CSCI 476: Computer Security

Operating Systems, Processes, and `forking()`

Reese Pearsall

Fall 2024

*all images are stolen from the internet

Announcements

NO CLASS ON THURSDAY

(I'll still be around if you need help with anything)

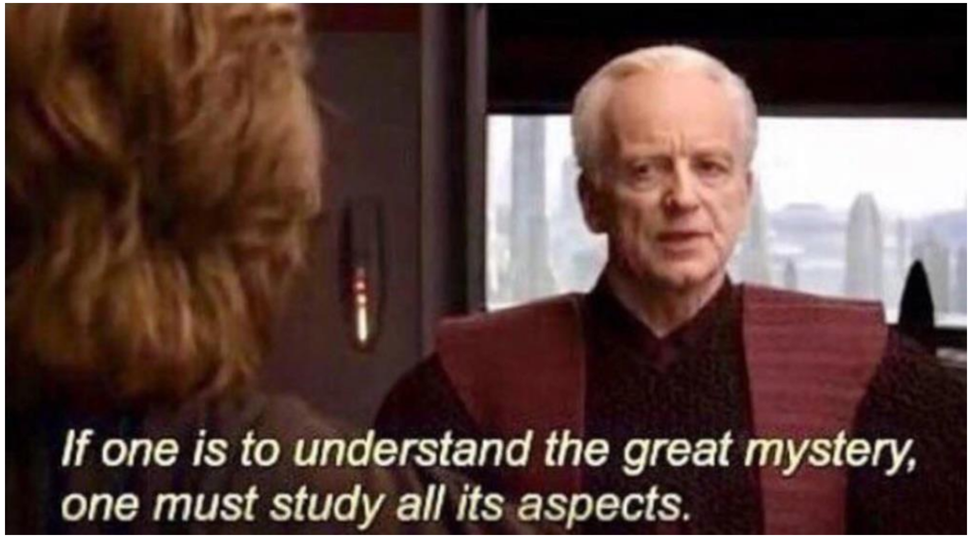
Lab 0 due on Sunday 9/8 @ 11:59 PM

(All assignments will be due on Sundays)

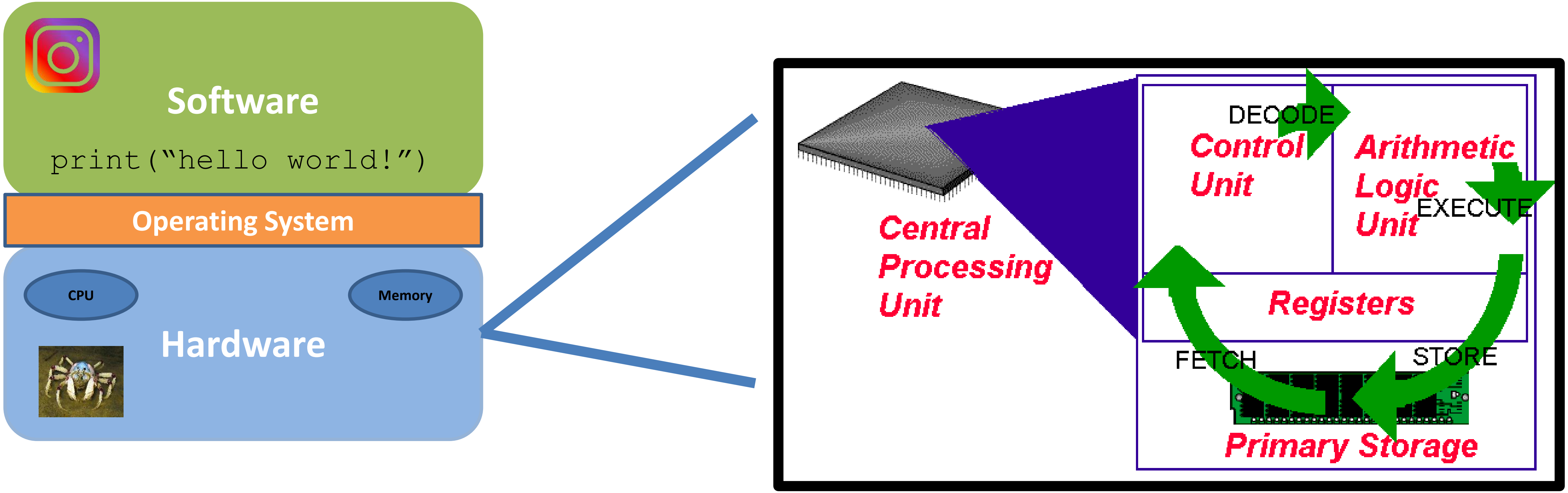
If you have an M1/M2 chip, or if you are still struggling with your VM, **check in with me this week**

To understand the technical aspects of security, we must have a good understanding of how ~~computers~~ work

operating systems


If one is to understand the great mystery,
one must study all its aspects.

The Operating System



Software

```
print("hello world!")
```

Operating System

CPU

Memory

Hardware

DECODE

Control Unit

Arithmetic Logic Unit

EXECUTE

Central Processing Unit

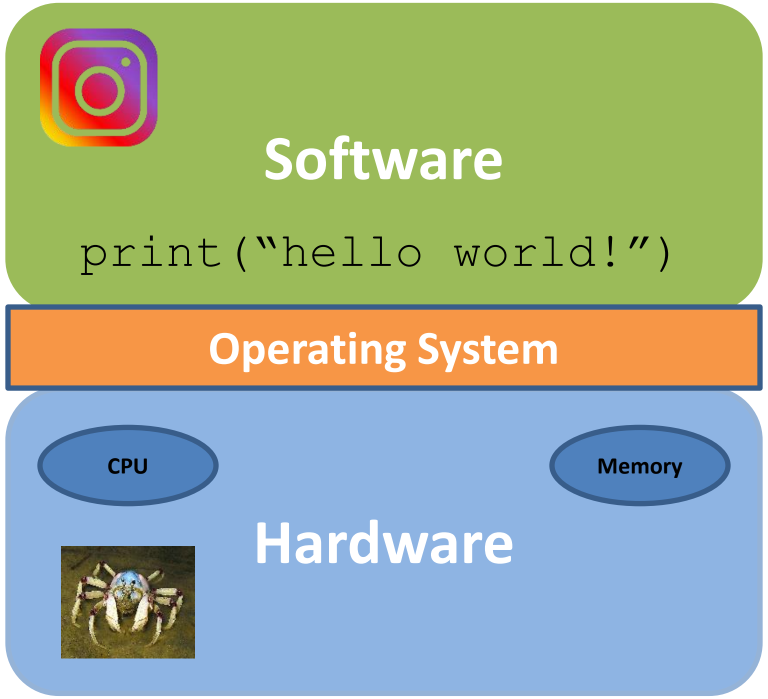
Registers

FETCH

STORE

Primary Storage

The Operating System



Software

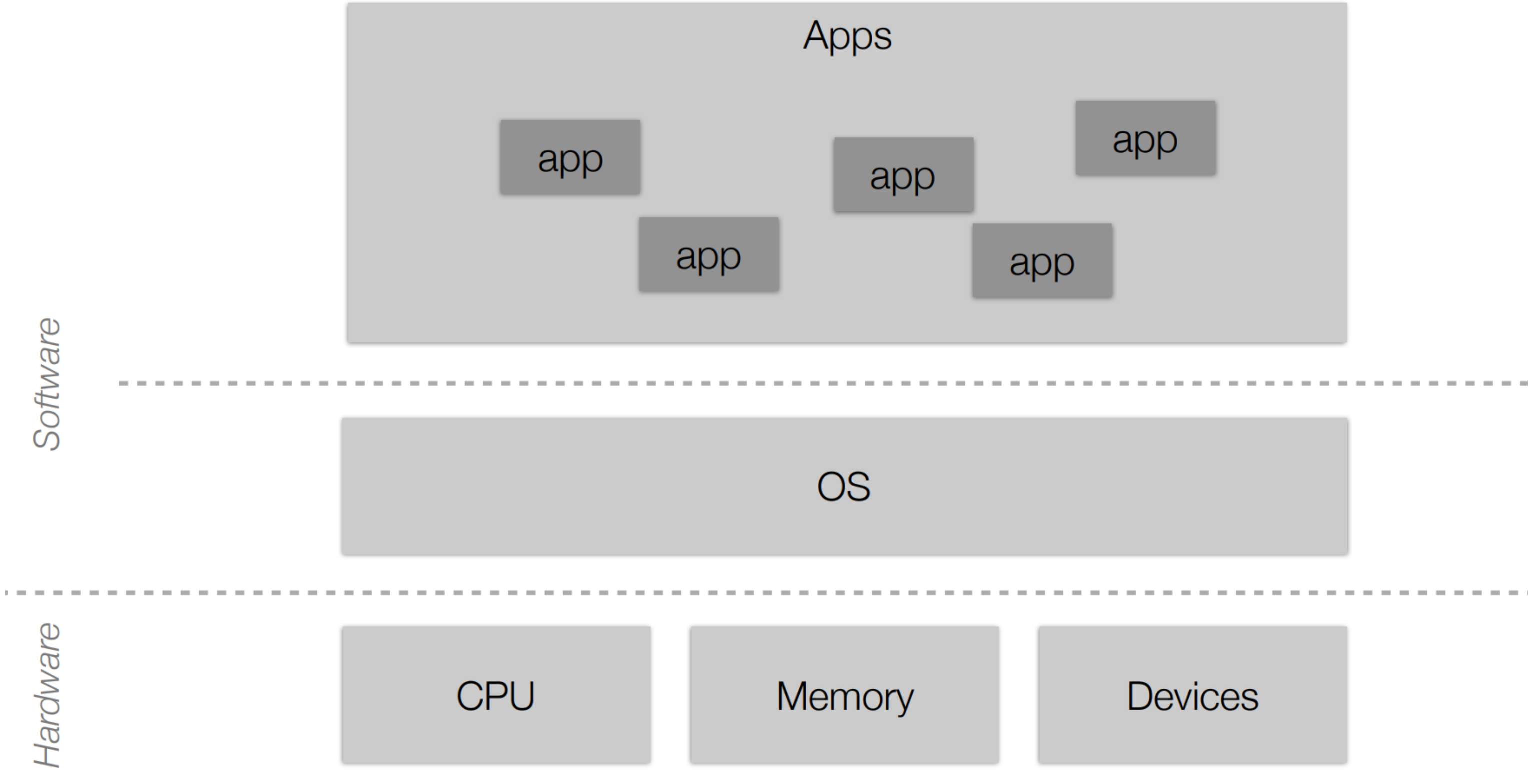
```
print(“hello world!”)
```

Operating System

CPU

Memory

Hardware



Apps

app

app

app

app

app

Software

OS

Hardware

CPU

Memory

Devices

The jobs of an Operating System

1. **Process Manager**
   “The Coach”
2. **Interface Manager**
   “The Bouncer”
3. **Memory Manager**
   “The Farmer”
4. **Traffic Manager**
   “The Judge”
5. **Illusion Manager**
   “The Illusionist”

The jobs of an Operating System

1. **Process Manager**
   "The Coach"
2. **Interface Manager**
   "The Bouncer"
3. **Memory Manager**
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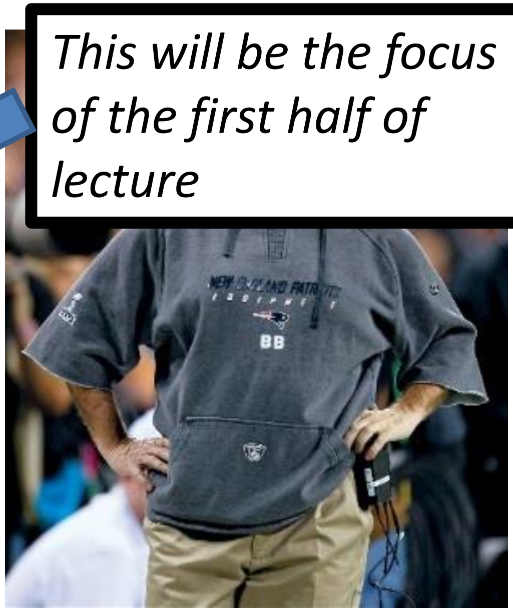
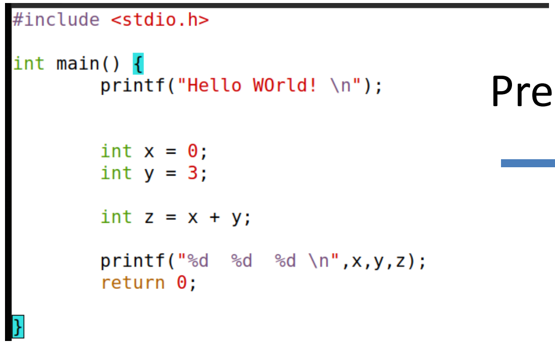
   "The Judge"
5. **Illusion Manager**
   "The Illusionist"

This will be the focus of the first half of lecture



Source code to binary



```c
#include <stdio.h>

int main() {
        printf("Hello WOrld! \n");

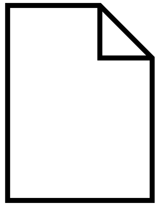

        int x = 0;
        int y = 3;

        int z = x + y;

        printf("%d  %d  %d \n",x,y,z);
        return 0;

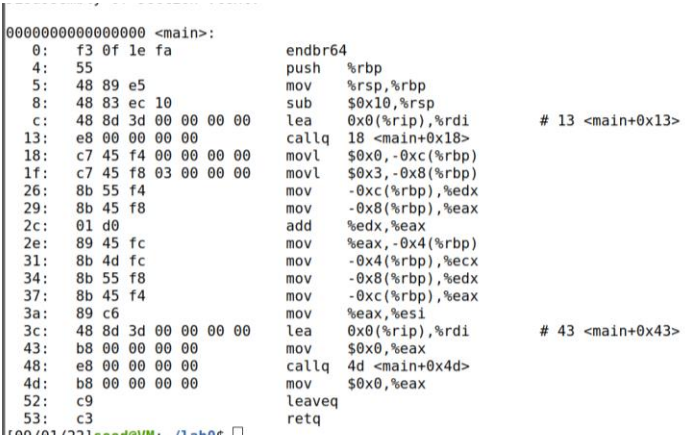
}
```

Preprocessor



- Removal of comments
- Expand Macros

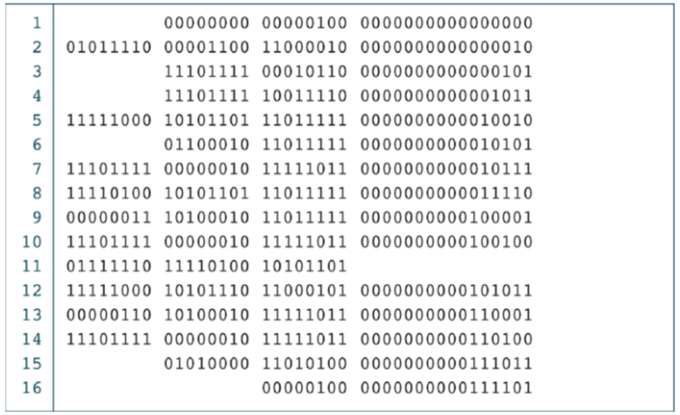
Compiler



```
0000000000000000 <main>:
   0:   f3 0f 1e fa             endbr64
   4:   55                      push   %rbp
   5:   48 89 e5                mov    %rsp,%rbp
   8:   48 83 ec 10             sub    $0x10,%rsp
   c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 13 <main+0x13>
  13:   e8 00 00 00 00          callq  18 <main+0x18>
  18:   c7 45 f4 00 00 00 00    movl   $0x0,-0xc(%rbp)
  1f:   c7 45 f8 03 00 00 00    movl   $0x3,-0x8(%rbp)
  26:   8b 55 f4                mov    -0xc(%rbp),%edx
  29:   8b 45 f8                mov    -0x8(%rbp),%eax
  2c:   01 d0                   add    %edx,%eax
  2e:   89 45 fc                mov    %eax,-0x4(%rbp)
  31:   8b 4d fc                mov    -0x4(%rbp),%ecx
  34:   8b 55 f8                mov    -0x8(%rbp),%edx
  37:   8b 45 f4                mov    -0xc(%rbp),%eax
  3a:   89 c6                   mov    %eax,%esi
  3c:   48 8d 3d 00 00 00 00    lea    0x0(%rip),%rdi        # 43 <main+0x43>
  43:   b8 00 00 00 00          mov    $0x0,%eax
  48:   e8 00 00 00 00          callq  4d <main+0x4d>
  4d:   b8 00 00 00 00          mov    $0x0,%eax
  52:   c9                      leaveq
  53:   c3                      retq
```

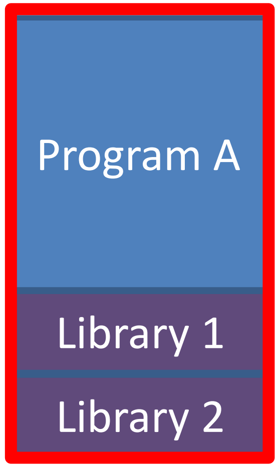
- Converted to assembly code
- .s file

Assembler



```
         00000000 00000100 0000000000000000
01011110 00001100 11000010 0000000000000010
         11101111 00010110 0000000000000101
         11101111 10011110 0000000000001011
11111000 10101101 11011111 0000000000010010
         01100010 11011111 0000000000010101
11101111 00000010 11111011 0000000000010111
11110100 10101101 11011111 0000000000011110
00000011 10100010 11011111 0000000000100001
11101111 00000010 11111011 0000000000100100
01111110 11110100 10101101
11111000 10101110 11000101 0000000000101011
00000110 10100010 11111011 0000000000110001
11101111 00000010 11111011 0000000000110100
         01010000 11010100 0000000000111011
                  00000100 0000000000111101
```

Linker



Program A

Library 1

Library 2

.exe

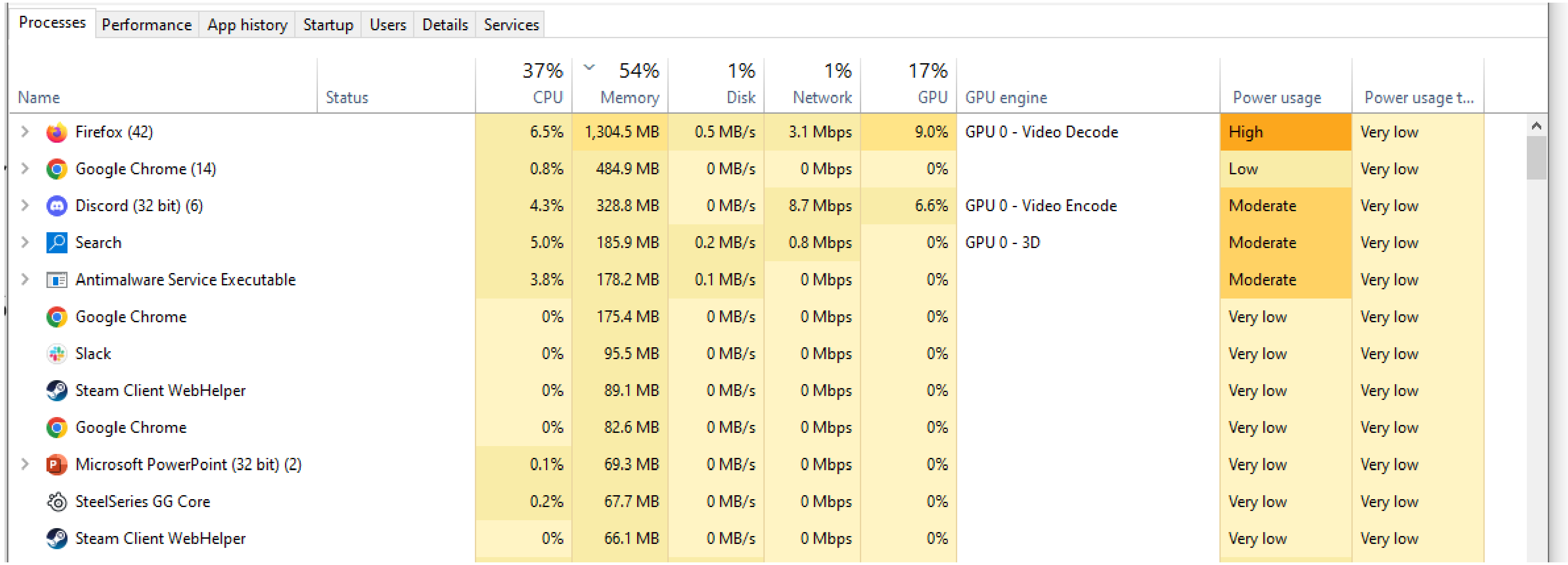
./hello_world

**THIS PROCESS IS NOT TRUE FOR EVERY LANGUAGE

What happens when we run `./hello_world` ?

It gets turned into a **process**

A **process** is an instance of a running program on a computer



Name	Status	37% CPU	54% Memory	1% Disk	1% Network	17% GPU	GPU engine	Power usage	Power usage t...
Firefox (42)		6.5%	1,304.5 MB	0.5 MB/s	3.1 Mbps	9.0%	GPU 0 - Video Decode	High	Very low
Google Chrome (14)		0.8%	484.9 MB	0 MB/s	0 Mbps	0%		Low	Very low
Discord (32 bit) (6)		4.3%	328.8 MB	0 MB/s	8.7 Mbps	6.6%	GPU 0 - Video Encode	Moderate	Very low
Search		5.0%	185.9 MB	0.2 MB/s	0.8 Mbps	0%	GPU 0 - 3D	Moderate	Very low
Antimalware Service Executable		3.8%	178.2 MB	0.1 MB/s	0 Mbps	0%		Moderate	Very low
Google Chrome		0%	175.4 MB	0 MB/s	0 Mbps	0%		Very low	Very low
Slack		0%	95.5 MB	0 MB/s	0 Mbps	0%		Very low	Very low
Steam Client WebHelper		0%	89.1 MB	0 MB/s	0 Mbps	0%		Very low	Very low
Google Chrome		0%	82.6 MB	0 MB/s	0 Mbps	0%		Very low	Very low
Microsoft PowerPoint (32 bit) (2)		0.1%	69.3 MB	0 MB/s	0 Mbps	0%		Very low	Very low
SteelSeries GG Core		0.2%	67.7 MB	0 MB/s	0 Mbps	0%		Very low	Very low
Steam Client WebHelper		0%	66.1 MB	0 MB/s	0 Mbps	0%		Very low	Very low

A **process** is an instance of a <u>running</u> program on a computer

All processes have the following data while they are running:

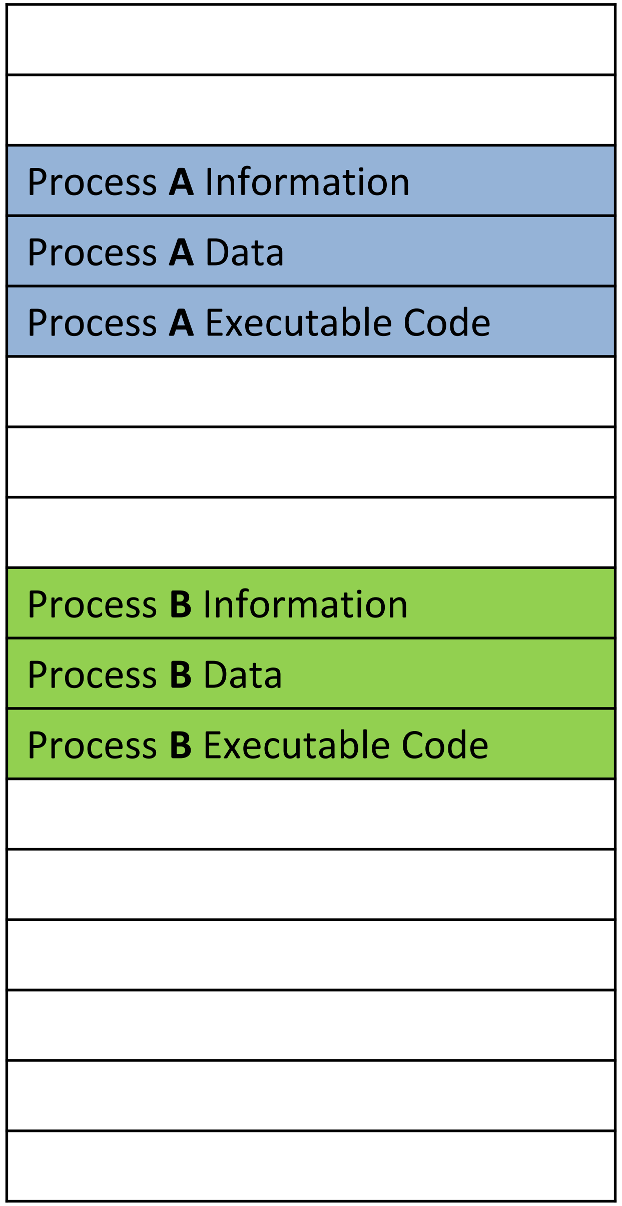
1. Executable Code

2. Associated Data

3. Execution Context/Bookkeeping information

(info that the OS needs to handle the process)

Main Memory



Process **A** Information

Process **A** Data

Process **A** Executable Code

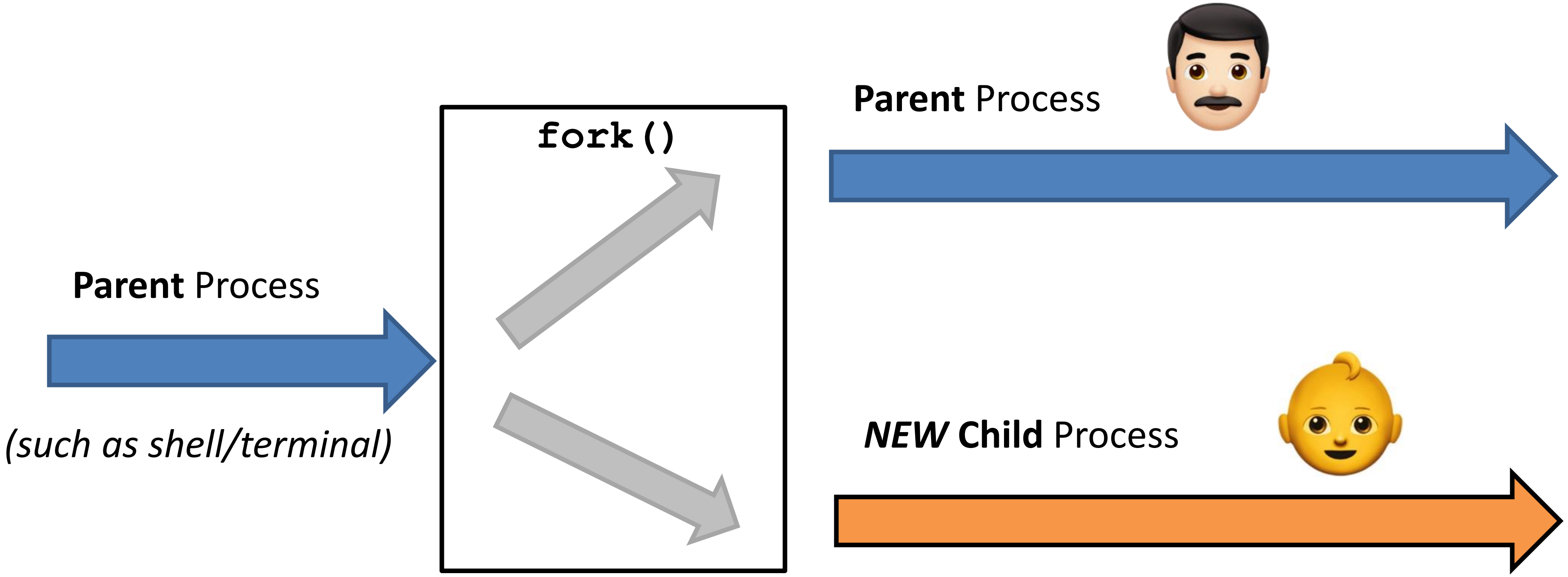
Process **B** Information

Process **B** Data

Process **B** Executable Code

Ok, but how do we *actually* create a process?

- In the Unix family (and others), we use **`fork()`** to create a new process



`fork()` duplicates a process so that instead of one process, you get two!

`fork()` duplicates a process so that instead of one process, you get two!

How can we tell the parent and child apart?

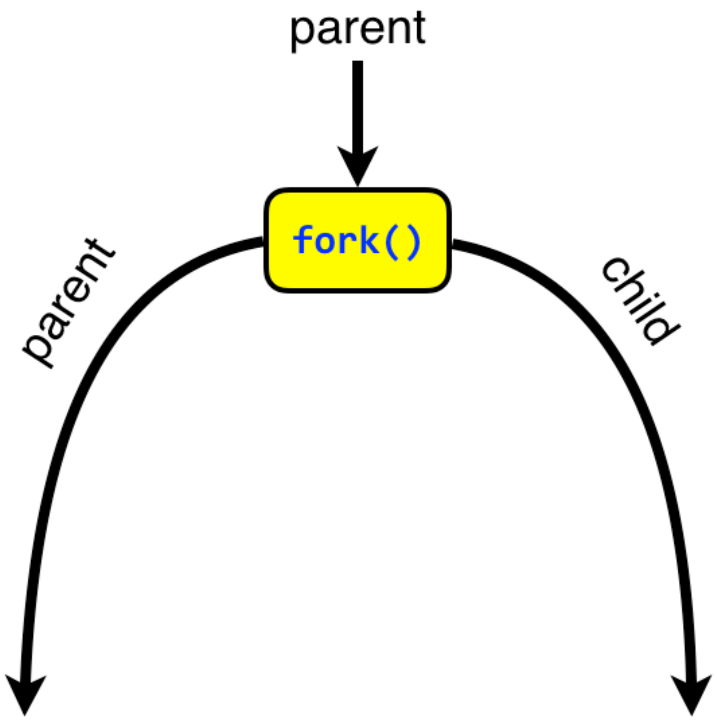
```
int main(void) {
    int pid;

    pid = fork();
    if (0 == pid) {
        // I'm the child
        printf("Hi, I'm the child. \n");
    }

    sleep(1);
    printf("I'm the parent.);

    return 0;
}
```

We check the return value of `fork()`!



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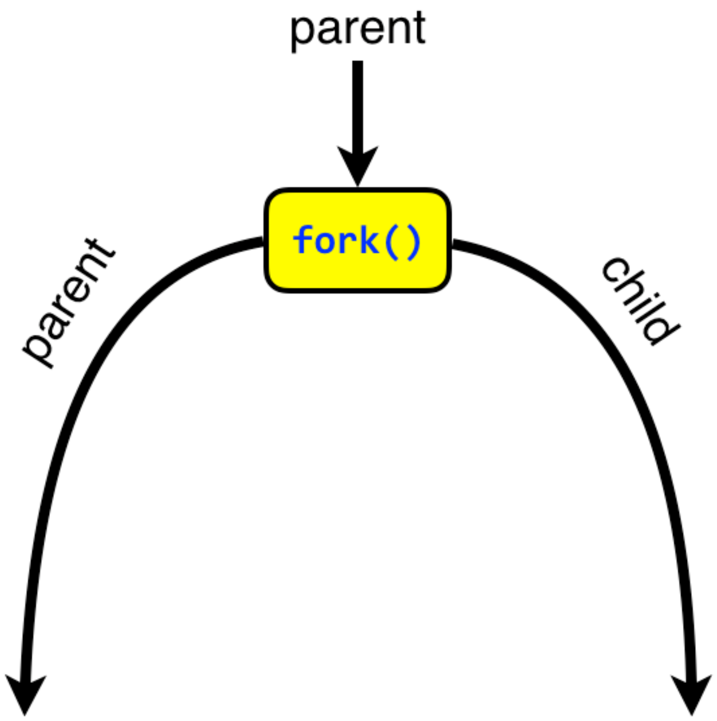
    return 0;
}
```

parent

child

We check the return value of **`fork()`**!



1. Remember, **`fork()`** creates two process that are both actively running

fork() duplicates a process so that instead of one process, you get two!

How can we tell the parent and child apart?

```
int main(void) {
    int pid;

    pid = fork();
    if (0 == pid) {
        // I'm the child
        printf("Hi, I'm the child. \n");
    }

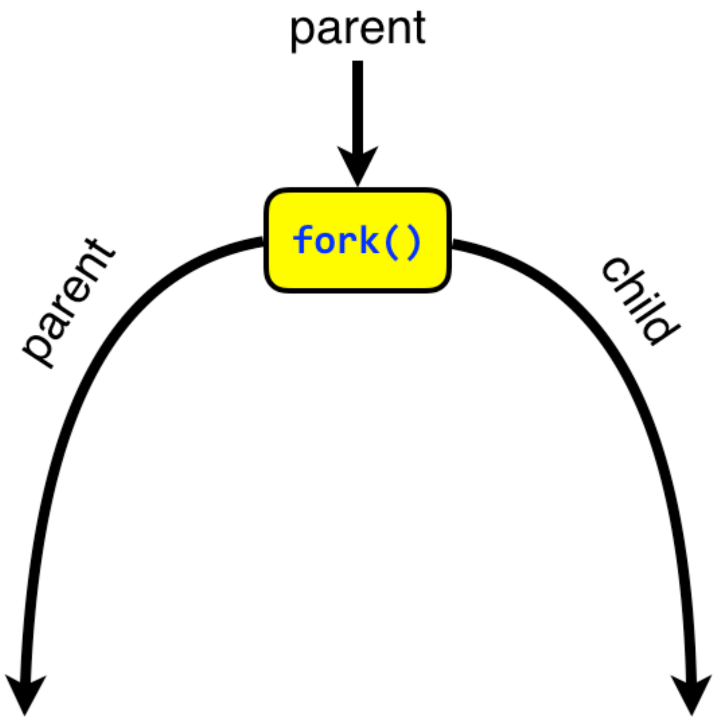
    sleep(1);
    printf("I'm the parent.);

    return 0;
}
```

We check the return value of **fork()**!

child

parent



2. **fork()** always returns 0 for the child process, the parent process jumps to the code after the if statement

`fork()` duplicates a process so that instead of one process, you get two!

How can we tell the parent and child apart?

```
int main(void) {
    int pid;

    pid = fork();
    if (0 == pid) {
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        printf("Hi, I'm the child. \n");
    }

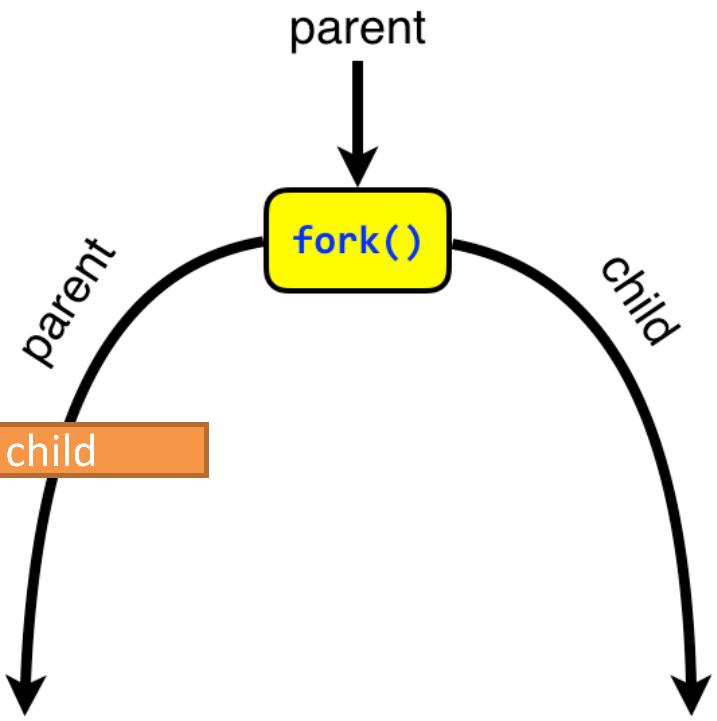
    sleep(1);
    printf("I'm the parent.);

    return 0;
}
```

We check the return value of **`fork()`**!

child

parent



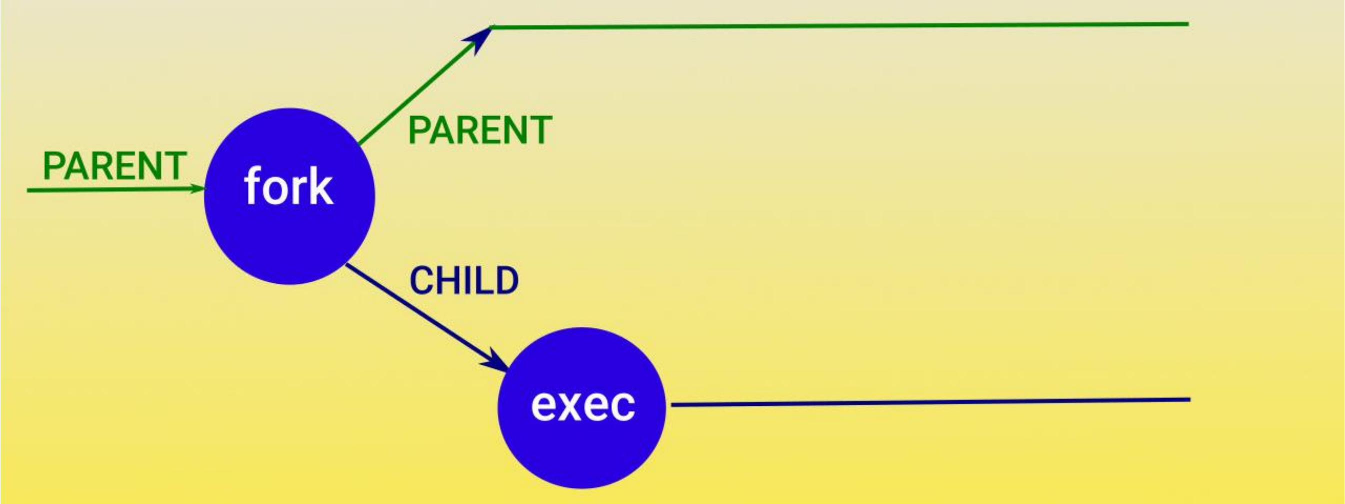
3. **`fork()`** always returns 0 for the child process, so the child process will execute the code in the if statement

Demo?

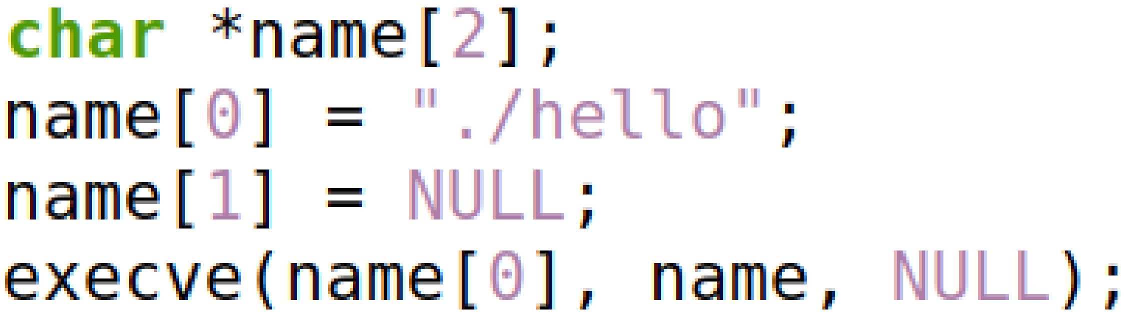
fork1.c

Issue: We want our child process to run an entirely new program (`hello_world` c program)

We use the **`exec()`** family of functions to execute a different program



There are many different forms of the **`exec()`** function call



```
char *name[2];
name[0] = "./hello";
name[1] = NULL;
execve(name[0], name, NULL);
```

Issue: We want our child process to run an entirely new program (`hello_world` c program)

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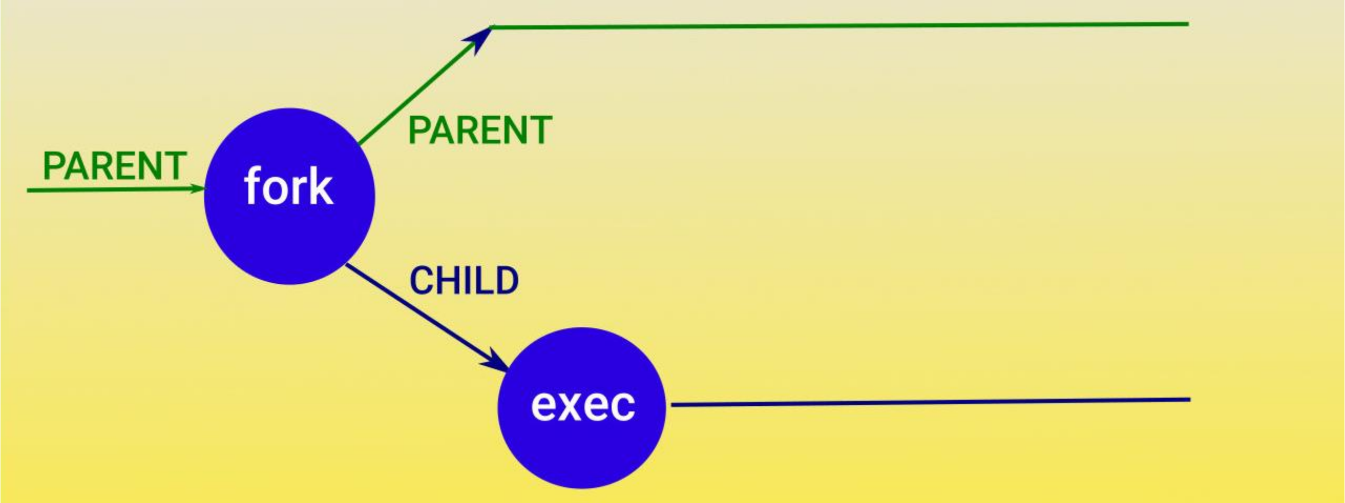
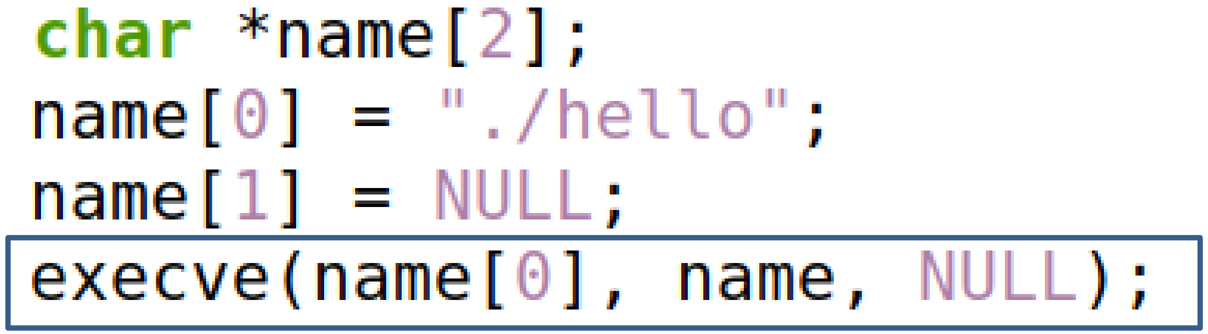


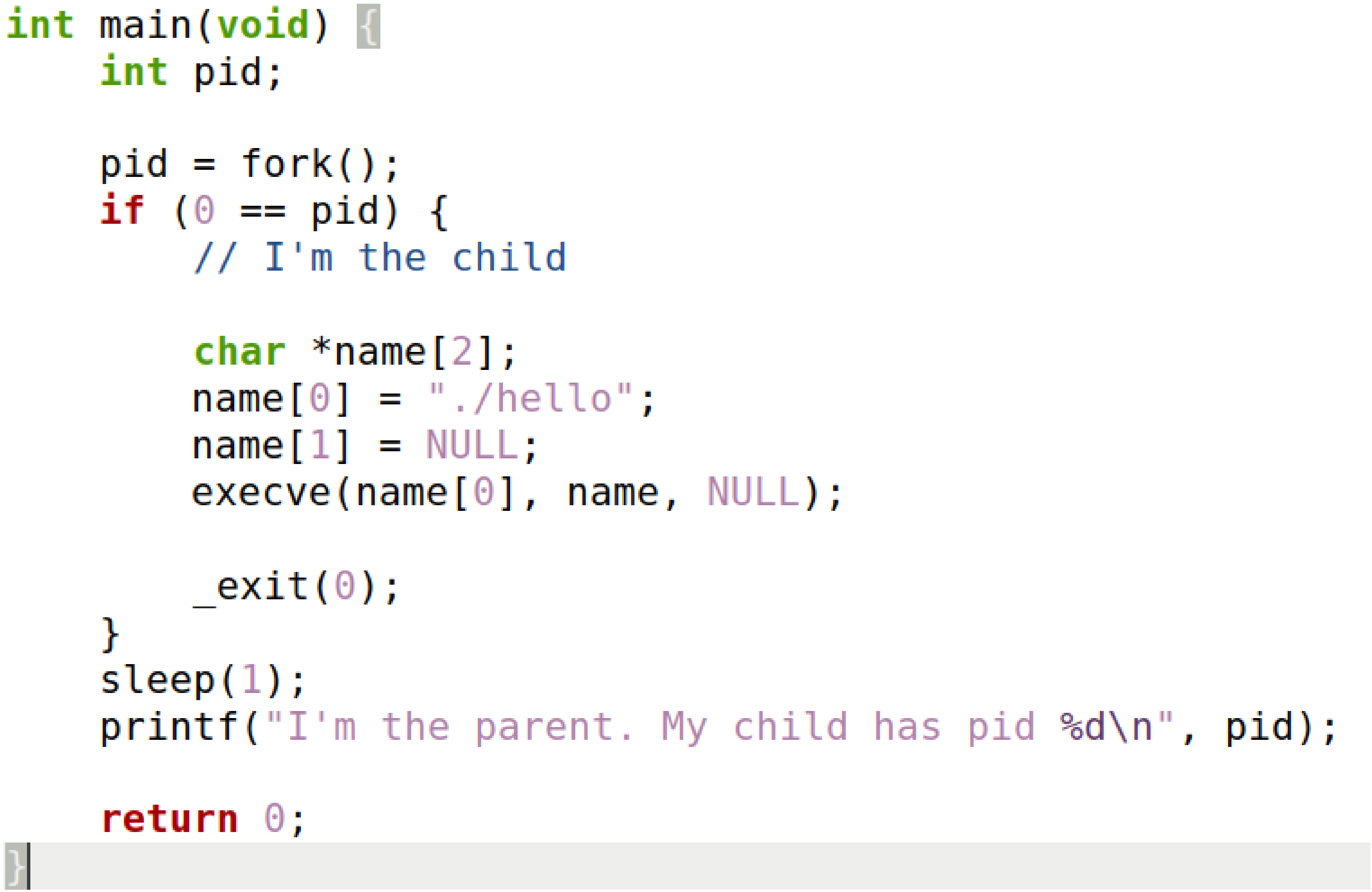
There are many different forms of the **`exec()`** function call



```
char *name[2];
name[0] = "./hello";
name[1] = NULL;
execve(name[0], name, NULL);
```

This will invoke a program called `hello`

Fork() and Exec()



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    int pid;

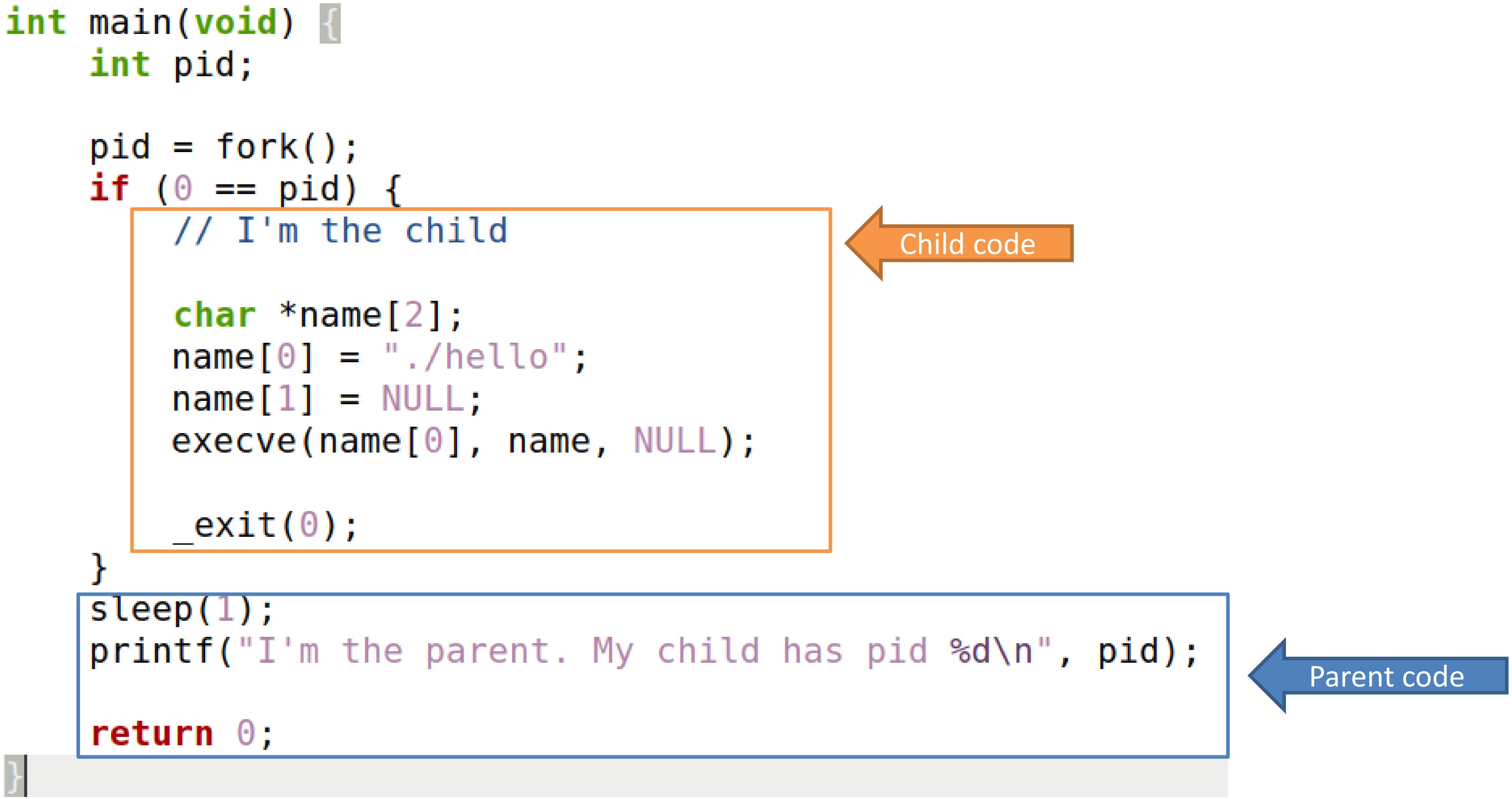
    pid = fork();
    if (0 == pid) {
        // I'm the child

        char *name[2];
        name[0] = "./hello";
        name[1] = NULL;
        execve(name[0], name, NULL);

        _exit(0);
    }
    sleep(1);
    printf("I'm the parent. My child has pid %d\n", pid);

    return 0;
}
```

Fork() and Exec()



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        char *name[2];
        name[0] = "./hello";
        name[1] = NULL;
        execve(name[0], name, NULL);

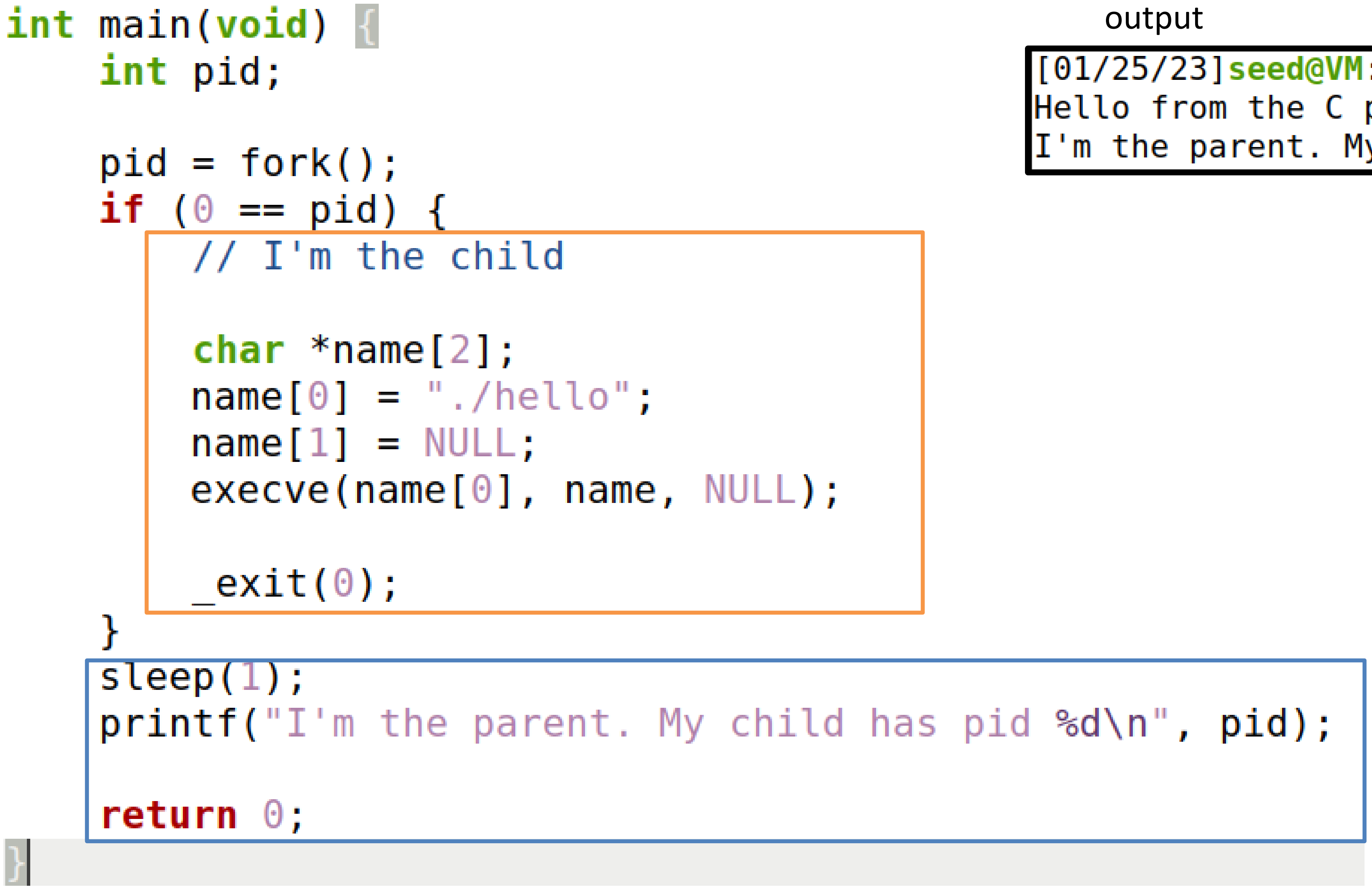
        _exit(0);
    }
    sleep(1);
    printf("I'm the parent. My child has pid %d\n", pid);

    return 0;
}
```

Child code

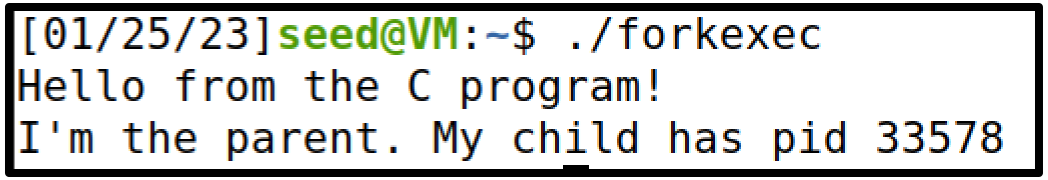
Parent code

Fork() and Exec()



```c
int main(void) {
    int pid;

    pid = fork();
    if (0 == pid) {
        // I'm the child

        char *name[2];
        name[0] = "./hello";
        name[1] = NULL;
        execve(name[0], name, NULL);

        _exit(0);
    }
    sleep(1);
    printf("I'm the parent. My child has pid %d\n", pid);

    return 0;
}
```

output



```
[01/25/23]seed@VM:~$ ./forkexec
Hello from the C program!
I'm the parent. My child has pid 33578
```

Demo?

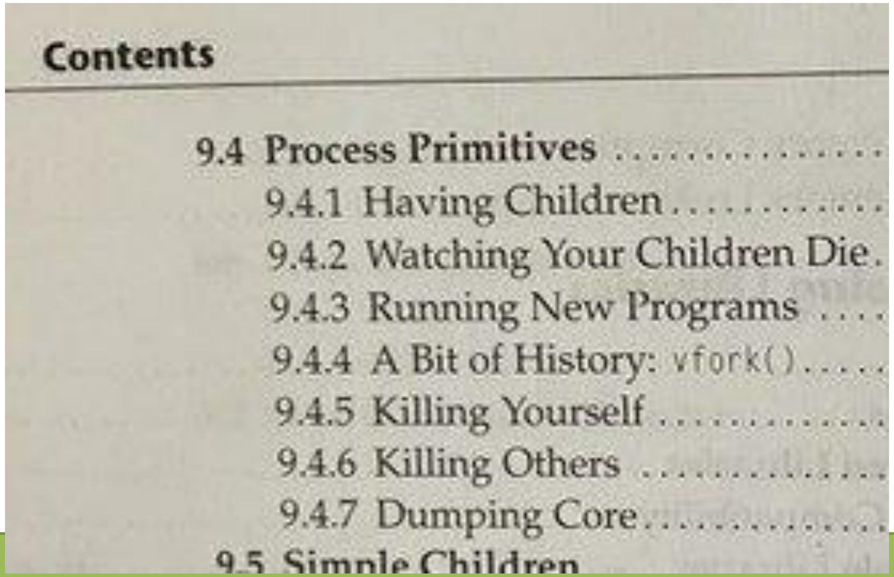
forkandexec.c

Tl;dr

The programs we run get turned into a **process**

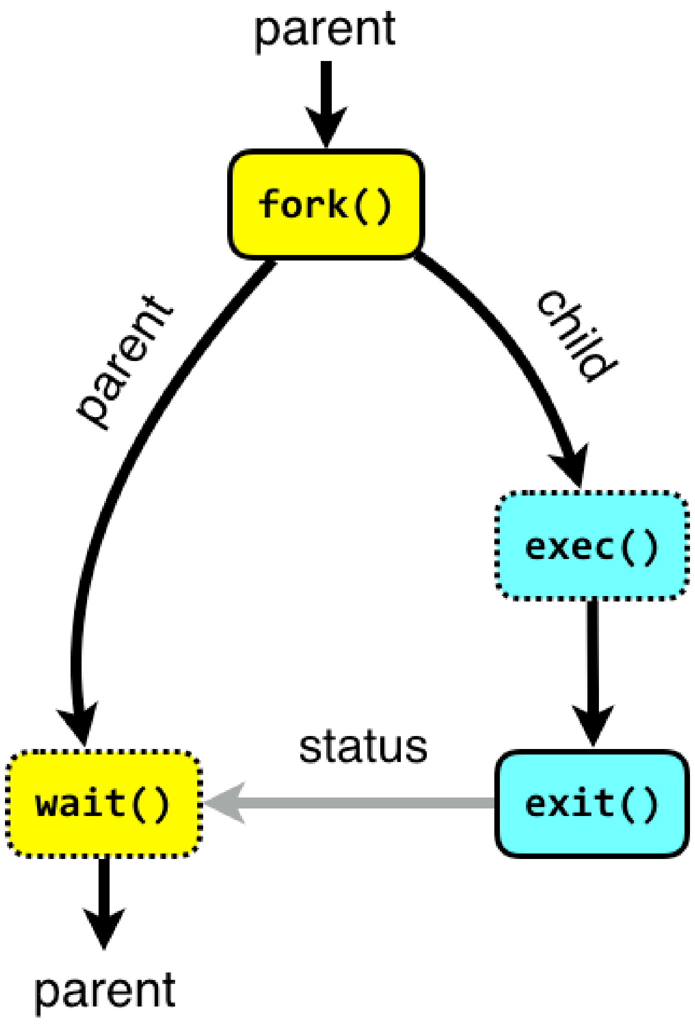
fork() is used to create a new process

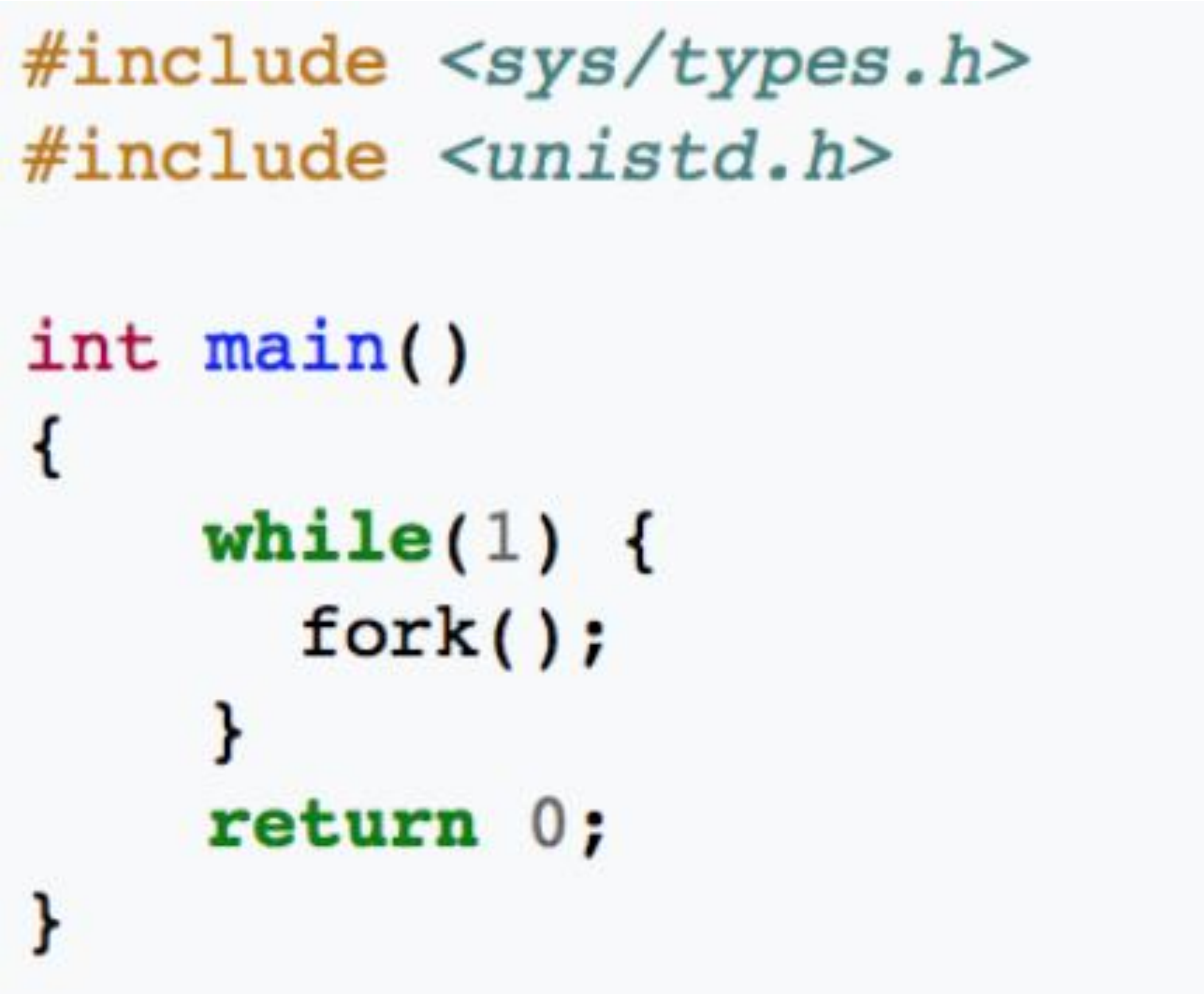
- The parent process is typically the shell/terminal, and waits for the child process to finish
- The child process runs **exec()** to run our program



Contents

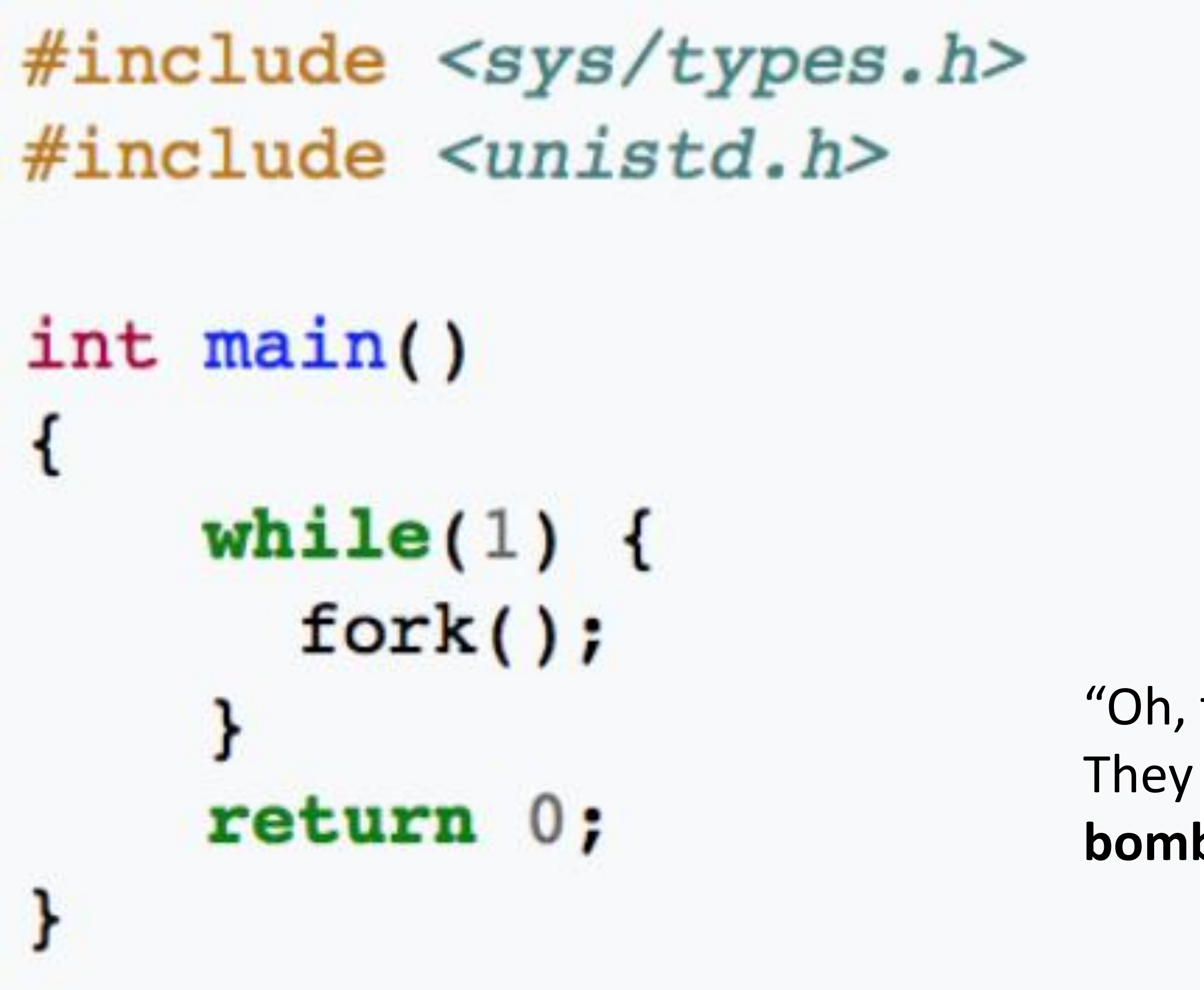
you can kill children with the `kill()` function or `kill` command





```c
#include <sys/types.h>
#include <unistd.h>

int main()
{
    while(1) {
      fork();
    }
    return 0;
}
```

Any ideas what might happen?



```c
#include <sys/types.h>
#include <unistd.h>

int main()
{
    while(1) {
      fork();
    }
    return 0;
}
```

“Oh, these forks() aren’t homemade. They were made in factory. A **fork() bomb** factory. This is a **fork() bomb**”

A **process** is an instance of a running program on a computer

All processes have the following data while they are running:

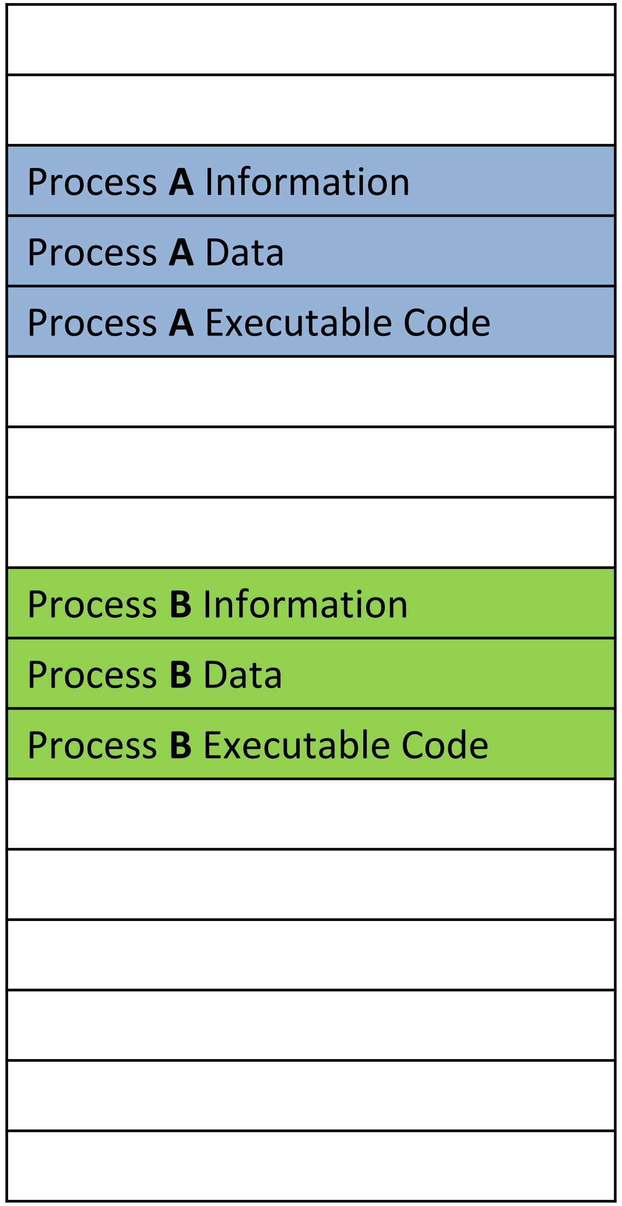
1. Executable Code

2. Associated Data

3. Execution Context/Bookkeeping information

(info that the OS needs to handle the process)

Main Memory



Process **A** Information

Process **A** Data

Process **A** Executable Code

Process **B** Information

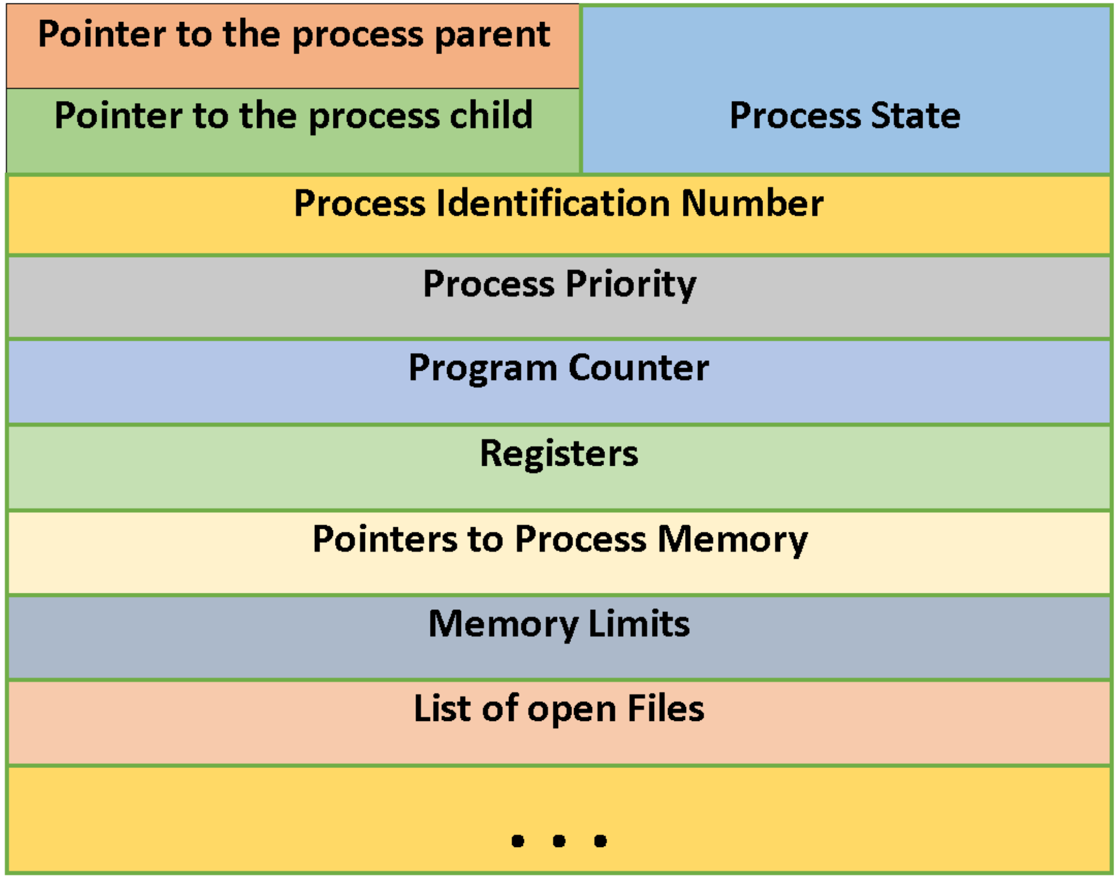
Process **B** Data

Process **B** Executable Code

3. Execution Context/Bookkeeping information

- Each process has a **Process Control Block (PCB)**
  - → Simply just a data structure that holds information
  - → The name of this varies by OS

Example PCB:



Pointer to the process parent

Pointer to the process child

Process State

Process Identification Number

Process Priority

Program Counter

Registers

Pointers to Process Memory

Memory Limits

List of open Files

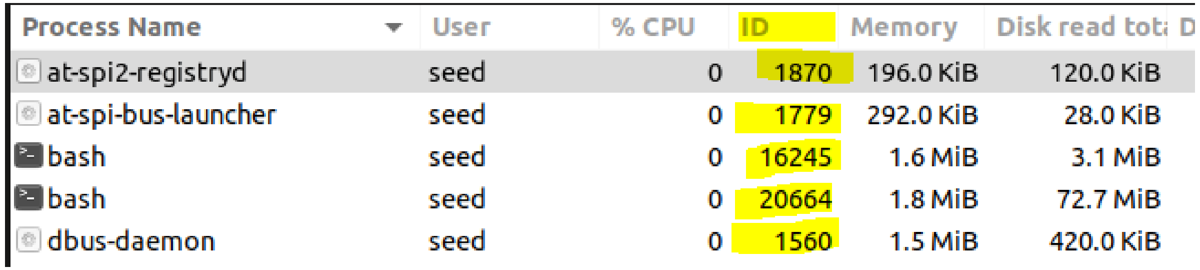
• • •

Created by Notes Jam

3. Execution Context/Bookkeeping information

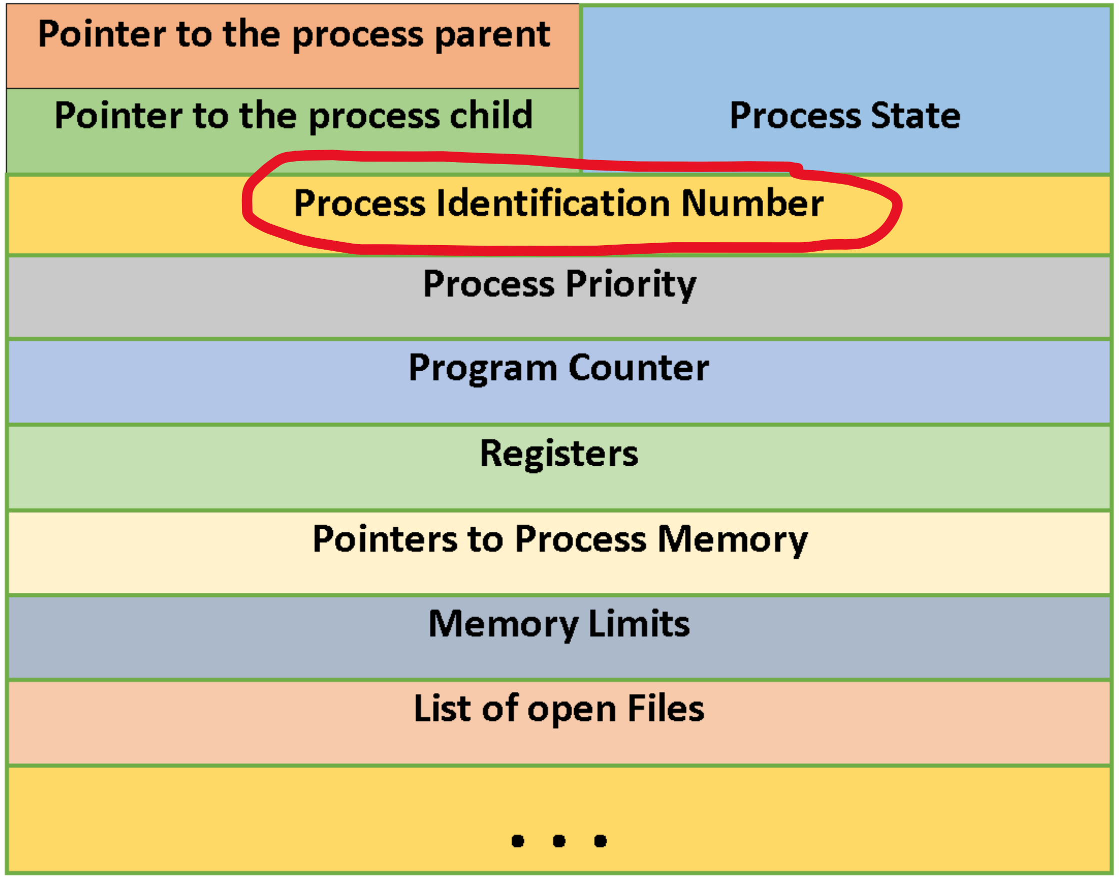
- Each process has a **Process Control Block (PCB)**
  → Simply just a data structure that holds information
  → The name of this varies by OS

Every process has a unique process ID (PID)



Process Name	User	% CPU	ID	Memory	Disk read tot:	D
at-spi2-registryd	seed	0	1870	196.0 KiB	120.0 KiB	
at-spi-bus-launcher	seed	0	1779	292.0 KiB	28.0 KiB	
bash	seed	0	16245	1.6 MiB	3.1 MiB	
bash	seed	0	20664	1.8 MiB	72.7 MiB	
dbus-daemon	seed	0	1560	1.5 MiB	420.0 KiB	

Example PCB:



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. . .

We can use the PID to search for process, kill process, fork new process, etc

3. Execution Context/Bookkeeping information

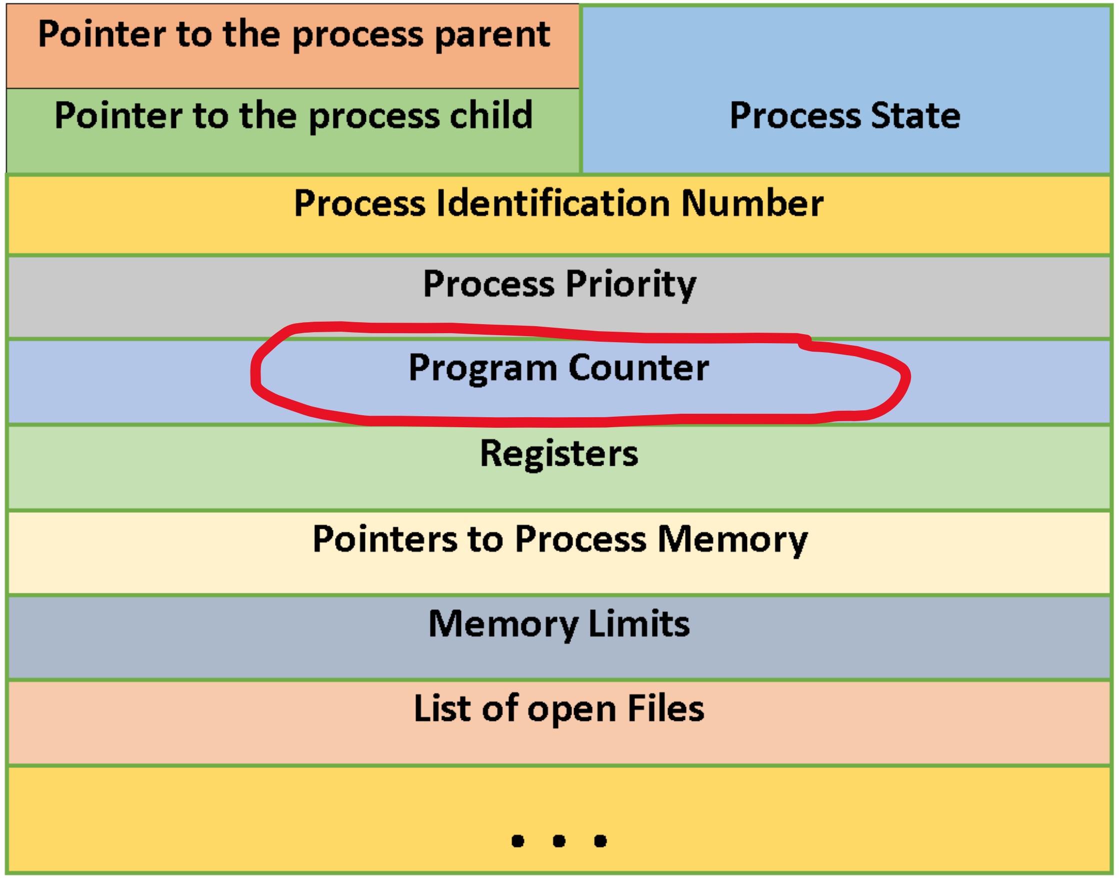
- Each process has a **Process Control Block (PCB)**

  → Simply just a data structure that holds information

  → The name of this varies by OS

Each process has a program counter (PC), which tells the CPU the next instruction to run in the process

Example PCB:



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3. Execution Context/Bookkeeping information

- Each process has a **Process Control Block (PCB)**
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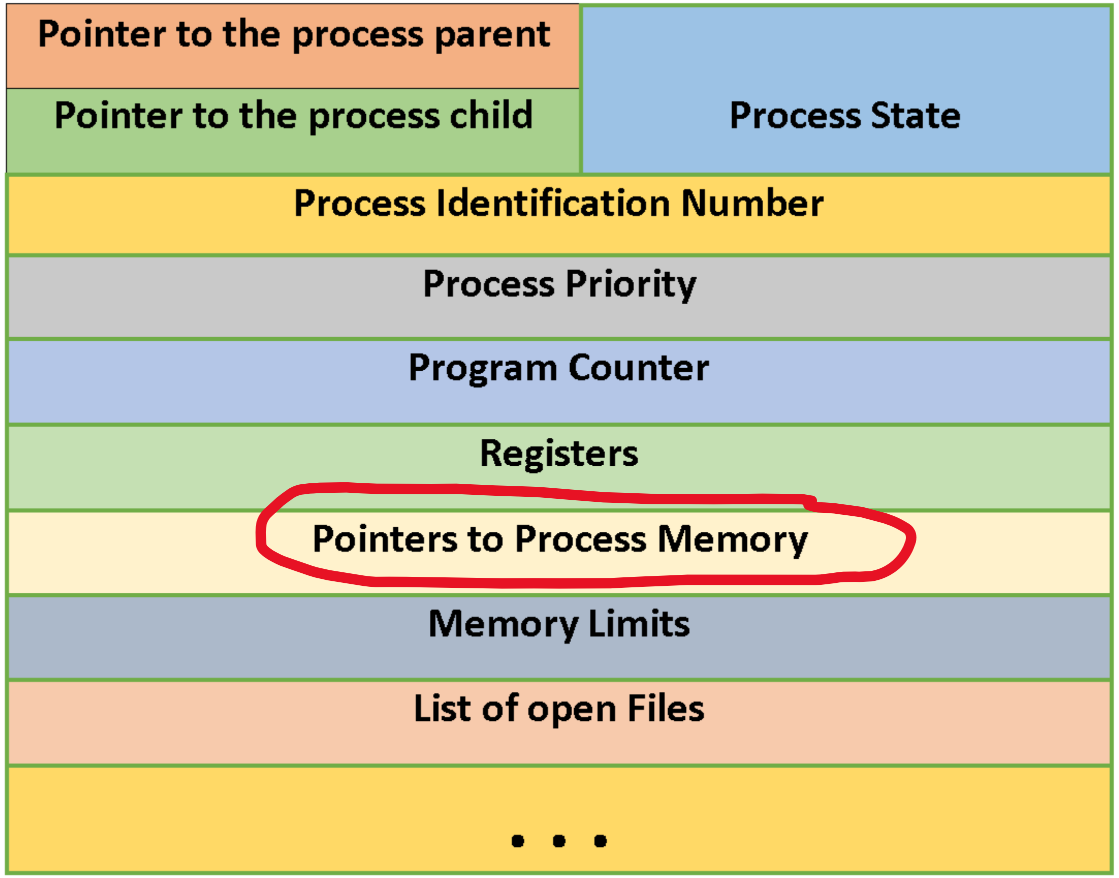
PCB also maintains locations for the process Data and Code

Example PCB:



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Memory Limits

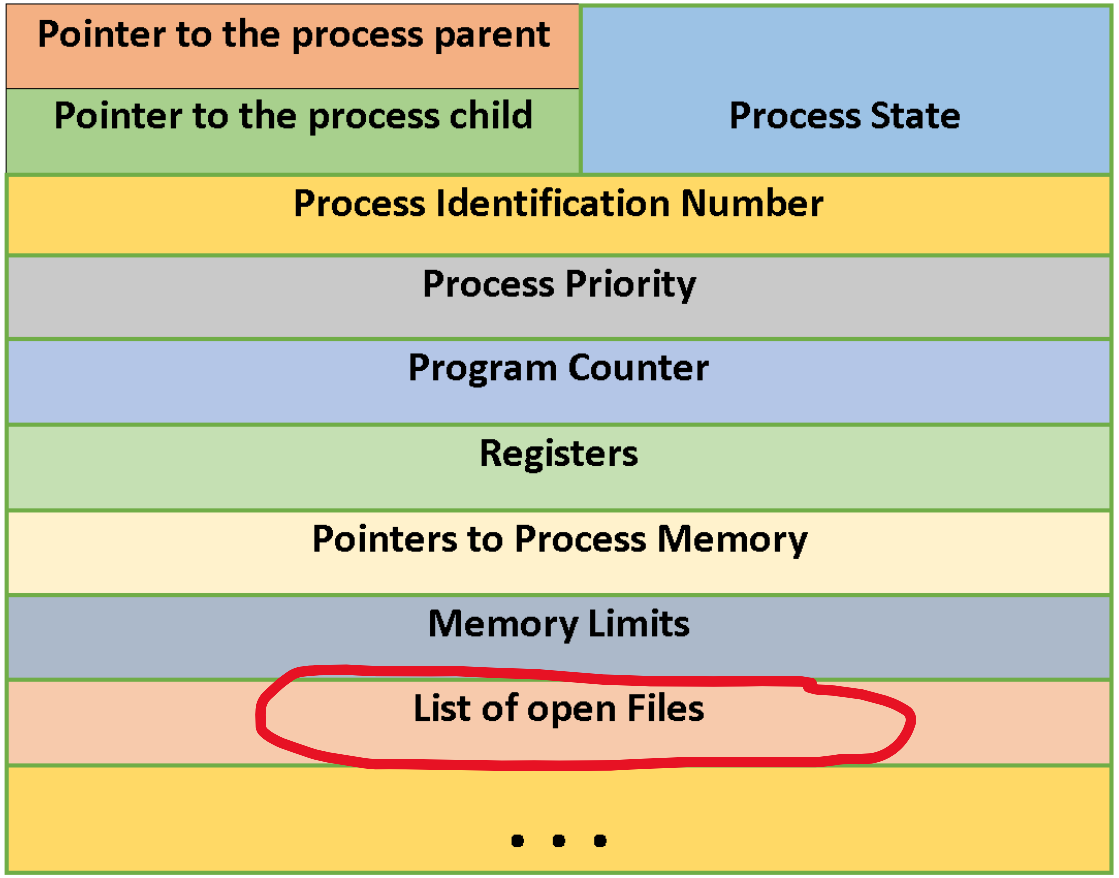
List of open Files

. . .

3. Execution Context/Bookkeeping information

- Each process has a **Process Control Block (PCB)**
  - → Simply just a data structure that holds information
  - → The name of this varies by OS

Example PCB:



Pointer to the process parent

Pointer to the process child

Process State

Process Identification Number

Process Priority

Program Counter

Registers

Pointers to Process Memory

Memory Limits

List of open Files

. . .

3. Execution Context/Bookkeeping information

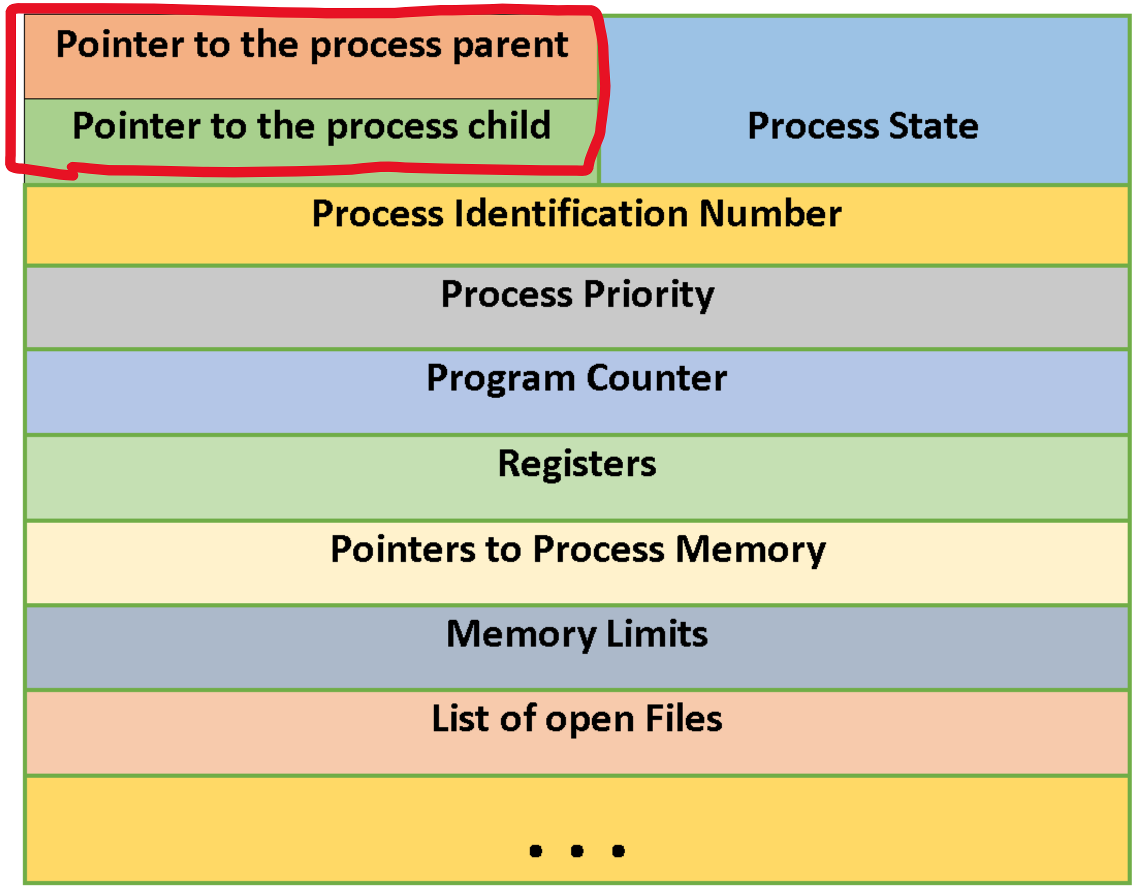
- Each process has a **Process Control Block (PCB)**

  → Simply just a data structure that holds information

  → The name of this varies by OS

PCB keeps track of who their parent is, and any child process (good parenting)

Example PCB:



Pointer to the process parent

Pointer to the process child

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List of open Files

. . .

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3. Execution Context/Bookkeeping information

- Each process has a **Process Control Block (PCB)**

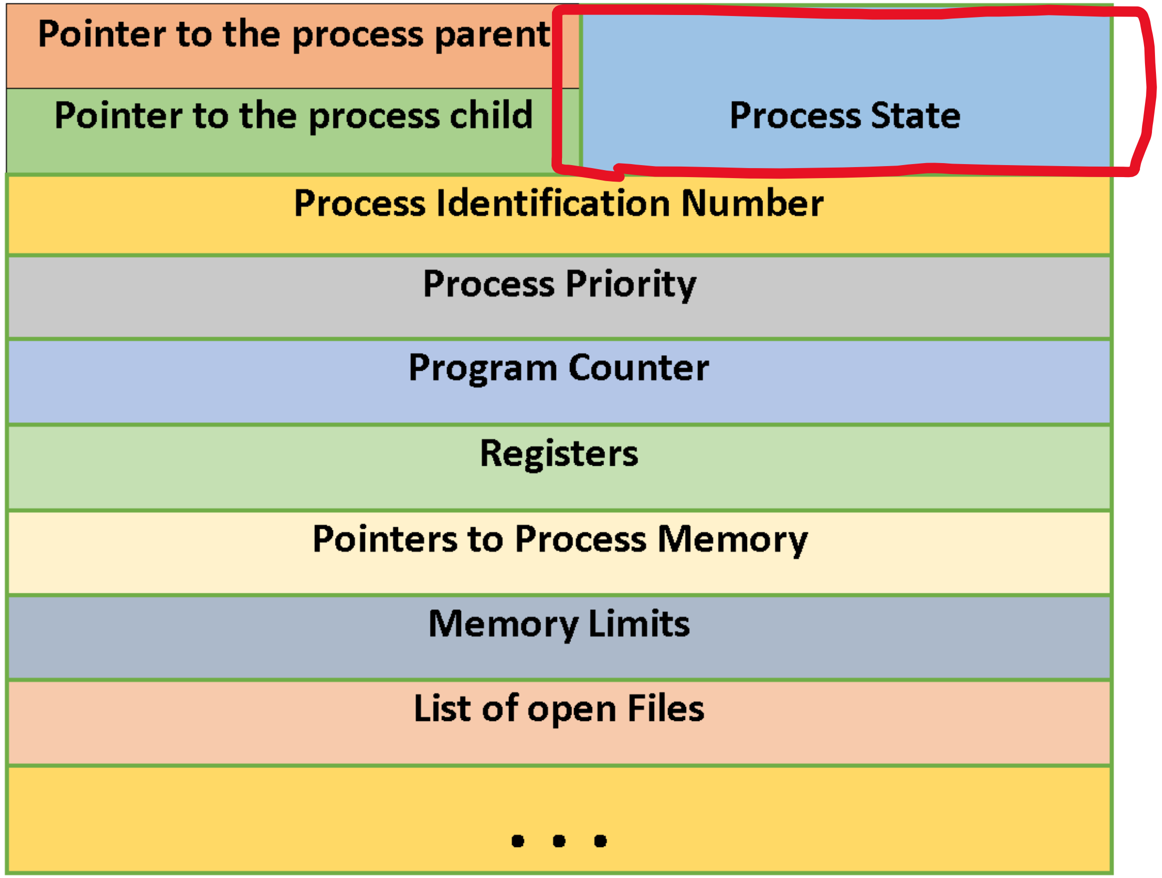
  → Simply just a data structure that holds information

  → The name of this varies by OS

A process goes through many **states**

- **Active (running)**
- **Blocked**
- **Waiting**
- **Suspended**

Example PCB:



Pointer to the process parent

Pointer to the process child

Process State

Process Identification Number

Process Priority

Program Counter

Registers

Pointers to Process Memory

Memory Limits

List of open Files

. . .

A **process** is an instance of a running program on a computer

All processes have the following data while they are running:

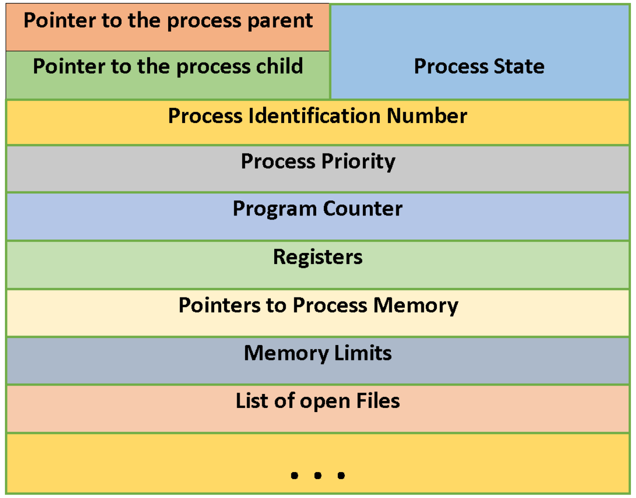
1. Executable Code

2. Associated Data

We will talk about what goes here shortly

3. Execution Context/Bookkeeping information

(info that the OS needs to handle the process)



Pointer to the process parent	Process State
Pointer to the process child	
Process Identification Number	
Process Priority	
Program Counter	
Registers	
Pointers to Process Memory	
Memory Limits	
List of open Files	
. . .	

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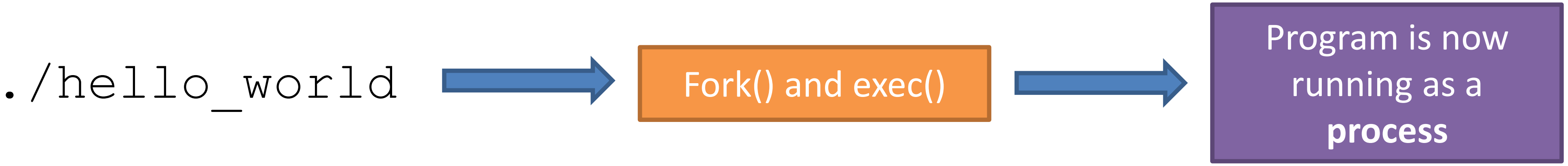
The jobs of an Operating System

1. Process Manager

"The Coach"

The OS manages many active processes all at once, and they must create processes, manage current process, and control which processes do what



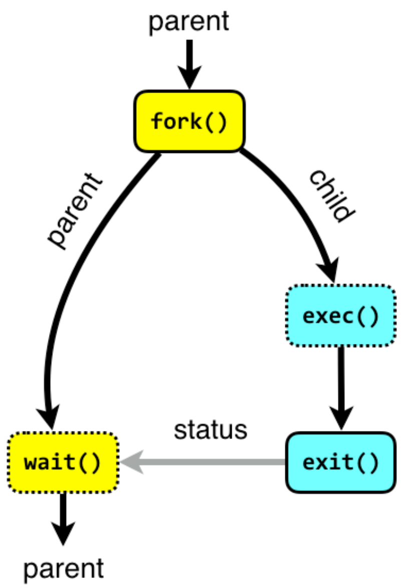
`./hello_world`

Fork() and exec()

Program is now running as a **process**

A **process** is an instance of a running program on a computer

All processes have the following data while they are running:



1. Executable Code

2. Associated Data

3. Execution Context/Bookkeeping information

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. . .	

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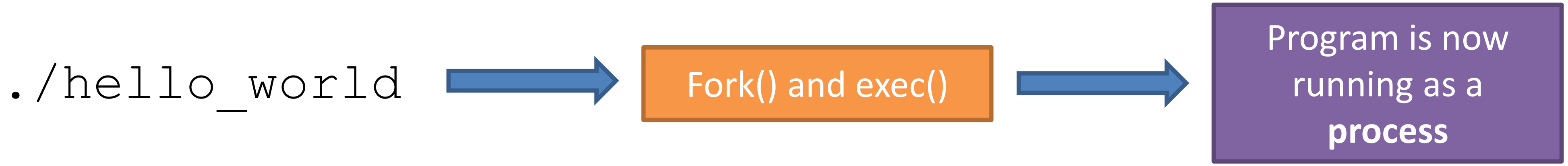


```
./hello_world
```

Fork() and exec()

Program is now running as a **process**

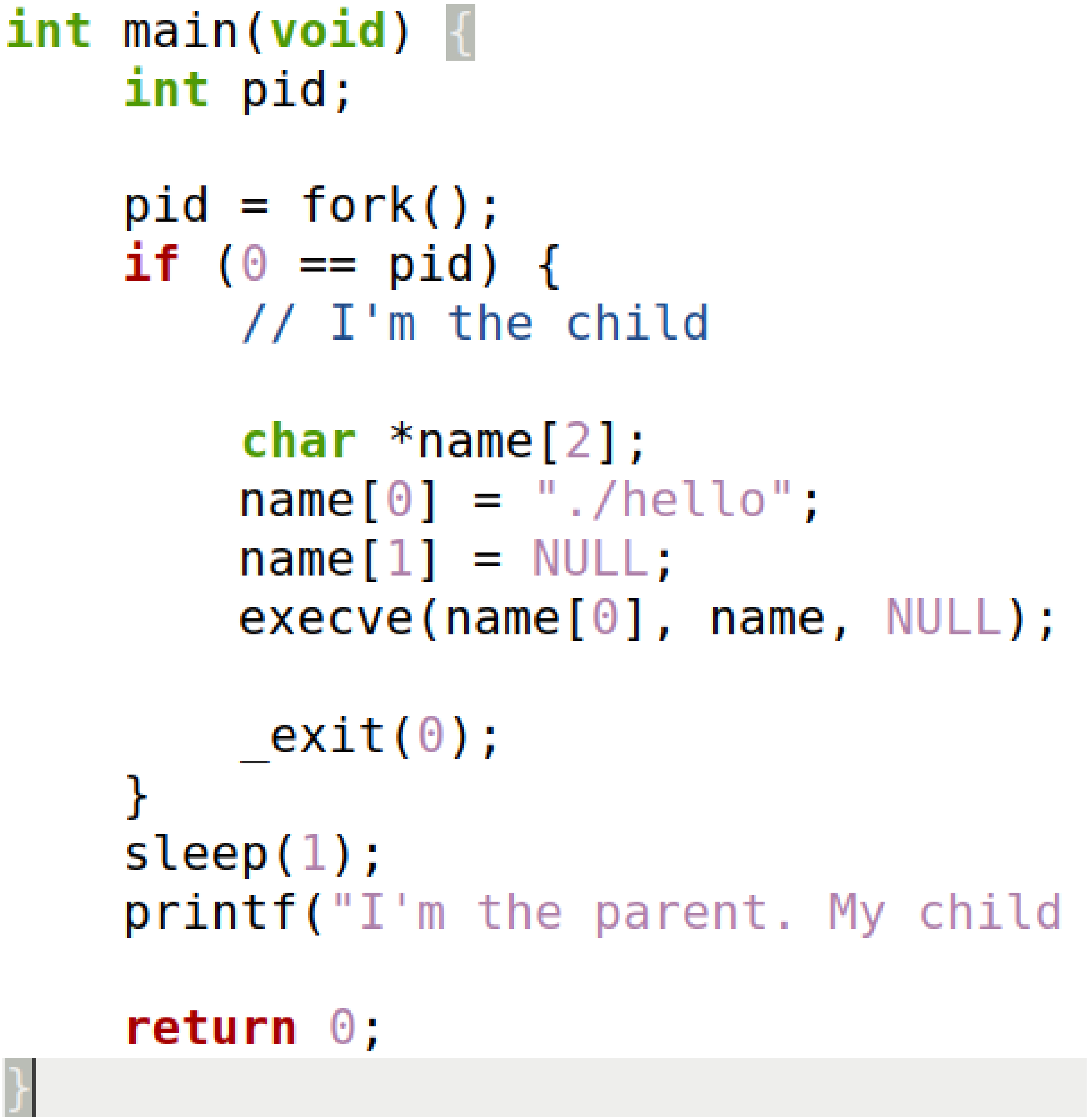
Demo time!

```
int main(void) {
    int pid;

    pid = fork();
    if (0 == pid) {
        // I'm the child
        printf("Hi, I'm the child. \n");
    }

    sleep(1);
    // we could wait() here
    printf("I'm the parent.);

    return 0;
}
```



```
int main(void) {
    int pid;

    pid = fork();
    if (0 == pid) {
        // I'm the child

        char *name[2];
        name[0] = "./hello";
        name[1] = NULL;
        execve(name[0], name, NULL);

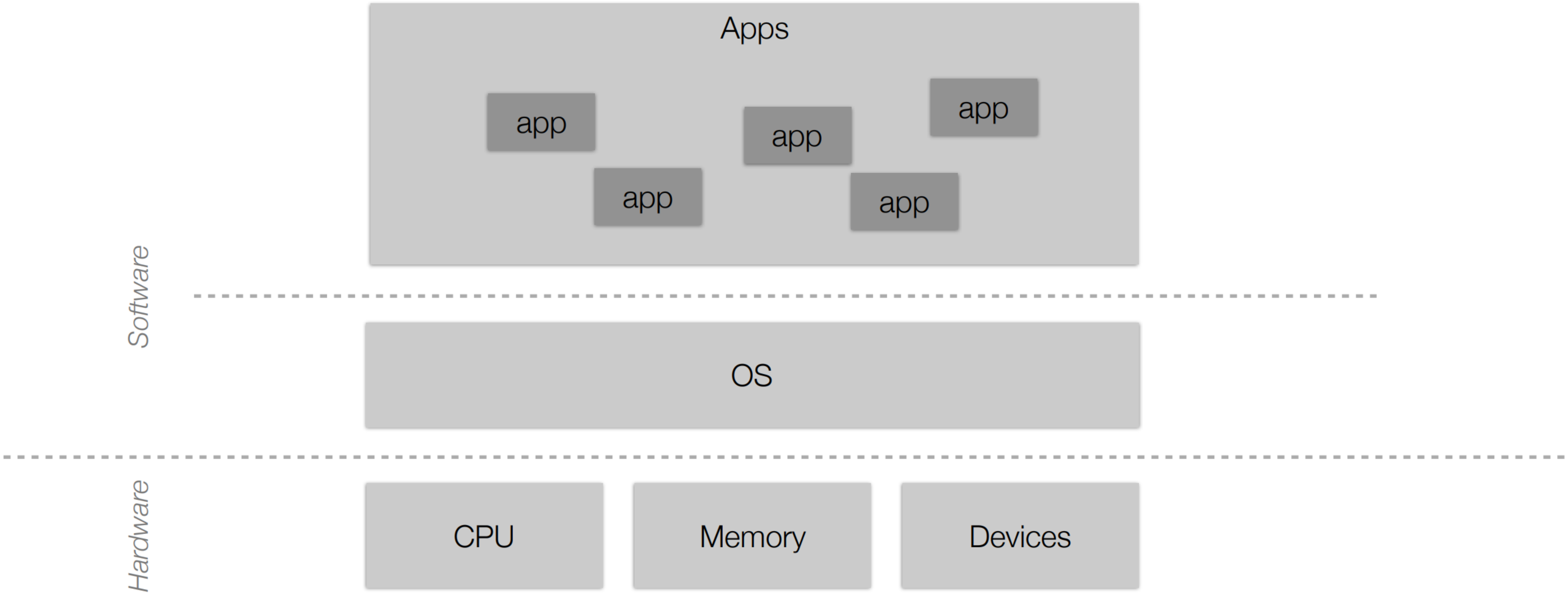
        _exit(0);
    }
    sleep(1);
    printf("I'm the parent. My child

    return 0;
}
```

The jobs of an Operating System

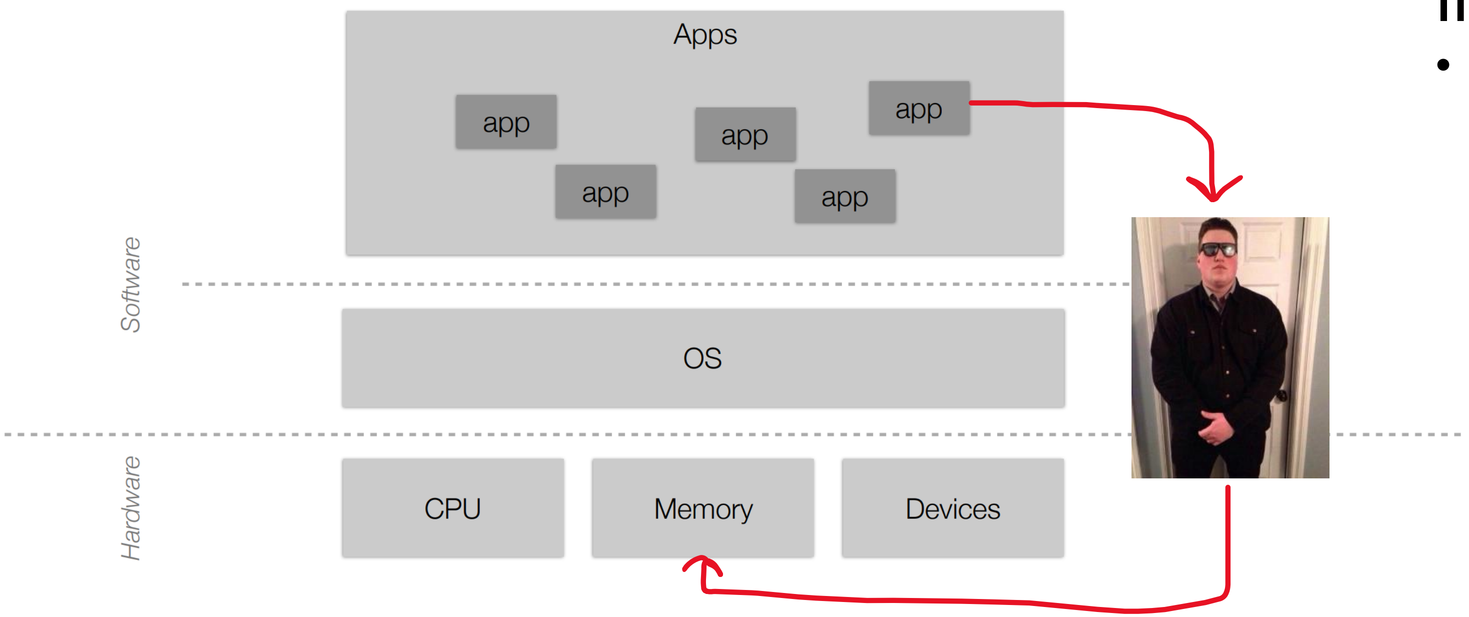
1. **Process Manager**
   “The Coach”
2. **Interface Manager**
   “The Bouncer”
3. **Memory Manager**
   “The Farmer”
4. **Traffic Manager**
   “The Judge”
5. **Illusion Manager**
   “The Illusionist”

Operating Systems Review



Operating Systems Review

Responsibilities of the OS?

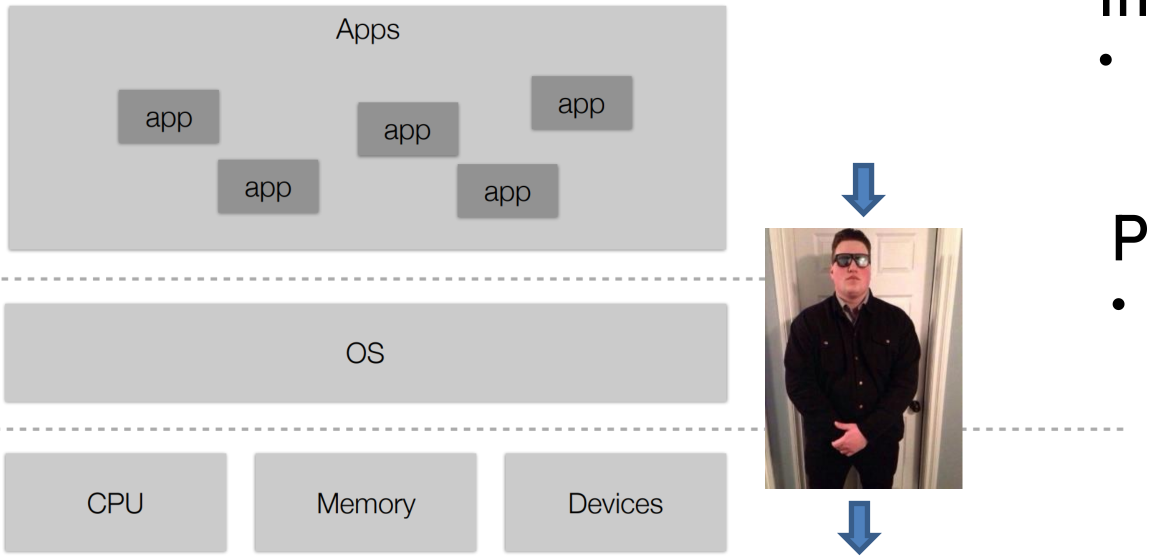


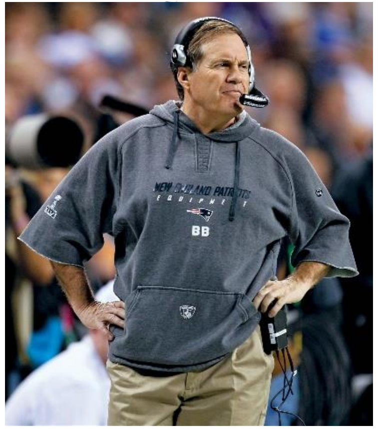
Interface Manager

- Manages communication between apps and hardware

Operating Systems Review

Responsibilities of the OS?





Interface Manager

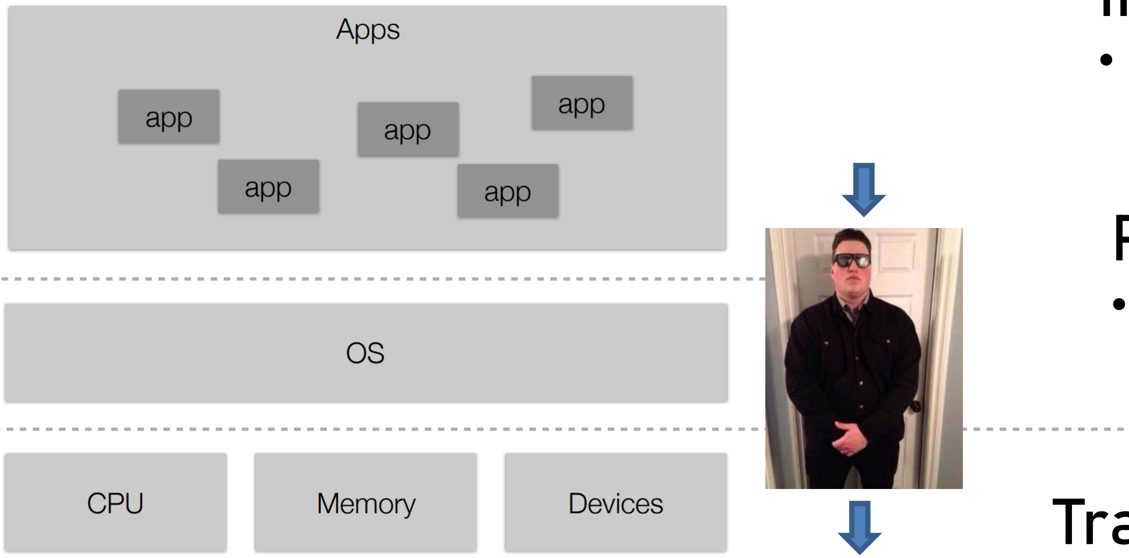
- Manages communication between apps and hardware

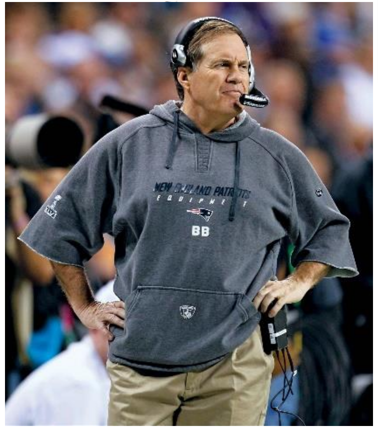
Process Manager

- Manages how processes are structured and how to handle many processes running at once

Operating Systems Review

Responsibilities of the OS?





Interface Manager

- Manages communication between apps and hardware

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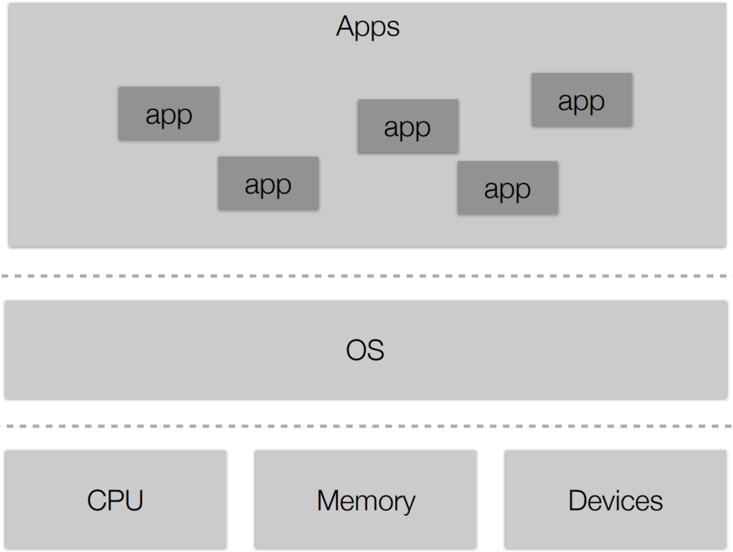
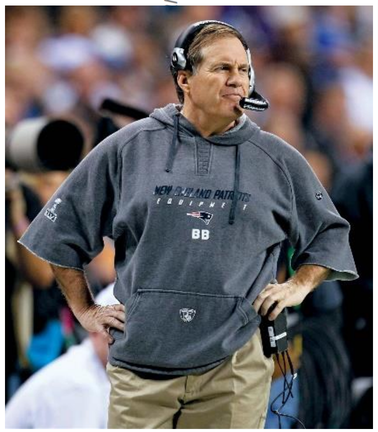
Traffic Manager

- Manages which programs should be executed by the CPU

Operating Systems Review

Responsibilities of the OS?





Interface Manager

- Manages communication between apps and hardware

Process Manager

- Manages how processes are structured and how to handle many processes running at once

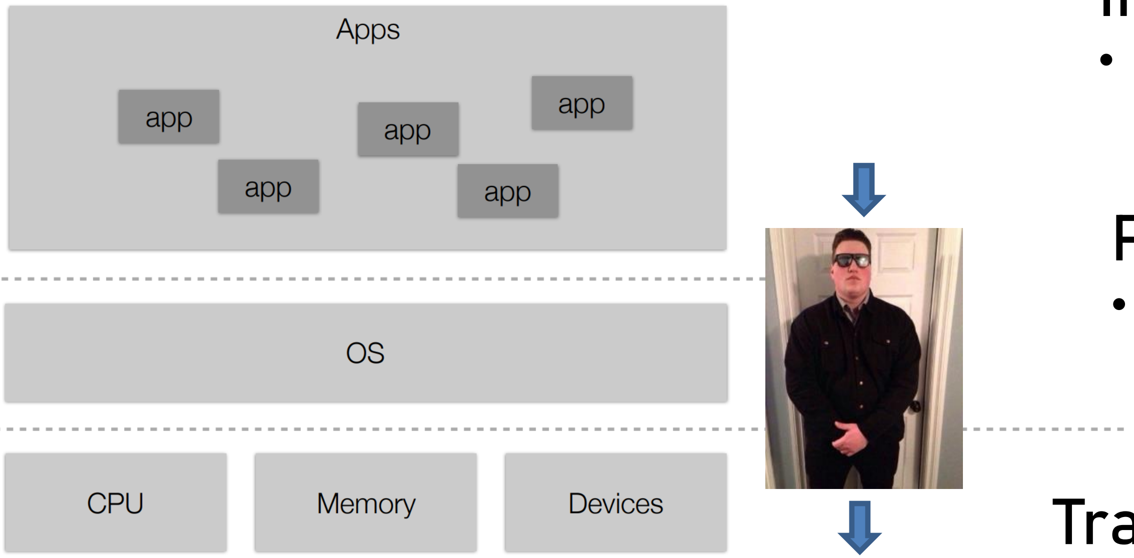
Traffic Manager

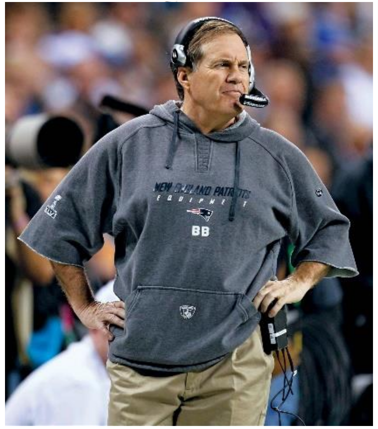
- Manages which programs should be executed by the CPU

Memory Manager

- Manages how physical memory is utilized

Operating Systems Review





Responsibilities of the OS?

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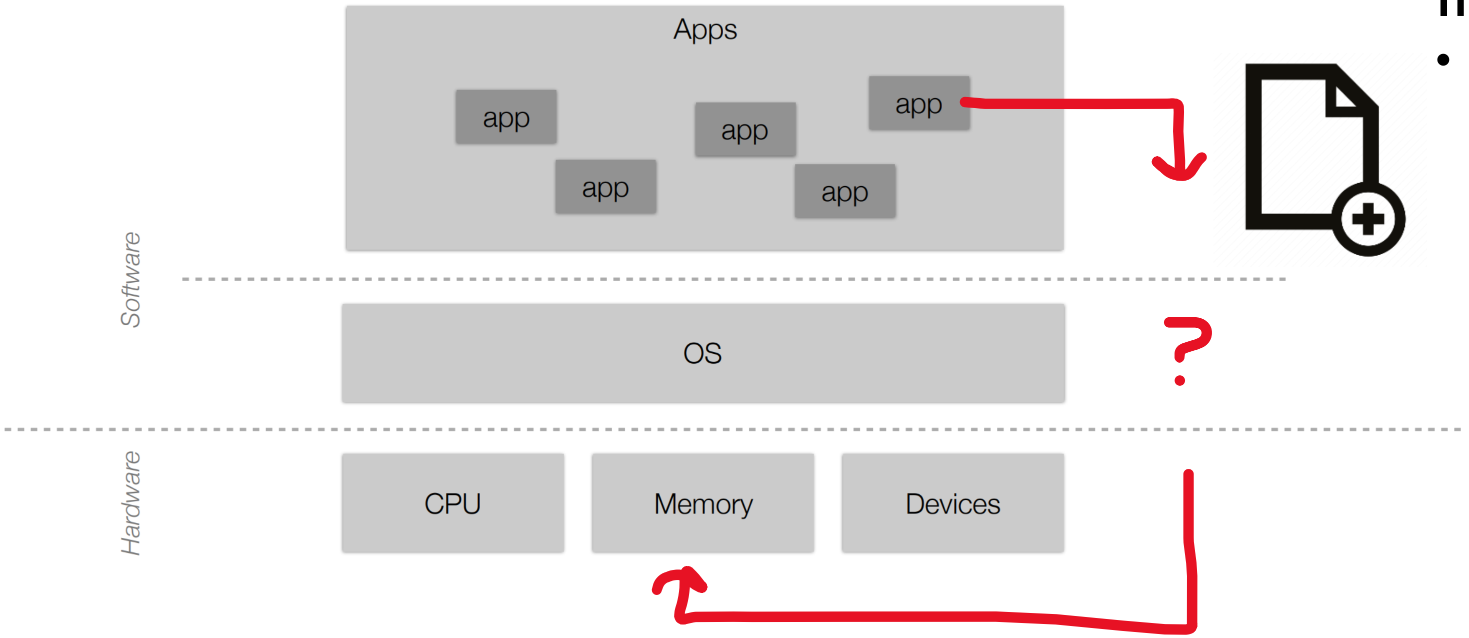
Operating Systems Review

Responsibilities of the OS?



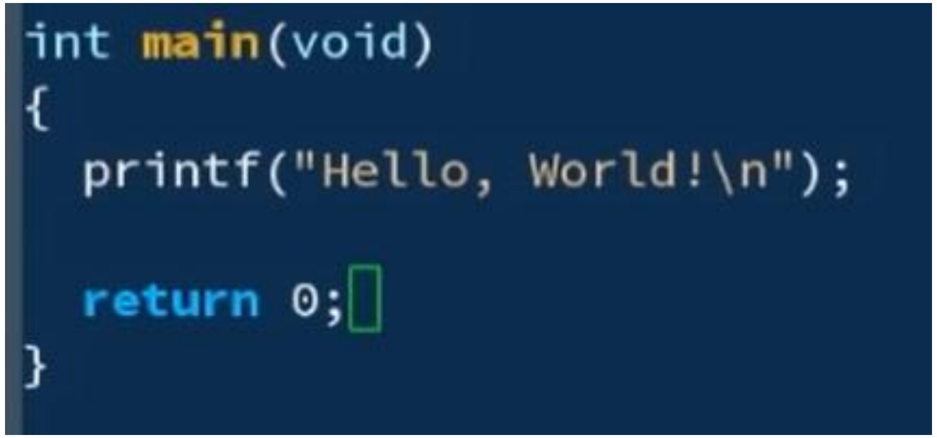
Interface Manager

- Manages communication between apps and hardware

How does an application get access to a computer's resources?

Syscalls

Applications evoke operating system defined functions, or **system calls** (**syscalls**), to access computing resources

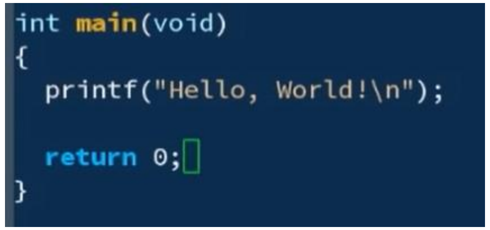


```
int main(void)
{
  printf("Hello, World!\n");

  return 0;
}
```

Syscalls

Applications evoke operating system defined functions, or **system calls** (**syscalls**), to access computing resources



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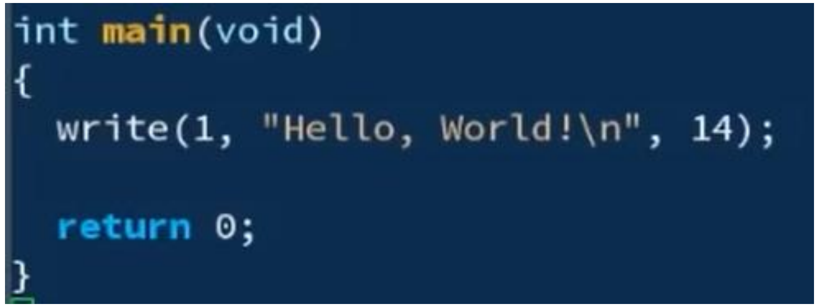
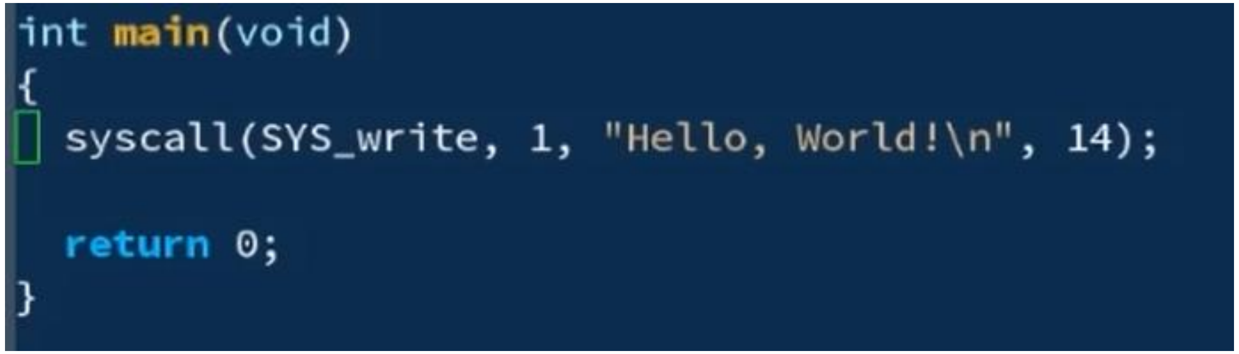


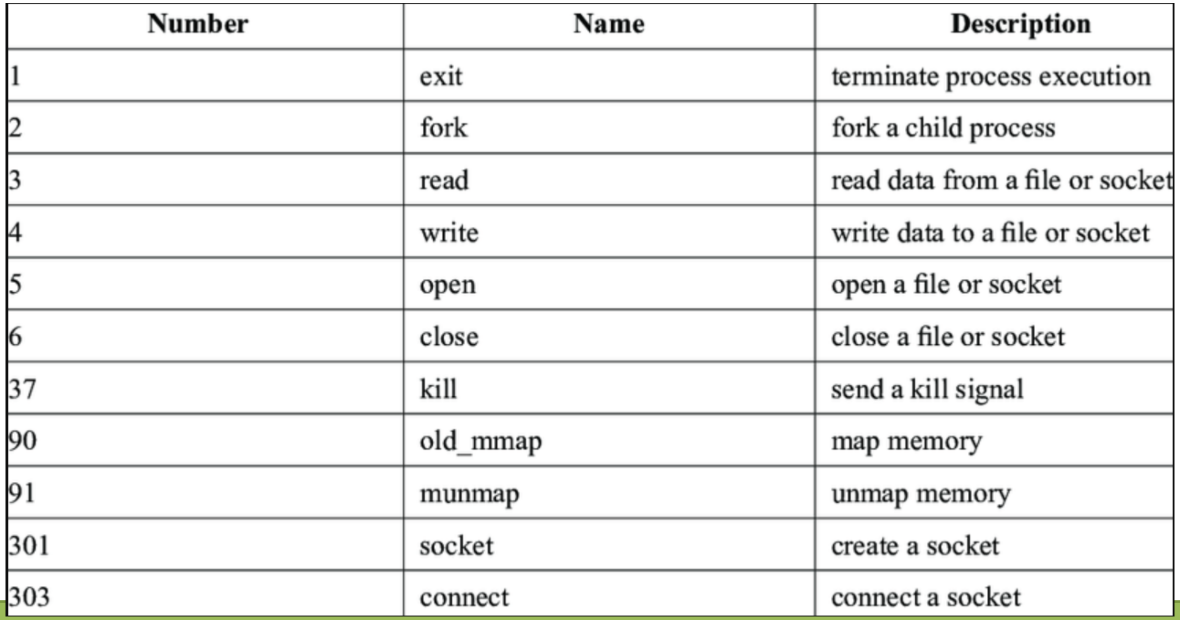
```
int main(void)
{
  write(1, "Hello, World!\n", 14);

  return 0;
}
```



```
int main(void)
{
  syscall(SYS_write, 1, "Hello, World!\n", 14);

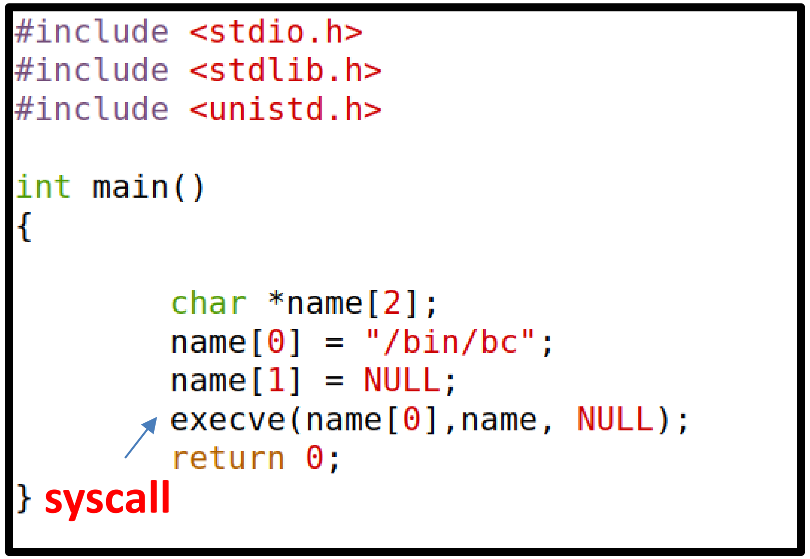
  return 0;
}
```



Number	Name	Description
1	exit	terminate process execution
2	fork	fork a child process
3	read	read data from a file or socket
4	write	write data to a file or socket
5	open	open a file or socket
6	close	close a file or socket
37	kill	send a kill signal
90	old_mmap	map memory
91	munmap	unmap memory
301	socket	create a socket
303	connect	connect a socket

Syscalls

Applications evoke operating system defined functions, or **system calls** (**syscalls**), to access computing resources

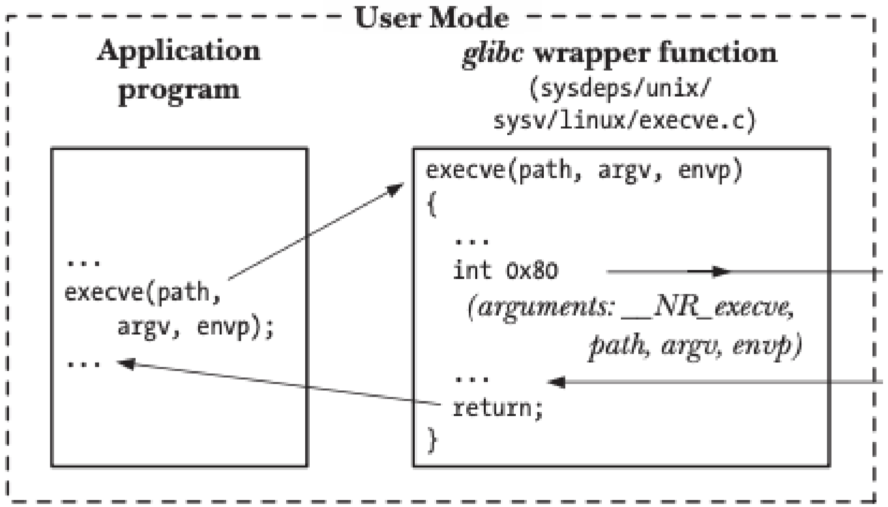


```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

int main()
{

        char *name[2];
        name[0] = "/bin/bc";
        name[1] = NULL;
        execve(name[0],name, NULL);
        return 0;
}
```

syscall



```
...
execve(path,
    argv, envp);
...
```

```
execve(path, argv, envp)
{
  ...
  int 0x80
   (arguments: __NR_execve,
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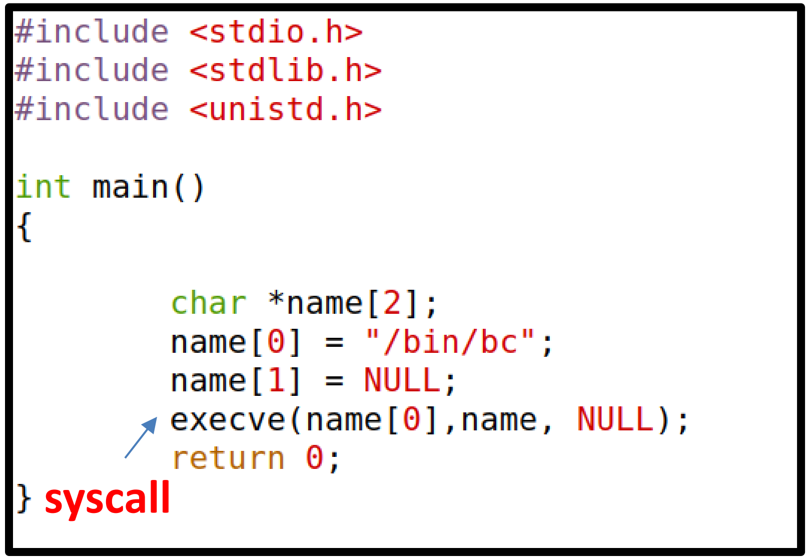
  ...
  return;
}
```

Syscalls

Applications evoke operating system defined functions, or **system calls** (**syscalls**), to access computing resources



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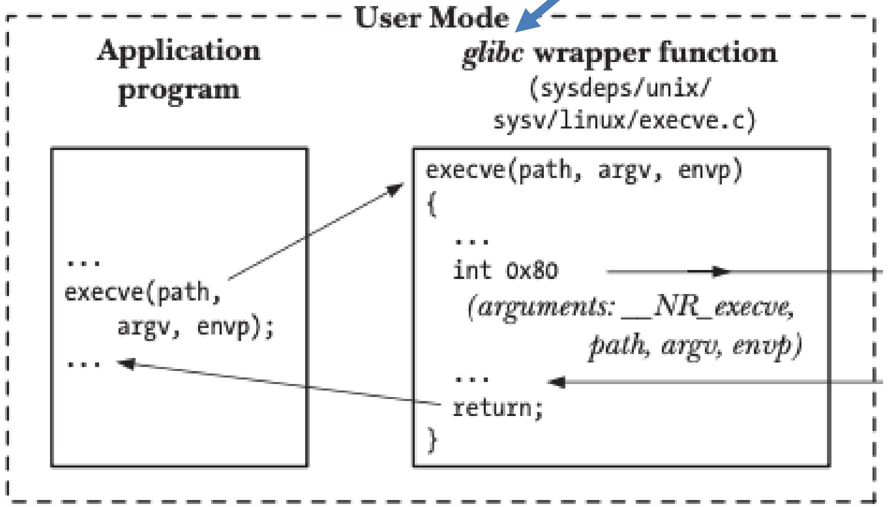
syscall

Libraries handle the system calls for us



Syscalls

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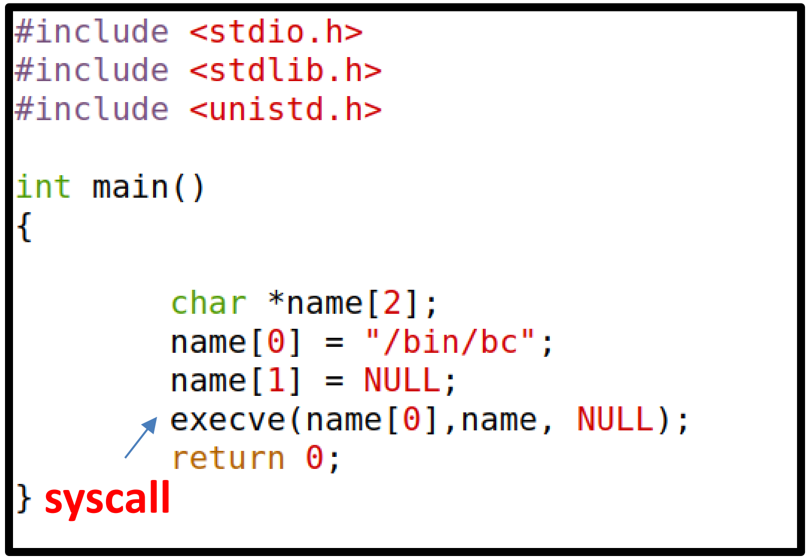

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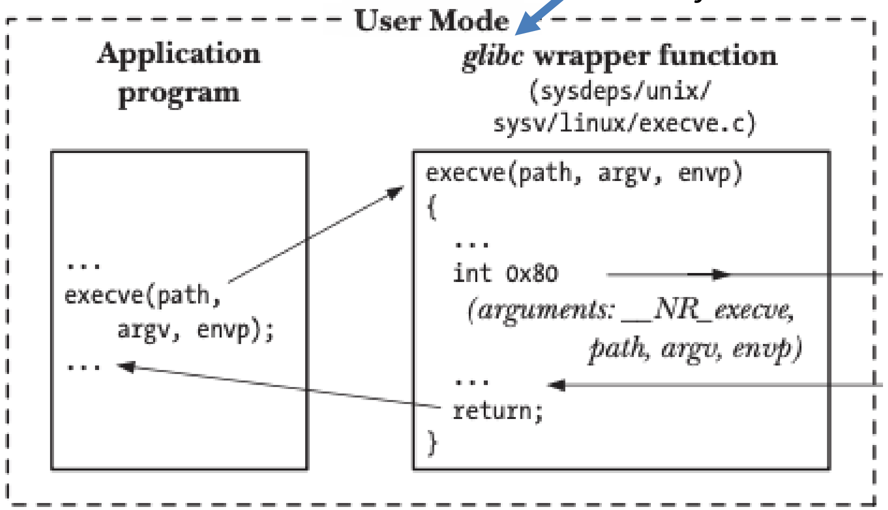
Libraries handle the system calls for us



The operating system have hundreds of different syscalls, and different syscalls have different parameters, we need a way to distinguish them

EAX

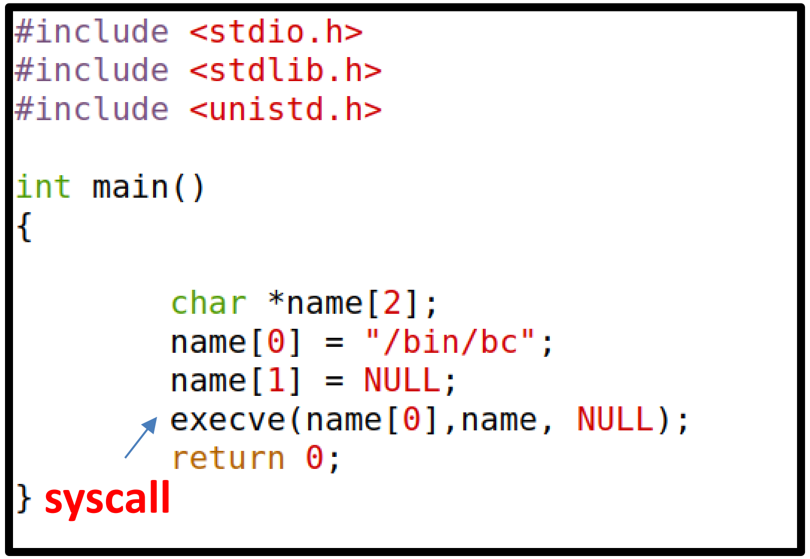
EBX

ECX

EDX

Syscalls

Applications evoke operating system defined functions, or **system calls** (**syscalls**), to access computing resources



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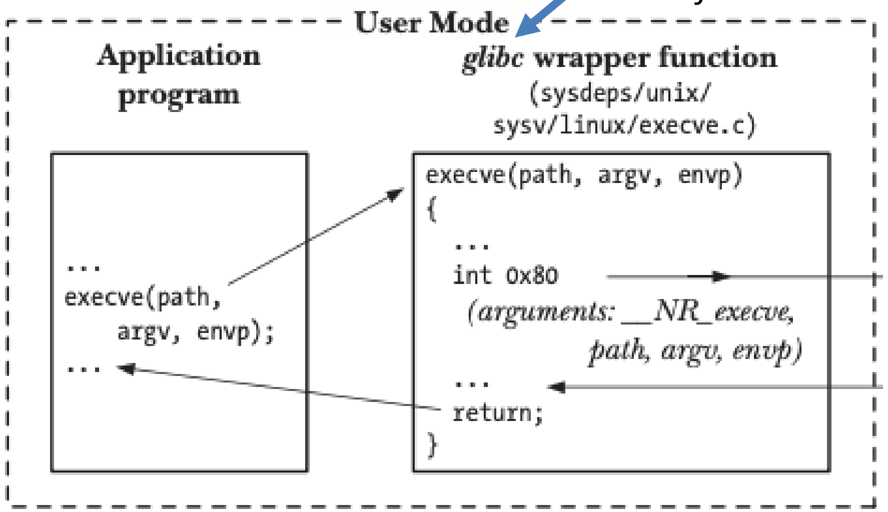
```

syscall



Libraries handle the system calls for us

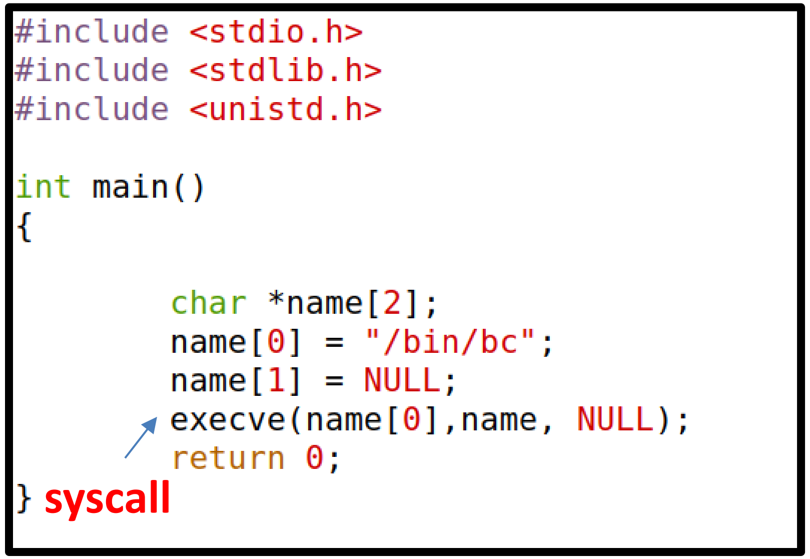
EAX	System Call Number	
EBX	Address of "/bin/bc"	
ECX	0 or 1	Environment variables
EDX	INT 0x80	send trap to kernel and invoke the syscall

The operating system have hundreds of different syscalls, and different syscalls have different parameters, we need a way to distinguish them

The OS will look at the values at certain registers!

Syscalls

Applications evoke operating system defined functions, or **system calls** (**syscalls**), to access computing resources



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        char *name[2];
        name[0] = "/bin/bc";
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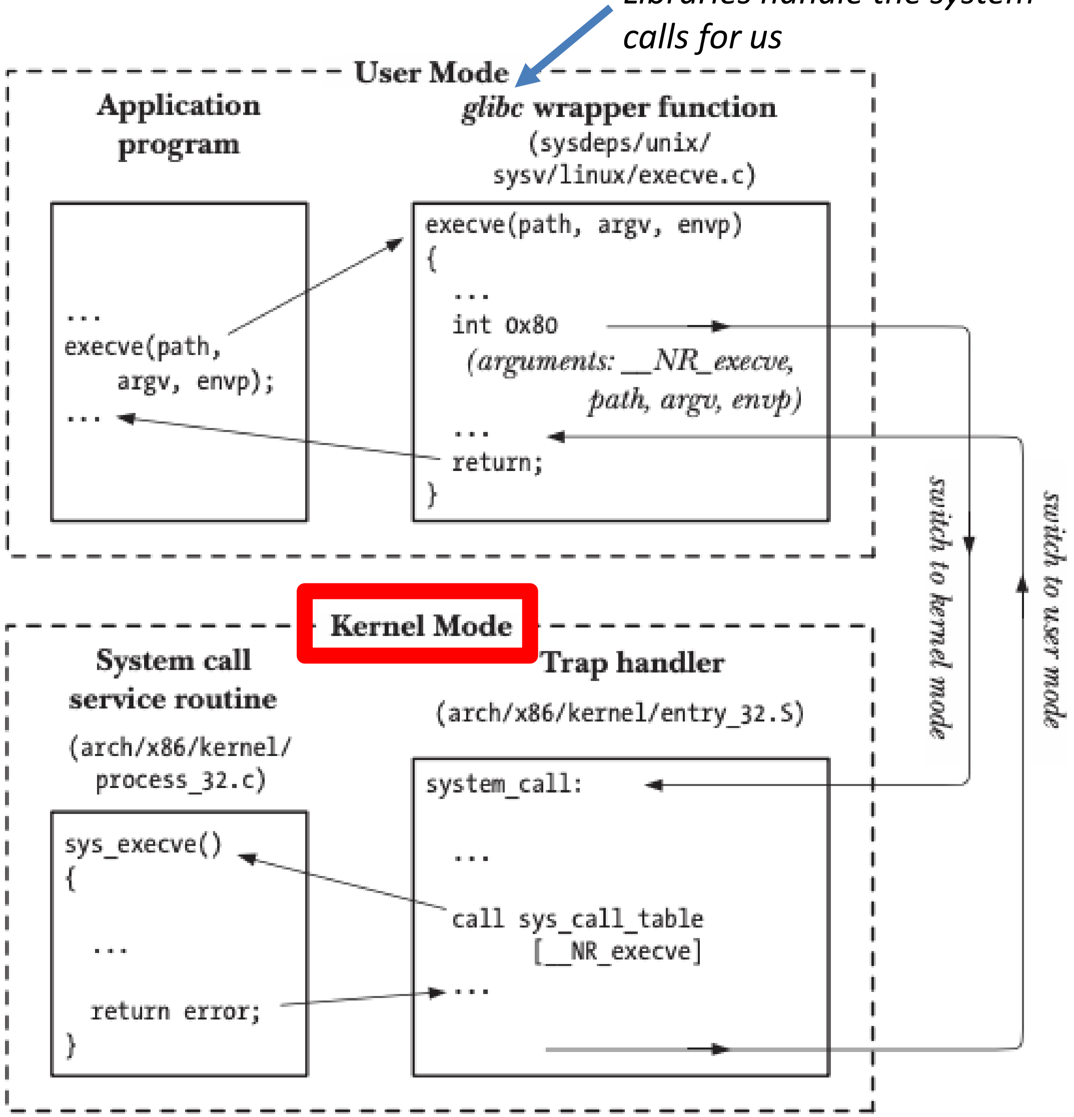
        execve(name[0],name, NULL);
        return 0;
}
```

syscall

Demo:
bc.c



Libraries handle the system calls for us

User Mode
Application program
glibc wrapper function
(sysdeps/unix/sysv/linux/execve.c)
Kernel Mode
System call service routine
(arch/x86/kernel/process_32.c)
Trap handler
(arch/x86/kernel/entry_32.S)
switch to kernel mode
switch to user mode

```
...
execve(path,
    argv, envp);
...
```

```
execve(path, argv, envp)
{
  ...
  int 0x80
   (arguments: __NR_execve,
        path, argv, envp)
  ...
  return;
}
```

```
system_call:

  ...

  call sys_call_table
       [__NR_execve]
  ...
```

```
sys_execve()
{

  ...

  return error;
}
```

EAX	System Call Number	
EBX	Address of "/bin/bc"	
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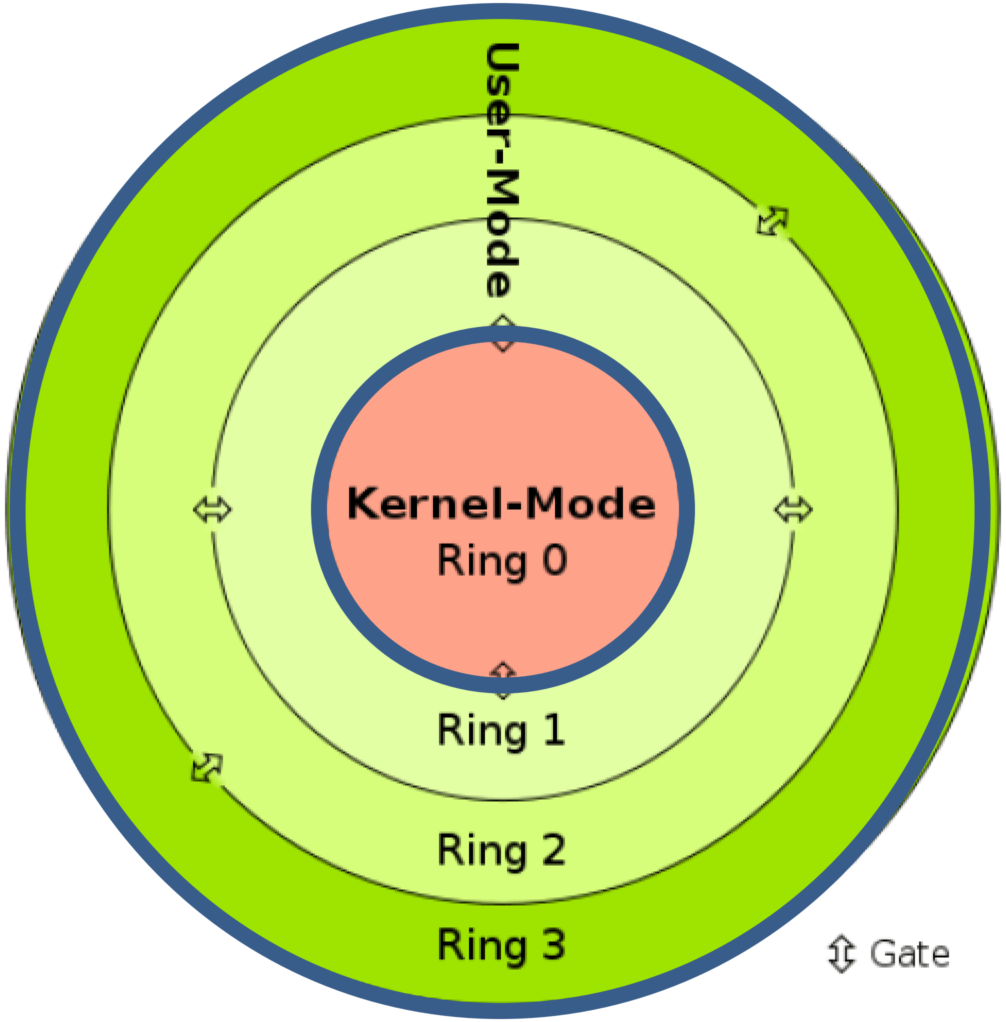
EDX	INT 0x80	send trap to kernel and invoke the syscall

normies seeing calculator open on its own
programmers seeing calculator open on its own

Syscalls

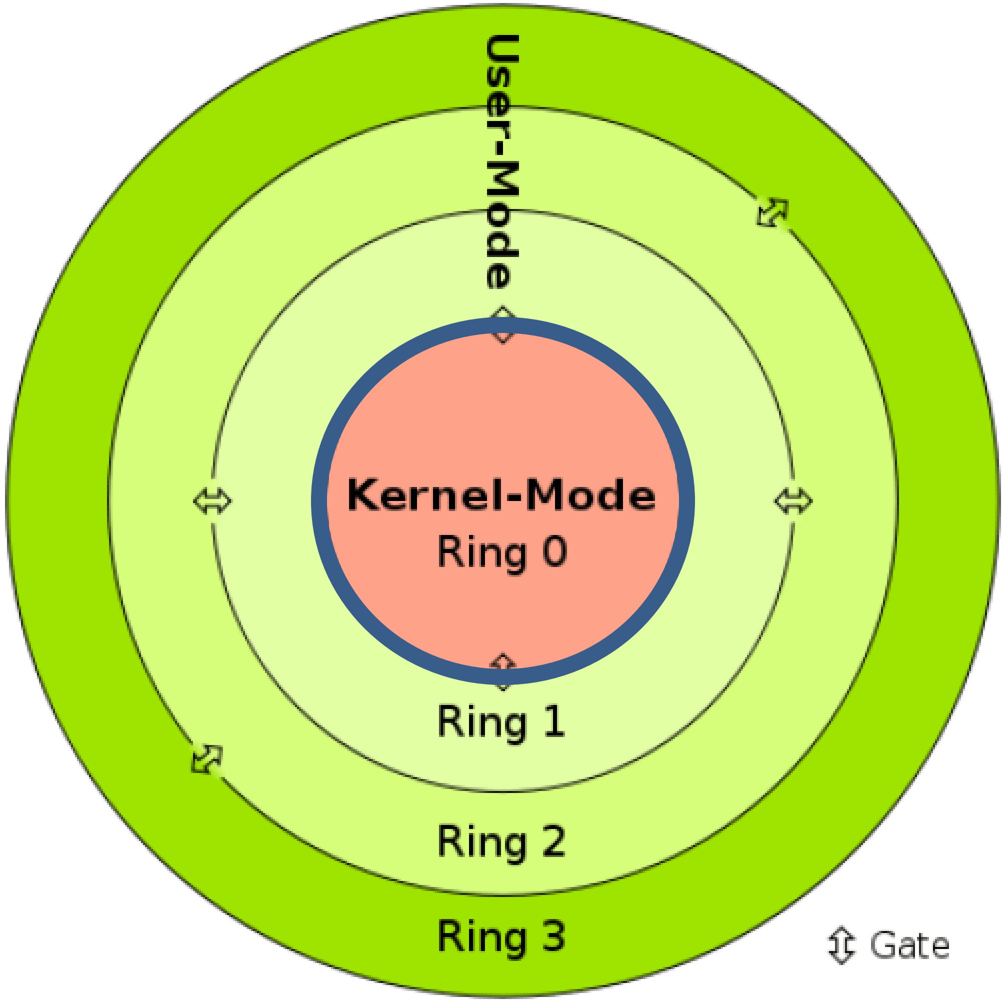


All applications run in user mode.

The code has no ability to directly access hardware

Code running in user mode must use API/syscalls to access hardware and memory

Syscalls



All applications run in user mode.

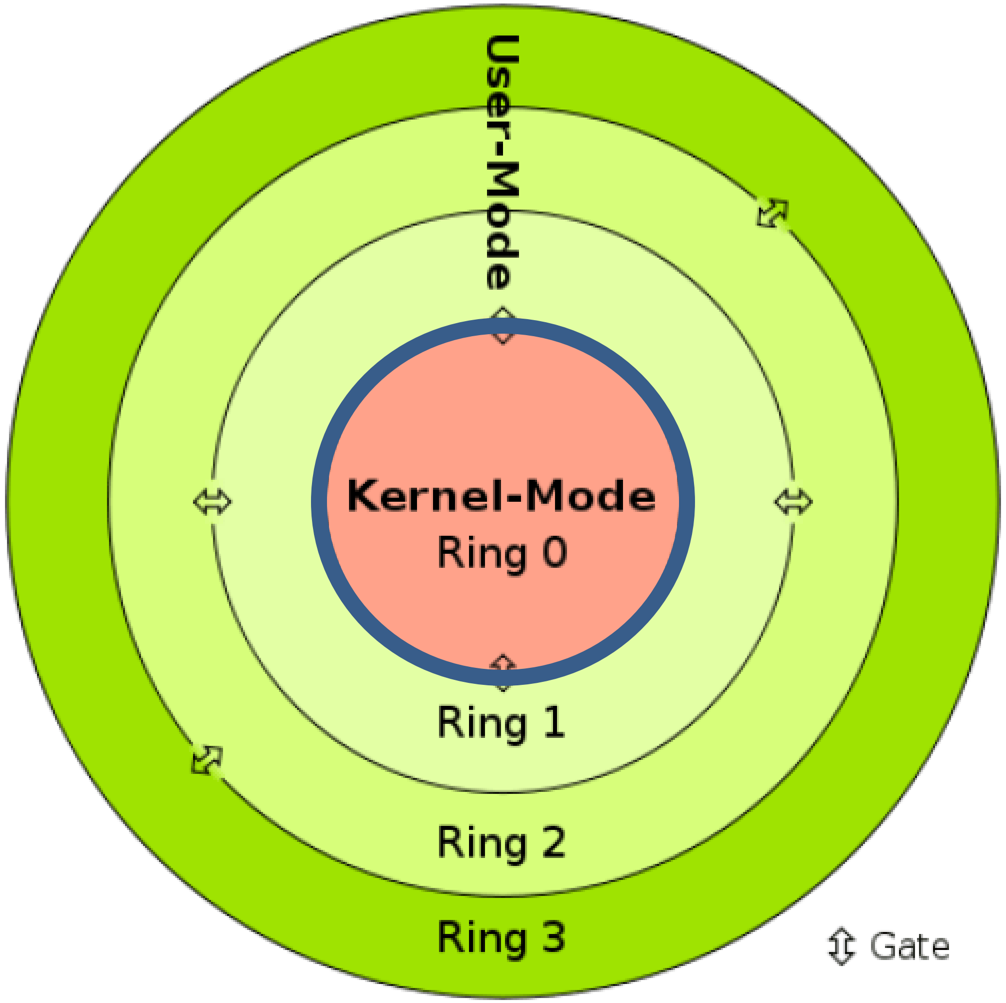
The code has no ability to directly access hardware

Code running in user mode must use API/syscalls to access hardware and memory

Code running in kernel-mode has complete, unrestricted access to computer resources

Reserved for the lowest-level trusted functions of the operating system

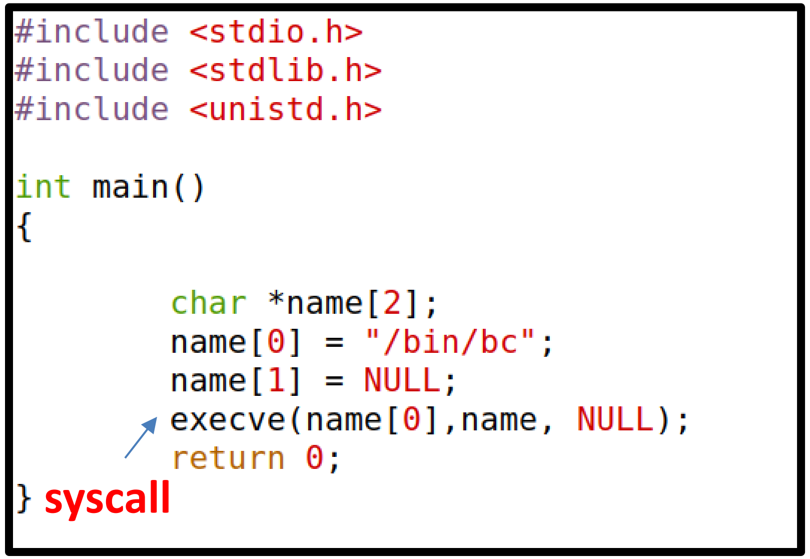
Syscalls



The collective functionality and services of the OS that manages the computer and its resources is called the **kernel**

Syscalls

Applications evoke operating system defined functions, or **system calls** (**syscalls**), to access computing resources



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}
```

syscall

EAX	System Call Number	
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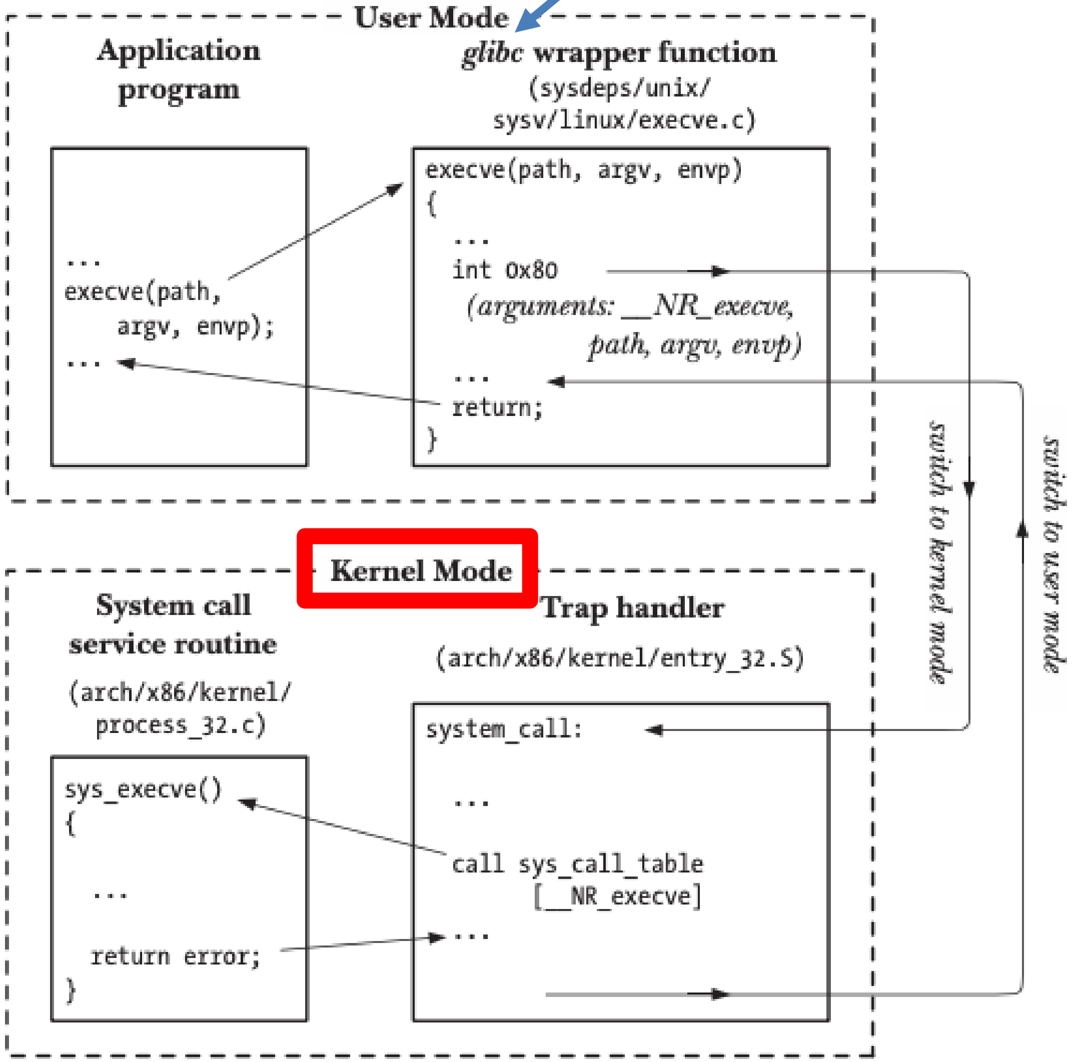
Libraries handle the system calls for us



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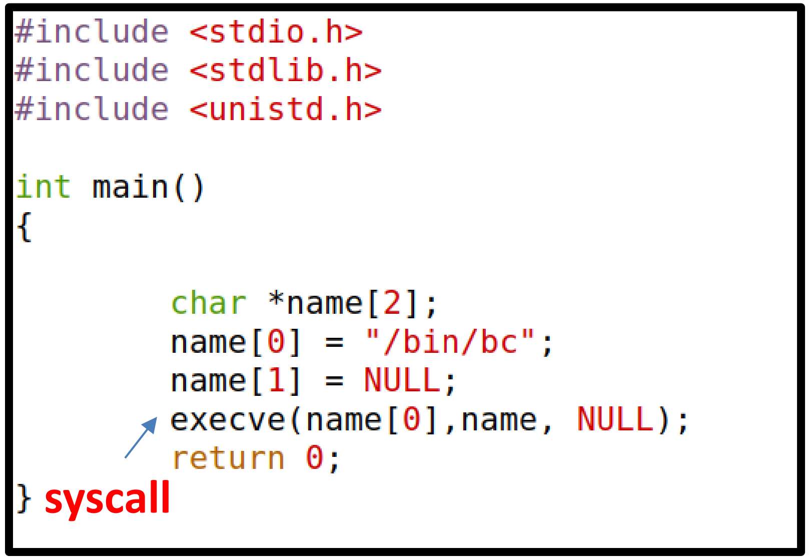
Syscalls

Applications evoke operating system defined functions, or **system calls** (**syscalls**), to access computing resources



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syscall

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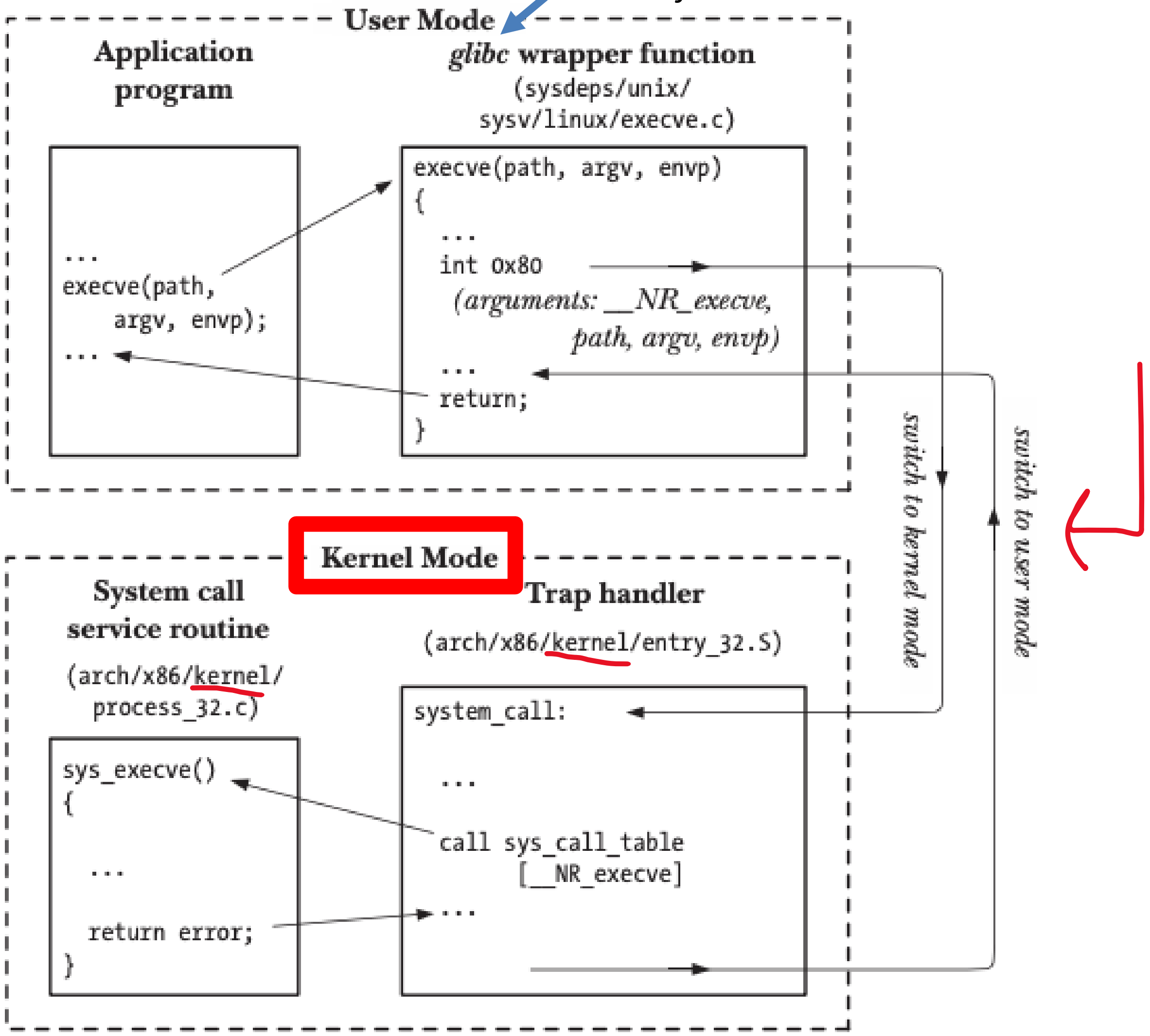
Libraries handle the system calls for us



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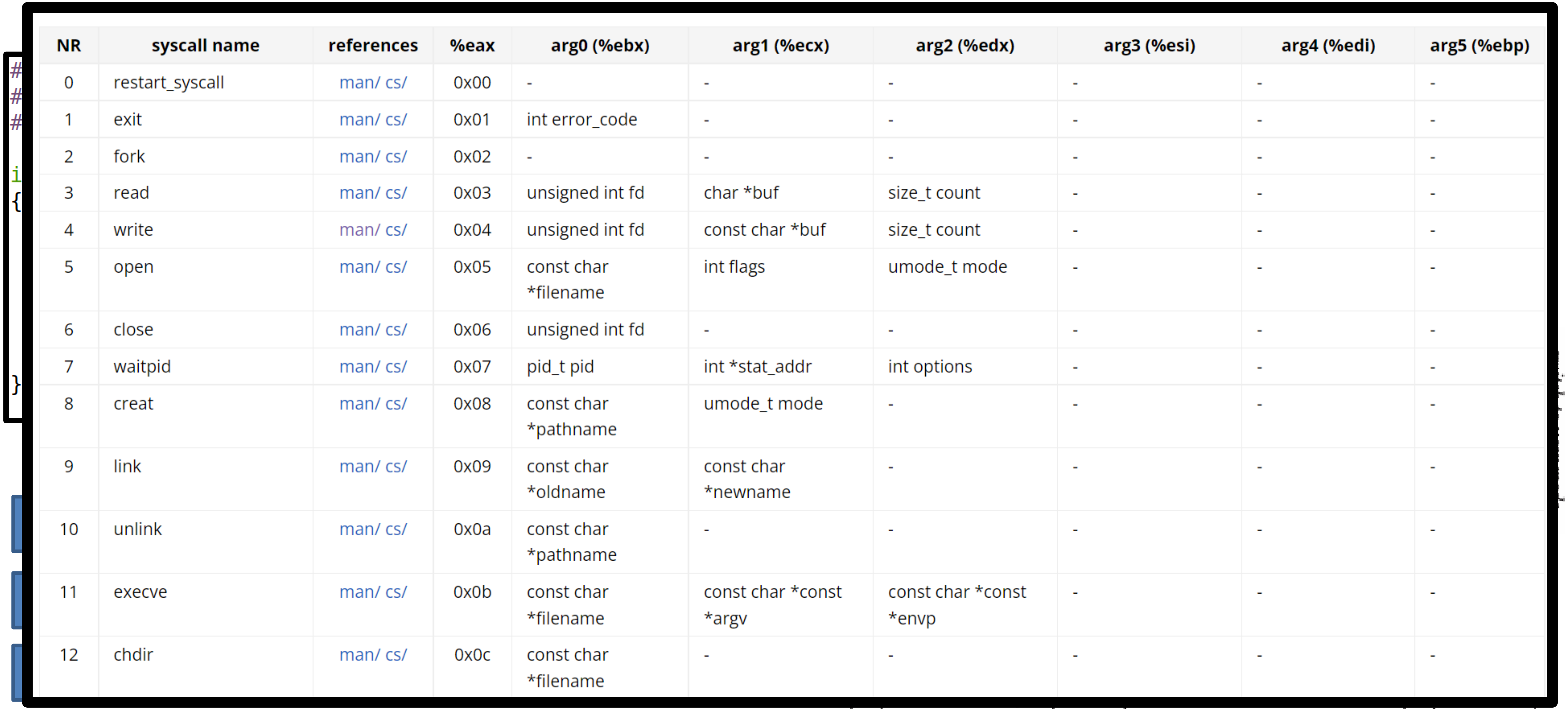
...
glibc wrapper function
(sysdeps/unix/sysv/linux/execve.c)
execve(path, argv, envp)
{
...
int 0x80
(arguments: __NR_execve, path, argv, envp)
...
return;
}
switch to kernel mode
switch to user mode
Kernel Mode
System call service routine
(arch/x86/kernel/process_32.c)
sys_execve()
{
...
return error;
}
Trap handler
(arch/x86/kernel/entry_32.S)
system_call:
...
call sys_call_table [__NR_execve]
...

Syscalls

Applications evoke operating system defined functions, or **system calls (syscalls)**, to access computing resources



NR	syscall name	references	%eax	arg0 (%ebx)	arg1 (%ecx)	arg2 (%edx)	arg3 (%esi)	arg4 (%edi)	arg5 (%ebp)
0	restart_syscall	man/ cs/	0x00	-	-	-	-	-	-
1	exit	man/ cs/	0x01	int error_code	-	-	-	-	-
2	fork	man/ cs/	0x02	-	-	-	-	-	-
3	read	man/ cs/	0x03	unsigned int fd	char *buf	size_t count	-	-	-
4	write	man/ cs/	0x04	unsigned int fd	const char *buf	size_t count	-	-	-
5	open	man/ cs/	0x05	const char *filename	int flags	umode_t mode	-	-	-
6	close	man/ cs/	0x06	unsigned int fd	-	-	-	-	-
7	waitpid	man/ cs/	0x07	pid_t pid	int *stat_addr	int options	-	-	-
8	creat	man/ cs/	0x08	const char *pathname	umode_t mode	-	-	-	-
9	link	man/ cs/	0x09	const char *oldname	const char *newname	-	-	-	-
10	unlink	man/ cs/	0x0a	const char *pathname	-	-	-	-	-
11	execve	man/ cs/	0x0b	const char *filename	const char *const *argv	const char *const *envp	-	-	-
12	chdir	man/ cs/	0x0c	const char *filename	-	-	-	-	-

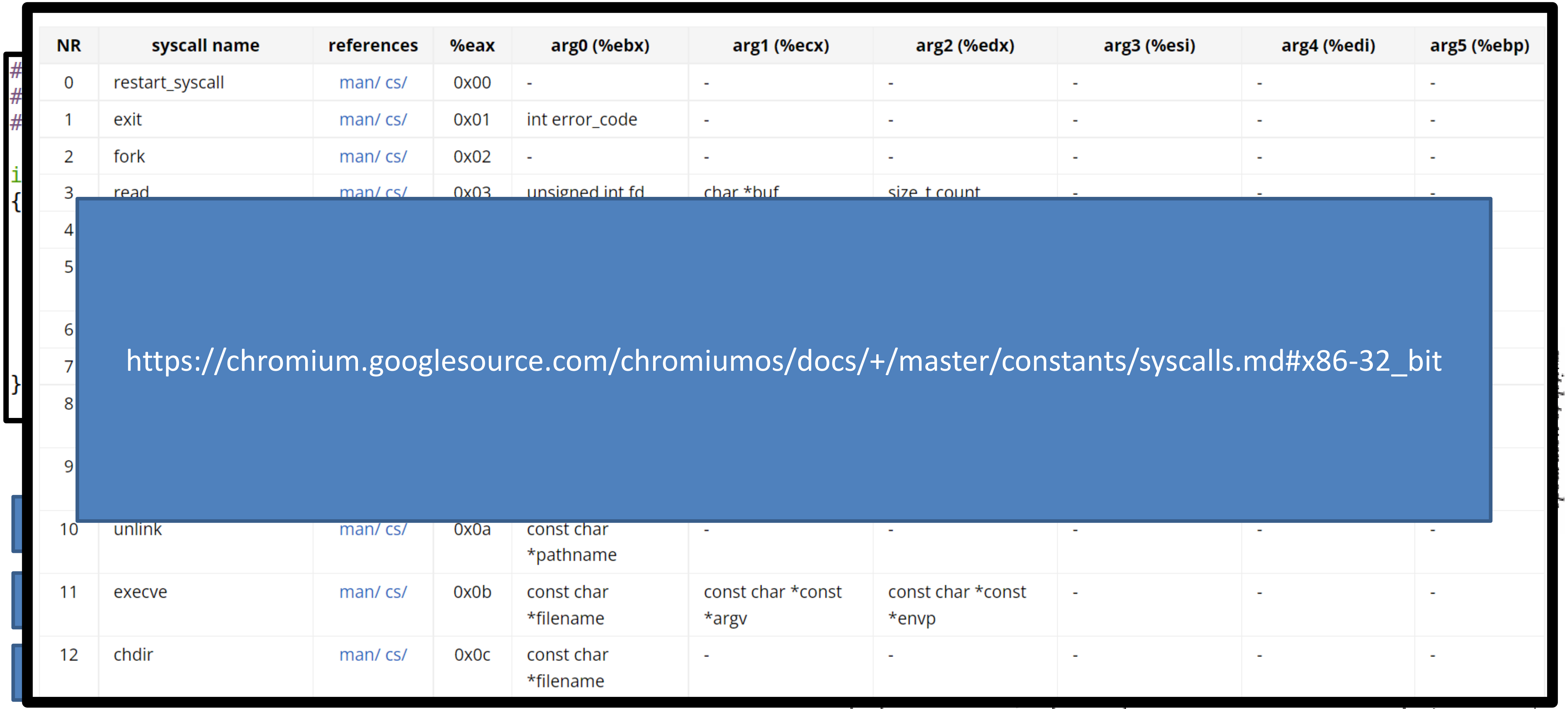
EDX

INT 0x80

send trap to kernel and invoke the syscall

Syscalls

Applications evoke operating system defined functions, or **system calls (syscalls)**, to access computing resources



NR	syscall name	references	%eax	arg0 (%ebx)	arg1 (%ecx)	arg2 (%edx)	arg3 (%esi)	arg4 (%edi)	arg5 (%ebp)
0	restart_syscall	man/ cs/	0x00	-	-	-	-	-	-
1	exit	man/ cs/	0x01	int error_code	-	-	-	-	-
2	fork	man/ cs/	0x02	-	-	-	-	-	-
3	read	man/ cs/	0x03	unsigned int fd	char *buf	size_t count	-	-	-
4									
5									
6									
7									
8									
9									
10	unlink	man/ cs/	0x0a	const char *pathname	-	-	-	-	-
11	execve	man/ cs/	0x0b	const char *filename	const char *const *argv	const char *const *envp	-	-	-
12	chdir	man/ cs/	0x0c	const char *filename	-	-	-	-	-

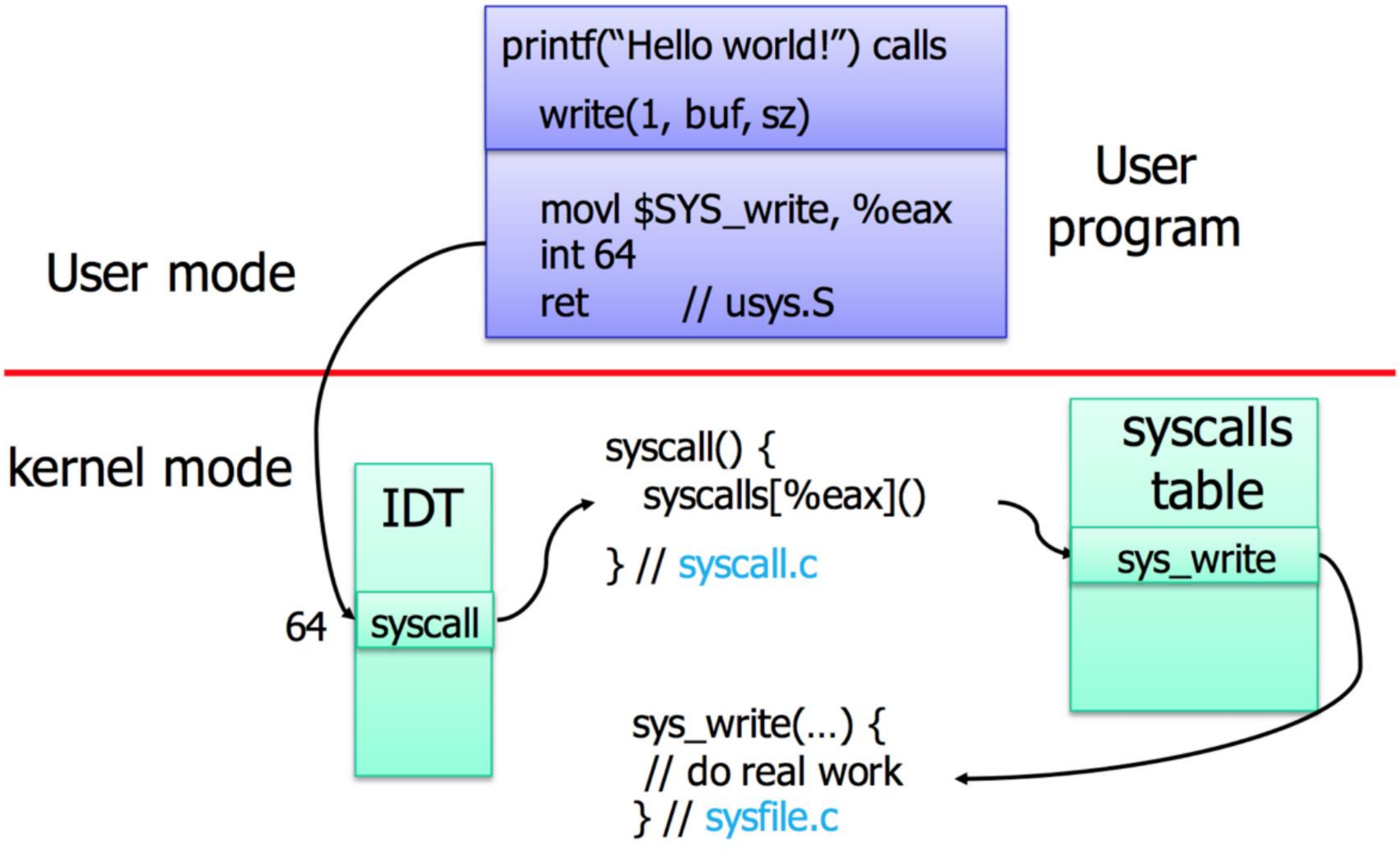
https://chromium.googlesource.com/chromiumos/docs/+/master/constants/syscalls.md#x86-32_bit

EDX

INT 0x80

send trap to kernel and invoke the syscall

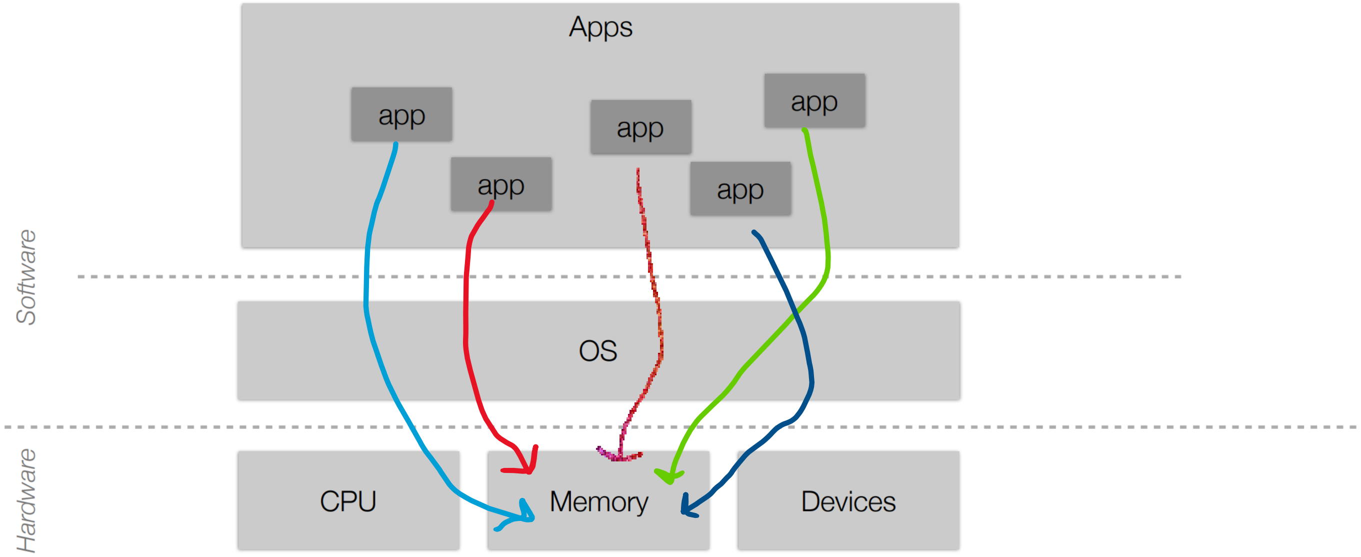
Syscalls


printf("Hello world!") calls
write(1, buf, sz)
movl $SYS_write, %eax
int 64
ret // usys.S
User program
User mode
kernel mode
IDT
64
syscall
syscall() {
syscalls[%eax]()
} // syscall.c
syscalls table
sys_write
sys_write(...) {
// do real work
} // sysfile.c

Applications Layout in Memory

Process Manager

- Manages how processes are structured and how to handle many processes running at once

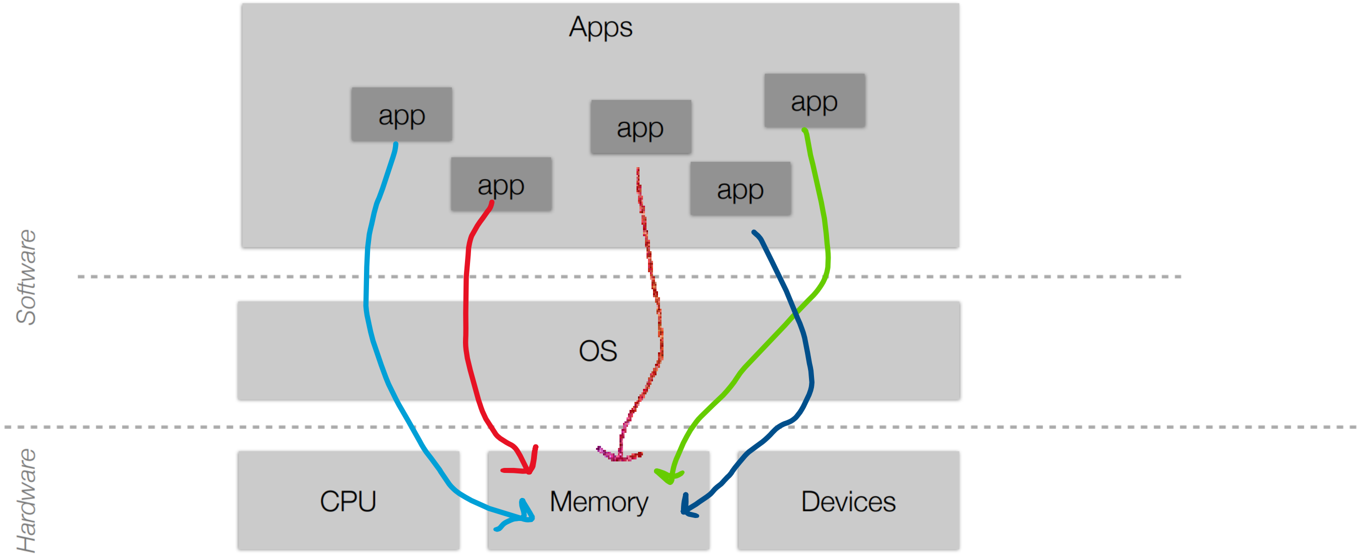


How does a **program** get loaded into memory?

Applications Layout in Memory

Process Manager

- Manages how processes are structured and how to handle many processes running at once



How does a **program** get loaded into memory?

An active program running on a computer is called a **process**

Applications Layout in Memory

Process Manager

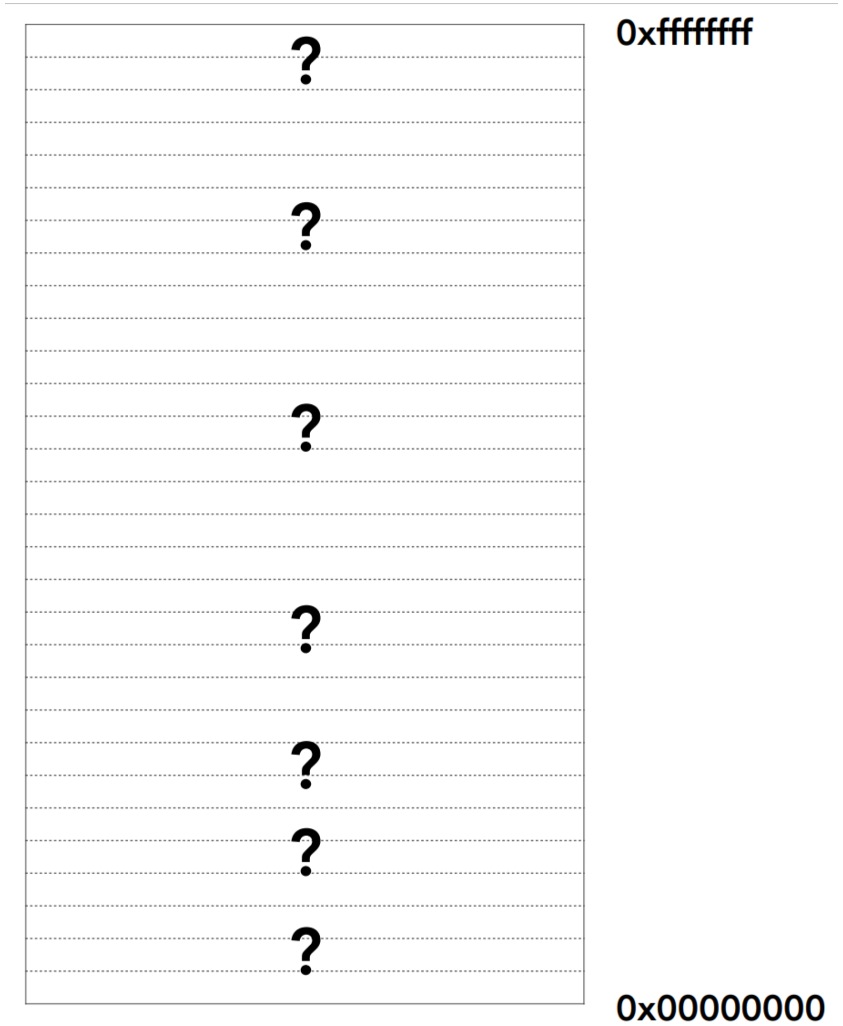
- Manages how processes are structured and how to handle many processes running at once

What does this look like?

1. Executable Code

2. Associated Data

3. Execution Context/Bookkeeping information

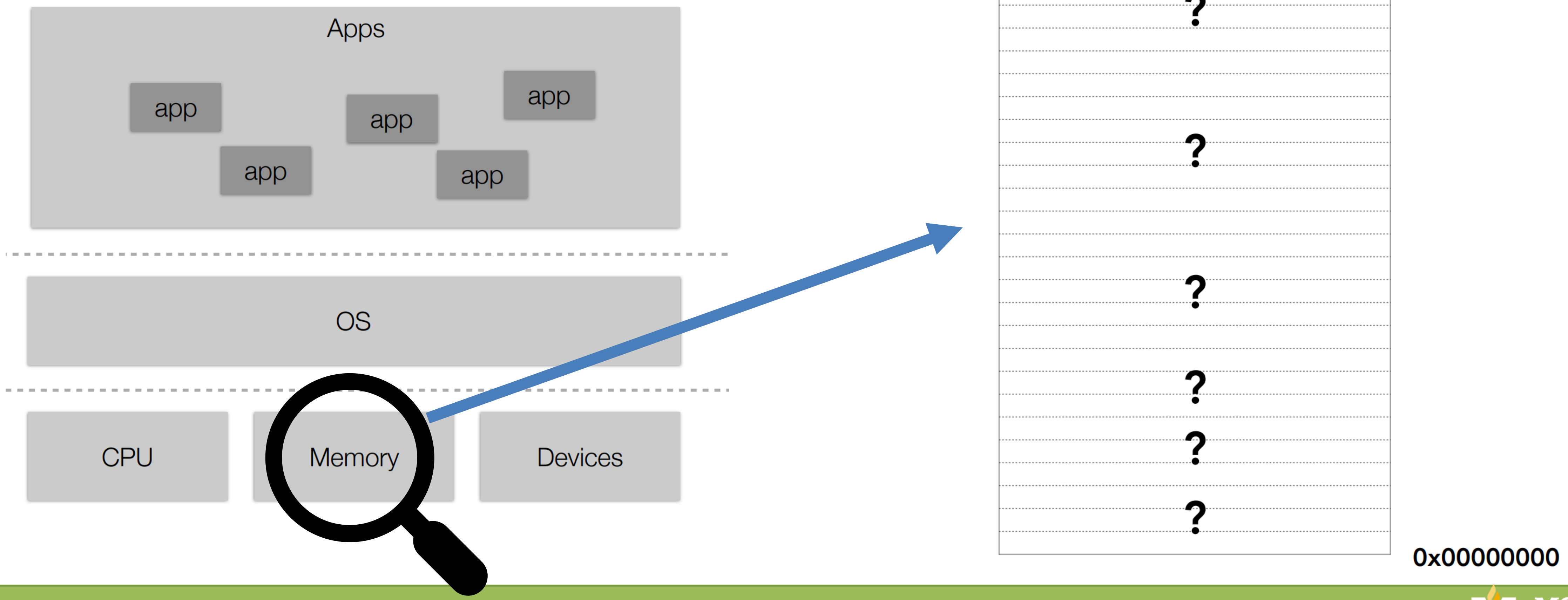


Applications Layout in Memory

Process Manager

- Manages how processes are structured and how to handle many processes running at once

What does a program look like in memory?



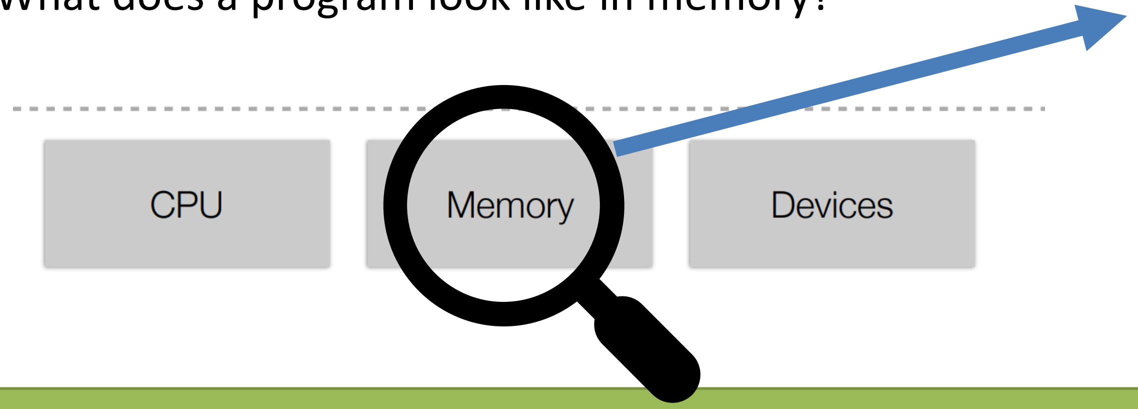
Applications Layout in Memory

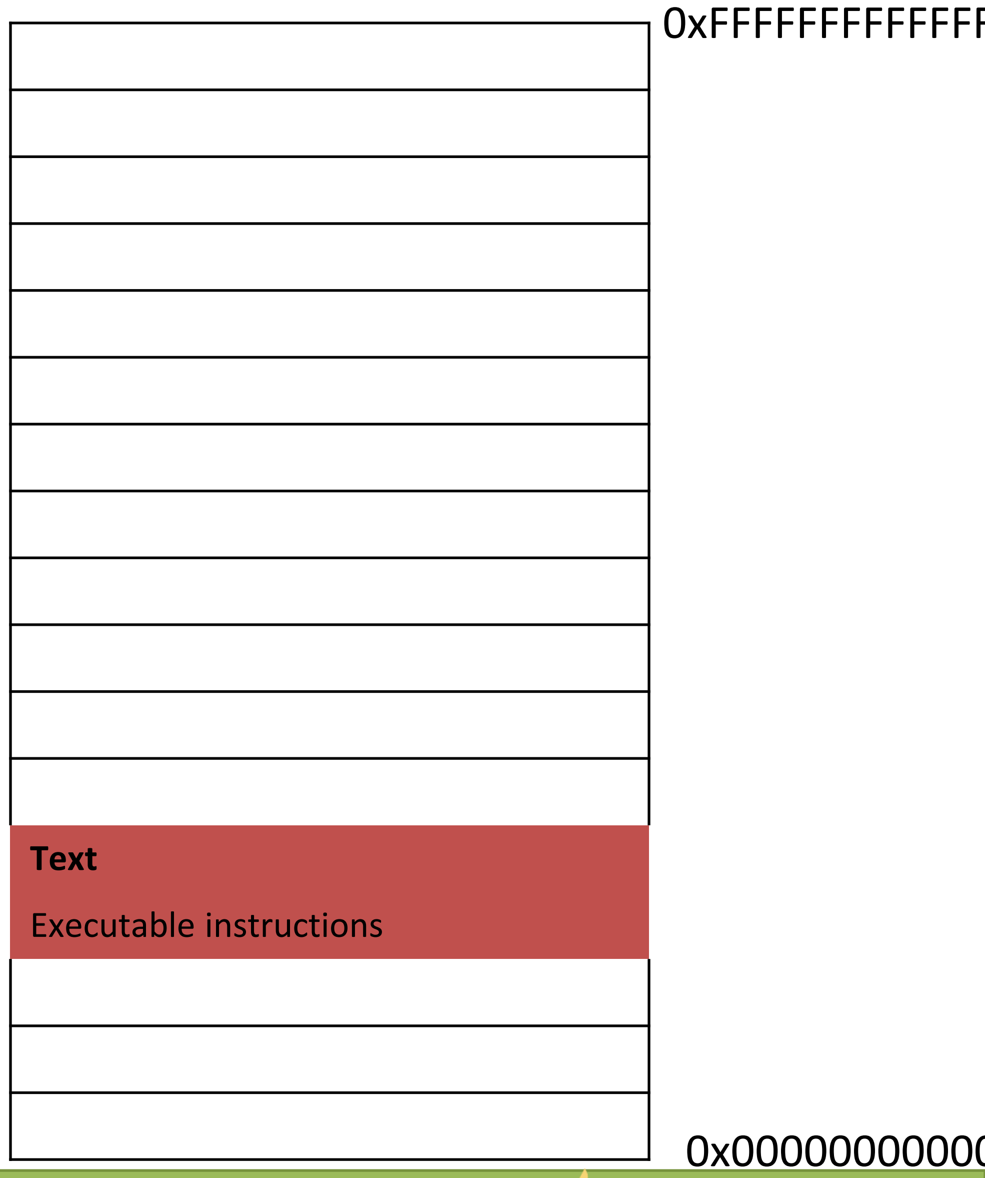
Process Manager

- Manages how processes are structured and how to handle many processes running at once

Text Segment- binary executable instructions for the process

What does a program look like in memory?





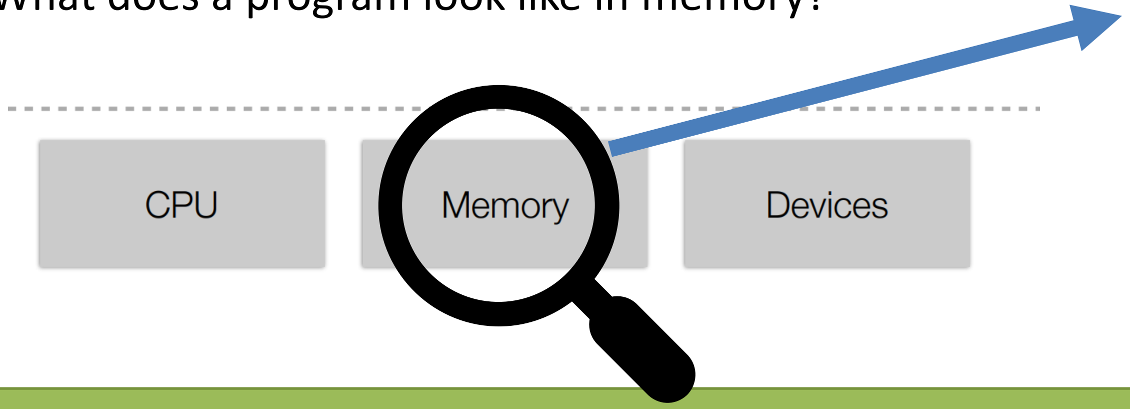
Applications Layout in Memory

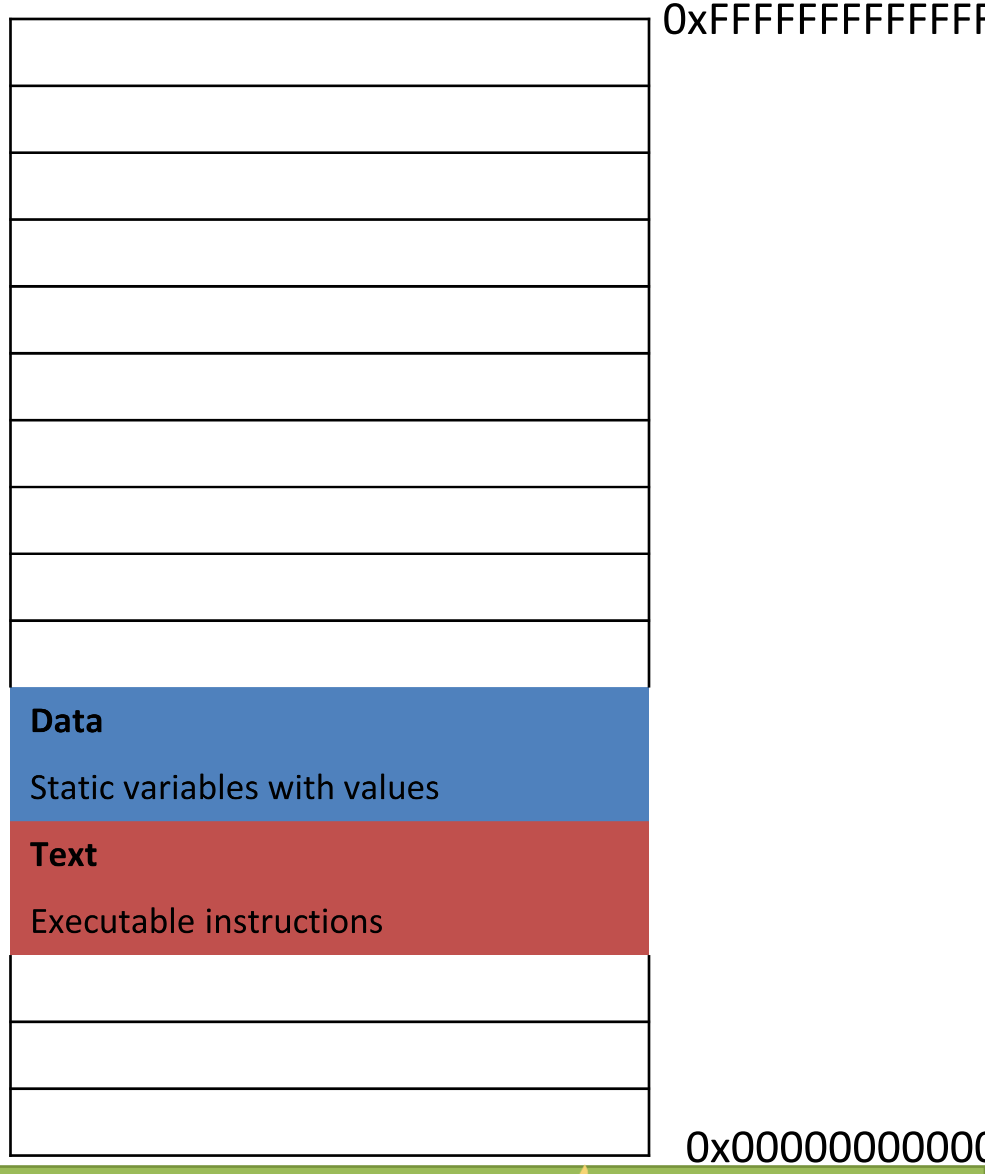
Process Manager

- Manages how processes are structured and how to handle many processes running at once

Data Segment- Static variables initialized by the programmer

What does a program look like in memory?




0xFFFFFFFFFFFF

Data

Static variables with values

Text

Executable instructions

0x00000000000

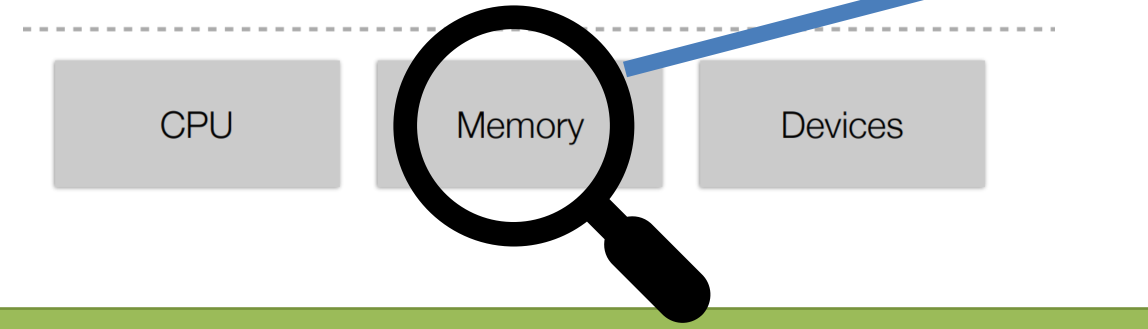
Applications Layout in Memory

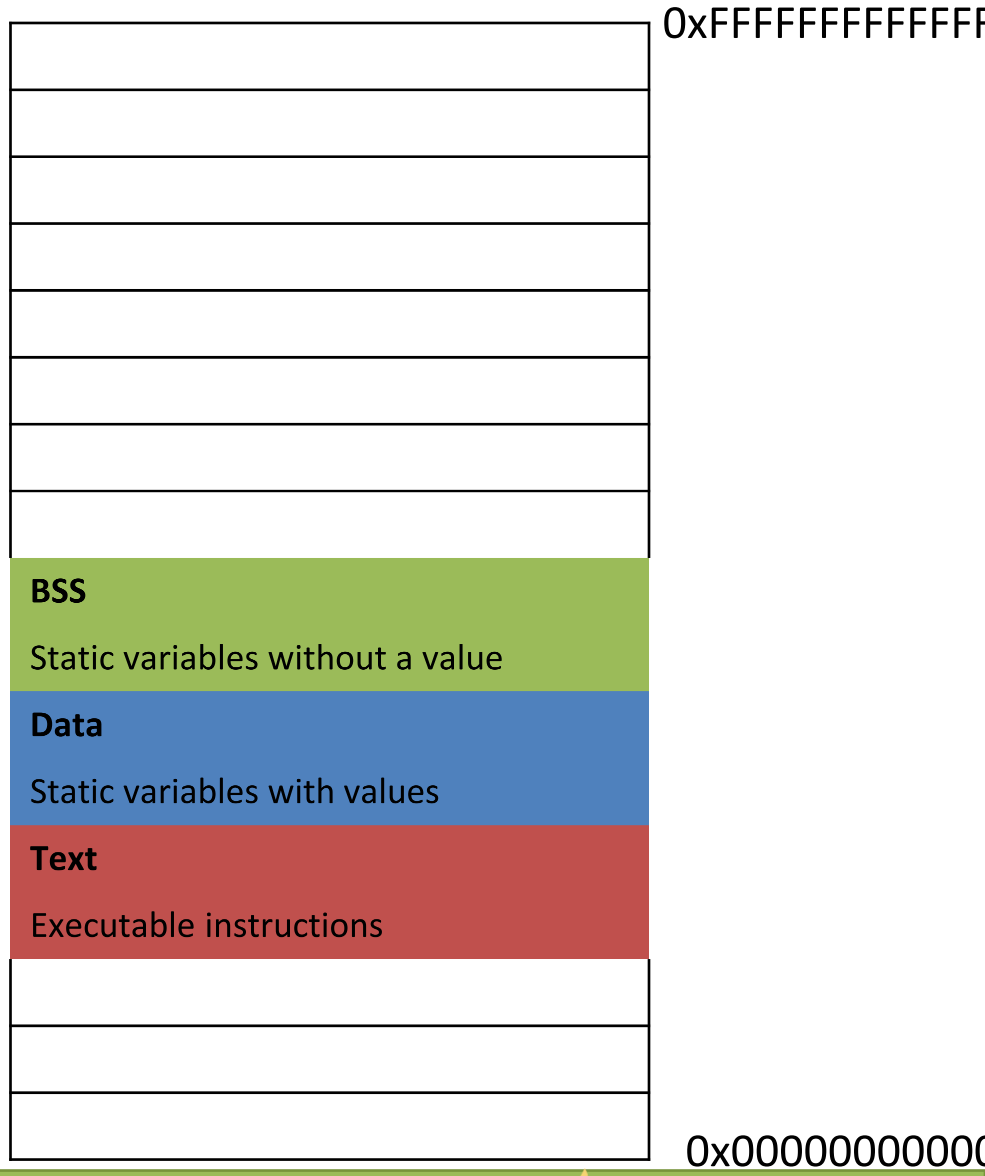
Process Manager

- Manages how processes are structured and how to handle many processes running at once

BSS Segment- contains statically allocated variables that are declared, but have not been assigned a value yet

What does a program look like in memory?





0xFFFFFFFFFFFFF

BSS

Static variables without a value

Data

Static variables with values

Text

Executable instructions

0x00000000000

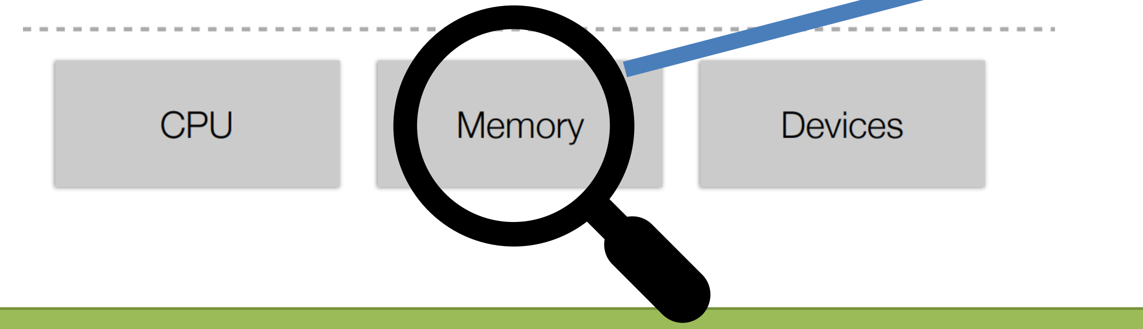
Applications Layout in Memory

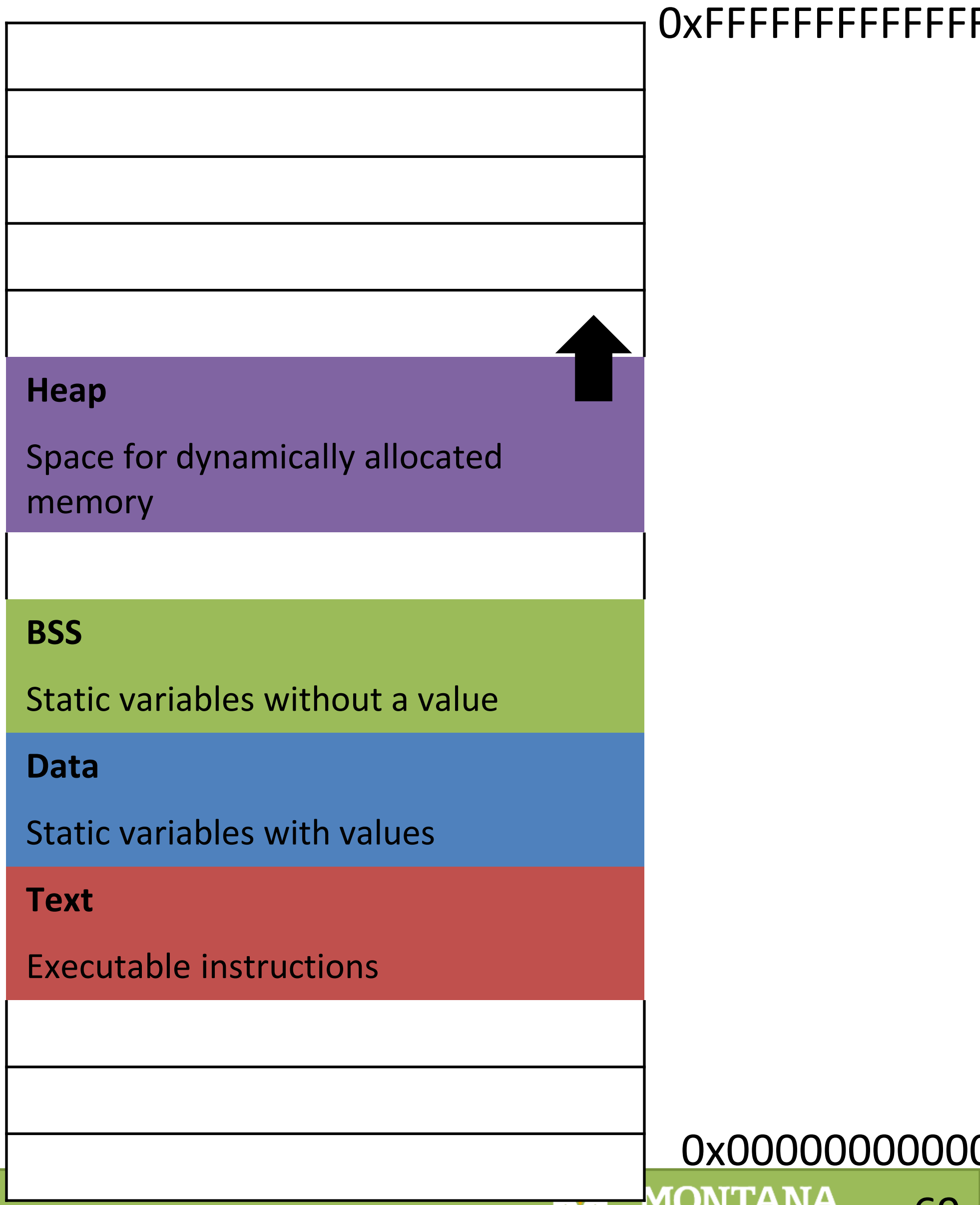
Process Manager

- Manages how processes are structured and how to handle many processes running at once

Heap- memory set aside for dynamic allocation (e.g. malloc). Grows "up" as more memory is allocated

What does a program look like in memory?



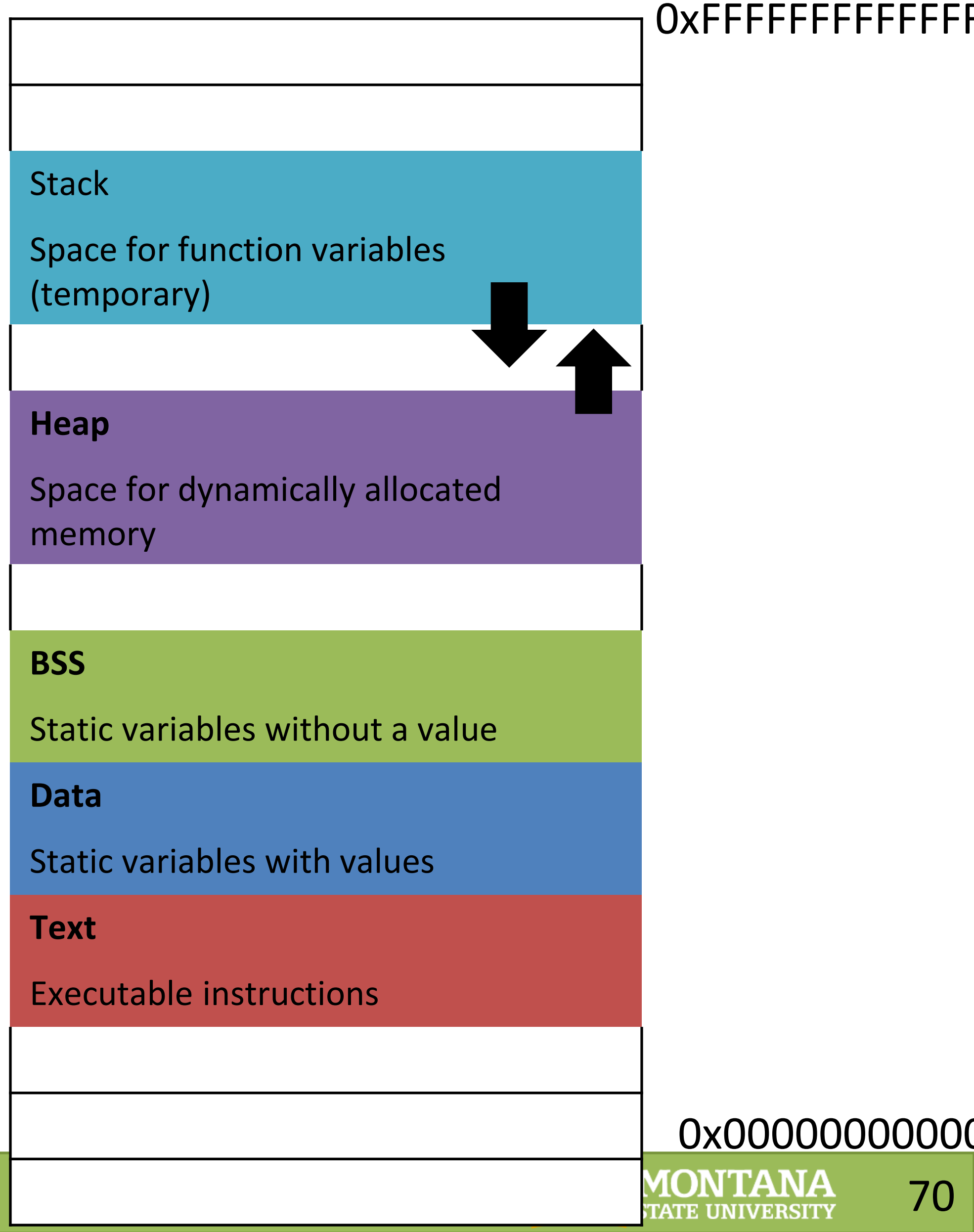

0xFFFFFFFFFFFF
Heap
Space for dynamically allocated memory
BSS
Static variables without a value
Data
Static variables with values
Text
Executable instructions
0x00000000000

Applications Layout in Memory

Process Manager

- Manages how processes are structured and how to handle many processes running at once

Stack – memory for storing function variables. Grows “down” as additional functions are called



0xFFFFFFFFFFFF

Stack

Space for function variables (temporary)

Heap

Space for dynamically allocated memory

BSS

Static variables without a value

Data

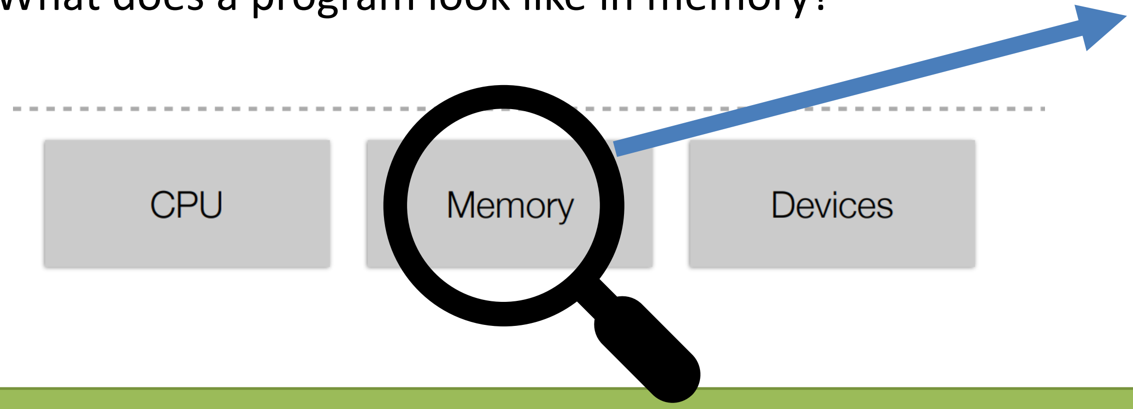
Static variables with values

Text

Executable instructions

0x00000000000

What does a program look like in memory?



Applications Layout in Memory

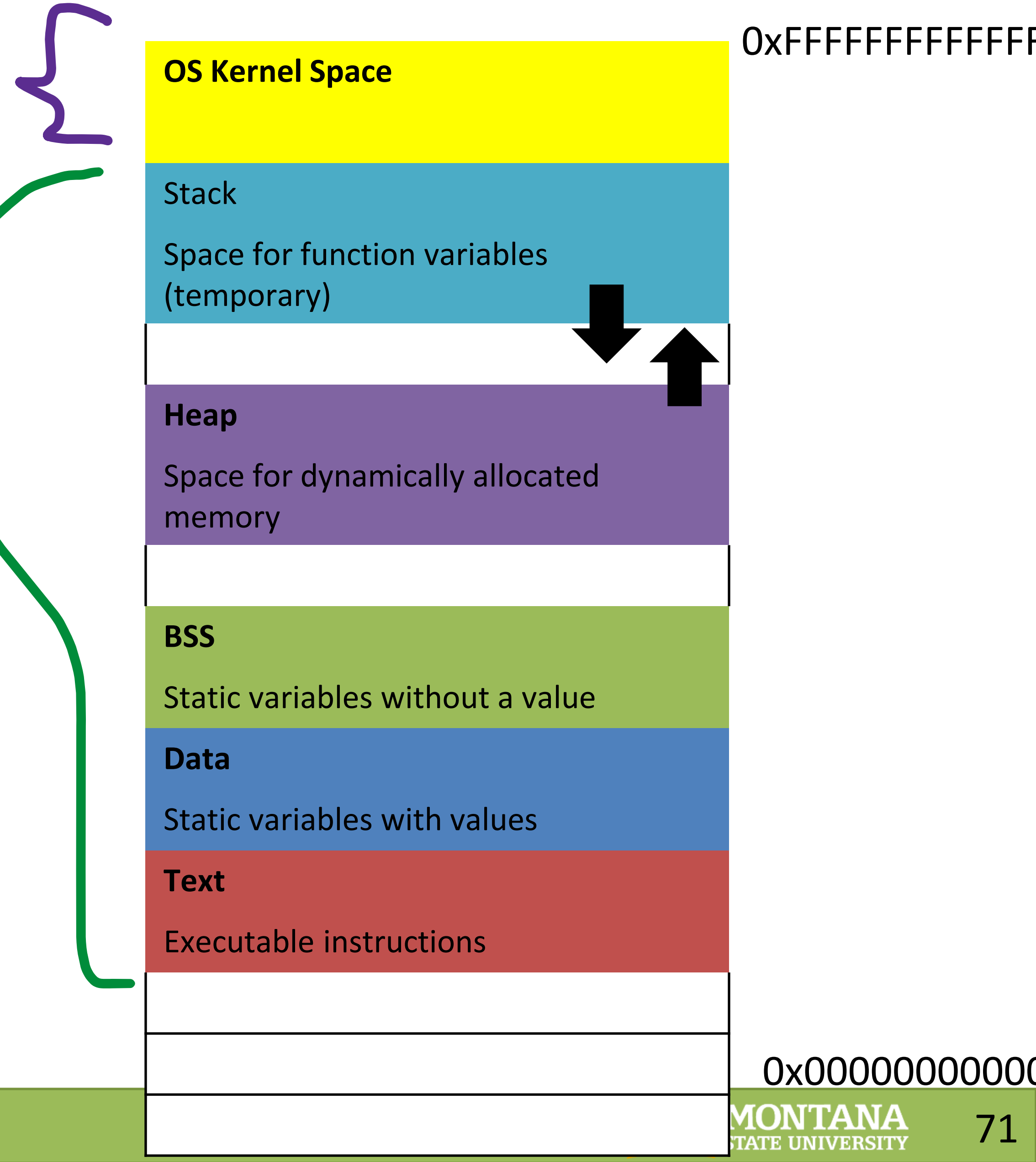
Process Manager

- Manages how processes are structured and how to handle many processes running at once

1. Executable Code

2. Associated Data

3. Execution Context/Bookkeeping information



0xFFFFFFFFFFFFF

OS Kernel Space

Stack

Space for function variables (temporary)

Heap

Space for dynamically allocated memory

BSS

Static variables without a value

Data

Static variables with values

Text

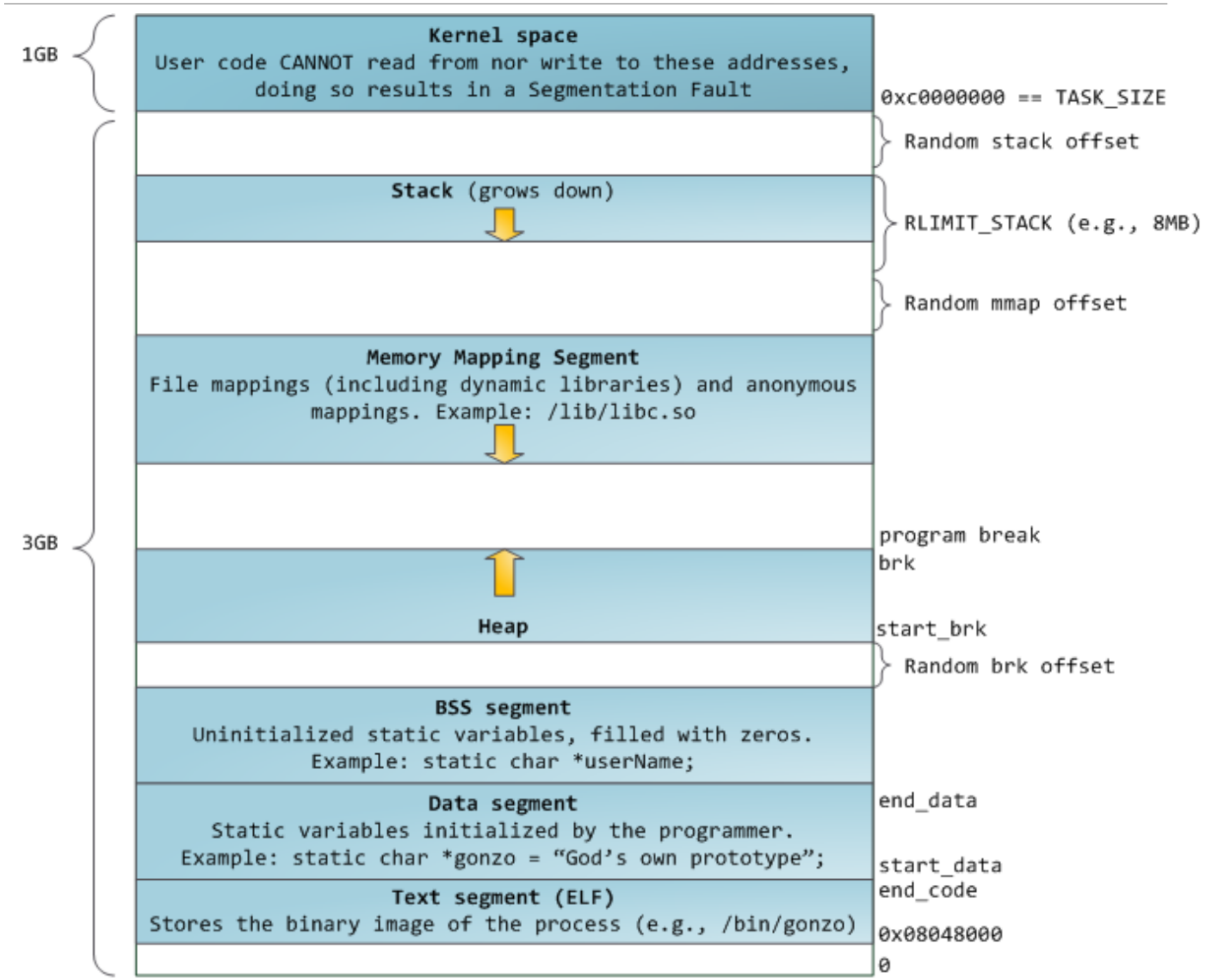
Executable instructions

0x00000000000

Applications Layout in Memory

Demo?

Makefile Demo



Kernel space
User code CANNOT read from nor write to these addresses, doing so results in a Segmentation Fault

Stack (grows down)

Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so

Heap

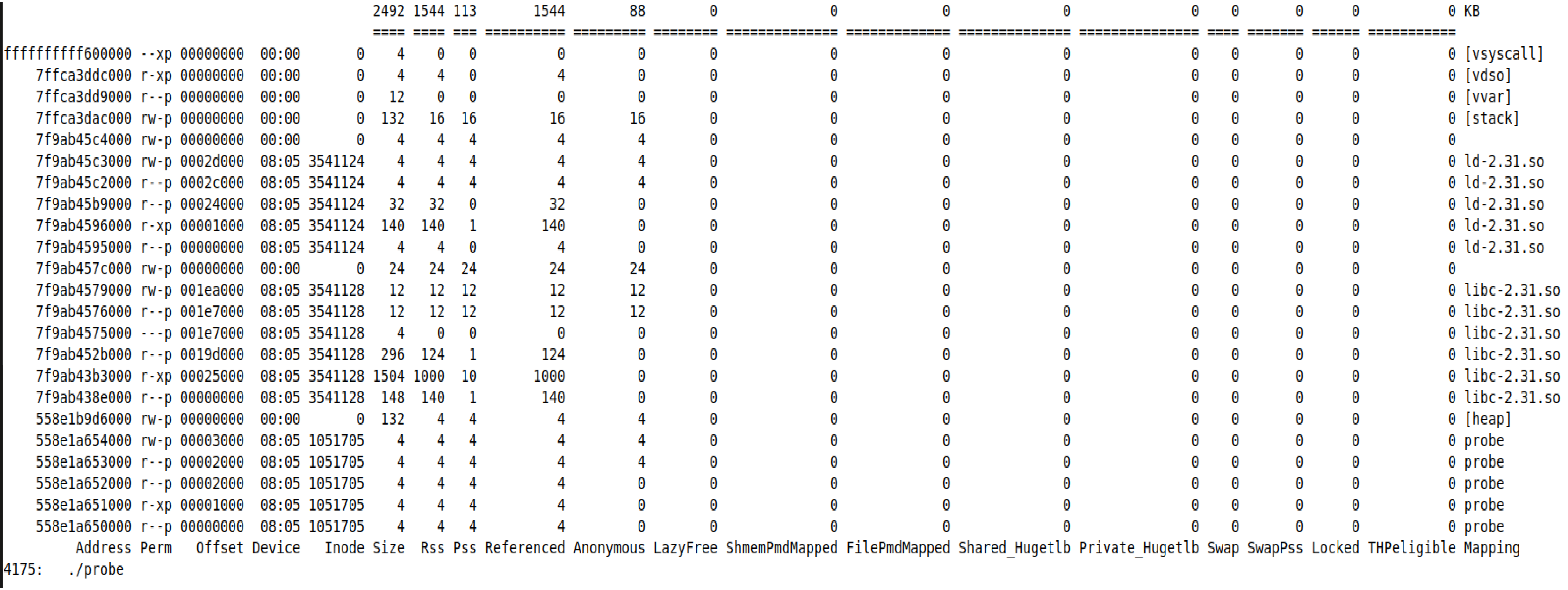
BSS segment
Uninitialized static variables, filled with zeros.
Example: static char *userName;

Data segment
Static variables initialized by the programmer.
Example: static char *gonzo = “God’s own prototype”;

Text segment (ELF)
Stores the binary image of the process (e.g., /bin/gonzo)

Applications Layout in Memory

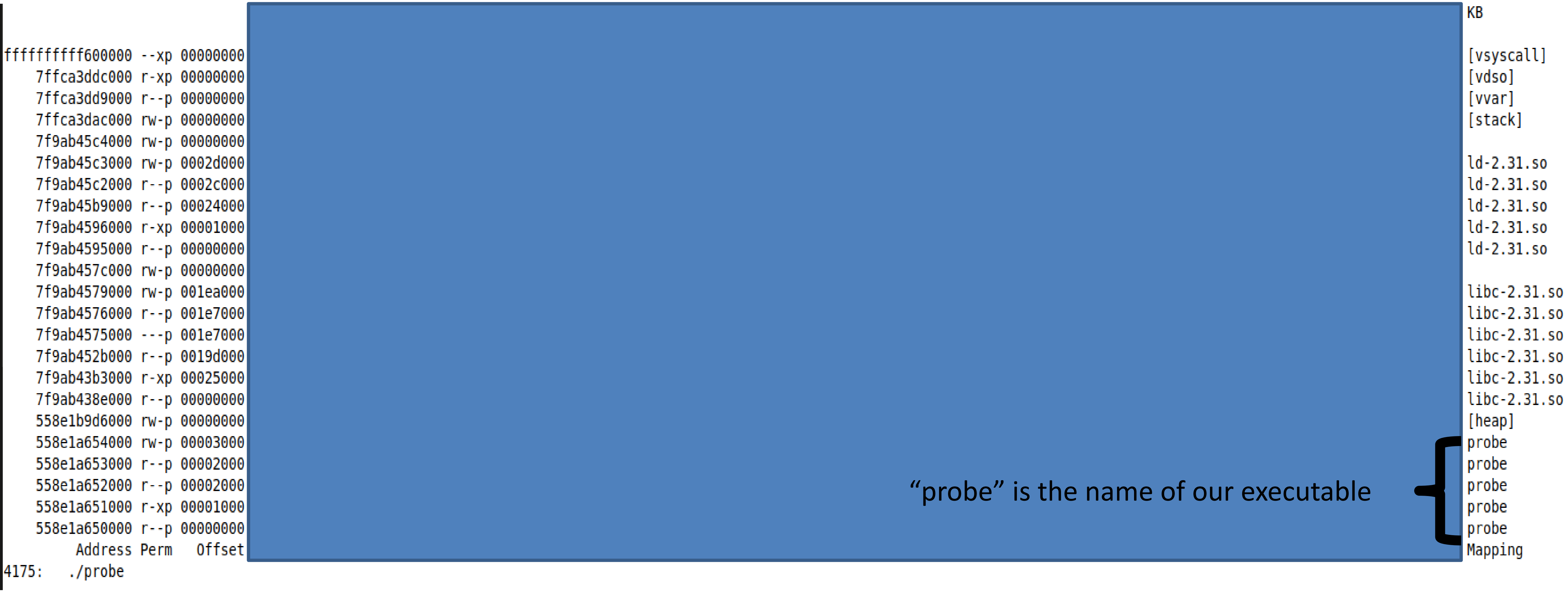
Ouput of `pmap` (process mapping tool)



```
                                               2492 1544 113       1544        88        0              0             0              0               0    0       0      0           0 KB
                                               ==== ==== === ========== ========= ======== ============== ============= ============== =============== ==== ======= ====== ===========
ffffffffff600000 --xp 00000000  00:00        0    4    0   0          0         0        0              0             0              0               0    0       0      0           0 [vsyscall]
    7ffca3ddc000 r-xp 00000000  00:00        0    4    4   0          4         0        0              0             0              0               0    0       0      0           0 [vdso]
    7ffca3dd9000 r--p 00000000  00:00        0   12    0   0          0         0        0              0             0              0               0    0       0      0           0 [vvar]
    7ffca3dac000 rw-p 00000000  00:00        0  132   16  16         16        16        0              0             0              0               0    0       0      0           0 [stack]
    7f9ab45c4000 rw-p 00000000  00:00        0    4    4   4          4         4        0              0             0              0               0    0       0      0           0
    7f9ab45c3000 rw-p 0002d000  08:05  3541124    4    4   4          4         4        0              0             0              0               0    0       0      0           0 ld-2.31.so
    7f9ab45c2000 r--p 0002c000  08:05  3541124    4    4   4          4         4        0              0             0              0               0    0       0      0           0 ld-2.31.so
    7f9ab45b9000 r--p 00024000  08:05  3541124   32   32   0         32         0        0              0             0              0               0    0       0      0           0 ld-2.31.so
    7f9ab4596000 r-xp 00001000  08:05  3541124  140  140   1        140         0        0              0             0              0               0    0       0      0           0 ld-2.31.so
    7f9ab4595000 r--p 00000000  08:05  3541124    4    4   0          4         0        0              0             0              0               0    0       0      0           0 ld-2.31.so
    7f9ab457c000 rw-p 00000000  00:00        0   24   24  24         24        24        0              0             0              0               0    0       0      0           0
    7f9ab4579000 rw-p 001ea000  08:05  3541128   12   12  12         12        12        0              0             0              0               0    0       0      0           0 libc-2.31.so
    7f9ab4576000 r--p 001e7000  08:05  3541128   12   12  12         12        12        0              0             0              0               0    0       0      0           0 libc-2.31.so
    7f9ab4575000 ---p 001e7000  08:05  3541128    4    0   0          0         0        0              0             0              0               0    0       0      0           0 libc-2.31.so
    7f9ab452b000 r--p 0019d000  08:05  3541128  296  124   1        124         0        0              0             0              0               0    0       0      0           0 libc-2.31.so
    7f9ab43b3000 r-xp 00025000  08:05  3541128 1504 1000  10       1000         0        0              0             0              0               0    0       0      0           0 libc-2.31.so
    7f9ab438e000 r--p 00000000  08:05  3541128  148  140   1        140         0        0              0             0              0               0    0       0      0           0 libc-2.31.so
    558e1b9d6000 rw-p 00000000  00:00        0  132    4   4          4         4        0              0             0              0               0    0       0      0           0 [heap]
    558e1a654000 rw-p 00003000  08:05  1051705    4    4   4          4         4        0              0             0              0               0    0       0      0           0 probe
    558e1a653000 r--p 00002000  08:05  1051705    4    4   4          4         4        0              0             0              0               0    0       0      0           0 probe
    558e1a652000 r--p 00002000  08:05  1051705    4    4   4          4         0        0              0             0              0               0    0       0      0           0 probe
    558e1a651000 r-xp 00001000  08:05  1051705    4    4   4          4         0        0              0             0              0               0    0       0      0           0 probe
    558e1a650000 r--p 00000000  08:05  1051705    4    4   4          4         0        0              0             0              0               0    0       0      0           0 probe
         Address Perm   Offset Device    Inode Size  Rss Pss Referenced Anonymous LazyFree ShmemPmdMapped FilePmdMapped Shared_Hugetlb Private_Hugetlb Swap SwapPss Locked THPeligible Mapping
4175:   ./probe
```

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



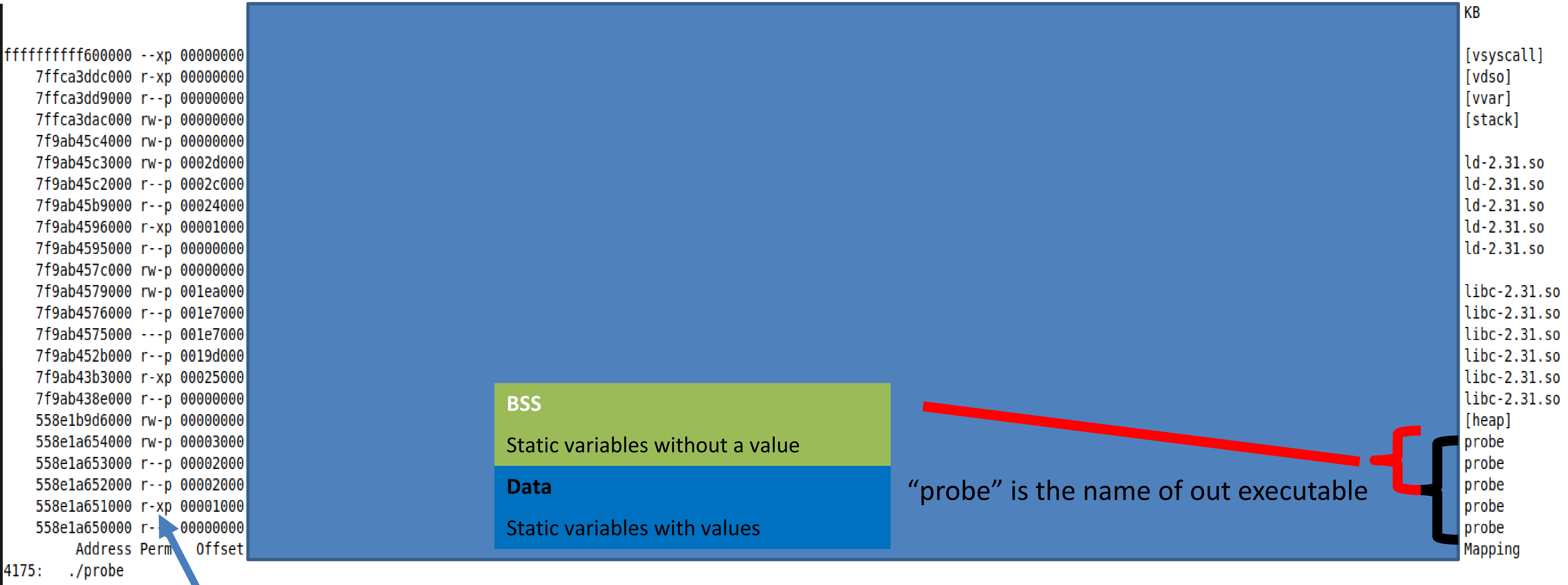
```
                                    [redacted]                    KB

ffffffffff600000 --xp 00000000                                    [vsyscall]
    7ffca3ddc000 r-xp 00000000                                    [vdso]
    7ffca3dd9000 r--p 00000000                                    [vvar]
    7ffca3dac000 rw-p 00000000                                    [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000                                    ld-2.31.so
    7f9ab45c2000 r--p 0002c000                                    ld-2.31.so
    7f9ab45b9000 r--p 00024000                                    ld-2.31.so
    7f9ab4596000 r-xp 00001000                                    ld-2.31.so
    7f9ab4595000 r--p 00000000                                    ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000                                    libc-2.31.so
    7f9ab4576000 r--p 001e7000                                    libc-2.31.so
    7f9ab4575000 ---p 001e7000                                    libc-2.31.so
    7f9ab452b000 r--p 0019d000                                    libc-2.31.so
    7f9ab43b3000 r-xp 00025000                                    libc-2.31.so
    7f9ab438e000 r--p 00000000                                    libc-2.31.so
    558e1b9d6000 rw-p 00000000                                    [heap]
    558e1a654000 rw-p 00003000                                    probe
    558e1a653000 r--p 00002000                                    probe
    558e1a652000 r--p 00002000                                    probe
    558e1a651000 r-xp 00001000                                    probe
    558e1a650000 r--p 00000000                                    probe
         Address Perm   Offset                                    Mapping
4175:   ./probe
```

"probe" is the name of our executable

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



```
                                      KB

ffffffffff600000 --xp 00000000        [vsyscall]
    7ffca3ddc000 r-xp 00000000        [vdso]
    7ffca3dd9000 r--p 00000000        [vvar]
    7ffca3dac000 rw-p 00000000        [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000        ld-2.31.so
    7f9ab45c2000 r--p 0002c000        ld-2.31.so
    7f9ab45b9000 r--p 00024000        ld-2.31.so
    7f9ab4596000 r-xp 00001000        ld-2.31.so
    7f9ab4595000 r--p 00000000        ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000        libc-2.31.so
    7f9ab4576000 r--p 001e7000        libc-2.31.so
    7f9ab4575000 ---p 001e7000        libc-2.31.so
    7f9ab452b000 r--p 0019d000        libc-2.31.so
    7f9ab43b3000 r-xp 00025000        libc-2.31.so
    7f9ab438e000 r--p 00000000        libc-2.31.so
    558e1b9d6000 rw-p 00000000        [heap]
    558e1a654000 rw-p 00003000        probe
    558e1a653000 r--p 00002000        probe
    558e1a652000 r--p 00002000        probe
    558e1a651000 r-xp 00001000        probe
    558e1a650000 r-   00000000        probe
         Address Perm   Offset        Mapping
4175:   ./probe
```

BSS

Static variables without a value

Data

Static variables with values

“probe” is the name of out executable

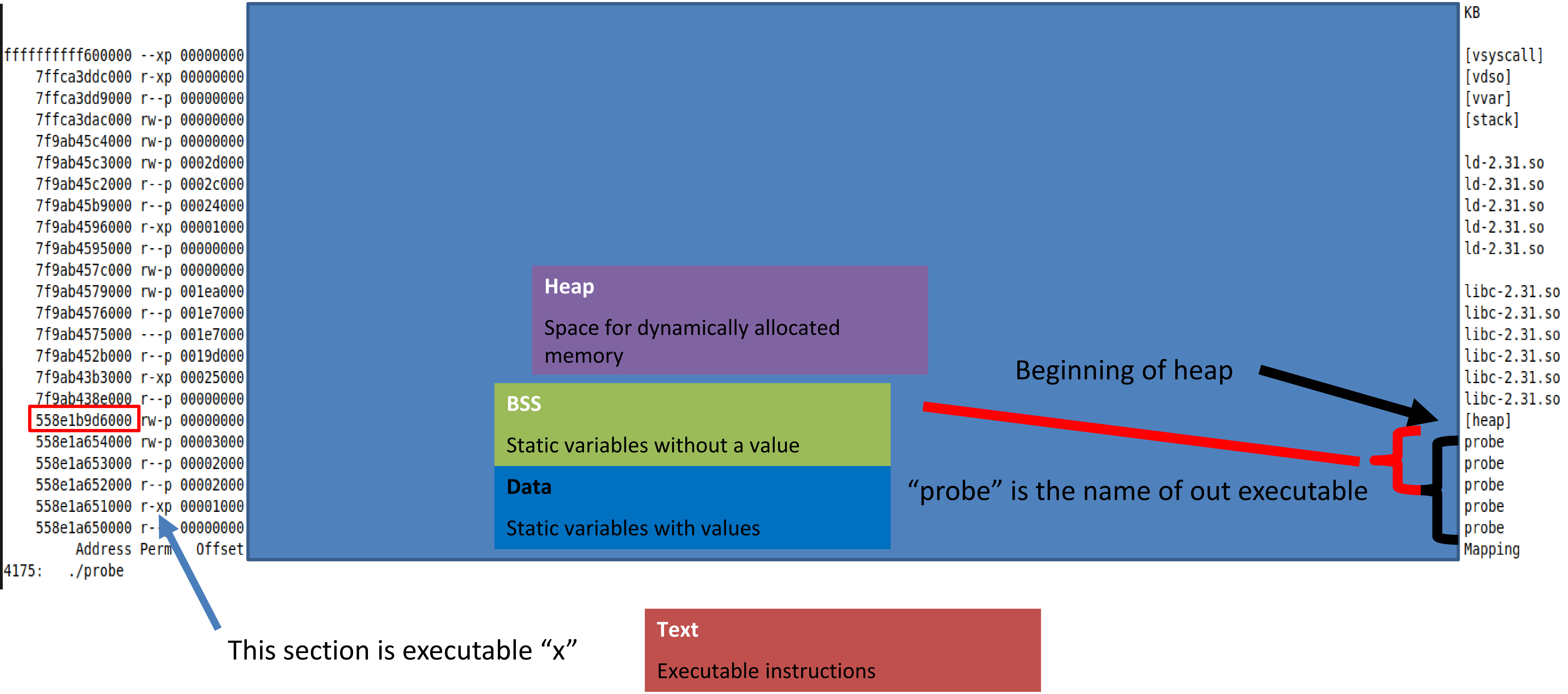
This section is executable “x”

Text

Executable instructions

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



```
                                                                  KB

ffffffffff600000 --xp 00000000                                    [vsyscall]
    7ffca3ddc000 r-xp 00000000                                    [vdso]
    7ffca3dd9000 r--p 00000000                                    [vvar]
    7ffca3dac000 rw-p 00000000                                    [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000                                    ld-2.31.so
    7f9ab45c2000 r--p 0002c000                                    ld-2.31.so
    7f9ab45b9000 r--p 00024000                                    ld-2.31.so
    7f9ab4596000 r-xp 00001000                                    ld-2.31.so
    7f9ab4595000 r--p 00000000                                    ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000                                    libc-2.31.so
    7f9ab4576000 r--p 001e7000                                    libc-2.31.so
    7f9ab4575000 ---p 001e7000                                    libc-2.31.so
    7f9ab452b000 r--p 0019d000                                    libc-2.31.so
    7f9ab43b3000 r-xp 00025000                                    libc-2.31.so
    7f9ab438e000 r--p 00000000                                    libc-2.31.so
    558e1b9d6000 rw-p 00000000                                    [heap]
    558e1a654000 rw-p 00003000                                    probe
    558e1a653000 r--p 00002000                                    probe
    558e1a652000 r--p 00002000                                    probe
    558e1a651000 r-xp 00001000                                    probe
    558e1a650000 r--p 00000000                                    probe
         Address Perm   Offset                                    Mapping
4175:   ./probe
```

Heap

Space for dynamically allocated memory

BSS

Static variables without a value

Data

Static variables with values

Beginning of heap

“probe” is the name of out executable

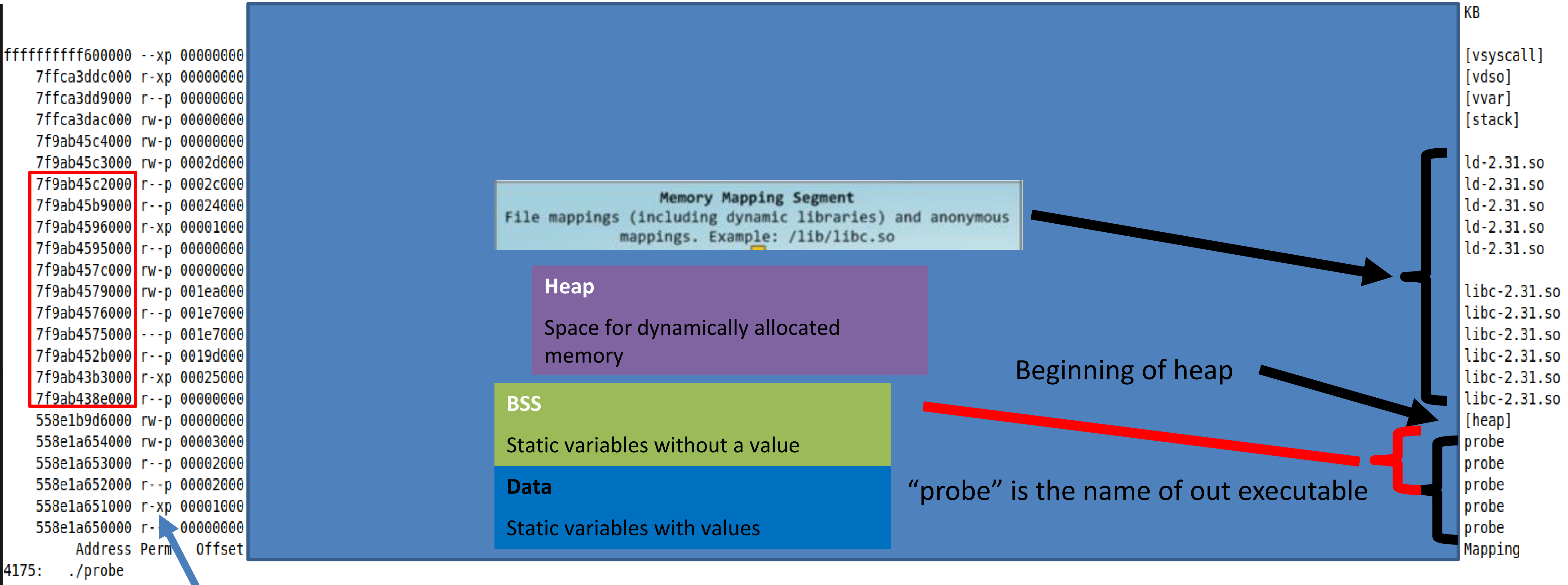
This section is executable “x”

Text

Executable instructions

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



```
                                                KB
ffffffffff600000 --xp 00000000                  [vsyscall]
    7ffca3ddc000 r-xp 00000000                  [vdso]
    7ffca3dd9000 r--p 00000000                  [vvar]
    7ffca3dac000 rw-p 00000000                  [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000                  ld-2.31.so
    7f9ab45c2000 r--p 0002c000                  ld-2.31.so
    7f9ab45b9000 r--p 00024000                  ld-2.31.so
    7f9ab4596000 r-xp 00001000                  ld-2.31.so
    7f9ab4595000 r--p 00000000                  ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000                  libc-2.31.so
    7f9ab4576000 r--p 001e7000                  libc-2.31.so
    7f9ab4575000 ---p 001e7000                  libc-2.31.so
    7f9ab452b000 r--p 0019d000                  libc-2.31.so
    7f9ab43b3000 r-xp 00025000                  libc-2.31.so
    7f9ab438e000 r--p 00000000                  libc-2.31.so
    558e1b9d6000 rw-p 00000000                  [heap]
    558e1a654000 rw-p 00003000                  probe
    558e1a653000 r--p 00002000                  probe
    558e1a652000 r--p 00002000                  probe
    558e1a651000 r-xp 00001000                  probe
    558e1a650000 r--p 00000000                  probe
         Address Perm   Offset                  Mapping
4175:   ./probe
```

Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so

Heap

Space for dynamically allocated memory

Beginning of heap

BSS

Static variables without a value

Data

Static variables with values

"probe" is the name of out executable

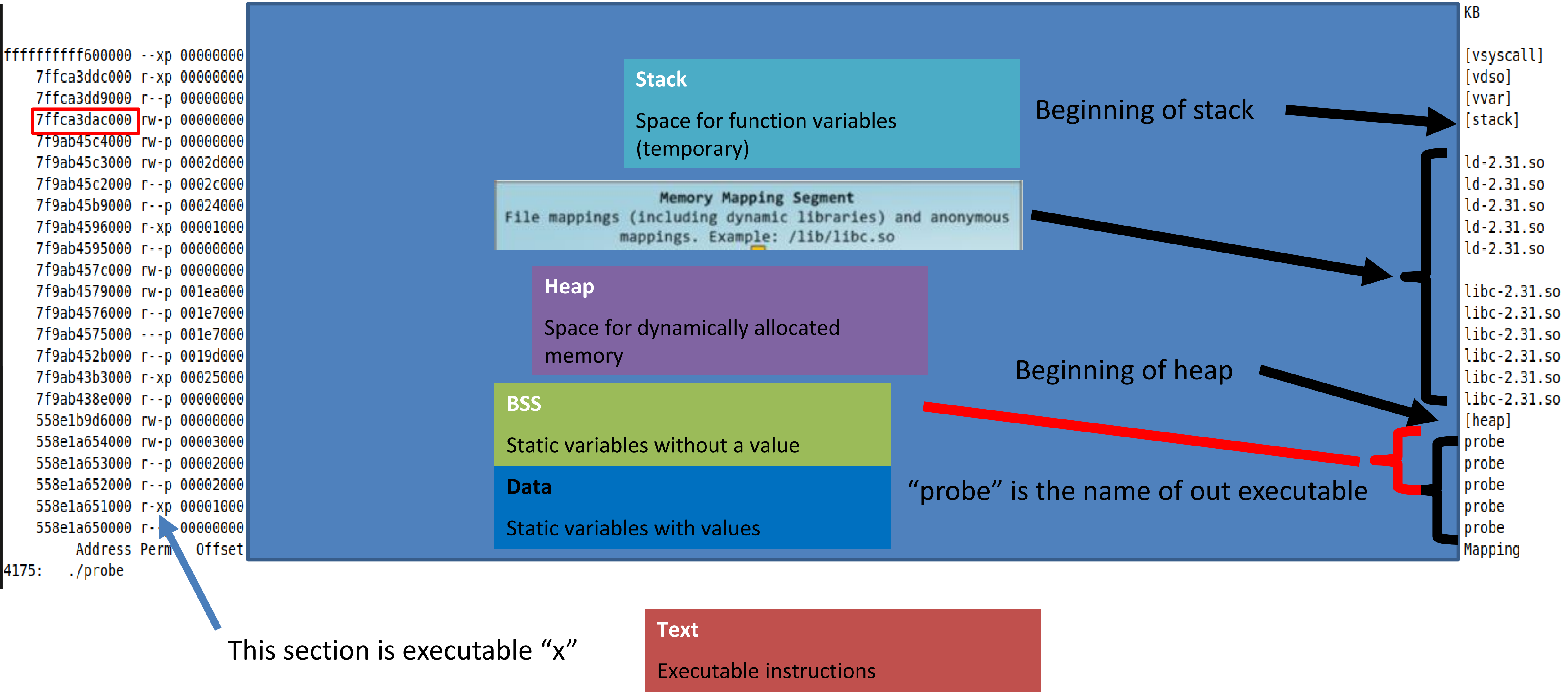
This section is executable "x"

Text

Executable instructions

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



```
4175:   ./probe
         Address Perm   Offset                                    Mapping
    558e1a650000 r--p 00000000                                    probe
    558e1a651000 r-xp 00001000                                    probe
    558e1a652000 r--p 00002000                                    probe
    558e1a653000 r--p 00002000                                    probe
    558e1a654000 rw-p 00003000                                    probe
    558e1b9d6000 rw-p 00000000                                    [heap]
    7f9ab438e000 r--p 00000000                                    libc-2.31.so
    7f9ab43b3000 r-xp 00025000                                    libc-2.31.so
    7f9ab452b000 r--p 0019d000                                    libc-2.31.so
    7f9ab4575000 ---p 001e7000                                    libc-2.31.so
    7f9ab4576000 r--p 001e7000                                    libc-2.31.so
    7f9ab4579000 rw-p 001ea000                                    libc-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4595000 r--p 00000000                                    ld-2.31.so
    7f9ab4596000 r-xp 00001000                                    ld-2.31.so
    7f9ab45b9000 r--p 00024000                                    ld-2.31.so
    7f9ab45c2000 r--p 0002c000                                    ld-2.31.so
    7f9ab45c3000 rw-p 0002d000                                    ld-2.31.so
    7f9ab45c4000 rw-p 00000000
    7ffca3dac000 rw-p 00000000                                    [stack]
    7ffca3dd9000 r--p 00000000                                    [vvar]
    7ffca3ddc000 r-xp 00000000                                    [vdso]
ffffffffff600000 --xp 00000000                                    [vsyscall]
                                                                  KB
```

Stack
Space for function variables (temporary)
Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so
Heap
Space for dynamically allocated memory
BSS
Static variables without a value
Data
Static variables with values
Text
Executable instructions

Beginning of stack

Beginning of heap

“probe” is the name of out executable

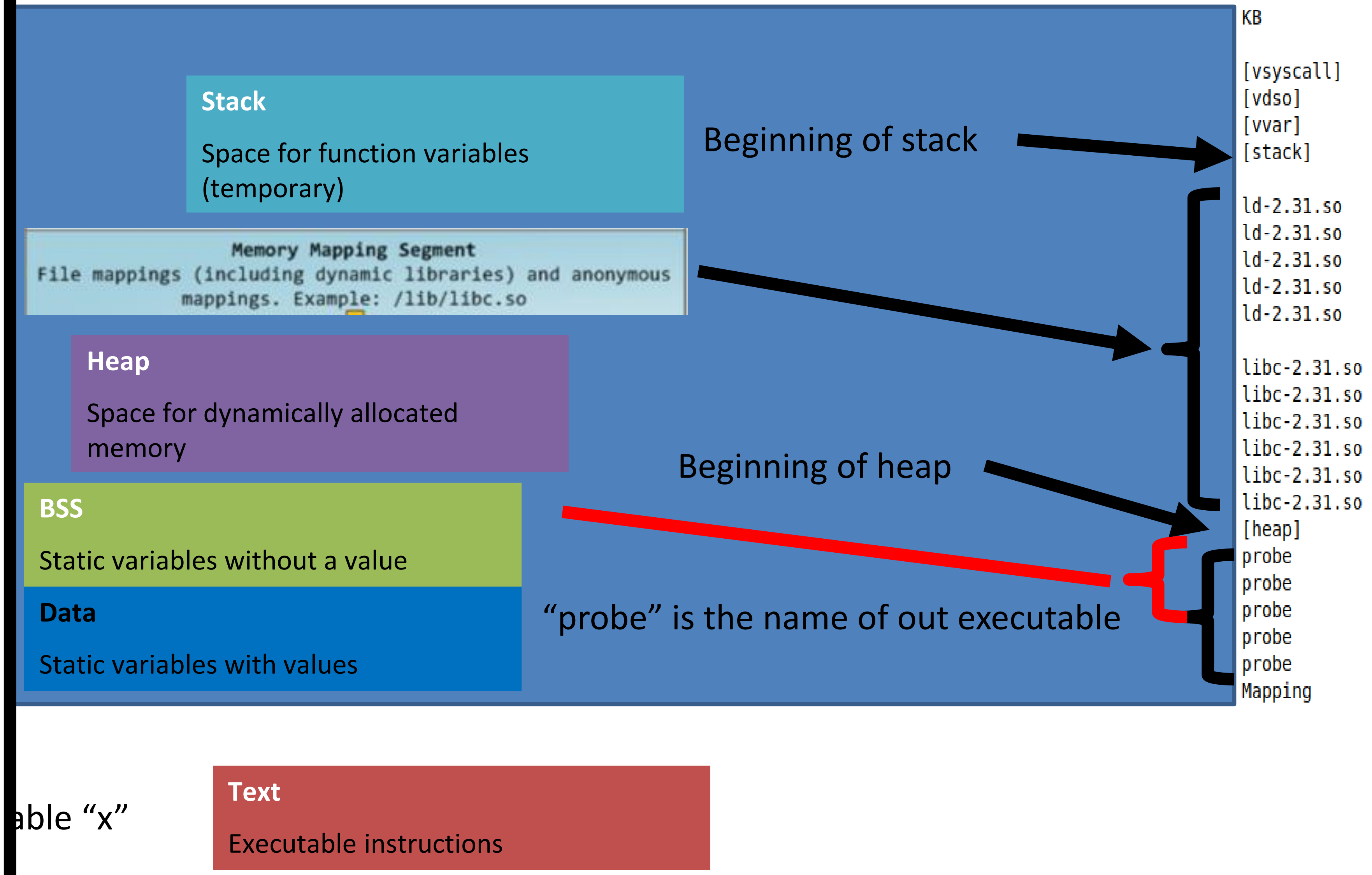
This section is executable “x”

Applications Layout in Memory

When you allocate variables on the stack

When you allocate variables on the heap

Ouput of pmap (process mapping tool)



Stack

Space for function variables (temporary)

Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so

Heap

Space for dynamically allocated memory

BSS

Static variables without a value

Data

Static variables with values

Text

Executable instructions

Beginning of stack

Beginning of heap

“probe” is the name of out executable

```
KB

[vsyscall]
[vdso]
[vvar]
[stack]

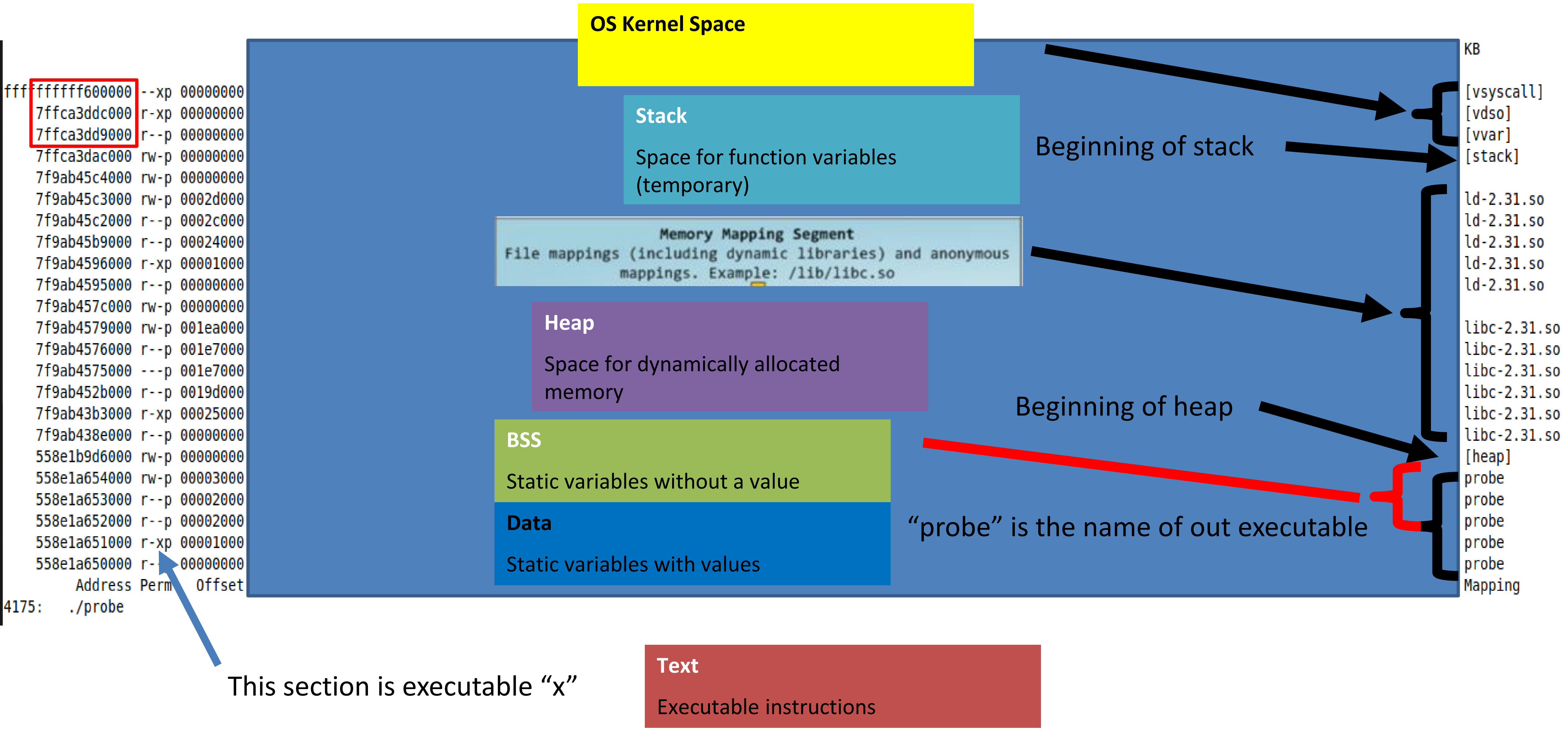
ld-2.31.so
ld-2.31.so
ld-2.31.so
ld-2.31.so
ld-2.31.so

libc-2.31.so
libc-2.31.so
libc-2.31.so
libc-2.31.so
libc-2.31.so
libc-2.31.so
[heap]
probe
probe
probe
probe
probe
Mapping
```

able “x”

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



```
                                                     KB
ffffffffff600000 --xp 00000000                       [vsyscall]
    7ffca3ddc000 r-xp 00000000                       [vdso]
    7ffca3dd9000 r--p 00000000                       [vvar]
    7ffca3dac000 rw-p 00000000                       [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000                       ld-2.31.so
    7f9ab45c2000 r--p 0002c000                       ld-2.31.so
    7f9ab45b9000 r--p 00024000                       ld-2.31.so
    7f9ab4596000 r-xp 00001000                       ld-2.31.so
    7f9ab4595000 r--p 00000000                       ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000                       libc-2.31.so
    7f9ab4576000 r--p 001e7000                       libc-2.31.so
    7f9ab4575000 ---p 001e7000                       libc-2.31.so
    7f9ab452b000 r--p 0019d000                       libc-2.31.so
    7f9ab43b3000 r-xp 00025000                       libc-2.31.so
    7f9ab438e000 r--p 00000000                       libc-2.31.so
    558e1b9d6000 rw-p 00000000                       [heap]
    558e1a654000 rw-p 00003000                       probe
    558e1a653000 r--p 00002000                       probe
    558e1a652000 r--p 00002000                       probe
    558e1a651000 r-xp 00001000                       probe
    558e1a650000 r-   00000000                       probe
         Address Perm   Offset                       Mapping
4175:   ./probe
```

OS Kernel Space

Stack

Space for function variables (temporary)

Beginning of stack

Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so

Heap

Space for dynamically allocated memory

Beginning of heap

BSS

Static variables without a value

Data

Static variables with values

“probe” is the name of out executable

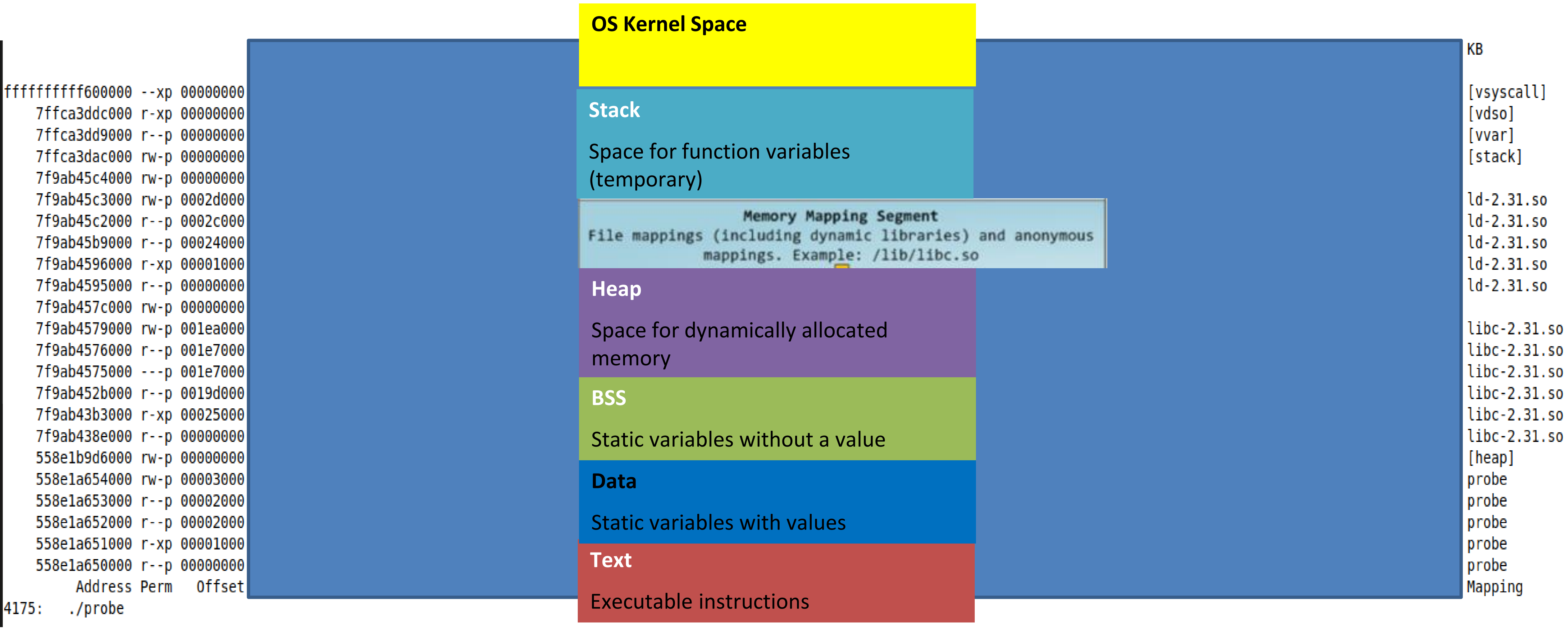
This section is executable “x”

Text

Executable instructions

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



```
                                  KB
ffffffffff600000 --xp 00000000    [vsyscall]
    7ffca3ddc000 r-xp 00000000    [vdso]
    7ffca3dd9000 r--p 00000000    [vvar]
    7ffca3dac000 rw-p 00000000    [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000    ld-2.31.so
    7f9ab45c2000 r--p 0002c000    ld-2.31.so
    7f9ab45b9000 r--p 00024000    ld-2.31.so
    7f9ab4596000 r-xp 00001000    ld-2.31.so
    7f9ab4595000 r--p 00000000    ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000    libc-2.31.so
    7f9ab4576000 r--p 001e7000    libc-2.31.so
    7f9ab4575000 ---p 001e7000    libc-2.31.so
    7f9ab452b000 r--p 0019d000    libc-2.31.so
    7f9ab43b3000 r-xp 00025000    libc-2.31.so
    7f9ab438e000 r--p 00000000    libc-2.31.so
    558e1b9d6000 rw-p 00000000    [heap]
    558e1a654000 rw-p 00003000    probe
    558e1a653000 r--p 00002000    probe
    558e1a652000 r--p 00002000    probe
    558e1a651000 r-xp 00001000    probe
    558e1a650000 r--p 00000000    probe
         Address Perm   Offset    Mapping
4175:   ./probe
```

OS Kernel Space

Stack

Space for function variables (temporary)

Memory Mapping Segment

File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so

Heap

Space for dynamically allocated memory

BSS

Static variables without a value

Data

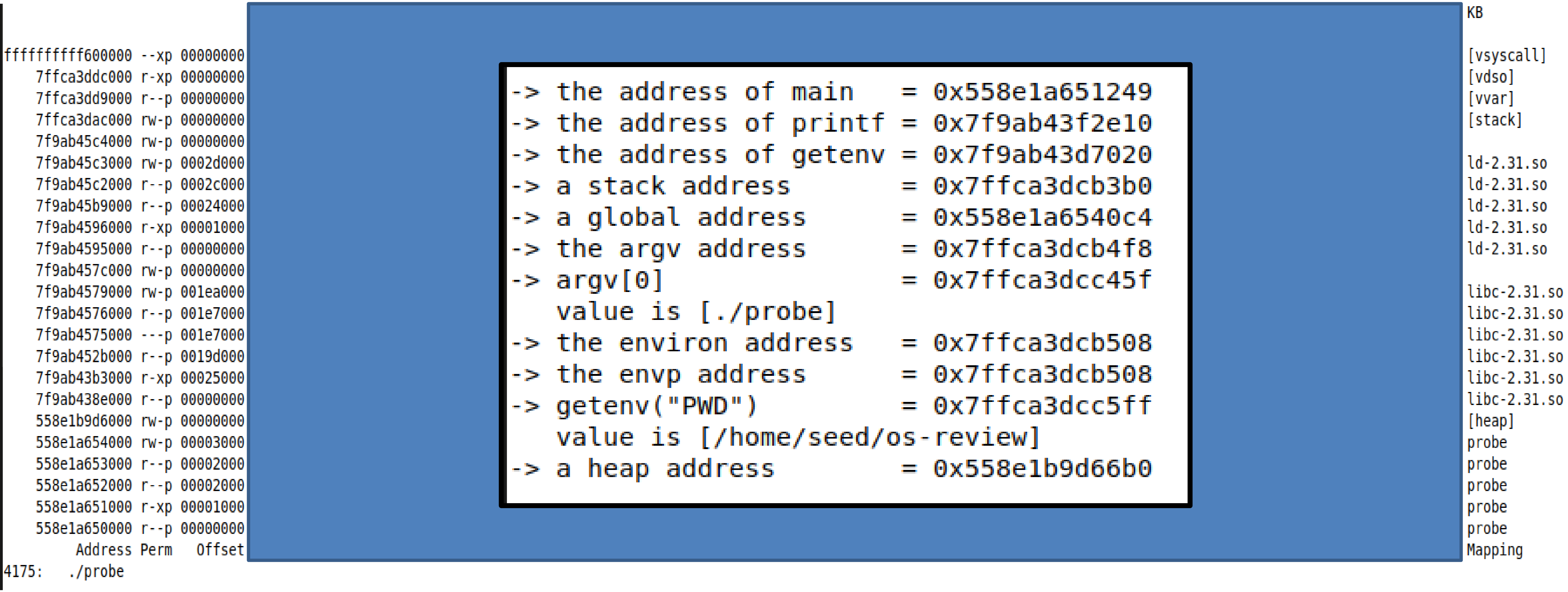
Static variables with values

Text

Executable instructions

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)

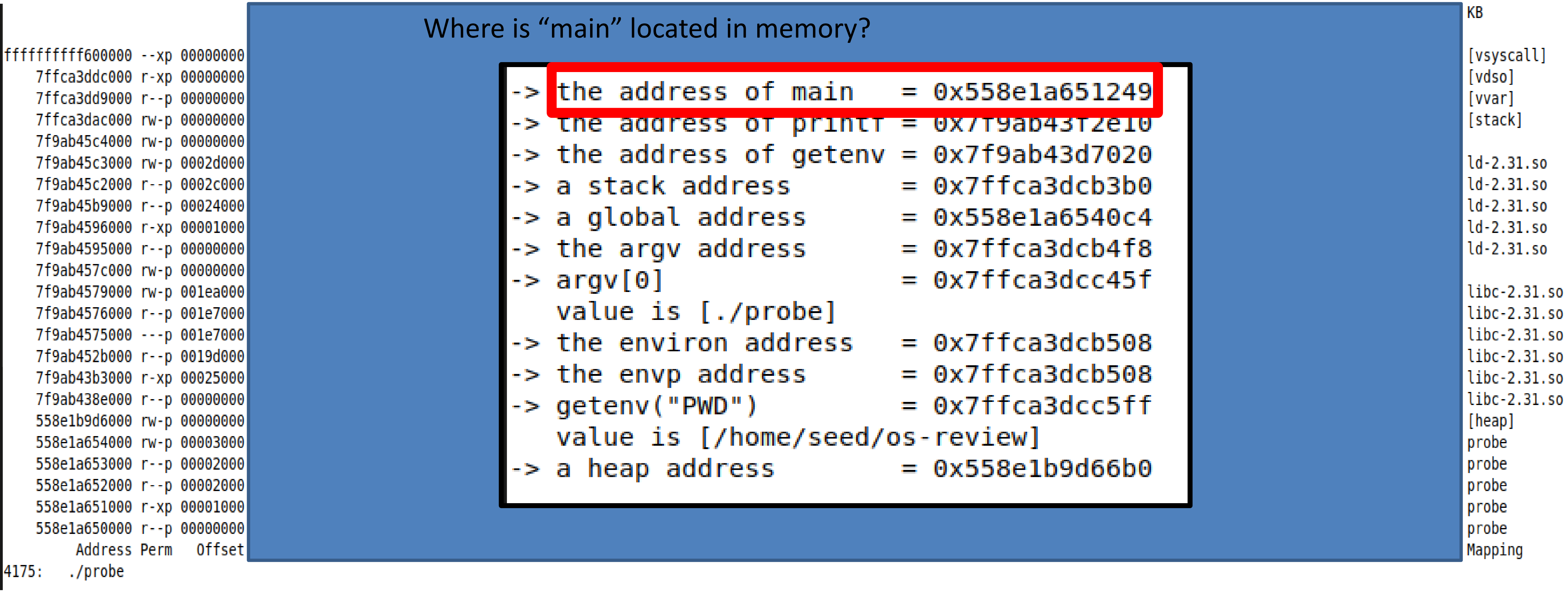


```
                                        KB
ffffffffff600000 --xp 00000000          [vsyscall]
    7ffca3ddc000 r-xp 00000000          [vdso]
    7ffca3dd9000 r--p 00000000          [vvar]
    7ffca3dac000 rw-p 00000000          [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000          ld-2.31.so
    7f9ab45c2000 r--p 0002c000          ld-2.31.so
    7f9ab45b9000 r--p 00024000          ld-2.31.so
    7f9ab4596000 r-xp 00001000          ld-2.31.so
    7f9ab4595000 r--p 00000000          ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000          libc-2.31.so
    7f9ab4576000 r--p 001e7000          libc-2.31.so
    7f9ab4575000 ---p 001e7000          libc-2.31.so
    7f9ab452b000 r--p 0019d000          libc-2.31.so
    7f9ab43b3000 r-xp 00025000          libc-2.31.so
    7f9ab438e000 r--p 00000000          libc-2.31.so
    558e1b9d6000 rw-p 00000000          [heap]
    558e1a654000 rw-p 00003000          probe
    558e1a653000 r--p 00002000          probe
    558e1a652000 r--p 00002000          probe
    558e1a651000 r-xp 00001000          probe
    558e1a650000 r--p 00000000          probe
         Address Perm   Offset          Mapping
4175:   ./probe
```

```
-> the address of main   = 0x558e1a651249
-> the address of printf = 0x7f9ab43f2e10
-> the address of getenv = 0x7f9ab43d7020
-> a stack address       = 0x7ffca3dcb3b0
-> a global address      = 0x558e1a6540c4
-> the argv address      = 0x7ffca3dcb4f8
-> argv[0]               = 0x7ffca3dcc45f
   value is [./probe]
-> the environ address   = 0x7ffca3dcb508
-> the envp address      = 0x7ffca3dcb508
-> getenv("PWD")         = 0x7ffca3dcc5ff
   value is [/home/seed/os-review]
-> a heap address        = 0x558e1b9d66b0
```

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



```
                                                            KB

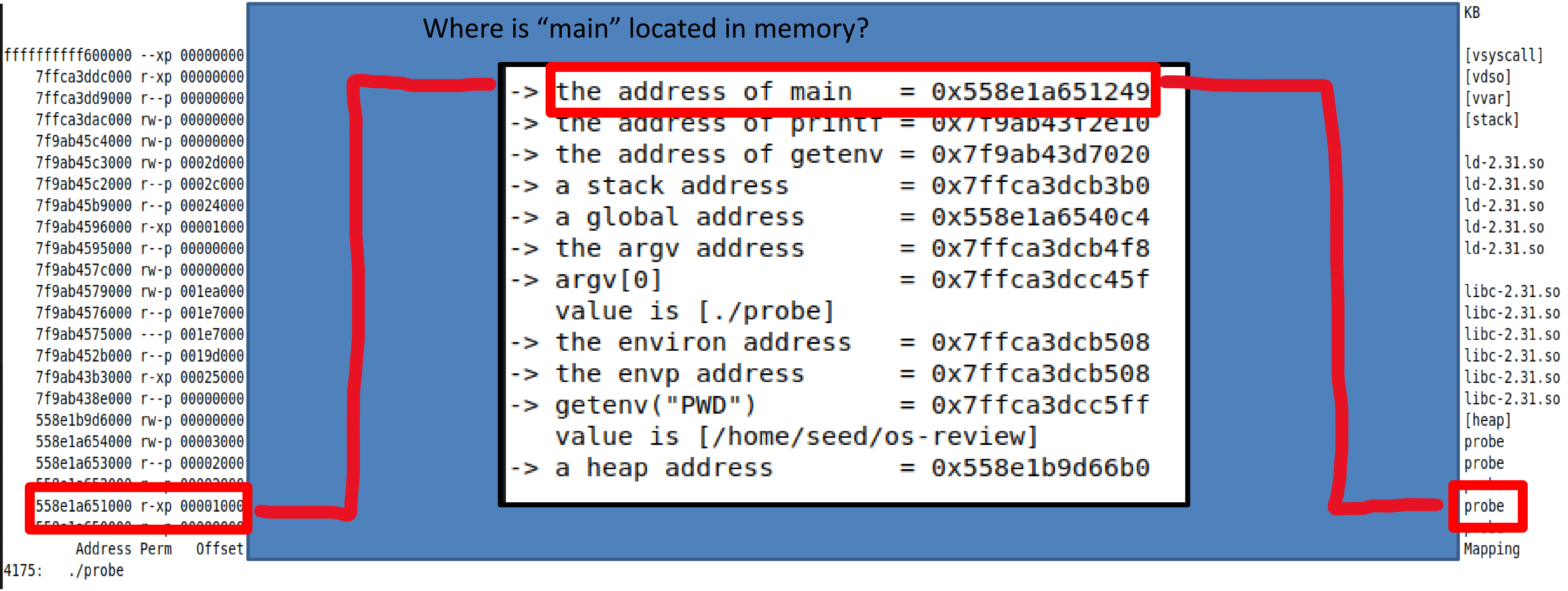
ffffffffff600000 --xp 00000000                              [vsyscall]
    7ffca3ddc000 r-xp 00000000                              [vdso]
    7ffca3dd9000 r--p 00000000                              [vvar]
    7ffca3dac000 rw-p 00000000                              [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000                              ld-2.31.so
    7f9ab45c2000 r--p 0002c000                              ld-2.31.so
    7f9ab45b9000 r--p 00024000                              ld-2.31.so
    7f9ab4596000 r-xp 00001000                              ld-2.31.so
    7f9ab4595000 r--p 00000000                              ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000                              libc-2.31.so
    7f9ab4576000 r--p 001e7000                              libc-2.31.so
    7f9ab4575000 ---p 001e7000                              libc-2.31.so
    7f9ab452b000 r--p 0019d000                              libc-2.31.so
    7f9ab43b3000 r-xp 00025000                              libc-2.31.so
    7f9ab438e000 r--p 00000000                              libc-2.31.so
    558e1b9d6000 rw-p 00000000                              [heap]
    558e1a654000 rw-p 00003000                              probe
    558e1a653000 r--p 00002000                              probe
    558e1a652000 r--p 00002000                              probe
    558e1a651000 r-xp 00001000                              probe
    558e1a650000 r--p 00000000                              probe
         Address Perm   Offset                              Mapping
4175:   ./probe
```

Where is “main” located in memory?

```
-> the address of main   = 0x558e1a651249
-> the address of printf = 0x7f9ab43f2e10
-> the address of getenv = 0x7f9ab43d7020
-> a stack address       = 0x7ffca3dcb3b0
-> a global address      = 0x558e1a6540c4
-> the argv address      = 0x7ffca3dcb4f8
-> argv[0]               = 0x7ffca3dcc45f
   value is [./probe]
-> the environ address   = 0x7ffca3dcb508
-> the envp address      = 0x7ffca3dcb508
-> getenv("PWD")         = 0x7ffca3dcc5ff
   value is [/home/seed/os-review]
-> a heap address        = 0x558e1b9d66b0
```

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



Where is “main” located in memory?

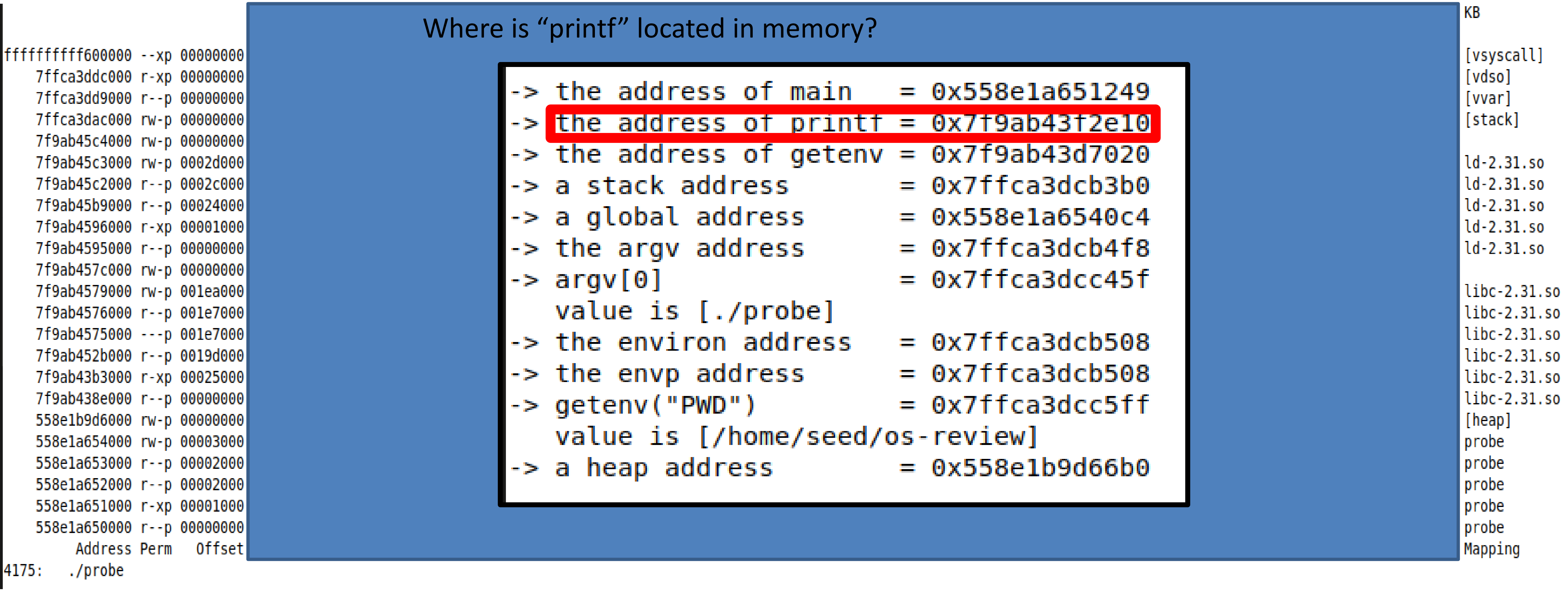
```
                                      KB
ffffffffff600000 --xp 00000000        [vsyscall]
    7ffca3ddc000 r-xp 00000000        [vdso]
    7ffca3dd9000 r--p 00000000        [vvar]
    7ffca3dac000 rw-p 00000000        [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000        ld-2.31.so
    7f9ab45c2000 r--p 0002c000        ld-2.31.so
    7f9ab45b9000 r--p 00024000        ld-2.31.so
    7f9ab4596000 r-xp 00001000        ld-2.31.so
    7f9ab4595000 r--p 00000000        ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000        libc-2.31.so
    7f9ab4576000 r--p 001e7000        libc-2.31.so
    7f9ab4575000 ---p 001e7000        libc-2.31.so
    7f9ab452b000 r--p 0019d000        libc-2.31.so
    7f9ab43b3000 r-xp 00025000        libc-2.31.so
    7f9ab438e000 r--p 00000000        libc-2.31.so
    558e1b9d6000 rw-p 00000000        [heap]
    558e1a654000 rw-p 00003000        probe
    558e1a653000 r--p 00002000        probe
    558e1a652000 r--p 00002000        probe
    558e1a651000 r-xp 00001000        probe
    558e1a650000 r--p 00000000        probe
         Address Perm   Offset        Mapping
4175:   ./probe
```

```
-> the address of main   = 0x558e1a651249
-> the address of printf = 0x7f9ab43f2e10
-> the address of getenv = 0x7f9ab43d7020
-> a stack address       = 0x7ffca3dcb3b0
-> a global address      = 0x558e1a6540c4
-> the argv address      = 0x7ffca3dcb4f8
-> argv[0]               = 0x7ffca3dcc45f
   value is [./probe]
-> the environ address   = 0x7ffca3dcb508
-> the envp address      = 0x7ffca3dcb508
-> getenv("PWD")         = 0x7ffca3dcc5ff
   value is [/home/seed/os-review]
-> a heap address        = 0x558e1b9d66b0
```

`main` is code in our program, so it goes inside the text segment

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



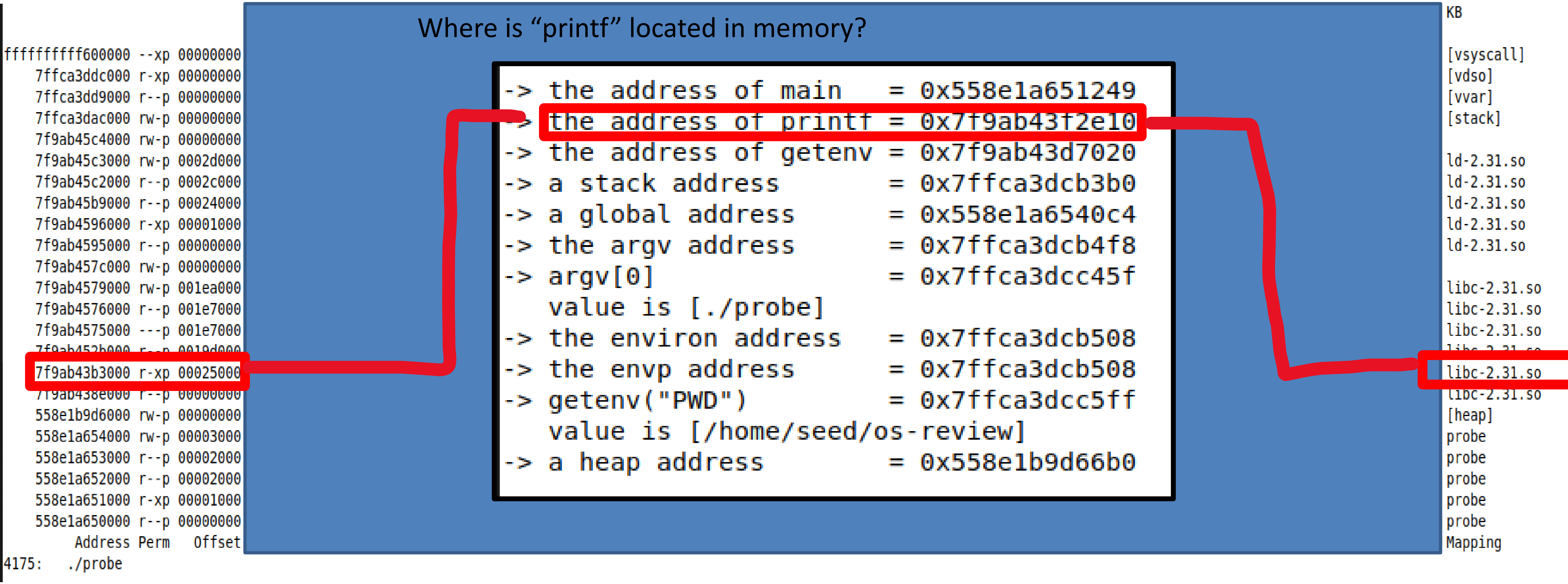
```
                                                KB
ffffffffff600000 --xp 00000000                  [vsyscall]
    7ffca3ddc000 r-xp 00000000                  [vdso]
    7ffca3dd9000 r--p 00000000                  [vvar]
    7ffca3dac000 rw-p 00000000                  [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000                  ld-2.31.so
    7f9ab45c2000 r--p 0002c000                  ld-2.31.so
    7f9ab45b9000 r--p 00024000                  ld-2.31.so
    7f9ab4596000 r-xp 00001000                  ld-2.31.so
    7f9ab4595000 r--p 00000000                  ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000                  libc-2.31.so
    7f9ab4576000 r--p 001e7000                  libc-2.31.so
    7f9ab4575000 ---p 001e7000                  libc-2.31.so
    7f9ab452b000 r--p 0019d000                  libc-2.31.so
    7f9ab43b3000 r-xp 00025000                  libc-2.31.so
    7f9ab438e000 r--p 00000000                  libc-2.31.so
    558e1b9d6000 rw-p 00000000                  [heap]
    558e1a654000 rw-p 00003000                  probe
    558e1a653000 r--p 00002000                  probe
    558e1a652000 r--p 00002000                  probe
    558e1a651000 r-xp 00001000                  probe
    558e1a650000 r--p 00000000                  probe
         Address Perm   Offset                  Mapping
4175:   ./probe
```

Where is “printf” located in memory?

```
-> the address of main   = 0x558e1a651249
-> the address of printf = 0x7f9ab43f2e10
-> the address of getenv = 0x7f9ab43d7020
-> a stack address       = 0x7ffca3dcb3b0
-> a global address      = 0x558e1a6540c4
-> the argv address      = 0x7ffca3dcb4f8
-> argv[0]               = 0x7ffca3dcc45f
   value is [./probe]
-> the environ address   = 0x7ffca3dcb508
-> the envp address      = 0x7ffca3dcb508
-> getenv("PWD")         = 0x7ffca3dcc5ff
   value is [/home/seed/os-review]
-> a heap address        = 0x558e1b9d66b0
```

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



```
ffffffffff600000 --xp 00000000
    7ffca3ddc000 r-xp 00000000
    7ffca3dd9000 r--p 00000000
    7ffca3dac000 rw-p 00000000
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000
    7f9ab45c2000 r--p 0002c000
    7f9ab45b9000 r--p 00024000
    7f9ab4596000 r-xp 00001000
    7f9ab4595000 r--p 00000000
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000
    7f9ab4576000 r--p 001e7000
    7f9ab4575000 ---p 001e7000
    7f9ab452b000 r--p 0019d000
    7f9ab43b3000 r-xp 00025000
    7f9ab438e000 r--p 00000000
    558e1b9d6000 rw-p 00000000
    558e1a654000 rw-p 00003000
    558e1a653000 r--p 00002000
    558e1a652000 r--p 00002000
    558e1a651000 r-xp 00001000
    558e1a650000 r--p 00000000
         Address Perm   Offset
4175:   ./probe
```

```
KB

[vsyscall]
[vdso]
[vvar]
[stack]

ld-2.31.so
ld-2.31.so
ld-2.31.so
ld-2.31.so
ld-2.31.so

libc-2.31.so
libc-2.31.so
libc-2.31.so
libc-2.31.so
libc-2.31.so
libc-2.31.so
[heap]
probe
probe
probe
probe
probe
Mapping
```

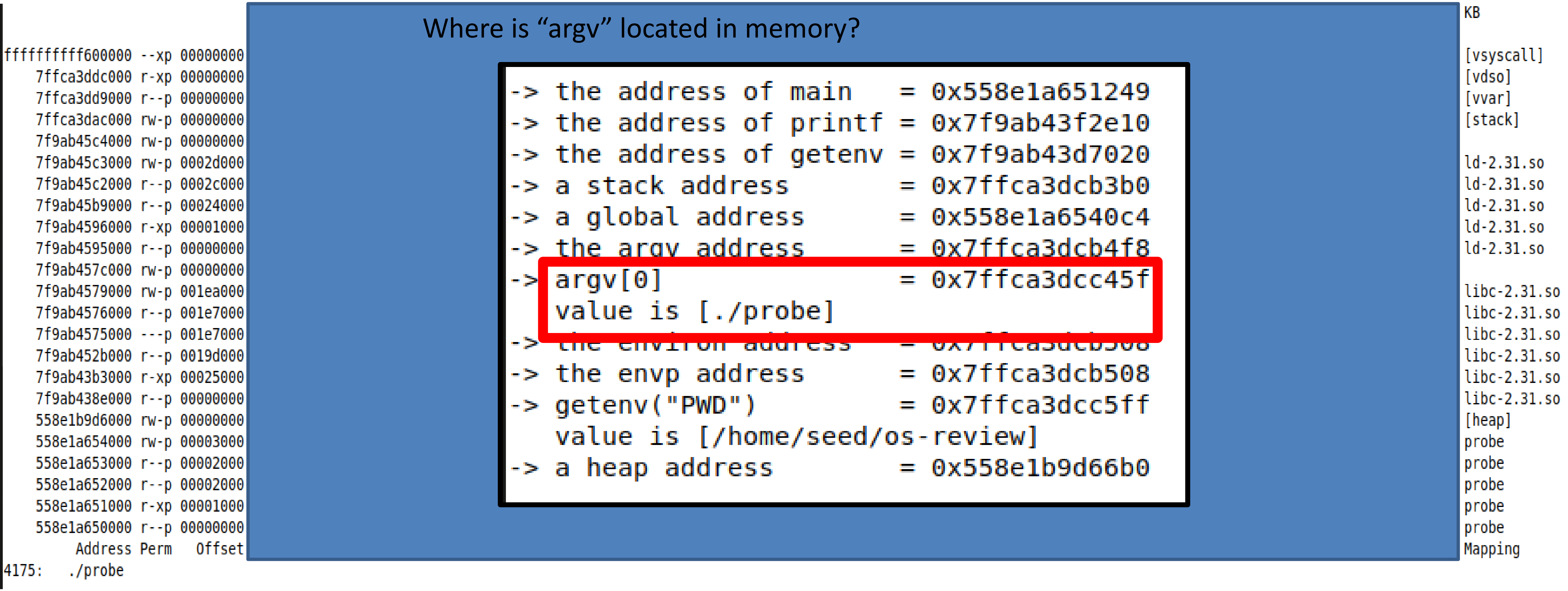
Where is “printf” located in memory?

```
-> the address of main   = 0x558e1a651249
-> the address of printf = 0x7f9ab43f2e10
-> the address of getenv = 0x7f9ab43d7020
-> a stack address       = 0x7ffca3dcb3b0
-> a global address      = 0x558e1a6540c4
-> the argv address      = 0x7ffca3dcb4f8
-> argv[0]               = 0x7ffca3dcc45f
   value is [./probe]
-> the environ address   = 0x7ffca3dcb508
-> the envp address      = 0x7ffca3dcb508
-> getenv("PWD")         = 0x7ffca3dcc5ff
   value is [/home/seed/os-review]
-> a heap address        = 0x558e1b9d66b0
```

`printf` is executable code from a shared library (libc) so we are in the memory mapping segment!

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



Where is “argv” located in memory?

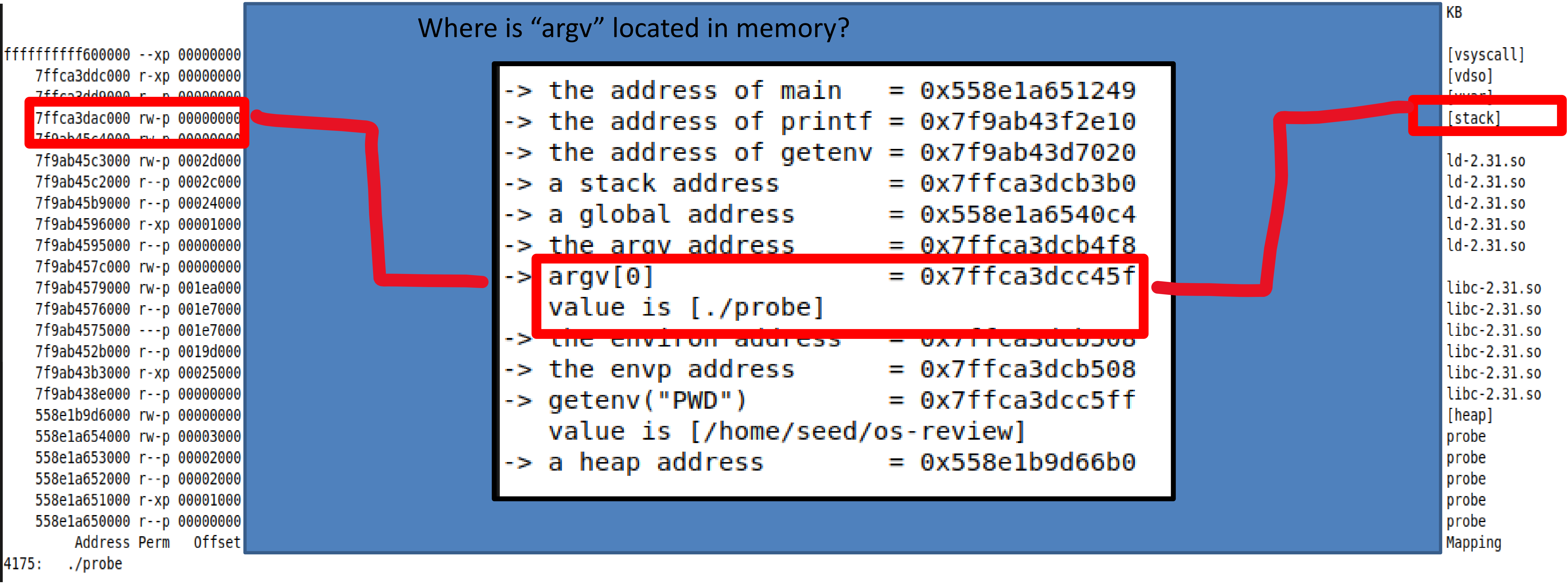
```
                                                  KB
ffffffffff600000 --xp 00000000                    [vsyscall]
    7ffca3ddc000 r-xp 00000000                    [vdso]
    7ffca3dd9000 r--p 00000000                    [vvar]
    7ffca3dac000 rw-p 00000000                    [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000                    ld-2.31.so
    7f9ab45c2000 r--p 0002c000                    ld-2.31.so
    7f9ab45b9000 r--p 00024000                    ld-2.31.so
    7f9ab4596000 r-xp 00001000                    ld-2.31.so
    7f9ab4595000 r--p 00000000                    ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000                    libc-2.31.so
    7f9ab4576000 r--p 001e7000                    libc-2.31.so
    7f9ab4575000 ---p 001e7000                    libc-2.31.so
    7f9ab452b000 r--p 0019d000                    libc-2.31.so
    7f9ab43b3000 r-xp 00025000                    libc-2.31.so
    7f9ab438e000 r--p 00000000                    libc-2.31.so
    558e1b9d6000 rw-p 00000000                    [heap]
    558e1a654000 rw-p 00003000                    probe
    558e1a653000 r--p 00002000                    probe
    558e1a652000 r--p 00002000                    probe
    558e1a651000 r-xp 00001000                    probe
    558e1a650000 r--p 00000000                    probe
         Address Perm   Offset                    Mapping
4175:   ./probe
```

```
-> the address of main   = 0x558e1a651249
-> the address of printf = 0x7f9ab43f2e10
-> the address of getenv = 0x7f9ab43d7020
-> a stack address       = 0x7ffca3dcb3b0
-> a global address      = 0x558e1a6540c4
-> the argv address      = 0x7ffca3dcb4f8
-> argv[0]               = 0x7ffca3dcc45f
   value is [./probe]
-> the environ address   = 0x7ffca3dcb508
-> the envp address      = 0x7ffca3dcb508
-> getenv("PWD")         = 0x7ffca3dcc5ff
   value is [/home/seed/os-review]
-> a heap address        = 0x558e1b9d66b0
```

`argv` is an array that holds the command line parameters passed into this program

Applications Layout in Memory

Ouput of `pmap` (process mapping tool)



```
                                                 KB
ffffffffff600000 --xp 00000000                   [vsyscall]
    7ffca3ddc000 r-xp 00000000                   [vdso]
    7ffca3dd9000 r--p 00000000                   [vvar]
    7ffca3dac000 rw-p 00000000                   [stack]
    7f9ab45c4000 rw-p 00000000
    7f9ab45c3000 rw-p 0002d000                   ld-2.31.so
    7f9ab45c2000 r--p 0002c000                   ld-2.31.so
    7f9ab45b9000 r--p 00024000                   ld-2.31.so
    7f9ab4596000 r-xp 00001000                   ld-2.31.so
    7f9ab4595000 r--p 00000000                   ld-2.31.so
    7f9ab457c000 rw-p 00000000
    7f9ab4579000 rw-p 001ea000                   libc-2.31.so
    7f9ab4576000 r--p 001e7000                   libc-2.31.so
    7f9ab4575000 ---p 001e7000                   libc-2.31.so
    7f9ab452b000 r--p 0019d000                   libc-2.31.so
    7f9ab43b3000 r-xp 00025000                   libc-2.31.so
    7f9ab438e000 r--p 00000000                   libc-2.31.so
    558e1b9d6000 rw-p 00000000                   [heap]
    558e1a654000 rw-p 00003000                   probe
    558e1a653000 r--p 00002000                   probe
    558e1a652000 r--p 00002000                   probe
    558e1a651000 r-xp 00001000                   probe
    558e1a650000 r--p 00000000                   probe
         Address Perm   Offset                   Mapping
4175:   ./probe
```

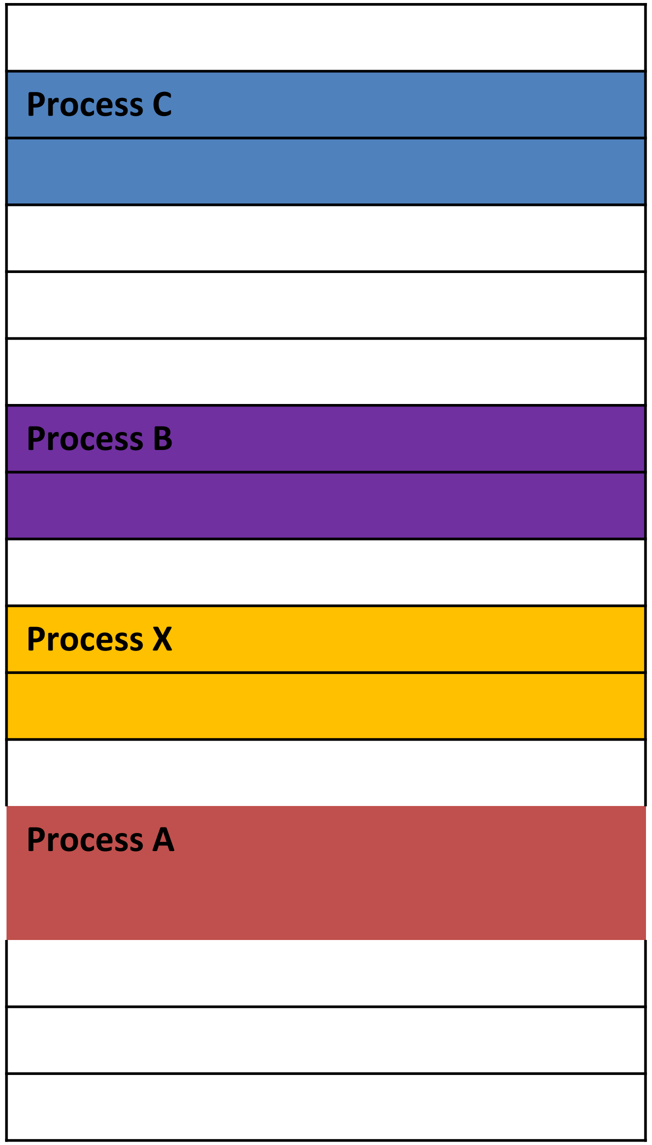
Where is “argv” located in memory?

```
-> the address of main   = 0x558e1a651249
-> the address of printf = 0x7f9ab43f2e10
-> the address of getenv = 0x7f9ab43d7020
-> a stack address       = 0x7ffca3dcb3b0
-> a global address      = 0x558e1a6540c4
-> the argv address      = 0x7ffca3dcb4f8
-> argv[0]               = 0x7ffca3dcc45f
   value is [./probe]
-> the environ address   = 0x7ffca3dcb508
-> the envp address      = 0x7ffca3dcb508
-> getenv("PWD")         = 0x7ffca3dcc5ff
   value is [/home/seed/os-review]
-> a heap address        = 0x558e1b9d66b0
```

`argv` is the argument to the main function, so we are in the stack!

Applications Layout in Memory

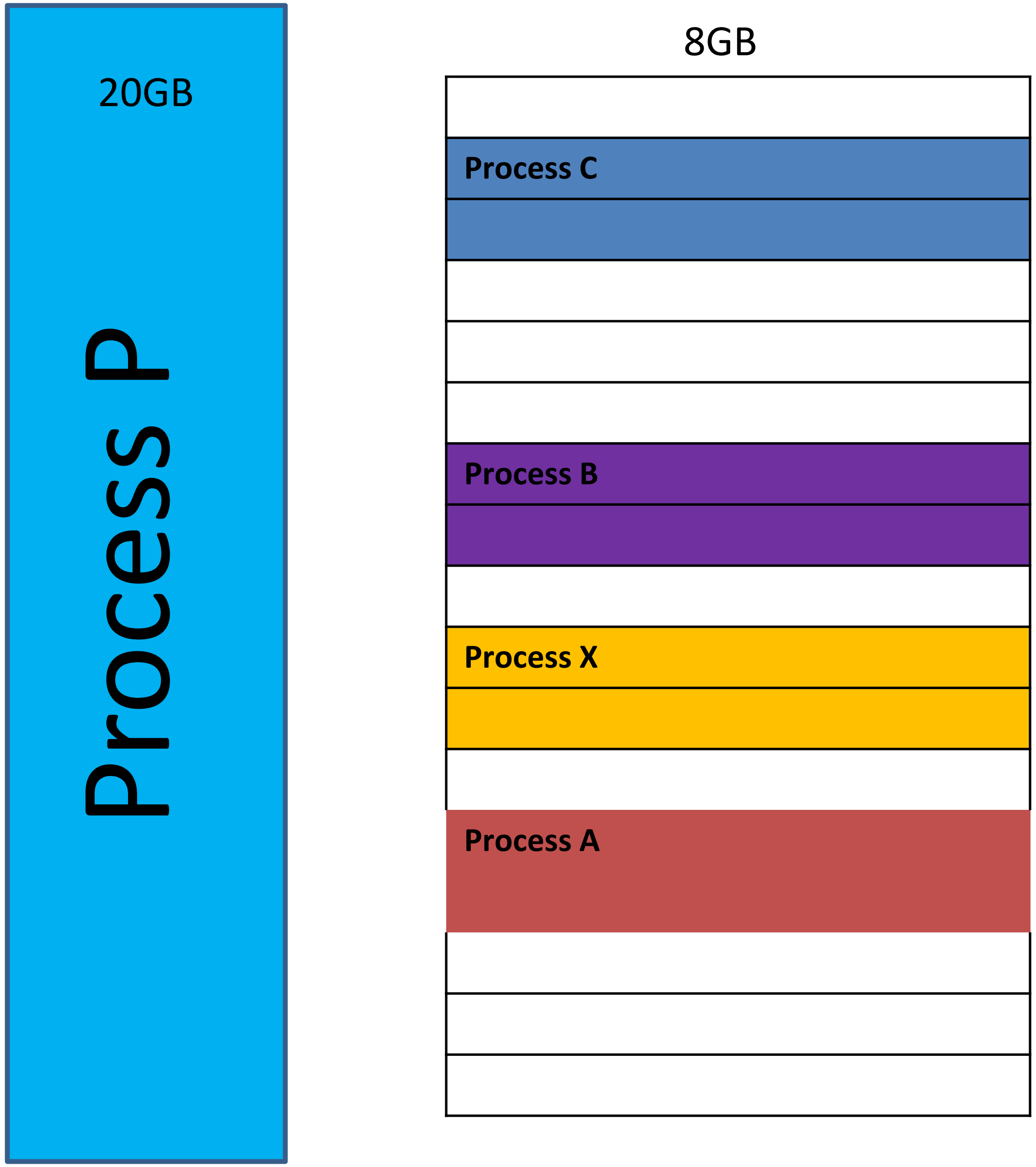
We have many programs that are actively running on our computer



Applications Layout in Memory

We have many programs that are actively running on our computer

What if we have a program that is bigger than out entire main memory?

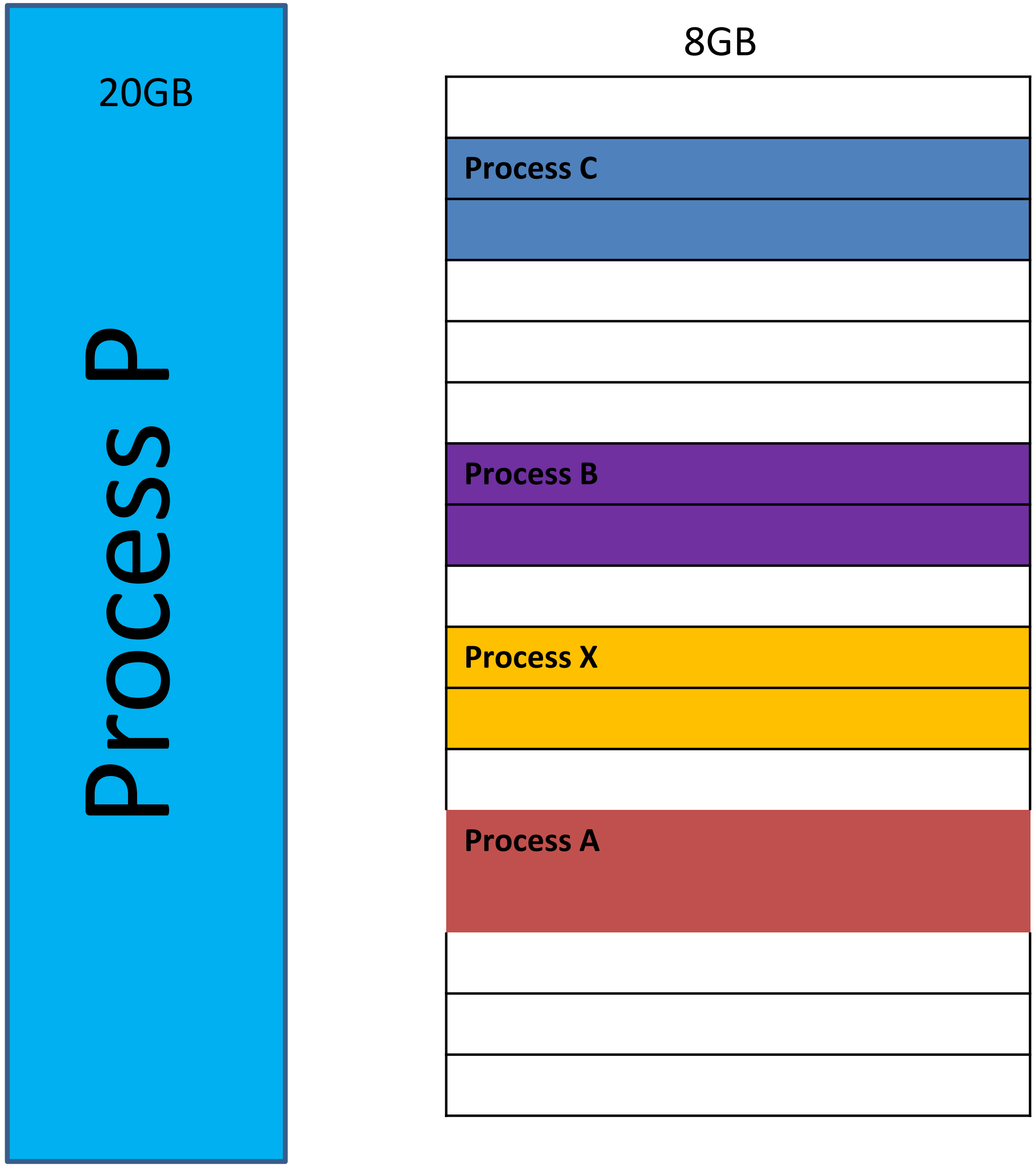


Applications Layout in Memory

We have many programs that are actively running on our computer

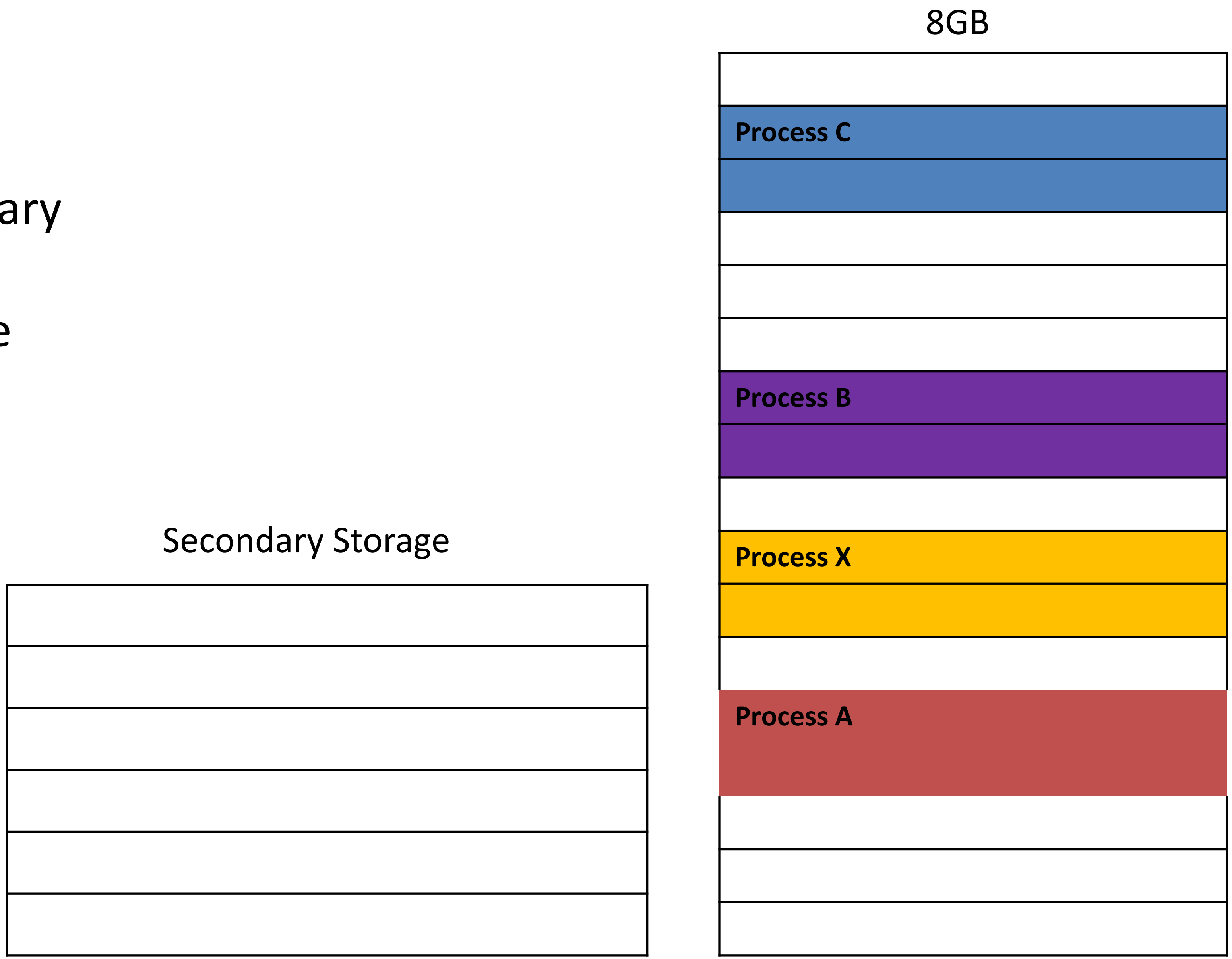
What if we have a program that is bigger than out entire main memory?

Does our computer crash?



Memory management

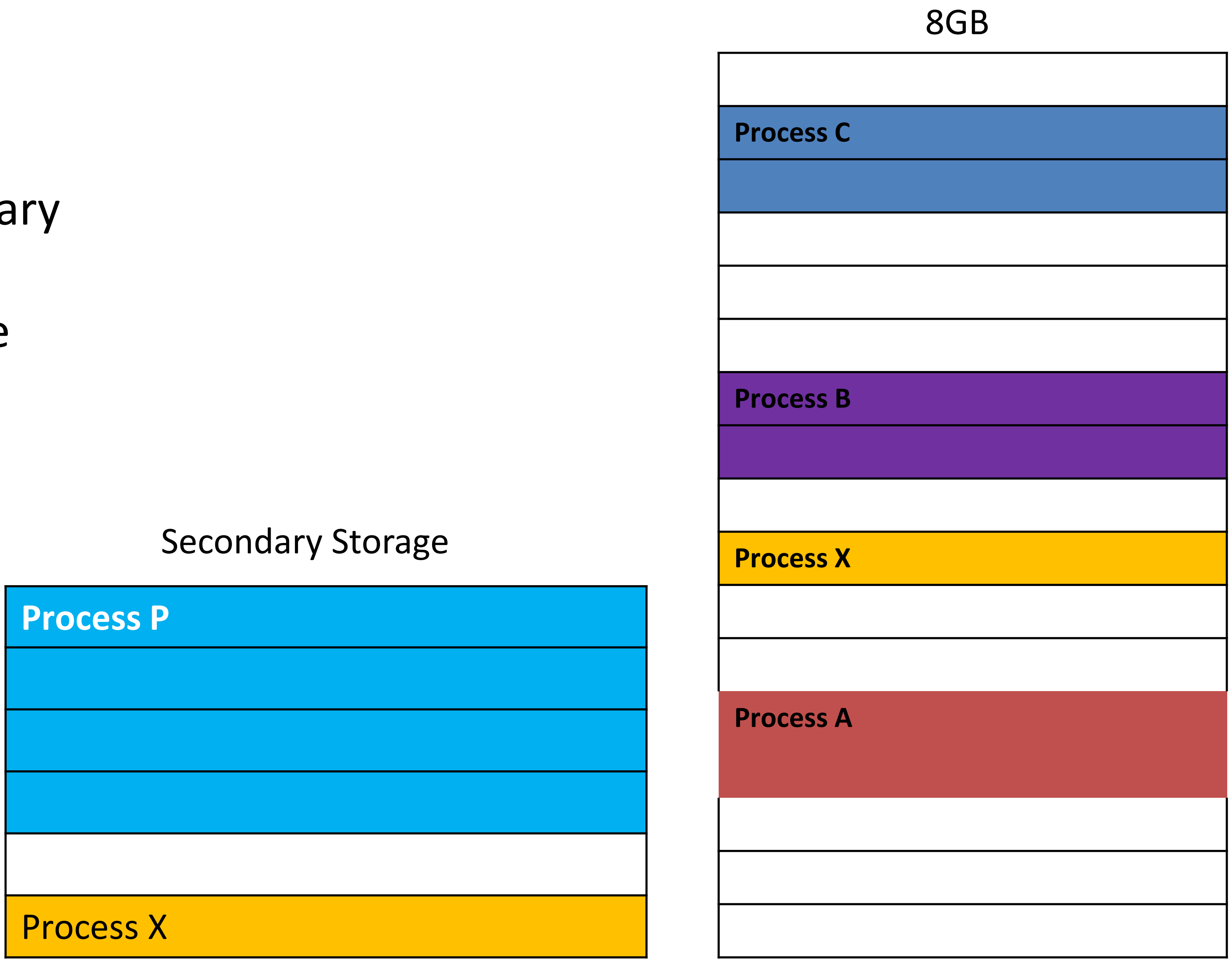
Virtual Memory uses secondary storage to give programs the illusion that they have infinite storage



Memory management

Virtual Memory uses secondary storage to give programs the illusion that they have infinite storage

We split the process into smaller **pages**. Load pages into memory only when needed



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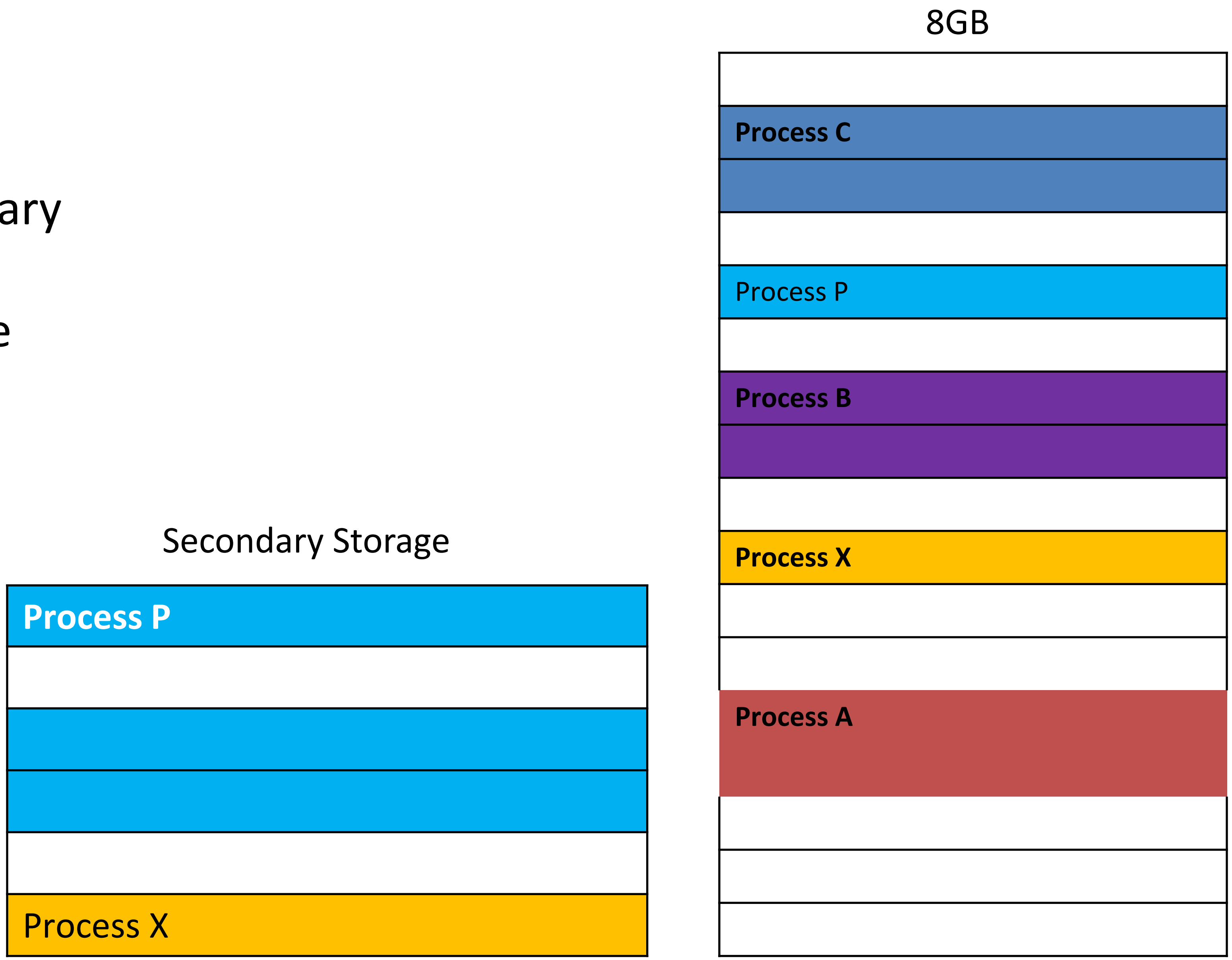
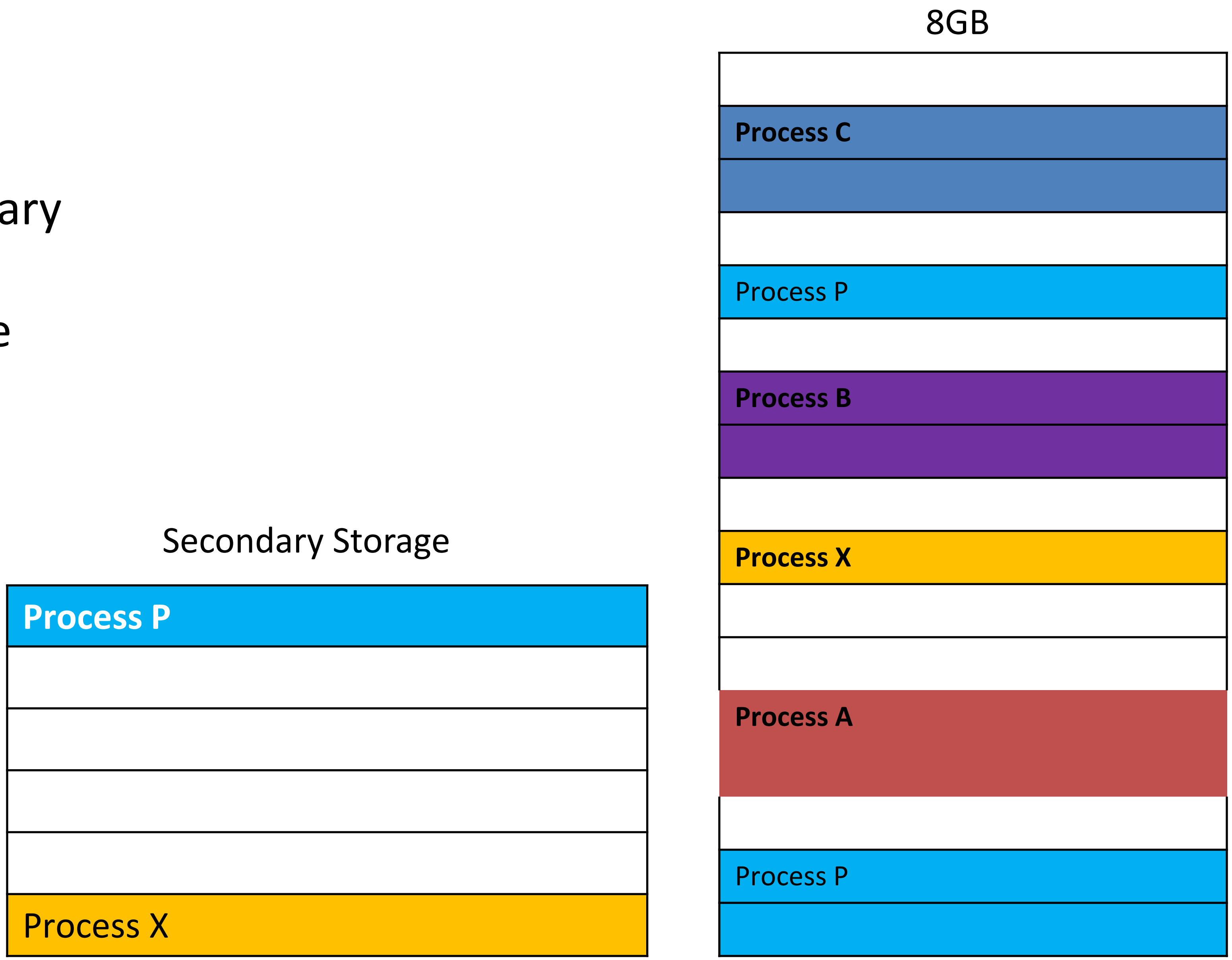


Memory management

Virtual Memory uses secondary storage to give programs the illusion that they have infinite storage

We split the process into smaller, fixed-size, **pages**. Load pages into memory only when needed



Memory management

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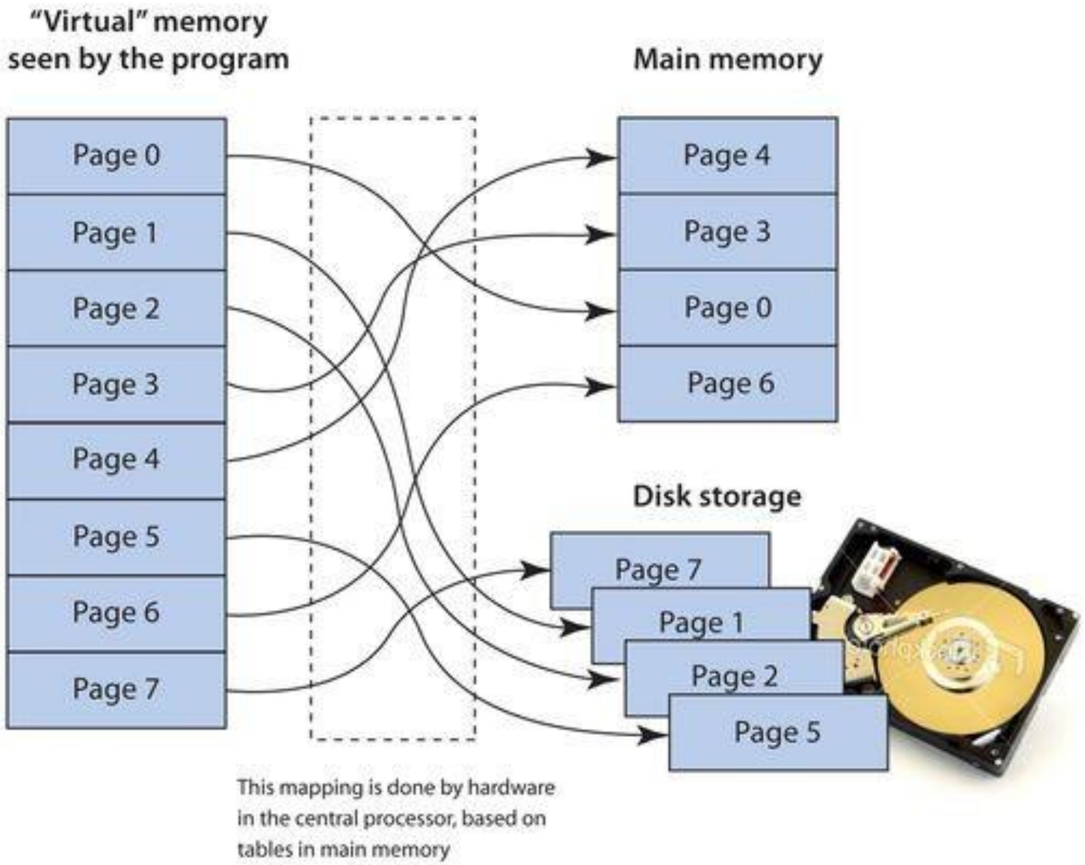
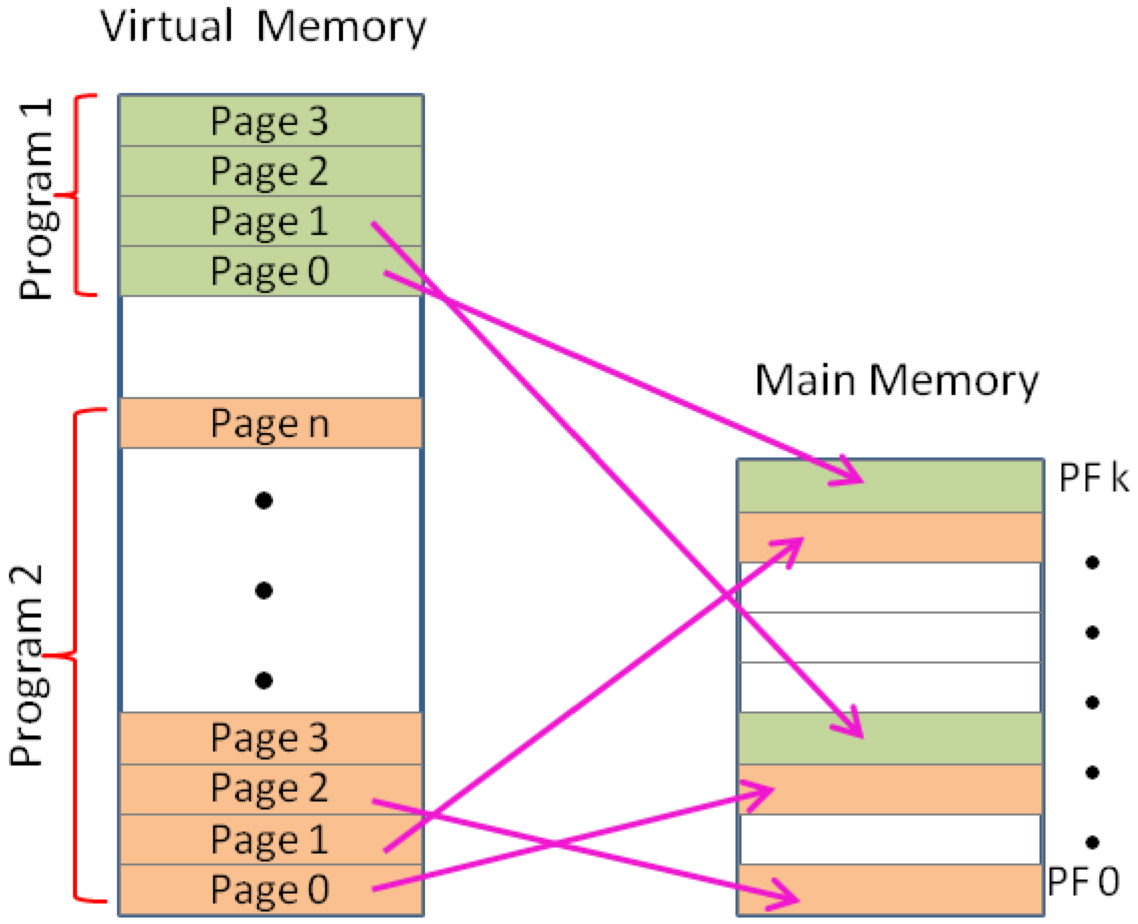

"Virtual" memory seen by the program
Page 0
Page 1
Page 2
Page 3
Page 4
Page 5
Page 6
Page 7
Main memory
Page 4
Page 3
Page 0
Page 6
Disk storage
Page 7
Page 1
Page 2
Page 5
This mapping is done by hardware in the central processor, based on tables in main memory

Constantly swapping stuff in and out of main memory

Memory management

Virtual Memory uses secondary storage to give programs the illusion that they have infinite storage

We split the process into smaller, fixed-size, **pages**. Load pages into memory only when needed

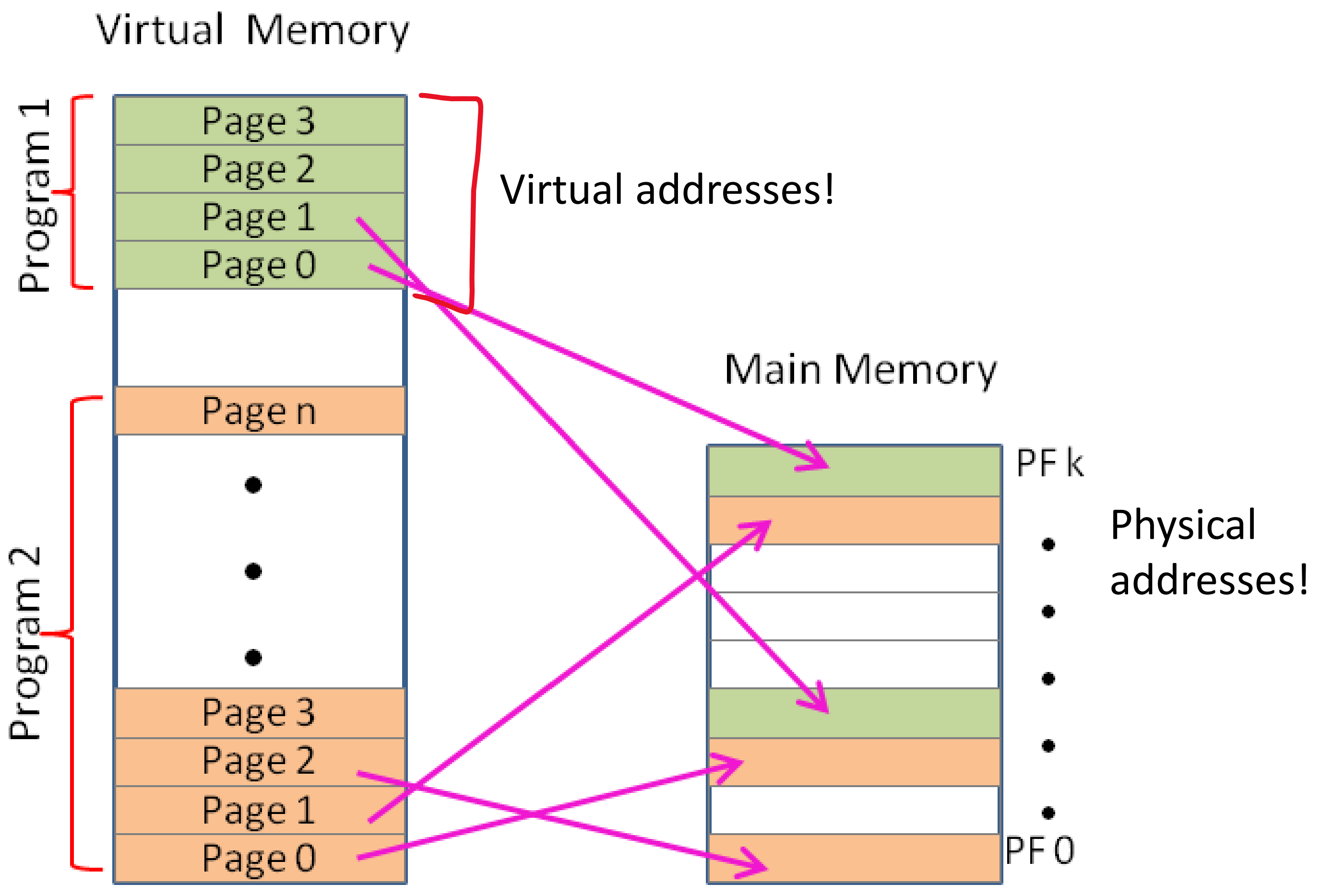


A process in memory is not contiguous

Memory management

Virtual Memory uses secondary storage to give programs the illusion that they have infinite storage

We split the process into smaller, fixed-size, **pages**. Load pages into memory only when needed



A process in memory is not contiguous

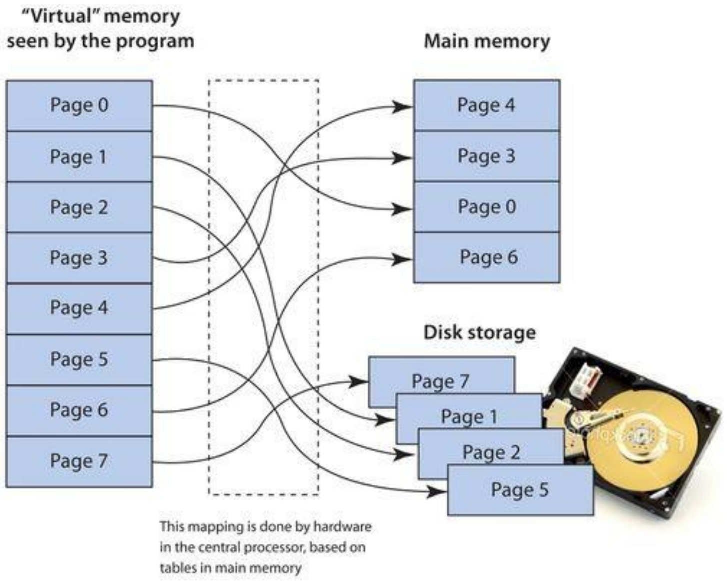
In probe.c, we are seeing virtual addresses!

Internal fragmentation vs external fragmentation

OS Review

Memory Manager

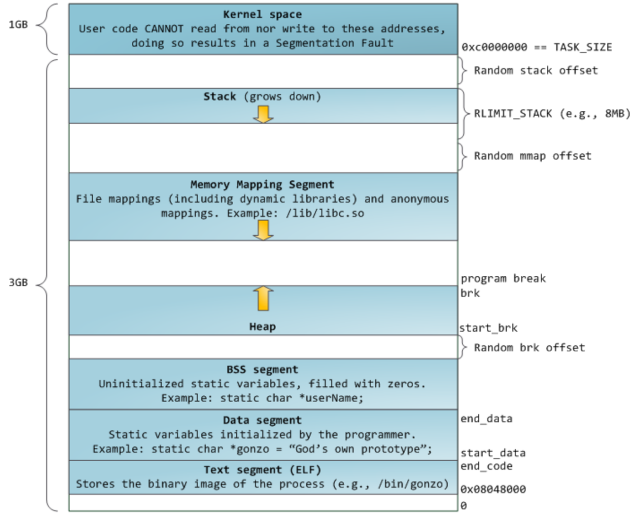
- Manages how physical memory is utilized



This mapping is done by hardware in the central processor, based on tables in main memory

Process Manager

- Manages how processes are structured and how to handle many processes running at once



Kernel space
User code CANNOT read from nor write to these addresses, doing so results in a Segmentation Fault

Stack (grows down)

Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so

Heap

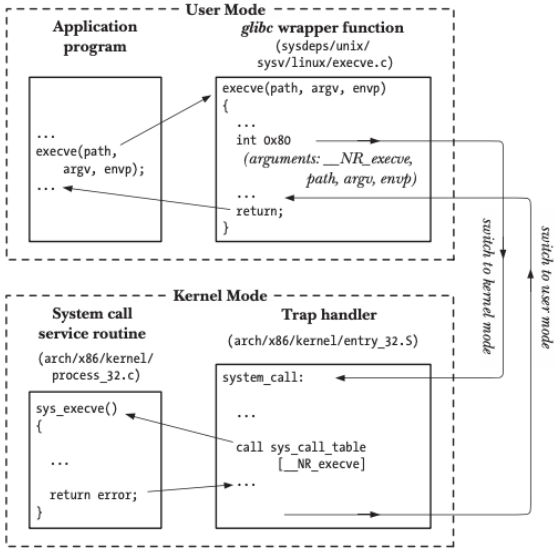
BSS segment
Uninitialized static variables, filled with zeros. Example: static char *userName;

Data segment
Static variables initialized by the programmer. Example: static char *gonzo = "God's own prototype";

Text segment (ELF)
Stores the binary image of the process (e.g., /bin/gonzo)

Interface Manager

- Manages communication between apps and hardware


User Mode
Application program
glibc wrapper function
(sysdeps/unix/sysv/linux/execve.c)
Kernel Mode
System call service routine
(arch/x86/kernel/process_32.c)
Trap handler
(arch/x86/kernel/entry_32.S)
switch to kernel mode
switch to user mode

```
...
execve(path,
    argv, envp);
...
```

```
execve(path, argv, envp)
{
  ...
  int 0x80
   (arguments: __NR_execve,
               path, argv, envp)
  ...
  return;
}
```

```
sys_execve()
{

  ...

  return error;
}
```

```
system_call:

  ...

  call sys_call_table
        [__NR_execve]
  ...
```

Traffic Manager

- Manages which programs should be executed by the CPU

Process A *(Ready)*

Process B *(Urgent)*

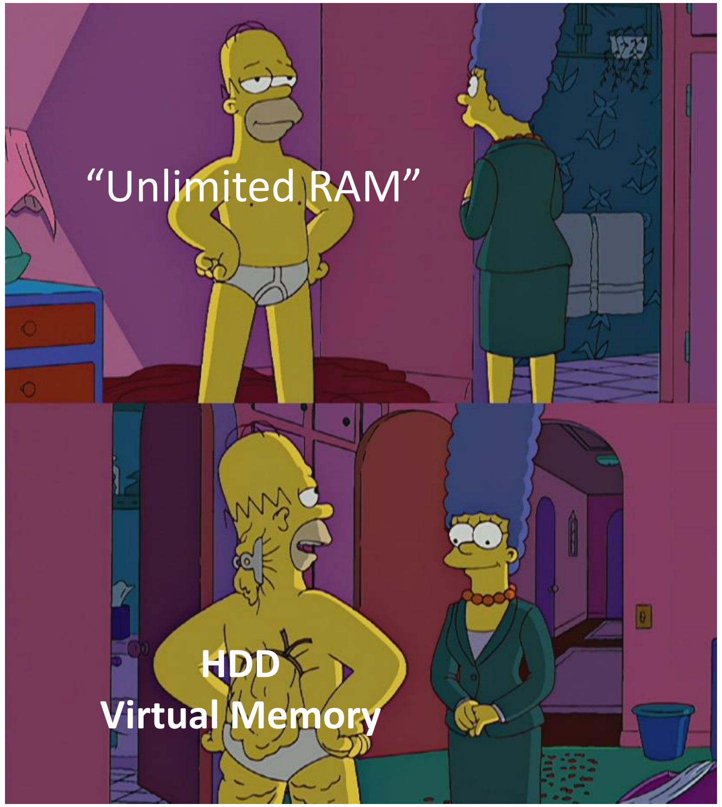
Process C *(Ready)*

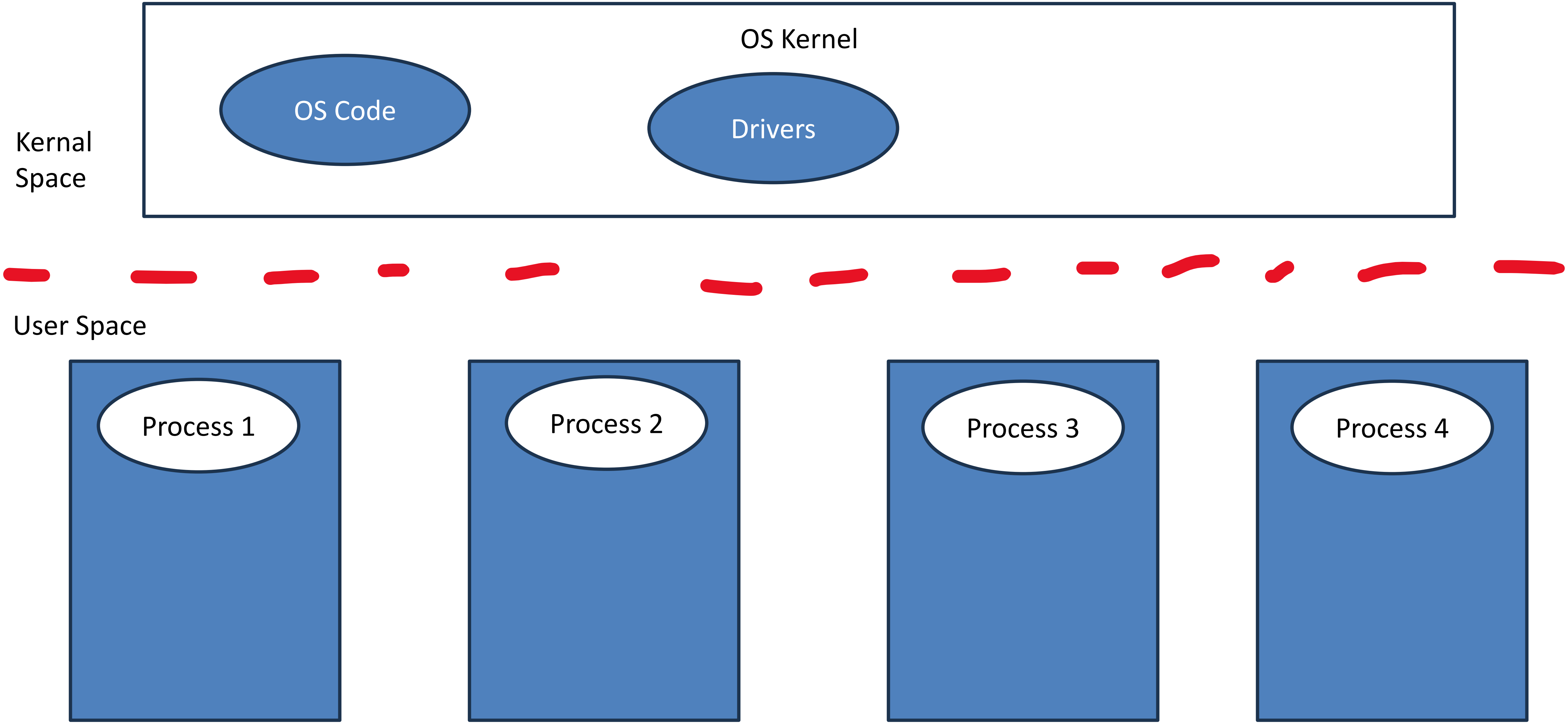
Process D *(Blocked)*

CPU

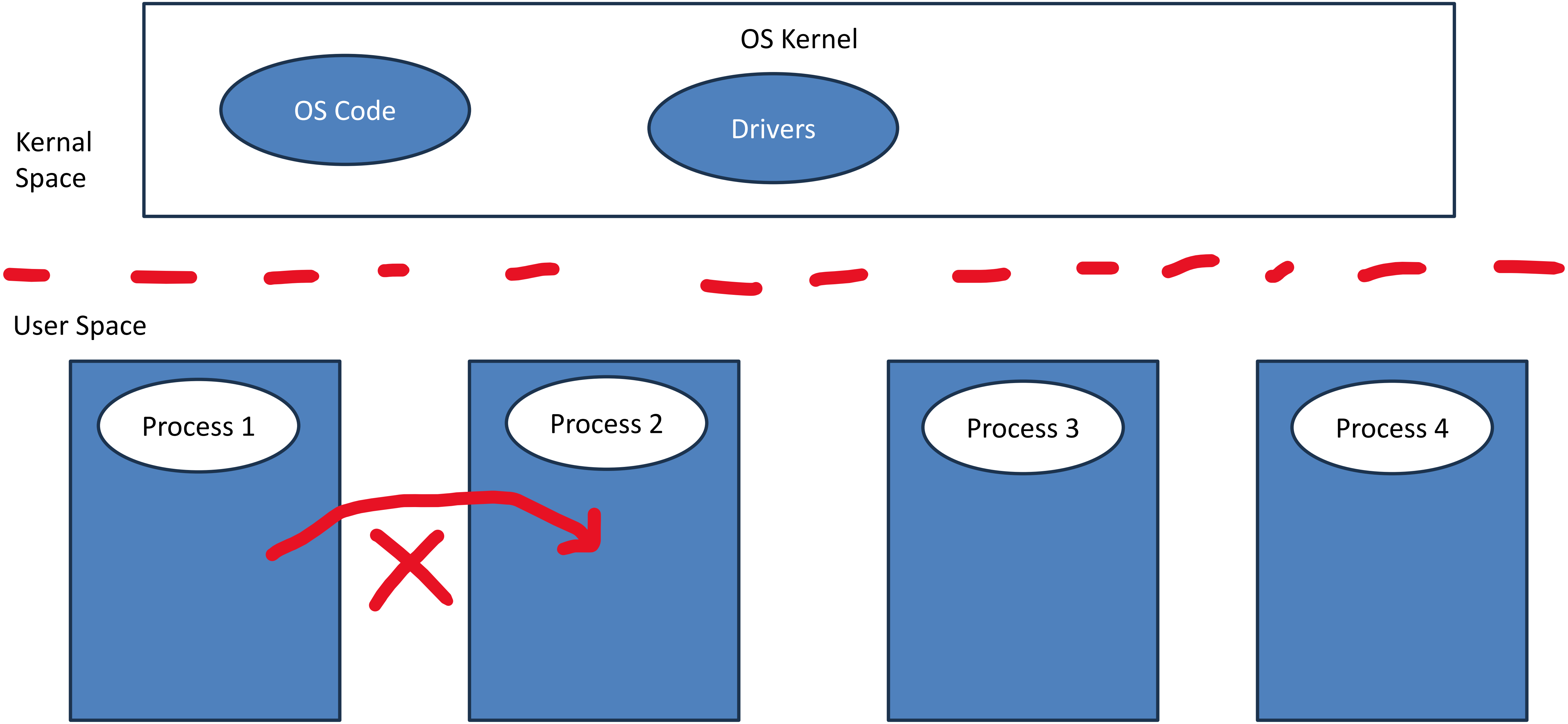
Illusion Manager

- Gives applications the illusion that they have infinite storage and resources





Processes in user space are **isolated**. This means that can normal processes not access other processes on the system*



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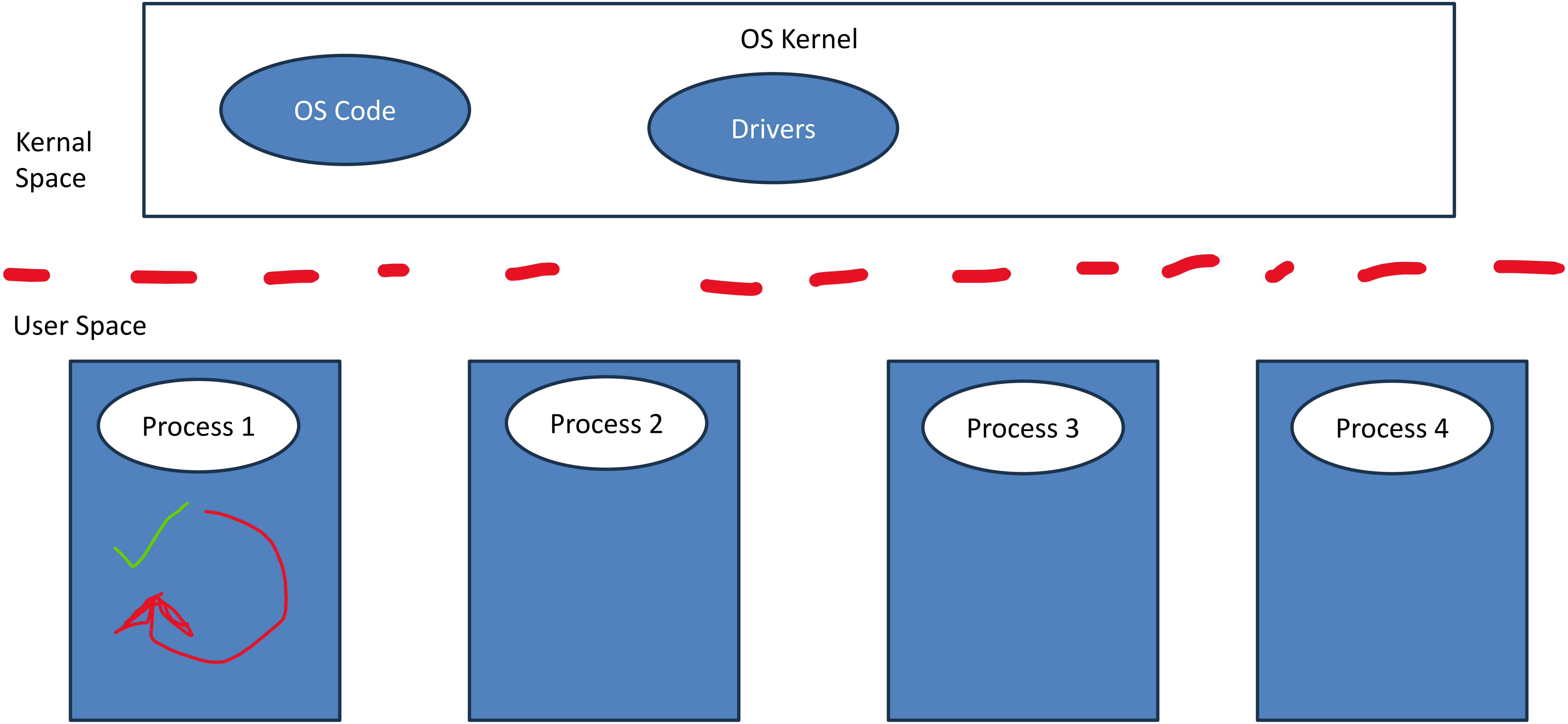

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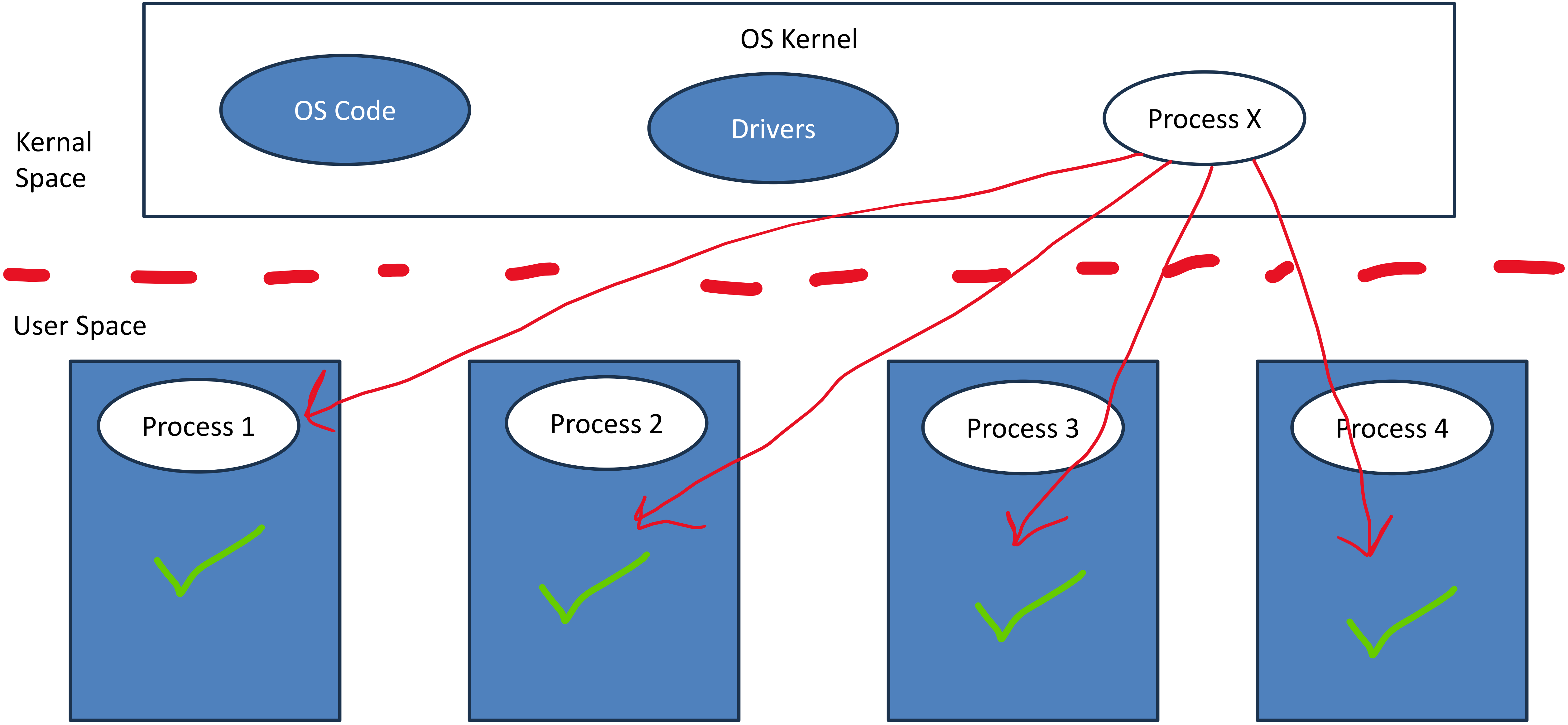


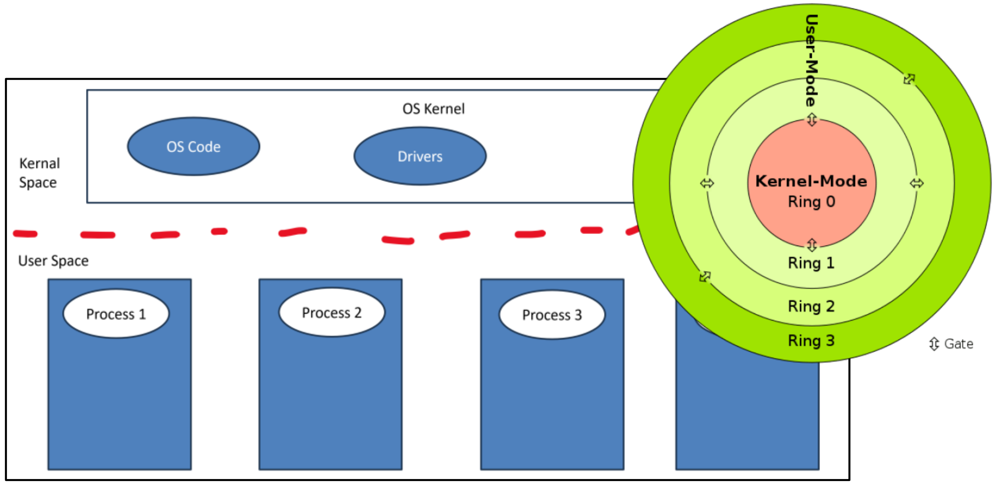
A process running in **kernel mode** has access to **every** process (a big deal!!!)

Case Study: Video Game Anticheat

The purpose of an anticheat program is to detect, prevent, and mitigate cheating in online games.

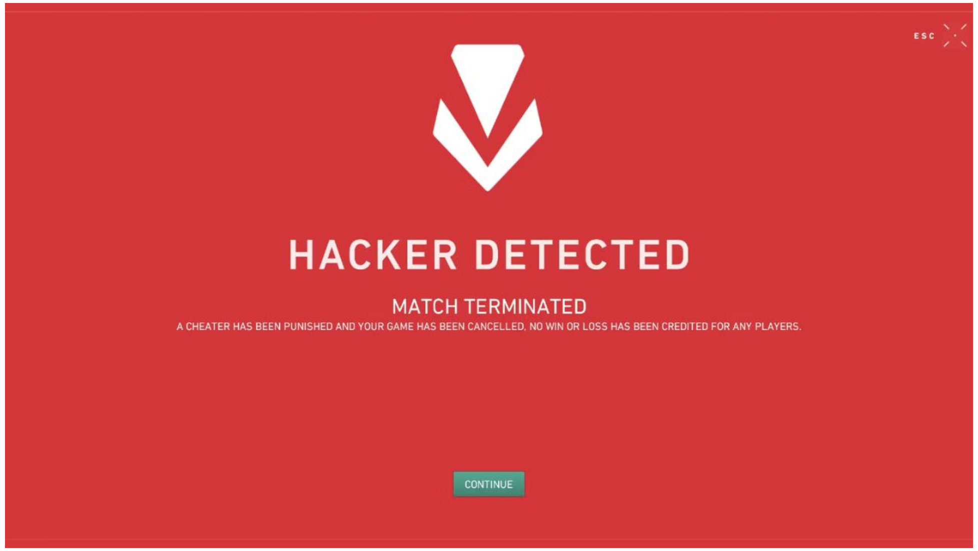
Active Cheating – A process currently running is giving a player unfair advantage while the game is running (aimbot)

Passive Cheating – A program that allows the player to change the game data, save data while the game is not running (hex editors)



Where should anticheat processes be running?

Case Study: Riot Vanguard



HACKER DETECTED

MATCH TERMINATED

A CHEATER HAS BEEN PUNISHED AND YOUR GAME HAS BEEN CANCELLED. NO WIN OR LOSS HAS BEEN CREDITED FOR ANY PLAYERS.

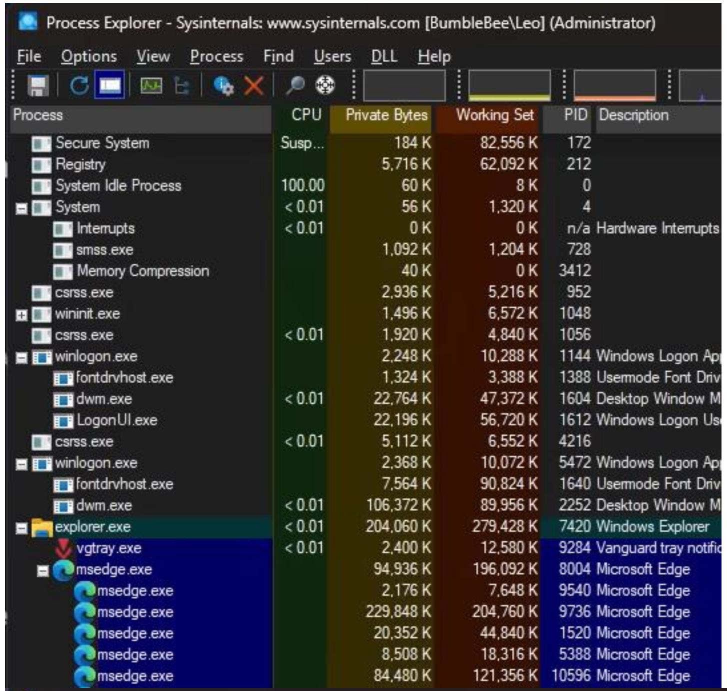
Riot Vanguard is the anticheat software for games made by Riot Games
→ League of Legends, Valorant

Riot Vanguard is a **kernel-level** anticheat

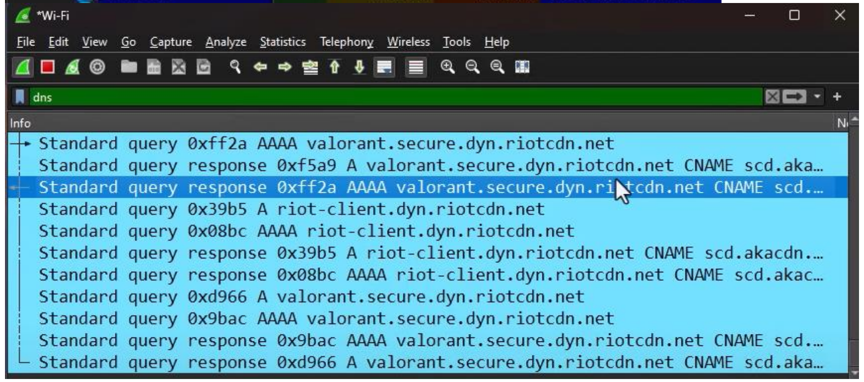
This means it has **very elevated** privileges, and can see almost everything on your system. There are different levels of kernel access, and Vanguard still requires **high** levels of access

Allegations have been made that Riot Vanguard is a suspicious program and that it is **spyware**

Case Study: Riot Vanguard


Process Explorer - Sysinternals: www.sysinternals.com [BumbleBee\Leo] (Administrator)
File Options View Process Find Users DLL Help

Process	CPU	Private Bytes	Working Set	PID	Description
Secure System	Susp...	184 K	82,556 K	172	
Registry		5,716 K	62,092 K	212	
System Idle Process	100.00	60 K	8 K	0	
System	< 0.01	56 K	1,320 K	4	
Interrupts	< 0.01	0 K	0 K	n/a	Hardware Interrupts
smss.exe		1,092 K	1,204 K	728	
Memory Compression		40 K	0 K	3412	
csrss.exe		2,936 K	5,216 K	952	
wininit.exe		1,496 K	6,572 K	1048	
csrss.exe	< 0.01	1,920 K	4,840 K	1056	
winlogon.exe		2,248 K	10,288 K	1144	Windows Logon Ap
fontdrvhost.exe		1,324 K	3,388 K	1388	Usermode Font Driv
dwm.exe	< 0.01	22,764 K	47,372 K	1604	Desktop Window M
LogonUI.exe		22,196 K	56,720 K	1612	Windows Logon Us
csrss.exe	< 0.01	5,112 K	6,552 K	4216	
winlogon.exe		2,368 K	10,072 K	5472	Windows Logon Ap
fontdrvhost.exe		7,564 K	90,824 K	1640	Usermode Font Driv
dwm.exe	< 0.01	106,372 K	89,956 K	2252	Desktop Window M
explorer.exe	< 0.01	204,060 K	279,428 K	7420	Windows Explorer
vgtray.exe	< 0.01	2,400 K	12,580 K	9284	Vanguard tray notific
msedge.exe		94,936 K	196,092 K	8004	Microsoft Edge
msedge.exe		2,176 K	7,648 K	9540	Microsoft Edge
msedge.exe		229,848 K	204,760 K	9736	Microsoft Edge
msedge.exe		20,352 K	44,840 K	1520	Microsoft Edge
msedge.exe		8,508 K	18,316 K	5388	Microsoft Edge
msedge.exe		84,480 K	121,356 K	10596	Microsoft Edge


*Wi-Fi
File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help
dns
Info

```
Standard query 0xff2a AAAA valorant.secure.dyn.riotcdn.net
Standard query response 0xf5a9 A valorant.secure.dyn.riotcdn.net CNAME scd.aka…
Standard query response 0xff2a AAAA valorant.secure.dyn.riotcdn.net CNAME scd.…
Standard query 0x39b5 A riot-client.dyn.riotcdn.net
Standard query 0x08bc AAAA riot-client.dyn.riotcdn.net
Standard query response 0x39b5 A riot-client.dyn.riotcdn.net CNAME scd.akacdn.…
Standard query response 0x08bc AAAA riot-client.dyn.riotcdn.net CNAME scd.akac…
Standard query 0xd966 A valorant.secure.dyn.riotcdn.net
Standard query 0x9bac AAAA valorant.secure.dyn.riotcdn.net
Standard query response 0x9bac AAAA valorant.secure.dyn.riotcdn.net CNAME scd.…
Standard query response 0xd966 A valorant.secure.dyn.riotcdn.net CNAME scd.aka…
```

How to determine if something is malware?

- Static Analysis
- Dynamic Analysis

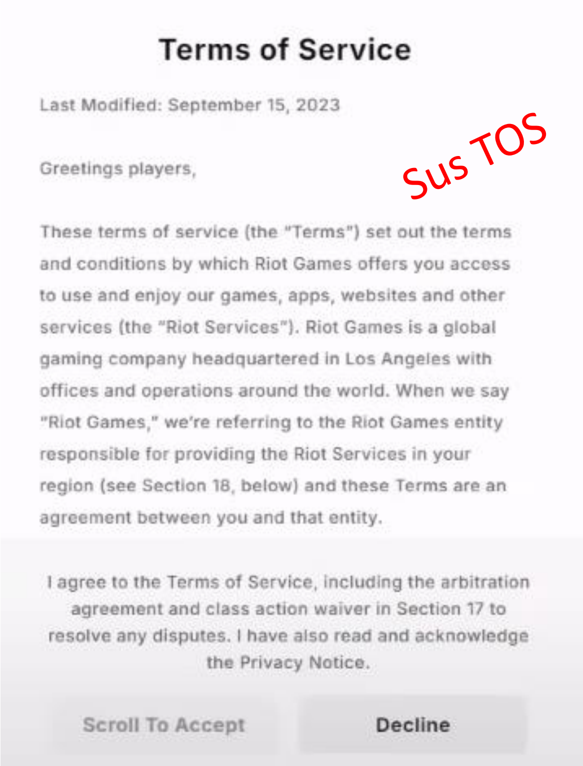
We can look at the network traffic being generated by Riot Vanguard, and we can look at the processes that it creates

<u>Where it gets weird</u>

Riot Vanguard is always running, even when you are not playing the game

If you stop the process, you have to restart your entire PC to play the game

Case Study: Riot Vanguard



Terms of Service

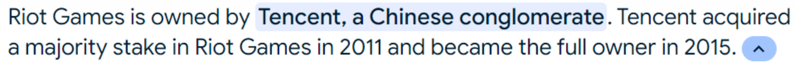
Last Modified: September 15, 2023

Greetings players,

These terms of service (the "Terms") set out the terms and conditions by which Riot Games offers you access to use and enjoy our games, apps, websites and other services (the "Riot Services"). Riot Games is a global gaming company headquartered in Los Angeles with offices and operations around the world. When we say "Riot Games," we're referring to the Riot Games entity responsible for providing the Riot Services in your region (see Section 18, below) and these Terms are an agreement between you and that entity.

I agree to the Terms of Service, including the arbitration agreement and class action waiver in Section 17 to resolve any disputes. I have also read and acknowledge the Privacy Notice.

Sus TOS



Riot Games is owned by Tencent, a Chinese conglomerate. Tencent acquired a majority stake in Riot Games in 2011 and became the full owner in 2015.

Is it malware?

Kernel Level privilege is a very powerful (and scary) power to grant a process

The fact that it is constantly running, even when not playing the game, raises red flags

Riot Games is also owned by a Chinese company, which also raises many concerns

Many security experts condone the development of kernel-level anticheat

The jobs of an Operating System

1. **Process Manager**
   “The Coach”
2. **Interface Manager**
   “The Bouncer”
3. **Memory Manager**
   “The Farmer”
4. **Traffic Manager**
   “The Judge”
5. **Illusion Manager**
   “The Illusionist”