ECE 353: Systems Software

Lecture 2

Kernel Mode

1.0.0

Jon Eyolfson

January 11, 2023

This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License

Make Sure You Try to Login to the GitLab Server

You’ll be greeted with a “Your account is pending approval” message

- Just try again a bit later, and you’ll be approved

Let me know your experience with Git/GitLab/GitHub

- Is everyone comfortable adding and using their SSH keys?

There’s 3 Major ISAs in Use Today

ISA stands for the *instruction set architecture*

It’s the machine code, or numbers the CPU understands

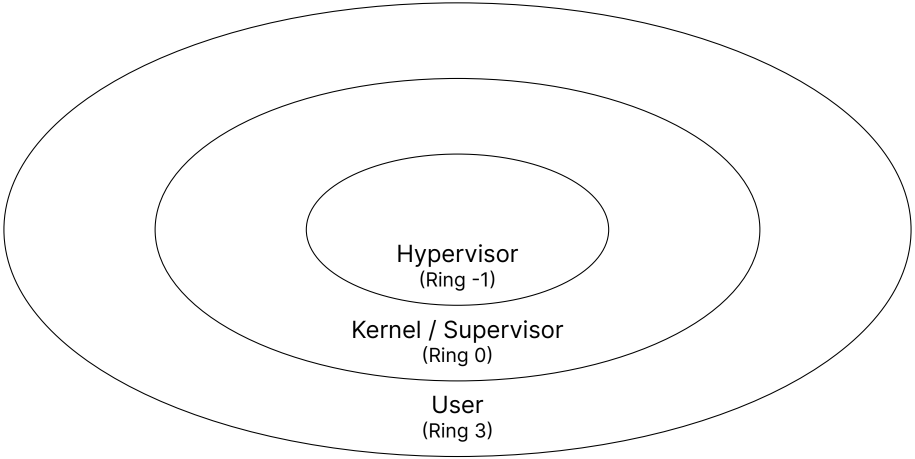
`x86-64` (aka `amd64`): for desktops, non-Apple laptops, servers

`aarch64` (aka `arm64`): for phones, tablets, Apple laptops

`riscv` (aka `rv64gc`): open-source implementation, similar to ARM

We’ll touch on all of them in this course

x86-64 CPUs Have “Rings” to Control Instruction Access



Each ring can access instructions in any of its outer rings

The Kernel of the Operating System Runs in Kernel Mode

User space

Kernel space

System Calls Transition between User and Kernel Mode

User space

```
read write open close stat mmap brk pipe clone fork
execve exit wait4 chdir mkdir rmdir creat mount
init_module delete_module clock_nanosleep exit_group
```

(451 total)

Kernel space

Quick Aside: API Tells You What and ABI Tells You How

Application Programming Interface (API) abstracts the details how how to communicate

e.g. A function takes 2 integer arguments

Application Binary Interface (ABI) specifies how to layout data and how to concretely communicate

e.g. The same function using the C calling convention

System Call ABI for Linux AArch64

Enter the kernel with a svc instruction, using registers for arguments:

- `x8` — System call number
- `x0` — 1st argument
- `x1` — 2nd argument
- `x2` — 3rd argument
- `x3` — 4th argument
- `x4` — 5th argument
- `x5` — 6th argument

What are the limitations of this?

Note: other registers are not used, whether they're saved isn't important for us

We Can Represent System Calls Like Regular C Functions

However, system calls run in kernel mode and can interact with hardware

For example:

```
ssize_t write(int fd, const void *buf, size_t count);
```

(writes bytes to a file descriptor)

API `fd`: A file descriptor to write bytes to

`buf`: An address to contiguous sequence of bytes

`count`: How many bytes to write from the sequence

```
void exit_group(int status);
```

(exits everything associated with the current running program)

API `status`: An exit code for the program (0-255)

Let’s Execute a 168 Byte “Hello World” on Linux AArch64

```
0x7F 0x45 0x4C 0x46 0x02 0x01 0x01 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00
0x02 0x00 0xB7 0x00 0x01 0x00 0x00 0x00 0x78 0x00 0x01 0x00 0x00 0x00 0x00 0x00
0x40 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00
0x00 0x00 0x00 0x00 0x40 0x00 0x38 0x00 0x01 0x00 0x40 0x00 0x00 0x00 0x00 0x00
0x01 0x00 0x00 0x00 0x05 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x00
0x00 0x00 0x01 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0x01 0x00 0x00 0x00 0x00 0x00
0xA8 0x00 0x00 0x00 0x00 0x00 0x00 0x00 0xA8 0x00 0x00 0x00 0x00 0x00 0x00 0x00
0x00 0x10 0x00 0x00 0x00 0x00 0x00 0x00 0x08 0x08 0x80 0xD2 0x20 0x00 0x80 0xD2
0x81 0x13 0x80 0xD2 0x21 0x00 0xA0 0xF2 0x82 0x01 0x80 0xD2 0x01 0x00 0x00 0xD4
0xC8 0x0B 0x80 0xD2 0x00 0x00 0x80 0xD2 0x01 0x00 0x00 0xD4 0x48 0x65 0x6C 0x6C
0x6F 0x20 0x77 0x6F 0x72 0x6C 0x64 0x0A
```

ELF is the Binary Format for Unix Operating Systems

Executable and Linkable Format (ELF) is a file format

Always starts with the 4 bytes: `0x7F 0x45 0x4C 0x46`
or with ASCII encoding: `0x7F 'E' 'L' 'F'`

Followed by a byte signifying 32 or 64 bit architectures
then a byte signifying little or big endian

Most file formats have different starting signatures (or magic numbers)

Use `readelf` to Read ELF File Headers

Command: `readelf -a <filename>` (for all information)

Contains the following:

- A header containing:
    - Information about the machine (e.g. the ISA)
    - The entry point of the program
- Any program headers (required for executables)
- Any section headers (required for libraries)

Our Minimal Executable Contains a Single Program Header

Tells the kernel to load the entire executable file into memory at address `0x10000`

The header is 64 bytes, and the program header is 56 bytes (120 bytes total)

The next 36 bytes are instructions, then 12 bytes for the string “Hello world\n”

- Instructions start at `0x10078` (`0x78` is 120)
- The string starts at `0x1009C` (`0x9C` is 156)

“Hello world” Needs 2 System Calls

Command: `strace <filename>`

This shows all the system calls our program makes:

```
execve("./hello_world", ["./hello_world"], 0x7ffd0489de40 /* 46 vars */) = 0
write(1, "Hello world\n", 12)           = 12
exit_group(0)                           = ?
+++ exited with 0 +++
```

Instructions for “Hello world”, Using the Linux AArch64 ABI

Plug in the next 36 bytes into a disassembler, such as:
https://onlinedisassembler.com/

Our disassembled instructions:

```
mov x8, #0x40           // #64
mov x0, #0x1            // #1
mov x1, #0x9C           // #156
movk x1, #0x1, lsl #16  // #0x10000
mov x2, #0x0C           // #12
svc #0x0
mov x8, #0x5E           // #94
mov x0, #0x0            // #0
svc #0x0
```

Finishing Up “Hello world” Example

The remaining 12 bytes is the “Hello world” string itself, ASCII encoded:

```
0x48 0x65 0x6C 0x6C 0x6F 0x20 0x77 0x6F 0x72 0x6C 0x64 0x0A
```

Low level ASCII tip: bit 5 is `0`/`1` for upper case/lower case (values differ by 32)

This accounts for every single byte of our 168 byte program, let’s see what C does...

Can you already spot a difference between strings in our example compared to C?

System Calls for “Hello world” in C, Finding Standard Library

```
execve("./hello_world_c", ["./hello_world_c"], 0x7ffcb3444f60 /* 46 vars */) = 0
brk(NULL)                                   = 0x5636ab9ea000
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=149337, ...}) = 0
mmap(NULL, 149337, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7f4d43846000
close(3)                                    = 0
openat(AT_FDCWD, "/usr/lib/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0000C"..., 832) = 832
lseek(3, 792, SEEK_SET)                     = 792
read(3, "\4\0\0\0\24\0\0\0\3\0\0\0GNU\0\201\336\t\36\251c\324"..., 68) = 68
fstat(3, {st_mode=S_IFREG|0755, st_size=2136840, ...}) = 0
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0)
  = 0x7f4d43844000
lseek(3, 792, SEEK_SET)                     = 792
read(3, "\4\0\0\0\24\0\0\0\3\0\0\0GNU\0\201\336\t\36\251c\324"..., 68) = 68
lseek(3, 864, SEEK_SET)                     = 864
read(3, "\4\0\0\0\20\0\0\0\5\0\0\0GNU\0\2\0\0\300\4\0\0\0\3\0\0", 32) = 32
```

System Calls for “Hello world” in C, Loading Standard Library

```
mmap(NULL, 1848896, PROT_READ, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f4d43680000
mprotect(0x7f4d436a2000, 1671168, PROT_NONE) = 0
mmap(0x7f4d436a2000, 1355776, PROT_READ|PROT_EXEC,
  MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x22000) = 0x7f4d436a2000
mmap(0x7f4d437ed000, 311296, PROT_READ,
  MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x16d000) = 0x7f4d437ed000
mmap(0x7f4d4383a000, 24576, PROT_READ|PROT_WRITE,
  MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1b9000) = 0x7f4d4383a000
mmap(0x7f4d43840000, 13888, PROT_READ|PROT_WRITE,
  MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7f4d43840000
close(3)                                = 0
arch_prctl(ARCH_SET_FS, 0x7f4d43845500) = 0
mprotect(0x7f4d4383a000, 16384, PROT_READ) = 0
mprotect(0x5636a9abd000, 4096, PROT_READ) = 0
mprotect(0x7f4d43894000, 4096, PROT_READ) = 0
munmap(0x7f4d43846000, 149337)          = 0
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(0x88, 0x1), ...}) = 0
```

System Calls for “Hello world” in C, Setting Up Heap and Printing

```
brk(NULL)                                   = 0x5636ab9ea000
brk(0x5636aba0b000)                         = 0x5636aba0b000
write(1, "Hello world\n", 12)               = 12
exit_group(0)                               = ?
+++ exited with 0 +++
```

The C version of “Hello world” ends with the exact same system calls we made

You Can Think of the Kernel as a Long Running Program

Writing kernel code is more like writing library code (there's no `main`)

The kernel lets you load code (called modules)

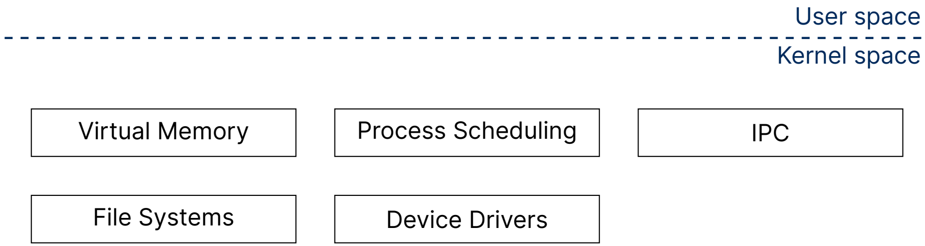
Your code executes on-demand

    e.g. when it's loaded manually, new hardware, or accessing a certain file

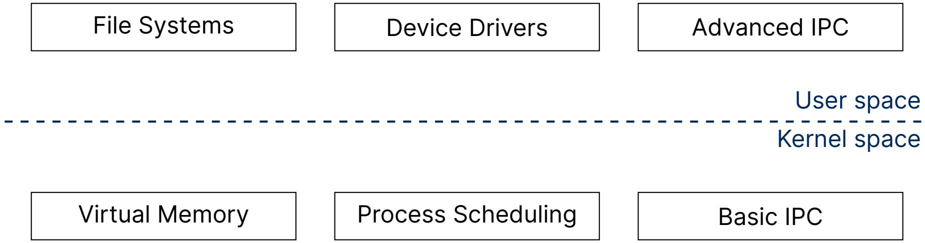
If you write a kernel module, you can execute privileged instructions

    and access any kernel data, so you could do anything

A Monolithic Kernel Runs Operating System Services in Kernel Mode



A Microkernel Runs the Minimum Amount of Services in Kernel Mode



Other Types of Kernels

“Hybrid” kernels are between monolithic and microkernels

- Emulation services to user mode (Windows)
- Device drivers to user mode (macOS)

Nanokernels and picokernels

- Move even more into user mode than traditional microkernels

There’s many different lines you can draw with different trade-offs

Kernel Interfaces Operate Between CPU Mode Boundaries

The lessons from the lecture:

- Code running in kernel mode is part of your kernel
- System calls are the interface between user and kernel mode
    - Every program must use this interface!
- File format and instructions to define a simple “Hello world” (in 168 bytes)
    - Difference between API and ABI
    - How to explore system calls
- Different kernel architectures shift how much code runs in kernel mode