143A: Operating Systems

Lecture 3: Stack, function invocations, and calling conventions

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Last two lectures: x86 instruction set

- Three main groups
  - Data movement (from memory and between registers)
  - Arithmetic operations (addition, subtraction, etc.)
  - Control flow (jumps, function calls)

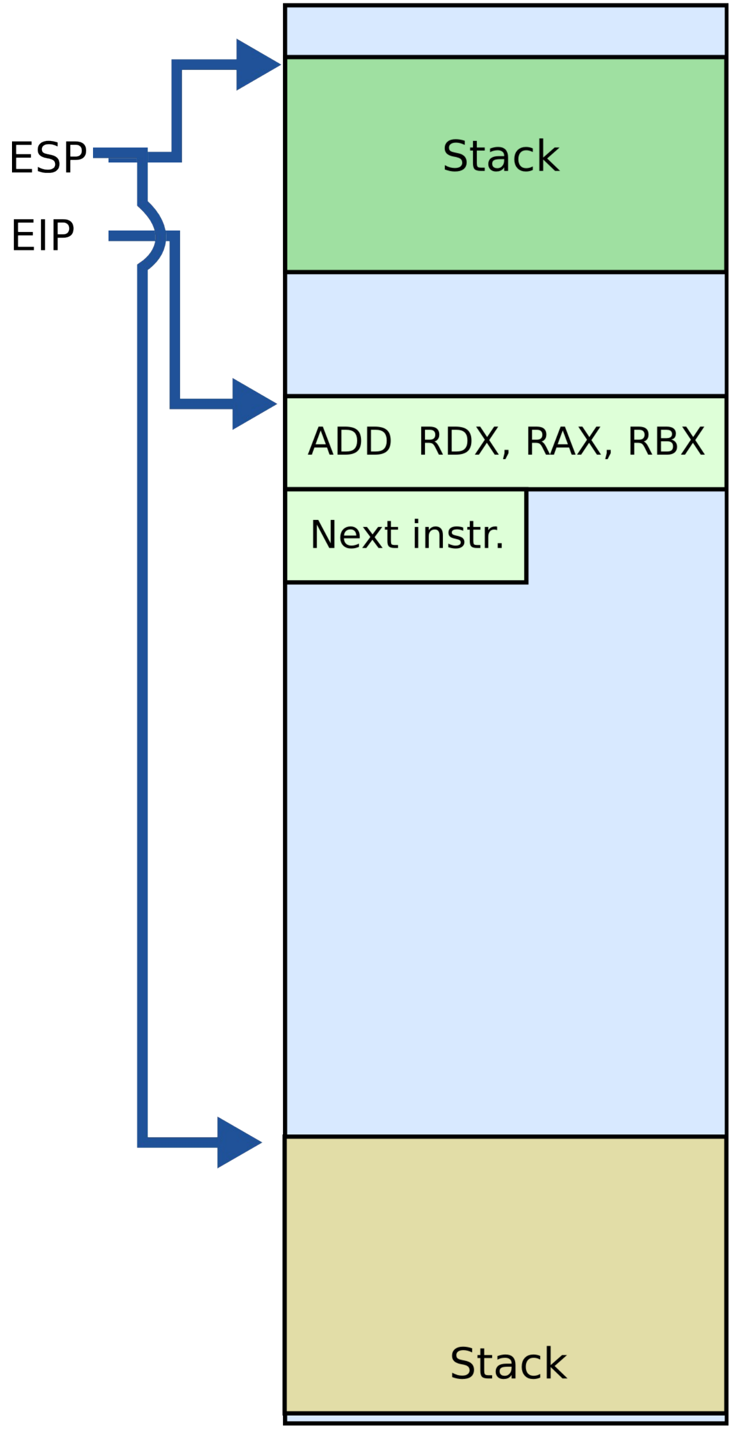
This is enough to write all programs you can think of

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..
```

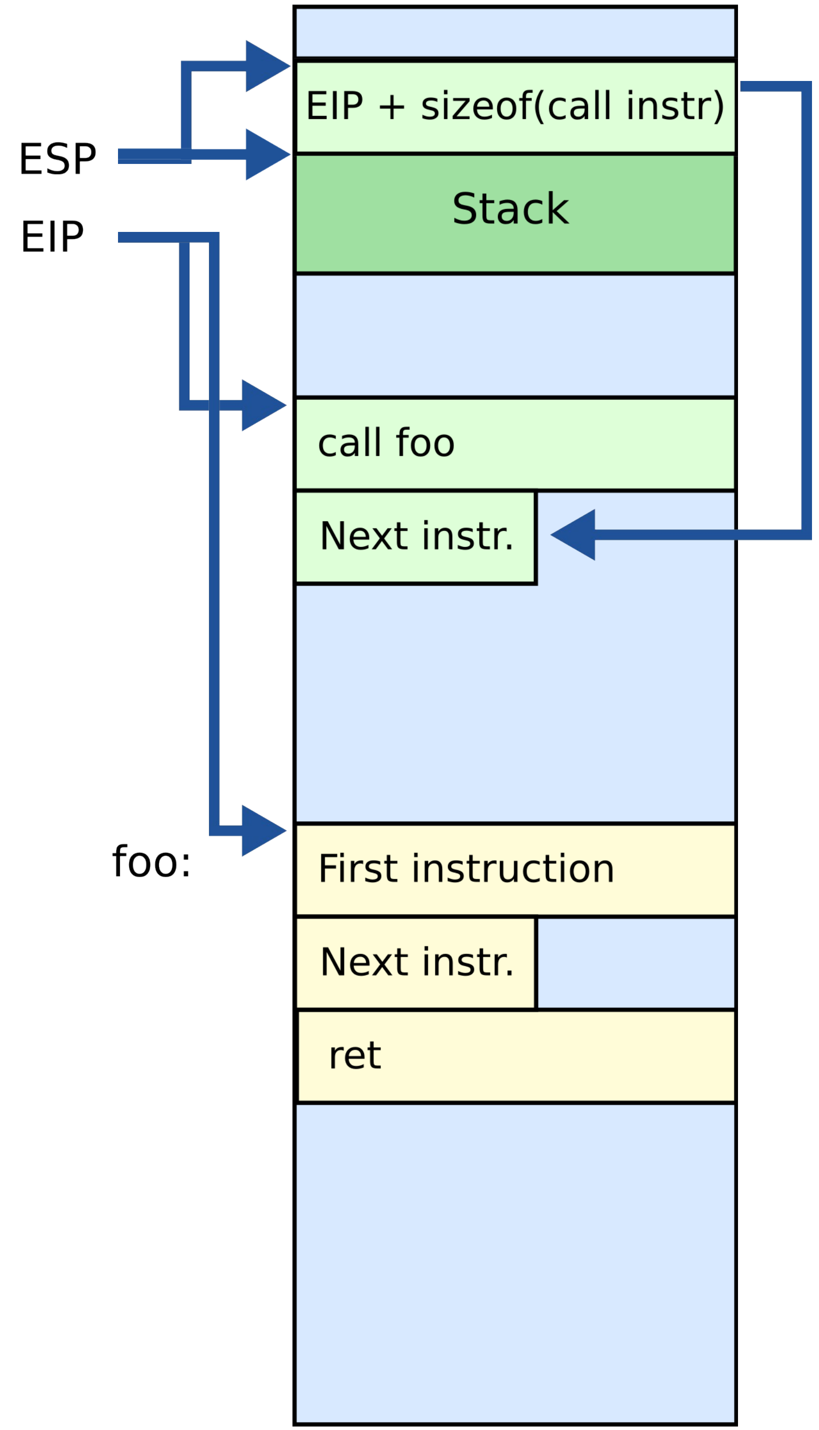
- Stack contains information for how to return from a subroutine
  - i.e., from foo()

- Functions can be called from different places in the program

```
if (a == 0) {
    foo();
    …
} else {
    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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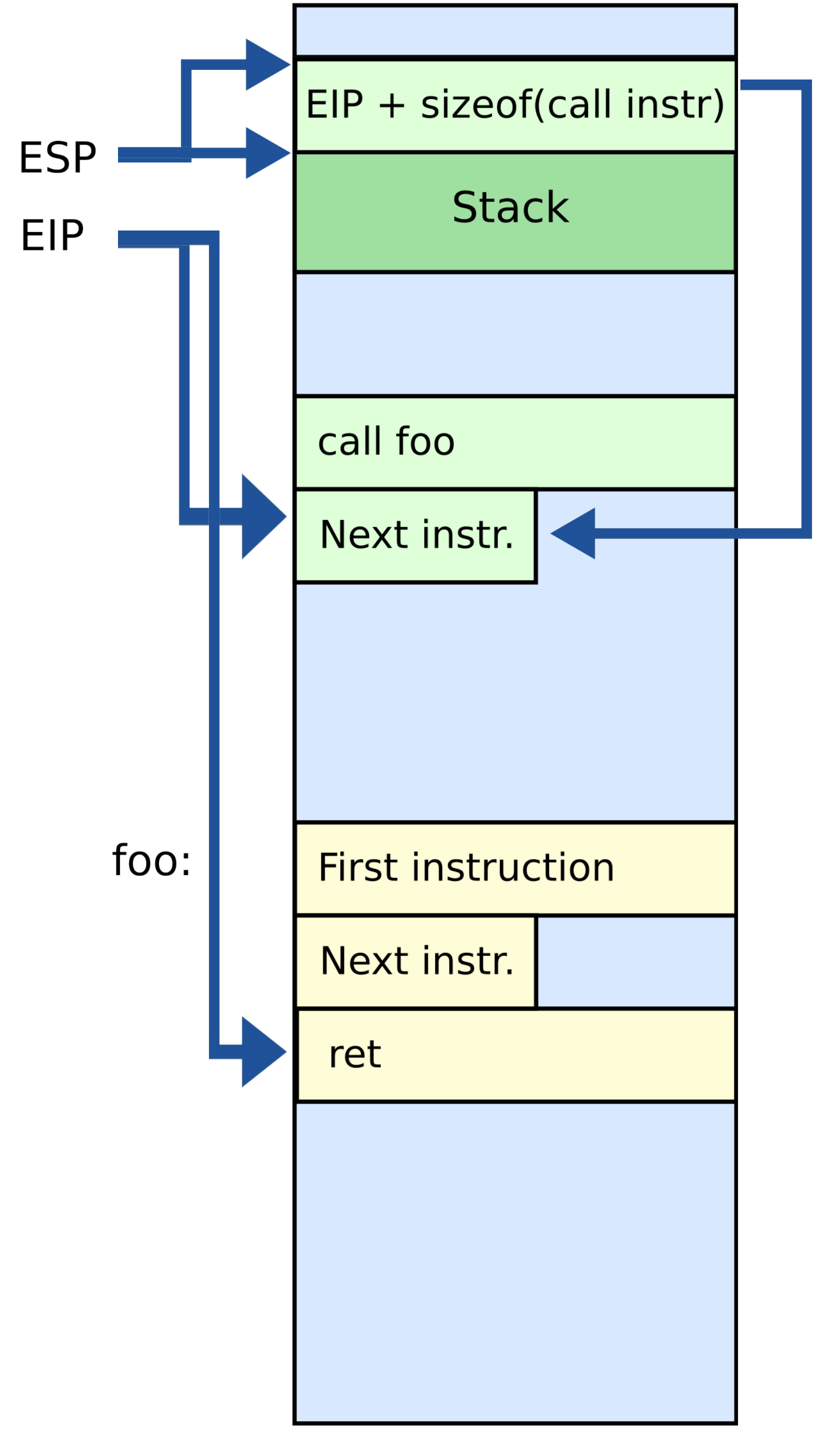


Call/return

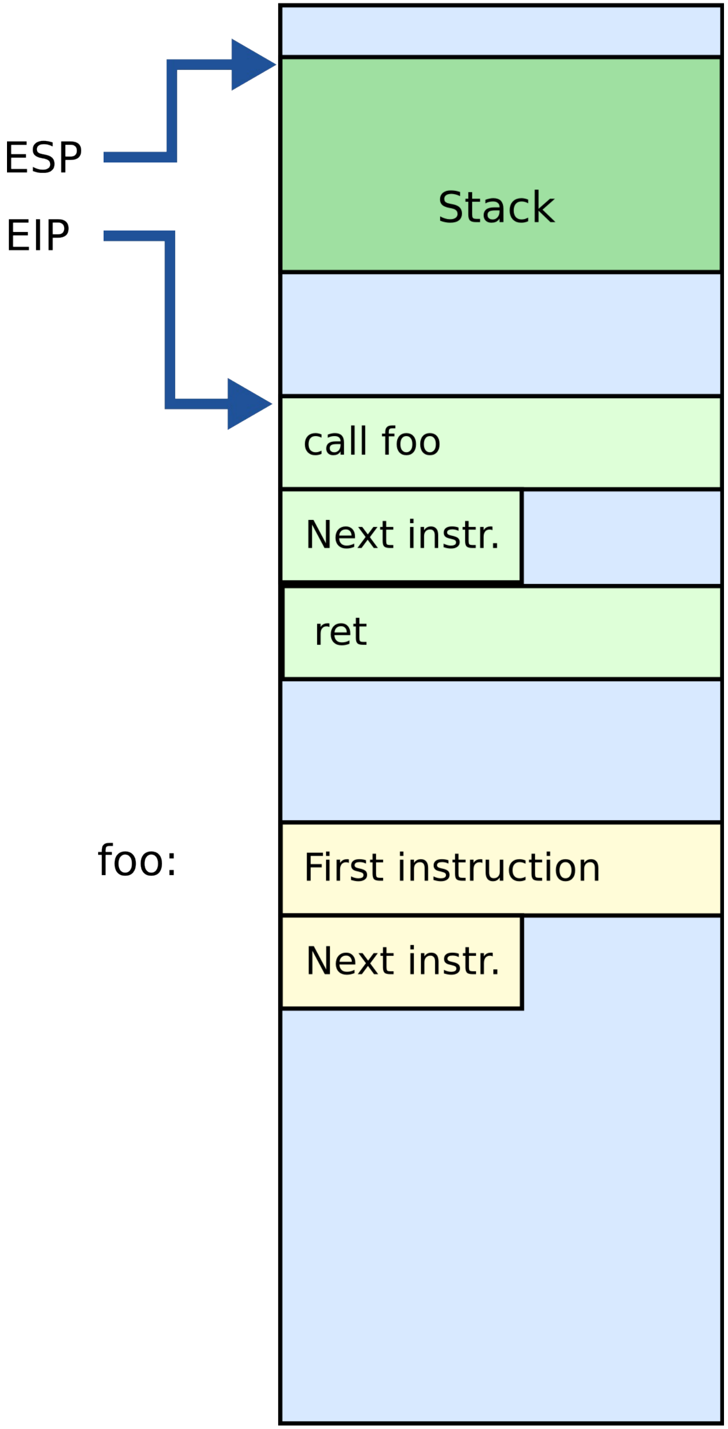
- CALL instruction
  - Makes an unconditional jump to a subprogram and pushes the address of the next instruction on the stack

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

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

Stack

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

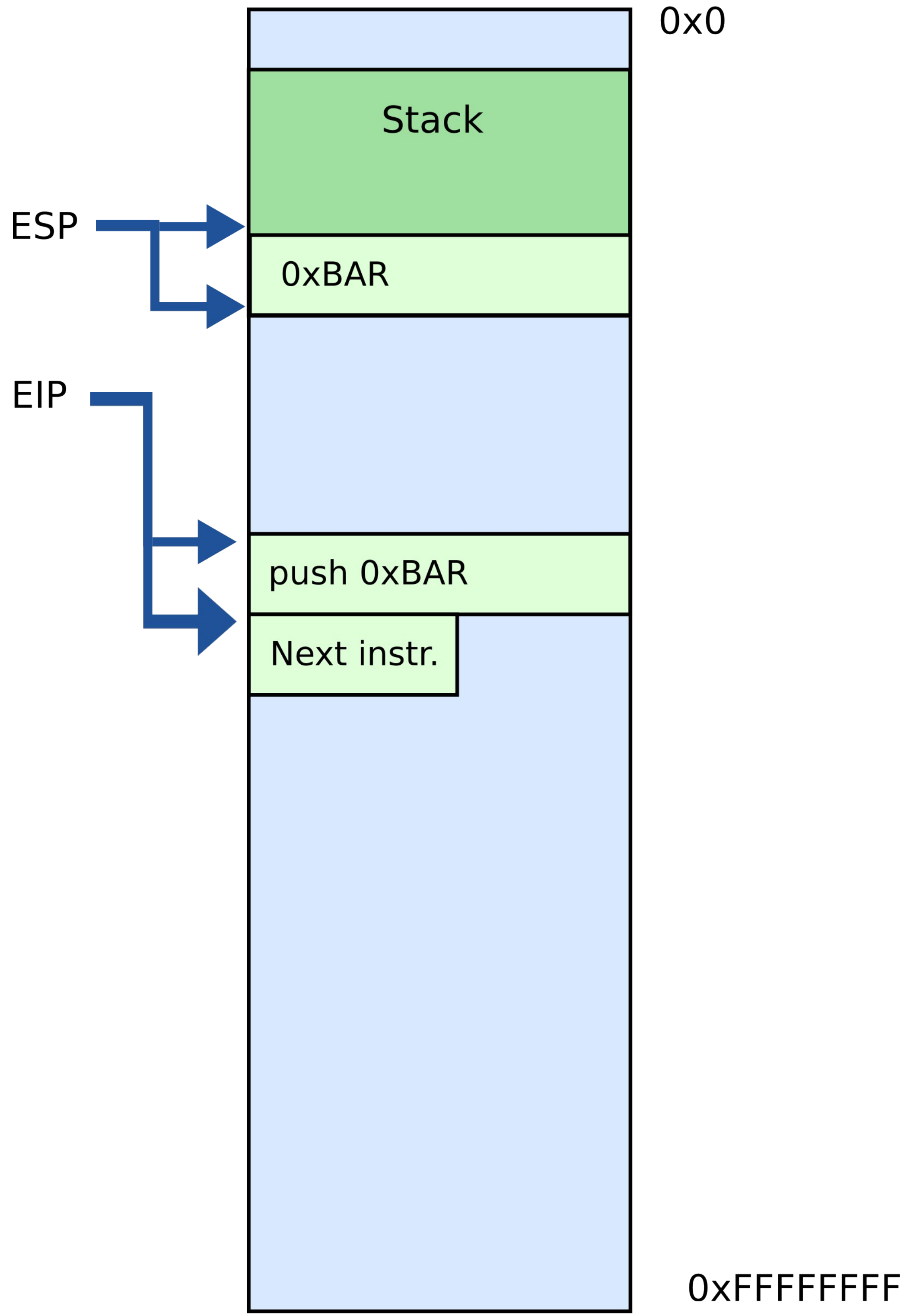


Manipulating stack

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

  `push 0xBAR`

  - Subtract 4 from ESP
  - Insert data on the stack

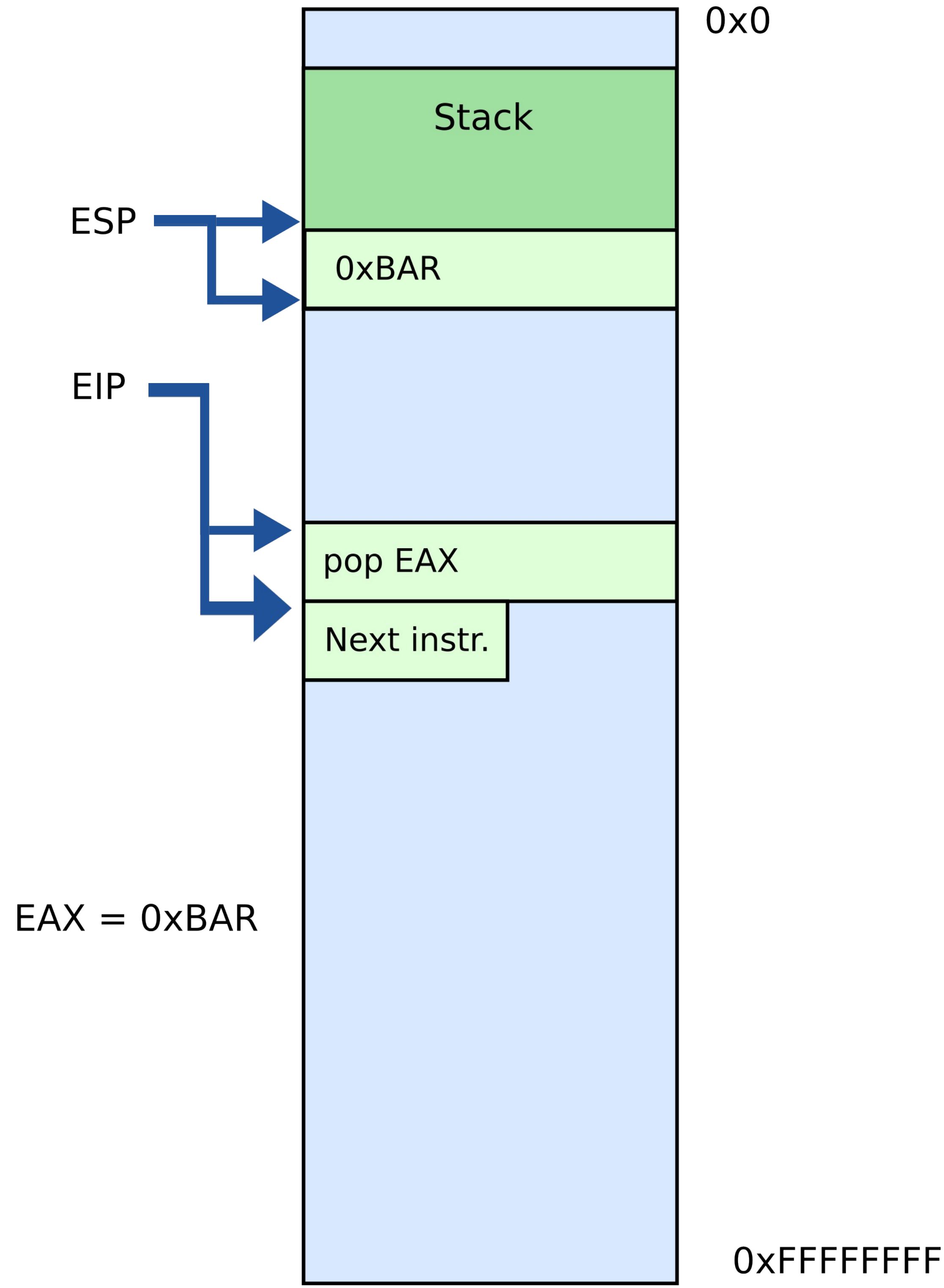


Manipulating stack

- POP instruction

  `pop EAX`

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



Calling conventions

Calling conventions

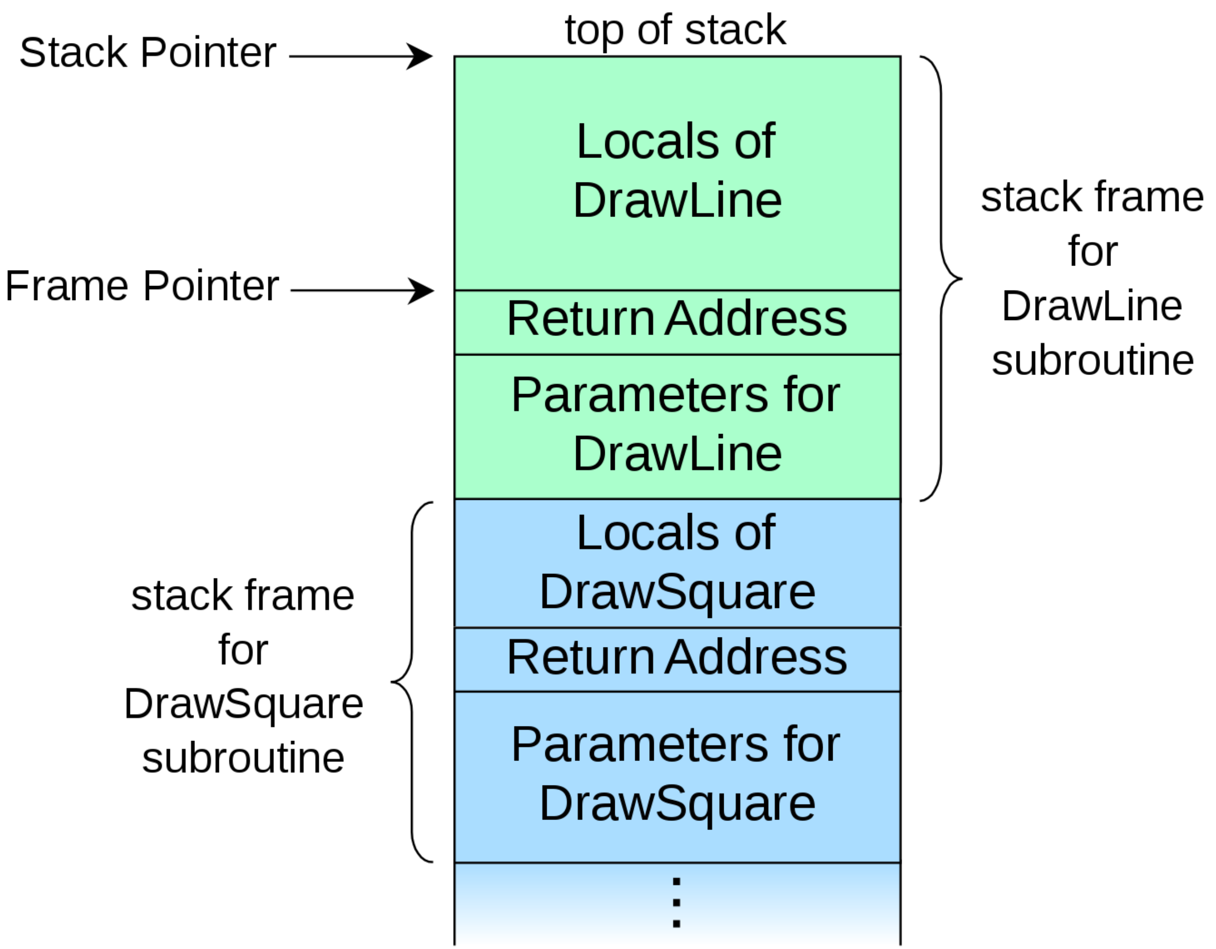
- Goal: re-entrant programs
  - How to pass arguments
    - On the stack?
    - In registers?
  - How to return values
    - On the stack?
    - In registers?
- Conventions differ from compiler, optimizations, etc.

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

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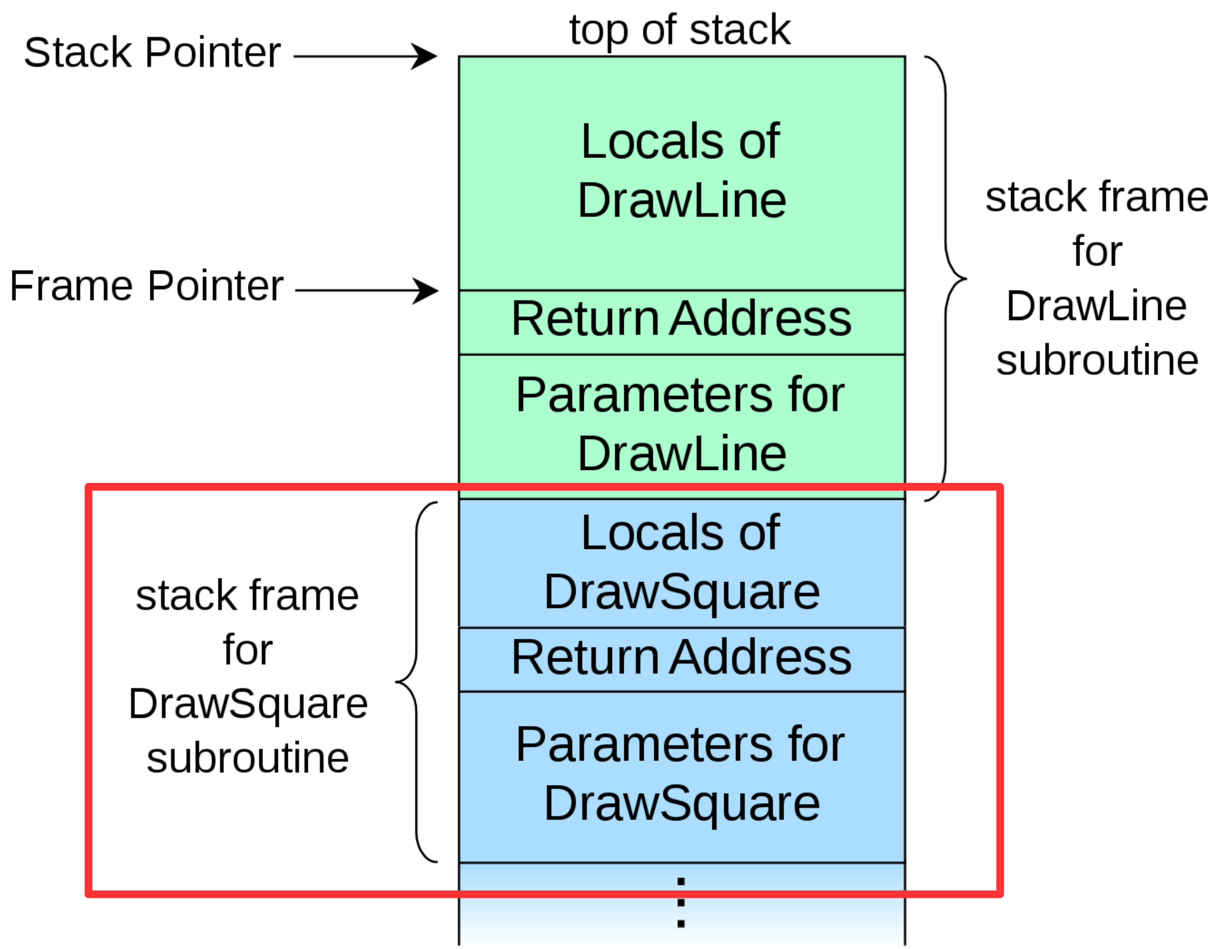
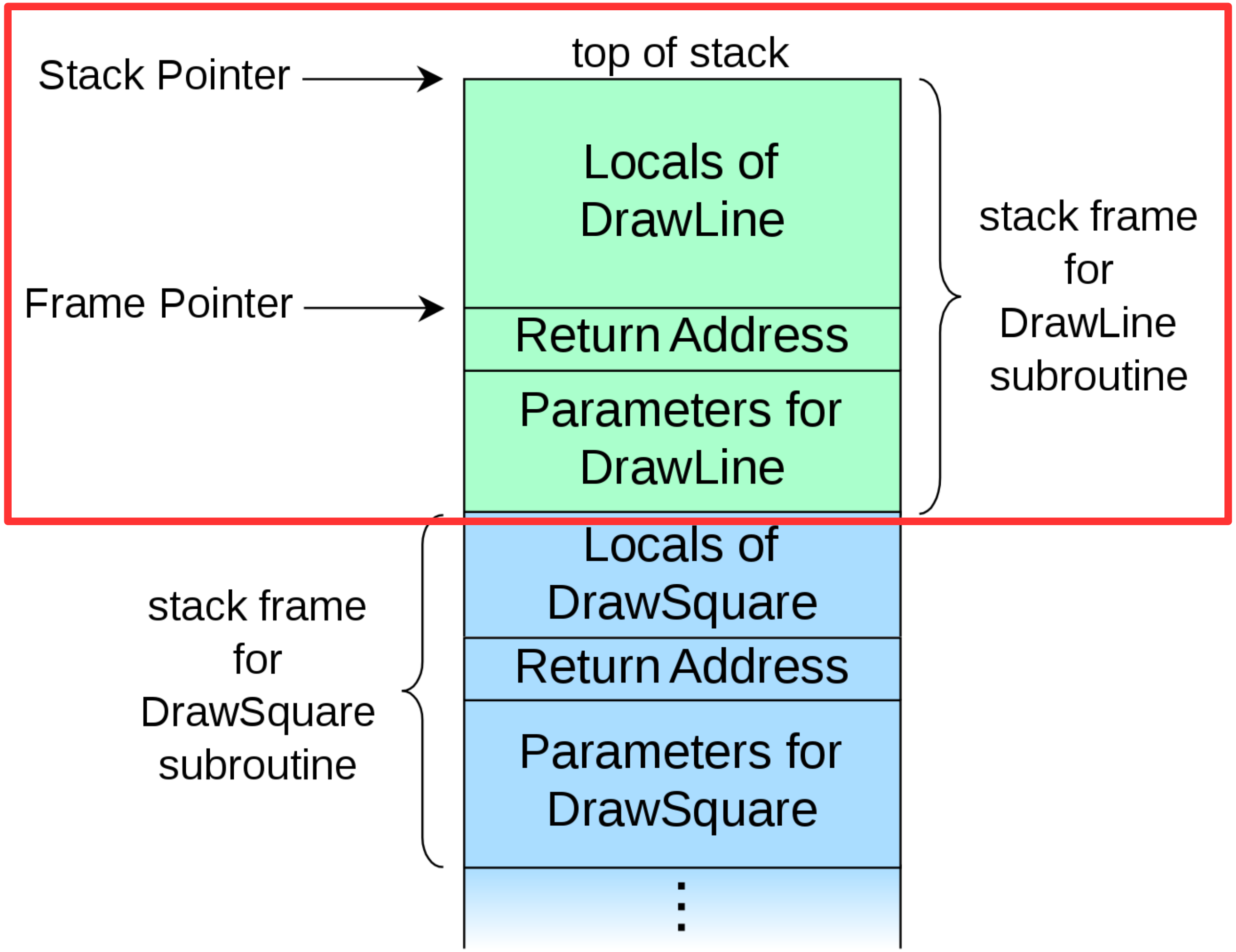


Stack consists of frames

- 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
```

Local variables

What types of variables do you know?

- Or where these variables are in memory?

What types of variables do you know?

- Global variables
  - Initialized → data section
  - Uninitalized → BSS
- Dynamic variables
  - Heap
- Local variables
  - Stack

Global variables

```c
#include <stdio.h>

char hello[] = "Hello";
int main(int ac, char **av)
{
	static char world[] = "world!";
	printf("%s %s\n", hello, world);
	return 0;
}
```

Global variables

```c
#include <stdio.h>

char hello[] = "Hello";
int main(int ac, char **av)
{
    static char world[] = "world!";
    printf("%s %s\n", hello, world);
    return 0;
}
```

- Allocated in the data section
  - It is split in initialized (non-zero), and non-initialized (zero)
  - As well as read/write, and read only data section

Global variables

Dynamic variables (heap)

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

char hello[] = "Hello";
int main(int ac, char **av)
{
    char world[] = "world!";
    char *str = malloc(64);
    memcpy(str, "beautiful", 64);
    printf("%s %s %s\n", hello, str, world);
    return 0;
}
```

Dynamic variables (heap)

```c
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

char hello[] = "Hello";
int main(int ac, char **av)
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    char *str = malloc(64);
    memcpy(str, "beautiful", 64);
    printf("%s %s %s\n", hello, str, world);
    return 0;
}
```

- Allocated on the heap
  - Special area of memory provided by the OS from where malloc() can allocate memory

Dynamic variables (heap)

Local variables

- Local variables

```
#include <stdio.h>

char hello[] = "Hello";
int main(int ac, char **av)
{
	//static char world[] = "world!";
	char world[] = "world!";
	printf("%s %s\n", hello, world);
	return 0;
}
```

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;
    …

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

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

```
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:      :
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```

Example: caller side code

```c
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
```

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  pop     ebp
  ; return
  ret
```

Wait, where is “return ret;” ?

```c
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```

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
  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

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Example: callee side code

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  ; 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;
}
```

```
_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
```

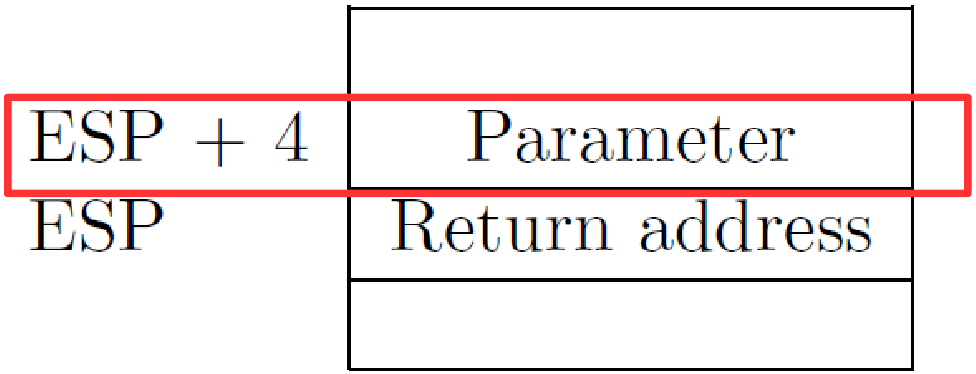
- x86 has a special instruction for this
  - `leave`

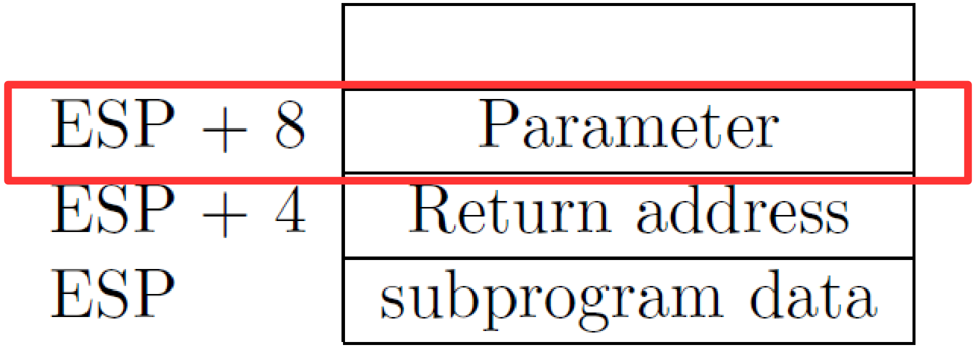
Back to stack frames, so why do we need them?

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