Shellcoding & Memory Defenses

ASLR, NX, and Canaries

Last week in class:

- Basic Assembly / Stack Layout
- ELF Format
- Buffer Overflows / Stack Smashing
- Control-Flow Hijacking
- Shellcode injection

Quiz!

(Won’t be graded, can work with person next to you.)

```
struct data {
    int  is_authorized;
    char attempted_password[30];
    char password[30];
}

struct data ptr; // Assume this is a pointer to data

void login(char *str) {
   ptr.is_authorized = strcmp(ptr->password,str);
   if (ptr.is_authorzed != 0) {
       printf(“Wrong password, this will be reported.\n”);
       strcpy(&ptr.attempted_password, str);
   }
}

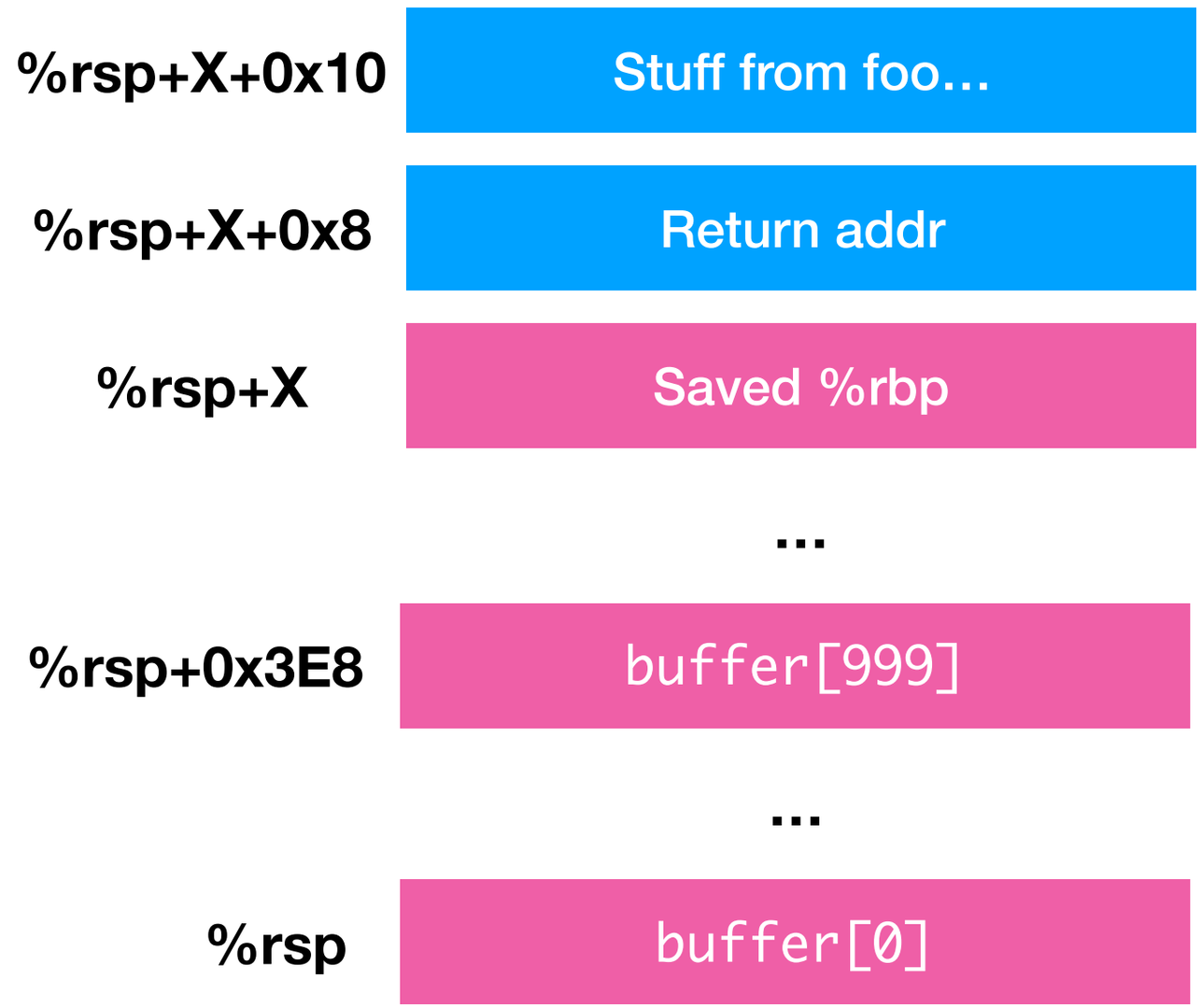
void main(int argc, char **argv) {
    login(argv[1]);
    if (ptr.is_authorized == 0) {
        printf(“Welcome to the system!”);
    } else {
        // …
    }
}
```

Check all that apply

(A) Stack Smashing
(B) Buffer overflow
(C) Data-Only attack
(D) Control-flow Hijacking

Upshot: if program **already contains** code we want to run, stash saved RIP, go to that address…

```
void bar(char *c) {
    char buffer[1000];
    strcpy(buffer,c);
}
```

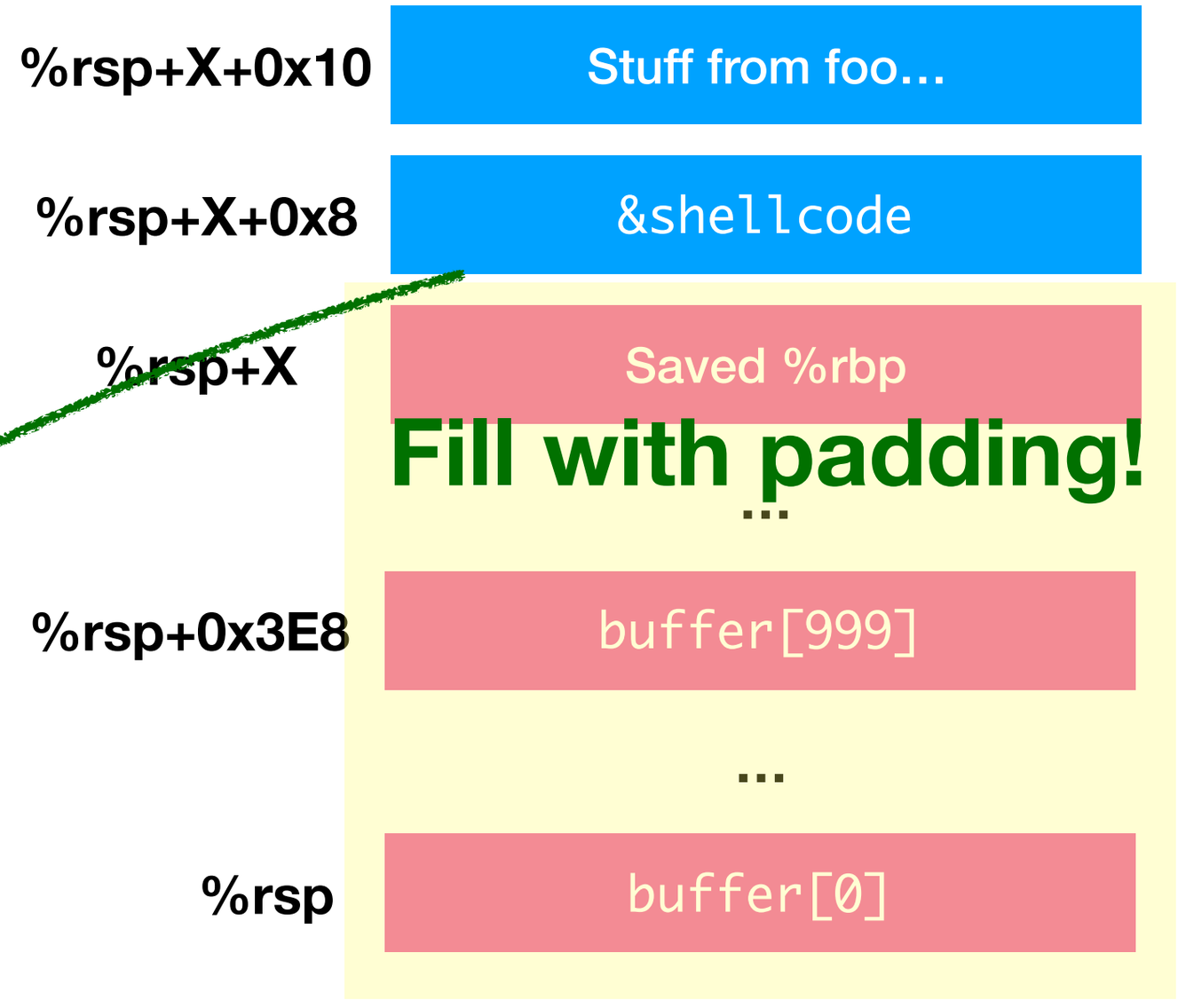


Upshot: if program **already contains** code we want to run, stash saved RIP, go to that address…

```
void bar(char *c) {
    char buffer[1000];
    strcpy(buffer,c);
}
```

Control **returns** here!

```
char shellcode[] = "…"
```



If that code isn't there, I have to **inject** it!

Two steps:

1. Figure out **some way** to get input into the program
   - Many ways: look for when it gets put in buffer
2. Get the **address** of that injected input

As an attacker, I look through the program and figure out how I can get the program to load my code into its memory…

Challenge!

https://github.com/kmicinski/file-server/blob/master/server.c

For each buffer in the program, find out how I could get something in to it

As you figure out how, come up and write the line number of the buffer on the board

Shellcoding

So, what code do I want to inject?

This is actually quite tricky!

Can't just compile arbitrary code

(Because it contains refs to funs I don't know)

"Hello, world!" translation (`gcc -S`)

```
_main:
    pushq  %rbp
    movq   %rsp, %rbp
    subq   $32, %rsp
    leaq   L_.str(%rip), %rdi
    leaq   -14(%rbp), %rsi
    movq   L_main.hello_world(%rip), %rax
    movq   %rax, -14(%rbp)
    movl   L_main.hello_world+8(%rip), %ecx
    movl   %ecx, -6(%rbp)
    movw   L_main.hello_world+12(%rip), %dx
    movw   %dx, -2(%rbp)
    movb   $0, %al
    callq  _printf
    xorl   %ecx, %ecx
    movl   %eax, -20(%rbp)
    movl   %ecx, %eax
    addq   $32, %rsp
    popq   %rbp
    retq
```

Question: why **can't** I just translate this to binary and stick it in the input?

```
    .section   __TEXT,__cstring,cstring_literals
L_main.hello_world:
    .asciz "hello, world\n"

L_.str:
    .asciz "%s"
```

"Hello, world!" translation (`gcc -S`)

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_main:
    pushq  %rbp
    movq   %rsp, %rbp
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    movl   %ecx, -6(%rbp)
    movw   L_main.hello_world+12(%rip), %dx
    movw   %dx, -2(%rbp)
    movb   $0, %al
    callq  _printf
    xorl   %ecx, %ecx
    movl   %eax, -20(%rbp)
    movl   %ecx, %eax
    addq   $32, %rsp
    popq   %rbp
    retq
```

Question: why **can't** I just translate this to binary and stick it in the input?

Don't know where `_printf` is

```
    .section   __TEXT,__cstring,cstring_literals
L_main.hello_world:
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"Hello, world!" translation (`gcc -S`)

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    movw   %dx, -2(%rbp)
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    callq  _printf
    xorl   %ecx, %ecx
    movl   %eax, -20(%rbp)
    movl   %ecx, %eax
    addq   $32, %rsp
    popq   %rbp
    retq
```

Question: why **can't** I just translate this to binary and stick it in the input?

Don't know where `_printf` is

This in different **section** (need contiguous string)!

```
    .section   __TEXT,__cstring,cstring_literals
L_main.hello_world:
    .asciz "hello, world\n"

L_.str:
    .asciz "%s"
```

Turns out, writing this “injectable” code can be pretty tough!

Consider line 227:

`strcpy(string,buffer+5)`

Copies everything from buffer+5 until NUL byte

Question: What happens if buffer+5 contains…
`[0x41, 0x43, 0x55, 0x00, 0x23, 0x12]`

Consider line 227:

`strcpy(string,buffer+5)`

Copies everything from buffer+5 until NUL byte

Question: What happens if buffer+5 contains…
`[0x41, 0x43, 0x55, 0x00, 0x23, 0x12]`

Observation: strcpy **stops copying** when hits 0x00

Upshot: Shellcode can't contain any 0x00 bytes if strcpy is used

Consider line 227:

`strcpy(string,buffer+5)`

Copies everything from buffer+5 until NUL byte

Question: What happens if buffer+5 contains…
`[0x41, 0x43, 0x55, 0x00, 0x23, 0x12]`

Observation: strcpy **stops copying** when hits 0x00

If some other mechanism is used, it may work, though!

So what's an example of easy shellcode?

Answer: system calls

System calls “call out” to the underlying OS kernel

`exit`	Exits the program
`write`	Writes to some file
`time`	Get system time

Hundreds of these…

https://filippo.io/linux-syscall-table/

System calls do **not** follow the normal calling convention!!

They use the special `syscall` instruction

Syscall Calling Conventions

- Different than System V (C-style) calls
- Pass **system call number** (look this up somewhere) in %rax
- Arguments are passed in certain registers
  - Have to look up which to use,
- Execute the special instruction `syscall`
  - This actually **performs** the system call

Example for **write**

- Put 1 in %rax (This is the syscall number for write)
- Put file descriptor (number) in %rdi
- Pointer to buffer in %rsi
- Number of bytes to write: %rdx
- Execute the special instruction `syscall`

Exercise: Figure out what this does

(Hint: Pull out an ASCII table)

```
main:
    movq    $1, %rax
    movq    $1, %rdi
    movq    $0x0A646c72, %r9
    pushq   %r9
    movq    $0x6f772c6f6c6c6548, %r9
    pushq   %r9
    movq    %rsp, %rsi
    movq    $12, %rdx
    syscall
    addq    $0x10, %rsp
    ret
```

But still many 0x00s :(

```
00000000000005fa <main>:
 5fa:  48 c7 c0 01 00 00 00   mov    $0x1,%rax
 601:  48 c7 c7 01 00 00 00   mov    $0x1,%rdi
 608:  49 c7 c1 72 6c 64 0a   mov    $0xa646c72,%r9
 60f:  41 51                  push   %r9
 611:  49 b9 48 65 6c 6c 6f   movabs $0x6f772c6f6c6c6548,%r9
 618:  2c 77 6f
 61b:  41 51                  push   %r9
 61d:  48 89 e6               mov    %rsp,%rsi
 620:  48 c7 c2 0c 00 00 00   mov    $0xc,%rdx
 627:  0f 05                  syscall
 629:  48 83 c4 10            add    $0x10,%rsp
 62d:  c3                     retq
 62e:  66 90                  xchg   %ax,%ax
```

Question: if I can't use "mov $1, %rax", what sequence of instructions could I do instead?

Remember, my goal is to find something that does work!

In this case… Clever use of xor, inc, and add

```
0000000000005fa <main>:
 5fa: 48 31 c0                   xor    %rax,%rax
 5fd: 48 ff c0                   inc    %rax
 600: 48 31 ff                   xor    %rdi,%rdi
 603: 48 ff c7                   inc    %rdi
 606: 49 c7 c1 72 6c 64 0a       mov    $0xa646c72,%r9
 60d: 41 51                      push   %r9
 60f: 49 b9 48 65 6c 6c 6f       movabs $0x6f772c6f6c6c6548,%r9
 616: 2c 77 6f
 619: 41 51                      push   %r9
 61b: 48 89 e6                   mov    %rsp,%rsi
 61e: 48 31 d2                   xor    %rdx,%rdx
 621: 48 83 c2 0c                add    $0xc,%rdx
 625: 0f 05                      syscall
 627: 48 83 c4 10                add    $0x10,%rsp
 62b: c3                         retq
 62c: 0f 1f 40 00                nopl   0x0(%rax)
```

In this case… Clever use of xor, inc, and add

My shellcode

```
00000000000005fa <main>:
 5fa: 48 31 c0                   xor    %rax,%rax
 5fd: 48 ff c0                   inc    %rax
 600: 48 31 ff                   xor    %rdi,%rdi
 603: 48 ff c7                   inc    %rdi
 606: 49 c7 c1 72 6c 64 0a       mov    $0xa646c72,%r9
 60d: 41 51                      push   %r9
 60f: 49 b9 48 65 6c 6c 6f       movabs $0x6f772c6f6c6c6548,%r9
 616: 2c 77 6f
 619: 41 51                      push   %r9
 61b: 48 89 e6                   mov    %rsp,%rsi
 61e: 48 31 d2                   xor    %rdx,%rdx
 621: 48 83 c2 0c                add    $0xc,%rdx
 625: 0f 05                      syscall
 627: 48 83 c4 10                add    $0x10,%rsp
 62b: c3                         retq
 62c: 0f 1f 40 00                nopl   0x0(%rax)
```

A lot of what makes exploitation so fun is playing these clever tricks!

Observations:

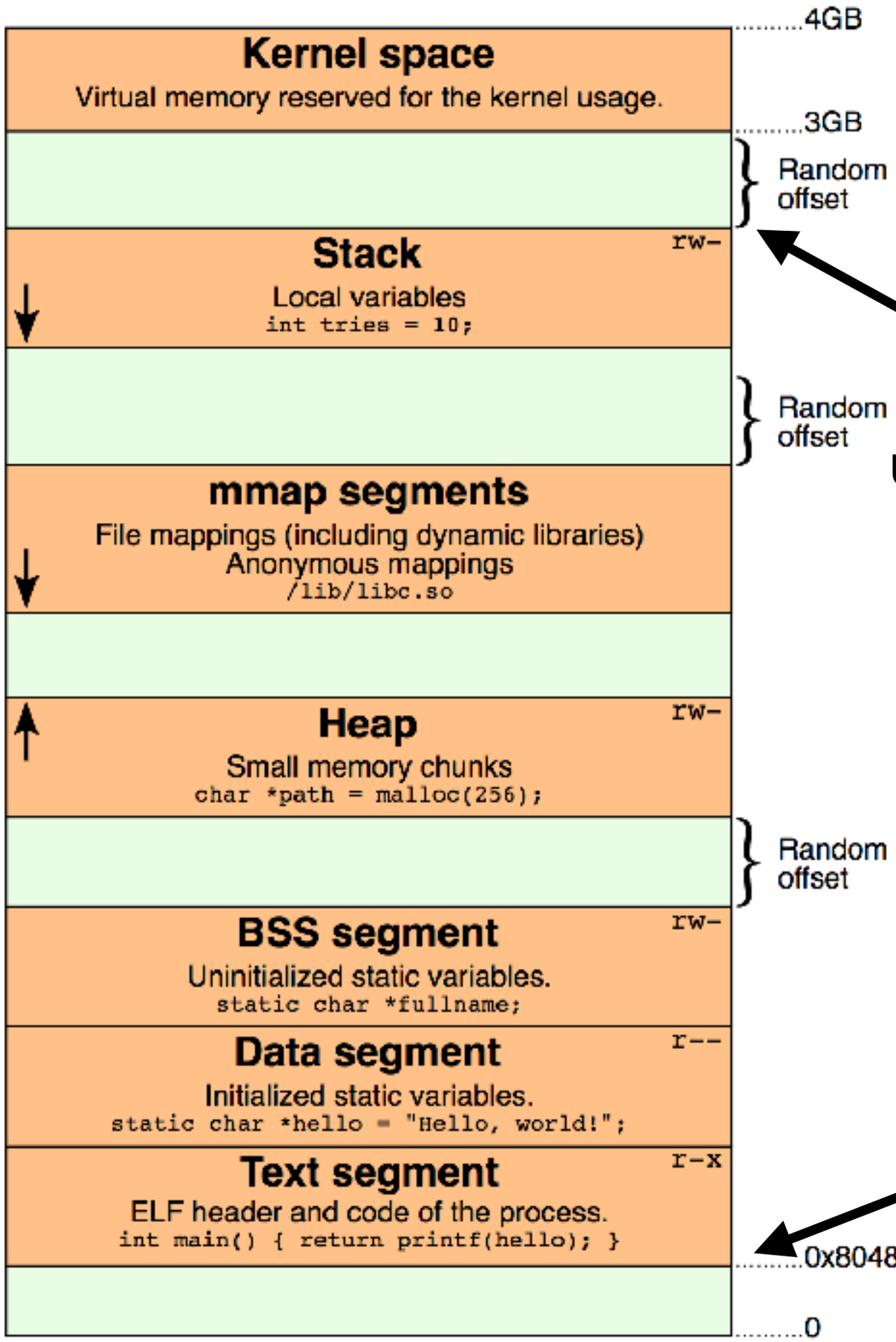
- Stack-allocate arguments to build strings
- Avoid NUL-bytes by being creative
- System calls are easy because don't need to know function addresses (avoid ASLR)

https://stackoverflow.com/questions/15593214/linux-shellcode-hello-world

Memory Defenses

Adress **S**pace **L**ayout **R**andomization

Randomizes the position of stack, heap, program, libraries



Upshot: Even if you can inject code into the stack, you won't be able to **find** it

Note that the text segment (binary code for program) **isn't** randomized here

Detour: Position Independent / Relocatable Code

- `.text` segment holds binary representation of program's code
  - All globbed together, each function one after other
- **Within** the text segment, the position of functions **not** changed
  - E.g., if `foo` is at `bar+0x300`, it will **always** be at `bar+0x300`

Program depends on offsets *within* text segment

Detour: Position Independent / Relocatable Code

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Program depends on offsets *within* text segment

However, **base address** of text could be randomized

- Code must be compiled with a flag -fPIE
  - (Position-Independent Execution)

Q: Why **wouldn't** code be compiled with PIE?

A: Can be **faster** to run code that knows its base address

Shows you the **memory maps** for the **current process**

```
cat /proc/self/maps
```

Exercise

```
micinski@micinski:~$ cat /proc/self/maps
00400000-0040c000 r-xp 00000000 08:01 1704116                            /bin/cat
0060b000-0060c000 r--p 0000b000 08:01 1704116                            /bin/cat
0060c000-0060d000 rw-p 0000c000 08:01 1704116                            /bin/cat
00d37000-00d58000 rw-p 00000000 00:00 0                                  [heap]
7fb458920000-7fb458bf8000 r--p 00000000 08:01 2635826                    /usr/lib/locale/locale-archive
7fb458bf8000-7fb458db8000 r-xp 00000000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458db8000-7fb458fb8000 ---p 001c0000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458fb8000-7fb458fbc000 r--p 001c0000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458fbc000-7fb458fbe000 rw-p 001c4000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458fbe000-7fb458fc2000 rw-p 00000000 00:00 0
7fb458fc2000-7fb458fe8000 r-xp 00000000 08:01 25562855                   /lib/x86_64-linux-gnu/ld-2.23.so
7fb45919f000-7fb4591c4000 rw-p 00000000 00:00 0
7fb4591e5000-7fb4591e7000 rw-p 00000000 00:00 0
7fb4591e7000-7fb4591e8000 r--p 00025000 08:01 25562855                   /lib/x86_64-linux-gnu/ld-2.23.so
7fb4591e8000-7fb4591e9000 rw-p 00026000 08:01 25562855                   /lib/x86_64-linux-gnu/ld-2.23.so
7fb4591e9000-7fb4591ea000 rw-p 00000000 00:00 0
7fff36194000-7fff361b5000 rw-p 00000000 00:00 0                          [stack]
7fff361f8000-7fff361fa000 r--p 00000000 00:00 0                          [vvar]
7fff361fa000-7fff361fc000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
```

Find text, static app data, and app global variables

Text segment (Read+Execute)

Data segment (Read)

Global variables (Read+Write)

```
micinski@micinski:~$ cat /proc/self/maps
00400000-0040c000 r-xp 00000000 08:01 1704116                            /bin/cat
0060b000-0060c000 r--p 0000b000 08:01 1704116                            /bin/cat
0060c000-0060d000 rw-p 0000c000 08:01 1704116                            /bin/cat
00d37000-00d58000 rw-p 00000000 00:00 0                                  [heap]
7fb458920000-7fb458bf8000 r--p 00000000 08:01 2635826                    /usr/lib/locale/locale-archive
7fb458bf8000-7fb458db8000 r-xp 00000000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458db8000-7fb458fb8000 ---p 001c0000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458fb8000-7fb458fbc000 r--p 001c0000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458fbc000-7fb458fbe000 rw-p 001c4000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458fbe000-7fb458fc2000 rw-p 00000000 00:00 0
7fb458fc2000-7fb458fe8000 r-xp 00000000 08:01 25562855                   /lib/x86_64-linux-gnu/ld-2.23.so
7fb45919f000-7fb4591c4000 rw-p 00000000 00:00 0
7fb4591e5000-7fb4591e7000 rw-p 00000000 00:00 0
7fb4591e7000-7fb4591e8000 r--p 00025000 08:01 25562855                   /lib/x86_64-linux-gnu/ld-2.23.so
7fb4591e8000-7fb4591e9000 rw-p 00026000 08:01 25562855                   /lib/x86_64-linux-gnu/ld-2.23.so
7fb4591e9000-7fb4591ea000 rw-p 00000000 00:00 0
7fff36194000-7fff361b5000 rw-p 00000000 00:00 0                          [stack]
7fff361f8000-7fff361fa000 r--p 00000000 00:00 0                          [vvar]
7fff361fa000-7fff361fc000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
```

Defeating ASLR

Two main methods: **brute force** and **derandomization**

Just try a bunch of different addresses and hope for the best

(Doesn't work so well in a 64-bit address space..)

Defeating ASLR

Two main methods: **brute force** and **derandomization**

Get program to **leak** the value of a pointer to you

Exercise: break this program

```
void insecure(char *str) {
  char buffer[100];
  if (str[3] == ‘H’) {
      send(“&x”, &buffer); // Assume this goes back to user
  }
  strcpy(buffer,str);
}
```

Exercise: break this program

```
void insecure(char *str) {
  char buffer[100];
  if (str[3] == ‘H’) {
      send(“&x”, &buffer); // Assume this goes back to user
  }
  strcpy(buffer,str);
}
```

This example is obviously fake

However, much more common is **error logs**

(If you can convince an app to throw an error to you that contains pointer, you win!)

https://fail0verflow.com/blog/2017/ps4-crashdump-dump/

PS4 Kernel dumped in 11 days via error logs attacker can control!

Careful: learning address of stack doesn't tell you where text segment is

```
micinski@micinski:~$ cat /proc/self/maps
00400000-0040c000 r-xp 00000000 08:01 1704116                            /bin/cat
0060b000-0060c000 r--p 0000b000 08:01 1704116                            /bin/cat
0060c000-0060d000 rw-p 0000c000 08:01 1704116                            /bin/cat
00d37000-00d58000 rw-p 00000000 00:00 0                                  [heap]
7fb458920000-7fb458bf8000 r--p 00000000 08:01 2635826                    /usr/lib/locale/locale-archive
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7fb458db8000-7fb458fb8000 ---p 001c0000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458fb8000-7fb458fbc000 r--p 001c0000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458fbc000-7fb458fbe000 rw-p 001c4000 08:01 25562894                   /lib/x86_64-linux-gnu/libc-2.23.so
7fb458fbe000-7fb458fc2000 rw-p 00000000 00:00 0
7fb458fc2000-7fb458fe8000 r-xp 00000000 08:01 25562855                   /lib/x86_64-linux-gnu/ld-2.23.so
7fb45919f000-7fb4591c4000 rw-p 00000000 00:00 0
7fb4591e5000-7fb4591e7000 rw-p 00000000 00:00 0
7fb4591e7000-7fb4591e8000 r--p 00025000 08:01 25562855                   /lib/x86_64-linux-gnu/ld-2.23.so
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7fb4591e9000-7fb4591ea000 rw-p 00000000 00:00 0
7fff36194000-7fff361b5000 rw-p 00000000 00:00 0                          [stack]
7fff361f8000-7fff361fa000 r--p 00000000 00:00 0                          [vvar]
7fff361fa000-7fff361fc000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
```

Non e**X**ecutable (stack / heap)

W^X is a simple concept: don't let the programmer execute parts of memory that they can also write

Simple and Effective Defense!

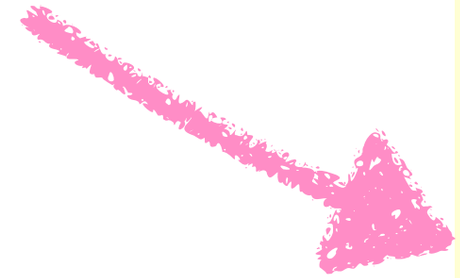
Coordinate w/ CPU

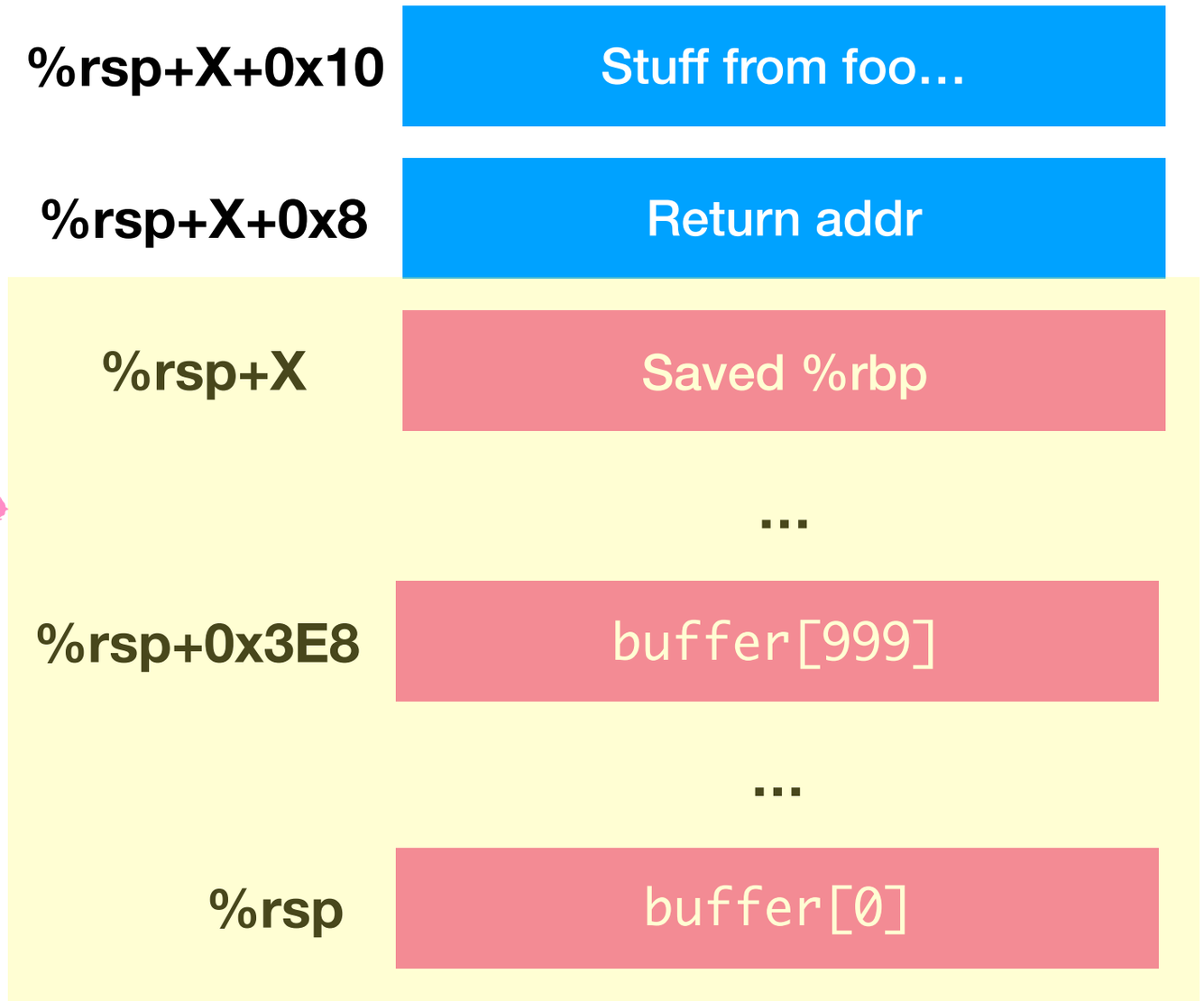
Defeating NX / W^X:

- Return-to-libc
- Return-oriented-programming

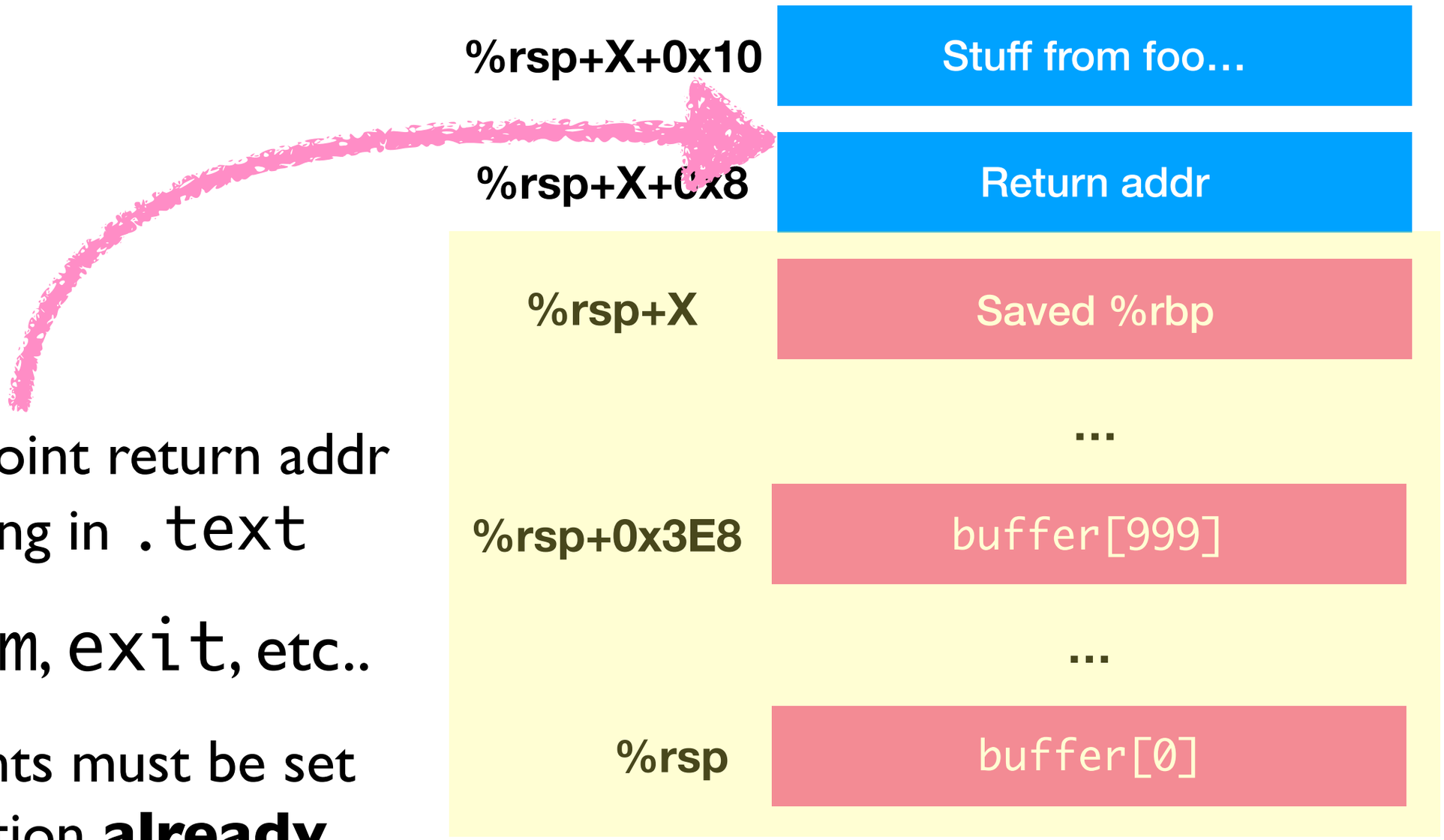
Return-to-libc

NX: If we try to execute shellcode here, program will **crash**!





Return-to-libc



But, can still point return addr at something in `.text`

E.g., `system`, `exit`, etc..

But, arguments must be set up for function **already**

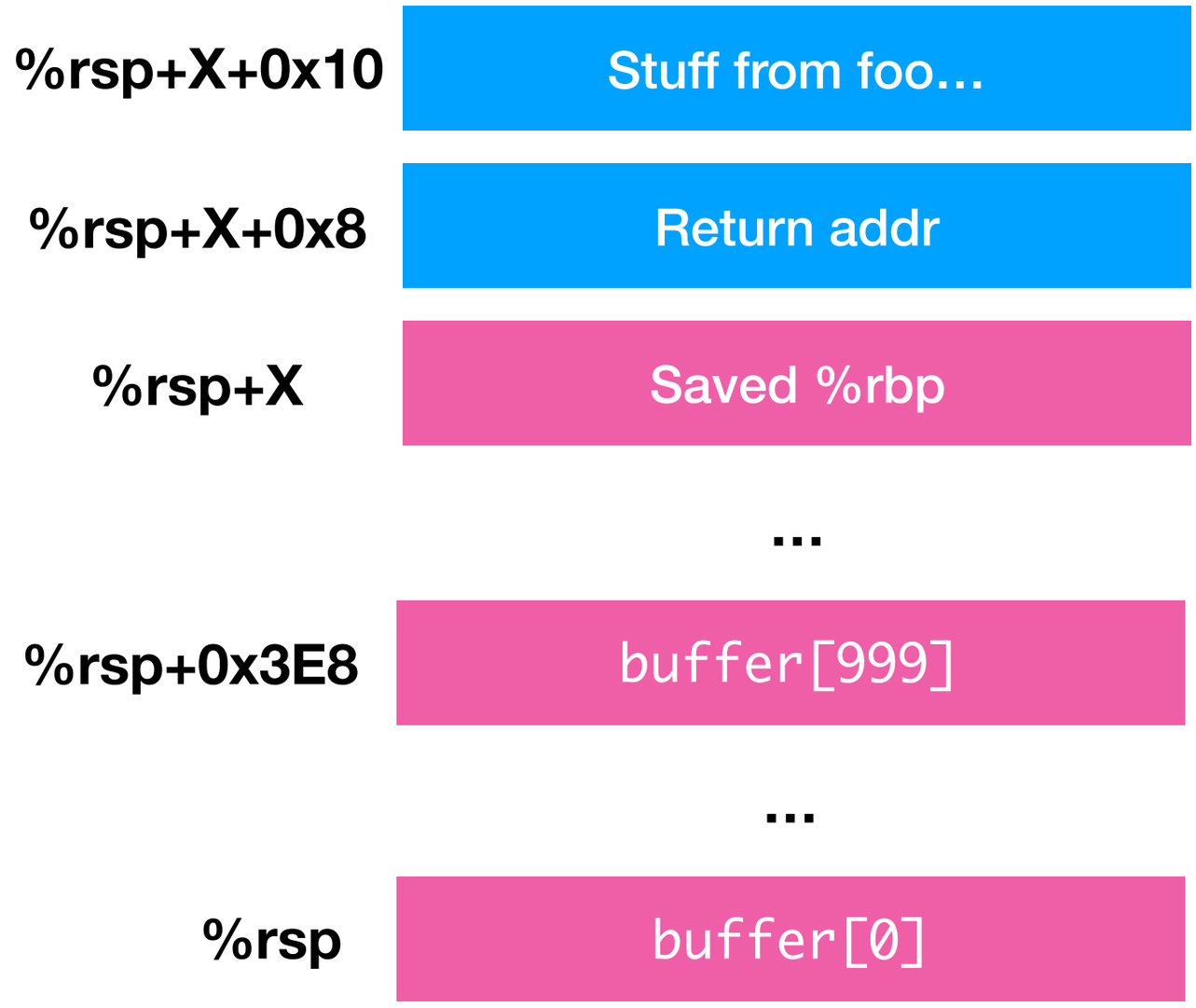
Return-Oriented-Programming

Way of "scavenging" through the program's binary code to trick it into doing **what you want**

Stack Canaries

Idea: use a **known value** that—if it gets smashed over—alerts you to presence

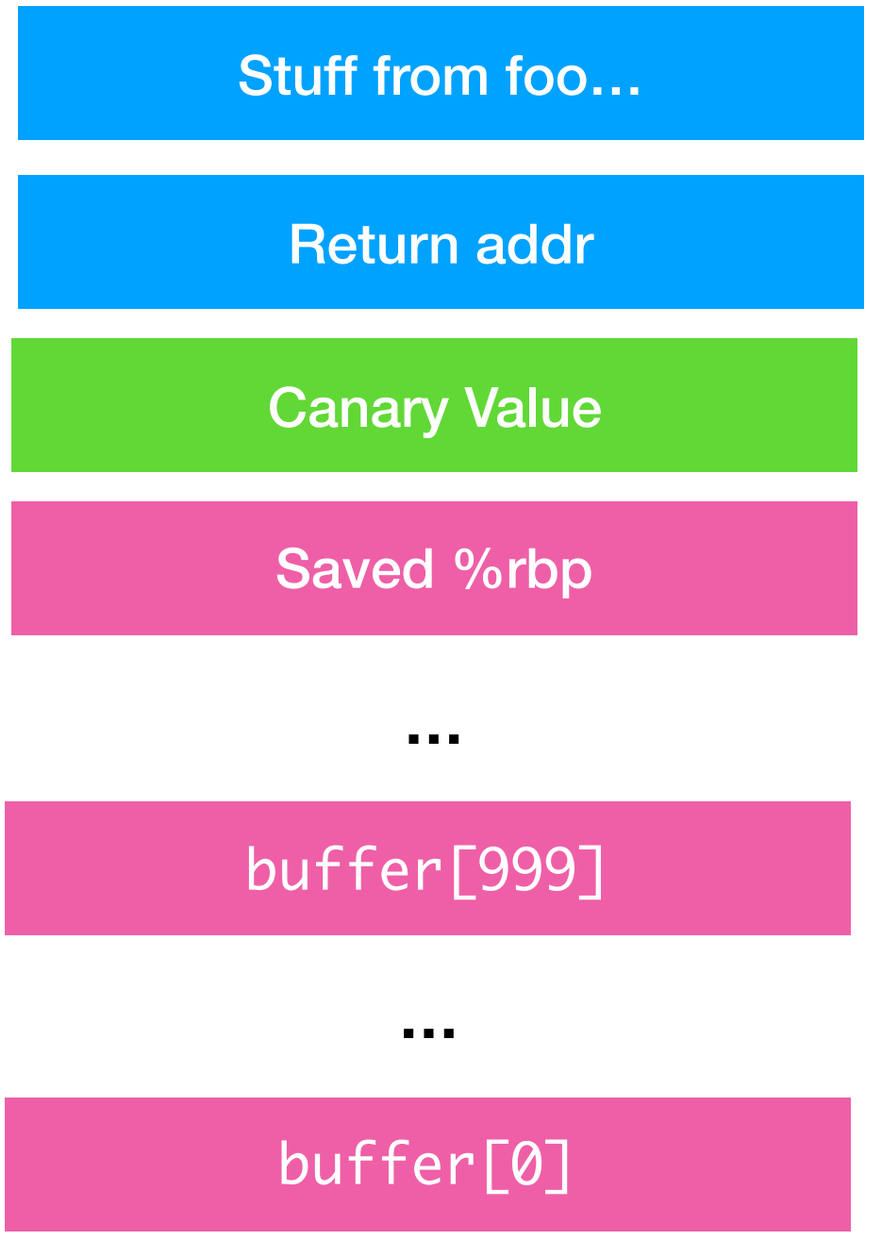
“Normal” execution



Canary Insertion

Compiler Inserts This Canary
(Upon function entry)

Before exiting, **check** canary to ensure same



Exercise: Compile with and *without* `-fno-stack-protector`

Defeating Canaries

Can still "skip past" canary occasionally

If attacks "owns" x, can set to skip canary

```
void foo(char *p, int x) {
    char buffer[100];
    strcpy(buffer+x,p);
}
```

Defeating Canaries

Even if stack overflows can't happen,
heap overflows can…

```
struct closure {
   int x;              closure *x =
   int y;                 malloc(sizeof(closure)));
   void (*f)(int);  strcpy(x->str,owned_string));
   char str[8];     x->f(42);
}
```

Exercise: Describe w/ partner how you would break **this** program

```
struct closure {
   int x;
   int y;
   void (*f)(int);
   char str[100];
}

int main(int argc, char **argv) {
  closure *x =
   malloc(sizeof(closure)));
  strcpy(x->str,argv[1]));
  x->f(42);
}
```

In practice, **many** of these defenses are employed, and they really do **pretty well**

However, the thinking here builds intuition for things we still see today…