

238P: Operating Systems

Lecture 3: Calling conventions

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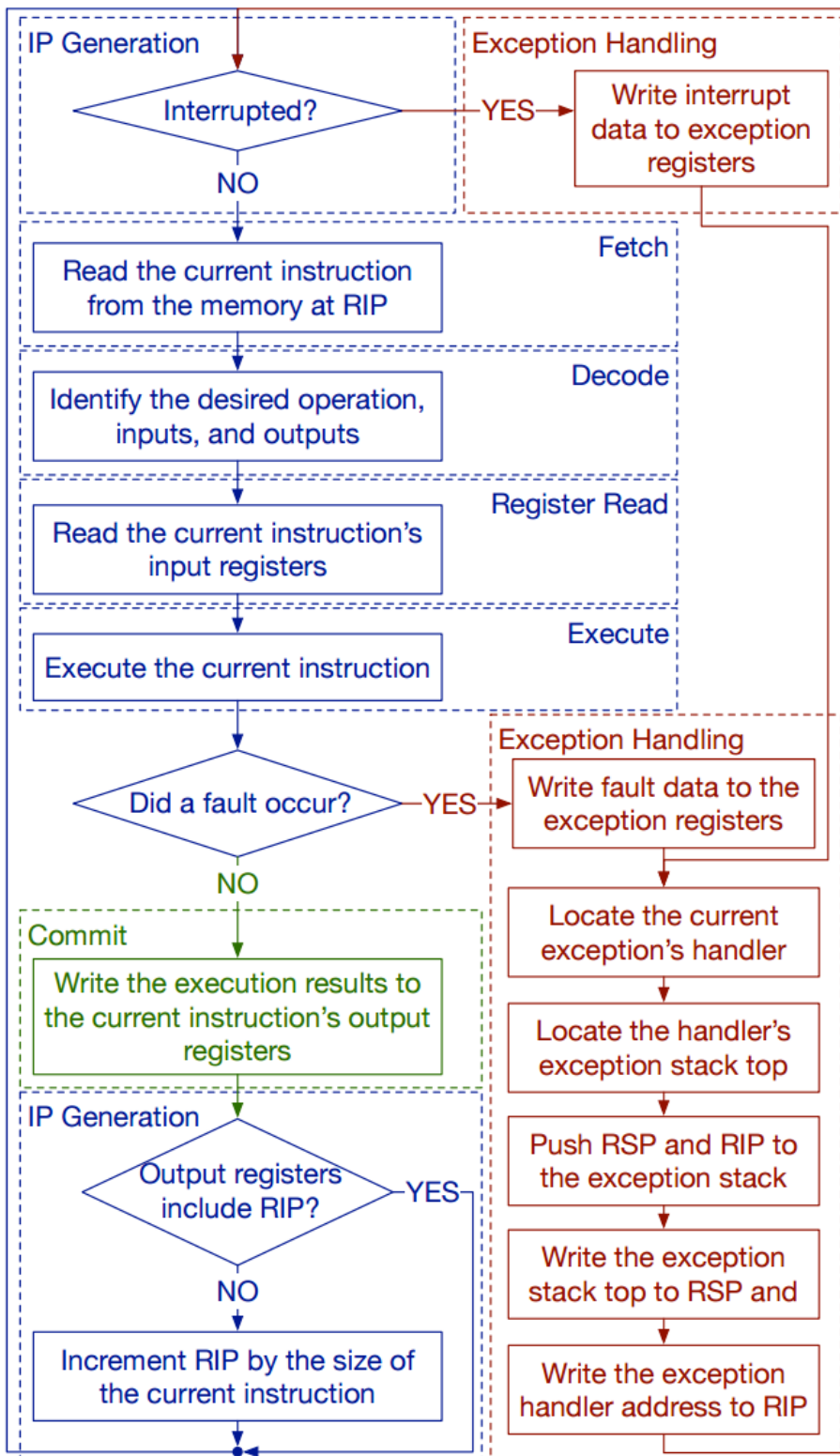
What does CPU do internally?
(Remember Lecture 01 - Introduction?)

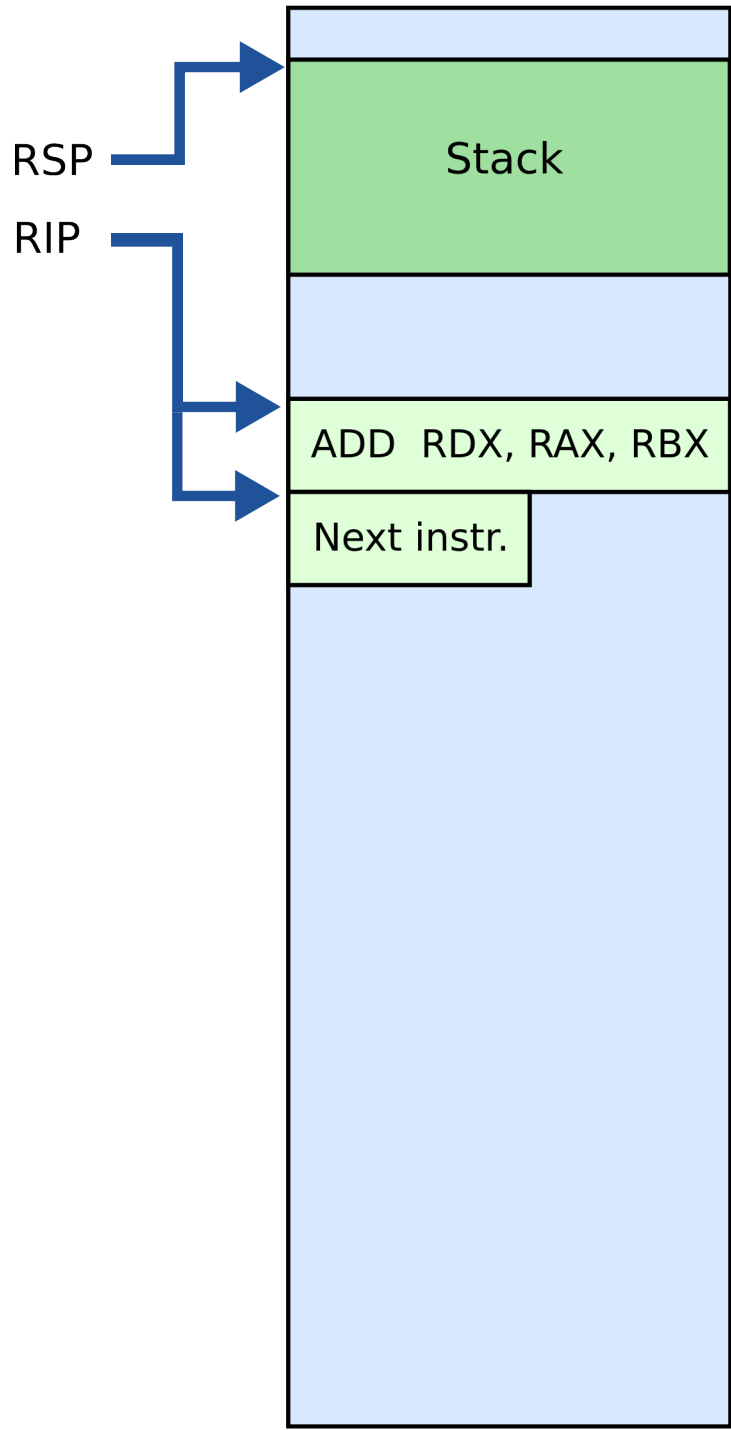
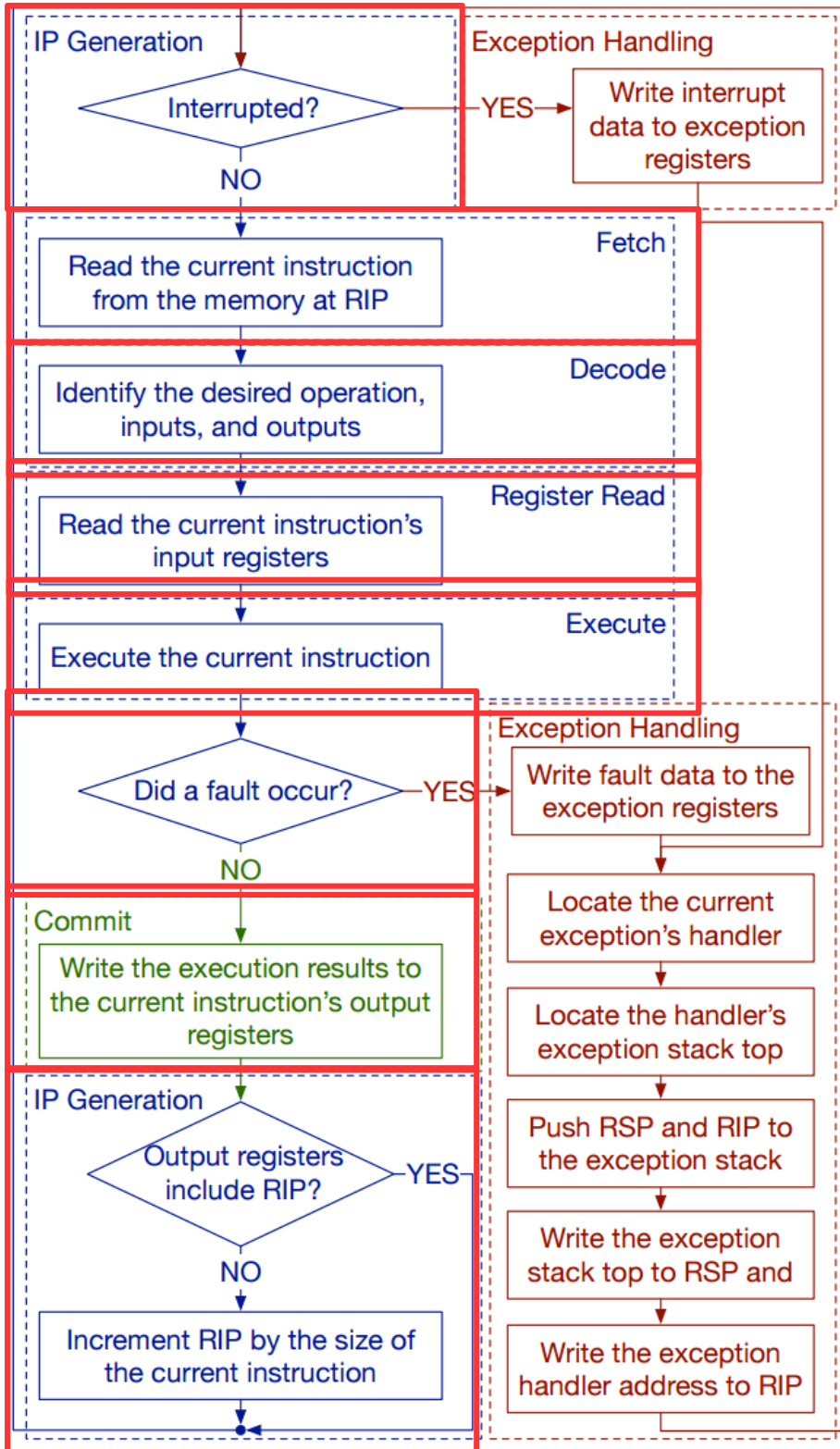
CPU execution loop

- CPU repeatedly reads instructions from memory
- Executes them
- Example

```
ADD EDX, EAX, EBX
```

```
// EDX = EAX + EBX
```



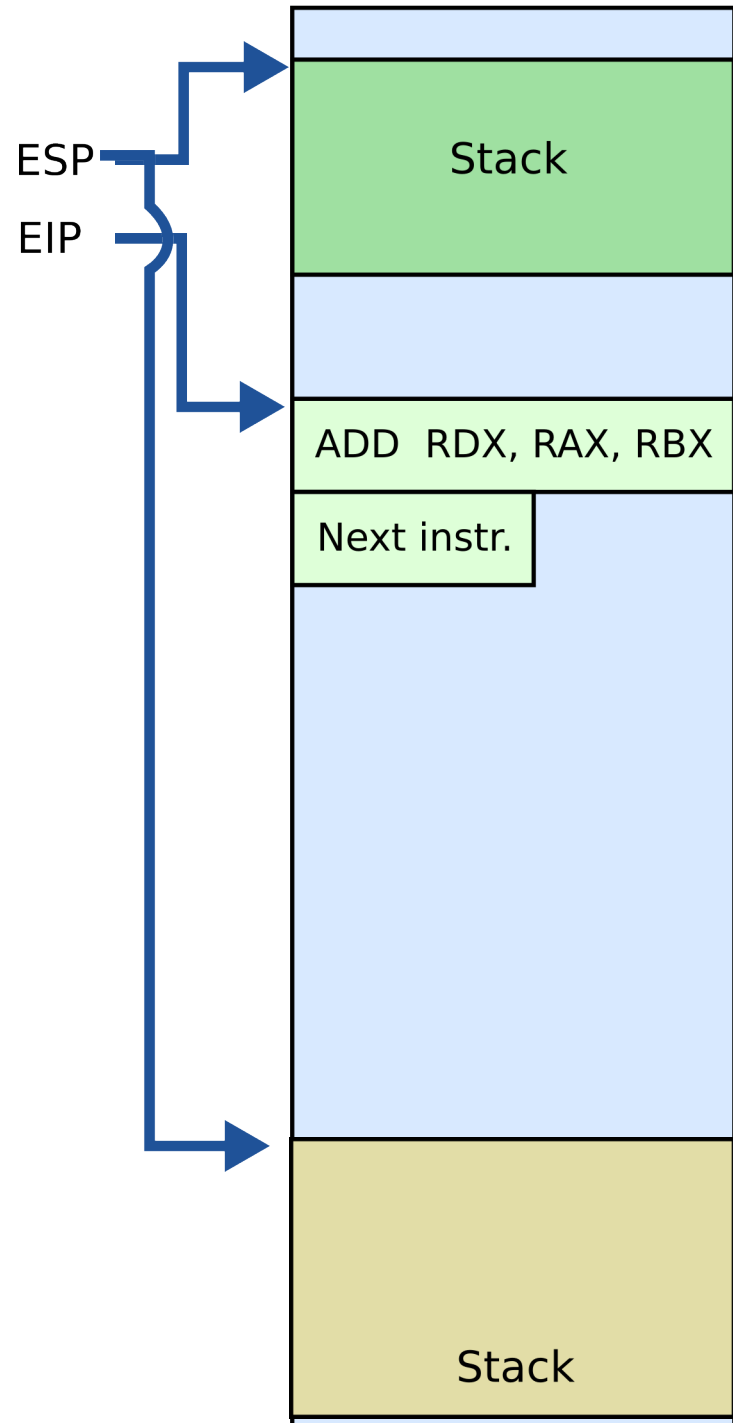


Stack and procedure calls

What is stack?

Stack

- It's just a region of memory
 - Pointed by a special register ESP
- You can change ESP
 - Get a new stack



Why do we need stack?

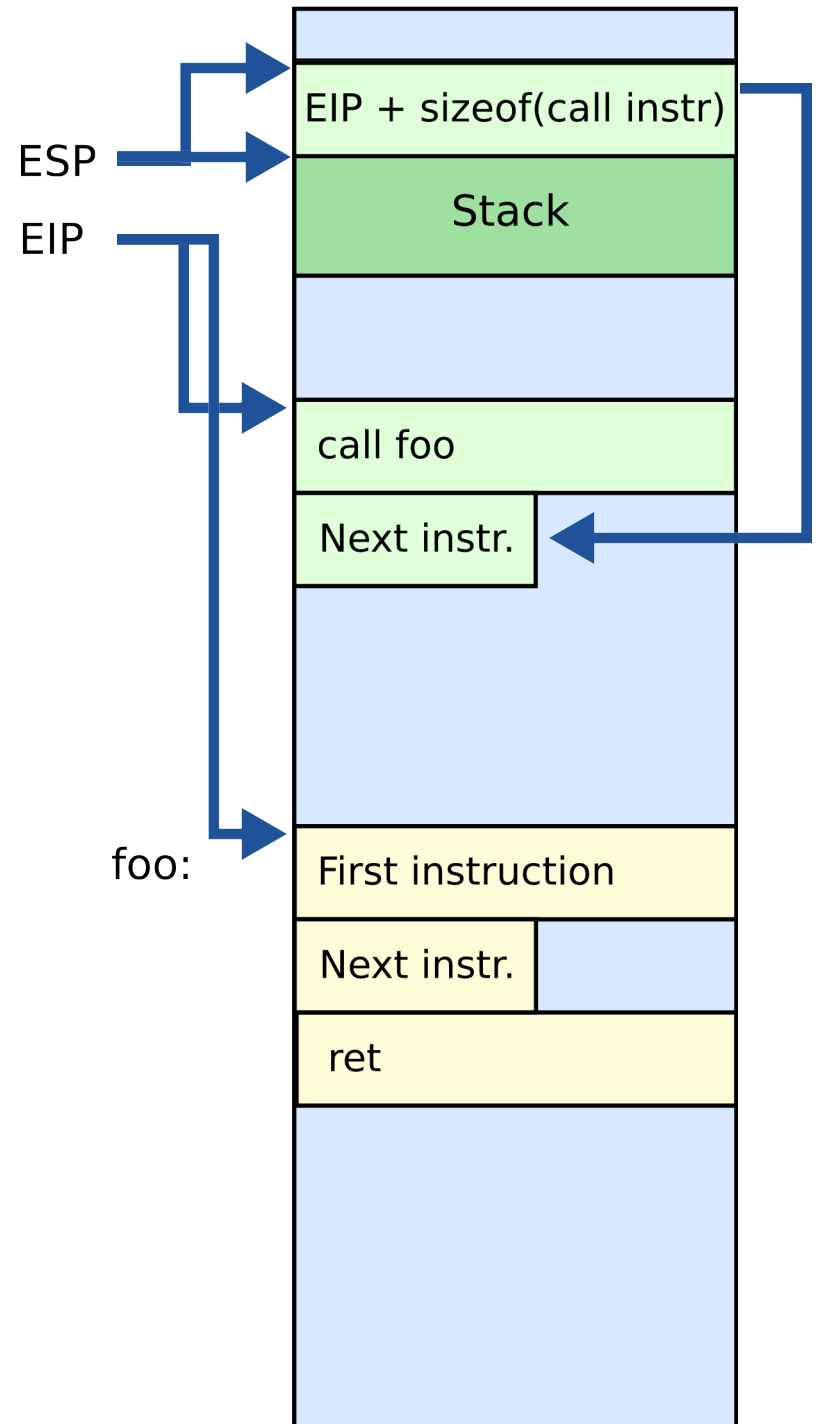
Calling functions

```
// some code...  
foo();  
// more code..
```

- Stack contains information for how to return from a subroutine
 - i.e., foo()

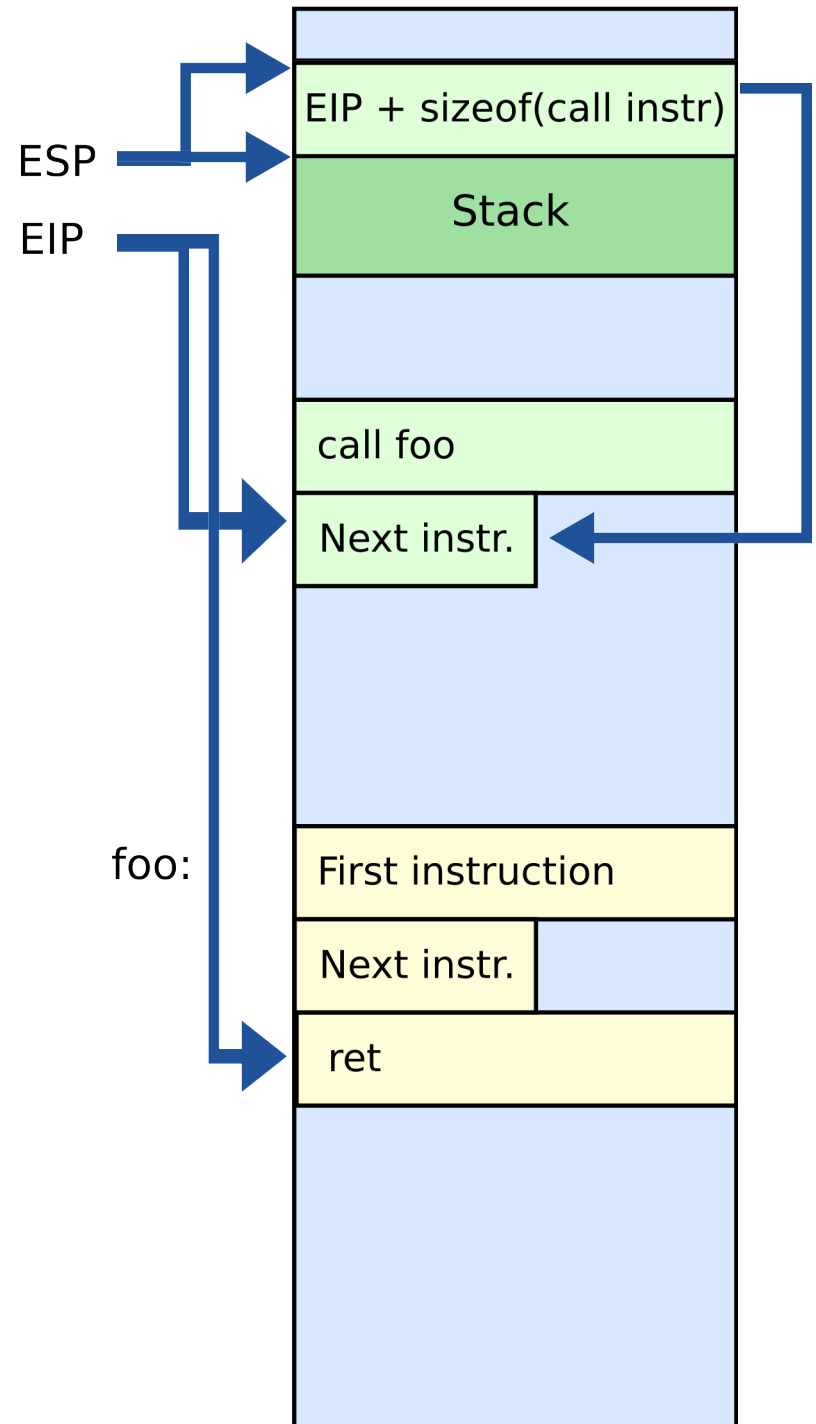
Stack

- Main purpose:
 - Store the return address for the current procedure
 - Caller pushes return address on the stack
 - Callee pops it and jumps



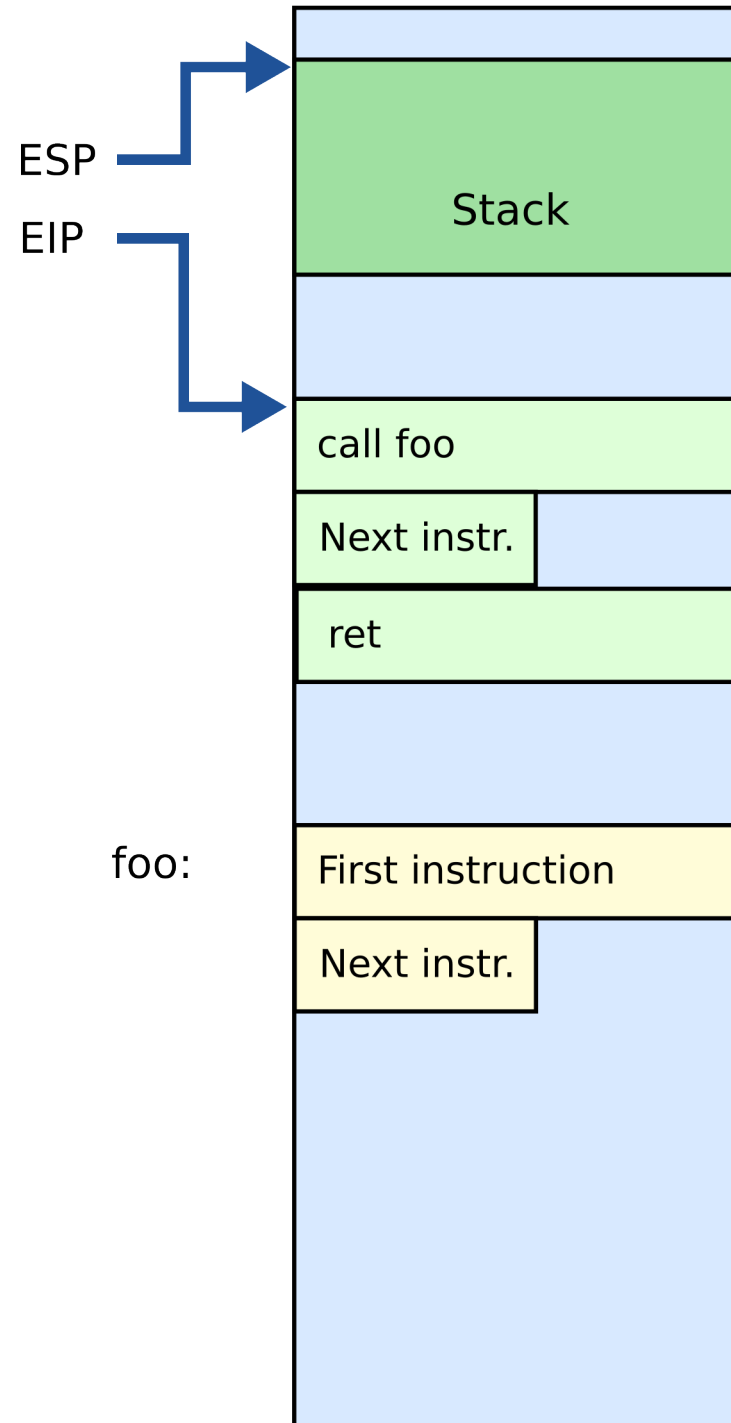
Stack

- Main purpose:
 - Store the return address for the current procedure
 - Caller pushes return address on the stack
 - Callee pops it and jumps



Stack

- Other uses:
 - Local data storage
 - Parameter passing
 - Evaluation stack
 - Register spill



Call/return

- CALL instruction

- Makes an unconditional jump to a subprogram and pushes the address of the next instruction on the stack

```
push eip + sizeof(CALL); save return  
                                ; address
```

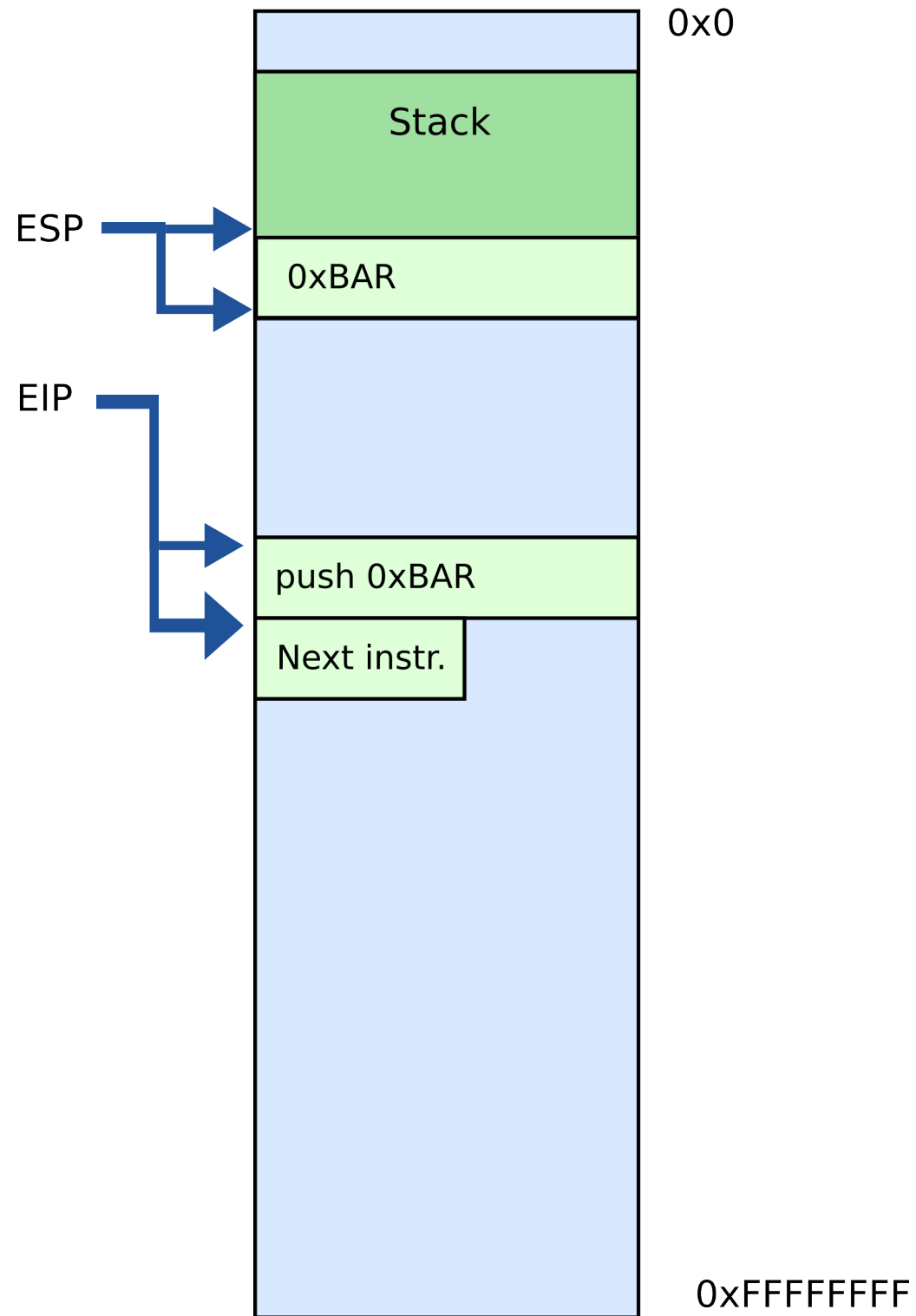
```
jmp _my_function
```

- RET instruction

- Pops off an address and jumps to that address

Manipulating stack

- ESP register
 - Contains the memory address of the topmost element in the stack
- PUSH instruction
 - `push 0xBAR`
 - Insert data on the stack
 - Subtract 4 from ESP

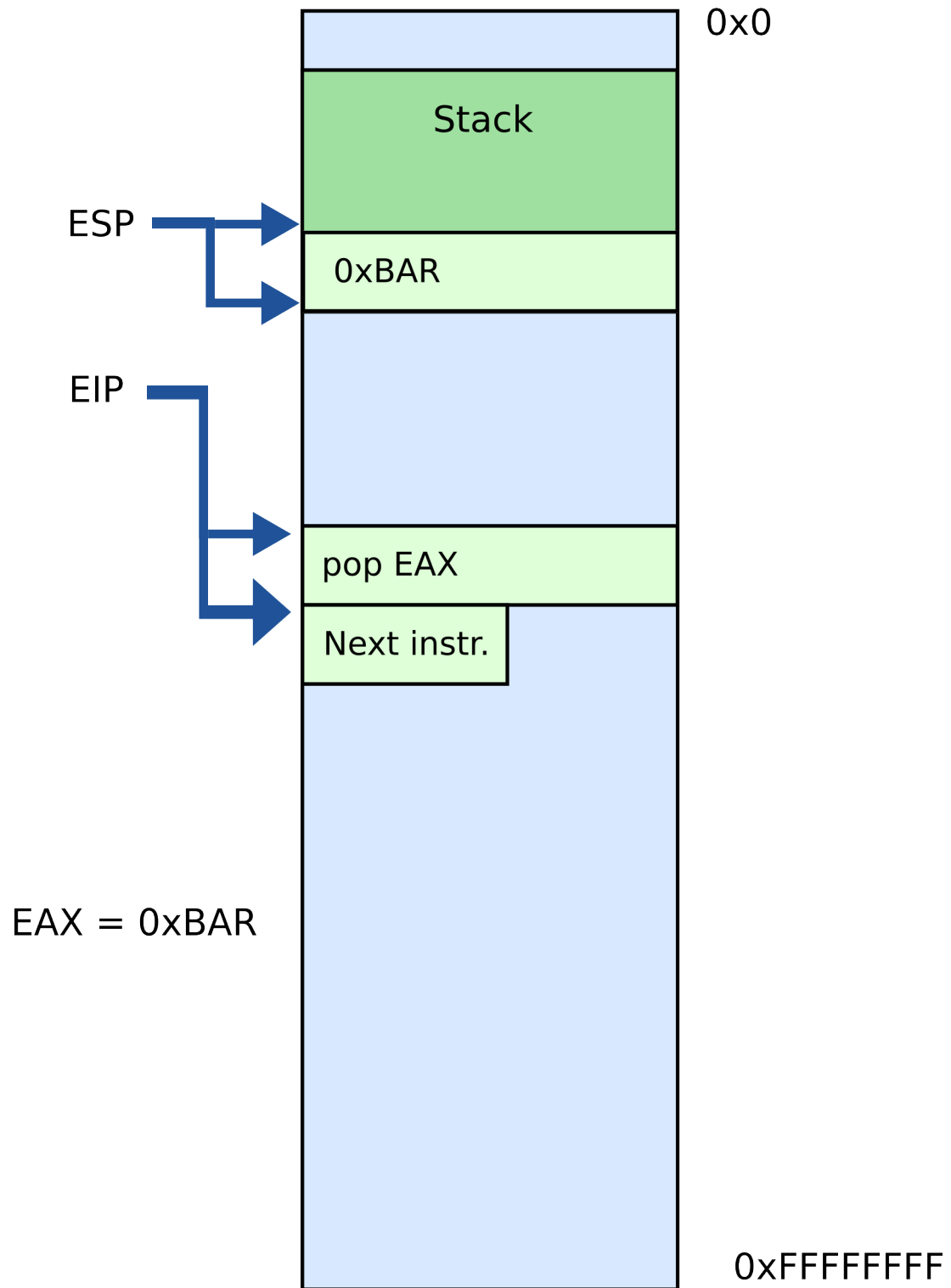


Manipulating stack

- POP instruction

`pop EAX`

- Removes data from the stack
- Saves in register or memory
- Adds 4 to ESP



Calling conventions

Calling conventions

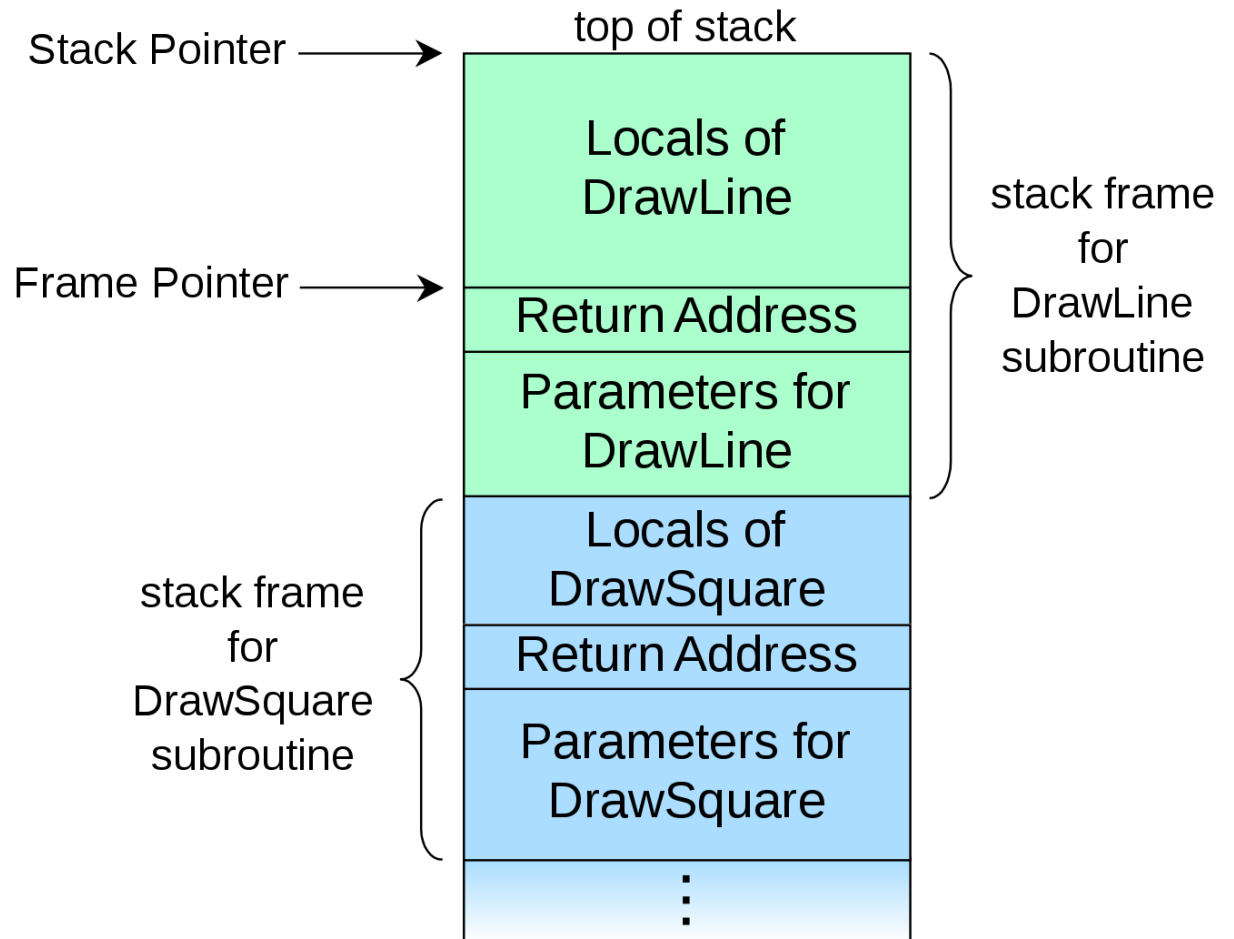
- Goal: reentrant programs
 - How to pass arguments
 - On the stack?
 - In registers?
 - How to return values
 - On the stack?
 - In registers?
- Conventions differ from compiler, optimizations, etc.

Maintain stack as frames

- Each function has a new frame

```
void DrawSquare(...)  
{  
    ...  
    DrawLine(x, y, z);  
}
```

- Use dedicated register **EBP** (frame pointer)
 - Points to the base of the frame

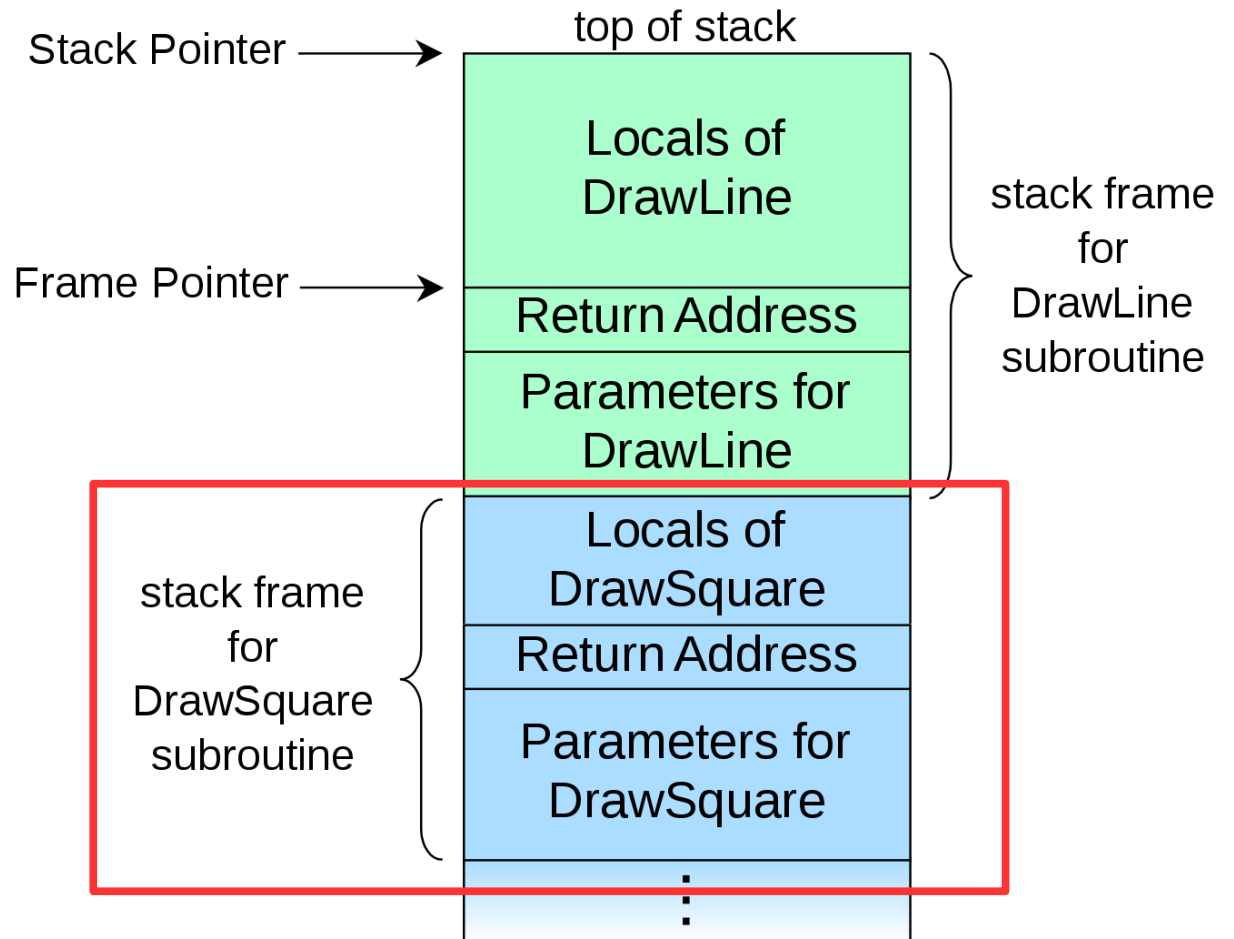


Maintain stack as frames

- Each function has a new frame

```
void DrawSquare(...)  
{  
    ...  
    DrawLine(x, y, z);  
}
```

- Use dedicated register **EBP** (frame pointer)
 - Points to the base of the frame

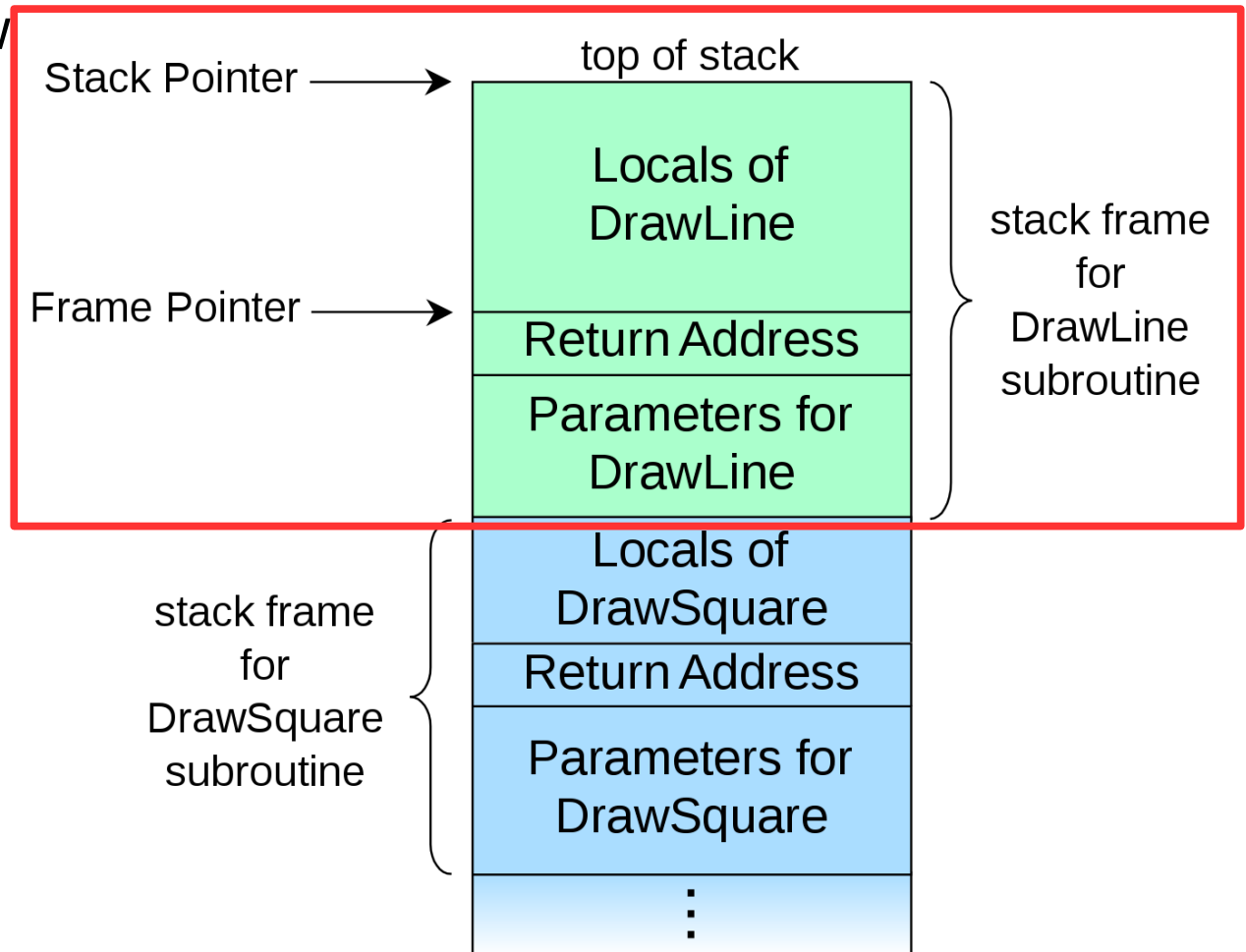


Stack consists of frames

- Each function has a new frame

```
void DrawSquare(...)  
{  
    ...  
    DrawLine(x, y, z);  
}
```

- Use dedicated register **EBP** (frame pointer)
 - Points to the base of the frame



Prologue/epilogue

- Each function maintains the frame
 - A dedicated register EBP is used to keep the frame pointer
 - Each function uses prologue code (blue), and epilogue (yellow) to maintain the frame

my_function:

```
push ebp      ; save original EBP value on stack
mov ebp, esp  ; new EBP = ESP
....          ; function body
pop ebp       ; restore original EBP value
ret
```

How to allocate local variables

- Each function has private instances of local variables

```
foo(int x) {  
    int a, b, c;  
    ...  
    return;  
}
```

- Function can be called recursively

```
foo(int x) {  
    int a, b, c;  
    a = x + 1;  
    if ( a < 100 )  
        foo(a);  
    return;  
}
```

How to allocate local variables?

```
void my_function()  
{  
    int a, b, c;  
    ...  
}
```

How to allocate local variables?

```
void my_function()  
{  
    int a, b, c;  
    ...  
}
```

- On the stack!

Allocating local variables

- Stored right after the saved EBP value in the stack
- Allocated by subtracting the number of bytes required from ESP

```
_my_function:  
  push ebp                ; save original EBP value on stack  
  mov  ebp, esp           ; new EBP = ESP  
  sub  esp, LOCAL_BYTES ; = # bytes needed by locals  
  ...                     ; function body  
  mov  esp, ebp           ; deallocate locals  
  pop  ebp                ; restore original EBP value  
  ret
```

Example

```
void my_function() {  
    int a, b, c;  
    ...  
}
```

`_my_function:`

```
    push ebp        ; save the value of ebp  
    mov  ebp, esp   ; ebp = esp, set ebp to be top of the stack (esp)  
    sub  esp, 12    ; move esp down to allocate space for the  
                    ; local variables on the stack
```

- With frames local variables can be accessed by dereferencing EBP

```
mov [ebp - 4], 10 ; location of variable a  
mov [ebp - 8], 5  ; location of b  
mov [ebp - 12], 2 ; location of c
```

Example

```
void my_function() {  
    int a, b, c;  
    ...  
}
```

`_my_function:`

```
push ebp      ; save the value of ebp  
mov  ebp, esp ; ebp = esp, set ebp to be top of the stack (esp)  
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mov [ebp - 12], 2 ; location of c
```

Example

```
void my_function() {  
    int a, b, c;  
    ...  
}
```

```
_my_function:
```

```
    push ebp        ; save the value of ebp
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```
    mov ebp, esp   ; ebp = esp, set ebp to be top of the stack (esp)
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    sub esp, 12    ; move esp down to allocate space for the  
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- With frames local variables can be accessed by dereferencing EBP

```
mov [ebp - 4], 10 ; location of variable a
```

```
mov [ebp - 8], 5  ; location of b
```

```
mov [ebp - 12], 2 ; location of c
```

Example

```
void my_function() {  
    int a, b, c;  
    ...  
}
```

`_my_function:`

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    push ebp        ; save the value of ebp  
    mov  ebp, esp   ; ebp = esp, set ebp to be top of the stack (esp)  
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mov [ebp - 4], 10 ; location of variable a  
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mov [ebp - 12], 2 ; location of c
```

How to pass arguments?

- Possible options:
 - In registers
 - On the stack

How to pass arguments?

- x86 32 bit
 - Pass arguments on the stack
 - Return value is in EAX and EDX
- x86 64 bit – more registers!
 - Pass first 6 arguments in registers
 - RDI, RSI, RDX, RCX, R8, and R9
 - The rest on the stack
 - Return value is in RAX and RDX

x86_32: passing arguments on the stack

- Example function

```
void my_function(int x, int y, int z)
{ ... }
```

- Example invocation

```
my_function(2, 5, 10);
```

- Generated code

```
push 10
push 5
push 2
call _my_function
```


Example stack

:	:
10	[ebp + 16] (3rd function argument)
5	[ebp + 12] (2nd argument)
2	[ebp + 8] (1st argument)
RA	[ebp + 4] (return address)
FP	[ebp] (old ebp value) ← EBP points here
	[ebp - 4] (1st local variable)
:	:
:	:
	[ebp - X] (esp - the current stack pointer)

Example stack

```
:      :
| 10 | [ebp + 16] (3rd function argument)
|  5 | [ebp + 12] (2nd argument)
|  2 | [ebp + 8]  (1st argument)
| RA | [ebp + 4]  (return address)
| FP | [ebp]      (old ebp value) ← EBP points here
|   | [ebp - 4]  (1st local variable)
:      :
:      :
|   | [ebp - X]  (esp - the current stack pointer)
```

Example stack

```
:      :  
| 10 | [ebp + 16] (3rd function argument)  
|  5 | [ebp + 12] (2nd argument)  
|  2 | [ebp + 8]  (1st argument)  
| RA | [ebp + 4]  (return address)  
| FP | [ebp]      (old ebp value) ← EBP points here  
|   | [ebp - 4]  (1st local variable)  
:      :  
:      :  
|   | [ebp - X]  (esp - the current stack pointer)
```

Example stack

```
:      :  
| 10 | [ebp + 16] (3rd function argument)  
|  5 | [ebp + 12] (2nd argument)  
|  2 | [ebp + 8]  (1st argument)  
| RA | [ebp + 4]  (return address)  
| FP | [ebp]      (old ebp value) ← EBP points here  
|    | [ebp - 4]  (1st local variable)  
:      :  
:      :  
|    | [ebp - X]  (esp - the current stack pointer)
```

Example: caller side code

```
int callee(int, int, int);
```

```
int caller(void)
```

```
{  
    int ret;  
  
    ret = callee(1, 2, 3);  
    ret += 5;  
    return ret;  
}
```

```
caller:
```

```
; manage own stack frame  
push    ebp  
mov     ebp, esp  
; push call arguments  
push    3  
push    2  
push    1  
; call subroutine 'callee'  
call    callee  
; remove arguments from frame  
add     esp, 12  
; use subroutine result  
add     eax, 5  
; restore old call frame  
pop     ebp  
; return  
ret
```

Example: caller side code

```
int callee(int, int, int);
```

```
int caller(void)
```

```
{
```

```
    int ret;
```

```
    ret = callee(1, 2, 3);
```

```
    ret += 5;
```

```
    return ret;
```

```
}
```

```
caller:
```

```
    ; manage own stack frame
```

```
    push    ebp
```

```
    mov     ebp, esp
```

```
    ; push call arguments
```

```
    push    3
```

```
    push    2
```

```
    push    1
```

```
    ; call subroutine 'callee'
```

```
    call    callee
```

```
    ; remove arguments from frame
```

```
    add     esp, 12
```

```
    ; use subroutine result
```

```
    add     eax, 5
```

```
    ; restore old call frame
```

```
    pop     ebp
```

```
    ; return
```

```
    ret
```

Example: caller side code

```
int callee(int, int, int);
```

```
int caller(void)
```

```
{
```

```
    int ret;
```

```
    ret = callee(1, 2, 3);
```

```
    ret += 5;
```

```
    return ret;
```

```
}
```

```
caller:
```

```
    ; manage own stack frame
```

```
    push    ebp
```

```
    mov     ebp, esp
```

```
    ; push call arguments
```

```
    push   3
```

```
    push   2
```

```
    push   1
```

```
    ; call subroutine 'callee'
```

```
    call   callee
```

```
    ; remove arguments from frame
```

```
    add    esp, 12
```

```
    ; use subroutine result
```

```
    add    eax, 5
```

```
    ; restore old call frame
```

```
    pop    ebp
```

```
    ; return
```

```
    ret
```

Example: caller side code

```
int callee(int, int, int);
```

```
int caller(void)
```

```
{
```

```
    int ret;
```

```
    ret = callee(1, 2, 3);
```

```
    ret += 5;
```

```
    return ret;
```

```
}
```

```
caller:
```

```
    ; manage own stack frame
```

```
    push    ebp
```

```
    mov     ebp, esp
```

```
    ; push call arguments
```

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    push    3
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```
    ; remove arguments from frame
```

```
    add     esp, 12
```

```
    ; use subroutine result
```

```
    add     eax, 5
```

```
    ; restore old call frame
```

```
    pop     ebp
```

```
    ; return
```

```
    ret
```


Example: caller side code

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int callee(int, int, int);
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int caller(void)
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```

```
    int ret;
```

```
    ret = callee(1, 2, 3);
```

```
    ret += 5;
```

```
    return ret;
```

```
}
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```
caller:
```

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    ; manage own stack frame
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    push    ebp
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    mov     ebp, esp
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    push    3
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```
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```
    ; call subroutine 'callee'
```

```
    call    callee
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```
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```

```
    add     esp, 12
```

```
    ; use subroutine result
```

```
    add     eax, 5
```

```
    ; restore old call frame
```

```
    pop     ebp
```

```
    ; return
```

```
    ret
```

Example: caller side code

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```

```
int caller(void)
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```
{
```

```
    int ret;
```

```
    ret = callee(1, 2, 3);
```

```
    ret += 5;
```

```
    return ret;
```

```
}
```

```
caller:
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    push    ebp
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    add     esp, 12
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    add     eax, 5
```

```
    ; restore old call frame
```

```
    pop     ebp
```

```
    ; return
```

```
    ret
```

Wait, where is return ret; ?

```
int callee(int, int, int);
```

```
int caller(void)
```

```
{
```

```
    int ret;
```

```
    ret = callee(1, 2, 3);
```

```
    ret += 5;
```

```
    return ret;
```

```
}
```

```
caller:
```

```
    ; manage own stack frame
```

```
    push    ebp
```

```
    mov     ebp, esp
```

```
    ; push call arguments
```

```
    push    3
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```
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```
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```

```
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```

```
    ; remove arguments from frame
```

```
    add     esp, 12
```

```
    ; use subroutine result
```

```
    add     eax, 5
```

```
    ; restore old call frame
```

```
    pop     ebp
```

```
    ; return
```

```
    ret
```

Example: callee side code

```
void my_function(int x, int y, int z)
{
    int a, b, c;
    ...
    return;
}
```

```
_my_function:
```

```
    push ebp
```

```
    mov  ebp, esp
```

```
    sub  esp, 12 ; allocate local variables
           ; sizeof(a) + sizeof(b) + sizeof(c)
```

```
    ; x = [ebp + 8], y = [ebp + 12], z = [ebp + 16]
```

```
    ; a=[ebp-4]=[esp+8],
```

```
    ; b=[ebp-8]=[esp+4], c=[ebp-12] = [esp]
```

```
    mov  esp, ebp ; deallocate local variables
```

```
    pop  ebp
```

```
    ret
```

Example: callee side code

```
void my_function(int x, int y, int z)
{
    int a, b, c;
    ...
    return;
}
```

```
_my_function:
```

```
    push ebp
```

```
    mov ebp, esp
```

```
    sub esp, 12 ; allocate local variables
```

```
                ; sizeof(a) + sizeof(b) + sizeof(c)
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    ; x = [ebp + 8], y = [ebp + 12], z = [ebp + 16]
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```
    ; a=[ebp-4]=[esp+8],
```

```
    ; b=[ebp-8]=[esp+4], c=[ebp-12] = [esp]
```

```
    mov esp, ebp ; deallocate local variables
```

```
    pop ebp
```

```
    ret
```

Example: callee side code

```
void my_function(int x, int y, int z)
{
    int a, b, c;
    ...
    return;
}
```

```
_my_function:
```

```
    push ebp
```

```
    mov ebp, esp ; ebp = esp
```

```
    sub esp, 12 ; allocate local variables
```

```
                ; sizeof(a) + sizeof(b) + sizeof(c)
```

```
    ; x = [ebp + 8], y = [ebp + 12], z = [ebp + 16]
```

```
    ; a=[ebp-4]=[esp+8],
```

```
    ; b=[ebp-8]=[esp+4], c=[ebp-12] = [esp]
```

```
    mov esp, ebp ; deallocate local variables (esp = ebp)
```

```
    pop ebp
```

```
    ret
```

Example: callee side code

```
void my_function(int x, int y, int z)
{
    int a, b, c;
    ...
    return;
}
```

```
_my_function:
```

```
    push ebp
```

```
    mov ebp, esp ; ebp = esp
```

```
    sub esp, 12 ; allocate local variables
```

```
                ; sizeof(a) + sizeof(b) + sizeof(c)
```

```
    ; x = [ebp + 8], y = [ebp + 12], z = [ebp + 16]
```

```
    ; a=[ebp-4]=[esp+8],
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    ; b=[ebp-8]=[esp+4], c=[ebp-12] = [esp]
```

```
    mov esp, ebp ; deallocate local variables (esp = ebp)
```

```
    pop ebp
```

```
    ret
```

Example: callee side code

```
void my_function(int x, int y, int z)
{
    int a, b, c;
    ...
    return;
}
```

```
_my_function:
```

```
    push ebp
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    mov ebp, esp ; ebp = esp
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    sub esp, 12 ; allocate local variables
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```
                ; sizeof(a) + sizeof(b) + sizeof(c)
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    ; x = [ebp + 8], y = [ebp + 12], z = [ebp + 16]
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    ; a=[ebp-4]=[esp+8],
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    ; b=[ebp-8]=[esp+4], c=[ebp-12] = [esp]
```

```
    mov esp, ebp ; deallocate local variables (esp = ebp)
```

```
    pop ebp
```

```
    ret
```


Leave instruction

```
void my_function(int x, int y, int z)
{
    int a, b, c;
    ...
    return;
}
```

```
_my_function:
```

```
    push ebp
```

```
    mov ebp, esp ; ebp = esp
```

```
    sub esp, 12 ; allocate local variables
```

```
                ; sizeof(a) + sizeof(b) + sizeof(c)
```

```
    ; x = [ebp + 8], y = [ebp + 12], z = [ebp + 16]
```

```
    ; a=[ebp-4]=[esp+8],
```

```
    ; b=[ebp-8]=[esp+4], c=[ebp-12] = [esp]
```

```
    mov esp, ebp
```

```
    pop ebp
```

```
    ret
```

- x86 has a special instruction for this

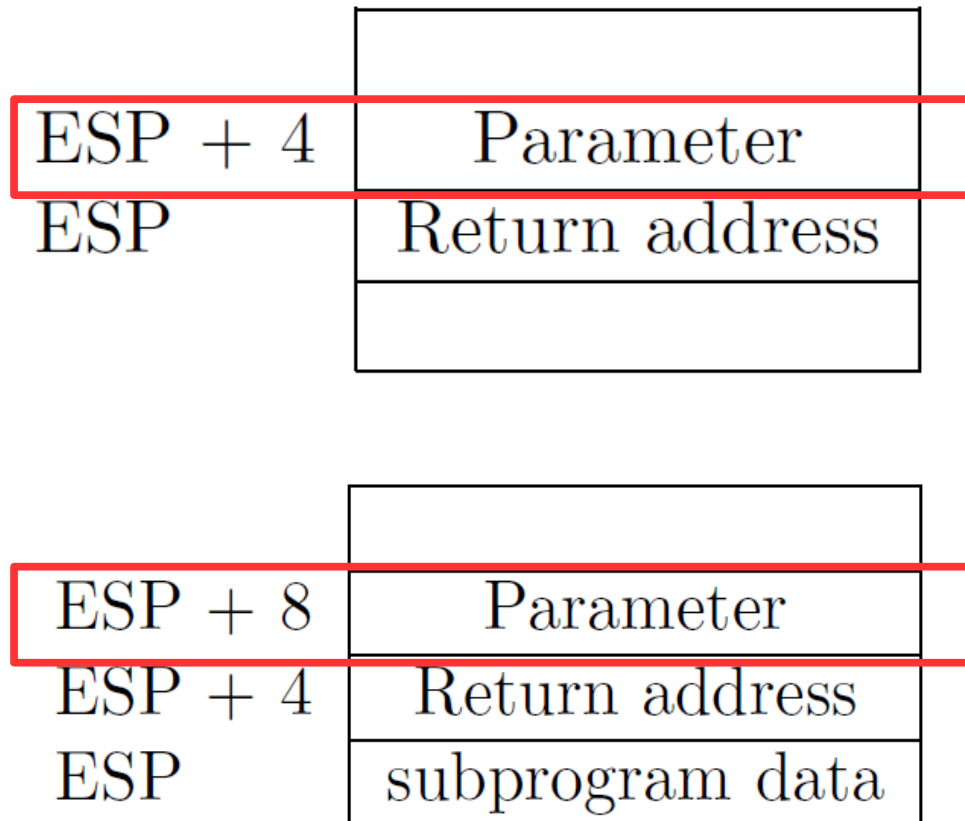
- `leave`

Back to stack frames, so why do we need them?

- ... They are not strictly required
- GCC compiler option `-fomit-frame-pointer` can disable them

Don't keep the frame pointer in a register for functions that don't need one. This avoids the instructions to save, set up and restore frame pointers; it also makes an extra register available in many functions. **It also makes debugging impossible on some machines.**

Referencing args without frames



Initially parameter is

- [ESP + 4]

Later as the function pushes things on the stack it changes, e.g.

- [ESP + 8]

- Debugging becomes hard
 - As ESP changes one has to manually keep track where local variables are relative to ESP (ESP + 4 or +8)
 - **Compiler can easily do this and generate correct code!**
 - **But it's hard for a human**
 - It's hard to unwind the stack in case of a crash
 - To print out a backtrace

And you only save...

- A couple instructions required to maintain the stack frame
- And 1 register (EBP)
 - x32 has 8 registers (and one is ESP)
 - So taking another one is 12.5% of register space
 - Sometimes its worse it!
 - x64 has 16 registers, so it doesn't really matter
- That said, GCC sets `-fomit-frame-pointer` to “on”
 - At -O, -O1, -O2 ...
 - Don't get surprised

Relevant part of the GCC manual

3.10 Options That Control Optimization

<https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html>

-O

-O1

With -O, the compiler tries to reduce code size and execution time, without performing any optimizations that take a great deal of compilation time.

-O turns on the following optimization flags:

-fauto-inc-dec

-fbranch-count-reg

...

-fomit-frame-pointer

-freorder-blocks

Saving and restoring registers

Saving register state across invocations

- Processor doesn't save registers
 - General purpose, segment, flags
- Again, a calling convention is needed
 - Agreement on what gets saved by the callee and the caller

Saving register state across invocations

- Registers EAX, ECX, and EDX are caller-saved
 - The function is free to use them
- ... the rest are callee-saved
 - If the function uses them it has to restore them to the original values

- In general there are multiple calling conventions
 - We described **cdecl**
 - **Make sure you know what you're doing**
 - https://en.wikipedia.org/wiki/X86_calling_conventions#List_of_x86_calling_conventions
- It's easy as long as you know how to read the table

Questions?

References

- https://en.wikibooks.org/wiki/X86_Disassembly/Functions_and_Stack_Frames
- https://en.wikipedia.org/wiki/Calling_convention
- https://en.wikipedia.org/wiki/X86_calling_conventions
- <http://stackoverflow.com/questions/14666665/trying-to-understand-gcc-option-fomit-frame-pointer>