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brain food for hackers

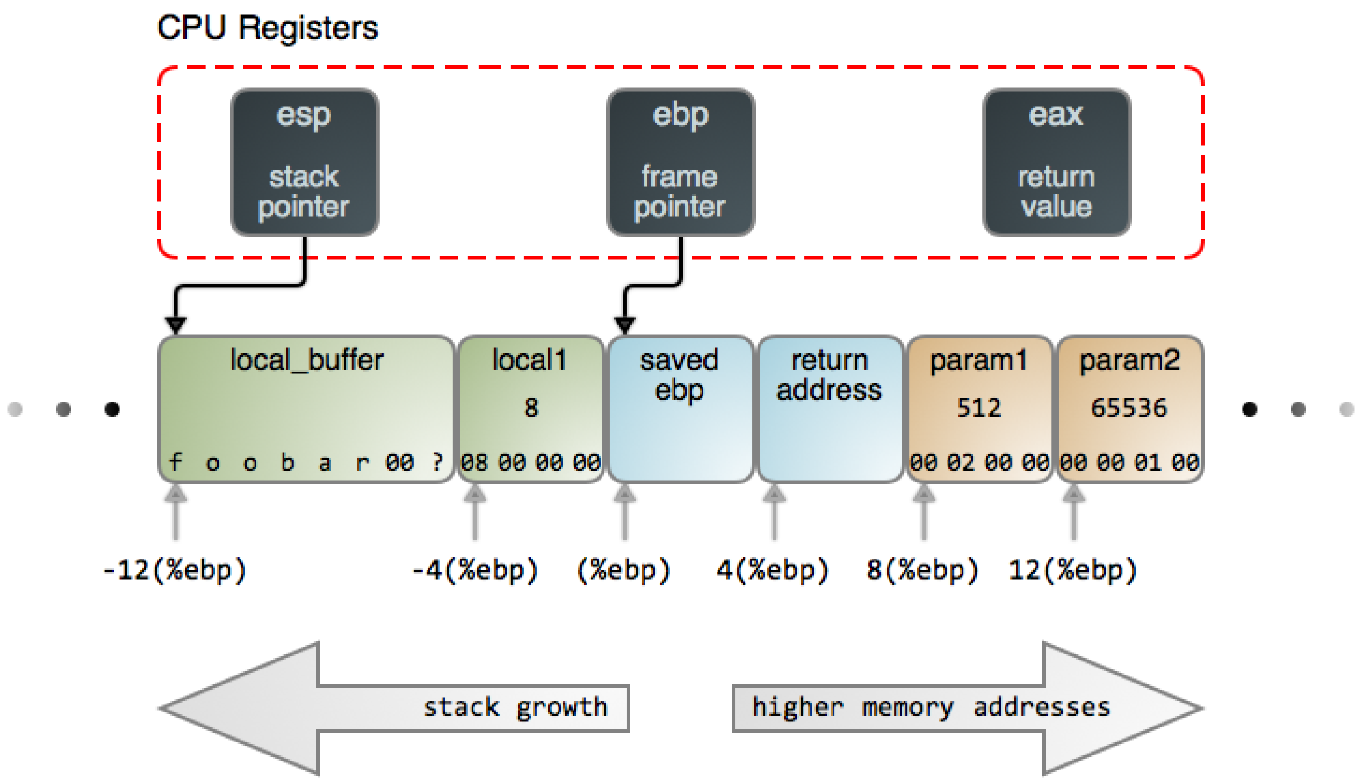
# Journey to the Stack, Part I

Mar 10th, 2014

Earlier we've explored the anatomy of a program in memory (http://duartes.org/gustavo/blog/post/anatomy-of-a-program-in-memory), the landscape of how our programs run in a computer. Now we turn to the *call stack*, the work horse in most programming languages and virtual machines. Along the way we'll meet fantastic creatures like closures, recursion, and buffer overflows. But the first step is a precise picture of how the stack operates.

The stack is so important because it keeps track of the *functions* running in a program, and functions are in turn the building blocks of software. In fact, the internal operation of programs is normally very simple. It consists mostly of functions pushing data onto and popping data off the stack as they call each other, while allocating memory on the heap for data that must survive across function calls. This is true for both low-level C software and VM-based languages like JavaScript and C#. A solid grasp of this reality is invaluable for debugging, performance tuning and generally knowing what the hell is going on.

When a function is called, a **stack frame** is created to support the function's execution. The stack frame contains the function's *local variables* and the *arguments* passed to the function by its caller. The frame also contains housekeeping information that allows the called function (the *callee*) to return to the caller safely. The exact contents and layout of the stack vary by processor architecture and function call convention. In this post we look at Intel x86 stacks using C-style function calls ( `cdecl` ). Here's a single stack frame sitting live on top of the stack:



Right away, three CPU registers burst into the scene. The *stack pointer*, `esp`, points to the top of the stack. The top is always occupied by the *last item that was pushed* onto the stack *but has not yet been popped off*, just as in a real-world stack of plates or $100 bills.

The address stored in `esp` constantly changes as stack items are pushed and popped, such that it always points to the last item. Many CPU instructions automatically update `esp` as a side effect, and it's impractical to use the stack without this register.

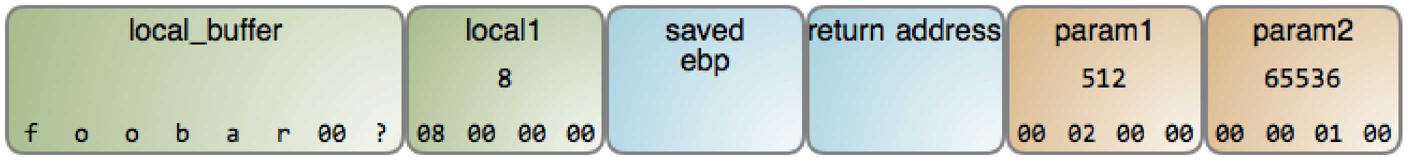
In the Intel architecture, as in most, the stack grows towards *lower memory addresses*. So the "top" is the lowest memory address in the stack containing live data: `local_buffer` in this case. Notice there's nothing vague about the arrow from `esp` to `local_buffer`. This arrow means business: it points *specifically* to the *first byte* occupied by `local_buffer` because that is the exact address stored in `esp`.

The second register tracking the stack is `ebp`, the *base pointer* or *frame pointer*. It points to a fixed location within the stack frame of the function *currently running* and provides a stable reference point (base) for access to arguments and local variables. `ebp` changes only when a function call begins or ends. Thus we can easily address each item in the stack as an offset from `ebp`, as shown in the diagram.

Unlike `esp`, `ebp` is mostly maintained by program code with little CPU interference. Sometimes there are performance benefits in ditching `ebp` altogether, which can be done via compiler flags (http://stackoverflow.com/questions/14666665/trying-to-understand-gcc-option-fomit-frame-pointer). The Linux kernel is one example where this is done.

Finally, the `eax` register is used by convention to transfer return values back to the caller for most C data types.

Now let's inspect the data in our stack frame. These diagram shows precise byte-for-byte contents as you'd see in a debugger, with memory growing left-to-right, top-to-bottom. Here it is:



The local variable `local_buffer` is a byte array containing a null-terminated ascii string, a staple of C programs. The string was likely read from somewhere, for example keyboard input or a file, and it is 7 bytes long. Since `local_buffer` can hold 8 bytes, there's 1 free byte left. The *content of this byte is unknown* because in the stack's infinite dance of pushes and pops, you never know what memory holds *unless you write to it*. Since the C compiler does not initialize the memory for a stack frame, contents are undetermined – and somewhat random – until written to. This has driven some into madness.

Moving on, `local1` is a 4-byte integer and you can see the contents of each byte. It looks like a big number, with all those zeros following the 8, but here your intuition leads you astray.

Intel processors are *little endian* machines, meaning that numbers in memory start with the *little end* first. So the least significant byte of a multi-byte number is in the lowest memory address. Since that is normally shown leftmost, this departs from our usual representation of numbers. It helps to know that this endian talk is borrowed from Gulliver's Travels: just as folks in Lilliput eat their eggs starting from the little end, Intel processors eat their numbers starting from the little byte.

So `local1` in fact holds the number 8, as in the legs of an octopus. `param1`, however, has a value of 2 in the second byte position, so its mathematical value is 2 * 256 = 512 (we multiply by 256 because each place value ranges from 0 to 255). Meanwhile, `param2` is carrying weight at 1 * 256 * 256 = 65536.

The housekeeping data in this stack frame consists of two crucial pieces: the address of the *previous* stack frame (saved ebp) and the address of the instruction to be executed upon the function's exit (the return address). Together, they make it possible for the function to return sanely and for the program to keep running along.

Now let's see the birth of a stack frame to build a clear mental picture of how this all works together. Stack growth is puzzling at first because it happens *in the opposite direction* you'd expect. For example, to allocate 8 bytes on the stack one *subtracts* 8 from `esp`, and subtraction is an odd way to grow something.

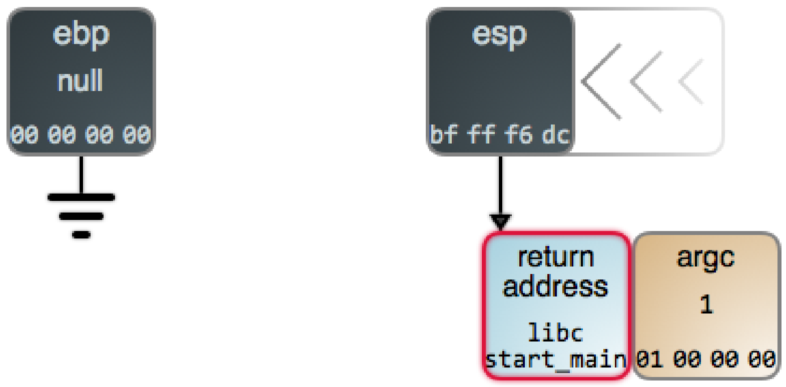
Let's take a simple C program:

**Simple Add Program - add.c**

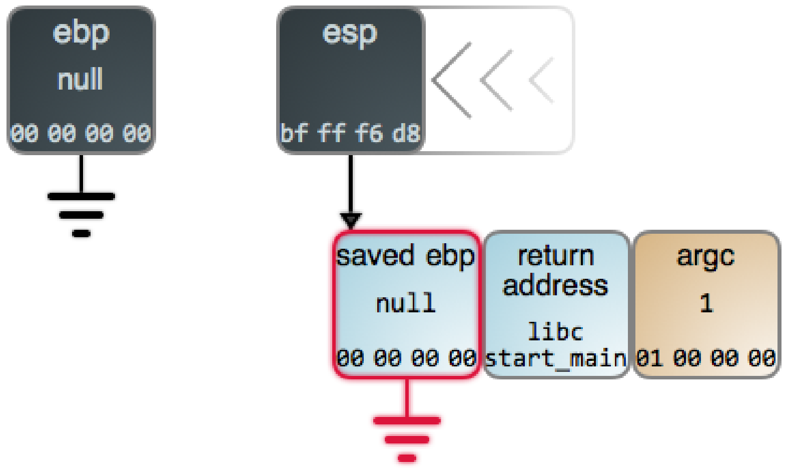
```
int add(int a, int b)
{
  int result = a + b;
  return result;
}

int main(int argc)
{
  int answer;
  answer = add(40, 2);
}
```

Suppose we run this in Linux without command-line parameters. When you run a C program, the first code to actually execute is in the C runtime library, which then calls our `main` function. The diagrams below show step-by-step what happens as the program runs. Each diagram links to GDB output showing the state of memory and registers. You may also see the GDB commands (https://github.com/gduarte/blog/blob/master/code/x86-stack/add-gdb-commands.txt) used and the whole GDB output (https://github.com/gduarte/blog/blob/master/code/x86-stack/add-gdb-output.txt). Here we go:

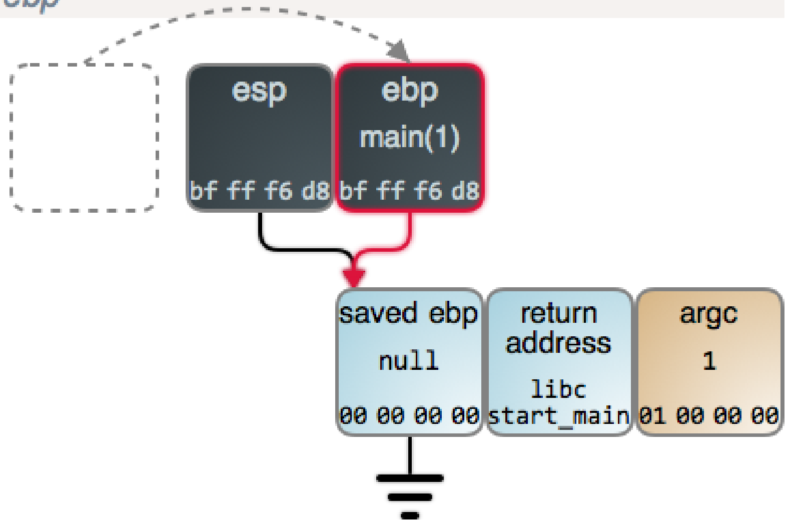
```
1.    call main # push return address onto stack, jump into main
```



```
2.    pushl %ebp # save current ebp register value
```



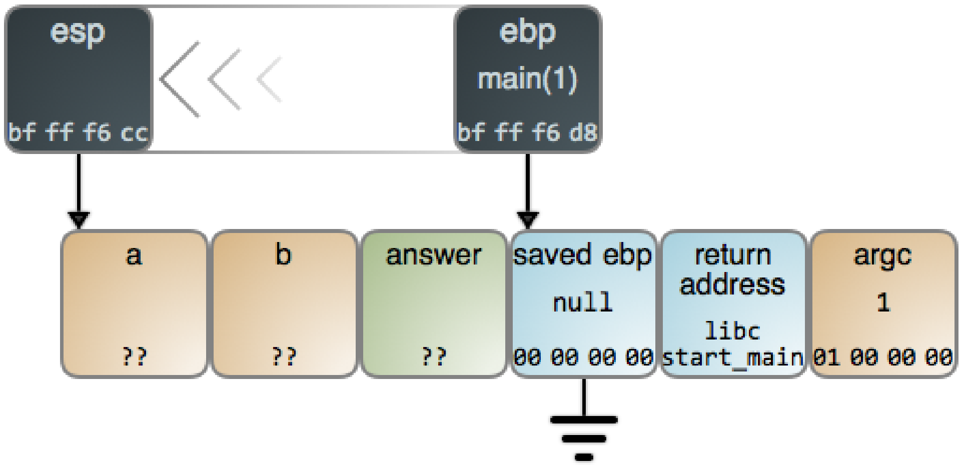
```
3.    movl %esp, %ebp # copy esp to ebp
```



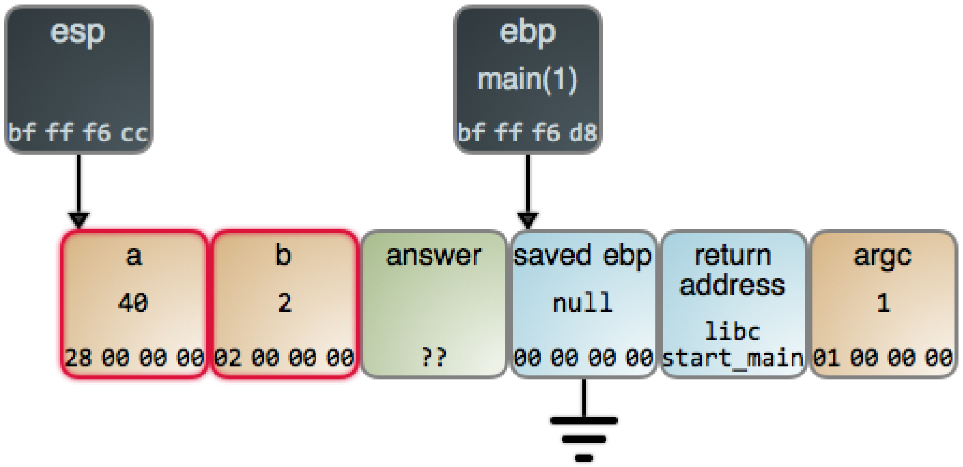
Steps 2 and 3, along with 4 below, are the **function prologue**, which is common to nearly all functions: the current value of ebp is saved to the top of the stack, and then `esp` is copied to `ebp`, establishing a new frame. main’s prologue is like any other, but with the peculiarity that `ebp` is zeroed out when the program starts.

If you were to inspect the stack below `argc` (to the right) you’d find more data, including pointers to the program name and command-line parameters (the traditional C `argv`), plus pointers to Unix environment variables and their actual contents. But that’s not important here, so the ball keeps rolling towards the `add()` call:

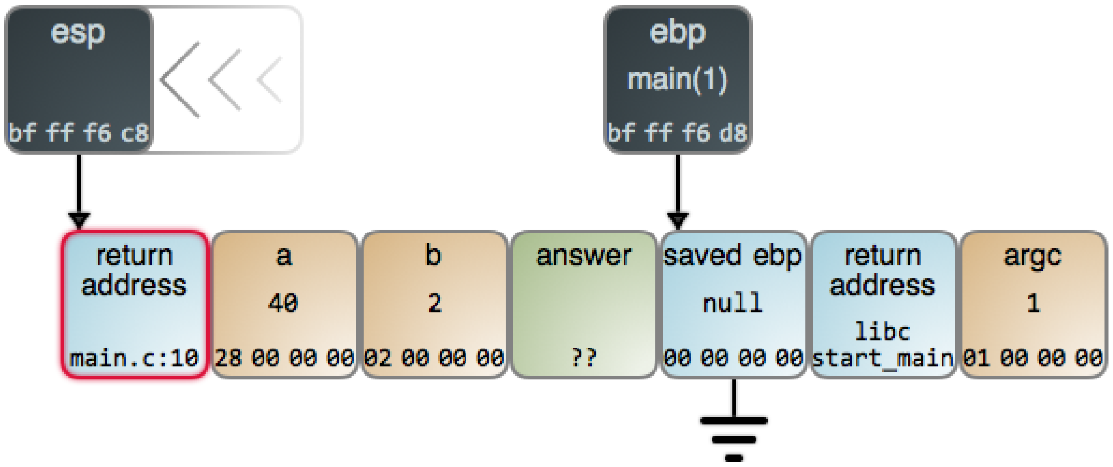
4. `subl $12, %esp` *# make room for stack data*



5. `movl $2, 4(%esp)` *# set b to 2*
   `movl $40, (%esp)` *# set a to 40*

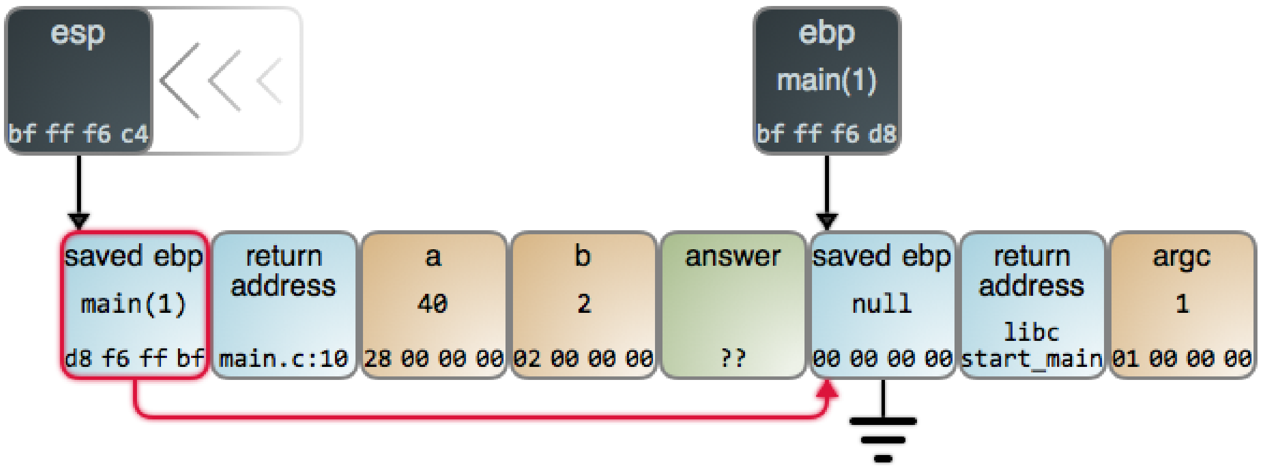


6. `call add` *# push return address onto stack, jump into add*

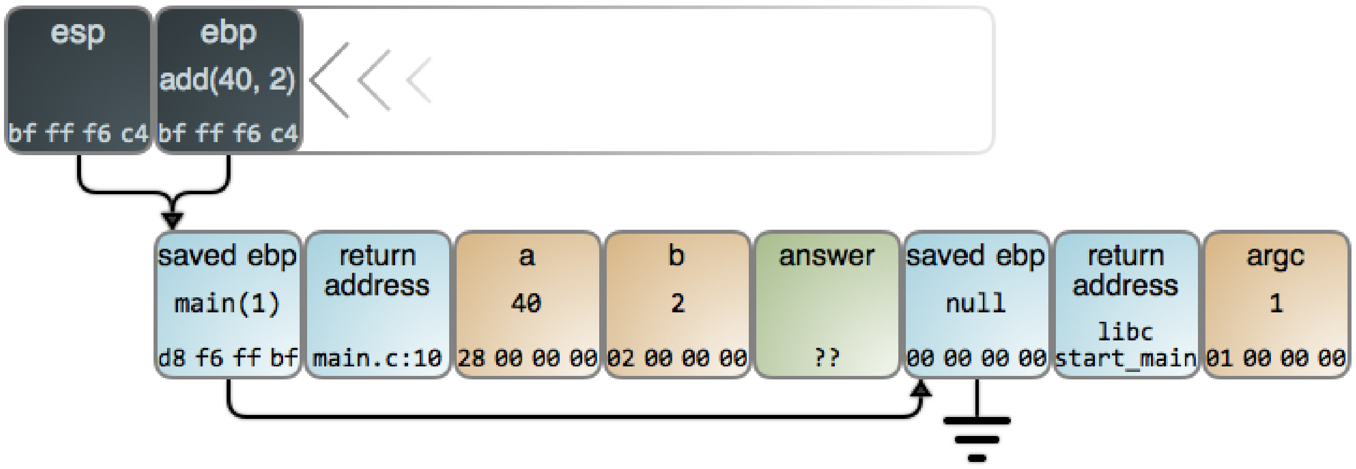


After `main` subtracts 12 from `esp` to get the stack space it needs, it sets the values for `a` and `b`. Values in memory are shown in hex and little-endian format, as you'd see in a debugger. Once parameter values are set, `main` calls `add` and it starts running:

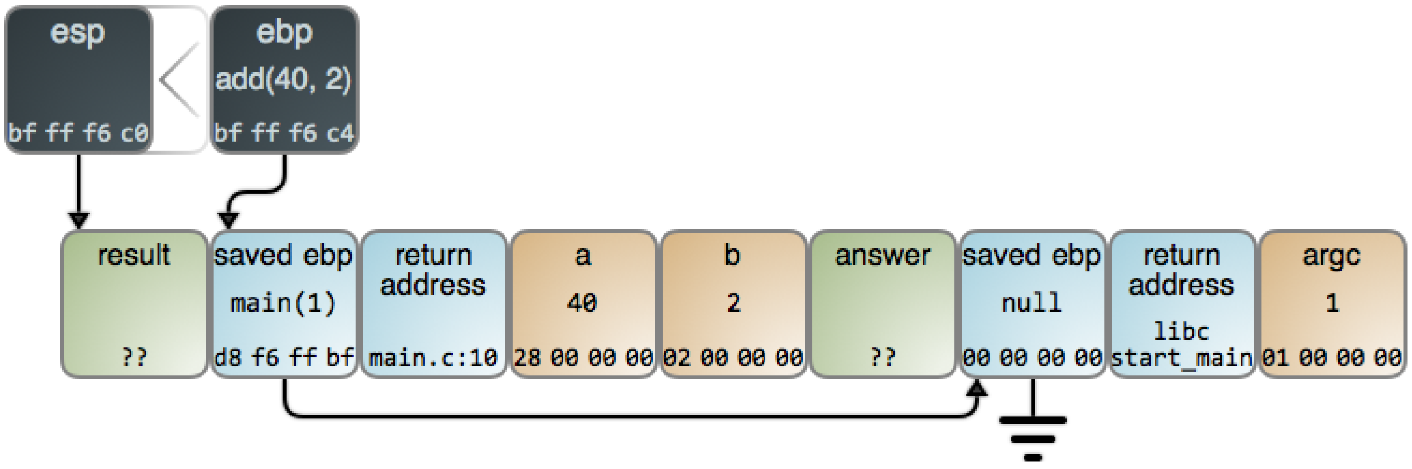
```
7.    pushl %ebp # save current ebp register value
```



```
8.    movl %esp, %ebp # copy esp to ebp
```



```
9.    subl $4, %esp # make room for result
```

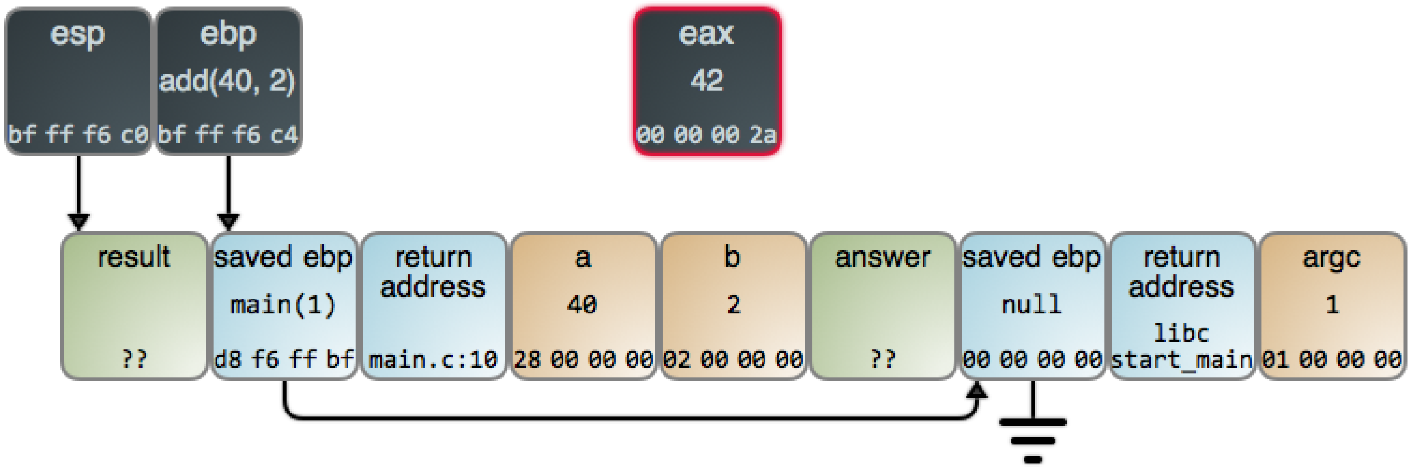


Now there’s some excitement! We get another prologue, but this time you can see clearly how the stack frames form a linked list, starting at `ebp` and going down the stack. This is how debuggers and `Exception` objects in higher-level languages get their stack traces. You can also see the much more typical catching up of `ebp` to `esp` when a new frame is born. And again, we subtract from `esp` to get more stack space.

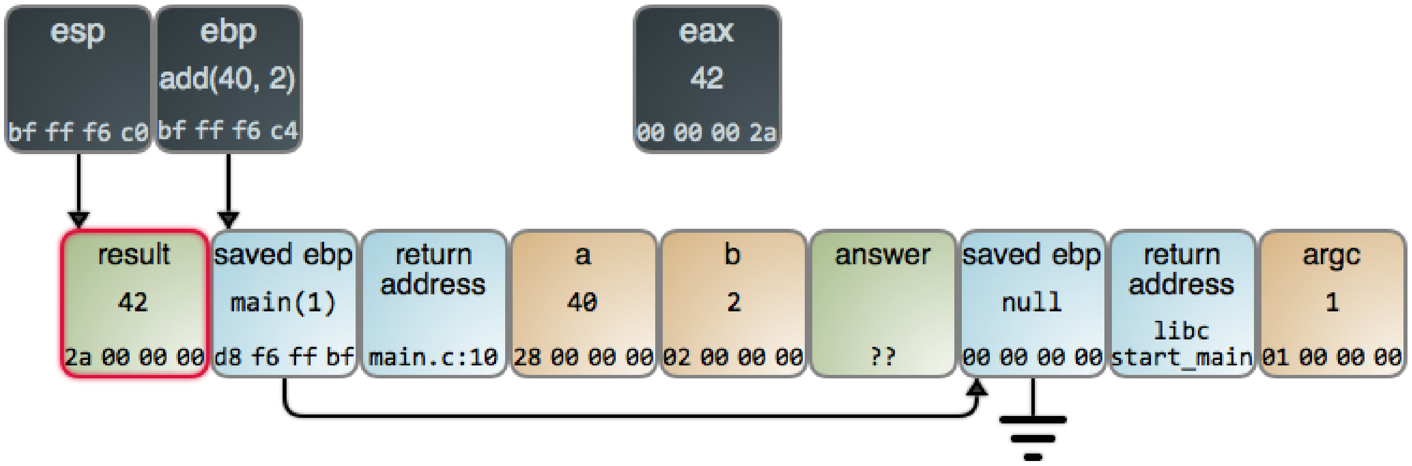
There’s also the slightly weird reversal of bytes when the `ebp` register value is copied to memory. What’s happening here is that registers don’t really have endianness: there are no “growing addresses” inside a register as there are for memory. Thus by convention debuggers show register values in the most natural format to humans: most significant to least significant digits. So the results of the copy in a little-endian machine appear reversed in the usual left-to-right notation for memory. I want the diagrams to provide an accurate picture of what you find in the trenches, so there you have it.

With the hard part behind us, we add:

```
    movl 12(%ebp), %eax # move b to eax
10. movl 8(%ebp), %edx  # move a to edx
    addl %edx, %eax     # add edx into eax. total is 42.
```



```
11. movl %eax, -4(%ebp) # copy eax to result
```



There are guest register appearances to help out with the addition, but otherwise no alarms and no surprises. `add` did its job, and at this point the stack action would go in reverse, but we'll save that for next time.

Anybody who's read this far deserves a souvenir, so I've made a large diagram showing all the steps combined (http://duartes.org/gustavo/blog/img/stack/callSequence.png) in a fit of nerd pride.

It looks tame once it's all laid out. Those little boxes help *a lot*. In fact, little boxes are the chief tool of computer science. I hope the pictures and register movements provide an intuitive mental picture that integrates stack growth and memory contents. Up close, our software doesn't look too far from a simple Turing machine.

This concludes the first part of our stack tour. There's some more byte spelunking ahead, and then it's on to see higher level programming concepts built on this foundation. See you next week.

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