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

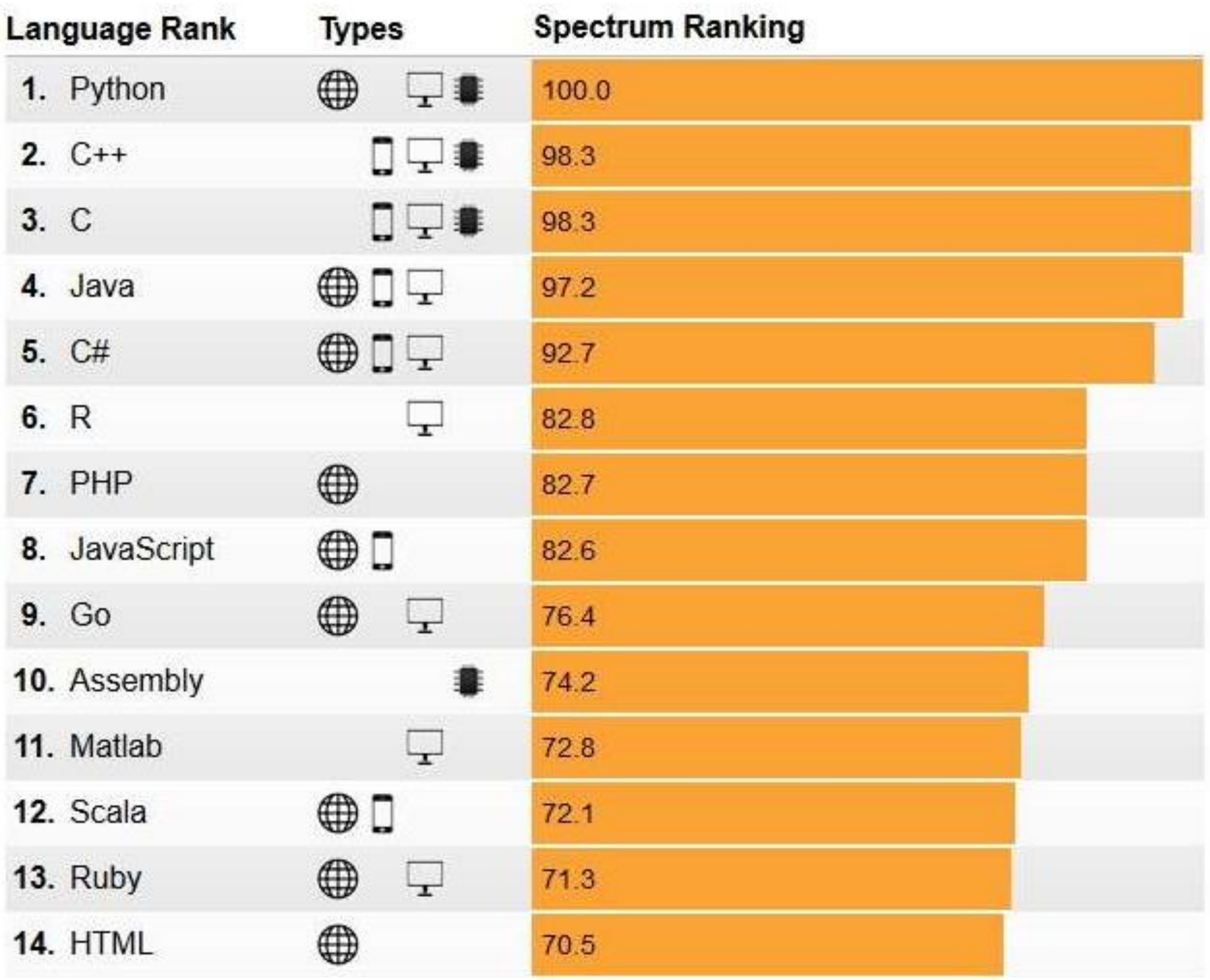
What is a buffer overflow?

- 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

Why study them?

- Buffer overflows are still **relevant** today
  - C and C++ are still popular
  - Buffer overflows still occur with regularity
- They have a **long history**
  - Many different approaches developed to defend against them, and bugs like them
- They share **common features** with other bugs we will study
  - In **how the attack works**
  - In **how to defend against it**

C and C++ still very popular



https://spectrum.ieee.org/at-work/innovation/the-2018-top-programming-languages

Critical systems in C/C++

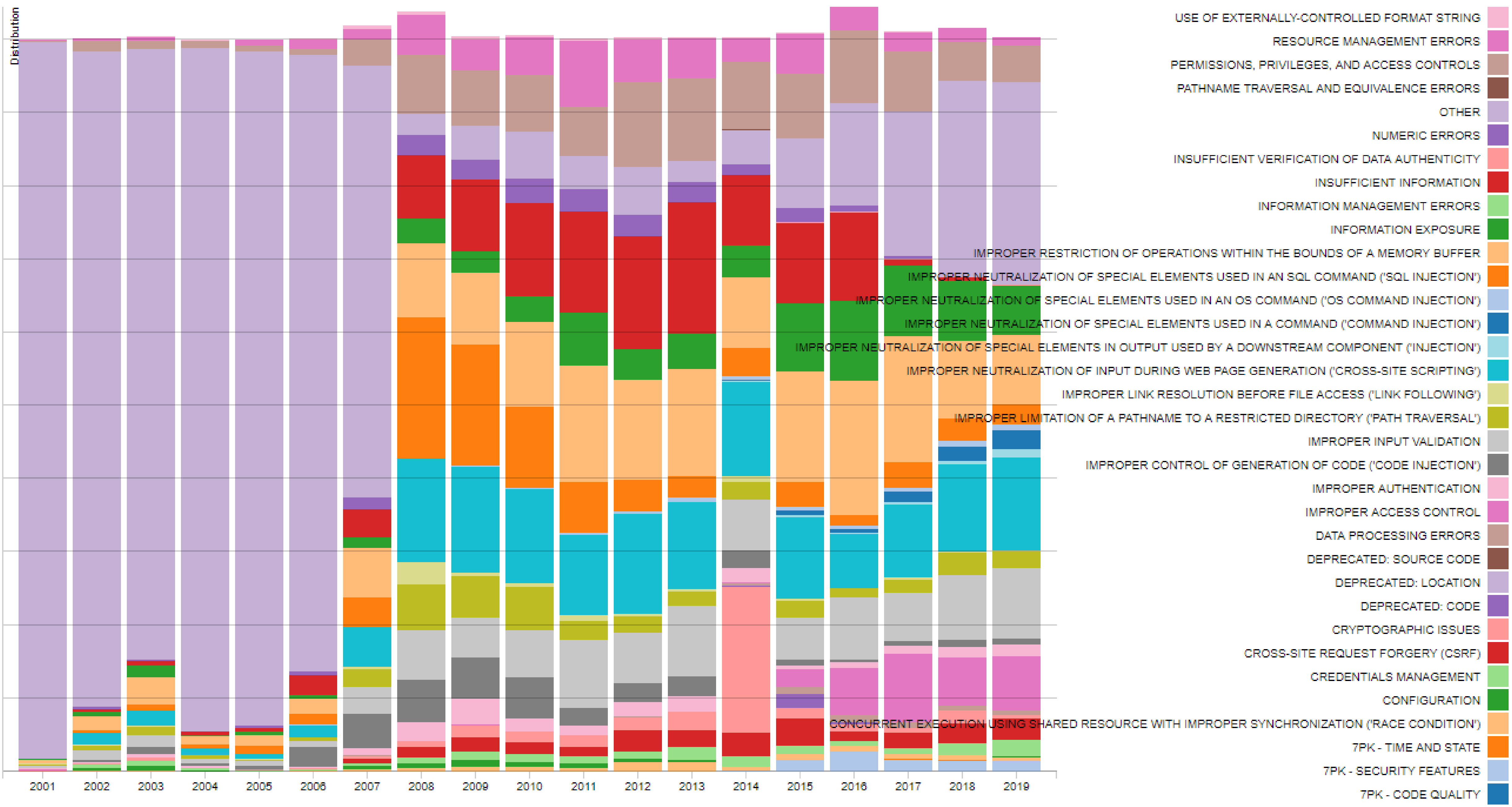
- Most **OS kernels** and utilities
  - fingerd, X windows server, shell
- Many **high-performance servers**
  - Microsoft IIS, Apache httpd, nginx
  - Microsoft SQL server, MySQL, redis, memcached
- Ma
  - Mars rover, industrial control systems, automobiles, healthcare devices, IoT

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

WhatsApp Buffer Overflow Vulnerability Reportedly Exploited In The Wild

JT Keating | Threat Research | May 15 2019 |

83 SHARES Facebook Twitter LinkedIn

A new WhatsApp vulnerability has attracted the attention of the press and security professionals around the world. Zimperium zLabs will be creating a detailed blog soon, but we wanted to provide our readers with preliminary information now.

Zero-day vulnerability announced byMcAfee at Defcon

Richard Harris in **Security** Monday, August 19, 2019

3,387

At DEFCON, McAfee has announced the discovery of a zero-day vulnerability in a commonly used Delta industrial control system.

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The vulnerability found in the Delta enteliBUS Manager could allow malicious actors complete control of the operating

Boeing 787 On-Board Network Vulnerable to Remote Hacking, Researcher Says

Boeing disputes IOActive findings ahead of security firm's Black Hat USA presentation.

BLACK HAT USA – Las Vegas – IOActive industrial cybersecurity expert Ruben Santamarta last fall discovered an Internet-exposed Boeing Co. server housing firmware specifications for the aviation manufacturer's 787 and 737 airplane networks.

Intrigued, Santamarta dug into the firmware for the 787, Boeing's highly networked plane. He meticulously reverse-engineered the binary code and analyzed configuration files – uncovering multiple security vulnerabilities that could allow an attacker to remotely gain access to the sensitive avionics network of the aircraft, also known as the crew information systems network.

"It turns out the firmware I was analyzing is part of the aircraft that is segregating between the different networks," he told Dark Reading prior to publicly disclosing his findings here today. The firmware belongs to a core network component in the 787's network and was riddled with buffer overflow, memory corruption, stack overflows, and denial-of-service flaws that he says could be exploited by a hacker to remotely reach the aircraft's sensitive crew information systems network module.

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

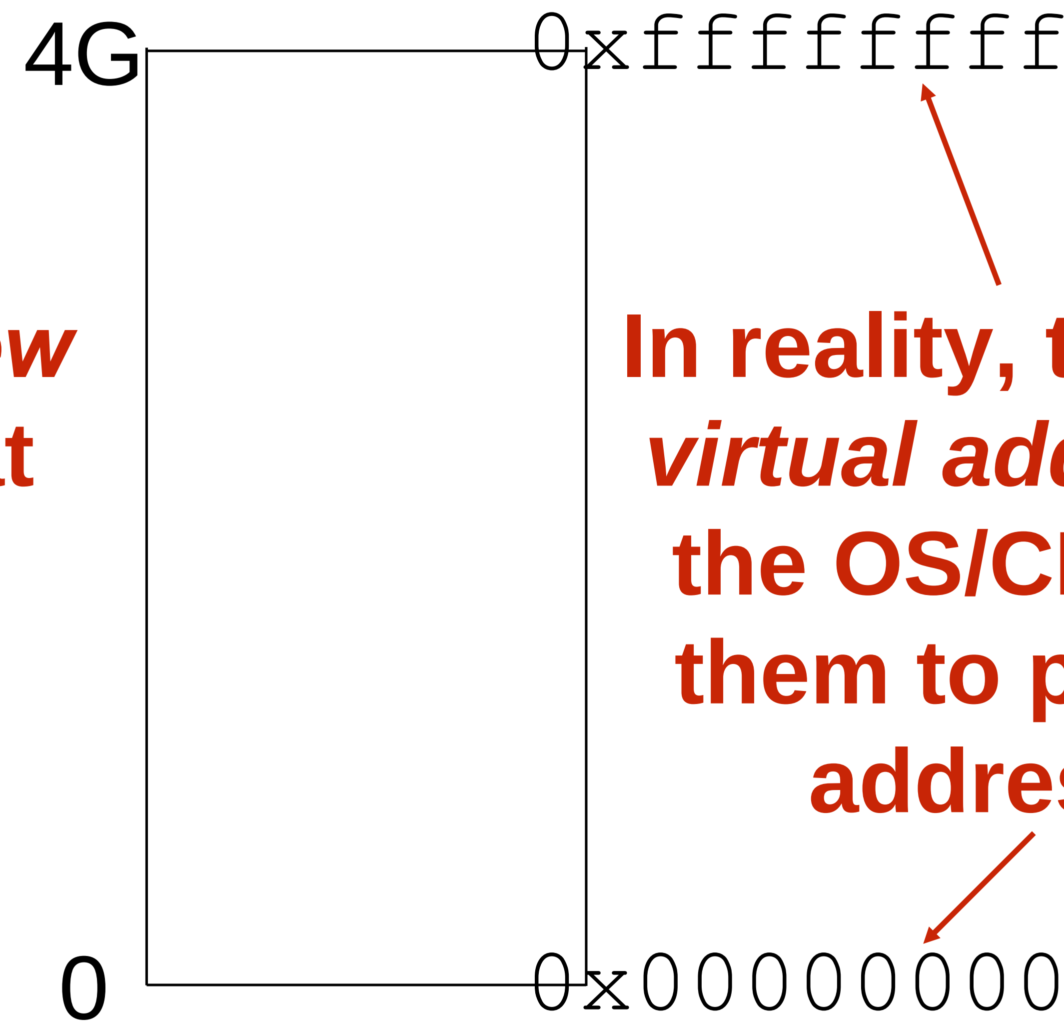
http://www.williesimpson.com/wp-content/uploads/2011/03/memory-lane.jpg

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

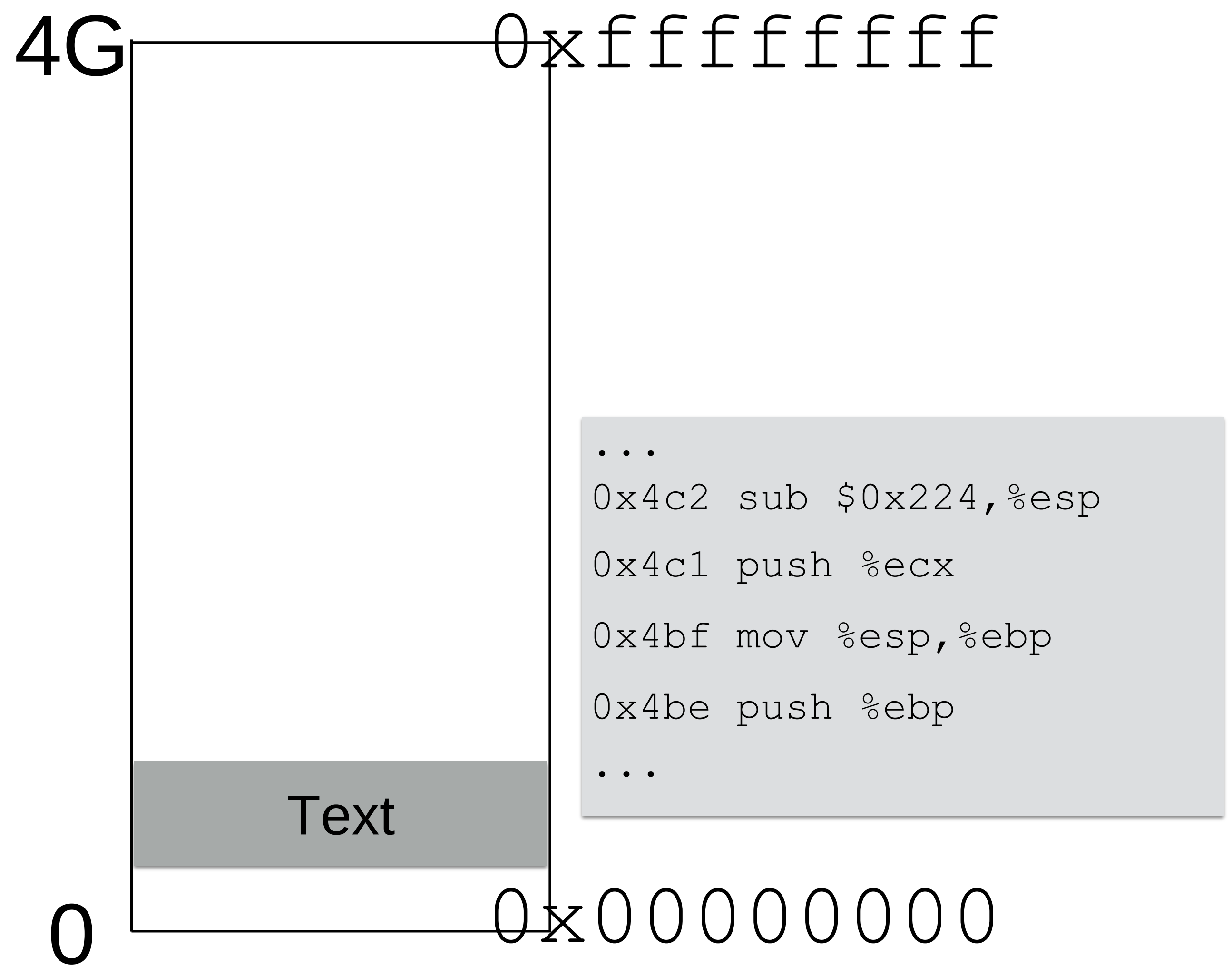
All programs stored in memory



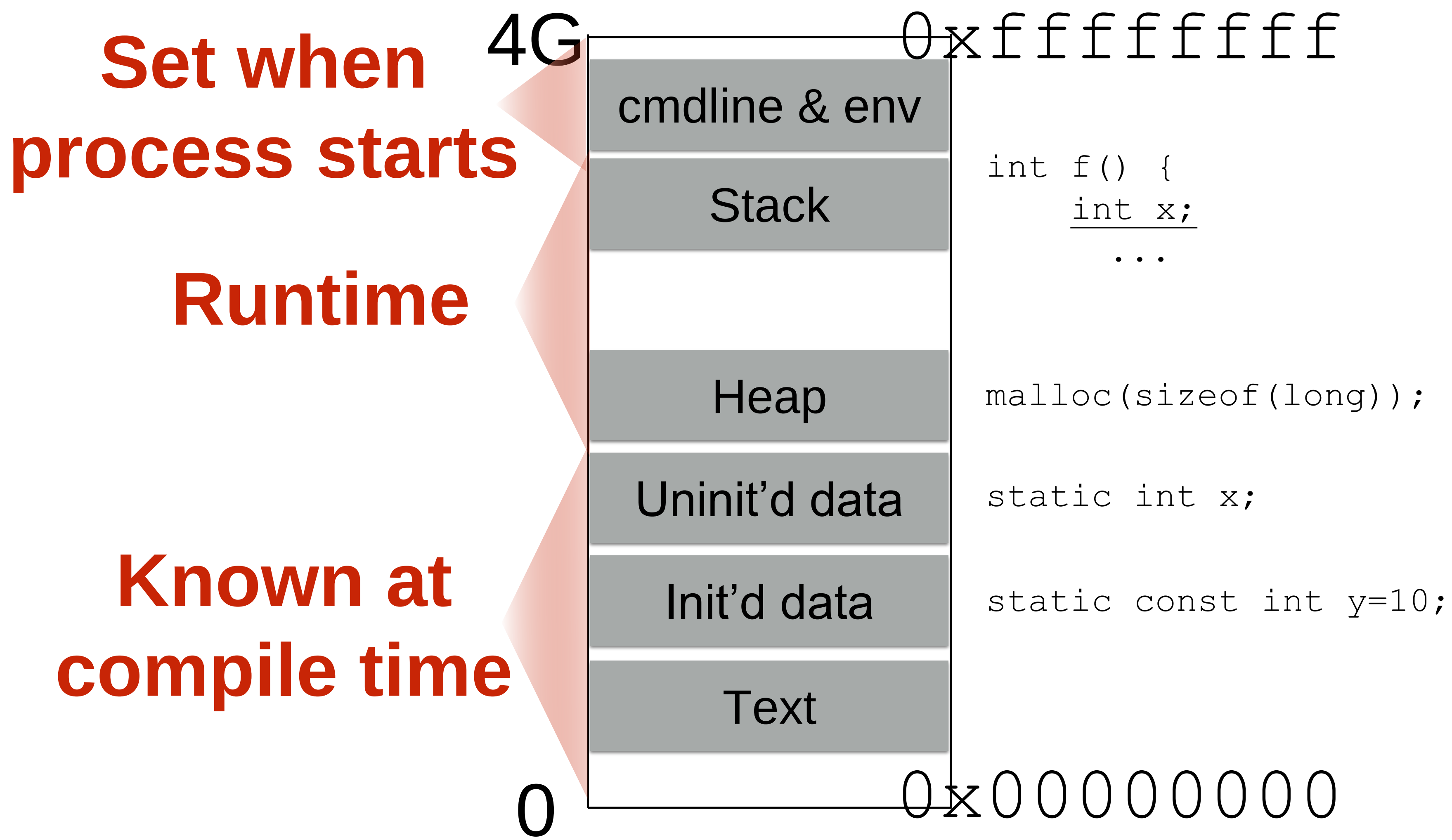
The *process's view* of memory is that it owns all of it

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

Program **instructions** are in memory



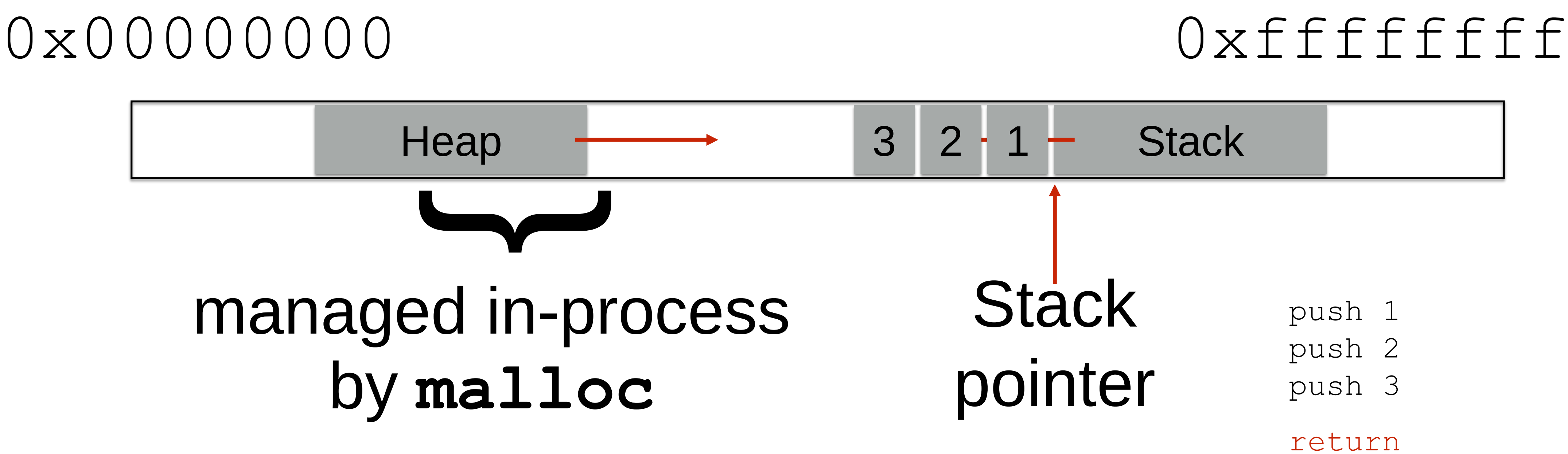
Location of data areas



Memory allocation

Stack and heap grow in opposite directions

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



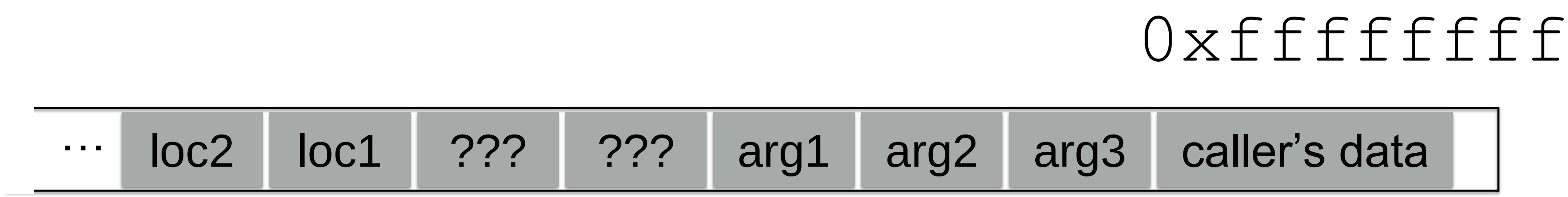
Focusing on the stack for now

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;
    ...
}
```



Local variables pushed in the same order as they appear in the code

Happens during callee

Arguments pushed in reverse order of code

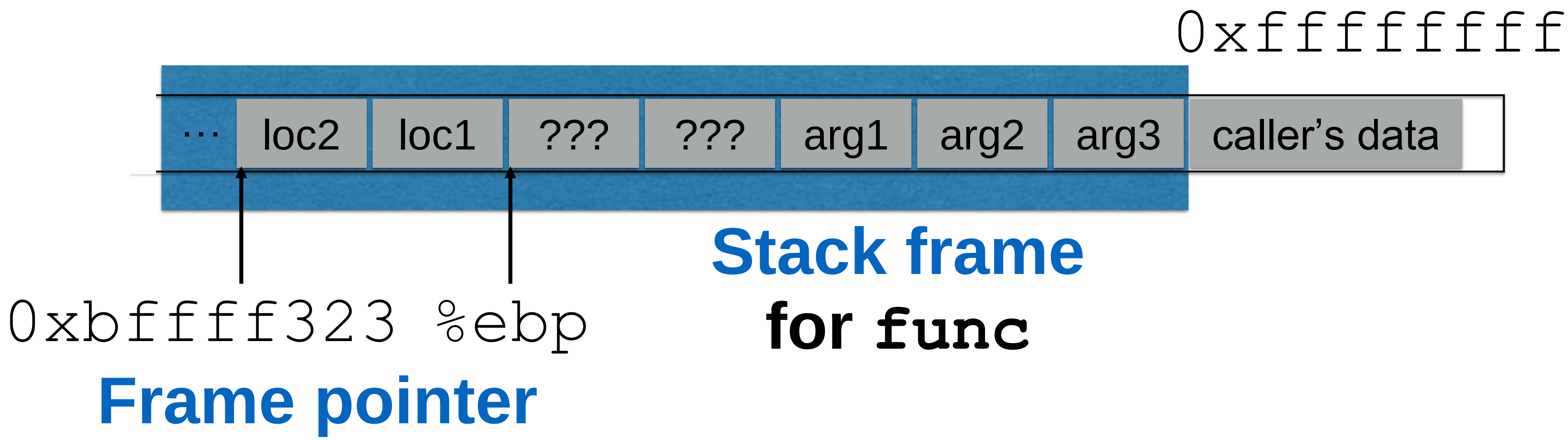
Happens during caller

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)



Can't know absolute address at compile time

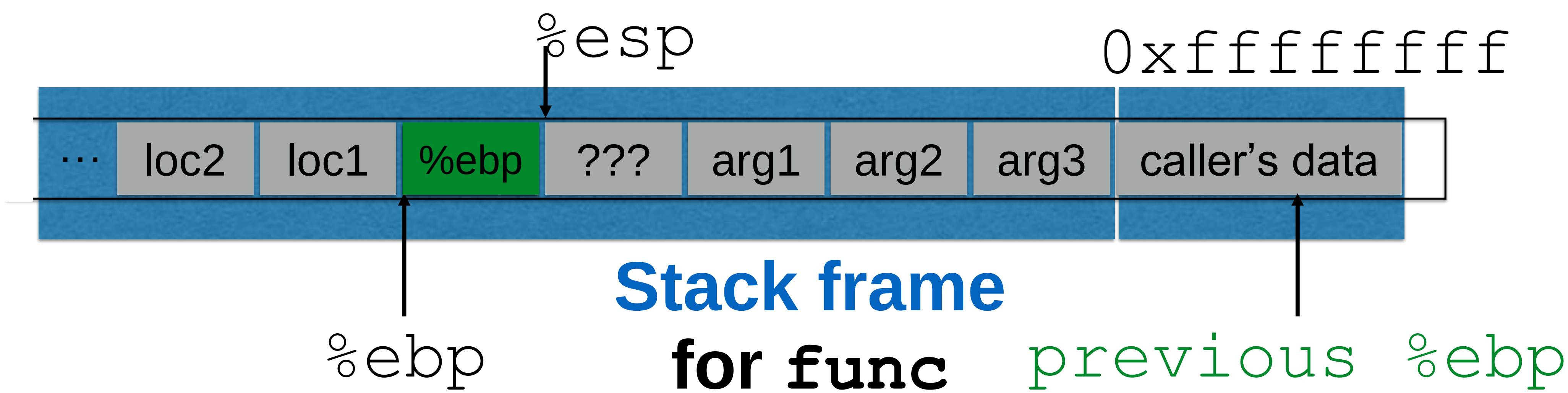
But can know the **relative** address

- **`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`

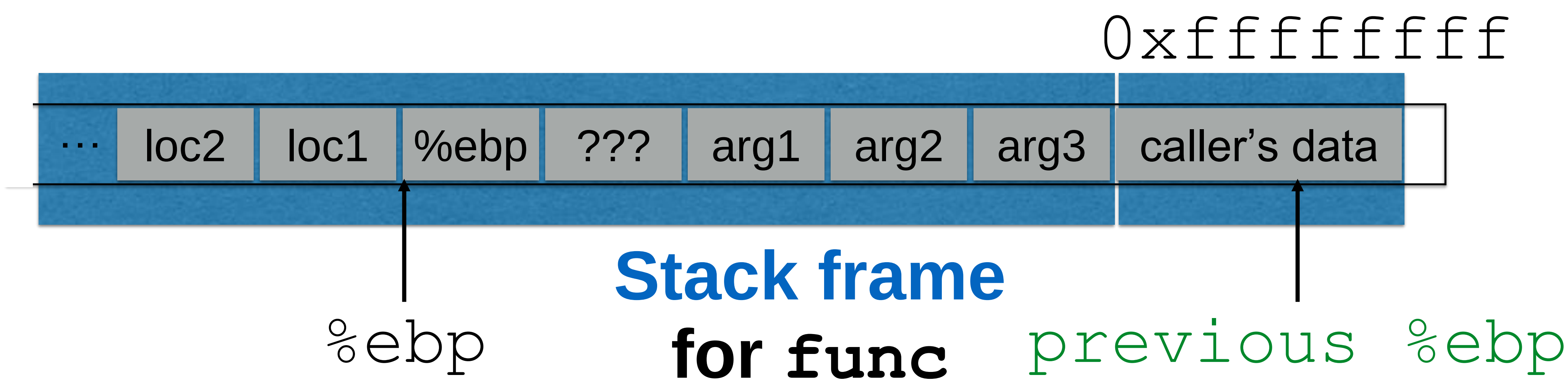
Set `%ebp` to current `%esp`

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

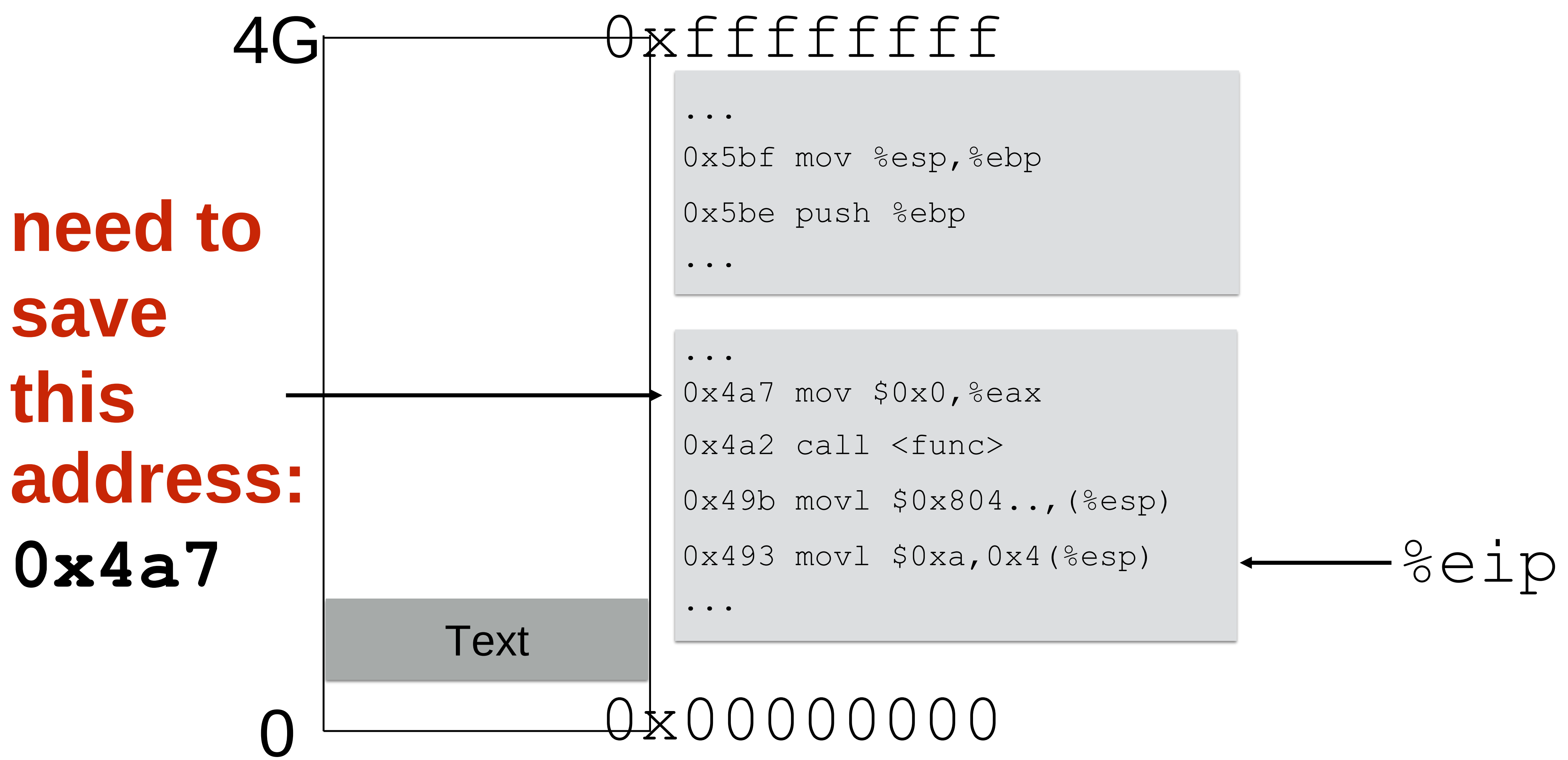
Returning from functions

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

Q: How do we resume here?



Instructions in memory



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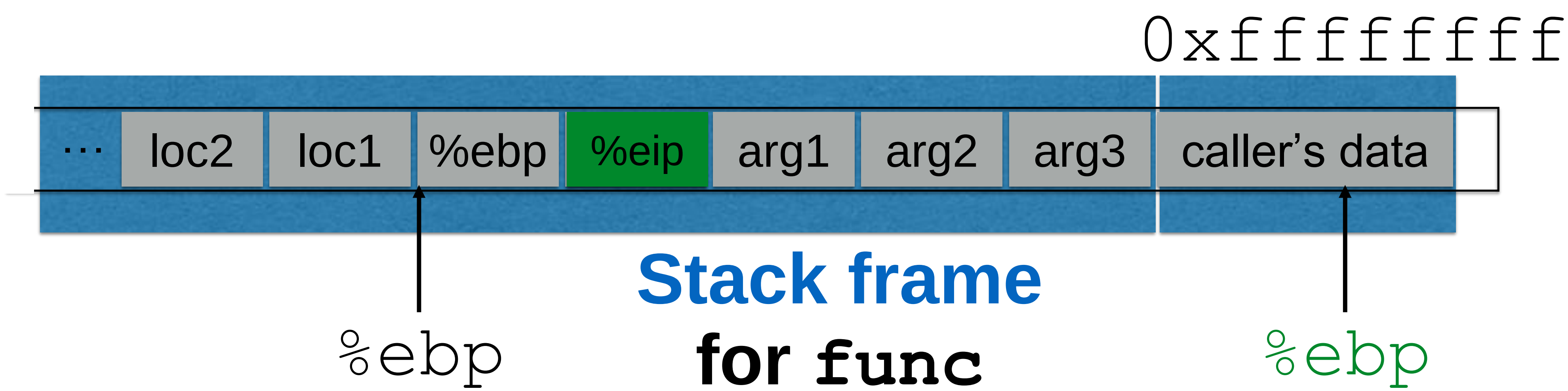


Set `%eip` to `4(%ebp)` at return

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

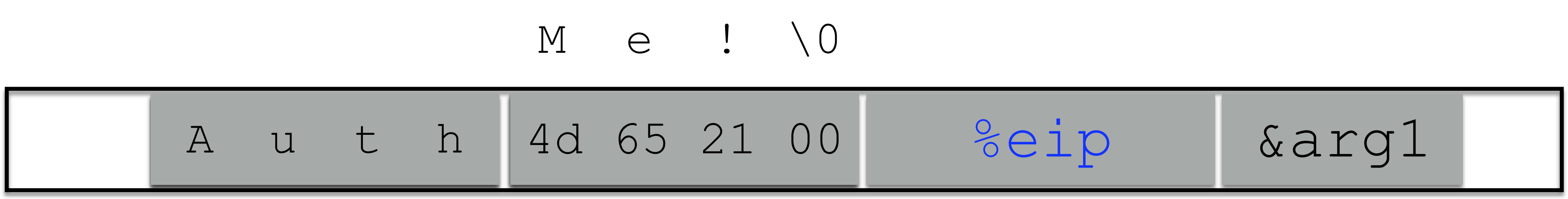
Buffer overflows from 10,000 ft

- **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`



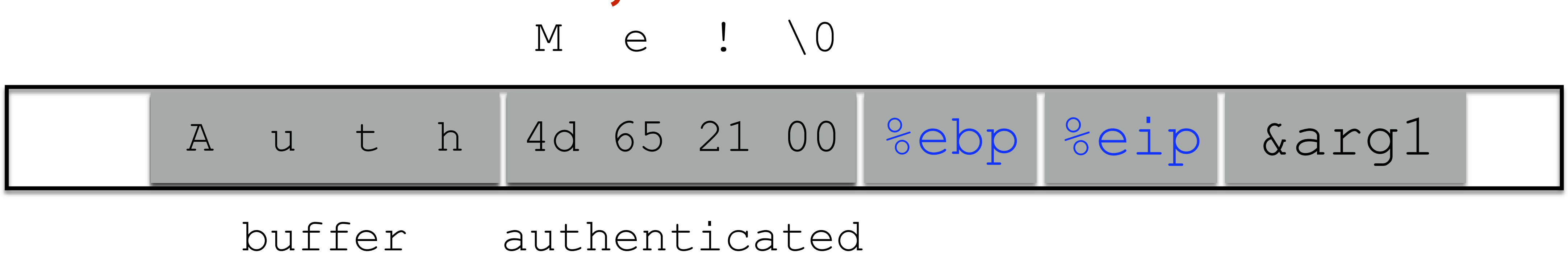
buffer

SEGFAULT (0x00216551)

Security-relevant outcome

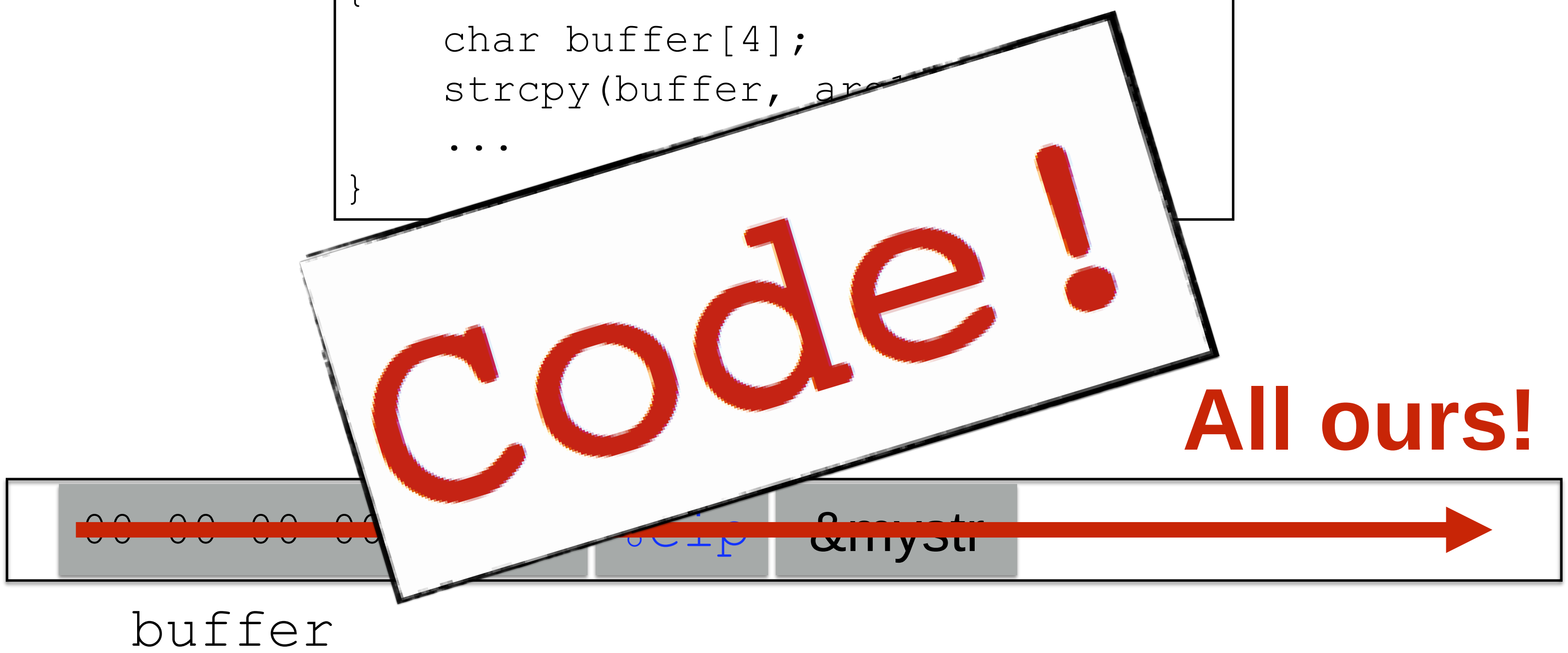
```
void func(char *arg1)
{
    int authenticated = 0;
    char buffer[4];
    strcpy(buffer, arg1);
    if(authenticated) { ...
}

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

Code still runs; user now 'authenticated'



Could it be worse?

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



`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

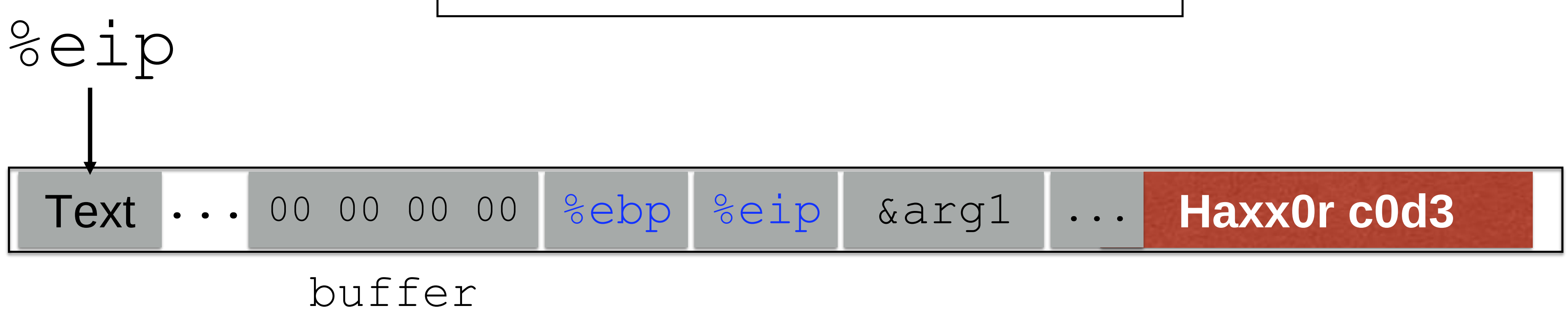
- These examples provide their own strings
- In reality strings come **from *users*** in myriad ways
  - Text input, packets, environment variables, file input…
- **Validating assumptions** about user input is critical!
  - We will discuss it later, and throughout the course

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
...
```

Machine code

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

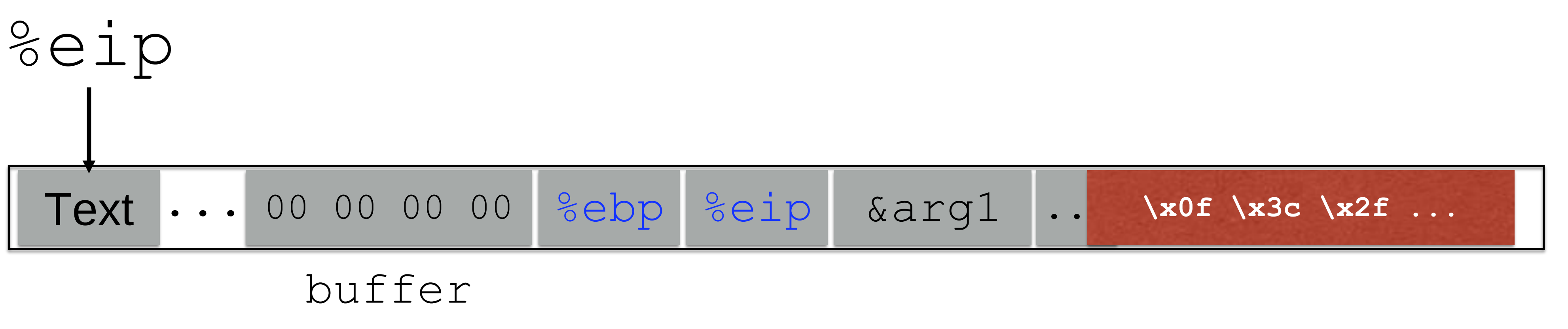
(Part of) your input

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

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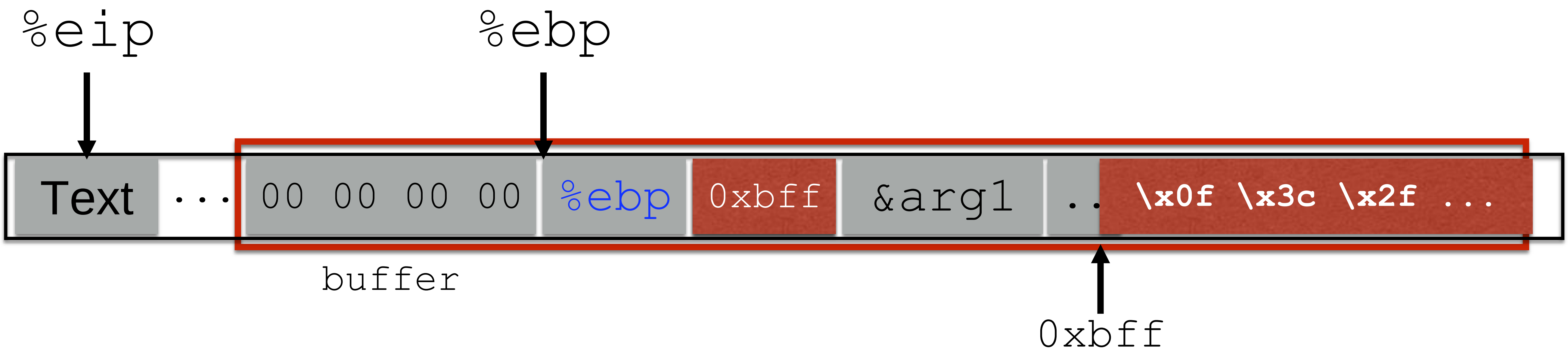
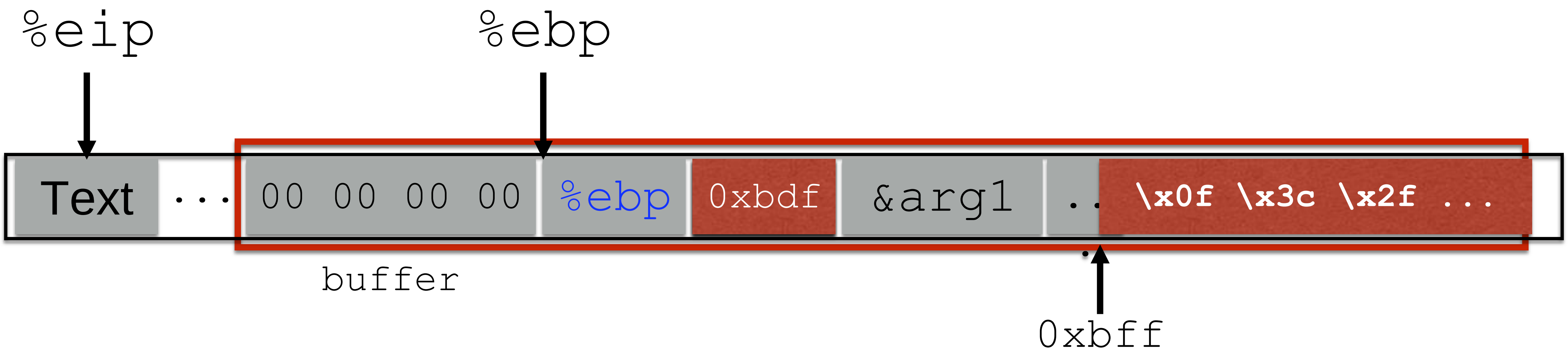
Hijacking the saved `%eip`



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

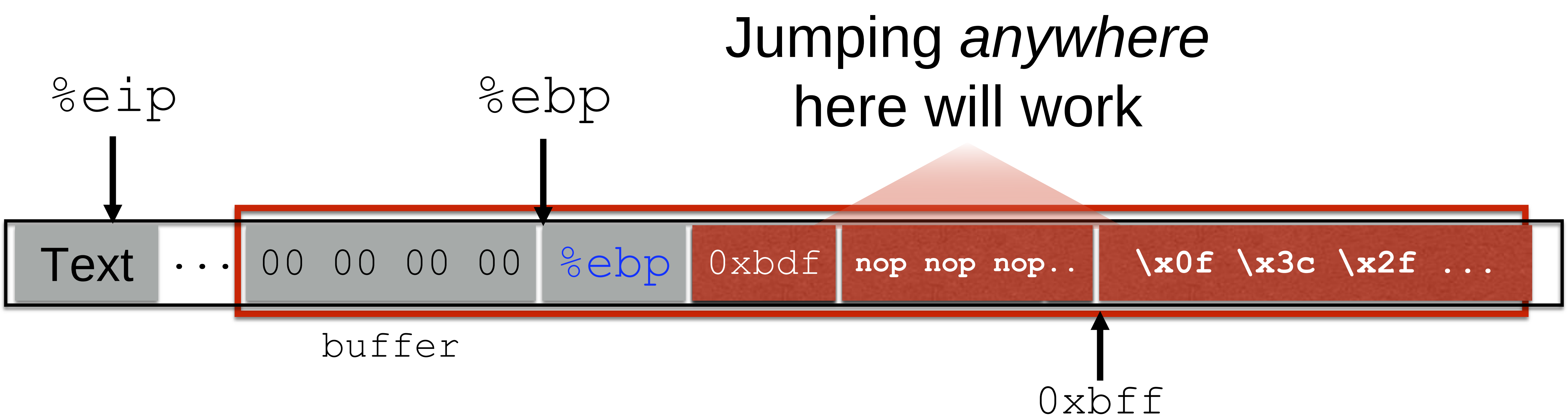
- If we don't have access to the code, we don't know how far the buffer is from the saved `%ebp`

- 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

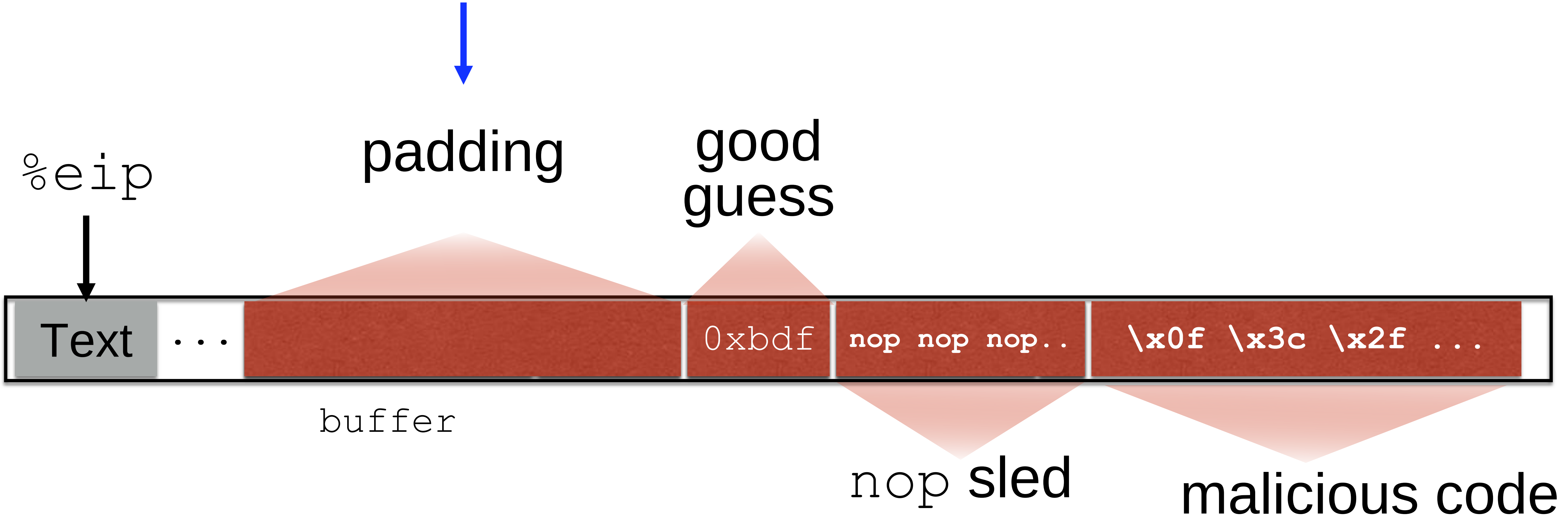
`nop` is a single-byte no-op instruction
(just moves to the next instruction)



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)