Welcome to the cybersecurity course

Fundamentally, security is about thinking hard about the way systems are designed

And then asking how weaknesses in that design allows you to launch an exploit

Along with your team

^

In this class, you’ll build an end-to-end system

Along the way, you’re going to be *learning* security

But…

The code I give you has **bugs**

During this course, we’ll learn how to exploit these bugs

And I’ll have you fix some of them

But I won’t tell you about all of them

At the end of the course, you’re going to break other teams’ code

The more you break, the more you’ll win, if you fix you get more points

We'll cover approximately these things…

- **Memory attacks**
- Crypto everyone should know
- Web attacks
- Social engineering and UI design for security
- Security foundations (info flow, full abstraction)
- Reverse engineering

We’ll be building an **encrypted chat** app

That can **store files on disc**

And has a **web-based** interface

You should know…

A bit of C/ASM

(File storage system written in this)

A high-level language (Python)

(Chat app written in this, using PyNaCl for crypto)

Be willing to pick up a bit of web programming

(We’ll be using sockets, a small bit of SQL, and maybe some JS)

A few logistical items to give you an idea of whether this is a good course for you…

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This course will cover security across the software stack, which will introduce some other topics by proxy

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A few logistical items to give you an idea of whether this is a good course for you…

This course will cover security across the software stack, which will introduce some other topics by proxy

I expect it will be **hard**

Expectation: you will be able to pick things up **without us going over them in class** explicitly

Projects

3 Projects followed by “break it” phase

Each project has two components:

Individual

Group

Projects

3 Projects followed by “break it” phase

Each project has two components:

Individual	Group
60%	40%

Projects

No extensions on these…

Exams

Two “take home” exams

Little over ~1/3 and ~2/3 into course

You can take up to eight hours on these, and they are open everything

Grades

Since I expect the course to be challenging, there **may** be a curve *at the end*

I'll let you know averages on exams


HOUSE

Memory-Based Attacks

Upshot

Just write in Java / Rust / Python / …

Basically *anything except C/C++!!*

If you write in these languages, you'll be automatically
immune to most of these attacks

Assembly Review

By which I mean x86-64 assembly...

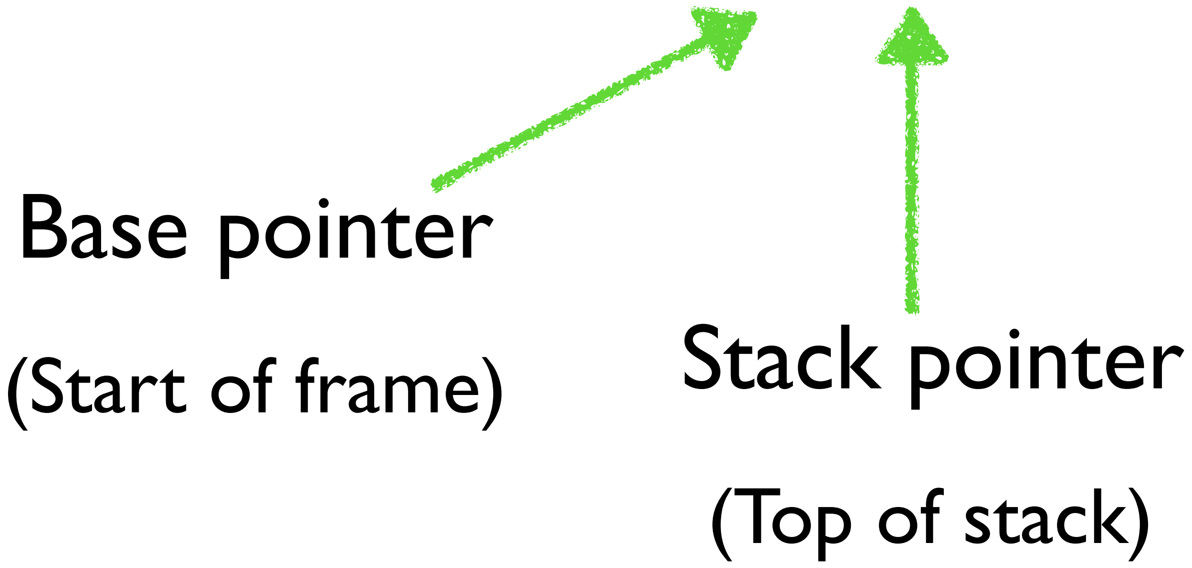
Note: you won't have to write significant amounts of assembly for this course, but you will need to be able to read small pieces of it and figure out what it's doing...

Registers

Originally, 8-bit registers: al, bl, cl, dl

Traditionally, x86 architectures only had **four** 16-bit general purpose registers: ax, bx, cx, dx

Also other registers: bp, sp, di, si



Base pointer

(Start of frame)

Stack pointer

(Top of stack)

Originally, 8-bit registers: al, bl, cl, dl

Traditionally, x86 architectures only had **four**
16-bit general purpose registers: ax, bx, cx, dx

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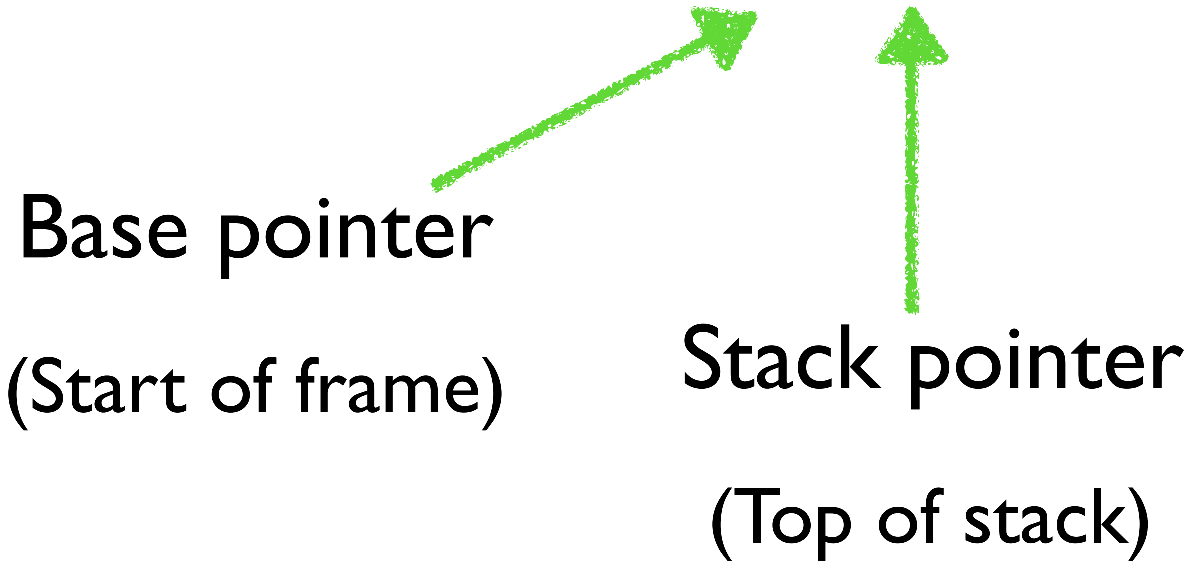


Base pointer

(Start of frame)

Stack pointer

(Top of stack)

IP: instruction pointer

Points at current instruction,
incremented after each instruction

FLAGS: holds flags

Set on subtraction, comparison, etc..

Traditionally, x86 architectures only had **four** 16-bit general purpose registers: ax, bx, cx, dx

Also other registers: bp, sp, di, si

As time progressed, also added 32-bit registers: eax, ebx, ecx, edx

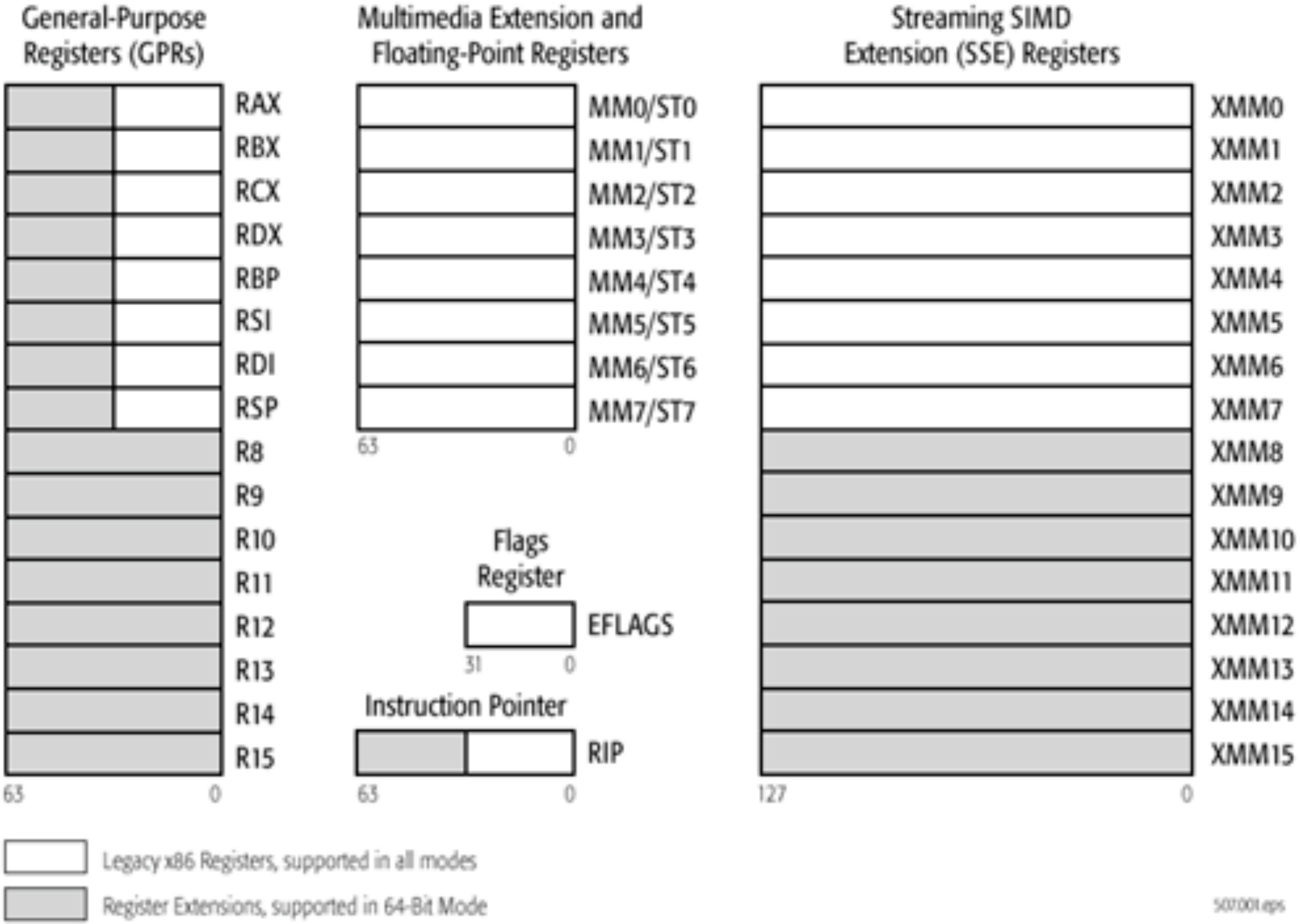
In past few years, 64-bit registers: rax, rbx, rcx, rdx

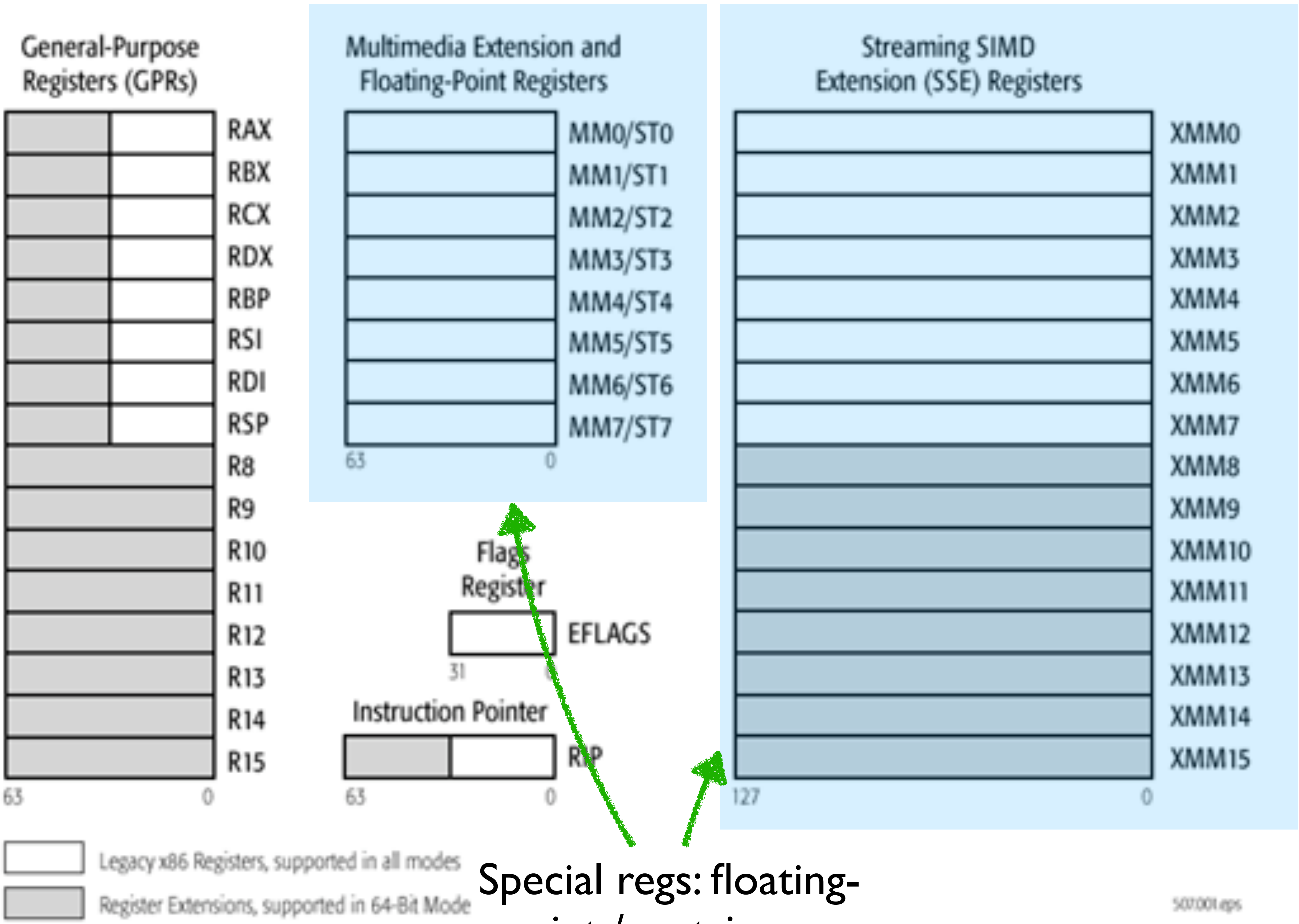
(Also 64-bit versions: rip, etc..)

We'll pretty much exclusively use 64-bit registers!

Note RAX is an **extension** of EAX

If you change EAX, you change lower 32 bits of RAX


General-Purpose Registers (GPRs)
RAX
RBX
RCX
RDX
RBP
RSI
RDI
RSP
R8
R9
R10
R11
R12
R13
R14
R15
63
0
Multimedia Extension and Floating-Point Registers
MM0/ST0
MM1/ST1
MM2/ST2
MM3/ST3
MM4/ST4
MM5/ST5
MM6/ST6
MM7/ST7
63
0
Flags Register
EFLAGS
31
0
Instruction Pointer
RIP
63
0
Streaming SIMD Extension (SSE) Registers
XMM0
XMM1
XMM2
XMM3
XMM4
XMM5
XMM6
XMM7
XMM8
XMM9
XMM10
XMM11
XMM12
XMM13
XMM14
XMM15
127
0
Legacy x86 Registers, supported in all modes
Register Extensions, supported in 64-Bit Mode
507001.eps



Special regs: floating-point / matrix ops

To represent `0x1234567890abcdef`

12	34	56	78	90	ab	cd	ef

Most Significant Byte

Least Significant Byte

x86 is a **little-endian** architecture

If an n-byte value is stored at addresses a to a+(n-1) in memory,
byte a will hold the **least significant byte**

`0x1234567890abcdef`

Exercise with partner

Instructions

Binary code is made up of giant sequences of “instructions”

Modern Intel / AMD chip has hundreds of them, some very complex

Moving memory around   Arithmetic   Branch / If

Matrix operations   Atomic-Instructions

Transactional memory instructions

Encoded as binary (as you may have seen from hardware-design course)

We (humans) write in a format named "assembly"

Confusingly: two types of assembly

AT&T	Intel
`mov 5, %rax`	`mov rax, 5`

I will basically always use AT&T

(Since that's what's used in GNU toolchain)

Several **addressing modes**

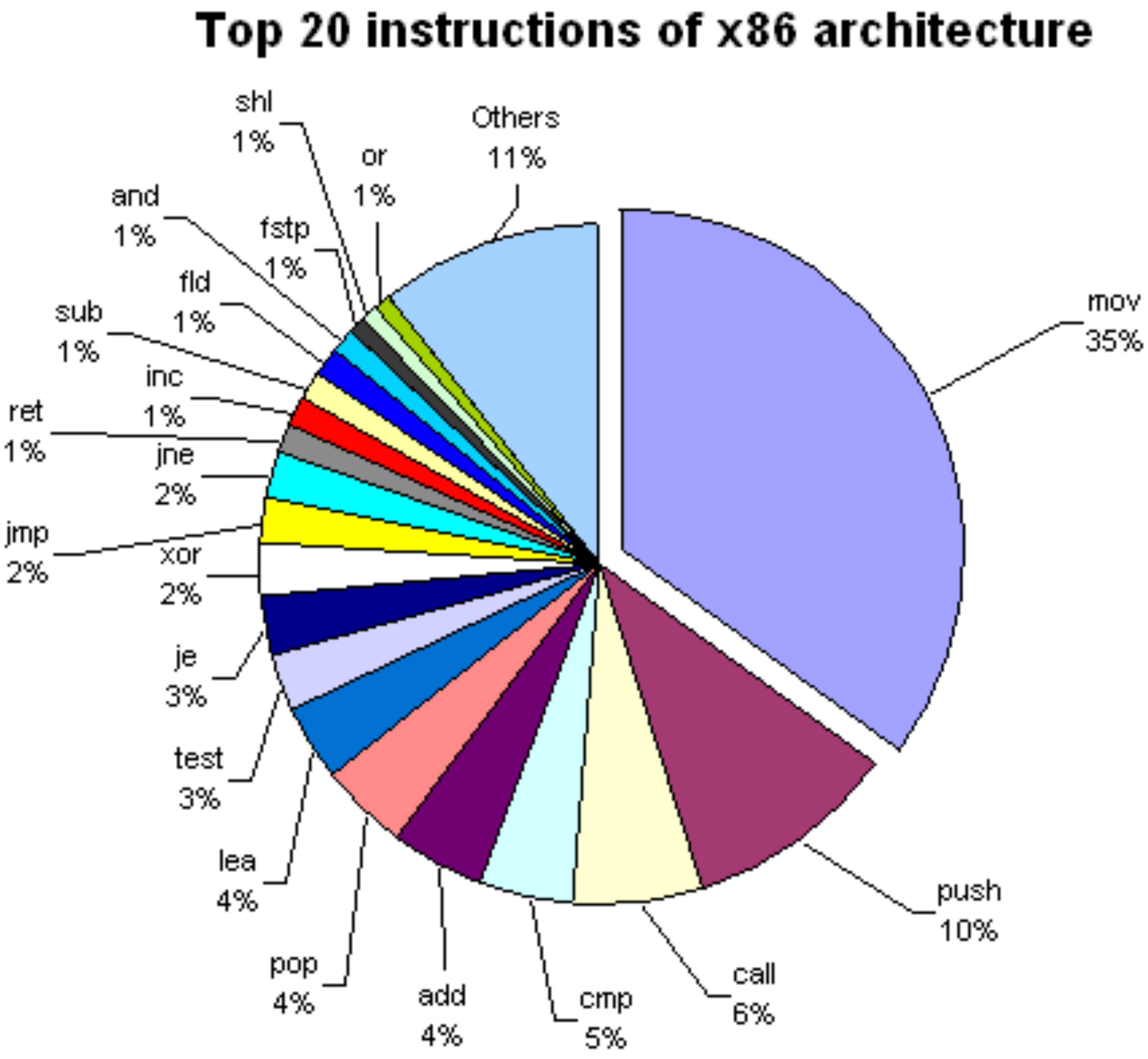
“Move the value from register rax into the register rbx”

Opcode name

Destination

```
mov  %rax, %rbx
```

Source



Plurality of instructions are **mov**s

Then **push**

Then **call**

Memory: a **giant chunk of bytes**

You can read from it and write to it in 1/2/4/8/16-byte increments

```
mov  (%rax), %rbx
```

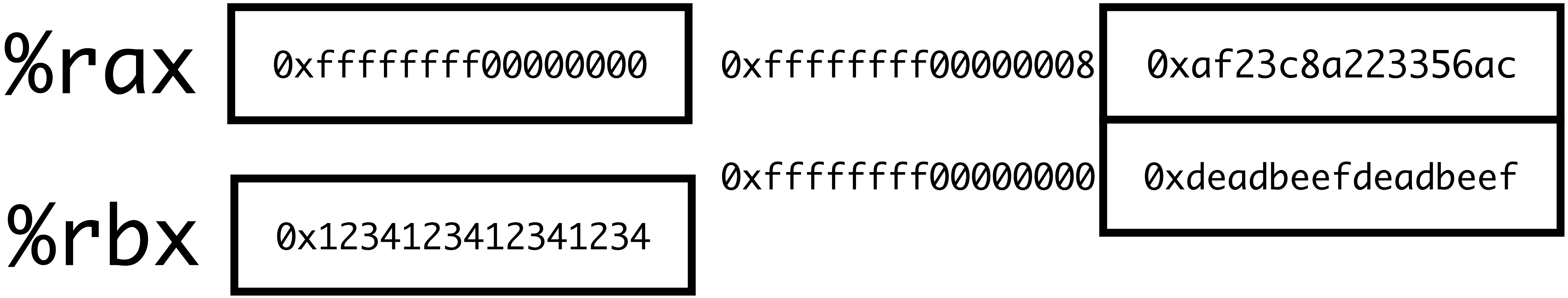
“Move the value **at address** %rax into register %rbx”

Opcode name

Destination

```
mov  (%rax), %rbx
```

Source



%rax

0xffffffff00000000

%rbx

0x1234123412341234

0xffffffff00000008

0xaf23c8a223356ac

0xffffffff00000000

0xdeadbeefdeadbeef

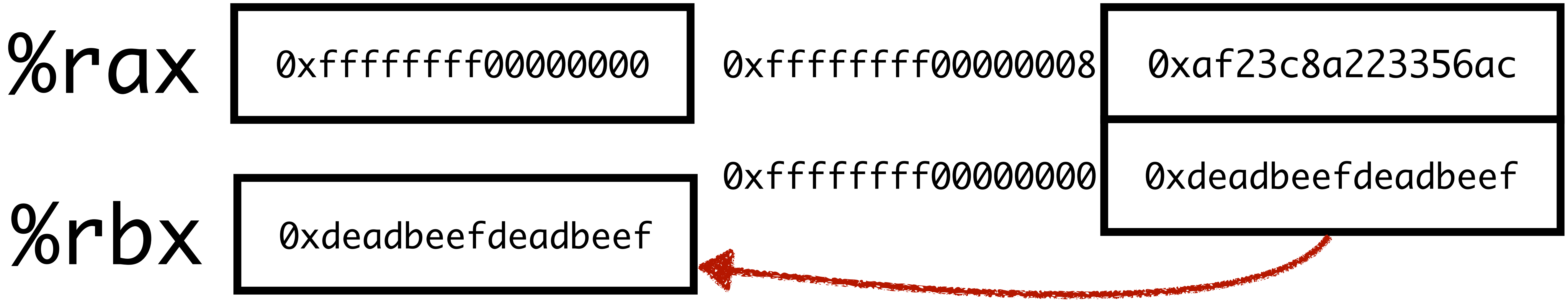
“Move the value **at address** %rax into register %rbx”

Opcode name

Destination

`mov (%rax), %rbx`

Source



%rax `0xffffffff00000000`

%rbx `0xdeadbeefdeadbeef`

`0xffffffff00000008`	`0xaf23c8a223356ac`
`0xffffffff00000000`	`0xdeadbeefdeadbeef`

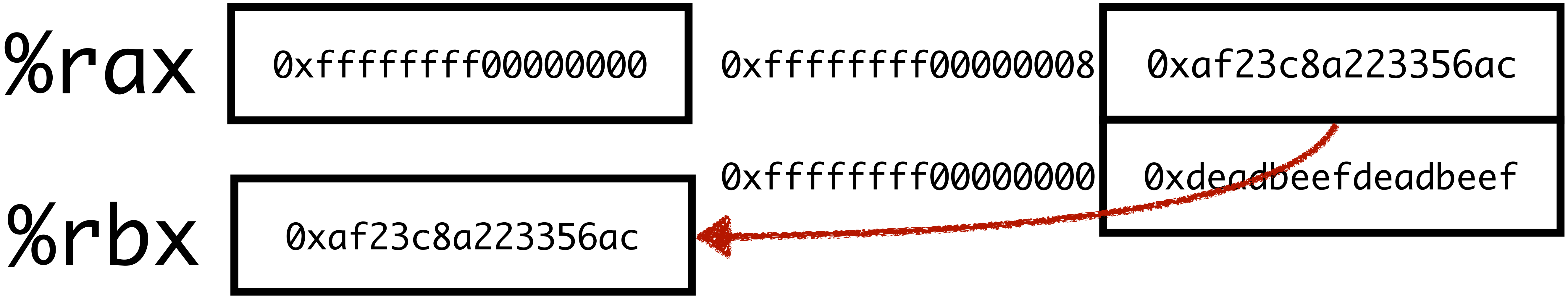
“Move the value **at address** %rax+8 into register %rbx”

Opcode name

Destination

```
mov  8(%rax), %rbx
```

Source



%rax

0xffffffff00000000

%rbx

0xaf23c8a223356ac

0xffffffff00000008

0xaf23c8a223356ac

0xffffffff00000000

0xdeadbeefdeadbeef

A few other more complicated ones that
allow you to add registers, offsets, etc…

Different instructions allow different addressing-modes

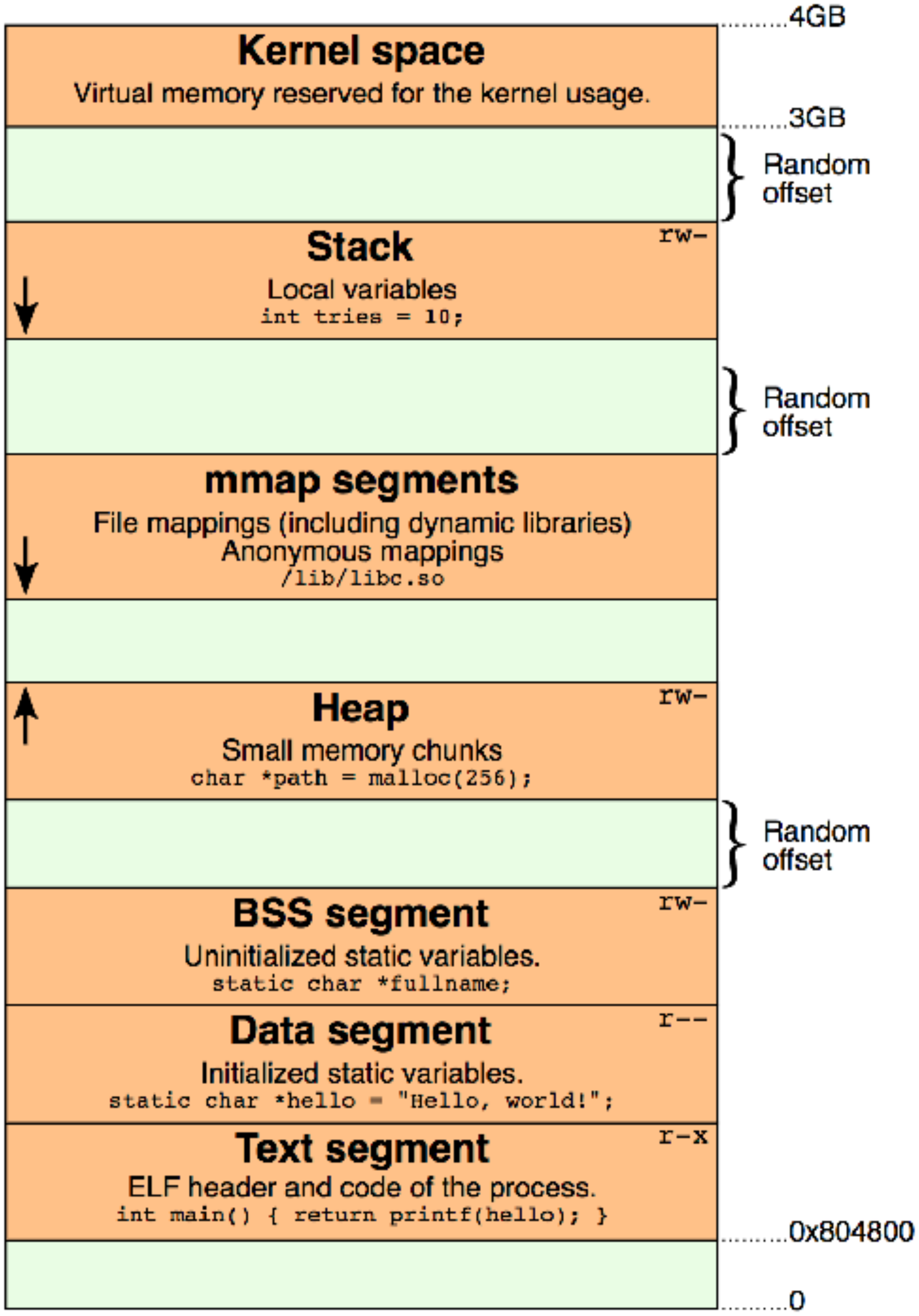
Memory is divided into different regions

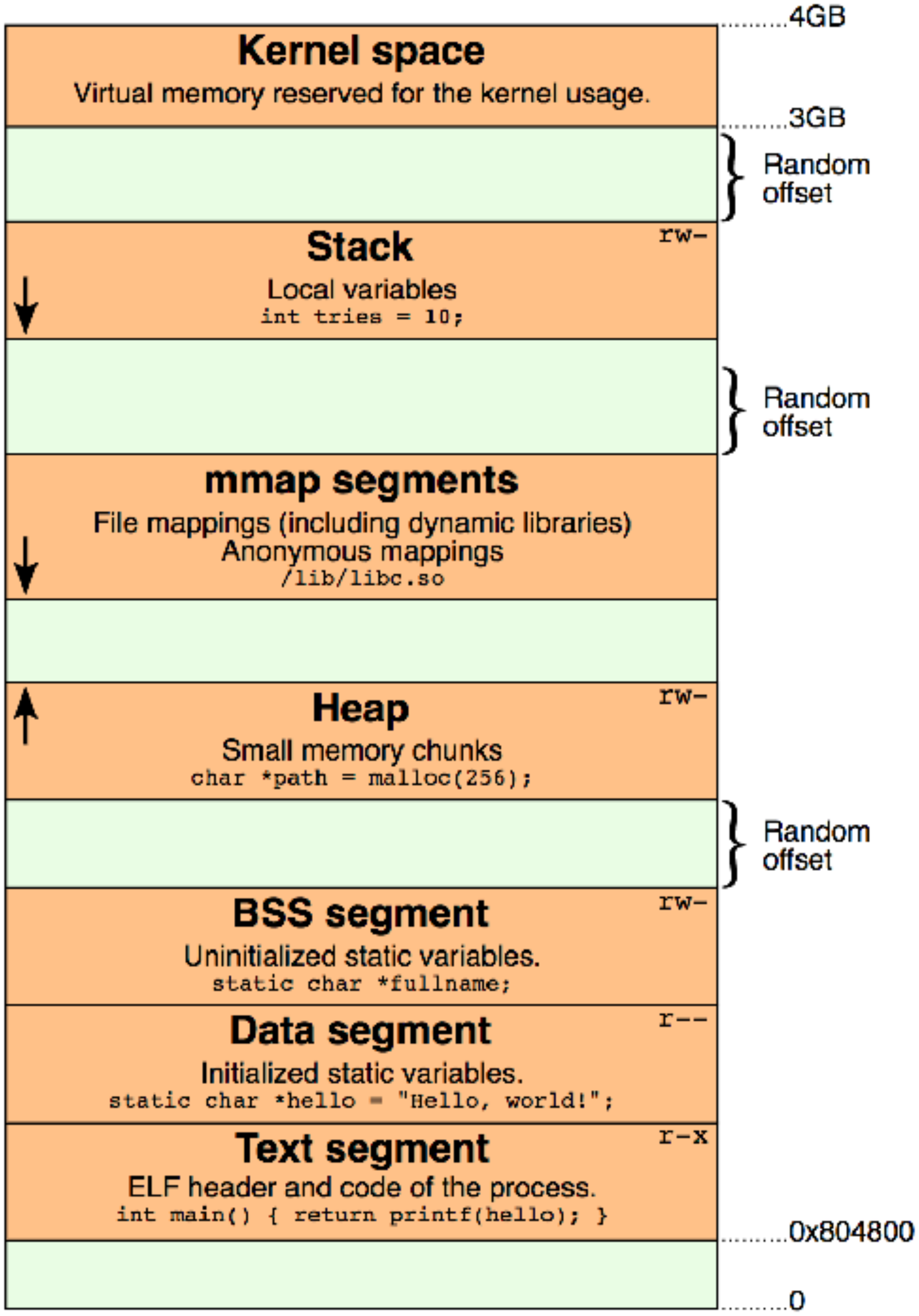
Name a few?

OS separates these into different **segments**

Kernel memory

Your OS uses it

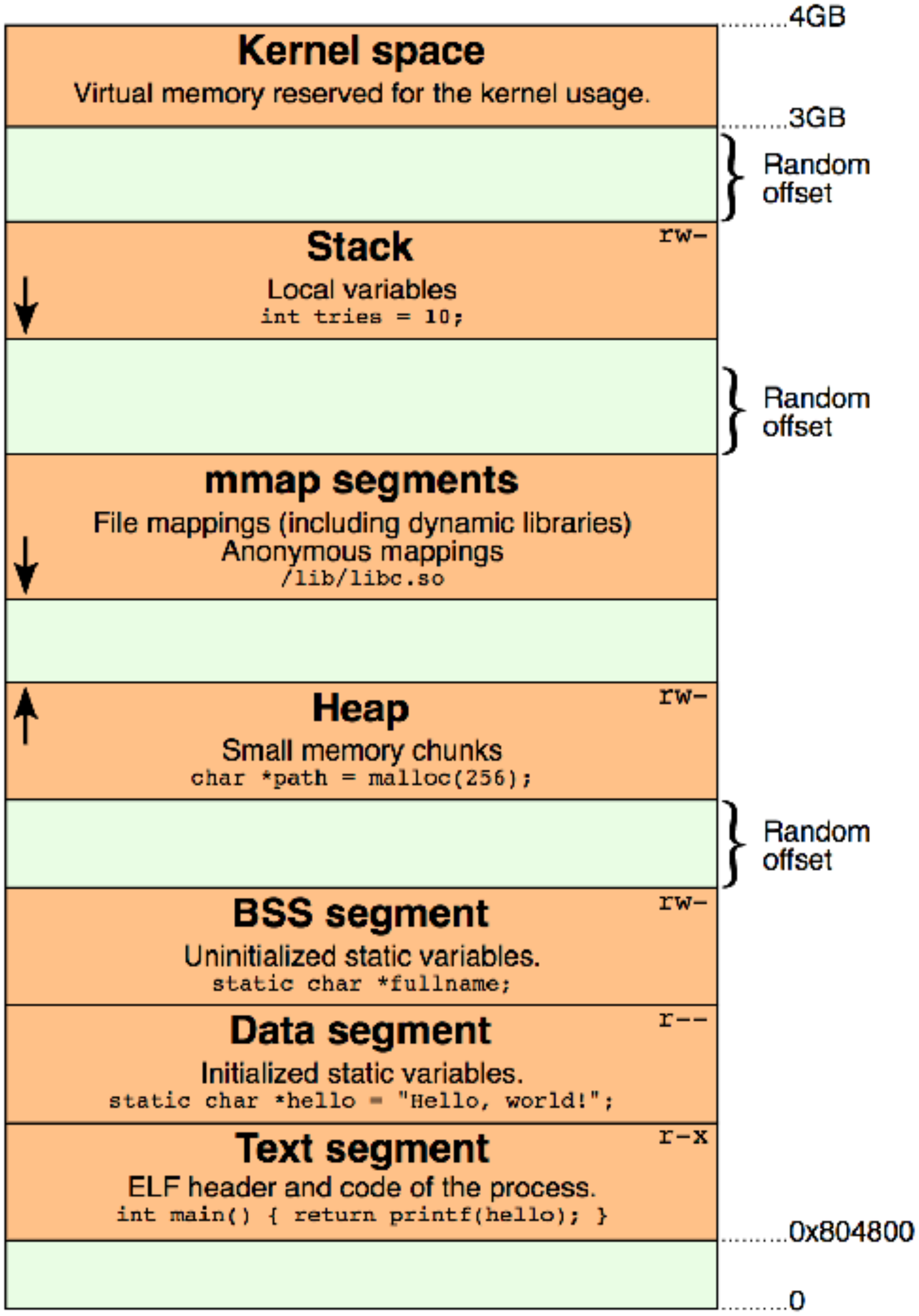




Stack: push / pop

Very important:

The stack grows **down**



Stack: push / pop

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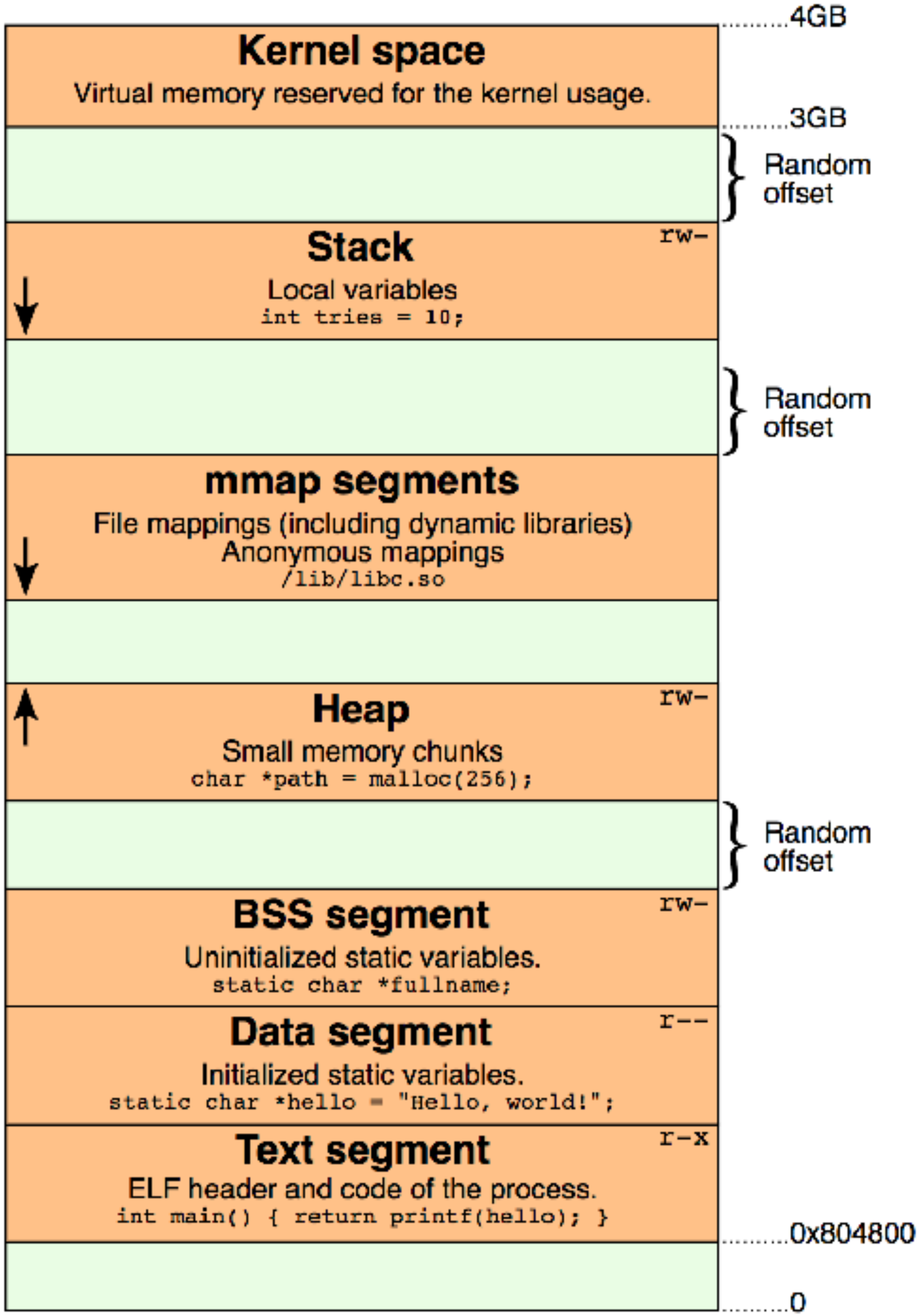
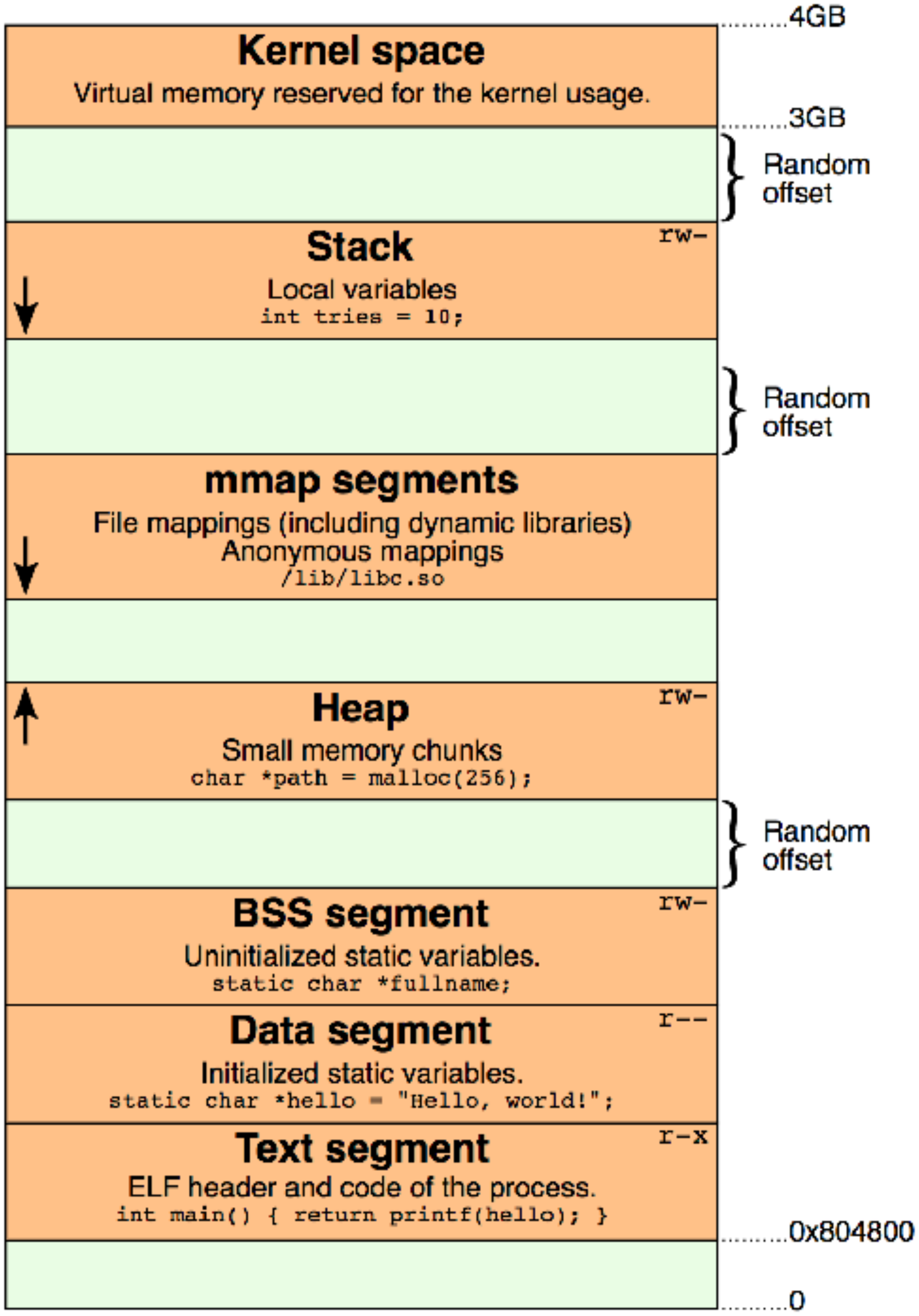


mmap segments

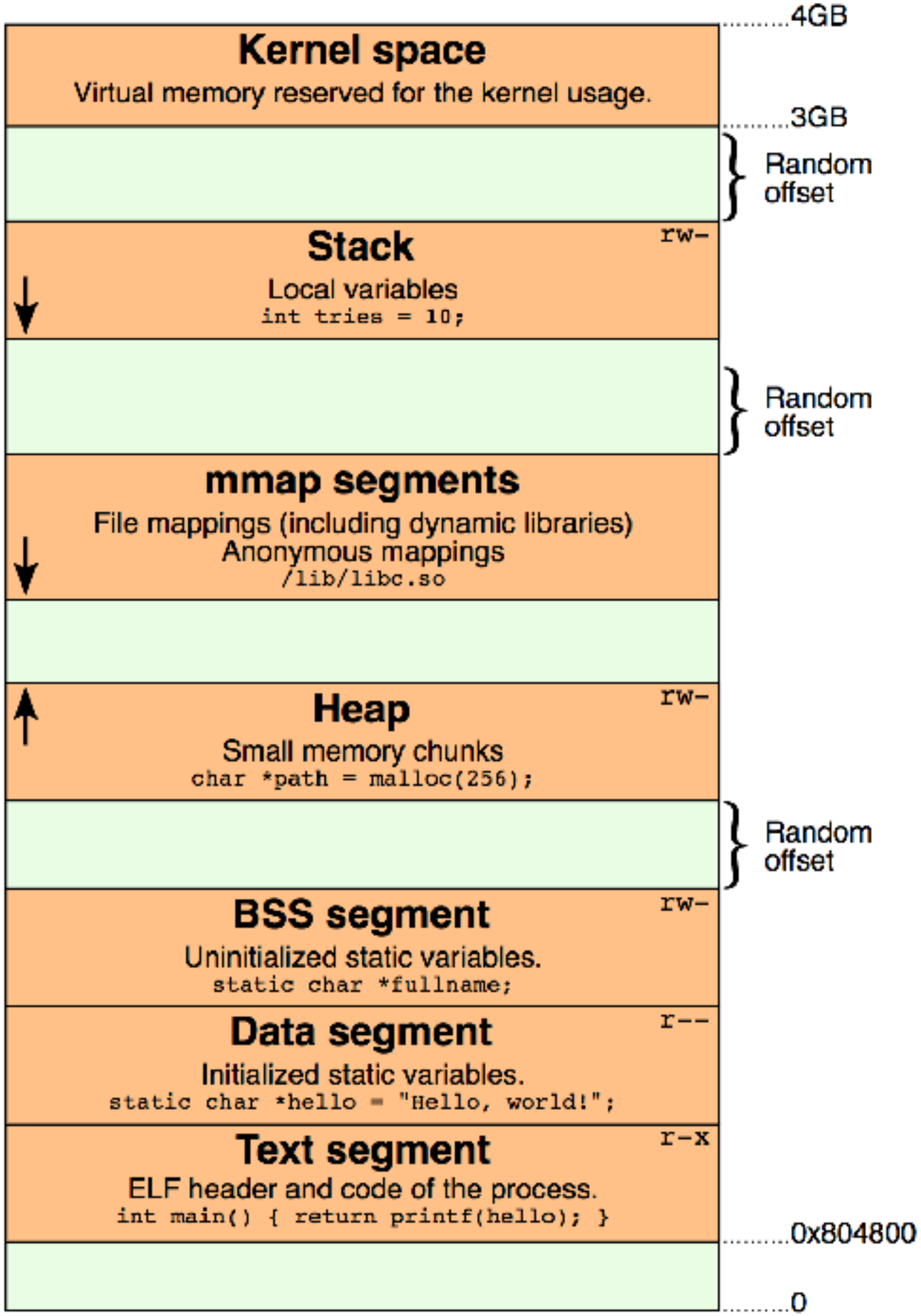
Allows you to **map** a file to memory



Heap: dynamic allocation

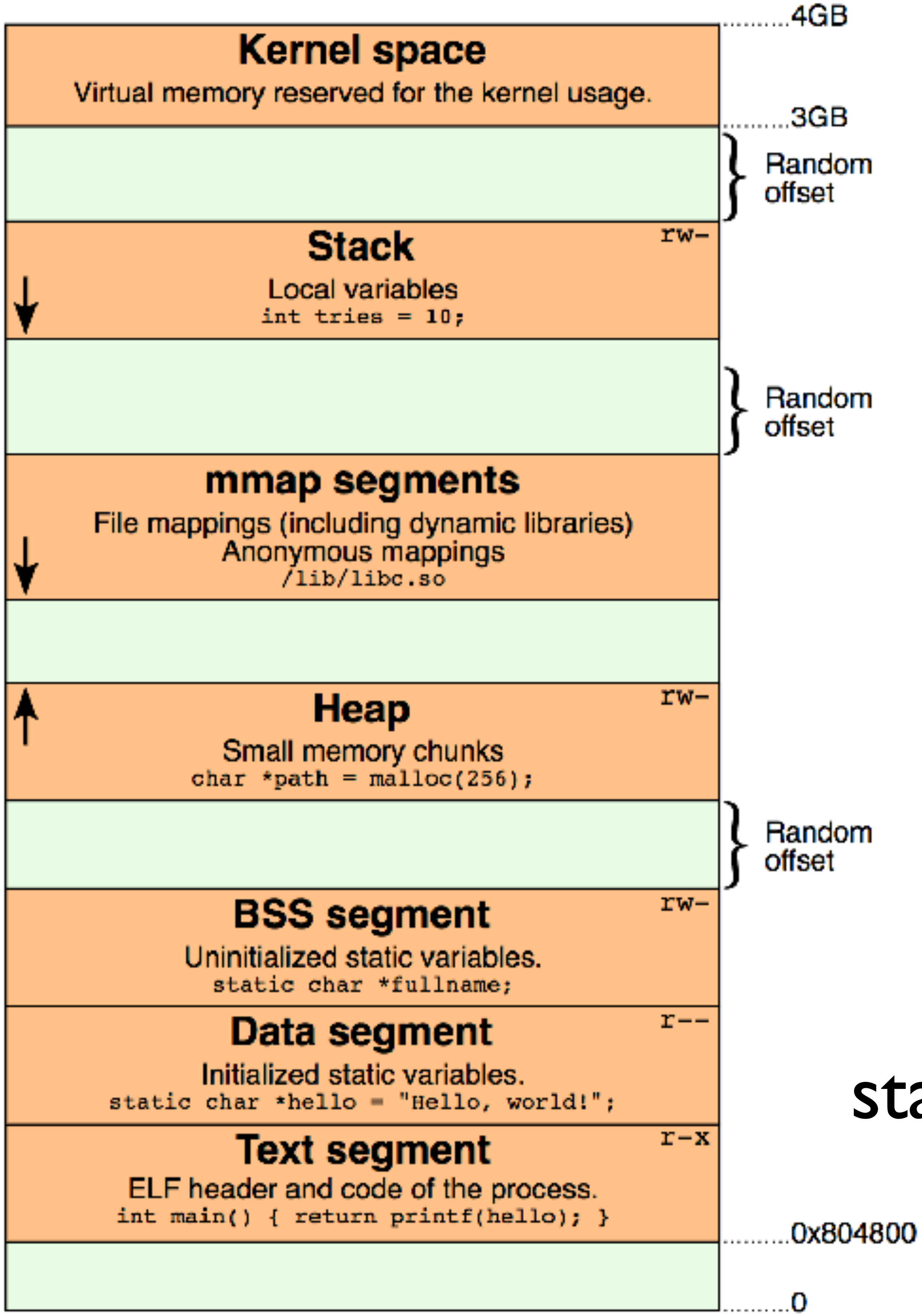
C++: New / delete

C: Malloc / free

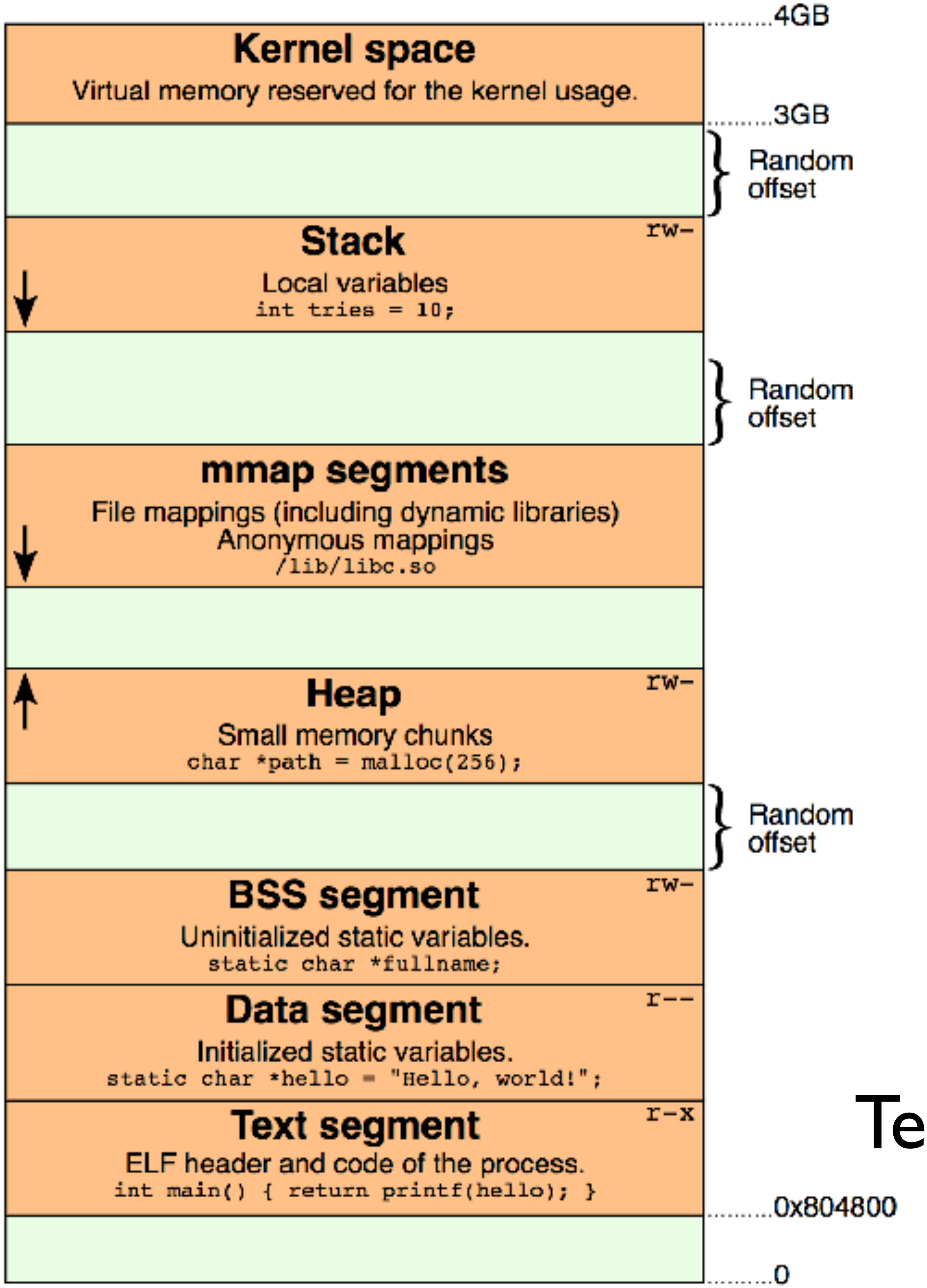


```
int tries = 10;
/lib/libc.so
char *path = malloc(256);
static char *fullname;
static char *hello = "Hello, world!";
int main() { return printf(hello); }
```

BSS: Uninitialized static vars (globals)

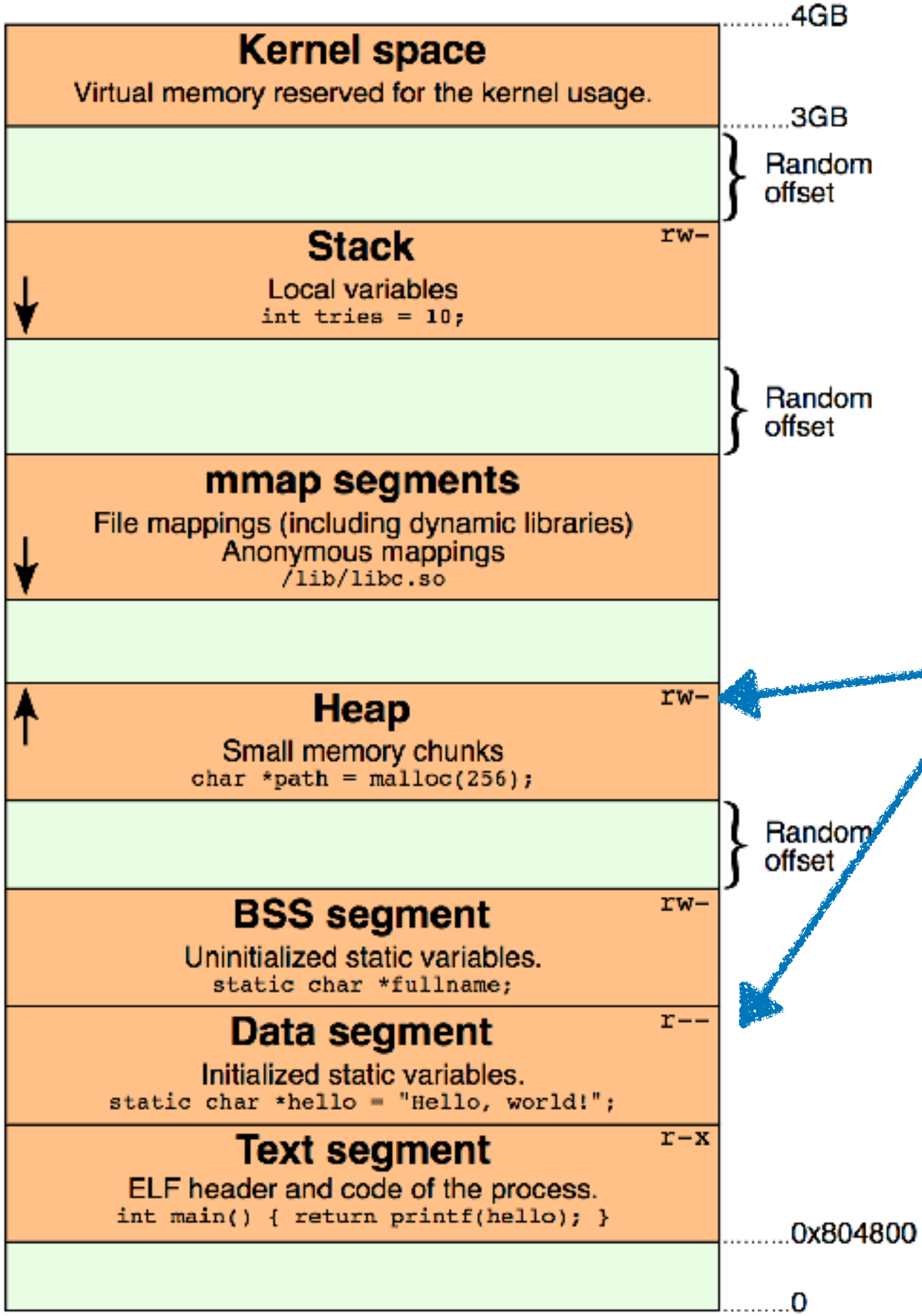


Data segment: initialized statics—e.g., constant strings

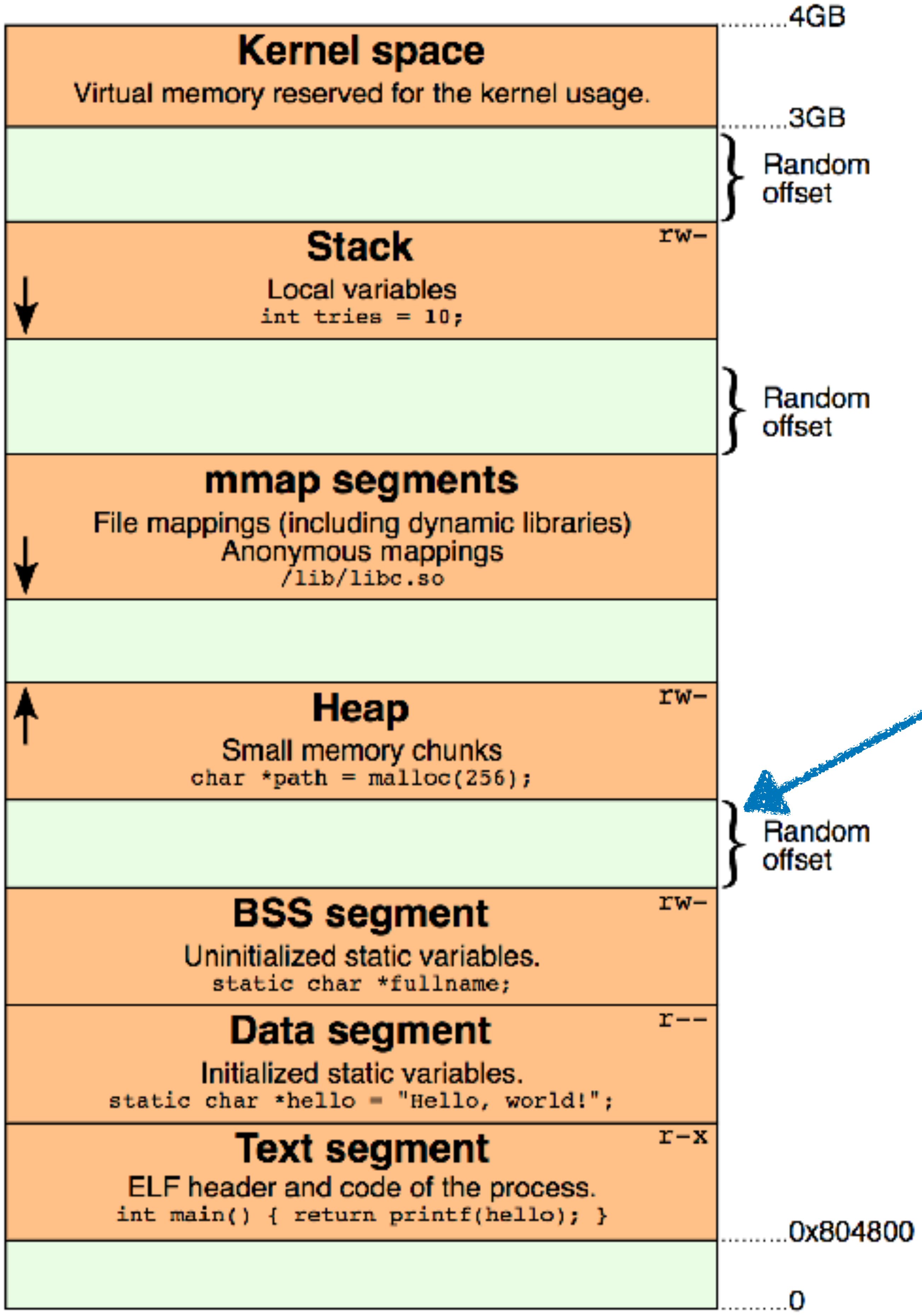


```
int tries = 10;
/lib/libc.so
char *path = malloc(256);
static char *fullname;
static char *hello = "Hello, world!";
int main() { return printf(hello); }
```

Text segment: program code



Note the **permissions**



This **random offset**
really security feature

Calling conventions

Touch-tone phones, send an acoustic wave over the wire

If Alice wants to call Bob, her phone needs to send the right sounds over the wire in the right order

Calling conventions

When function A wants to call function B, it has to do the same

- Where do arguments go?
- How to store return address?
- Who saves registers?
- Where is result stored?

Calling conventions

Modern computers use a few **different** calling conventions

De-facto standard (Linux / MacOS / etc..) : **x86-64 System V ABI**

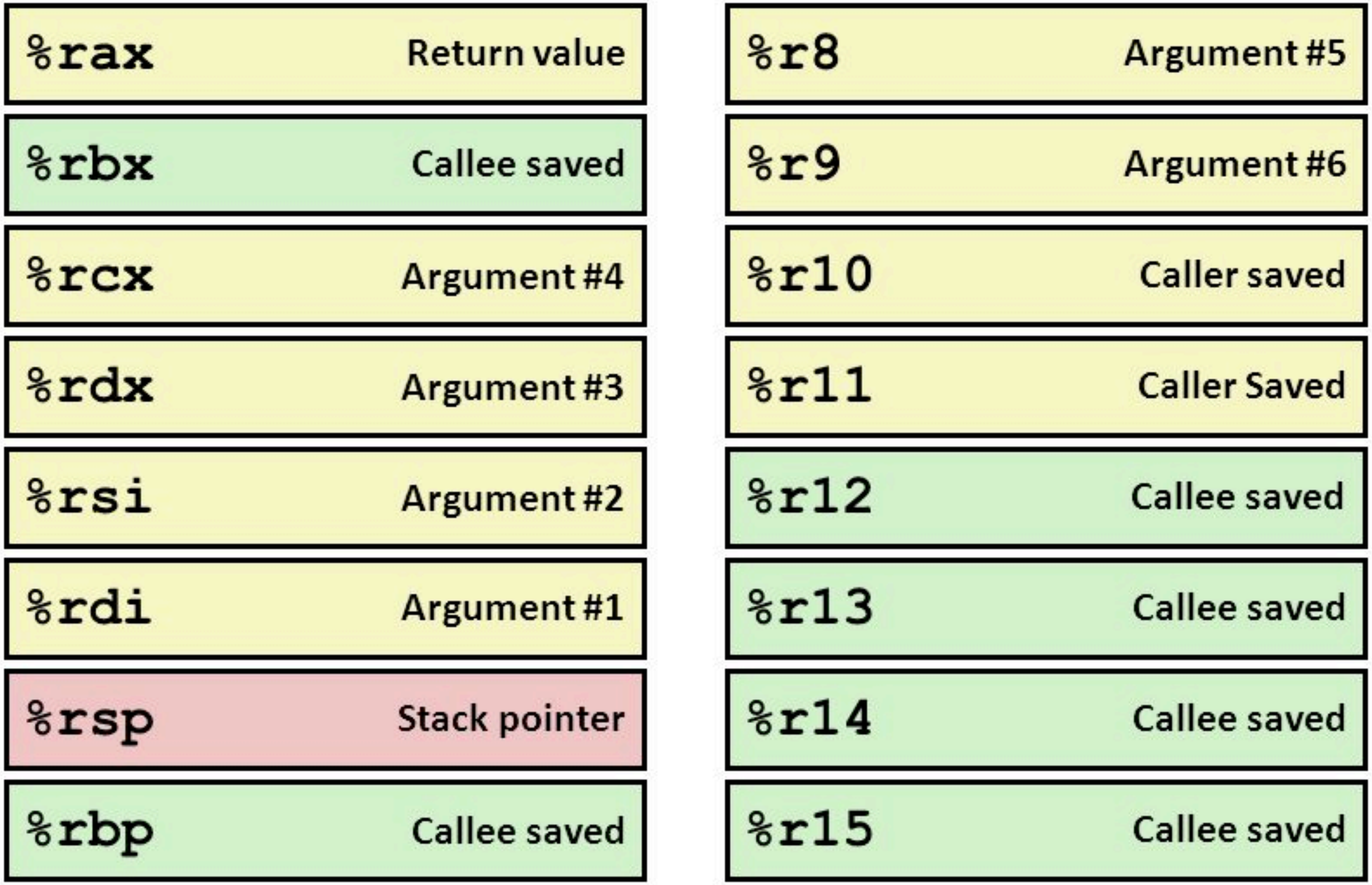
- Where do arguments go?
- How to store return address?
- Who saves registers?
- Where is result stored?

Note: this is **new** for the 64 bit API. You might see stuff online for the 32-bit API that is **different**

Calling conventions: x86-64 System V ABI

- Where do arguments go?
  - First six: rdi,rsi,rdx,rcx,r8,r9
- How to store return address?
  - `call` instruction puts on top of stack
- Who saves registers?
  - Caller saves caller-save registers
    - R10,R11, any ones used for args
- Where is result stored?
  - Result stored in %rax

x86-64 Integer Registers: Usage Conventions



`%rax`	Return value	`%r8`	Argument #5
`%rbx`	Callee saved	`%r9`	Argument #6
`%rcx`	Argument #4	`%r10`	Caller saved
`%rdx`	Argument #3	`%r11`	Caller Saved
`%rsi`	Argument #2	`%r12`	Callee saved
`%rdi`	Argument #1	`%r13`	Callee saved
`%rsp`	Stack pointer	`%r14`	Callee saved
`%rbp`	Callee saved	`%r15`	Callee saved

http://slideplayer.com/slide/9679824/

x86-64 System V ABI

Rules for **caller**:

- Save caller-save registers
- First six args in registers, after that put on stack
- Execute `call`—pushes ret addr

Afterwards:

- Pop saved registers
- Result now in %rax

x86-64 System V ABI

Rules for **callee**:

- First six args available in registers
- Push %rbp—caller’s base pointer
- Move %rsp to %rbp—Setup new frame
- Subtract necessary stack space
- Push callee-save registers
- Before exit: restore rbp/callee-saved regs
  - `leave` instruction restores rbp
- When function done, put result in %rax
- Use `ret` instruction to pop return rip

These rules are cumbersome: I frequently look them up, they change depending on the kind of function you're calling, etc…

Upshot: don't feel you have to memorize, just get the gist / know how to recognize them

Small examples: interactive demo of x86-64 ABI

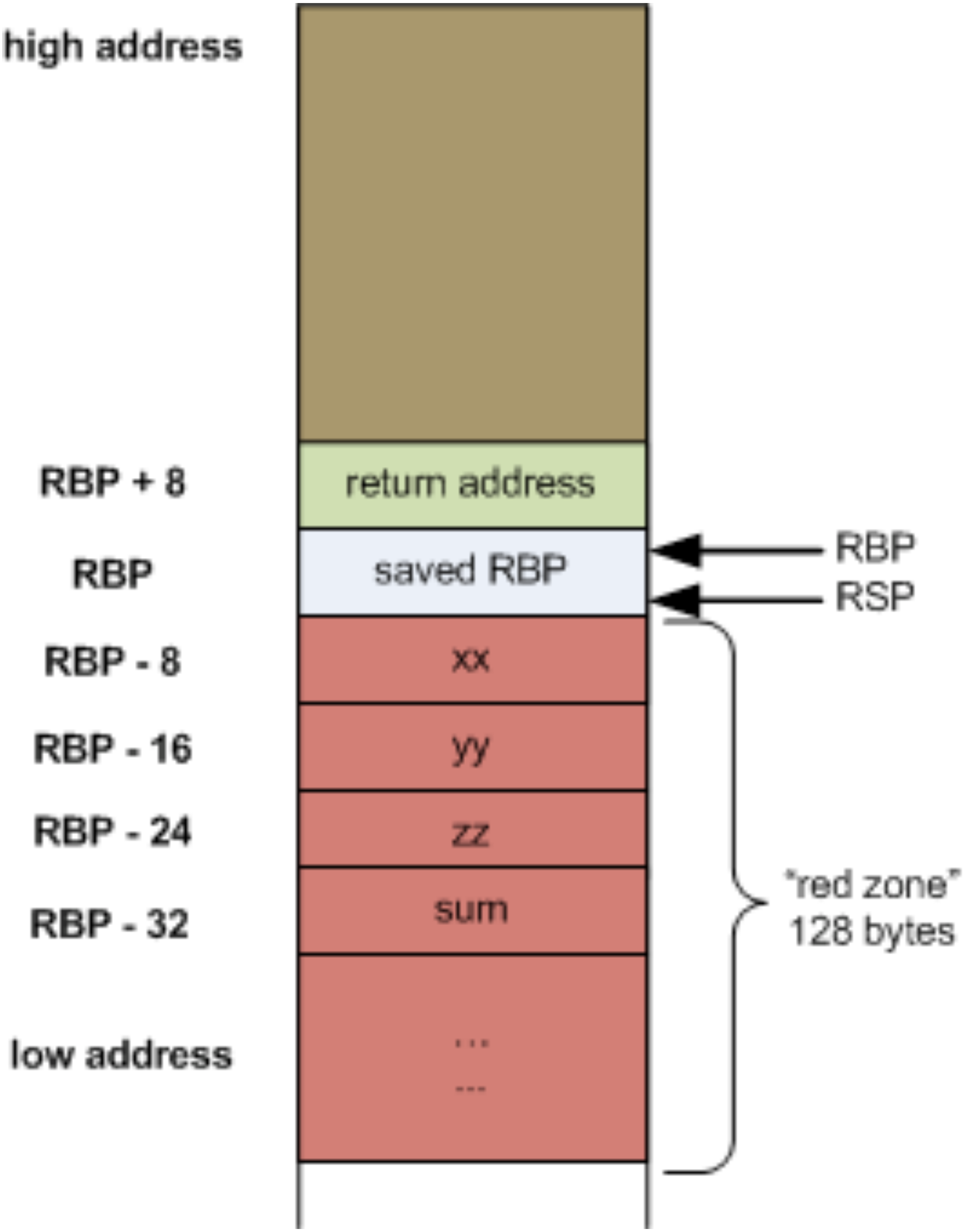
Trivia: the red zone

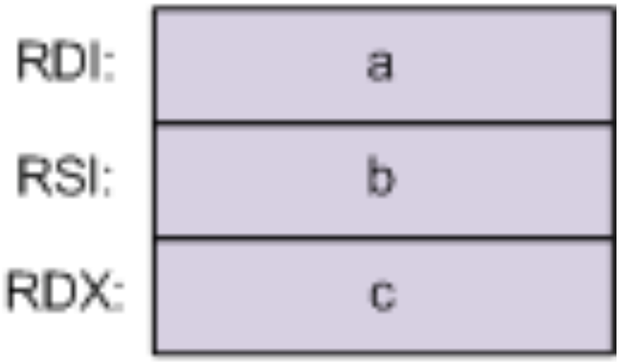
```
int bar(int a, int b) {
  return a + b;
}
```

Weird! This code using -4(%rbp) before decrementing the stack pointer!!

Turns out: x86-64 **guarantees** there are always 128 bytes below %rsp

```
bar:
    pushq   %rbp
    movq    %rsp, %rbp
    movl    %edi, -4(%rbp)
    movl    %esi, -8(%rbp)
    movl    -4(%rbp), %edx
    movl    -8(%rbp), %eax
    addl    %edx, %eax
    popq    %rbp
    ret
```





Upshot: if a function uses at most 128 bytes below RSP, doesn't have to subtract anything from RSP

This is an optimization for "small" functions: so they never have to subtract from RSP

Question: why does GCC generate such stupid code?

Answer: code unoptimized, add -O(1/2/3) to optimize it

-O0 generates code that is predictable and easy to read


Coffee

First attack: Stack Smashing

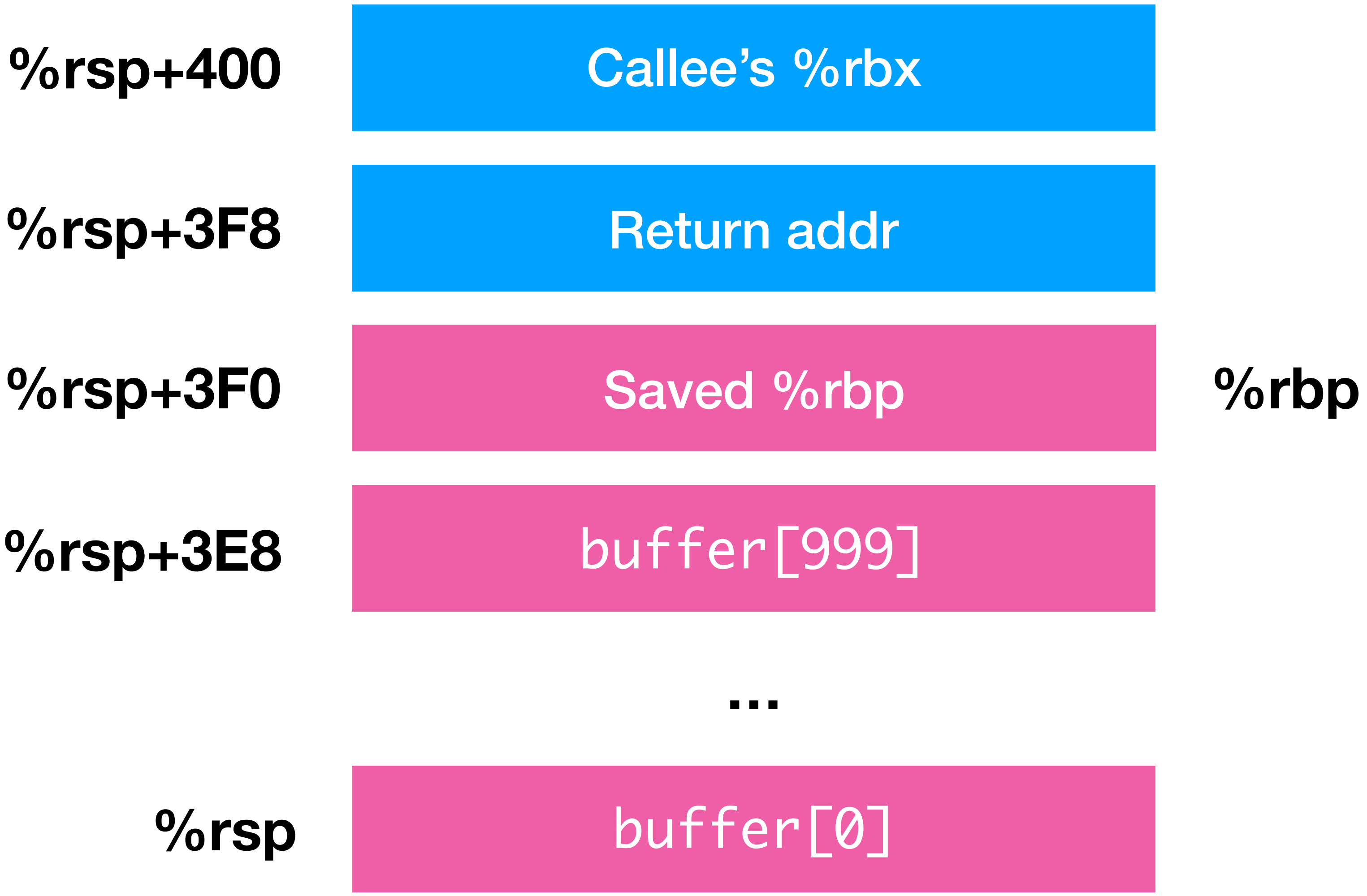
This code is bad because it doesn't check the length of the string in `ptr`…

```
void foo(char *ptr) {
    char buffer[1000];
    strcpy(buffer, ptr);
    printf(“length: %d\n”, strlen(buffer));
}
```

After `foo` starts

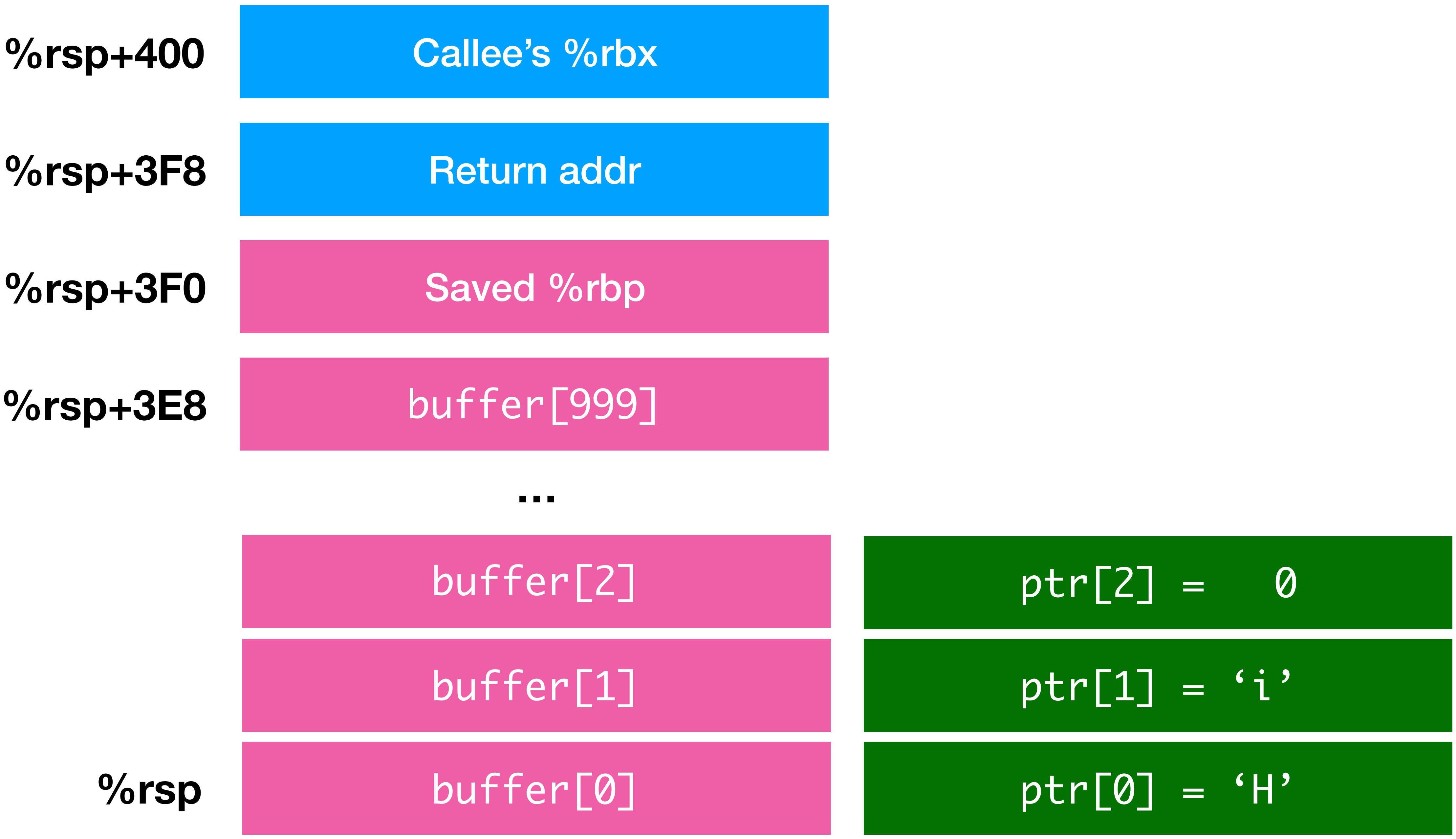
%rsp+400	Stuff from foo…	
%rsp+3F8	Return addr	
%rsp+3F0	Saved %rbp	**%rbp**
%rsp+3E8	`buffer[999]`	
	…	
%rsp	`buffer[0]`	

After `foo` starts



%rsp+400	Callee’s %rbx	
%rsp+3F8	Return addr	
%rsp+3F0	Saved %rbp	%rbp
%rsp+3E8	`buffer[999]`	
	…	
%rsp	`buffer[0]`	

Key observation: the stack **grows down**



%rsp+400 Callee’s %rbx

%rsp+3F8 Return addr

%rsp+3F0 Saved %rbp

%rsp+3E8 `buffer[999]`

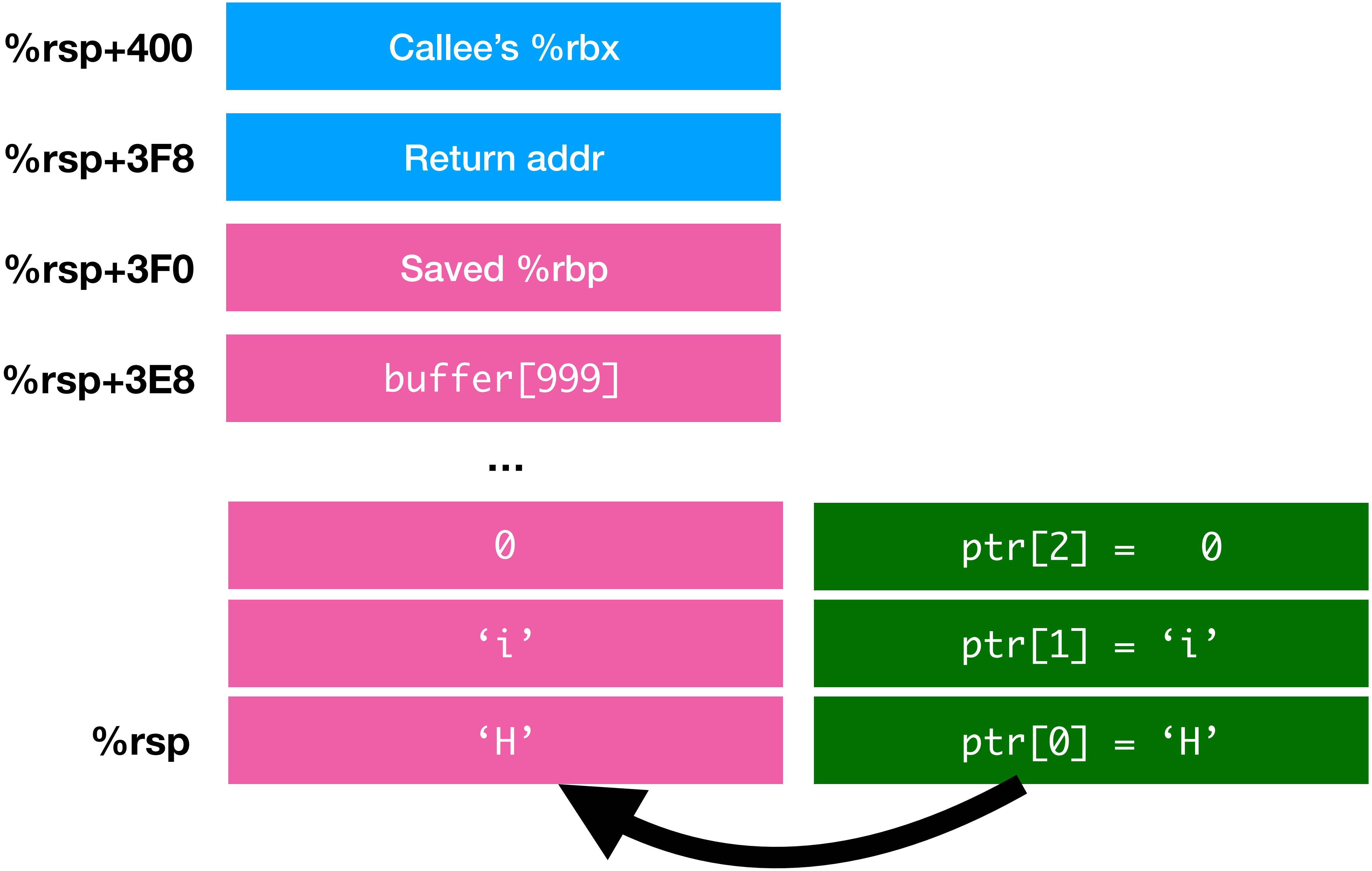
...

`buffer[2]` `ptr[2] = 0`

`buffer[1]` `ptr[1] = ‘i’`

%rsp `buffer[0]` `ptr[0] = ‘H’`

Consider what happens when `strcpy(buffer,ptr)`



%rsp+400 Callee’s %rbx

%rsp+3F8 Return addr

%rsp+3F0 Saved %rbp

%rsp+3E8 `buffer[999]`

...

`0`

`‘i’`

%rsp `‘H’`

`ptr[2] =   0`

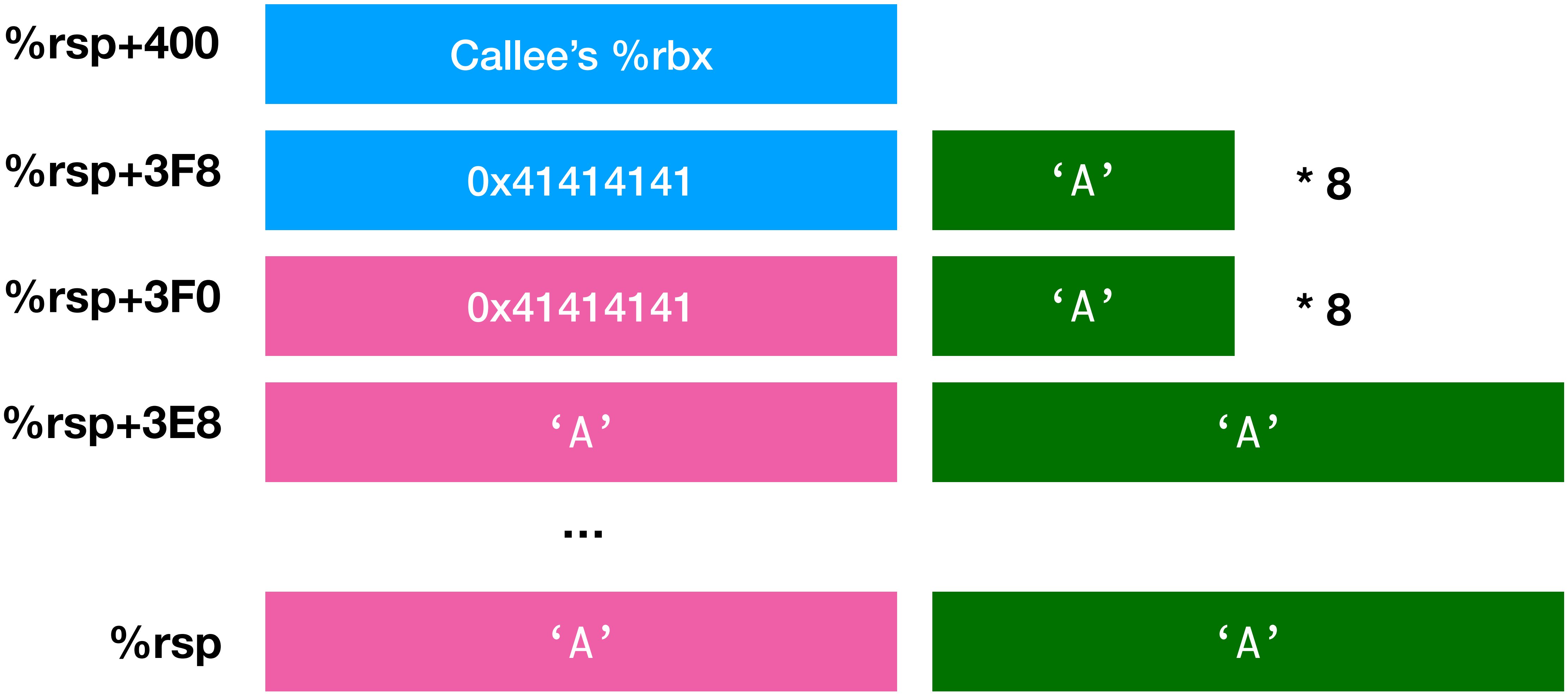
`ptr[1] = ‘i’`

`ptr[0] = ‘H’`

Consider what happens when `strcpy(buffer,ptr)`

(This one is fine..)

Now consider what happens when we provide input ‘A’ * 1008



%rsp+400 Callee’s %rbx

%rsp+3F8 0x41414141 ‘A’ * 8

%rsp+3F0 0x41414141 ‘A’ * 8

%rsp+3E8 ‘A’ ‘A’

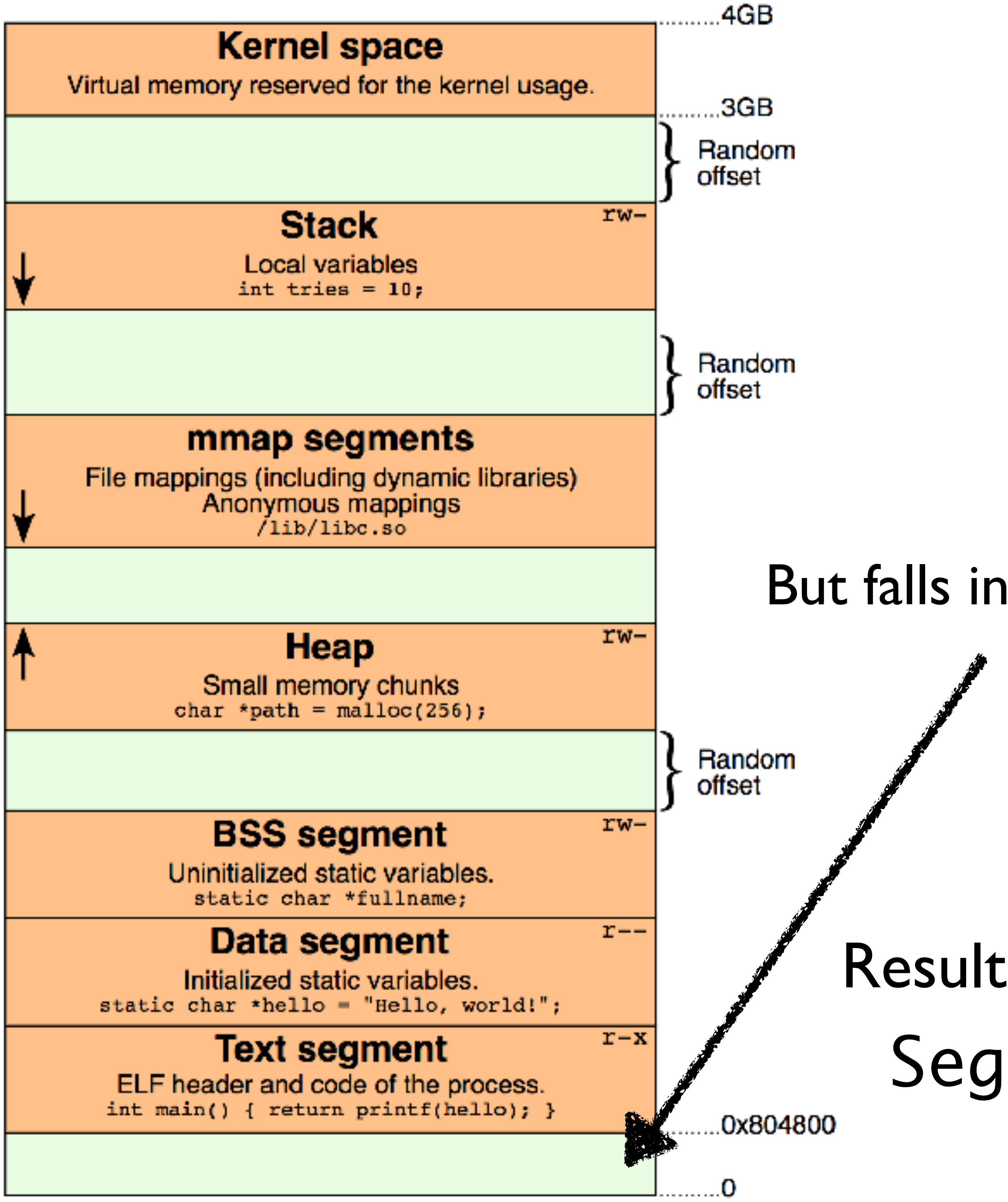
…

%rsp ‘A’ ‘A’

Return addr becomes `0x41414141` (‘A’ four times)

Upon return, control goes to 0x41414141

If anything at this address, program will execute it



But falls in here, unmapped memory

Result: most common C crash

Segmentation Fault

The compiler translates binary code into machine code

`execve("/bin/sh")`

↓

Compiler

↓

We'll cover this assembly later in class!

```
"\x48\x31\xd2"                              // xor    %rdx, %rdx
"\x48\xbb\x2f\x2f\x62\x69\x6e\x2f\x73\x68" // mov $0x68732f6e69622f2f, %rbx
"\x48\xc1\xeb\x08"                          // shr    $0x8, %rbx
"\x53"                                      // push   %rbx
"\x48\x89\xe7"                              // mov    %rsp, %rdi
"\x50"                                      // push   %rax
"\x57"                                      // push   %rdi
"\x48\x89\xe6"                              // mov    %rsp, %rsi
"\xb0\x3b"                                  // mov    $0x3b, %al
"\x0f\x05";                                 // syscall
```

man execve

All that code is **loaded** by the kernel at a specific place in memory

Let’s assume for a second that the compiler loads that code at
`0x41414141`

In the next few slides we’ll see what happens if it’s **not** there

Return pointer: 0x41414141

After returning, we *expect* the code to go back here

```
// foo’s caller
foo(p);
x = x+1;

void foo(char *ptr) {
    char buffer[ptr];
    strcpy(buffer, ptr);
    printf(“length: %d\n”, strlen(buffer));
}
```

0x41414141

```
"\x48\x31\xd2"                                 // xor    %rdx, %rdx
"\x48\xbb\x2f\x2f\x62\x69\x6e\x2f\x73\x68"     // mov $0x68732f6e69622f2f, %rbx
"\x48\xc1\xeb\x08"                             // shr    $0x8, %rbx
"\x53"                                         // push   %rbx
"\x48\x89\xe7"                                 // mov    %rsp, %rdi
"\x50"                                         // push   %rax
"\x57"                                         // push   %rdi
"\x48\x89\xe6"                                 // mov    %rsp, %rsi
"\xb0\x3b"                                     // mov    $0x3b, %al
"\x0f\x05";                                    // syscall
```

Return pointer: 0x41414141

But the return address has been *overwritten* (stack has been smashed)

```
// foo’s caller
foo(p);
x = x+1;

void foo(char *ptr) {
    char buffer[ptr];
    strcpy(buffer, ptr);
    printf(“length: %d\n”, strlen(buffer));
}
```

Instead, return goes here

```
0x41414141 "\x48\x31\xd2"                                 // xor     %rdx, %rdx
           "\x48\xbb\x2f\x2f\x62\x69\x6e\x2f\x73\x68"     // mov $0x68732f6e69622f2f, %rbx
           "\x48\xc1\xeb\x08"                             // shr     $0x8, %rbx
           "\x53"                                         // push    %rbx
           "\x48\x89\xe7"                                 // mov     %rsp, %rdi
           "\x50"                                         // push    %rax
           "\x57"                                         // push    %rdi
           "\x48\x89\xe6"                                 // mov     %rsp, %rsi
           "\xb0\x3b"                                     // mov     $0x3b, %al
           "\x0f\x05";                                    // syscall
```

Now, the computer executes a shell instead!!!

Might not be so bad if it’s a local program

But bad if it’s a connection to a remote server!

In your first project, you'll mount one of these attacks on a vulnerable file server

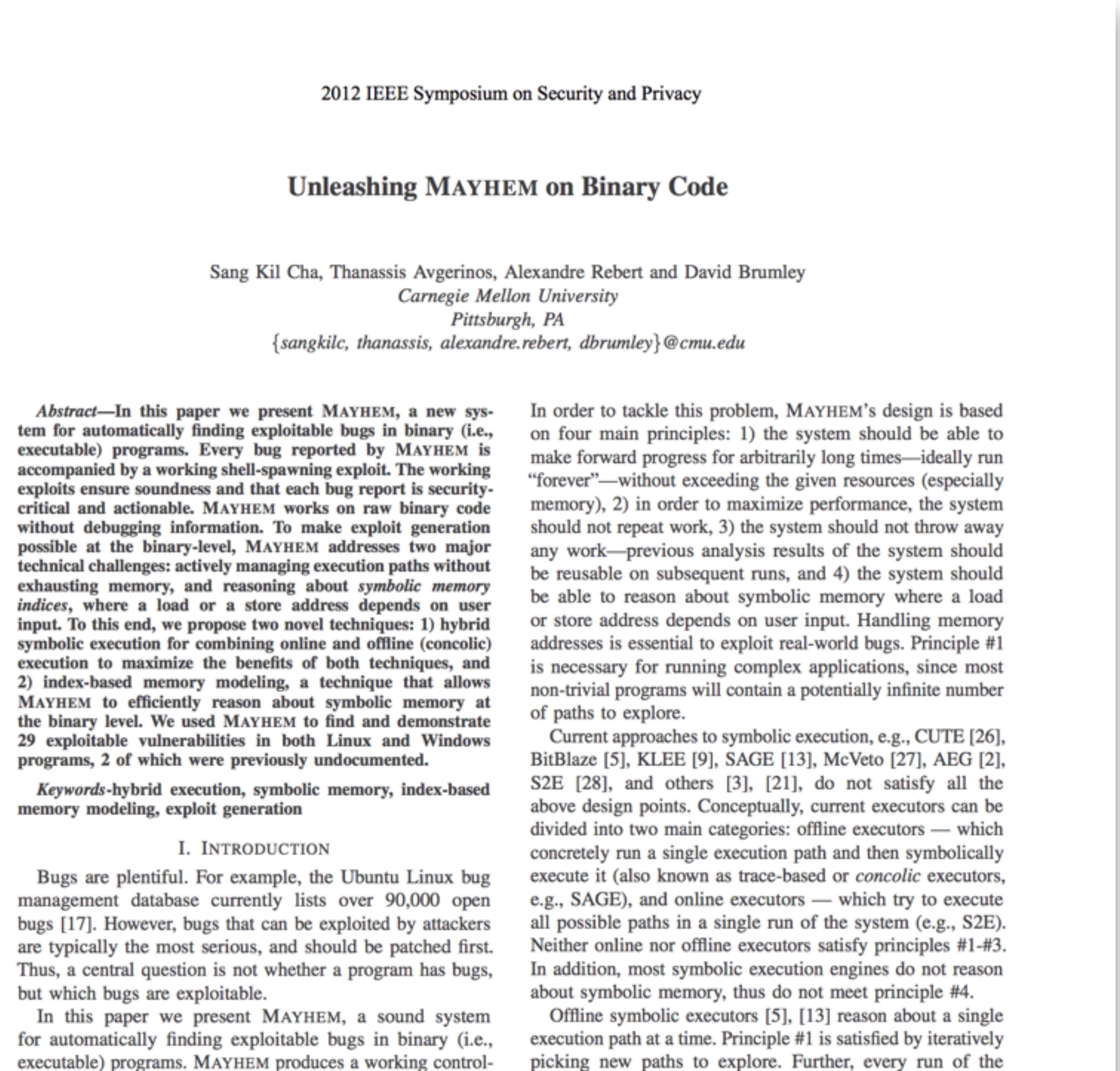
So my job **as an attacker** is to find a buffer overflow in the program and then craft an input that sends the code where I want

Question 1: How do I find a bug?

A: Dig through the source manually, if source is available

(If source unavailable, use a ***decompiler***)

A: Some automated testing tools



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Unleashing Mayhem on Binary Code

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***Abstract*—In this paper we present Mayhem, a new system for automatically finding exploitable bugs in binary (i.e., executable) programs. Every bug reported by Mayhem is accompanied by a working shell-spawning exploit. The working exploits ensure soundness and that each bug report is security-critical and actionable. Mayhem works on raw binary code without debugging information. To make exploit generation possible at the binary-level, Mayhem addresses two major technical challenges: actively managing execution paths without exhausting memory, and reasoning about *symbolic memory indices*, where a load or a store address depends on user input. To this end, we propose two novel techniques: 1) hybrid symbolic execution for combining online and offline (concolic) execution to maximize the benefits of both techniques, and 2) index-based memory modeling, a technique that allows Mayhem to efficiently reason about symbolic memory at the binary level. We used Mayhem to find and demonstrate 29 exploitable vulnerabilities in both Linux and Windows programs, 2 of which were previously undocumented.**

***Keywords*-hybrid execution, symbolic memory, index-based memory modeling, exploit generation**

I. Introduction

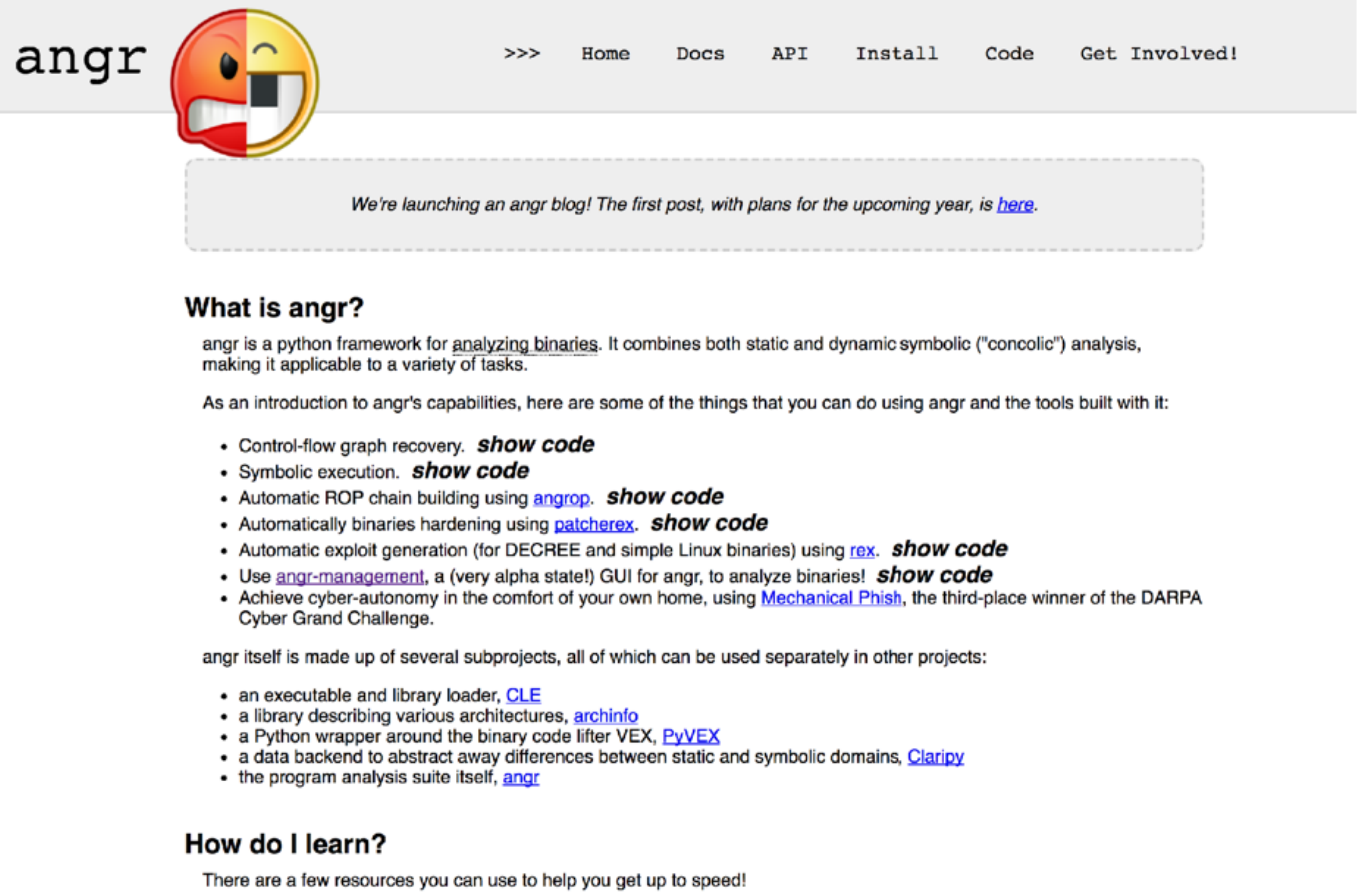
Bugs are plentiful. For example, the Ubuntu Linux bug management database currently lists over 90,000 open bugs [17]. However, bugs that can be exploited by attackers are typically the most serious, and should be patched first. Thus, a central question is not whether a program has bugs, but which bugs are exploitable.

In this paper we present Mayhem, a sound system for automatically finding exploitable bugs in binary (i.e., executable) programs. Mayhem produces a working control-

In order to tackle this problem, Mayhem's design is based on four main principles: 1) the system should be able to make forward progress for arbitrarily long times—ideally run "forever"—without exceeding the given resources (especially memory), 2) in order to maximize performance, the system should not repeat work, 3) the system should not throw away any work—previous analysis results of the system should be reusable on subsequent runs, and 4) the system should be able to reason about symbolic memory where a load or store address depends on user input. Handling memory addresses is essential to exploit real-world bugs. Principle #1 is necessary for running complex applications, since most non-trivial programs will contain a potentially infinite number of paths to explore.

Current approaches to symbolic execution, e.g., CUTE [26], BitBlaze [5], KLEE [9], SAGE [13], McVeto [27], AEG [2], S2E [28], and others [3], [21], do not satisfy all the above design points. Conceptually, current executors can be divided into two main categories: offline executors — which concretely run a single execution path and then symbolically execute it (also known as trace-based or *concolic* executors, e.g., SAGE), and online executors — which try to execute all possible paths in a single run of the system (e.g., S2E). Neither online nor offline executors satisfy principles #1-#3. In addition, most symbolic execution engines do not reason about symbolic memory, thus do not meet principle #4.

Offline symbolic executors [5], [13] reason about a single execution path at a time. Principle #1 is satisfied by iteratively picking new paths to explore. Further, every run of the



We're launching an angr blog! The first post, with plans for the upcoming year, is here.

What is angr?

angr is a python framework for analyzing binaries. It combines both static and dynamic symbolic ("concolic") analysis, making it applicable to a variety of tasks.

As an introduction to angr's capabilities, here are some of the things that you can do using angr and the tools built with it:

- Control-flow graph recovery. ***show code***
- Symbolic execution. ***show code***
- Automatic ROP chain building using angrop. ***show code***
- Automatically binaries hardening using patcherex. ***show code***
- Automatic exploit generation (for DECREE and simple Linux binaries) using rex. ***show code***
- Use angr-management, a (very alpha state!) GUI for angr, to analyze binaries! ***show code***
- Achieve cyber-autonomy in the comfort of your own home, using Mechanical Phish, the third-place winner of the DARPA Cyber Grand Challenge.

angr itself is made up of several subprojects, all of which can be used separately in other projects:

- an executable and library loader, CLE
- a library describing various architectures, archinfo
- a Python wrapper around the binary code lifter VEX, PyVEX
- a data backend to abstract away differences between static and symbolic domains, Claripy
- the program analysis suite itself, angr

How do I learn?

There are a few resources you can use to help you get up to speed!

So my job **as an attacker** is to find a buffer overflow in the program and then craft an input that sends the code where I want

Question 2: What if program doesn’t have bugs!?

A: You’re hosed, can’t perform this attack

But some other attacks we’ll talk about on Thursday

The best way to prevent these attacks is to write in languages where these bugs can’t occur!!

So my job **as an attacker** is to find a buffer overflow in the program and then craft an input that sends the code where I want

Question 3: How do I know what code to execute?

A: Find the code you want in the binary

A: We'll also learn how you can **inject your own** code

So my job **as an attacker** is to find a buffer overflow in the program and then craft an input that sends the code where I want

Question 4: How do I know **where the code is**

A: Use GDB to find it after booting up the binary

But there's a critical catch!

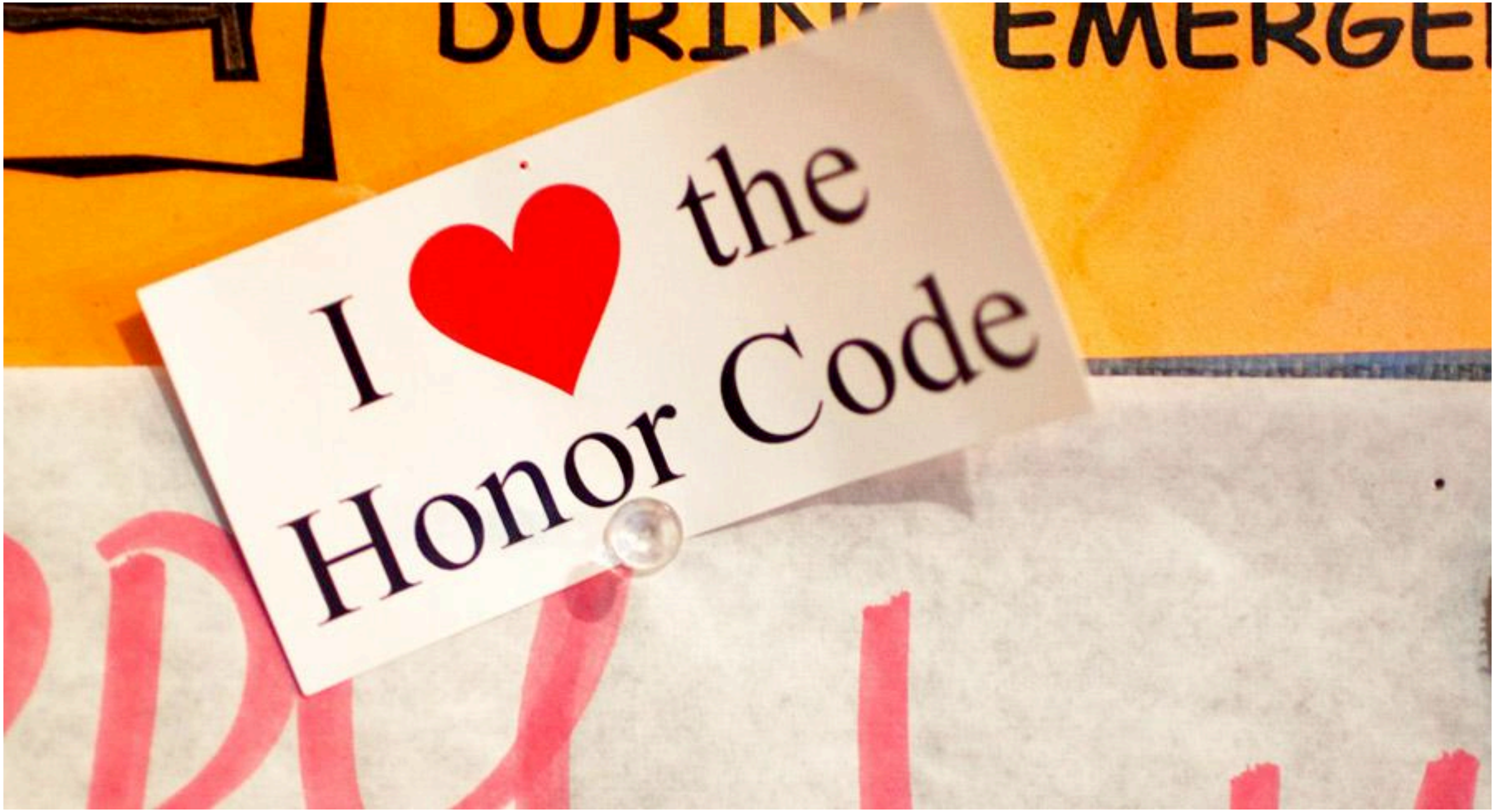
The compiler includes a variety of **protections** against stack smashing

Stack canaries (which we'll learn about next week)

Address **S**pace **L**ayout **R**andomization

Loads code into random addr each run!

(We'll see some techniques to help defeat this)


I ♥ the
Honor Code

Goal of this course isn't to teach you "how to hack"

Instead, we focus on core principles

To do that, just go download metasploit

How are most systems hacked in the “real world?”

https://www.youtube.com/watch?v=msX4oAXpvUE

https://www.youtube.com/watch?v=iSr7kOCdPTc

https://www.youtube.com/watch?v=dxIPcbmo1_U

How are most systems hacked in the "real world?"

Answer: bad system configurations, out-of-date software, weak passwords

Almost never a hacker sitting in a dark room custom-writing an exploit

In addition to all of the **standard** things in the honor code…

Don’t use things from this course to unethically infiltrate systems

Upshot: we can control where the code returns by smashing the stack exploiting a buffer overflow

Next time:
- Stack smashing—live demo
- Using GDB to understand binaries
- Objdump and the ELF format

Lab tomorrow: Using the VM for the course, P1 intro

Before tomorrow: Download VirtualBox!