04 Assembly Language and Dissasembly Primer

> When analysing a malicious program, you only have it's executable, without it's source code. To gain the understanding of the malware's inner workings and to understand the critical aspects of a malicious binary, code analysis needs to be performed

We will cover the following topics from a code analysis (reverse engineering) perspective.

- Computer basics, memory and the CPU
- Data transfer, arithmetic, and bitwise operations
- Branching and Looping
- Functions and Stack
- Arrays, Strings and Structures
- Concepts of the x64 architecture

1. Computer Basics

All information is represented in *bits*. A bit, can be either a 0 or a 1. The collection of bits can represent a number, a character, or any other piece of information.

Fundamental Data Types

8 bits makes a *byte*. A single byte is represented in two hex digits. Each hexadecimal digit is made up of 4 bits, and is called a *nibble*. A *word* is two bytes in size. A *double word (dword)* is four bytes in size. A *quadword (qword)* is eight bytes in size.

1.1 Memory

- The RAM stores the mahcine code and data of the computer.
- RAM is an array of bytes with eack byte labeled in a unique number, known as it's address.
- The first address starts at 0, and the last is defined by the computer's HW and SW.
- The address and values are represented in hexadecimal.

1.1.1 How Data Resides in Memory

- Data is stored in *little-endian* format
- Low-order byte is stored at the lowe address, and subsequent bytes are stored in successively higher addresses in the memory

1.2 CPU

- CPU executes instructions (Stored in memory, as a sequence of bytes)

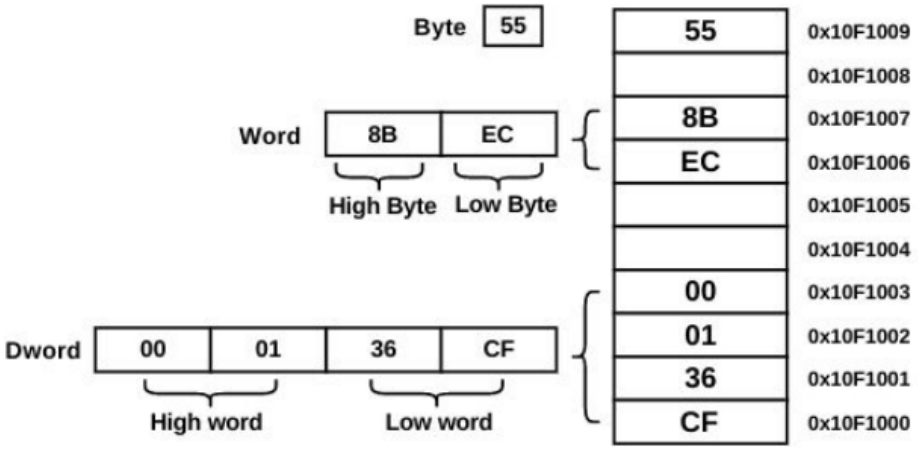


Figure 1: How Data Resides in Memory

- While executing the instructions, the required data is fetched from memory
- CPU contains a register set, wich stores values fetched from memory during execution

1.2.1 Machine Language

- Each CPU has a set of instructions that it can execute (These make up the CPU's Machine Language)
- A compiler translates a program (like C or C++) into machine language

1.3 Program Basics

Program Compilation

1. Source code is written in a high level language
2. Source code is run through a compiler
3. Object code is passed through a linker, wich links the object code with it's required libraries

1.3.2 Program On Disk

When a program is compiled, it generates a `.exe` file, wich, if viewed by *pe-internals* displays the 5 sections generated by the compiler (`.text, .rdata, .data, .rsrc, .reloc`)

- In `.data`, we store the data, used by our program
- In `.rdata`, we store read-only data and sometimes, import-export information
- In `.rsrc`, we store resources used by the executable

- In `.text`, we store the machine code (Our program translated to machine code by the compiler)

1.3.3 Program in Memory

When the executable is double-clicked a process memory is allocated by the operating system, and the executable is loaded into the allocated memory by the operation system loader.

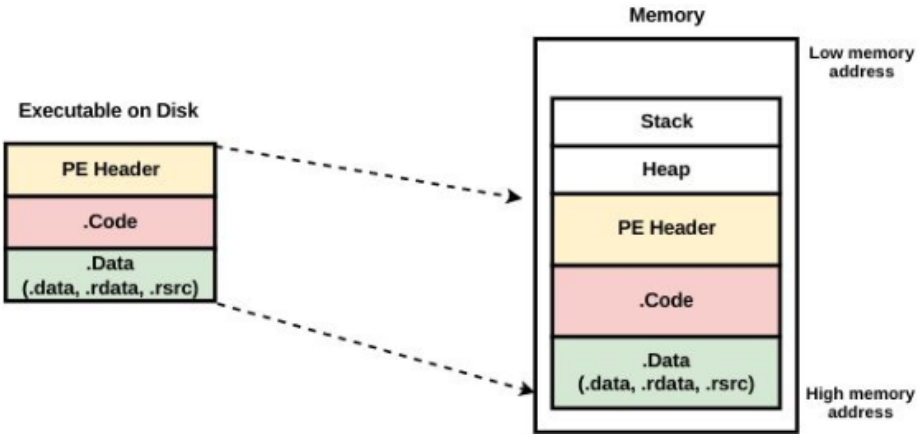


Figure 2: Loading executable from memory

Once the executable that contains the code is loaded into the memory, the CPU fetches the machine code from memory, interprets it, and executes it. While executing the machine instructions, the required data will also be fetched from memory.

1.3.4 Program Dissasembly (From Machine code To Assembly code)

A *dissasembler/debugger* is a program that translates machine code into a low-level code called *assambly* wich can be read and analysed to determine the workings of a program.

2. CPU Registers

CPU can access data in registers much faster than data in Memory, this is why the values stored in memory are stored in these registers to perform operations

2.1 General Purpose Registers

- The x86 CPU has 8 general purpose registers:
  - `eax, ebx, ecx, edx, esp, ebp, esi, edi`

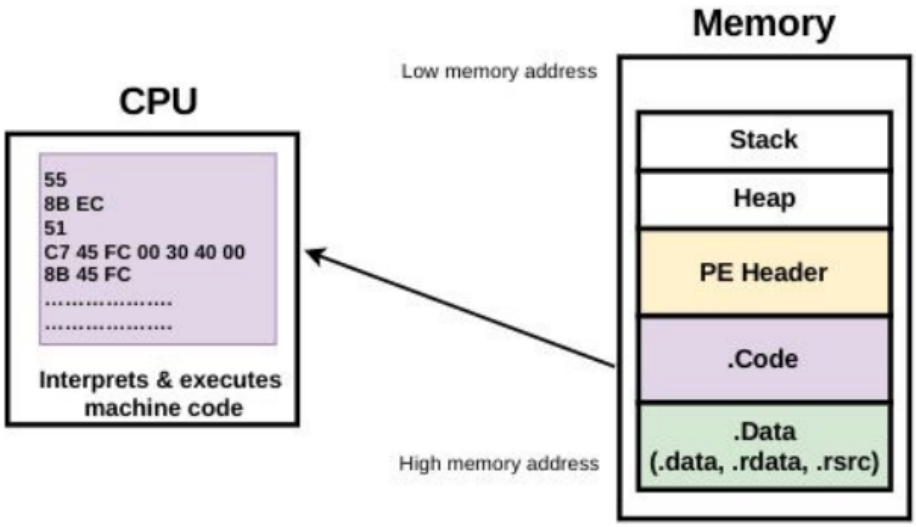


Figure 3: Interaction between the CPU and the memory-loaded program

- These registers are 32 bits (4 bytes) in size.
- A program can access registers as 32-bits, 16-bits or 8-bits
- The lower 16 bits of each of these registers can be accessed as `ax, bx, cx, dx, sp, bp, si, di`
- The lower 8 bits of `eax, ebx, ecx, edx` can be referenced as `al, bl, cl, dl`
- The higher 8 bits can be accessed as `ah, bh, ch, dh`

As an example:

> The `eax` register contains the 4-byte value `0xC6A93174` A program can access the lower 2 bytes (`0x3174`) by accessiong register `ax` It can access the lower byte (`0x74`) by accessing register `al` and the next byte (`0x31`) can be accessed using register `ah`

2.2 Instruction Pointer (EIP)

The CPU has a special register called the `eip`; it contains the address of the next instruction to execute. When the instruction is executed, the `eip` will point to the next instruction in the memory.

2.3 EFLAGS Register

The `eflags` register is a 32-bit register, each bit in this register is a flag. There are also additional registers called *segment registers* (`cs, ss, ds, es, fs, gs`) which keep track of sections in the memory.

3. Data Transfer Instructions

The `mov` instruction is one of the basic instructions in the assambly language. It moves data from one location to another.

```
mov dst,src
```

There are also different variations of the `mov` instruction

3.1 Moving a constant into register

A variation of the `mov` command. Moves a constant or a immediate value into a register.

```
mov eax,10 ; moves 10 into EAX register, same as eax=10
```

3.2 Moving Values From Register to Register

Done by placing the manes of the registers in the operands

```
mov eax,ebx ; moves content of ebx into eax
```

3.3 Moving values from Memory to Registers

1. An integer is 4 bytes in length, so the integer 100 is stored as a sequence of 4 bytes (`00 00 00 64`) in the memory.
2. The sequence of 4 bytes is stored in *little-endian* format
3. The integer 100 is stored at some memory address.

To move a value from the memory into a register in the assambly language, you must use the address of the value. The dest (`eax`) will automatically determine how many bytes to move.

```
mov eax,[0x403000] ; eax will now contain 00 00 00 64 (i.e 100)
```

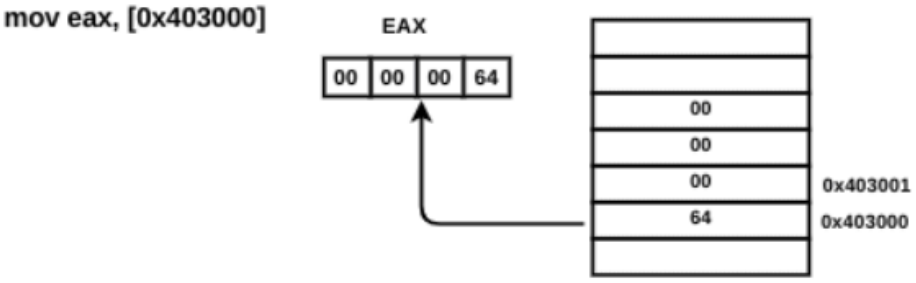


Figure 4: Moving value of register to register

The square brackets may contain a *register*, a *constant added to a register*, or a *register added to a register*.

Another common instruction is the `lea` instruction. This stands for *Loat Effective Address*. This instruction will load the address instead of the value

```
lea ebx,[0x403000] ; loads the address 0x403000 into ebx
lea eax,[ebx] ; if ebx = 0x403000, then eax will also
contain 0x403000
```

Moving Values From Registers To Memory

Swapping the operands, you can move a value from a register to memory

```
mov [0x403000],eax ; moves 4 byte value in eax to memory
location starting at 0x403000
```

```
mov [ebx],eax ; moves 4 byte value in eax to the memory
address specified by ebx
```

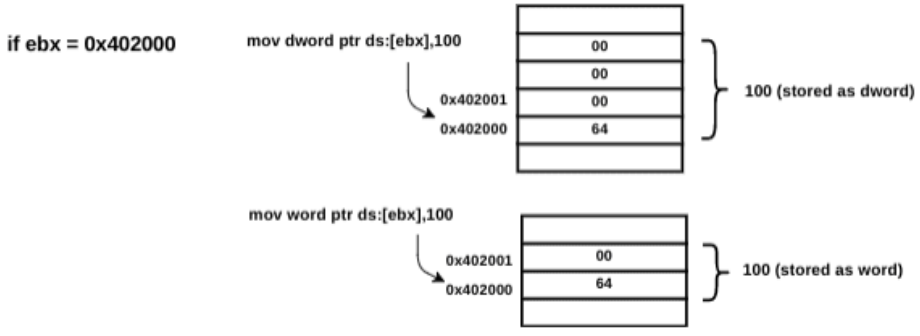
`dword ptr` just specifies that a `dword` value (4 bytes) is moved into the memory location.

```
mov dword ptr [402000],13498h ; moves dword value
0x13496 into the address 0x402000
```

```
mov dword ptr [ebx],100 ; moves dword value 100 into the
address specified by ebx
```

```
mov word ptr [ebx],100 ; moves a word 100 into the
address specified by ebx
```

In the preceding case, if `ebx` contained the memory address `0x402000`, then the second instruction copies `100` as `00 00 00 64` (4 bytes) and the third instruction copies `100` as `00 64` (2 bytes) into the memory location starting at `0x402000`, as shown below:



4. Arithmetic Operations

You can perform addition, subtraction, multiplication and division in assambly language. Addition adds src + dest and stores it id dest. Same with Subtraction. These instructions set or clear flags in the `eflags` register. These flags can be

used in conditional statements. The `sub` instruction sets the zero flag `(zf)` if the result is zero, and the carrt flag `(cf)` if the destination value is less than the source.

```
add eax,42 ; same as eax = eax+42

add eax, ebx ; same as eax = eax+ebx

add [ebx],42 ; adds 42 to the value in the address
specified by ebx

sub eax, 64h ; subtracts hex value 0x64 from eax, same
as eax = eax-0x64
```

There are special increments `(inc)` and decrements `(dec)` instructions. These add 1 or subtract 1 from either a register or a memory location.

```
inc eax ; same as eax = eax + 1

dec eax ; same as eax = eax - 1
```

Multiplication is done with the `(mul)` instruction. This instruction takes only one operand; wich is multiplied by the content of the `al, ax, eax` register. The result of the multiplication is stored in either `ax, dx, edx, eax` registers. If the operand of the `mul` instruction is *8 bits (1 byte)*, then it is multiplied by the 8-bit `al` register, and the product is stored in the `ax` register. If the operand is *16 bits (2 bytes)*, then it is multiplied with the `ax` register, and the product is stored in the `dx` and `ax` register. If the operand is *32 bit (4 bytes)*, then it is multiplied with the `eax` register, and the product is stored in the `edx` and `eax` register.

```
mul ebx ; ebx is multiplied with eax and the result is
stored in EDX and EAX

mul bx ; bx is multiplied with ax and the result is
stored in DX and AX
```

Division is performed using the `div` instruction. The `div` takes only one operand, wich is either a register or a memory reference. To perform division, you place the dividend (number to divide) in the `edx` and `eax` registers, with `edx` holding the most significant *dword*. After the `div` instruction is executed, the quotient is stored in `eax`, and the remainder is stored in the `edx` register:

```
div ebx ; divides the vaule in EDX:EAX by EBX
```

5. Bitwise operations

Assembly instructions that operate on the bits The bits are numbered starting from the far right (rightmots (least significant bit) bit has a bit position of 0) The leftmost bit, is called the most significant bit

`not` instruction:

Takes only one operand, serves as `src` and `dst` and inverts all of the bits.

> `not eax` Converts 11100110 to 00011001 and stores it in the same register

`and` instruction:

```
and bl,cl
bl: 0000 0101
cl: 0000 0110
```

After the operation:

```
bl: 0000 0100
```

`or` instruction:

```
or bl,cl
bl: 0000 0101
cl: 0000 0110
```

After the operation:

```
bl: 0000 0111
```

`xor` instruction:

```
xor bl,cl
bl: 0000 0101
cl: 0000 0110
```

After the operation:

```
bl: 0000 0011
```

`shr` (Shift right)

Takes two operands, the destination and the count The destination can be either a register or a memory reference

```
shr bl,4
bl: 0000 0101
```

After the operation:

```
bl: 0000 0000
```

`shl` (Shift left)

Takes two operands, the destination and the count The destination can be either a register or a memory reference

```
shl bl,3
```

```
bl: 0000 0110
```

After the operation:

```
bl: 0011 0000
```

`rol` and `ror` (rotate left and rotate right)

Are similar to shift, but instead of removing the shifter bits, they are rotated to the other end.

```
rol al,2
```

```
al: 0100 0100
```

After the operation:

```
al: 0001 0001
```

6. Branching and conditionals

Branching instructions transfer the control of execution to a different memory address. To perform branching, jump instructions are typically used. There are two types: *conditional* and *unconditional*

6.1 Unconditional jumps

```
jmp <jump address>
```

The jump is always taken.

6.2 Conditional jumps

Control is transfered to a memory address based on some condition. To use conditional jumps, we need instructions that can alter the flags (*set* or *clear*). These instructions can be performing a *arithmetic operation* or a *bitwise operation*

`cmp` instruction

Subtracts the second operand from the first one without altering the dest (first operand)

```
cmp eax,5 ; if eax has a value of 5
```

Would set the *zero flag* (`zf=1`) because the result is 0. used with conditional `jump` instruction for decision-making

`test` instruction

Alters flags, without storing the result in `dst` Performs a bitwise `and` and alters *zero flag* `(zf=1)` because when you and 0 with 0, you get 0. used with conditional `jump` instruction for decision-making

Variations of conditional jumps

These conditions are evaluated based on the bits in the `eflags` register.

Instruction	Description	Aliases	Flags
`jz`	jump if zero	`je`	`zf=1`
`jnz`	jump if not zero	`jne`	`zf=0`
`jl`	jump if less	`jnge`	`sf=1`
`jle`	jump if less or equal	`jng`	`zf=1 or sf=1`
`jg`	jump if greater	`jnle`	`zf=0 and sf=0`
`jge`	jump if greater or equal	`jnl`	`sf=0`
`jc`	jump if carry	`jb,jnae`	`cf=1`
`jnc`	jump if not carry	`jnb,jae`	.

Figure 5: Conditional jumps

6.3 If statements

In order to reverse-engineer a program, we have to understand how the `if`, `if-else` and `if-else if-else` statements are translated into assambly.

In the following example, translated to assambly, the *jump* will be taken when the condition **is not met**.

```
if (x == 0) {
      x = 5;
  }

  x = 2
```

This code, will be translated in assambly into:

```
cmp dword ptr [x], 0

jne end_if

mov dword ptr [x], 5

end_if:

mov dword ptr [x], 2
```

6.4 If-else statement

There are two conditions in this case.

```
if (x == 0) {
  x = 5;
} else {
  x = 1;
}
```

If `x == 0` the code inside the if statement will be executed and then, the program will jump the else statement. If `x != 0` the code inside the if will be jumped and the code inside the else will be executed.

in assambly:

```
cmp dword ptr [x], 0

jne else

mov dword ptr [x], 5

jmp end

else:

mov dword ptr [x], 1

end:
```

6.5 If-Elseif-Else Statements

In the next example, there are two conditional statements, if `x != 0` it will jump to the second conditional statement, if this one is not met, it will jump this one, and go to the else.

```
if (x == 0) {
  x = 5;
}
else if (x == 1) {
  x = 6;
}
else {
  x = 7;
}
```

wich translated into assambly:

```
    cmp dword ptr [ebp-4], 0
    jnz else_if
    mov dword ptr [ebp-4], 5
    jmp short end
    else_if:
    cmp dword ptr [ebp-4], 1
    jnz else
    mov dword ptr [ebp-4], 6
    jmp short end
    else:
    mov dword ptr [ebp-4], 7
    end:
```

7. Loops

To create a loop, the `goto` operation must jump backward Two of the most common loops are `for` loops, and `while` loops.

For example:

```
int i;
for (i = 0; i < 5; i++) {
}
```

or

```
int i = 0;
while (i < 5) {
  i++;
}
```

can be translated into assambly as follows:

```
mov [i], 0

while_start:

cmp [i], 5

jge end

mov eax, [i]

add eax, 1

mov [i], eax

jmp while_start

end:
```

8. Functions

When a function is called, the control is transfered to a different memory address. The code in that memory address is run, and once finished, goes back to the original memory address. The function's parameters, local variables, and function flow controls are stored in an important area of the memory called the *stack*.

8.1 Stack

The *stack* is an area of memory that gets allocated by the operating system when the threat is created. It is organized in a *Last-in-First-out (LIFO)* structure. To use the stack, there are two instructions:

- `push` wich pushes a *4-byte* value onto the stack
  - `push source ; pushes source on top of the stack`
- `pop` wich pops a *4-byte* value from the top of the stack
  - `pop destination ; copies value from the top of the stack to the destination`

The stack grows from higher address to lower address. When you push data into the stack, the `esp` register decrements by `4` (`esp - 4`) to a lower address. When you `pop` a value, the `esp` increments by `4` (`esp + 4`).

8.2 Calling Function

Used to call a function.

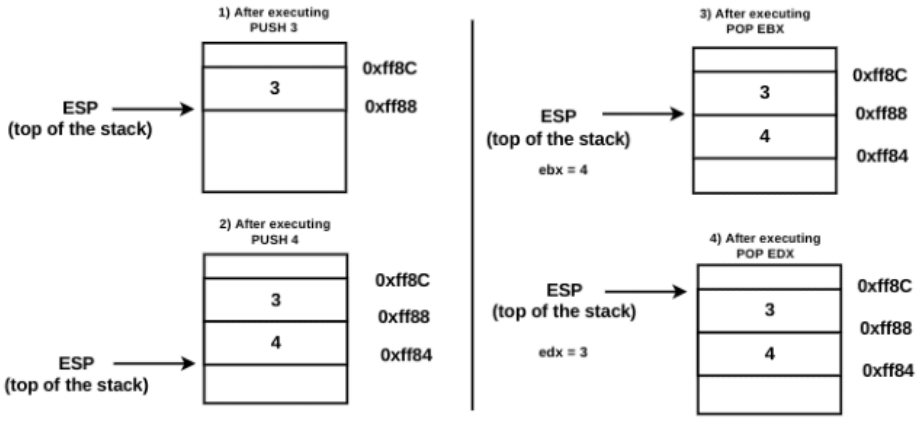


Figure 6: Push and Pop from stack

`call <some_function>`

The control is transfered to `some_function`, but before that, it stores the address (*return address*) of the next instruction (the one following `call <some_function>`) by pushing it to the stack. Once `<some_function>` has finished execution, the return address is poped from the stack, and the execution continues from the popped address.

8.3 Returning From Function

`ret` instruction

This instruction pops the address from the top of the stack; The popped address is placed in the `eip` register, and the control is transfered to the popped address.

8.4 Function Parameters and Return Values

In the `x86` architecture, the paremeters that a function accepts are pushed onto the stack, and return value is placed in the `eax` register.

Given this program:

```
int test(int a, int b) {
  int x, y;
  x = a;
  y = b;
  return 0;
}

int main() {
  test(2, 3);
```

```
  return 0;
}
```

The statements inside the `main()` function are translated into assembly instructions like so:

```
push 3

push 2

call test

add esp, 8 ; after test is executed, the control is
returned here

xor eax, eax
```

The first 3 instructions, represent the function call `test(2, 3)`. Note the parameters are pushed to the stack in reverse order. Then, the function `test()` is called

The assambly translation for `test()` function:

```
push ebp

mov ebp, esp

sub esp, 8

mov eax, [ebp+8]

mov [ebp-4], eax

mov ecx, ebp+0Ch]

mov [ebp-8], ecx

xor eax, eax

mov esp, ebp

pop ebp

ret
```

The first instruction `push ebp` saves the `ebp` (also called the frame pointer) on the stack. This way, it can be restored when the function returns. In the next instruction, (`mov ebp, esp`) the value of `esp` is copied into `ebp`; as a result, both `esp` and `ebp` point at the top of the stack. The `ebp` from now on, will be kept at a fixed position, and the application will use `ebp` to reference function arguments and the local variables.

In most functions, you will see instructions

```
push ebp

mov ebp, esp
```

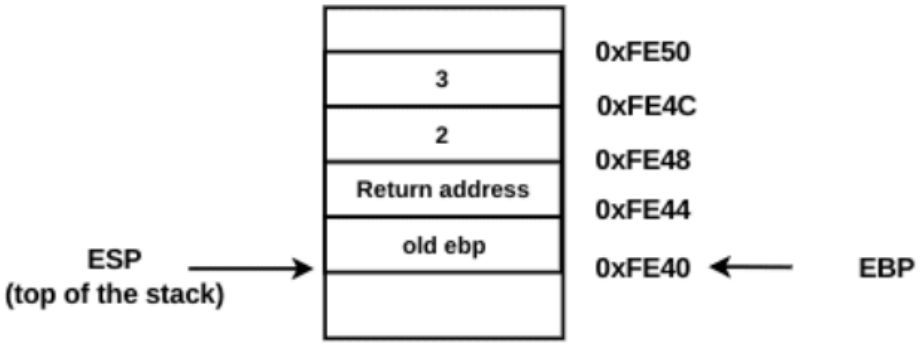


Figure 7: State of EBP and ESP

at the start, these two instructions are called *function prologue*. They setup the function environment.

The following two functions, perform the reverse operation. They are called *function epilogue* They restore the environment to before the function was executed.

```
mov esp, ebp
pop ebp
```

The instruction `sub esp, 8` further decrements the `esp` register. This is done to allocate space for the local variables (`x` and `y`). Now, the stack looks like this:

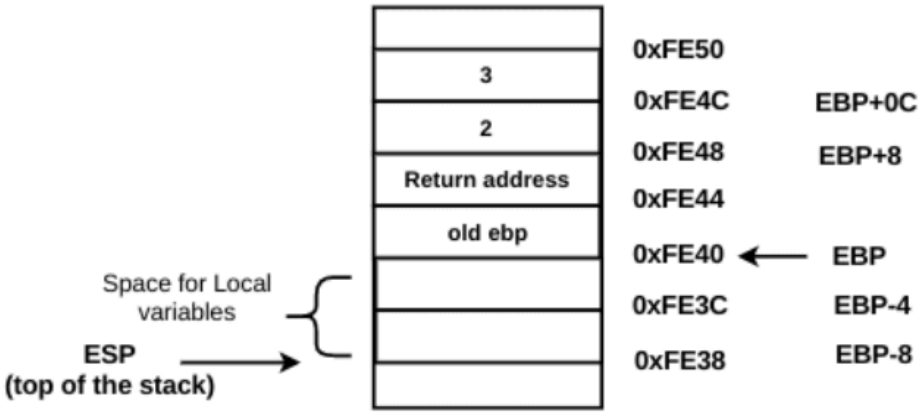


Figure 8: State of EBP and ESP after the function setup

`ebp` is at a fixed position, and **function arguments can be accessed at a positive offset** from `ebp` (`ebp + some value`).

Local variables can be accessed at a negative offset from `ebp` (`ebp -`

`some value`).

The actual code inside the function is:

```
mov eax, [ebp+8]
mov [ebp-4], eax
mov ecx, ebp+0Ch]
mov [ebp-8], ecx
```

The instruction `xor eax, eax` sets the return register `eax` (always the return register) to `0`.

The function epilogue restore the function environment.

`mov esp, ebp`

copies the value of `ebp` into `esp`; as a result, `esp` will be pointing to the same address as `ebp`. ### `pop ebp`

Restores the old `ebp` from the stack; After this, `esp` will be incremented by 4. To the state the program was before executing the function.

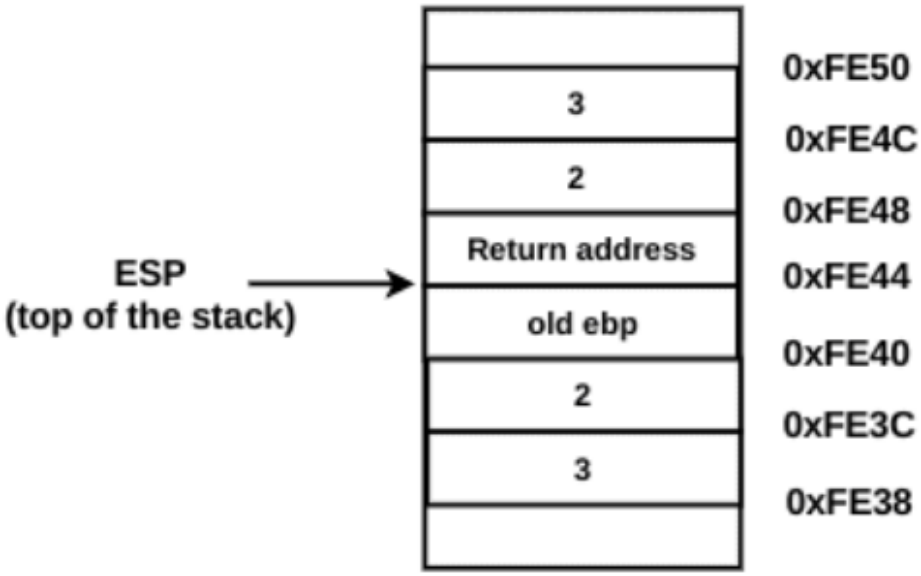


Figure 9: State of ESP after the epilogue

When the `ret` instruction is executed, the return address on top of the stak is popped out and placed in the `eip` register. Also, the control is transfered to the return address (`add esp, 8` in the `main()` function. As a result of popping the return adress, `esp` is incremented by `4`. At this point, the control is returned to

the `main` function from the `test` function. The instruction `add esp, 8` inside of the `main` cleans up the stack, and the `esp` isreturned to it's original position.

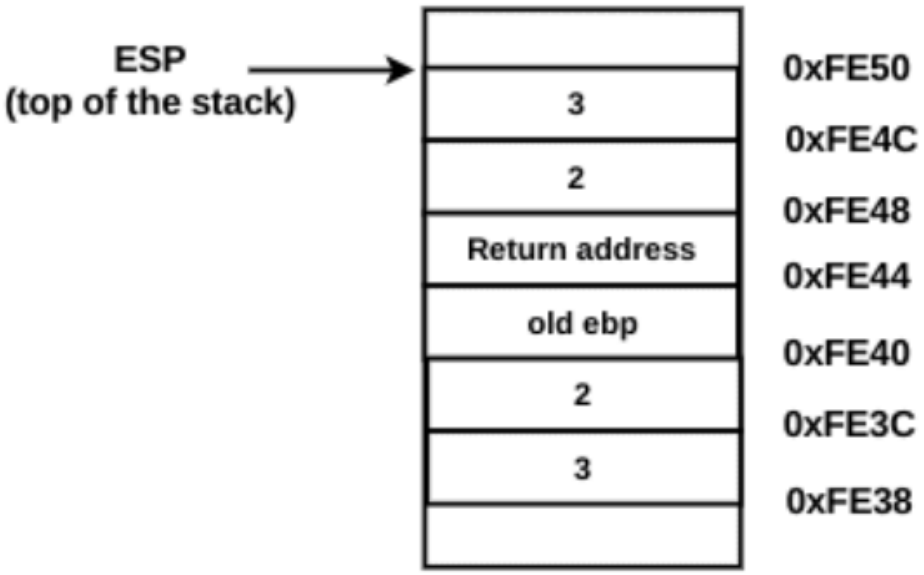


Figure 10: State of the ESP when the function call has ended

Function call conventions

- `cdecl`
  - The caller function passes parameters to the callee function right to left
  - The caller function is responsible of cleaning the stack after the callee function returns control to the caller function
- `stdcall`
  - Used by Windows for the functions (API) exported by the DLL files
  - The caller function passes parameters to the callee function right to left
  - The callee function is responsible of cleaning the stack
- `fastcall`
  - `x64bit` programs will use this convention