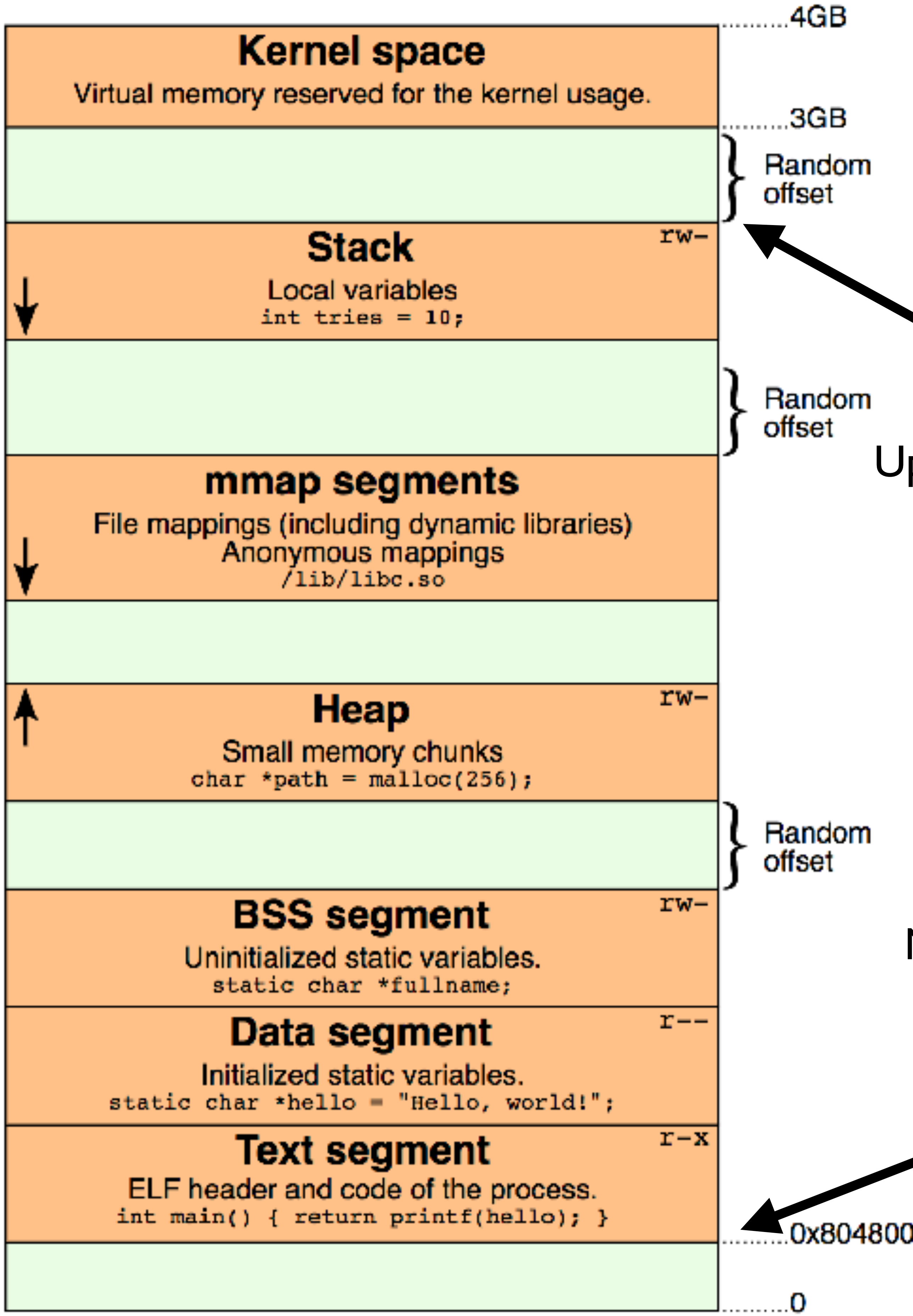
And review of last time..

Return-Oriented Programming


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

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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
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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]
```

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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7fb458fbe000-7fb458fc2000 rw-p 00000000 00:00 0
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7fb45919f000-7fb4591c4000 rw-p 00000000 00:00 0
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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!

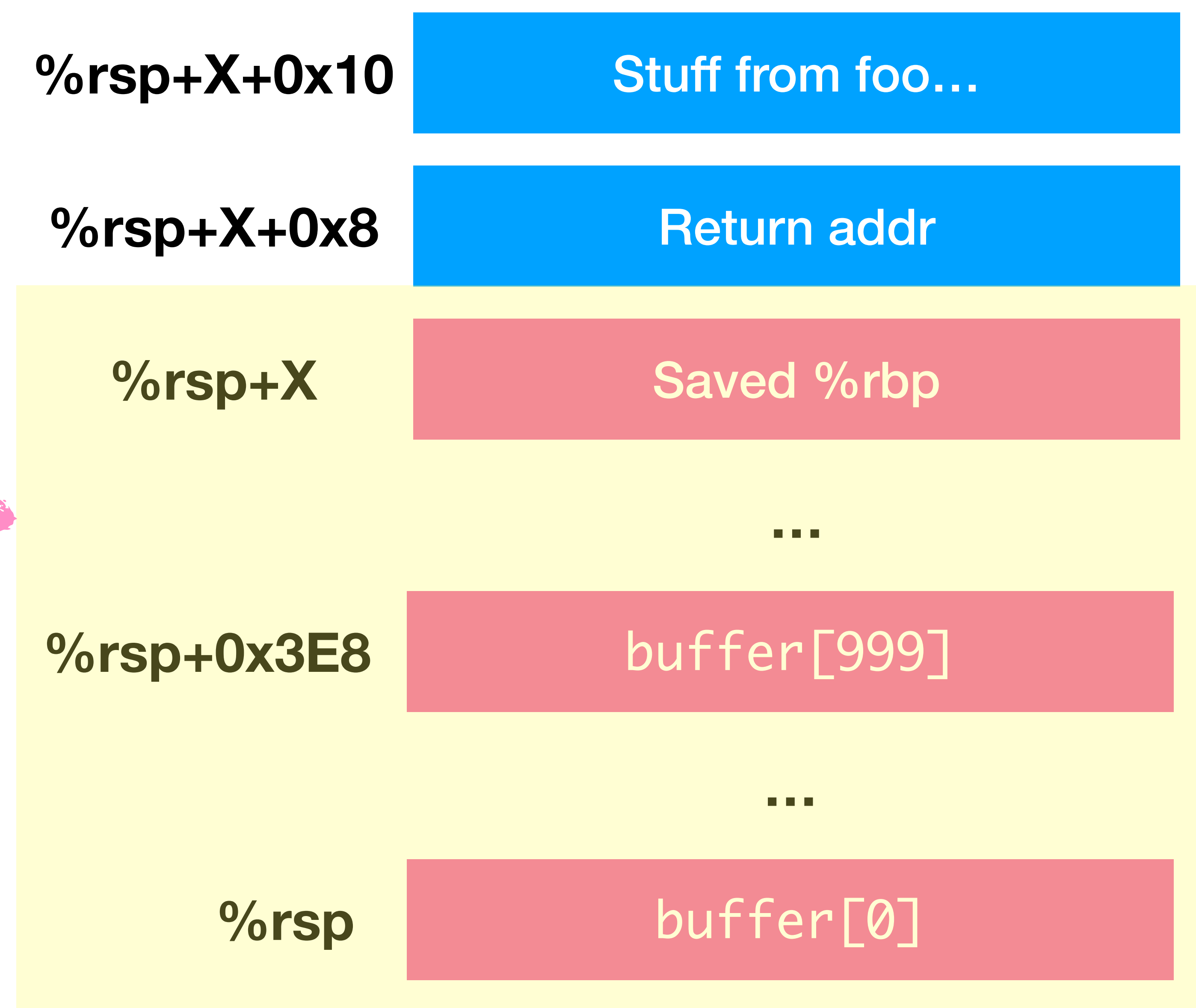
Coordinate w/ CPU

Defeating NX / W^X:

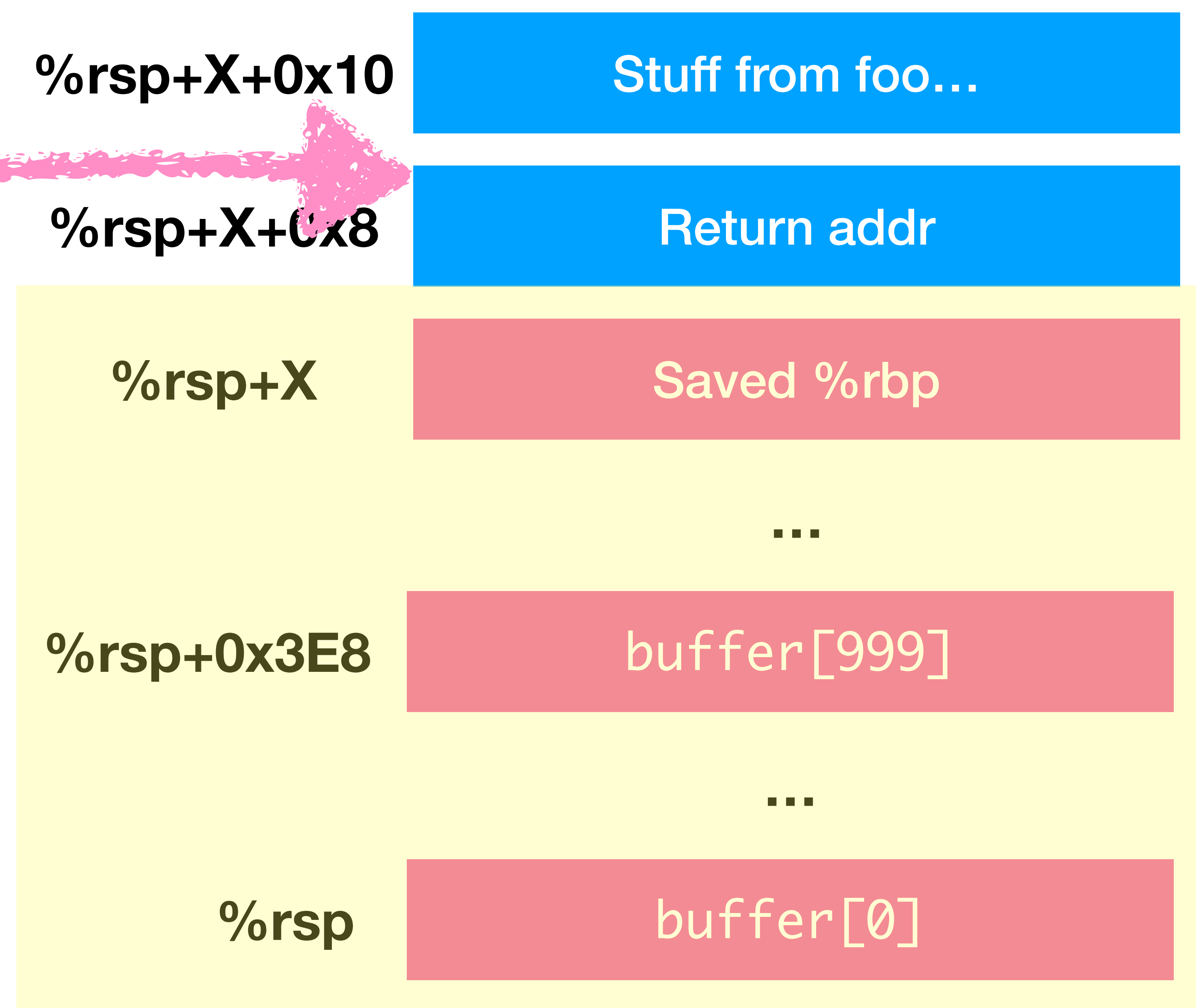
- Return-to-libc
- Return-oriented-programming

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**

Stack Canaries

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

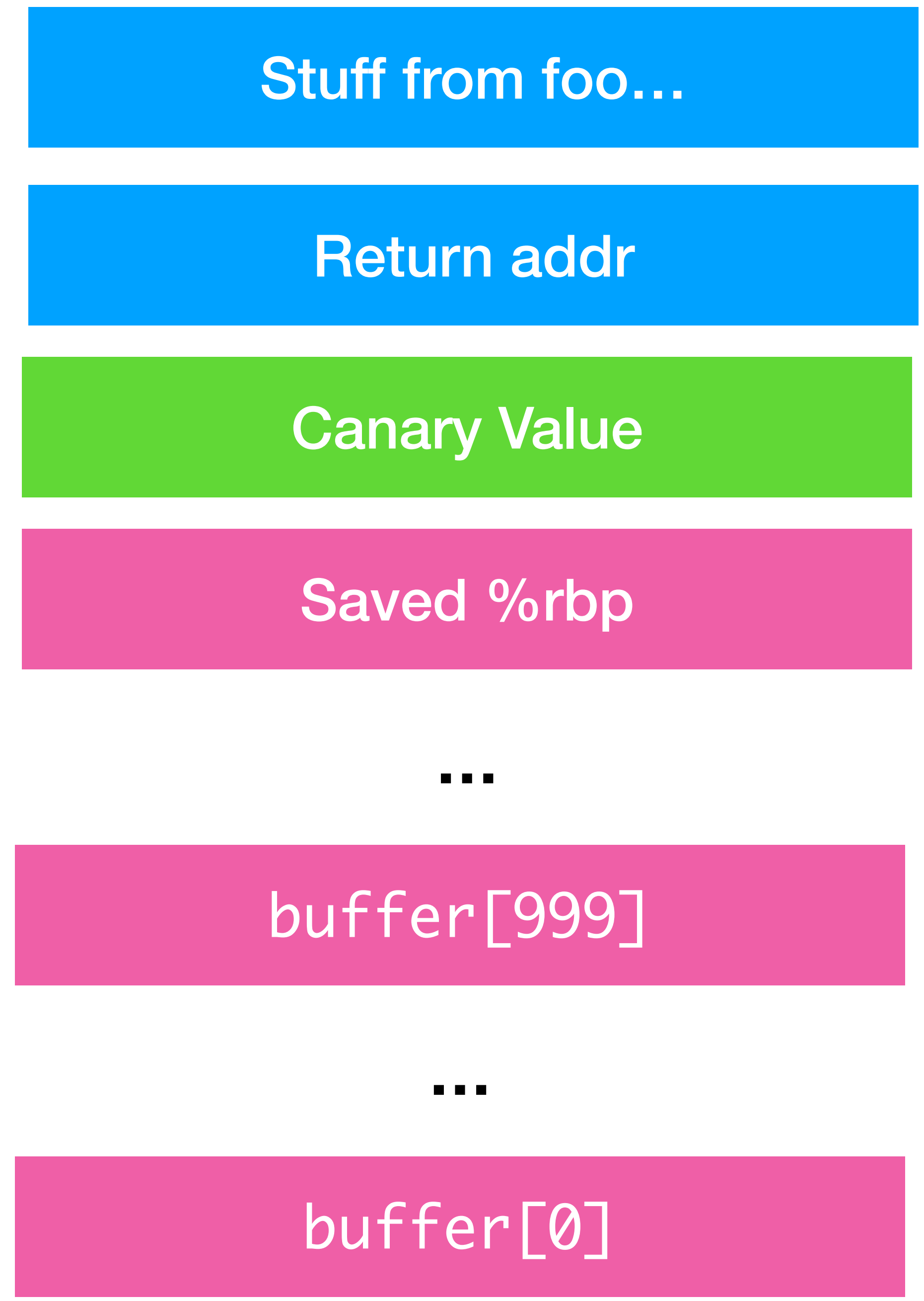
“Normal” execution

%rsp+X+0x10	Stuff from foo…
%rsp+X+0x8	Return addr
%rsp+X	Saved %rbp
	…
%rsp+0x3E8	`buffer[999]`
	…
%rsp	`buffer[0]`

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;
   char str[100];
   void (*f)(int);
}

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…

Return-Oriented-Programming

Way of “scavenging” through the program’s binary code to trick it into doing **what you want**

Say I wanted to do the following:

- Set %rax to 0
- Execute the “syscall” instruction

@Kris: Write this on board

Say I wanted to do the following:

- Set %rdi to 1 (arg for exit)
- Set %rax to 60 (exit)
- Execute the "syscall" instruction

If I have NX turned on, I can't just **inject** this into the program:

```
movq $1, %rdi
movq $60, %rax
syscall
```

What might I do instead?

What might I do instead?

I could try to see the program already has a function that does this already and use that.

(I.e., return-to-libc)

What might I do instead?

What if I can’t find a whole function that does this?

Normally… Function starts here and continues until (either) **ret**

```
0xF000: pushq %rbp
0xF002: movq %rsp, %rbp
0xF004: subq $12, %rsp
0xF007: mov %eax, -4(%rbp)
0xF009: mov %eax, -8(%rbp)
0xF00b: mov %eax, -12(%rbp)
0xF00e: add %eax, %eax
0xF010: compl %eax, %eax
0xF013: jmpg 0xF01d
0xF015: addq $12, %rsp
0xF018: leave
0xF019: mov $60, %rax
0xF01b: syscall
0xF01c: ret
0xF01d: addq $12, %rsp
0xF01f: leave
0xF020: ret
```

Normally… Function starts here and continues until (either) **ret**

But nothing stops me from jumping right **here**!

```
0xF000: pushq %rbp
0xF002: movq %rsp, %rbp
0xF004: subq $12, %rsp
0xF007: mov %eax, -4(%rbp)
0xF009: mov %eax, -8(%rbp)
0xF00b: mov %eax, -12(%rbp)
0xF00e: add %eax, %eax
0xF010: compl %eax, %eax
0xF013: jmpg 0xF01d
0xF015: addq $12, %rsp
0xF018: leave
0xF019: mov $60, %rax
0xF01b: syscall
0xF01c: ret
0xF01d: addq $12, %rsp
0xF01f: leave
0xF020: ret
```

So I could look through binary and find all places with **ret** and jump to any number of bytes before that.

Observation: can execute sequences of code that weren't **technically** in program to begin with

Observation: x86_64 instructions are **variable length**

Like words…

“the address”

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Like words…

“the ad**dress**”

Observation: x86_64 instructions are **variable length**

Like words…

“t**he ad**dress”

```
f7 c7 07 00 00 00       test $0x00000007 %edi
0f 95 45 c3             setnzb -61(%ebp)
```

Read starting at c7

```
c7 07 00 00 00 0f       movl $0x0f000000, (%edi)
95                      xchg %ebp, %eax
45                      inc %ebp
c3                      ret
```

Let's say that I want to call D01F and **then** F019

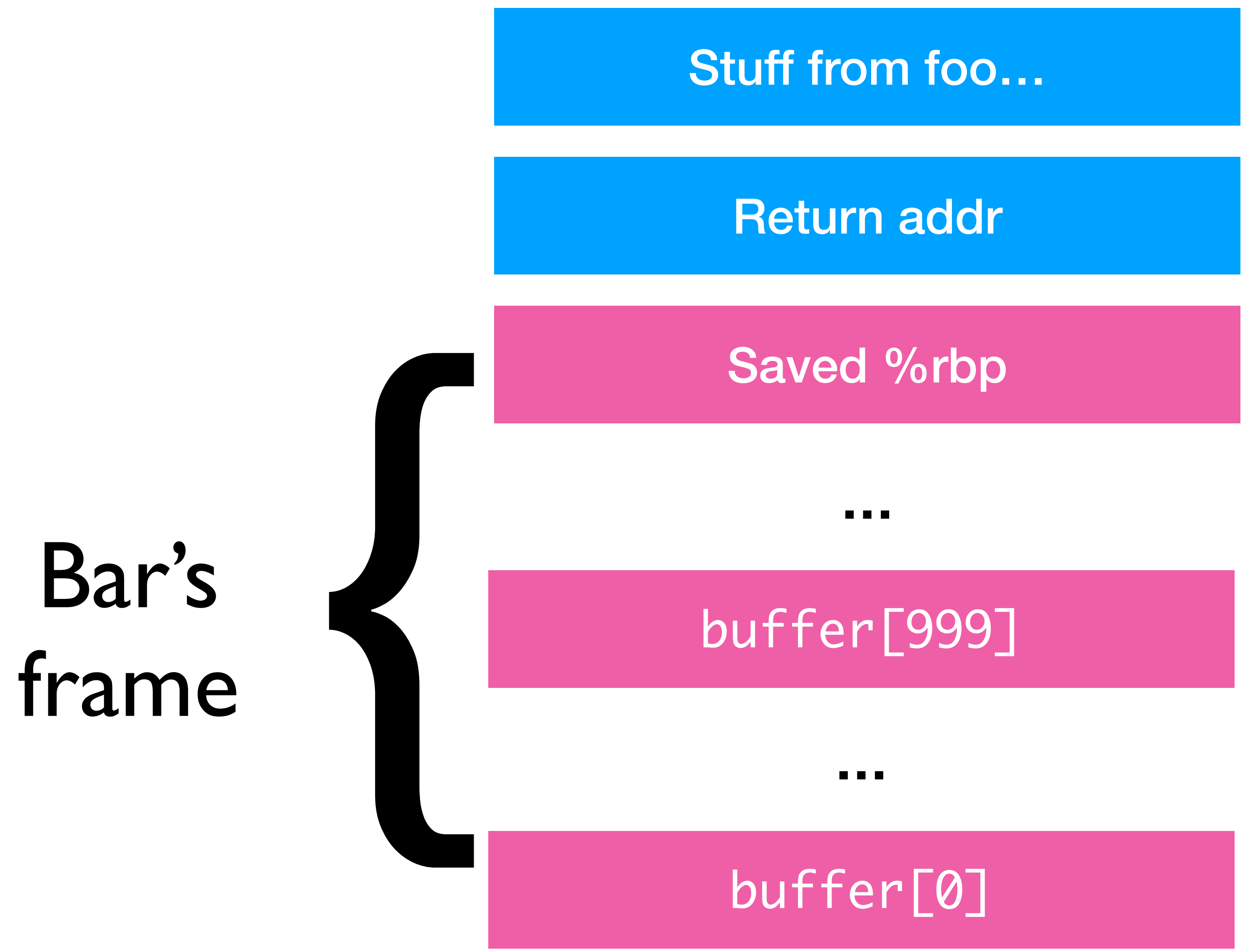
```
…
0xD01F: pop %rdi
0xD020: ret
…
```

```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```

To “set up” the attack we put 0xD01F in saved RIP

```
…
0xD01F: pop %rdi
0xD020: ret
…
```

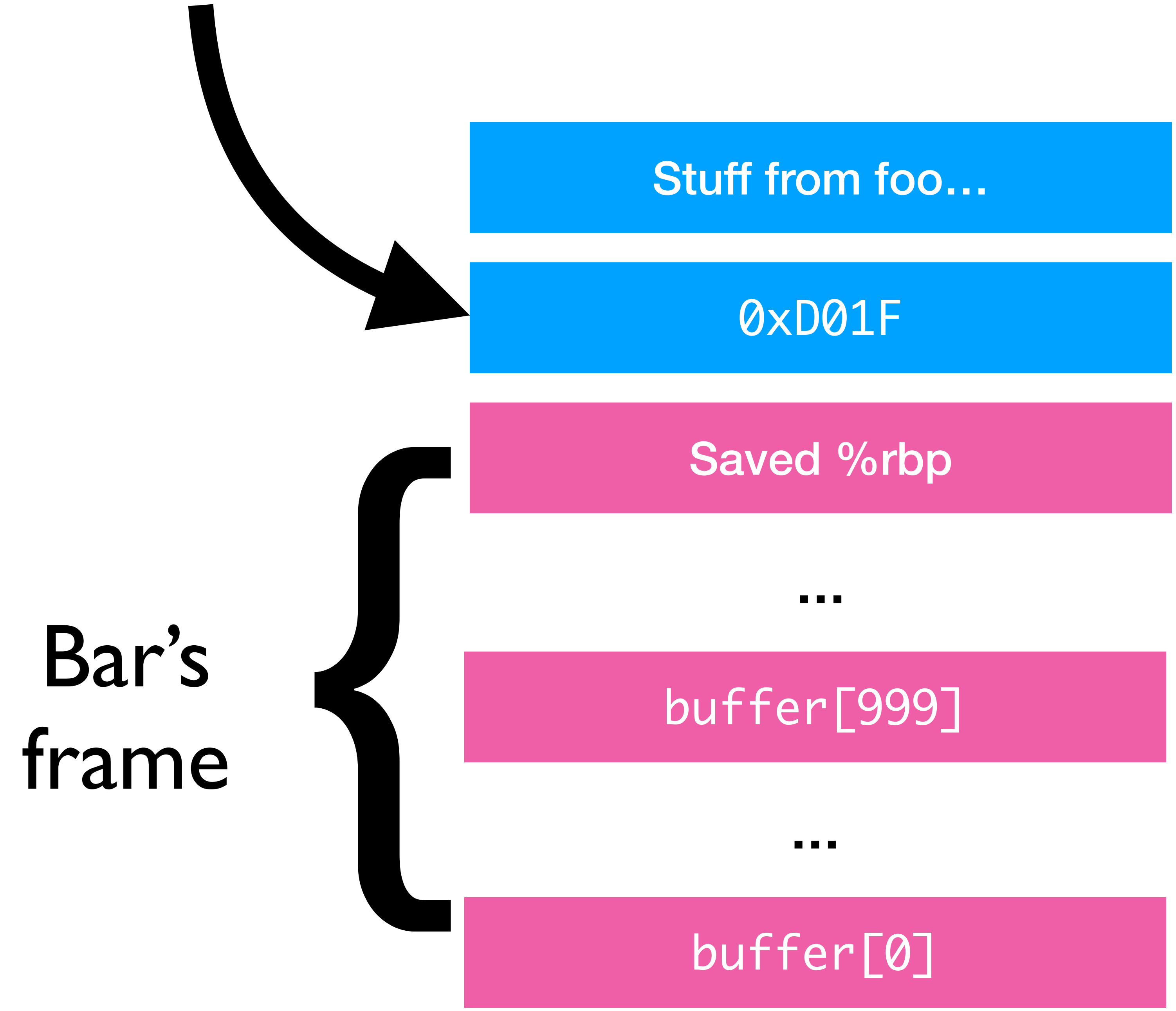
```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```



To “set up” the attack we put 0xD01F in saved RIP

```
...
0xD01F: pop %rdi
0xD020: ret
...
```

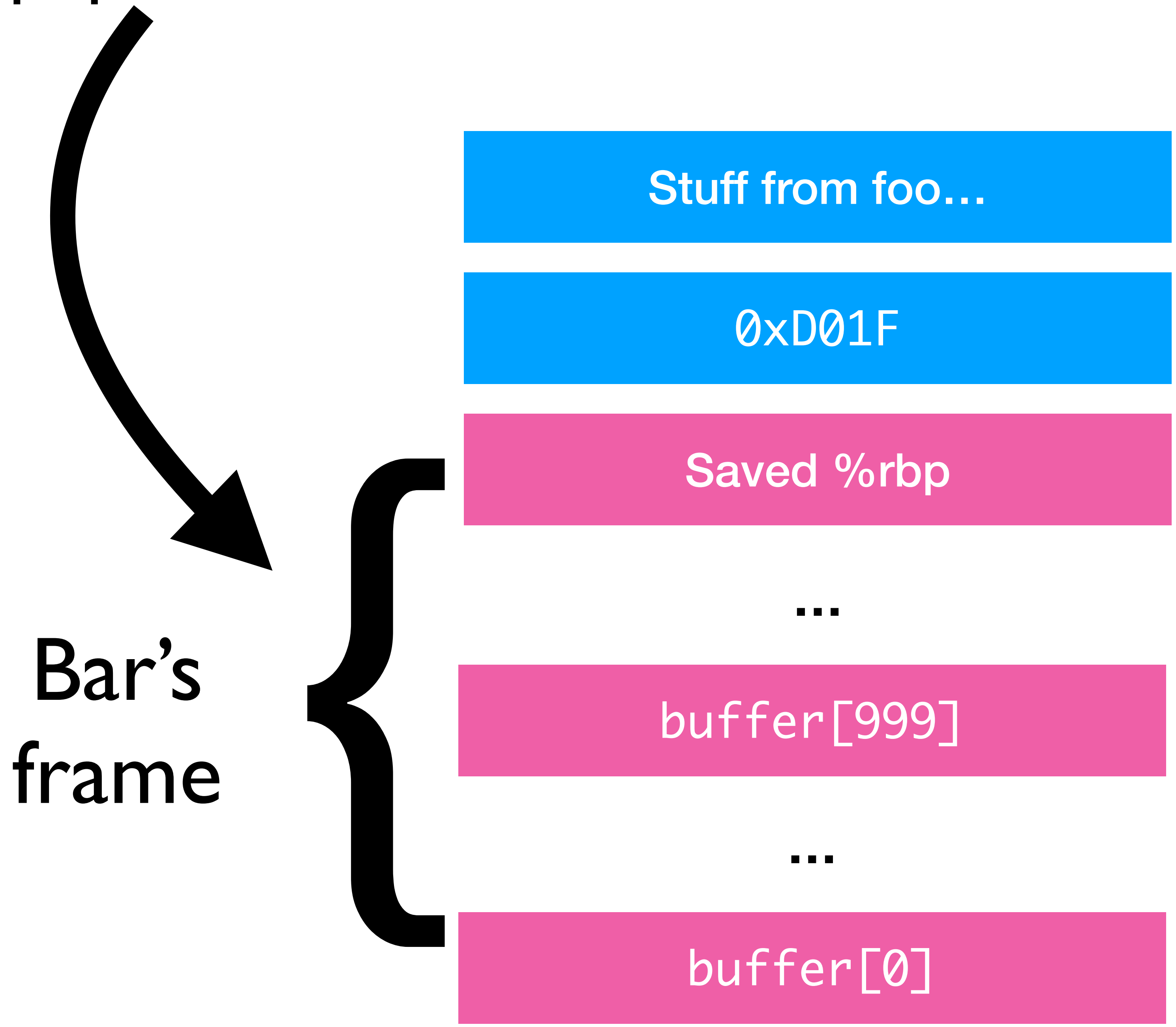
```
...
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
...
```



Before **foo** returns, it pops all of this stuff from the stack

```
…
0xD01F: pop %rdi
0xD020: ret
…
```

```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```



Now it goes here

Stuff from foo...

0xD01F

```
…
0xD01F: pop %rdi
0xD020: ret
…
```

```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```

(Rather than it’s caller **foo**)

Super Critical: pops 0xD01F from stack!

%rsp

Stuff from foo…

```
…
0xD01F: pop %rdi
0xD020: ret
…
```

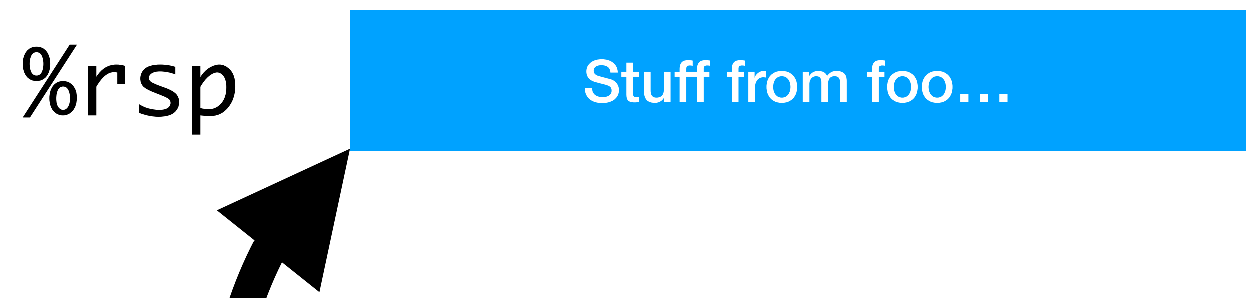
```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```

So **now** whatever's on stack will be popped into %rdi

(Which is previously stuff in **foo**'s stack)

```
…
0xD01F: pop %rdi
0xD020: ret
…
```

```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```



So if I want to put 1 in RDI, I put it **here**

(Which is previously stuff in **foo**'s frame)

%rsp

0x0000000000000001

```
…
0xD01F: pop %rdi
0xD020: ret
…
```

```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```

So if I want to put 1 in RDI, I put it **here**

(Which is previously stuff in **foo**'s frame)

%rsp ....

```
…
0xD01F: pop %rdi
0xD020: ret
…
```

Now, when the code hits **this** point, it's going to execute a return

```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```

Which will **yet again** go to whatever address is in %rsp

%rsp `0xF019`

```
…
0xD01F: pop %rdi
0xD020: ret
…
```

```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```

Critical observation: if %rsp is **now** `0xF019`, we'll get what we want

%rsp `0xF019`

```
…
0xD01F: pop %rdi
0xD020: ret
…
```

```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```

Critical observation: if %rsp is **now** `0xF019`, we'll get what we want

- Set %rdi to 1 (arg for exit)
- Set %rax to 60 (exit)
- Execute the "syscall" instruction

```
…
0xD01F: pop %rdi
0xD020: ret
…
```

```
…
0xF019: mov $60, %rax
0xF01B: syscall
0xF01C: ret
…
```

Critical observation: if %rsp is **now** `0xF019`, we'll get what we want

Observation: We can **chain** multiple sequences (that all end in **ret**) by setting up the stack right

Exercise

```
write(1, "Hello, world!", 13);

%rax = 1 %rdi = 1 %rsi = &"Hello, world", %rdx = 13

0xC110: pop %rsi
0xC112: ret

0x1029: pop %edx
0x102a: ret

0xD235: xchang %rdx, %rdi
0xD238: ret

0xF019: pop %eax
0xF01B: ret

0xB0FF: pop %rdx
0xB102: ret

0xCA2F: syscall
```

Assume this is 128

Saved %rbp

...

buffer[999]

...

buffer[0]

buffer = 0x40000