Memory Safety and Buffer Overflows

(with material from Mike Hicks, Dave Levin and Michelle Mazurek)

Today's agenda

- Why care about buffer overflows?
- Memory layout refresher
- Overflows and how they work

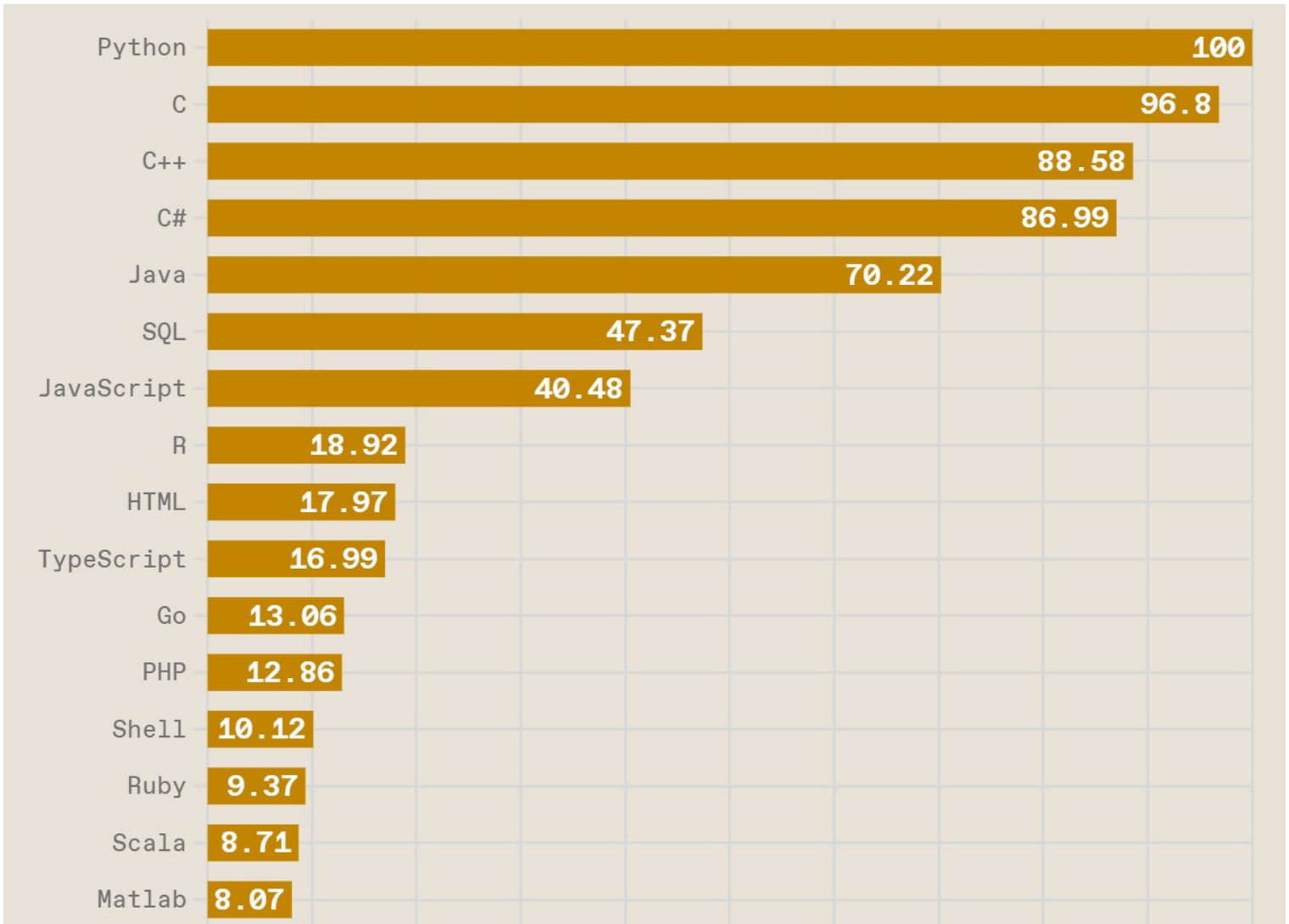
What is a buffer overflow?

- A **low-level** bug, typically in **C/C++**
  - Significant security implications!

- If accidentally triggered, causes a crash

- If maliciously triggered, can be **much worse**
  - **Steal** private info
  - **Corrupt** important info
  - **Run** arbitrary code

C and C++ still very popular



https://spectrum.ieee.org/top-programming-languages-2022

Critical systems in C/C++

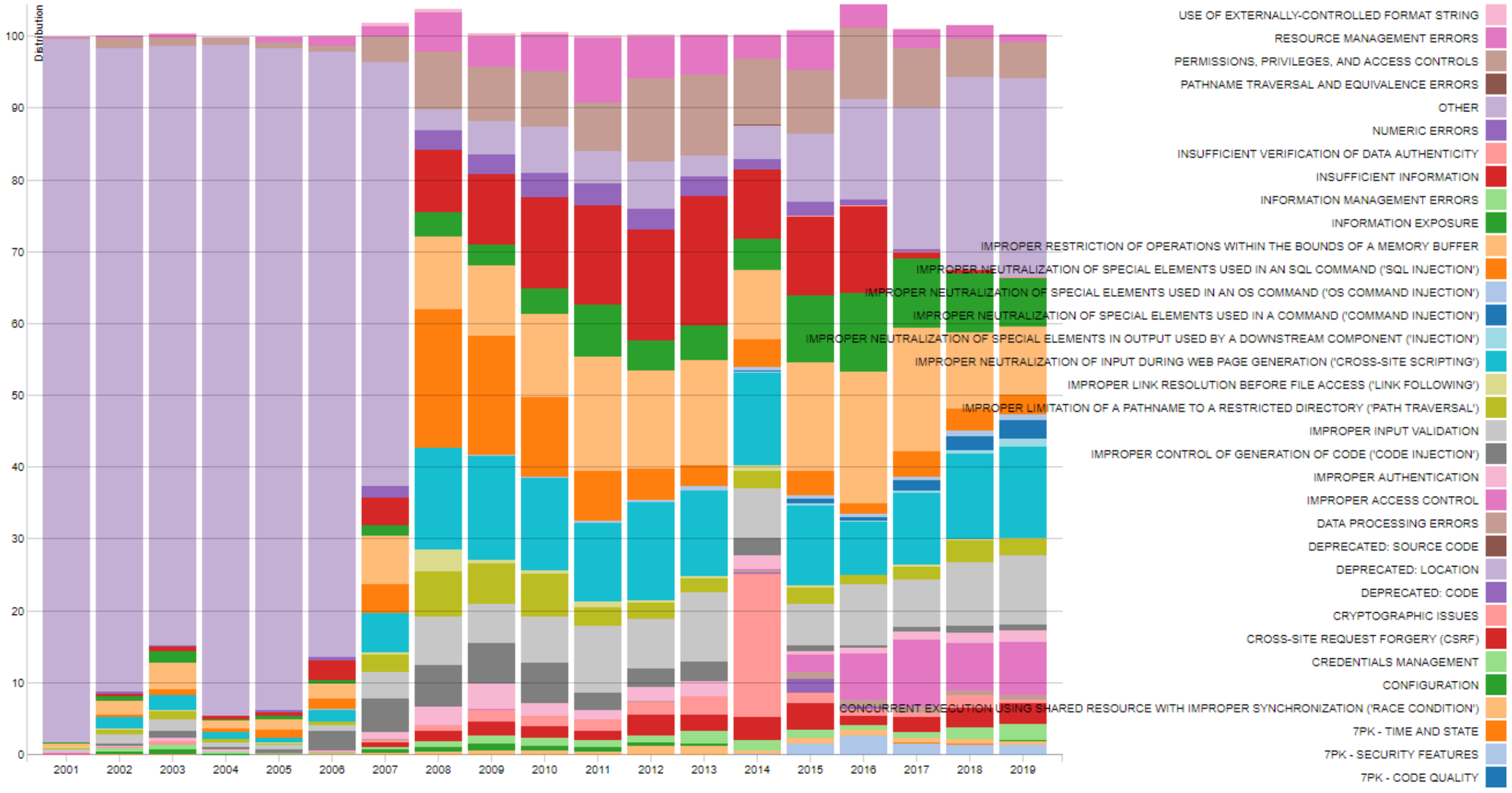
- Most **OS kernels** and utilities
  - fingerd, X windows server, shell
- Many **high-performance servers**
  - Microsoft IIS, Apache httpd, nginx
  - Microsoft SQL server, MySQL, redis, memcached
- Ma
  - Mars rover, industrial control systems, automobiles, healthcare devices, IoT

A successful attack on these systems is particularly dangerous!

Trends

Relative Vulnerability Type Totals By Year

The vulnerabilties in the NVD are assigned a CWE based on a slice of the total CWE Dictionary. The visualization below shows a stacked bar graph of the total number of vulnerabilities assigned a CWE for each year. It is possible (although not common) that a vulnerability has multiple CWEs assigned.



https://nvd.nist.gov/vuln/visualizations/cwe-over-time

History of Buffer Overflows

- Morris Worm (1988)
  - First internet worm
  - Spread across Unix Machines
- Code Red (2001)
  - Vulnerability in Microsoft Internet Information Services (for hosting web applications)
  - DDoS attack on White House's servers
- SQL Slammer (2003)
  - Vulnerability in Microsoft SQL Server 2000.
  - Worm spread across more than 250,000 computers and caused a massive internet outage

Recent Examples

Critical RCE vulnerability impacts 29 models of DrayTek routers

By **Bill Toulas** August 4, 2022 07:18 PM 0

Researchers at Trellix have discovered a critical unauthenticated remote code execution (RCE) vulnerability impacting 29 models of the DrayTek Vigor series of business routers.

The vulnerability is tracked as CVE-2022-32548 and carries a maximum CVSS v3 severity score of 10.0, categorizing it as critical.

Google Patches Actively Exploited Chrome Bug

The heap buffer overflow issue in the browser's WebRTC engine could allow attackers to execute arbitrary code.

The vulnerability, tracked as CVE-2022-2294 and reported by Jan Vojtesek from the Avast Threat Intelligence team on July 1, is described as a buffer overflow, "where the buffer that can be overwritten is allocated in the heap portion of memory," according to the vulnerability's listing on the Common Weakness Enumeration (CWE) website.

CERT-In issues threat alert for high severity vulnerabilities in Linux, Unix and Realtek SDK

Nabeel Ahmed

AUGUST 23, 2022 16:22 IST
UPDATED: AUGUST 23, 2022 16:22 IST

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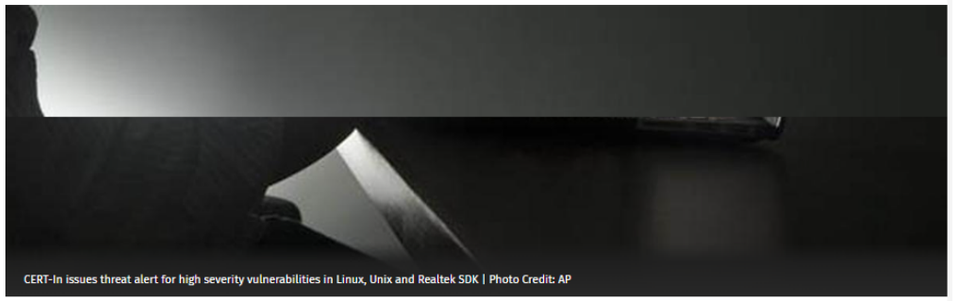

CERT-In issues threat alert for high severity vulnerabilities in Linux, Unix and Realtek SDK | Photo Credit: AP

The Indian Computer Emergency Response Team (CERT-In) revealed details about the vulnerabilities on Monday

Vulnerabilities in Linux and Unix can be exploited to execute arbitrary code while the critical vulnerability in Realtek could be affecting networking devices, revealed the Indian Computer Emergency Response Team (CERT-In) on Monday.

What we'll do

- Understand how these attacks work, and how to defend against them
- These require knowledge about:
  - The compiler
  - The OS
  - The architecture

Analyzing security requires a whole-systems view

Note about terminology

- We will use **buffer overflow** to mean ***any access of a buffer outside of its allotted bounds***
  - An over-*read*, or an over-*write*
  - During *iteration* (“running off the end”) or by *direct access*
  - Could be to addresses that *precede* or *follow* the buffer

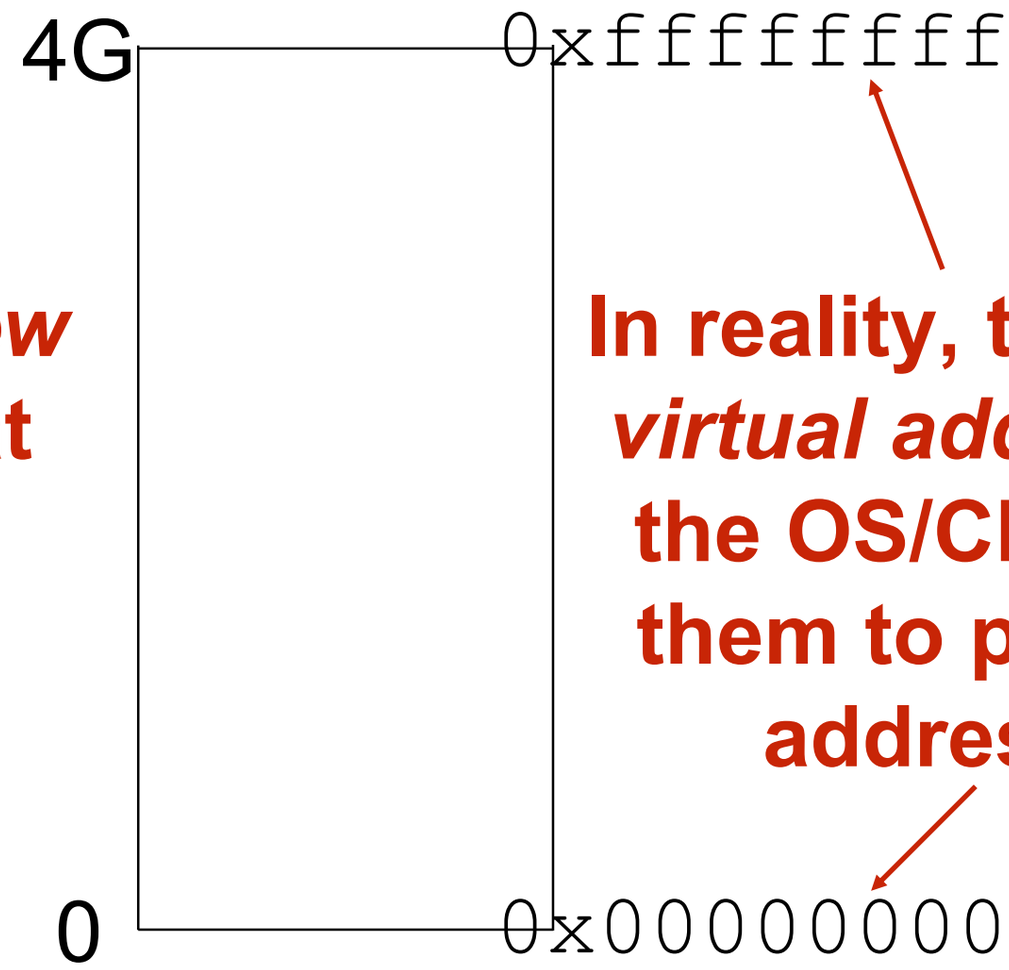
http://www.williesimpson.com/wp-content/uploads/2011/03/memory-lane.jpg

Memory layout

Memory Layout Refresher

- How is program data laid out in memory?
- What does the stack look like?
- What effect does calling (and returning from) a function have on memory?
- We are focusing on the Linux process model
  - Similar to other operating systems

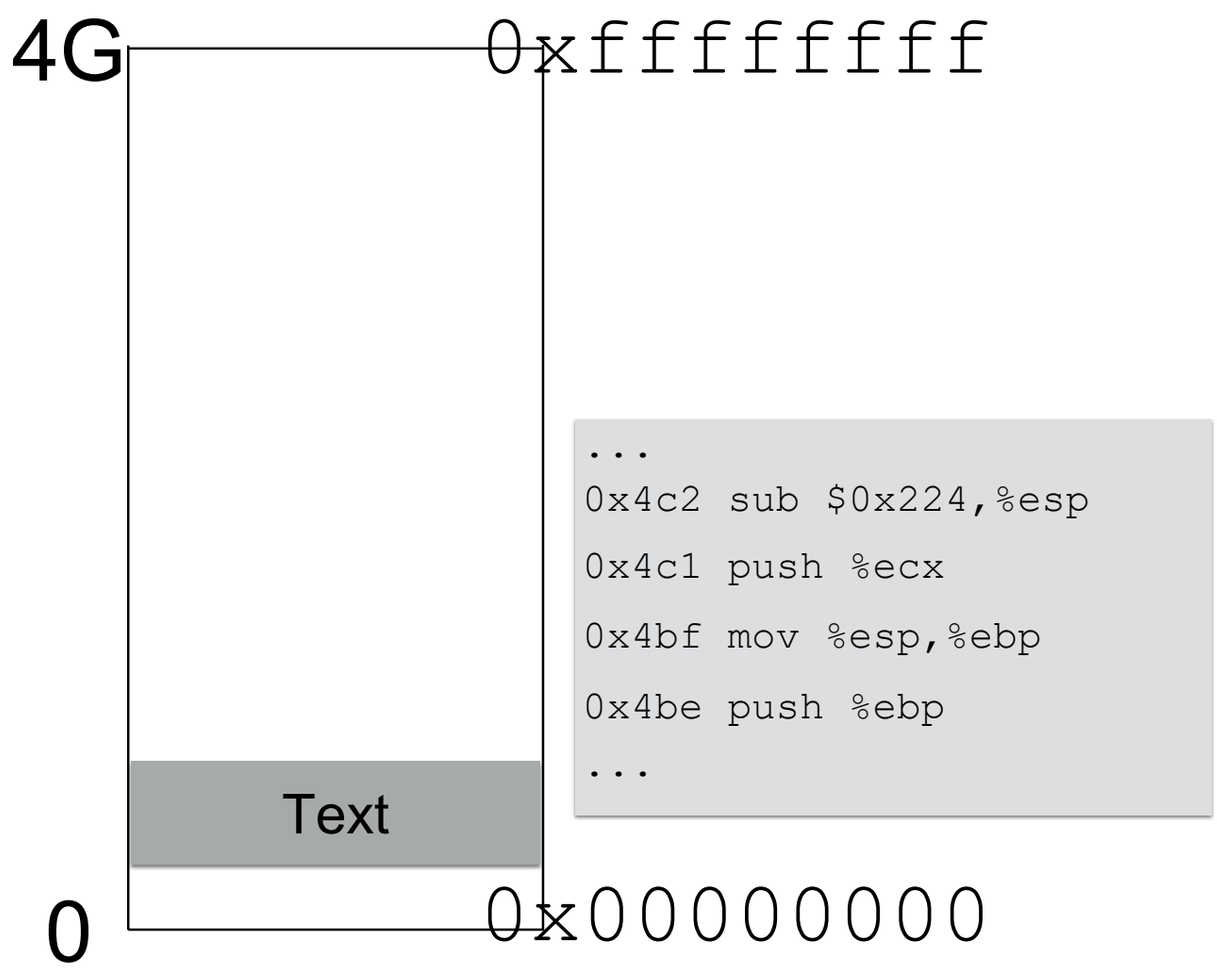
All programs stored in memory



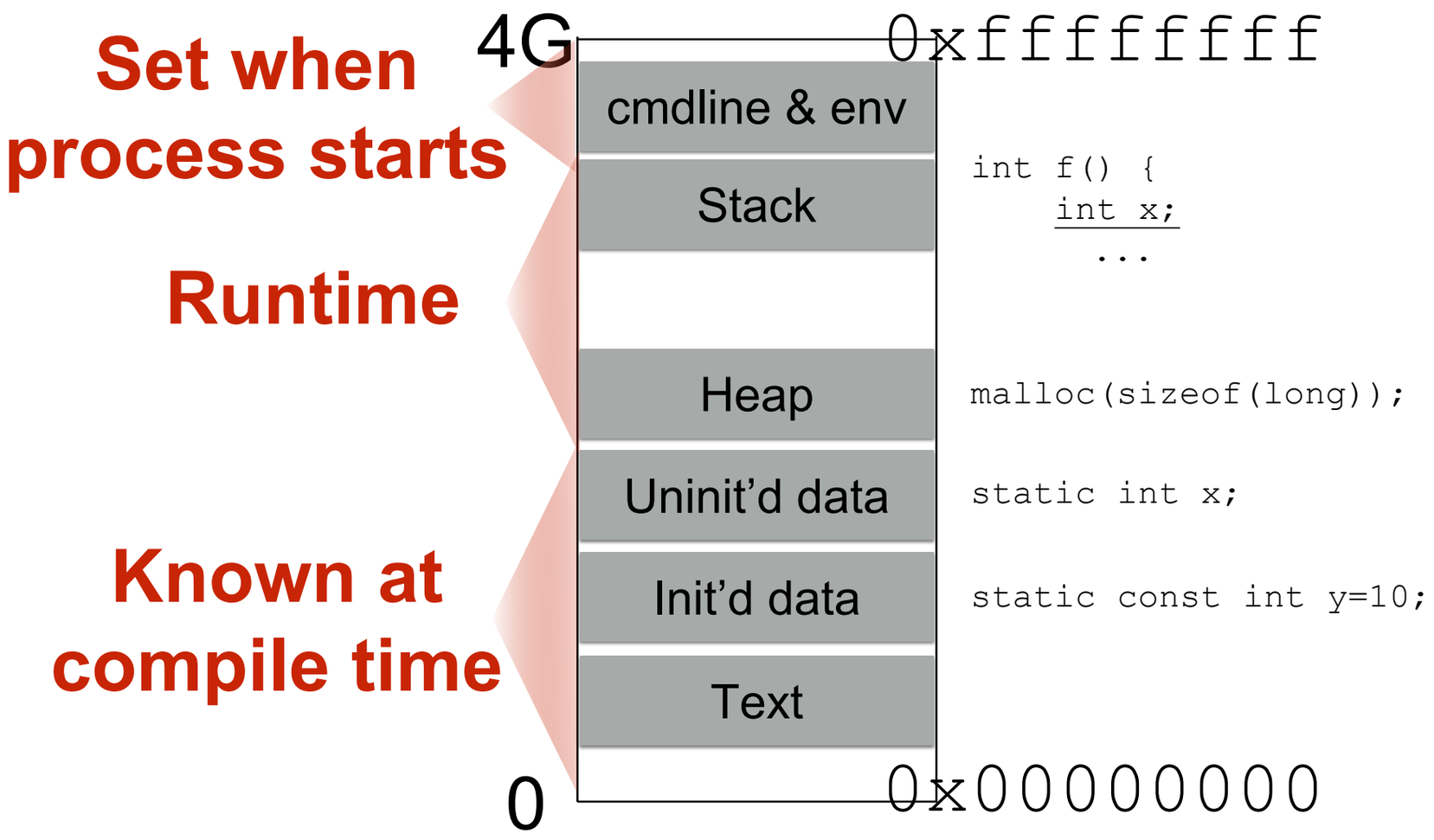
The *process's view* of memory is that it owns all of it

In reality, these are *virtual addresses*; the OS/CPU map them to physical addresses

Program **instructions** are in memory



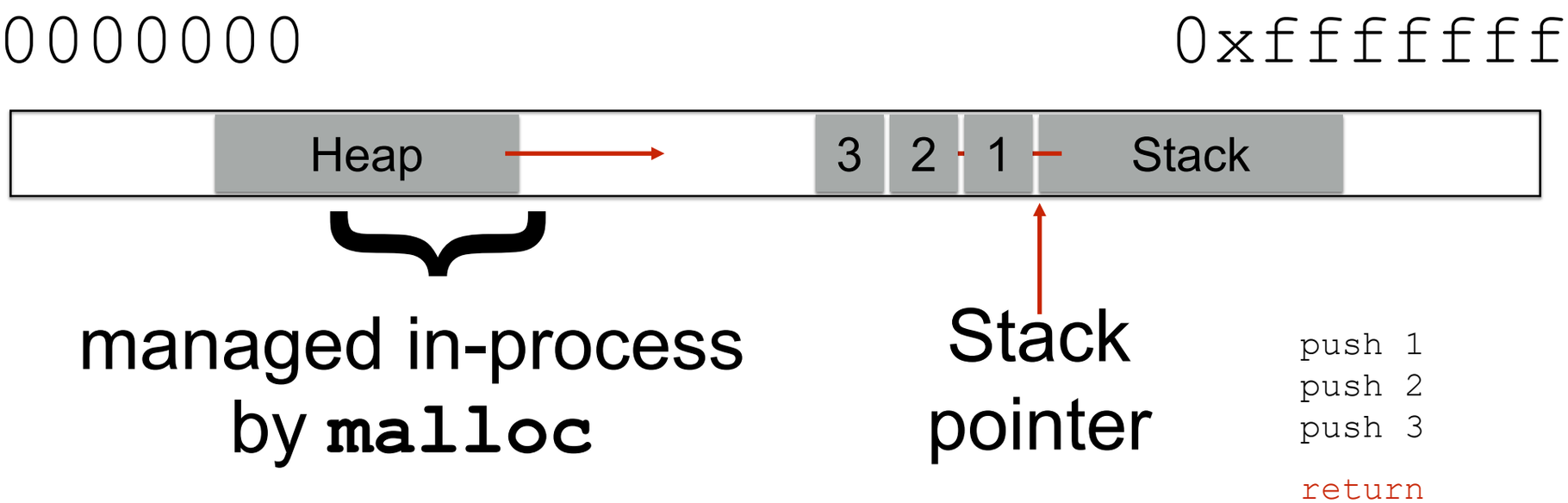
Location of data areas



Memory allocation

Stack and heap grow in opposite directions

Compiler emits instructions to
adjust the size of the stack at run-time



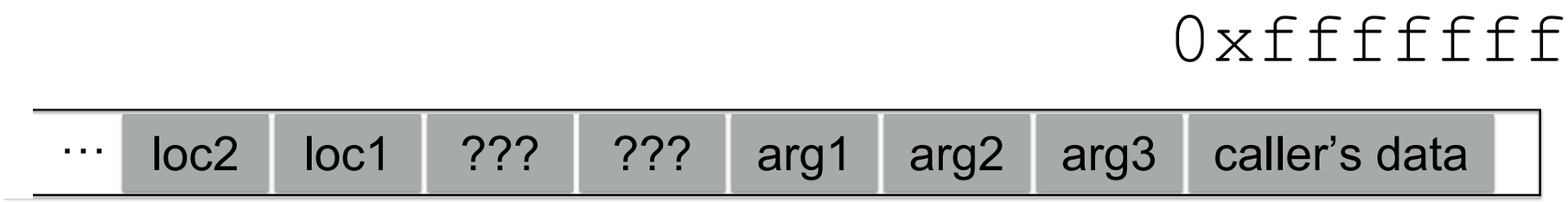
Focusing on the stack for now

Stack and function calls

- What happens when we **call** a function?
  - What data needs to be stored?
  - Where does it go?
- What happens when we **return** from a function?
  - What data needs to be *restored*?
  - Where does it come from?

Basic stack layout

```
void func(char *arg1, int arg2, int arg3)
{
    char loc1[4]
    int  loc2;
    ...
}
```

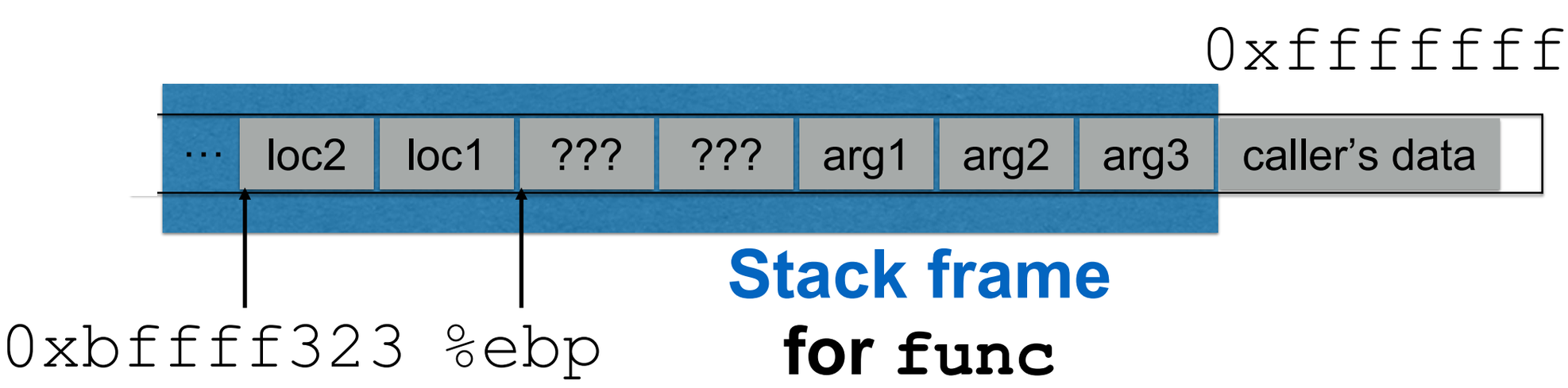


The local variable allocation is ultimately up to the compiler: Variables could be allocated in any order, or not allocated at all and stored only in registers, depending on the optimization level used.

Accessing variables

```
void func(char *arg1, int arg2, int arg3)
{
    ...
    loc2++;
    ...
}
```

Q: Where is (this) `loc2`?
A: -8(%ebp)



Stack frame for `func`

Frame pointer

Can't know absolute address at compile time

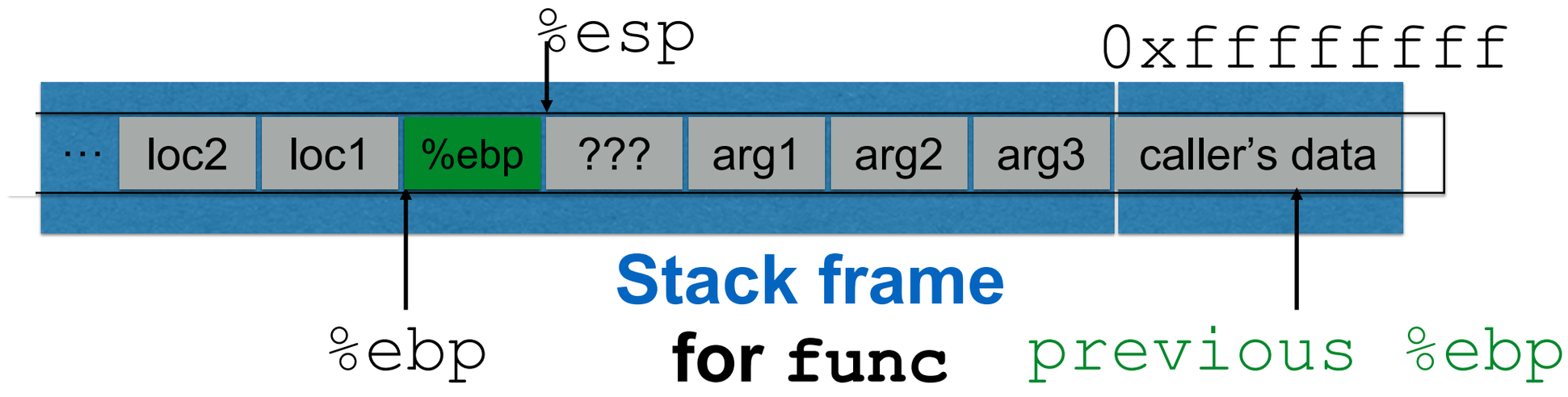
But can know the **relative** address

- `loc2` is always 8B before ???s

Returning from functions

Q: How do we restore previous %ebp?

```
int main()
{
     ...
     func("Hey", 10, -3);
     ...
}
```



Push current `%ebp` before `locals`

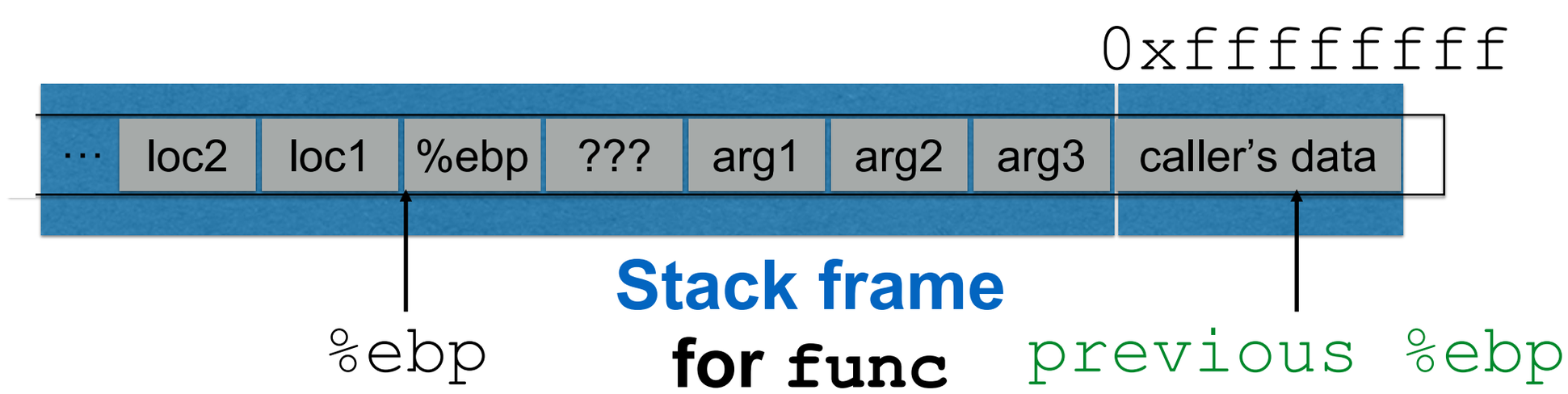
Set `%ebp` to current `%esp`

Set `%ebp` to `(%ebp)` at return

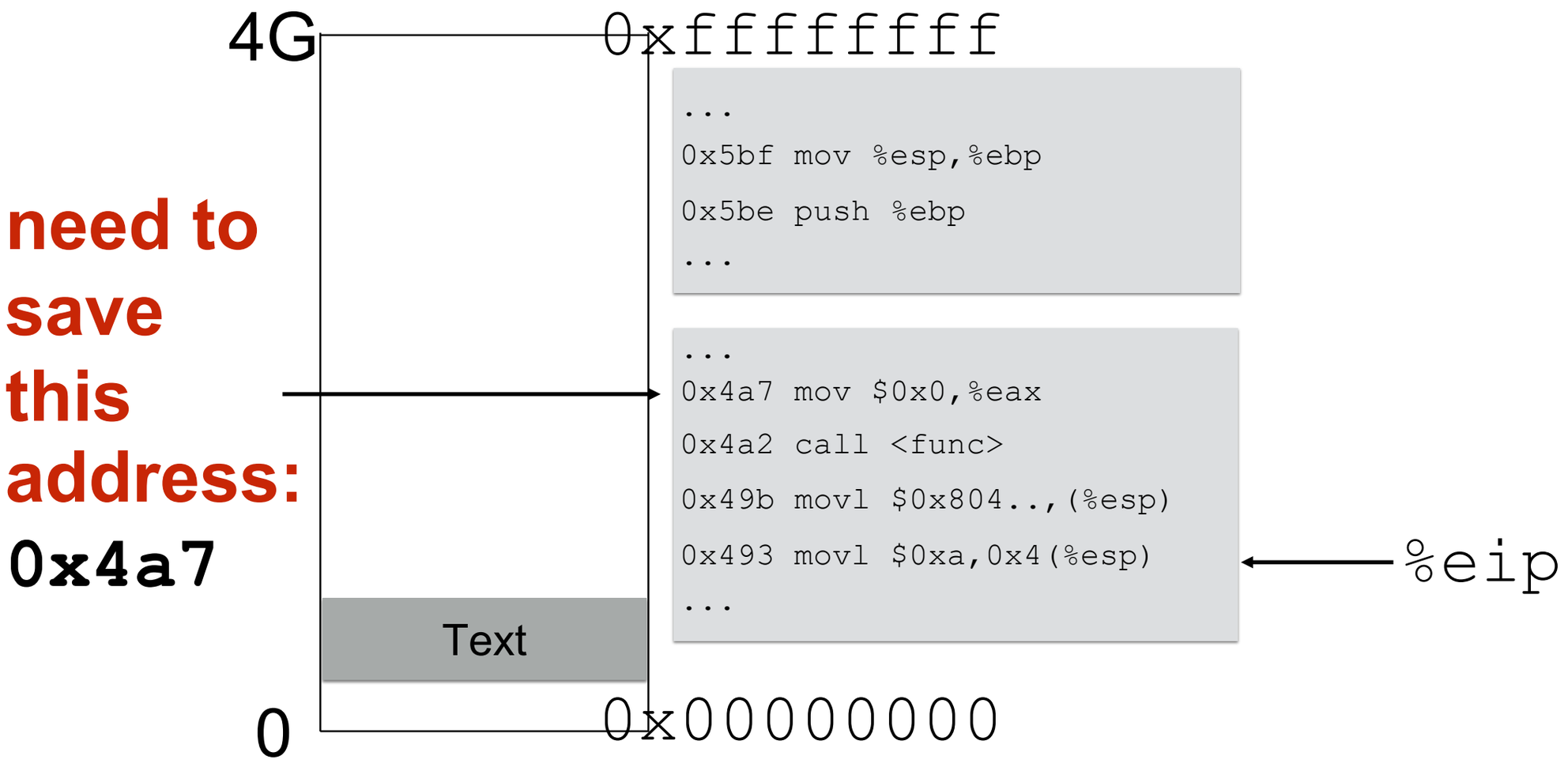
Returning from functions

```
int main()
{
    ...
    func("Hey", 10, -3);
    ...
}
```

Q: How do we resume here?



Instructions in memory



Returning from functions

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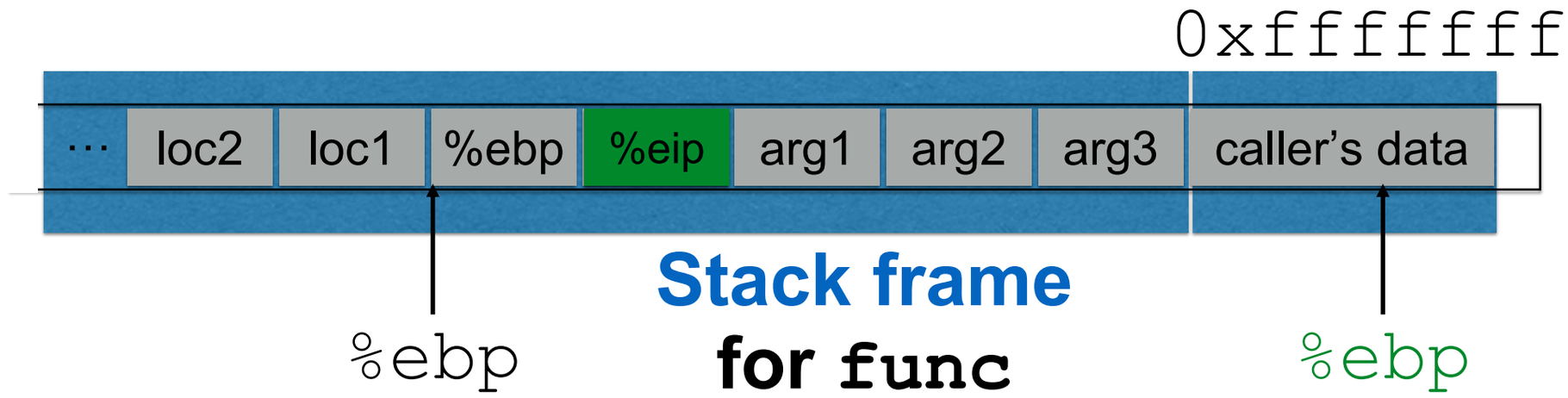


Set `%eip` to `4(%ebp)` at return

Push next `%eip` before `call`

Stack and functions: Summary

Calling function:

1. **Push arguments** onto the stack (in reverse)
2. **Push the return address**, i.e., the address of the instruction you want run after control returns to you
3. **Jump** to the function's address

Called function:

4. **Push the old frame pointer** onto the stack: %ebp
5. **Set frame pointer** to where the end of the stack is right now: %ebp = %esp
6. **Push local variables** onto the stack

Returning from function:

7. **Reset the previous stack frame**: %esp = %ebp, pop %ebp
8. **Jump back** to return address: pop %eip

http://rustedreality.com/stack-overflow/

Buffer overflows

Buffer overflows from 10,000 ft

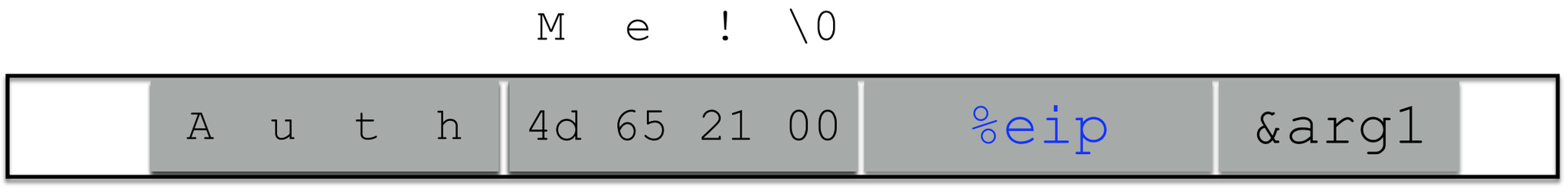
- **Buffer =**
  - Contiguous memory associated with a variable or field
  - Common in C
    - All strings are (NUL-terminated) arrays of `char`'s
- **Overflow =**
  - Put more into the buffer than it can hold
- Where does the overflowing data **go**?
  - Well, now that you are experts in memory layouts…

Benign outcome

```
void func(char *arg1)
{
    char buffer[4];
    strcpy(buffer, arg1);
    ...
}

int main()
{
    char *mystr = "AuthMe!";
    func(mystr);
    ...
}
```

Upon return, sets `%ebp` to `0x0021654d`



SEGFAULT (0x00216551)

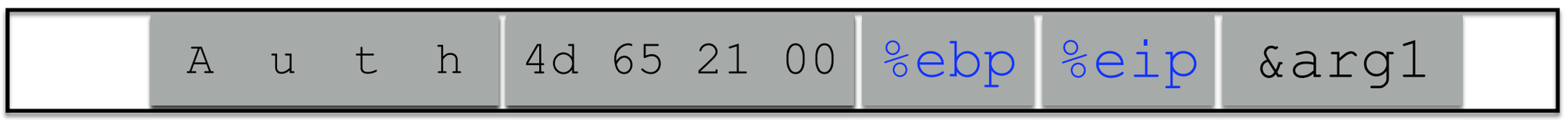
Security-relevant outcome

```
void func(char *arg1)
{
    int authenticated = 0;
    char buffer[4];
    strcpy(buffer, arg1);
    if(authenticated) { ...
}

int main()
{
    char *mystr = "AuthMe!";
    func(mystr);
    ...
}
```

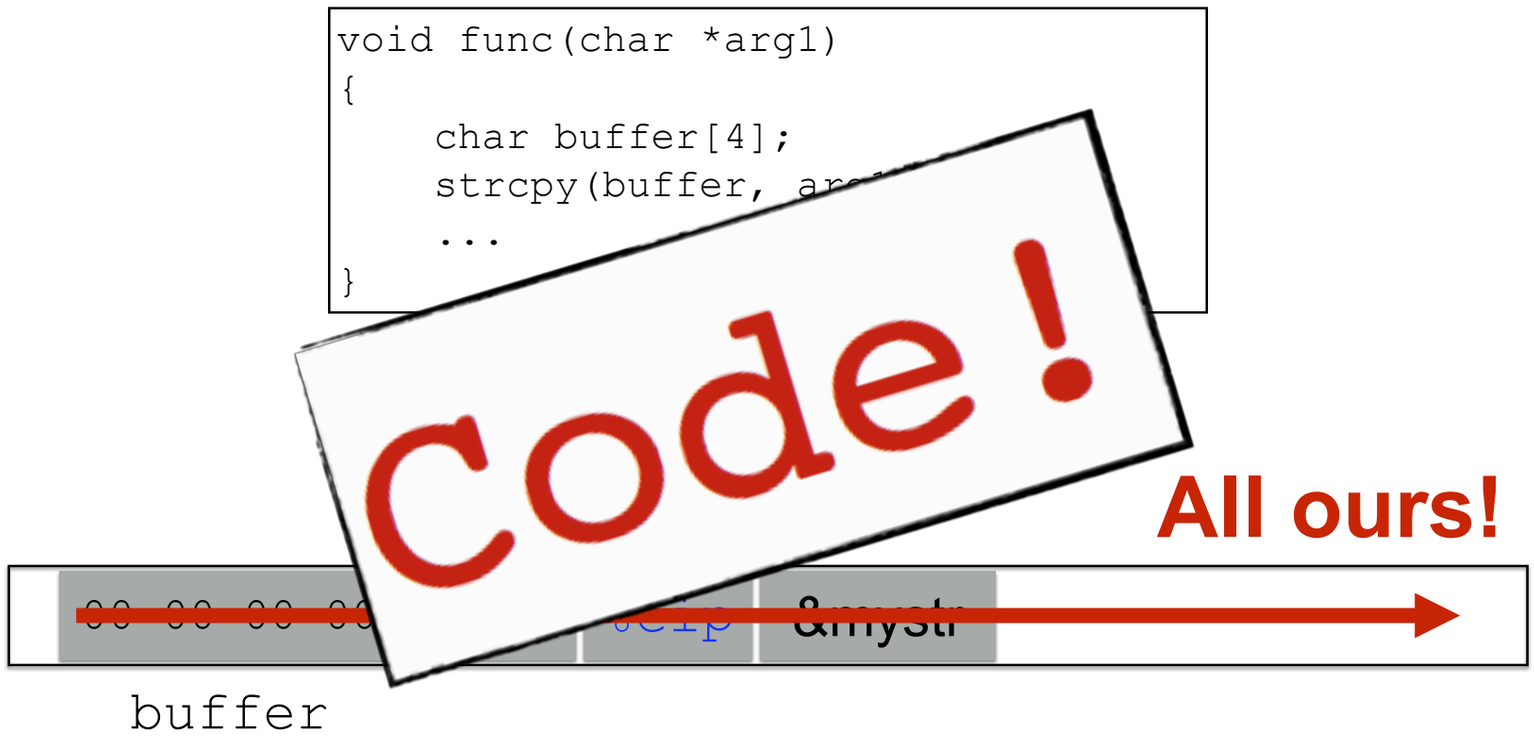
Code still runs; user now ‘authenticated’

M e ! \0



buffer authenticated

Could it be worse?



`strcpy` will let you write as much as you want (til a '\0')

What could you write to memory to wreak havoc?

Aside: User-supplied strings

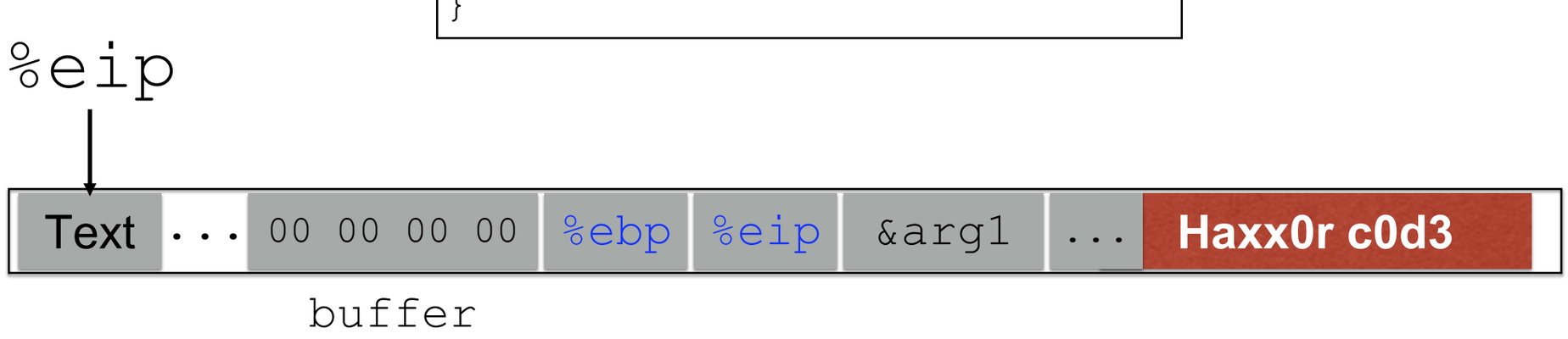
- These examples provide their own strings
- In reality strings come **from *users*** in myriad ways
  - Text input, packets, environment variables, file input…
- **Validating assumptions** about user input is critical!
  - We will discuss it later, and throughout the course

Code Injection

http://images.clipartpanda.com/injection-clipart-color-medical-injection-21941863.jpg

Code Injection: Main idea

```
void func(char *arg1)
{
    char buffer[4];
    sprintf(buffer, arg1);
    ...
}
```



(1) Load my own code into memory

(2) Somehow get `%eip` to point to it

Challenge 1
Loading code into memory

- It **must be the machine code** instructions (i.e., already compiled and ready to run)

- We have to be careful in how we construct it:
  - It **can't contain** any **all-zero bytes**
    - Otherwise, sprintf / gets / scanf / … will stop copying
    - How to write assembly to never contain a full zero byte?
  - It **can't use the loader** (we're injecting)
    - How to find addresses we need?

What code to run?

- One goal: **general-purpose shell**
  - Command-line prompt that gives attacker **general access to the system**
- The code to launch a shell is called **shellcode**
- Other stuff you could do?

Shellcode

```
#include <stdio.h>
int main( ) {
   char *name[2];
   name[0] = "/bin/sh";
   name[1] = NULL;
   execve(name[0], name, NULL);
}
```

filename

argv

envp

xor to avoid zero byte

Assembly

```
xorl %eax, %eax
pushl %eax
pushl $0x68732f2f
pushl $0x6e69622f
movl %esp,%ebx
pushl %eax
...
```

```
"\x31\xc0"
"\x50"
"\x68" "//sh"
"\x68" "/bin"
"\x89\xe3"
"\x50"
...
```

Machine code

(Part of) your input

Challenge 2

Getting injected code to run

- We have code somewhere in memory
  - We don't know precisely where
- We need to move %eip to point at it

Recall

Stack and functions: Summary

Calling function:

1. **Push arguments** onto the stack (in reverse)
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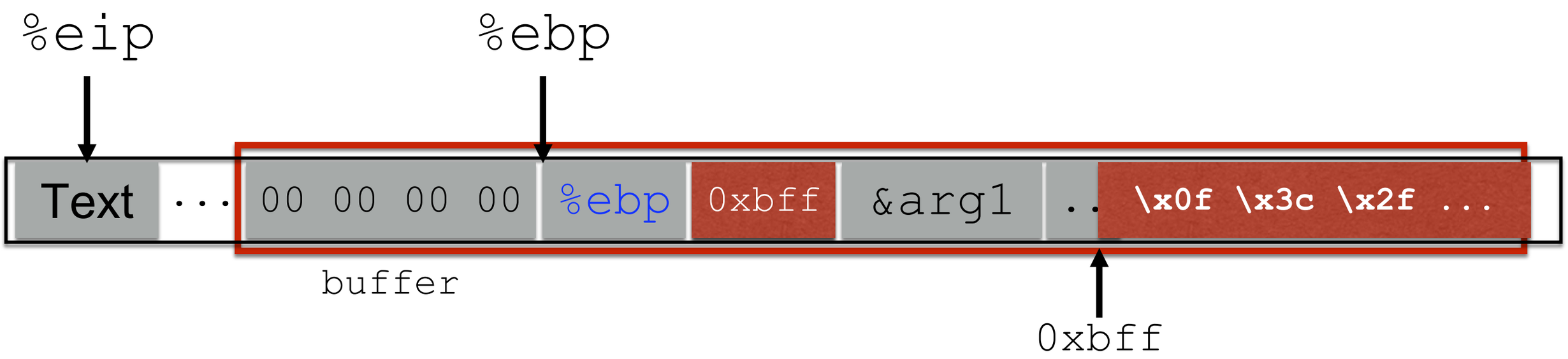
Returning from function:

7. **Reset the previous stack frame**: %esp = %ebp, pop %ebp
8. **Jump back** to return address: pop %eip

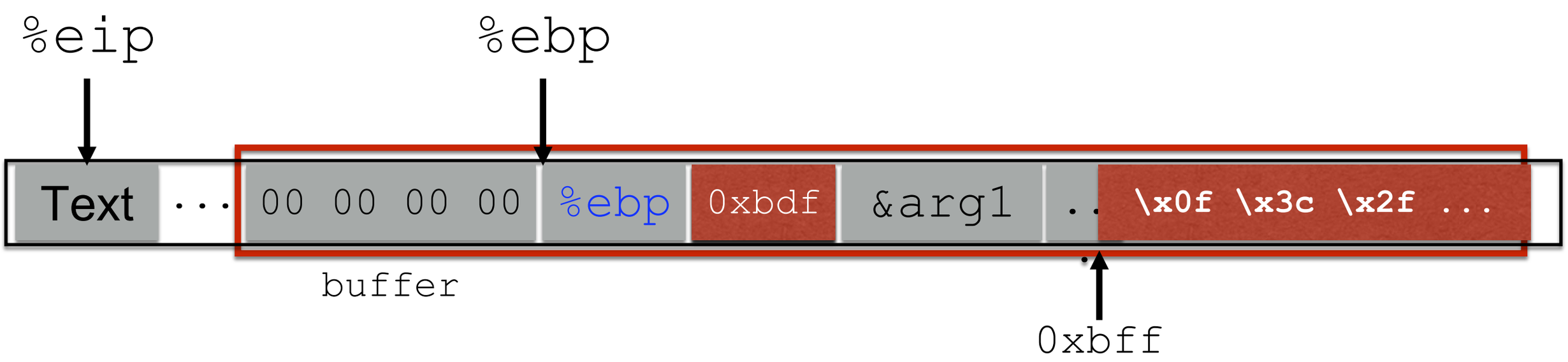
Hijacking the saved %eip



But how do we know the address?

Hijacking the saved %eip

What if we are wrong?



This is most likely data, so the CPU will panic (Invalid Instruction)

Challenge 3

Finding the return address

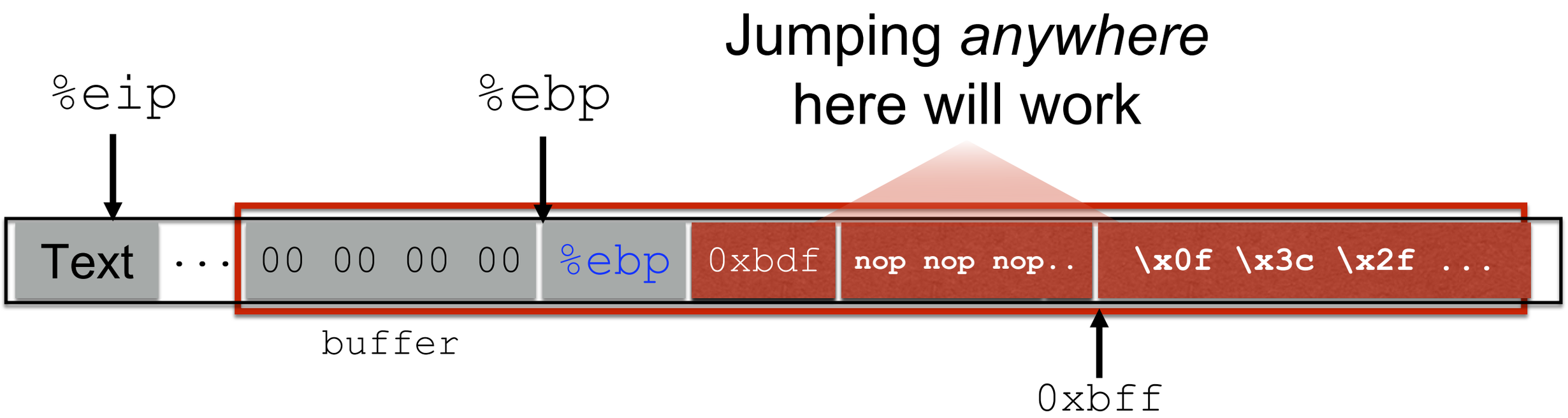
- If we don't have access to the code, we don't know how far the buffer is from the saved `%ebp`

- One approach: try a lot of different values!
  - Worst case scenario: it's a 32 (or 64) bit memory space, which means 2^{32} (2^{64}) possible answers

- Without address randomization (discussed later):
  - Stack **always** starts from the same **fixed address**
  - Stack will grow, but usually it **doesn't grow very deeply** (unless the code is heavily recursive)

Improving our chances: `nop` sleds

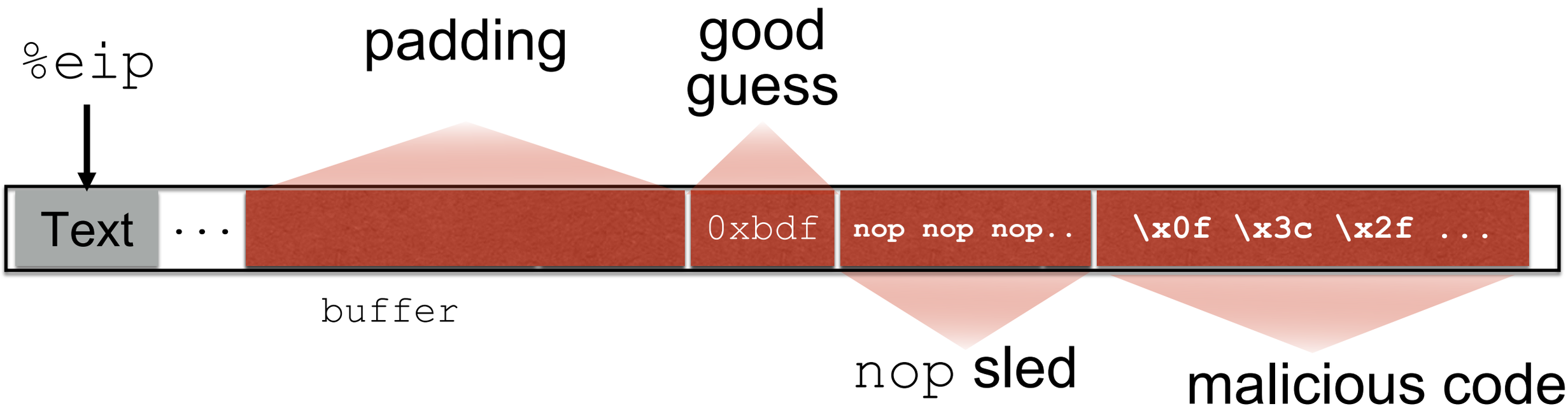
`nop` is a single-byte no-op instruction
(just moves to the next instruction)



Now we improve our chances of guessing by a factor of #nops

Putting it all together

Fill in the space between the target buffer and the `%eip` to overwrite



gdb tutorial

Your new best friends

```
i f
```

Show **info** about the current **frame**
(prev. frame, locals/args, %ebp/%eip)

```
i r
```

Show **info** about **reg**isters
(%eip, %ebp, %esp, etc.)

```
x/<n> <addr>
```

E**x**amine <n> bytes of memory
starting at address <addr>

```
b <function>
s
```

Set a **b**reakpoint at <function>
step through execution (into calls)