CMSC414 Computer and Network Security

Memory Safety Vulnerabilities

Yizheng Chen | University of Maryland
surrealyz.github.io

Feb 5, 2026

Announcements

- Project 1
- Gitlab:
  - Submissions, backup your work, version control
- Sarah (TA) Tutorial Session on gdb: Feb 6, Friday, 1pm, on Zoom

Agenda

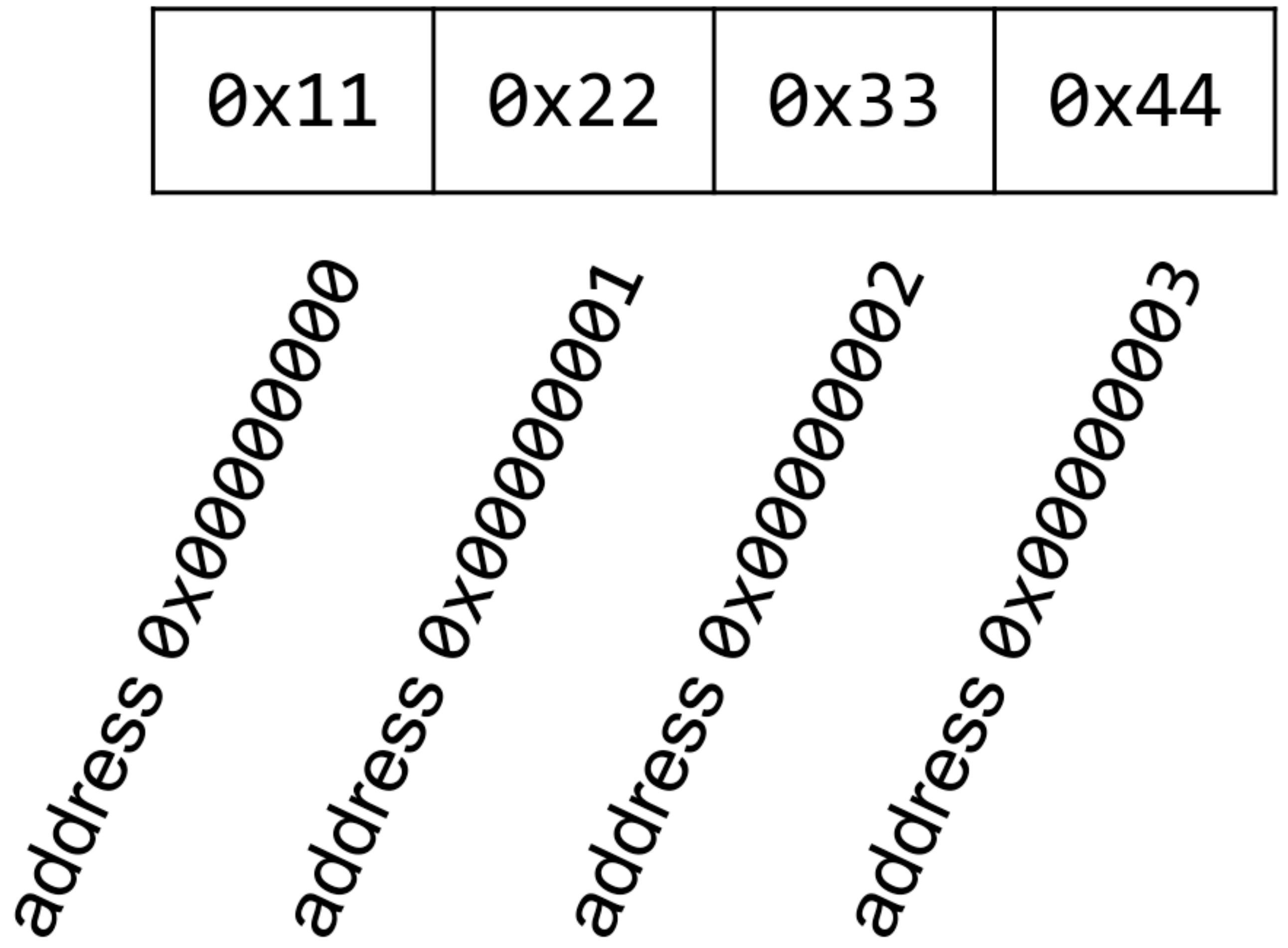
- Recap
- Buffer overflow
- Stack smashing
- Format string vulnerabilities
- Integer conversion vulnerabilities
- Recap
- Off-by-one vulnerabilities

Memory Address vs Content in Memory

- In a 32 bit system, a memory address is 32 bits
  - Could be represented in 8 hex digits
  - esp, ebp, eip store addresses that point to somewhere in memory
  - **eip, instruction pointer, points to the instruction to execute**
- In C, the basic unit of content in the memory is a byte.
- If we just index into a byte, or store a byte, it is read or written as is in memory.

Little-Endian System

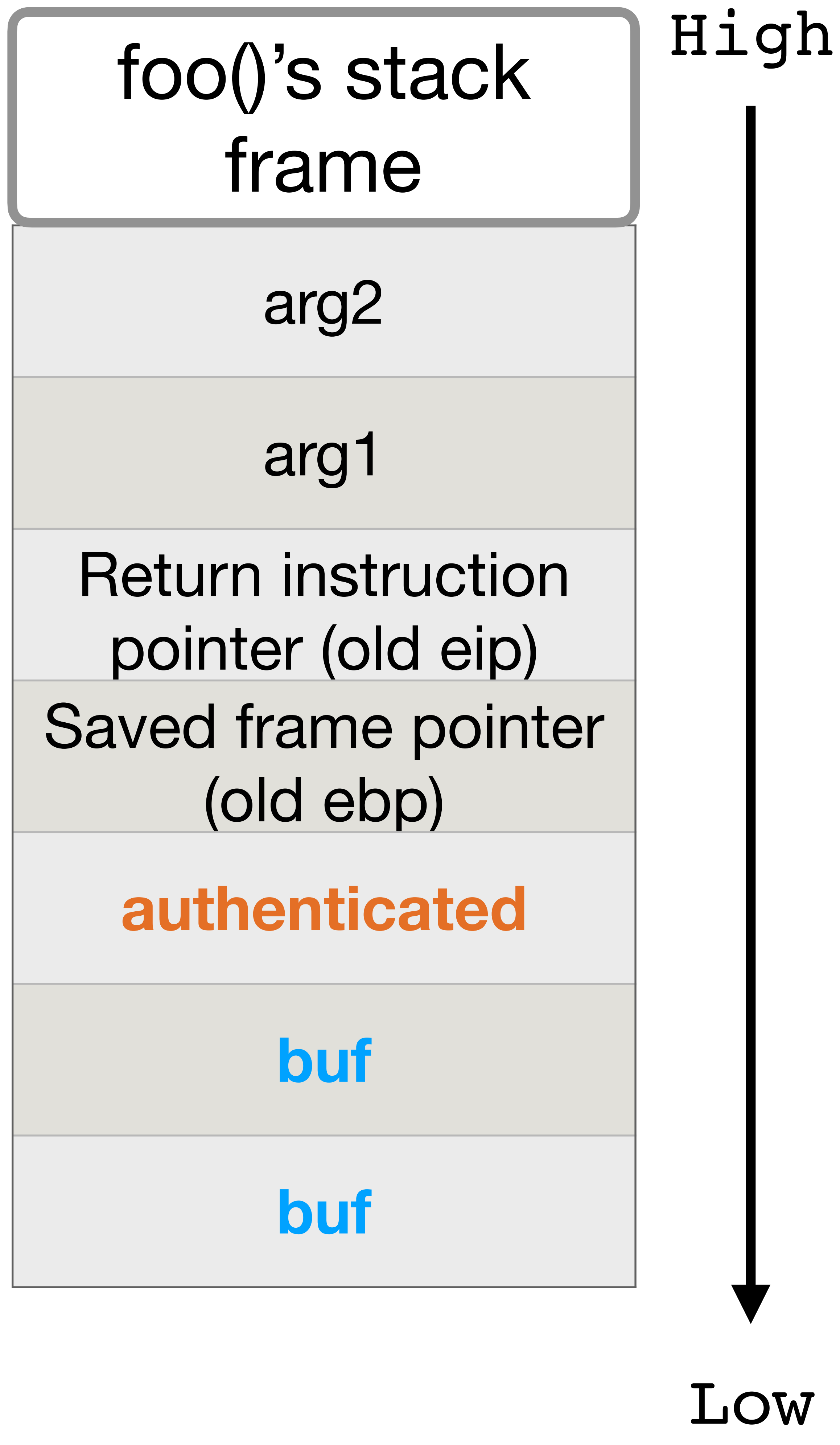
- For data types larger than one byte (8 bits)
  - e.g., short, int, long, pointers (to anything)
  - If we refer to a char, it is only one byte, so it is stored as is
- When we **increase an index** for referencing items in an array, or **increase a pointer** by some number of bytes: memory address always goes up



0x11	0x22	0x33	0x44
address 0x00000000	address 0x00000001	address 0x00000002	address 0x00000003

How to change authenticated to 1?

```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1, int arg2) {
    int  authenticated = 0;
    char buf[8];
    ...
}
```

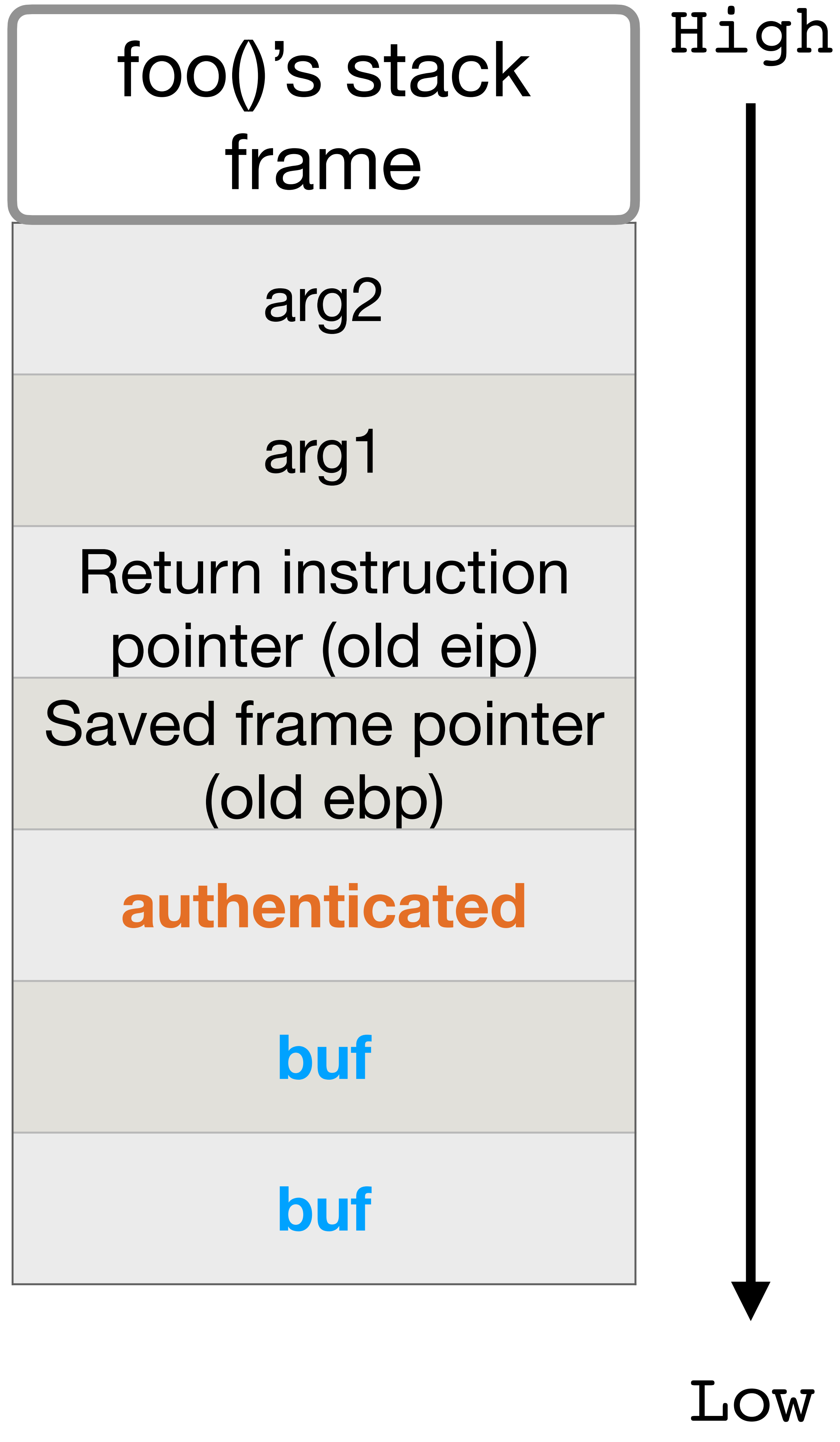

foo()’s stack frame
arg2
arg1
Return instruction pointer (old eip)
Saved frame pointer (old ebp)
authenticated
buf
buf
High
Low

Buffer Overflow

```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1, int arg2) {
    int  authenticated = 0;
    char buf[8];
    ...
}
```

Set buf[8] to '\x01'

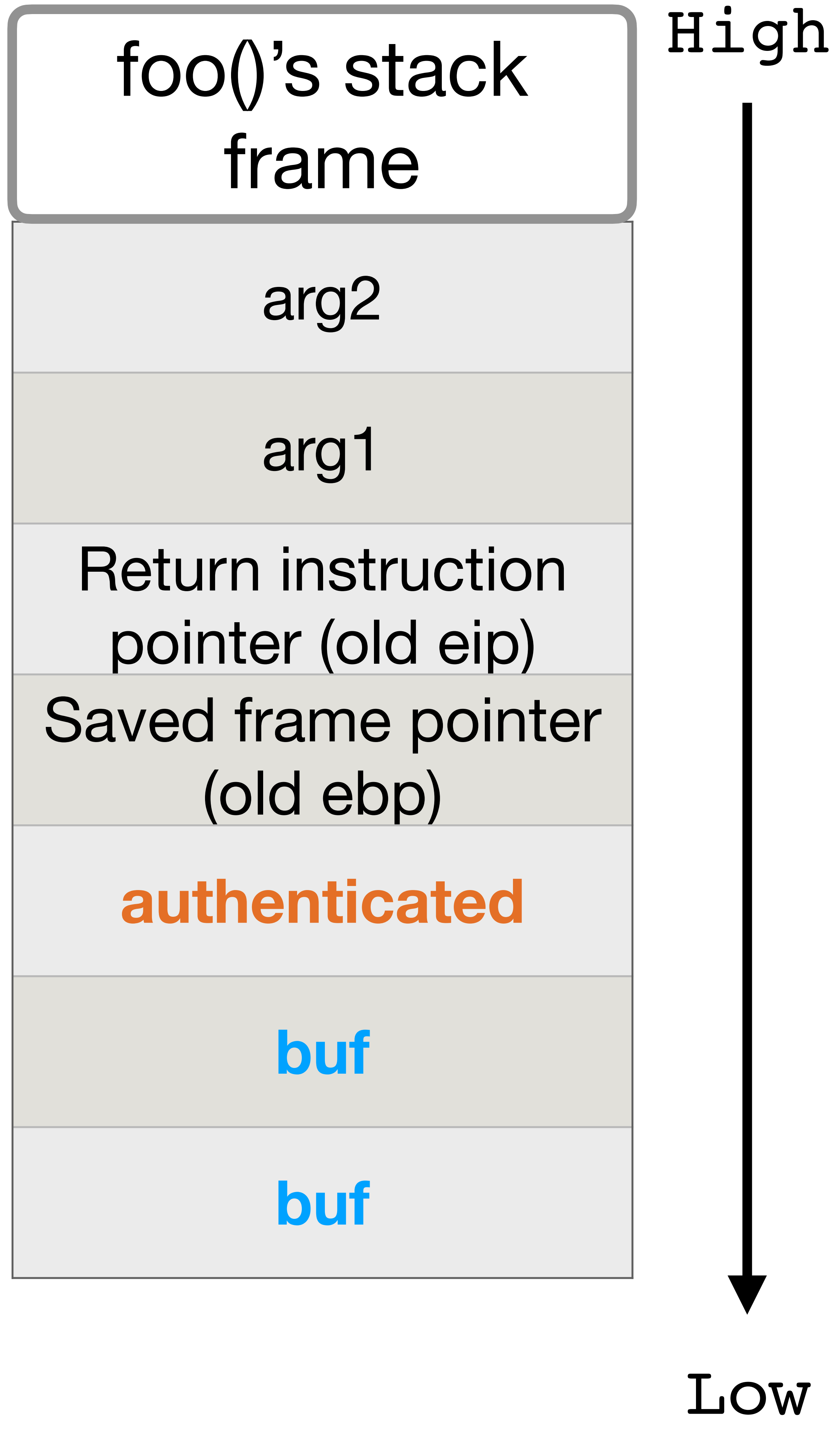
Hint: little-endian


foo()'s stack frame
arg2
arg1
Return instruction pointer (old eip)
Saved frame pointer (old ebp)
authenticated
buf
buf
High
Low

Buffer Overflow

```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1, int arg2) {
    int  authenticated = 0;
    char buf[8];
    ...
}
```

Exercise: write out the memory layout for **buf** and **authenticated** if we set **buf** as **“abcdefgh!”**



High

foo()’s stack frame

arg2

arg1

Return instruction pointer (old eip)

Saved frame pointer (old ebp)

authenticated

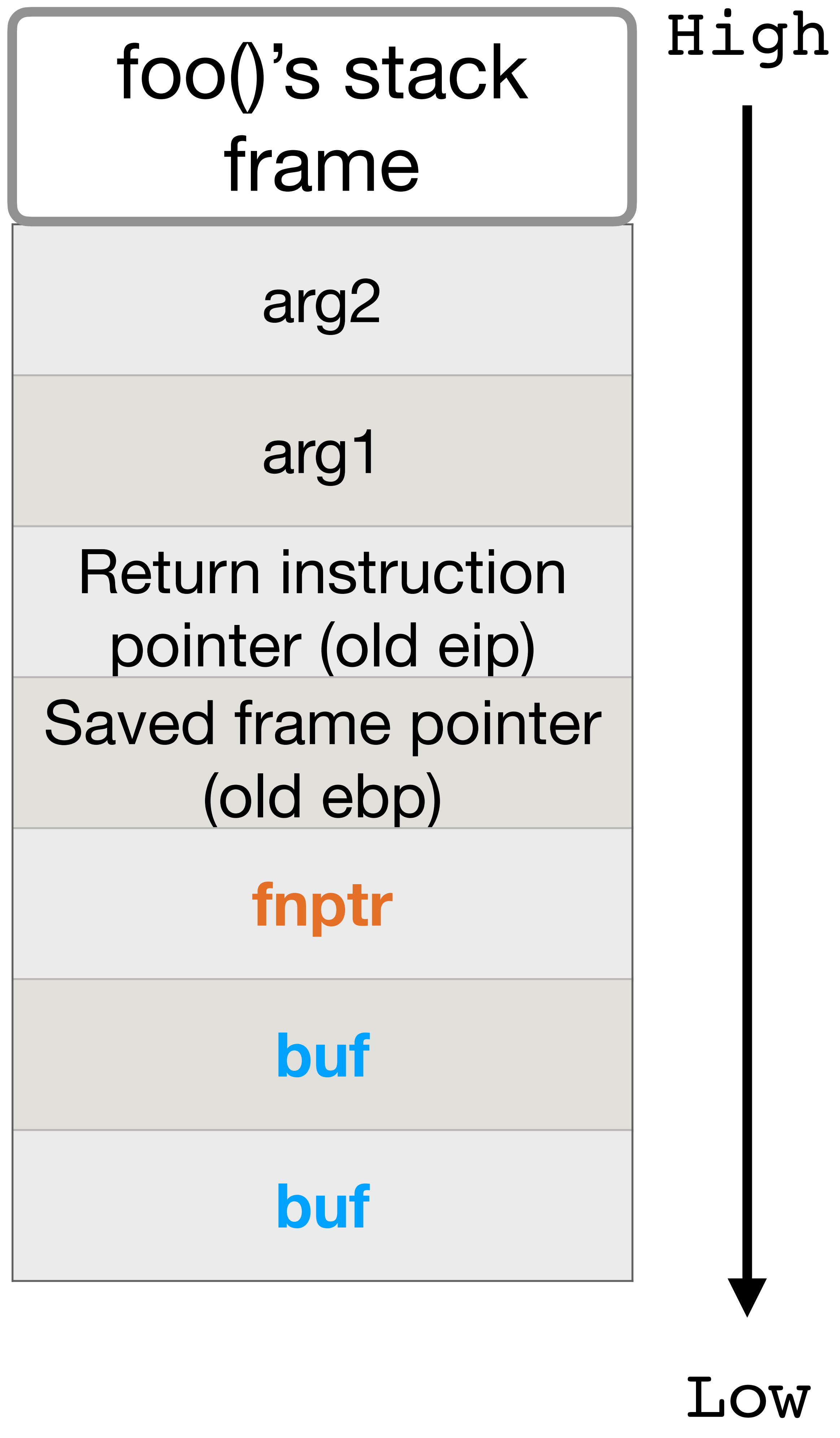
buf

buf

Low

Special Opportunity: Overwrite Function Pointer

```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1, int arg2) {
    int  (*fnptr)();
    char buf[8];
    ...
}
```



foo()'s stack frame
arg2
arg1
Return instruction pointer (old eip)
Saved frame pointer (old ebp)
fnptr
buf
buf
High
Low

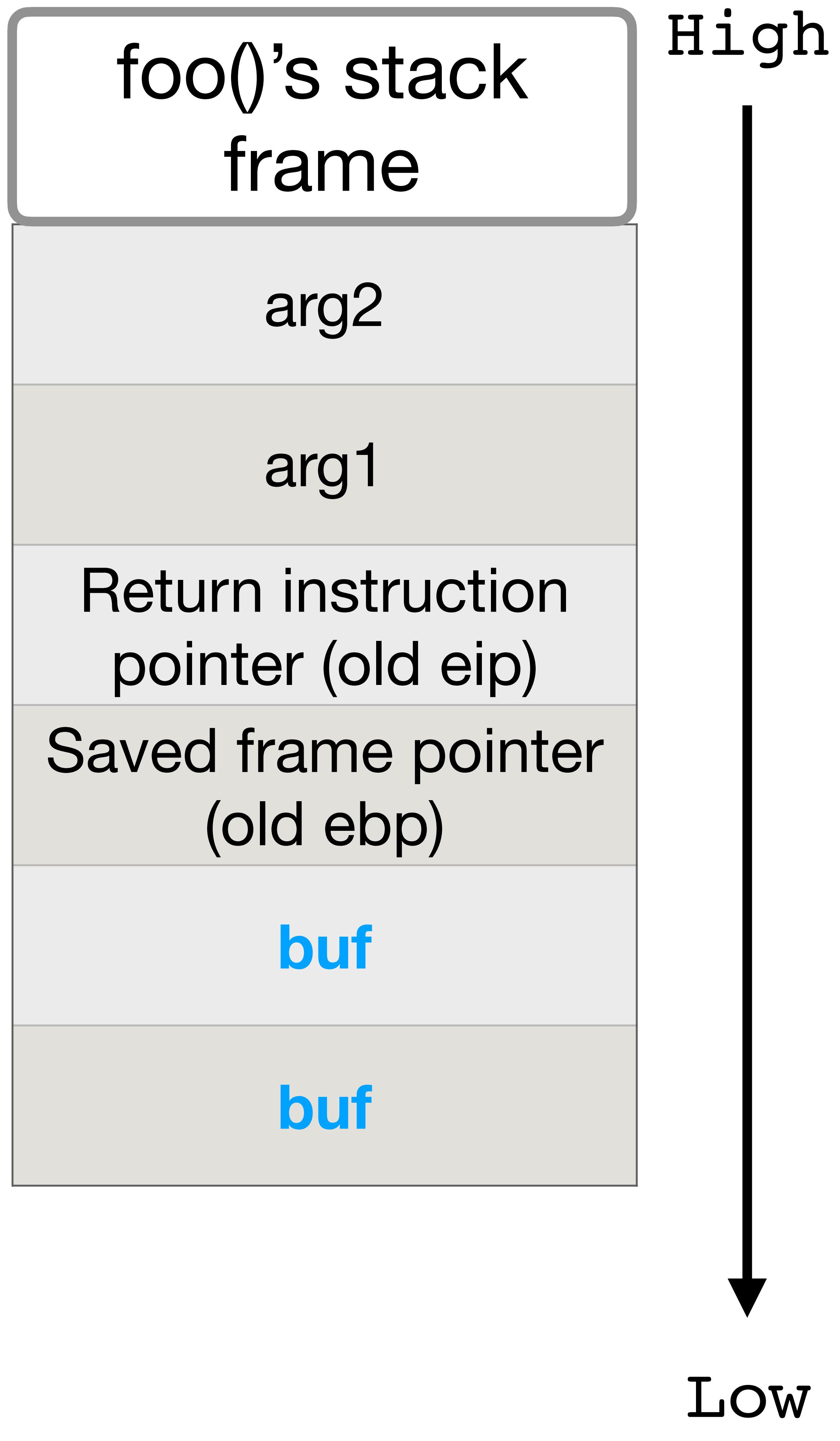
In previous examples, buffer that can be overflowed must be followed in memory by some security-critical data (e.g., a function pointer, or a special flag).

But these conditions rarely occur in practice…

How to inject and execute malicious code in general?

Stack Smashing

```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1, int arg2) {
    ~~int  authenticated = 0;~~
    char buf[8];
    ...
}
```



High

foo()'s stack frame

arg2

arg1

Return instruction pointer (old eip)

Saved frame pointer (old ebp)

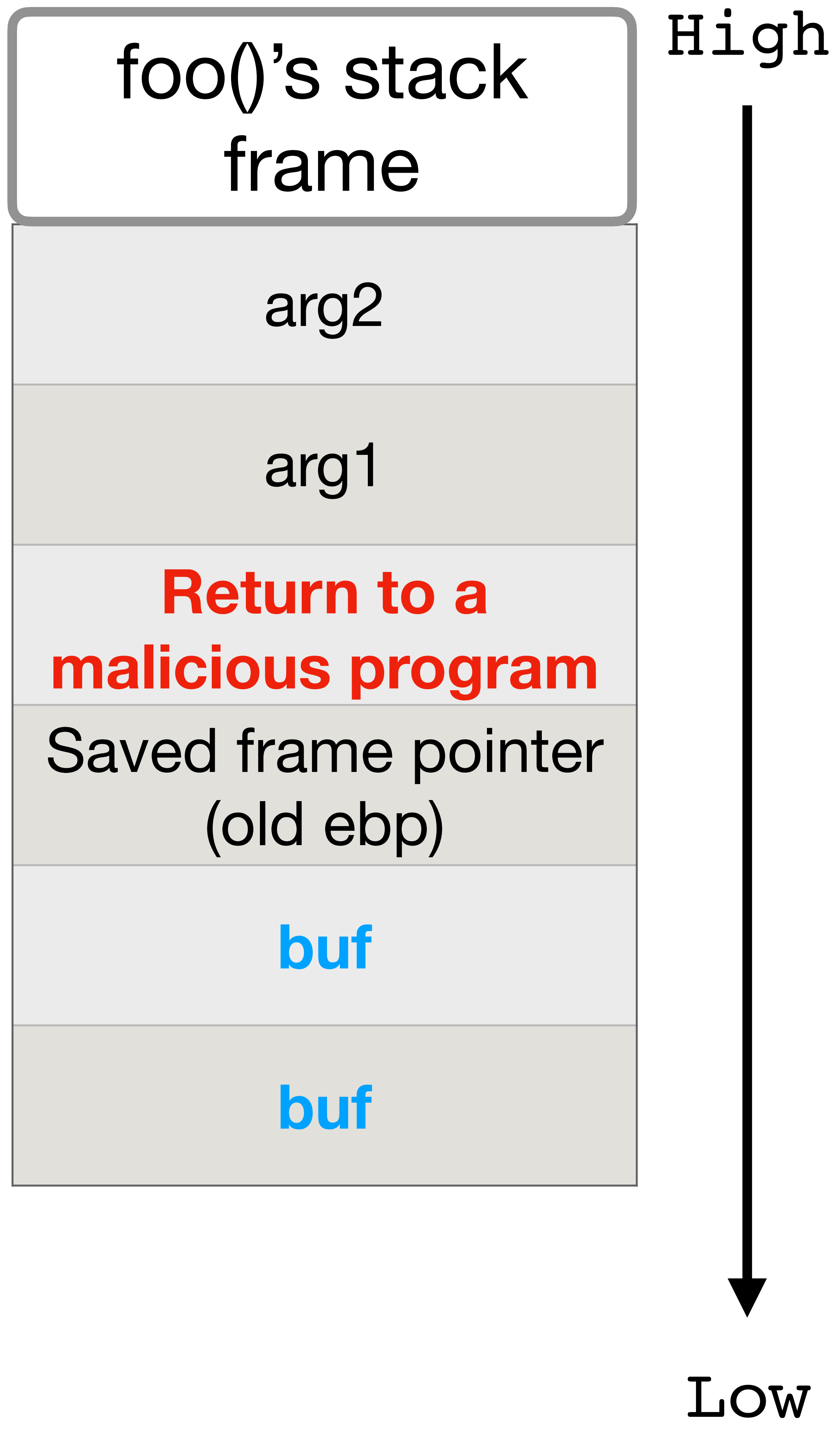
buf

buf

Low

Stack Smashing

```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1, int arg2) {
    ~~int  authenticated = 0;~~
    char buf[8];
    ...
}
```



foo()'s stack frame

arg2

arg1

Return to a malicious program

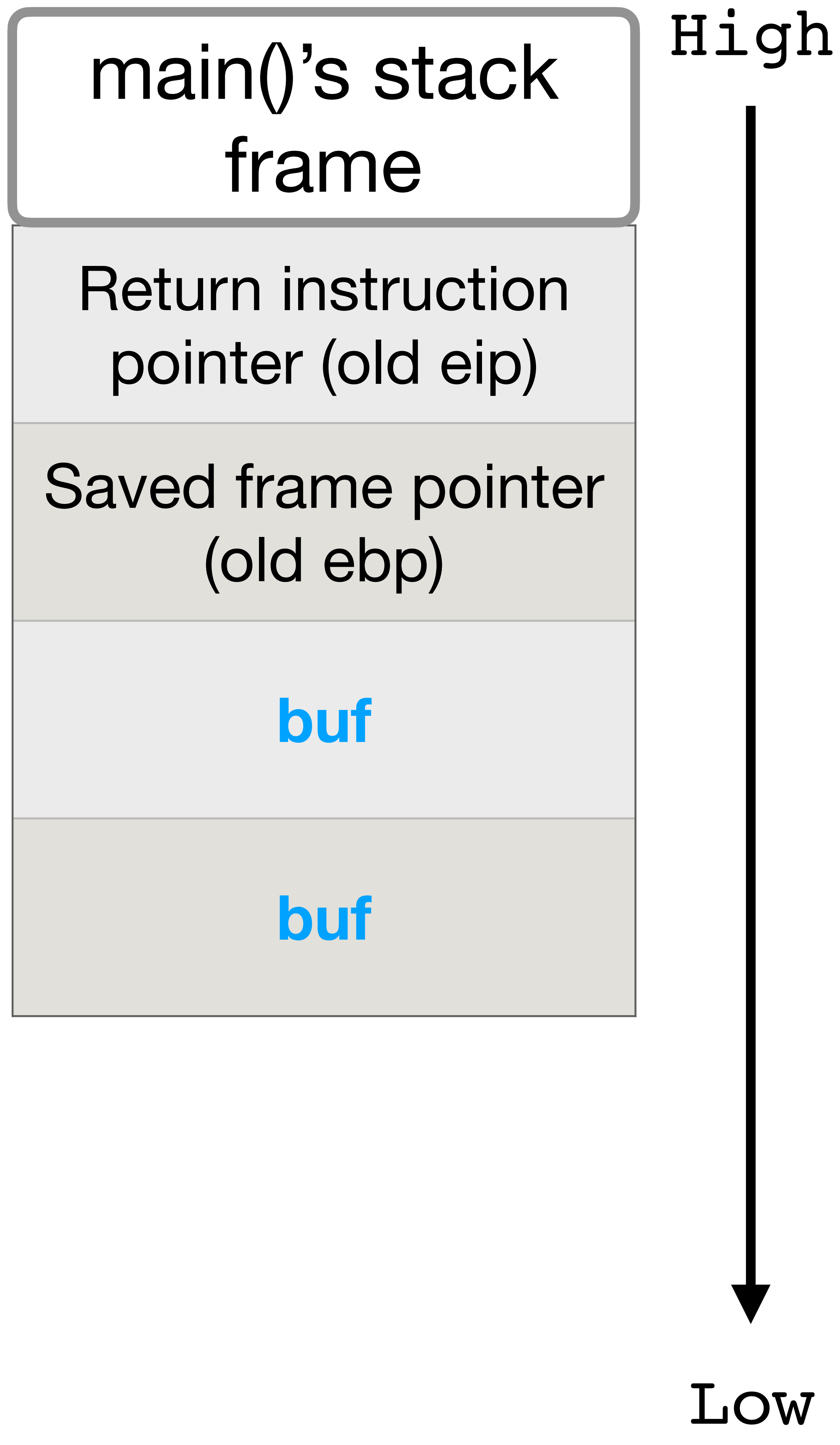
Saved frame pointer (old ebp)

buf

buf

Malicious Code Injection

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[8];
    gets(buf)
    ...
}
```



High

main()’s stack frame

Return instruction pointer (old eip)

Saved frame pointer (old ebp)

buf

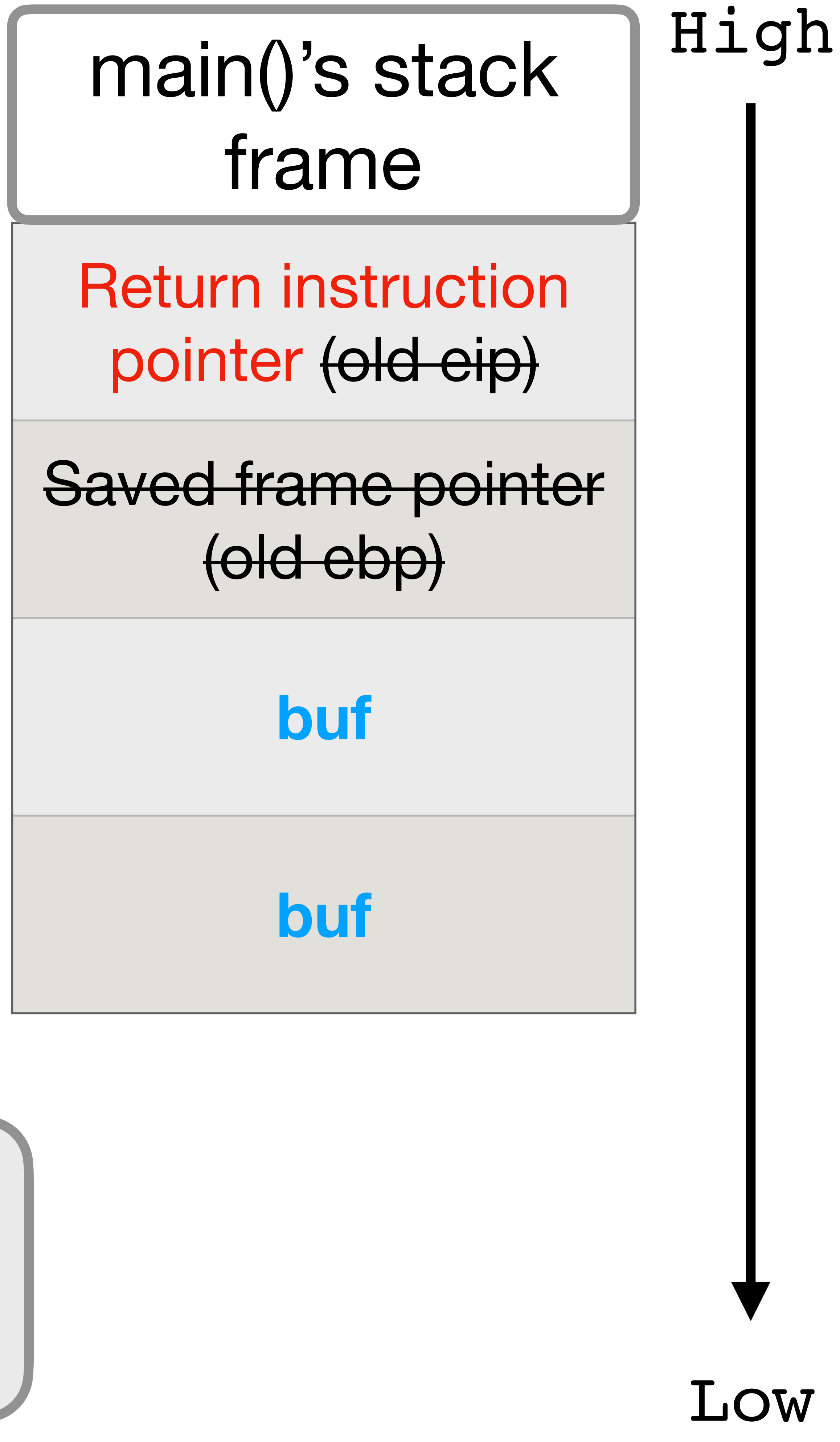
buf

Low

How to point to malicious code at 0xdeadbeef?

Stack Smashing

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[8];
    gets(buf)
    ...
}
```


main()'s stack frame
Return instruction pointer ~~(old eip)~~
~~Saved frame pointer (old ebp)~~
buf
buf
High
Low

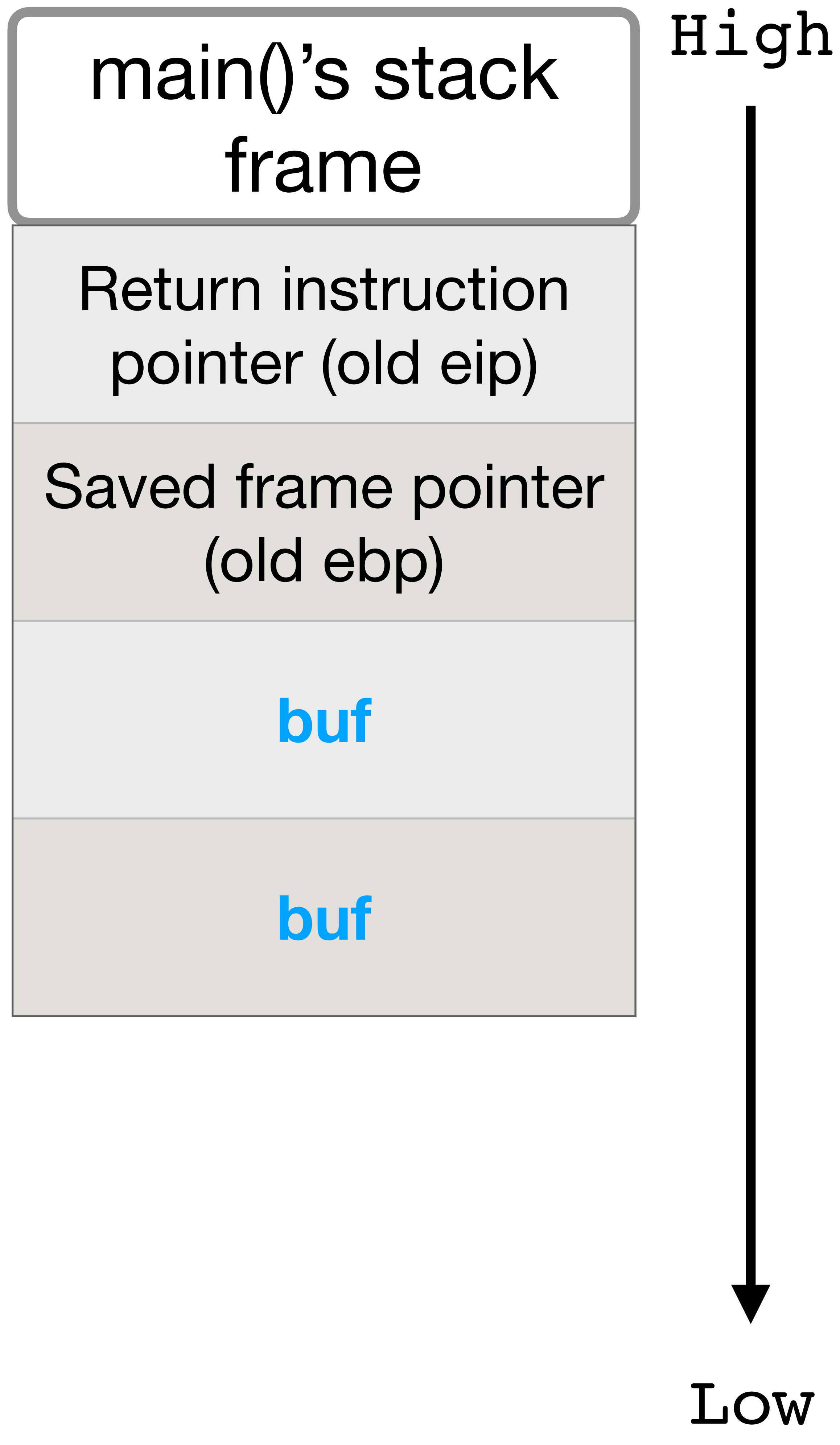
AAAAAAAAAAAA\xef\xbe\xad\xde

Shellcode

- The malicious code is often written to spawn an interactive shell that lets the attacker perform arbitrary actions.

What if malicious code isn’t in memory yet?

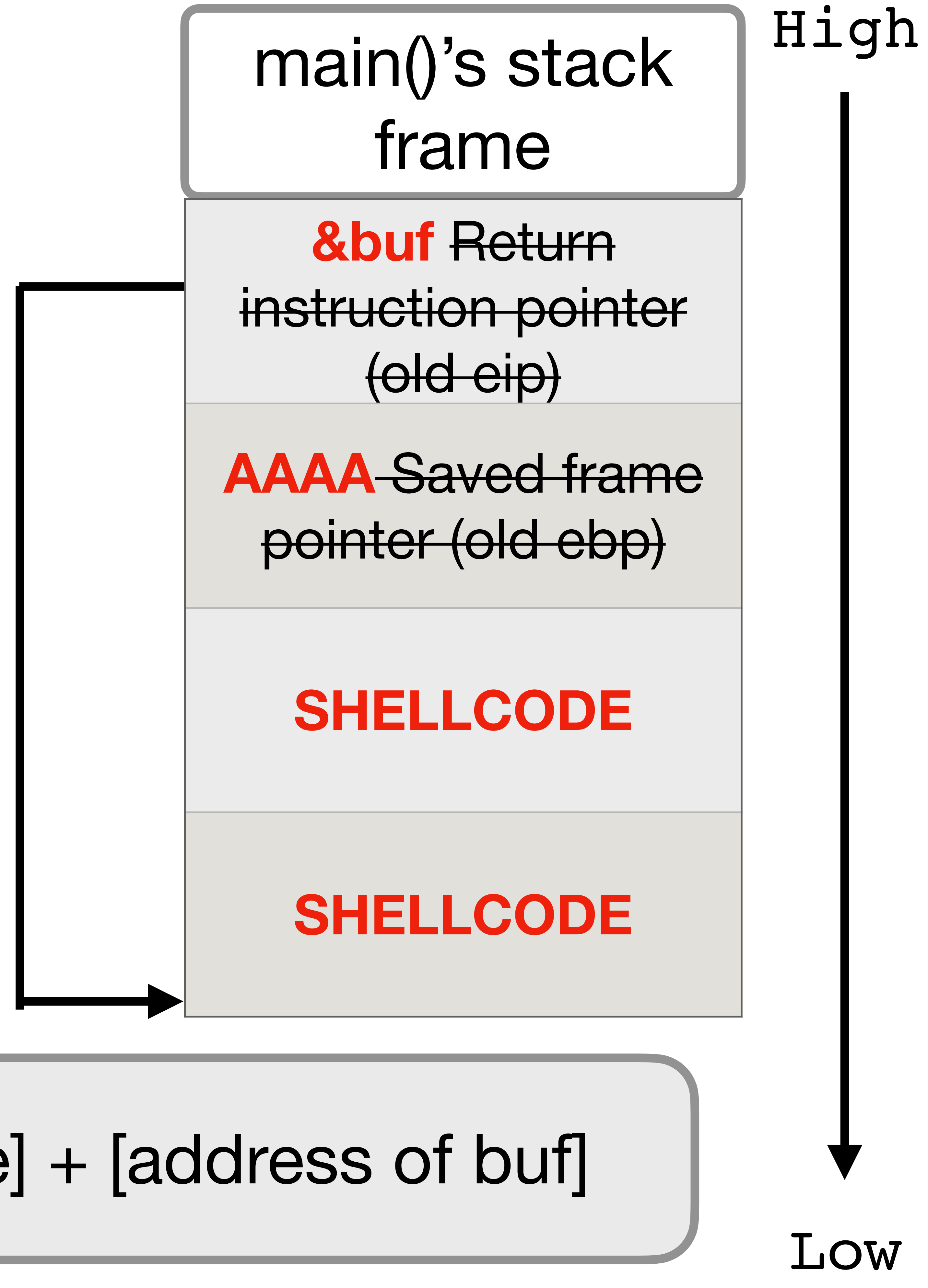
```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[8];
    gets(buf)
    ...
}
```



High
main()’s stack frame
Return instruction pointer (old eip)
Saved frame pointer (old ebp)
buf
buf
Low

Simple case: if shell code is only 8 bytes

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[8];
    gets(buf)
    ...
}
```



High

main()'s stack frame

&buf ~~Return instruction pointer (old eip)~~

AAAA ~~Saved frame pointer (old ebp)~~

SHELLCODE

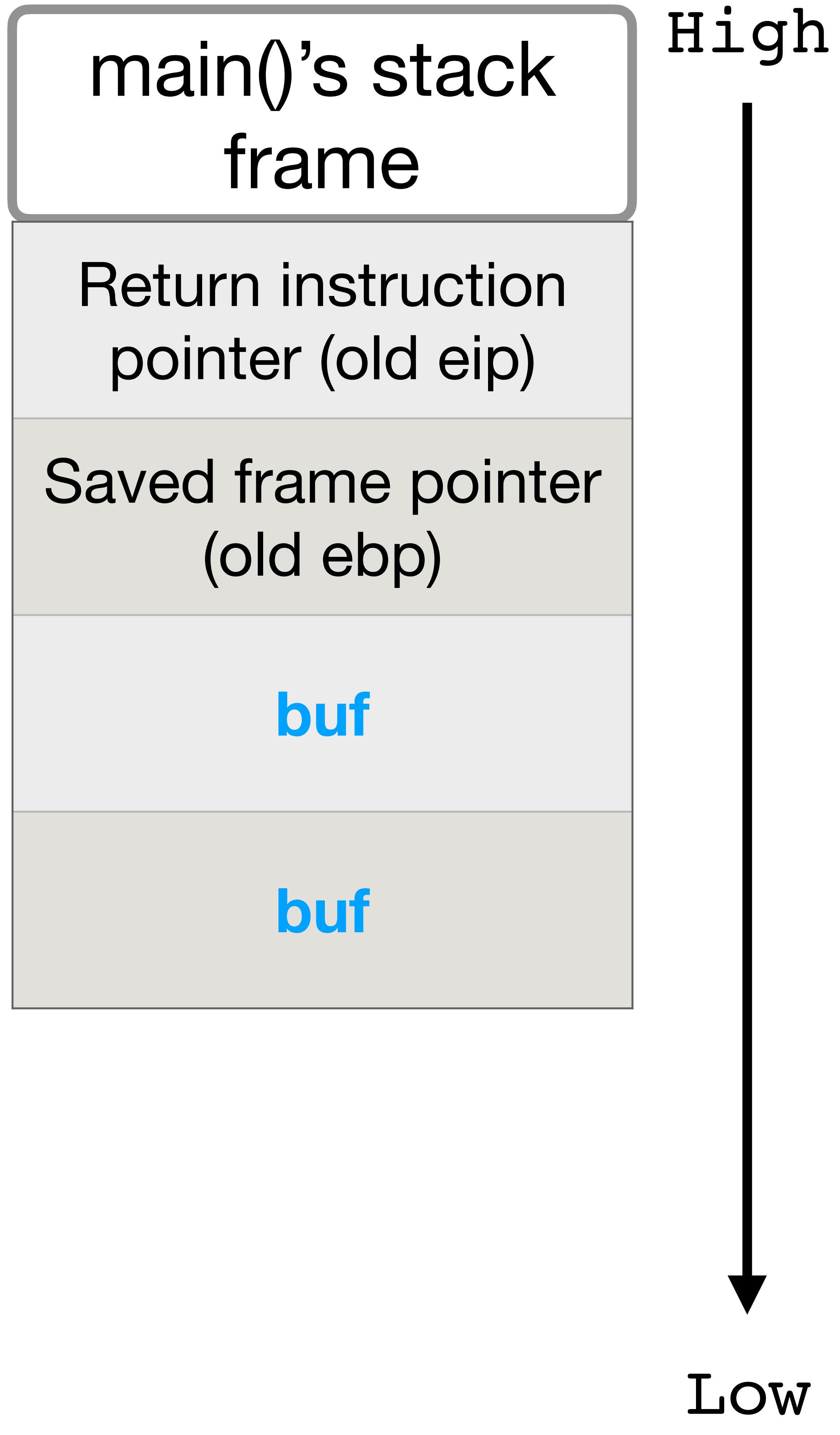
SHELLCODE

Low

[8 bytes of SHELLCODE] + [4 bytes of garbage] + [address of buf]

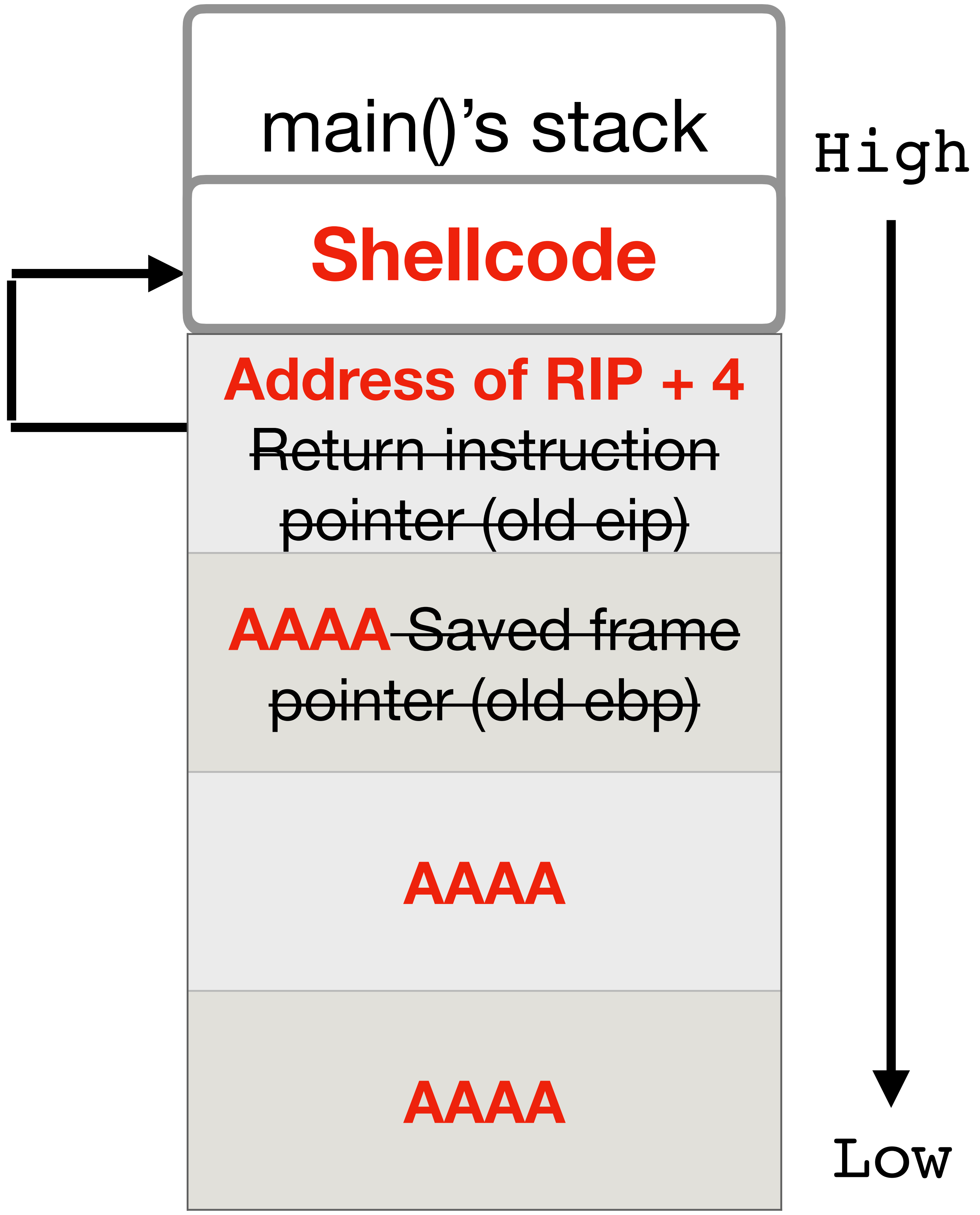
What if shell code is longer than 8 bytes?

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[8];
    gets(buf)
    ...
}
```


main()'s stack frame
Return instruction pointer (old eip)
Saved frame pointer (old ebp)
buf
buf
High
Low

What if shell code is longer than 8 bytes?

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[8];
    gets(buf)
    ...
}
```

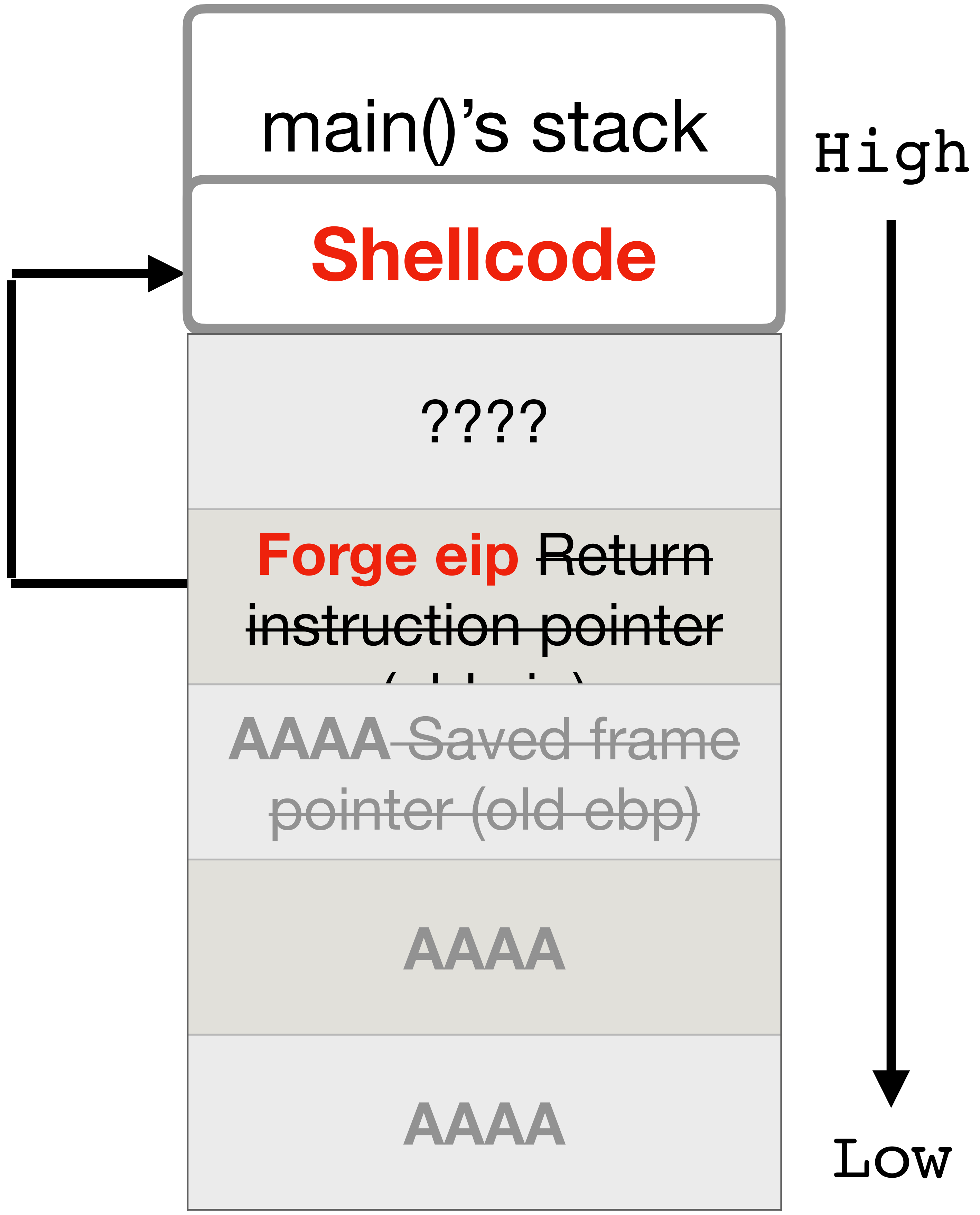

main()'s stack
Shellcode
Address of RIP + 4
~~Return instruction pointer (old eip)~~
AAAA ~~Saved frame pointer (old ebp)~~
AAAA
AAAA
High
Low

[12 bytes of garbage] + [address of RIP + 4] + [shellcode]

Hint: need to find the address of Return Instruction Pointer (RIP)

Threat Model: Attacker Has No Access to Source Code

```
void main() {
    vulnerable();
}

void vulnerable(???) {
    char buf[8];
    gets(buf)
    ...
}
```



main()'s stack
Shellcode
????
Forge eip ~~Return instruction pointer~~
AAAA ~~Saved frame pointer (old ebp)~~
AAAA
AAAA
High
Low

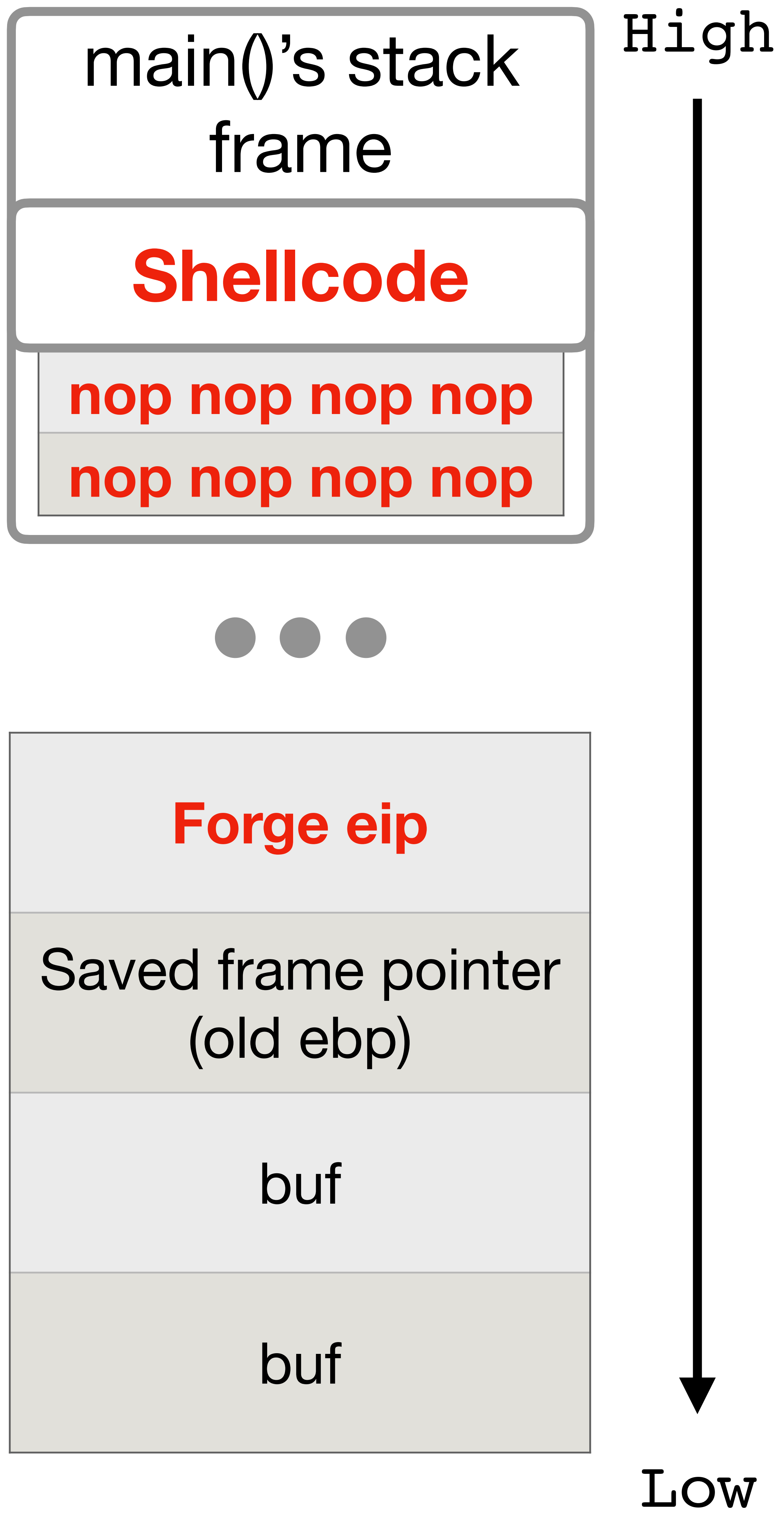
- Overriding ??? can make the CPU panic
- How to know what is the starting address of shell code? (Make eip point there)

NOP

- nop is a single-byte instruction (just moves to the next instruction)
- 0x90

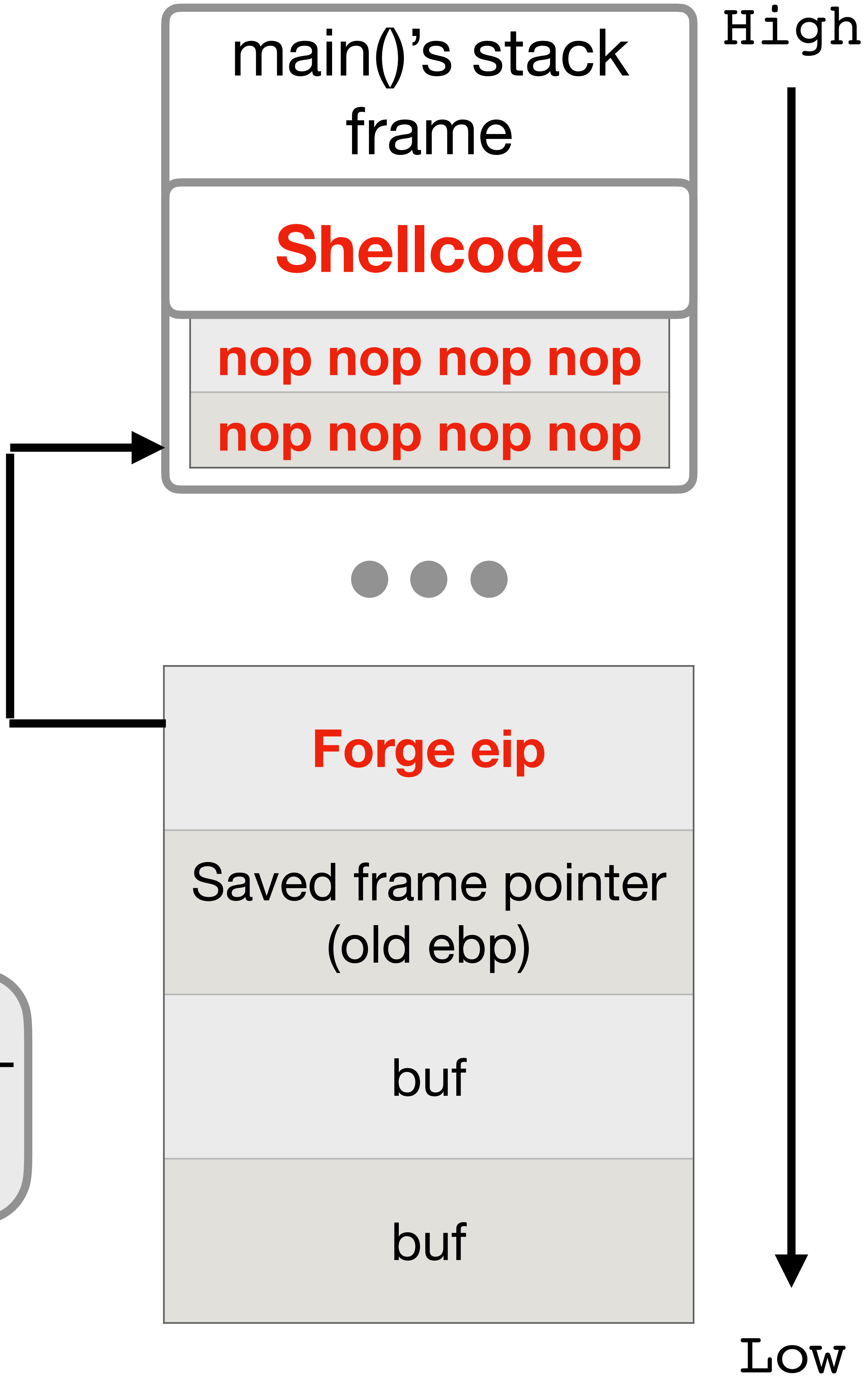
NOP Sled

```
void main() {
    vulnerable();
}

void
vulnerable(?????????) {
    char buf[8];
    gets(buf)
    ...
}
```



NOP Sled

```
void main() {
    vulnerable();
}

void
vulnerable(?????????) {
    char buf[8];
    gets(buf)
    ...
}
```



[12 bytes of garbage] + **[guess somewhere in the NOP]** + [a lot of NOPs] + [shellcode]

Sophisticated Attacks

- The malicious code is stored at an unknown location.
- The buffer is stored on the heap instead of on the stack.
- The characters that can be written to the buffer are limited (e.g., to only lowercase letters).
- There is no way to introduce *any malicious code* into the program’s address space.

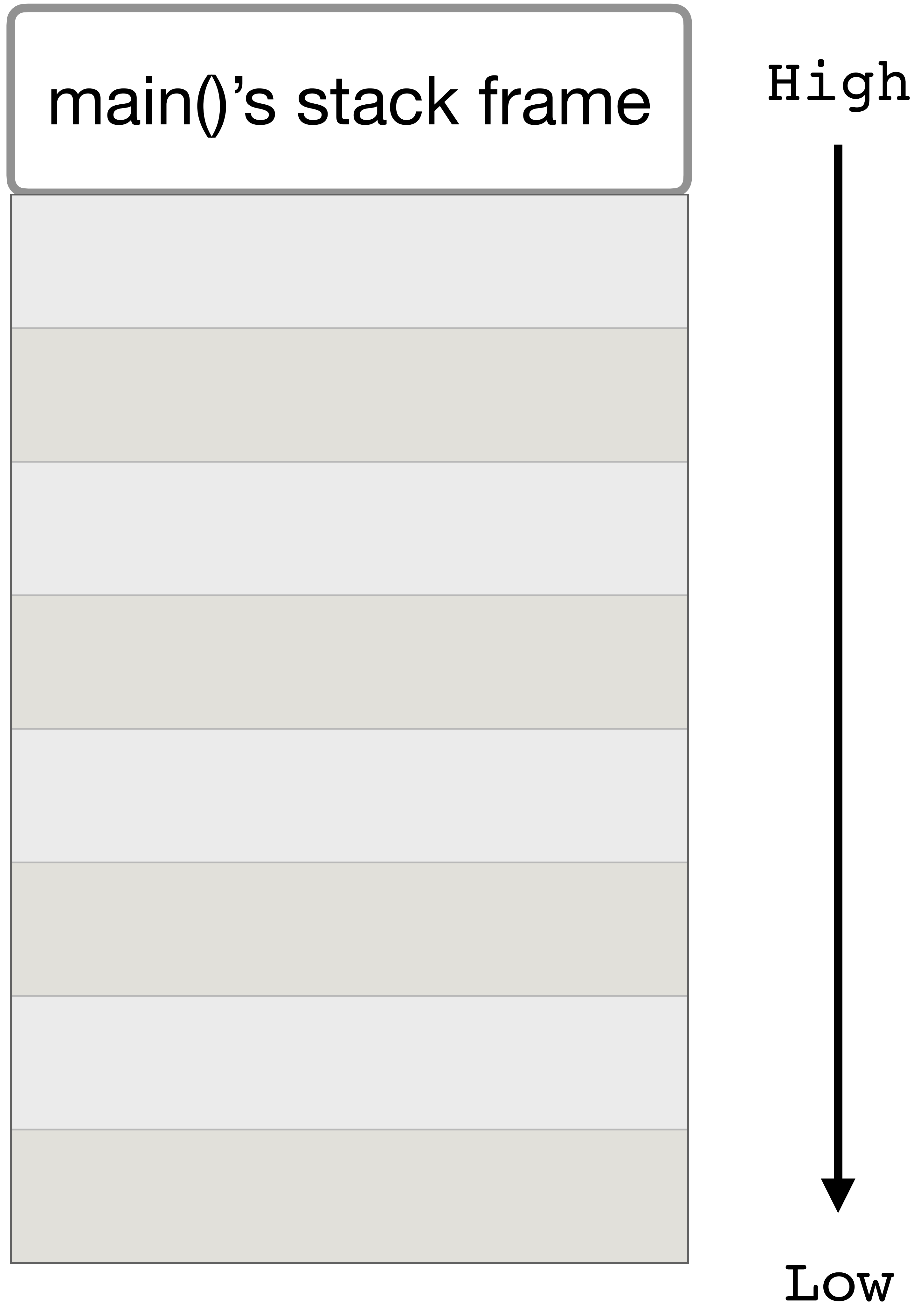
If your program has a buffer overflow bug, you should assume that the bug is exploitable and an attacker can take control of your program.

Agenda

- Recap
- Buffer overflow
- Stack smashing
- Format string vulnerabilities
- Integer conversion vulnerabilities
- Recap
- Off-by-one vulnerabilities

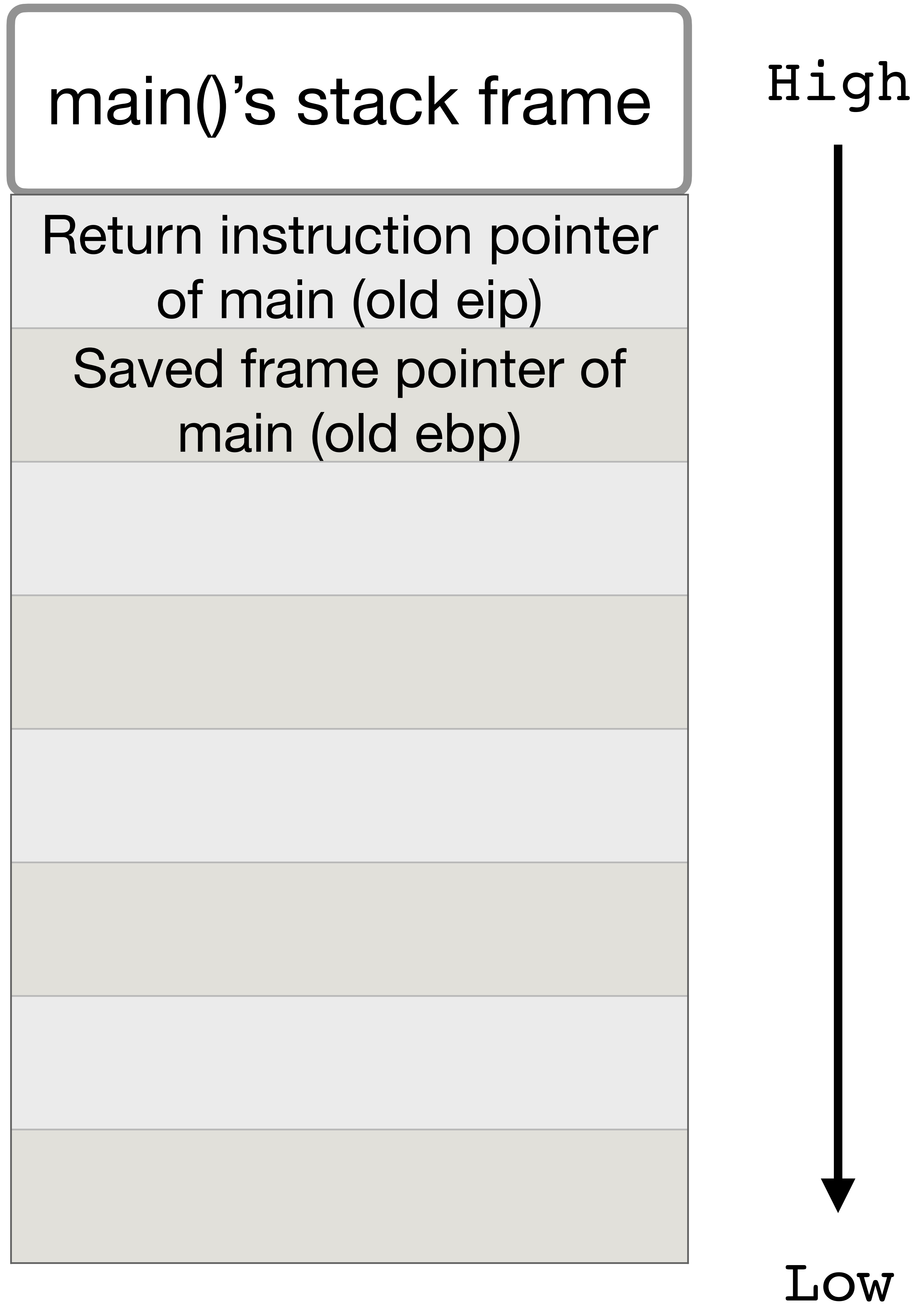
printf

```
void main() {
    not_vulnerable();
}

void not_vulnerable() {
    printf("x val: %d, y val:
%d, z val: %d\n", x, y, z);
}
```



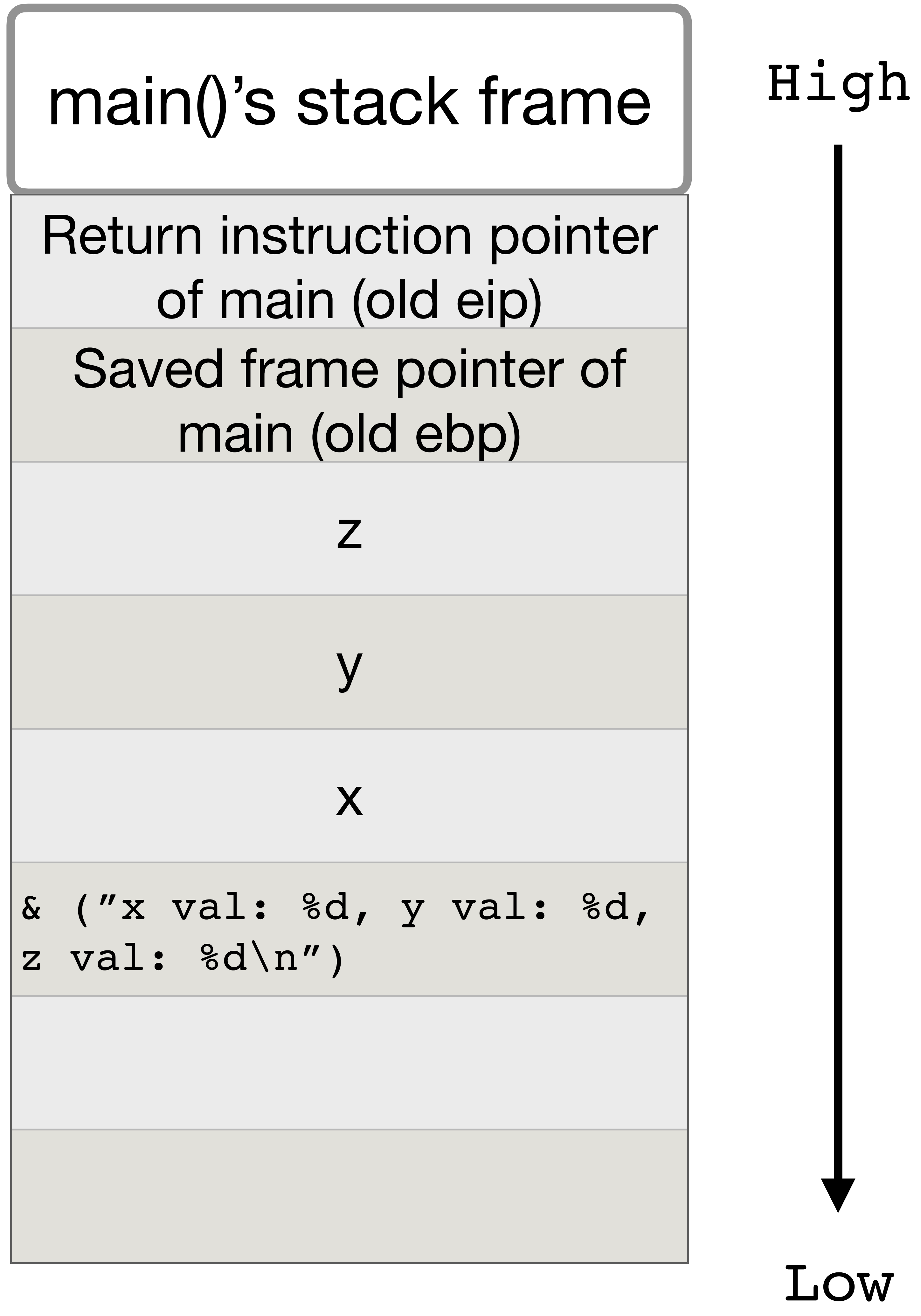
printf

```
void main() {
    not_vulnerable();
}

void not_vulnerable() {
    printf("x val: %d, y val:
%d, z val: %d\n", x, y, z);
}
```


main()'s stack frame
Return instruction pointer of main (old eip)
Saved frame pointer of main (old ebp)
High
Low

printf

```
void main() {
    not_vulnerable();
}

void not_vulnerable() {
    printf("x val: %d, y val:
%d, z val: %d\n", x, y, z);
}
```



main()'s stack frame

Return instruction pointer of main (old eip)

Saved frame pointer of main (old ebp)

z

y

x

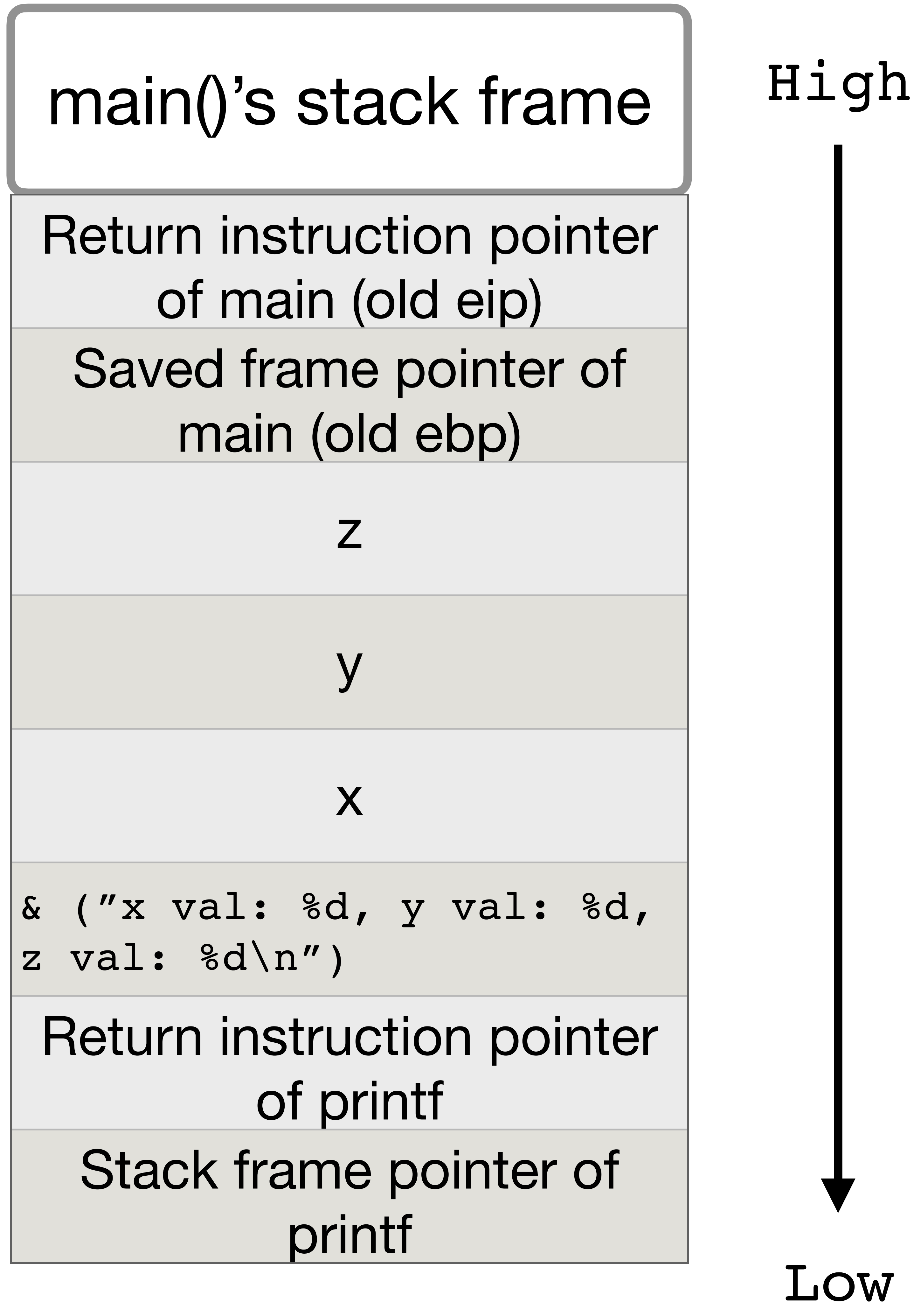
`& (”x val: %d, y val: %d, z val: %d\n”)`

High

Low

printf

```
void main() {
    not_vulnerable();
}

void not_vulnerable() {
    printf("x val: %d, y val:
%d, z val: %d\n", x, y, z);
}
```



High

main()'s stack frame

Return instruction pointer of main (old eip)

Saved frame pointer of main (old ebp)

z

y

x

`& (”x val: %d, y val: %d, z val: %d\n”)`

Return instruction pointer of printf

Stack frame pointer of printf

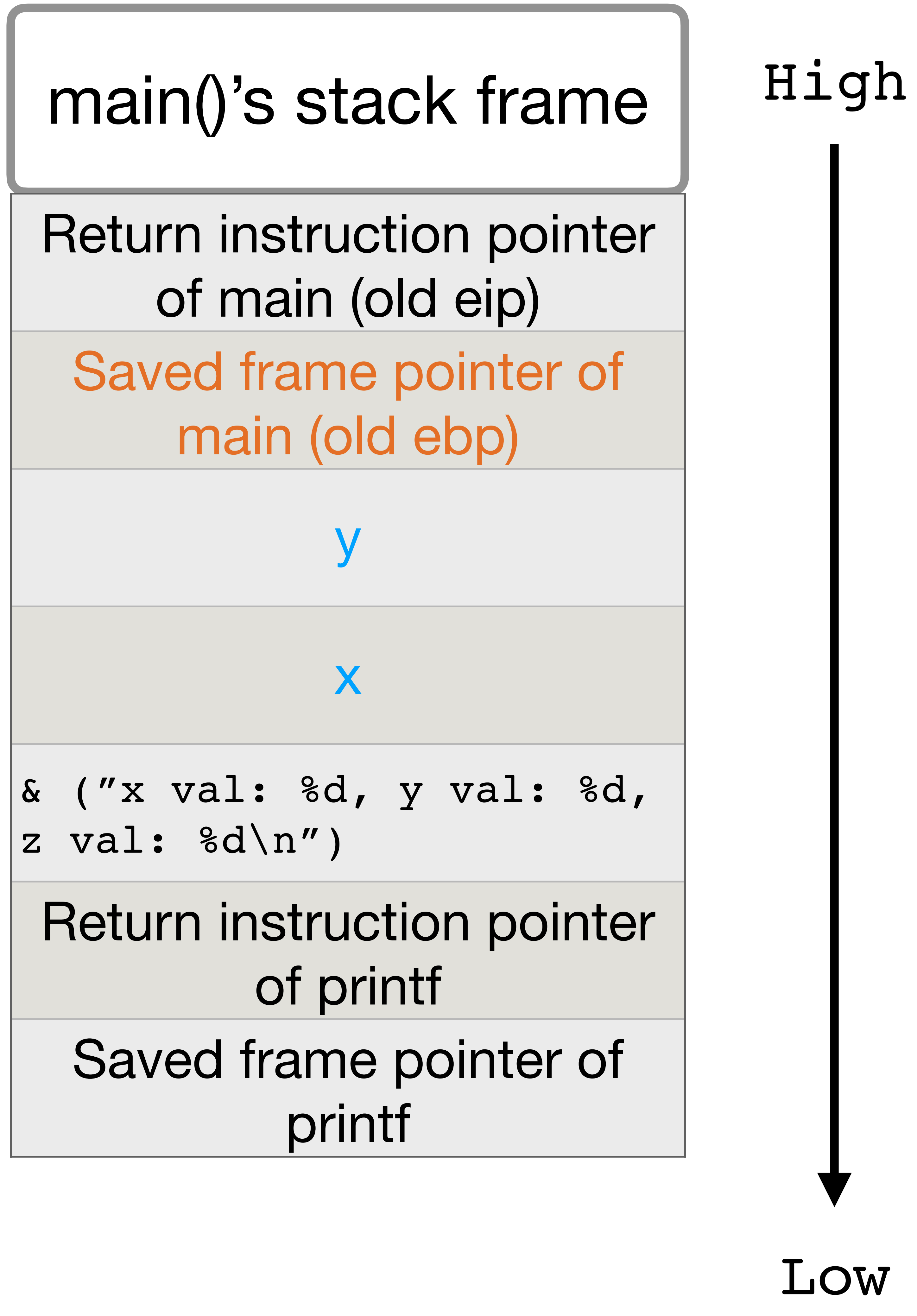
Low

The format string “x val: … %d\n” controls the behavior of printf

Internal pointer in printf looks for content on the stack

Format String Vulnerability

```
void main() {
    vulnerable();
}

void vulnerable() {
    printf("x val: %d, y val:
%d, z val: %d\n", x, y);
}
```


main()'s stack frame
Return instruction pointer of main (old eip)
Saved frame pointer of main (old ebp)
y
x
& ("x val: %d, y val: %d, z val: %d\n")
Return instruction pointer of printf
Saved frame pointer of printf
High
Low

The format string "x val: … %d\n" controls the behavior of printf

Internal pointer in printf looks for content on the stack

Other Formats

- %s → Treat the argument as an address and print the string at that address up until the first null byte
- %n → Treat the argument as an address and write the number of characters that have been printed so far to that address
- %c → Treat the argument as a value and print it out as a character
- %x → Print the variable as unsigned hexadecimal integer
- %[b]u → Print out [b] bytes starting from the argument

Format string vulnerability: the attacker can learn any value stored in memory and can take control of your program.

Exercise

- Try %p format specifier with printf
- Useful for project 1

What’s wrong with this code?

```
char buf[8];
void vulnerable() {
    int len = read_int_from_network();
    char *p = read_string_from_network();
    if (len > 8) {
        error("length too large: bad dog, no cookie for
you!");
        return;
    }
    memcpy(buf, p, len);
}
```

```
void *memcpy(void *dest, const void *src, size_t n);

typedef unsigned int size_t;
```

Integer Conversion Vulnerabilities

```
char buf[8];
void vulnerable() {
    int len = read_int_from_network();
    char *p = read_string_from_network();
    if (len > 8) {
        error("length too large: bad dog, no cookie for
you!");
        return;
    }
    memcpy(buf, p, len);
}
```

If len is a negative integer, casting it to unsigned int could make it a very large int.

=> buffer overflow

Integer Wraparound

- Unsigned int: 0 ~ 2^32 - 1
  - Adding 1 to 2^32 - 1 becomes 0
- If an unsigned integer x = 0, x - 1 = 2^32 - 1

Exercise: What’s wrong with this code?

```c
void vulnerable() {
    size_t len;
    char *buf;

    len = read_int_from_network();
    buf = malloc(len+5);
    read(fd, buf, len);
    ...
}
```

Agenda

- Recap
- Buffer overflow
- Stack smashing
- Format string vul
- Integer conversio
- Recap
- Off-by-one vulnerabilities

Off by one byte can lead to malicious code injection

- < vs <=
- i = 0 vs i = 1

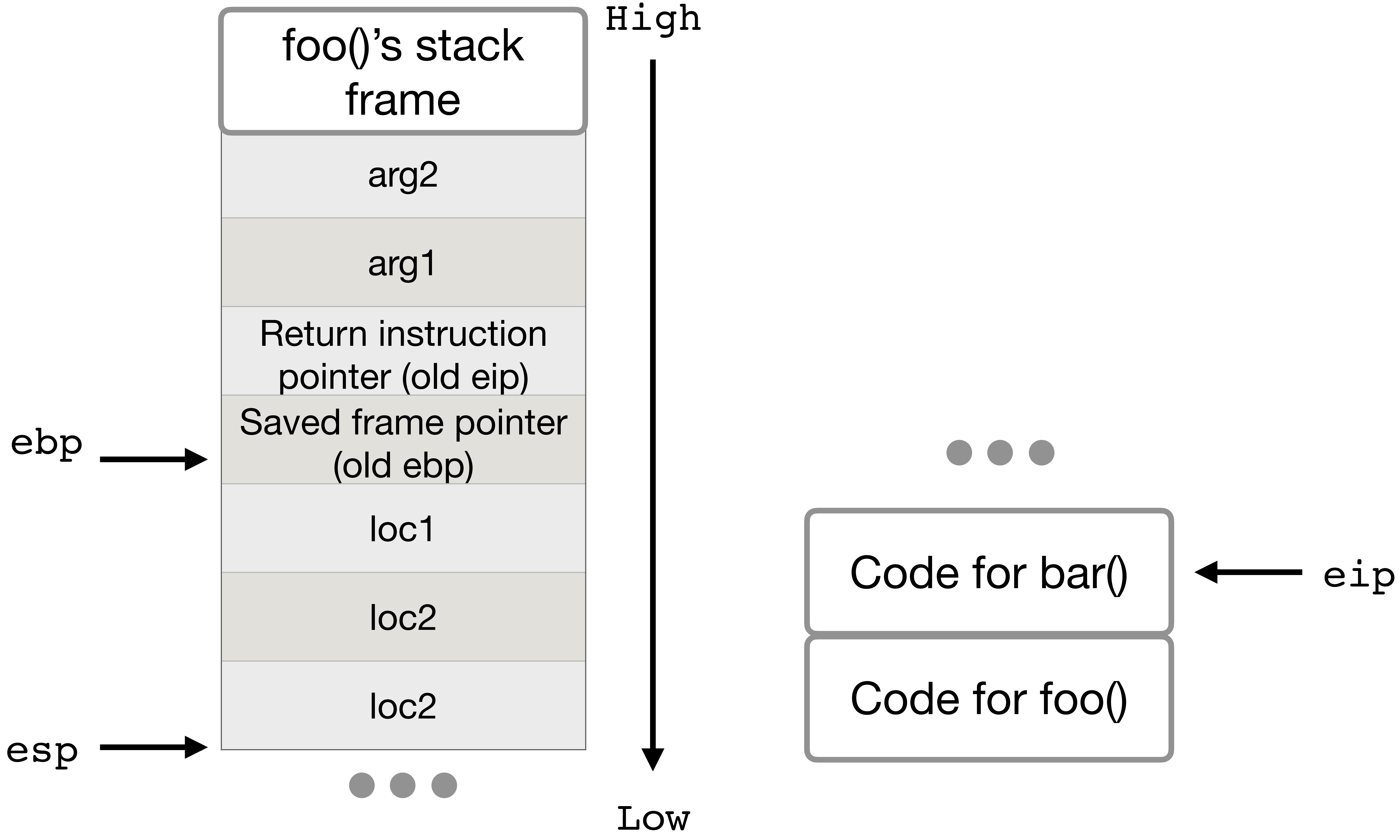
How to make eip point to malicious code?

x86 Assembly Syntax

- This class follows the AT&T x86 syntax, what gdb uses
- mov instruction: the source is the first argument, and the destination is the second argument
  - mov %esp, %ebp
  - take the value in esp and put it in ebp
- Note: if you do research online, you may read Intel syntax where source and destination is reversed

Stack Frames: Return from a Function

```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1,
int arg2) {
    int  loc1;
    long loc2;
    ...
}
```

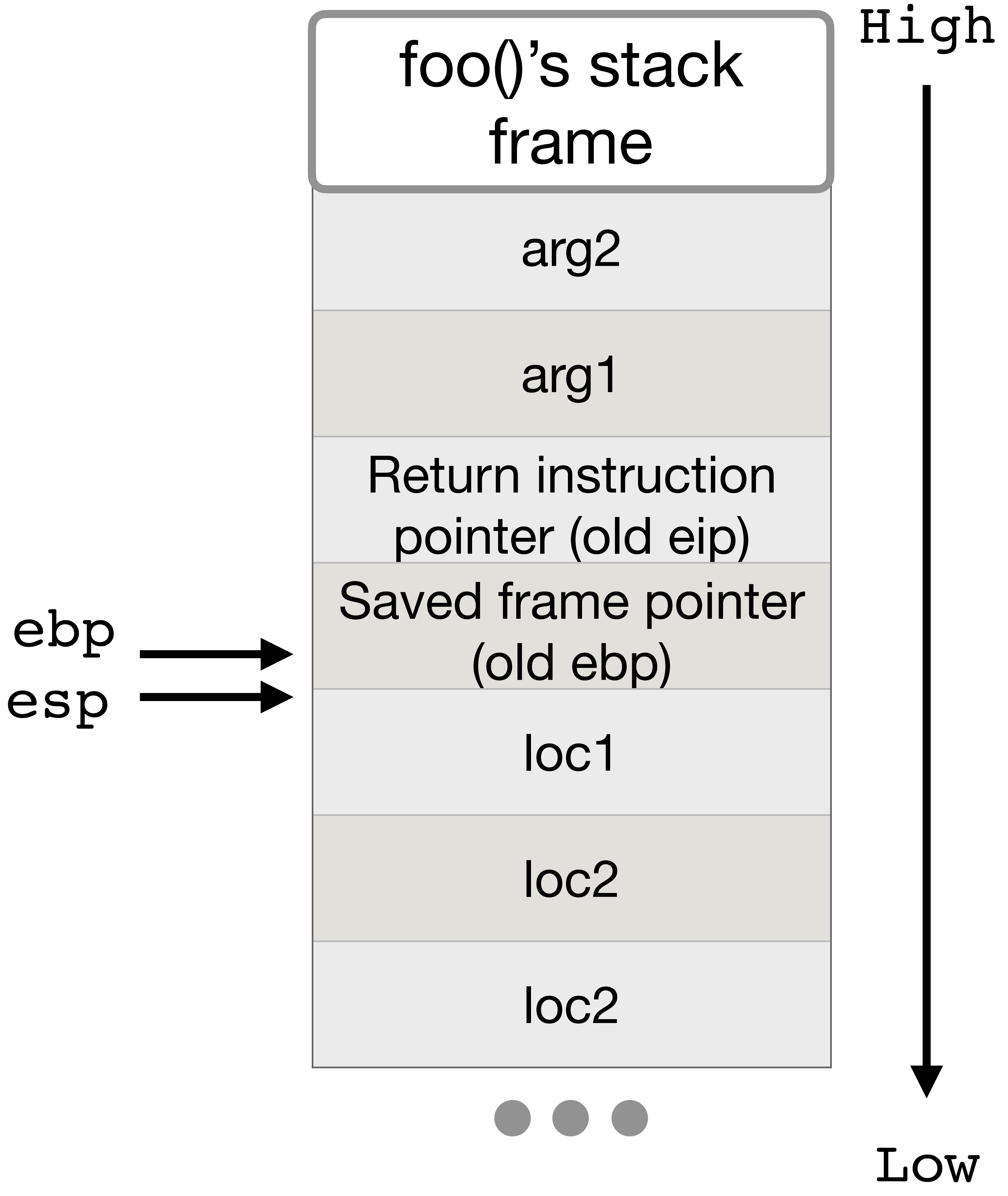


Note:

- Arguments
- Return address
- Saved Frame Pointer
- Local Variables

Stack Frames: Return from a Function

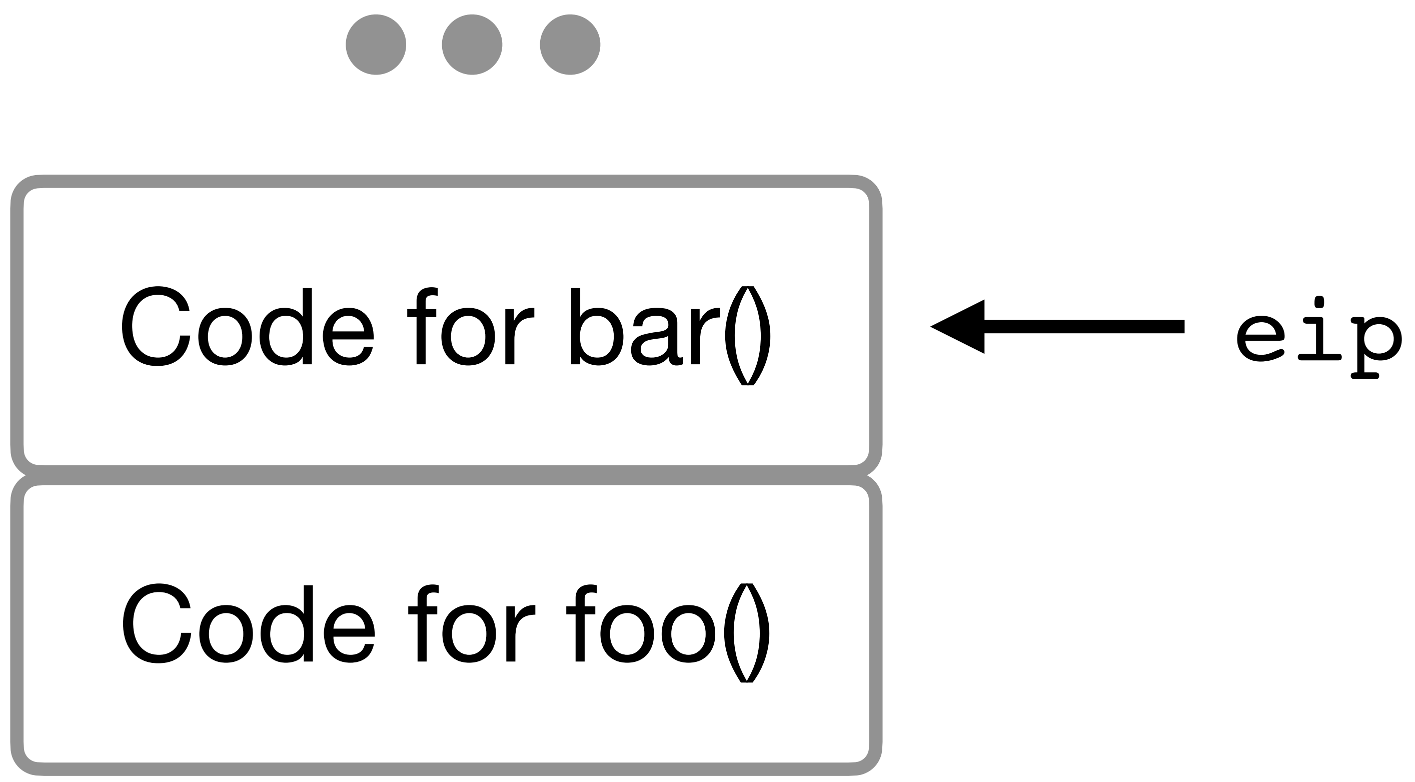
```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1,
int arg2) {
    int  loc1;
    long loc2;
    ...
}
```



foo()'s stack frame
arg2
arg1
Return instruction pointer (old eip)
Saved frame pointer (old ebp)
loc1
loc2
loc2
ebp
esp
High
Low

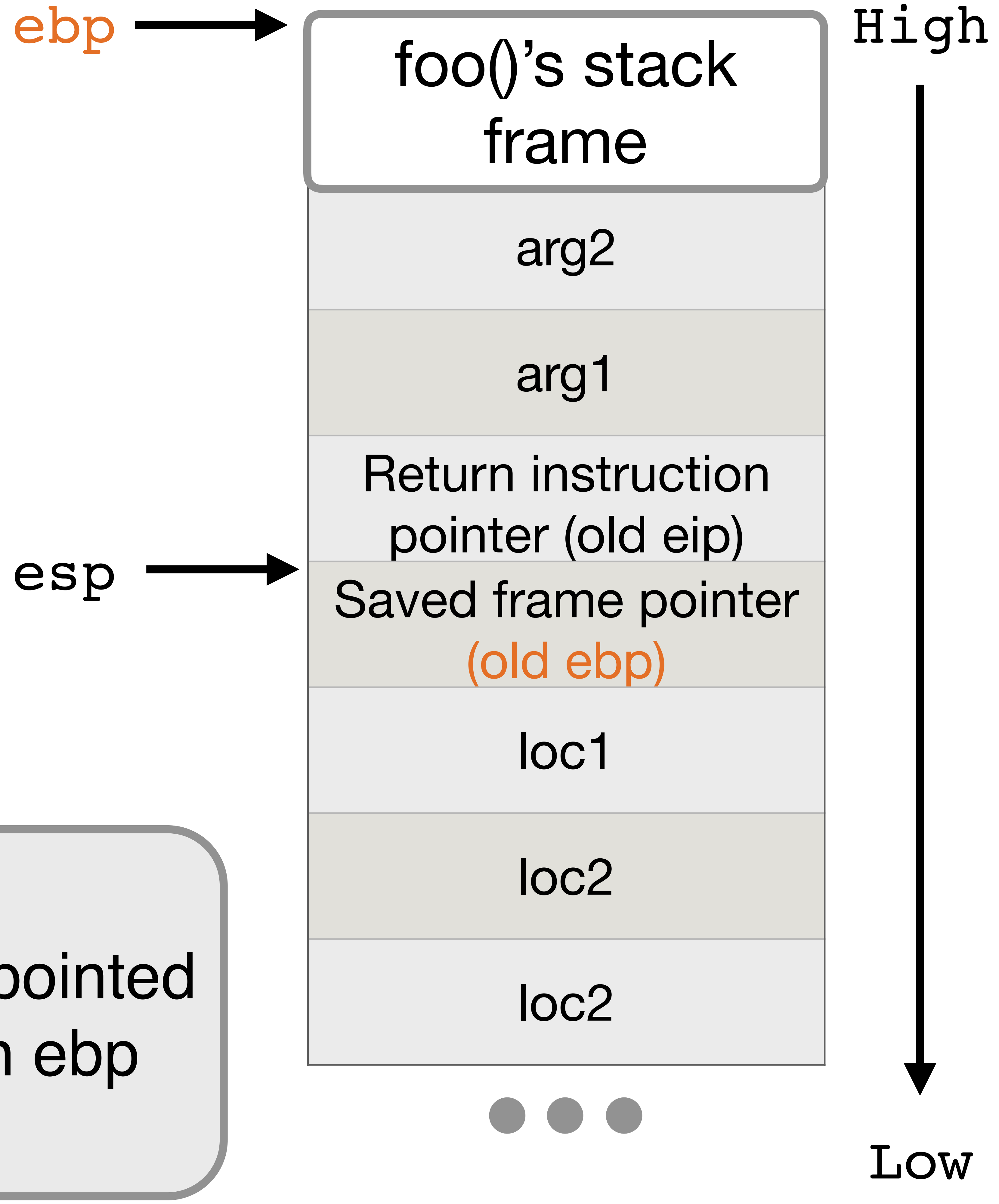
Restore the stack pointer

- **mov %ebp, %esp**



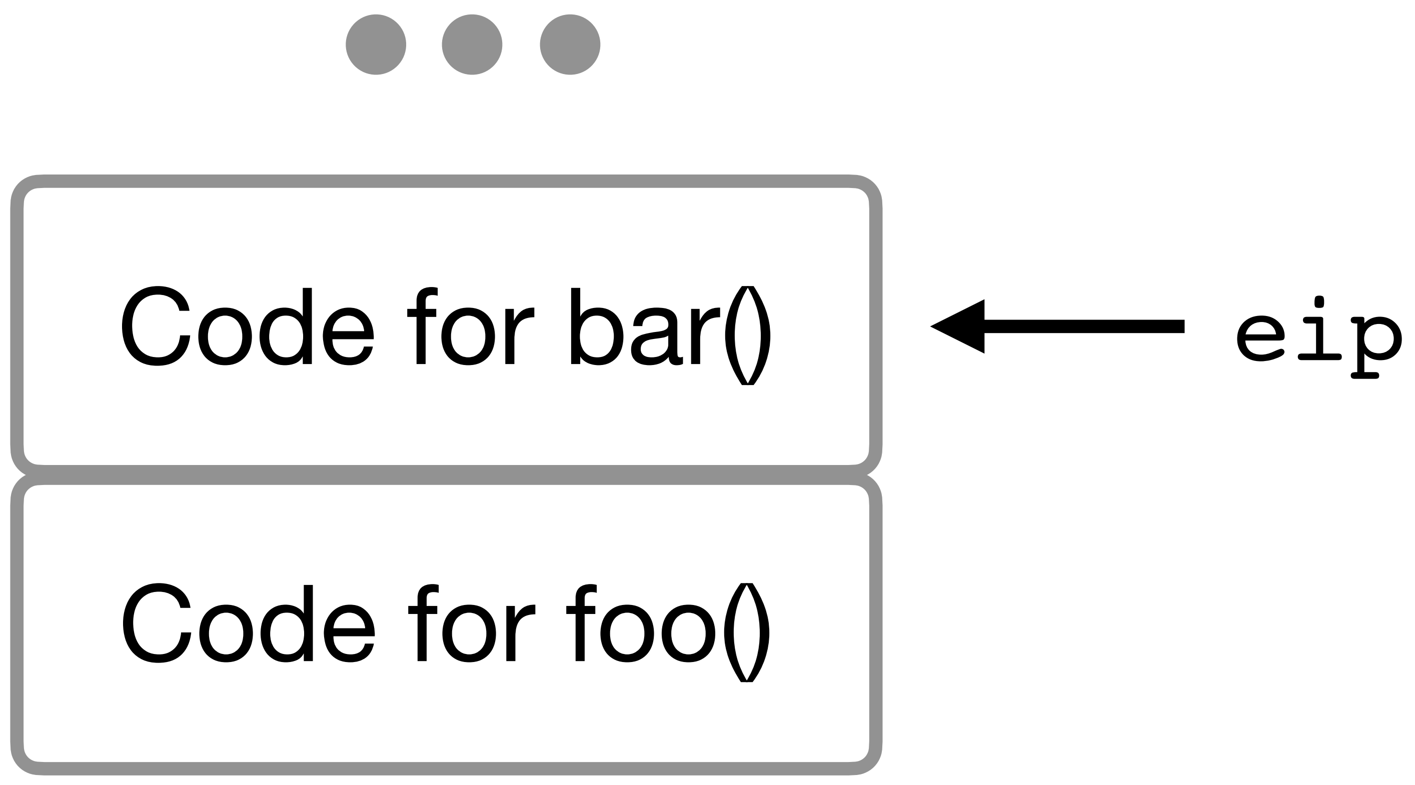
Stack Frames: Return from a Function

```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1,
int arg2) {
    int  loc1;
    long loc2;
    ...
}
```


ebp
esp
foo()'s stack frame
arg2
arg1
Return instruction pointer (old eip)
Saved frame pointer (old ebp)
loc1
loc2
loc2
High
Low

Restore the old ebp

- **pop, %ebp**

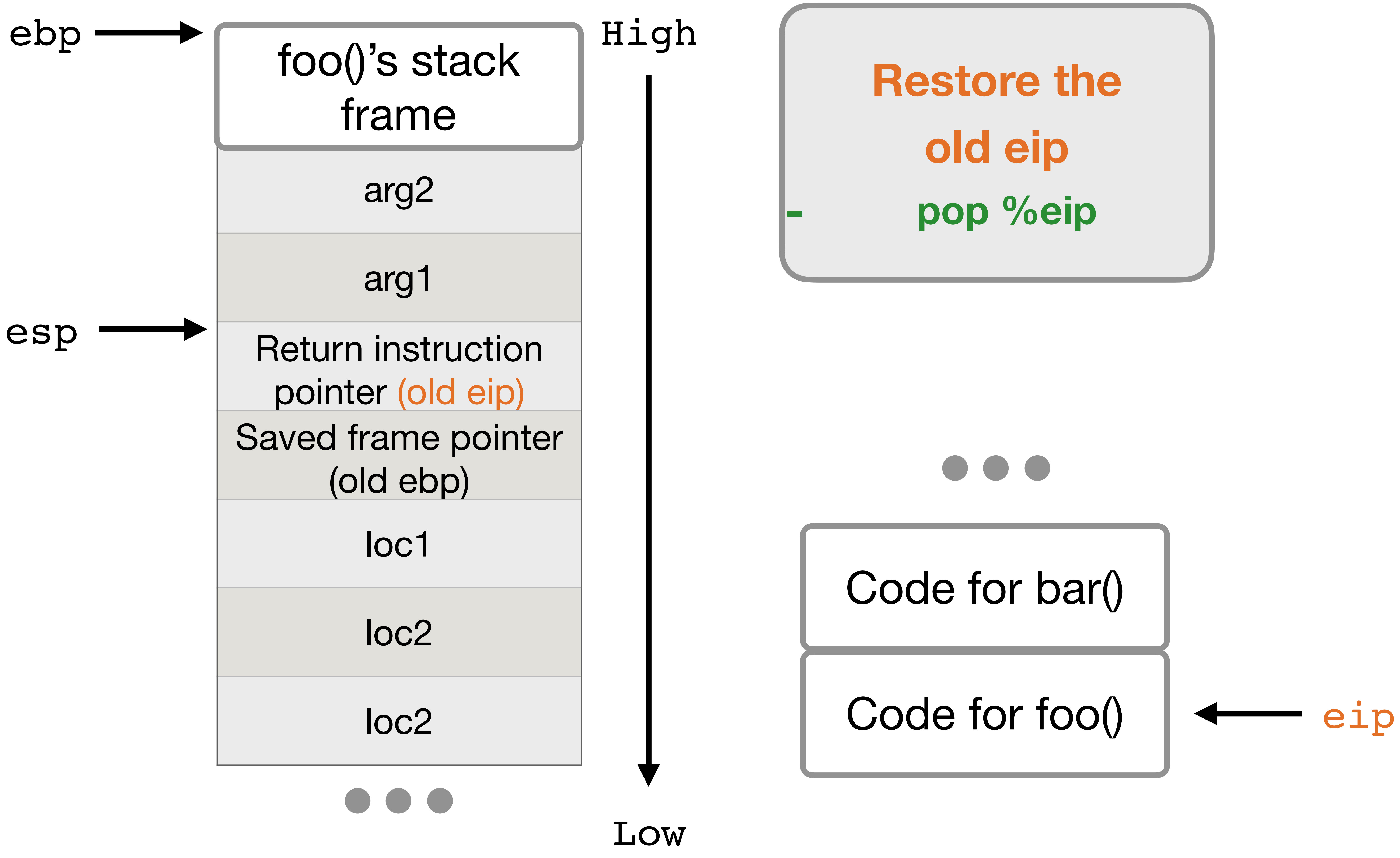


pop %ebp

- Takes the next value on stack (pointed to by esp), store it at destination ebp
- Move esp up by 4 bytes

Stack Frames: Return from a Function

```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1,
int arg2) {
    int  loc1;
    long loc2;
    ...
}
```



ebp

esp

foo()'s stack frame

arg2

arg1

Return instruction pointer (old eip)

Saved frame pointer (old ebp)

loc1

loc2

loc2

High

Low

Restore the old eip

- pop %eip

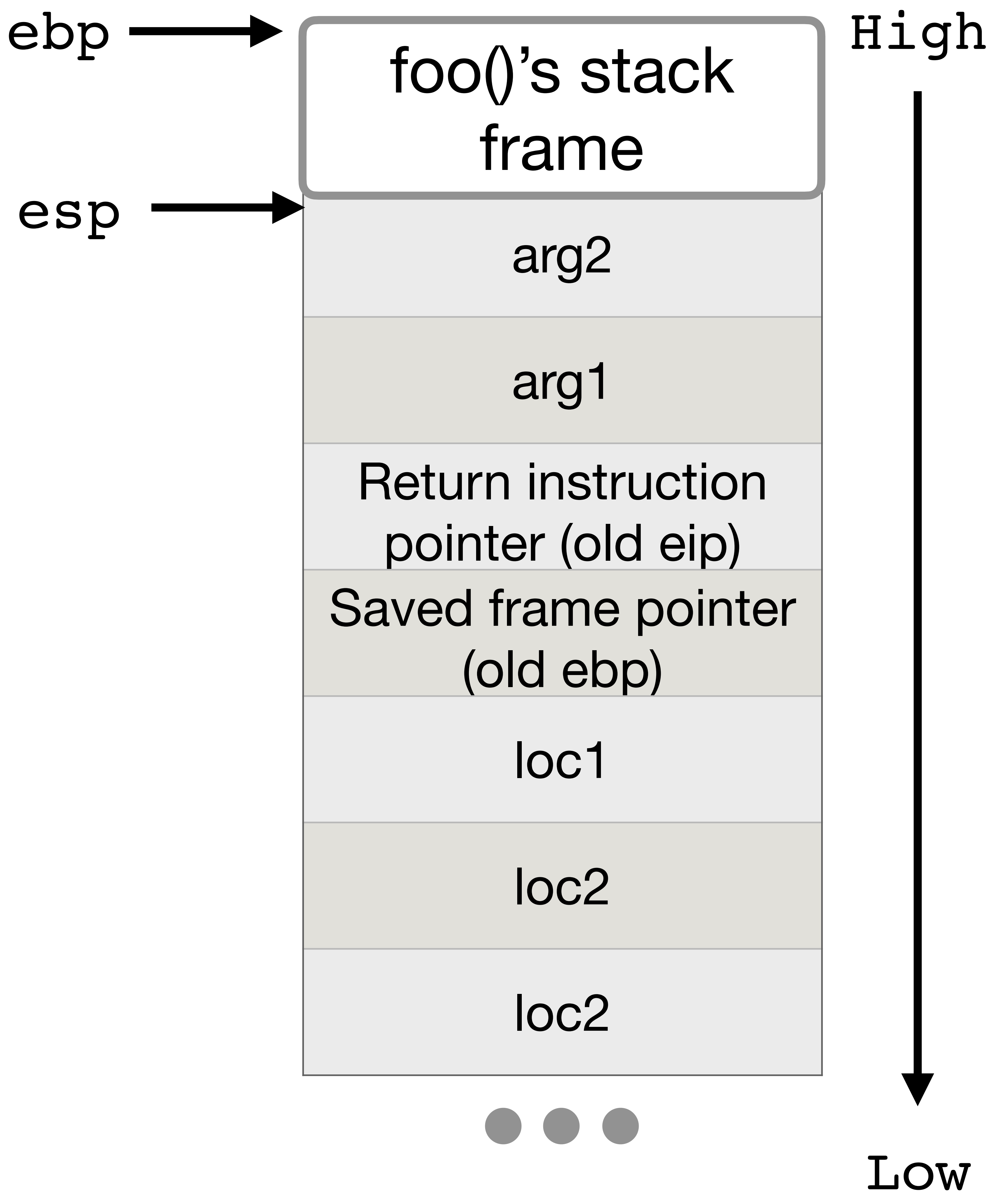
Code for bar()

Code for foo()

eip

Stack Frames: Return from a Function

```
void foo() {
    …
    bar(arg1, arg2);
}

void bar(char *arg1,
int arg2) {
    int  loc1;
    long loc2;
    ...
}
```

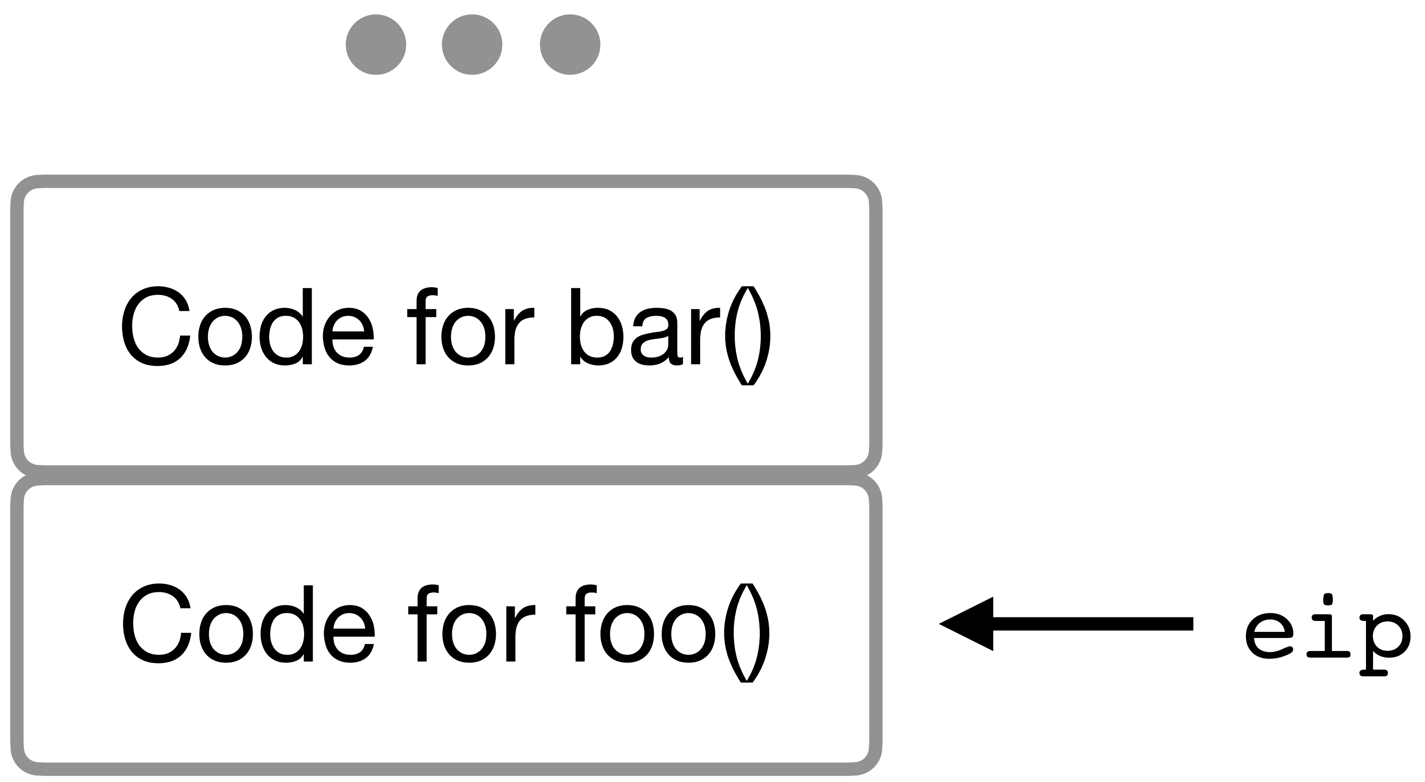


ebp
esp
foo()'s stack frame
arg2
arg1
Return instruction pointer (old eip)
Saved frame pointer (old ebp)
loc1
loc2
loc2
High
Low

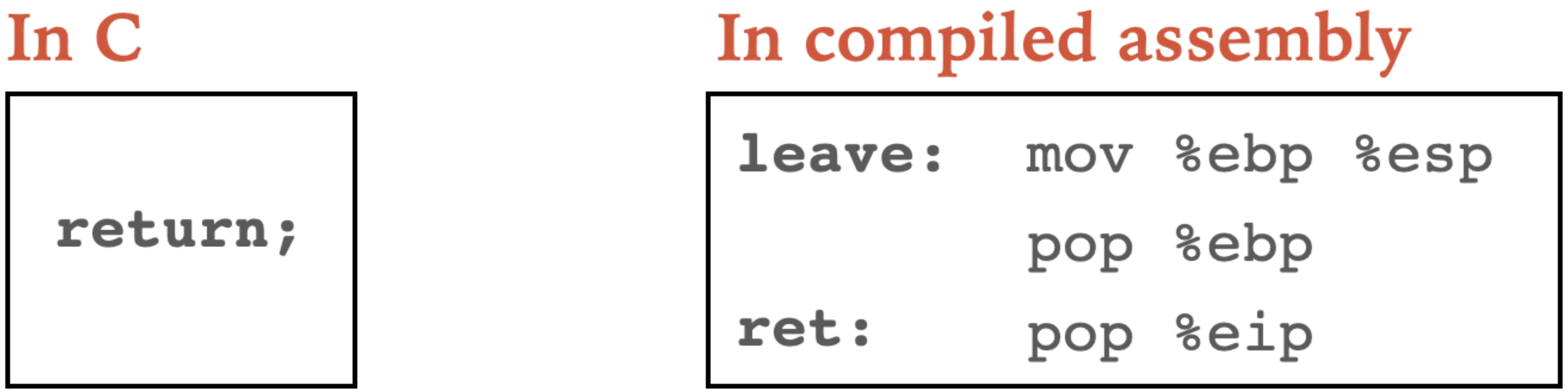
Remove arguments from the stack

- add $8, %esp

- anything below esp is undefined



Return from a Function



In C

```
return;
```

In compiled assembly

```
leave:    mov %ebp %esp
          pop %ebp
ret:      pop %eip
```

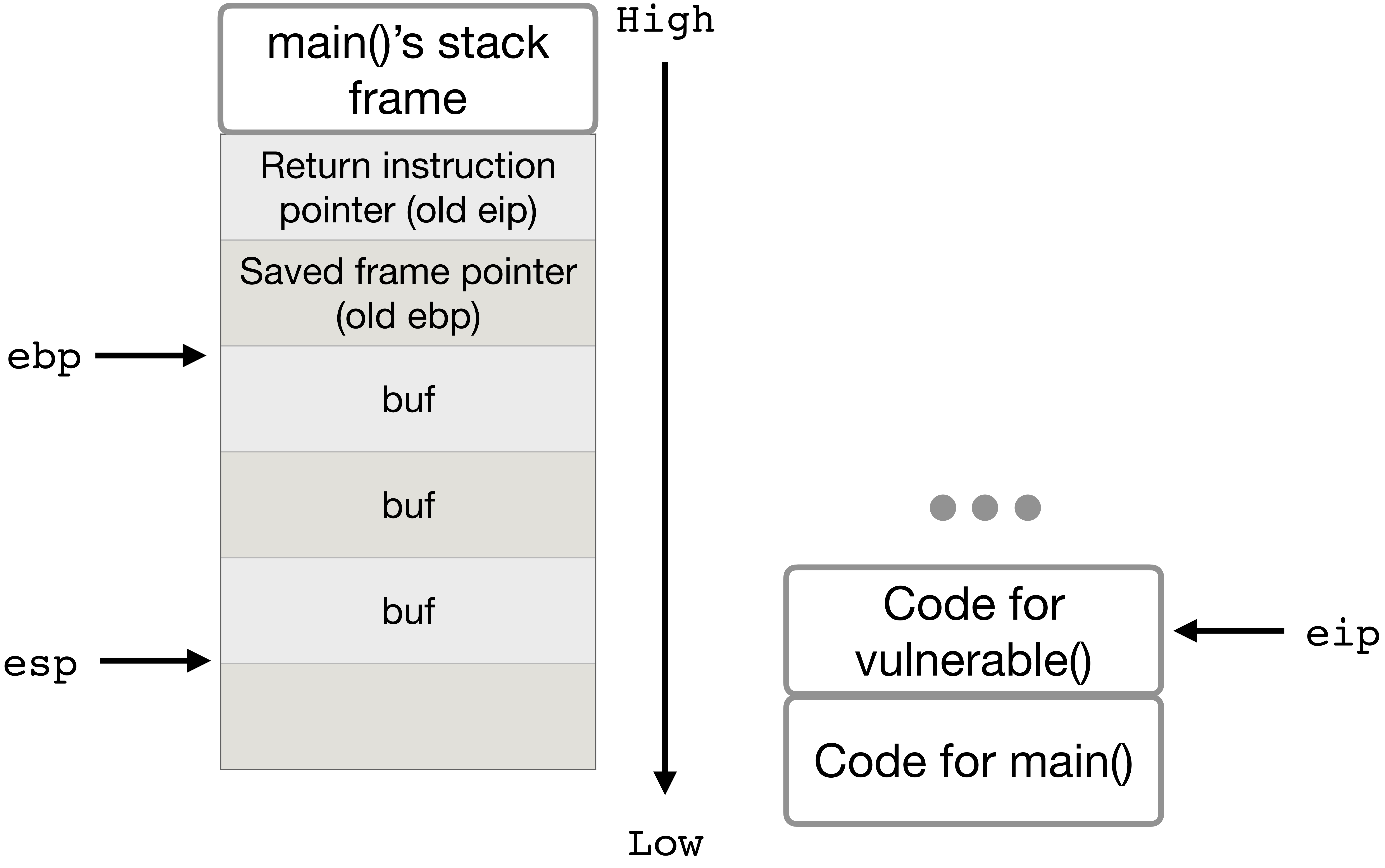
- Leave: leave the stack frame of the callee
  - **restore** the **stack pointer** (mov %ebp %esp)
  - **restore** the **base pointer** (pop %ebp)
- Ret: **restore** the **instruction pointer** (pop %eip)

Great opportunity to make eip point to malicious code

restore the **instruction pointer** (pop %eip)

What if we only overwrite buf by one byte?

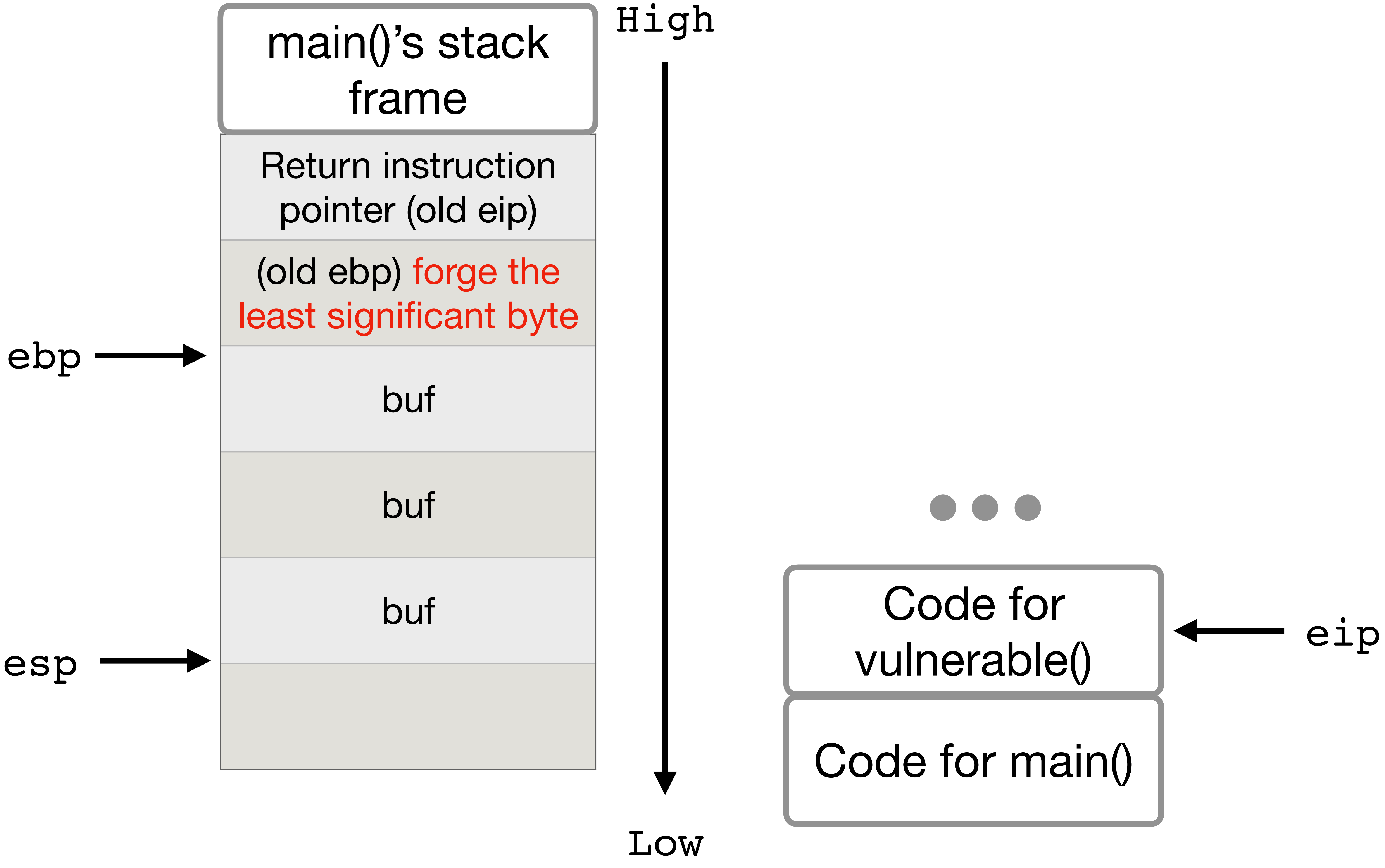
```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```



What if we only overwrite buf by one byte?

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```

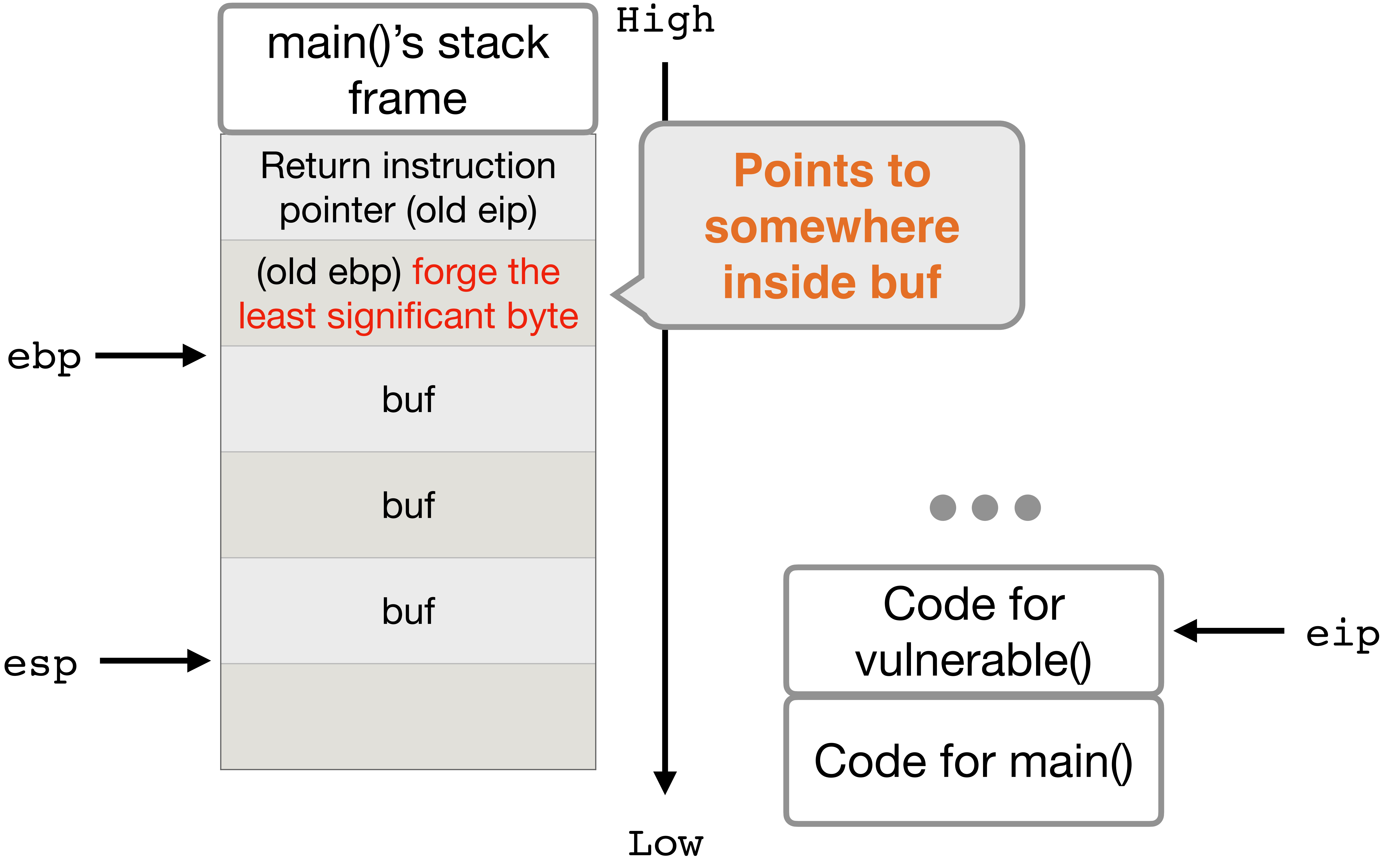
- leave
  - mov %ebp %esp
  - pop %ebp
- ret: pop %eip



What happens during function return?

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```

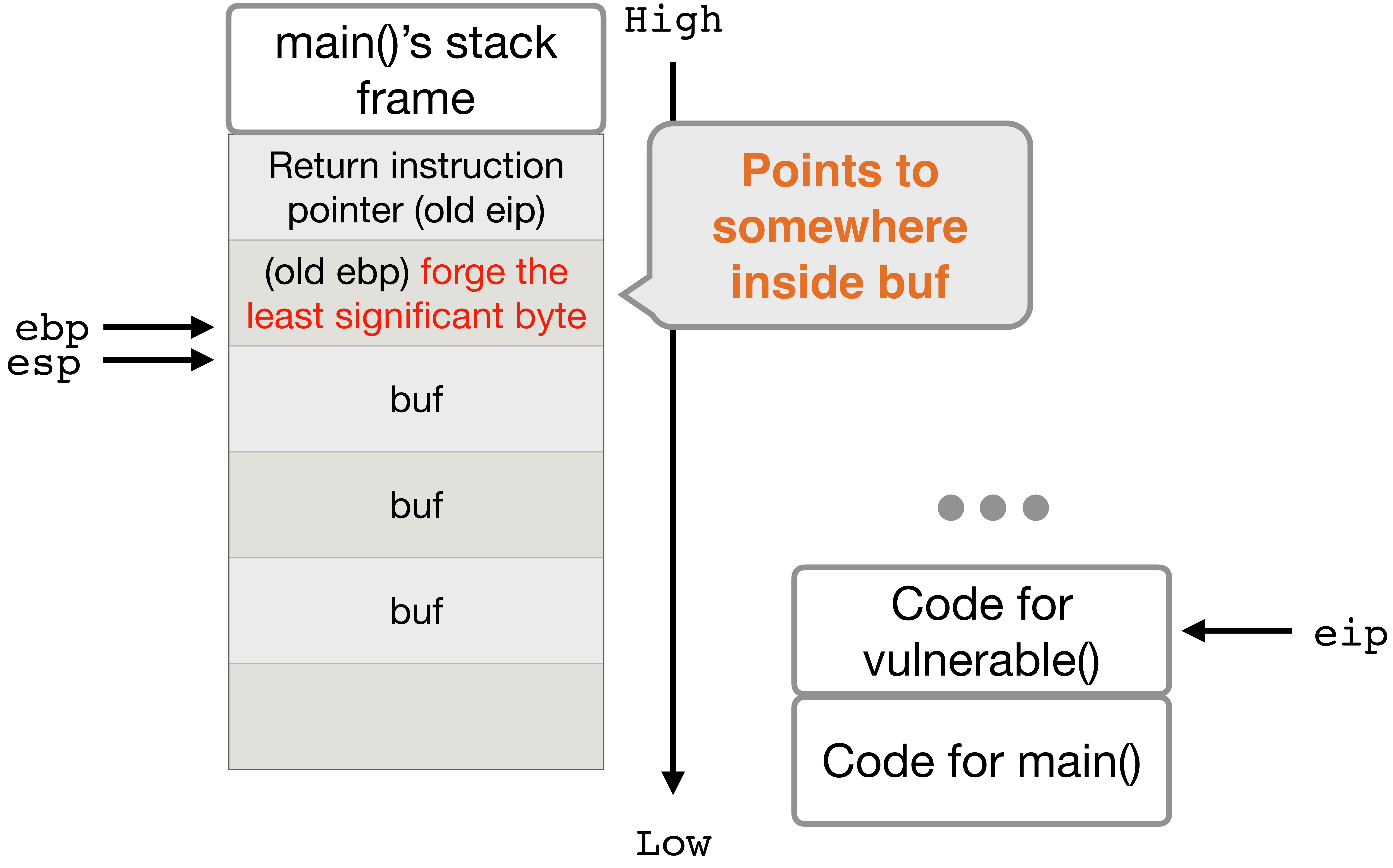
- leave
  - mov %ebp %esp
  - pop %ebp
- ret: pop %eip


main()'s stack frame
Return instruction pointer (old eip)
(old ebp) forge the least significant byte
buf
buf
buf
ebp
esp
High
Low
Points to somewhere inside buf
Code for vulnerable()
Code for main()
eip

Function Return

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```

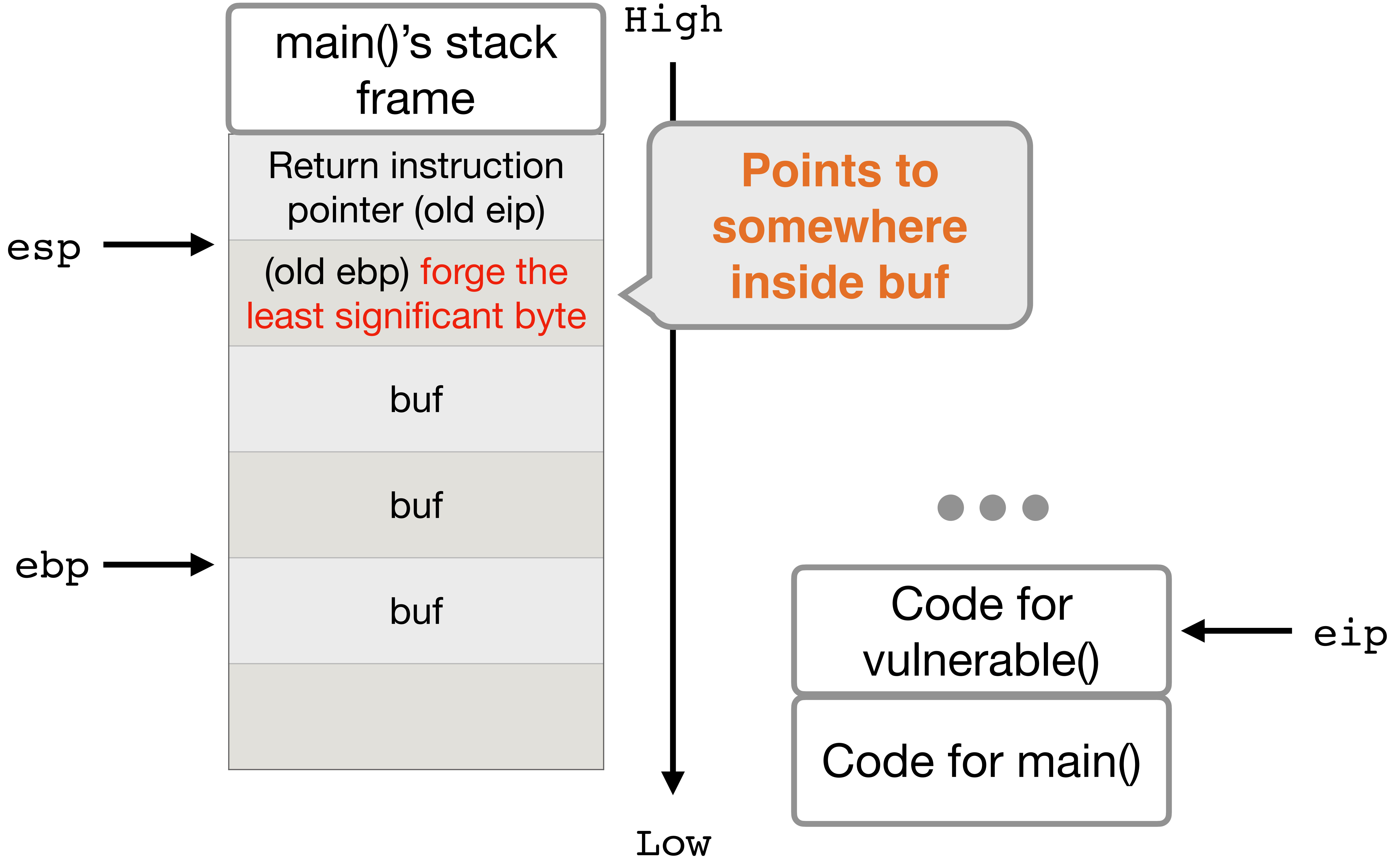
- leave
  - mov %ebp %esp
  - pop %ebp
- ret: pop %eip


main()'s stack frame
Return instruction pointer (old eip)
(old ebp) forge the least significant byte
buf
buf
buf
ebp
esp
High
Low
Points to somewhere inside buf
Code for vulnerable()
Code for main()
eip

Function Return

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```

- leave
  - mov %ebp %esp
  - pop %ebp
- ret: pop %eip



main()'s stack frame

Return instruction pointer (old eip)

(old ebp) forge the least significant byte

buf

buf

buf

esp

ebp

High

Low

Points to somewhere inside buf

Code for vulnerable()

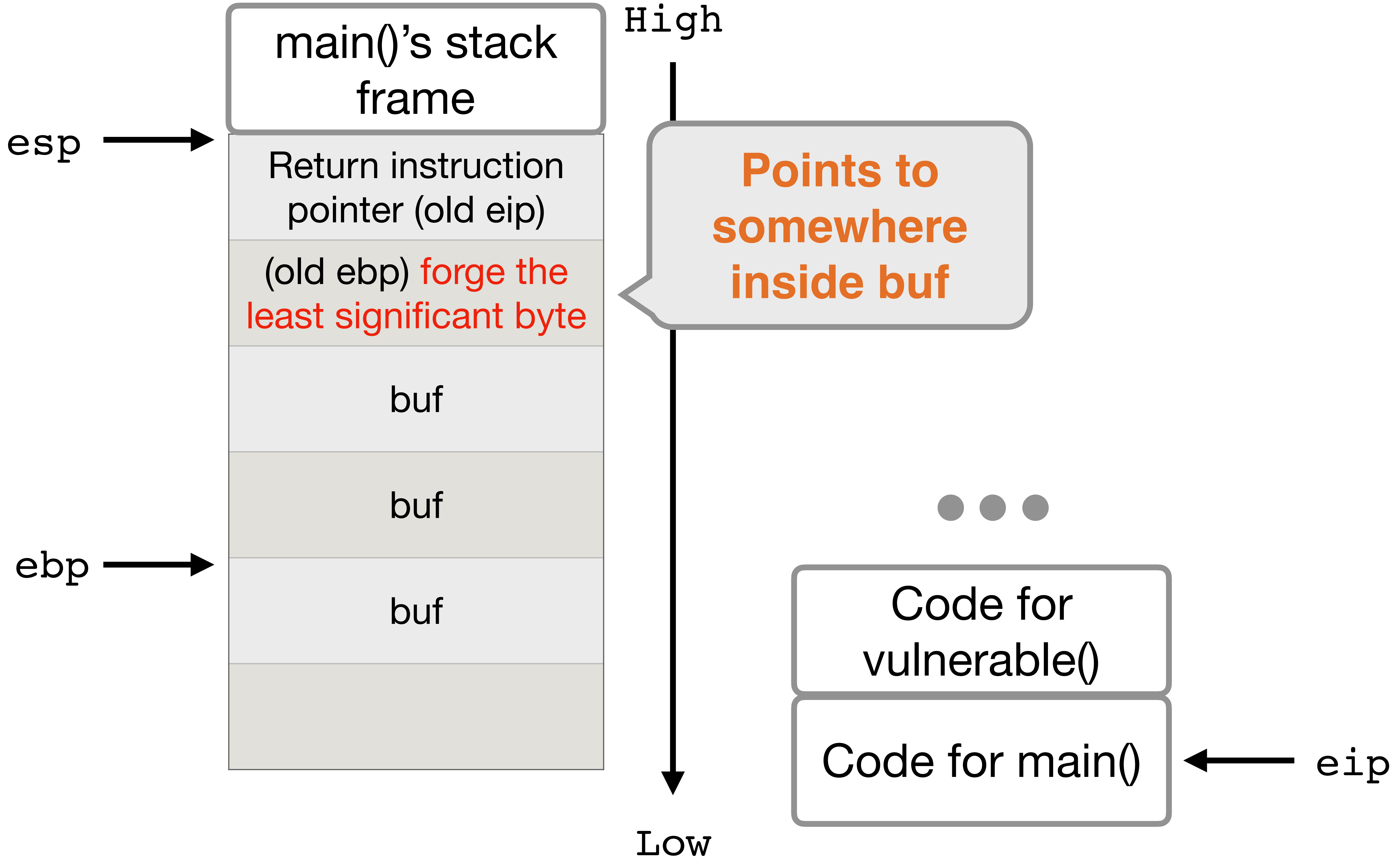
Code for main()

eip

Function Return

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```

- leave
  - mov %ebp %esp
  - pop %ebp
- ret: pop %eip

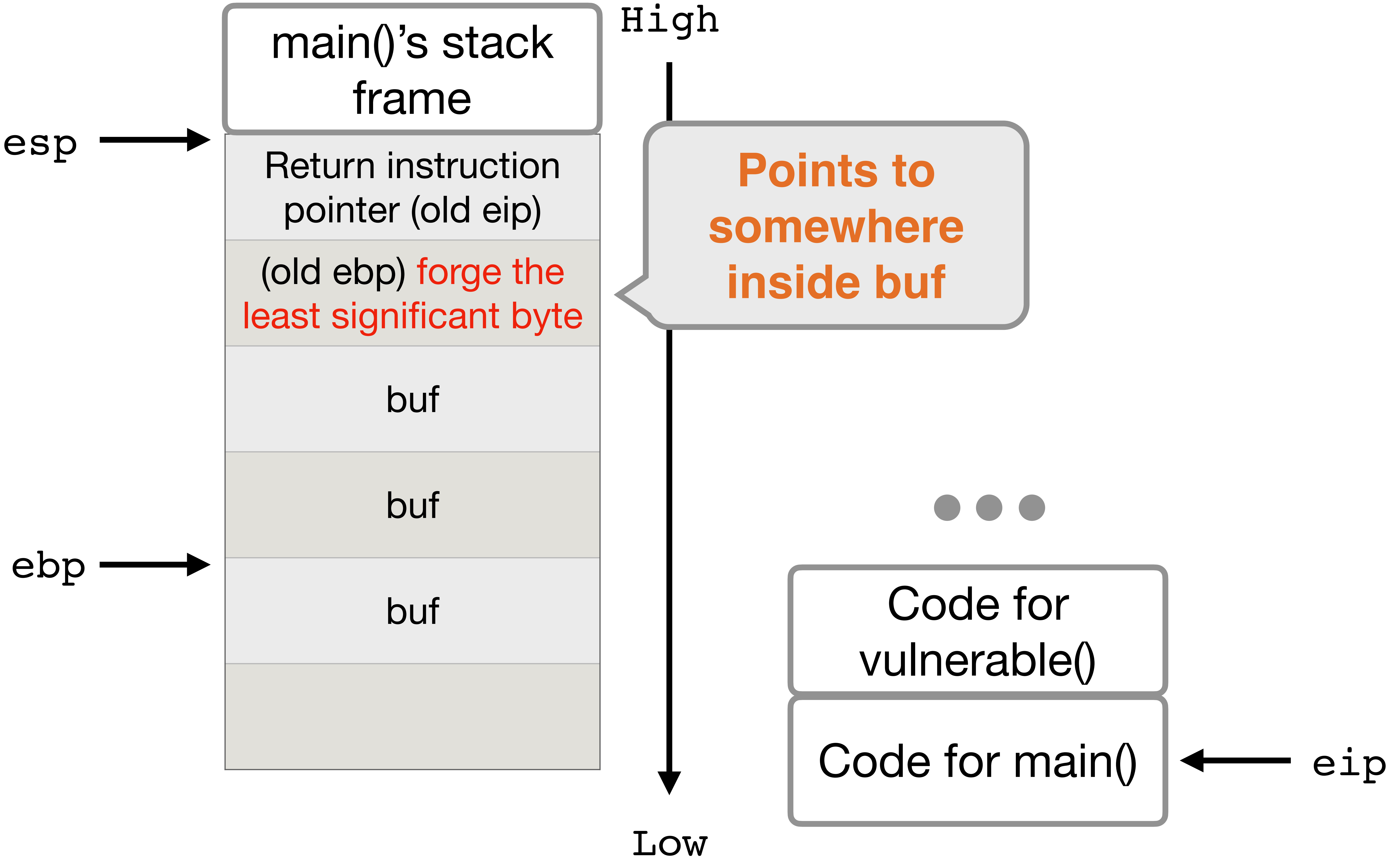


esp
ebp
main()'s stack frame
Return instruction pointer (old eip)
(old ebp) forge the least significant byte
buf
buf
buf
High
Low
Points to somewhere inside buf
Code for vulnerable()
Code for main()
eip

A Second Function Return

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```

- leave
  - mov %ebp %esp
  - pop %ebp
- ret: pop %eip

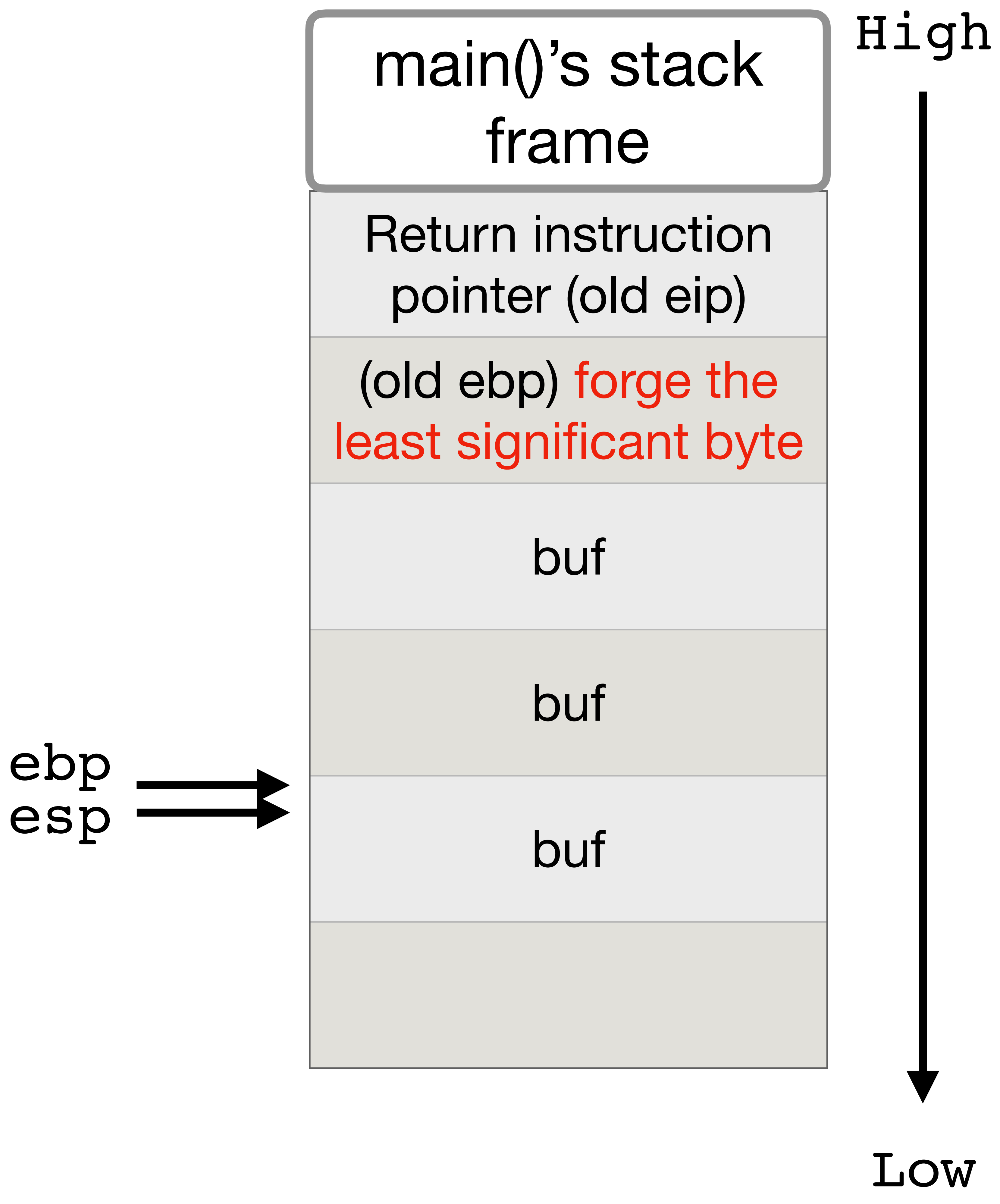


main()'s stack frame
Return instruction pointer (old eip)
(old ebp) forge the least significant byte
buf
buf
buf
esp
ebp
High
Low
Points to somewhere inside buf
• • •
Code for vulnerable()
Code for main()
eip

A Second Function Return

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```

- leave
  - mov %ebp %esp
  - pop %ebp
- ret: pop %eip



main()'s stack frame

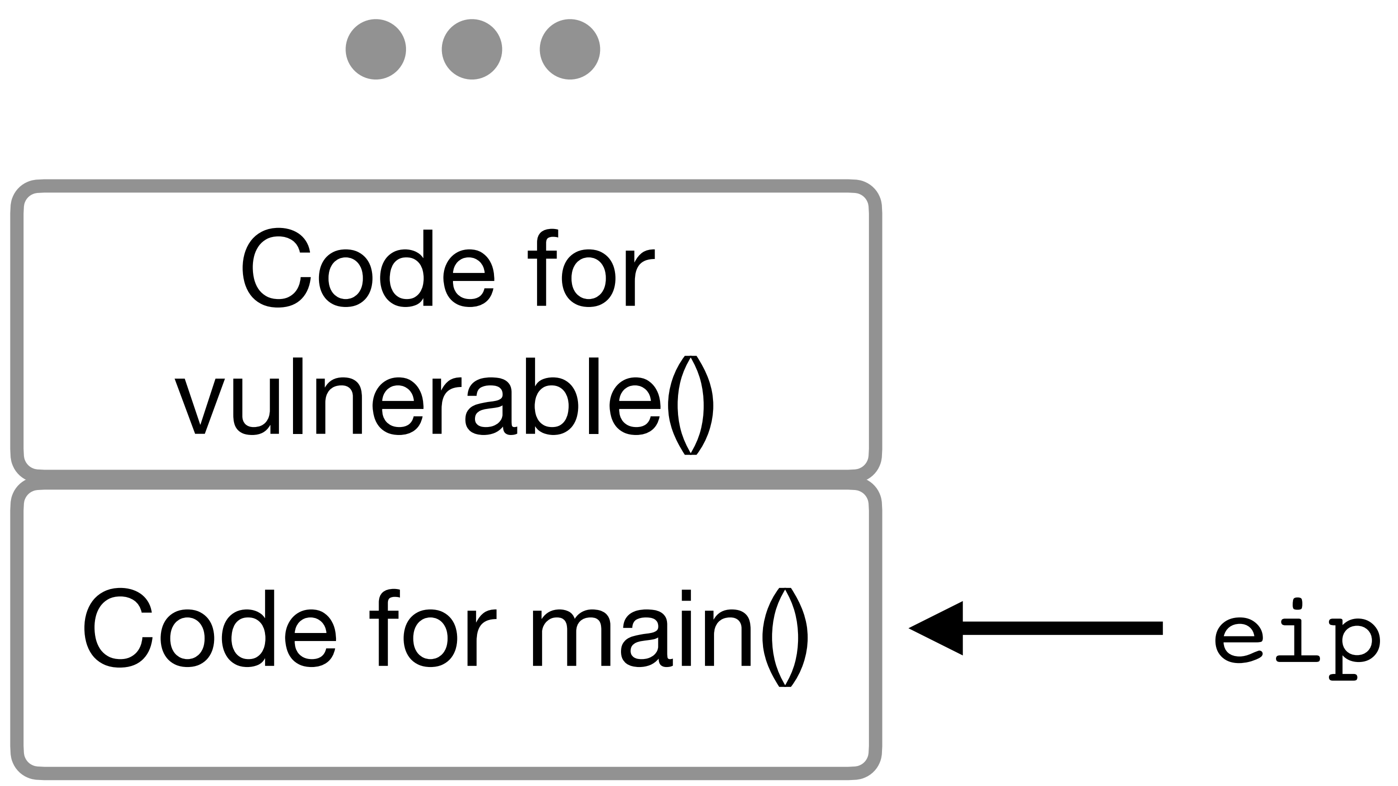
Return instruction pointer (old eip)

(old ebp) forge the least significant byte

buf

buf

buf



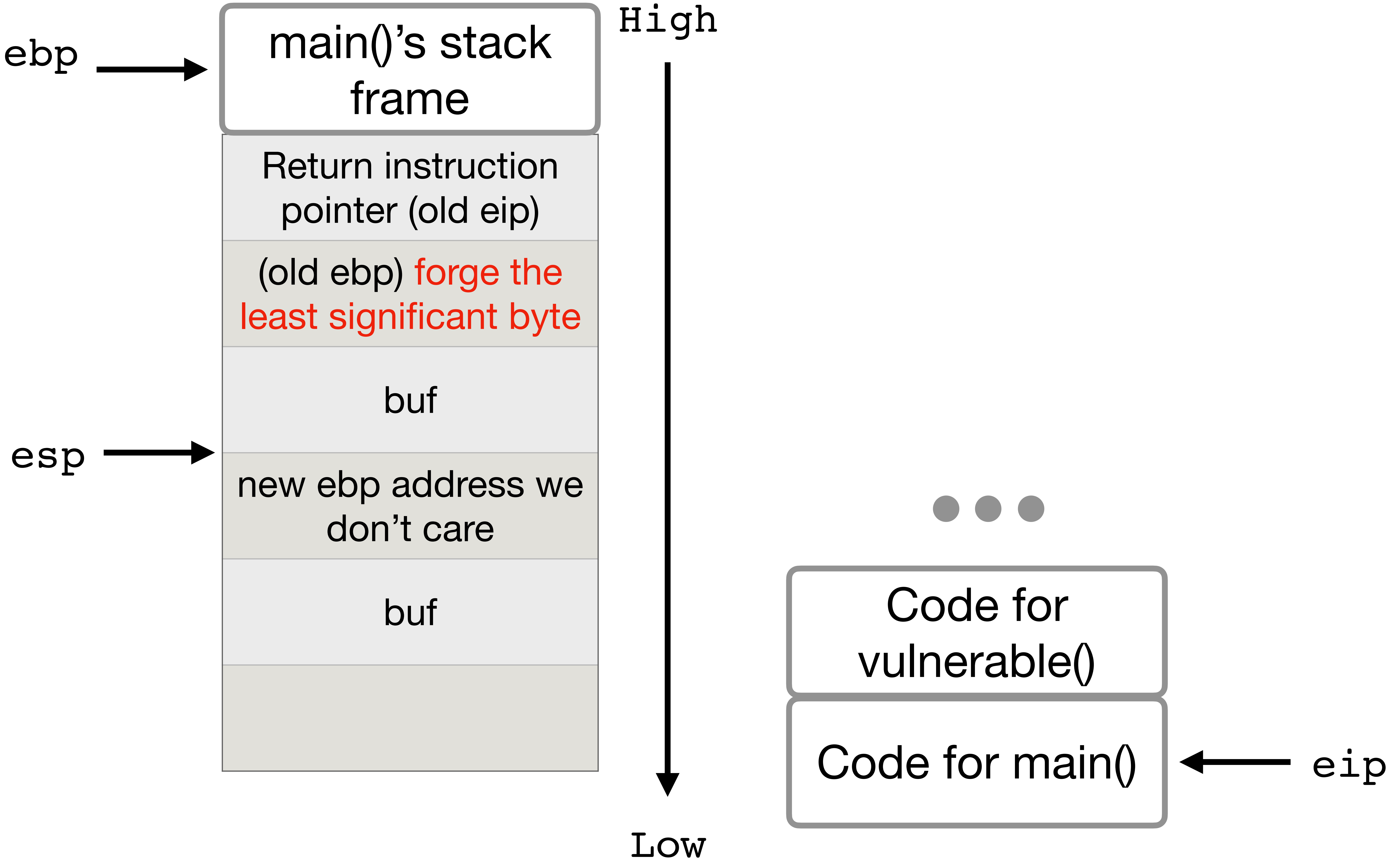
Code for vulnerable()

Code for main()

A Second Function Return

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```

- leave
  - mov %ebp %esp
  - pop %ebp
- ret: pop %eip



ebp

esp

main()'s stack frame

Return instruction pointer (old eip)

(old ebp) forge the least significant byte

buf

new ebp address we don't care

buf

High

Low

Code for vulnerable()

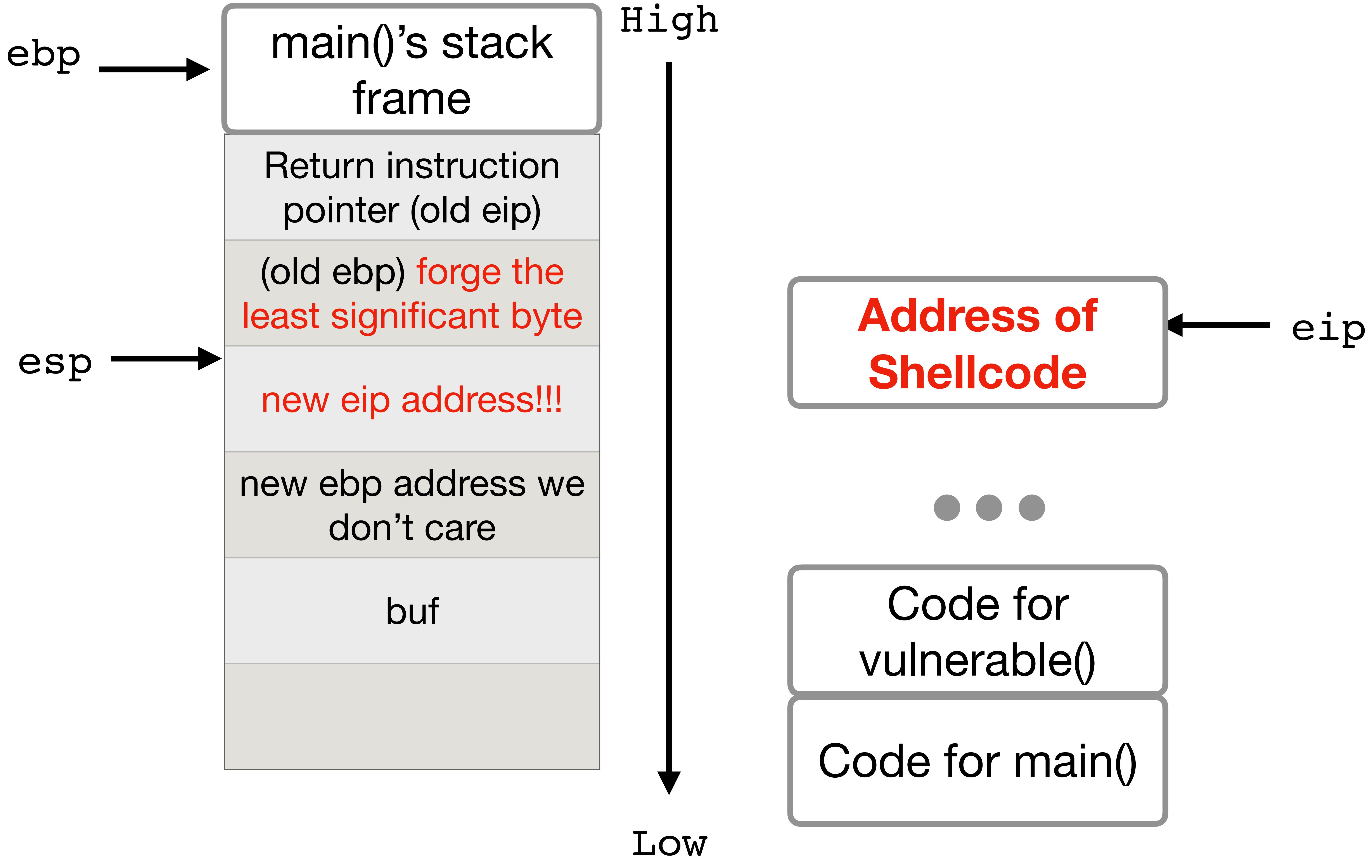
Code for main()

eip

A Second Function Return

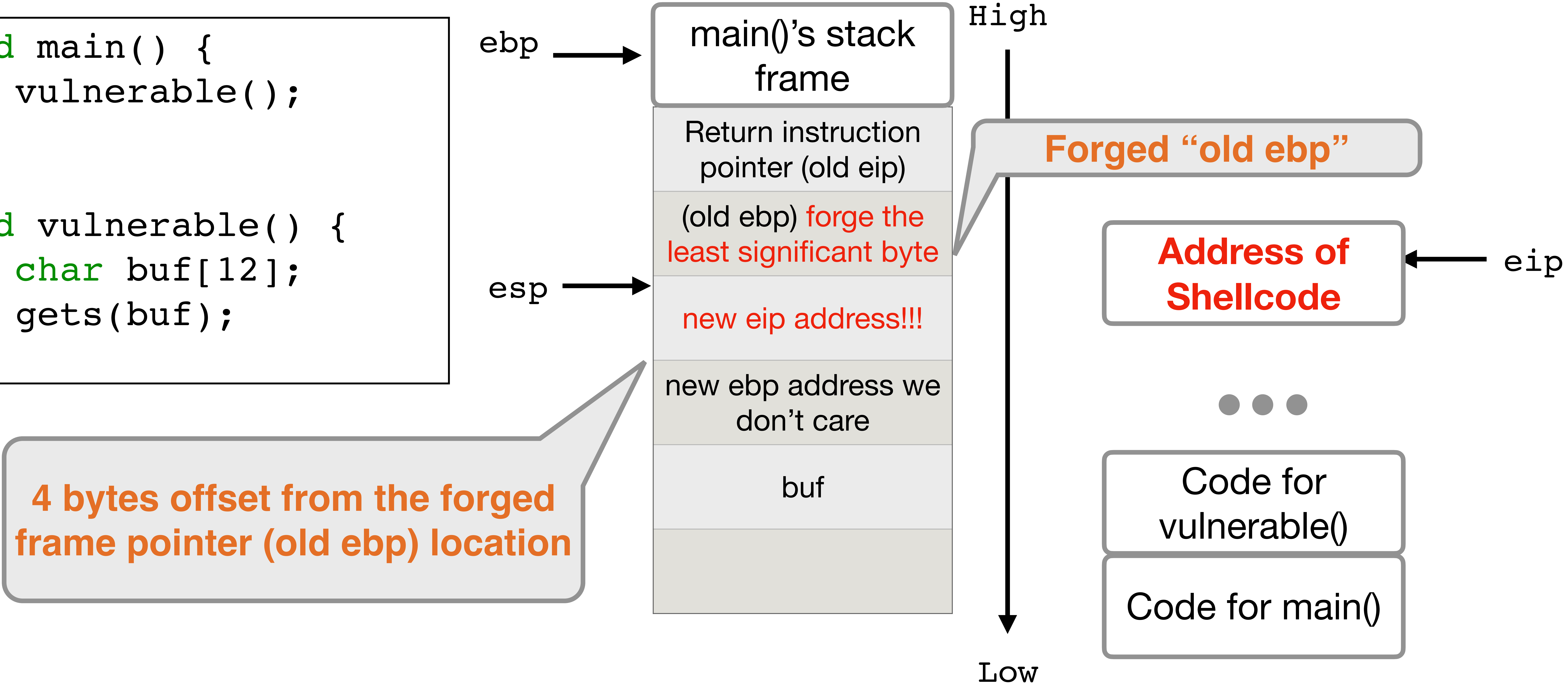
```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```

- leave
  - mov %ebp %esp
  - pop %ebp
- ret: pop %eip



A Second Function Return

```
void main() {
    vulnerable();
}

void vulnerable() {
    char buf[12];
    gets(buf);
}
```



main()'s stack frame

Return instruction pointer (old eip)

(old ebp) forge the least significant byte

new eip address!!!

new ebp address we don't care

buf

Forged "old ebp"

4 bytes offset from the forged frame pointer (old ebp) location

Address of Shellcode

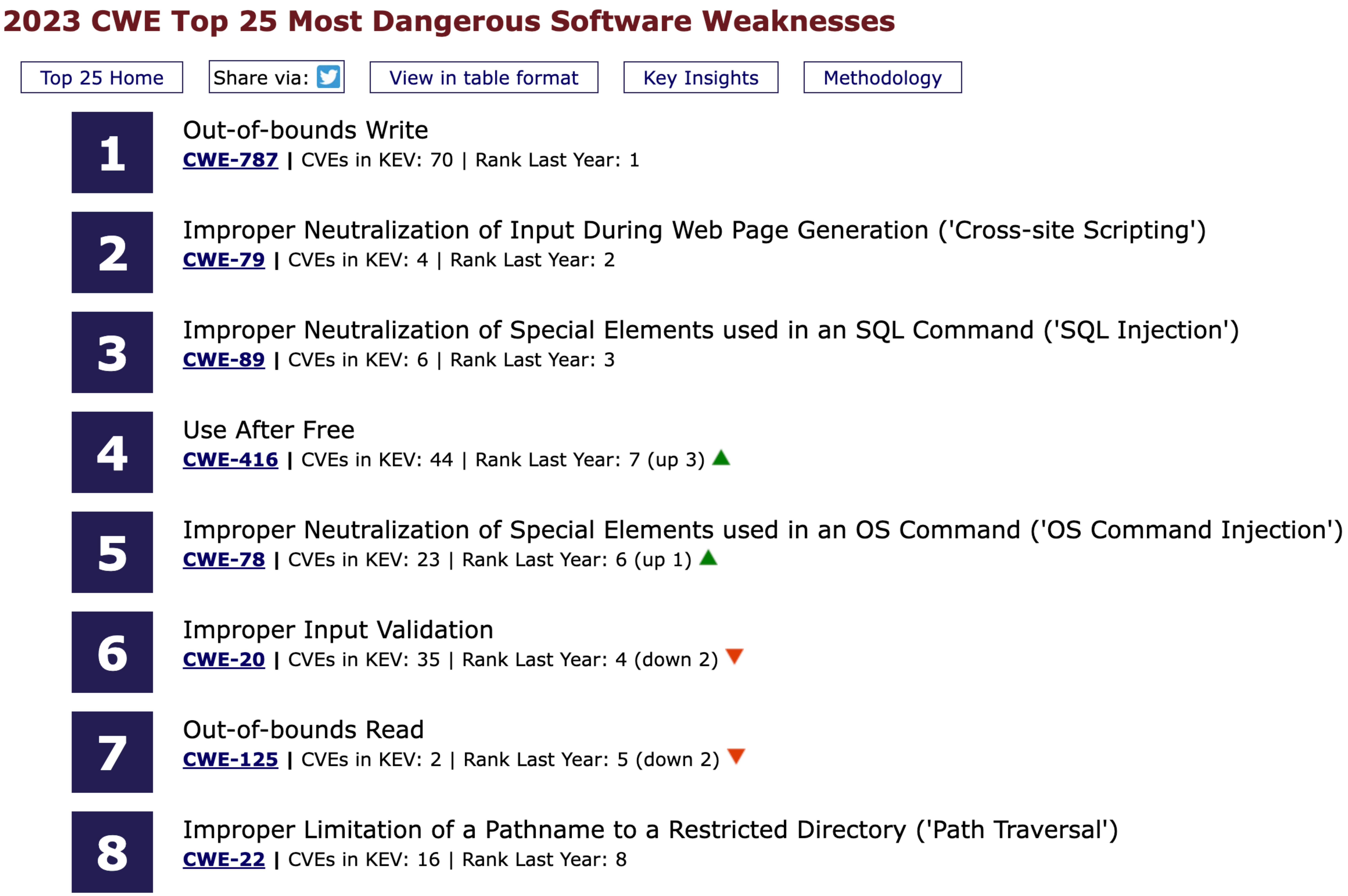
• • •

Code for vulnerable()

Code for main()

Other Memory Safety Vulnerabilities

- Use after free
- Heap overflow
- …



2023 CWE Top 25 Most Dangerous Software Weaknesses

1 Out-of-bounds Write
CWE-787 | CVEs in KEV: 70 | Rank Last Year: 1

2 Improper Neutralization of Input During Web Page Generation ('Cross-site Scripting')
CWE-79 | CVEs in KEV: 4 | Rank Last Year: 2

3 Improper Neutralization of Special Elements used in an SQL Command ('SQL Injection')
CWE-89 | CVEs in KEV: 6 | Rank Last Year: 3

4 Use After Free
CWE-416 | CVEs in KEV: 44 | Rank Last Year: 7 (up 3) ▲

5 Improper Neutralization of Special Elements used in an OS Command ('OS Command Injection')
CWE-78 | CVEs in KEV: 23 | Rank Last Year: 6 (up 1) ▲

6 Improper Input Validation
CWE-20 | CVEs in KEV: 35 | Rank Last Year: 4 (down 2) ▼

7 Out-of-bounds Read
CWE-125 | CVEs in KEV: 2 | Rank Last Year: 5 (down 2) ▼

8 Improper Limitation of a Pathname to a Restricted Directory ('Path Traversal')
CWE-22 | CVEs in KEV: 16 | Rank Last Year: 8

https://cwe.mitre.org/top25/archive/2023/2023_top25_list.html