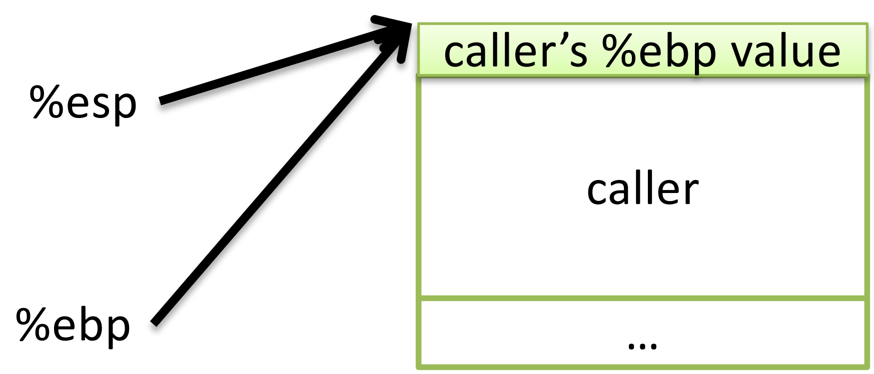

Frame Pointer

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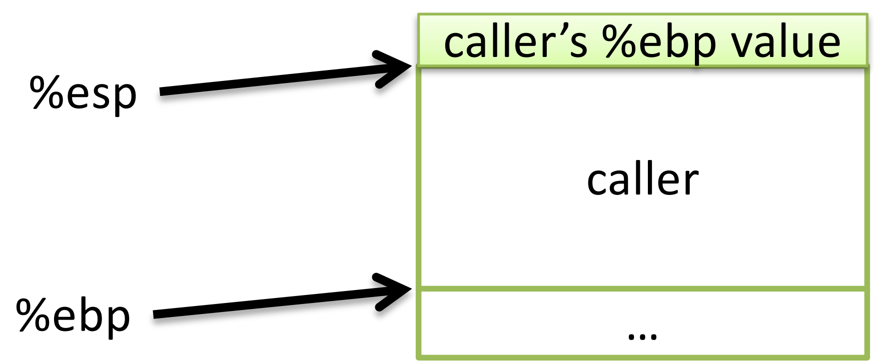
  1. set %esp = %ebp
  2. popl %ebp



Frame Pointer

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

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  1. set %esp = %ebp
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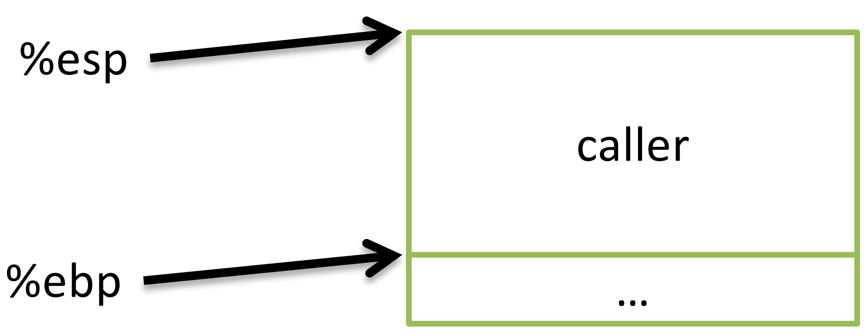
IA32 has another convenience instruction for this: leave



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.

Store return value in %eax.

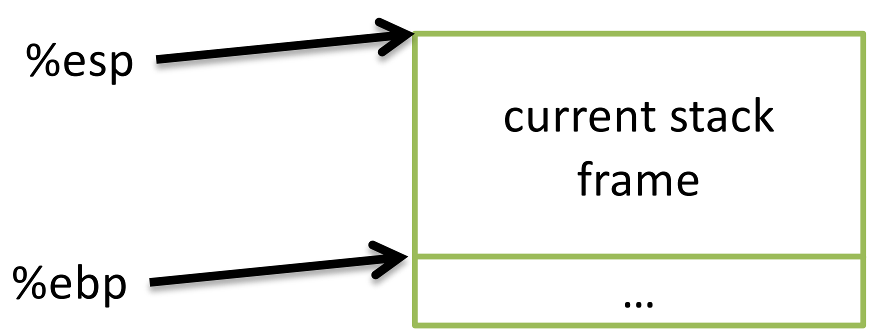
Restore caller's %esp, %ebp.

Recap

- The stack memory region keeps state for the sequence of function calls we've made
- The state for one function is a *stack frame*
- If function A calls function B:
  - function A is the *caller*
  - function B is the *callee*

Recap

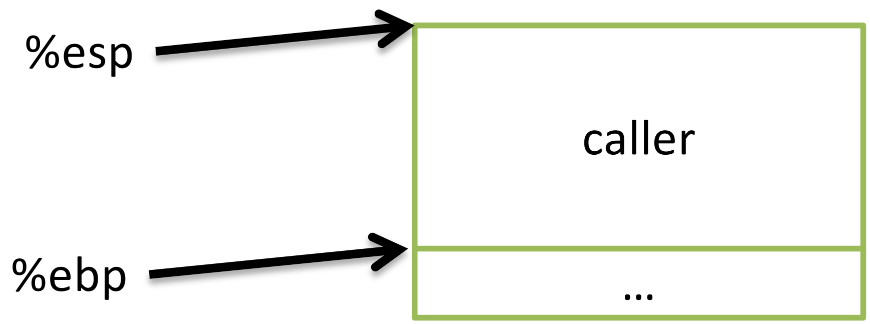
- Dedicate CPU registers for stack bookkeeping
  - %esp (stack pointer): Top of current stack frame
  - %ebp (frame pointer): Base of current stack frame
- Compiler maintains these pointers by inserting instructions on function call/return.
  - It doesn't know (or care about) the exact addresses they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



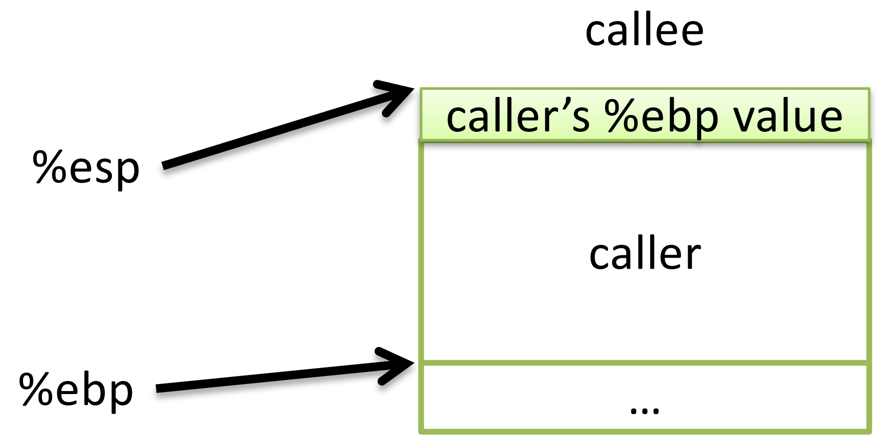
Recap: IA32 Calling Convention (gcc)

- 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)

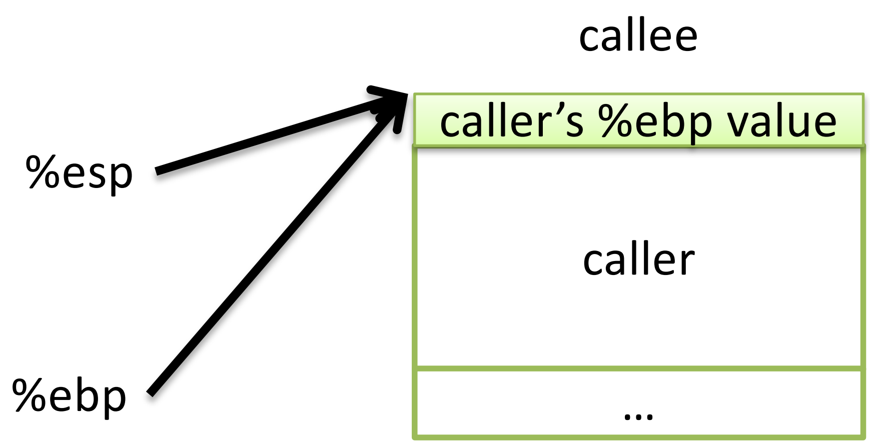
Frame Pointer: Function Call



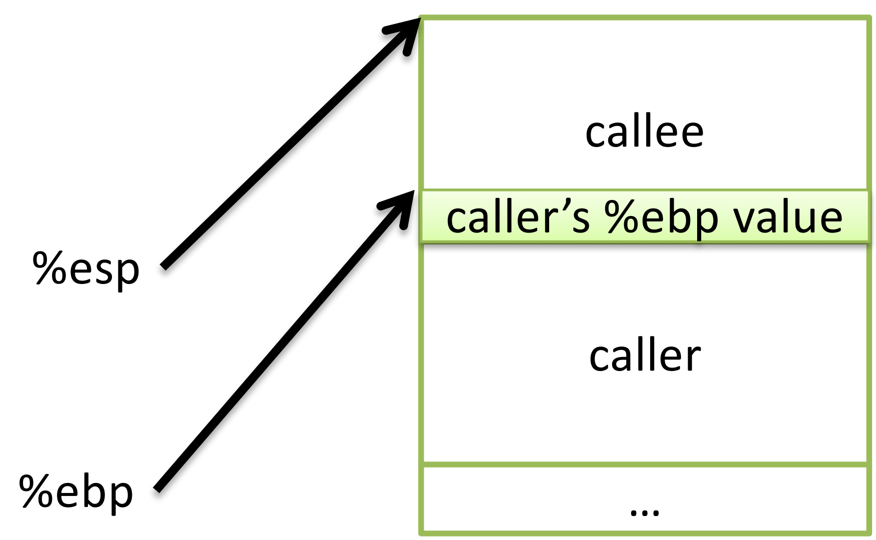
Initial state



pushl %ebp (store caller's frame pointer)

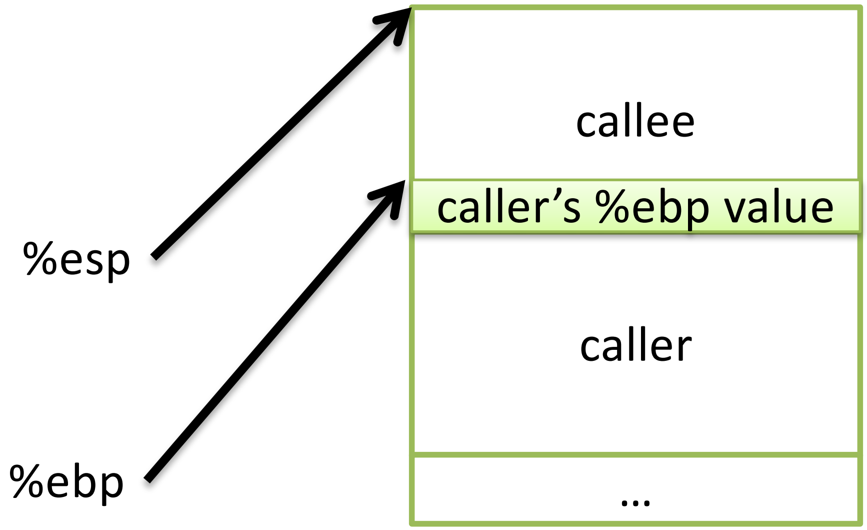


movl %esp, %ebp
(establish callee's frame pointer)

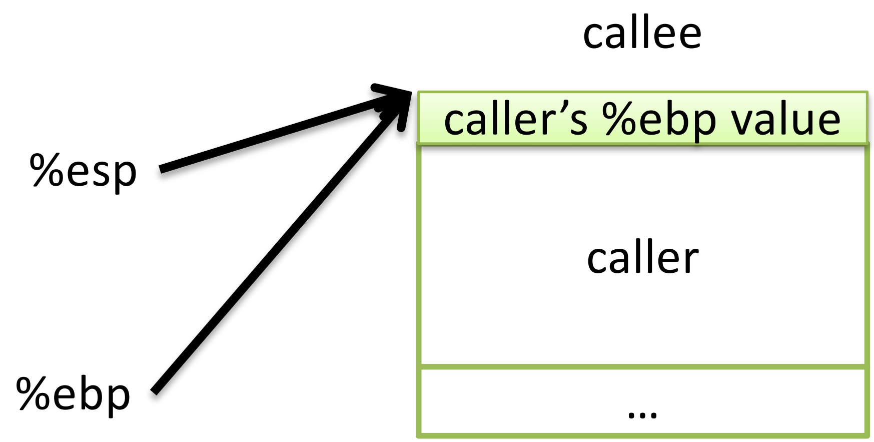


subl $SIZE, %esp
(allocate space for callee's locals)

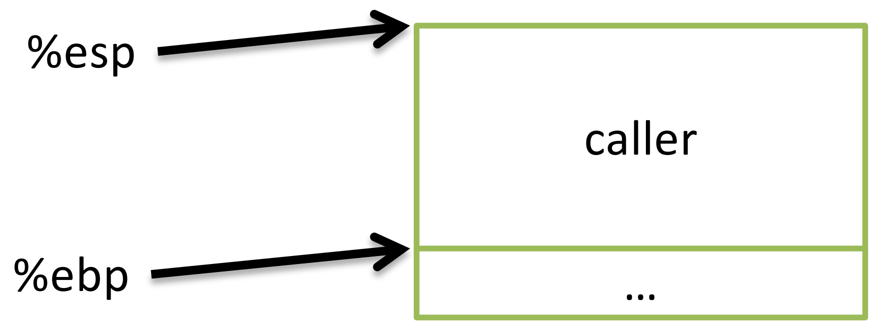
Frame Pointer: Function Return



Want to restore caller's frame.



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



popl %ebp (restore caller's frame pointer)

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

Lab 4: swap.s

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

    # Your code here

    leave
    ret
```

IA32 Calling Convention (gcc)

- In register %eax:
  - The return value
- In the callee's stack frame:
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- In the caller's frame (shared with callee):
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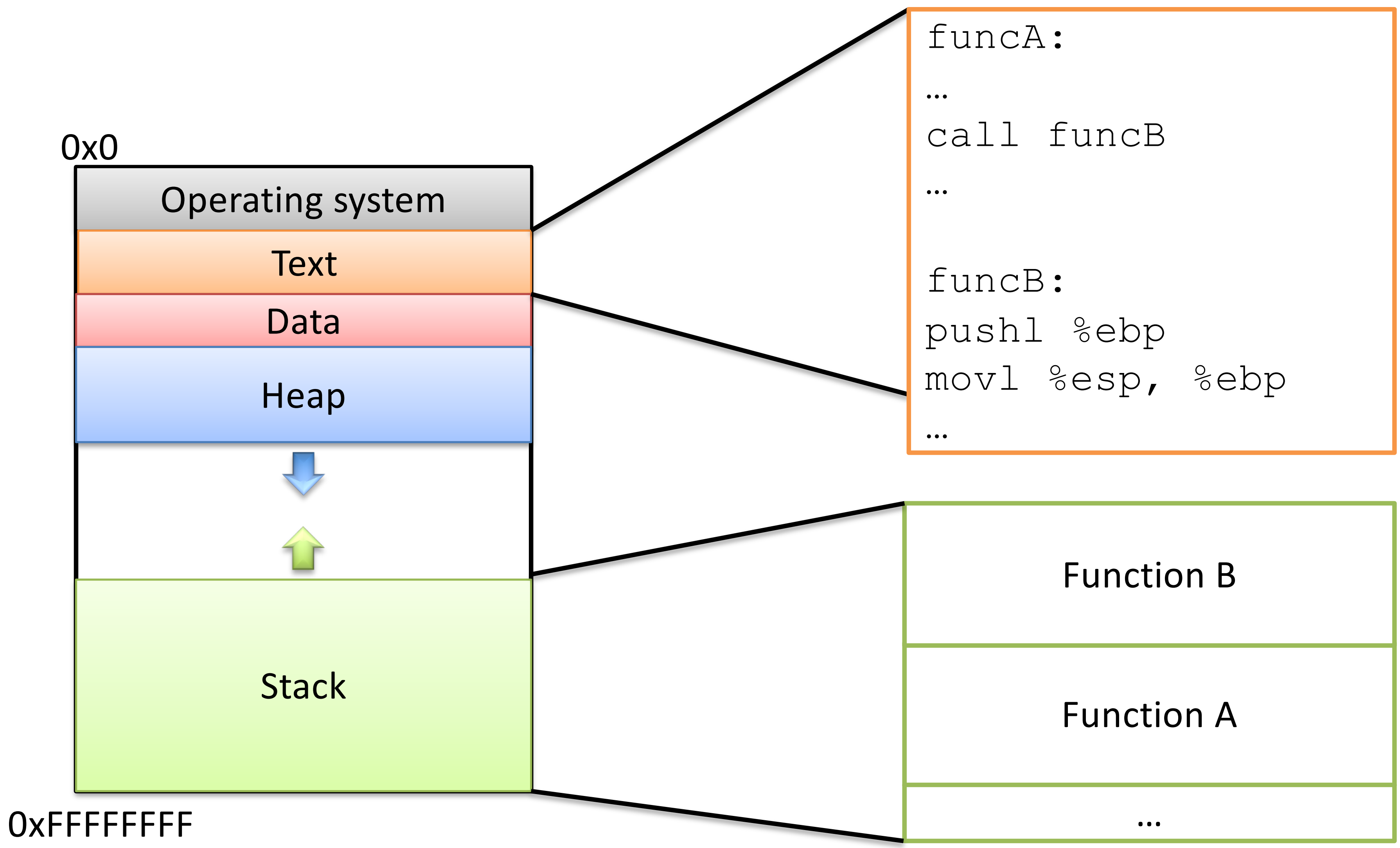
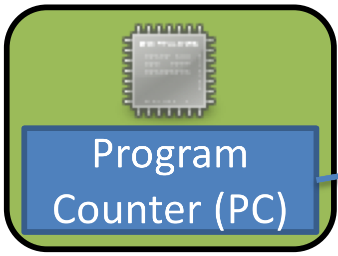
Instructions in Memory



Program Counter

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



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`

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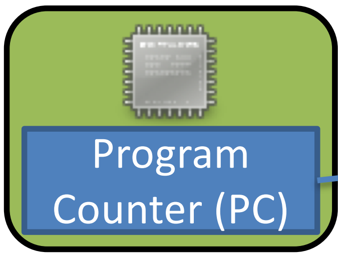

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…

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

What do we do now?

Follow PC, fetch instruction:

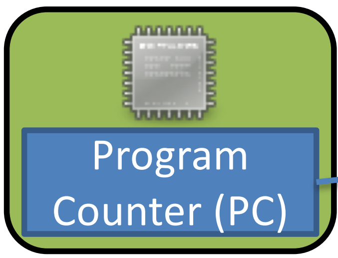
`addl $5, %ecx`

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)
```

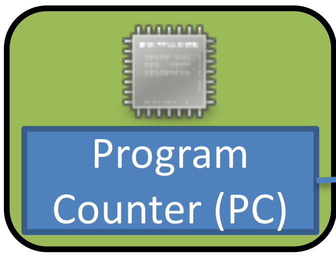
Text Memory Region

```
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
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…
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:

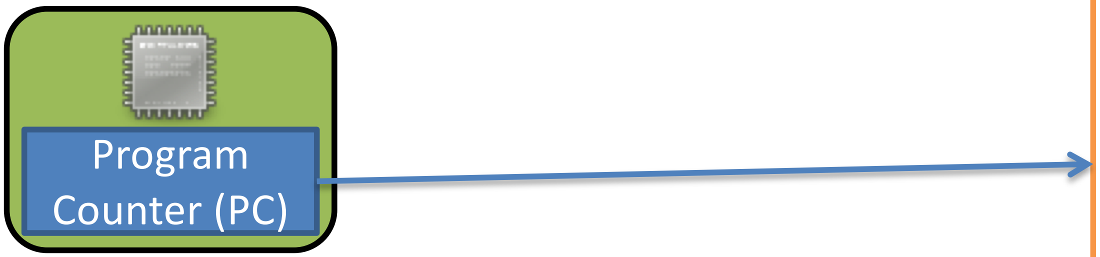
`movl $ecx, -4(%ebp)`

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.)



What do we do now?

Keep executing in a straight line downwards like this until:

We hit a jump instruction.
We call a function.

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
```

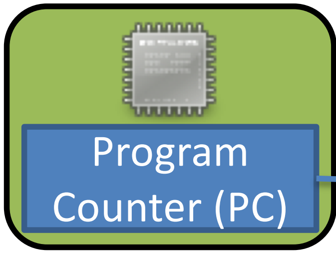
Changing the PC: Jump

- 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



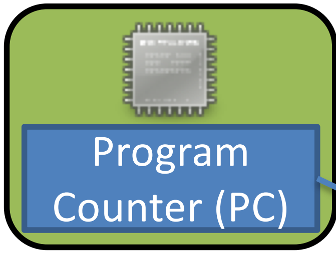
Text Memory Region

```
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:

Changing the PC: Functions



What we'd like this to do:

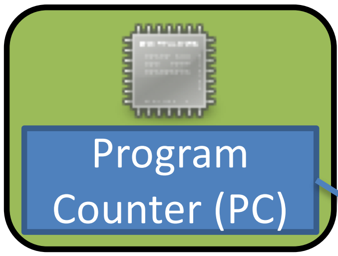
Set up function B's stack.

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



What we'd like this to do:

Set up function B's stack.

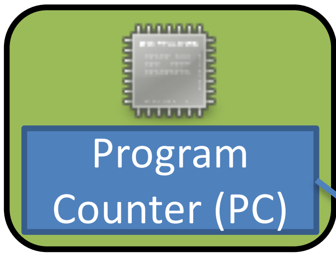
Execute the body of B, produce result (stored in %eax).

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



What we'd like this to do:

Set up function B's stack.

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

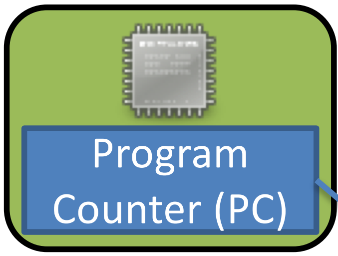
Restore function A's stack.

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:

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:

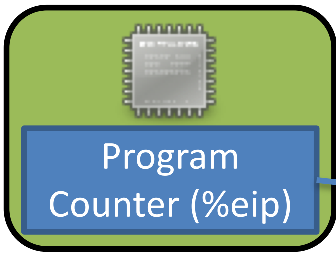
Like `push`, `pop`, and `leave`, `call` and `ret` are convenience instructions.
What should they do to support the PC-changing behavior we need? (The PC is %eip.)

call	ret
In words:	In words:
save the PC jump to func	restore PC
In instructions:	In instructions:
pushl %eip jmp func_label	popl %eip

Functions and the Stack

Executing instruction:
`call funcB`

PC points to <u>next instruction</u>



Text Memory Region

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

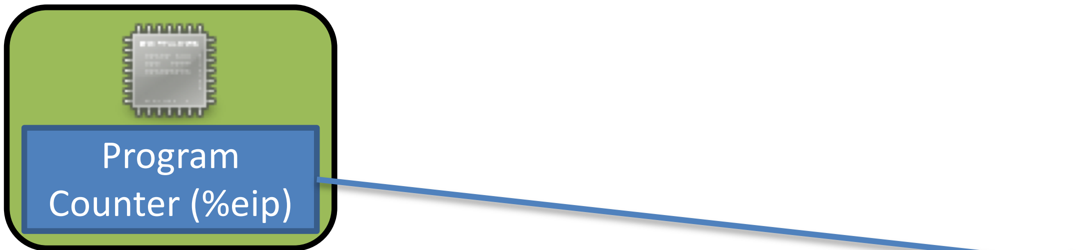
funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

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
…

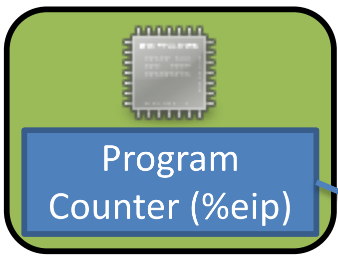
funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Stack Memory Region

Stored PC in funcA
Function A
…

Functions and the Stack

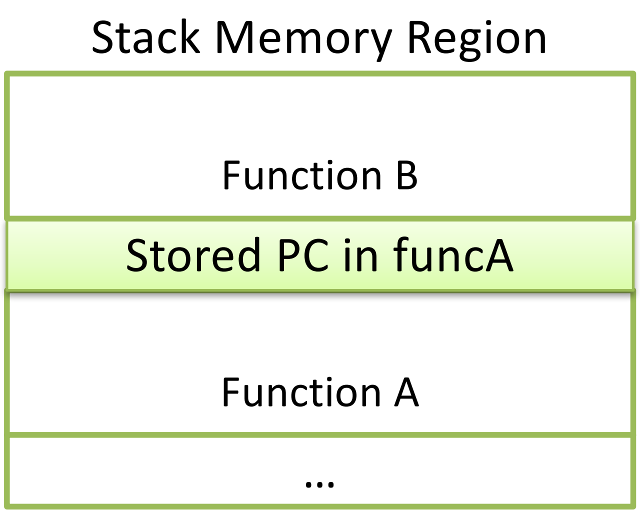
1. pushl %eip
2. jump funcB
3. (execute funcB)



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
```



Functions and the Stack

Program Counter (%eip)

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

Stack Memory Region

Stored PC in funcA
Function A
…

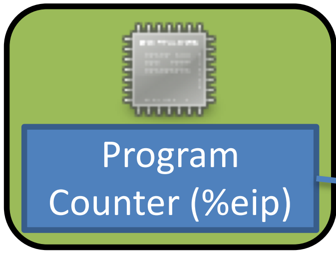
Text Memory Region

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

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

Functions and the Stack

6. (resume funcA)



Text Memory Region

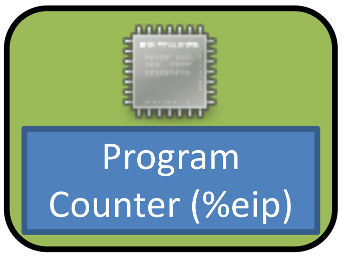
```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

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

Stack Memory Region

Function A
…

Functions and the Stack



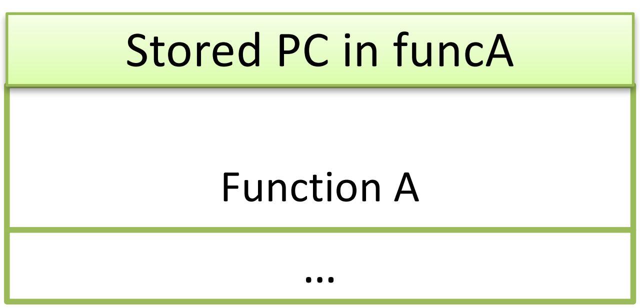
1. pushl %eip
2. jump funcB
3. (execute funcB)
4. restore stack
5. popl %eip
6. (resume funcA)

Text Memory Region

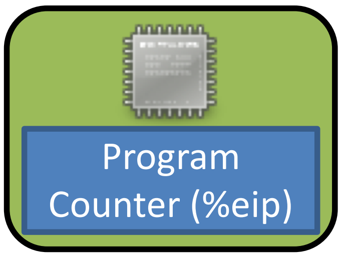
```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

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

Stack Memory Region



Functions and the Stack



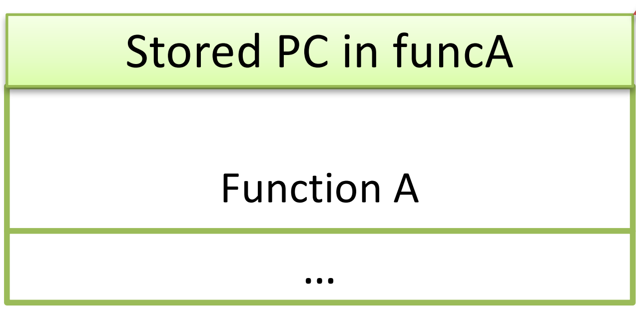
1. pushl %eip
2. jump funcB
3. (execute funcB)
4. restore stack
5. popl %eip
6. (resume funcA)

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)

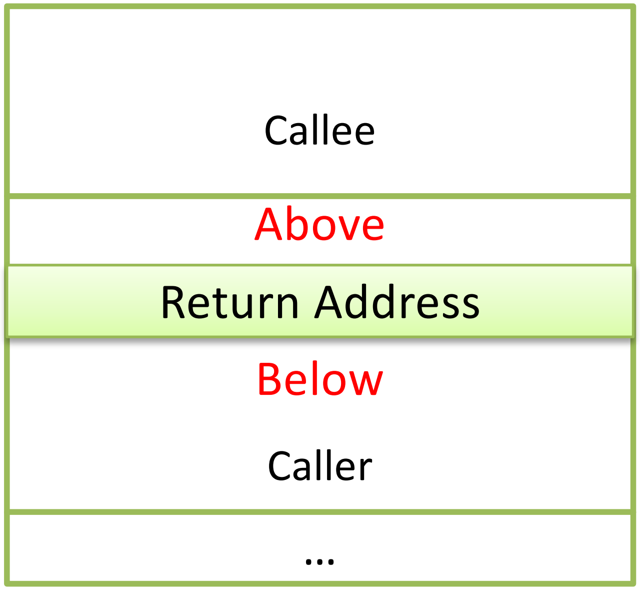
- In register %eax:
  - The return value
- In the callee's stack frame:
  - The caller's %ebp value (previous frame pointer)
- In the caller's frame (shared with callee):
  - Function arguments
  - Return address (saved PC value)

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

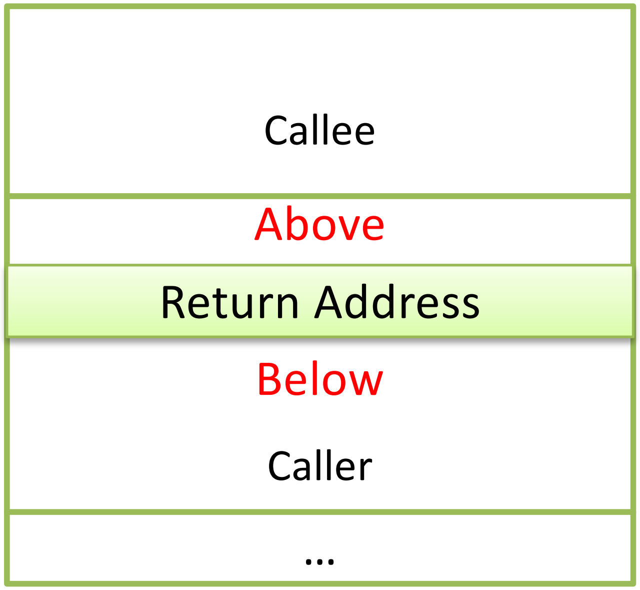


We know we're going to place arguments on the stack, in the caller's frame. Should they go above or below the return address?

A. Above

B. Below
   – have the arguments below, because we want to be able to pop off the return address on top of the stack

C. Somewhere else



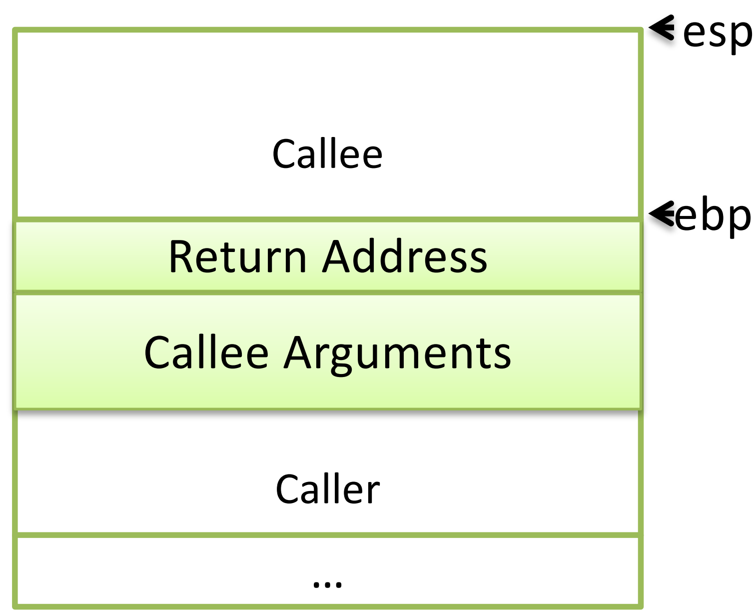
IA32 Stack / Function Call Instructions

`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`

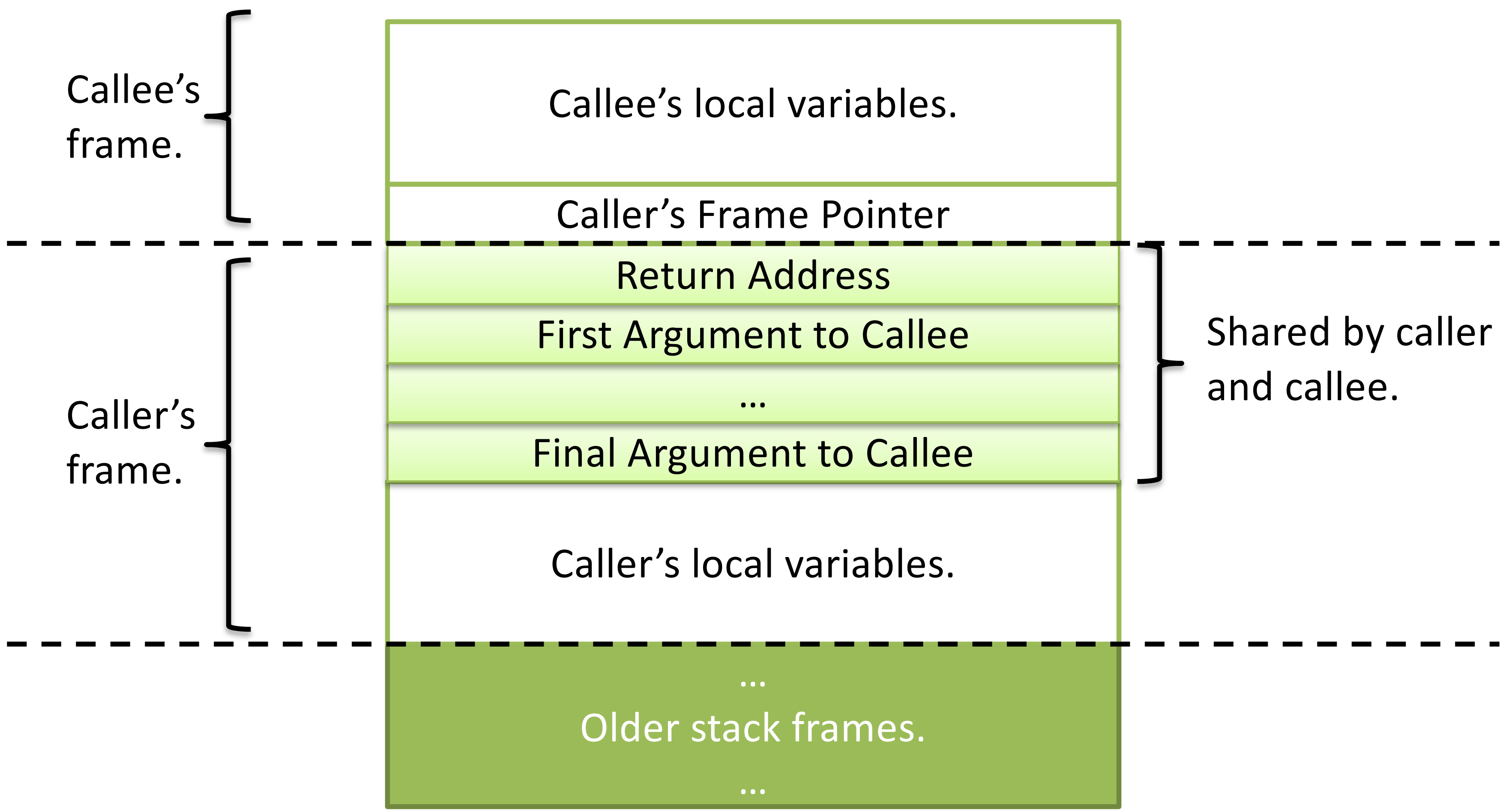
Arguments

- 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…

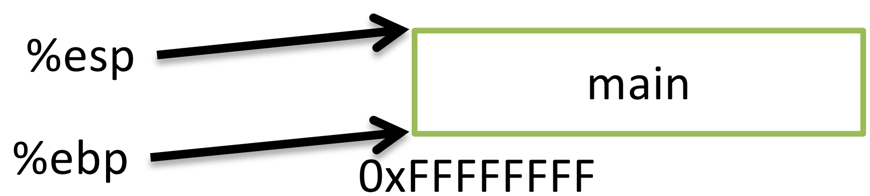


How would we translate this to IA32? What should be on the stack?

```
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

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

main:

1. push $3
2. push $2
3. push $1
4. call func

func:

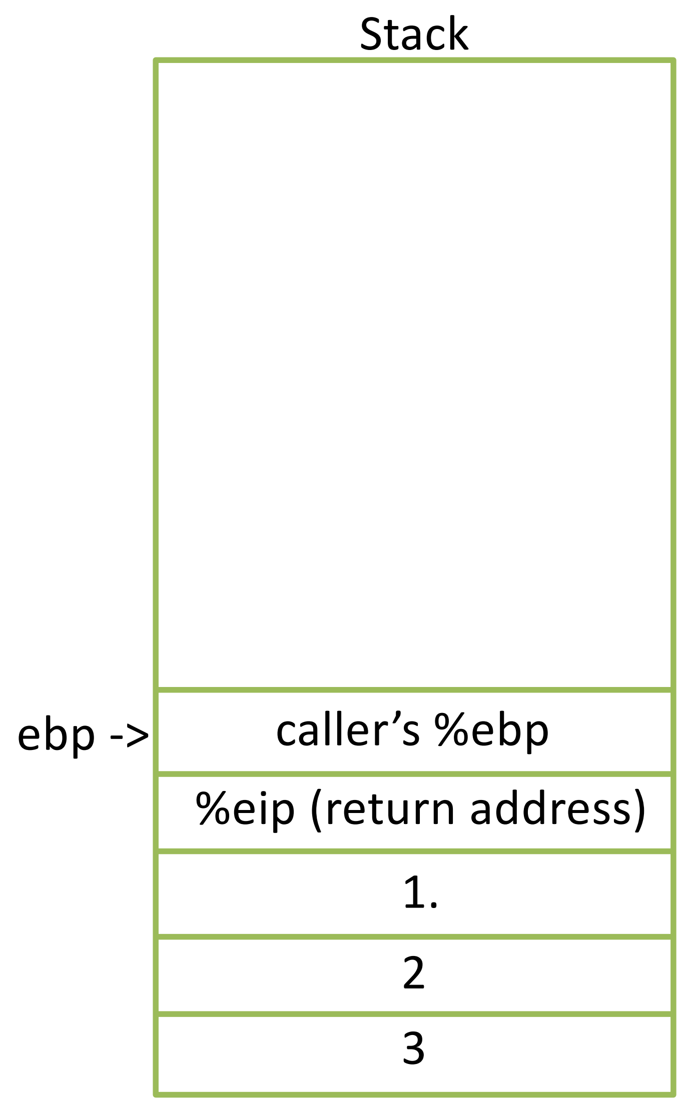
How would we translate this to IA32? What should be on the stack?

main:

1. push $3
2. push $2
3. push $1
4. call func

func:

1. push %ebp
2. movl %esp, %ebp
   (move %ebp up)
3. subl $N, %esp
   (if we needed space)



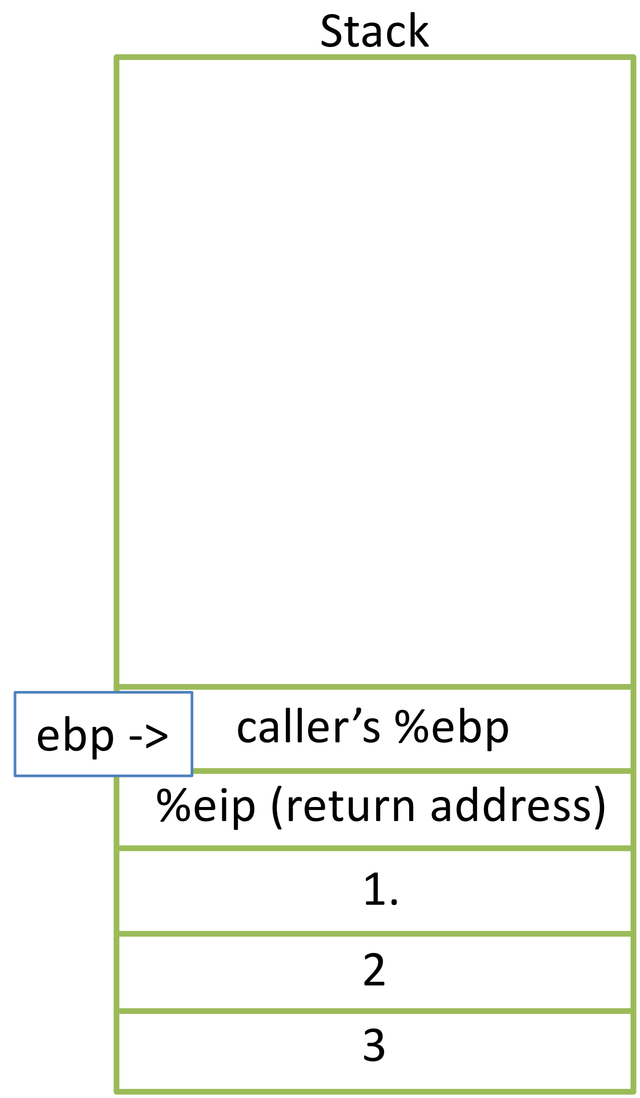
How would we translate this to IA32? What should be on the stack?

main:

1. push $3
2. push $2
3. push $1
4. call func

func:

1. push %ebp
2. movl %esp, %ebp (move %ebp up)
3. subl $N, %esp (if we needed space)
4. movl 12(%ebp), %eax
5. add 16(%ebp), %eax
6. leave
7. ret

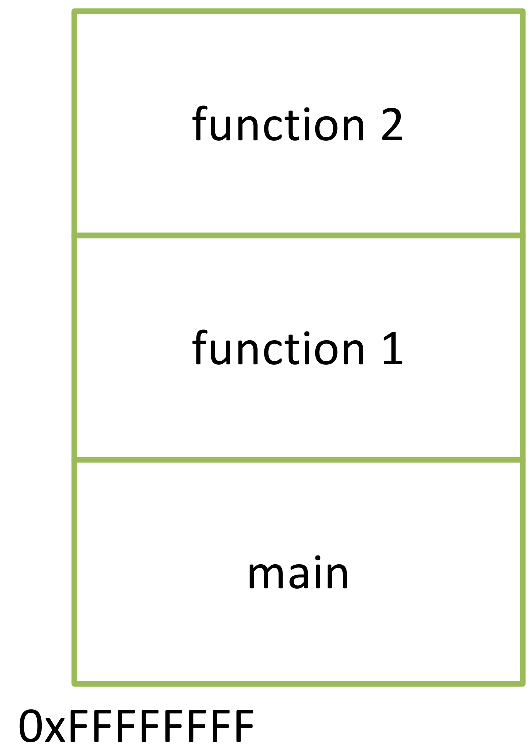


Stack Frame Contents

- 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



Stack Frame Contents

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- Local variables
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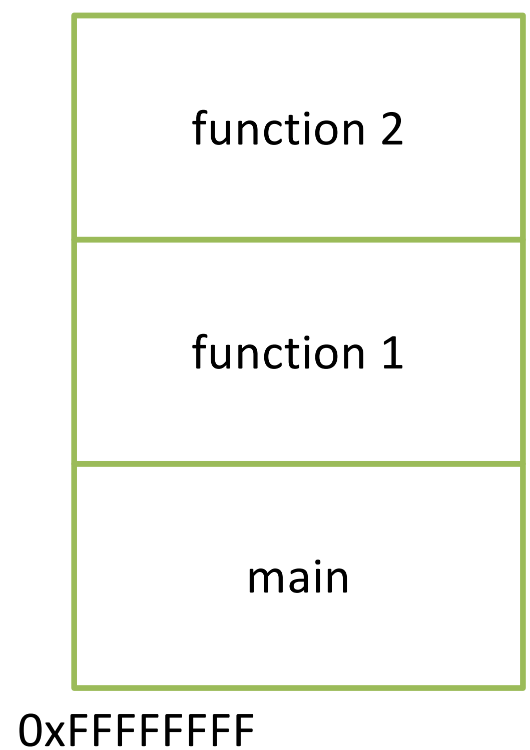
- Saved registers
- Spilled temporaries



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