238P: Operating Systems

Lecture 3: Calling conventions

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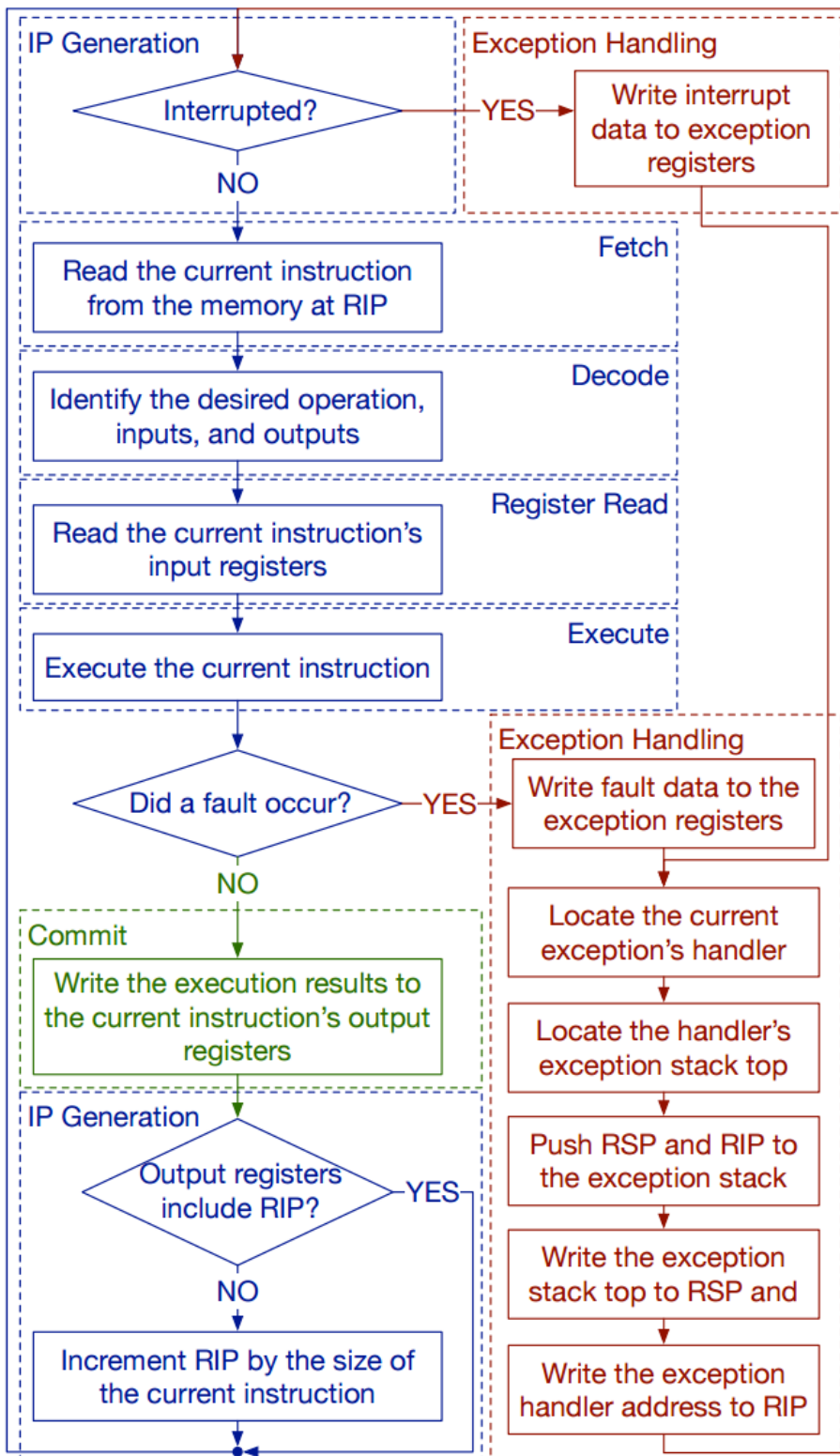
What does CPU do internally?
(Remember Lecture 01 - Introduction?)
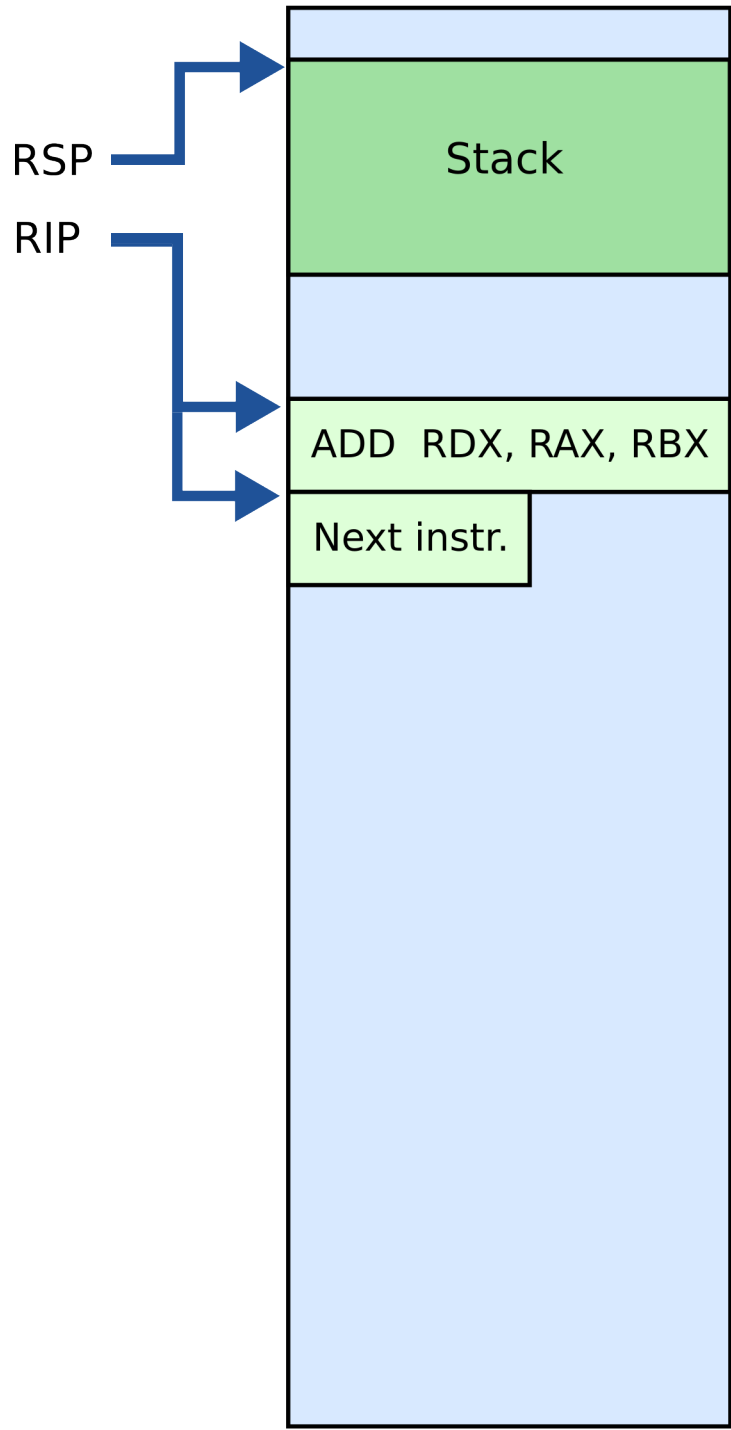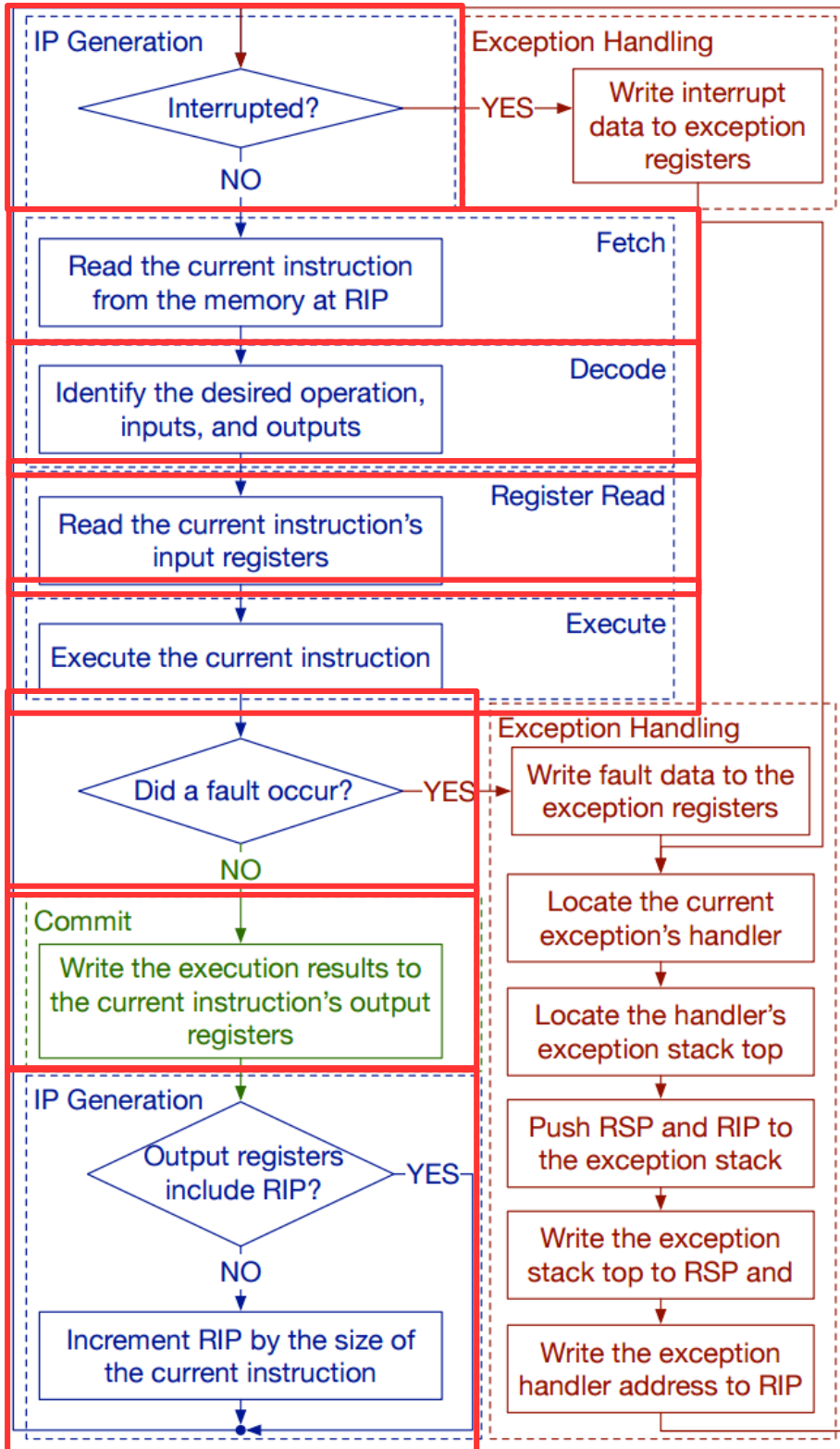
CPU execution loop

- CPU repeatedly reads instructions from memory

- Executes them

- Example

```
ADD EDX, EAX, EBX

// EDX = EAX + EBX
```

IP Generation

Interrupted?
- YES → **Exception Handling**: Write interrupt data to exception registers
- NO ↓

Fetch: Read the current instruction from the memory at RIP

Decode: Identify the desired operation, inputs, and outputs

Register Read: Read the current instruction's input registers

Execute: Execute the current instruction

Did a fault occur?
- YES → **Exception Handling**: Write fault data to the exception registers
- NO ↓

Commit: Write the execution results to the current instruction's output registers

IP Generation

Output registers include RIP?
- YES →
- NO ↓

Increment RIP by the size of the current instruction

Exception Handling (continued):
- Locate the current exception's handler
- Locate the handler's exception stack top
- Push RSP and RIP to the exception stack
- Write the exception stack top to RSP and
- Write the exception handler address to RIP

RSP →

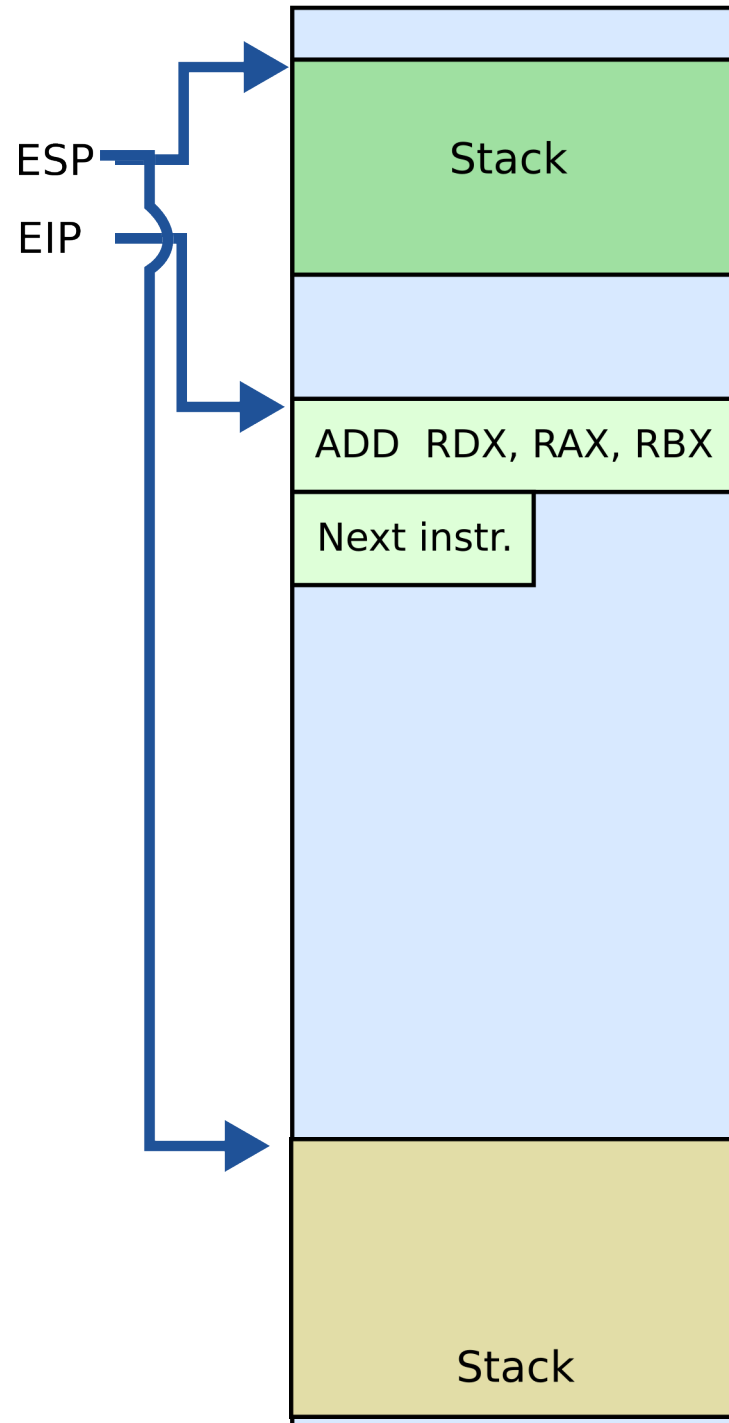RIP →

Stack

ADD RDX, RAX, RBX

Next instr.

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

ESP

EIP

Stack

ADD RDX, RAX, RBX

Next instr.

Stack
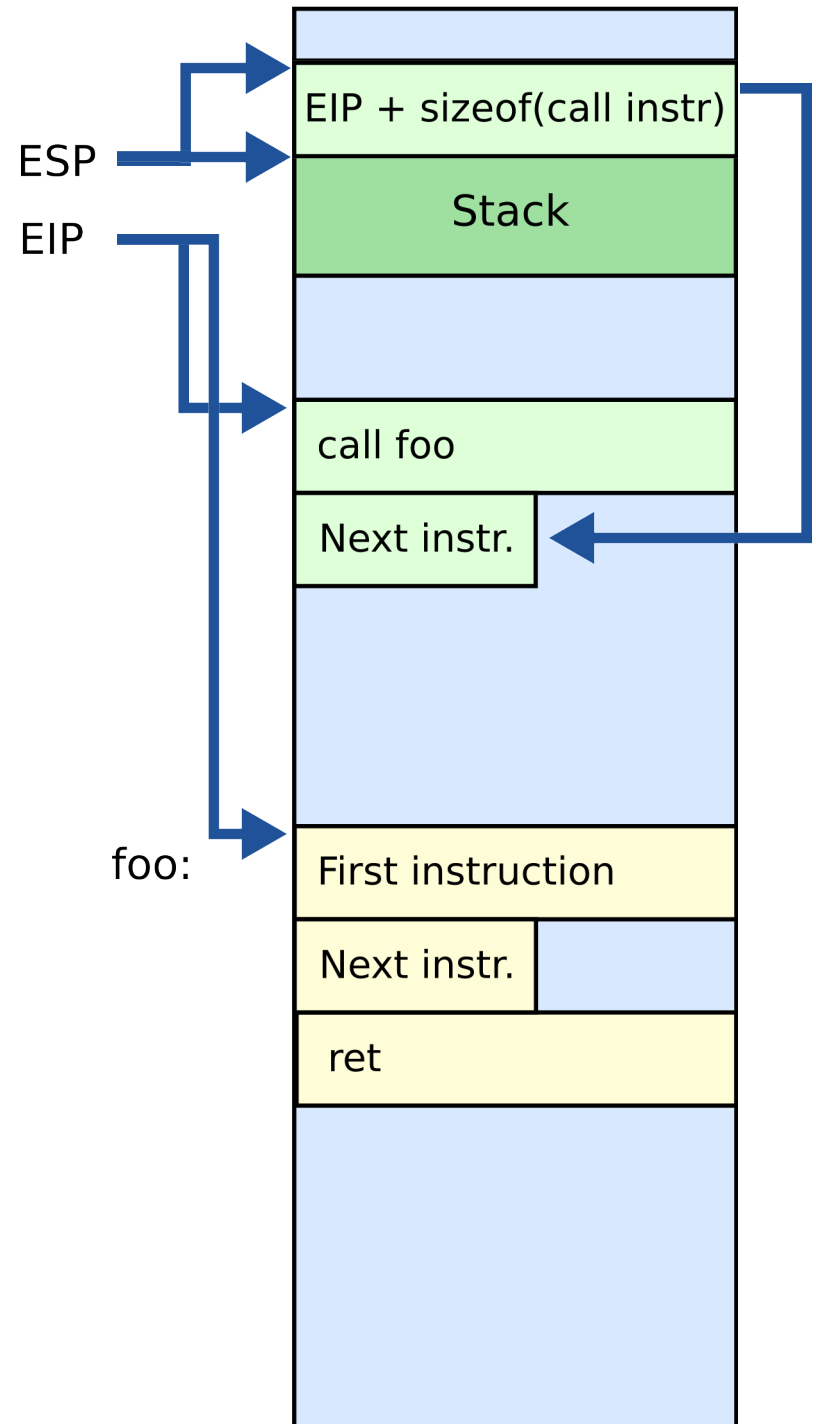
Why do we need stack?

Calling functions

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

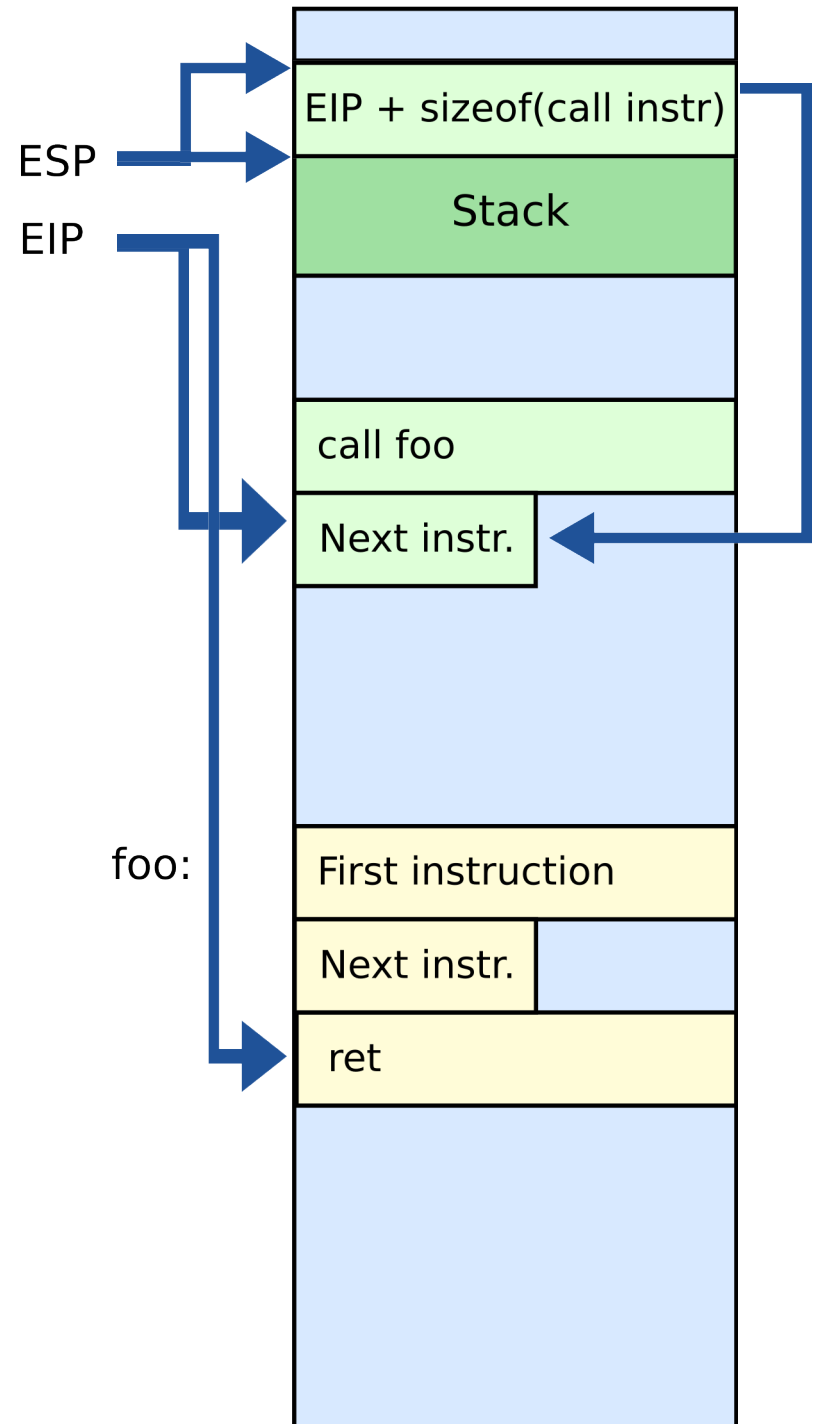- Stack contains information for how to return from a subroutine
  - i.e., foo()

Stack

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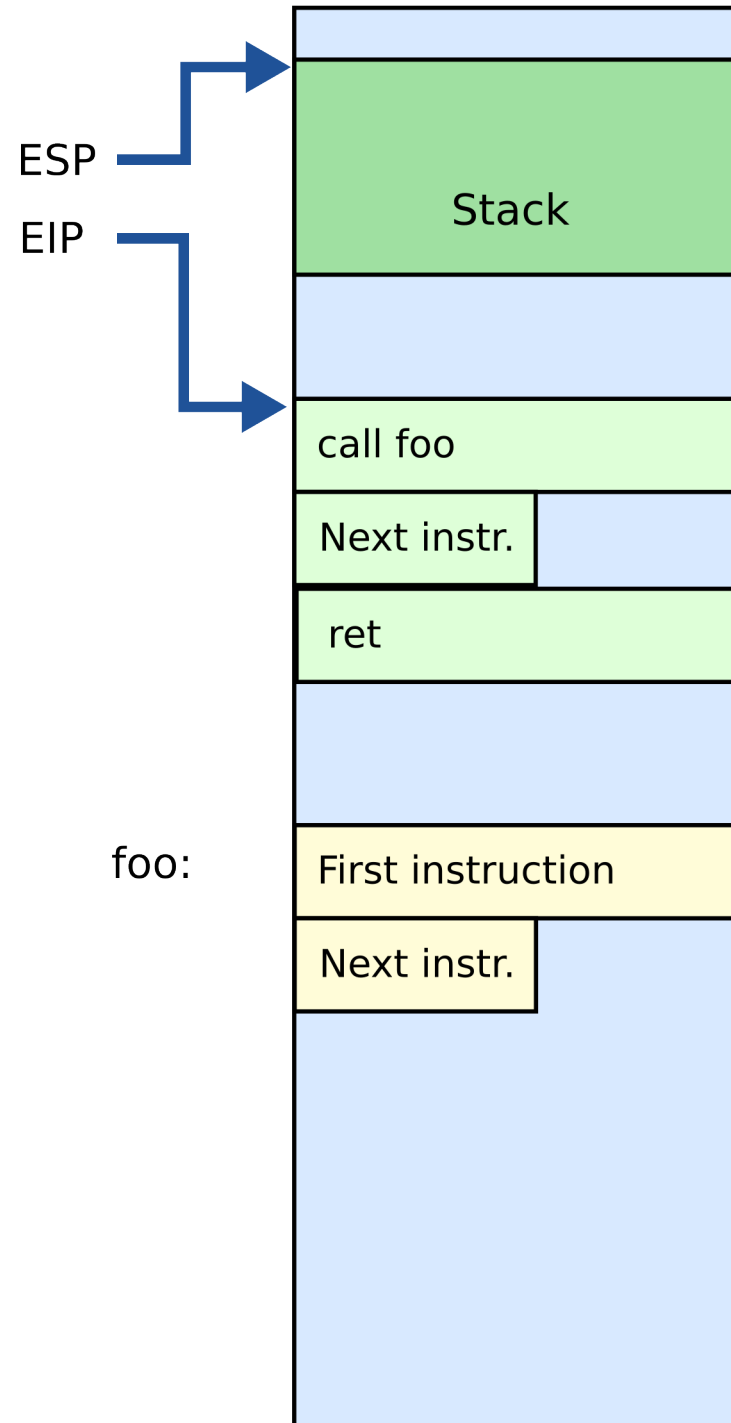 - Callee pops it and jumps

ESP

EIP

EIP + sizeof(call instr)

Stack

call foo

Next instr.

foo:

First instruction

Next instr.

ret

Stack

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

EIP + sizeof(call instr)

ESP

Stack

EIP

call foo

Next instr.

foo:

First instruction

Next instr.

ret

Stack

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

ESP

EIP

Stack

call foo

Next instr.

ret

foo:

First instruction

Next instr.

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
  ```
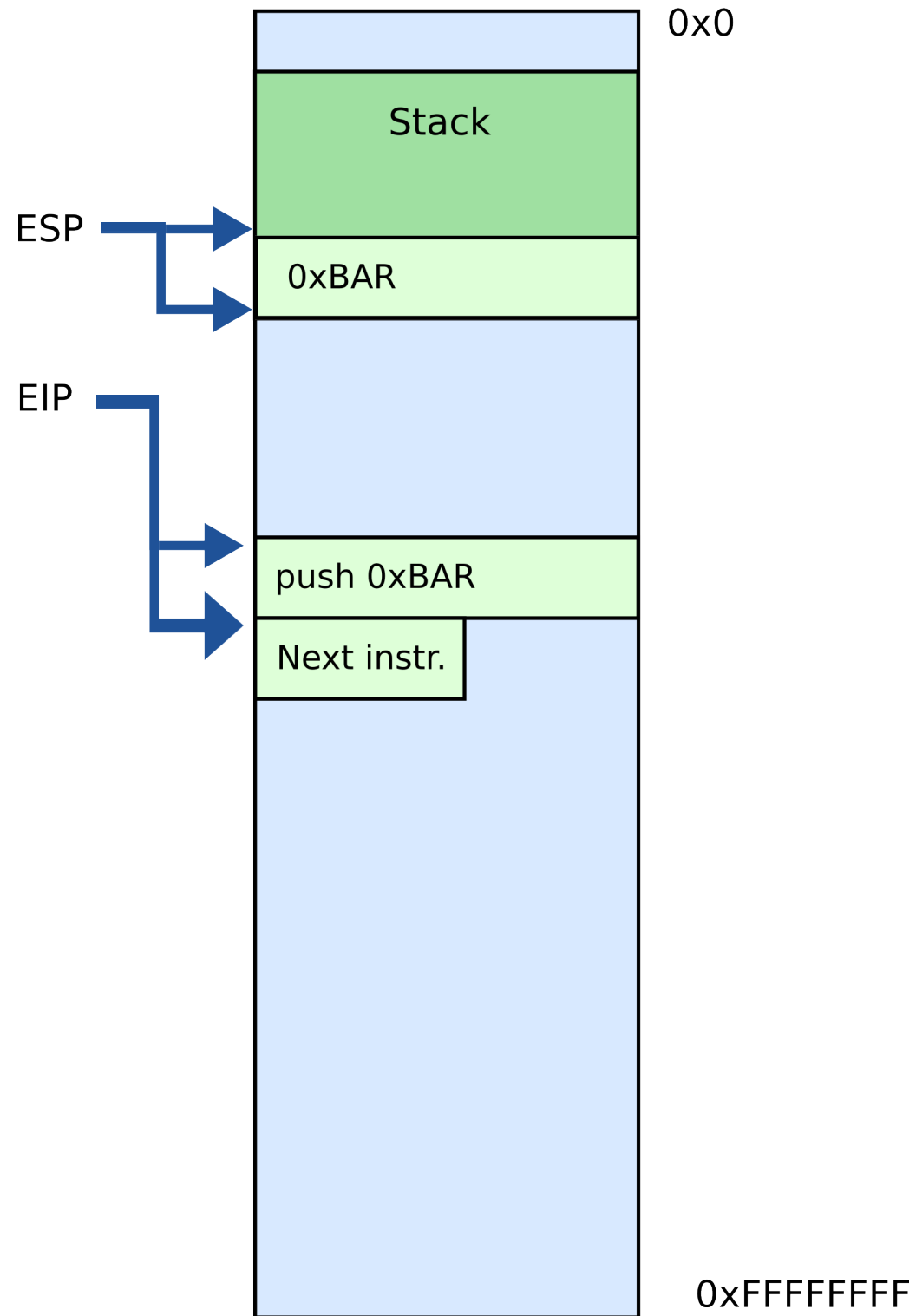
- RET instruction
  - Pops off an address and jumps to that address

Manipulating stack

- ESP register
  - Contains the memory address of the topmost element in the stack

- PUSH instruction

  `push 0xBAR`
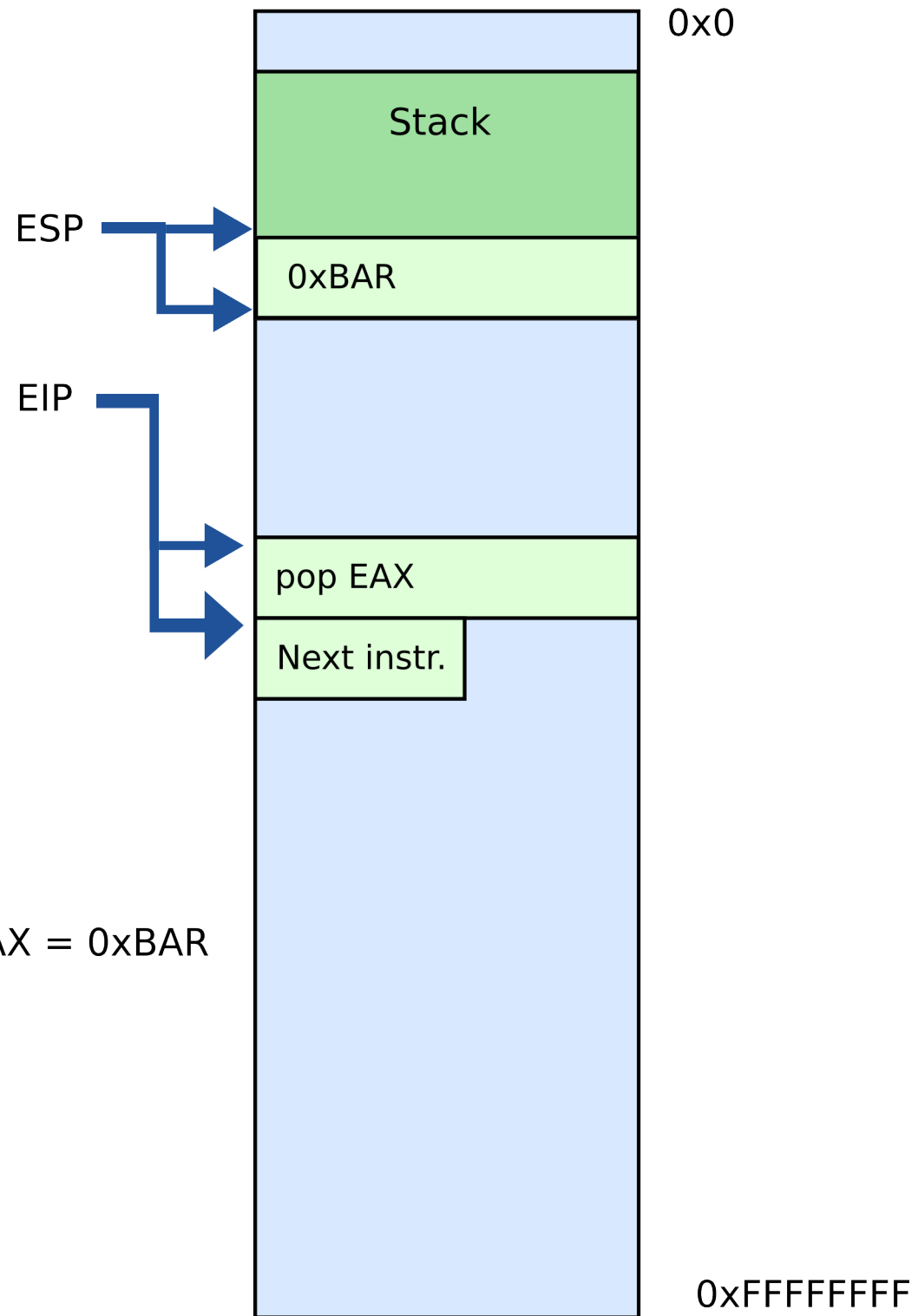
  - Insert data on the stack
  - Subtract 4 from ESP

0x0

Stack

ESP → 0xBAR

EIP

push 0xBAR

Next instr.

0xFFFFFFFF

Manipulating stack

- POP instruction

  `pop EAX`

  - Removes data from the stack

  - Saves in register or memory

  - Adds 4 to ESP

EAX = 0xBAR

0x0

ESP

Stack

0xBAR

EIP

pop EAX

Next instr.

0xFFFFFFFF

Calling conventions
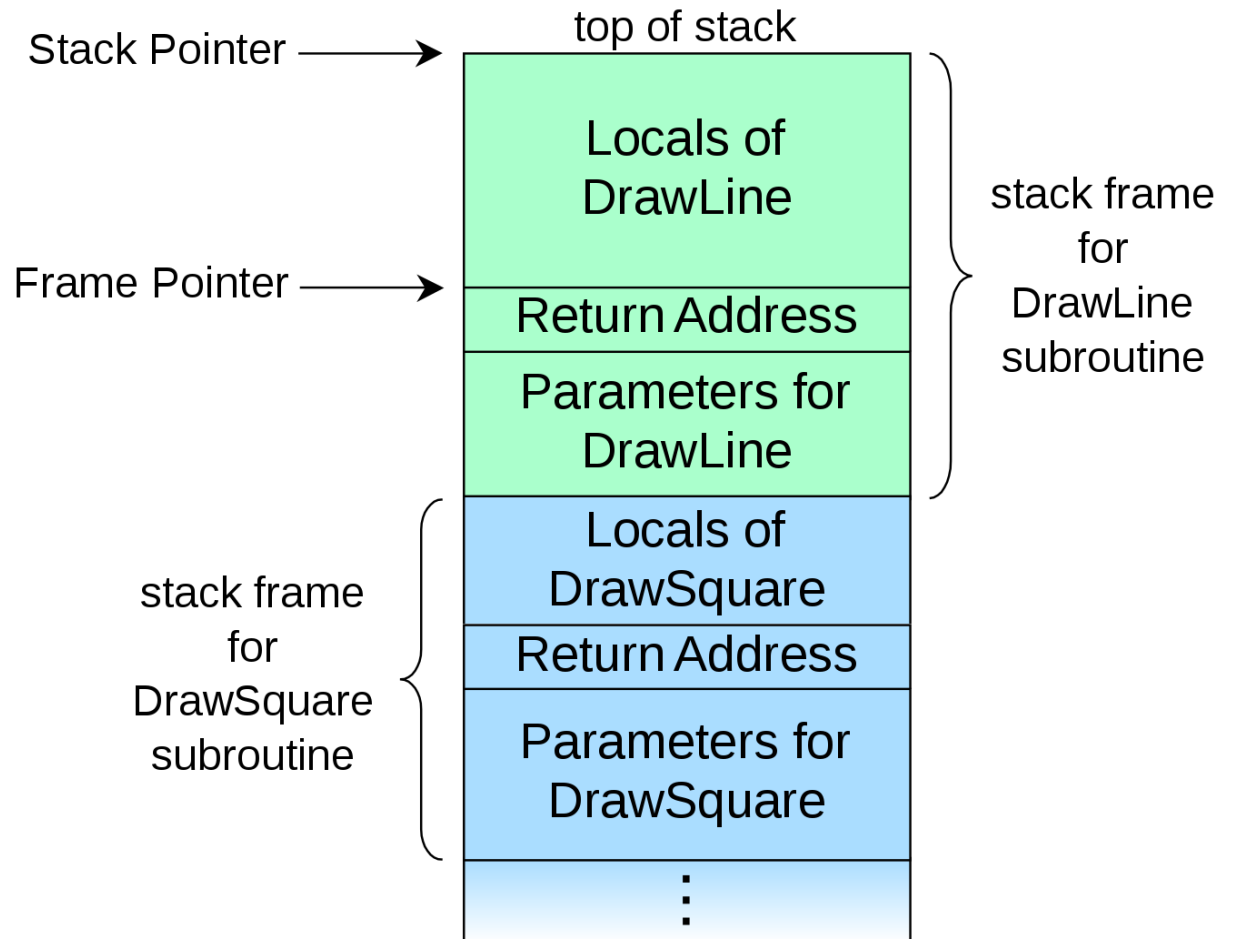
Calling conventions

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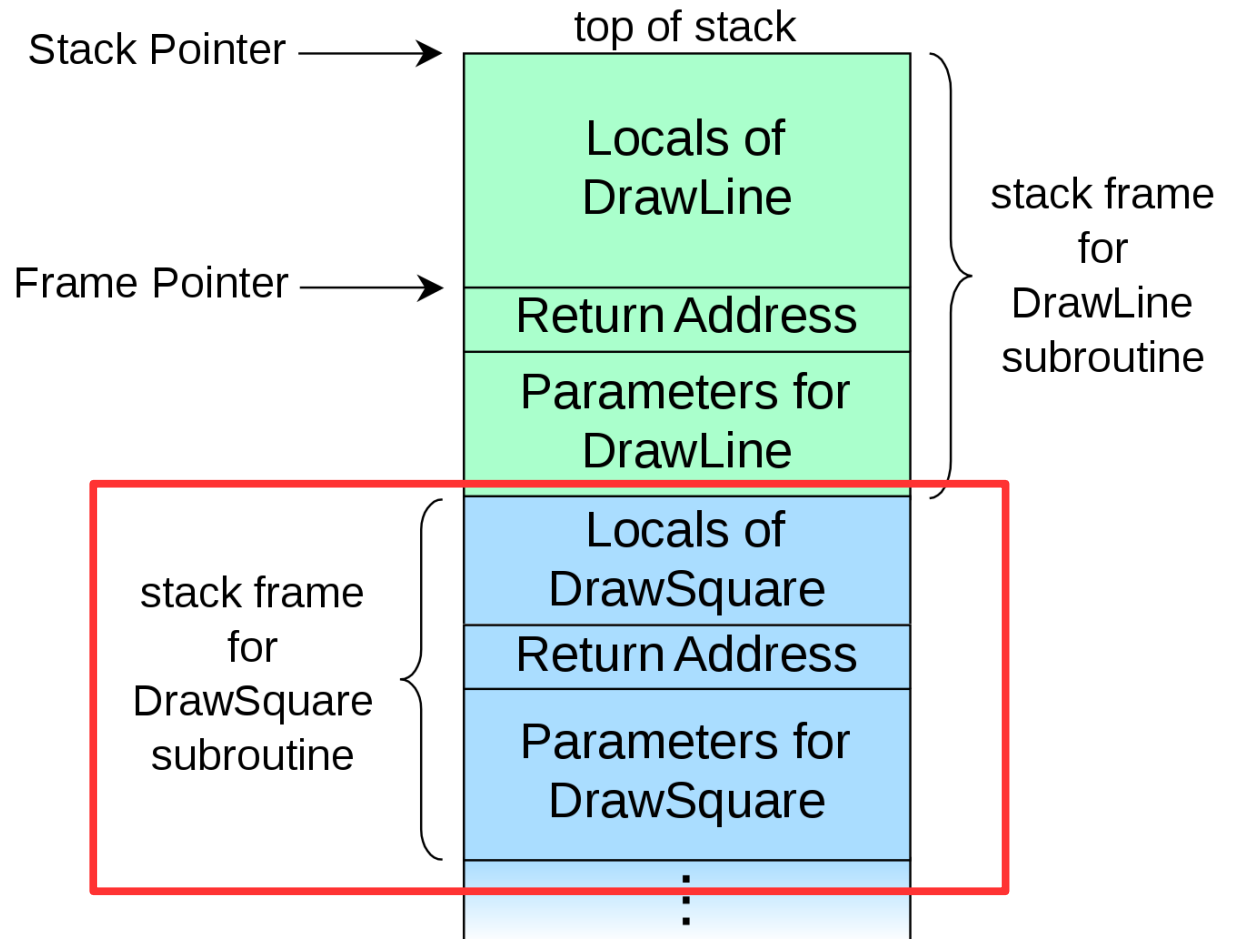- Conventions differ from compiler, optimizations, etc.

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

top of stack

Stack Pointer →

Locals of DrawLine

Frame Pointer →

Return Address
Parameters for DrawLine

stack frame for DrawLine subroutine

Locals of DrawSquare
Return Address
Parameters for DrawSquare

stack frame for DrawSquare subroutine

⋮

Maintain stack as frames

- Each function has a new frame

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

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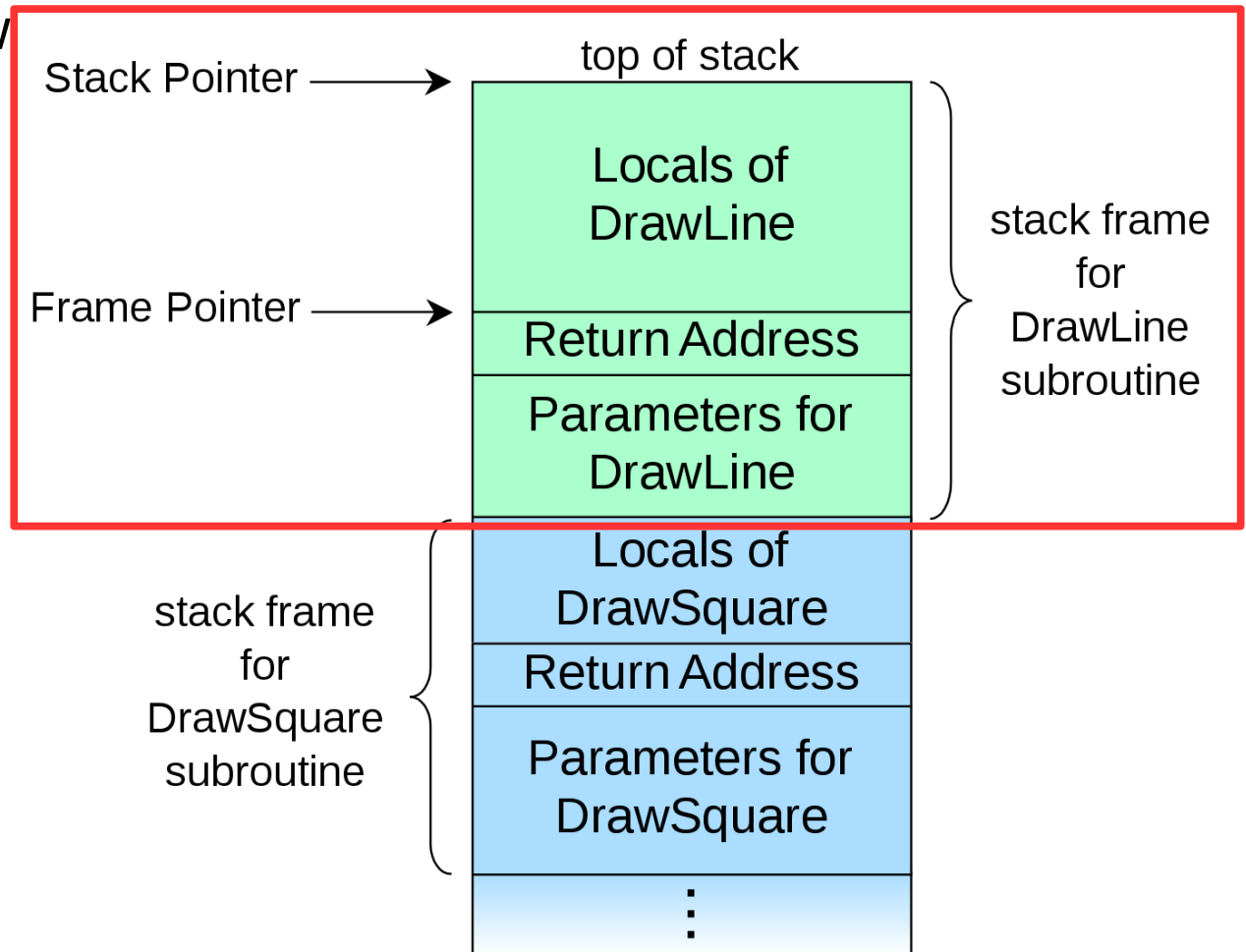 - Points to the base of the frame

Stack Pointer →

top of stack

Locals of DrawLine

Frame Pointer →

Return Address

Parameters for DrawLine

stack frame for DrawLine subroutine

Locals of DrawSquare

stack frame for DrawSquare subroutine

Return Address

Parameters for DrawSquare

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

Stack Pointer →

top of stack

Frame Pointer →

| Locals of DrawLine |
| Return Address |
| Parameters for DrawLine |

stack frame for DrawLine subroutine

| Locals of DrawSquare |
| Return Address |
| Parameters for DrawSquare |

stack frame for DrawSquare subroutine

⋮

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
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Example

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void my_function() {
    int a, b, c;
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Example

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


_my_function:
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mov [ebp -  4], 10  ; location of variable a
mov [ebp -  8], 5   ; location of b
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)
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:    :
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```

Example stack

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| 10 | [ebp + 16] (3rd function argument)
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:    :
:    :
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Example stack

```
:    :
| 10 |  [ebp + 16]  (3rd function argument)
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| 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

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

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

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    pop     ebp
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    call    callee
    ; remove arguments from frame
    add     esp, 12
    ; use subroutine result
    add     eax, 5
    ; restore old call frame
    pop     ebp
    ; return
    ret
```

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int caller(void)
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    call      callee
    ; remove arguments from frame
    add       esp, 12
    ; use subroutine result
    add       eax, 5
    ; restore old call frame
    pop       ebp
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    ret
```

Example: caller side code

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int callee(int, int, int);

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    return ret;
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    push      ebp
    mov       ebp, esp
    ; push call arguments
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    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
```

Wait, where is "return ret;" ?

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

int caller(void)
{
    int ret;

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

```asm
caller:
    ; manage own stack frame
    push    ebp
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    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: callee side code

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

```asm
_my_function:
  push ebp
  mov ebp, esp
  sub esp, 12 ; allocate local varaibles
             ; 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

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

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

Example: callee side code

```c
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 varaibles
             ; 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
```

leave instruction

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

```asm
_my_function:
  push ebp
  mov ebp, esp ; ebp = esp
  sub esp, 12 ; allocate local varaibles
              ; 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
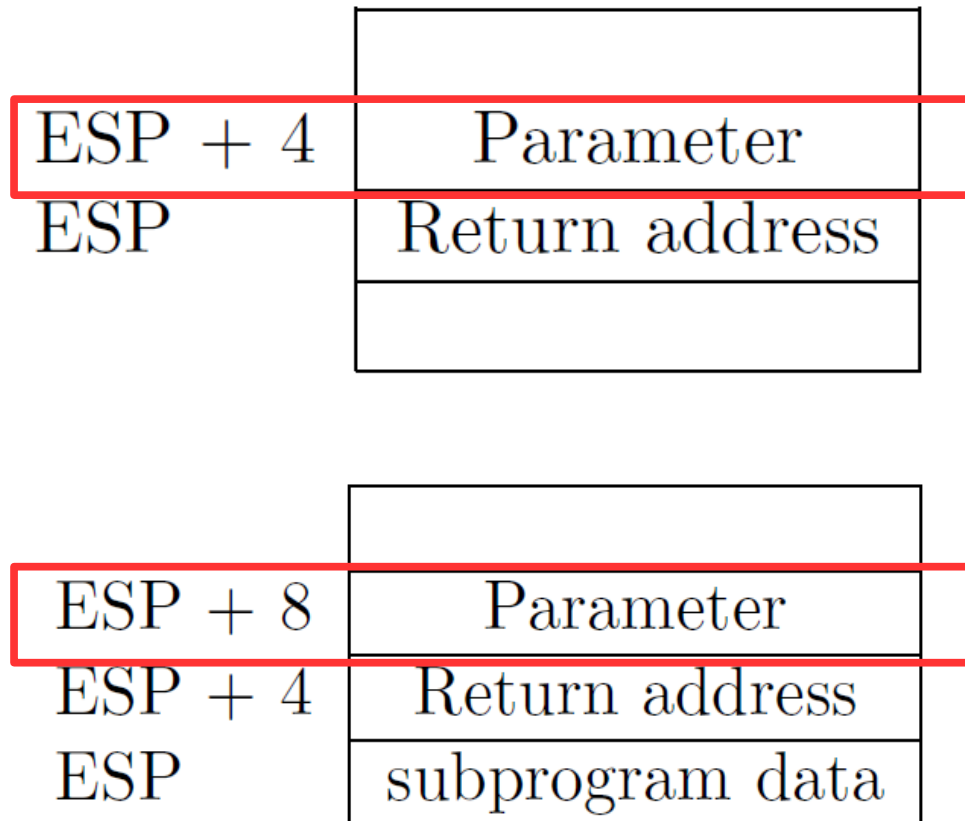 - leave

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 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

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