Buffer Overflow

Attacker Goal

- Take over target machine (such as a web server)
  - Execute arbitrary *(bad)* code on target by altering application control flow

- Examples:
  - Buffer overflows ← Today
  - Format string vulnerability
  - Other hijacking attacks (e.g., Integer overflow)

Buffer Overflows

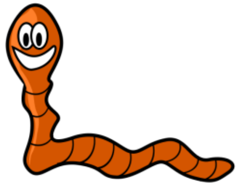
- Result from mistakes in memory management when writing code
  - very common *coding flaws* because C functions are exposed to memory management
    - Common even from experienced programmers!
- They often happen in programs written in C/C++
  - Why?
  - Why not in programs written with other languages such as Java or Go?

Buffer overflows are common in languages/runtimes that let programmers manage the memory

Buffer Overflows

- One of the most used attack techniques
- From attacker perspective:

  - Pros
    - very effective: attack code runs with privileges of exploited process
    - can be exploited locally and remotely
  - Cons
    - Architecture-dependent: inject bytecode
    - OS-dependent: use of system calls
    - guesswork involved (correct addresses)

History: Morris Worm 

- Released in 1988 by Robert Morris
  - Grad student at Cornell
  - First felony conviction in the US under cybersecurity law
  - Now a professor at MIT
- Unintentional harm:
  - Worm was intended to propagate slowly and harmlessly measure the size of the Internet
- Due to a coding error, it created new copies as fast as it could and overloaded infected machines
- $10-100M worth of damage

History: Morris Worm and Buffer Overflow

- One of the propagation techniques was a buffer overflow attack against a vulnerable version of `fingerd` on VAX systems
  - By sending special string to finger daemon, worm caused it to execute code creating a new worm copy

```
> char buffer[512];
> gets(buffer);
```

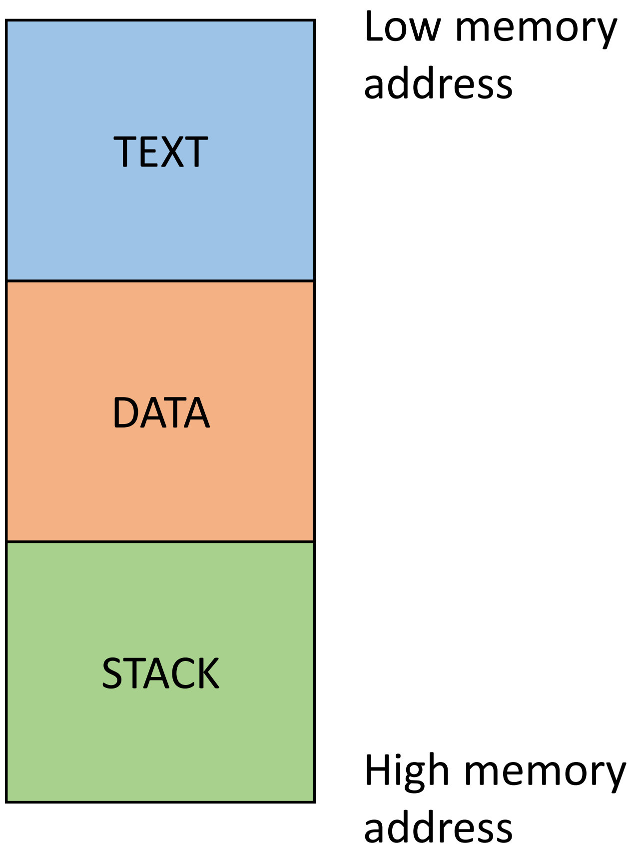
Recent Incidents

- WhatsApp
- “…the phone starts revealing its encrypted content, mirrored on a computer screen halfway across the world. It then transmits back the most intimate details such as private messages and location, and even turns on the camera and microphone to live-stream meetings.”
- The vulnerability was reported as a buffer overflow bug.
- Vulnerabilities reported as “memory corruption”, or “memory safety” are often buffer overflow bugs

https://www.ft.com/content/7f2f39b2-733e-11e9-bf5c-6eeb837566c5

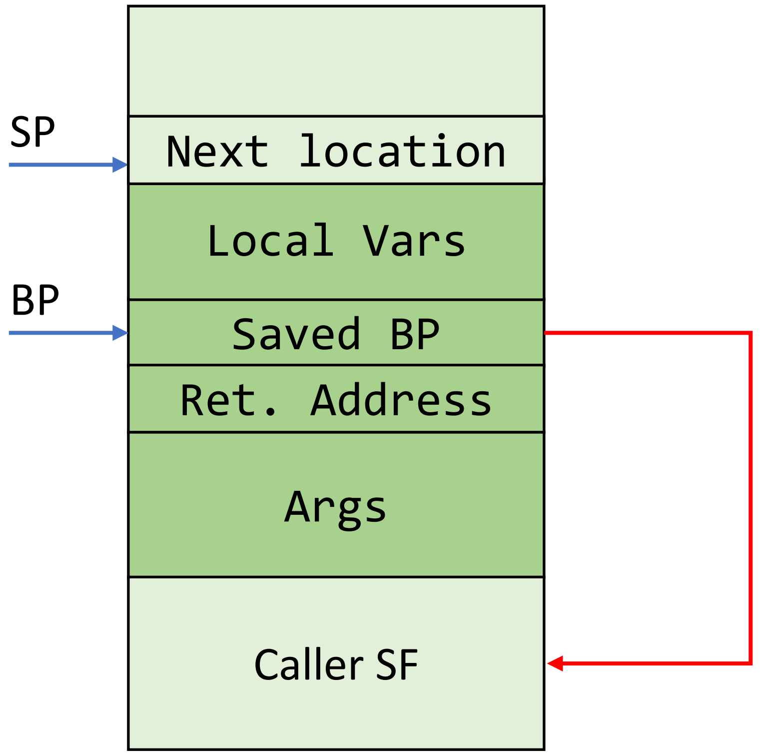
Recall: Process Memory Organization

- A process is divided into three regions.
- Text
  - Fixed region
  - Includes instructions and Read-only data
- Data
  - Initialized and uninitialized data
  - Dynamic vars (heap)
- Stack (LIFO abstraction)
  - Maintains state of caller/callee of functions
  - Used for storing:
    - Local variables
    - Parameters
    - Return value



Overflow Types

- Overflow memory region on the stack
  - overflow function return address
  - overflow function base pointer
- Overflow (dynamically allocated) memory region on the heap
- Overflow function pointers



We will focus on Stack Buffer Overflow

Stack Region: Function Call

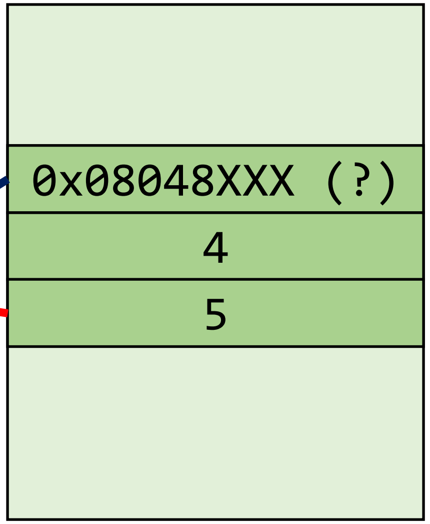
```
int func(int a, int b) {
        int i = 3;
        return (a+b)*i;
}

int main() {
        int result = 0;
        result = func(4, 5);
        printf("%d\n", result);
}
```

3
Saved BP
Ret. Address
4
5

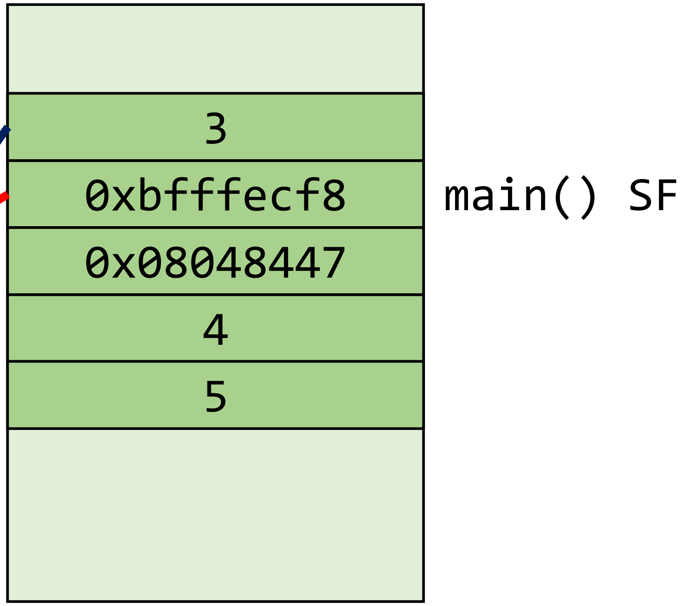
func() Stack Frame

A Closer Look

```
gdb-peda$ disas main
Dump of assembler code for function main:
   0x08048426 <+0>:     lea    ecx,[esp+0x4]
   0x0804842a <+4>:     and    esp,0xfffffff0
   0x0804842d <+7>:     push   DWORD PTR [ecx-0x4]
   0x08048430 <+10>:    push   ebp
   0x08048431 <+11>:    mov    ebp,esp
   0x08048433 <+13>:    push   ecx
   0x08048434 <+14>:    sub    esp,0x14
   0x08048437 <+17>:    mov    DWORD PTR [ebp-0xc],0x0
   0x0804843e <+24>:    push   0x5
   0x08048440 <+26>:    push   0x4
   0x08048442 <+28>:    call   0x804840b <func>
   0x08048447 <+33>:    add    esp,0x8
```

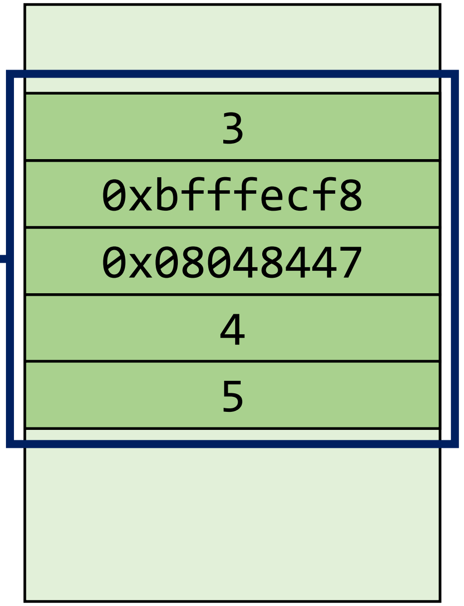


```
gdb-peda$ break func
Breakpoint 1 at 0x8048411
gdb-peda$ run
Starting program: /home/seed/CMPT_479_980/stack_ex
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib/i386-linux-gnu/l

[----------------------------------registers----------
EAX: 0xb7f1ddbc --> 0xbfffedac --> 0xbfffefbe ("XDG_VT
EBX: 0x0
ECX: 0xbfffed10 --> 0x1
EDX: 0xbfffed34 --> 0x0
ESI: 0xb7f1c000 --> 0x1b1db0
EDI: 0xb7f1c000 --> 0x1b1db0
EBP: 0xbfffecd0 --> 0xbfffecf8 --> 0x0
ESP: 0xbfffecc0 --> 0xb7fd44e8 --> 0xb7fd3aa8 --> 0xb7
   ebx)
EIP: 0x8048411 (<func+6>:       mov    DWORD PTR [ebp-
EFLAGS: 0x286 (carry PARITY adjust zero SIGN trap INTE
[-------------------------------------code------------
   0x804840b <func>:      push   ebp
   0x804840c <func+1>:    mov    ebp,esp
   0x804840e <func+3>:    sub    esp,0x10
=> 0x8048411 <func+6>:    mov    DWORD PTR [ebp-0x4],0x3
   0x8048418 <func+13>:   mov    edx,DWORD PTR [ebp+0x8]
   0x804841b <func+16>:   mov    eax,DWORD PTR [ebp+0xc]
   0x804841e <func+19>:   add    eax,edx
   0x8048420 <func+21>:   imul   eax,DWORD PTR [ebp-0x4]
```



The `func` Stack Frame

```
gdb-peda$ x/12wx $ebp-16
0xbfffecc0:     0xb7fd44e8      0xb7fd445c      0xb7fd27bc      0x00000003
0xbfffecd0:     0xbfffecf8      0x08048447      0x00000004      0x00000005
```



x/<fmt> <address>
<fmt>: is a repeat count followed by a format letter and a size letter.

- **Format letters** are o(octal), x(hex), d(decimal), u(unsigned decimal), t(binary), f(float), a(address), i(instruction), c(char), s(string) and z(hex, zero padded on the left).
- **Size letters** are b(byte), h(halfword), w(word), g(giant, 8 bytes).

Let’s Take Control of a Program

- Code (or parameters) get injected because
  - program accepts more input than there is space allocated

- In particular, an array (or buffer) has not enough space
  - especially easy with C strings (character arrays)
  - plenty of vulnerable library functions

  `strcpy, strcat, gets, fgets, sprintf …`

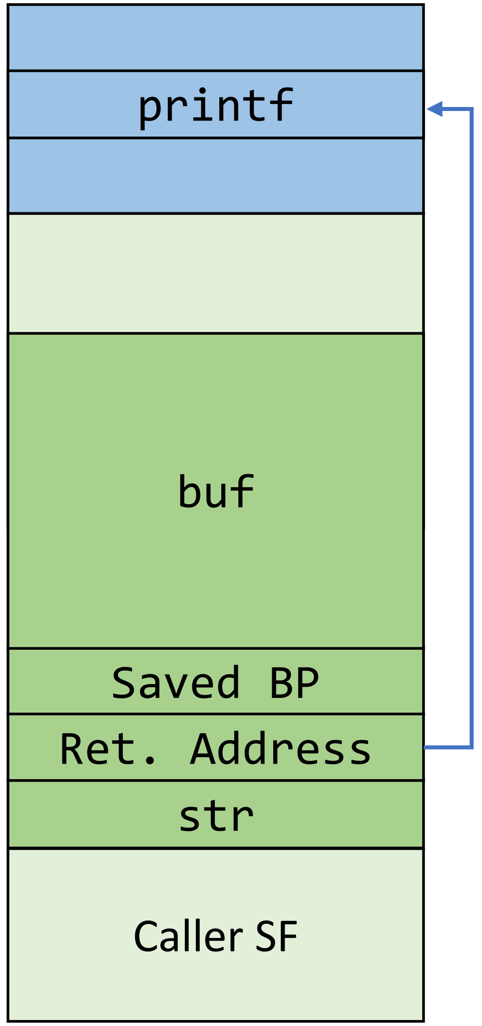
- Input spills to adjacent regions and modifies, two possibilities:
  1. “normally”, this just crashes the program (e.g., SIGSEGV)
  2. code pointer or application data
     - all the possibilities that we have enumerated before

Example: Simple Web Server

```
void serve(char *str) {
        char buf[100];
        strcpy(buf, str);
}
int main(int argc, char* argv[]) {
        serve(argv[1]);
        printf(“Bye\n");
}
```

Allocate 100 bytes on the stack

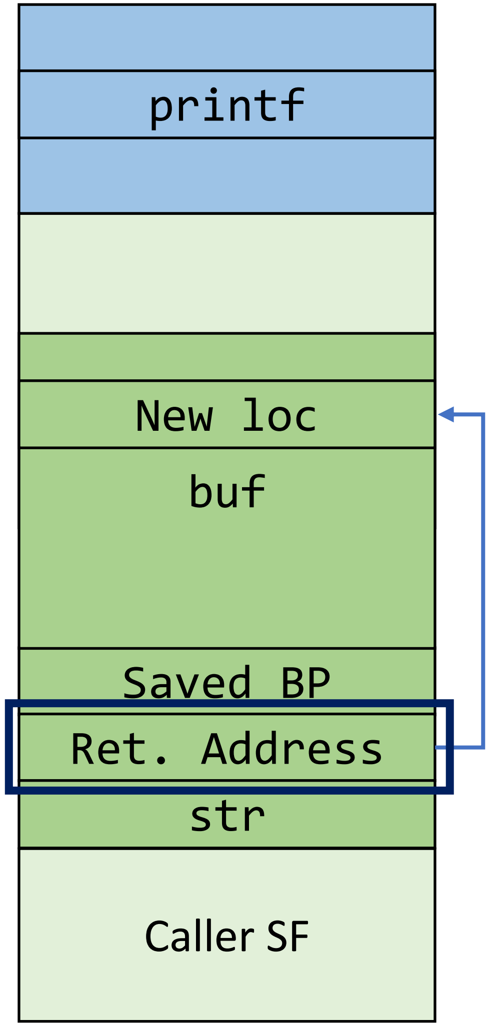
Copy str to local buffer



What if **buf** exceeds the 100 bytes?

```
void serve(char *str) {
        char buf[100];
        strcpy(buf, str);
}
int main(int argc, char* argv[]) {
        serve(argv[1]);
        printf("Bye\n");
}
```

strcpy does NOT check whether the string at *str contains fewer than 100 bytes!



- If a string longer than 100 bytes is copied into buffer, it will overwrite adjacent stack locations.

Example: Let's Crash the Server

```
$ ./server_vuln hello
$ Bye
```

Input length < 100 bytes

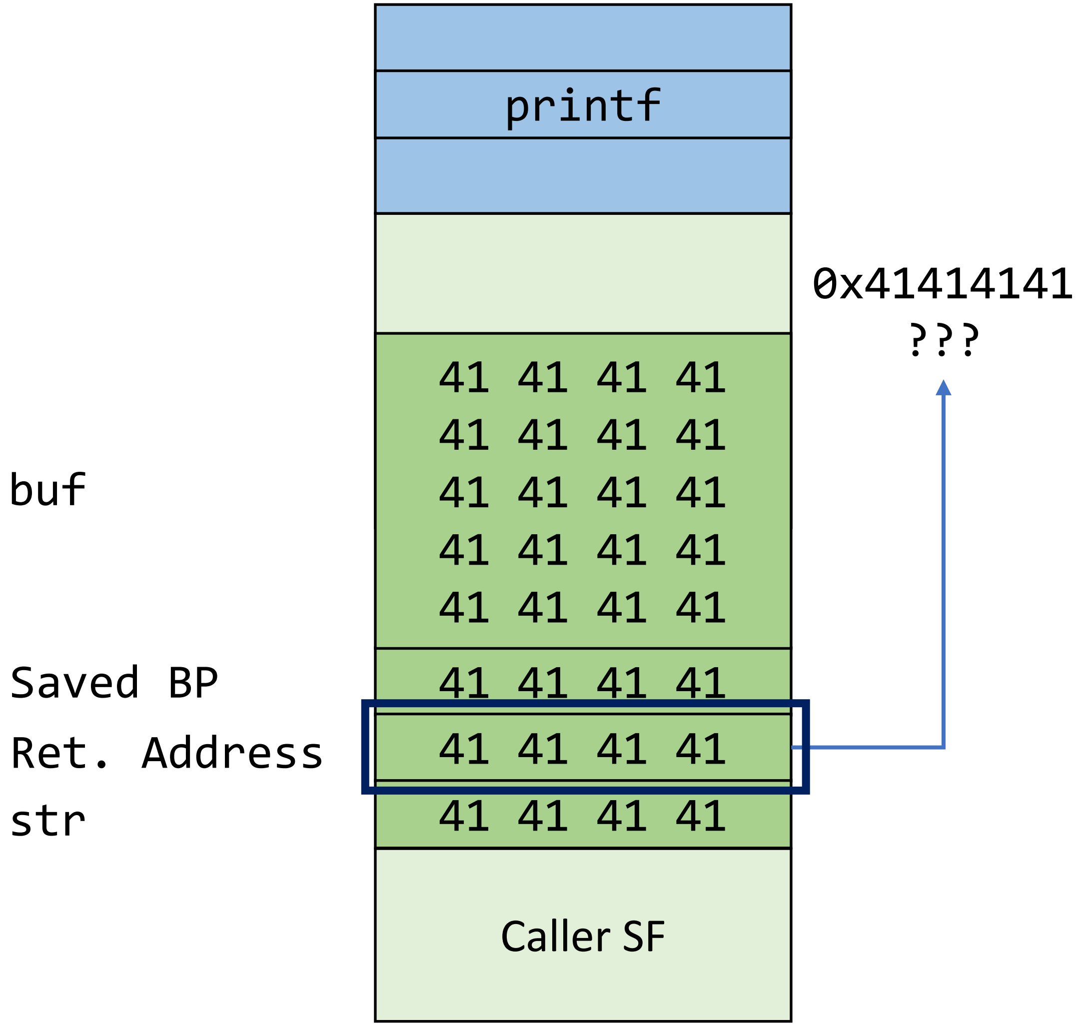
Input length > 100 bytes

```
$ ./server_vuln
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Segmentation fault
$
```

Why?

What happened?

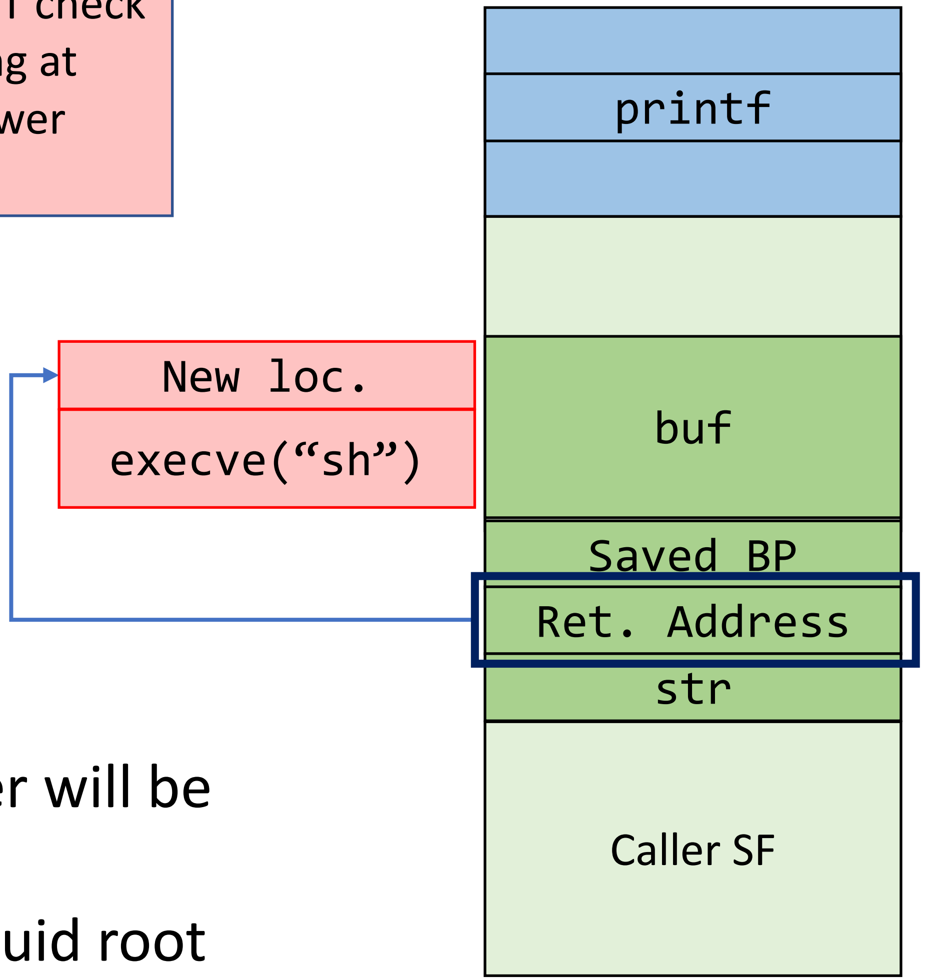
```
[-----------------------------------registers----
EAX: 0xbfffeb5c ('A' <repeats 200 times>...)
EBX: 0x0
ECX: 0xbfffefb0 ("AAAAAAAAAA")
EDX: 0xbfffec5e ("AAAAAAAAAA")
ESI: 0xb7f1c000 --> 0x1b1db0
EDI: 0xb7f1c000 --> 0x1b1db0
EBP: 0x41414141 ('AAAA')
ESP: 0xbfffebd0 ('A' <repeats 152 times>)
EIP: 0x41414141 ('AAAA')
EFLAGS: 0x10286 (carry PARITY adjust zero SIGN t
[--------------------------------------code------
Invalid $PC address: 0x41414141
[-------------------------------------stack------
0000| 0xbfffebd0 ('A' <repeats 152 times>)
0004| 0xbfffebd4 ('A' <repeats 148 times>)
0008| 0xbfffebd8 ('A' <repeats 144 times>)
0012| 0xbfffebdc ('A' <repeats 140 times>)
0016| 0xbfffebe0 ('A' <repeats 136 times>)
0020| 0xbfffebe4 ('A' <repeats 132 times>)
0024| 0xbfffebe8 ('A' <repeats 128 times>)
0028| 0xbfffebec ('A' <repeats 124 times>)
[------------------------------------------------
Legend: code, data, rodata, value
Stopped reason: SIGSEGV
0x41414141 in ?? ()
```



What if **buf** contains bad code?

```
void serve(char *str) {
        char buf[100];
        strcpy(buf,str);
}
int main(int argc, char* argv[]) {
        serve(argv[1]);
        printf("Bye\n");
}
```

strcpy does NOT check whether the string at *str contains fewer than 100 bytes!



- When function returns, code in the buffer will be executed, giving attacker a shell
  - Root shell if the victim program is setuid root

Problem: Choosing Where to Jump

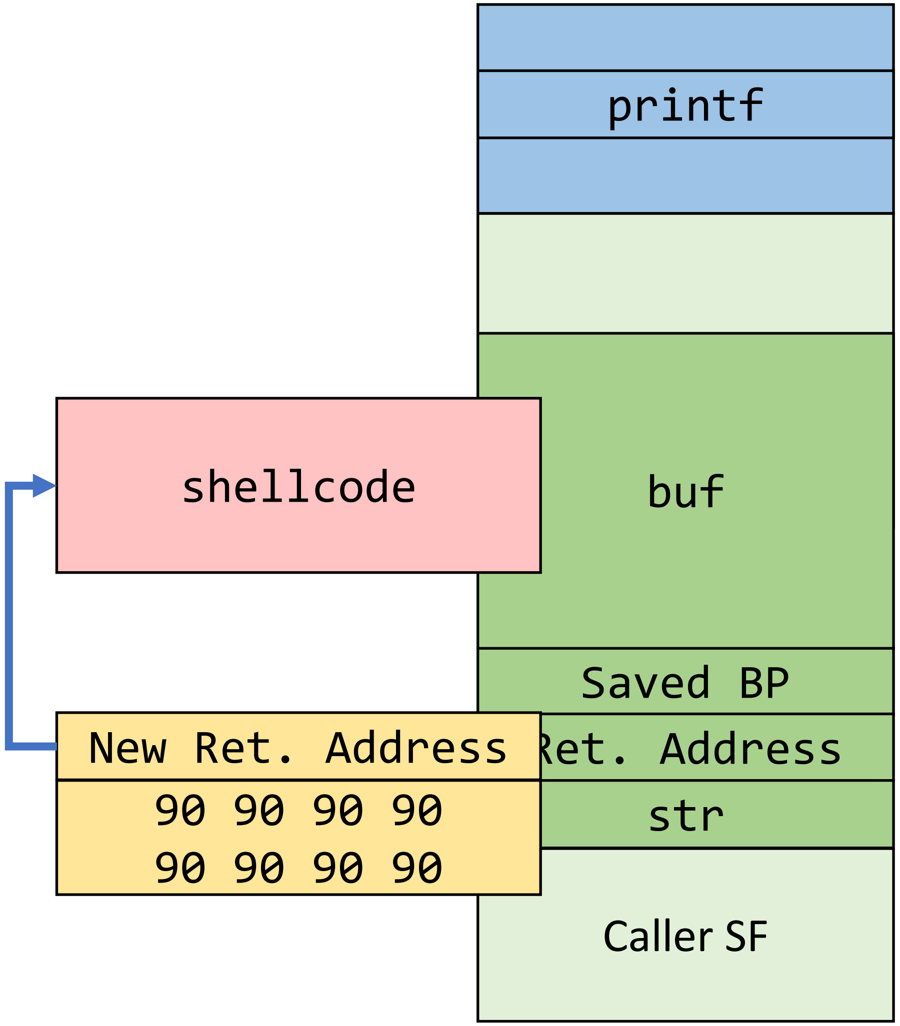
- **Address inside a buffer of which the attacker controls the content**
  - works for remote attacks
  - the attacker need to know the address of the buffer, the memory page containing the buffer must be executable
- **Address of a function inside the program**
  - works for remote attacks, does not require an executable stack
  - need to find the right code, one or more fake frames must be put on the stack
- **Address of a environment variable**
  - easy to implement, works with tiny buffers
  - only for local exploits, some programs clean the environment, the stack must be executable

Jumping into the Buffer

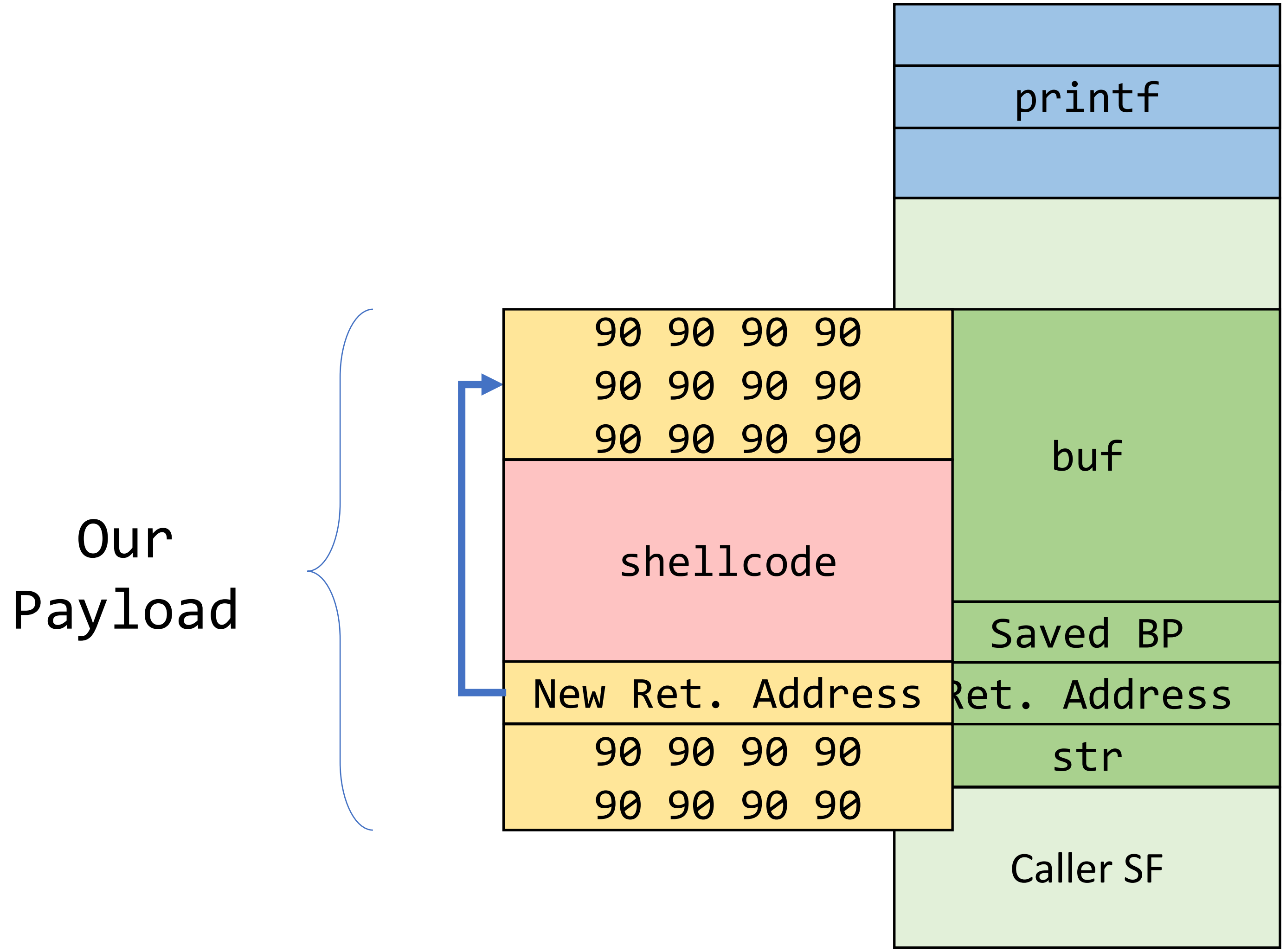
- The buffer that we are overflowing is usually a good place to put the code (bytecode) that we want to execute
- The buffer is somewhere on the stack, but in most cases the exact address is unknown
  - The address must be precise: jumping one byte before or after could make the application crash
    - NOP sled (later) partly weakens this requirement
  - On the local system, it is possible to calculate the address with a debugger, but it is very unlikely to be the same address on a different machine

Scenario 1 – Jump to Shellcode

How to find this address?



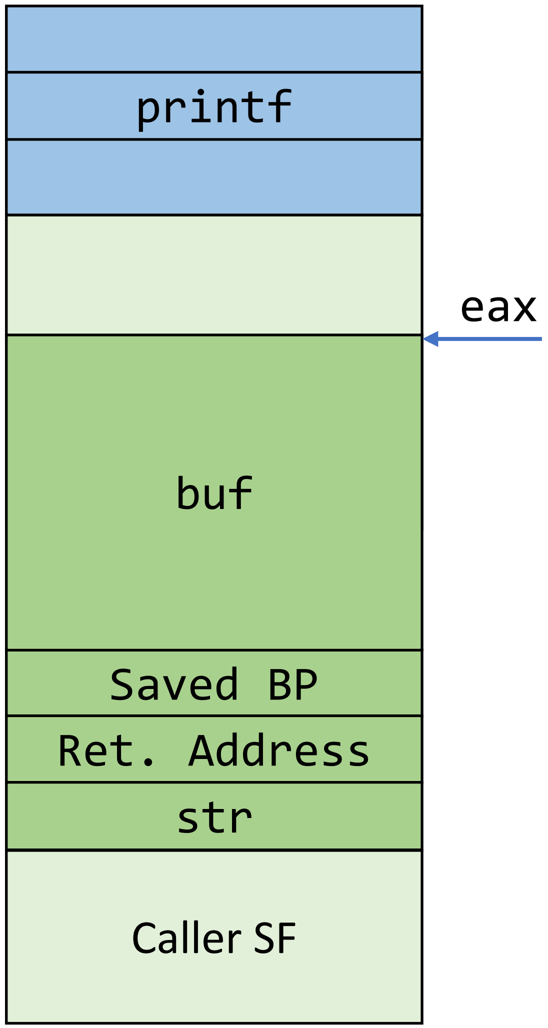
Scenario 1 – Jump to Shellcode



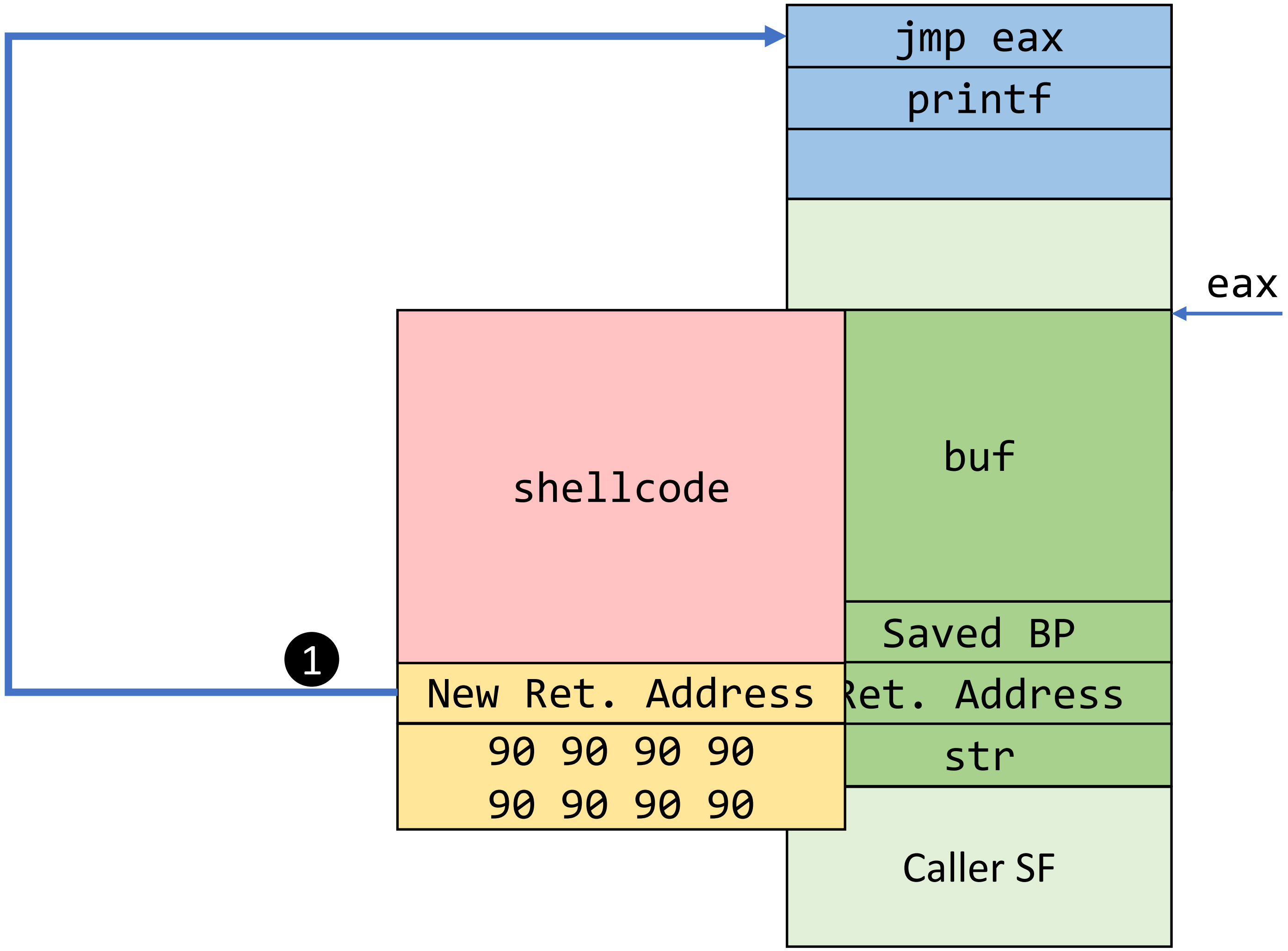
We don't need the **exact** address

We need to add **dummy** instructions that will lead to our shellcode!

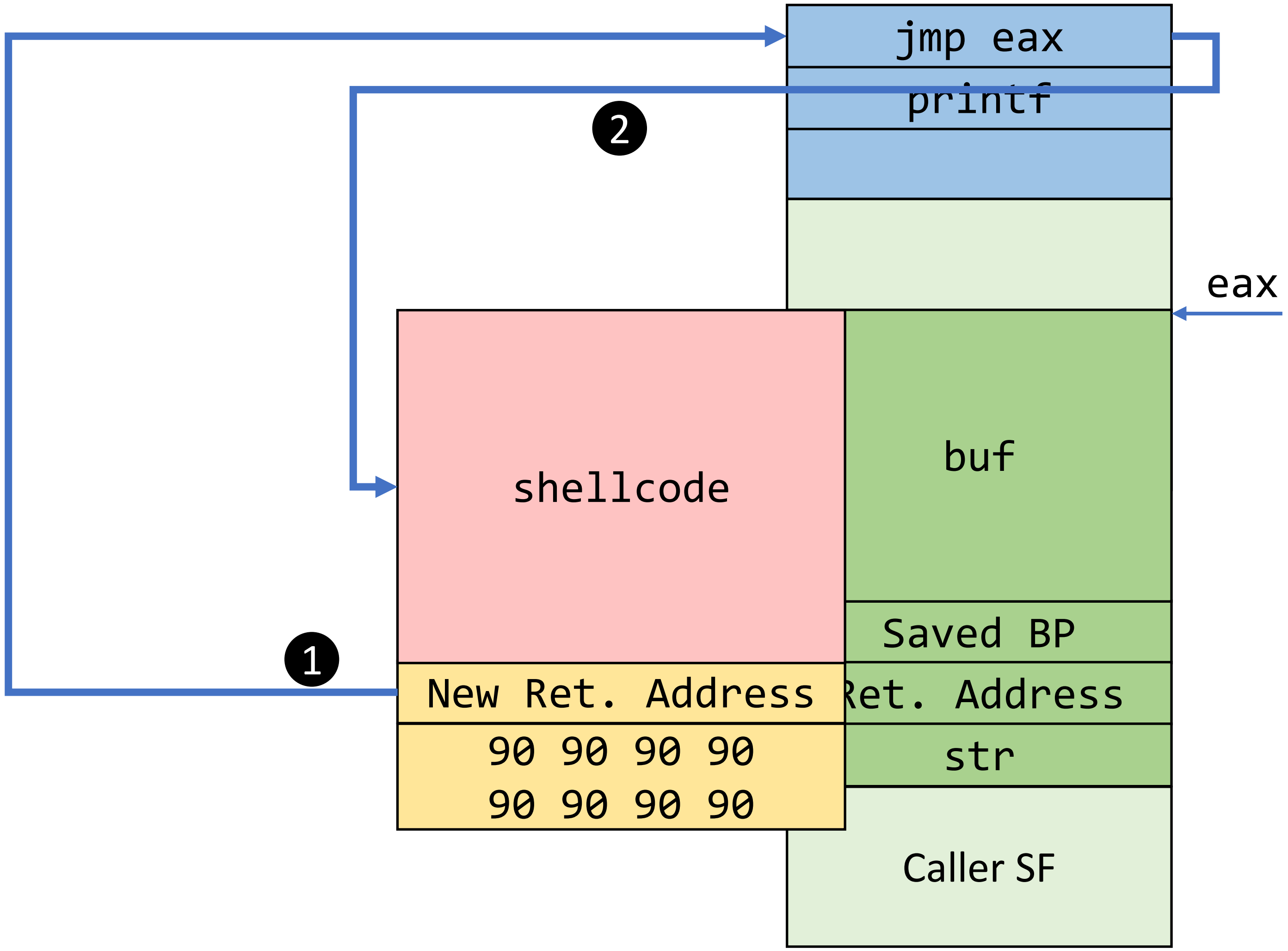
Scenario 2 – JMP to Register (ret2reg)



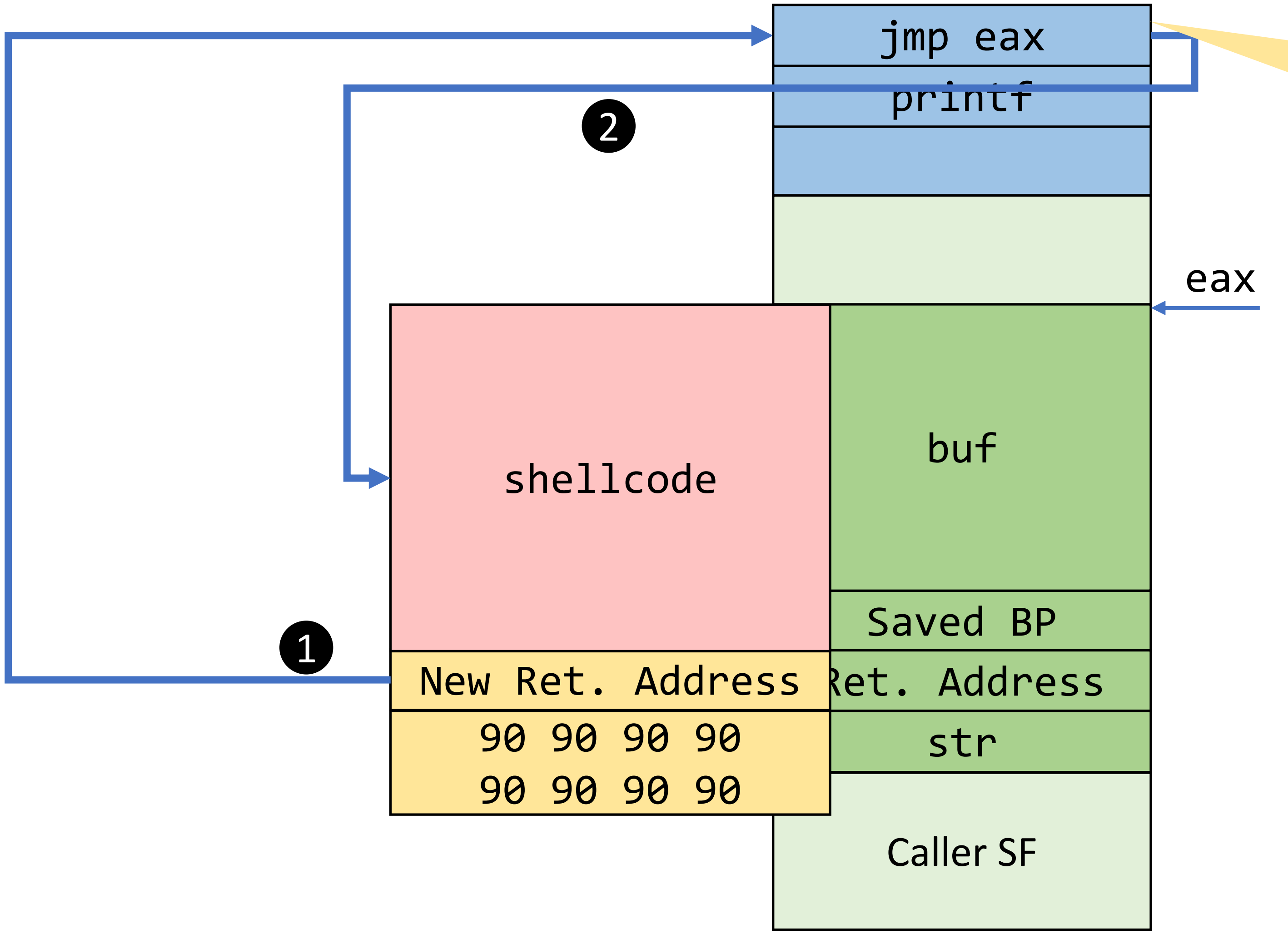
Scenario 2 – JMP to Register (ret2reg)



Scenario 2 – JMP to Register (ret2reg)



Scenario 2 – JMP to Register (ret2reg)



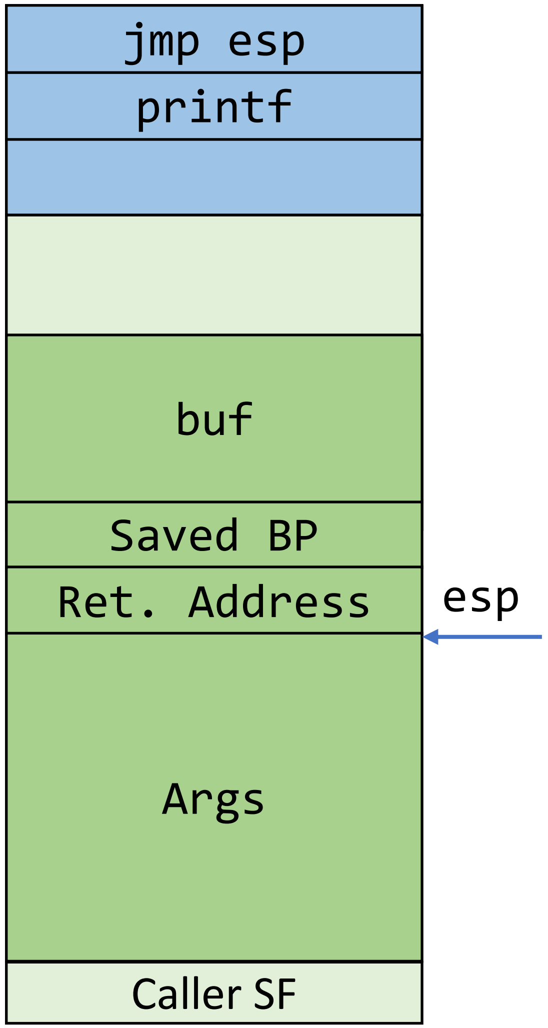
How to find this instruction?

Hint 1: the bytecode is `FF E0`

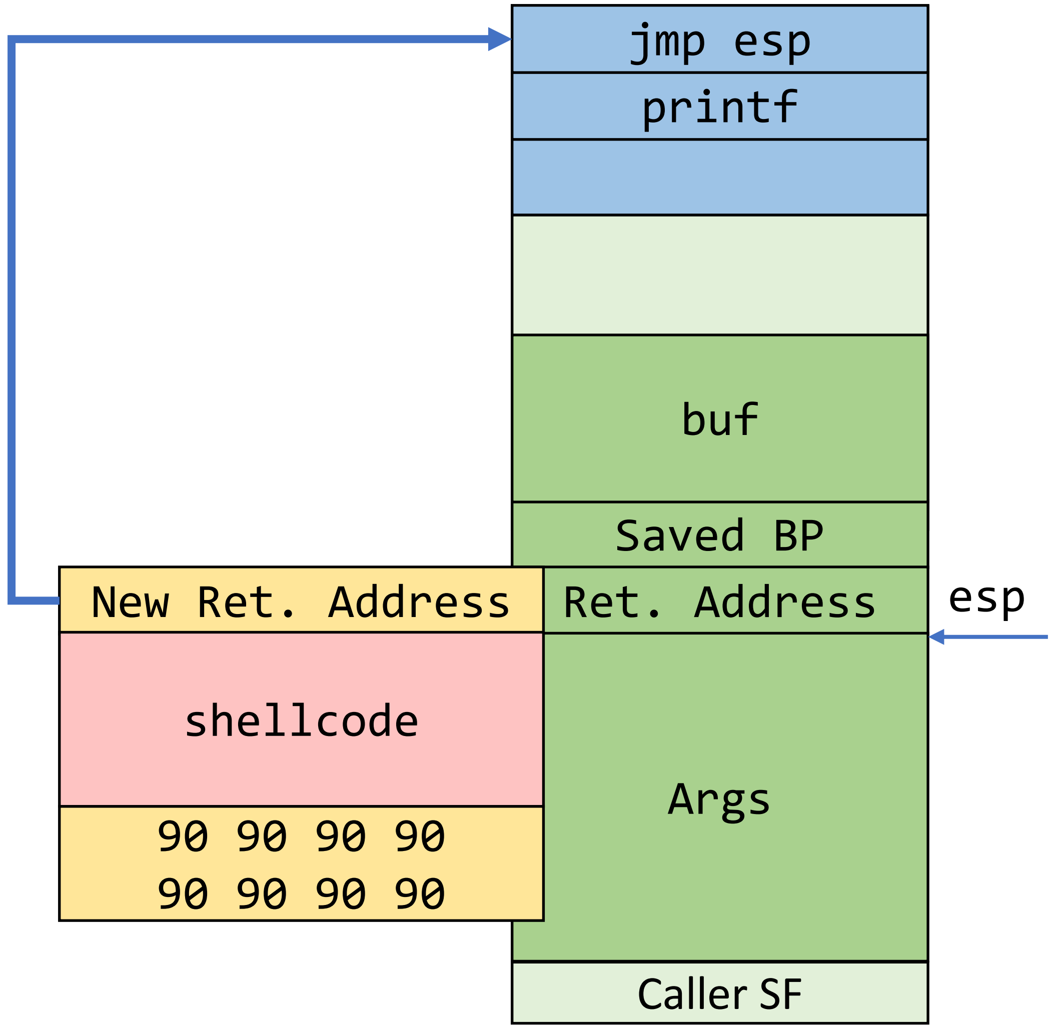
Hint 2: What is loaded besides our code?

Can we use other registers?

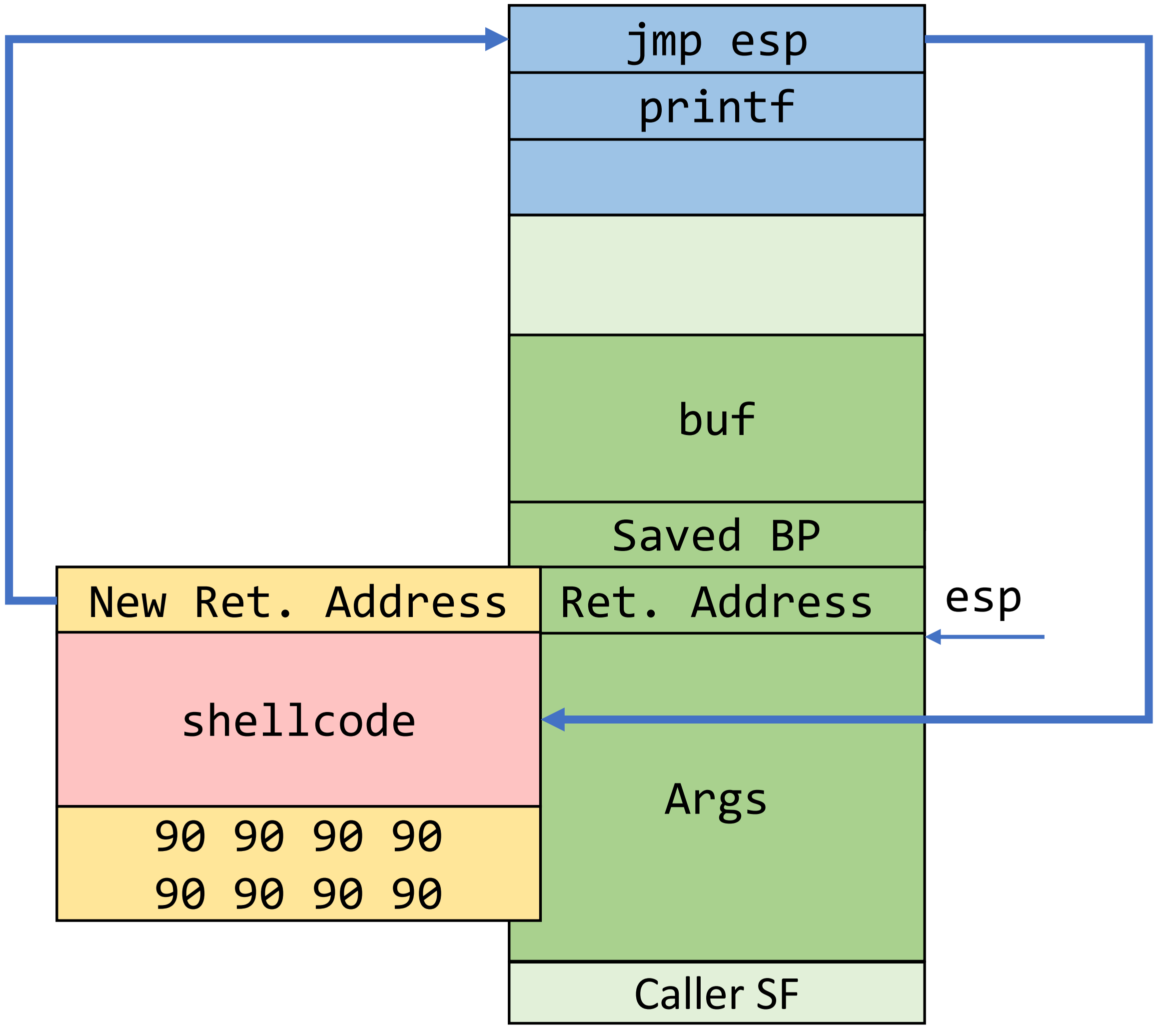
Scenario 3 – JMP to ESP



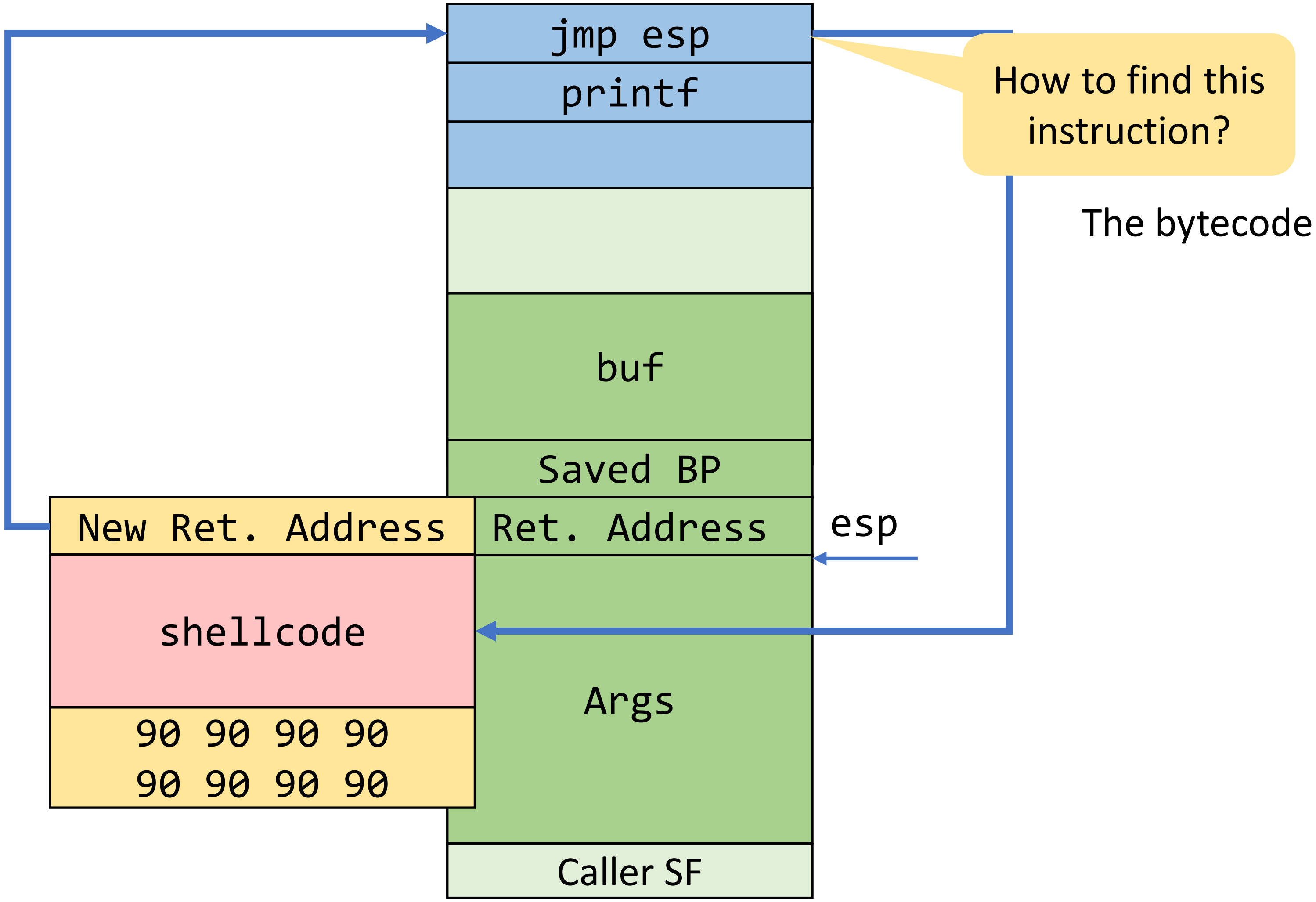
Scenario 3 – JMP to ESP



Scenario 3 – JMP to ESP

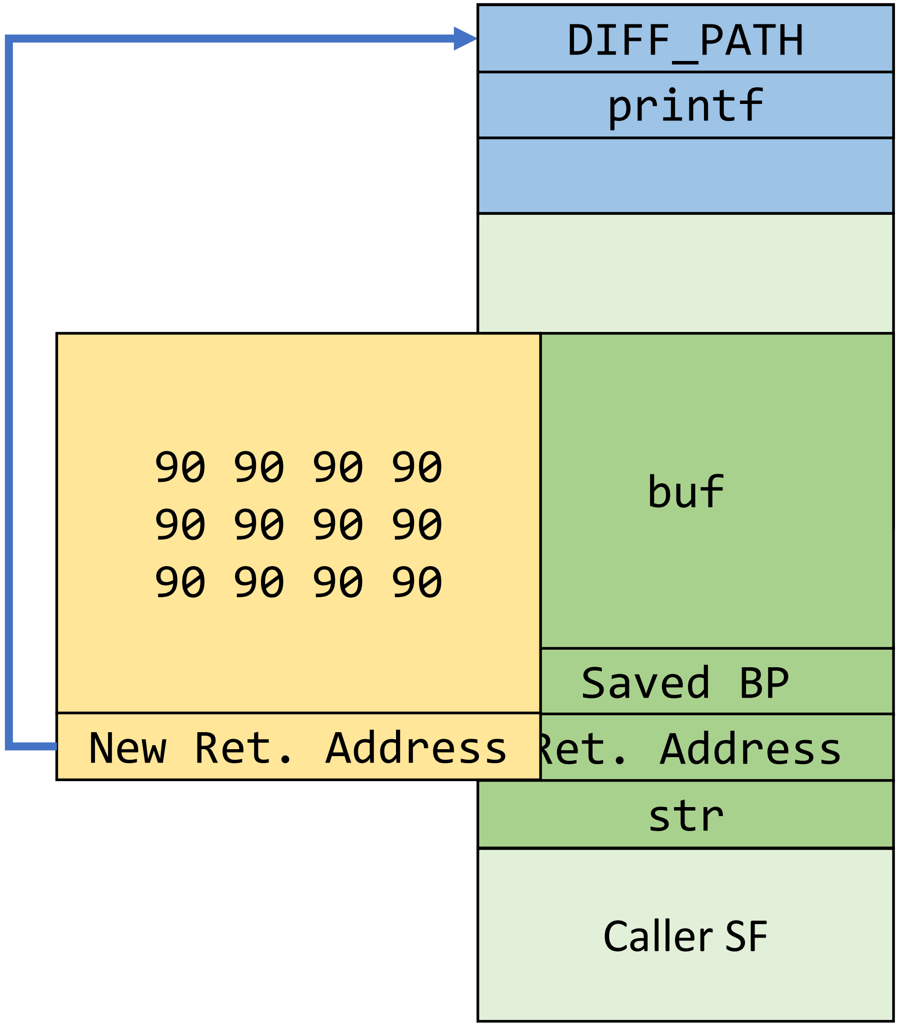


Scenario 3 – JMP to ESP



The bytecode is FF E4

Scenario 4 – JMP to different code path



Recap: The NOP Sled (`0x90`)

- A sled is a “landing area” that is put in front of the shellcode
- Must be created in a way such that wherever the program jump into it always
  1. finds a valid instruction
  2. reaches the end of the sled and the beginning of the shellcode
- The simplest sled is a sequence of no operation (NOP) instructions
  - single byte instruction (0x90) that does not do anything
- It mitigates the problem of finding the **exact address** to the buffer by increasing the size of the target are area

Recap: JMP using a register

1. Find a register that points to the buffer (or somewhere into it)
   - ESP
   - EAX (return value of a function call)

2. Locate an instruction that jump/call using that register
   - can also be in one of the libraries
   - does not need to be a real instruction (**just the right sequence of bytes**)
   - you can search for a pattern with gdb find `jmp ESP = 0xFF 0xE4`

3. Overwrite the return address with the address of that instruction

Tip 1: Copying Shellcode

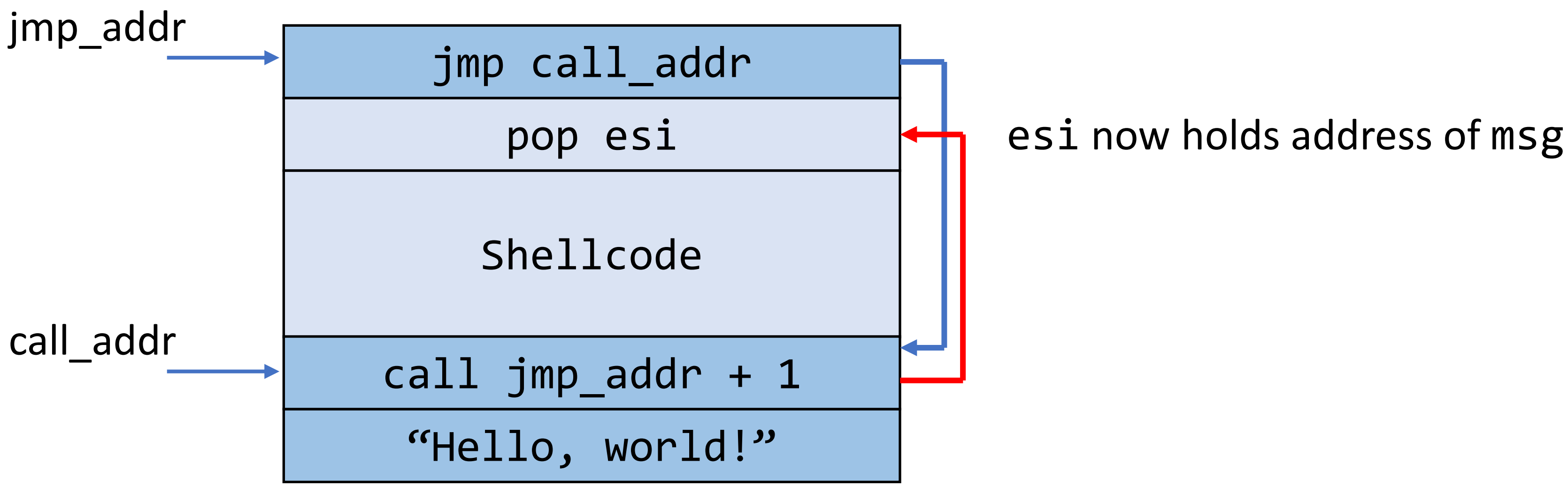
- Shellcode is usually copied into a string buffer
- Problem
  - any null byte would stop copying

  → null bytes must be eliminated from the shellcode!

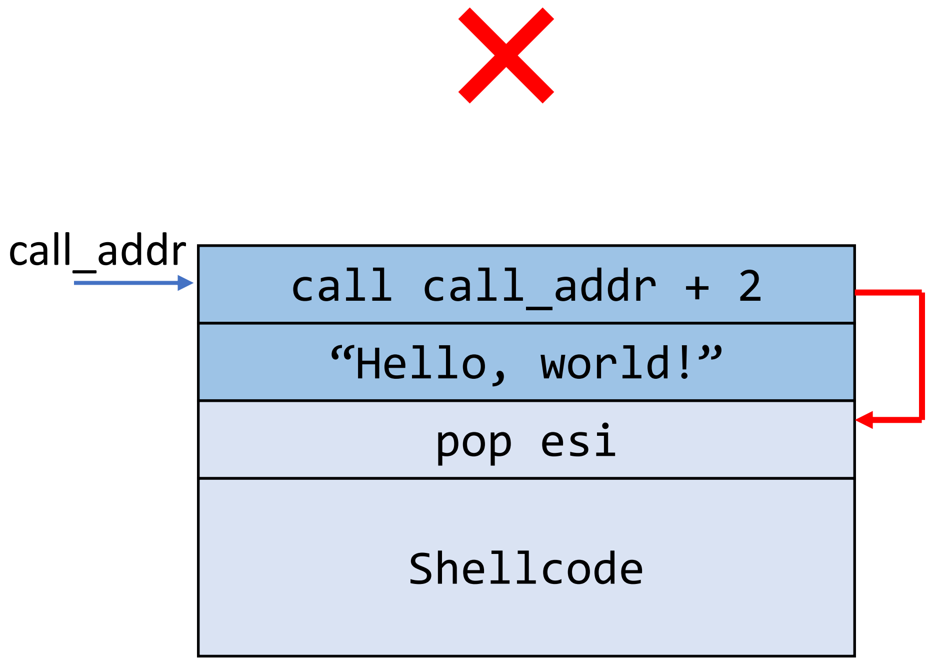
`mov eax, 0x4   b8 04 00 00 00` — replace with → `mov al, 0x4` **`b0 04`**

`mov eax, 0x0` — replace with → `xor eax, eax`

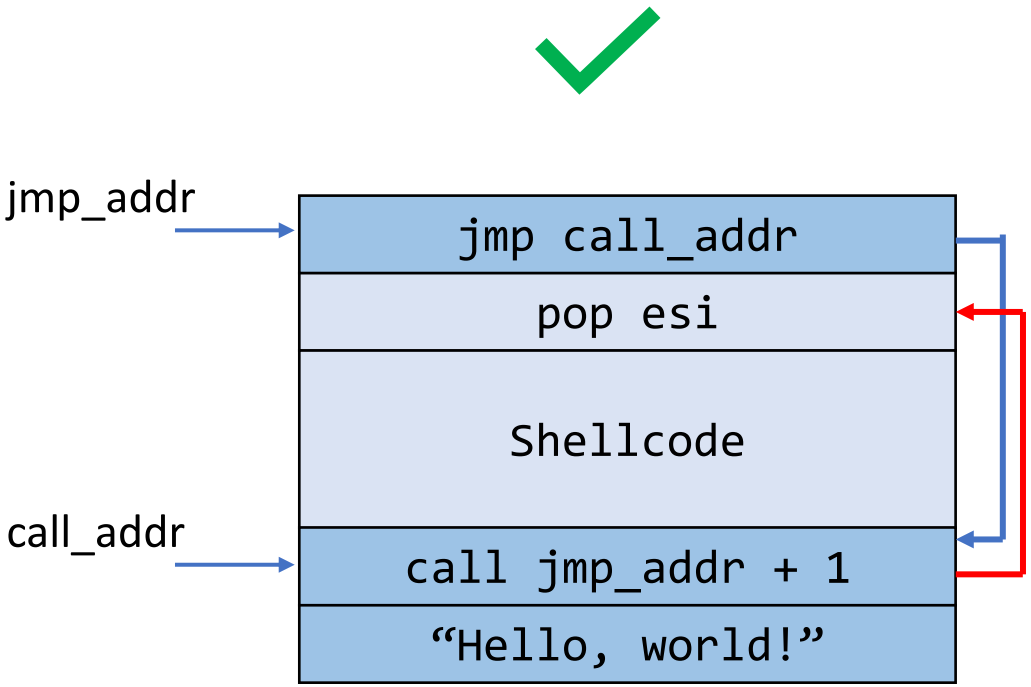
Tip 2: Relative Addressing Technique



Relative Addressing Technique



Why not this one?



Tip 3: Enable Privileges

- Problem:
  - exploited program could have temporarily dropped privileges
- Technique:
  - Shellcode has to enable privileges again (using setuid)
  - How? What is setuid?

Small Buffers

- Buffer can be too small to hold exploit code
- Store exploit code in environment variable
  - environment stored on stack
  - return address has to be redirected to environment variable

- Advantage
  - exploit code can be arbitrary long
- Disadvantage
  - access to environment needed

Tip 4: Every Byte Matters (Examples)

Initialize a register:

4 bytes

```
xor eax, eax
mov al, 0x5
```

replace with

```
push 0x5
pop eax
```

3 bytes

Zero out multiple registers:

6 bytes

```
xor eax, eax
xor ecx, ecx
xor edx, edx
```

replace with

```
xor ecx, ecx
mul ecx
```

4 bytes

Zero out edx (some times):

4 bytes

```
xor eax, eax
xor edx, edx
```

replace with

```
xor eax, eax
cdq
```

3 bytes

Tip 5: Strings and their addresses

- Instead of jmp-call-pop technique, we can directly push bytes to the stack

```
xor eax, eax
push eax
push 0x21756673 ; little-endian

mov ebx, esp    ; ebx = 0xbfffea00
push eax
push ebx

mov ecx, esp    ; ecx = 0xbfffe9f8
```

0xbfffea00	0xbfffe9f8
0	
“SFU!”	0xbfffea00
0	

Recap: Requirements for Shellcode

- No zero bytes!
- Position-independent code (PIC)
- Doesn’t use absolute addresses
- Better: be as small as possible

Questions?