



# CSE 127: Computer Security

# Low-level mitigations

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Some slides adopted from Nadia Heninger, Kirill Levchenko, Stefan Savage,  
and Stephen Checkoway

# Today: mitigating buffer overflows

Lecture objectives:

- Understand how to mitigate buffer overflow attacks
- Understand the trade-offs of different mitigations
- Understand how mitigations can be bypassed

# Buffer overflow mitigations

➔ Avoid unsafe functions

- Stack canaries
- Separate control stack
- Memory writable or executable, not both ( $W^X$ )
- Address space layout randomization (ASLR)

# Avoiding Unsafe Functions

- strcpy, strcat, gets, etc.
- **Plus:** Good idea in general
- **Minus:** Requires manual code rewrite
- **Minus:** Non-library functions may be vulnerable
  - E.g. user creates their own strcpy
- **Minus:** No guarantee you found everything
- **Minus:** alternatives are also error-prone

# Even printf is tricky

If buf is under control of attacker  
is: `printf(“%s\n”, buf)` safe?

# Even printf is tricky

If buf is under control of attacker  
is: `printf(buf)` safe?

# Even printf is tricky

Is `printf(“%s\n”)` safe?

# Even printf is tricky

printf can be used to read and write memory  
➡ control flow hijacking!

Exploiting Format String Vulnerabilities

scut / team teso

September 1, 2001



# Buffer overflow mitigations

- Avoid unsafe functions

➔ Stack canaries

- Separate control stack
- Memory writable or executable, not both ( $W^X$ )
- Address space layout randomization (ASLR)

## Miner's canary [\[ edit \]](#)

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Canaries were used as [sentinel species](#) for use in detecting carbon monoxide in [coal mining](#) from around 1913 when the idea was suggested by [John Scott Haldane](#).<sup>[14]</sup> [Toxic gases](#) such as [carbon monoxide](#) or [asphyxiant gases](#) such as [methane](#)<sup>[15]</sup> in the mine would affect the bird before affecting the miners. Signs of distress from the bird indicated to the miners that conditions were unsafe. The birds were generally kept in carriers which had small oxygen bottles attached to revive the birds, so that they could be used multiple times within the mine.<sup>[16]</sup> The use of miners' canaries in [British](#) mines was phased out in 1986.<sup>[17][18]</sup>

The phrase "[canary in a coal mine](#)" is frequently used to refer to a person or thing which serves as an early warning of a coming crisis. By analogy, the term "climate canary" is used to refer to a species (called an [indicator species](#)) that is affected by an environmental danger prior to other species, thus serving as an early warning system for the other species with regard to the danger.<sup>[19]</sup>

# Stack canaries

- **Goal:** Prevent control flow hijacking by detecting stack-buffer overflows
- **Idea:**
  - Place canary between local variables and saved frame pointer (and return address)
  - Check canary before jumping to return address
- **Approach:**
  - Modify function prologues and epilogues

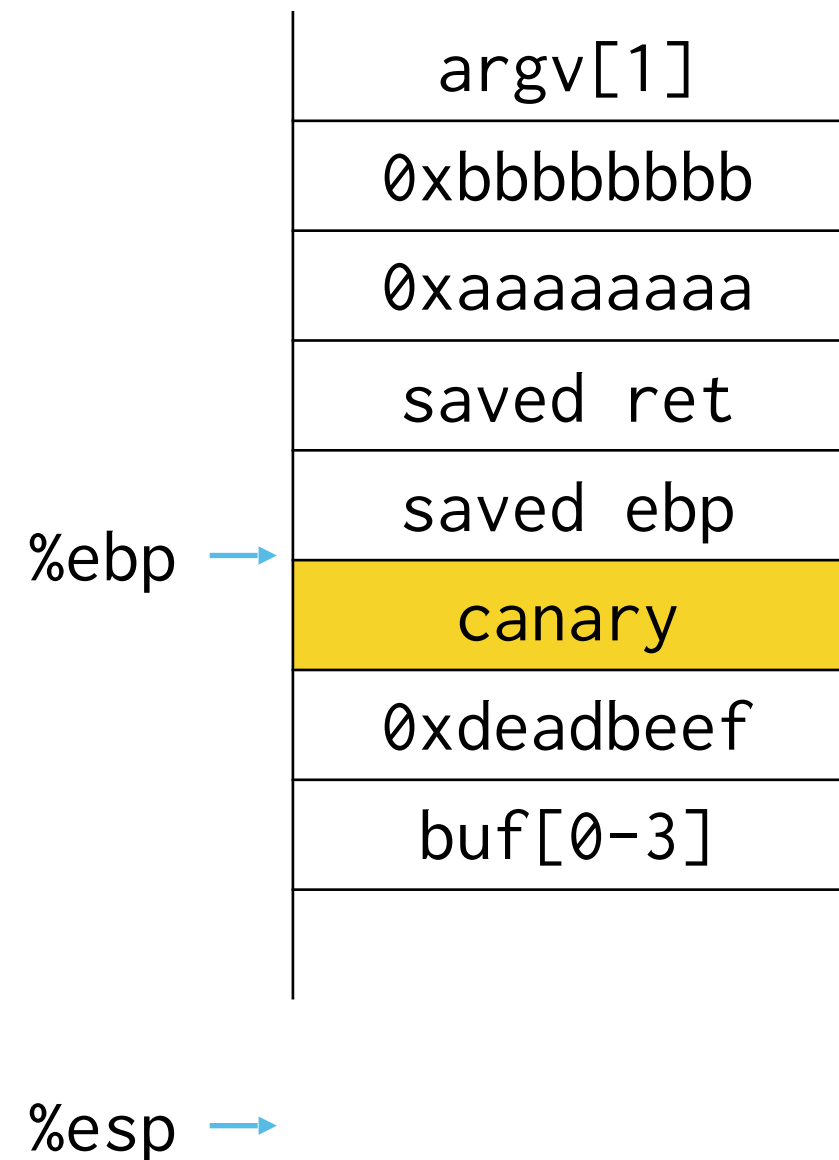
# Example (at a high level)

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

void foo() {
    printf("hello all!!\n");
    exit(0);
}

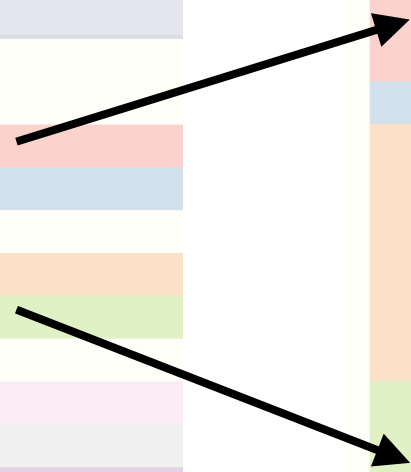
void func(int a, int b, char *str) {
    int c = 0xdeadbeef;
    char buf[4];
    strcpy(buf, str);
}

int main(int argc, char**argv) {
    func(0xaaaaaaaa, 0xbbbbbbbb, argv[1]);
    return 0;
}
```



# Compiled, without canaries

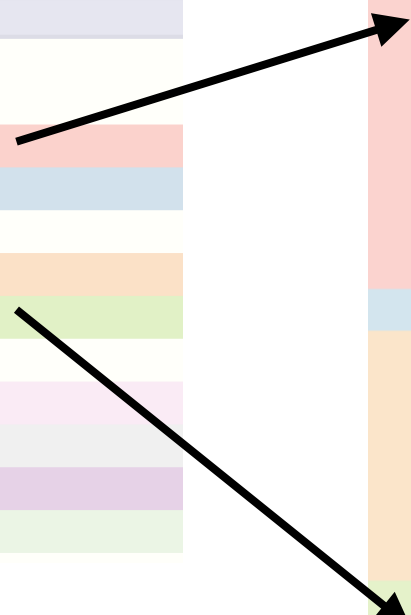
```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <string.h>
4
5  void foo() {
6      printf("hello all!!\n");
7      exit(0);
8  }
9
10 void func(int a, int b, char *str) {
11     int c = 0xdeadbeef;
12     char buf[4];
13     strcpy(buf, str);
14 }
15
16 int main(int argc, char**argv) {
17     func(0xaaaaaaaa, 0xbbbbbbbb, argv[1]);
18     return 0;
19 }
```



```
func(int, int, char*):
    pushl    %ebp
    movl     %esp, %ebp
    subl     $24, %esp
    movl     $-559038737, -12(%ebp)
    subl     $8, %esp
    pushl    16(%ebp)
    leal     -16(%ebp), %eax
    pushl    %eax
    call     strcpy
    addl     $16, %esp
    nop
    leave
    ret
```

# With -fstack-protector-strong

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <string.h>
4
5  void foo() {
6      printf("hello all!!\n");
7      exit(0);
8  }
9
10 void func(int a, int b, char *str) {
11     int c = 0xdeadbeef;
12     char buf[4];
13     strcpy(buf, str);
14 }
15
16 int main(int argc, char**argv) {
17     func(0xaaaaaaaa, 0xbbbbbbbb, argv[1]);
18     return 0;
19 }
```



```
func(int, int, char*):
    pushl    %ebp
    movl     %esp, %ebp
    subl     $40, %esp
    movl     16(%ebp), %eax
    movl     %eax, -28(%ebp)
    movl     %gs:20, %eax
    movl     %eax, -12(%ebp)
    xorl     %eax, %eax
    movl     $-559038737, -20(%ebp)
    subl     $8, %esp
    pushl     -28(%ebp)
    leal     -16(%ebp), %eax
    pushl     %eax
    call     strcpy
    addl     $16, %esp
    nop
    movl     -12(%ebp), %eax
    xorl     %gs:20, %eax
    je       .L3
    call     __stack_chk_fail
.L3:
    leave
    ret
```

# With -fstack-protector-strong

write canary from %gs:20 to stack -12(%ebp)

compare canary in %gs:20 to that on stack -12(%ebp)

```
func(int, int, char*):  
    pushl    %ebp  
    movl     %esp, %ebp  
    subl     $40, %esp  
    movl     16(%ebp), %eax  
    movl     %eax, -28(%ebp)
```

```
    movl     %gs:20, %eax  
    movl     %eax, -12(%ebp)  
    xorl     %eax, %eax
```

```
    movl     $-559038737, -20(%ebp)
```

```
    subl     $8, %esp  
    pushl    -28(%ebp)  
    leal     -16(%ebp), %eax  
    pushl    %eax  
    call     strcpy  
    addl     $16, %esp
```

```
    nop
```

```
    movl     -12(%ebp), %eax  
    xorl     %gs:20, %eax  
    je       .L3  
    call     __stack_chk_fail
```

```
.L3:
```

```
    leave  
    ret
```

# Trade-offs

- **Easy to deploy:** Can implement mitigation as compiler pass (i.e., don't need to change your code)
- **Performance:** Every protected function is more expensive

## No stack protection

```
func(int, int, char*):
    pushl    %ebp
    movl    %esp, %ebp
    subl    $24, %esp
    movl    $-559038737, -12(%ebp)
    subl    $8, %esp
    pushl    16(%ebp)
    leal    -16(%ebp), %eax
    pushl    %eax
    call    strcpy
    addl    $16, %esp
    nop
    leave
    ret
```

## -fstack-protector-strong

```
func(int, int, char*):
    pushl    %ebp
    movl    %esp, %ebp
    subl    $40, %esp
    movl    16(%ebp), %eax
    movl    %eax, -28(%ebp)
    movl    %gs:20, %eax
    movl    %eax, -12(%ebp)
    xorl    %eax, %eax
    movl    $-559038737, -20(%ebp)
    subl    $8, %esp
    pushl    -28(%ebp)
    leal    -16(%ebp), %eax
    pushl    %eax
    call    strcpy
    addl    $16, %esp
    nop
    movl    -12(%ebp), %eax
    xorl    %gs:20, %eax
    je      .L3
    call    __stack_chk_fail
.L3:
    leave
    ret
```



# When do we add canaries?

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- -fstack-protector
  - Functions with character buffers  $\geq$  ssp-buffer-size (default is 8)
  - Functions with variable sized alloca()s

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- -fstack-protector
  - Functions with character buffers  $\geq$  ssp-buffer-size (default is 8)
  - Functions with variable sized alloca()s
- -fstack-protector-strong
  - + Functions with local arrays of any size/type
  - + Functions that have references to local stack variables

# When do we add canaries?

- -fstack-protector
  - Functions with character buffers  $\geq$  ssp-buffer-size (default is 8)
  - Functions with variable sized alloca()s
- -fstack-protector-strong
  - + Functions with local arrays of any size/type
  - + Functions that have references to local stack variables
- -fstack-protector-all:
  - All functions!

# There is a cost even for same func:

No stack protection

```
func(int, int, char*):
    pushl    %ebp
    movl     %esp, %ebp
    subl     $24, %esp
    movl     $-559038737, -12(%ebp)
    subl     $8, %esp
    pushl     16(%ebp)
    leal     -16(%ebp), %eax
    pushl     %eax
    call     strcpy
    addl     $16, %esp
    nop
    leave
    ret
```

-fstack-protector-strong

```
func(int, int, char*):
    pushl    %ebp
    movl     %esp, %ebp
    subl     $40, %esp
    movl     16(%ebp), %eax
    movl     %eax, -28(%ebp)
    movl     %gs:20, %eax
    movl     %eax, -12(%ebp)
    xorl     %eax, %eax
    movl     $-559038737, -20(%ebp)
    subl     $8, %esp
    pushl     -28(%ebp)
    leal     -16(%ebp), %eax
    pushl     %eax
    call     strcpy
    addl     $16, %esp
    nop
    movl     -12(%ebp), %eax
    xorl     %gs:20, %eax
    je       .L3
    call     __stack_chk_fail
.L3:
    leave
    ret
```

-fstack-protector-all

```
func(int, int, char*):
    pushl    %ebp
    movl     %esp, %ebp
    subl     $40, %esp
    movl     8(%ebp), %eax
    movl     %eax, -28(%ebp)
    movl     12(%ebp), %eax
    movl     %eax, -32(%ebp)
    movl     16(%ebp), %eax
    movl     %eax, -36(%ebp)
    movl     %gs:20, %eax
    movl     %eax, -12(%ebp)
    xorl     %eax, %eax
    movl     $-559038737, -20(%ebp)
    subl     $8, %esp
    pushl     -36(%ebp)
    leal     -16(%ebp), %eax
    pushl     %eax
    call     strcpy
    addl     $16, %esp
    nop
    movl     -12(%ebp), %eax
    xorl     %gs:20, %eax
    je       .L4
    call     __stack_chk_fail
.L4:
    leave
    ret
```

(we'll see why in just a bit)

# How can we defeat canaries?

# How can we defeat canaries?

- Assumption: impossible to subvert control flow without corrupting the canary
- Attack vectors
  - Use targeted write gadget (e.g., with format strings)
  - Pointer subterfuge
  - Overwrite function pointer elsewhere on the stack/heap
  - memcpy buffer overflow with fixed canary
  - Learn the canary

# Pointer subterfuge

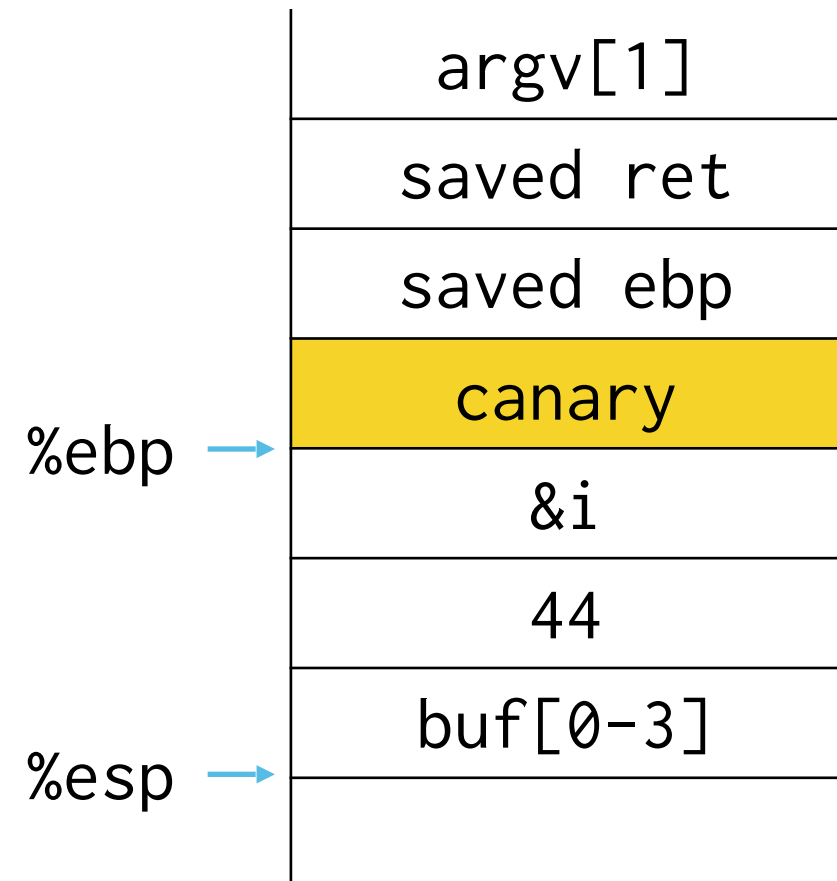
```
#include <stdio.h>
#include <string.h>
```

```
void foo() {
    printf("hello all!!\n");
    exit(0);
}
```

```
int i = 42;
```

```
void func(char *str) {
    int *ptr = &i;
    int val = 44;
    → char buf[4];
    strcpy(buf, str);
    *ptr = val;
}
```

```
int main(int argc, char**argv) {
    func(argv[1]);
    return 0;
}
```





# Pointer subterfuge

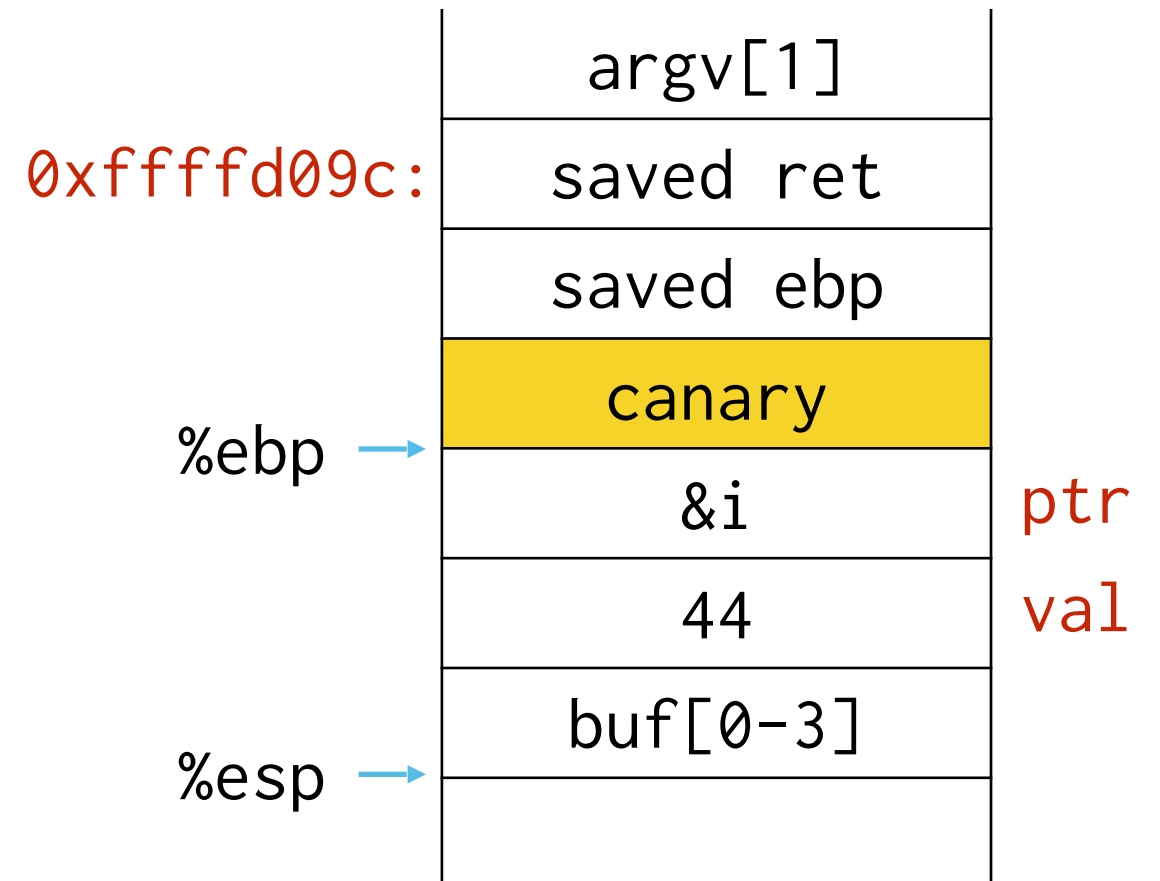
```
#include <stdio.h>
#include <string.h>
```

```
0x08049b95: void foo() {
    printf("hello all!!\n");
    exit(0);
}
```

```
int i = 42;
```

```
void func(char *str) {
    int *ptr = &i;
    int val = 44;
    → char buf[4];
    strcpy(buf, str);
    *ptr = val;
}
```

```
int main(int argc, char**argv) {
    func(argv[1]);
    return 0;
}
```



# Pointer subterfuge

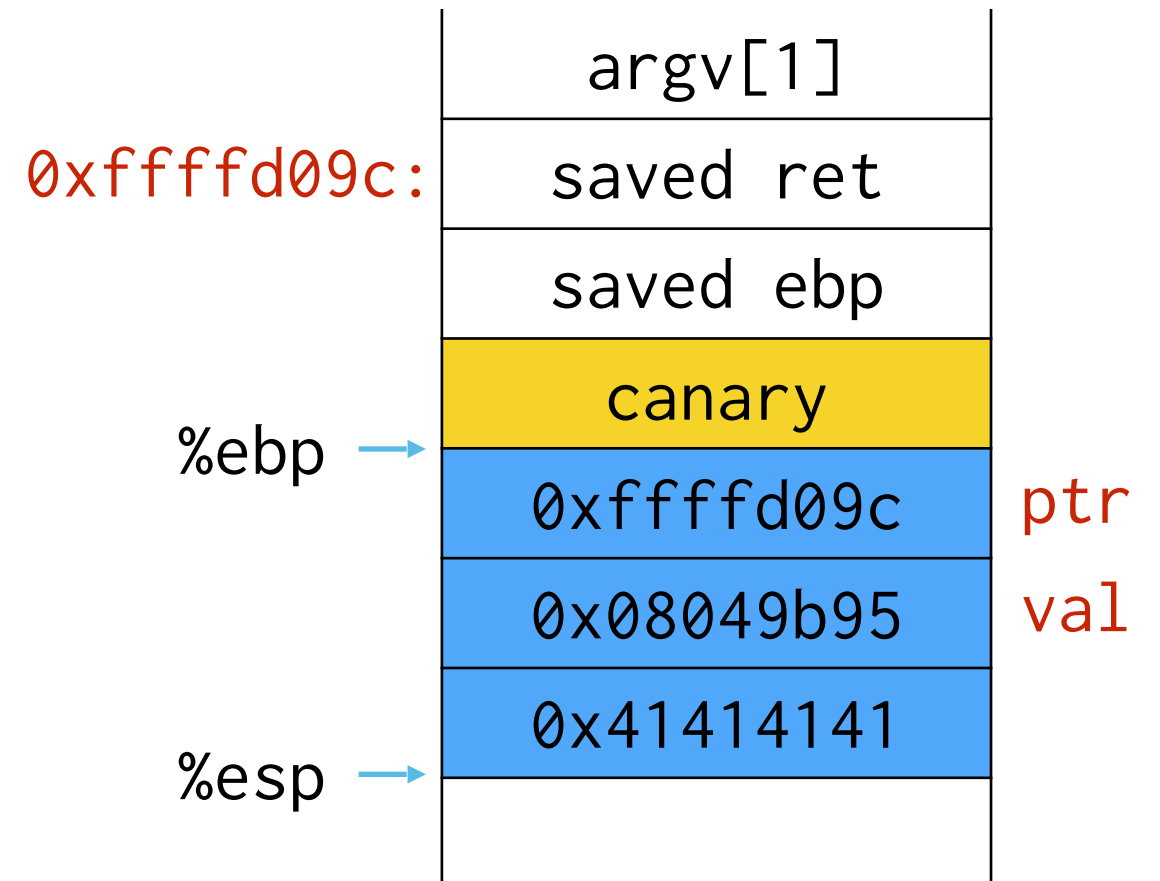
```
#include <stdio.h>
#include <string.h>
```

```
0x08049b95: void foo() {
    printf("hello all!!\n");
    exit(0);
}
```

```
int i = 42;
```

```
void func(char *str) {
    int *ptr = &i;
    int val = 44;
    char buf[4];
    → strcpy(buf, str);
    *ptr = val;
}
```

```
int main(int argc, char**argv) {
    func(argv[1]);
    return 0;
}
```



# Pointer subterfuge

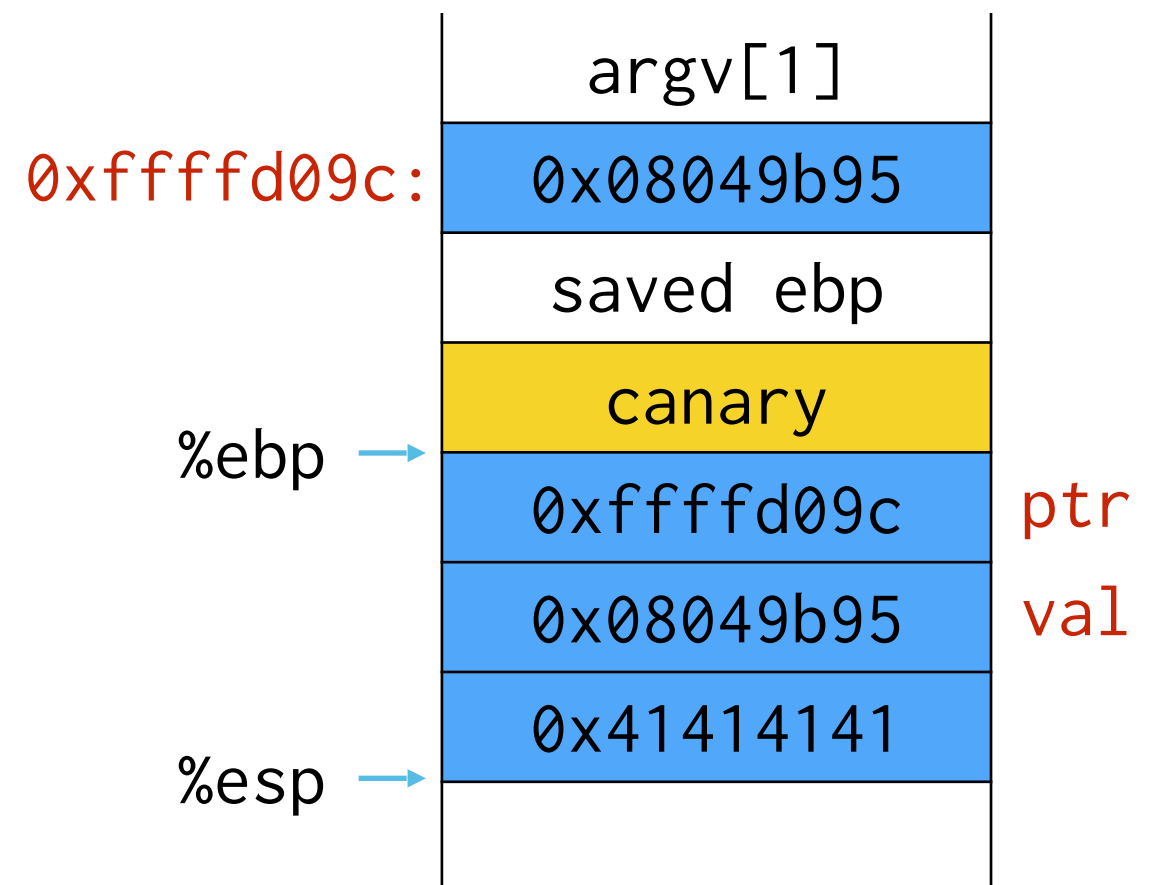
```
#include <stdio.h>
#include <string.h>
```

```
0x08049b95: void foo() {
    printf("hello all!!\n");
    exit(0);
}
```

```
int i = 42;
```

```
void func(char *str) {
    int *ptr = &i;
    int val = 44;
    char buf[4];
    strcpy(buf, str);
    → *ptr = val;
}
```

```
int main(int argc, char**argv) {
    func(argv[1]);
    return 0;
}
```



# Overwrite function pointer on stack

- Similar to previous example, but overwrite function pointer on stack
  - Tricky: compiler can load it into register before strcpy()

```
void func(char *str) {  
    void (*fptr)() = &bar;  
    char buf[4];  
    strcpy(buf, str);  
    fptr()  
}
```

# Can we do anything about this?

- **Problem:** overflowing local variables can allow attacker to hijack control flow
- **Solution:** some implementations reorder local variables, place buffers closer to canaries vs. lexical order

arg	arg
saved ret	saved ret
saved ebp	saved ebp
canary	canary
local var	buf[0-3]
local var	local var
buf[0-3]	local var

# What about function arguments?

# What about function arguments?

- Same problem!

```
void func(char *str, void (*fptr)()) {  
    char buf[4];  
    strcpy(buf, str);  
    fptr()  
}
```

- **Solution:** also copy args to the top of the stack to make overwriting them via local variables less likely

arg	arg
saved ret	saved ret
saved ebp	saved ebp
canary	canary
local var	local var
local var	local var
buf[0-3]	buf[0-3]
	arg

# That's what we were seeing before

## No stack protection

```
func(int, int, char*):
    pushl    %ebp
    movl     %esp, %ebp
    subl     $24, %esp
    movl     $-559038737, -12(%ebp)
    subl     $8, %esp
    pushl     16(%ebp)
    leal     -16(%ebp), %eax
    pushl     %eax
    call     strcpy
    addl     $16, %esp
    nop
    leave
    ret
```

## -fstack-protector-strong

```
func(int, int, char*):
    pushl    %ebp
    movl     %esp, %ebp
    subl     $40, %esp
    movl     16(%ebp), %eax
    movl     %eax, -28(%ebp)
    movl     %gs:20, %eax
    movl     %eax, -12(%ebp)
    xorl     %eax, %eax
    movl     $-559038737, -20(%ebp)
    subl     $8, %esp
    pushl     -28(%ebp)
    leal     -16(%ebp), %eax
    pushl     %eax
    call     strcpy
    addl     $16, %esp
    nop
    movl     -12(%ebp), %eax
    xorl     %gs:20, %eax
    je       .L3
    call     __stack_chk_fail
.L3:
    leave
    ret
```

## -fstack-protector-all

```
func(int, int, char*):
    pushl    %ebp
    movl     %esp, %ebp
    subl     $40, %esp
    movl     8(%ebp), %eax
    movl     %eax, -28(%ebp)
    movl     12(%ebp), %eax
    movl     %eax, -32(%ebp)
    movl     16(%ebp), %eax
    movl     %eax, -36(%ebp)
    movl     %gs:20, %eax
    movl     %eax, -12(%ebp)
    xorl     %eax, %eax
    movl     $-559038737, -20(%ebp)
    subl     $8, %esp
    pushl     -36(%ebp)
    leal     -16(%ebp), %eax
    pushl     %eax
    call     strcpy
    addl     $16, %esp
    nop
    movl     -12(%ebp), %eax
    xorl     %gs:20, %eax
    je       .L4
    call     __stack_chk_fail
.L4:
    leave
    ret
```



# -fstack-protector-strong

```
func(int, int, char*):
    pushl    %ebp
    movl     %esp, %ebp
    subl     $40, %esp
    movl     8(%ebp), %eax
    movl     %eax, -28(%ebp)
    movl     12(%ebp), %eax
    movl     %eax, -32(%ebp)
    movl     16(%ebp), %eax
    movl     %eax, -36(%ebp)
    movl     %gs:20, %eax
    movl     %eax, -12(%ebp)
    xorl     %eax, %eax
    movl     $-559038737, -20(%ebp)
    subl     $8, %esp
    pushl     -36(%ebp)
    leal     -16(%ebp), %eax
    pushl     %eax
    call     strcpy
    addl     $16, %esp
    nop
    movl     -12(%ebp), %eax
    xorl     %gs:20, %eax
    je       .L4
    call     __stack_chk_fail
.L4:
    leave
    ret
```

# -fstack-protector-strong

copy arg1

```
func(int, int, char*):
```

```
    pushl   %ebp
    movl    %esp, %ebp
    subl    $40, %esp
```

```
    movl    8(%ebp), %eax
    movl    %eax, -28(%ebp)
```

```
    movl    12(%ebp), %eax
    movl    %eax, -32(%ebp)
    movl    16(%ebp), %eax
    movl    %eax, -36(%ebp)
    movl    %gs:20, %eax
    movl    %eax, -12(%ebp)
    xorl    %eax, %eax
```

```
    movl    $-559038737, -20(%ebp)
```

```
    subl    $8, %esp
    pushl    -36(%ebp)
    leal    -16(%ebp), %eax
    pushl    %eax
    call     strcpy
    addl    $16, %esp
```

```
    nop
    movl    -12(%ebp), %eax
    xorl    %gs:20, %eax
    je      .L4
    call     __stack_chk_fail
```

```
.L4:
```

```
    leave
    ret
```

# -fstack-protector-strong

copy arg1

copy arg2

```
func(int, int, char*):
```

```
    pushl   %ebp
    movl    %esp, %ebp
    subl    $40, %esp
```

```
    movl    8(%ebp), %eax
    movl    %eax, -28(%ebp)
```

```
    movl    12(%ebp), %eax
    movl    %eax, -32(%ebp)
```

```
    movl    16(%ebp), %eax
    movl    %eax, -36(%ebp)
    movl    %gs:20, %eax
    movl    %eax, -12(%ebp)
    xorl    %eax, %eax
```

```
    movl    $-559038737, -20(%ebp)
```

```
    subl    $8, %esp
    pushl    -36(%ebp)
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    pushl    %eax
    call     strcpy
    addl     $16, %esp
```

```
    nop
    movl     -12(%ebp), %eax
    xorl     %gs:20, %eax
    je       .L4
    call     __stack_chk_fail
```

```
.L4:
```

```
    leave
    ret
```

# -fstack-protector-strong

	<pre>func(int, int, char*):     pushl    %ebp     movl     %esp, %ebp     subl     \$40, %esp</pre>
copy arg1	<pre>    movl     8(%ebp), %eax     movl     %eax, -28(%ebp)</pre>
copy arg2	<pre>    movl     12(%ebp), %eax     movl     %eax, -32(%ebp)</pre>
copy arg3	<pre>    movl     16(%ebp), %eax     movl     %eax, -36(%ebp)</pre>
	<pre>    movl     %gs:20, %eax     movl     %eax, -12(%ebp)     xorl     %eax, %eax</pre>
	<pre>    movl     \$-559038737, -20(%ebp)</pre>
	<pre>    subl     \$8, %esp     pushl    -36(%ebp)     leal     -16(%ebp), %eax     pushl    %eax     call     strcpy     addl     \$16, %esp</pre>
	<pre>    nop     movl     -12(%ebp), %eax     xorl     %gs:20, %eax     je       .L4     call     __stack_chk_fail</pre>
	<pre>.L4:     leave     ret</pre>

# -fstack-protector-strong

	<pre>func(int, int, char*):     pushl    %ebp     movl     %esp, %ebp     subl     \$40, %esp</pre>
copy arg1	<pre>    movl     8(%ebp), %eax     movl     %eax, -28(%ebp)</pre>
copy arg2	<pre>    movl     12(%ebp), %eax     movl     %eax, -32(%ebp)</pre>
copy arg3	<pre>    movl     16(%ebp), %eax     movl     %eax, -36(%ebp)</pre>
write canary	<pre>    movl     %gs:20, %eax     movl     %eax, -12(%ebp)</pre>
	<pre>    xorl     %eax, %eax</pre>
	<pre>    movl     \$-559038737, -20(%ebp)</pre>
	<pre>    subl     \$8, %esp     pushl    -36(%ebp)     leal     -16(%ebp), %eax     pushl    %eax     call     strcpy     addl     \$16, %esp</pre>
	<pre>    nop     movl     -12(%ebp), %eax     xorl     %gs:20, %eax     je       .L4     call     __stack_chk_fail</pre>
	<pre>.L4:     leave     ret</pre>

# How can we defeat canaries?

- Assumption: impossible to subvert control flow without corrupting the canary
  - Ideas?
    - Use targeted write (e.g., with format strings)
    - Pointer subterfuge
    - Overwrite function pointer elsewhere on the stack/heap
- ➔ memcpy buffer overflow with fixed canary
- Learn the canary

# memcpy with fixed canary

- Canary values like 0x000d0aff (0, CR, NL, -1) are designed to terminate string ops like strcpy and gets
- Even random canaries have null bytes
- How do we defeat this?
  - Find memcpy/memmove/read vulnerability

# How can we defeat canaries?

- Assumption: impossible to subvert control flow without corrupting the canary
  - Ideas?
    - Use targeted write (e.g., with format strings)
    - Pointer subterfuge
    - Overwrite function pointer elsewhere on the stack/heap
    - memcpy buffer overflow with fixed canary
- ➔ Learn the canary



# Learn the canary

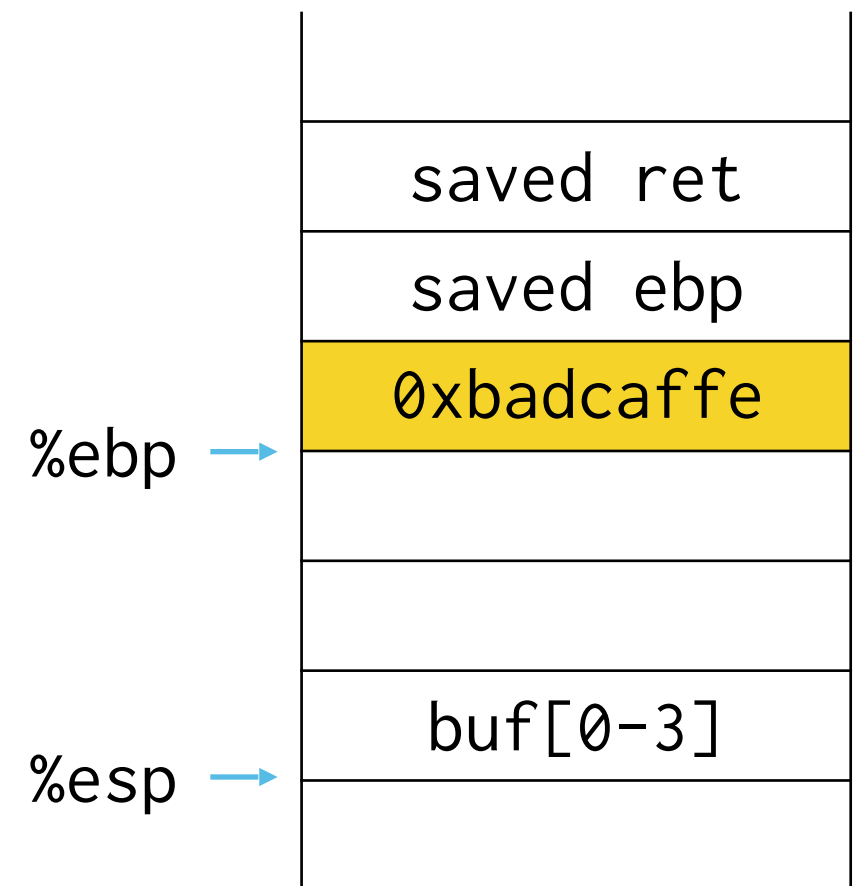
- Approach 1: chained vulnerabilities
  - Exploit one vulnerability to read the value of the canary
  - Exploit a second to perform stack buffer overflow
- Modern exploits chain multiple vulnerabilities
  - Recent Chinese gov iPhone exploit: 14 vulns!

# Learn the canary

- Approach 2: brute force servers (e.g., Apache2)
  - Main server process:
    - Establish listening socket
    - Fork several workers: if any die, fork new one!
  - Worker process:
    - Accept connection on listening socket & process request

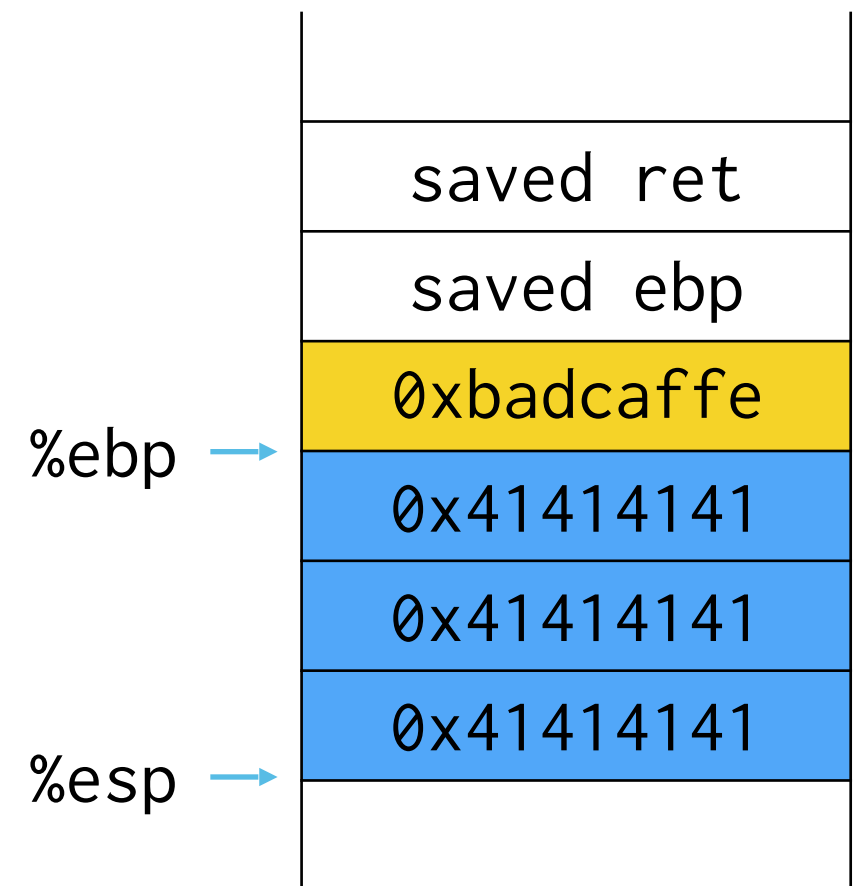
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- Forked process has same memory layout and contents as parent, including canary values!
- The fork on crash lets us try different canary values



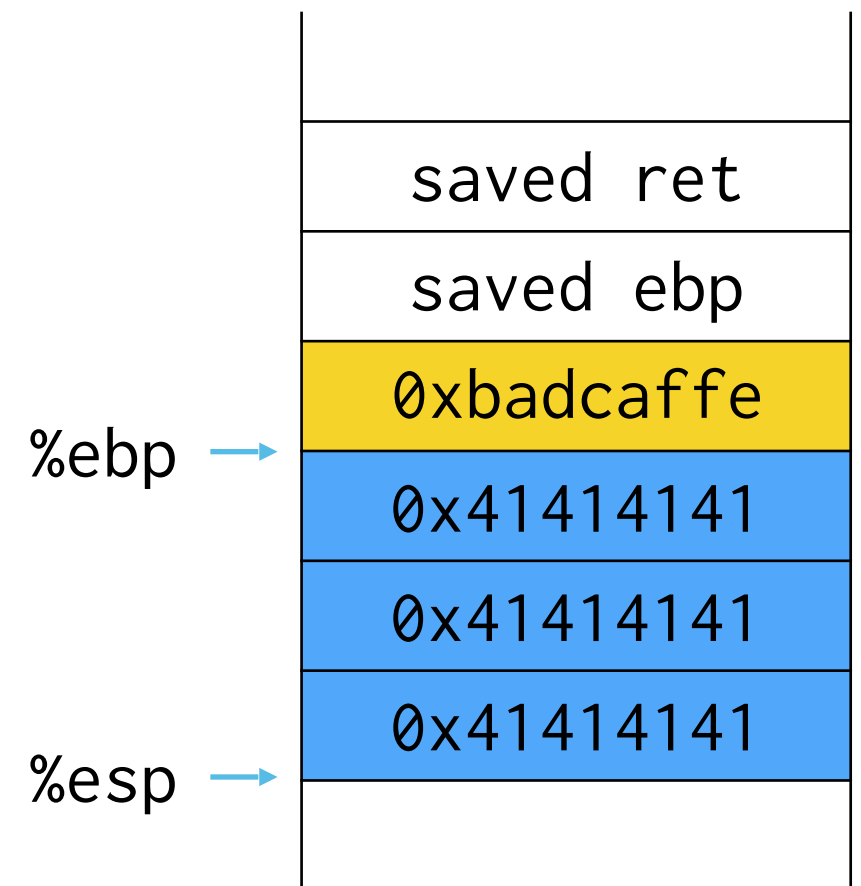
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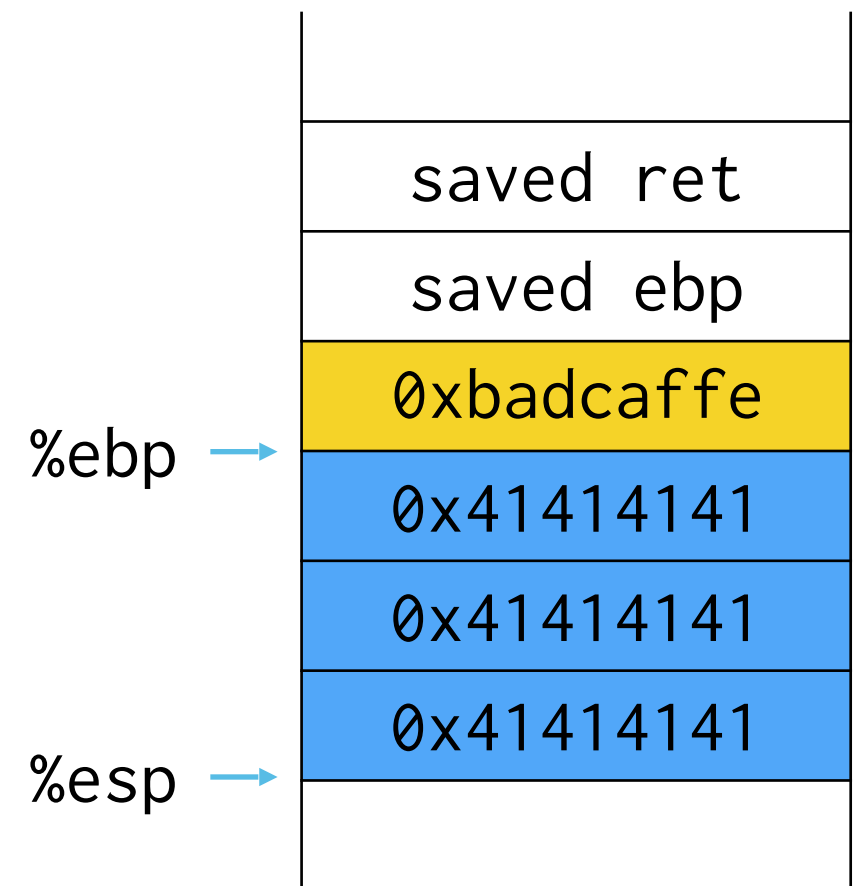
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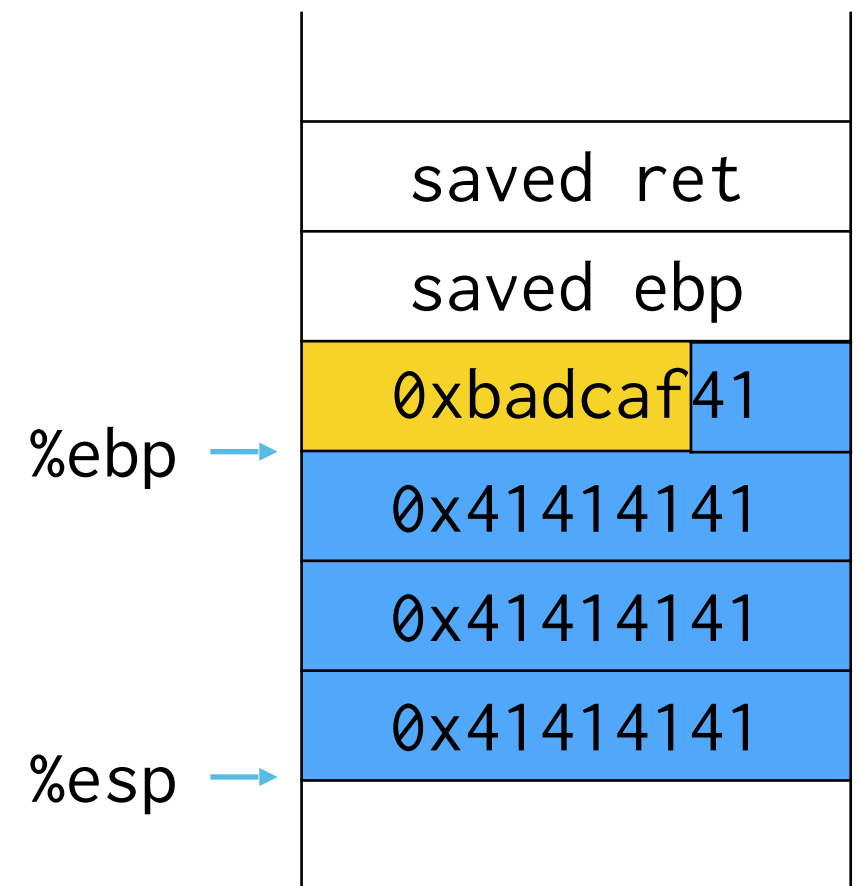
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we know size of buffer!

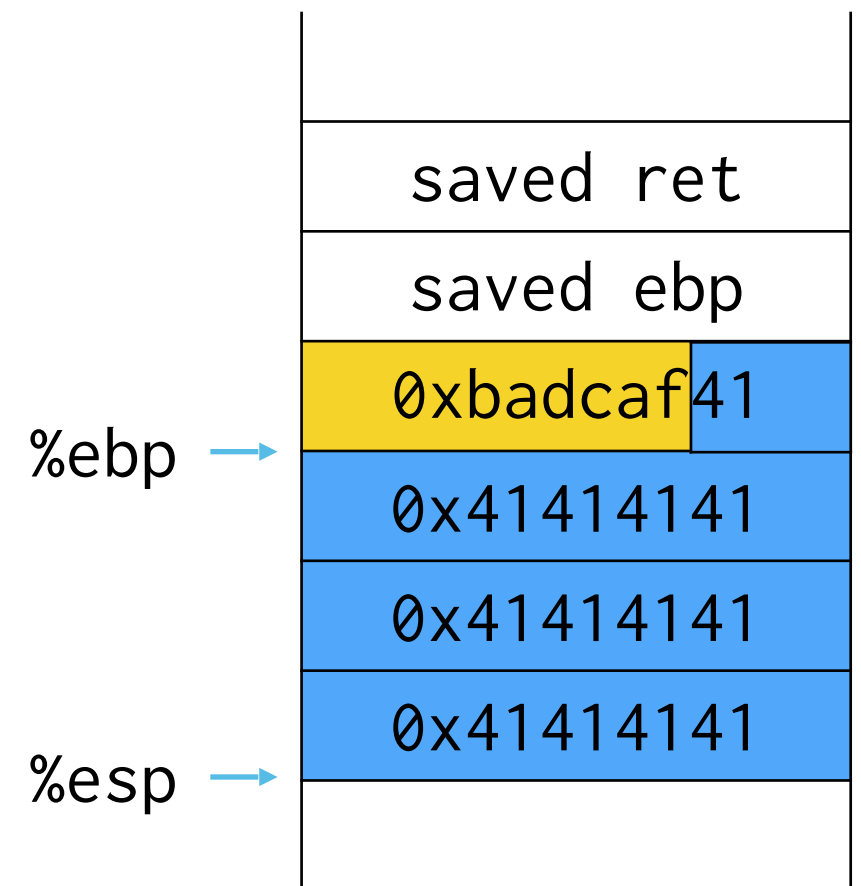
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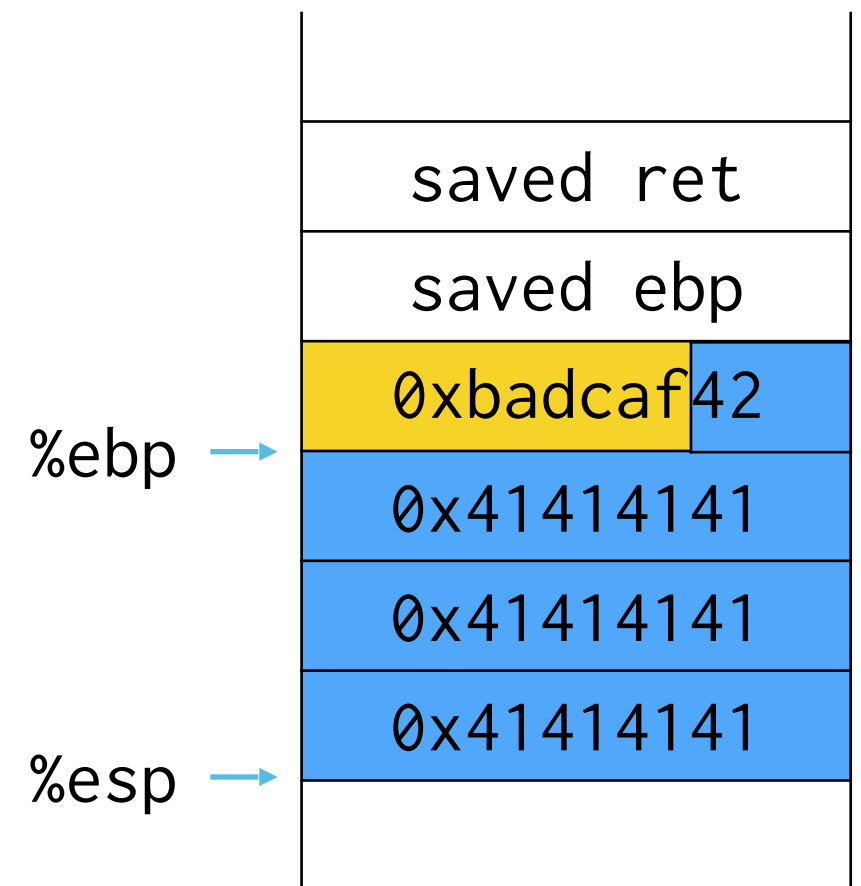
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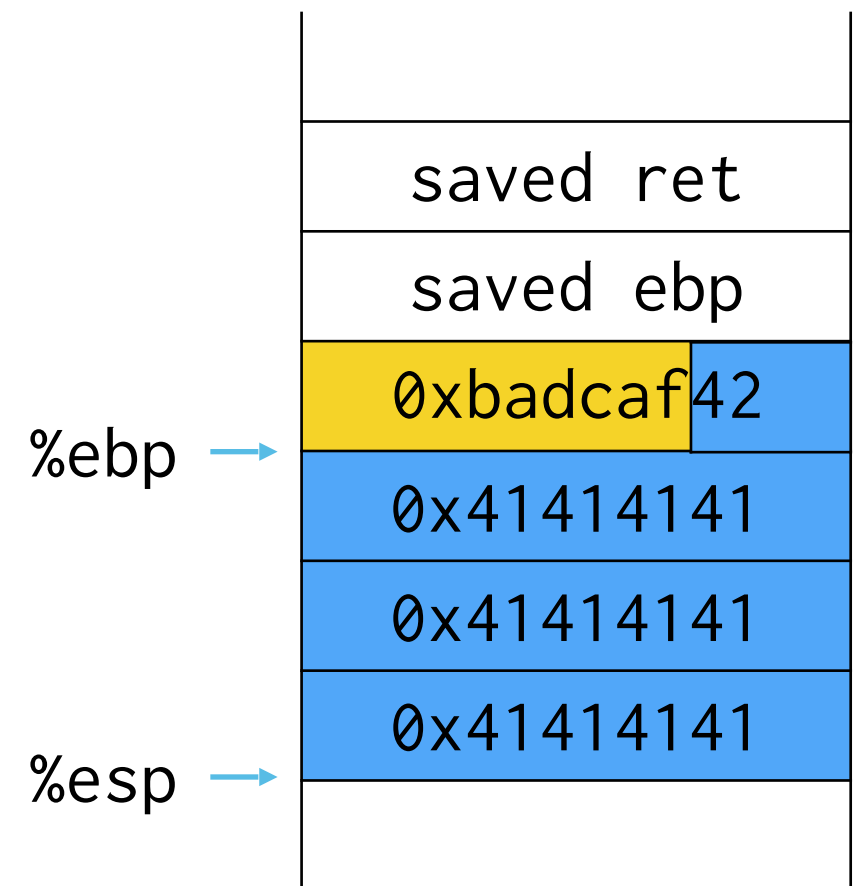
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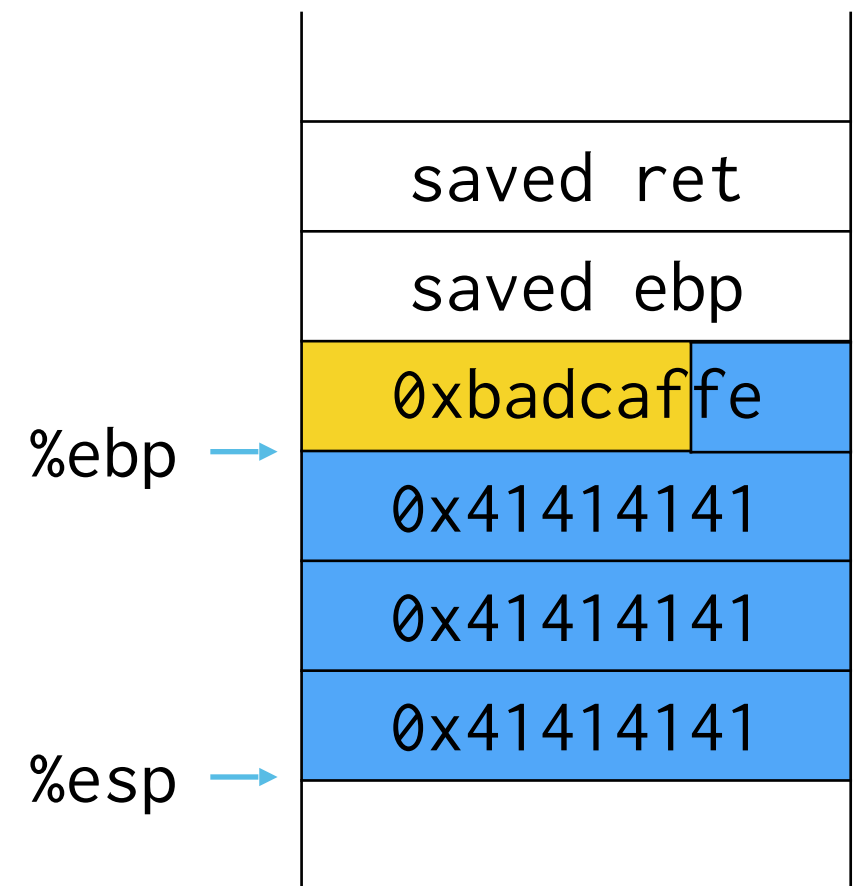
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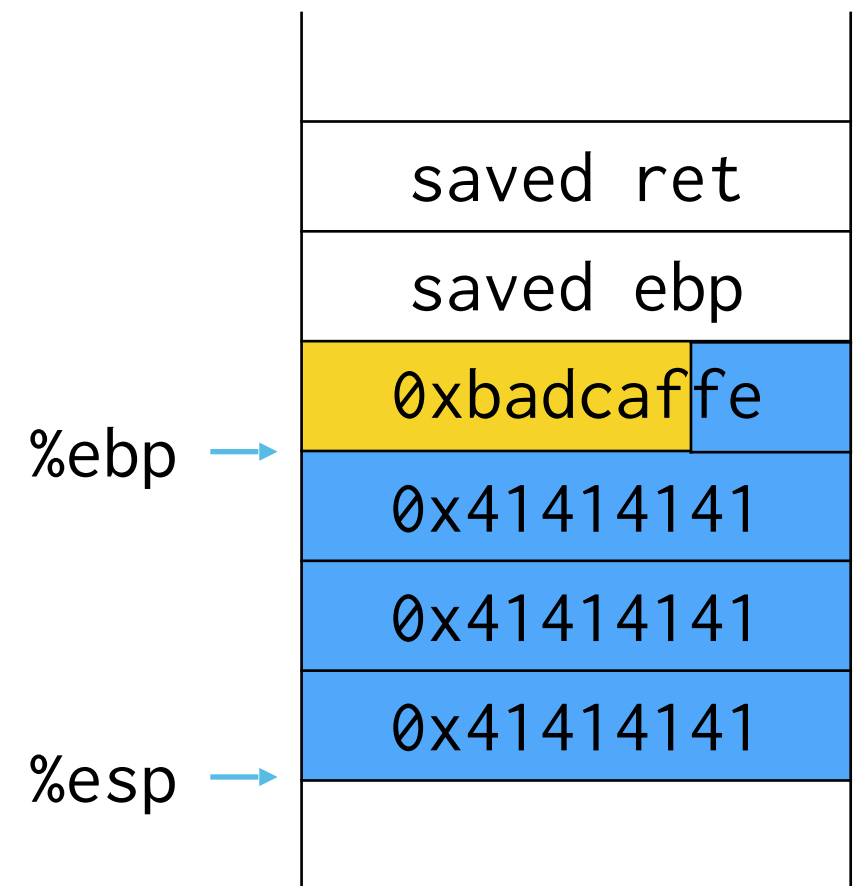
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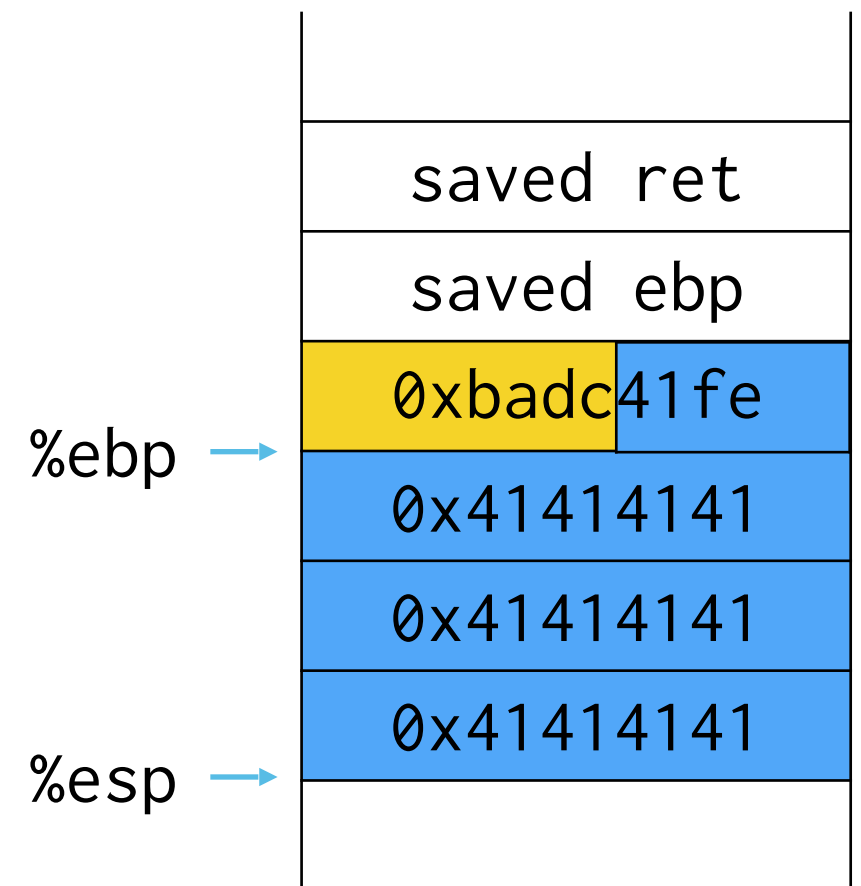
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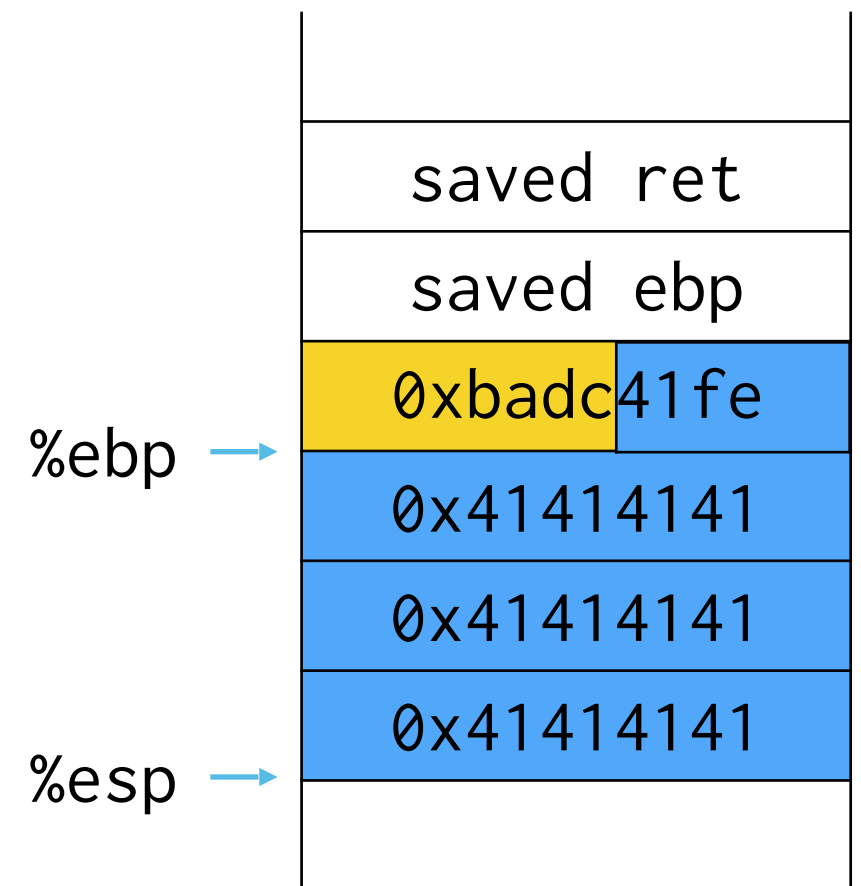
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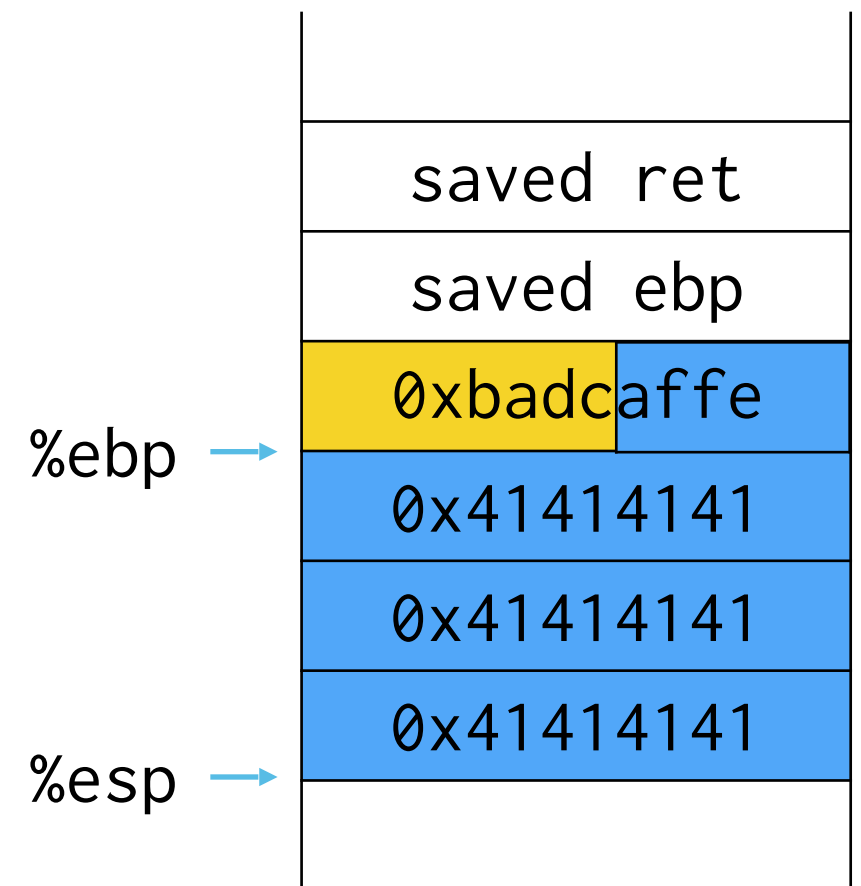
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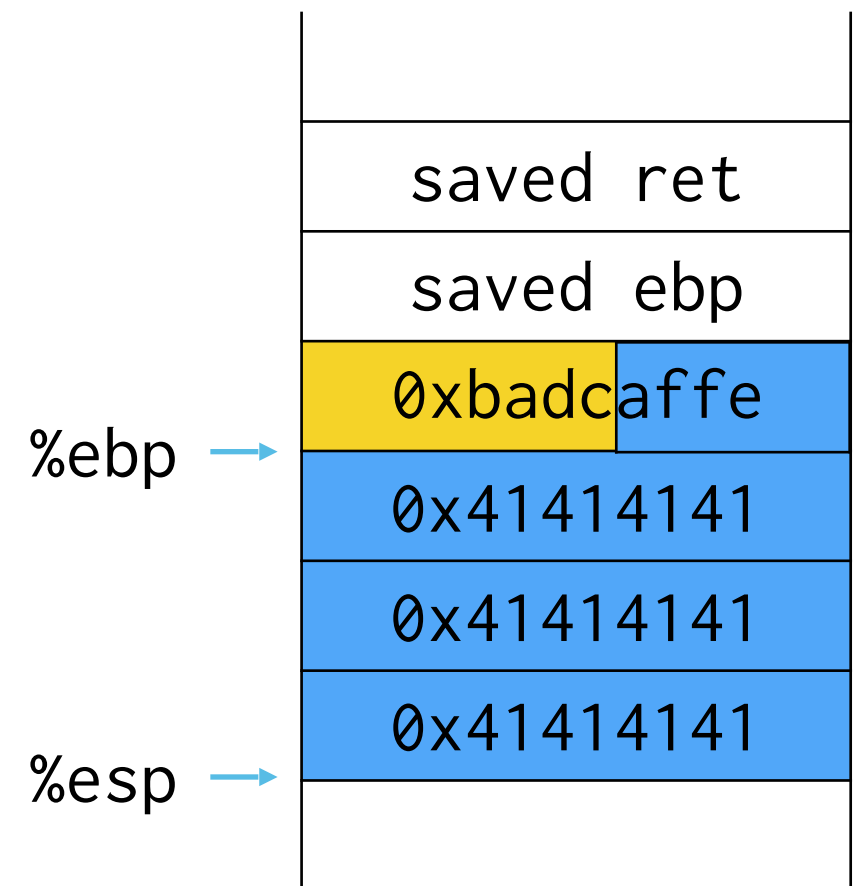
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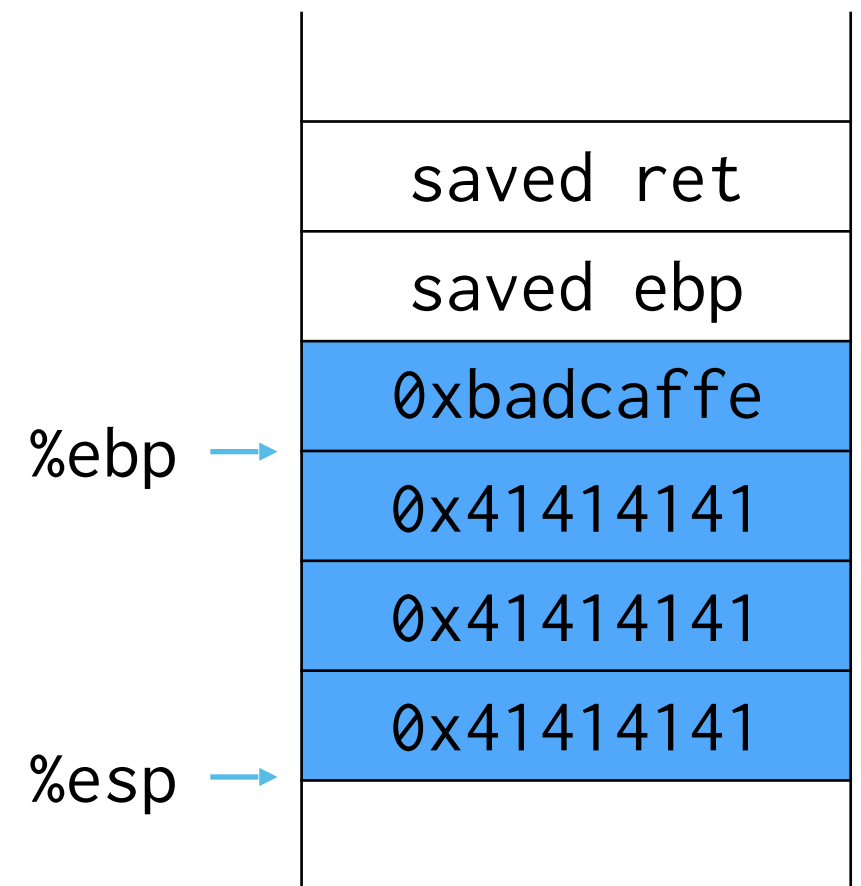
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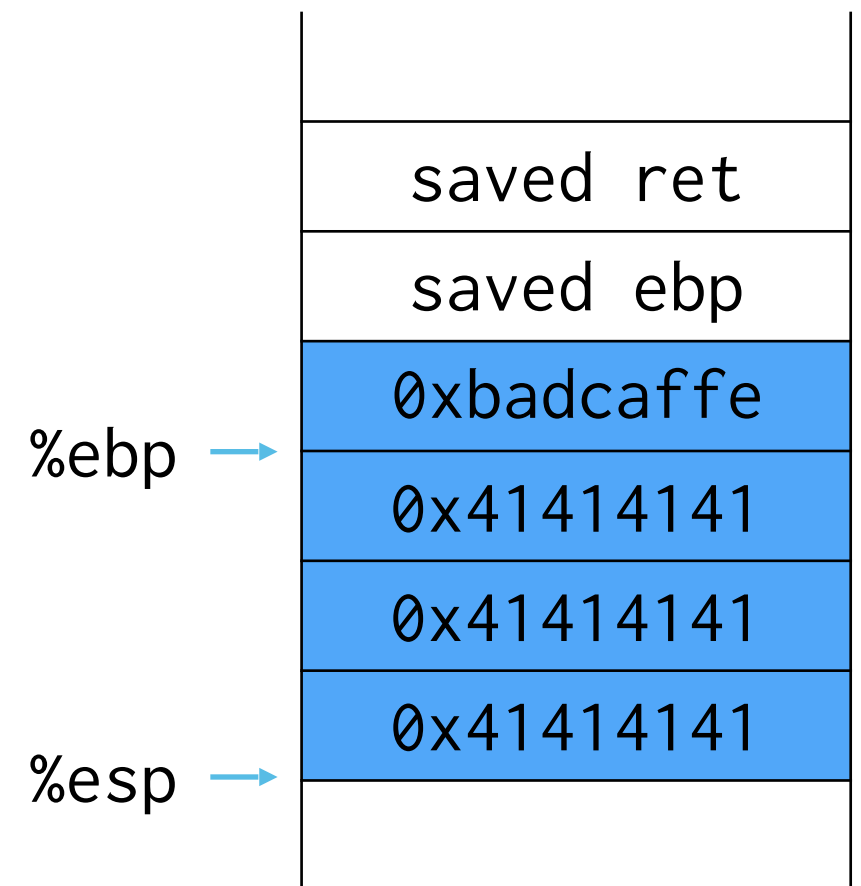
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# Buffer overflow mitigations

- Avoid unsafe functions (last lecture)
- Stack canaries

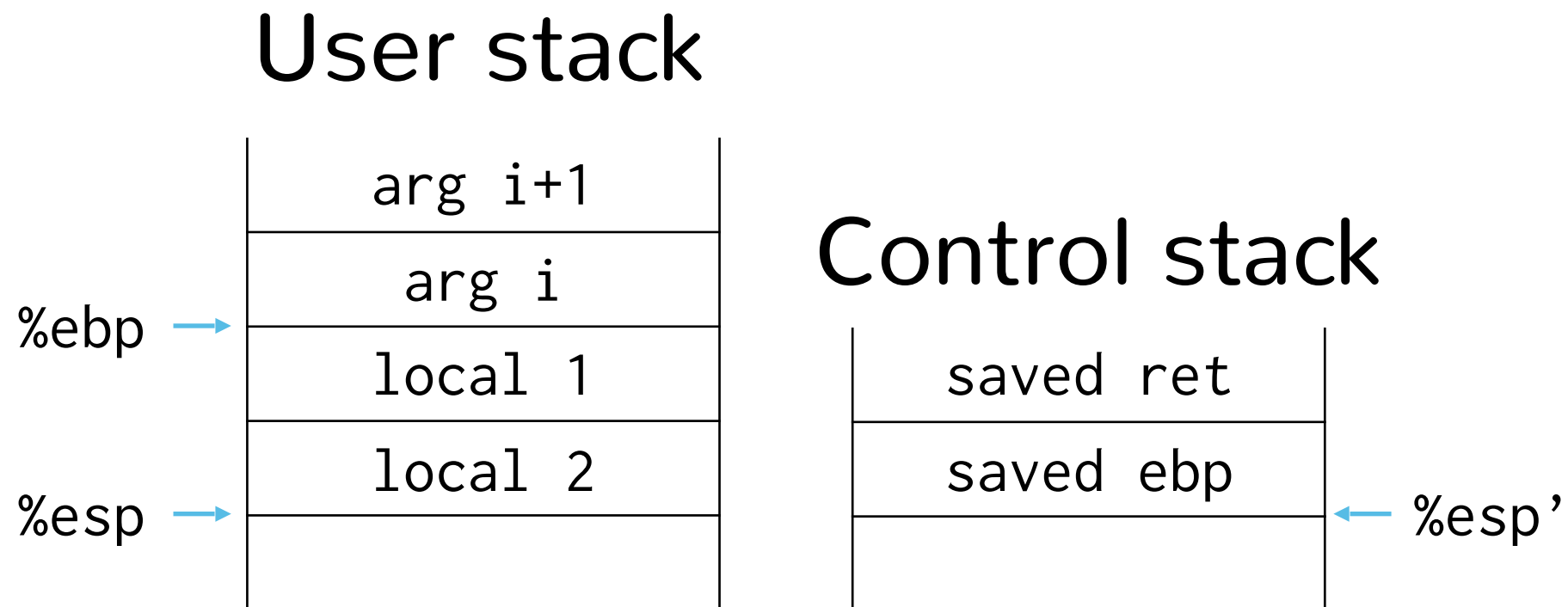
➔ Separate control stack

- Memory writable or executable, not both ( $W^X$ )
- Address space layout randomization (ASLR)

# Separate control stack

**Problem:** The stack smashing attacks take advantage of the weird machine: control data is stored next to user data

**Solution:** Make it less weird by bridging the implementation and abstraction gap: separate the control stack



# Separate control stack

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- WebAssembly (Wasm) has a separate stack
  - At the Wasm layer: can't read or manipulate control stack

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  - Challenge: we need to compile C/C++ to Wasm
  - How do we compile buffers, &var, and function ptrs?

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- WebAssembly (Wasm) has a separate stack
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- By construction: can't express stack smashing in Wasm
  - Challenge: we need to compile C/C++ to Wasm
  - How do we compile buffers, &var, and function ptrs?
    - Put them on user stack!
    - So? C programs compiled to Wasm: overwrite function pointers!

# Separate control stack

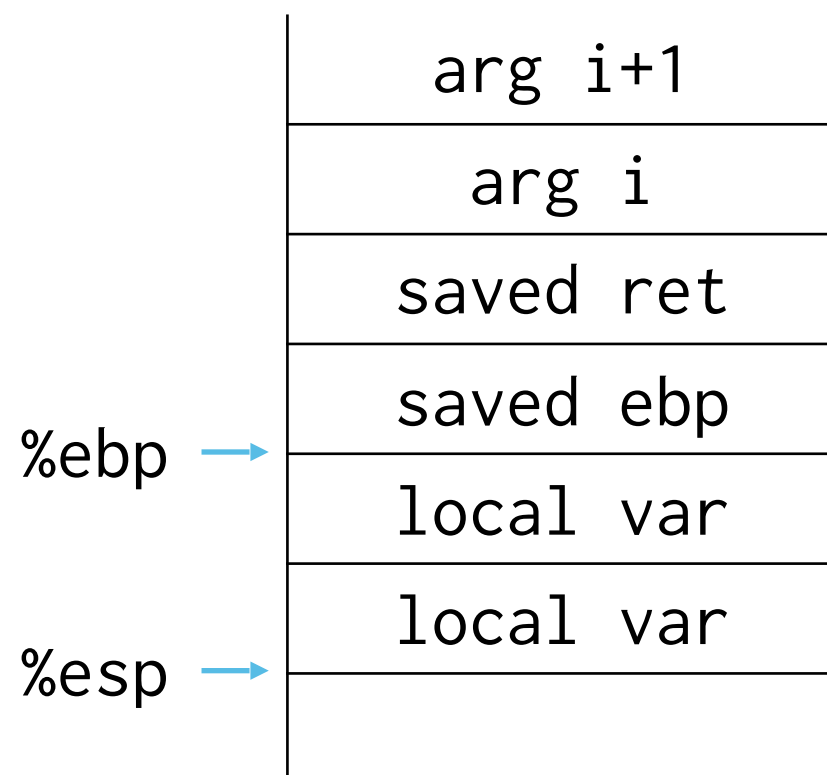
Wasm is not special.

Other byte codes and languages are similar: compiling C to X will inevitably preserve some of C's bugs.

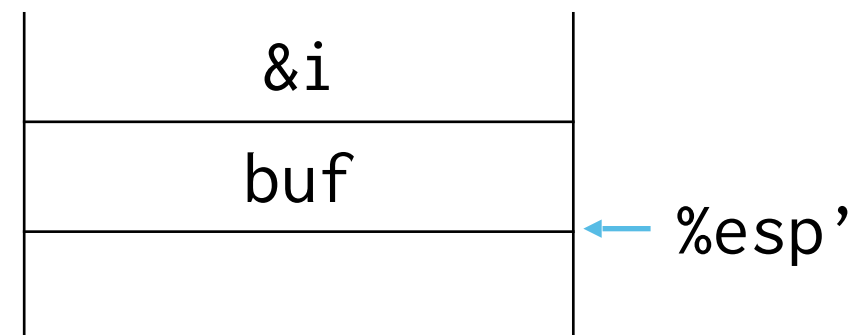
# Safe stack

“SafeStack is an instrumentation pass that protects programs against attacks based on stack buffer overflows, without introducing any measurable performance overhead. It works by separating the program stack into two distinct regions: the safe stack and the unsafe stack. The safe stack stores **return addresses**, **register spills**, and **local variables that are always accessed in a safe way**, while the unsafe stack stores everything else. This separation ensures that buffer overflows on the unsafe stack cannot be used to overwrite anything on the safe stack.”

## Safe stack



## Unsafe stack

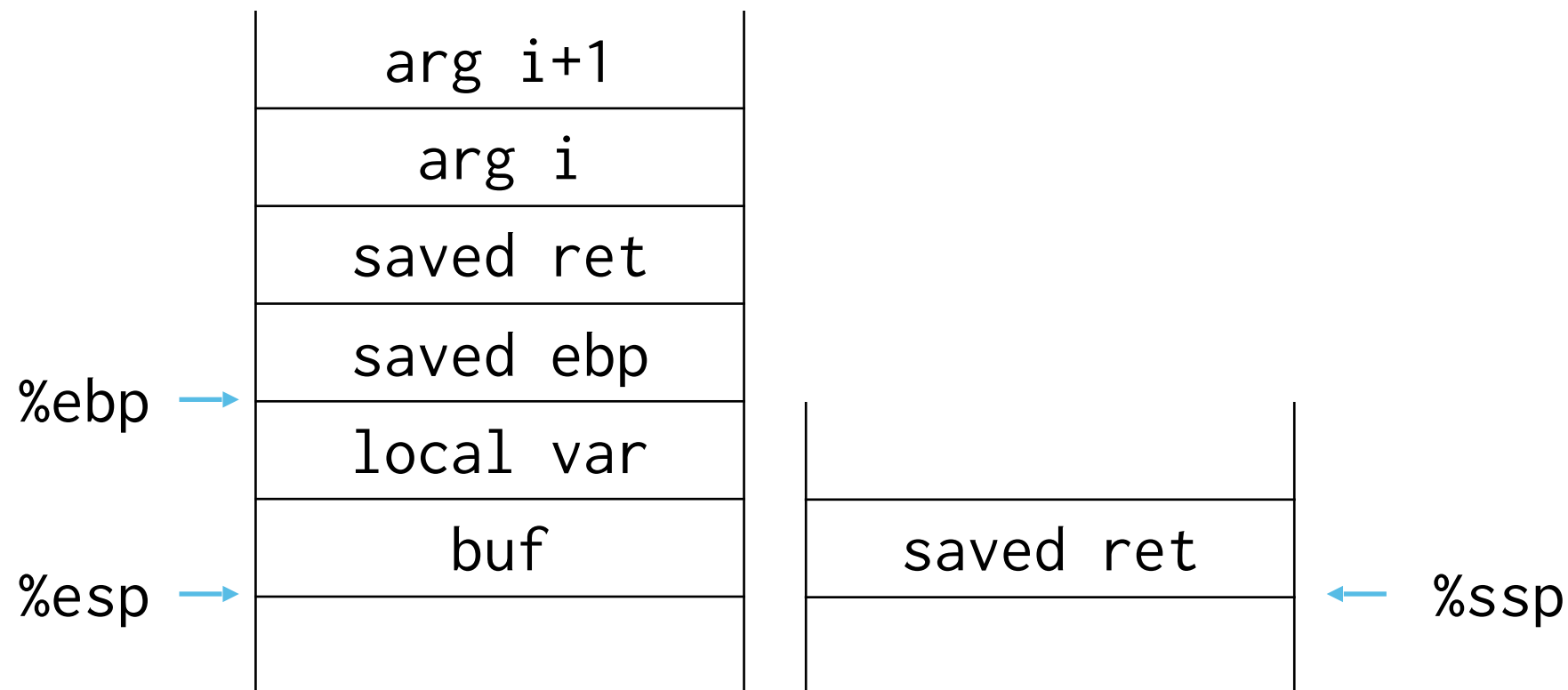


# How do we implement these?

- There is no actual separate stack, we only have linear memory and loads/store instructions
- Put the safe/separate stack in a random place in the address space
  - Assumption: location of control/stack stack is secret
  - How do we defeat this?

# Intel's shadow stack

- Addresses both the performance and security issues
  - New shadow stack pointer (%ssp)
    - call and ret automatically update %esp and %ssp
    - Can't update shadow stack manually
  - May need to rewrite code that manipulates stack manually



# How do we defeat this?

Find a function pointer and overwrite it to point to shellcode!

# Buffer overflow mitigations

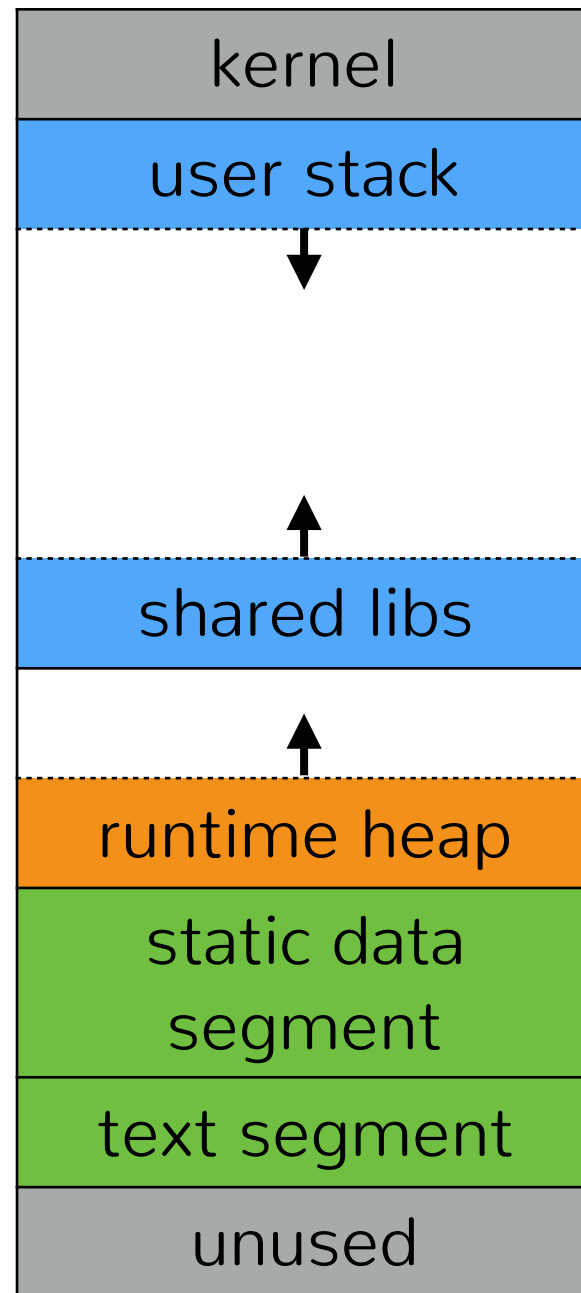
- Avoid unsafe functions (last lecture)
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  - Separate control stack
- ➔ Memory writable or executable, not both ( $W^X$ )
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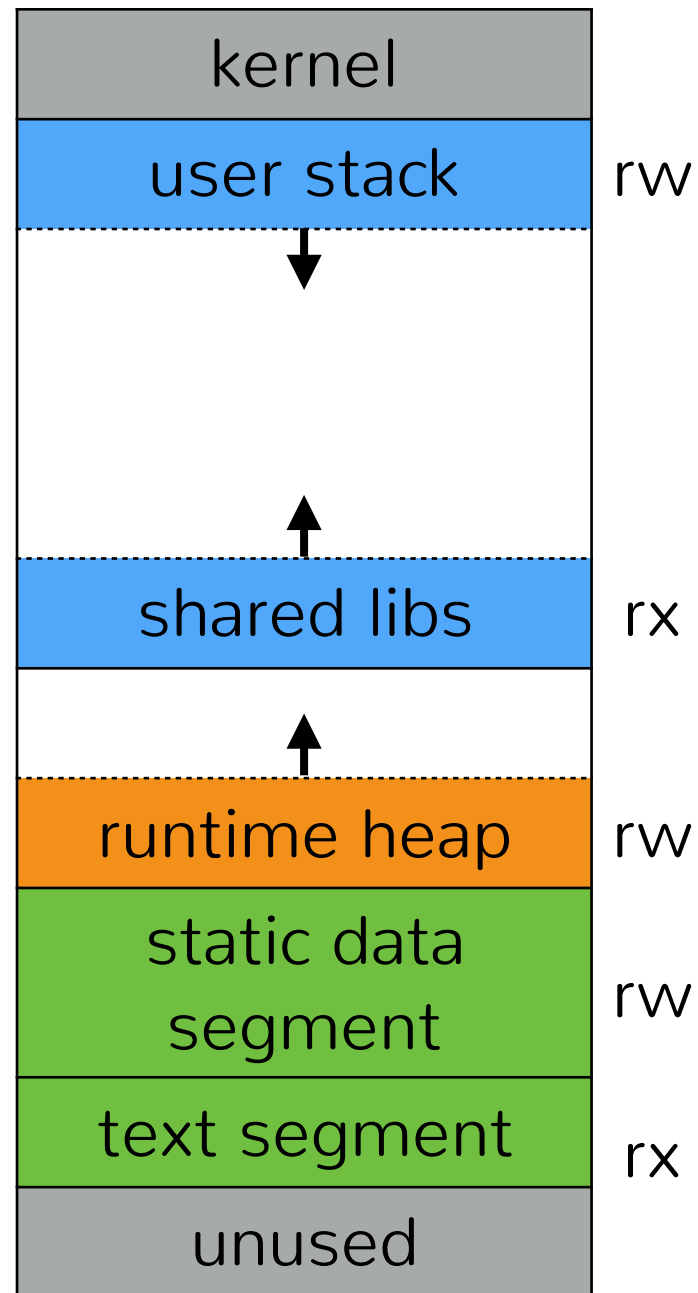
# $W^X$ : write XOR execute

- **Goal:** prevent execution of shell code from the stack
- **Insight:** use memory page permission bits
  - Use MMU to ensure memory cannot be both writeable and executable at same time
- Many names for same idea:
  - XN: eXecute Never
  - $W^X$ : Write XOR eXecute
  - DEP: Data Execution Prevention

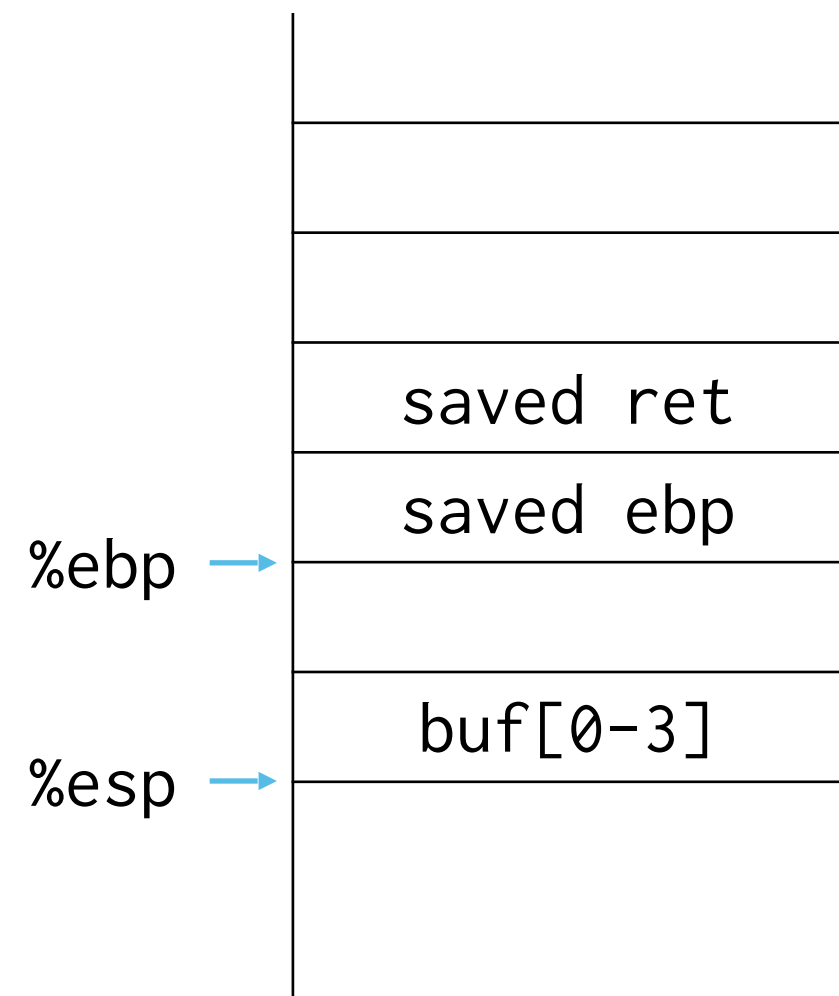
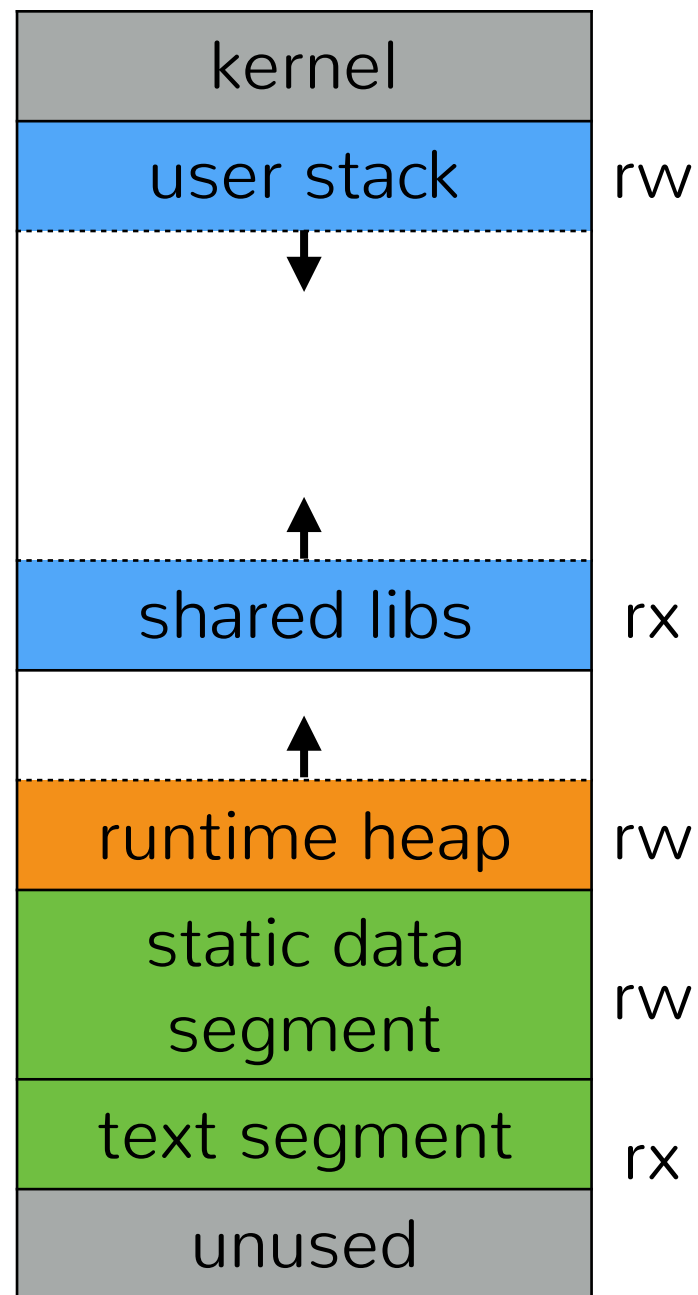
# Recall our memory layout



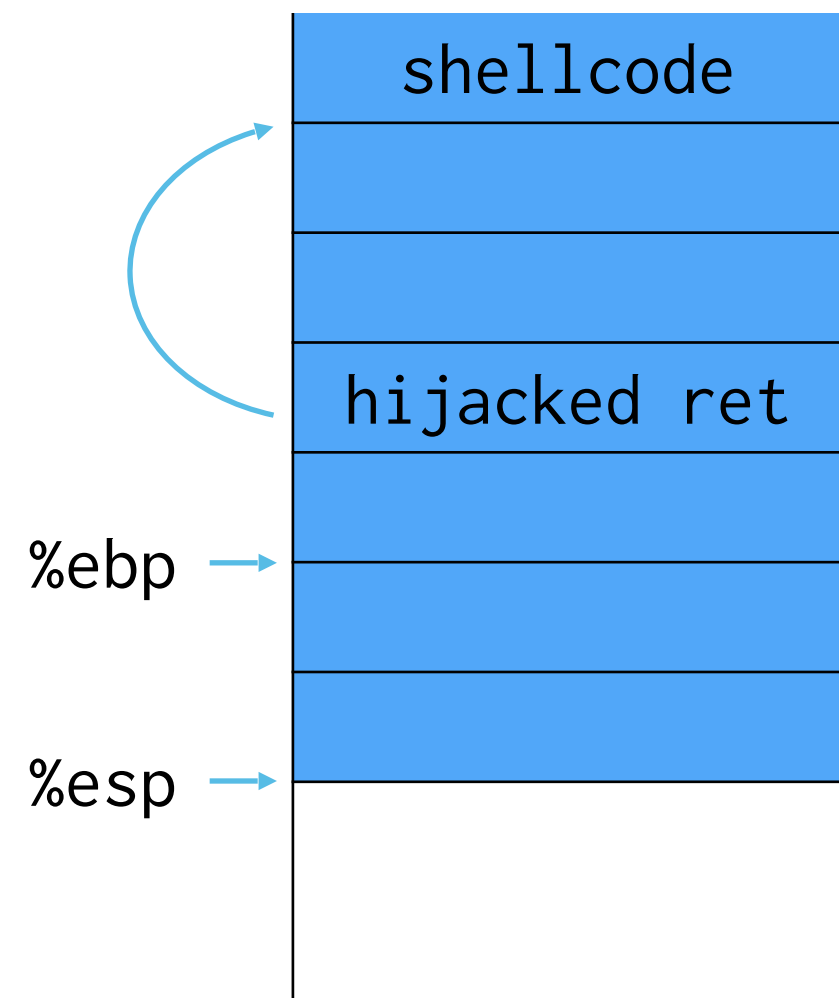
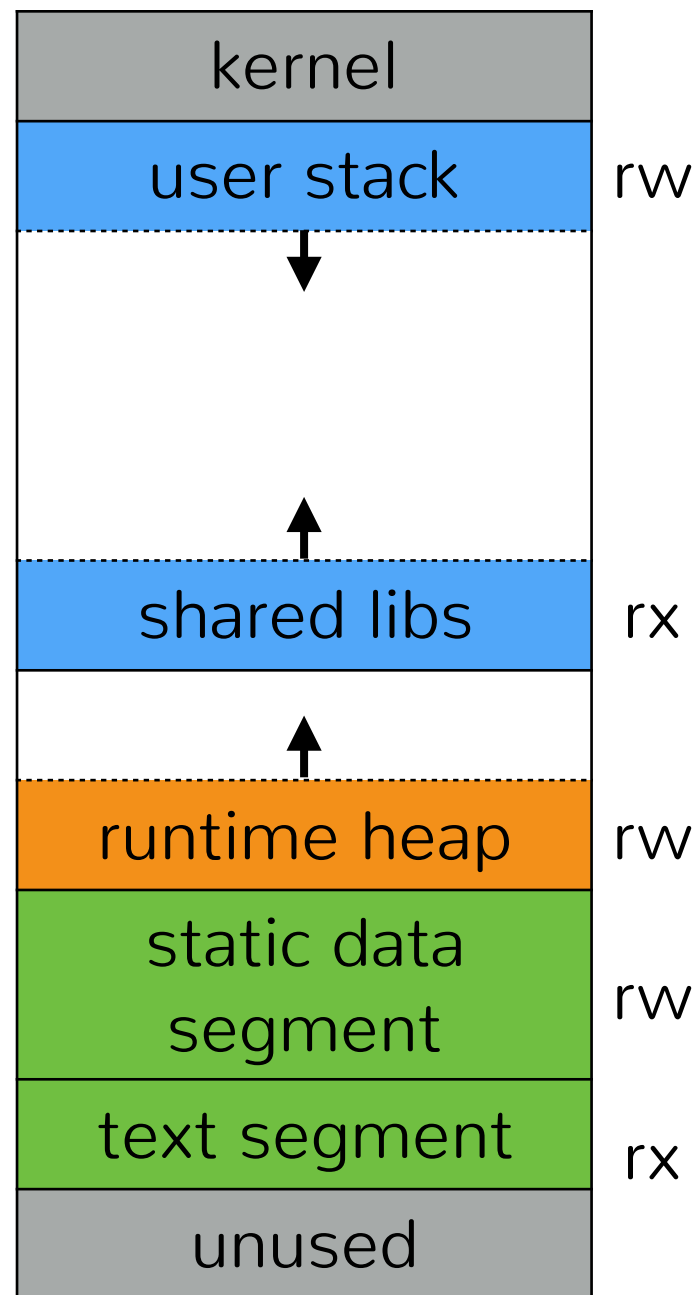
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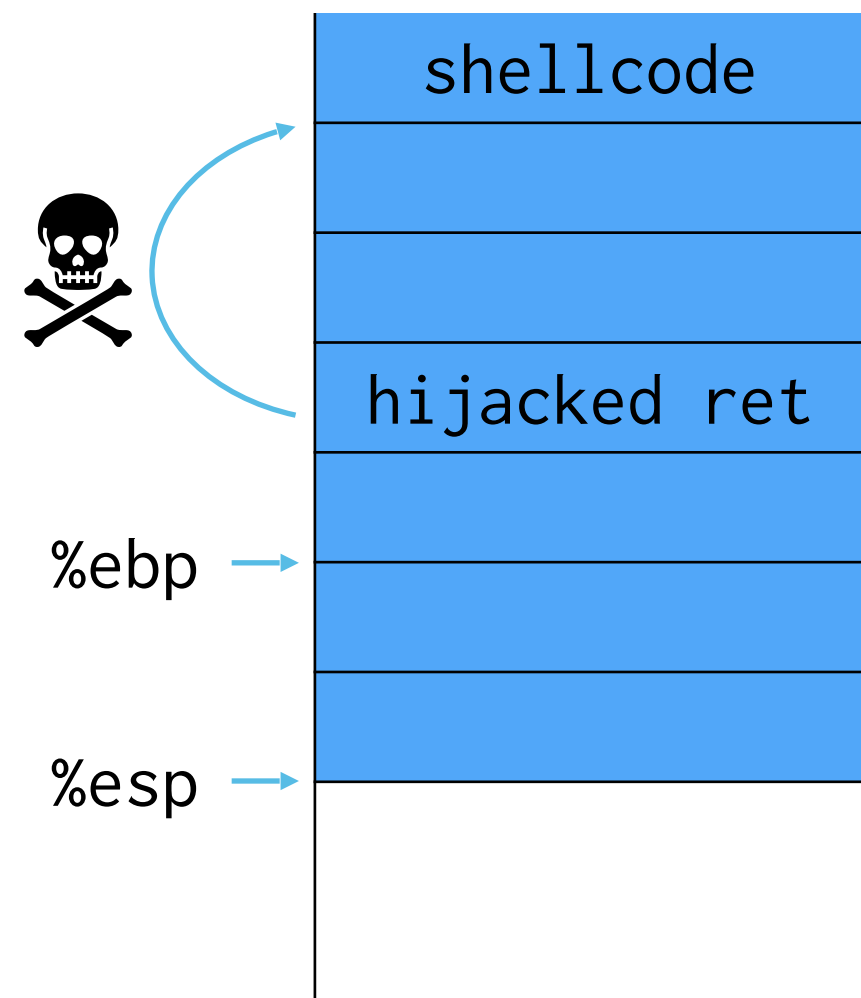
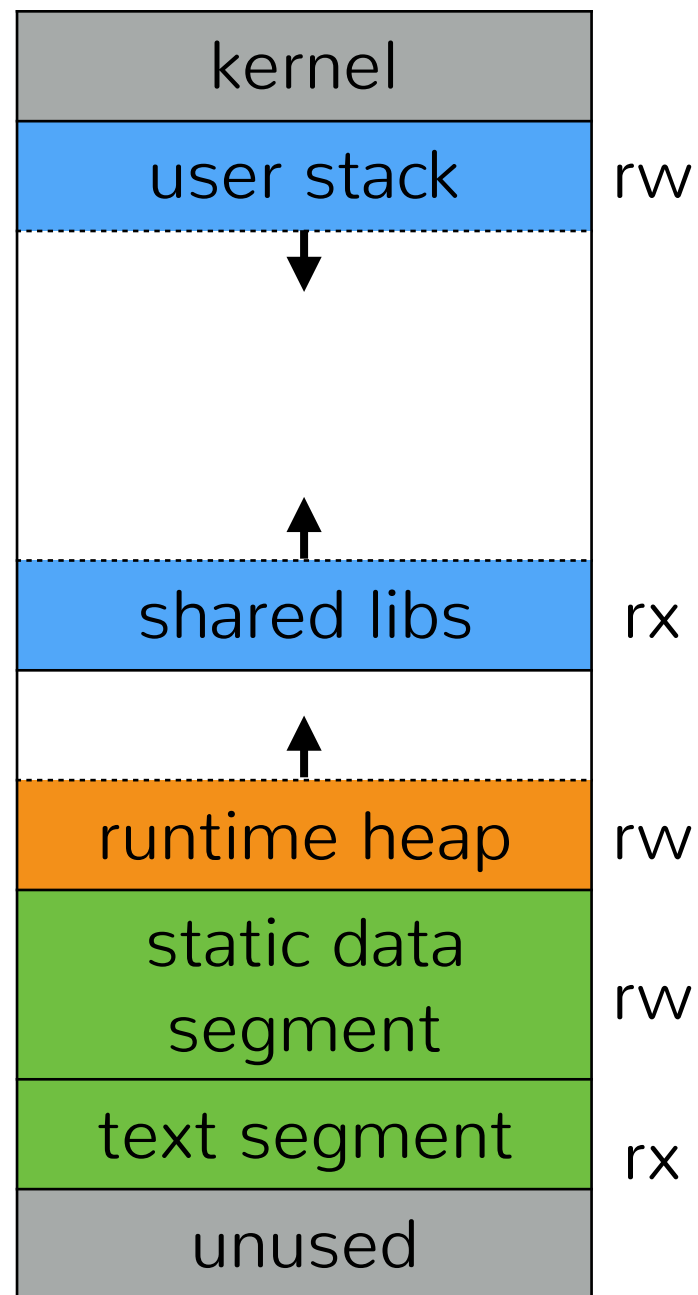
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# Recall our memory layout



# W^X tradeoffs

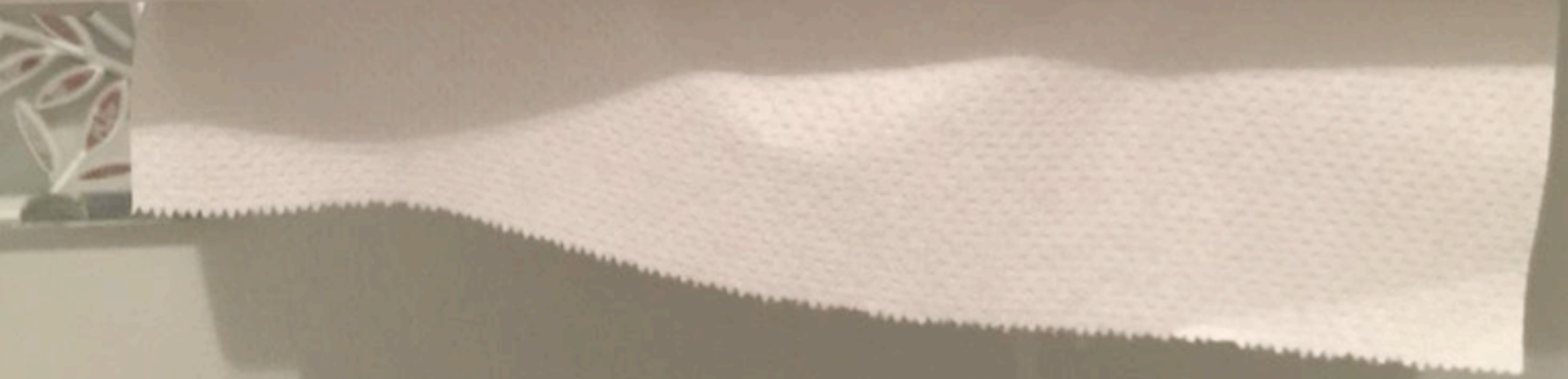
- **Easy to deploy:** No code changes or recompilation
- **Fast:** Enforced in hardware
  - Also a downside: what do you do on embedded devices?
- What if some pages need to be both writeable and executable?
  - What programs do you use that need this?

# How can we defeat W^X?

- Can still write to stack
  - Jump to existing code
- Search executable for code that does what you want
  - E.g. if program calls `system( "/bin/sh" )` you're done
  - libc is a good source of code (return-into-libc attacks)



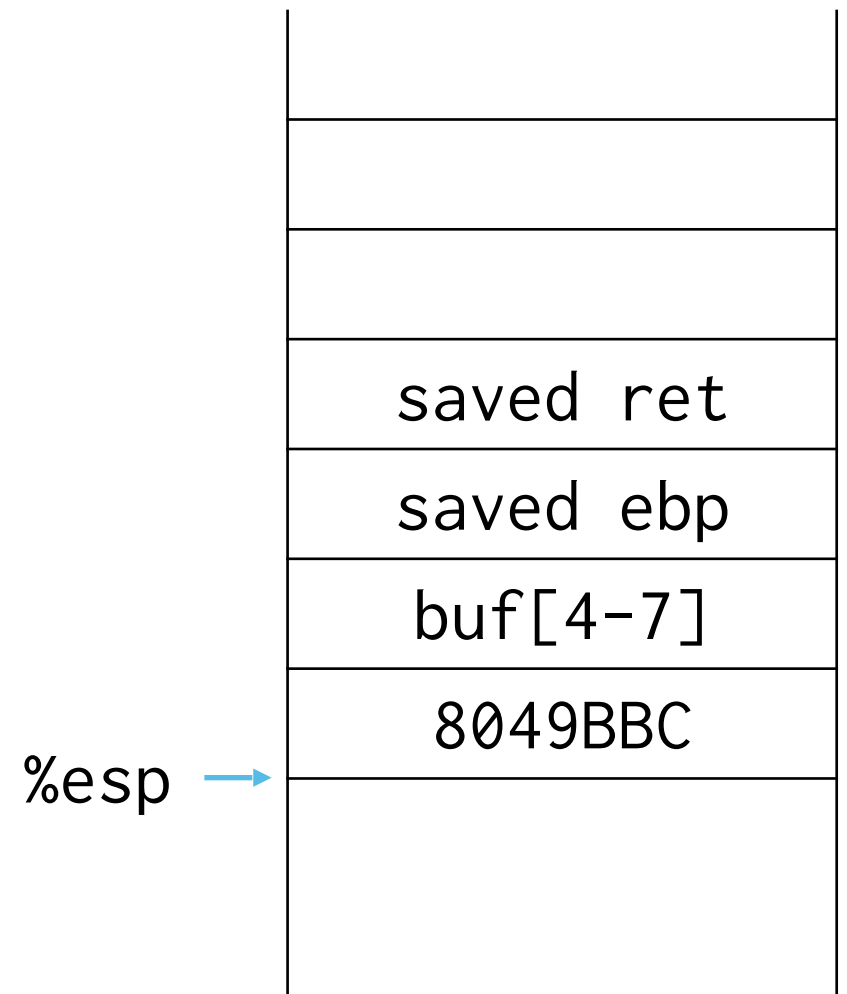
**Employees must  
wash hands before  
returning to libc**



# Calling system

- We already did this with foo
- Calling `system()` is the same, but need to argument to string `“/bin/sh”`

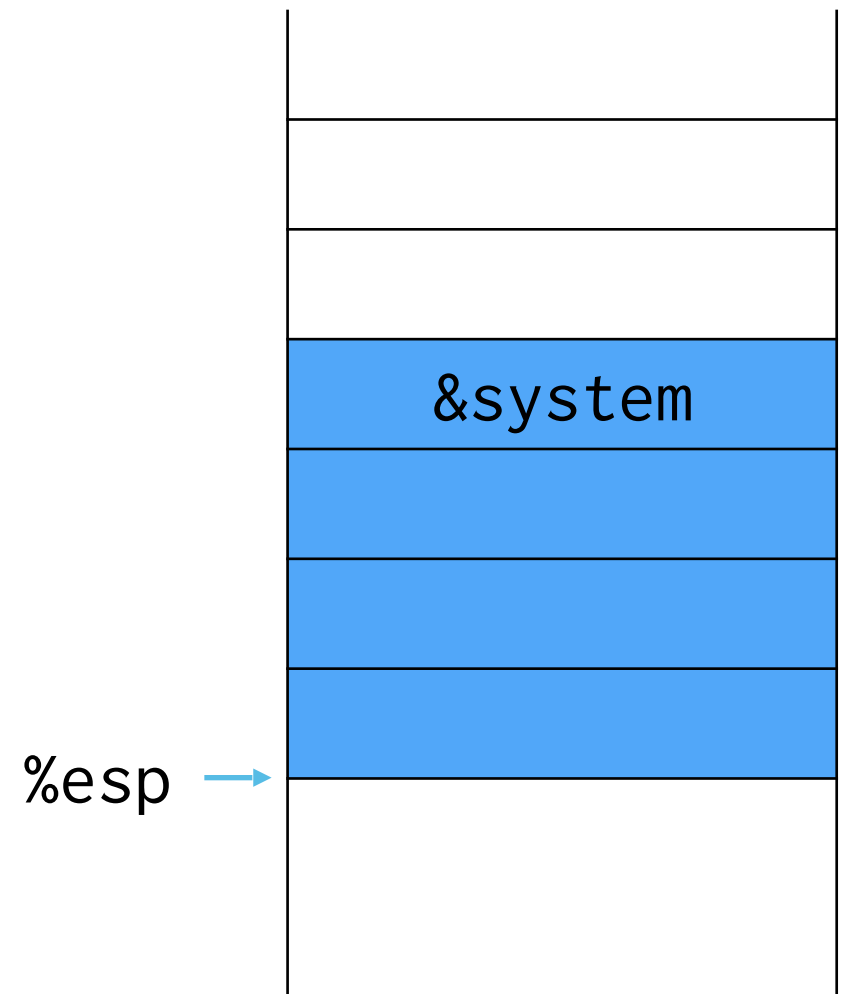
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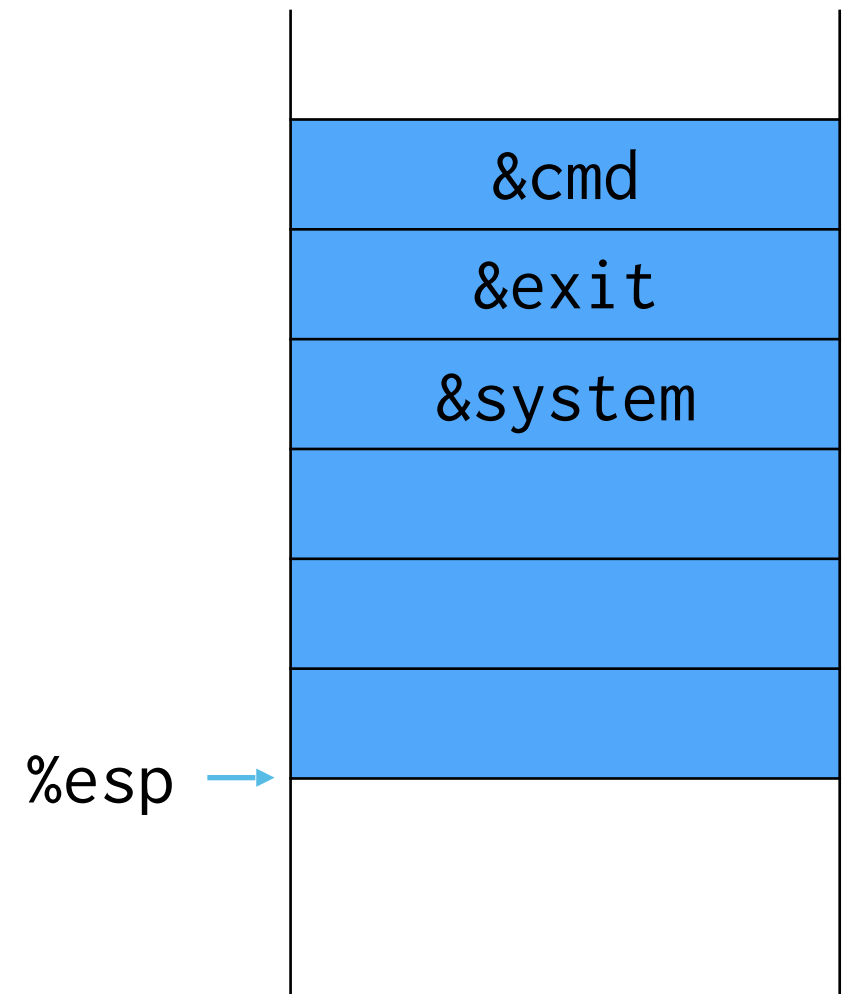
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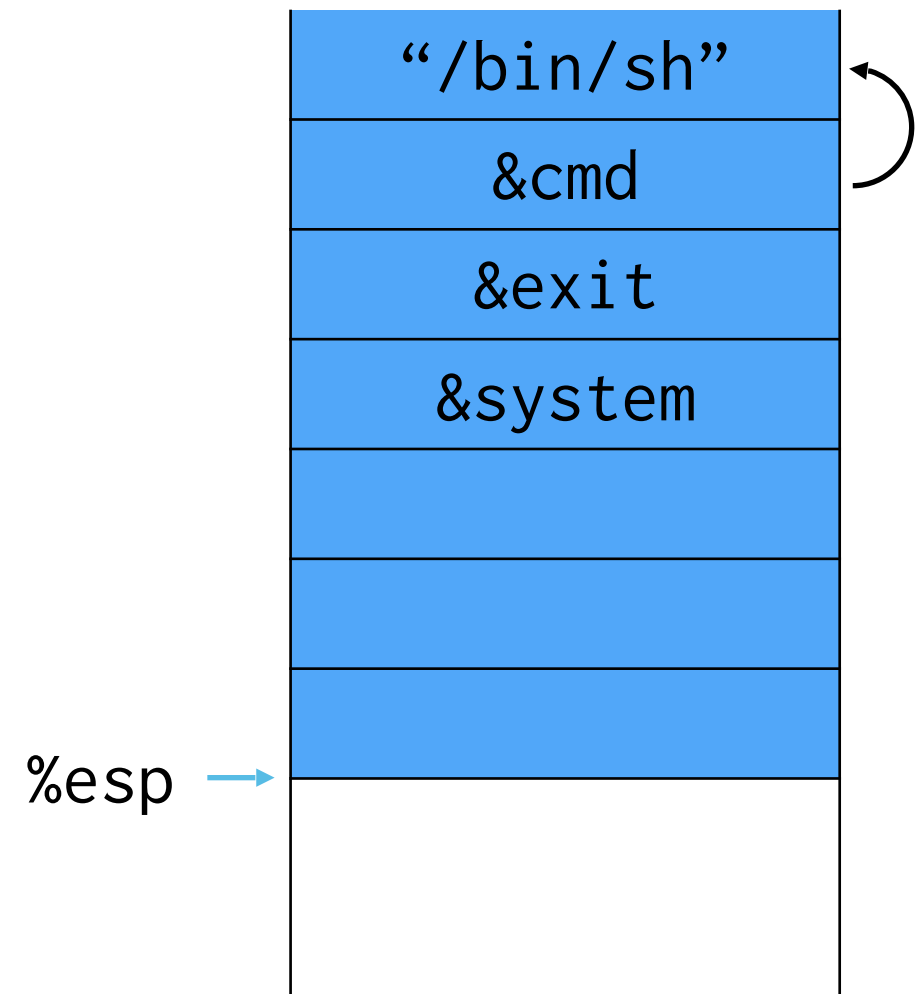
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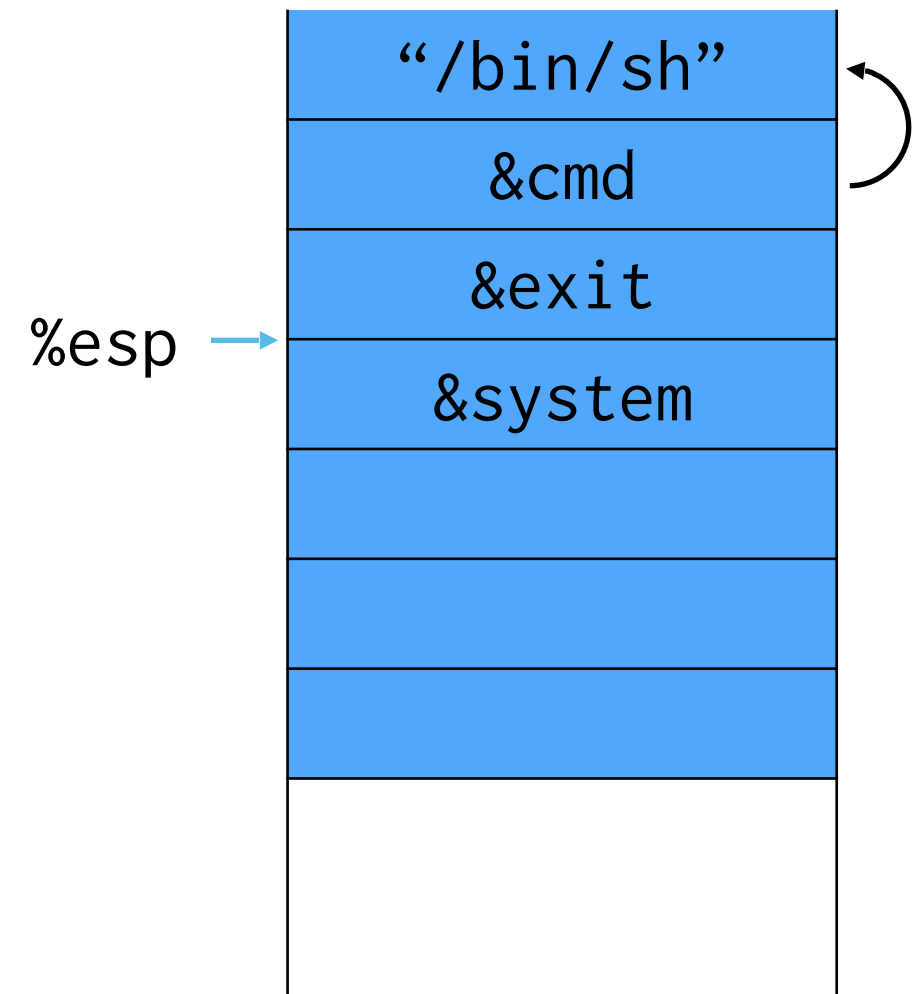
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Our vulnerable function:



Can we inject code?

# Can we inject code?

MPROTECT(2)

Linux Programmer's Manual

MPROTECT(2)

## NAME [top](#)

`mprotect`, `pkey_mprotect` - set protection on a region of memory

## SYNOPSIS [top](#)

```
#include <sys/mman.h>

int mprotect(void *addr, size_t len, int prot);

#define _GNU_SOURCE          /* See feature_test_macros(7) */
#include <sys/mman.h>

int pkey_mprotect(void *addr, size_t len, int prot, int pkey);
```

## DESCRIPTION [top](#)

**mprotect()** changes the access protections for the calling process's memory pages containing any part of the address range in the interval `[addr, addr+len-1]`. `addr` must be aligned to a page boundary.

If the calling process tries to access memory in a manner that violates the protections, then the kernel generates a **SIGSEGV** signal for the process.

`prot` is a combination of the following access flags: **PROT\_NONE** or a bitwise-or of the other values in the following list:

**PROT\_NONE** The memory cannot be accessed at all.

**PROT\_READ** The memory can be read.

**PROT\_WRITE** The memory can be modified.

**PROT\_EXEC** The memory can be executed.



# Can we inject code?

- Just-in-time compilers produce data that becomes executable code
- JIT spraying:
  - 1. Spray heap with shellcode (and NOP slides)
  - 2. Overflow code pointer to point to spray area

# What does JIT shellcode look like?

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```
var g1 = 0;
...
var g7 = 0;

for (var i=0; i<100000; ++i) {
    g1 = 50011;    \\ pop ebx; ret;
    g2 = 50009;    \\ pop ecx; ret;
    g3 = 12828721; \\ xor eax, eax; ret;
    g4 = 12811696; \\ mov 0x7d, al; ret;
    g5 = 12833329; \\ xor edx, edx; ret;
    g6 = 12781490; \\ mov 0x7, dl; ret;
    g7 = 12812493; \\ int 0x80; ret;
}
```

# What does JIT shellcode look like?

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## The Devil is in the Constants: Bypassing Defenses in Browser JIT Engines

Michalis Athanasakis	Elias Athanasopoulos	Michalis Polychronakis	Georgios Portokalidis	Sotiris Ioannidis
FORTH, Greece	FORTH, Greece	Stony Brook University	Stevens Institute of Tech.	FORTH, Greece
michath@ics.forth.gr	elathan@ics.forth.gr	mikepo@cs.stonybrook.edu	gportoka@stevens.edu	sotiris@ics.forth.gr

# How do we defend against this?

- Modify the JavaScript JIT
  - Store JavaScript strings in separate heap from rest
  - Blind constants
- Ongoing arms race
  - E.g., Wasm makes it easier for attackers: gap between Wasm and x86/ARM is much smaller than JavaScript

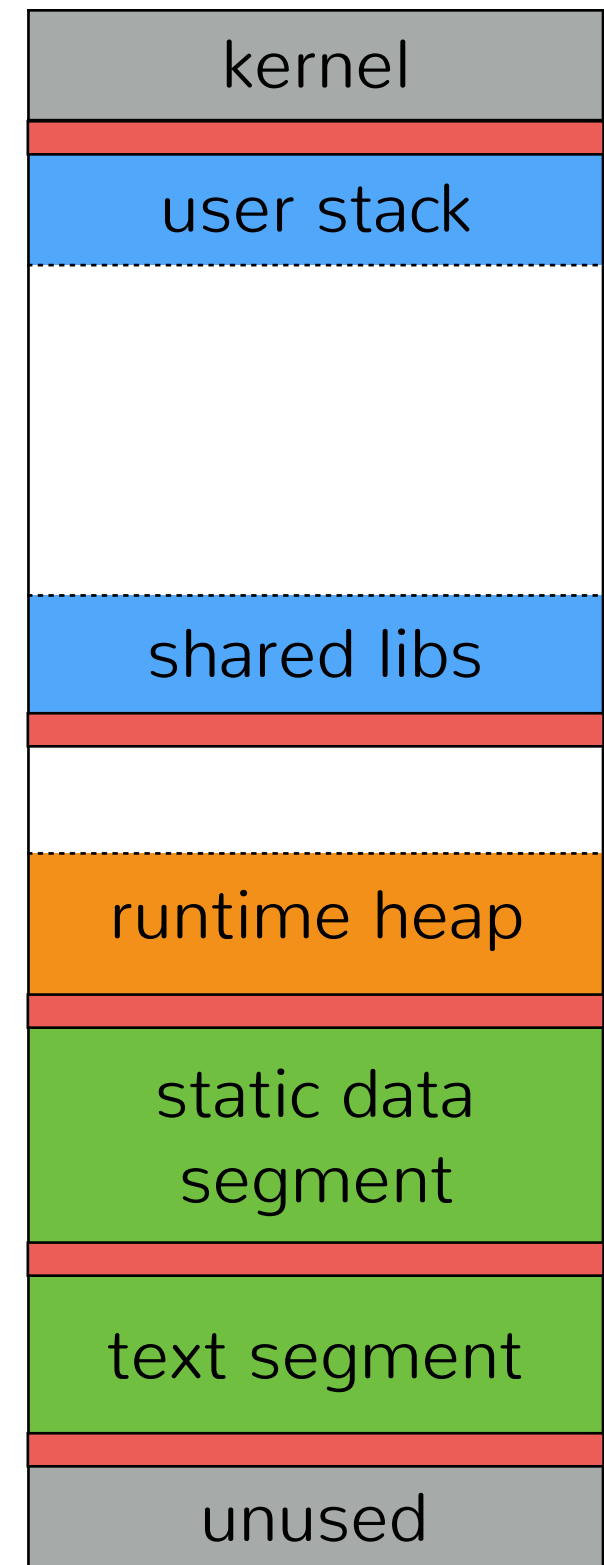
# Buffer overflow mitigations

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➔ Address space layout randomization (ASLR)

# ASLR

- Traditional exploits need precise addresses
  - stack-based overflows: location of shellcode
  - return-into-libc: library addresses
- **Insight:** Make it harder for attacker to guess location of shellcode/libc by randomizing the address of different memory regions



# When do we randomize?



# When do we randomize?

```
[d@bedsty code master*]  
└─> cat /proc/self/maps | egrep '(libc|heap|stack)'  
5555555f000-55555558000 rw-p 00000000 00:00 0 [heap]  
7ffff7dce000-7ffff7df3000 r--p 00000000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7df3000-7ffff7f3d000 r-xp 00025000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7f3d000-7ffff7f86000 r--p 0016f000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7f86000-7ffff7f87000 ---p 001b8000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7f87000-7ffff7f8a000 r--p 001b8000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7f8a000-7ffff7f8d000 rw-p 001bb000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7f8d000-7ffff7f8e000 rw-p 00000000 00:00 0 [stack]  
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5555555f000-55555558000 rw-p 00000000 00:00 0 [heap]  
7ffff7dce000-7ffff7df3000 r--p 00000000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7df3000-7ffff7f3d000 r-xp 00025000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7f3d000-7ffff7f86000 r--p 0016f000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7f86000-7ffff7f87000 ---p 001b8000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7f87000-7ffff7f8a000 r--p 001b8000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7f8a000-7ffff7f8d000 rw-p 001bb000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ffff7f8d000-7ffff7f8e000 rw-p 00000000 00:00 0 [stack]  
[d@bedsty code master*]  
└─> echo 2 | sudo tee /proc/sys/kernel/randomize_va_space  
2  
[d@bedsty code master*]  
└─> cat /proc/self/maps | egrep '(libc|heap|stack)'  
564346042000-564346063000 rw-p 00000000 00:00 0 [heap]  
7ff28472c000-7ff284751000 r--p 00000000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ff284751000-7ff28489b000 r-xp 00025000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ff28489b000-7ff2848e4000 r--p 0016f000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ff2848e4000-7ff2848e5000 ---p 001b8000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ff2848e5000-7ff2848e8000 r--p 001b8000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ff2848e8000-7ff2848eb000 rw-p 001bb000 fe:02 2100102 /usr/lib/libc-2.29.so  
7ff2848eb000-7ff2848ec000 rw-p 00000000 00:00 0 [stack]  
[d@bedsty code master*]  
└─> cat /proc/self/maps | egrep '(libc|heap|stack)'  
55945b021000-55945b042000 rw-p 00000000 00:00 0 [heap]  
7fd596208000-7fd59622d000 r--p 00000000 fe:02 2100102 /usr/lib/libc-2.29.so  
7fd59622d000-7fd596377000 r-xp 00025000 fe:02 2100102 /usr/lib/libc-2.29.so  
7fd596377000-7fd5963c0000 r--p 0016f000 fe:02 2100102 /usr/lib/libc-2.29.so  
7fd5963c0000-7fd5963c1000 ---p 001b8000 fe:02 2100102 /usr/lib/libc-2.29.so  
7fd5963c1000-7fd5963c4000 r--p 001b8000 fe:02 2100102 /usr/lib/libc-2.29.so  
7fd5963c4000-7fd5963c7000 rw-p 001bb000 fe:02 2100102 /usr/lib/libc-2.29.so  
7fd5963c7000-7fd5963c8000 rw-p 00000000 00:00 0 [stack]
```

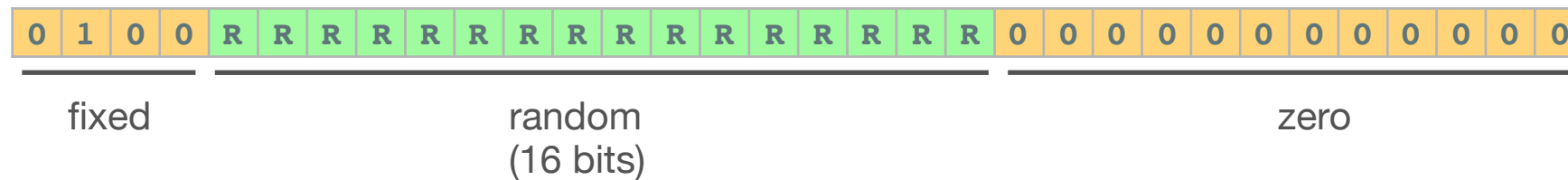
# How much randomness?

## 32-bit PaX ASLR (x86)

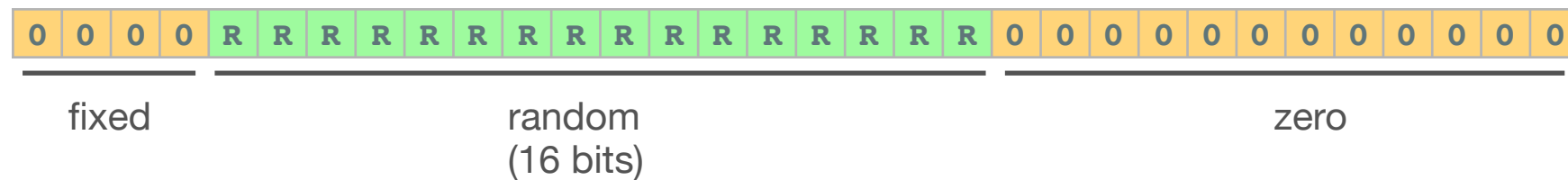
*Stack:*



*Mapped area:*



*Executable code, static variables, and heap:*



# Tradeoff

- **Intrusive:** Need compiler, linker, loader support
  - Process layout must be randomized
  - Programs must be compiled to not have absolute jumps
- **Incurs overhead:** increases code size & perf overhead
- **Also mitigates heap-based overflow attacks**

# How can we defeat ASLR?

- Older Linux would let local attacker read the stack start address from `/proc/<pid>/stat`
- `-fno-pie` binaries have fixed code and data addresses
  - Enough to carry out control-flow-hijacking attacks
- Each region has random offset, but layout is fixed
  - Single address in a region leaks every address in region
- Brute force for 32-bit binaries and/or pre-fork binaries
- Heap spray for 64-bit binaries

# Derandomizing ALSR

- **Attack goal:** call `system()` with attacker arg
- **Target:** Apache daemon
  - **Vulnerability:** buffer overflow in `ap_getline()`

```
char buf[64];  
...  
strcpy(buf, s); // overflow
```

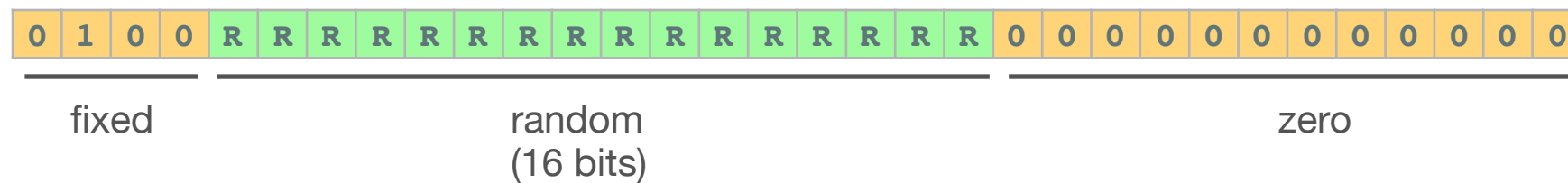
# Assumptions

- $W^X$  enabled
- PaX ASLR enabled
  - Apache forks child processes to handle client interaction
  - Recall how re-randomization works?

# Attack steps

- **Stage 1: Find base of mapped region**

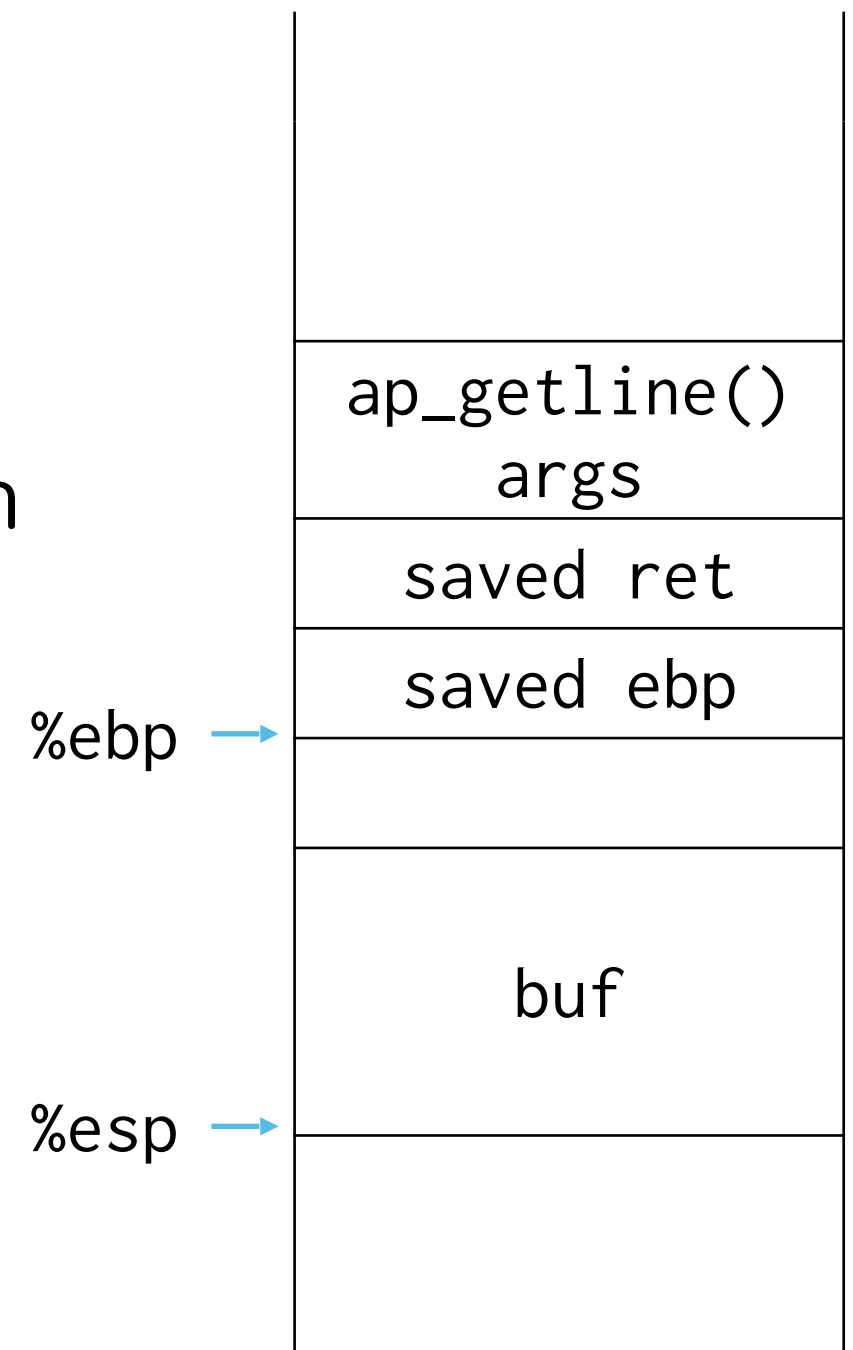
*Mapped area:*



- **Stage 2: Call `system()` with command string**

# How do we find the mapped

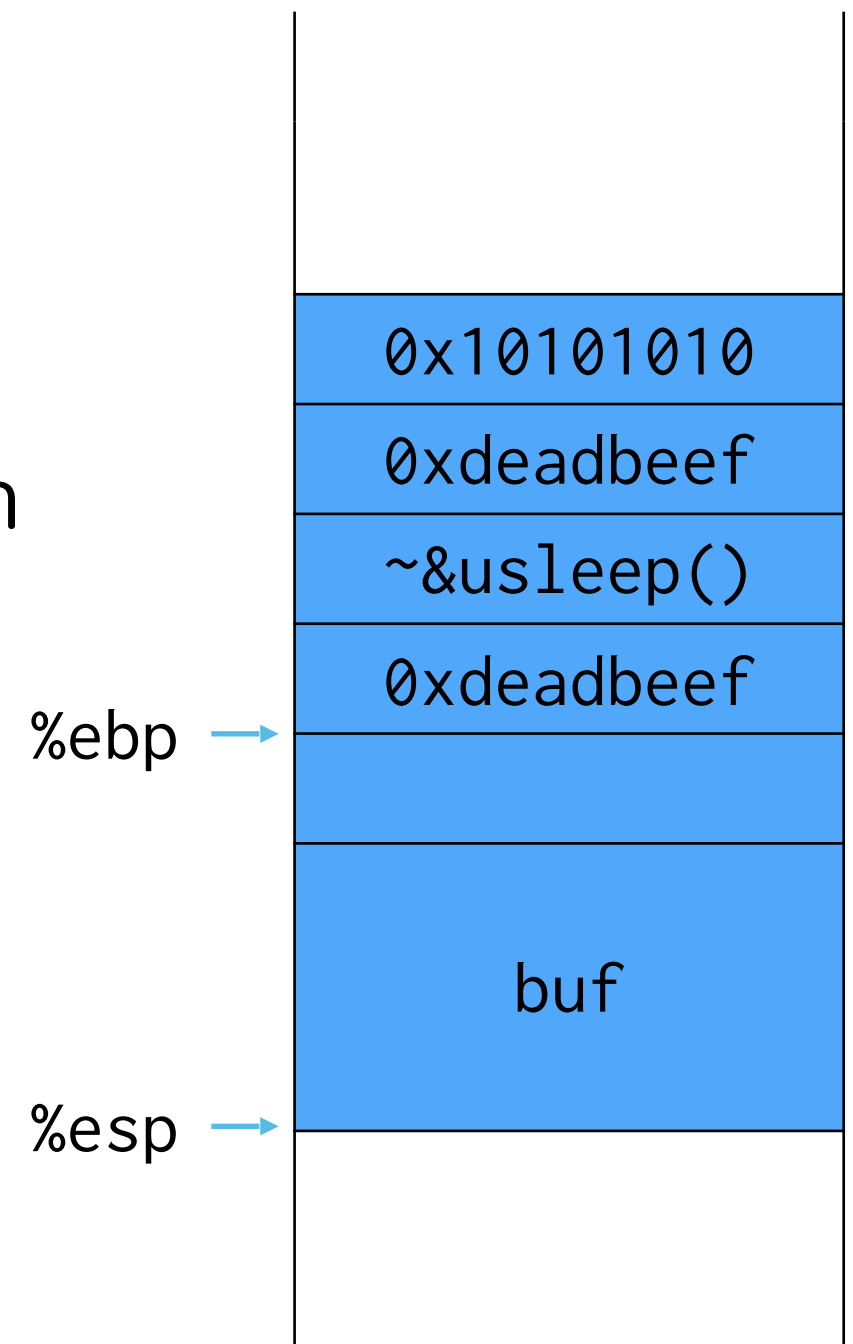
- Observation: layout of mapped region (libc) is fixed
- Overwrite saved return pointer with a guess to `usleep()`
  - base + offset of `usleep`
  - non-negative argument





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# Finding base of mapped region

- If we guessed `usleep()` address right
  -
- If we guessed `usleep()` address wrong
  -
- Use this to tell if we guessed base of mapped region correctly

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# Finding base of mapped region

- If we guessed `usleep()` address right
  - Server will freeze for 16 seconds, then crash
- If we guessed `usleep()` address wrong
  - Server will (likely) crash immediately
- Use this to tell if we guessed base of mapped region correctly

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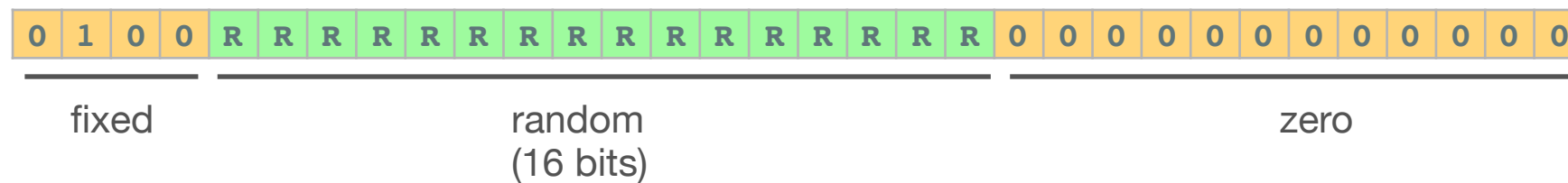
# Derandomizing ASLR

- What is the success probability?
  - $1/2^{16}$  — 65,536 tries maximum
- Do we need to derandomize the stack base?
  - No!

# Attack steps

- **Stage 1:** Find base of mapped region (libc)

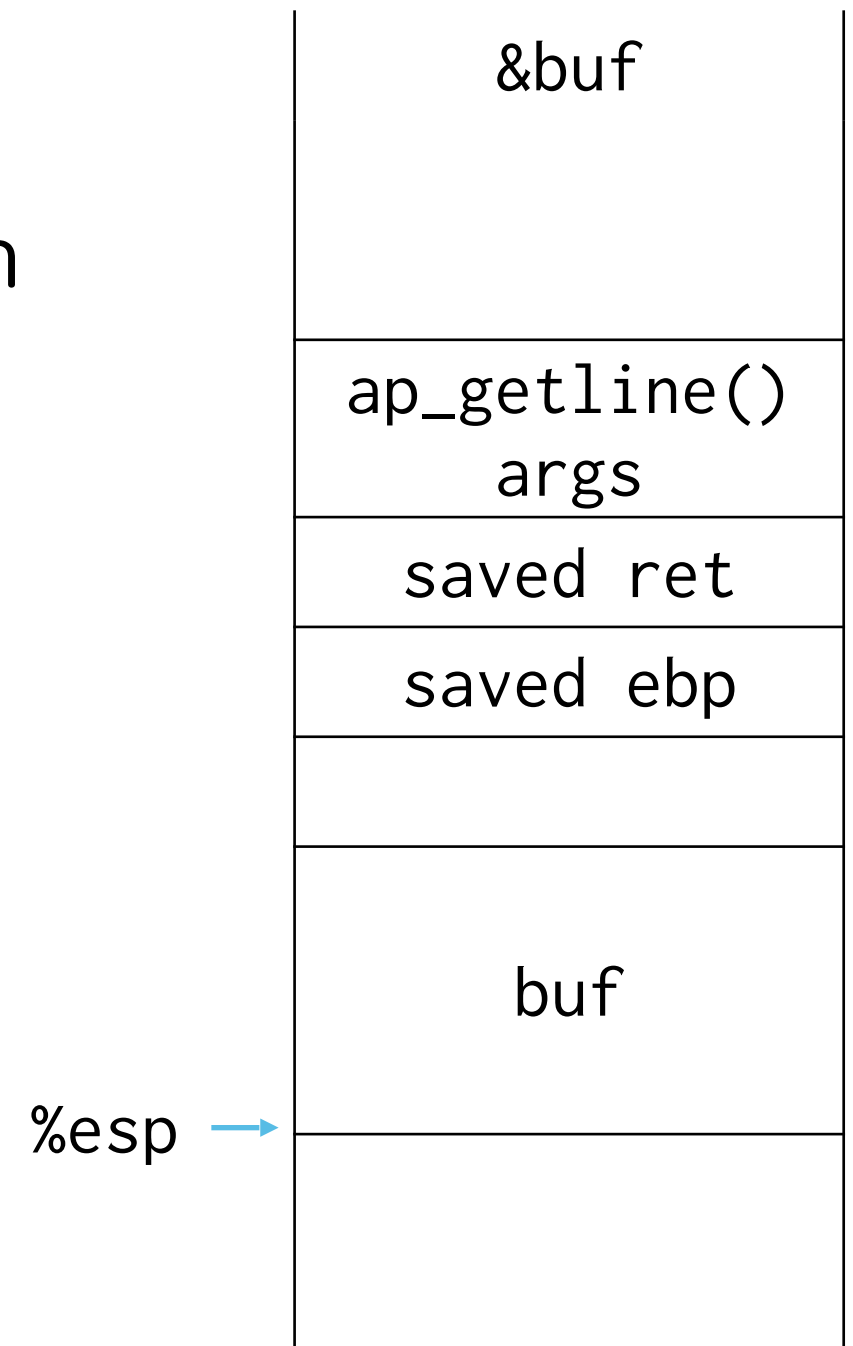
*Mapped area:*



- **Stage 2:** Call `system()` with command string

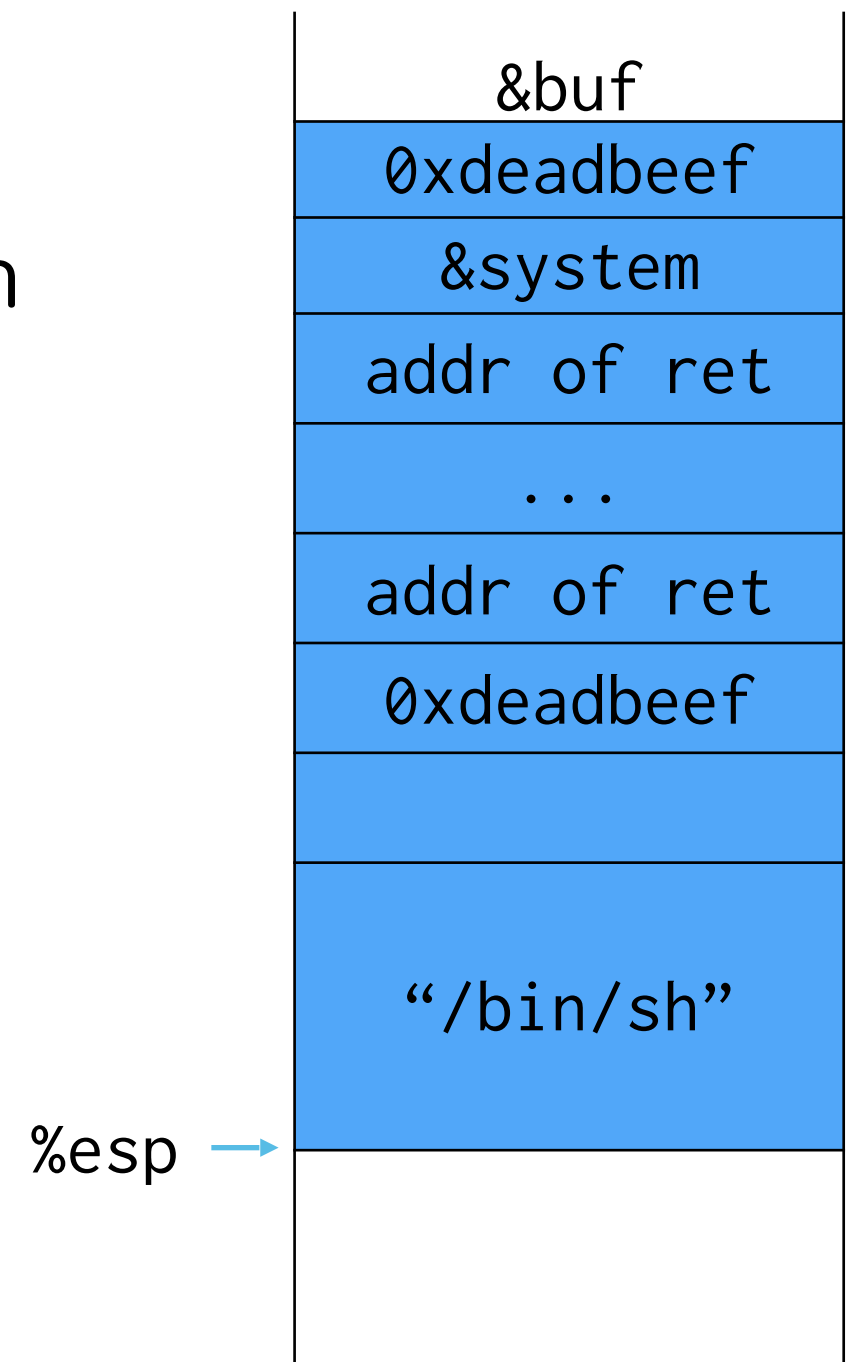
# How do we call system?

- Overwrite saved return pointer with address of ret instruction in libc
- Repeat until address of buf looks like argument to system()
- Append address of system()



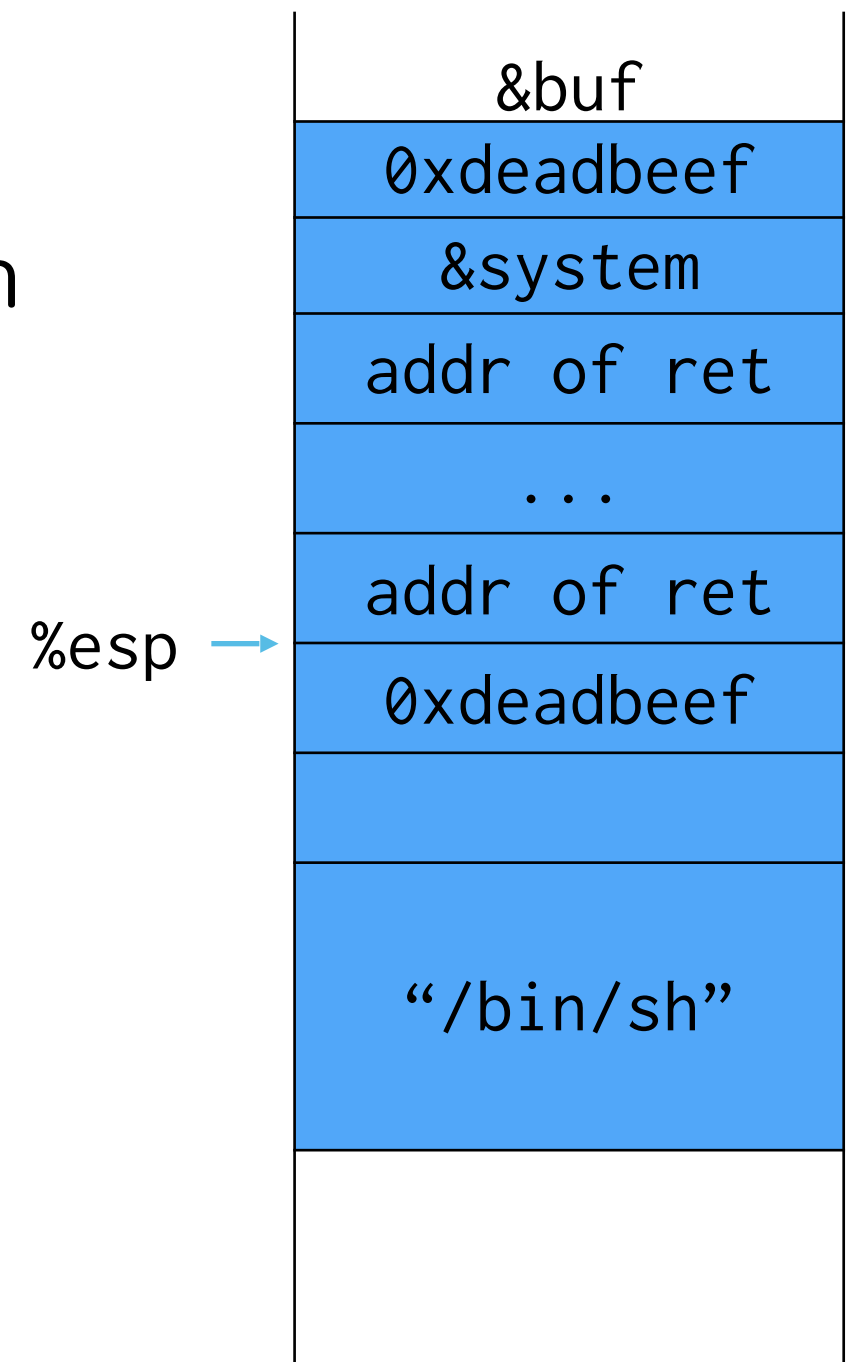
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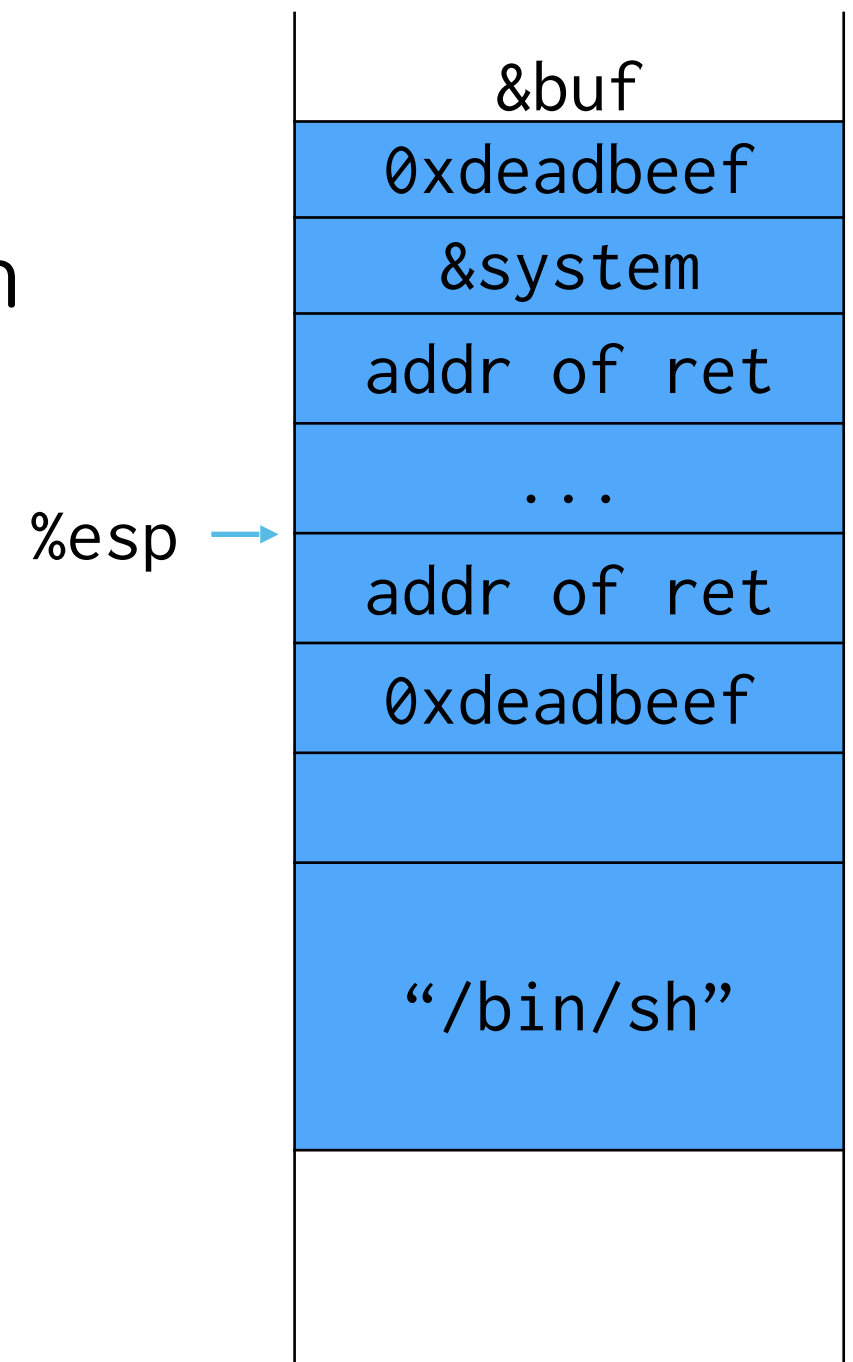
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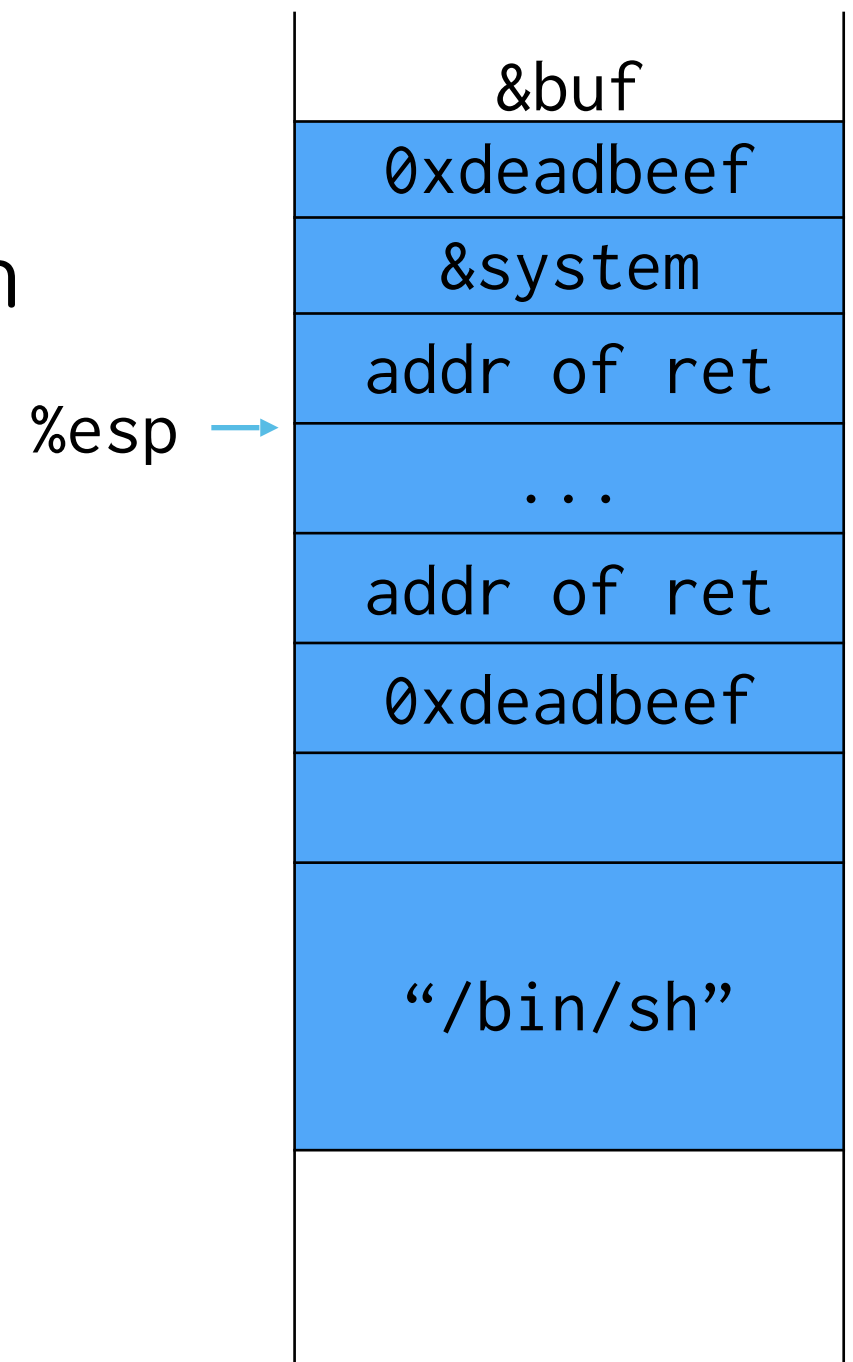
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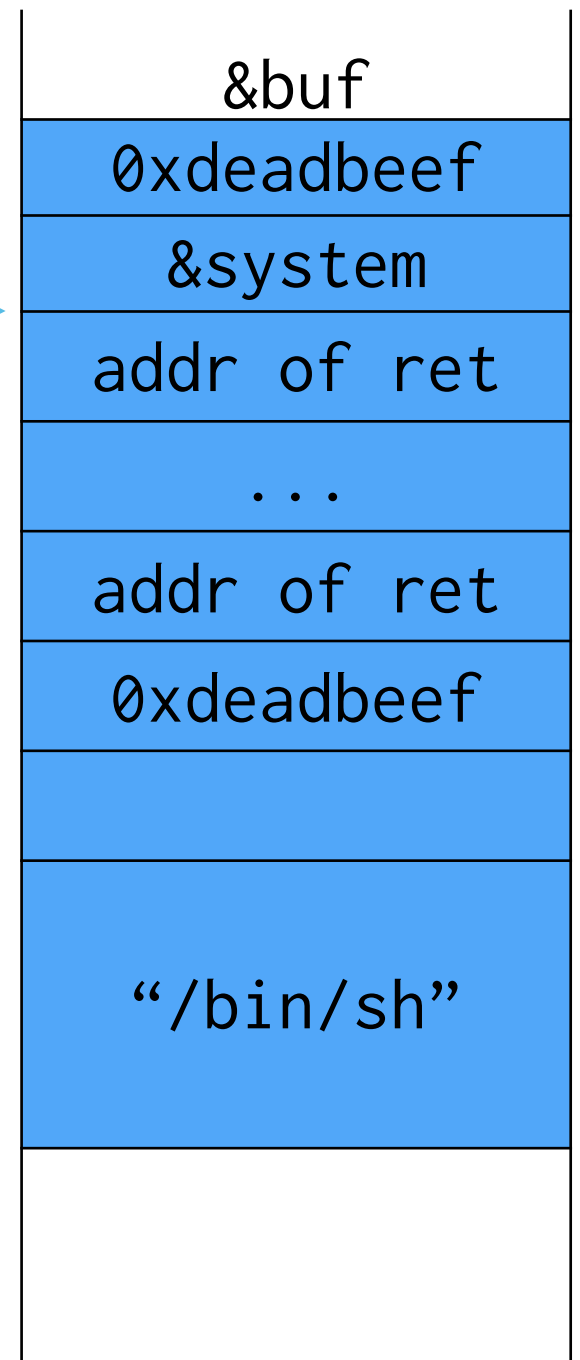
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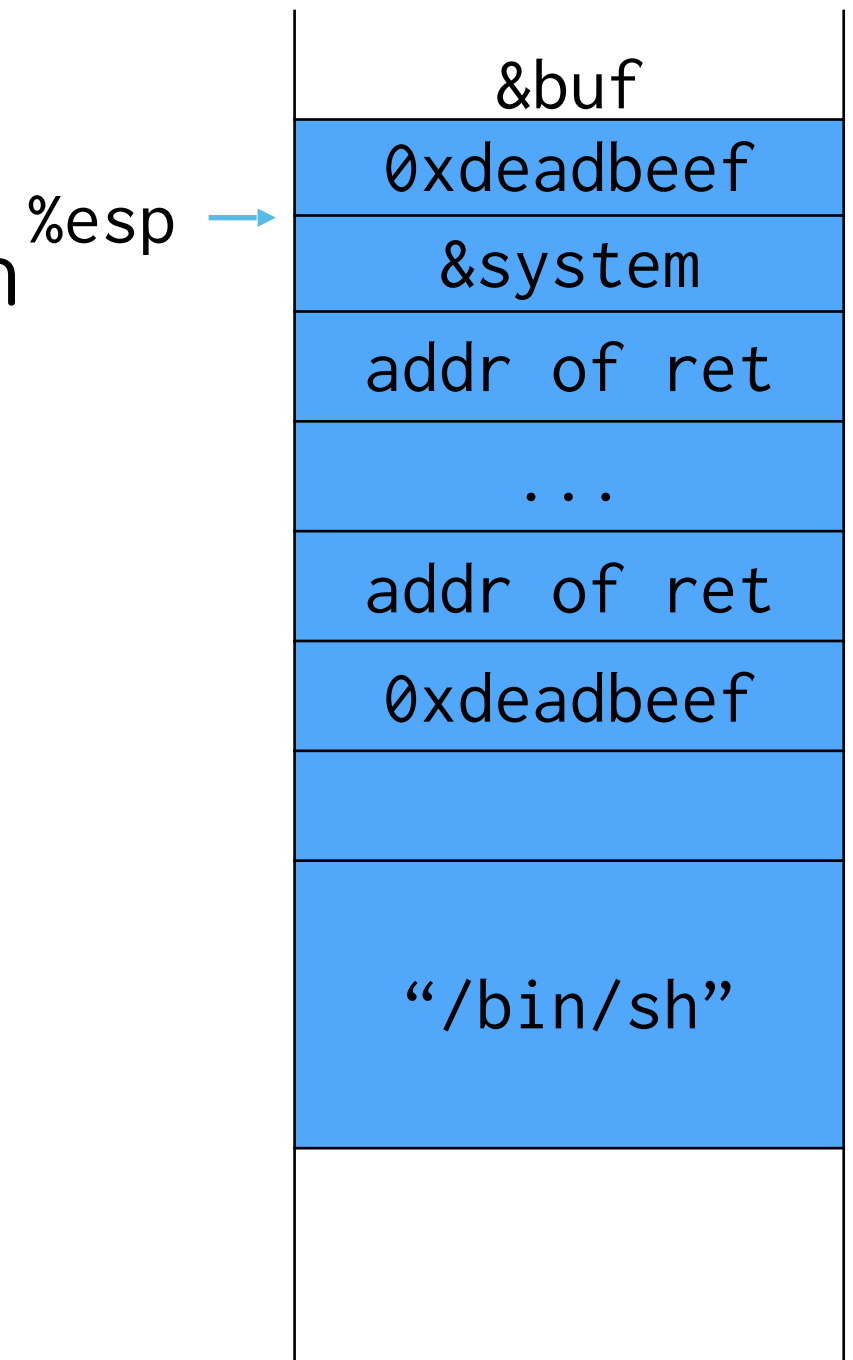
- Overwrite saved return pointer with `%esp` → address of ret instruction in libc
- Repeat until address of buf looks like argument to `system()`
- Append address of `system()`





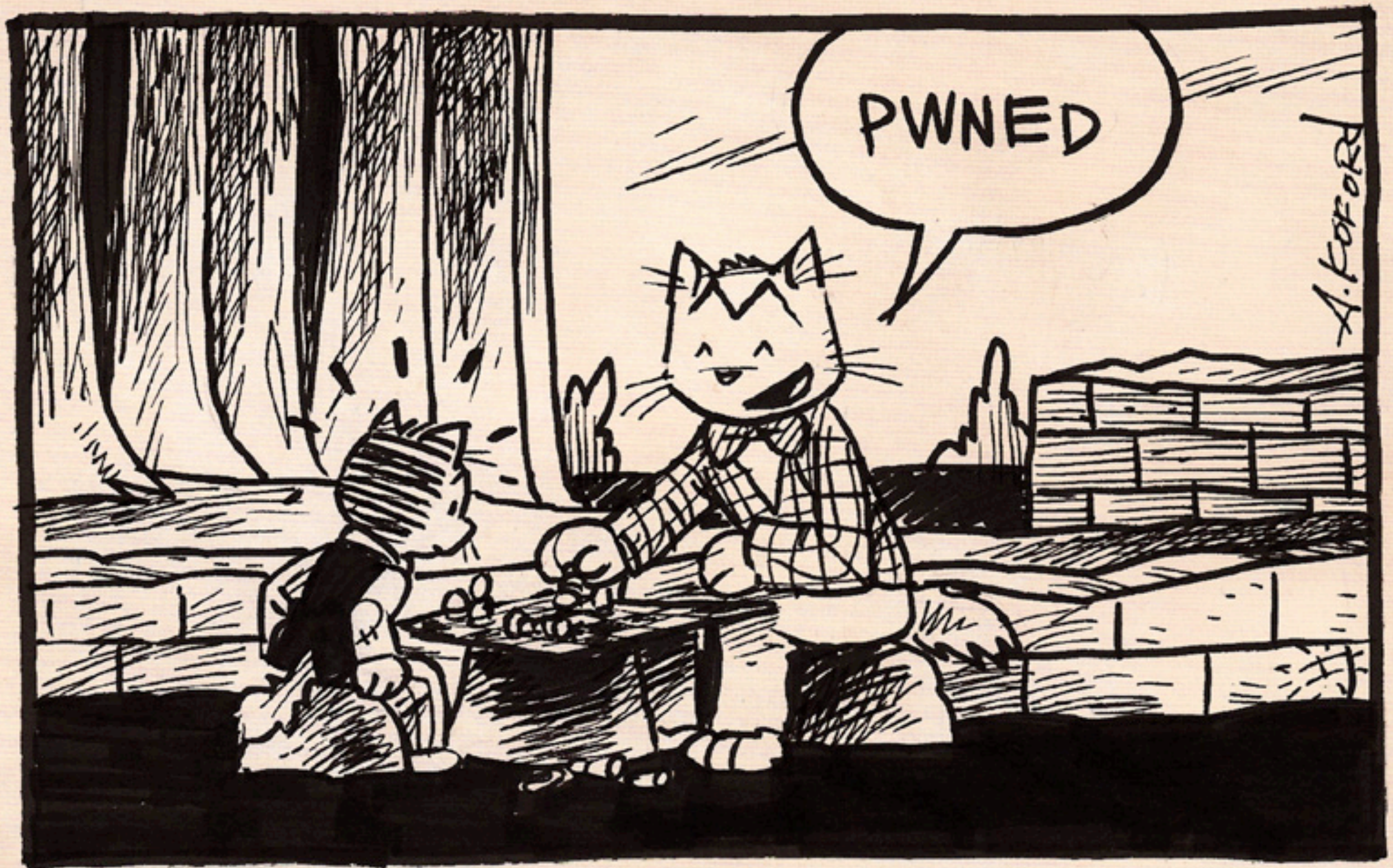
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# How do we call system?





# Buffer Overflow Defenses

- Avoid unsafe functions
- Stack canary
- Separate control stack
- Memory writable or executable, not both ( $W^X$ )
- Address Space Layout Randomization (ASLR)

None are perfect, but in practice  
they raise the bar dramatically