Software Security: Attacks & Defenses

CMSC 23200, Spring 2025, Lecture 3

Grant Ho

University of Chicago

Logistics

Assignment 1 Due on Thursday, 11:59pm

- Part A: Write-up submitted to Gradescope
- Part B: Write-up submitted to Gradescope & Code Files to Canvas
- **Both parts & all components must be submitted on time**

- Make sure you can SSH into your Course VM: ***no extensions*** will be given for SSH login issues, so post on Ed by today if you have SSH issues.

Discussion Section #1: tomorrow (Wed) @ assigned section times

- Must fill out & submit attendance form in-person

Today's Class

1. **Memory Safety Attacks**:
   How can attackers exploit software bugs to force a program to run code or commands they want?

2. **Memory Safety Protections**:
   How can we prevent these kinds of software attacks or minimize the damage they can do?

Outline: Memory Safety: Attacks & Defenses

1. Review: Memory layout and function calls in a process
2. Attacks:
    1. Stack-based buffer overflow attacks
    2. Heap vulnerabilities (briefly)
3. Defenses:
    1. Stack Canaries
    2. Address-Space Layout Randomization (ASLR)
    3. W ^ X and ROP
    4. Fuzzing and Memory Safe Languages

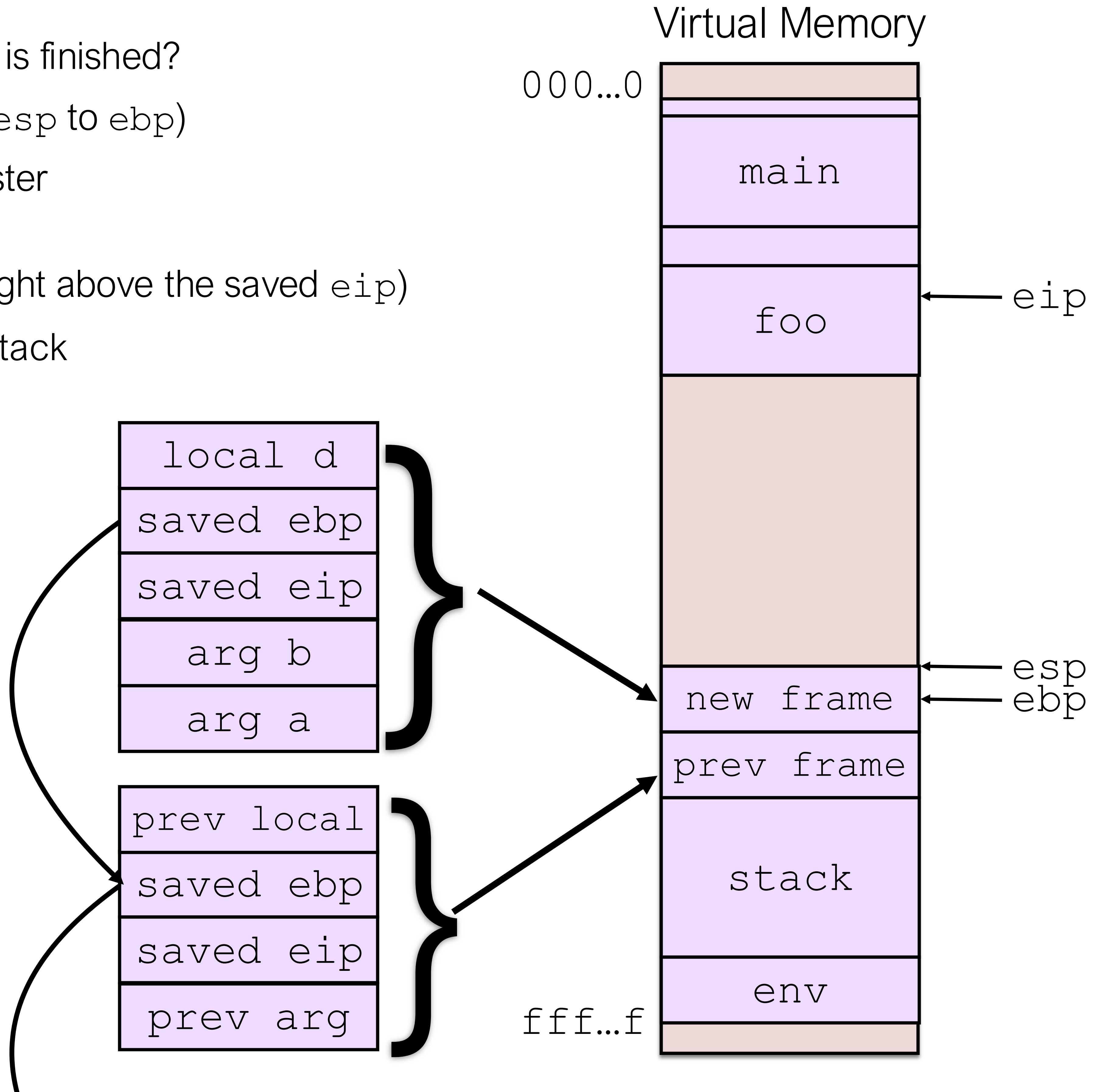
Returning from a function

What happens after code of `foo(a,b)` is finished?

- Pop the function’s stack frame (move `esp` to `ebp`)
- Pop (moves) saved `ebp` into `ebp` register
- RET: Pop saved `eip` into `eip` register
  (CPU assumes `ebp` was pointing right above the saved `eip`)
- Caller (main) pops foo’s arg from the stack

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

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

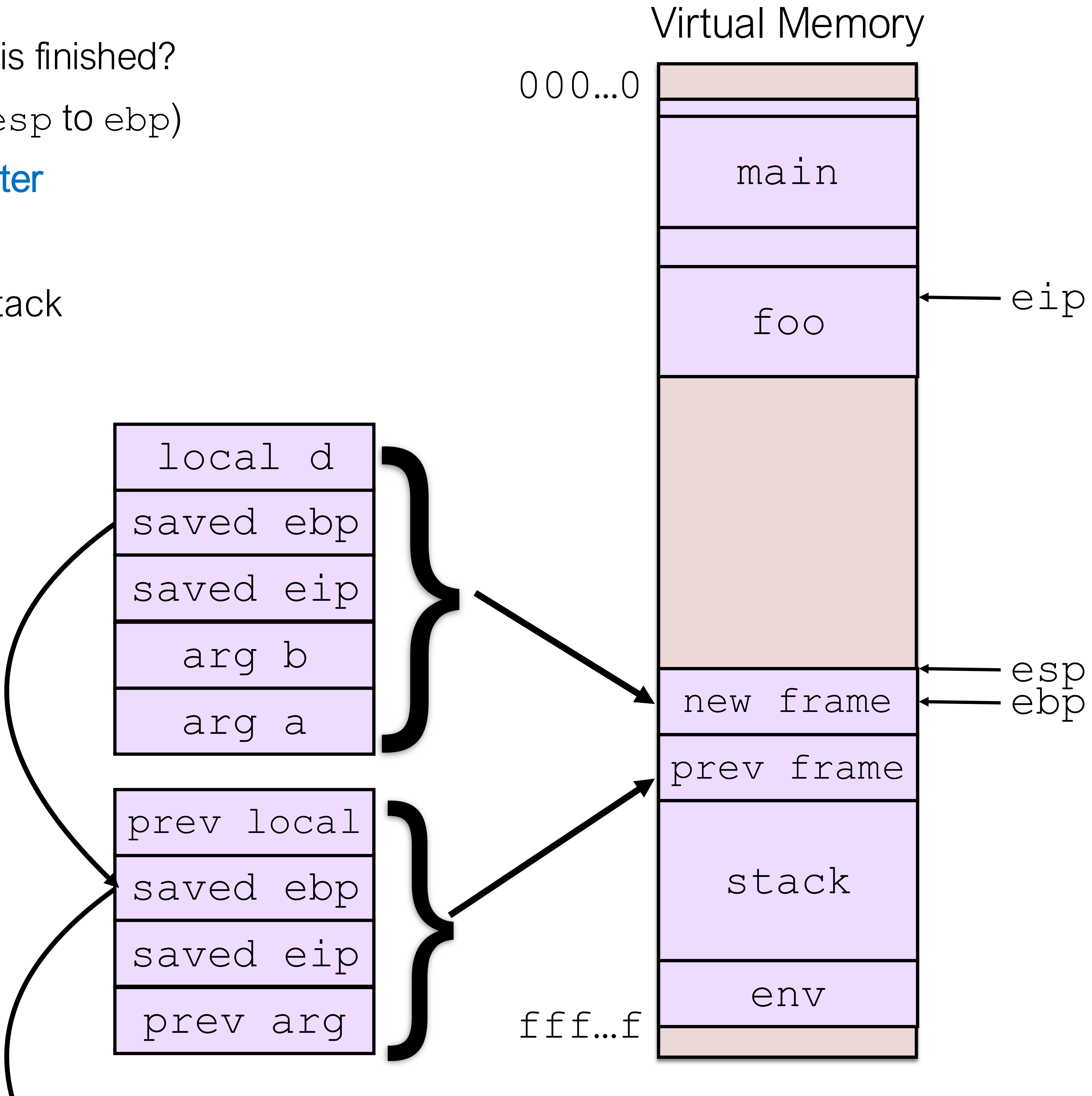


Returning from a function

What happens after code of `foo(a,b)` is finished?

- Pop the function's stack frame (move `esp` to `ebp`)
- Pop (moves) saved **`ebp`** into **`ebp`** register
- RET: Pop saved **`eip`** into **`eip`** register
- Caller (main) pops foo's arg from the stack

Key Point:
The CPU determines what code & data to execute next, based on values stored on the stack



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Classic Attack: 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);
}
```

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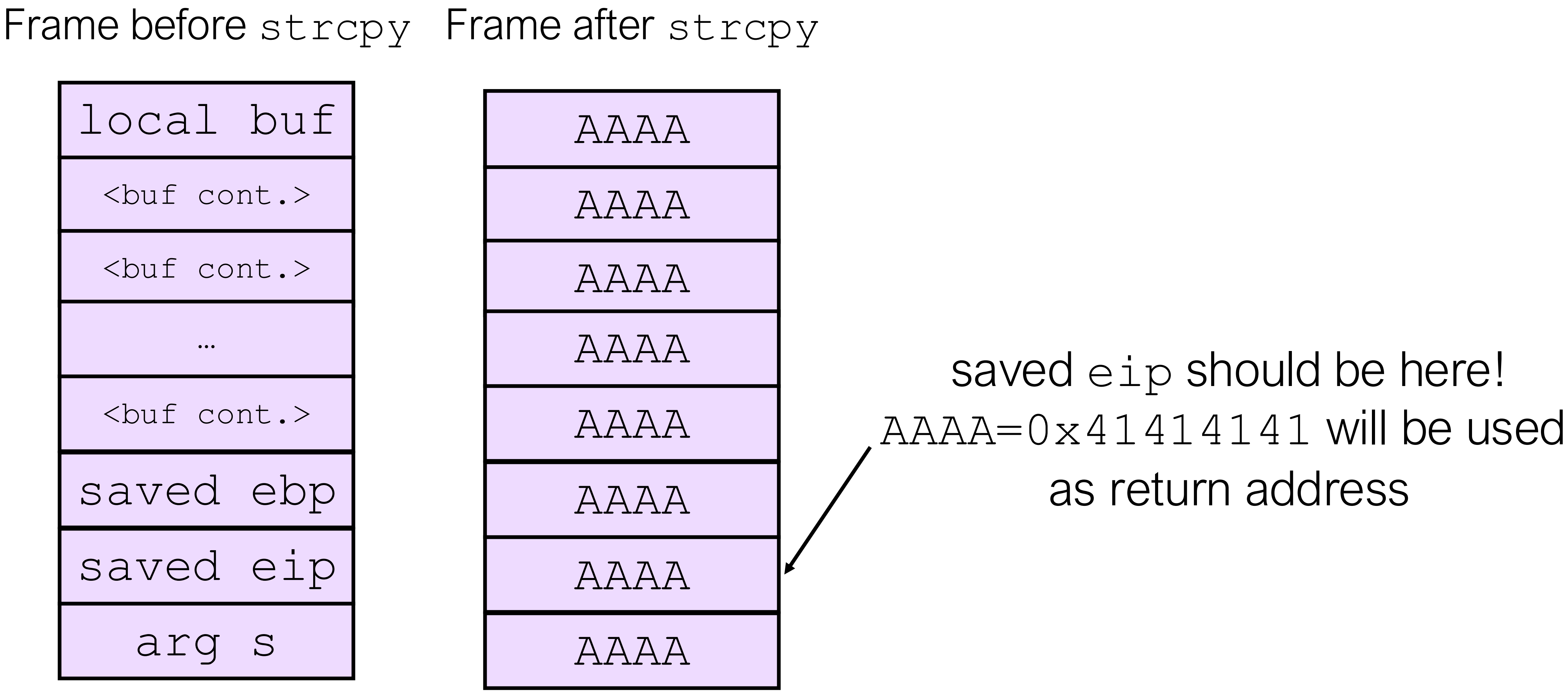
```
void bad(char *s)  {
  char buf[64];
  strcpy(buf, s);
}
```

`s="AAAA...AAAA"` (72 or more characters)



saved `eip` should be here!
`AAAA=0x41414141` will be used
as return address

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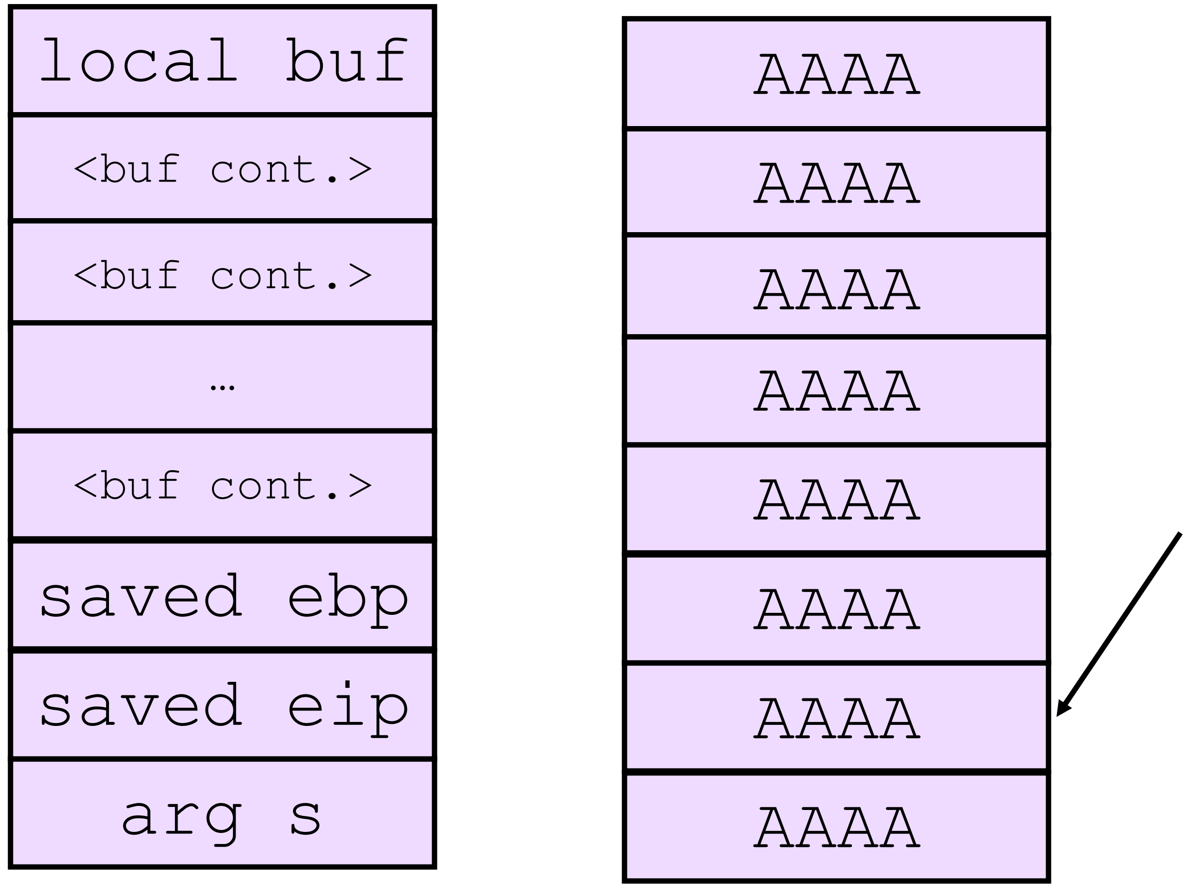
Frame before `strcpy` Frame after `strcpy`



saved `eip` should be here!
`AAAA=0x41414141` will be used
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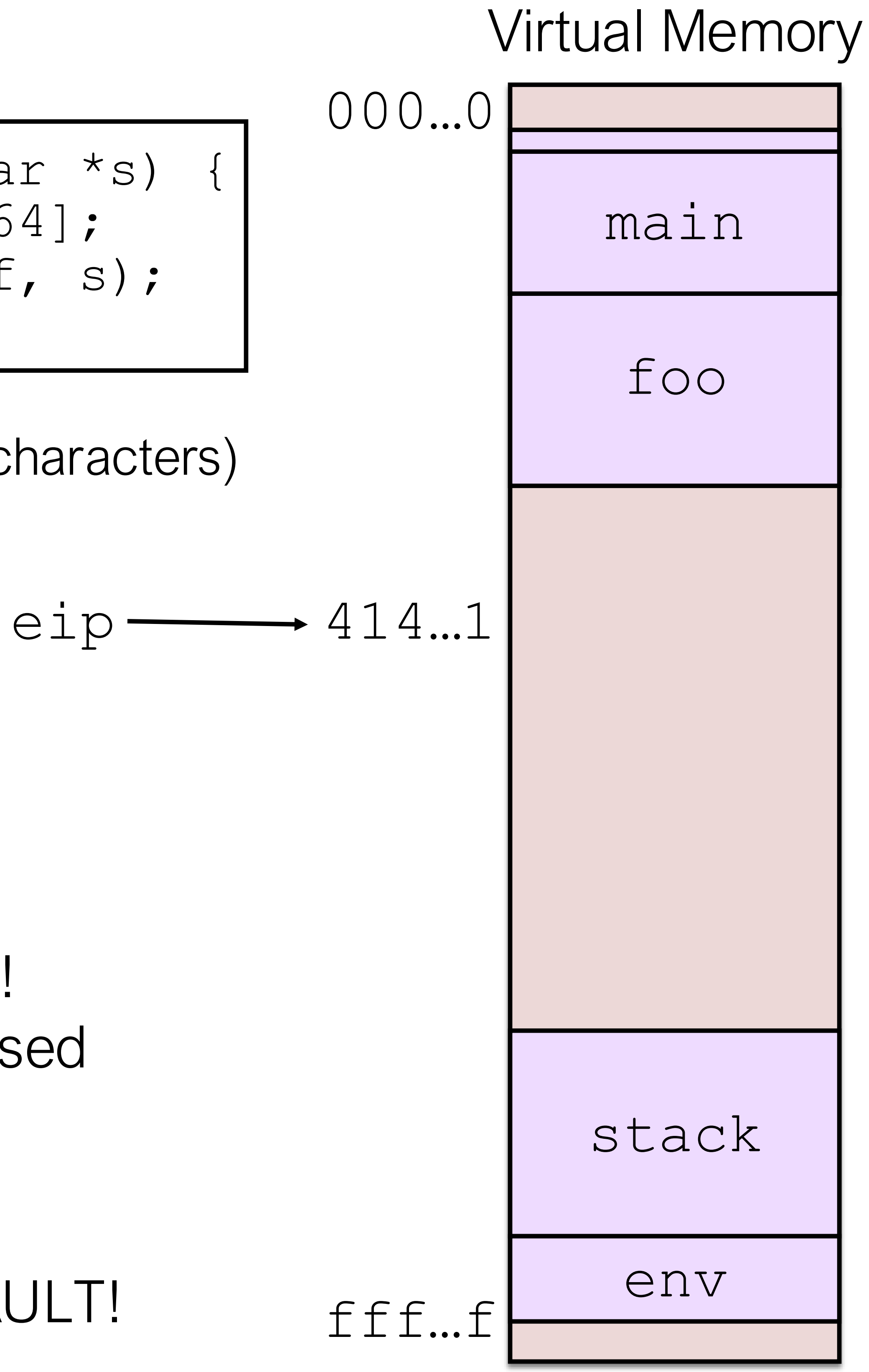
What will happen? SEGFAULT!



How to exploit a stack buffer overflow

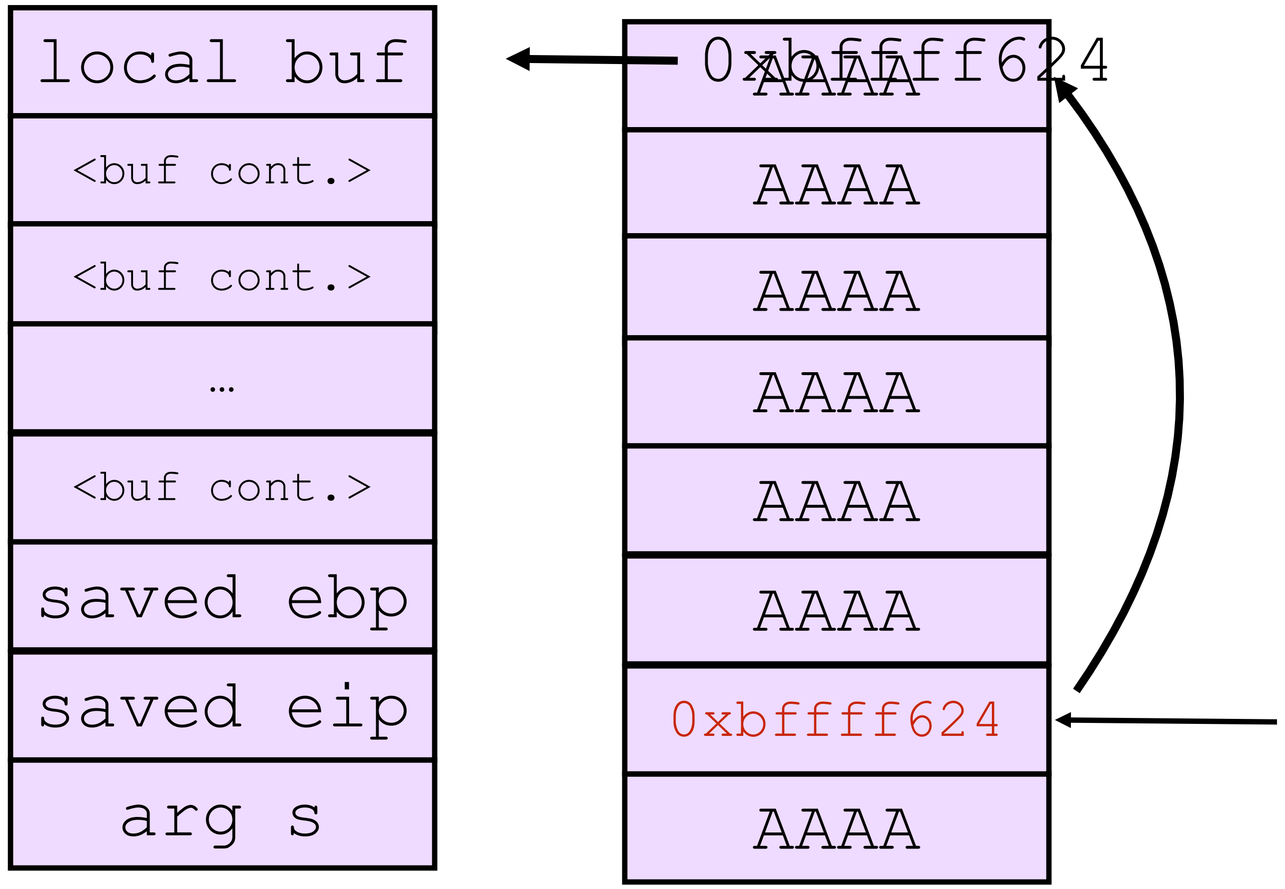
Suppose attacker can cause bad to run with an `s` it chooses.

- Step 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…"

Frame before strcpy   Frame after strcpy



Well-chosen characters used as an address when overwriting the saved `eip`!

What will happen? Illegal instruction!

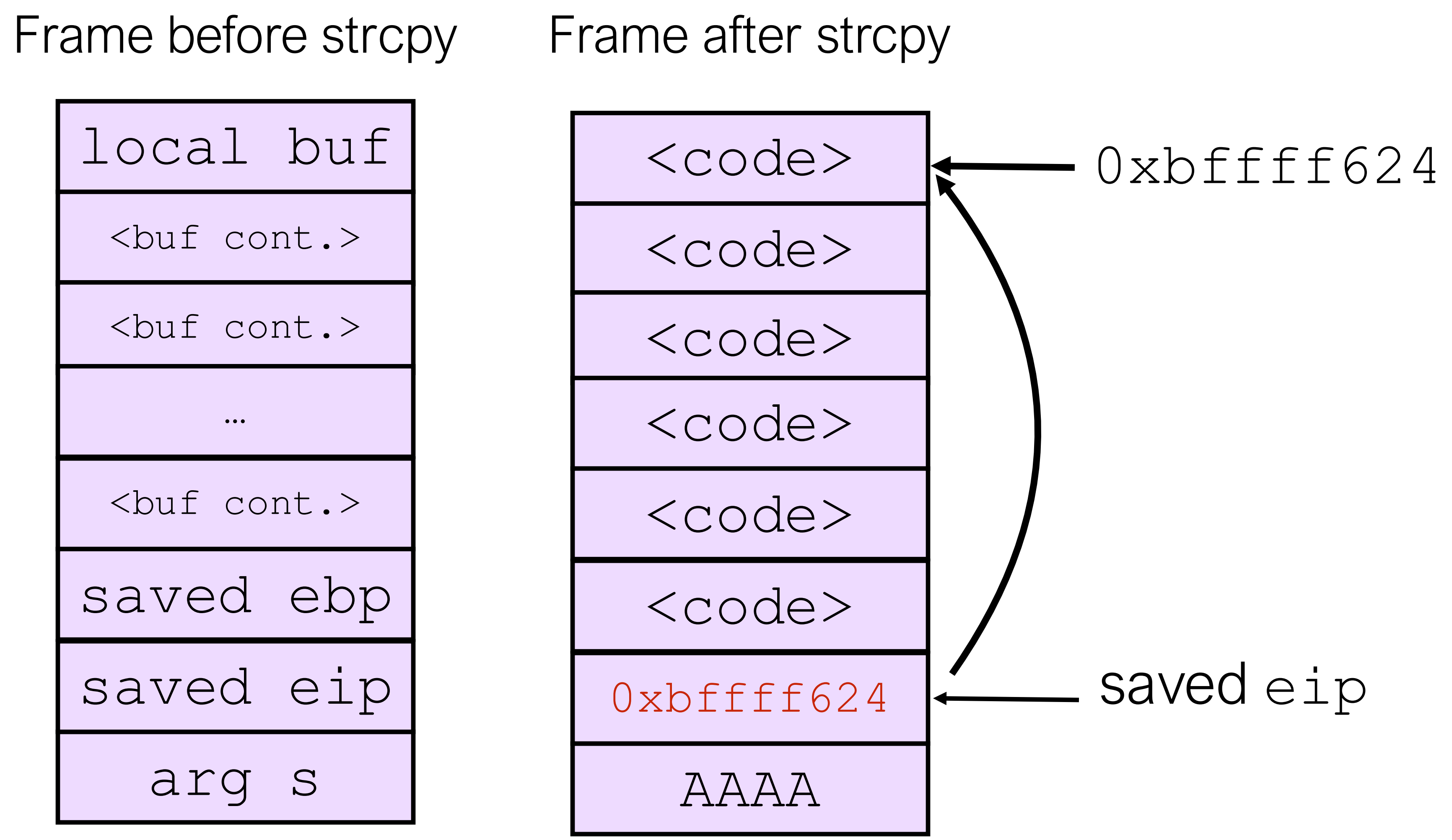
How to exploit a stack buffer overflow

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

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

Program runs attacker's code once the function (bad) returns!

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…"`

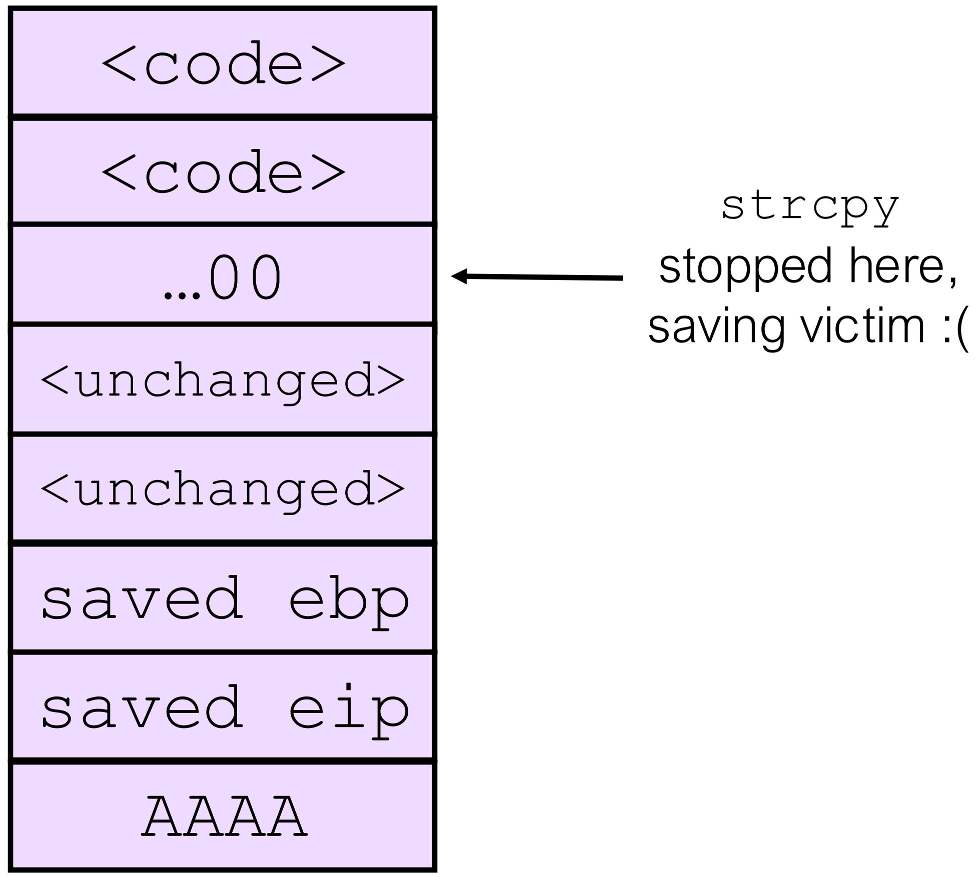
(code contains 0x0)

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);
}
```

Finally, where did that magic address come from?

Assignment: GDB is your friend ☺

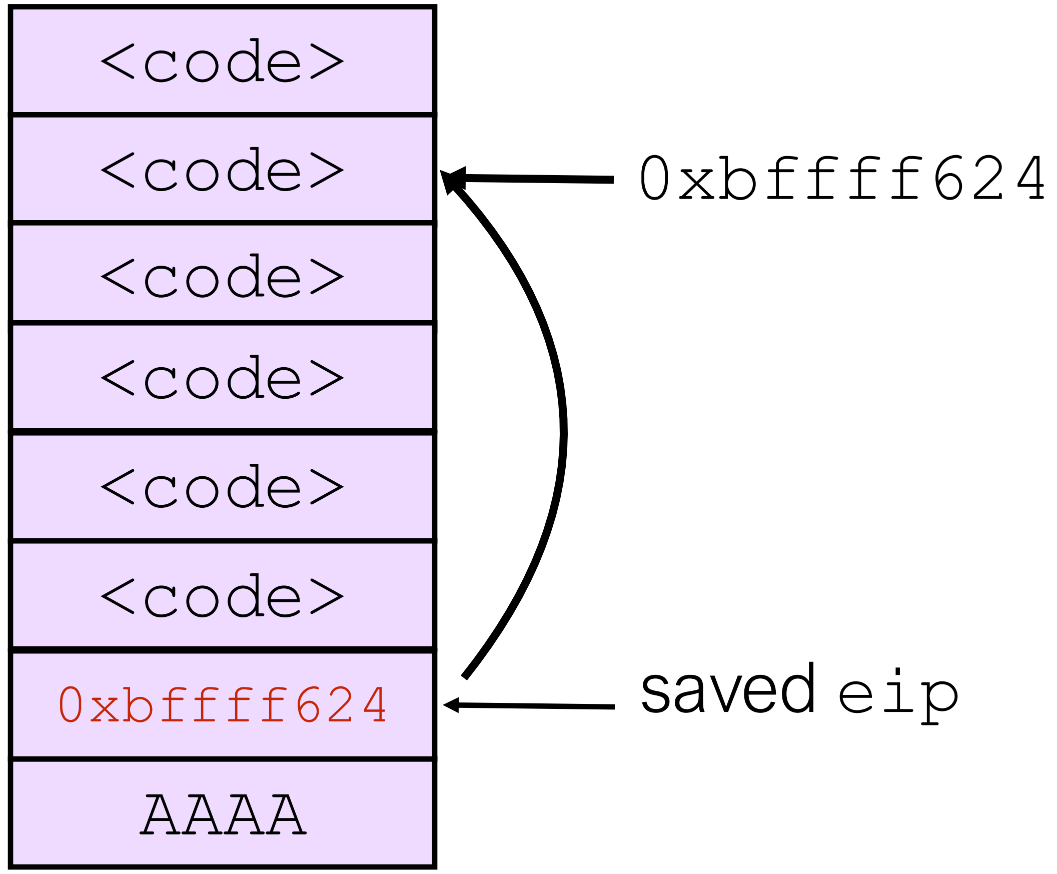
Two challenges:

— Need that address to jump to beginning of shellcode

— Need to precisely place it to overwrite saved EIP

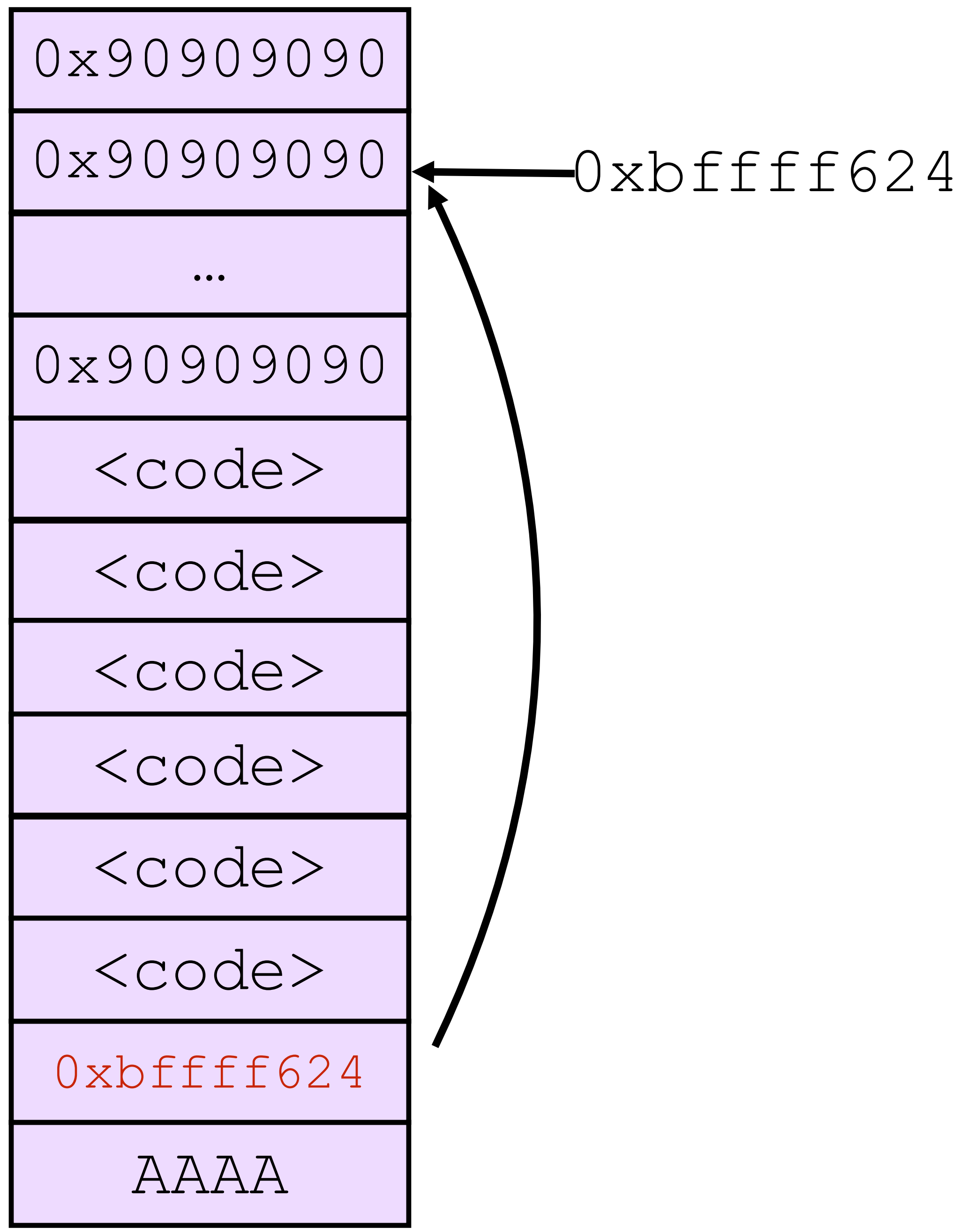
```
void bad(char *s) {
  char buf[64];
  strcpy(buf, s);
}
```

s="<code>\x24\xf6\xff\xbfAAA…"



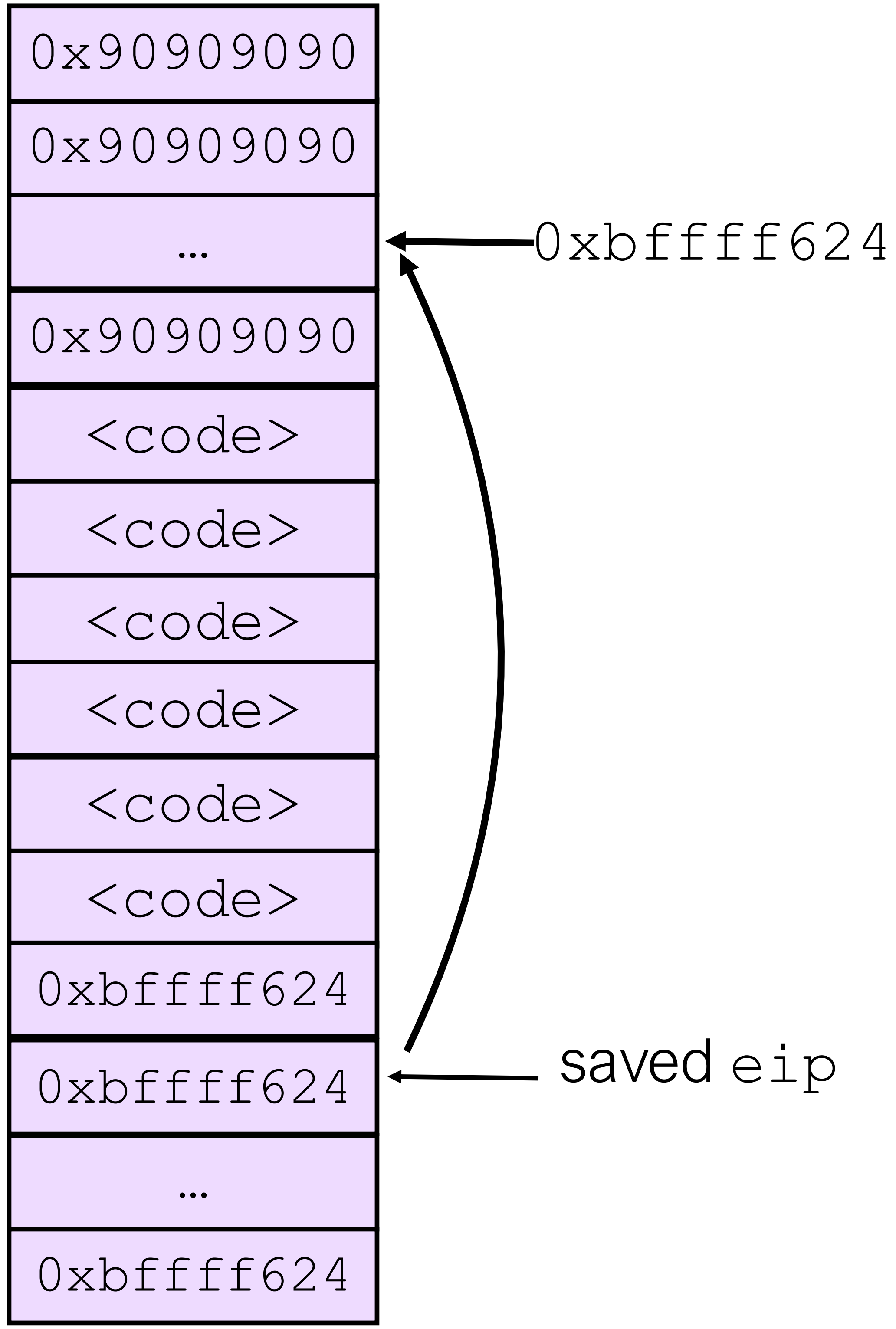
Technique #1: NOP Sleds

- Instruction `0x90` is “`xchg eax, eax`”, i.e. does not thing. 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



Brief Recap: Stack Buffer Overflows

- Bugs in code can allow attackers to bypass OS security and access control policies

- The CPU stores critical “control flow” information on the stack
  - Saved EIP & Saved EBP: controls what the CPU does after a function returns
  - Buffer overflow attack: vulnerable program doesn’t check if a (stack) buffer has enough space to hold copied data
  - Attacker can provide input that overflows buffer & has: {malicious code} + {new return address, that points to the malicious code}
  - After returning from current function, the CPU will run the attacker’s code, instead of the program’s actual code

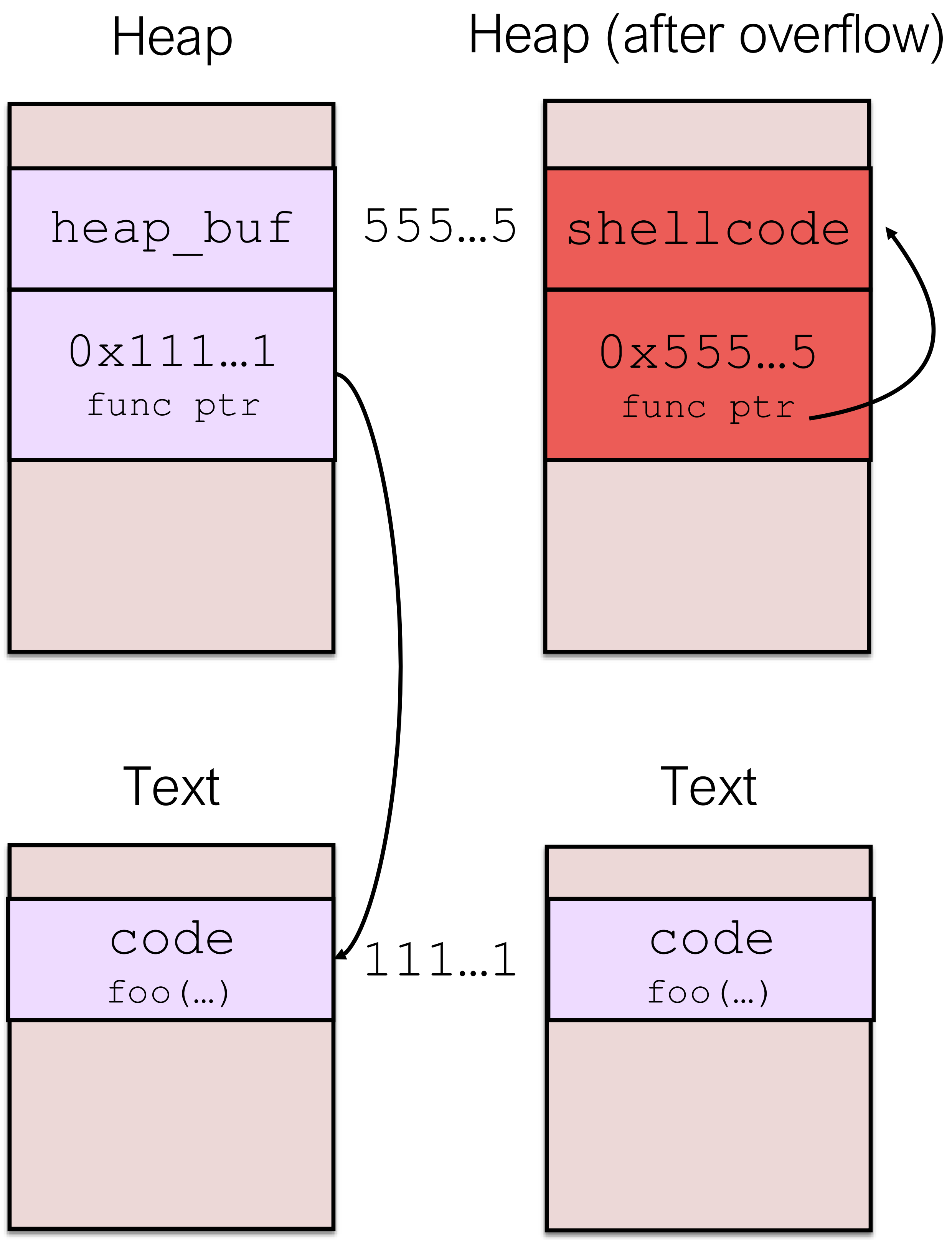
Heap Memory: Many Kinds of Vulnerabilities

Initially, the program has:

- A heap variable (heap_buf)
- A function pointer allocated on the heap that points to foo(…)

Attack:

- Overflowing heap_buf can overwrite the heap func ptr
- Later, when program calls the func ptr, it will execute the attacker's code in heap_buf



Heap overflow attacks can also overwrite variables that get used later in code
(e.g., admin = False -> admin = True)

Many other heap bugs:

- Use-after-free,
- Double Free,
- Corrupting metadata…

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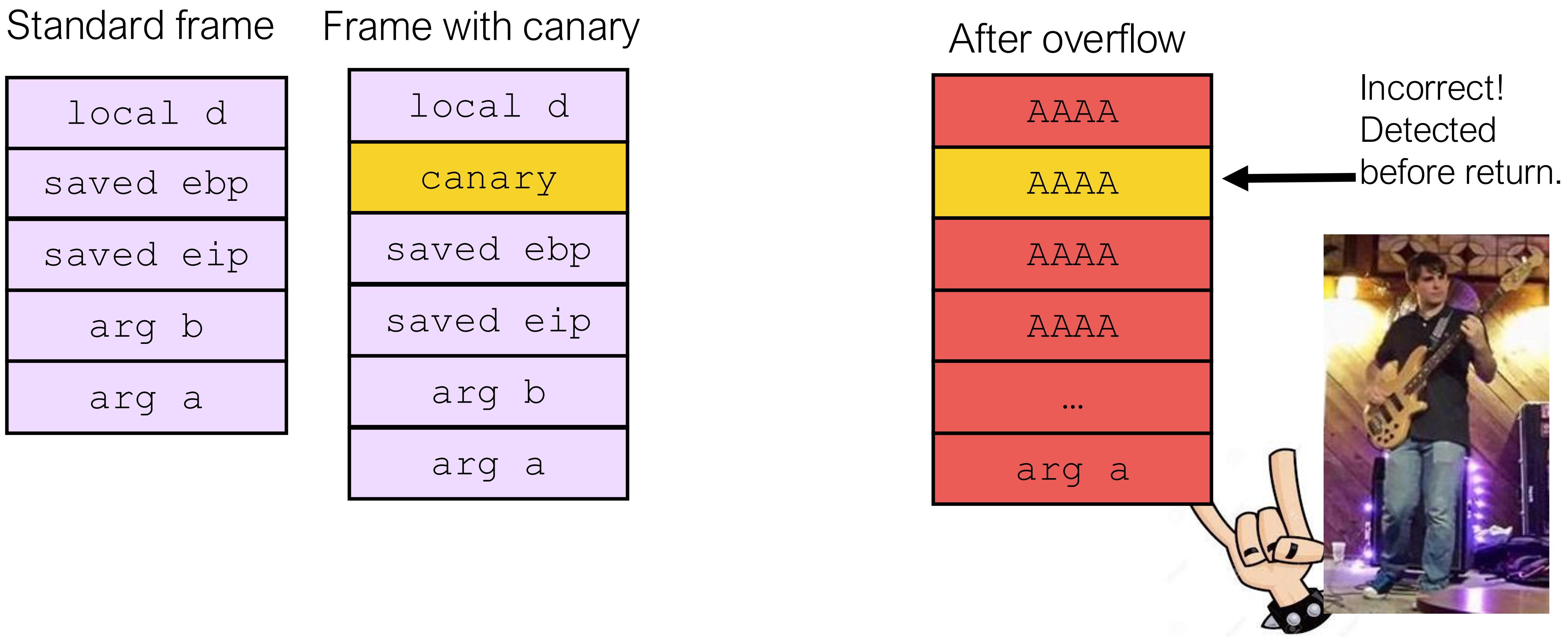
Countermeasure #1: Stack Canaries

Stack Canaries (a.k.a. Stack Protectors)

- **Idea:** Try to detect if stack data is corrupted, before using it after the function returns.
- **Compiler** inserts additional instructions (code) to each function:
  - At the start of every function, push a “canary” value onto stack between local variables and saved ebp/eip
  - Before returning, additional code checks if canary value is still correct; If not, ABORT.



Standard frame

local d
saved ebp
saved eip
arg b
arg a

Frame with canary

local d
canary
saved ebp
saved eip
arg b
arg a

After overflow

AAAA
AAAA
AAAA
AAAA
…
arg a

Incorrect!
Detected
before return.

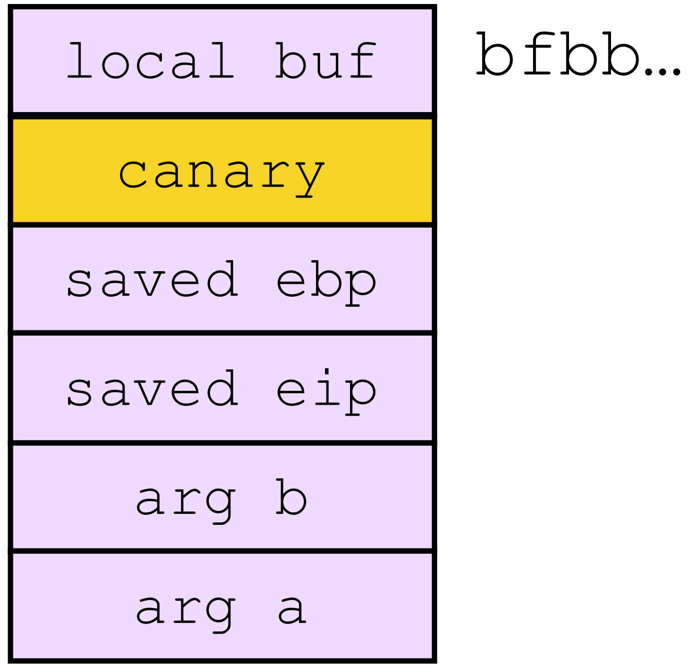
How should we (defender) pick the canary value?

Null: Set to `0x00000000`. Hard for attacker to copy NULLs onto stack.

Terminator: `0x000d0aff` (for example.) `0x0d=CR`, `0x0a=LF`, `0xff=EOF`. Some buggy code will stop at these characters.

Random: Process chooses random value at start, uses same value in every call.

Frame with canary



local buf

canary

saved ebp

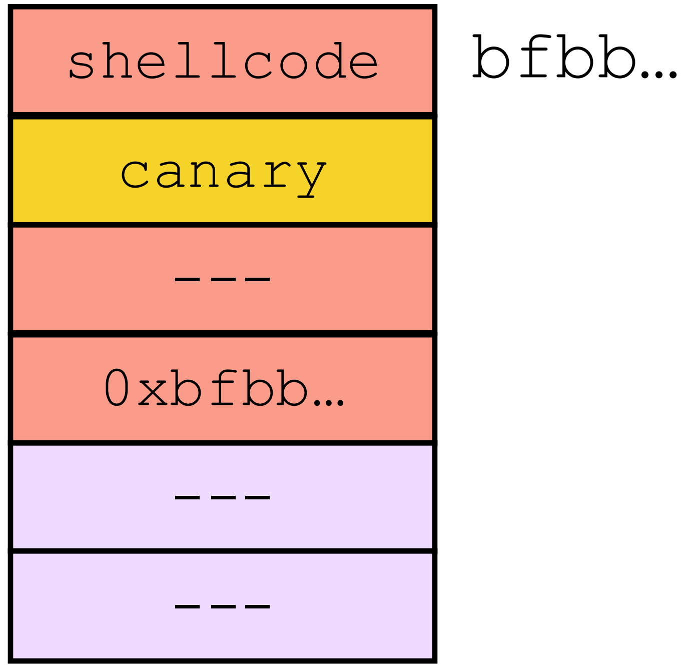
saved eip

arg b

arg a

bfbb…

Successful Overflow Requirement



shellcode

canary

0xbfbb…

---

bfbb…

Stack Canaries in gcc

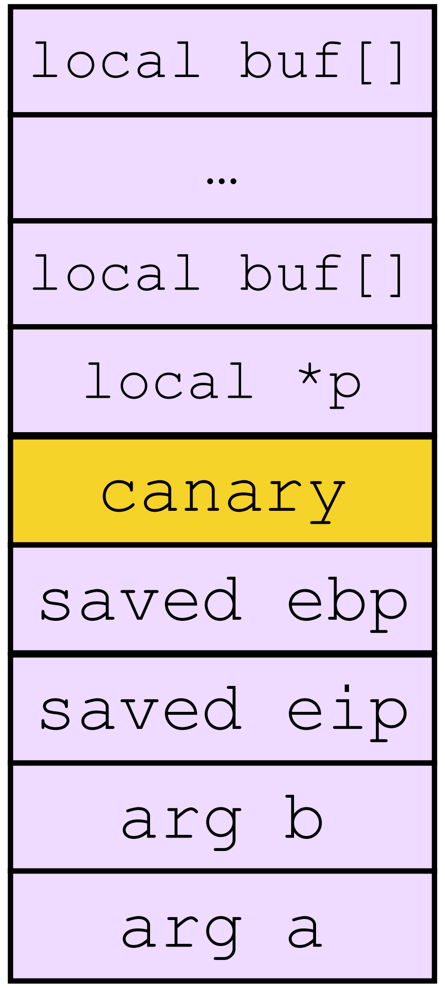
Flag	Default?	Notes
-fno-stack-protector	No	Turns off protections
-fstack-protector	Yes	Adds to funcs that call alloca() & w/ arrays larger than 8 chars (--param=ssp-buffer-size changes 8)
-fstack-protector-strong	No	Also funcs w/ any arrays & refs to local frame addresses. Introduced by ChromeOS team.
-fstack-protector-all	No	All funcs

- With -fstack-protector, 2.5% of functions in kernel covered, 0.33% larger binary
- With -fstack-protector-strong, 20.5% of functions in kernel covered, 2.4% larger binary

Related ProPolice Feature: Rearranging Locals

- gcc puts local arrays below other locals, even if declared in other order

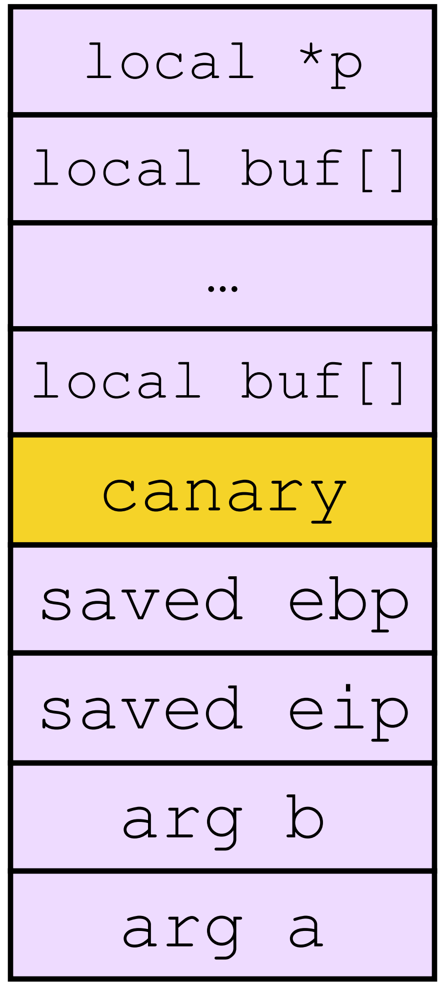
```
int foo(…) {
  char *p;
  char buf[64];
  …
}
```



local buf[]
…
local buf[]
local *p
canary
saved ebp
saved eip
arg b
arg a

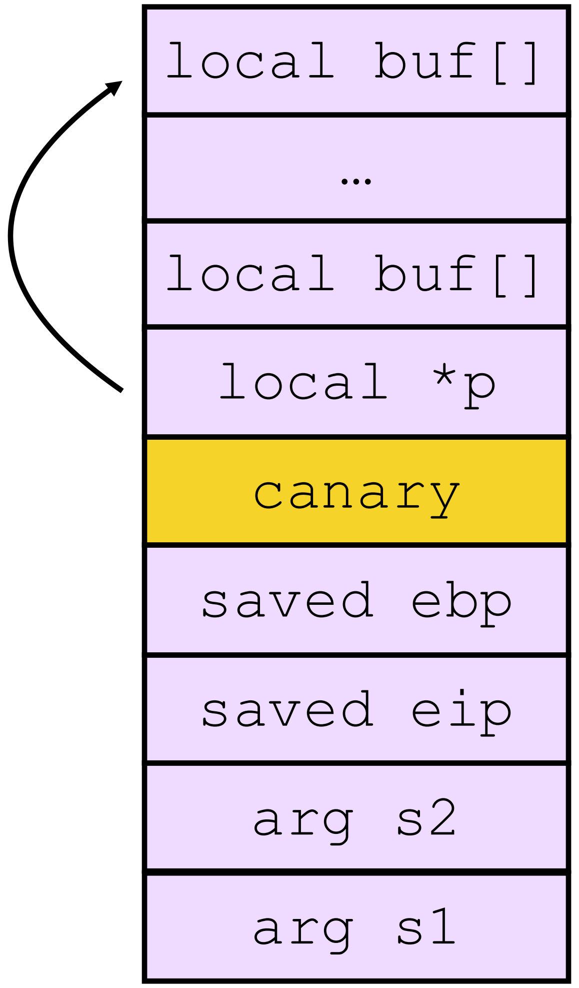
vs

```
int foo(…) {
  char buf[64];
  char *p;
  …
}
```



local *p
local buf[]
…
local buf[]
canary
saved ebp
saved eip
arg b
arg a

Bypassing Canaries via Complex Bugs



local buf[]

…

local buf[]

local *p

canary

saved ebp

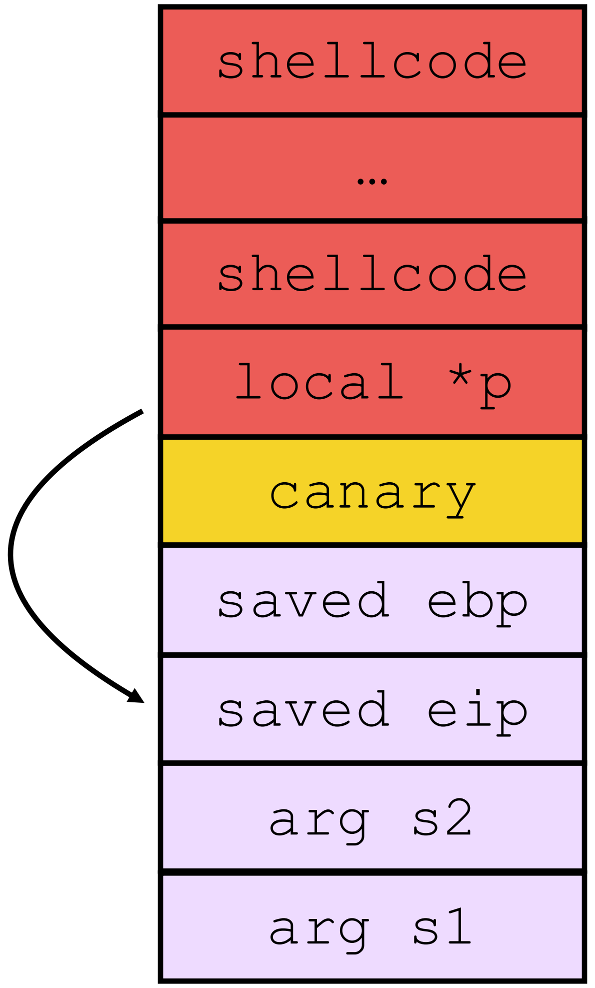
saved eip

arg s2

arg s1

```
int foo(char *s1, char *s2) {
  char *p;
  char buf[64];
  p = buf;
  strcpy(p, s1); // oh no :(
  …
  strncpy(p, s2, 16);
  …
}
```

Bypassing Canaries via Complex Bugs



shellcode

…

shellcode

local *p

canary

saved ebp

saved eip

arg s2

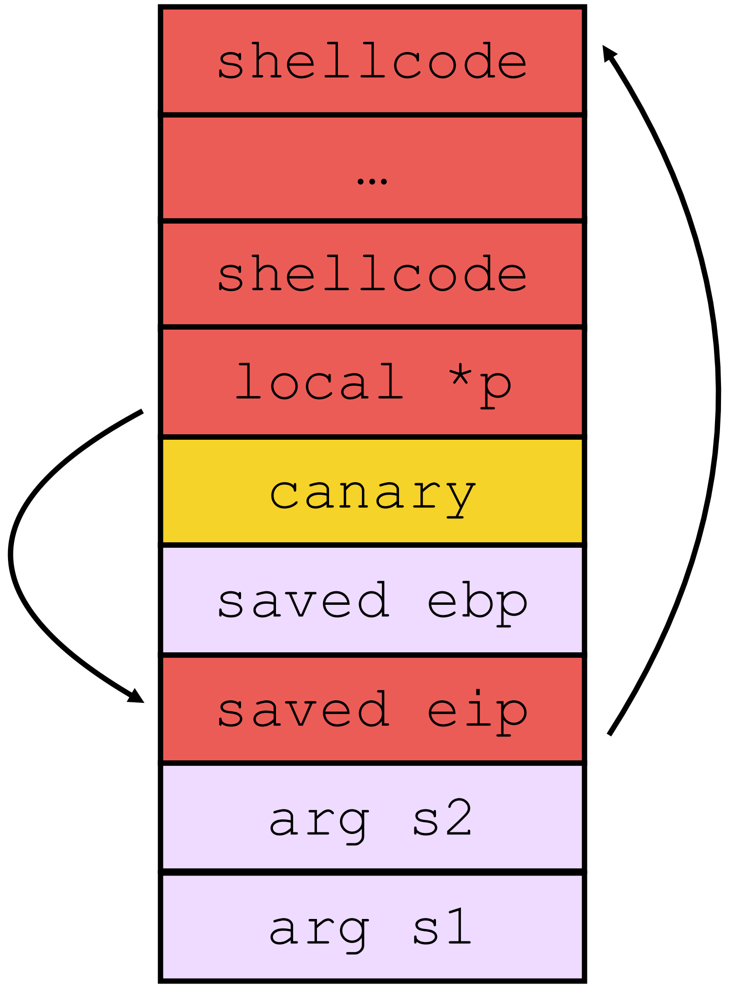
arg s1

```
int foo(char *s1, char *s2) {
  char *p;
  char buf[64];
  p = buf;
  strcpy(p, s1); // oh no :(
  …
  strncpy(p, s2, 16);
  …
}
```

Attacker crafts s1 to:

1) Fill buff with shellcode
2) Overwrite p to point to the saved eip
   (by overflowing one word longer than buf)

Bypassing Canaries via Complex Bugs



shellcode

…

shellcode

local *p

canary

saved ebp

saved eip

arg s2

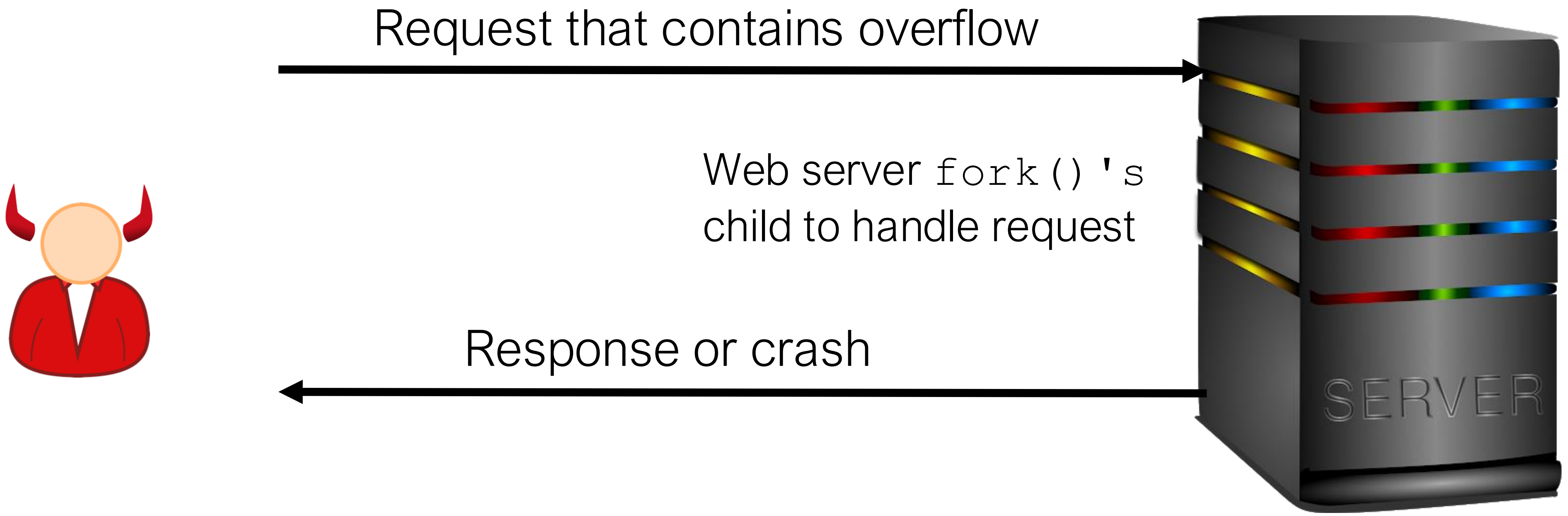
arg s1

```
int foo(char *s1, char *s2) {
  char *p;
  char buf[64];
  p = buf;
  strcpy(p, s1); // oh no :(
  …
  strncpy(p, s2, 16);
  …
}
```

<u>Attacker crafted s2 to:</u>

- Point into buf
  (where shellcode was copied)

Bypassing Canaries via “Reading the Stack”

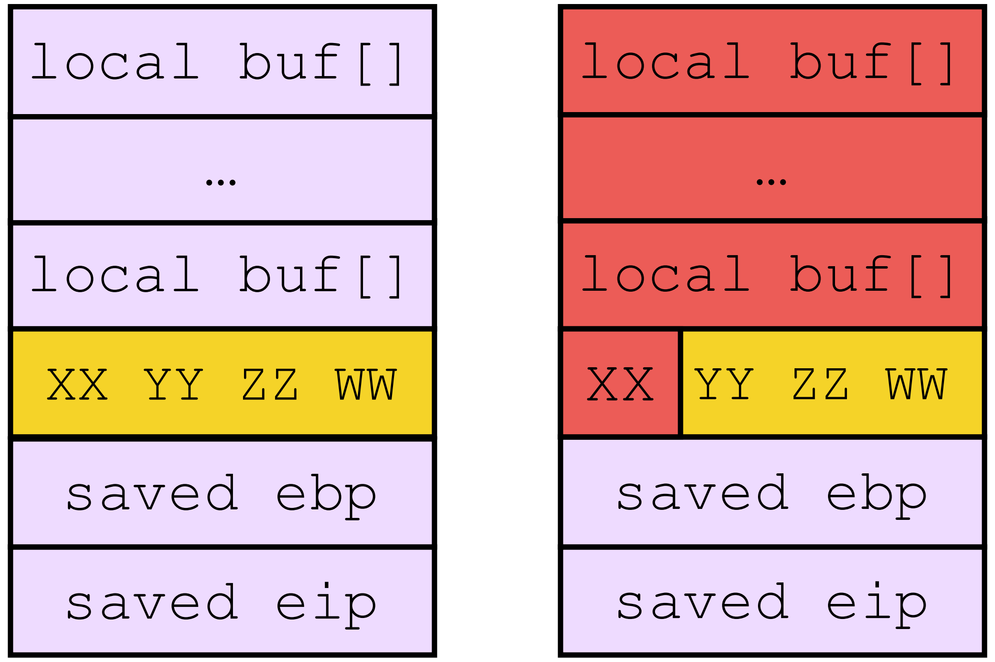


Request that contains overflow

Web server `fork()'s` child to handle request

Response or crash

Child inherits same random canary value `0xXXYYZZWW`.



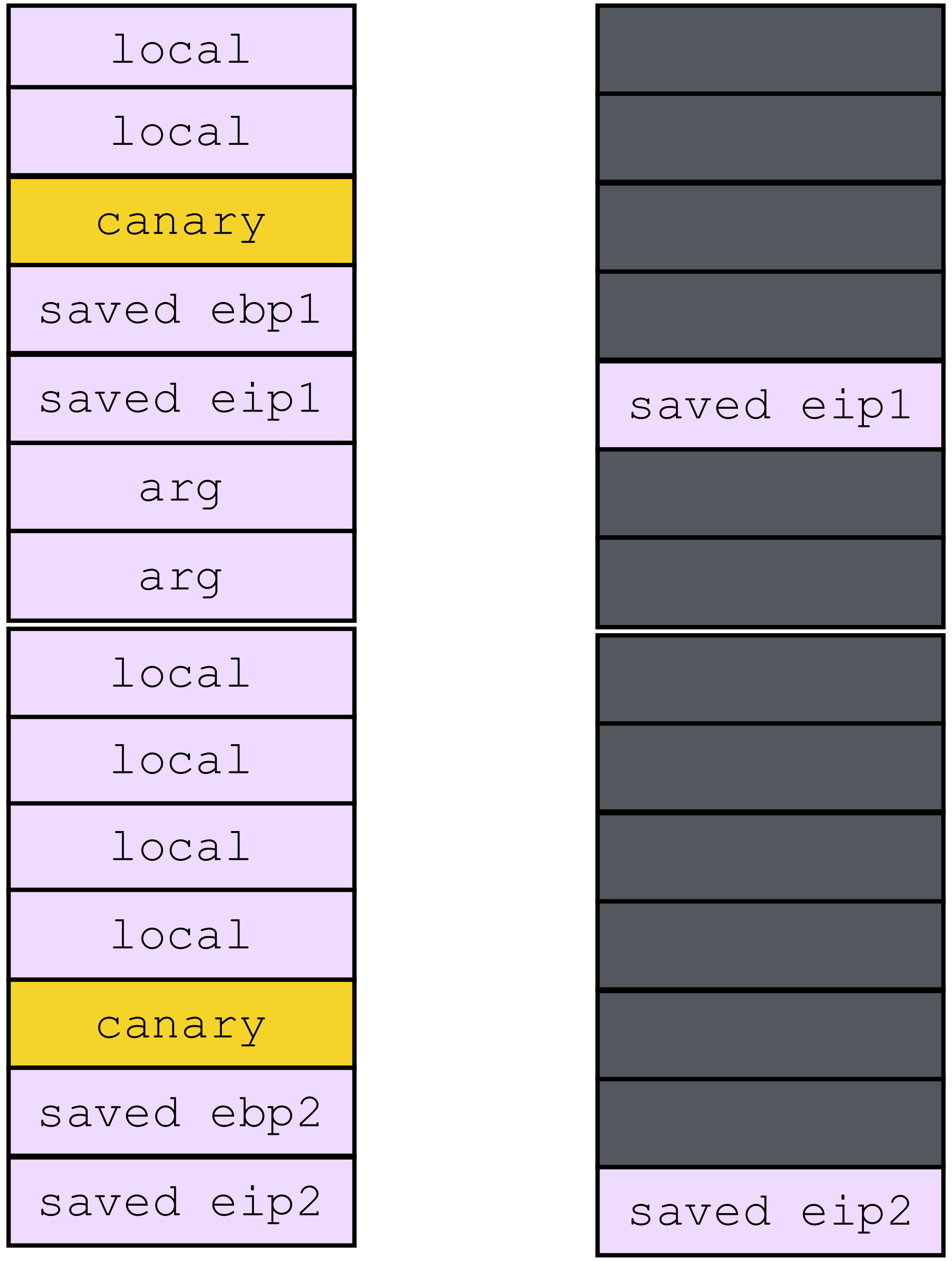
local buf[]
…
local buf[]
XX YY ZZ WW
saved ebp
saved eip

local buf[]
…
local buf[]
XX | YY ZZ WW
saved ebp
saved eip

Overflow 1 byte and observe if process crashes.

- If no crash: we guessed that canary byte value correctly!
- Learn byte `XX` after max of 256 tries! Repeat for rest.

Another Similar Countermeasure: Shadow Stacks



Parallel Shadow Stack

Idea: Have the compiler add additional code to each function that:

- Makes a copy of func’s saved eip in separate memory segment (outside stack)
- Checks whether func’s saved eip on the stack matches this “shadow” copy before returning

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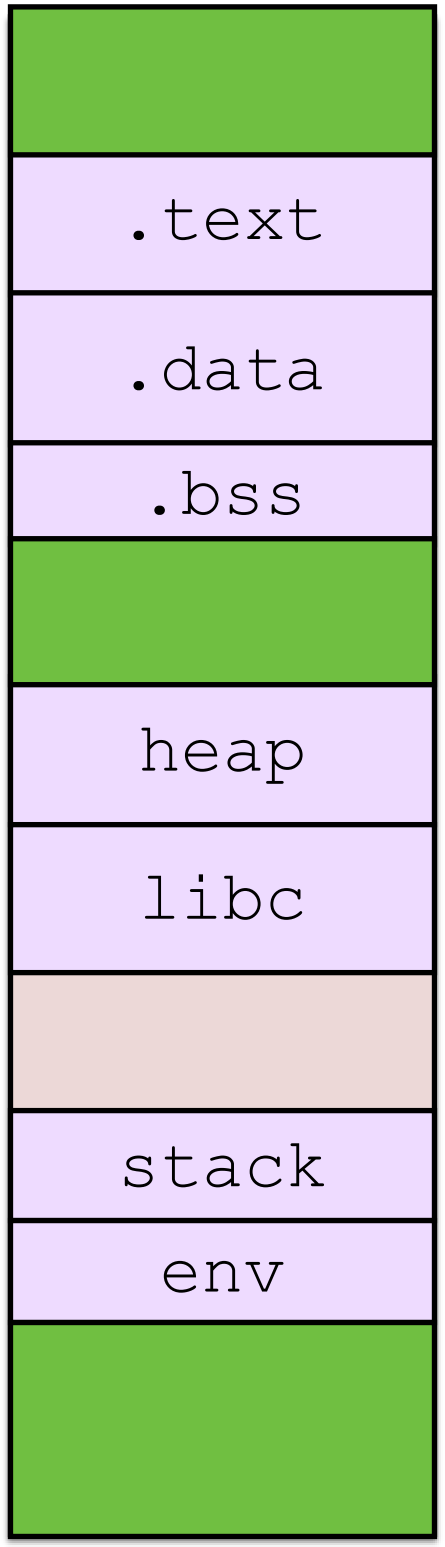
Address-Space Layout Randomization (ASLR)

Virtual Memory



Idea: OS makes it hard to know / guess function return addresses (what value the attacker should overwrite the saved eip with)

Linux PaX implementation:

- OS adds random offsets in green areas (location of stack, heap and text)
- 16 bits, 16 bits, 24 bits or randomness respectively

Possible attacks:

- Huge NOP sleds + Copy shellcode many times in heap.
- Side channels (or printf bugs) can leak random choice
- Brute force with large number of forks

Modern machines have 64-bit addresses, making ASLR stronger.

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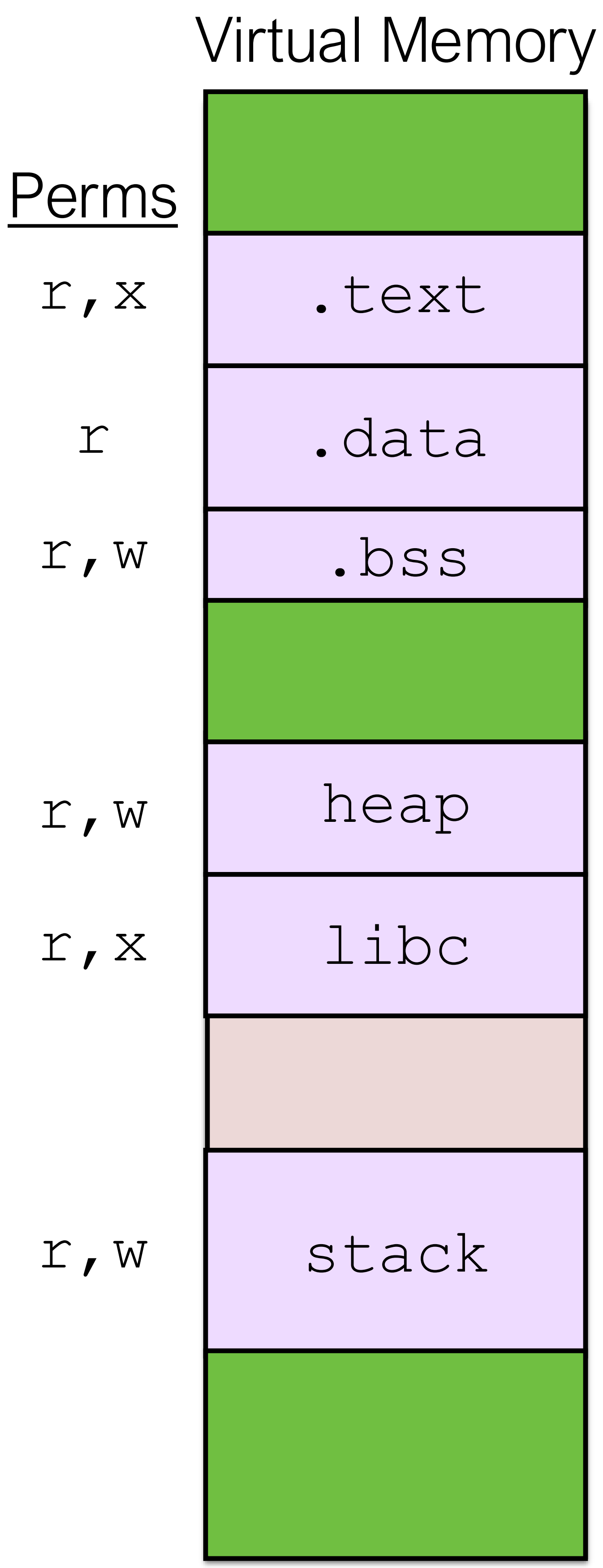
W ^ X (“Write XOR Execute”)



Idea: Code should not be writable & Data should not be executable

- e.g., stack memory = writable, but not executable

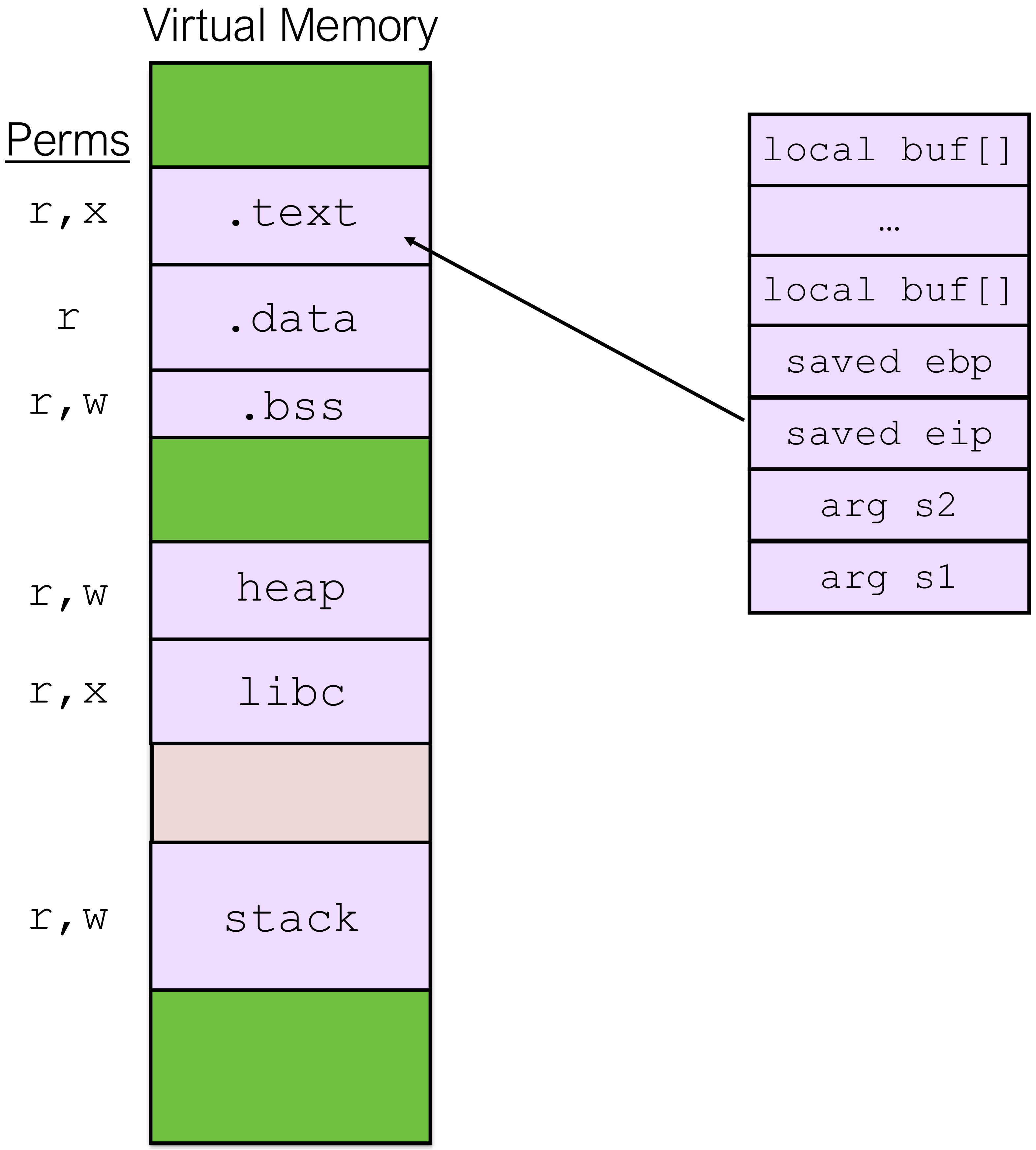
OS will mark each memory segment* as either writeable or executable, but never both.

- Modern hardware support: x64 (the x86 successor)
- All major OS implement (PaX/ExecShield - Linux, DEP - Windows, …)
- Also used in virtual machine / sandboxes

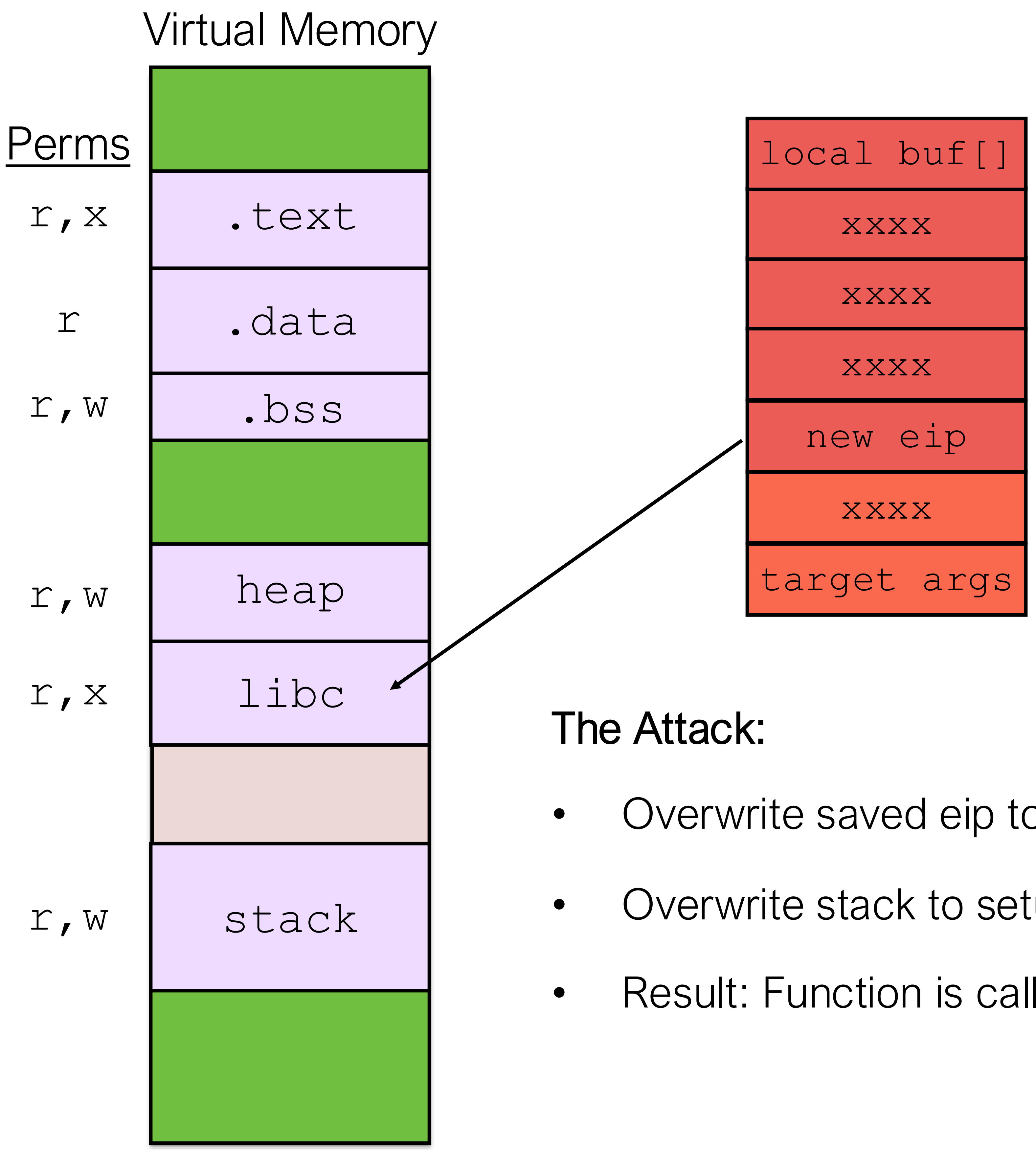
In past buffer overflows, the attacks included shellcode in the input

- But doesn’t work now: the shellcode will exist on *the stack*, which is (r,w) but *non-executable*!

Bypassing W ^ X: Return-to-libc



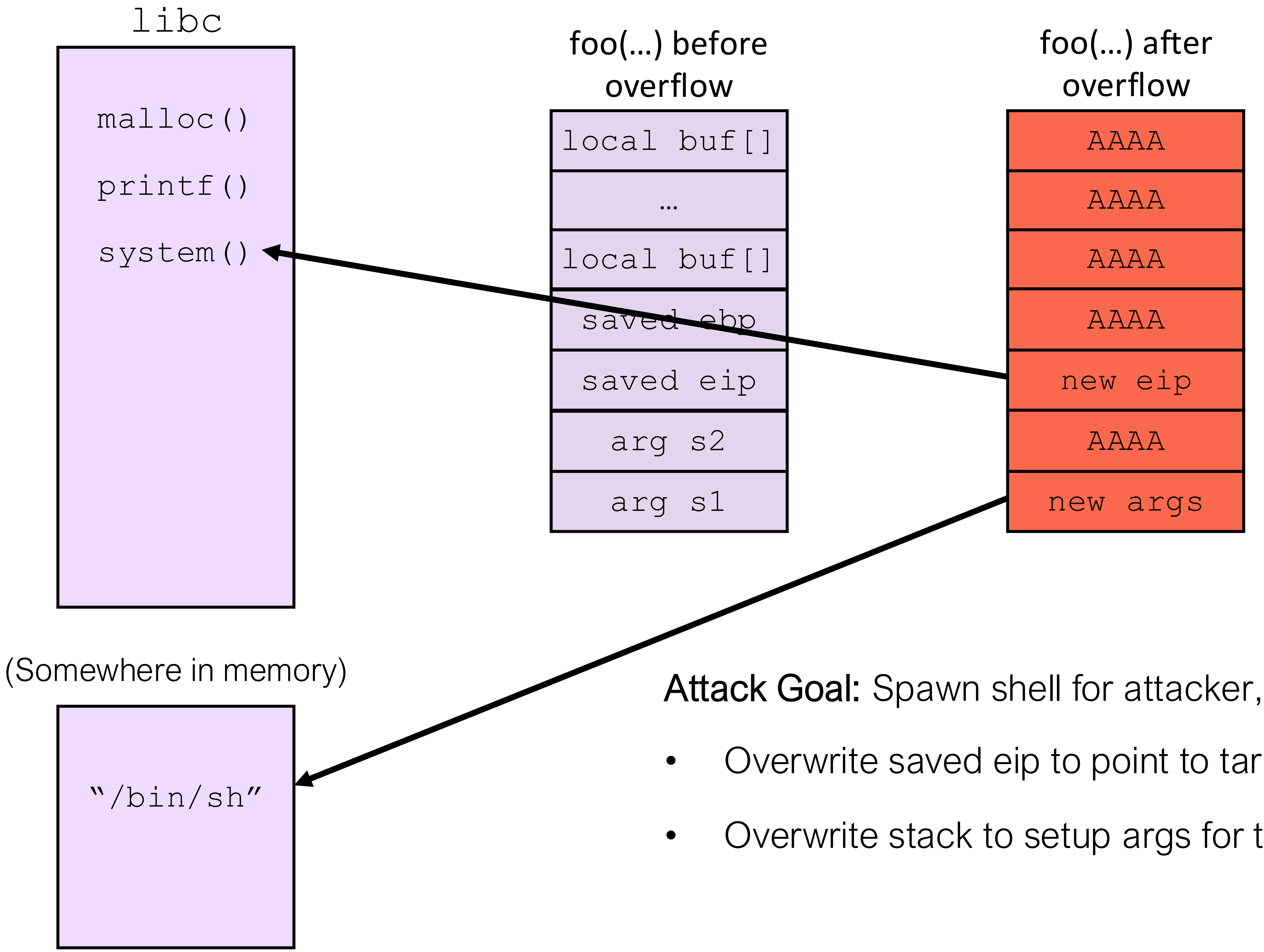
Bypassing W ^ X: Return-to-libc



The Attack:

- Overwrite saved eip to point to target func in libc (`system`)
- Overwrite stack to setup args for the target func
- Result: Function is called w/ specific args!

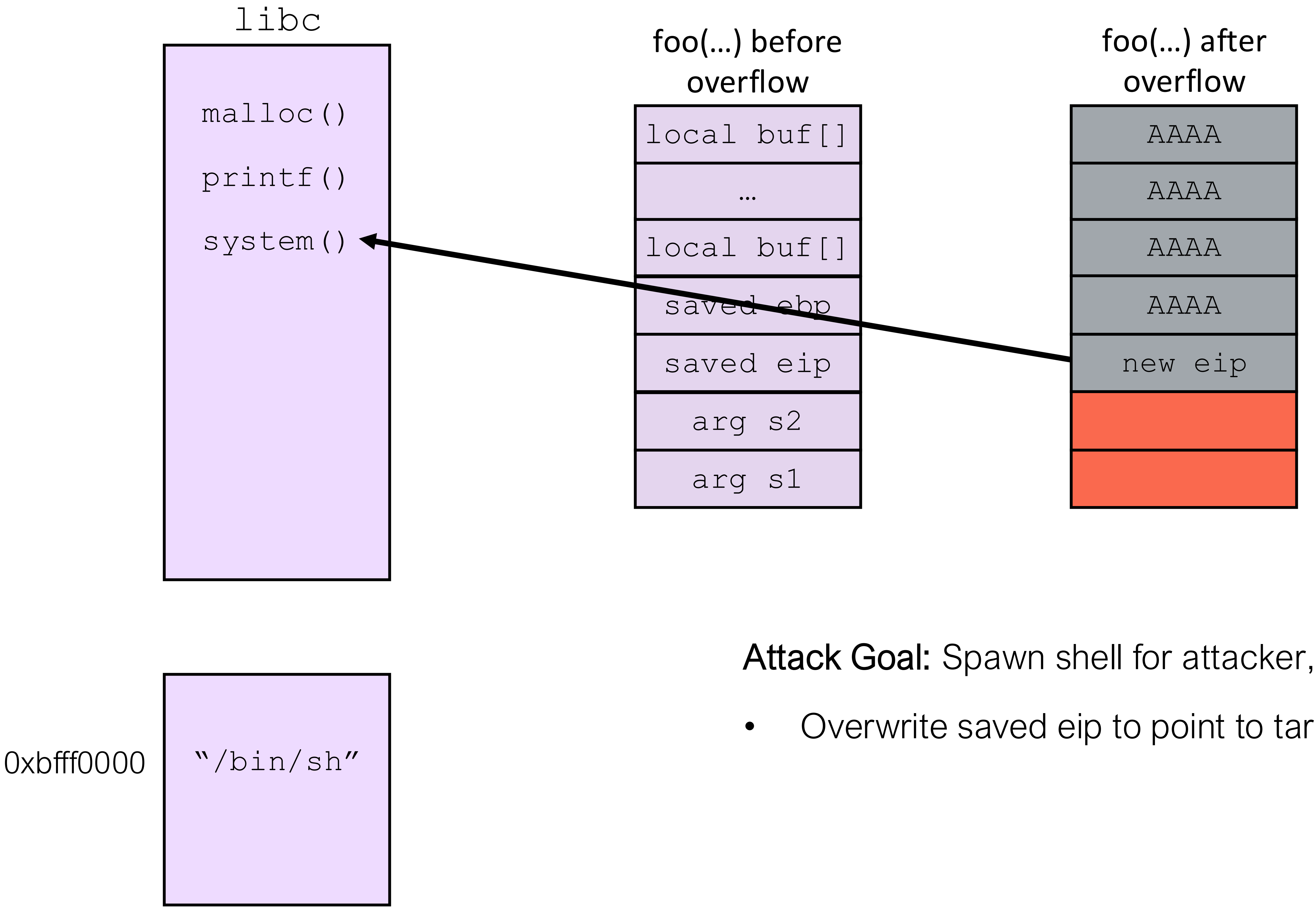
Bypassing W ^ X: Return-to-libc Details



Attack Goal: Spawn shell for attacker, e.g., system("/bin/sh/")

- Overwrite saved eip to point to target func in libc (`system`)
- Overwrite stack to setup args for target func (`"/bin/sh"`)

Bypassing W ^ X: Return-to-libc Details



Now when foo returns, EIP jumps to system()'s assembly code.

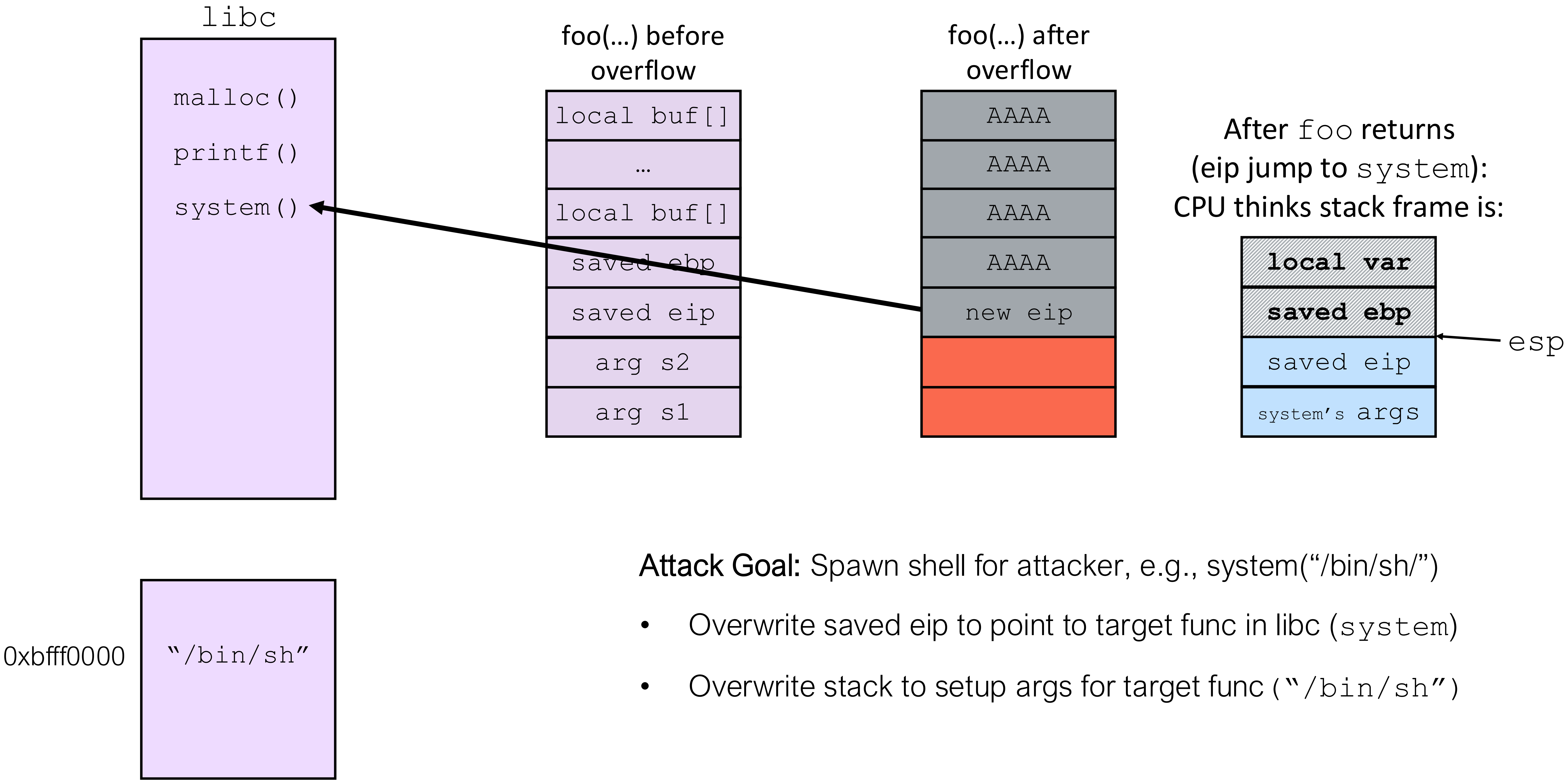
Recall:

- Caller pushes (1) func args & (2) saves EIP value onto stack, then (3) moves EIP into callee's code
- Callee trusts that caller did that setup properly

Attack Goal: Spawn shell for attacker, e.g., system("/bin/sh/")

- Overwrite saved eip to point to target func in libc (system)

Bypassing W ^ X: Return-to-libc Details



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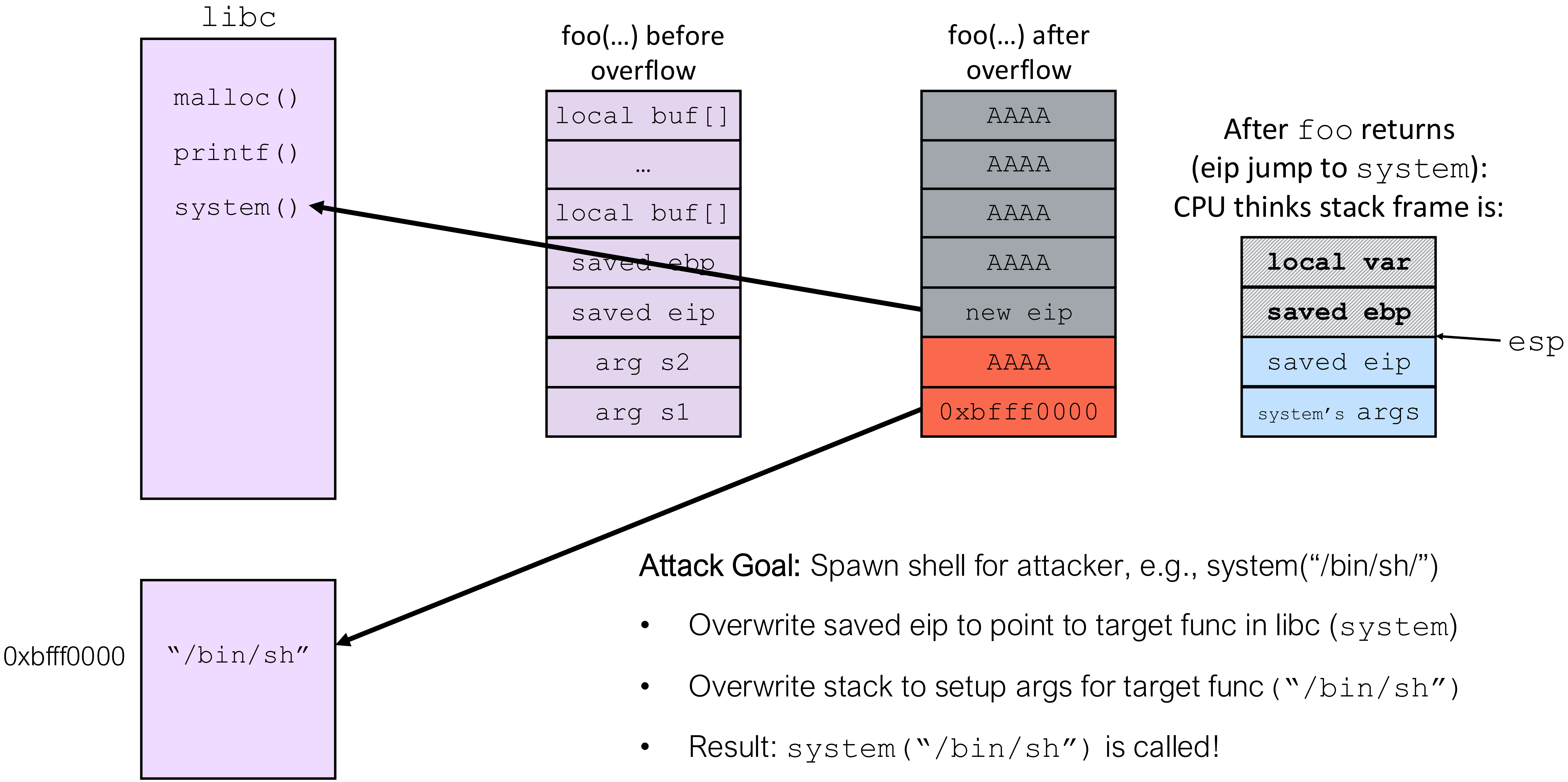

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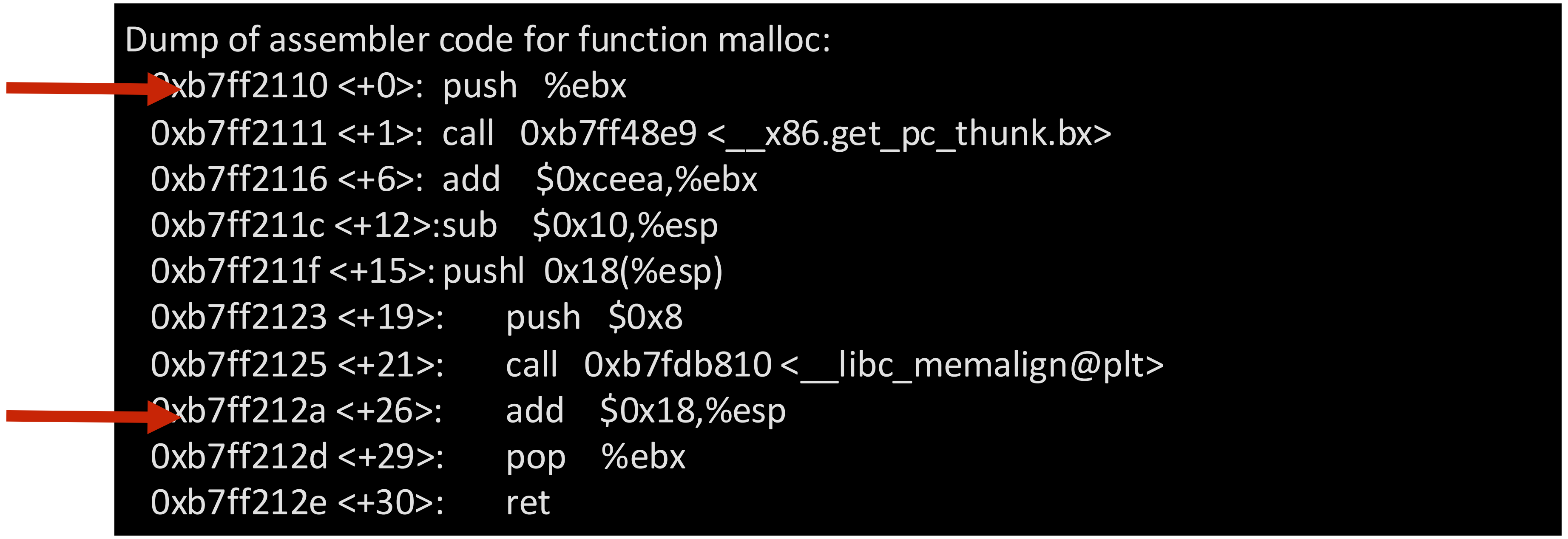
- Overwrite saved eip to point to target func in libc (`system`)
- Overwrite stack to setup args for target func (`"/bin/sh"`)
- Result: `system("/bin/sh")` is called!

Going Further: Return-Oriented Programming (ROP)

- Return-to-libc enables attacker to call existing functions (e.g., from libc)
- Going further: Why not “return” into the middle of functions, and only execute final instructions?
  - Finer-grain control: can execute a few select instructions, rather than entire predefined functions



return-to-libc
jumps here…

… but we could jump
here instead to execute
two instructions, then
regain control

```
Dump of assembler code for function malloc:
  0xb7ff2110 <+0>:  push   %ebx
  0xb7ff2111 <+1>:  call   0xb7ff48e9 <__x86.get_pc_thunk.bx>
  0xb7ff2116 <+6>:  add    $0xceea,%ebx
  0xb7ff211c <+12>:sub    $0x10,%esp
  0xb7ff211f <+15>: pushl  0x18(%esp)
  0xb7ff2123 <+19>:      push   $0x8
  0xb7ff2125 <+21>:      call   0xb7fdb810 <__libc_memalign@plt>
  0xb7ff212a <+26>:      add    $0x18,%esp
  0xb7ff212d <+29>:      pop    %ebx
  0xb7ff212e <+30>:      ret
```

General ROP attack (Shacham 2008):

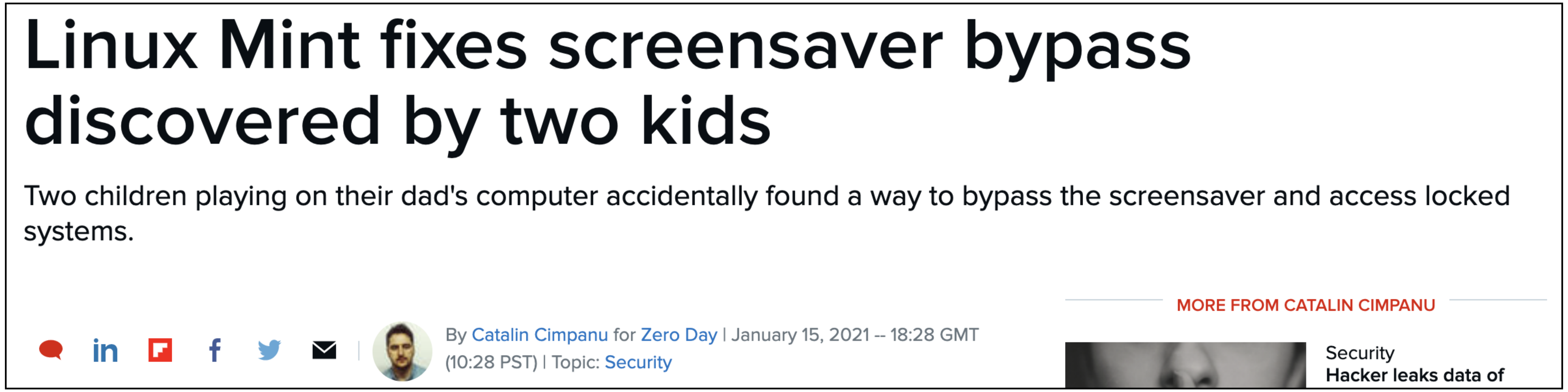
- Search through common library code (e.g., libc) for functions that end in useful instructions.
- Build shellcode as a series of “return addr’s” that point to useful instructions.
  (RET instruction pops next word on the stack into %eip)

Outline: Memory Safety: Attacks & Defenses

1. Review: Memory layout and function calls in a process
2. Attacks:
    1. Stack-based buffer overflow attacks
    2. Heap vulnerabilities (briefly)
3. Defenses:
    1. Stack Canaries
    2. Address-Space Layout Randomization (ASLR)
    3. W ^ X and ROP
    4. Fuzzing and Memory Safe Languages

Program Fuzzing: Find bugs before release

Idea: Developer runs their program on huge number of automatically-generated inputs, searches for crashes, and fixes bugs before releasing software



Linux Mint fixes screensaver bypass discovered by two kids

Two children playing on their dad's computer accidentally found a way to bypass the screensaver and access locked systems.

By Catalin Cimpanu for Zero Day | January 15, 2021 -- 18:28 GMT (10:28 PST) | Topic: Security

MORE FROM CATALIN CIMPANU

Security
Hacker leaks data of

"A few weeks ago, my kids wanted to hack my Linux desktop, so they typed and clicked everywhere while I was standing behind them looking at them play," wrote a user identifying themselves as robo2bobo.

According to the bug report, the two kids pressed random keys on both the physical and on-screen keyboards, which eventually led to a crash of the Linux Mint screensaver, allowing the two access to the desktop.

"I thought it was a unique incident, but they managed to do it a second time," the user added.

Two Types of Fuzzing Strategies

Mutation-based (dumb): Take an initial set of examples (program inputs) and make random changes to them.

- Millions of inputs (can run fuzzing forever)

- Possibly lower quality, unlikely to find certain bugs / types of inputs

Generative (smart): Describe inputs to fit format/protocol, then generate inputs from that grammar with changes.

- Run with fewer inputs, which can be directed to certain bug types or code logic

Problems with Fuzzing

Mutation-based (dumb): How long to run? And we need a strong server.

Generative (smart): Run out of test cases. A lot more work.

General problems:

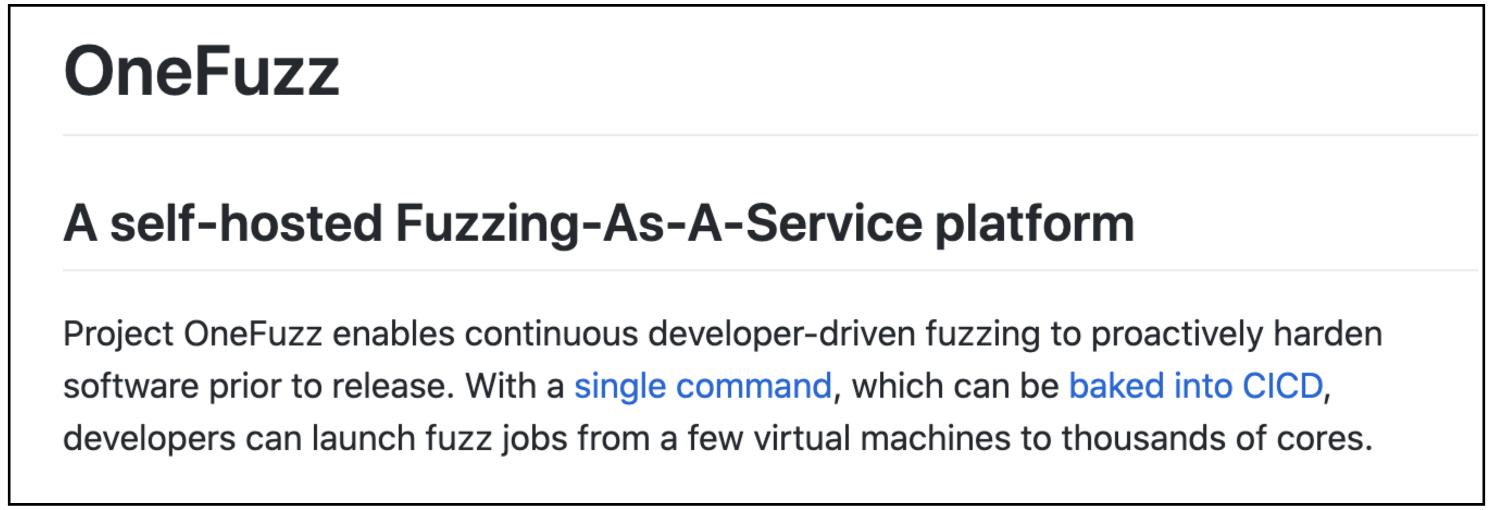
- Need to identify when bug/crash occurs automatically.
- Don't want to report same bug 1000s of times.
- How do we prioritize bugs?

Fuzzing in Production

AFL: Popular open-source fuzzer released by Google

Google/Microsoft constantly fuzz products with dedicated servers/VMS.

Anecdote: Found 95 vulnerabilities in Chrome during 2011.



OneFuzz

A self-hosted Fuzzing-As-A-Service platform

Project OneFuzz enables continuous developer-driven fuzzing to proactively harden software prior to release. With a single command, which can be baked into CICD, developers can launch fuzz jobs from a few virtual machines to thousands of cores.

Memory-Safe Languages

Many of our problems can be solved by using “memory-safe” languages.

- The programming model for these languages ***does not allow*** for such bugs (e.g., no access to pointers / mem addr’s and built-in object bounds checking).

Not Memory-Safe	**Memory Safe**
C	Java
C++	Python
Assembly	Javascript
	Rust, Go, Haskell, …

Ideally, we’d avoid writing programs in unsafe languages, but lots of legacy code (and low-level stuff) are written in C/C++.

Recap: Software Defenses

Pre-deployment, before the program runs: find or prevent bugs

- Fuzzing: proactively finding & fixing bugs by testing many program inputs
- Memory safe languages: automatically avoid exploitable memory bugs
- Done by the application developer

Program runtime: stopping exploits / violations of program’s memory

- Stack Canaries, ASLR, DEP/W+X, etc.
- Implemented by the compiler (stack canary) or operating system (ASLR, W+X)
- Attacks adapt & evolve (Stack reading, ROP attacks, etc.)

Post-exploitation (not covered): limit possible damage from compromise

- Sandboxing and VMs
- Done by user/admin of the system or the app developer (e.g., web browsers)

The End