Kernels

2024 Winter ECE 353: Systems Software
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Lecture 2
2.0.0

Let's Execute This Program and Verify It's "Hello world"

```
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
```

Execute using: `./hello-world-linux-aarch64`

Aside: 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

Our Next Abstraction is a File Descriptor

Since our processes are independent, we need an explicit way to transfer data

IPC: inter-process communication is transferring data between two processes

File descriptor: a resource that users may either read bytes from or write bytes to
(identified by an index stored in a process)

A file descriptor could represent a file, or your terminal

System Calls Make Requests to the Operating System

We can represent system calls like regular C functions

Here are two system calls we need for a basic “Hello world” program:

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

Description: writes bytes from a byte array to a file descriptor

`fd` - the file descriptor
`buf` - the address of the start of the byte array (called a buffer)
`count` - how many bytes to write from the buffer

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

Description: exits the current process and sets an exit status code

`status` - the exit status code (0-255)

A Hypothetical “Hello world” Program

By convention there’s some expected file descriptors:

- 0 - standard input (read)
- 1 - standard output (write)
- 2 - standard error (write)

The most basic “Hello world” program would start executing the following:

```
void _start(void) {
  write(1, "Hello world\n", 12);
  exit_group(0);
}
```

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

Application Programming Interface (API) abstracts the details and describes the arguments and return value of a function

e.g. A function takes 2 integer arguments

Application Binary Interface (ABI) specifies the details, specifically how to pass arguments and where the return value is

e.g. The same function using the C calling convention (arguments on the stack)

System Call ABI for Linux AArch64

The operating system "functions" do not have an address,
instead we can generate an interrupt for the OS

Generate an interrupt 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?

Last Aside: C ABI, or Calling Convention for x86-64

System calls use registers, while C is stack based:

- Arguments pushed on the stack from right-to-left order
- `rax`, `rcx`, `rdx` are caller saved
- Remaining registers are callee saved
- Some arguments may be passed in registers instead of the stack

See Wikipedia for more details (there's lots of conventions, think ECE 243)

What advantages does this give us vs system call ABI? Disadvantages?

Programs on Linux Use the ELF File Format

Executable and Linkable Format (ELF) specifies both executables and libraries

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

These 4 bytes are called “magic”, and that’s how you know what kind of file this is (other file formats may have a different number of bytes)

See: `https://en.wikipedia.org/wiki/List_of_file_signatures`
  e.g., PDF files start with `%PDF-`

Our Bytes Represent an ELF File

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

The file 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 (data) starts at `0x1009C` (`0x9C` is 156)

You can use: `readelf -a <FILE>` to see the gory details

Visually How Our ELF File Gets Divided

File Header: endianness, ISA, ABI, entry point, etc.

```
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
```

Program Header: e.g. what to load into memory (and where)

Instructions

```
                                        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
```

Data

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

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

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

Our disassembled instructions:

```
mov  x8, 0x40          #64
mov  x0, 0x01          #1
mov  x1, 0x9C          #156
movk x1, 0x01, lsl 16  #0x10000
mov  x2, 0x0C          #12
svc  0x0
mov  x8, 0x5E          # 94
mov  x0, 0x0           # 0
svc  0x0
```

Data for Our “Hello world” Example

The 12 bytes of data 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?

The Kernel is a Core Part of Your Operating System

Kernel mode is a privilege level on your CPU that gives access to more instructions

Different architectures have a different name for this mode
- e.g., this is S-mode on RISC-V

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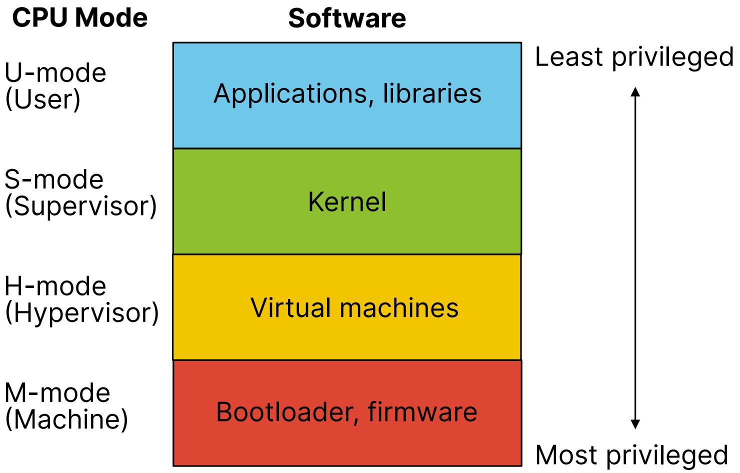
The kernel is the part of your operating system that runs in kernel mode

These instructions allow only trusted software to interact with hardware
- e.g., only the kernel can manage virtual memory for processes

More Privileged CPU Modes Can Access More Instructions



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`

(453 total)

Kernel space

System Calls Are Traceable

We can trace all the system calls a process makes on Linux using the command:

```
strace <PROGRAM>
```

We can see all the system calls our “Hello world” program makes:

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

Now, let’s really see what C does...

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\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 Process

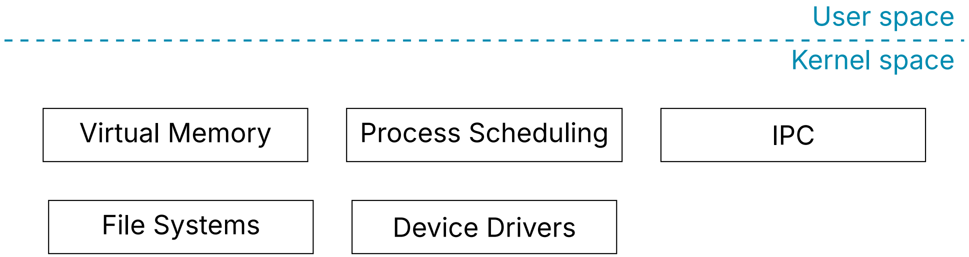
Writing kernel code is more like writing library code (there's no `main`)

The kernel lets you load code (called modules)

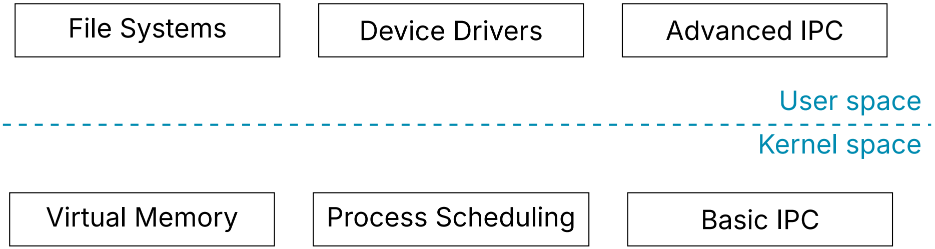
Your code executes on-demand
  e.g. when it's loaded manually, new hardware, or accessing a certain file

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 different architectural lines you can draw with different trade-offs

Kernel Interfaces Operate Between CPU Mode Boundaries

The lessons from the lecture:

- The kernel is the part of the OS that interacts with hardware (it runs in kernel mode)
- 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