143A: Principles of Operating Systems

Lecture 4: Calling conventions

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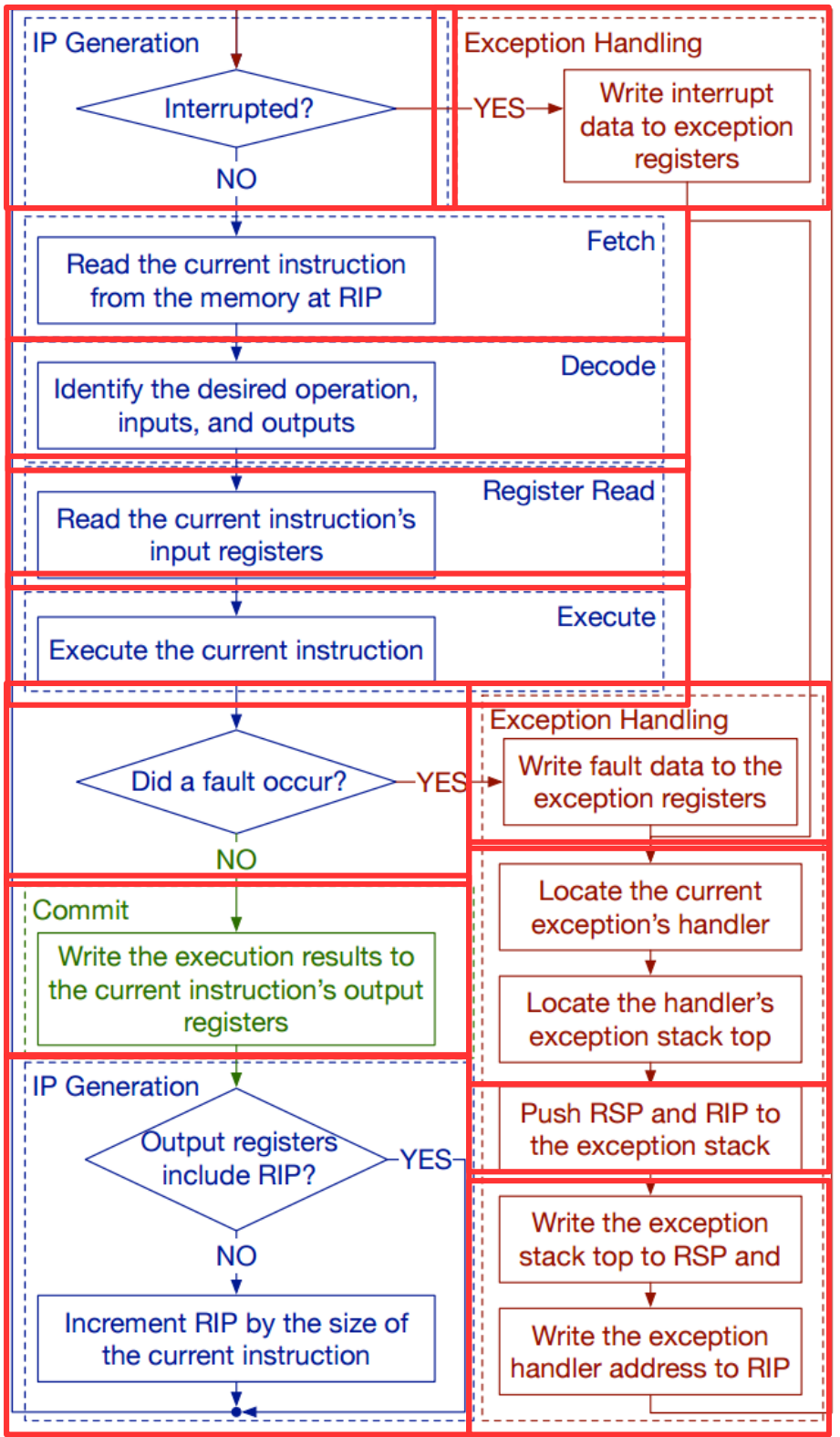
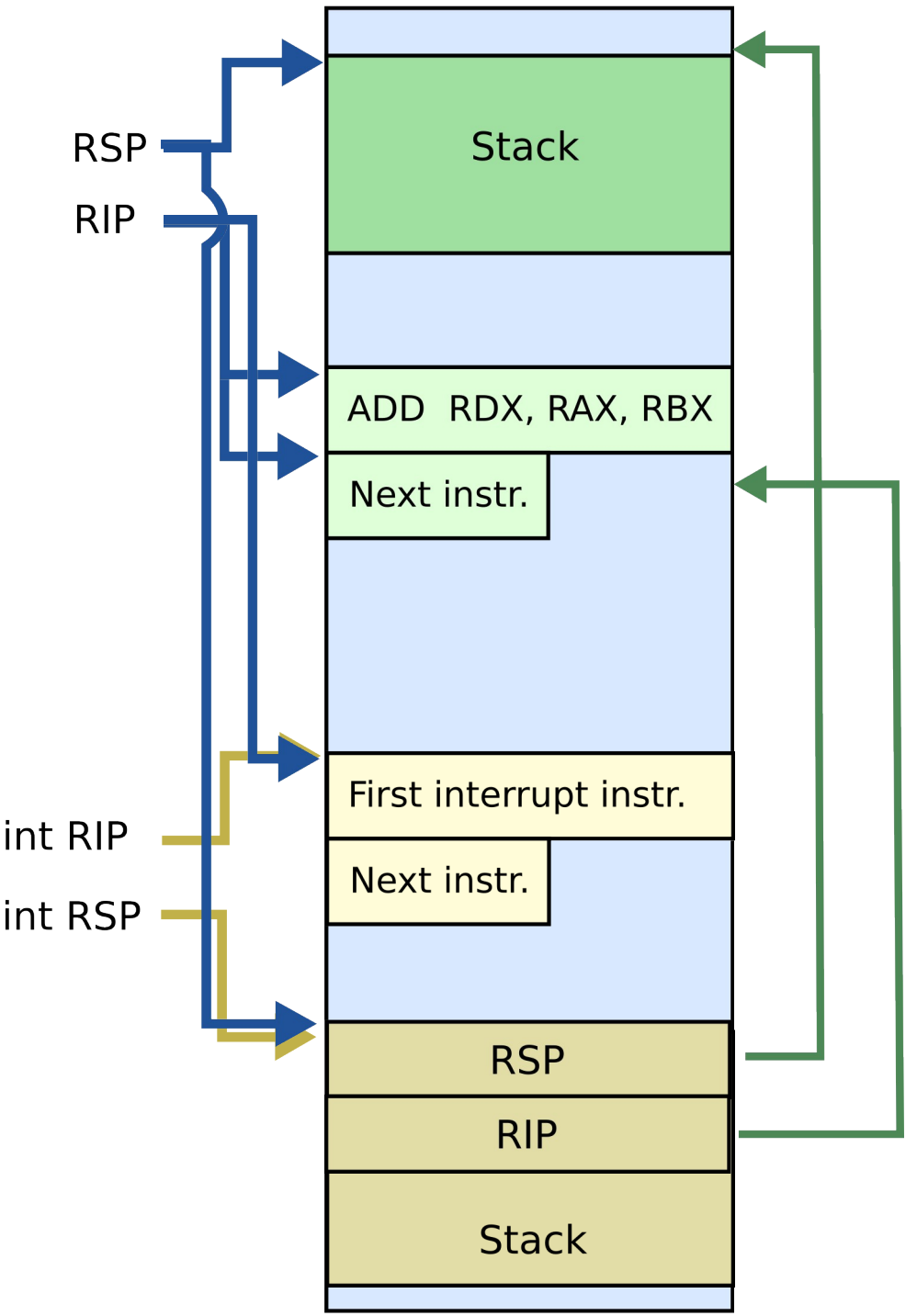
Recap from last time


IP Generation
Interrupted?
YES
NO
Exception Handling
Write interrupt data to exception registers
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
NO
Exception Handling
Write fault data to the exception registers
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
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

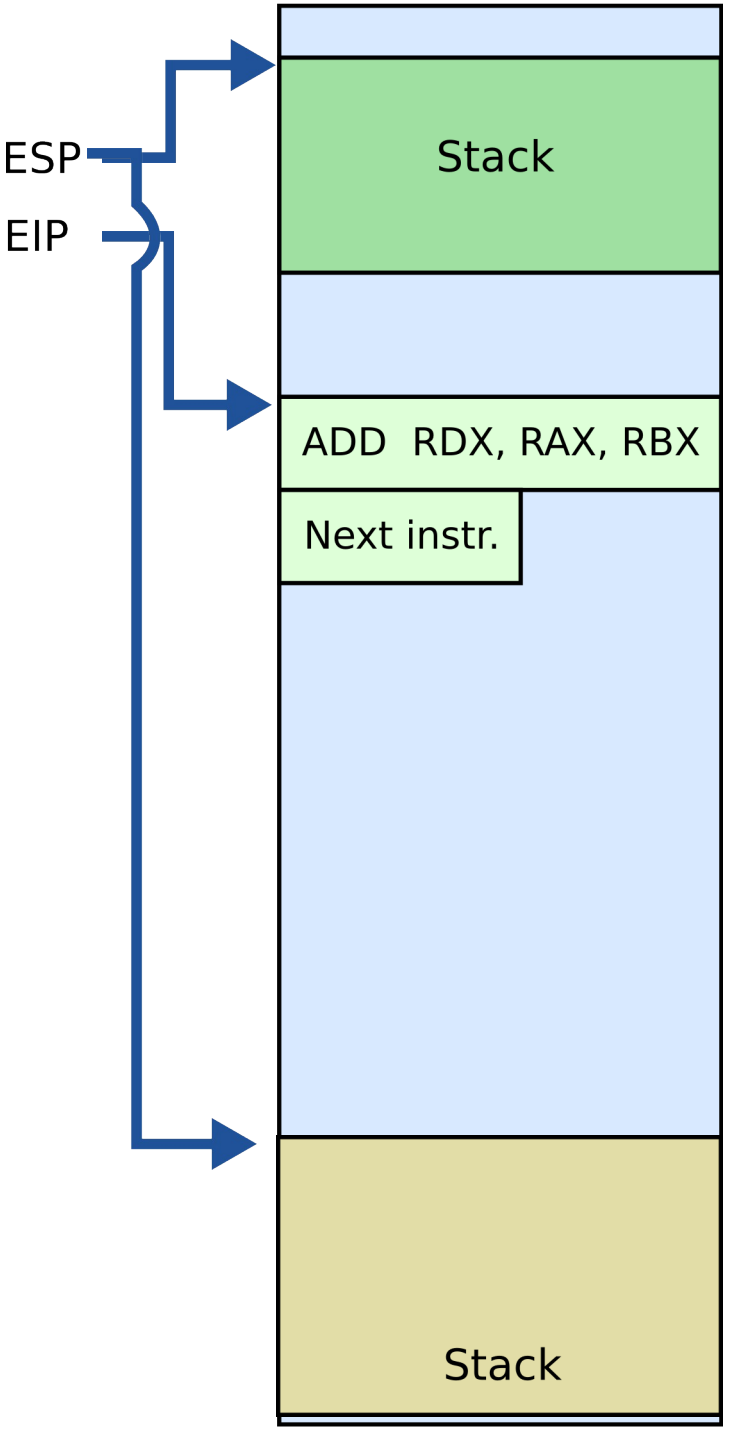

RSP
RIP
int RIP
int RSP
Stack
ADD RDX, RAX, RBX
Next instr.
First interrupt instr.
Next instr.
RSP
RIP
Stack

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?

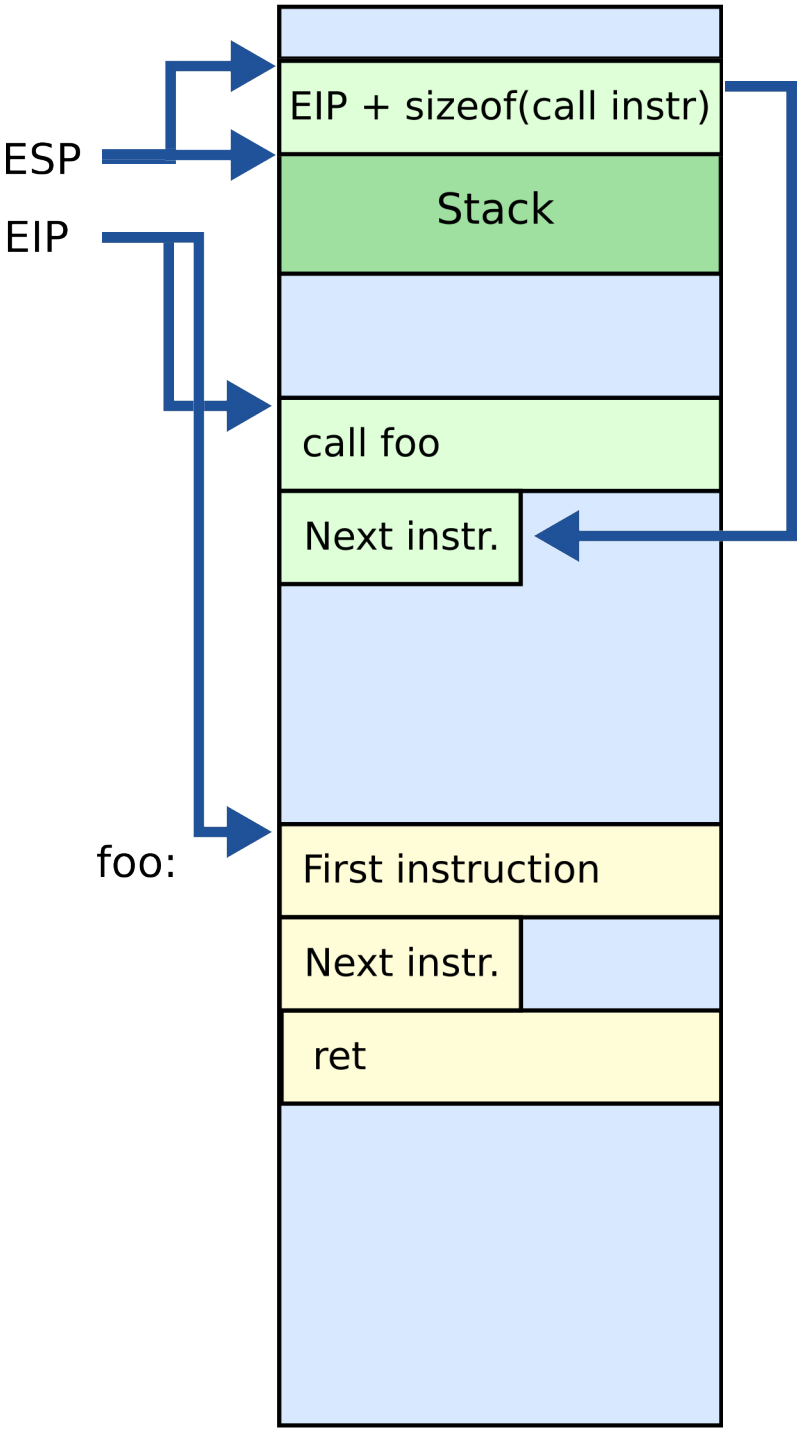
Calling functions

```
// 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



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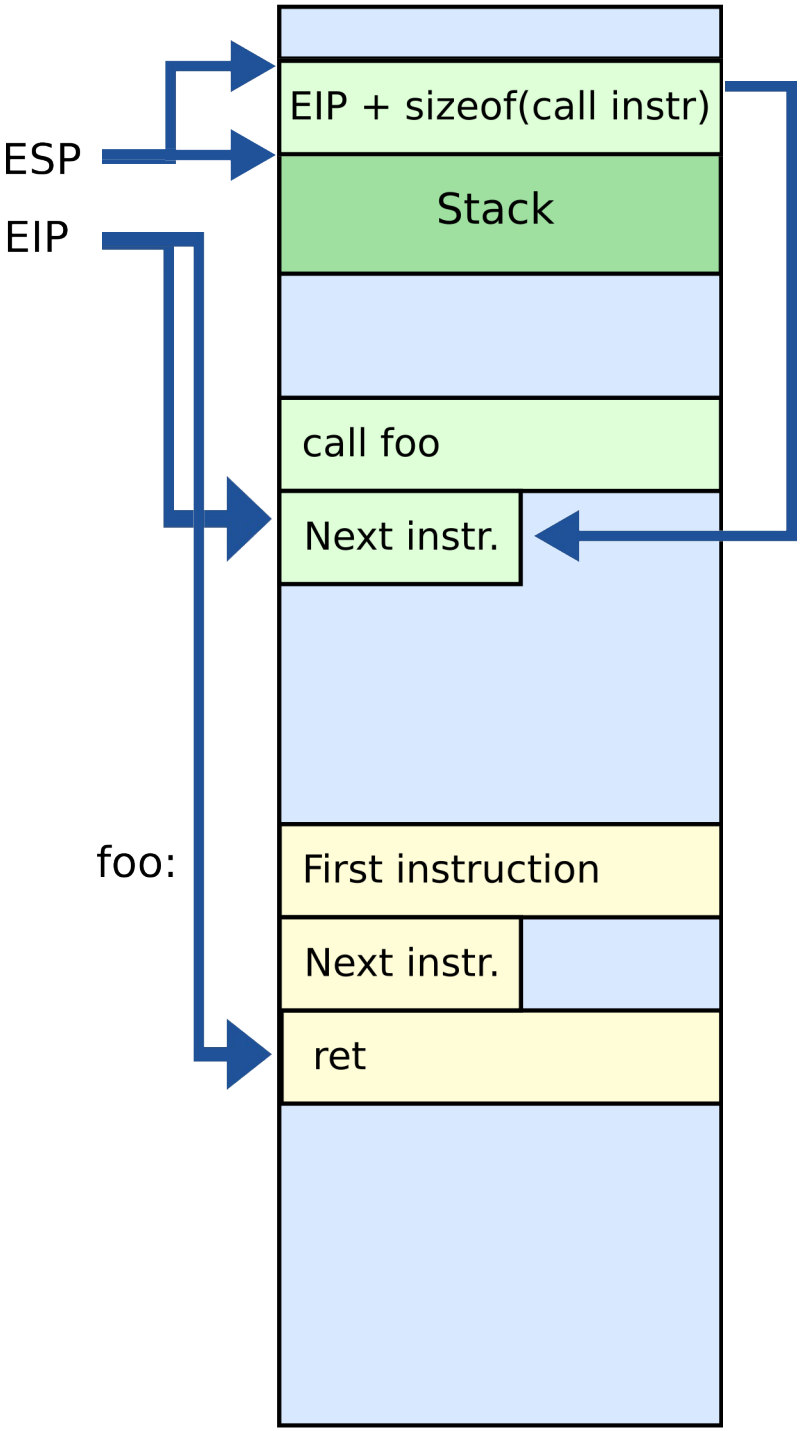
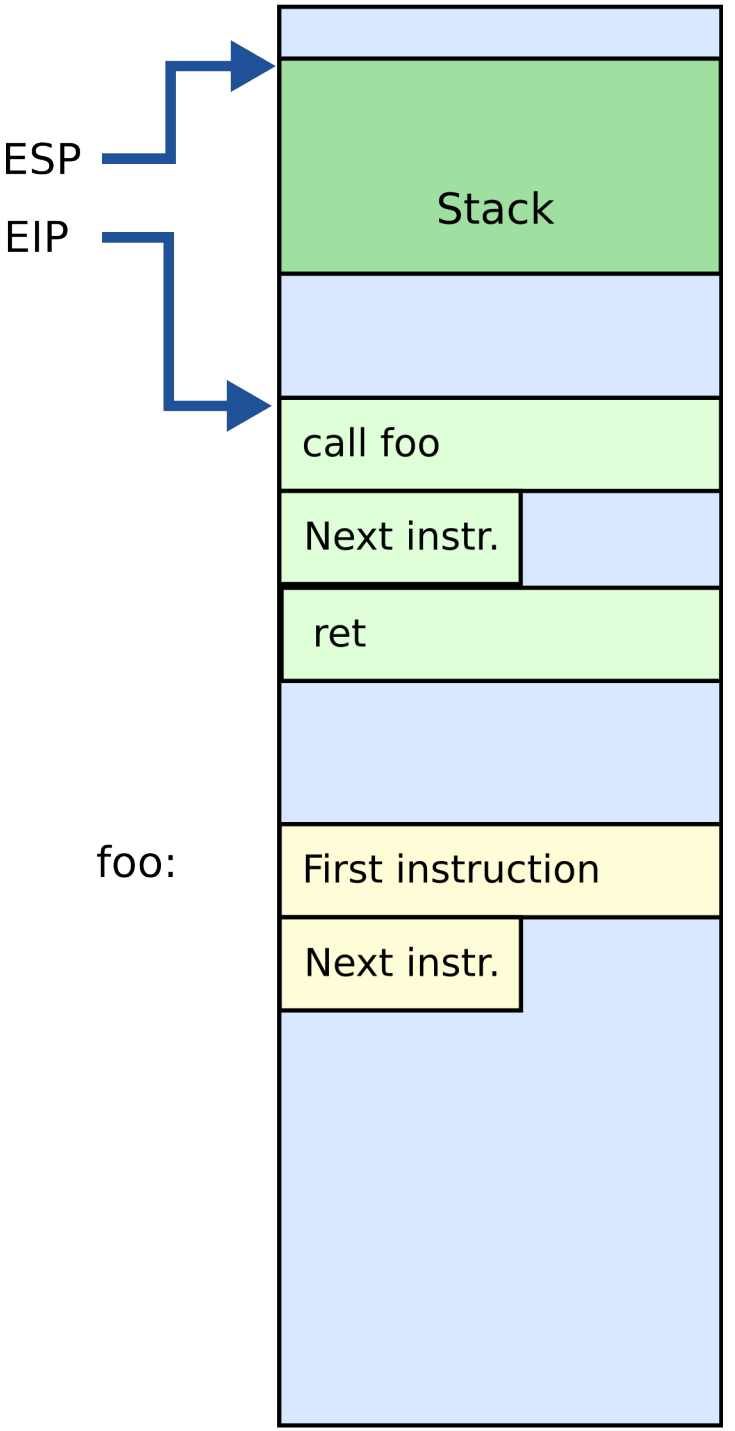


Stack

- 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
```

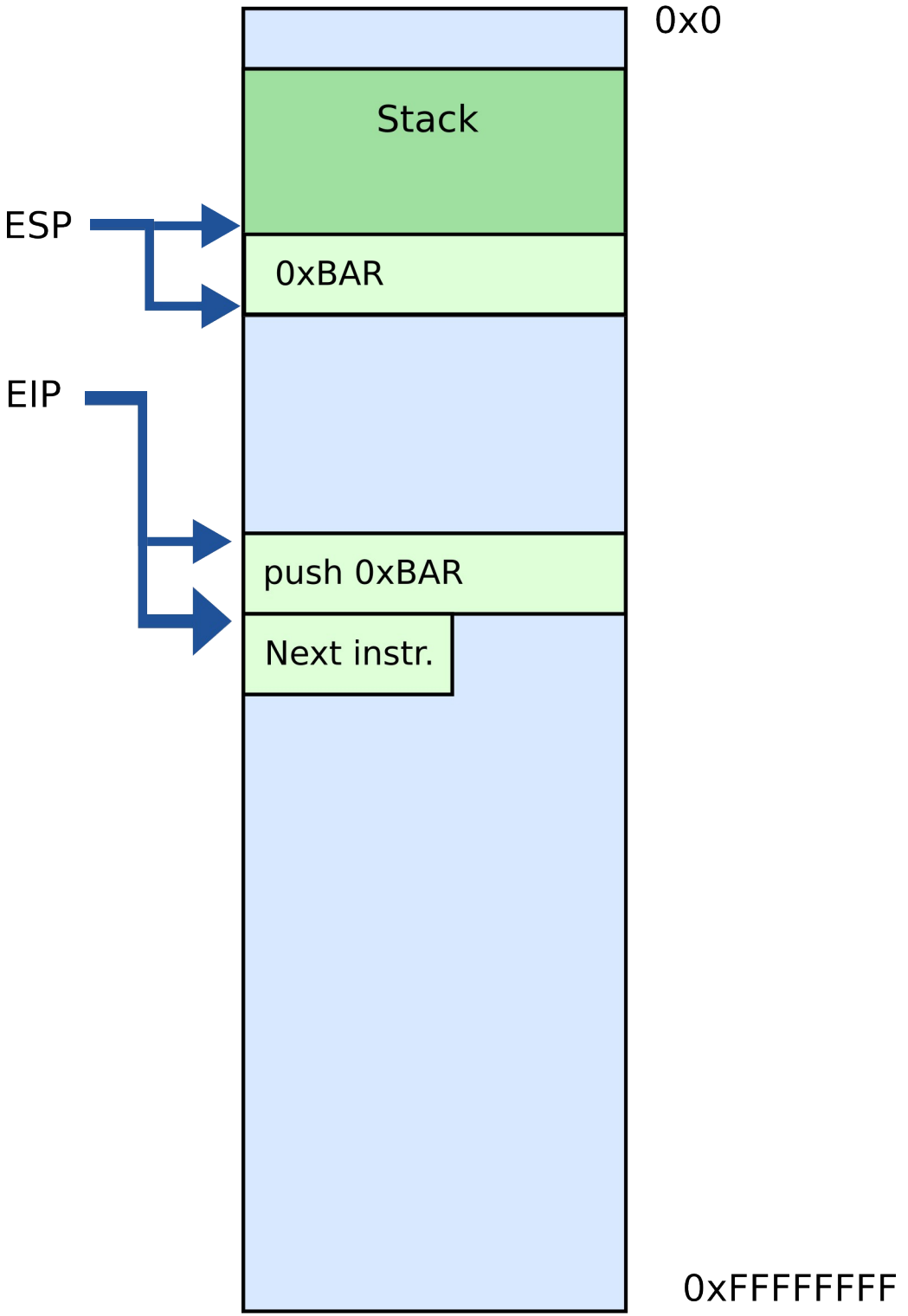
- RET instruction
  - Pops off an address and jumps to that address

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

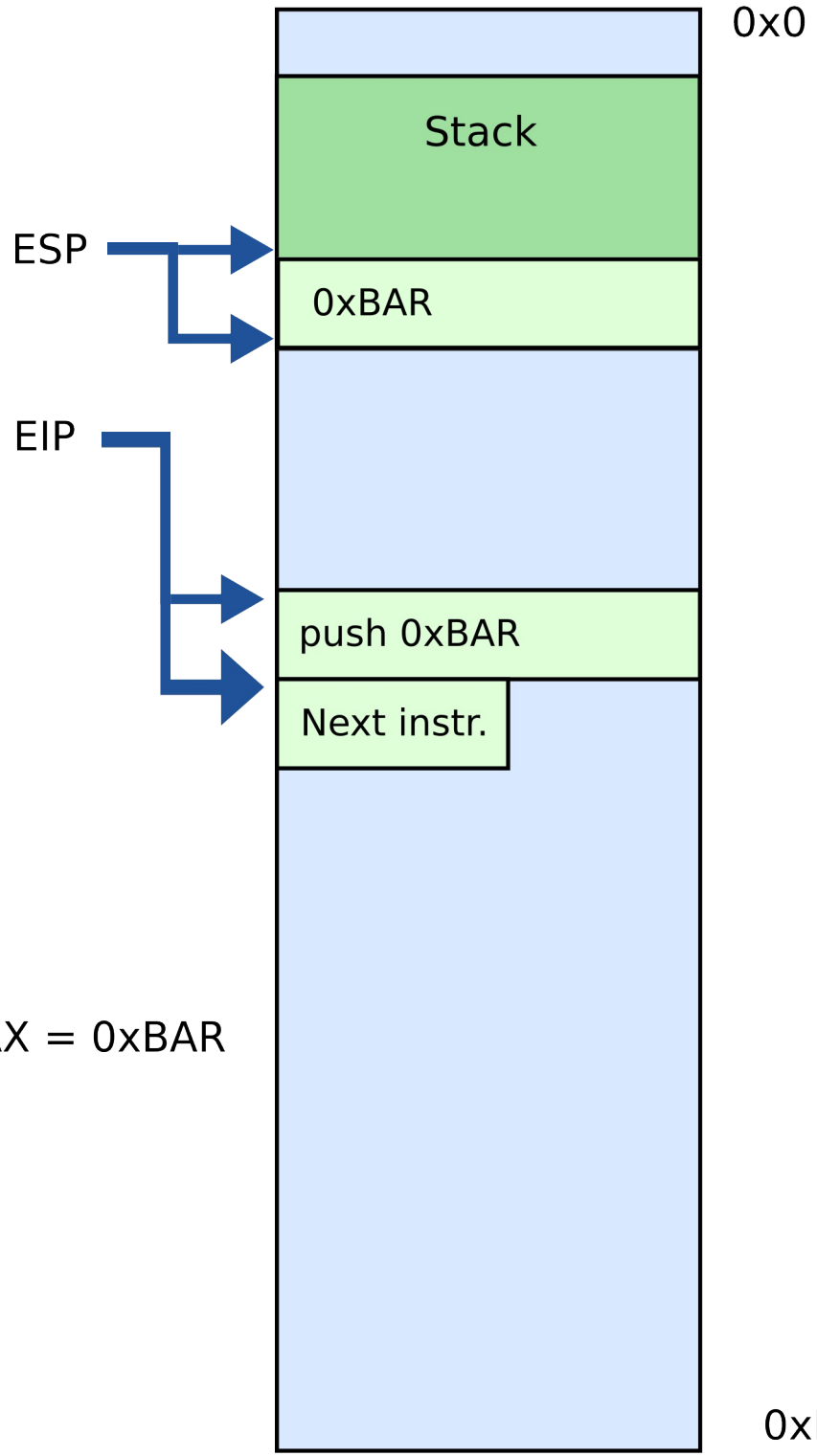


Manipulating stack

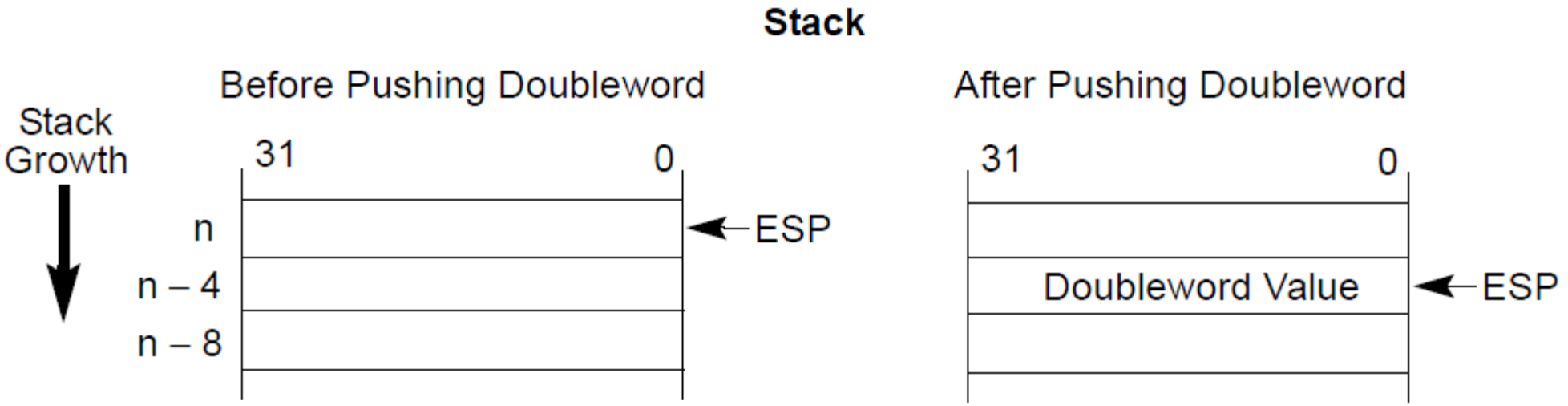
- POP instruction

```
pop EAX
```

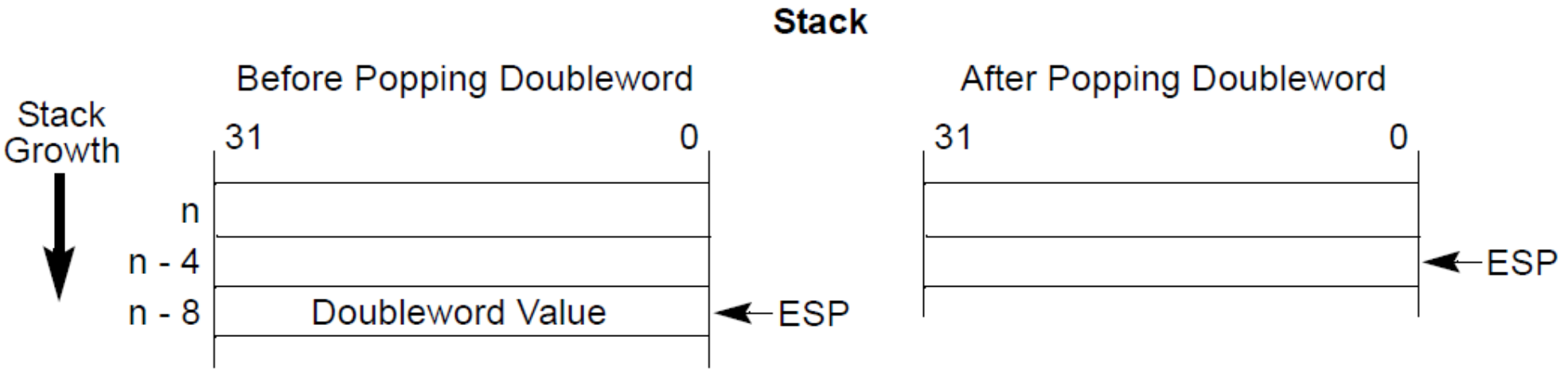
  - Removes data from the stack
  - Saves in register or memory
  - Adds 4 to ESP



Example: PUSH



Example: POP


Stack
Before Popping Doubleword
Stack Growth
31
0
n
n - 4
n - 8
Doubleword Value
ESP
After Popping Doubleword
31
0
ESP

Calling conventions

Calling conventions

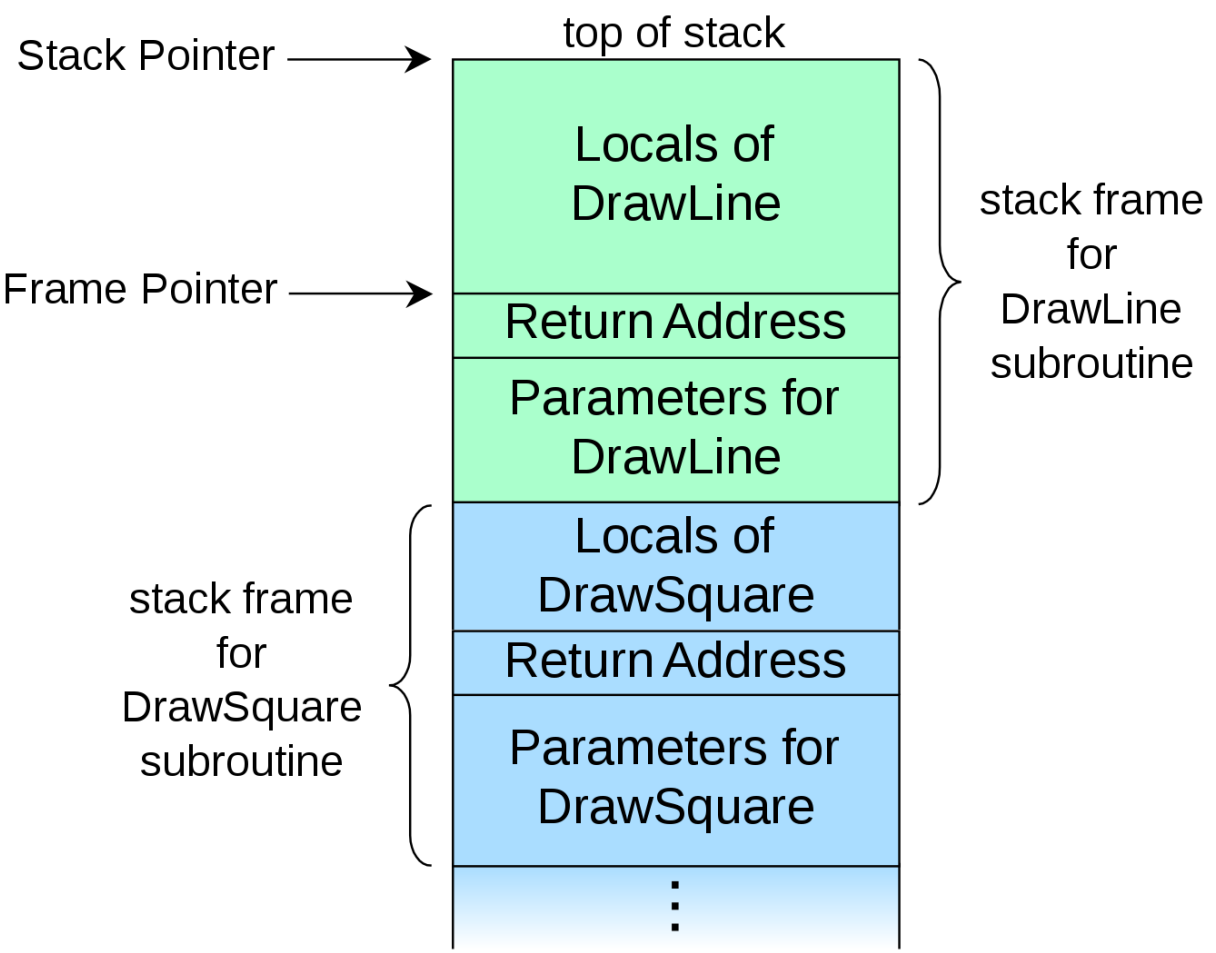
- Goal: reentrant programs
  - How to pass arguments
    - On the stack?
    - In registers?
  - How to return values
    - On the stack?
    - In registers?
- Conventions differ from compiler, optimizations, etc.

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



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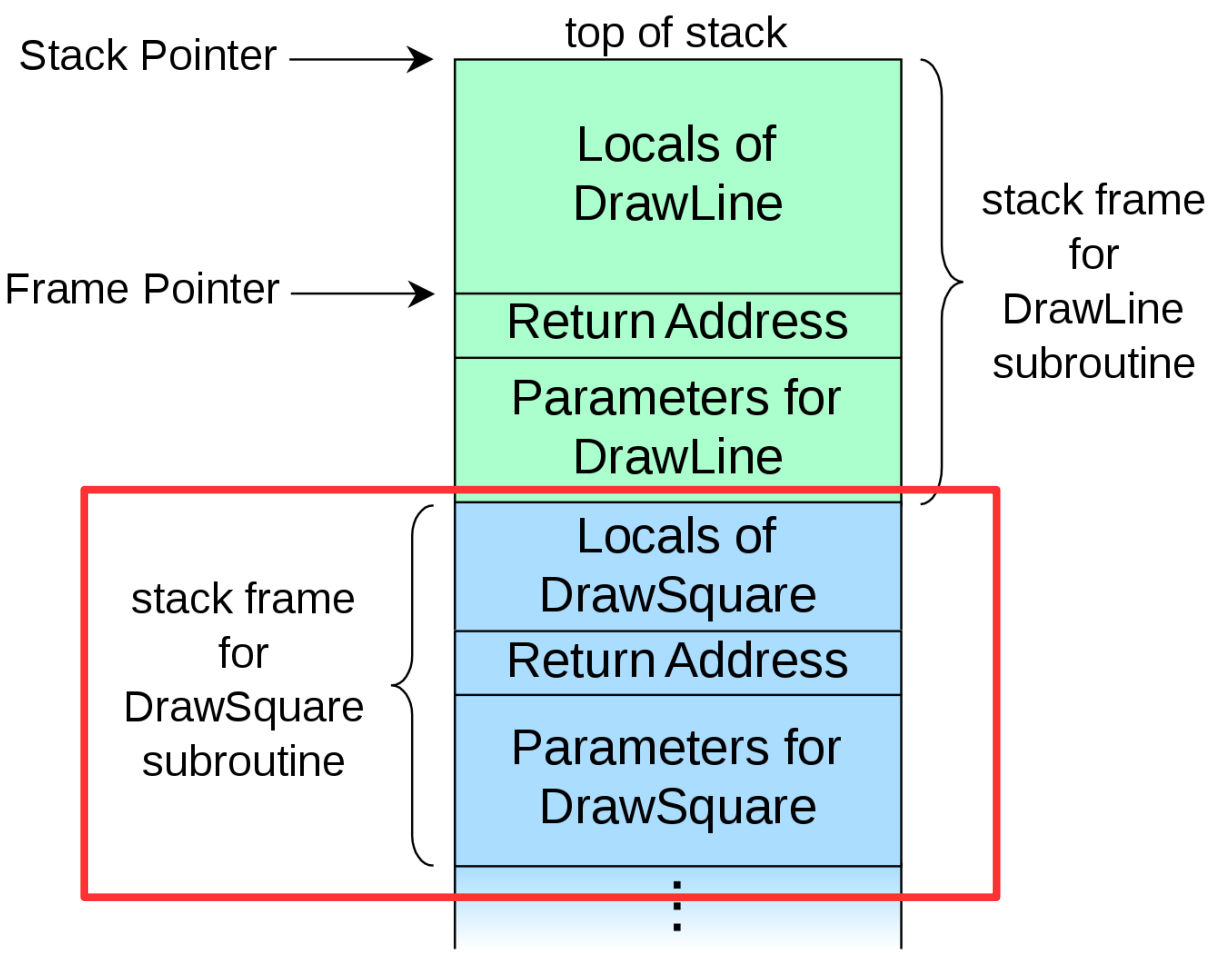

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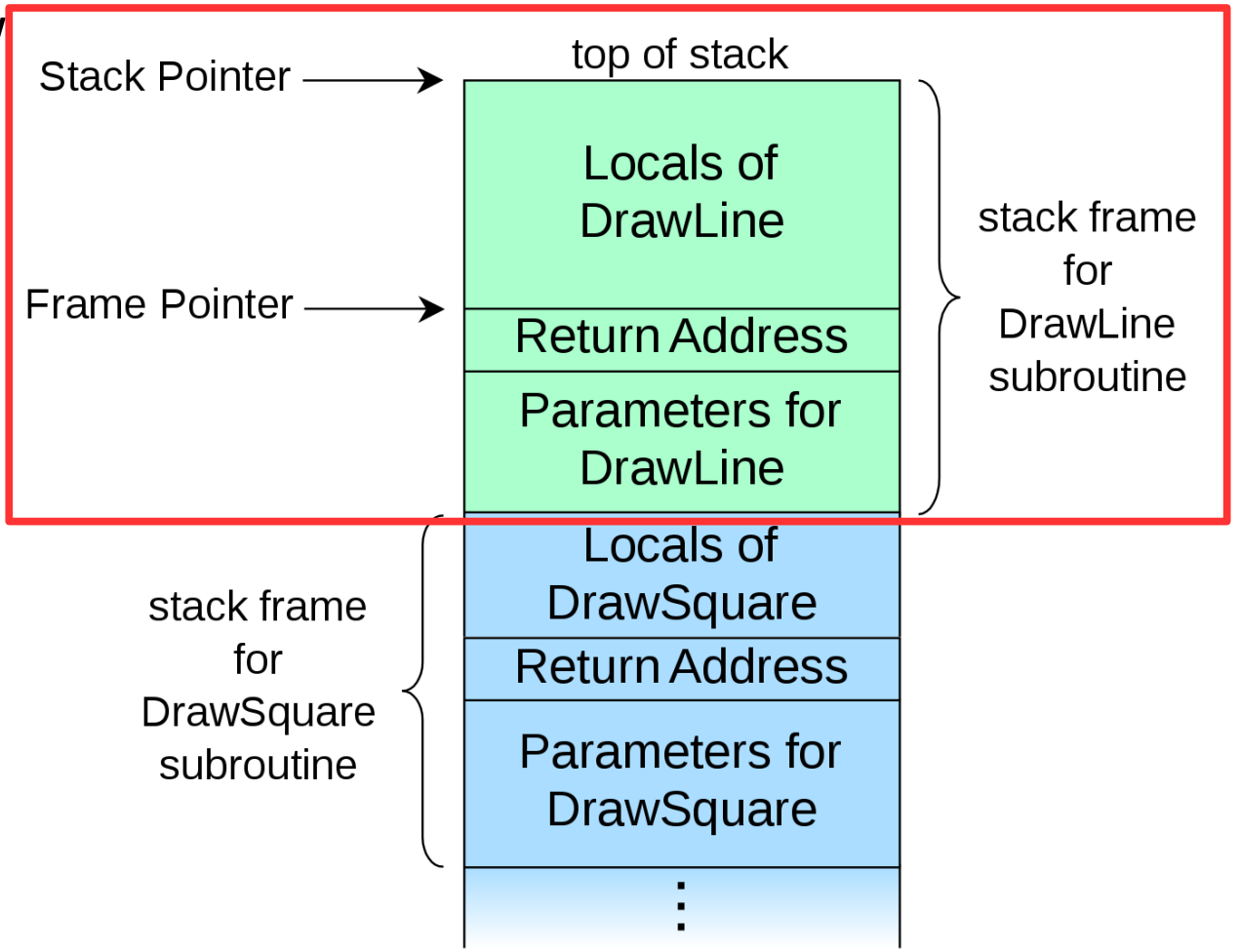

Prologue/epilogue

- 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?

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

Allocating local variables

On the stack!

- Each function has private instances of local variables
- Can call recursively

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

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

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    int a, b, c;
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```

How to pass arguments?

- Options
  - 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)
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|  2 | [ebp + 8]  (1st argument)
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Example stack

```
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| 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: 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 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

```
void my_function(int x, int y, int z)
{
    int a, b, c;
    …
    return;
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_my_function:
  push ebp
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  ; a=[ebp-4]=[esp+8],
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  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
              ; 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: caller side code

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

int caller(void)
{
    int ret;

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

```
caller:
  ; make new call 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

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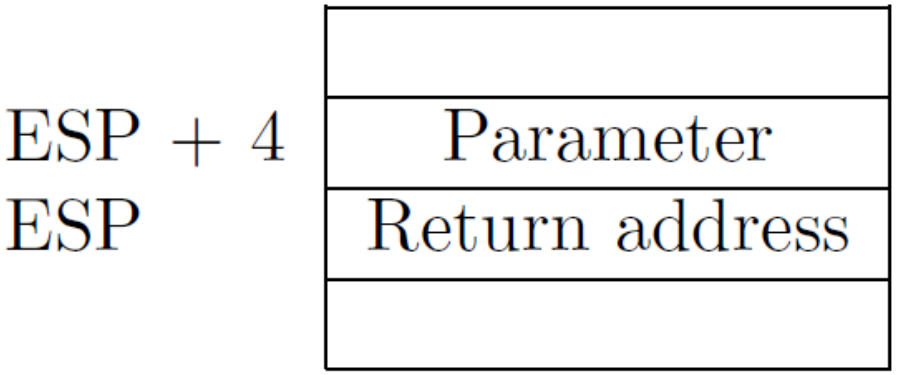
  ; remove arguments from frame
  add     esp, 12
  ; use subroutine result
  add     eax, 5
  ; restore old call frame
  pop     ebp
  ; return
  ret
```

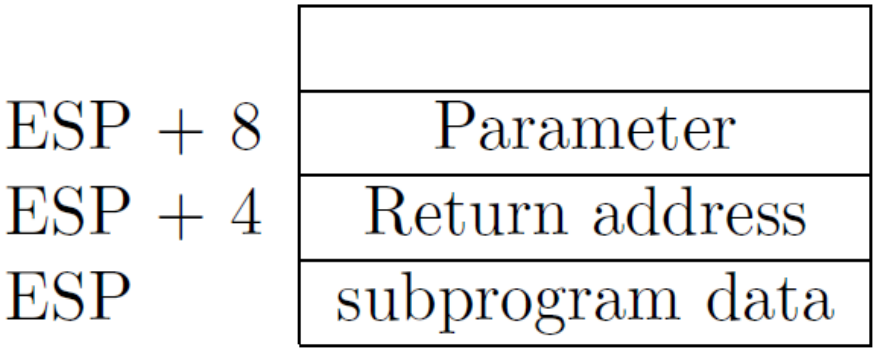
Back to stack frames, so why do we need them?

- … 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 do this!
    - 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

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 a callee and 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
- https://en.wikipedia.org/wiki/X86_calling_conventions
- http://stackoverflow.com/questions/14666665/trying-to-understand-gcc-option-fomit-frame-pointer