

Introduction to the x86 computer architecture

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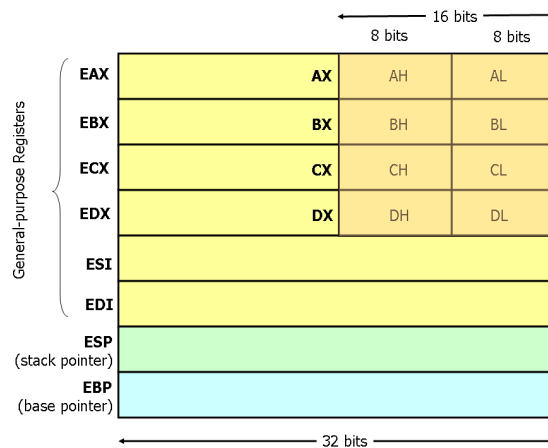
1 Introduction

The goal of this document is to explain some basic notions of computer architecture for use in an Operating System course.

First, we will explain the use of the stack to implement functions calls in C. Therefore, we will briefly recall some notion of computer architecture and assembler for the Intel 32bit x86 architecture (also referred to as i386).

2 Registers and memory

Processors of the x86 family use internal registers to perform operations. We will describe here only the ones that are relevant to our goal.



- **eip** : instruction pointer

This register holds the address in memory of the next instruction to be executed by the processor. Every time the processor executes one instruction, the EIP register is automatically incremented so to point to the next instruction in memory. The register can also be modified by jump instruction like `jmp`, `je`, `call`, `ret`, etc. (see below).

- **eax, ebx, ecx, etc.**

These are generic registers used as temporary working variables when executing the code. Some of these registers are conventionally used for specific purposes. For example, the **eax** register is often used to store the return value of functions.

- **esp and ebp**

These register hold the addresses in memory for the stack. As we will see later on, the stack is a range of addresses in memory used by C programs to store local variables and the parameters of function calls. In particular, **esp** points to the top of the stack, where **ebp** points to the base of the current stack *frame*.

3 Machine instructions for Intel x86 architectures

There are 2 formats specifications for x86 assembler: the Intel specification and the AT&T specification. GCC uses the latter, so we will also use the AT&T specification. The main differences are:

- **The order or parameters**: in AT&T the source comes before the destination, in Intel specification the destination comes before the source.
- **Size**: In AT&T, the instructions are suffixed with a letter indicating the size of the operands, *q* for qwords (64 bits), *l* for long (32 bits), *w* for word (16 bits), *b* for byte (8 bits).
- **Sigils**: In AT&T, immediate values are prefixed with the dollar sign \$, and register are prefixed with the percentage sign %.
- **Effective addresses**: the syntax for calculating an address is the following :

```
movl 1234(%ebx,%ecx,4), %eax
```

which means : take the value at the address $1234 + \text{ebx} + \text{ecx} * 4$ and move it to register `eax`. The general syntax for calculating the addresses is `DISP(BASE, INDEX, SCALE)`.

The complete syntax for the GNU assembler is available [here](#). Now, let's see a few interesting instructions.

- **mov** - Move (Opcodes: 88, 89, 8A, 8B, 8C, 8E, ...)

The `mov` instruction copies the data item referred to by its second operand (i.e. register contents, memory contents, or a constant value) into the location referred to by its first operand (i.e. a register or memory). While register-to-register moves are possible, direct memory-to-memory moves are not. In cases where memory transfers are desired, the source memory contents must first be loaded into a register, then can be stored to the destination memory address.

– Example:

```
mov %ebx, %eax - copy the value in ebx into eax
```

When the size of the operands is not completely clear from context, it is possible to use the `movl` or `movq` instruction to move 32 bits (4 bytes) or 64 bits (8 bytes). This may be necessary for example when moving from/to memory.

– Example:

```
movl %1, %%eax
```

will move 32 bits from the address specified in `%1` to register `eax`.

- **push** — Push stack (Opcodes: FF, 89, 8A, 8B, 8C, 8E, ...)

The `push` instruction places its operand onto the top of the hardware supported stack in memory. Specifically, `push` first decrements `ESP` by 4, then places its operand into the contents of the 32-bit location at address `[ESP]`. `ESP` (the stack pointer) is decremented by `push` since the x86 stack grows down - i.e. the stack grows from high addresses to lower addresses.

– Examples :

```
push %eax - push eax on the stack
```

- **pop** — Pop stack

The `pop` instruction removes the 4-byte data element from the top of the hardware-supported stack into the specified operand (i.e. register or memory location). It first moves the 4 bytes located at memory location `[ESP]` into the specified register or memory location, and then increments `ESP` by 4.

– Examples:

```
pop %edi - pop the top element of the stack into EDI.
```

- **lea** — Load effective address

The `lea` instruction places the address specified by its first operand into the register specified by its second operand. Note, the contents of the memory location are not loaded, only the effective address is computed and placed into the register. This is useful for obtaining a pointer into a memory region.

– Examples :

```
lea (%ebx,%esi,4), %edi - the quantity EBX+4*ESI is placed in EDI.
```

- **and, or, xor** — Bitwise logical and, or and exclusive or

These instructions perform the specified logical operation (logical bitwise and, or, and exclusive or, respectively) on their operands, placing the result in the second operand location.

- **test** — bitwise logical and on two operands

Unlike the **and** instruction, the result of the test is not stored in the register, only the flags are modified, in particular the Zero Flag (ZF) is set to 1 if the result of the operation is 0.

- **cmp** — Compare

Compare the values of the two specified operands, setting the condition codes in the machine status word appropriately. This instruction is equivalent to the **sub** instruction, except the result of the subtraction is discarded.

– Example :

```
cmpl ($var), $10
jeq $loop
```

If the 4 bytes stored at location `var` are equal to the 4-byte integer constant 10, jump to the location labeled `loop`.

- **jmp** — Jump

Transfers program control flow to the instruction at the memory location indicated by the operand.

- **jcondition** — Conditional Jump

These instructions are conditional jumps that are based on the status of a set of condition codes that are stored in a special register called the machine status word. The contents of the machine status word include information about the last arithmetic operation performed. For example, one bit of this word indicates if the last result was zero. Another indicates if the last result was negative. Based on these condition codes, a number of conditional jumps can be performed. For example, the **jz** instruction performs a jump to the specified operand label if the result of the last arithmetic operation was zero. Otherwise, control proceeds to the next instruction in sequence.

A number of the conditional branches are given names that are intuitively based on the last operation performed being a special compare instruction, **cmp** (see below). For example, conditional branches such as **jle** and **jne** are based on first performing a **cmp** operation on the desired operands.

– Syntax

```
je <label> (jump when equal)
jne <label> (jump when not equal)
jz <label> (jump when last result was zero)
jg <label> (jump when greater than)
jge <label> (jump when greater than or equal to)
jl <label> (jump when less than)
jle <label> (jump when less than or equal to)
```

– Example:

```
    cmp %eax, %ebx
    jle done
```

- **call, ret** — Subroutine call and return

These instructions implement a subroutine call and return. The `call` instruction first pushes the current code location onto the hardware supported stack in memory (see the `push` instruction for details), and then performs an unconditional jump to the code location indicated by the label operand. Unlike the simple jump instructions, the `call` instruction saves the location to return to when the subroutine completes.

The `ret` instruction implements a subroutine return mechanism. This instruction first pops a code location off the hardware supported in-memory stack (see the `pop` instruction for details). It then performs an unconditional jump to the retrieved code location.

- **leave**

This instruction is equivalent to the following sequence :

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

4 The stack frame

When calling a function, the compiler follows a specific *calling convention* which is widely used by all compilers. Many other languages follow the same convention: in this way, it is possible to call C functions from other languages, and inversely call non-C function from within C programs.

The C language call convention makes use of the stack to store:

- the parameters of the function call
- the return address of the caller
- the local variables of the function.

To do this, the compiler uses two registers:

- The `esp` register (stack pointer)
- the `ebp` register (base pointer)

The memory space containing the parameters, the return address and the local variables of the function is called **stack frame**. A general schema is presented in Figure 1.

4.1 Example

Consider the C program in Listing 1 (also available in file `example/stack-example.c`).

```
1  #include <stdio.h>
2
3  int function(int a, const char *s)
4  {
5      int c = 0;
6      while (s[c] != 0) c++;
7
```

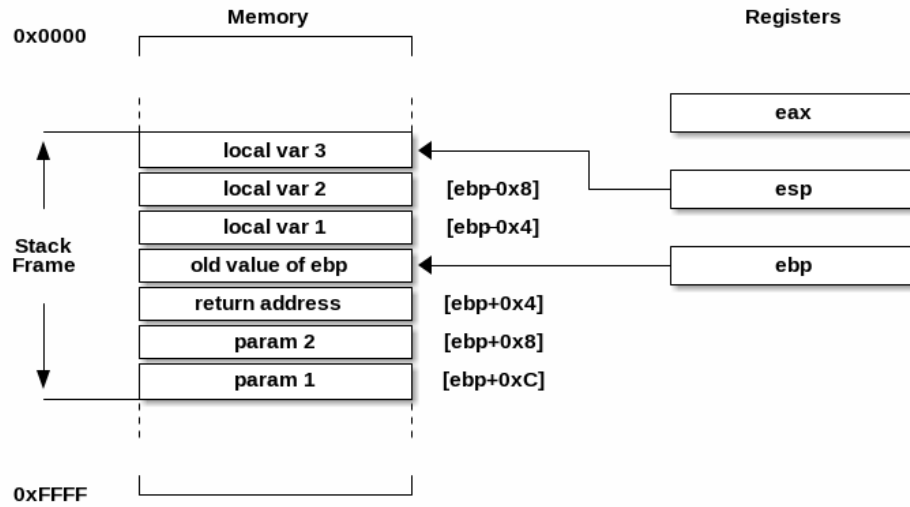


Figure 1: Structure of the stack frame

```

8     return c - a;
9 }
10
11 const char string[] = "Hello world!";
12
13 int main()
14 {
15     int x, y;
16     y = 10;
17     x = function(y, string);
18
19     printf("x = %d\n", x);
20     return 0;
21 }

```

Listing 1: The example program (example/stack-example.c)

In Listing 2 we show the translation of `function()` in machine code interleaved by the source code, obtained by running the command `objdump` on the object file (see `example/Makefile`). In Listing 3 we report the translation of the function call in the main.

```

1 int function(int a, const char *s)
2 {
3     119d:      55                push    %ebp
4     119e:      89 e5            mov     %esp,%ebp
5     11a0:      83 ec 10         sub     $0x10,%esp
6     int c = 0;
7     11a3:      c7 45 fc 00 00 00 00    movl    $0x0,-0x4(%ebp)
8     while (s[c] != 0) c++;
9     11aa:      eb 04            jmp     11b0 <function+0x13>
10    11ac:      83 45 fc 01       addl    $0x1,-0x4(%ebp)

```

11	11b0:	8b 55 fc	mov	-0x4(%ebp),%edx
12	11b3:	8b 45 0c	mov	0xc(%ebp),%eax
13	11b6:	01 d0	add	%edx,%eax
14	11b8:	0f b6 00	movzbl	(%eax),%eax
15	11bb:	84 c0	test	%al,%al
16	11bd:	75 ed	jne	11ac <function+0xf>
17				
18	return c - a;			
19	11bf:	8b 45 fc	mov	-0x4(%ebp),%eax
20	11c2:	2b 45 08	sub	0x8(%ebp),%eax
21	}			
22	11c5:	c9	leave	
23	11c6:	c3	ret	

Listing 2: The compiled code for function

1	int x, y;		
2	y = 10;		
3	11d8:	c7 45 f4 0a 00 00 00	movl \$0xa, -0xc(%ebp)
4	x = function(y, string);		
5	11df:	68 08 20 00 00 00	push \$0x2008
6	11e4:	ff 75 f4	push -0xc(%ebp)
7	11e7:	e8 b1 ff ff ff	call 119d <function>
8	11ec:	83 c4 08	add \$0x8,%esp
9	11ef:	89 45 f0	mov %eax, -0x10(%ebp)

Listing 3: Function call in the main

Let us start by analysing Listing 3. First of all, `main()` is also a function, so it also has a stack frame. The state of the stack before executing the code snippet of Listing 3 is shown in Figure 2.

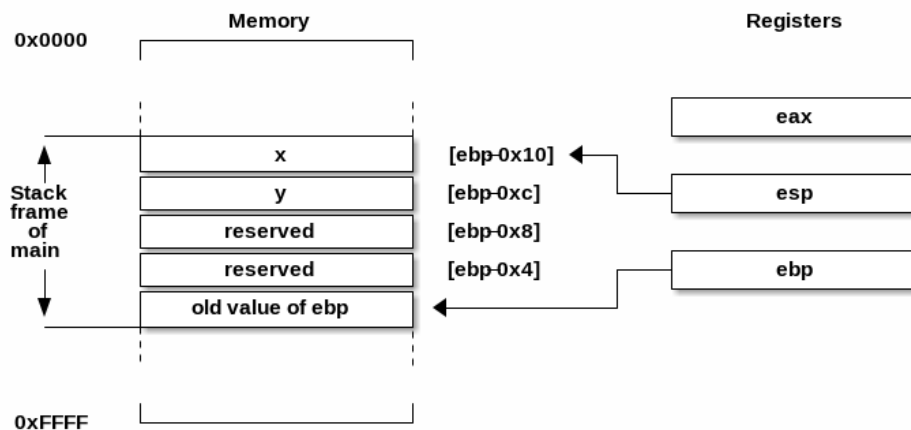


Figure 2: Stack frame of main (before executing the code in the body).

Here is what happens :

- line 3: the value `0xa` (10 in decimal) is loaded at address `[ebp-0xc]` where the local variable `y` is stored

- line 5: the address `0x2008` (which correspond to the start of array `string`) is pushed onto the stack.
- line 6: the value of `y` is pushed into the stack

This creates the first part of the *stack frame* of `function` which contains the value of the parameters.

- line 7: the current `eip` address is pushed in the stack (it corresponds to the address of the next instructions after the `call`, which is `0x11fc`).

Now the execution continues from address `0x11ad` which is the first instruction of the function (Listing 2).

- line 3: the value of `ebp` is saved on the stack
- line 4: `ebp` now contains the current value of the stack pointer `esp`
- line 5 the function subtracts `0x10` (16 in decimal) from `esp`: this is used to make space for the local variable. For alignment reasons, the compiler allocates more than needed, in the following it will just use the first position of the stack.
- line 7: variable `c` (which is stored at position `ebp`) is initialized to 0
- line 9-16: the code of the while loop. Notice how the compiler accesses local variables and parameters using `ebp` and a offset (*displacement*). In particular, for local variables a negative offset is used, and for parameters a positive offset.
- line 19-10: the value to be returned is stored into register `eax`
- line 22: the compiler uses the `leave` instruction to restore the value of `esp` and `ebp`, thus eliminating the local variables
- line 23: the function returns to the address from where it was called by getting it from the stack

Finally, going back to main (Listing 3):

- line 8: the parameter of the function are removed by adding `0x8` to the stack pointer
- the return value is stored into variable `x`.

4.2 Summary

To call a function, the caller:

- prepares the parameters on the stack;
- calls the function (by storing the return address on the stack);
- after returning from the call, removes the parameters from the stack.

The function:

- saves the old value of `ebp` and makes space for the local variables on the stack;
- after completing execution, restores the values of `ebp` and `esp` and returns.

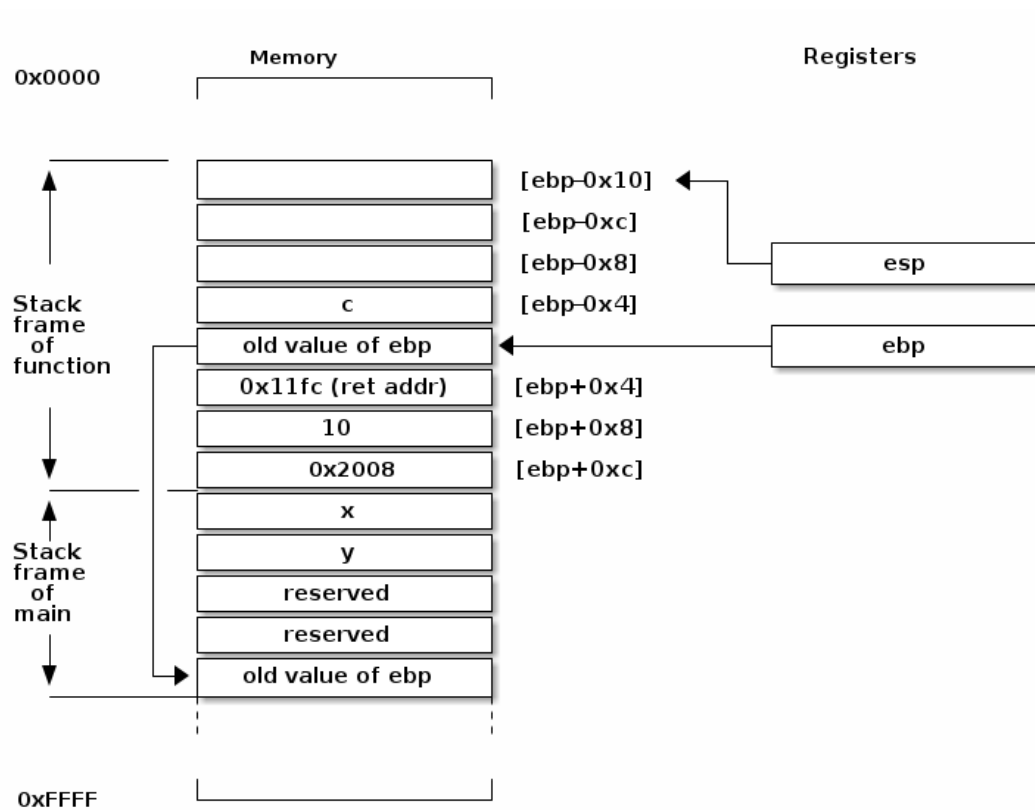


Figure 3: Stack frame of function

5 Acknowledgements

Section 3 has been borrowed from the "x86 Assembly Guide" (<https://www.cs.virginia.edu/~evans/cs216/guides/x86.html>). The guide was originally created by Adam Ferrari, and later updated by Alan Batson, Mike Lack, and Anita Jones. It was revised for 216 Spring 2006 by David Evans (evans@cs.virginia.edu). Last visited on 7/01/2022.

6 Bibliography

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