CS 88: Security and Privacy

06: Software Security – Defenses

02-08-2024

SWARTHMORE COLLEGE

Announcements

- Clicker mappings on edstem.
  - please use the google sheet link to update your clicker choices
- Midterm dates:
- Speak to me about accommodations now!

Reading Quiz

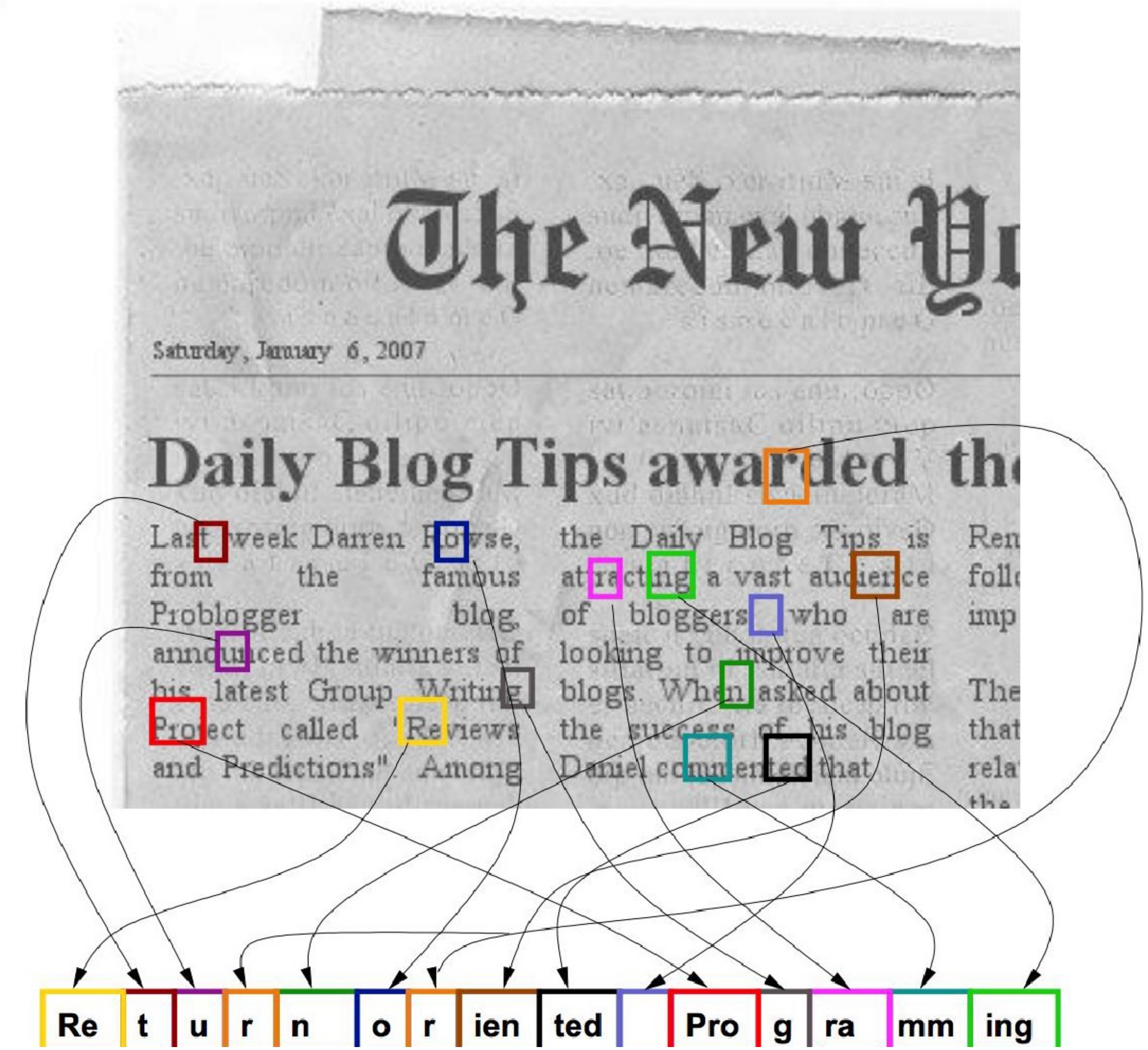
Last Class

- Stack Buffer Overflow
- Integer Overflow Vulnerabilities

Today

- Format String Attacks
- Return Oriented Programming
- S/w Defenses

Return-Oriented Programming



Return Oriented Programming: Code Reuse

- Can’t inject code onto the stack (non-executable stack)
  - How about assembly instructions that already exist in our code?
  - What if we string together a few instructions at a time?
- *A short sequence of instructions that we construct are called gadget*
  - A gadget usually ends in a `ret` instruction.
    - Once we execute `ret:`
      - the address of the next gadget off the stack is popped
      - and control flow jumps to that address.

Source: RPISEC: Return Oriented Programming

Attacks on Non-executable pages

Return into libc: set up the stack and “return” to exec()

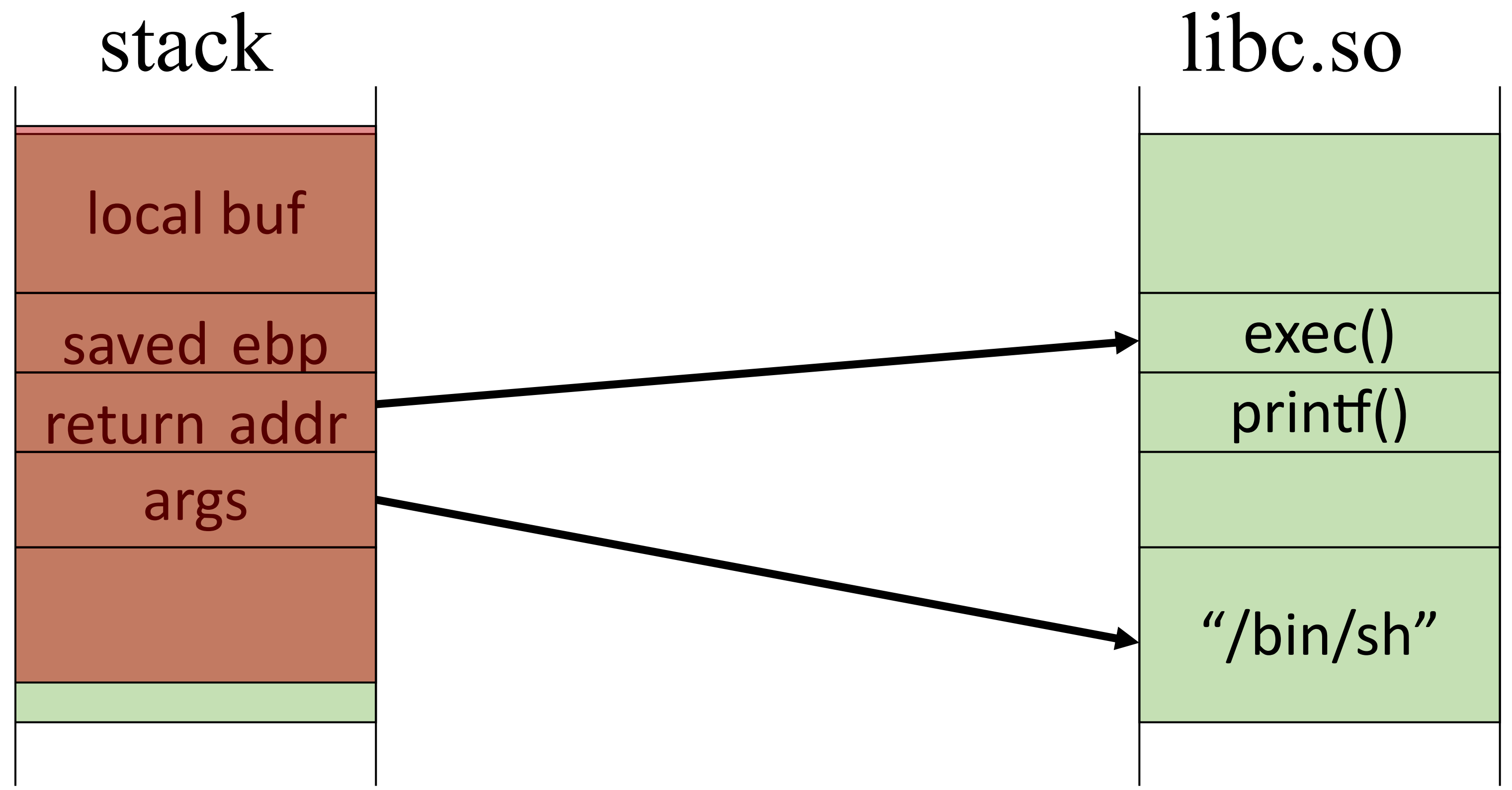
- Overwrite stuff above saved return address with a “fake call stack”, overwrite saved return address to point to the beginning of exec() function
- Especially easy on x86 since arguments are passed on the stack

Return Oriented Programming

- Idea: chain together "return-to-libc" idea many times
- ROP compiler
- Tools democratize things for attackers:
  - Find a set of short code fragments (gadgets) that when called in sequence execute the desired function
  - Inject into memory a sequence of saved "return addresses" that will invoke them Sample gadget: add one to EAX, then return
  - Find enough gadgets scattered around existing code that they're Turing-complete Compile your malicious payload to a sequence of these gadgets
- *Yesterday's Ph.D. thesis or academic paper is today's Intelligence Agency tool and tomorrow's Script Kiddie download*

Attack: Return Oriented Programming (ROP)

Control hijacking **without injecting code:**



Return Oriented Programming: Code Reuse

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Source: RPISEC: Return Oriented Programming

Return Oriented Programming: Code Reuse

- We can get each sequence to end in a “`ret`” instruction
  - i.e.:
    - pop the value at the top of the stack
    - store this value in `eip`
    - decrement the `stack pointer` 4 bytes below.
  - *now eip executes whatever instruction is present at this memory address*
- at the next call to `ret`,
  - we again pop the top value of the stack
  - store this value in `eip`,
  - and so on…

Source: RPISEC: Return Oriented Programming

Return Oriented Programming: chain gadgets to form a ROP chain

0x401d70

```
pop rbx
pop rdx
ret
```
(1)

```
pop rax
ret
```
(2)

```
add rax, 0x4
ret
```
(3)

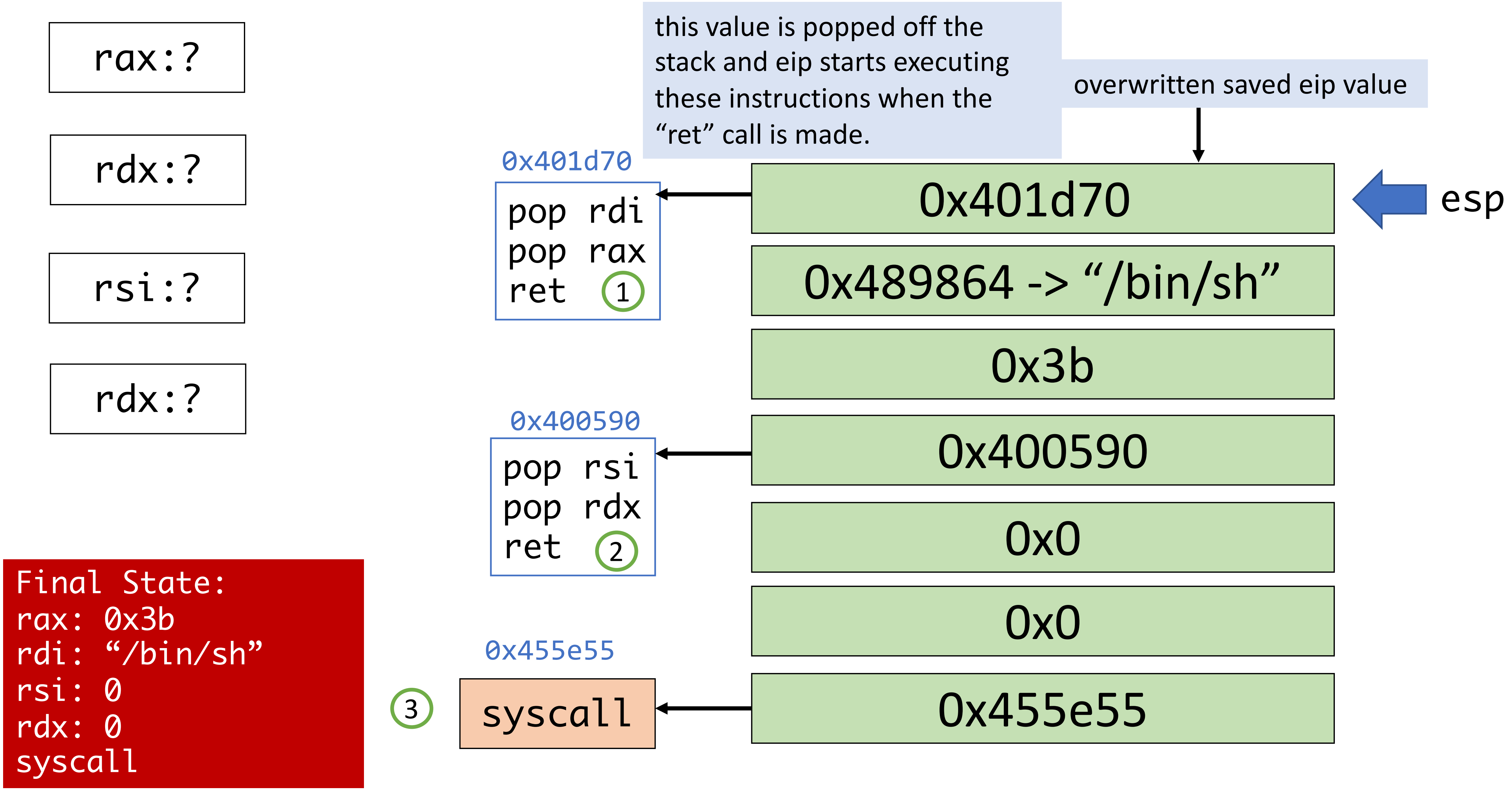
0x455e55

```
syscall
ret
```
(4)

Objective: set the execve shellcode register state

```
rax: 0x3b
rdi: "/bin/sh"
rsi: 0
rdx: 0
syscall
```

Return Oriented Programming: chain gadgets to form a ROP chain



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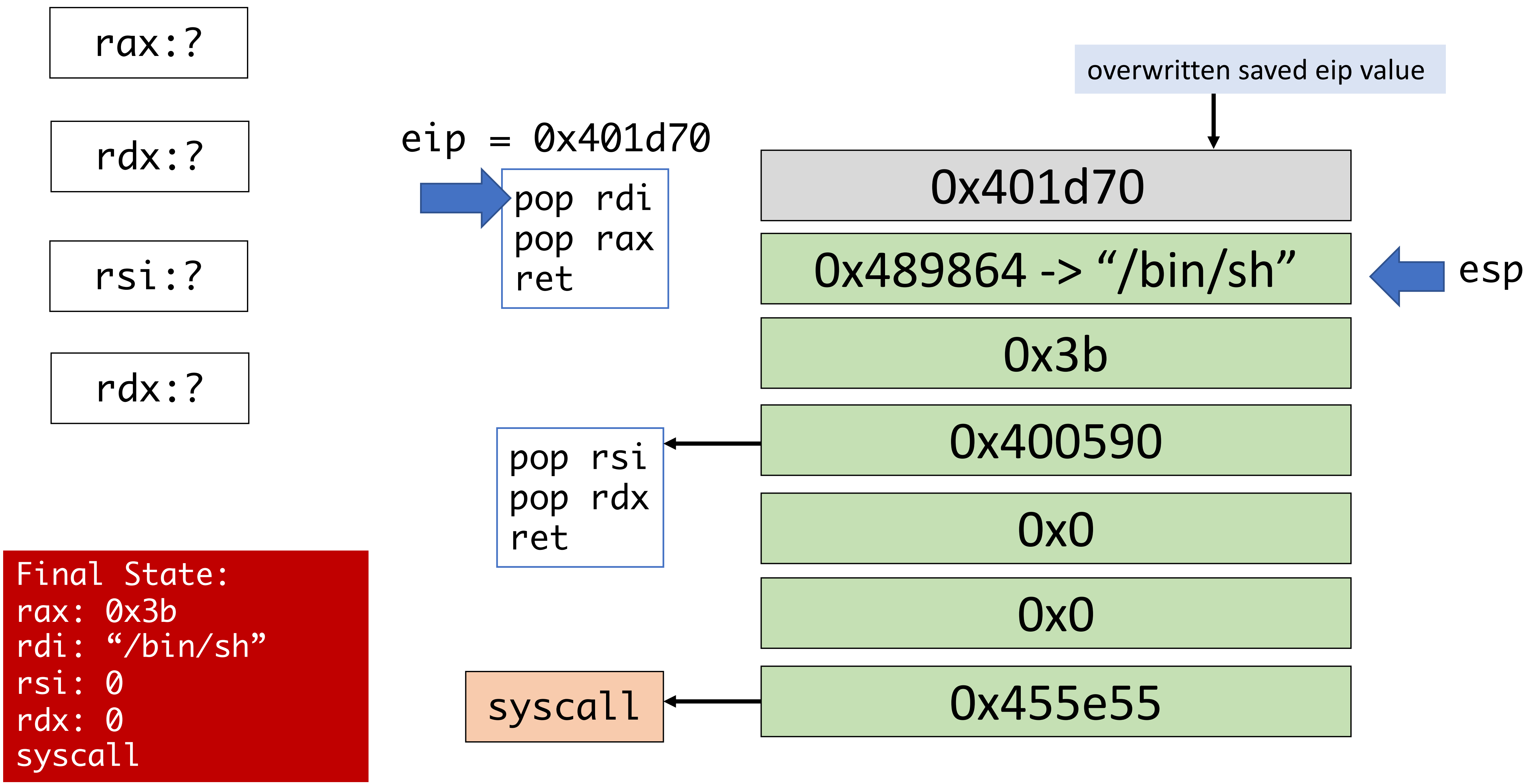

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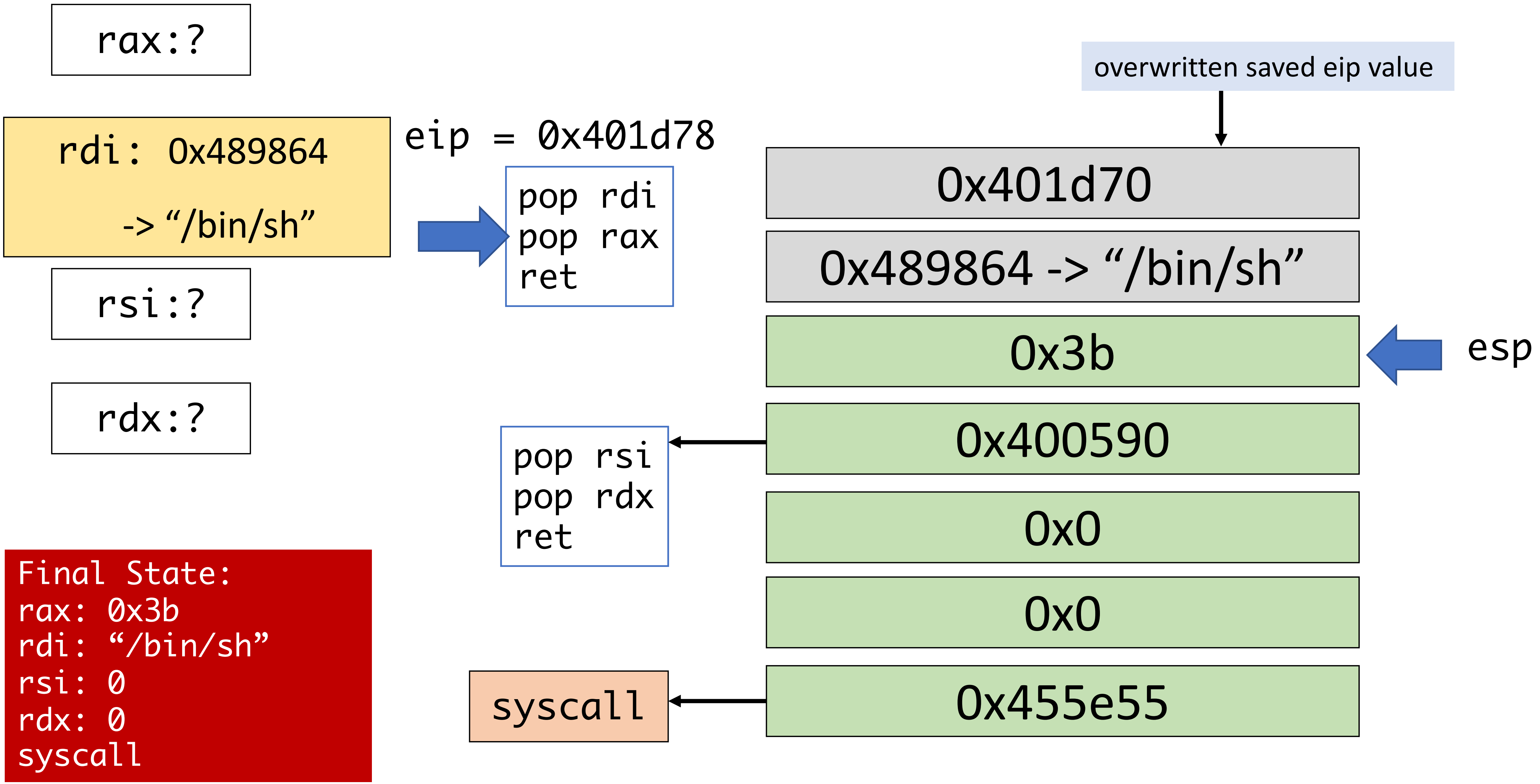

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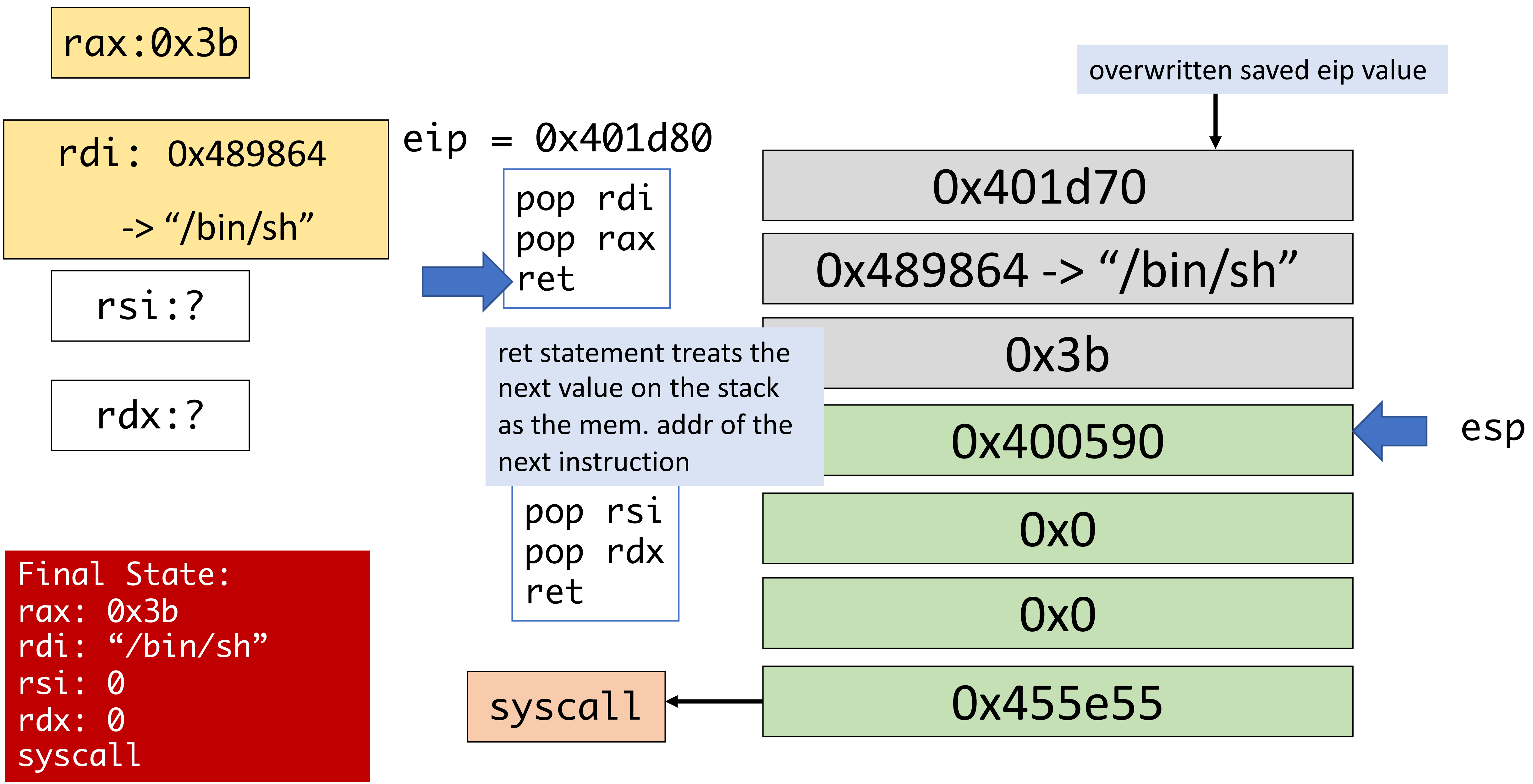

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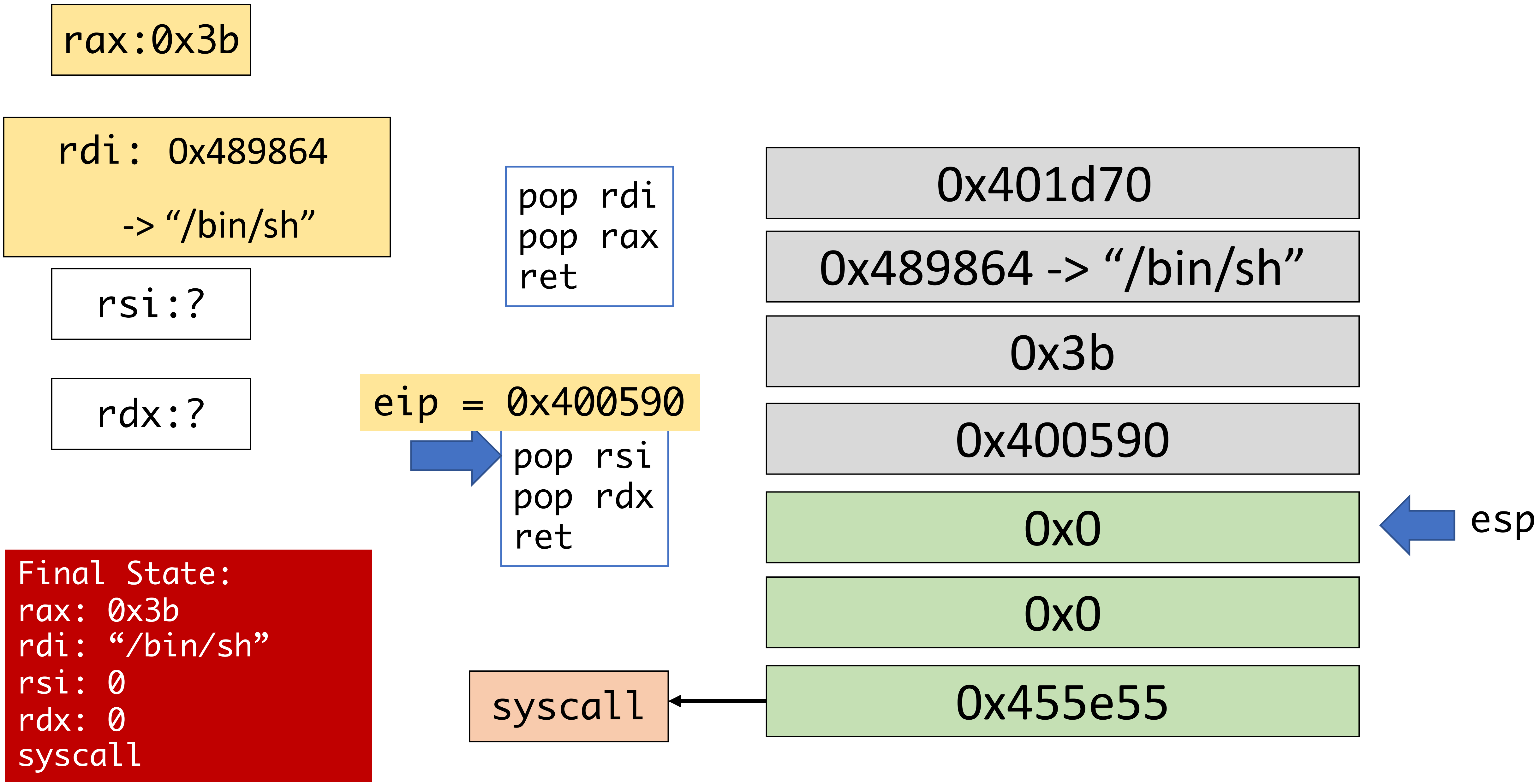

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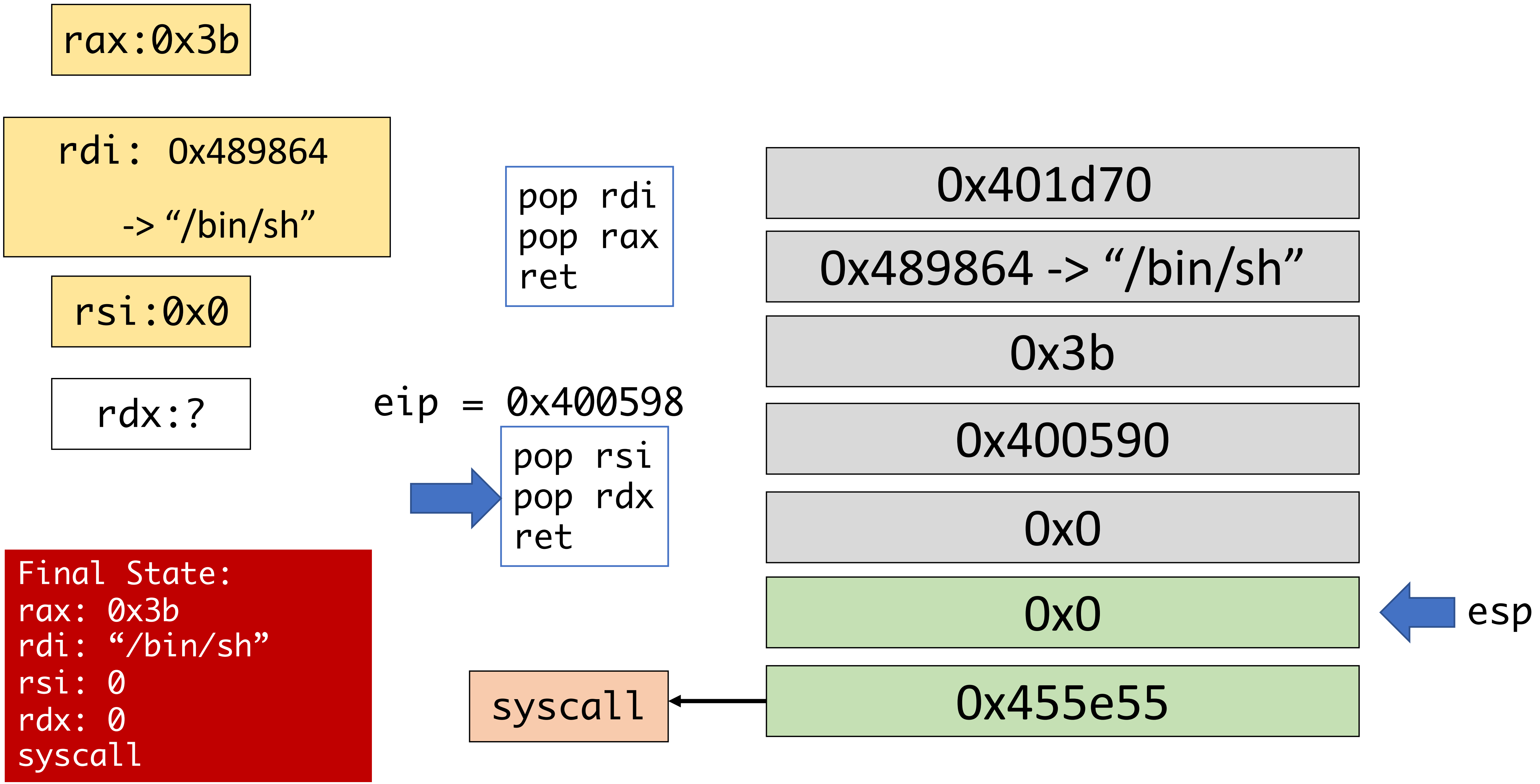

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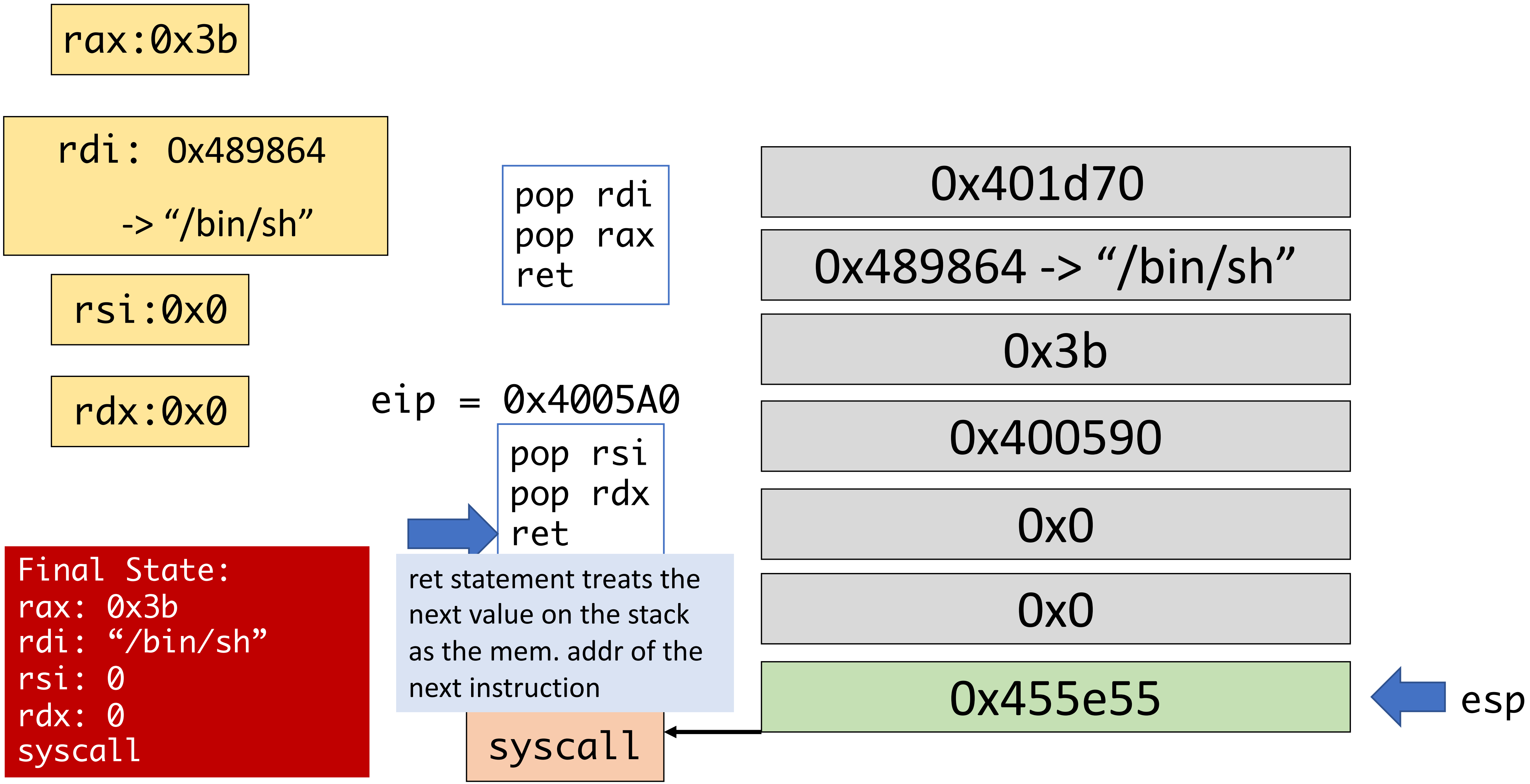
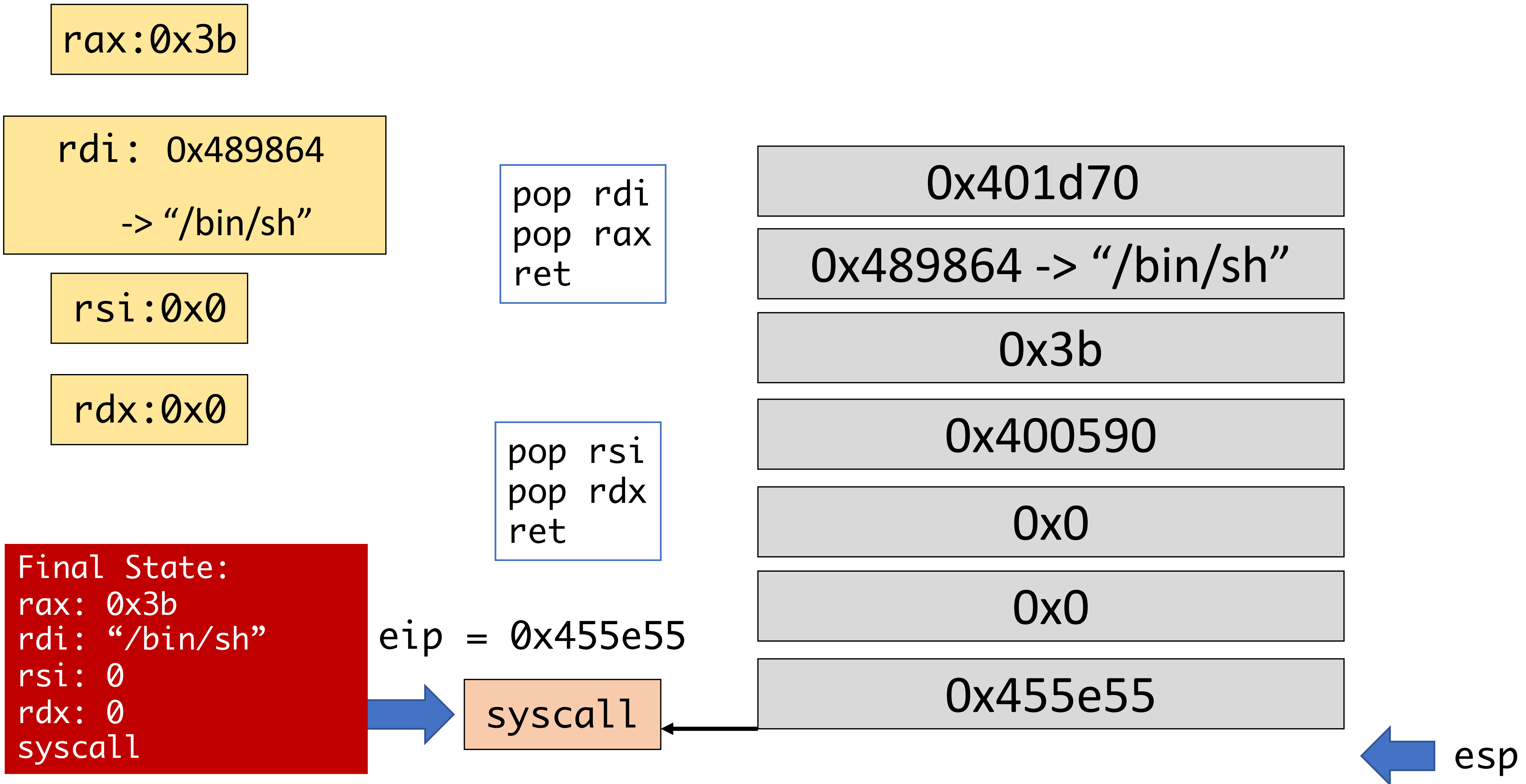


Return Oriented Programming: chain gadgets to form a ROP chain



Exactly the state we set out to achieve! We have successfully launched our shell without injecting any code!

rax:0x3b

rdi: 0x489864

-> “/bin/sh”

rsi:0x0

rdx:0x0

eip = 0x455e55

syscall

Objective: set the execve shellcode register state

```
rax: 0x3b
rdi: “/bin/sh”
rsi: 0
rdx: 0
syscall
```

Zooming out

What happened?

Programmer:

This program crashes if the input is too big

Hacker:

Let’s change some local variables!

Actually, let’s call some functions…

Well as long as we’re already here...let’s call some of *our* specially cherry picked instructions (err.. functions).

Buffer Overflow: Cures

Idea: prevent execution of untrusted code

- Make stack and other data areas non-executable
  - Note: messes up useful functionality (e.g., Flash, JavaScript)
- Digitally sign all code
- Ensure that all control transfers are into a trusted, approved code image

Validating input

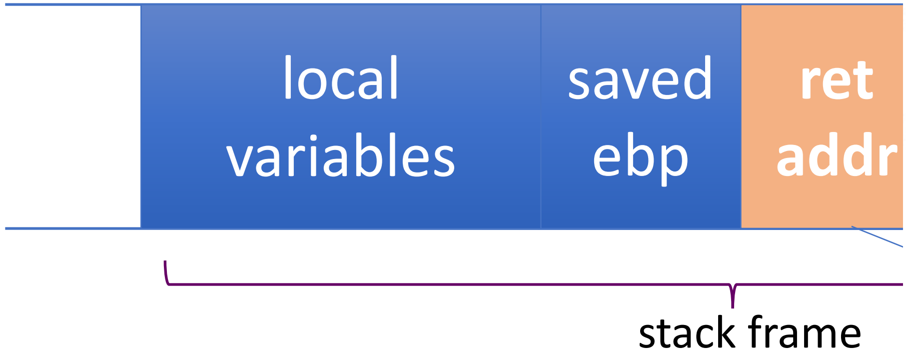
- Determine acceptable input, check for match --- don’t just check against list of “non-matches”
- Limit maximum length
- Watch out for special characters, escape chars.
- Check bounds on integer values
- Check for negative inputs
- Check for large inputs that might cause overflow!

Validating input

- Filenames
- Command-line arguments
- Even argv[0]…
- Commands
  - E.g., URLs, http variables., SQL
  - E.g., cross site scripting, (next lecture)

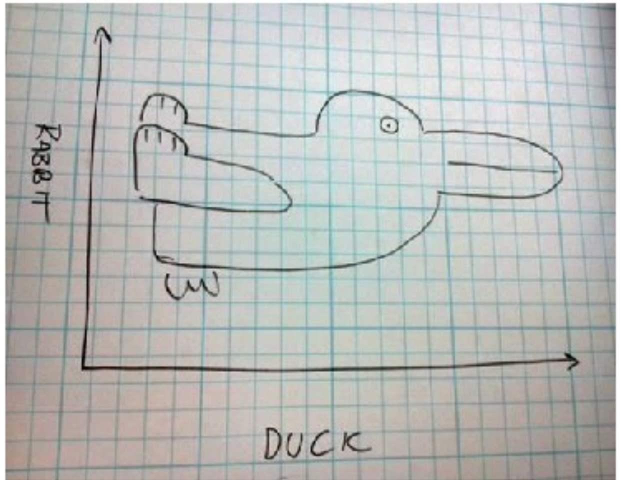
Memory attacks

The problem: mixing data with control flow in memory



Your program manipulates data

Data manipulates your program



Memory Attacks: Causes

"Classic" memory exploit involves code injection

- malicious code @ predictable location in memory -> masquerading as data
- trick vulnerable program into passing control

Memory Attacks: Causes and Cures

"Classic" memory exploit involves code injection

Idea: prevent execution of untrusted code

Developer approaches:

- Use of safer functions like strlcpy(), strlcat() etc.
- safer dynamic link libraries that check the length of the data before copying.

Hardware approaches: Non-Executable Stack

OS approaches: ASLR (Address Space Layout Randomization)

Compiler approaches: Stack-Guard Pro-Police

Data Execution Prevention: a.k.a Mark memory as non-executable

Each page of memory has separate access permissions:

- R -> Can Read, W -> Can Write, X -> Can Execute

Mark all writeable memory locations as non-executable

NX-bit on AMD64, **XD-bit** on Intel x86 (2005), **XN-bit** on ARM

- Now you can't write code to the stack or heap
- No noticeable performance impact

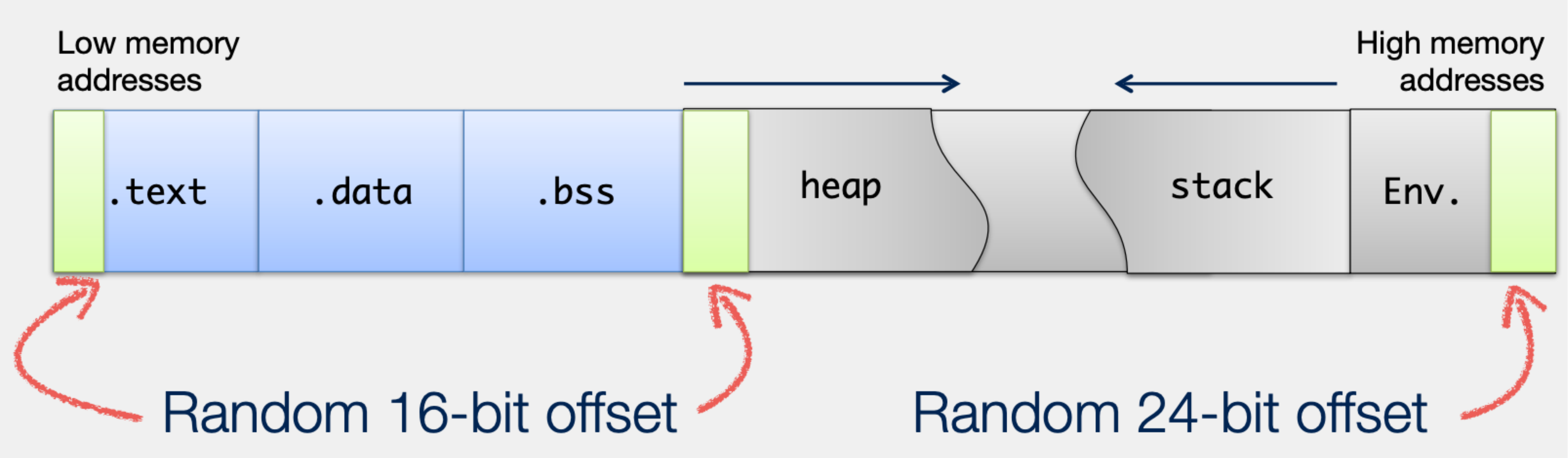
Address Space Layout Randomization

Onload: Randomly relocate the base address of everything in memory

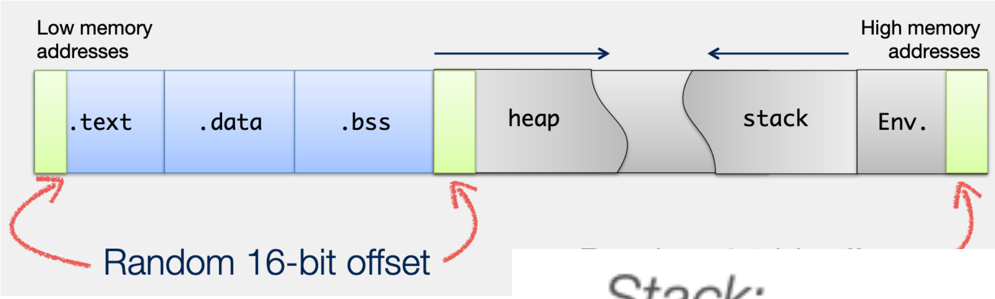
- libraries (DLLs, shared libs), application code, stack heap

⇒ attacker does not no location

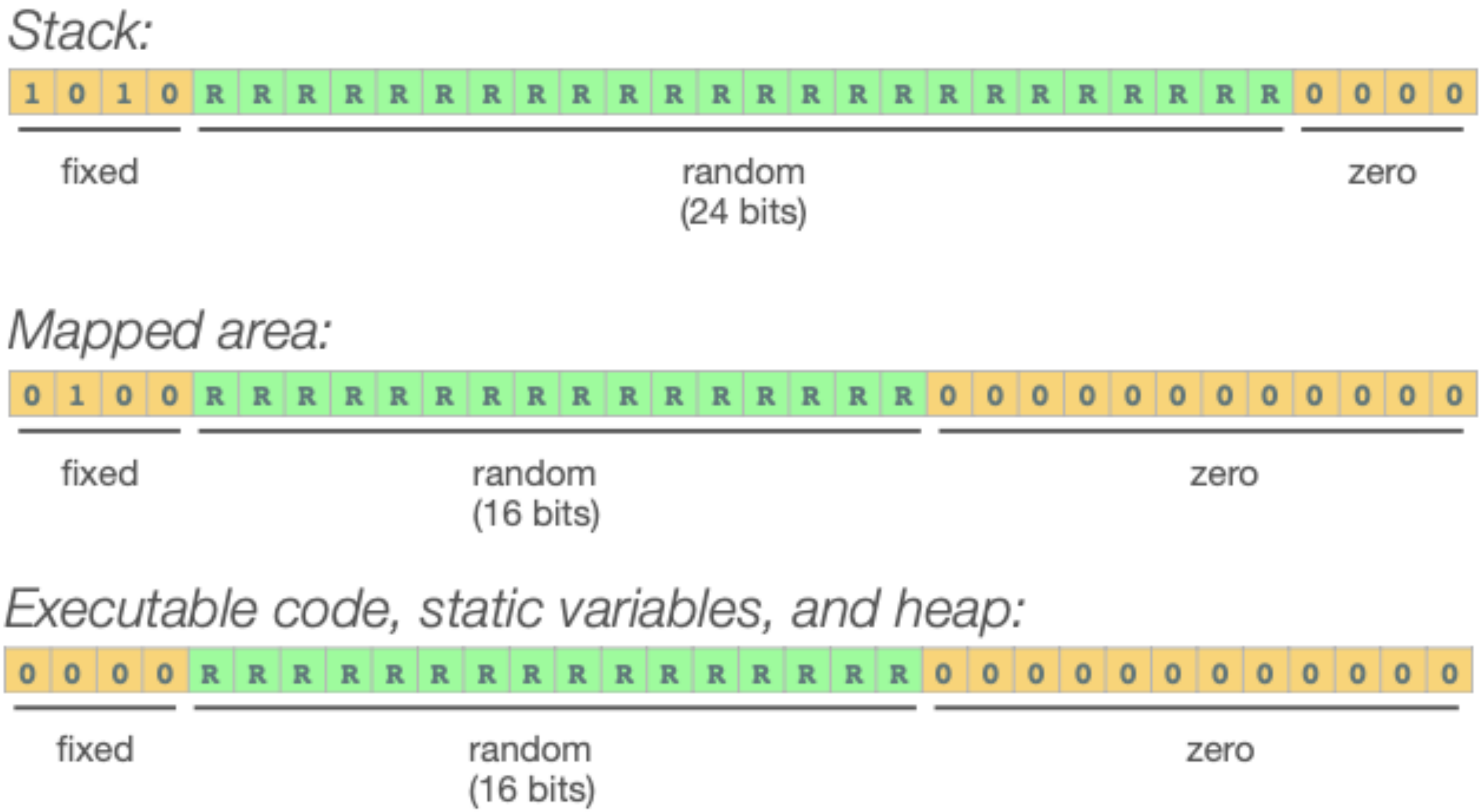
Example: PAX implementation

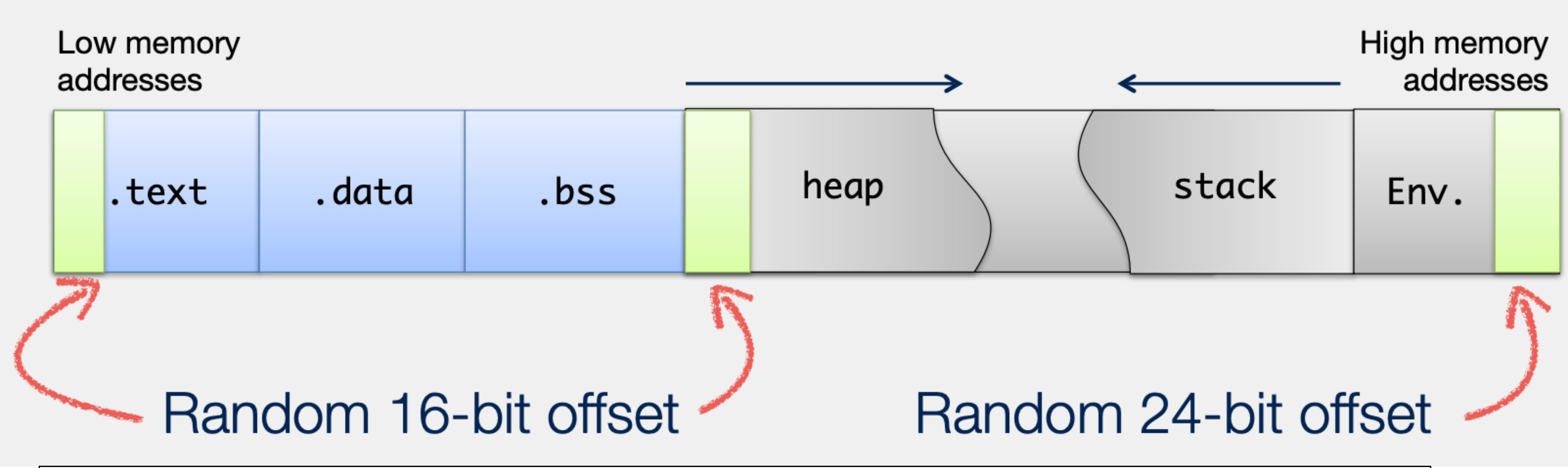


Address Space Layout Randomization



32-bit PaX ASLR (x86)





randomize the start location of stack, code data.

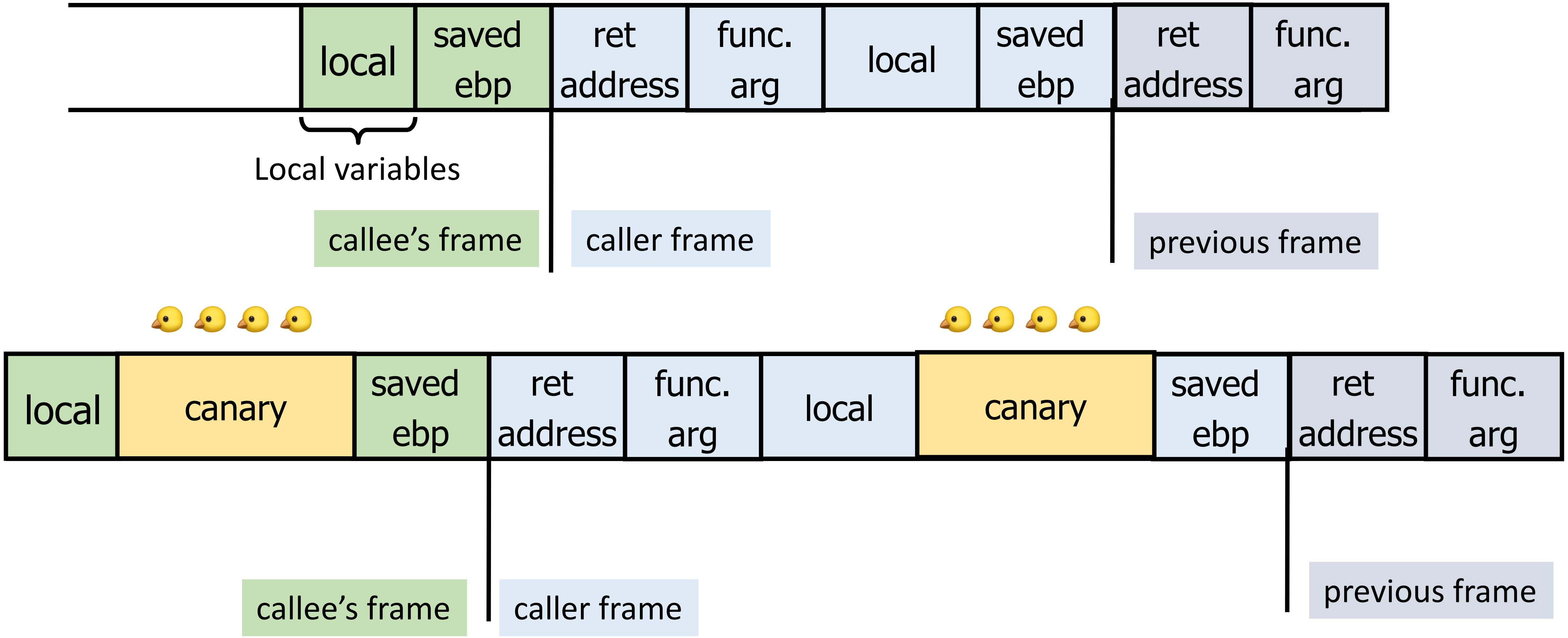
Launch buffer overflow? Difficult to guess the stack address!

Difficult to guess %ebp address and address of the malicious code

Compiler Defenses: Stack Canary

Method 1: StackGuard

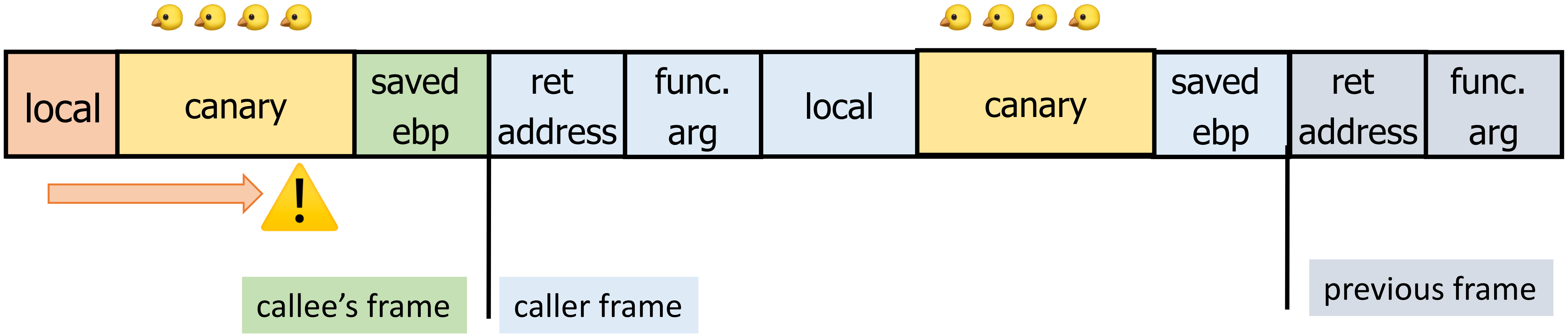
- Embed “canaries” (stack cookies) in stack frames and verify their integrity prior to function return.



StackGuard

Minimal performance effects: 8% for Apache
Program must be recompiled

Overflow canary? Segfault!



Random canary:

- Random string **chosen at program startup**
- To corrupt, attacker must learn/guess current random string

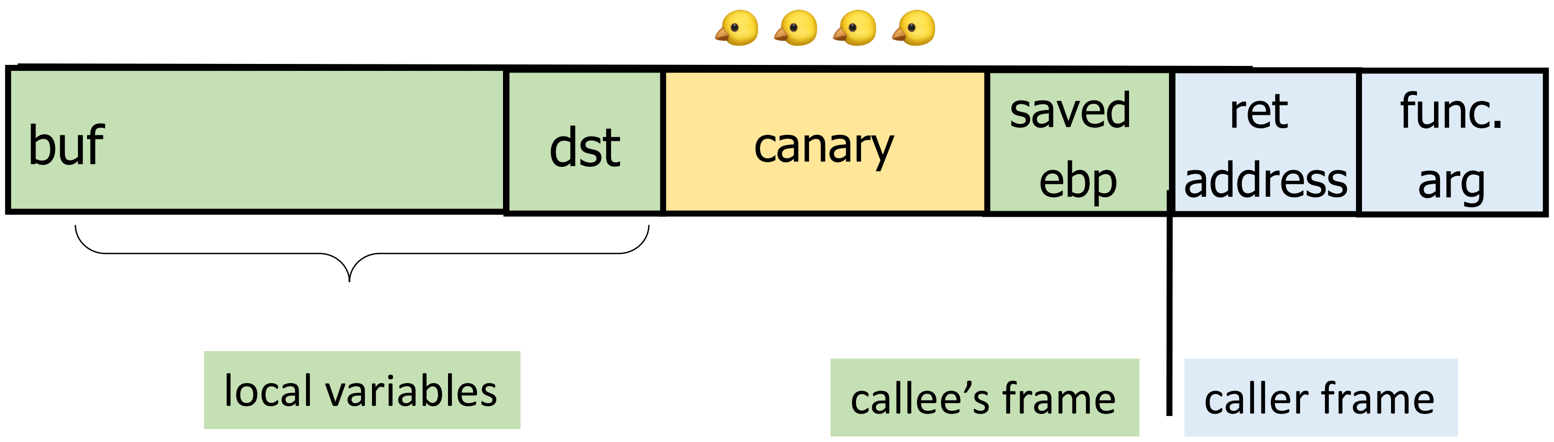
Terminator canary:

- {0, newline, linefeed, EOF}
- String functions will not copy beyond terminator
- Attacker cannot use string functions to corrupt the stack

Canary check in gcc:

```
Dump of assembler code for function foo:
   0x0000120d <+0>:     endbr32
   0x00001211 <+4>:     push   %ebp
   0x00001212 <+5>:     mov    %esp,%ebp
   0x00001214 <+7>:     push   %ebx
   0x00001215 <+8>:     sub    $0x24,%esp
   0x00001218 <+11>:    call   0x12b4 <__x86.get_pc_thunk.ax>
   0x0000121d <+16>:    add    $0x2db3,%eax
   0x00001222 <+21>:    mov    0x8(%ebp),%edx
   0x00001225 <+24>:    mov    %edx,-0x1c(%ebp)
   0x00001228 <+27>:    mov    %gs:0x14,%ecx
   0x0000122f <+34>:    mov    %ecx,-0xc(%ebp)
   0x00001232 <+37>:    xor    %ecx,%ecx
   0x00001234 <+39>:    sub    $0x8,%esp
   0x00001237 <+42>:    pushl  -0x1c(%ebp)
   0x0000123a <+45>:    lea    -0x18(%ebp),%edx
   0x0000123d <+48>:    push   %edx
   0x0000123e <+49>:    mov    %eax,%ebx
   0x00001240 <+51>:    call   0x10a0 <strcpy@plt>
   0x00001245 <+56>:    add    $0x10,%esp
   0x00001248 <+59>:    nop
   0x00001249 <+60>:    mov    -0xc(%ebp),%eax
   0x0000124c <+63>:    xor    %gs:0x14,%eax
   0x00001253 <+70>:    je     0x125a <foo+77>
   0x00001255 <+72>:    call   0x1340 <__stack_chk_fail_local>
   0x0000125a <+77>:    mov    -0x4(%ebp),%ebx
   0x0000125d <+80>:    leave
   0x0000125e <+81>:    ret
End of assembler dump.
```

Defeating StackGuard



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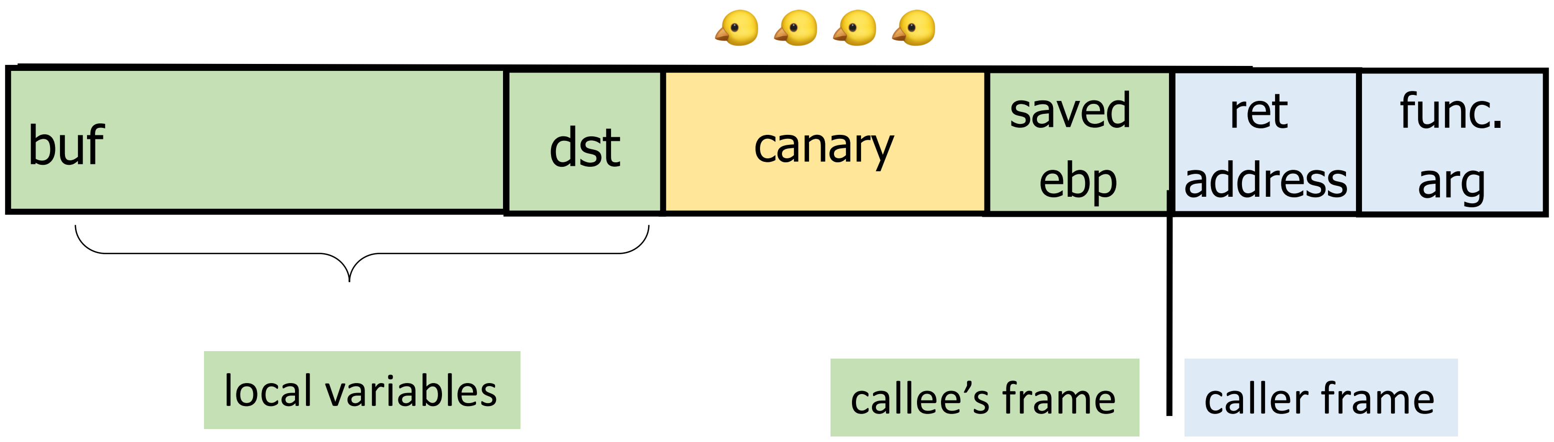

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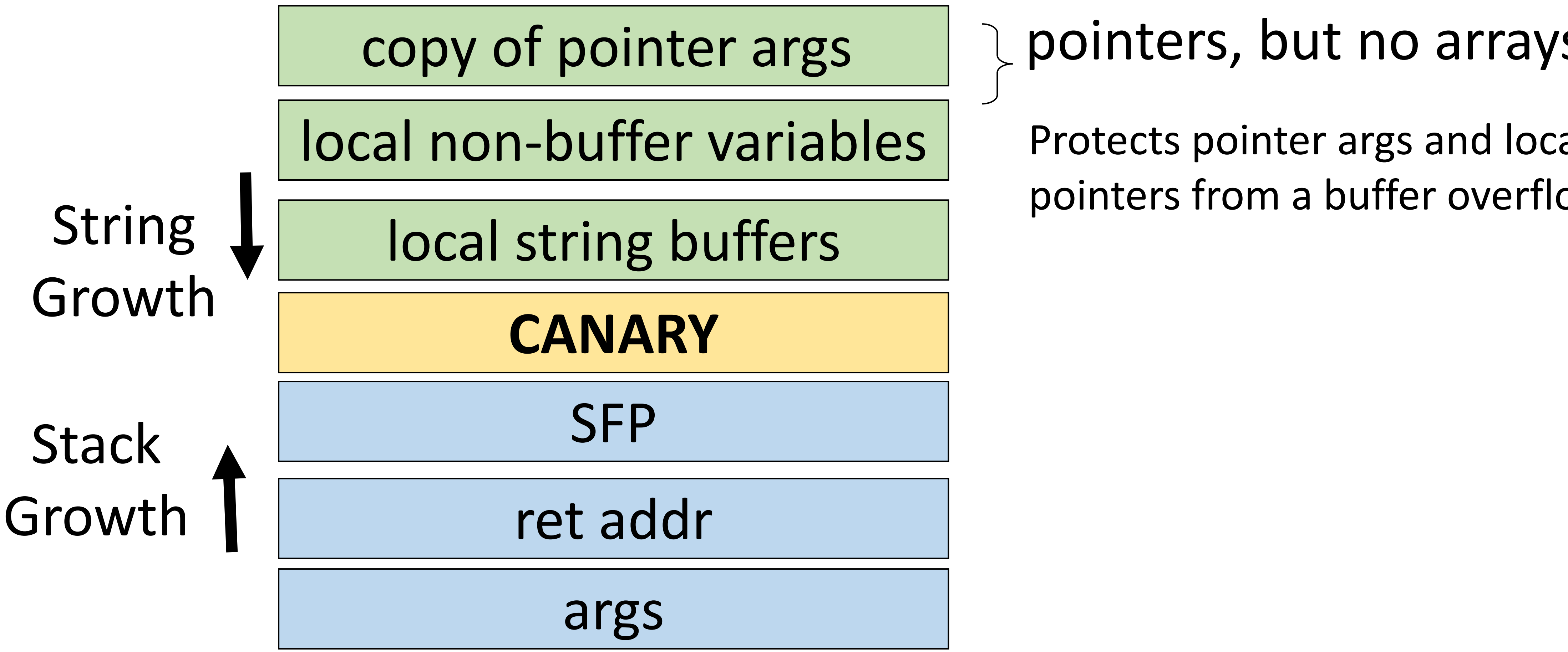
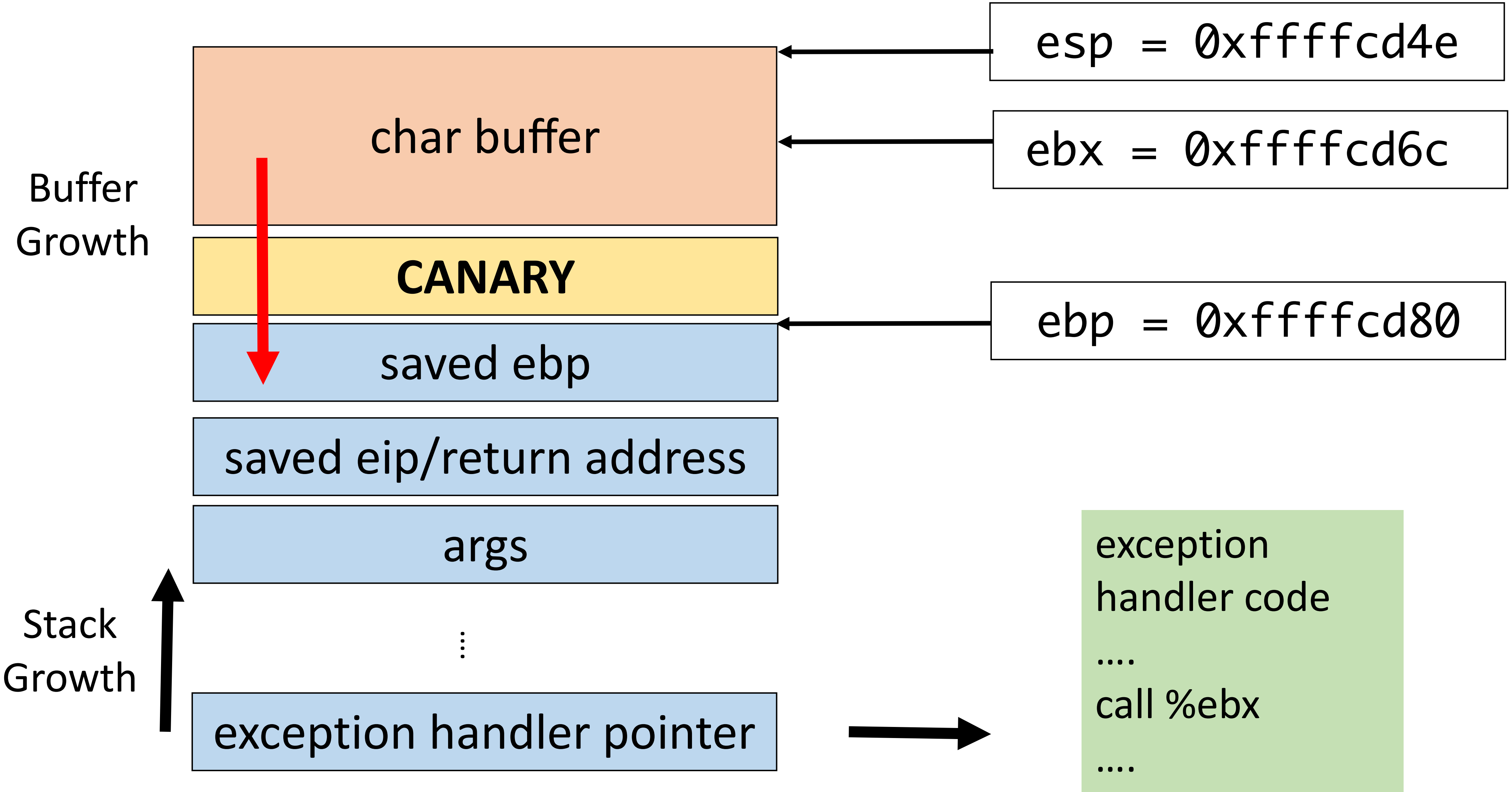
StackGuard Variations

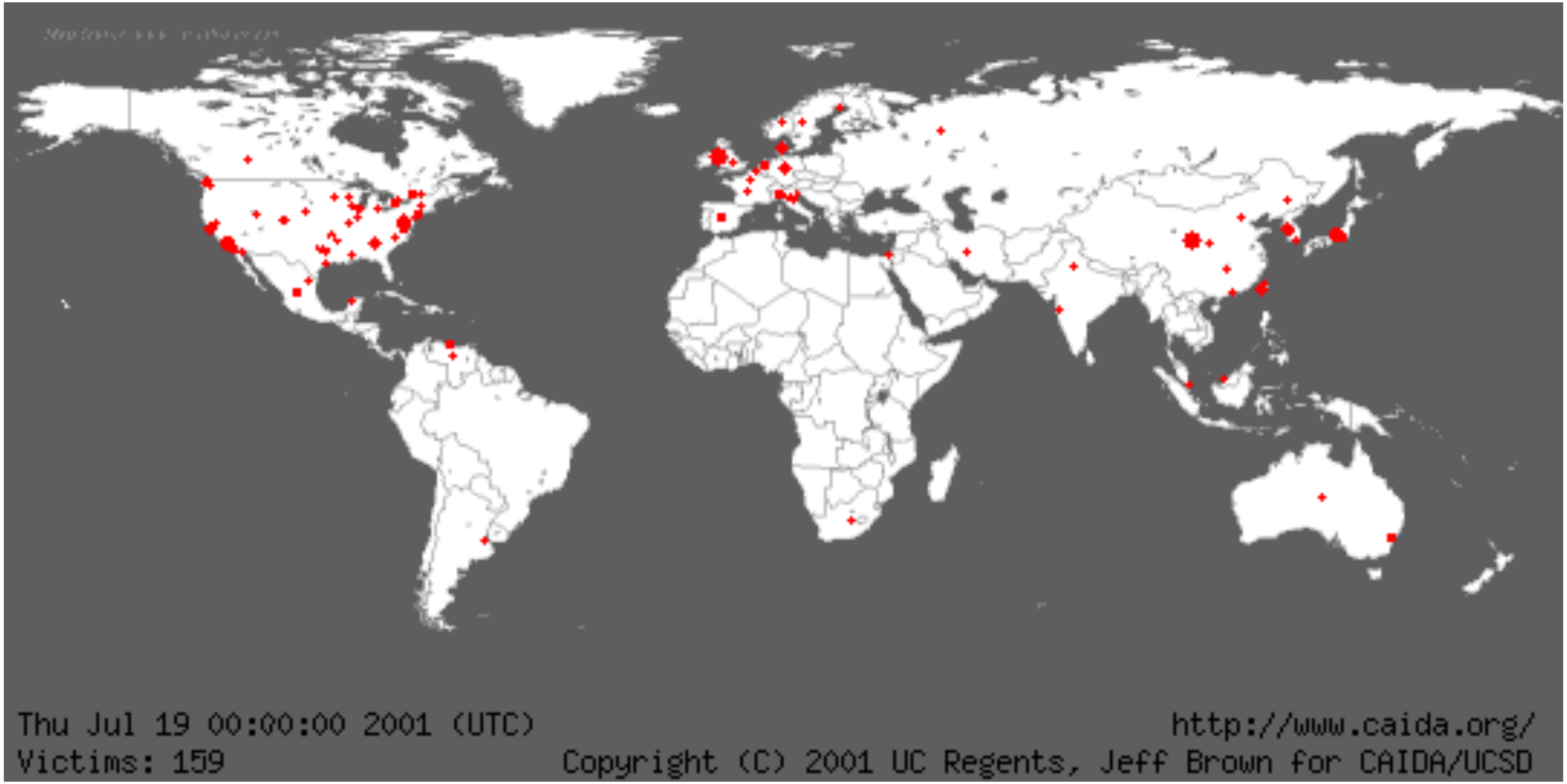
- Rearrange stack layout to prevent ptr overflow.



Protects pointer args and loca
pointers from a buffer overflo

StackGuard Variations



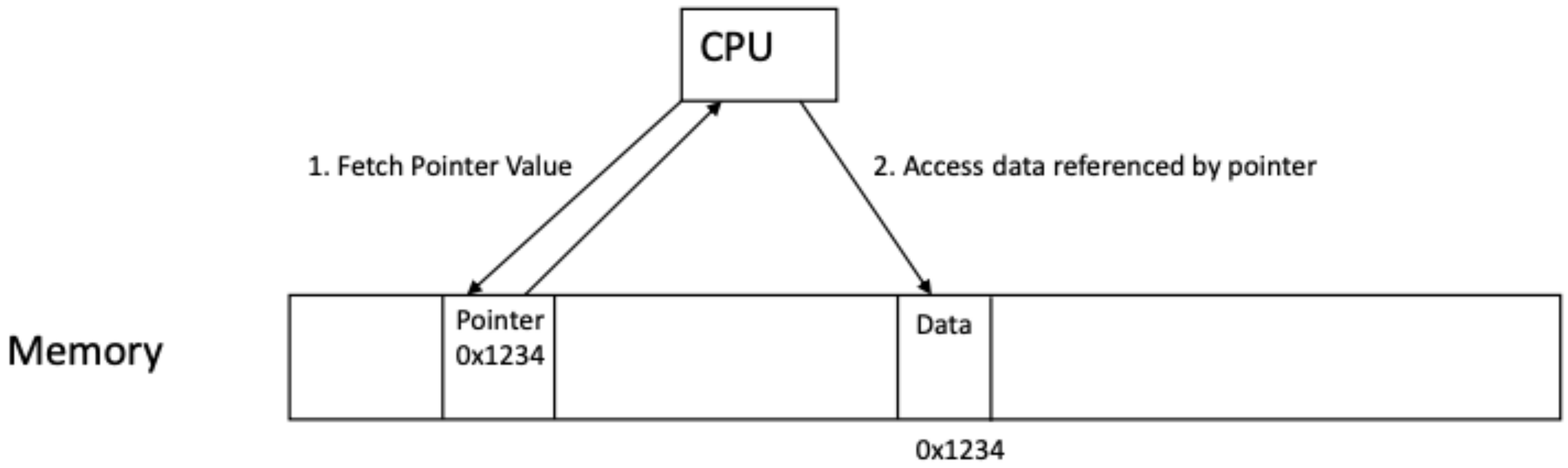


https://www.caida.org/archive/code-red/coderedv2_analysis/#animations

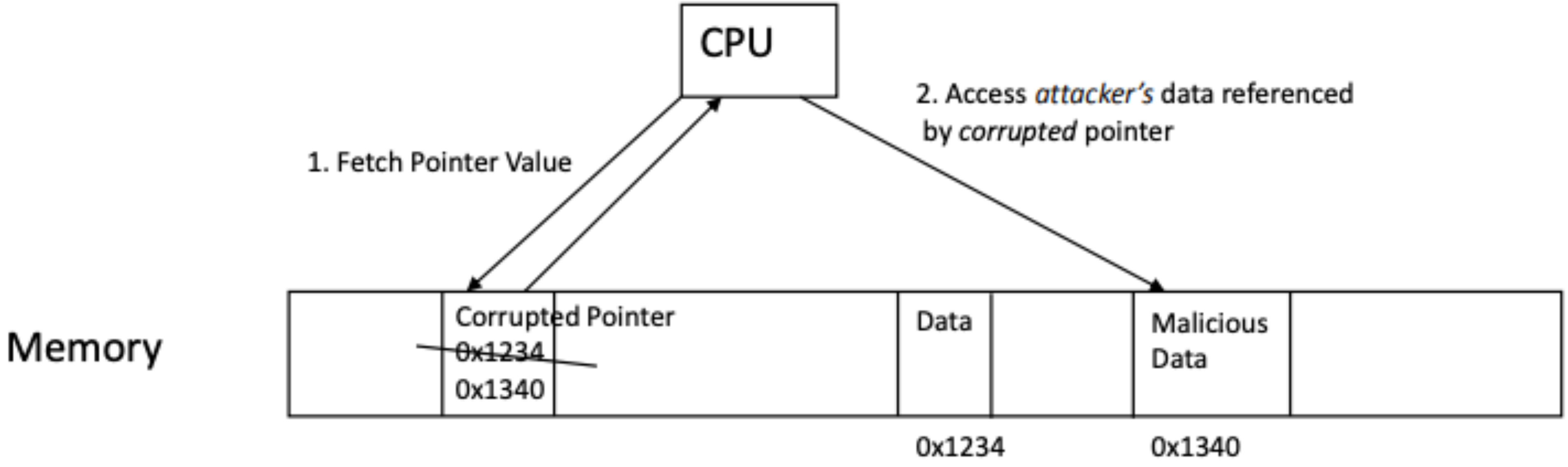
PointGaurd

- Insight:
  - pointers in memory corrupted via overflow
  - pointers in registers are not overflowable
- Solution:
  - Store pointers encrypted in memory
  - To dereference a pointer: decrypt it as you load it unto a register

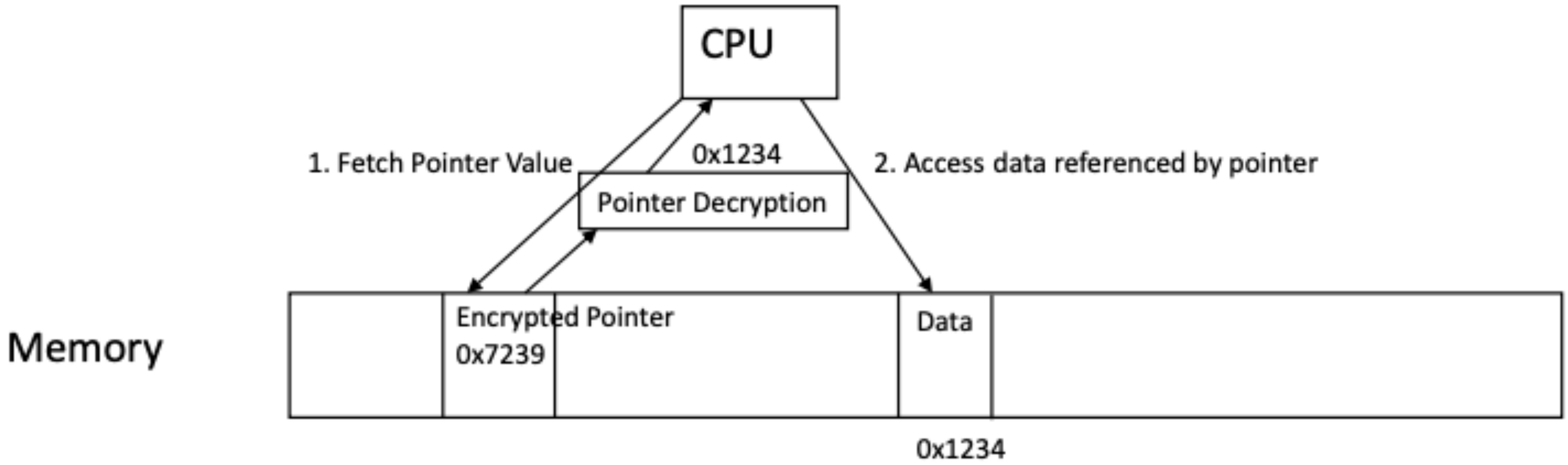
Normal Pointer Dereference



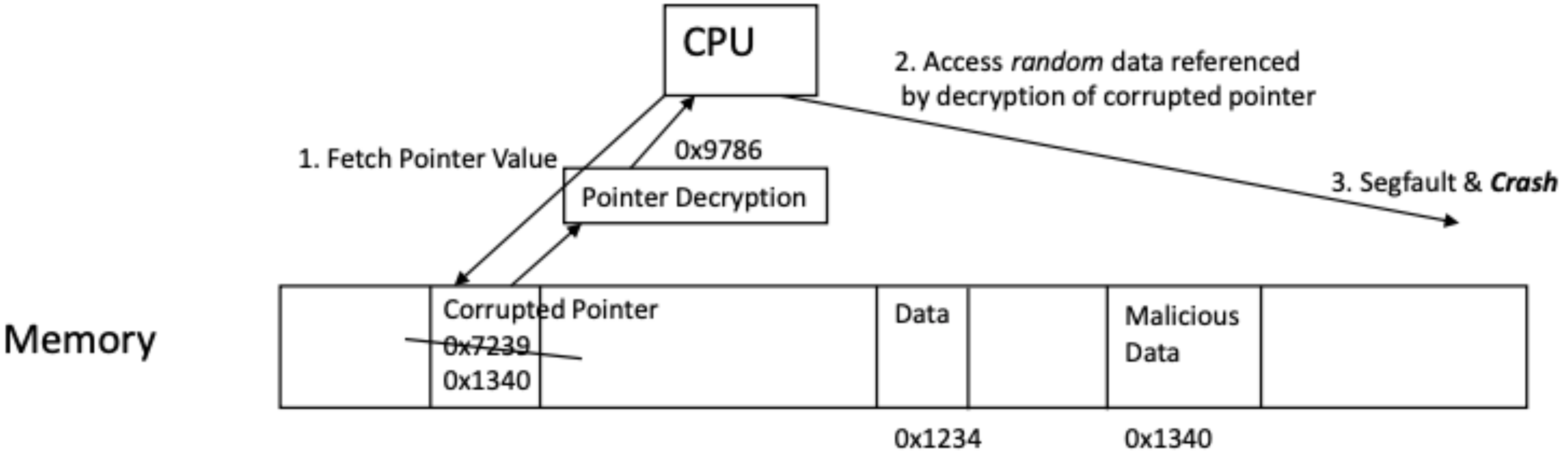
Normal Pointer Dereference under attack



PointerGuard Pointer Dereference



PointerGuard Pointer Dereference Under Attack



Formal Verification

Approaches for Ensuring Memory Safety

- How do we reason about the code to get some confidence that the result will be memory safe?

- Approach using formal mathematical logic, induction to verify that your code is memory safe.

GOAL: You shouldn't have to know what the code inside the function is,
the details of how it works is secondary, the pre- and post-conditions should be sufficient.

General correctness proof strategy for memory safety:
- Identify each point of memory access
- Write down precondition that it requires
- Propagate that requirement up to the beginning of the function

Setting up pre-and post-conditions

Going through our code base, one function at a time we are specifying the contract or API for each function. Also known as contract-based coding.

Pre-conditions

- When a function is invoked, and before it starts executing, the properties of the input variables, that need to be true for the function execution to be memory safe.
- **caller's responsibility to setup**

Post-conditions

- the function ***assumes*** the caller has setup the pre-conditions correctly, then the post-conditions are what should hold after the function finishes executing.
- post-conditions ***are guarantees*** the function provides about the return value or the results of the computation

Setting up pre-and post-conditions

```
int deref(int *p){
        return *p;
}
```

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Setting up pre-and post-conditions

```
/* requires: p! = NULL
             and p as a valid
              pointer
*/
int deref(int *p){
      return *p;
}
```

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Setting up pre-and post-conditions

```
/* ALTERNATE IMPLEMENTATION
requires: p as a valid pointer
*/
int deref(int *p){
      if ( p!= NULL)
            return *p;
}
```

Pre-conditions

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Setting up pre-and post-conditions

```c
/* requires:
   Ensures:
*/
void *mymalloc (unsigned int n){
      void *p = malloc(n);
      if (!p){
            perror("malloc");
            exit(1);
      }
      return p;
}
```

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Setting up pre-and post-conditions

```
/*
   Ensures: return value != NULL
         (and a valid pointer)
*/
void *mymalloc (unsigned int n){
      void *p = malloc(n);
      if (!p){
//code checks if malloc returns with valid pointer
            perror("malloc");
            exit(1);
      }
      return p;
}
```

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