Lecture 10:
Device Drivers

CS343 – Operating Systems

Branden Ghena – Spring 2024

Some slides borrowed from:
Stephen Tarzia (Northwestern), Jaswinder Pal Singh (Princeton), and UC Berkeley CS162

Administrivia

- PC Lab due tonight
  - There was a bugfix for the starter code posted to Piazza
    - Not required that you use it. We’ll apply it when grading your code

- Driver Lab will be up tonight or maybe tomorrow

Today’s Goals

- Explore how software for device I/O is architected.

- Discuss OS considerations at multiple software layers.

- Investigate example device drivers
  - One in Nautilus
  - One in Linux and Tock

Outline

- **Abstractions**
- Device I/O layers
  - Application Layer
  - Kernel I/O Subsystem
  - Device Driver
  - Interrupt Handler
- Example Driver: Nautilus Character Device
- Example Driver: Temperature Sensor

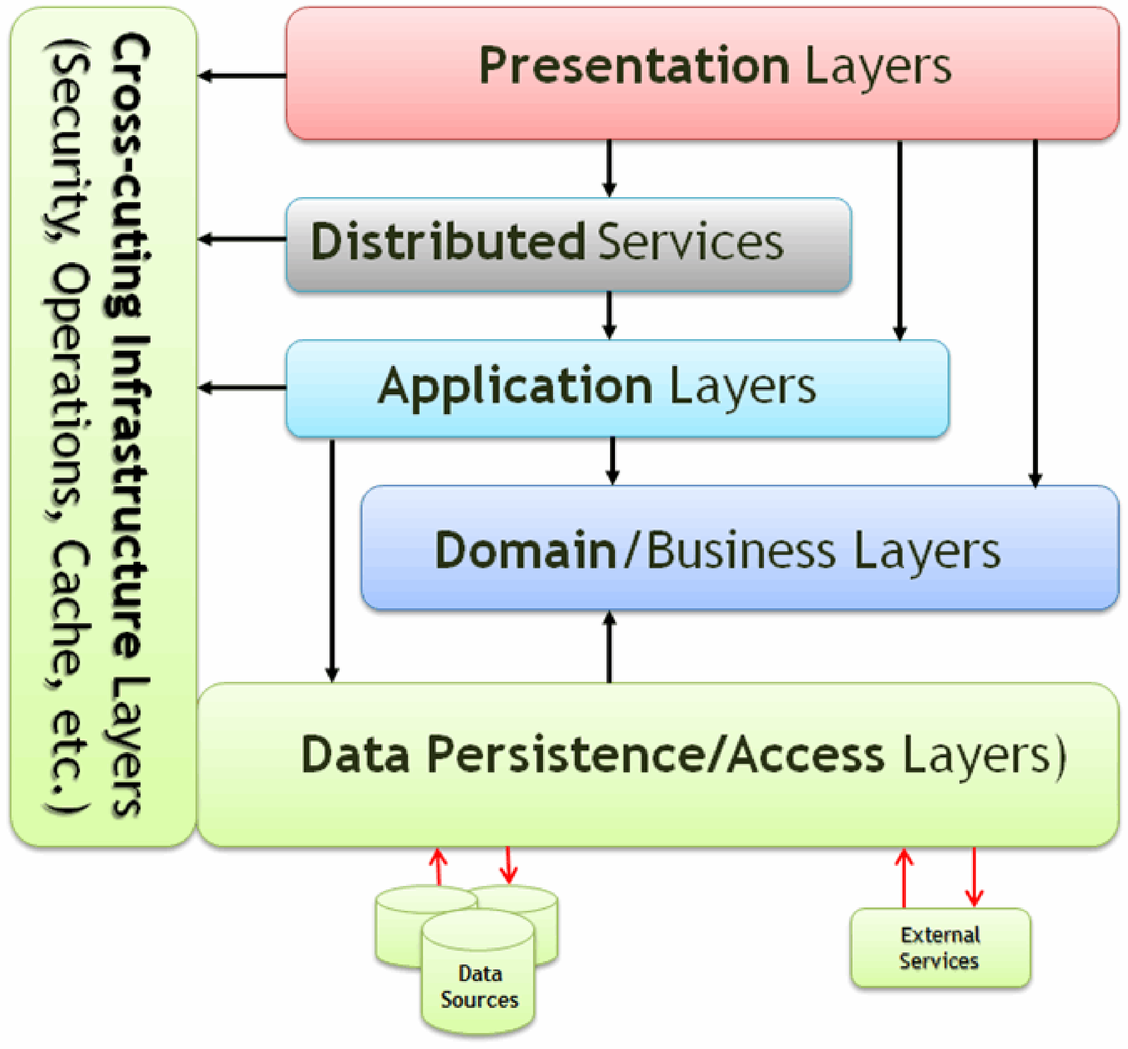
Writing software to manage devices

- Kernel software for managing a device is a *device driver*
  - 70% of Linux code is device drivers
  - 15.3 Million lines of source code

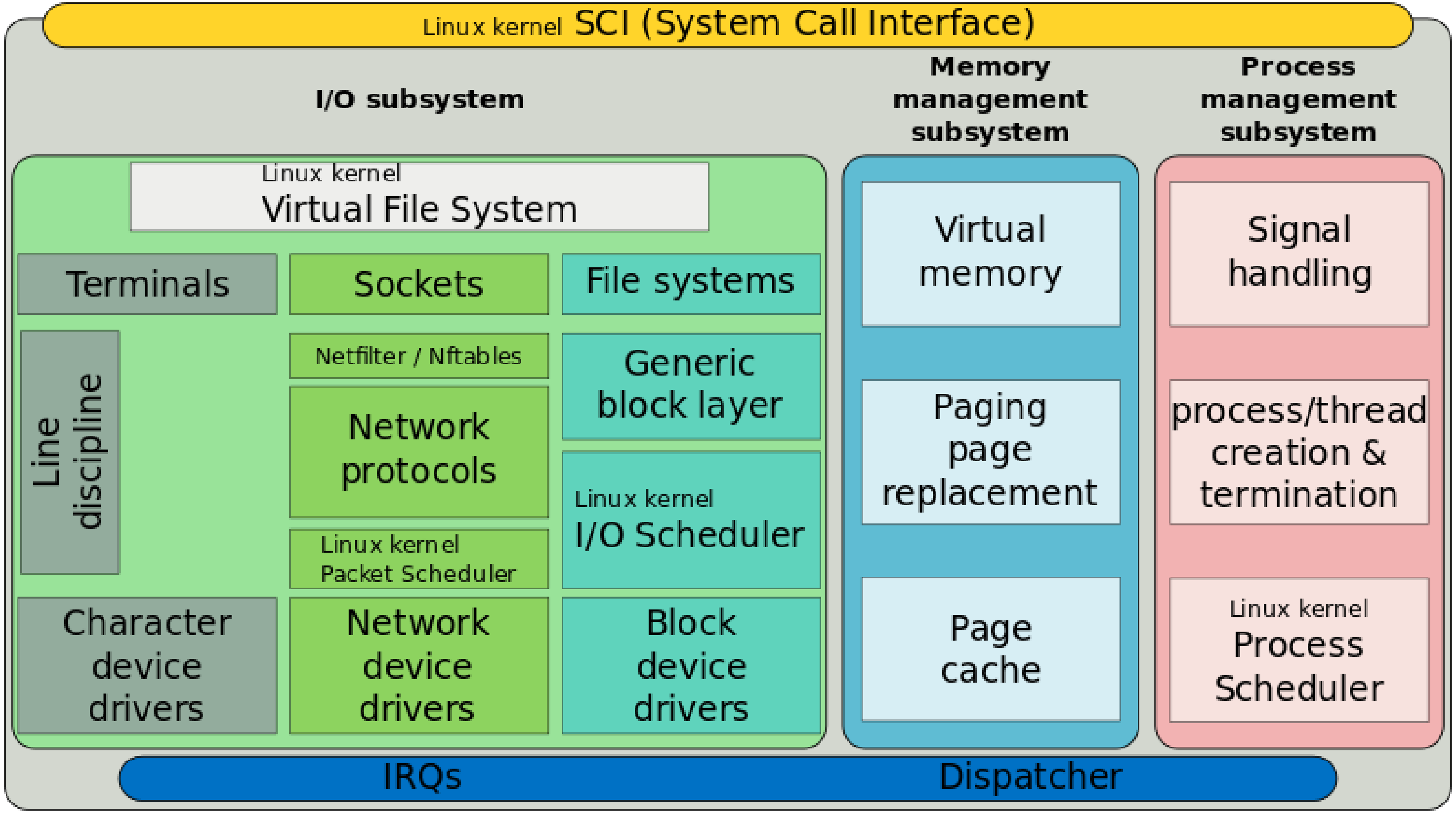
- Big challenge for device drivers
  - How do we enable interactions with so many varied devices?
    - Need abstractions to allow software to interact with them easily
    - Need mechanisms to reuse a lot of code for commonalities

General software abstractions

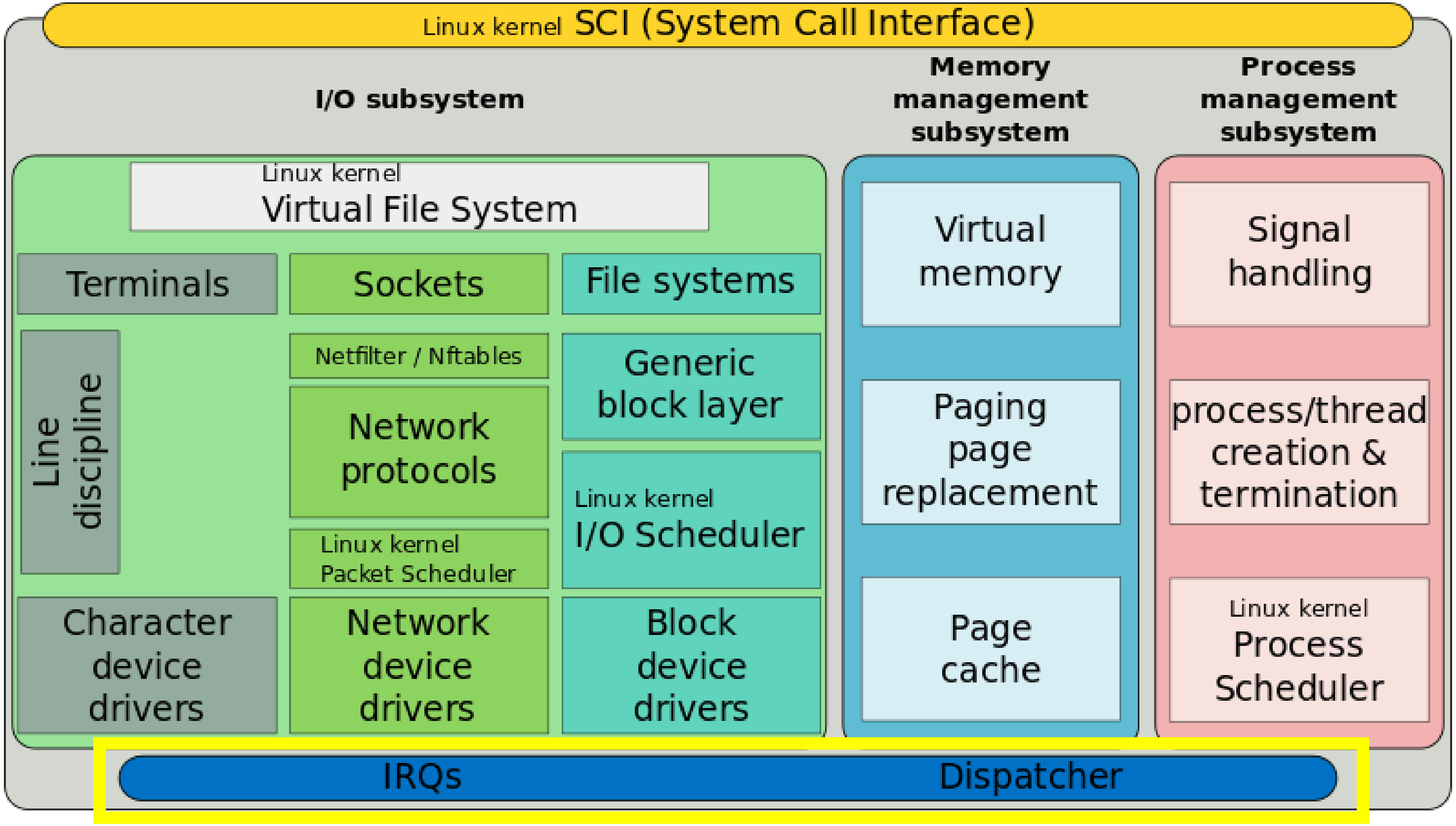
- When building large software projects, we like to define layers of code
  - Makes it clear what is handled where
  - Enables swapping out implementations when desired



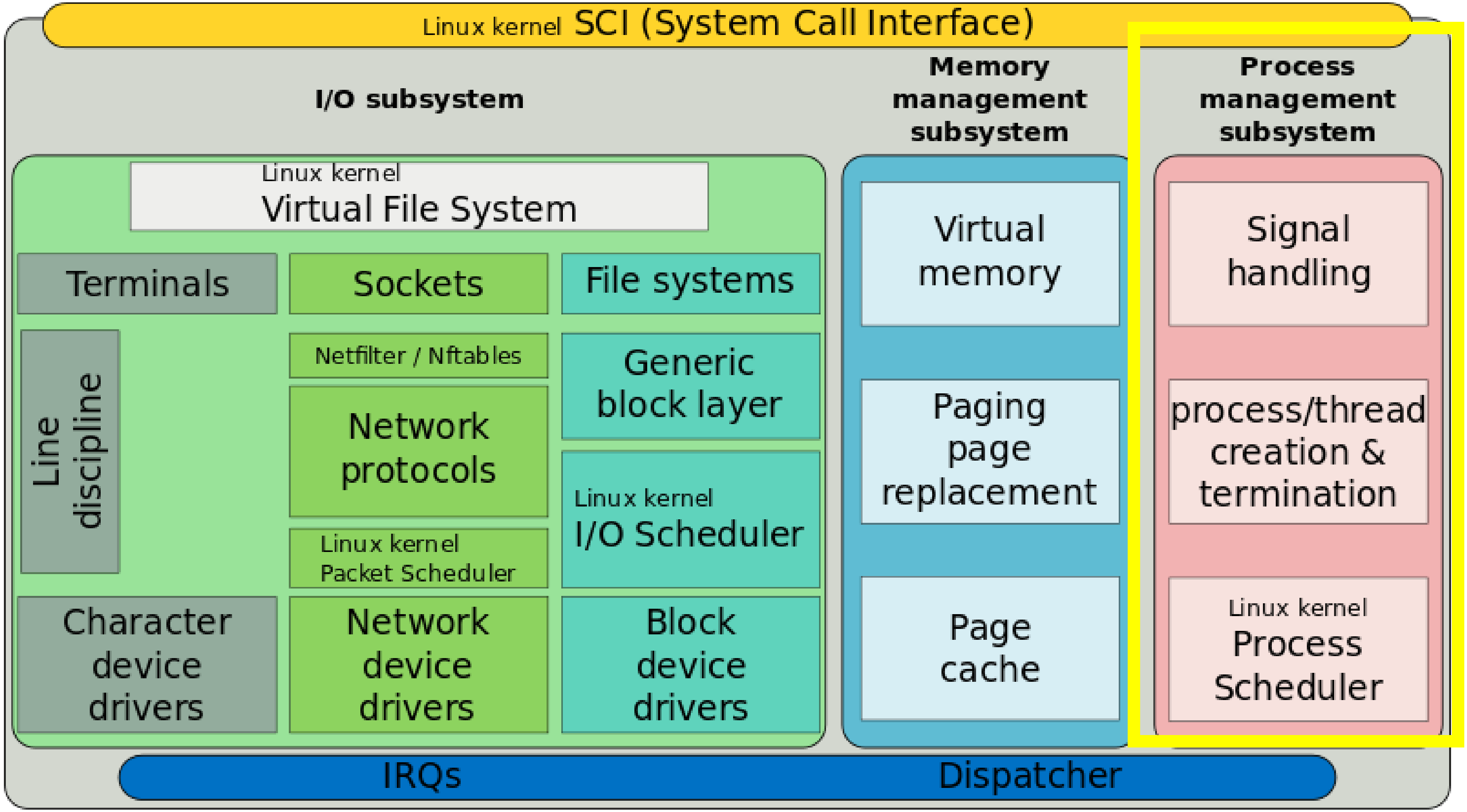
Linux Kernel Layering



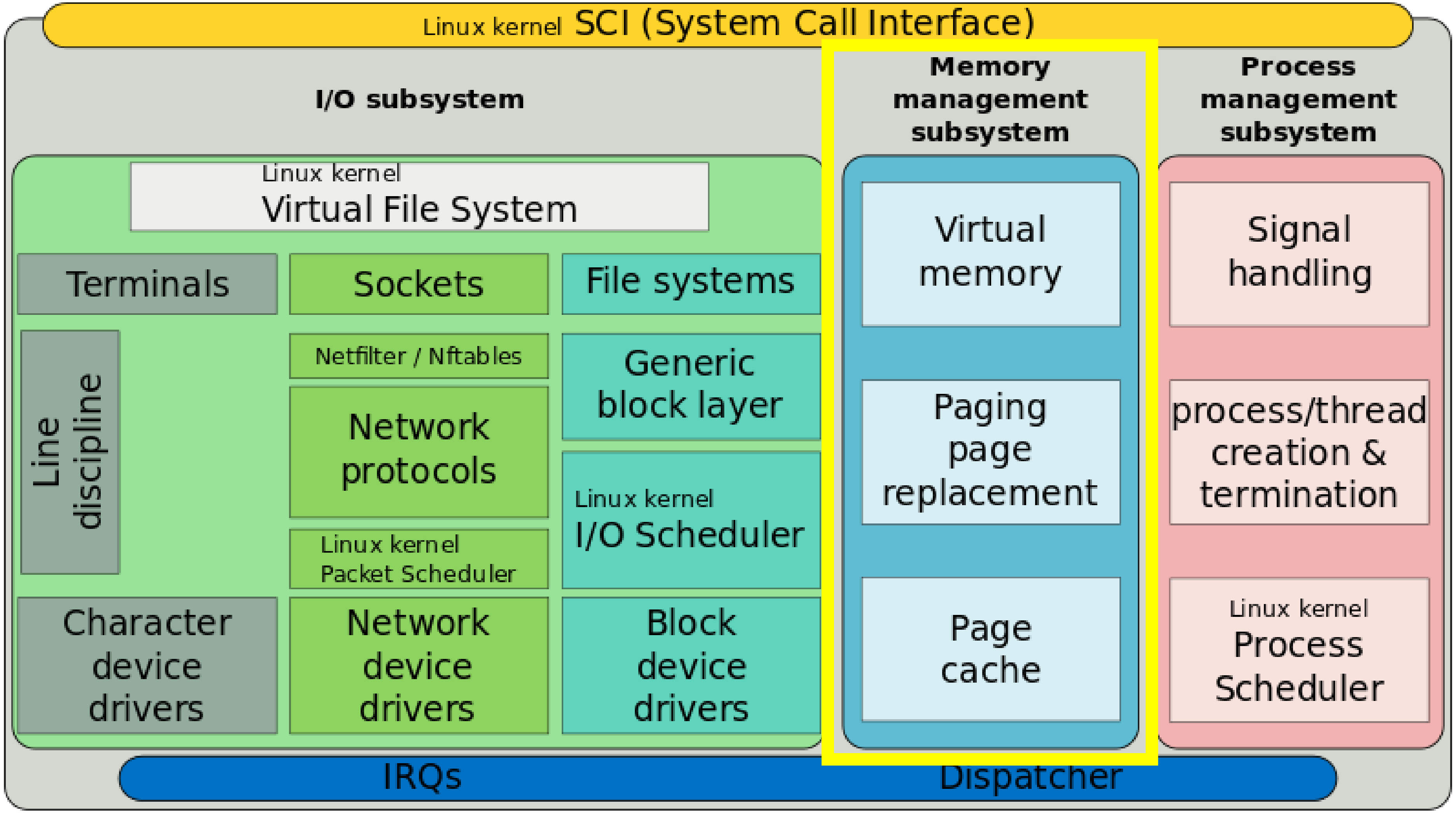
Linux Kernel Layering



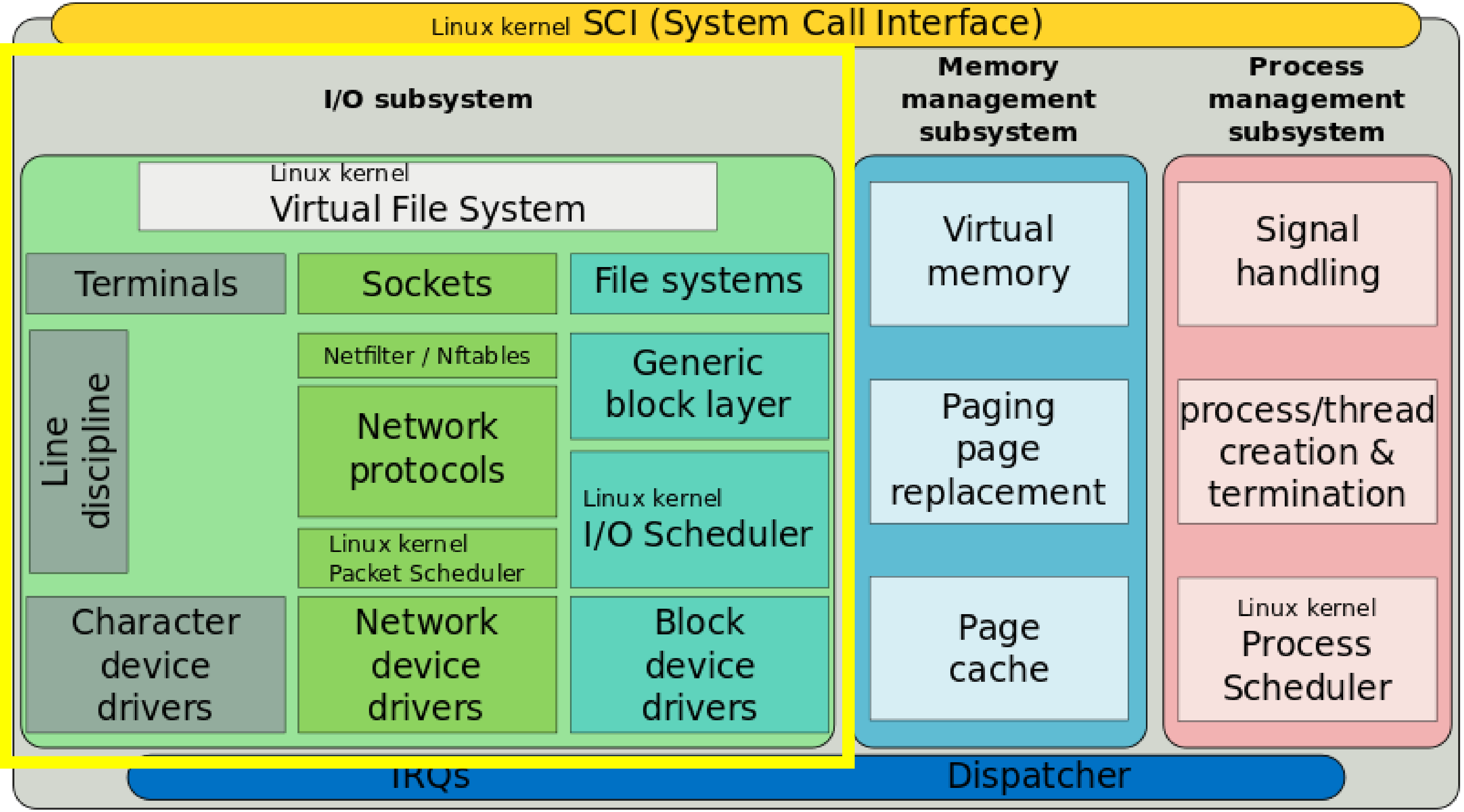
Linux Kernel Layering



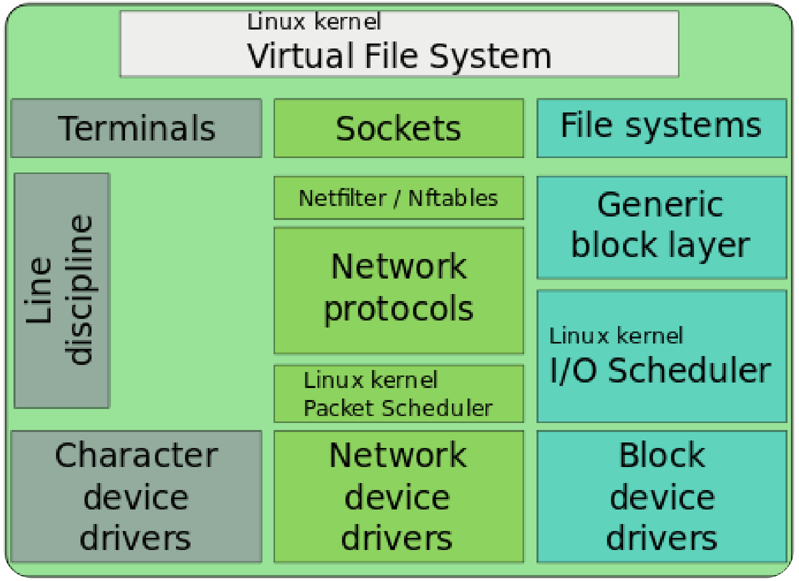
Linux Kernel Layering



Linux Kernel Layering



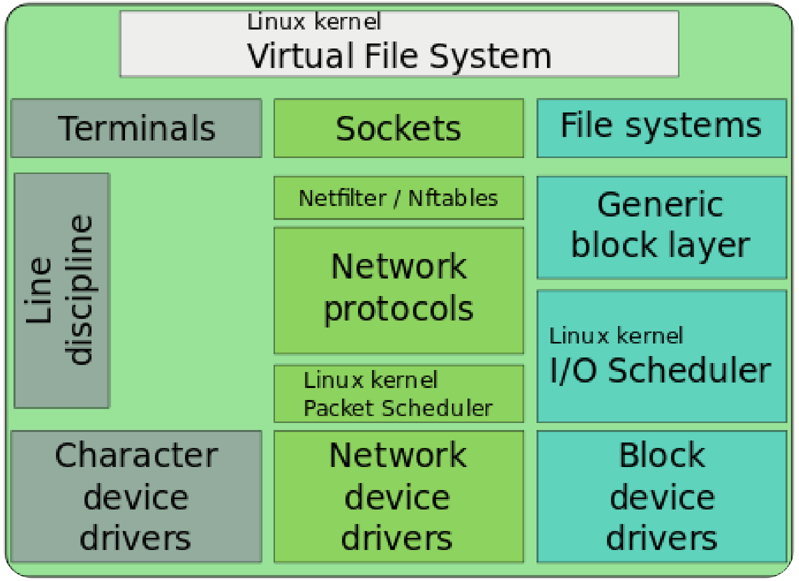
Abstraction: everything is a file!

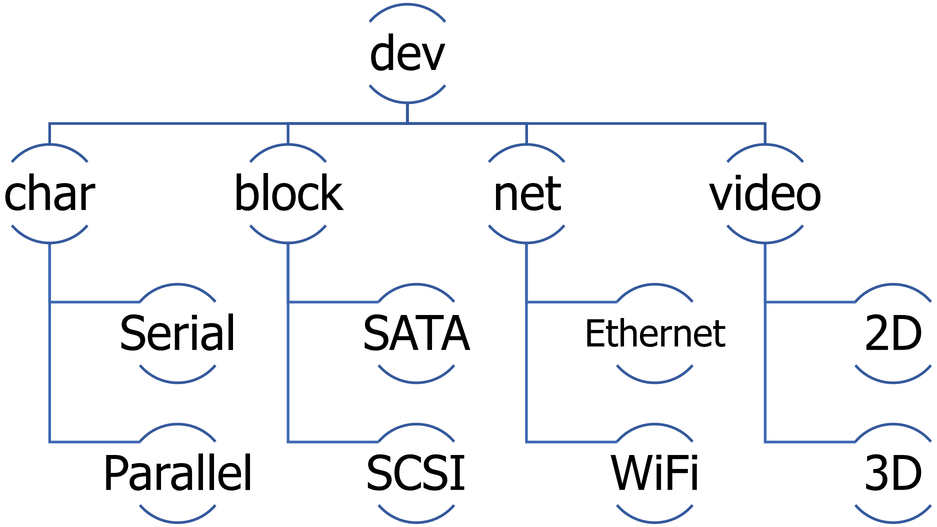


- Hardware: treat devices like memory
  - They can be read and written at addresses
- Software: treat devices like files
  - They can be read and written
  - They may be created or destroyed (plugged/unplugged)
  - They can be created in hierarchies. Example:
    - SATA devices
      - SSD
    - USB devices
      - Webcam
      - Microphone

Linux device classes

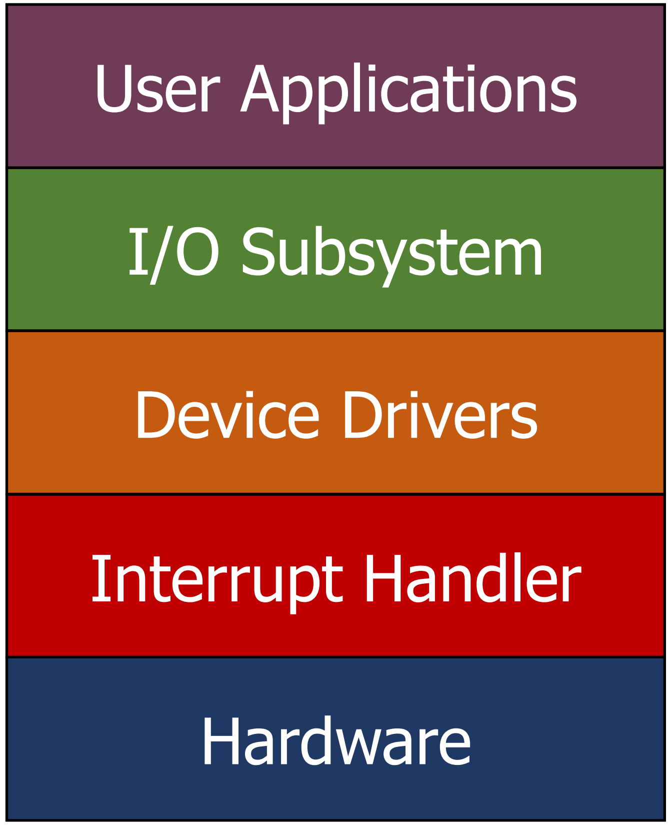
- Character devices
  - Accessed as a stream of bytes (like a file)
  - Example: Webcam, Keyboard, Headphones
  - We will focus on these
- Block devices
  - Accessed in blocks of data (like a disk)
  - Can hold entire filesystems
  - Example: Disks, Flash drives
- Network interfaces
  - See CS340 (Computer Networking)
  - Accessed through transfer of data packets





System layers when interacting with devices

- User applications
  - Do useful things
- I/O subsystem
  - Receive syscalls, route to device drivers
- Device drivers
  - Translate application requests into device interactions
- Interrupt Handler
  - Receive events from hardware
- Hardware
  - Do useful things



Outline

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  - **Application Layer**
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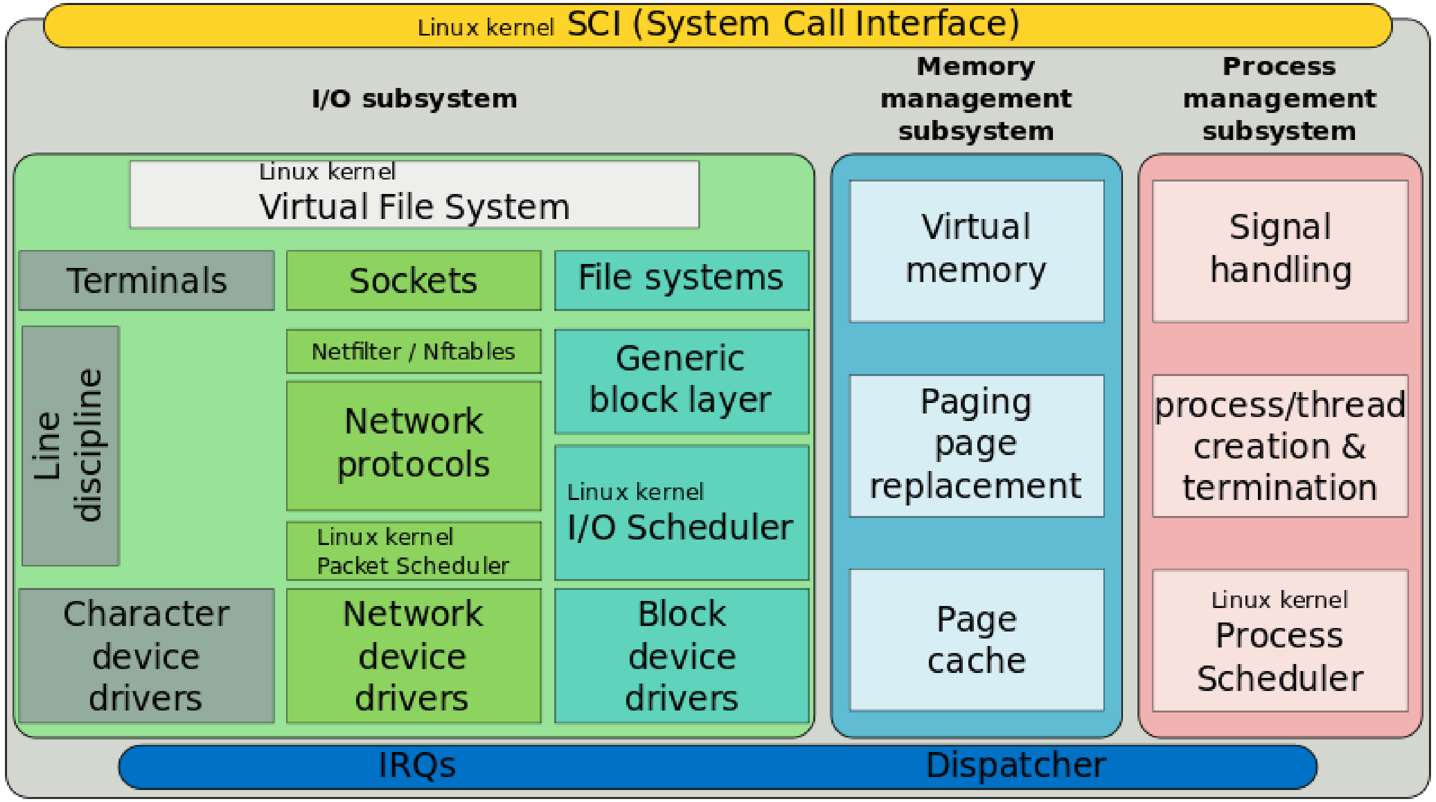
  - Interrupt Handler

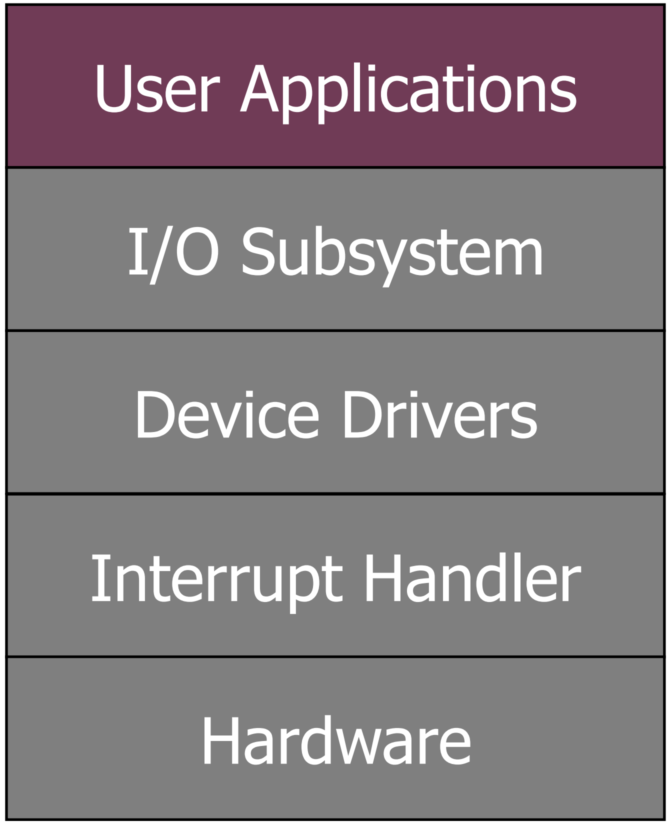
- Example Driver: Nautilus Character Device

- Example Driver: Temperature Sensor

Where we are at in the system

Processes




User Applications

I/O Subsystem

Device Drivers

Interrupt Handler

Hardware

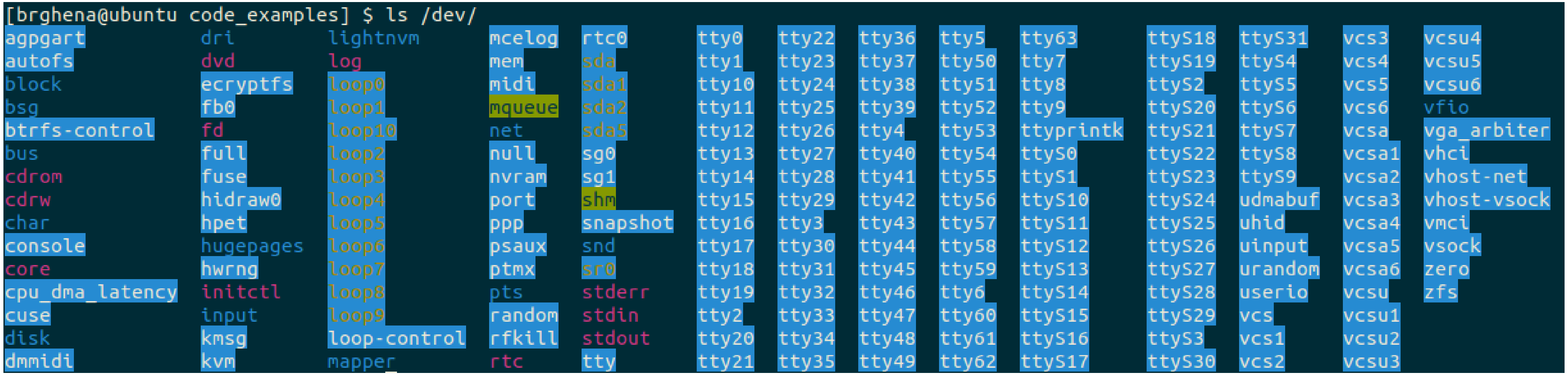
Communication with devices

- Interactions occur through system calls
  - Open/Close
  - Read/Write
  - Seek, Flush
  - Ioctl
  - And various others

Accessing devices

- Open/Close
  - Inform device that something is using it (or not)
  - Argument is path to device (like path to file)
  - Get a file descriptor that the other operations act on

- "/dev" directory is populated with devices



```
[brghena@ubuntu code_examples] $ ls /dev/
agpgart          dri        lightnvm      mcelog  rtc0      tty0   tty22  tty36  tty5   tty63      ttyS18  ttyS31   vcs3   vcsu4
autofs           dvd        log           mem     sda       tty1   tty23  tty37  tty50  tty7       ttyS19  ttyS4    vcs4   vcsu5
block            ecryptfs   loop0         midi    sda1      tty10  tty24  tty38  tty51  tty8       ttyS2   ttyS5    vcs5   vcsu6
bsg              fb0        loop1         mqueue  sda2      tty11  tty25  tty39  tty52  tty9       ttyS20  ttyS6    vcs6   vfio
btrfs-control    fd         loop10        net     sda5      tty12  tty26  tty4   tty53  ttyprintk  ttyS21  ttyS7    vcsa   vga_arbiter
bus              full       loop2         null    sg0       tty13  tty27  tty40  tty54  ttyS0      ttyS22  ttyS8    vcsa1  vhci
cdrom            fuse       loop3         nvram   sg1       tty14  tty28  tty41  tty55  ttyS1      ttyS23  ttyS9    vcsa2  vhost-net
cdrw             hidraw0    loop4         port    shm       tty15  tty29  tty42  tty56  ttyS10     ttyS24  udmabuf  vcsa3  vhost-vsock
char             hpet       loop5         ppp     snapshot  tty16  tty3   tty43  tty57  ttyS11     ttyS25  uhid     vcsa4  vmci
console          hugepages  loop6         psaux   snd       tty17  tty30  tty44  tty58  ttyS12     ttyS26  uinput   vcsa5  vsock
core             hwrng      loop7         ptmx    sr0       tty18  tty31  tty45  tty59  ttyS13     ttyS27  urandom  vcsa6  zero
cpu_dma_latency  initctl    loop8         pts     stderr    tty19  tty32  tty46  tty6   ttyS14     ttyS28  userio   vcsu   zfs
cuse             input      loop9         random  stdin     tty2   tty33  tty47  tty60  ttyS15     ttyS29  vcs      vcsu1
disk             kmsg       loop-control  rfkill  stdout    tty20  tty34  tty48  tty61  ttyS16     ttyS3   vcs1     vcsu2
dmmidi           kvm        mapper        rtc     tty       tty21  tty35  tty49  tty62  ttyS17     ttyS30  vcs2     vcsu3
```

Interacting with devices

- Same read/write commands you've likely seen before
  - These are actually syscalls!

- Read
  - `ssize_t read(int fd, void *buf, size_t count);`

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

Arbitrary device interactions

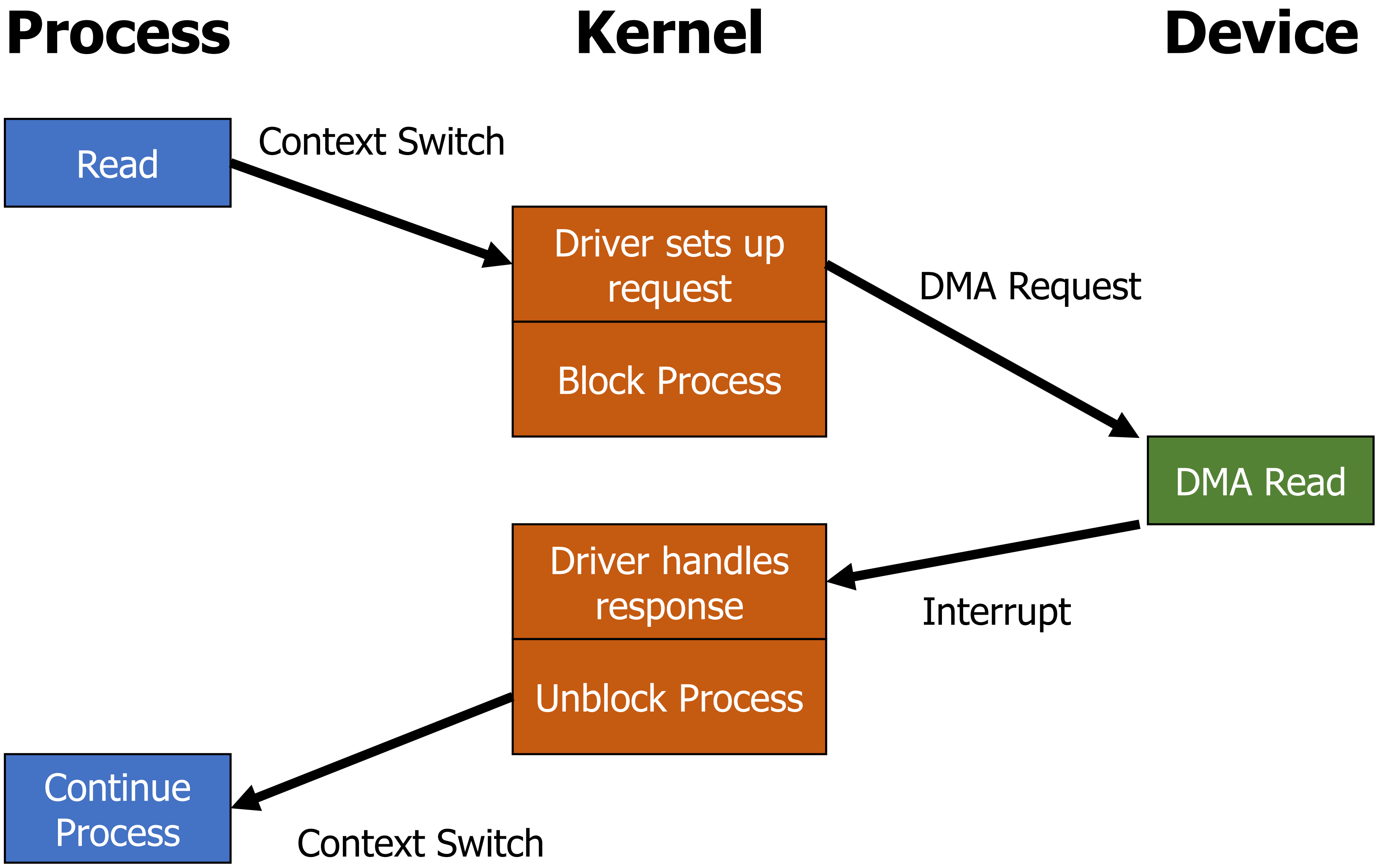
- ioctl – I/O Control
    - `int ioctl(int fd, unsigned long request, ...);`
- Request number followed by an arbitrary list of arguments
    - “request” may be broken in fields: command, size, direction, etc.
- Catch-all for device operations that don’t fit into file I/O model
    - Combine with “magic numbers” to form some special action
    - Reset device, Start action, Change setting, etc.
    - Read the device documentation to find these

Asynchronous I/O operations

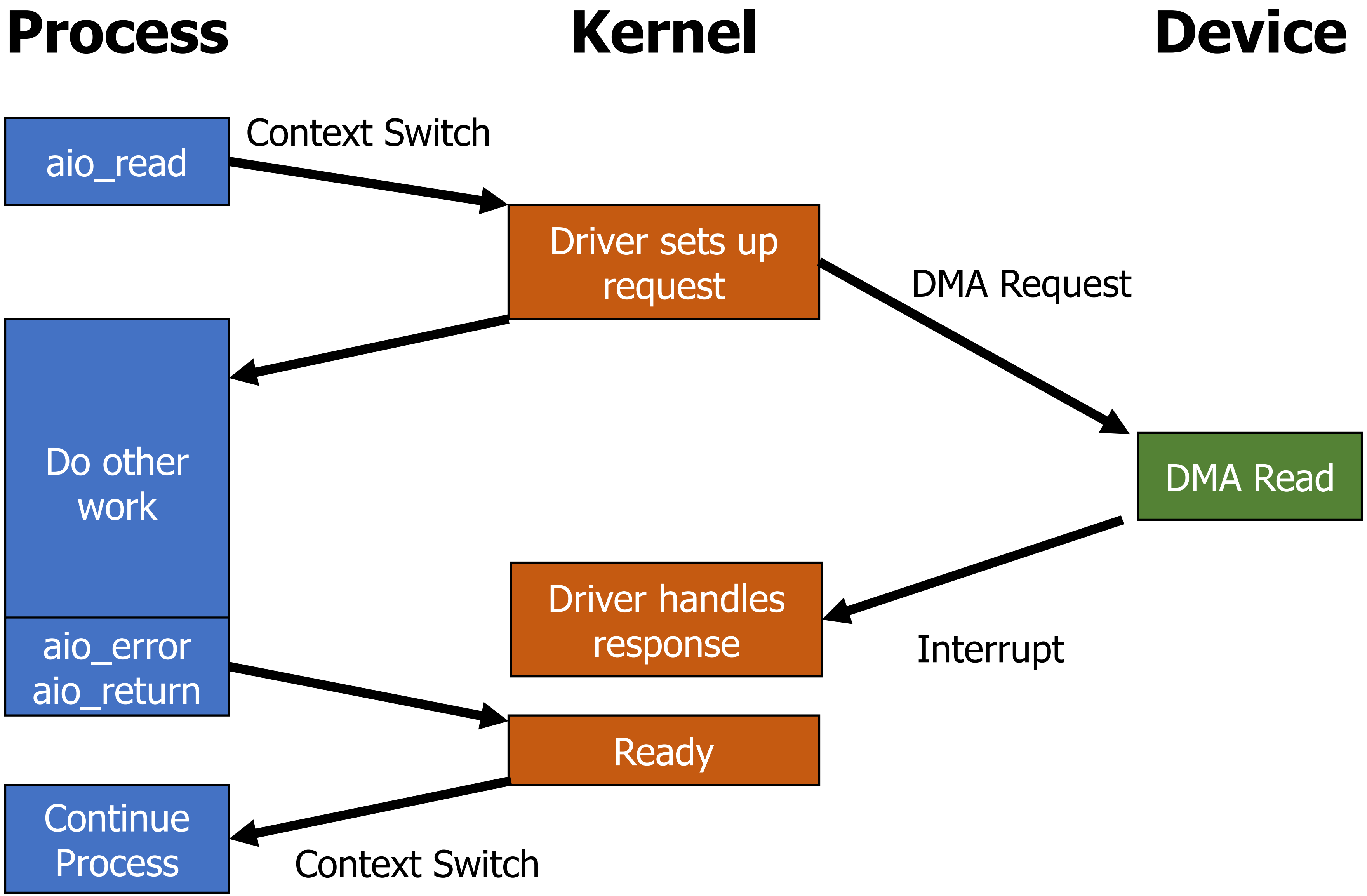
- Previous examples were all synchronous I/O calls
    - Read/Write will block process until complete
    - Easy to use, but not always most efficient method

- Asynchronous I/O calls also exist
    - POSIX AIO library
        - aio_read/aio_write – enqueue read/write request
        - aio_error – check status of an I/O request
        - aio_return – get result of a completed I/O request

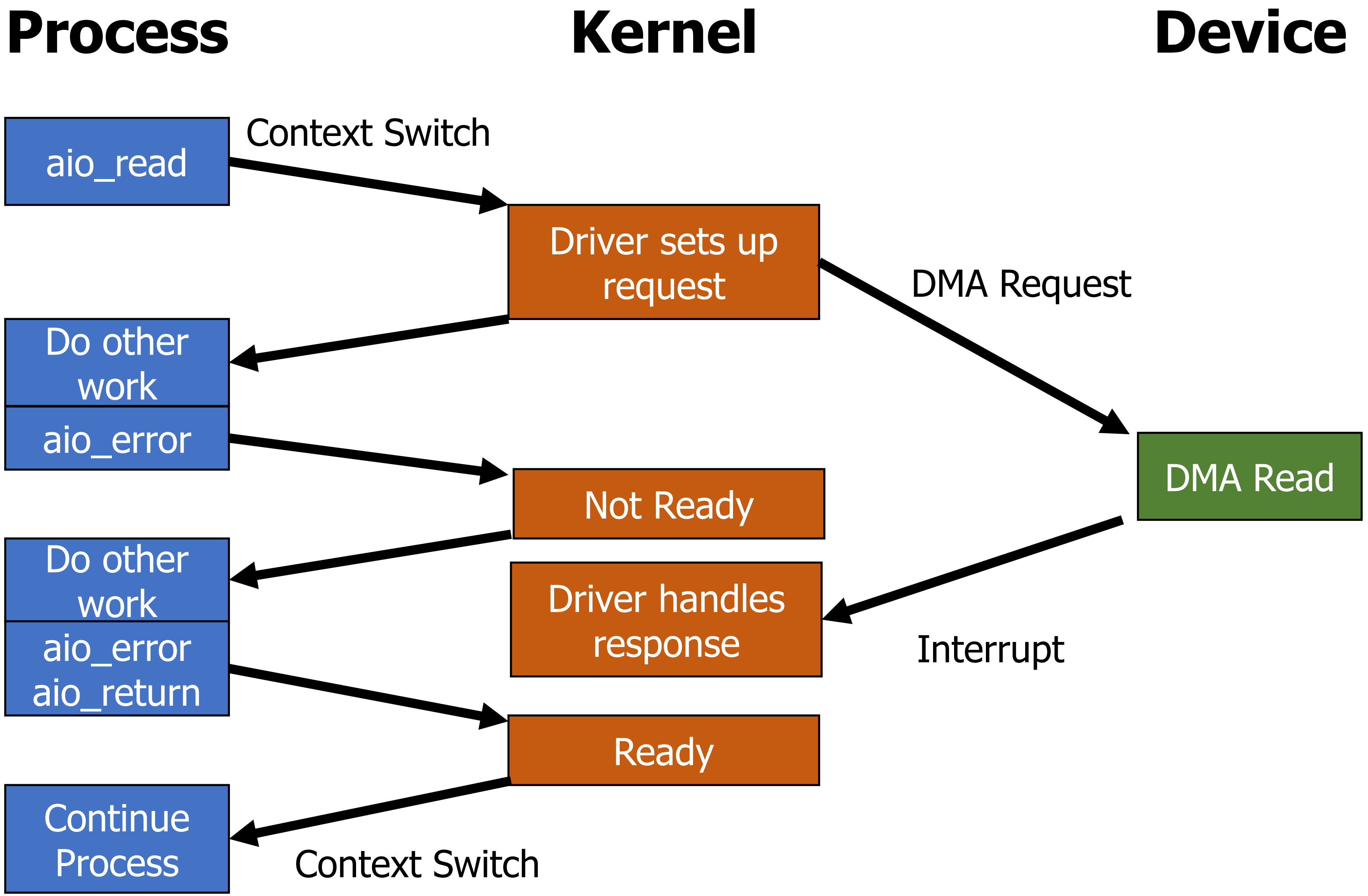
Synchronous blocking read example



Asynchronous read example



Asynchronous read example with early request



Break + Open Question

- Could you re-create the asynchronous I/O interface using threads?

Break + Open Question

- Could you re-create the asynchronous I/O interface using threads?
  - aio_read creates a new thread, which does the actual blocking read
    - Thread will essentially block immediately
  - aio_error / aio_return get data from that worker thread
    - Synchronized with locks
    - Thread exits after aio_return occurs
  - This is basically the underlying implementation for glibc POSIX AIO

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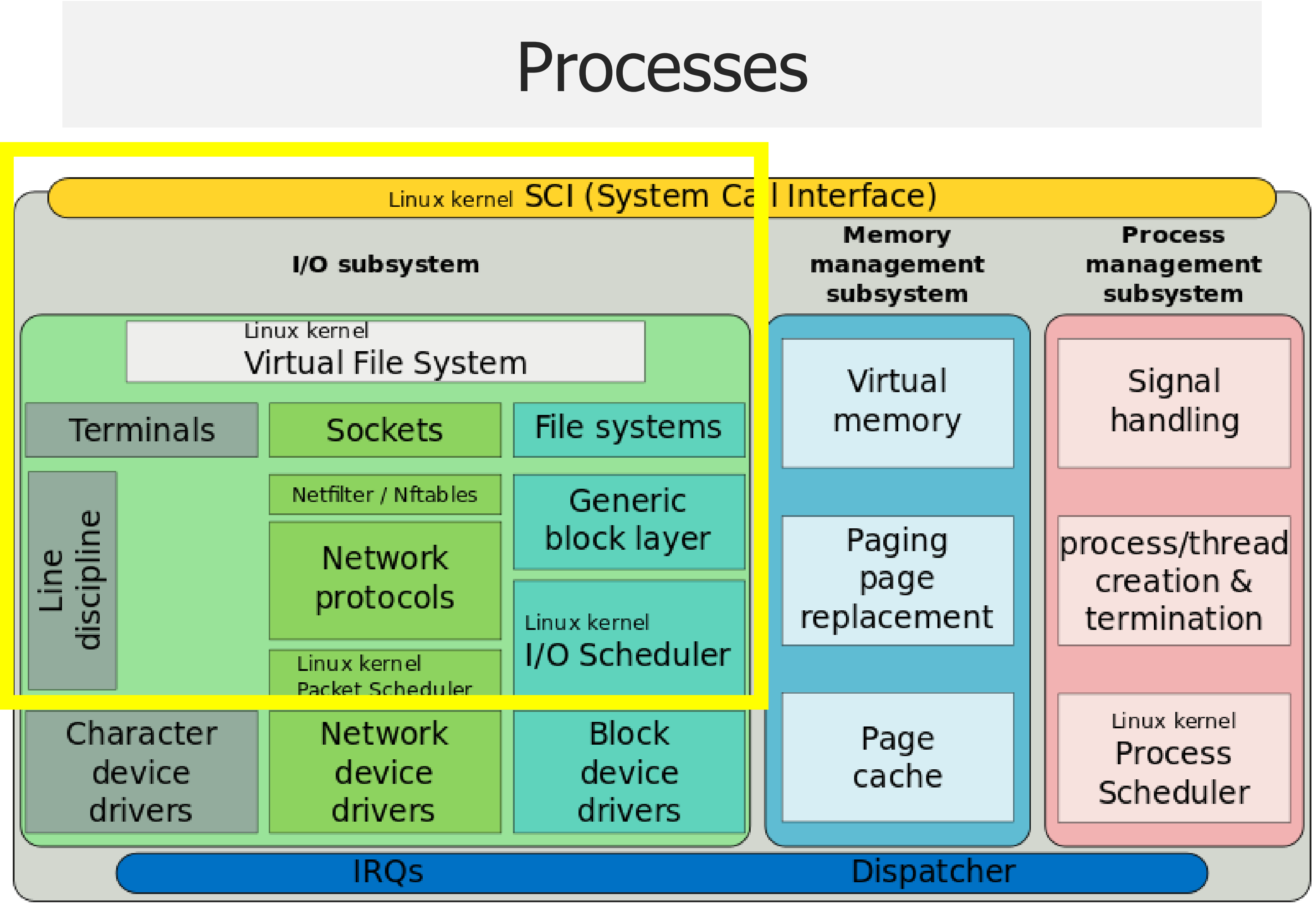
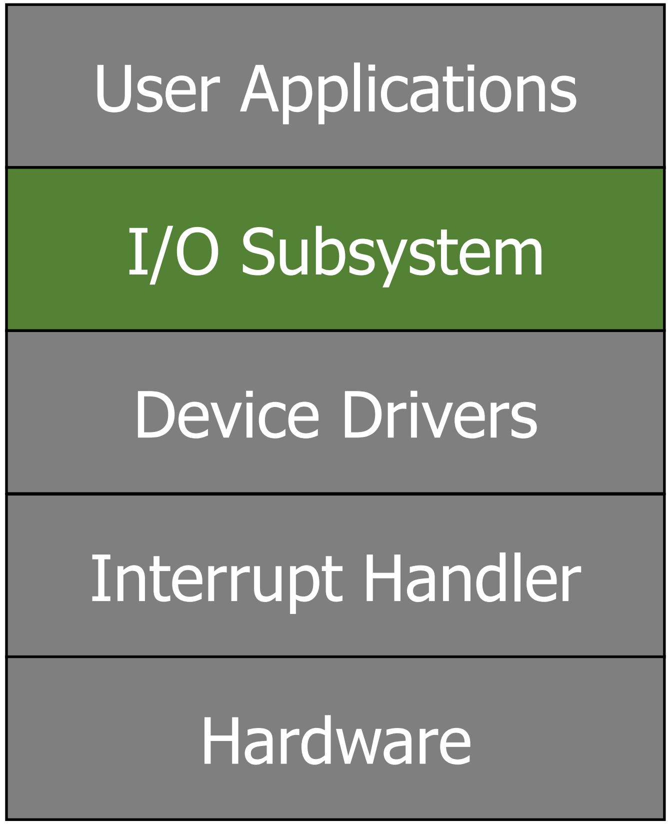
- Example Driver: Nautilus Character Device
- Example Driver: Temperature Sensor

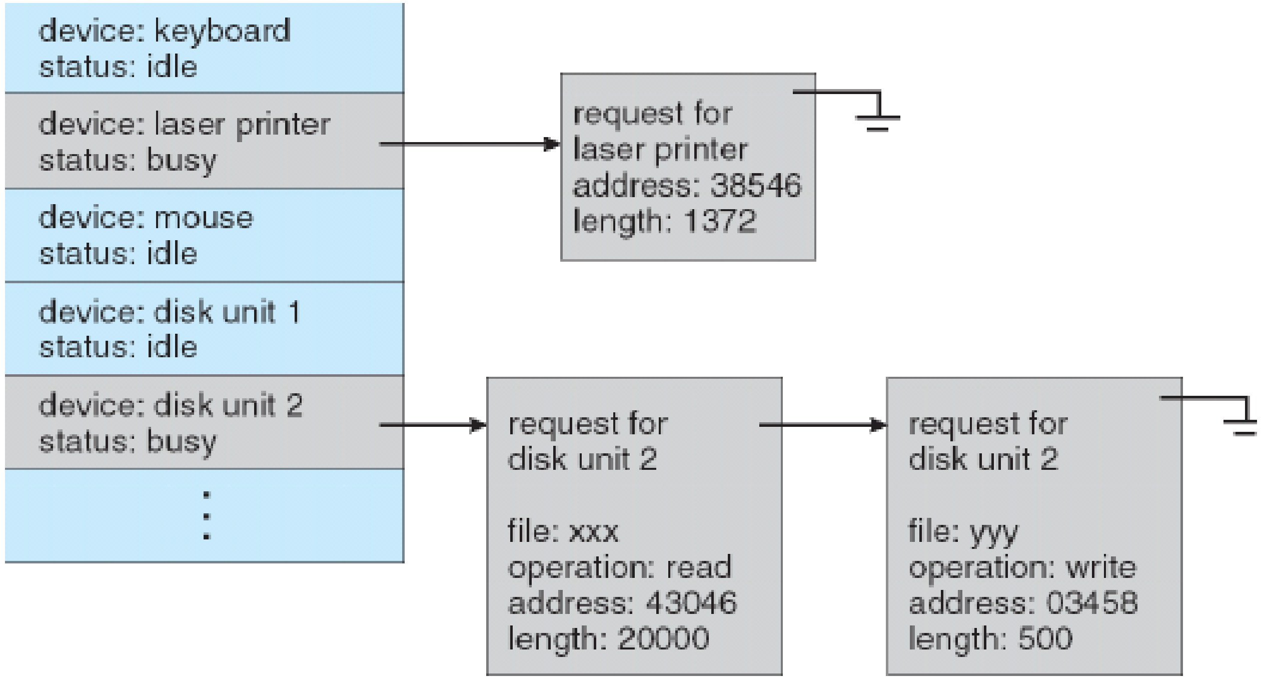
Where we are at in the system





Kernel I/O subsystem

- The OS kernel does various things for devices that are not specific to the individual device
  - Manages permissions
  - Routes call to appropriate driver
  - Schedules requests to drivers



device: keyboard
status: idle

device: laser printer
status: busy

device: mouse
status: idle

device: disk unit 1
status: idle

device: disk unit 2
status: busy

⋮

request for
laser printer
address: 38546
length: 1372

request for
disk unit 2

file: xxx
operation: read
address: 43046
length: 20000

request for
disk unit 2

file: yyy
operation: write
address: 03458
length: 500

Kernel needs to handle process memory

- Address translation
  - All the data user processes give to the kernel comes with virtual addresses
  - Pointers are either going to have to be translated
  - Or memory is going to need to be copied

- Buffering
  - Kernel may need to hold on to a copy of data
    - Especially in asynchronous case
  - When copies are done and how many times is a big kernel efficiency question

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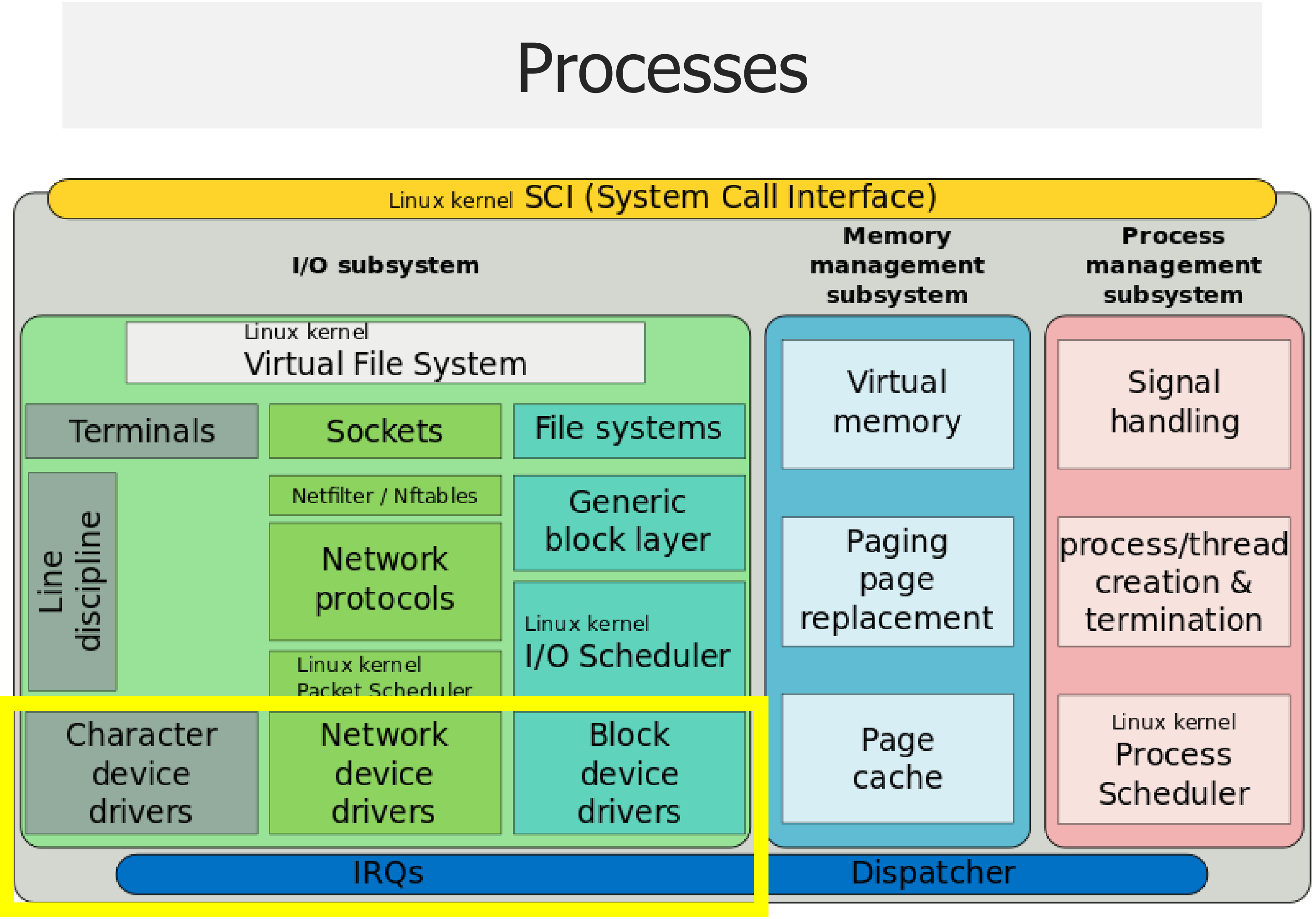


Processes

Linux kernel SCI (System Call Interface)

I/O subsystem

Memory management subsystem

Process management subsystem

Linux kernel Virtual File System

Terminals

Sockets

File systems

Line discipline

Netfilter / Nftables

Network protocols

Linux kernel Packet Scheduler

Generic block layer

Linux kernel I/O Scheduler

Character device drivers

Network device drivers

Block device drivers

Virtual memory

Paging page replacement

Page cache

Signal handling

process/thread creation & termination

Linux kernel Process Scheduler

IRQs

Dispatcher

User Applications

I/O Subsystem

Device Drivers

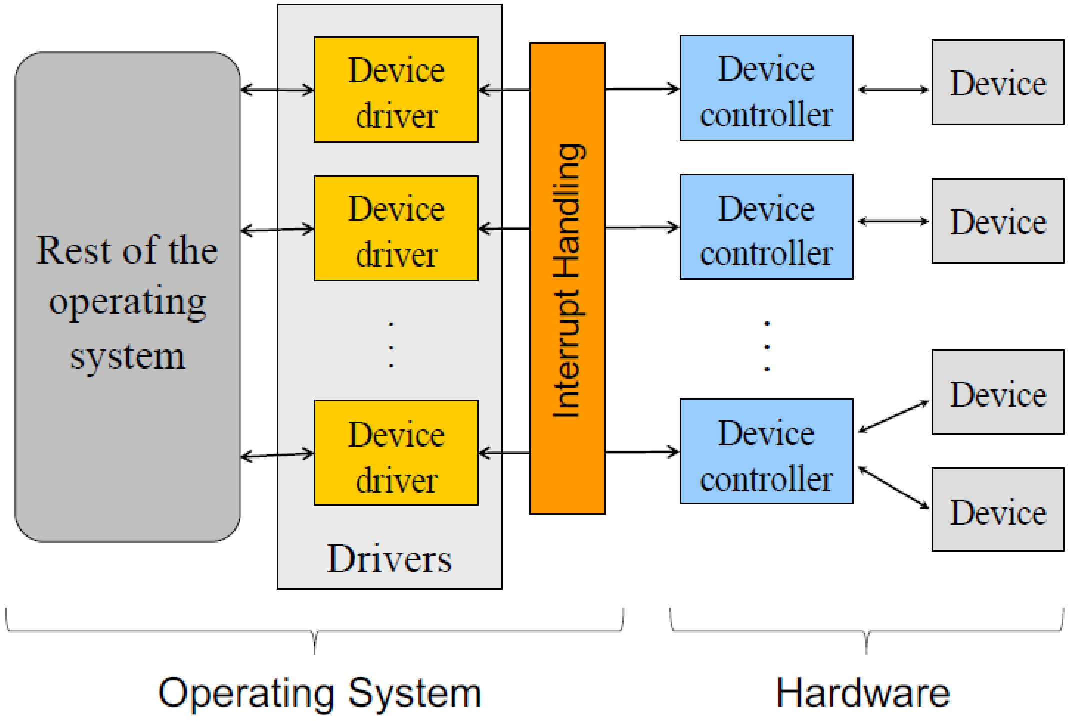
Interrupt Handler

Hardware

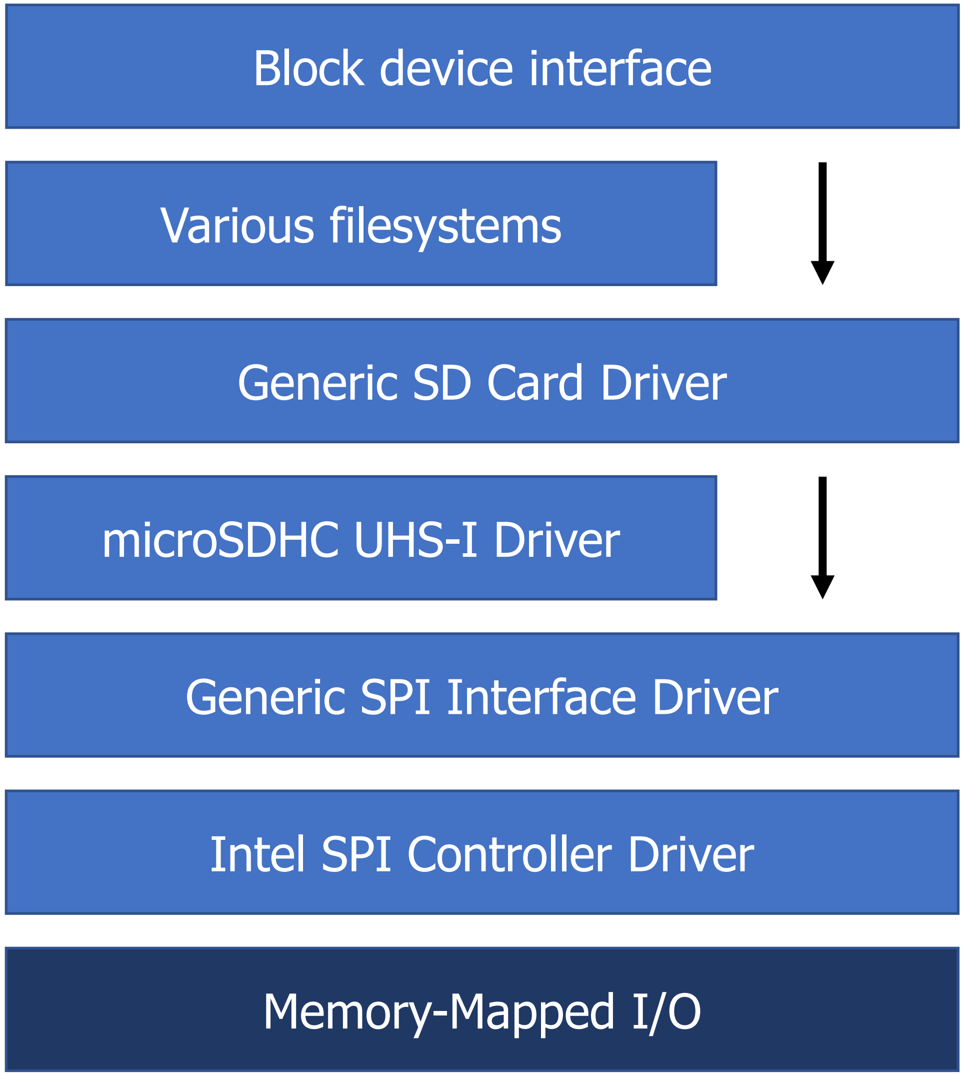
Device drivers

- Device-specific code for communicating with device
  - Supports some interfaces above and below
    - Possibly file syscalls above and memory-mapped I/O below
    - Possibly internal API above and below..

- Examples
  - Specific disk drivers are layered on top of SATA driver
  - Keyboard driver is layered on top of USB driver
  - Ethernet driver has various network interfaces layered above it



Example: possible driver layers for an SD card



Block device interface

Various filesystems

Generic SD Card Driver

microSDHC UHS-I Driver

Generic SPI Interface Driver

Intel SPI Controller Driver

Memory-Mapped I/O

Device I/O is handled by device drivers

- Communication is up to the hardware
  - Port-mapped I/O or memory-mapped I/O
  - Or function calls to a lower-level driver

- Interaction design is up to the driver (and OS)
  - Programed I/O
    - Synchronous or with interrupts
  - Direct Memory Access
    - Needs hardware support
    - With interrupts

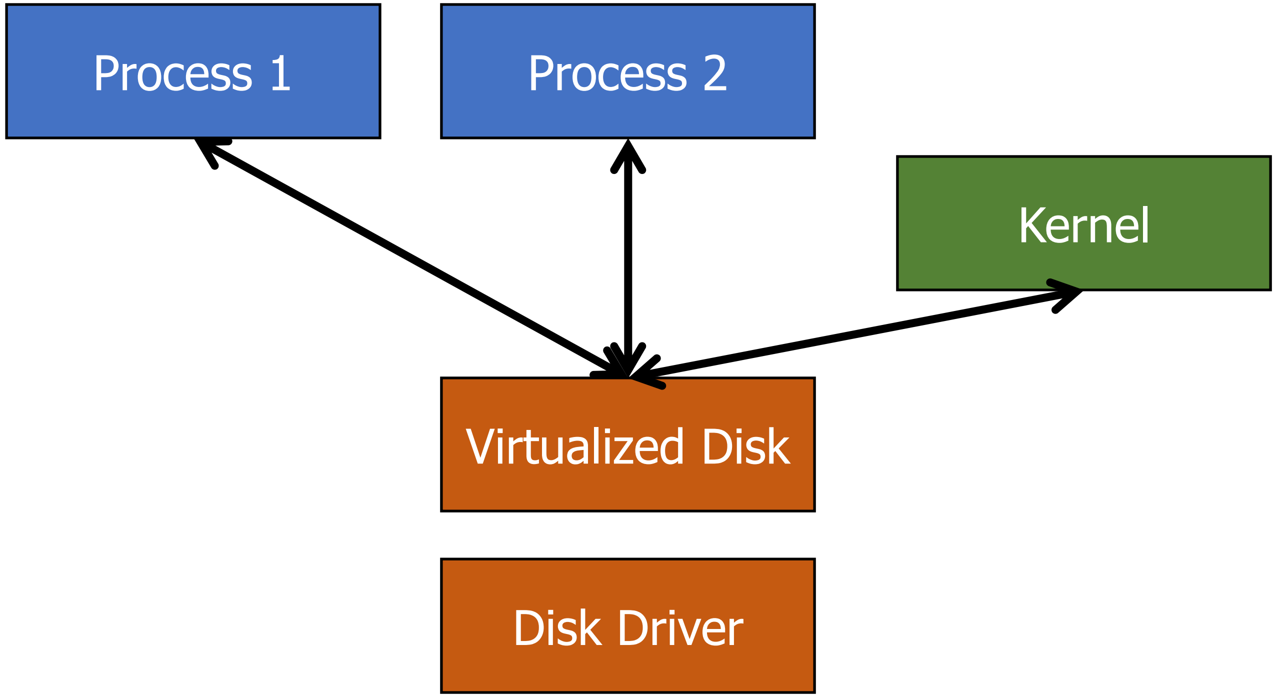
Device drivers are often designed with two “halves”

- Top half
  - Interrupt handler
    - Continues next transaction
    - Or signals for bottom half to continue (often with shared variable)

- Bottom half
  - Implements interface that higher layers require
  - Performs logic to start device requests
  - Wait for I/O to be completed
    - Synchronously (blocking) or asynchronously (return to kernel)
  - Handle responses from the device when complete

Virtualizing one device for many users

- Some devices need to be *virtualized*
  - Software that emulates unique devices for each higher level user even though only a single hardware resource actually exists



Life cycle of an I/O request

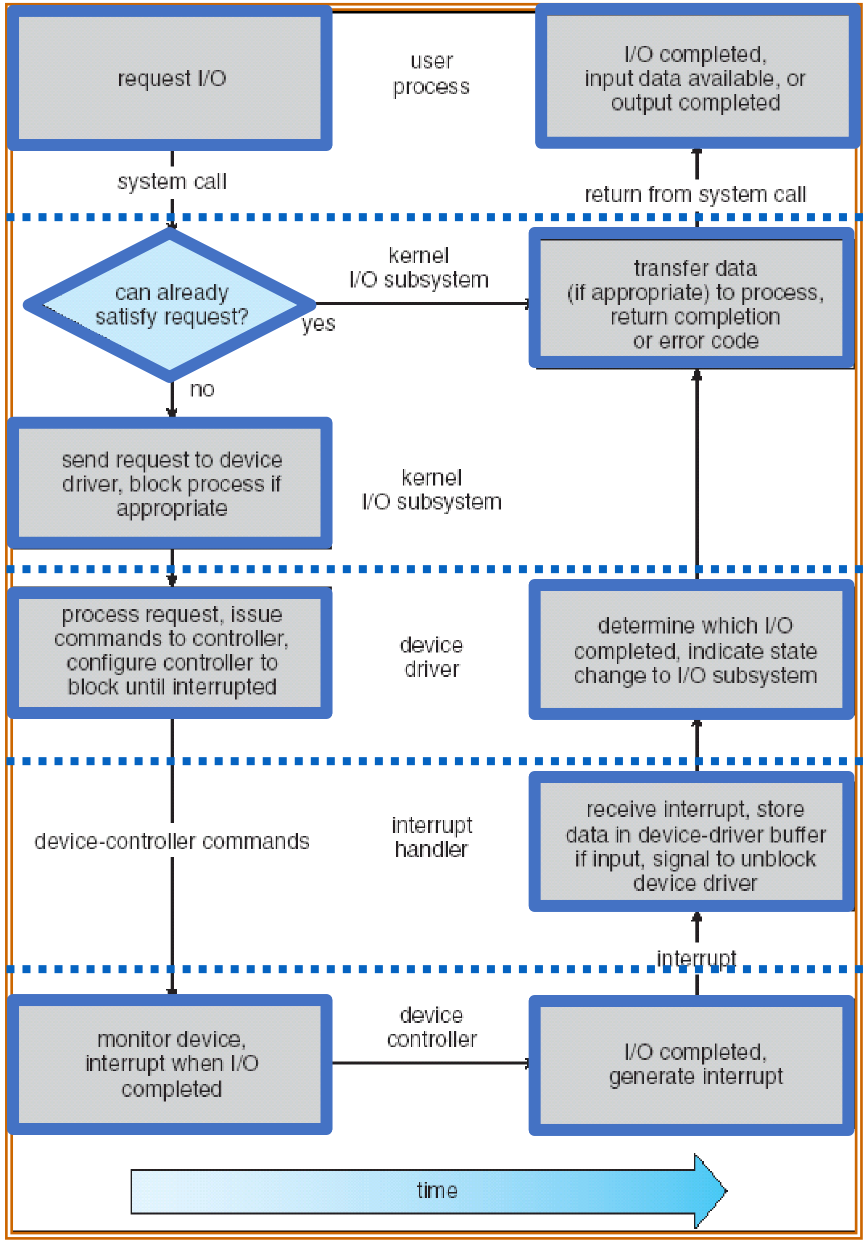
User Program

Kernel I/O Subsystem

Device Driver Bottom Half

Device Driver Top Half

Device Hardware


request I/O
user process
I/O completed, input data available, or output completed
system call
return from system call
can already satisfy request?
yes
no
kernel I/O subsystem
transfer data (if appropriate) to process, return completion or error code
send request to device driver, block process if appropriate
kernel I/O subsystem
process request, issue commands to controller, configure controller to block until interrupted
device driver
determine which I/O completed, indicate state change to I/O subsystem
device-controller commands
interrupt handler
receive interrupt, store data in device-driver buffer if input, signal to unblock device driver
interrupt
monitor device, interrupt when I/O completed
device controller
I/O completed, generate interrupt
time

How are devices found anyways?

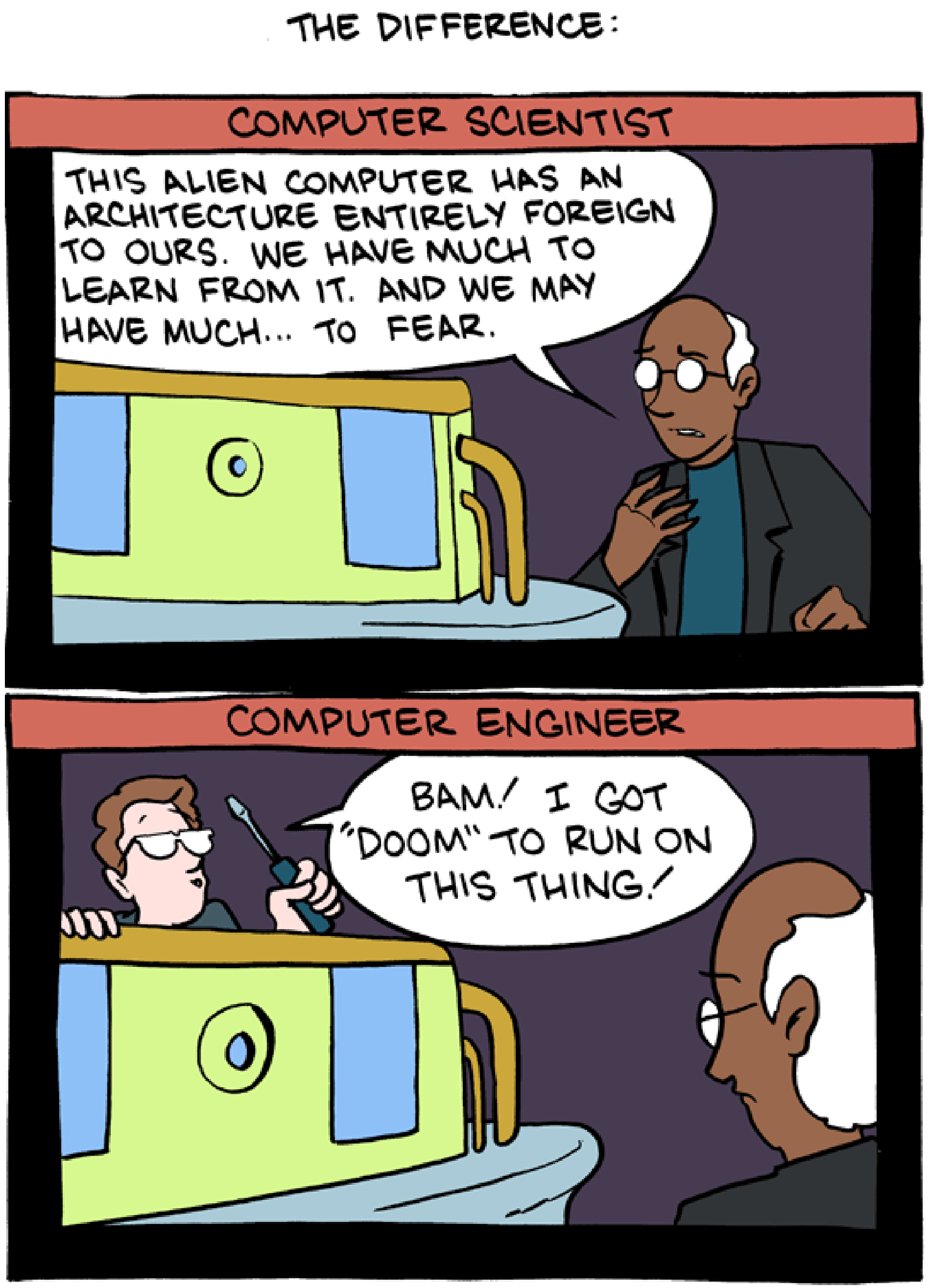
- At boot, the OS kernel searches for devices attached to it
  - Action is usually called “probe”
  - Starts up drivers for each device it finds
  - A significant amount of time is spent in device discovery

- Run “dmesg” on linux to see printouts from this process
  - Live demo!

Break + SMBC webcomic

- Not really relevant to class, just amuses me

- Take a break and reset your brains for a minute


THE DIFFERENCE:
COMPUTER SCIENTIST
THIS ALIEN COMPUTER HAS AN ARCHITECTURE ENTIRELY FOREIGN TO OURS. WE HAVE MUCH TO LEARN FROM IT. AND WE MAY HAVE MUCH... TO FEAR.
COMPUTER ENGINEER
BAM! I GOT "DOOM" TO RUN ON THIS THING!

https://www.smbc-comics.com/comic/2011-02-18

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- Example Driver: Temperature Sensor

Nautilus kernel

- http://cs.iit.edu/~khale/nautilus/

- Small, light-weight kernel for research use
  - All the basic features for getting an x86-64 computer to boot
  - And just about nothing else

- Created by Kyle Hale (Illinois Institute of Technology) and Peter Dinda (Northwestern)

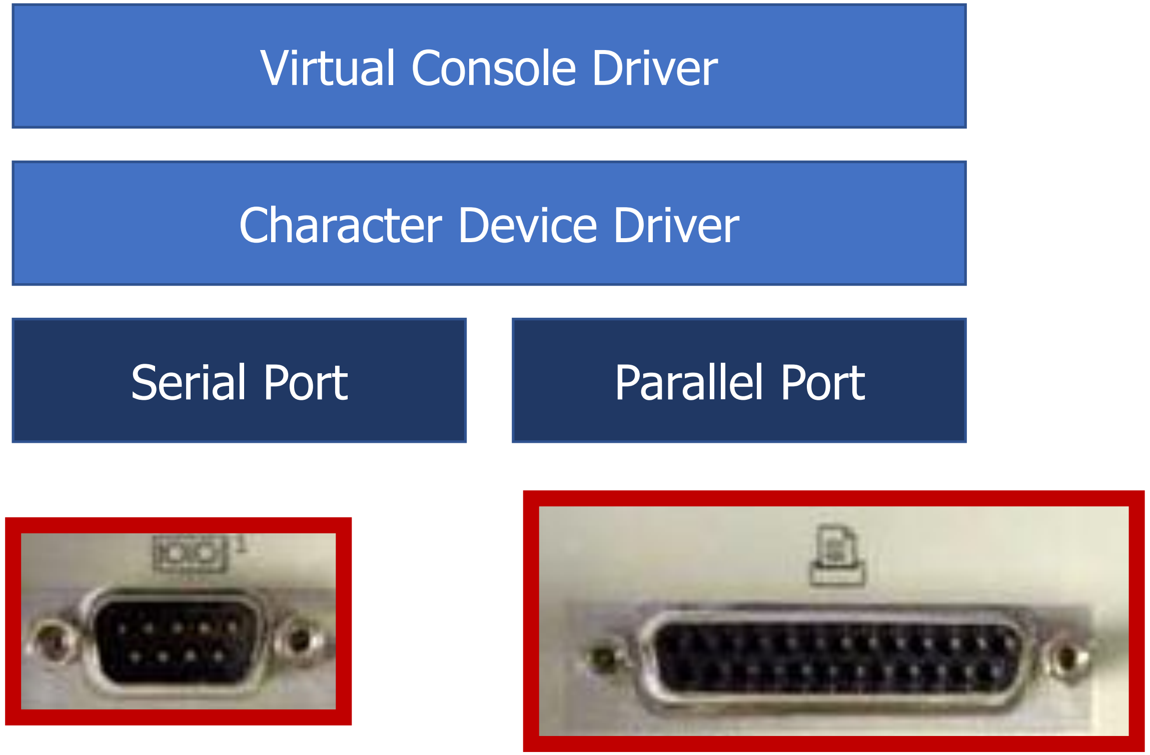
- Example use case: experiment with virtual memory strategies

Nautilus character device abstraction

- Character device: a device that can read/write arbitrary characters
  - (as compared to Block devices that must read/write in chunks)

- Nautilus says every character device must have the following:
  - get_characteristics() – every device has this, none particularly for chardev
  - read() – single byte
  - write() – single byte
  - status() – determine if device is readable or writeable or both

Layering in Nautilus



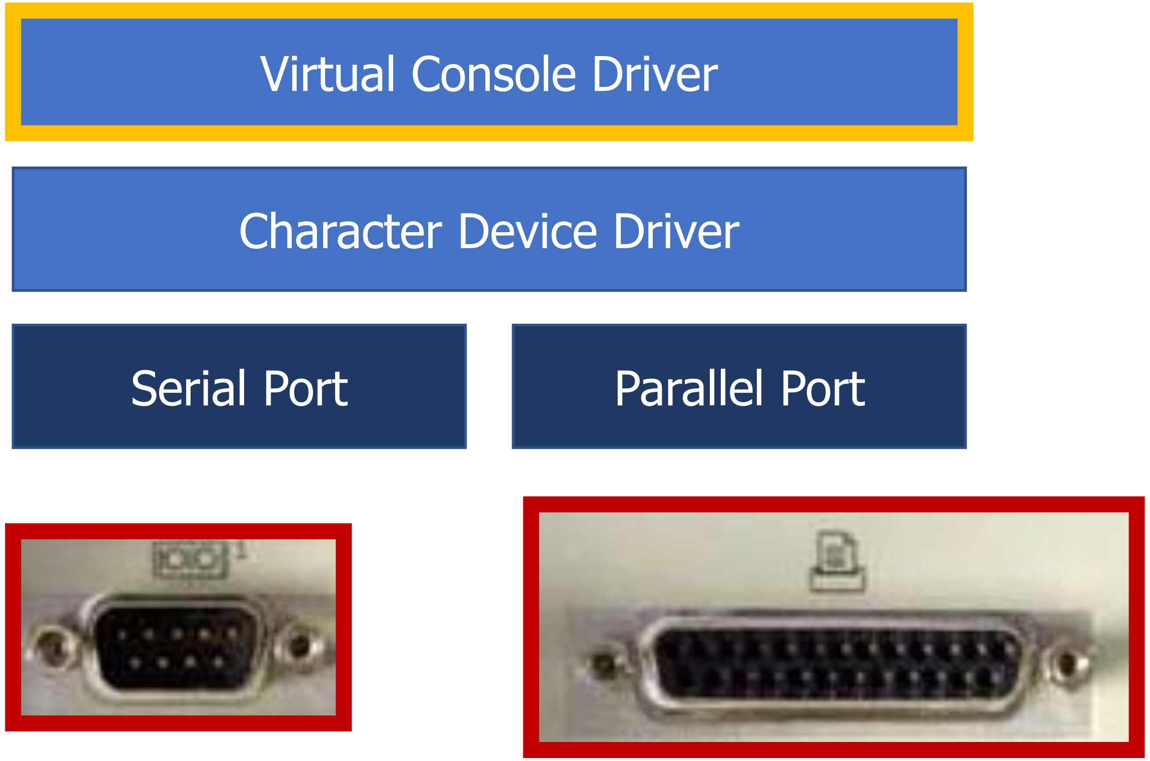
Virtual Console Driver

Character Device Driver

Serial Port

Parallel Port

Layering in Nautilus



Virtual Console Driver

Character Device Driver

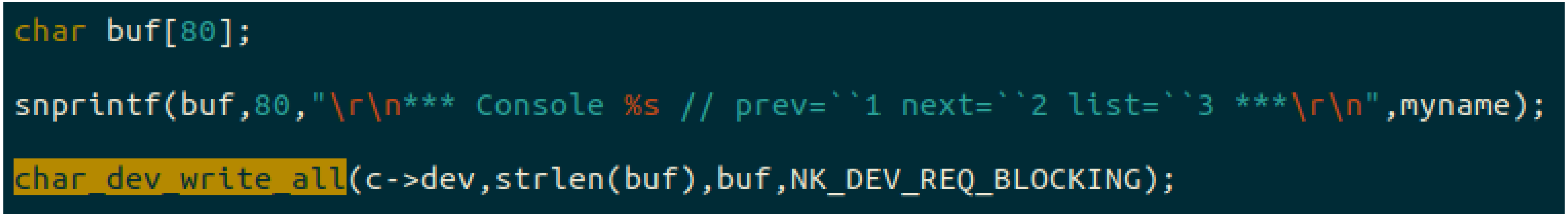
Serial Port

Parallel Port

Virtual console

- Allows keyboard input and text output for a user
    - Generally, the basic terminal that you have open
    - Could be implemented in all kinds of ways though
        - Example: keyboard input plus printer output
    - Any device that can read/write individual characters could act as a console
    - So the virtual console just contains a `nk_char_dev`
        - Passed into the virtual console at initialization
        - Could be implemented with any hardware

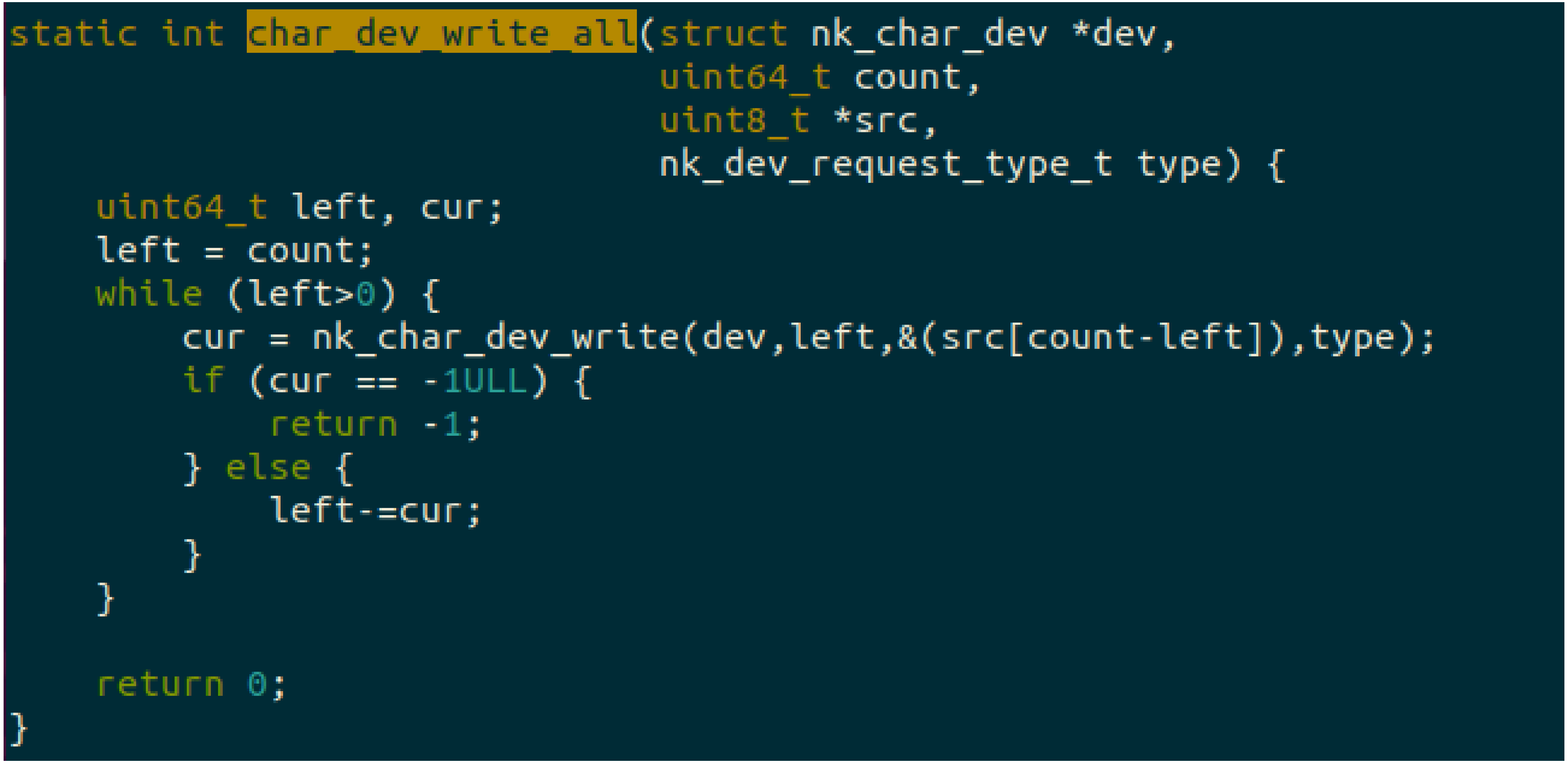
Virtual console reads and writes to generic char_dev



```
char buf[80];

snprintf(buf,80,"\r\n*** Console %s // prev=``1 next=``2 list=``3 ***\r\n",myname);

char_dev_write_all(c->dev,strlen(buf),buf,NK_DEV_REQ_BLOCKING);
```

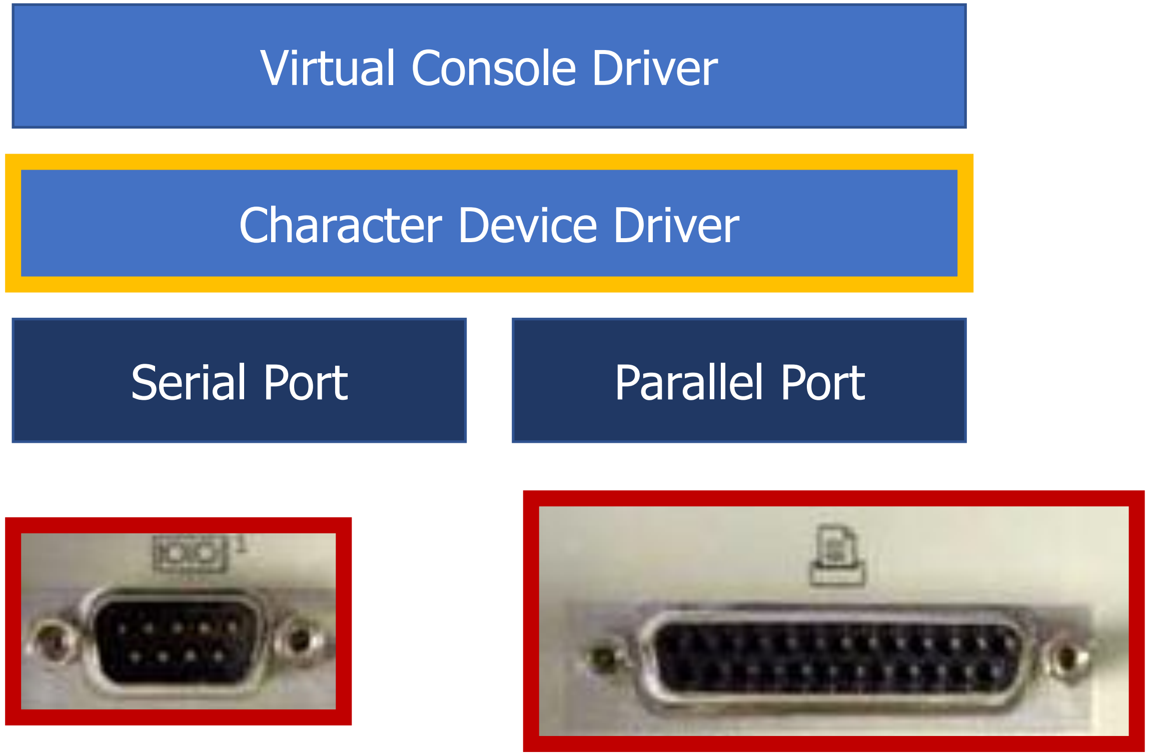
- Tries to write an entire string in blocking mode
  - Should not return until the entire string is displayed

Virtual Console implements by calling into nk_char_dev



```
static int char_dev_write_all(struct nk_char_dev *dev,
                              uint64_t count,
                              uint8_t *src,
                              nk_dev_request_type_t type) {
    uint64_t left, cur;
    left = count;
    while (left>0) {
        cur = nk_char_dev_write(dev,left,&(src[count-left]),type);
        if (cur == -1ULL) {
            return -1;
        } else {
            left-=cur;
        }
    }

    return 0;
}
```

Layering in Nautilus



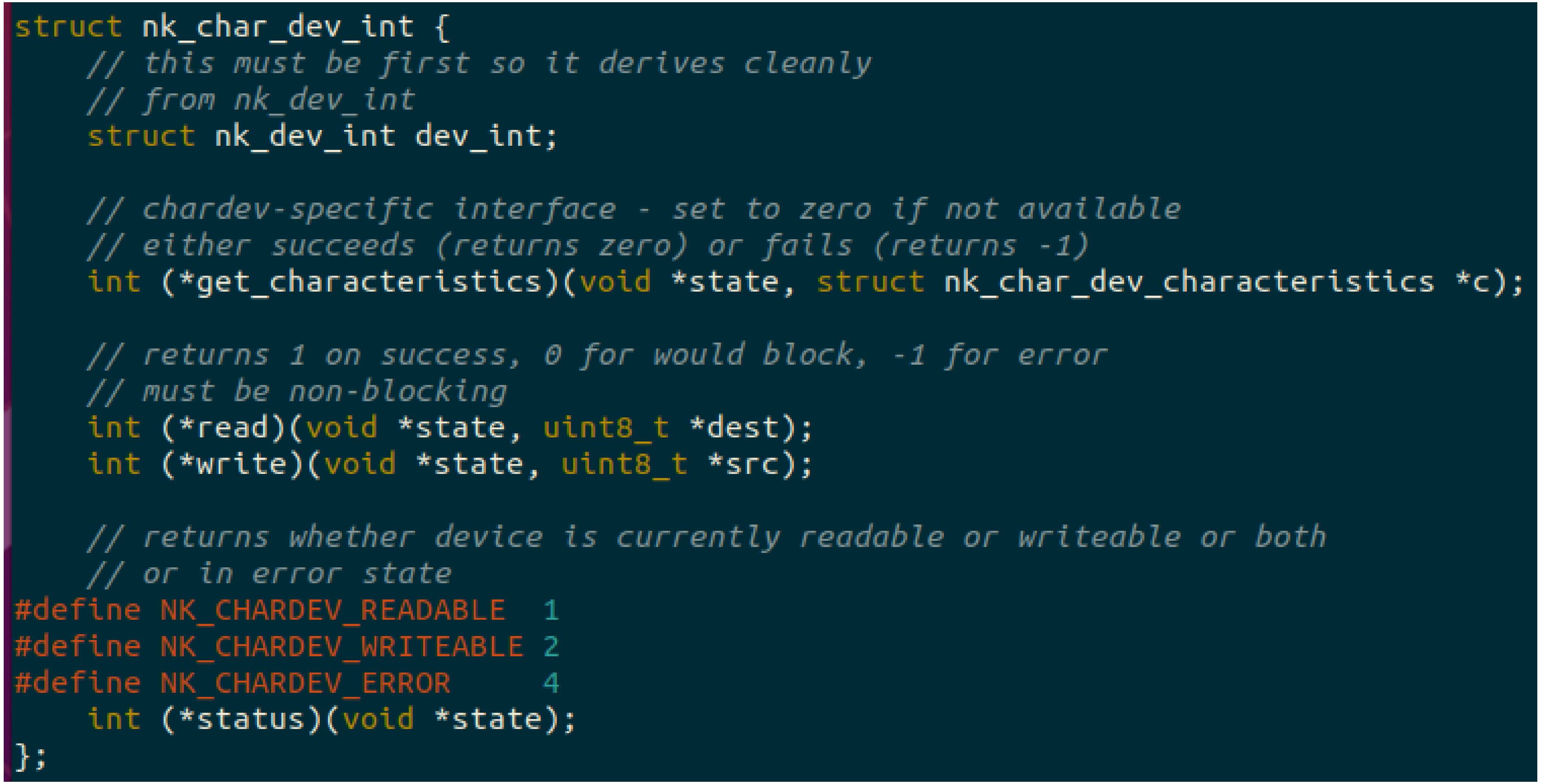
Virtual Console Driver

Character Device Driver

Serial Port

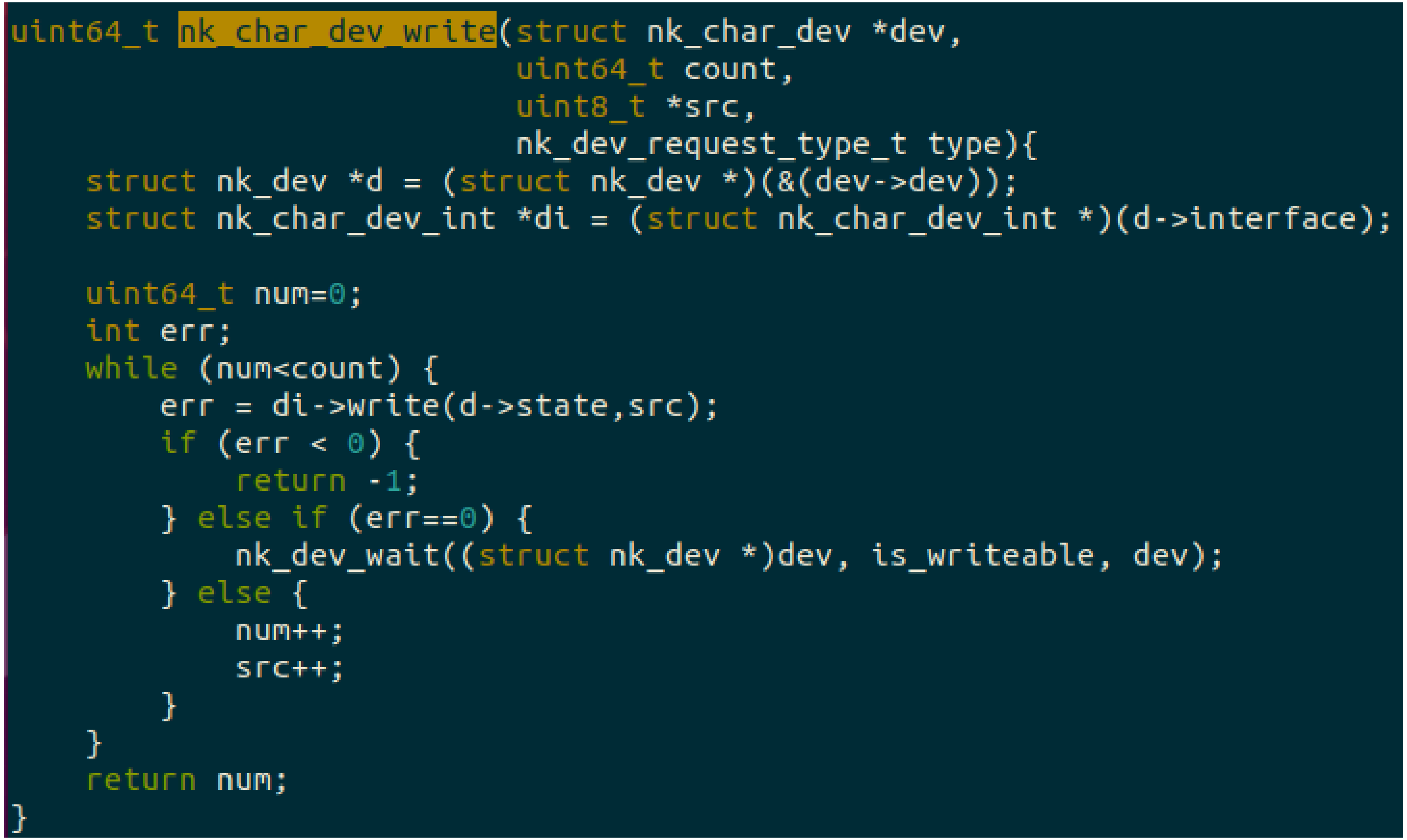
Parallel Port

Each nk_char_dev holds an interface of function pointers



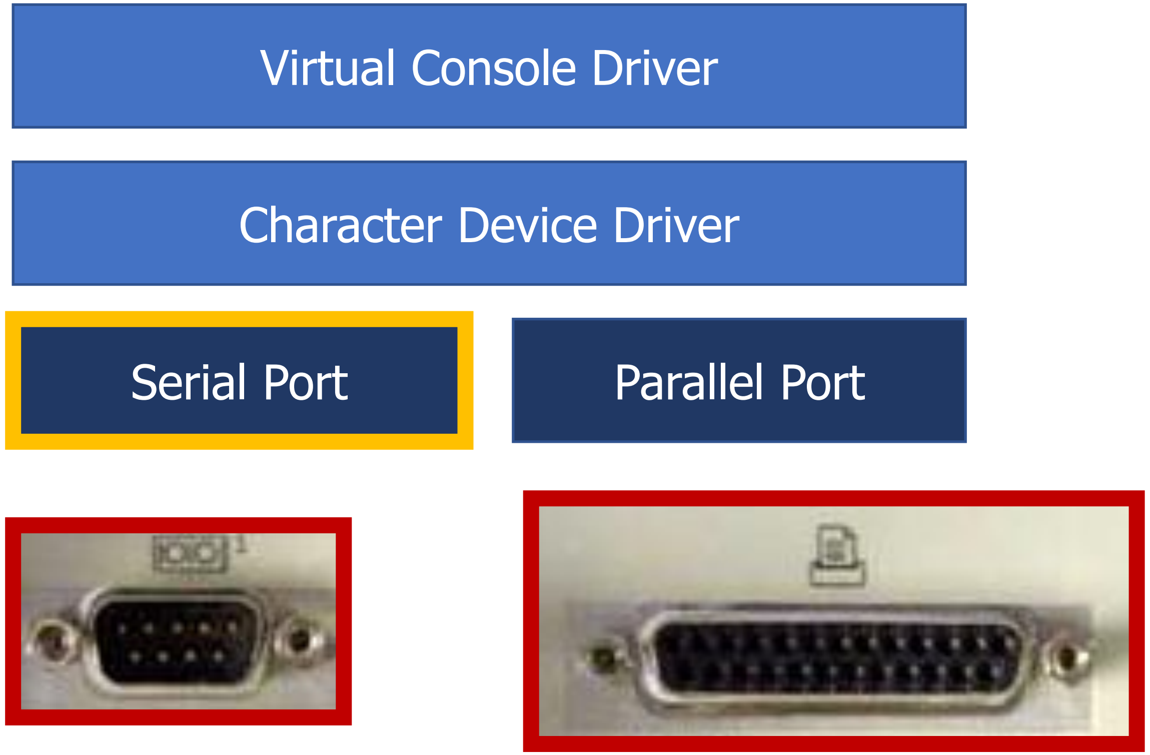
```c
struct nk_char_dev_int {
    // this must be first so it derives cleanly
    // from nk_dev_int
    struct nk_dev_int dev_int;

    // chardev-specific interface - set to zero if not available
    // either succeeds (returns zero) or fails (returns -1)
    int (*get_characteristics)(void *state, struct nk_char_dev_characteristics *c);

    // returns 1 on success, 0 for would block, -1 for error
    // must be non-blocking
    int (*read)(void *state, uint8_t *dest);
    int (*write)(void *state, uint8_t *src);

    // returns whether device is currently readable or writeable or both
    // or in error state
#define NK_CHARDEV_READABLE  1
#define NK_CHARDEV_WRITEABLE 2
#define NK_CHARDEV_ERROR     4
    int (*status)(void *state);
};
```

Simplified nk_char_dev_write: calls write() operation



```
uint64_t nk_char_dev_write(struct nk_char_dev *dev,
                           uint64_t count,
                           uint8_t *src,
                           nk_dev_request_type_t type){
    struct nk_dev *d = (struct nk_dev *)(&(dev->dev));
    struct nk_char_dev_int *di = (struct nk_char_dev_int *)(d->interface);

    uint64_t num=0;
    int err;
    while (num<count) {
        err = di->write(d->state,src);
        if (err < 0) {
            return -1;
        } else if (err==0) {
            nk_dev_wait((struct nk_dev *)dev, is_writeable, dev);
        } else {
            num++;
            src++;
        }
    }
    return num;
}
```

Layering in Nautilus



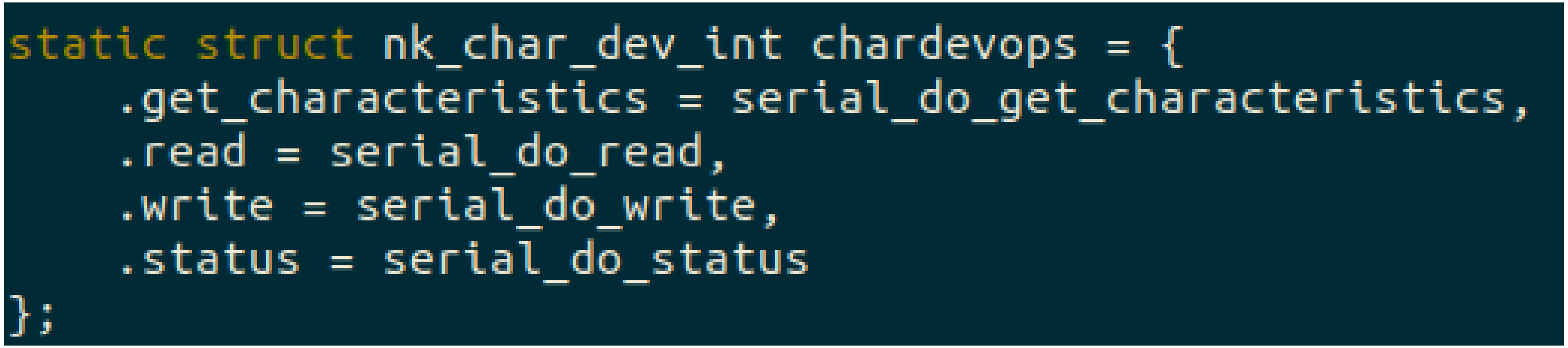
Virtual Console Driver

Character Device Driver

Serial Port

Parallel Port

A serial device implements the nk_char_dev operations

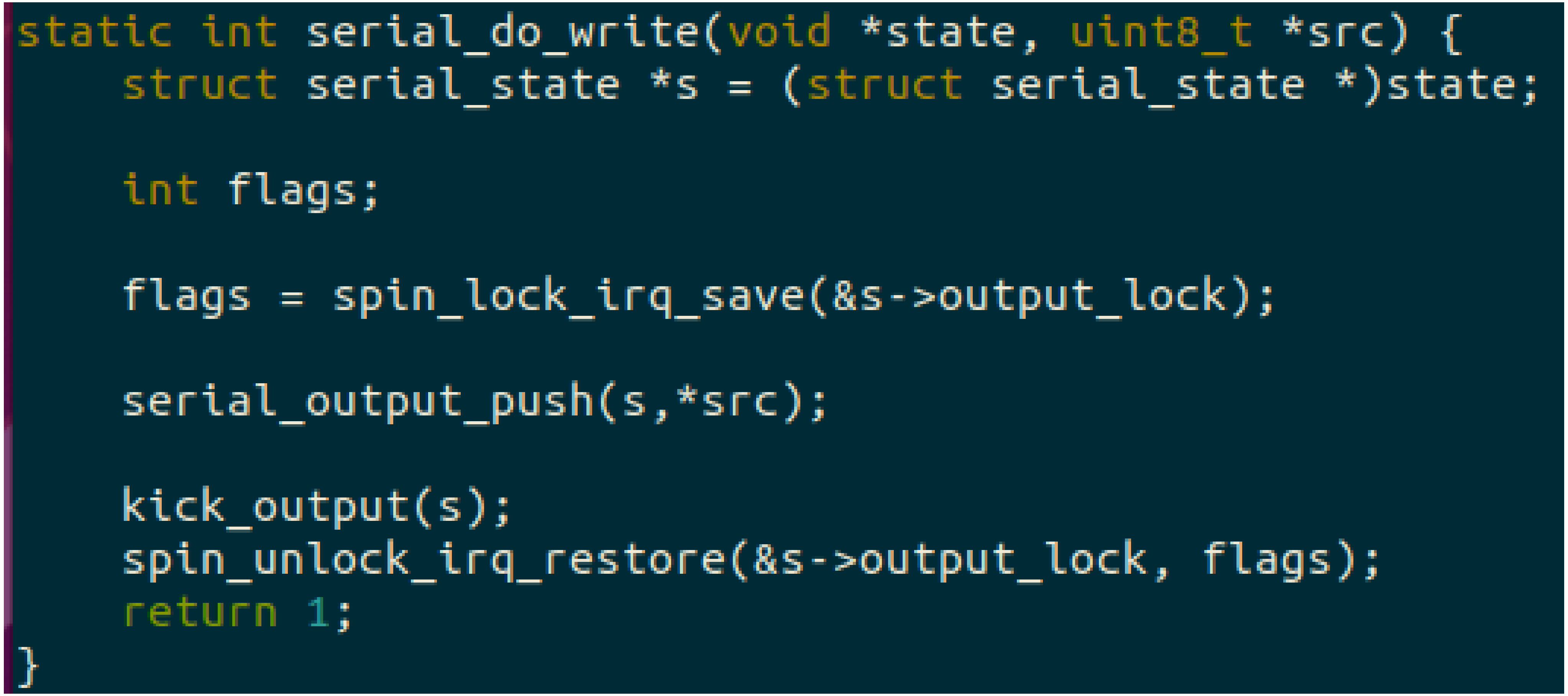


```
static struct nk_char_dev_int chardevops = {
    .get_characteristics = serial_do_get_characteristics,
    .read = serial_do_read,
    .write = serial_do_write,
    .status = serial_do_status
};
```

- Serial device implements all of those operations

- When you create a serial device, you actually make an `nk_char_dev` and initialize it with a `chardevops`
    - All of the generic device operations call into the actual serial device

Simplified Serial device: pushes data into a queue

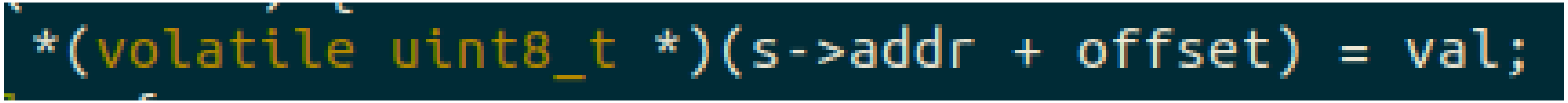


```
static int serial_do_write(void *state, uint8_t *src) {
    struct serial_state *s = (struct serial_state *)state;

    int flags;

    flags = spin_lock_irq_save(&s->output_lock);

    serial_output_push(s,*src);

    kick_output(s);
    spin_unlock_irq_restore(&s->output_lock, flags);
    return 1;
}
```

Serial queue operation

- Whenever a write comes in, we push data byte into a queue
  - Serial output goes slowly, so many bytes could be queued up

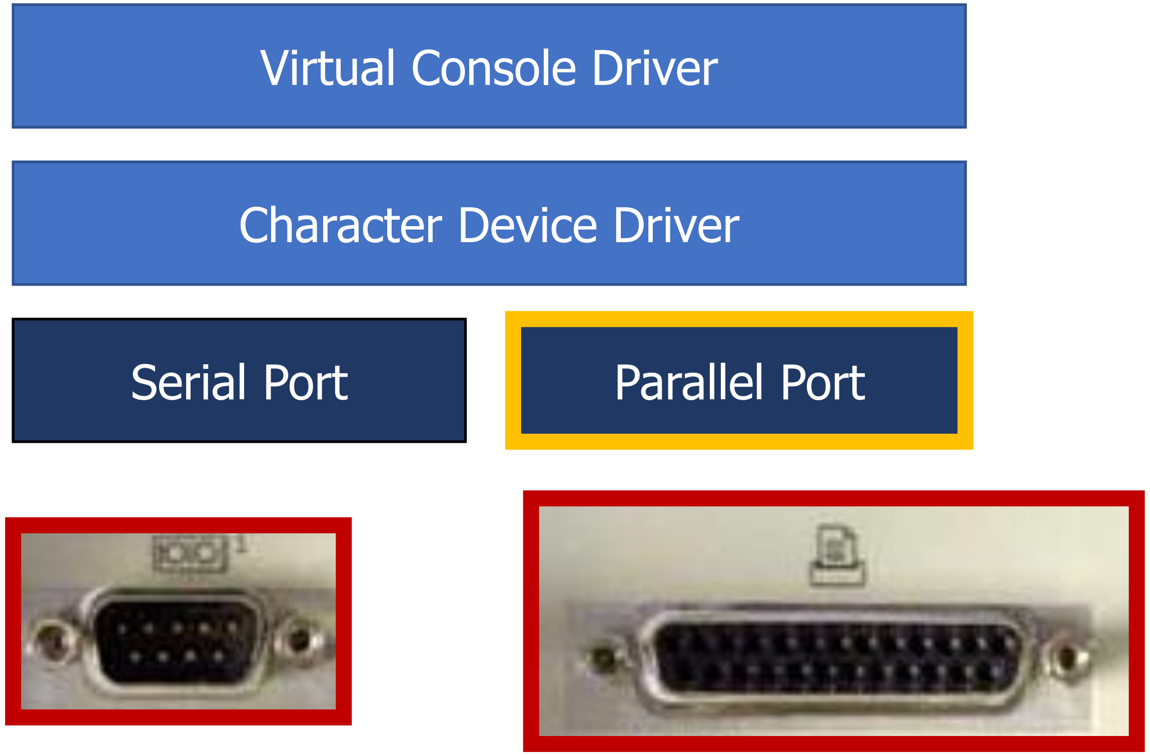
- Then we enable interrupts and write the first byte to the MMIO register



```
*(volatile uint8_t *)(s->addr + offset) = val;
```

- Then when an interrupt comes in, we pop the next byte from the queue and write it to the MMIO register
  - Repeats until the queue is empty

Layering in Nautilus



Parallel port will be implemented by you!

- A little simpler than the serial port version
  - Never queues bytes and instead only writes one at a time
  - Reject additional bytes while the system is in operation
  - Whenever an interrupt comes in, that byte is complete so you're ready for the next one

- Same idea though, parallel port supports all the basic operations of an `nk_char_dev`
  - When initialized, creates an `nk_char_dev` connected to its operations

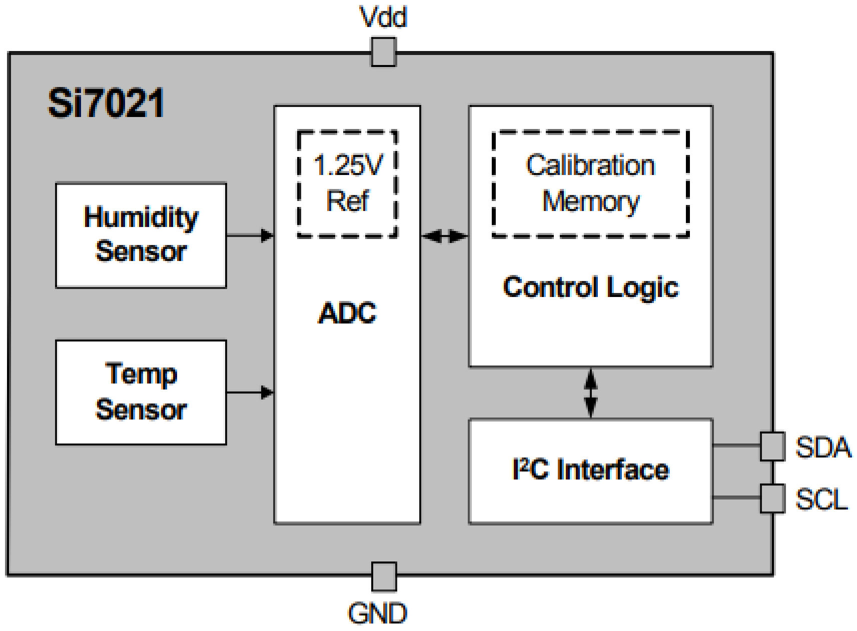
Outline

- Abstractions
- Device I/O layers
  - Application Layer
  - Kernel I/O Subsystem
  - Device Driver
  - Interrupt Handler
- Example Driver: Nautilus Character Device
- **Example Driver: Temperature Sensor**

Si7021 temperature and humidity sensor

- Popular on embedded devices
  - Also has a Linux driver!

- Connects to computer over I^{2}C bus
  - Two-wire, 100 Kbps low-power bus
  - Like any other bus
    - Takes an address
    - Whether it's a read or write transaction
    - And an amount of data



- https://www.silabs.com/documents/public/data-sheets/Si7021-A20.pdf

How do we make it do anything?

- Typically with I^{2}C devices, you write a 1-2 byte command
  - Then you read the data in the next transaction
  - Commands are found in the datasheet

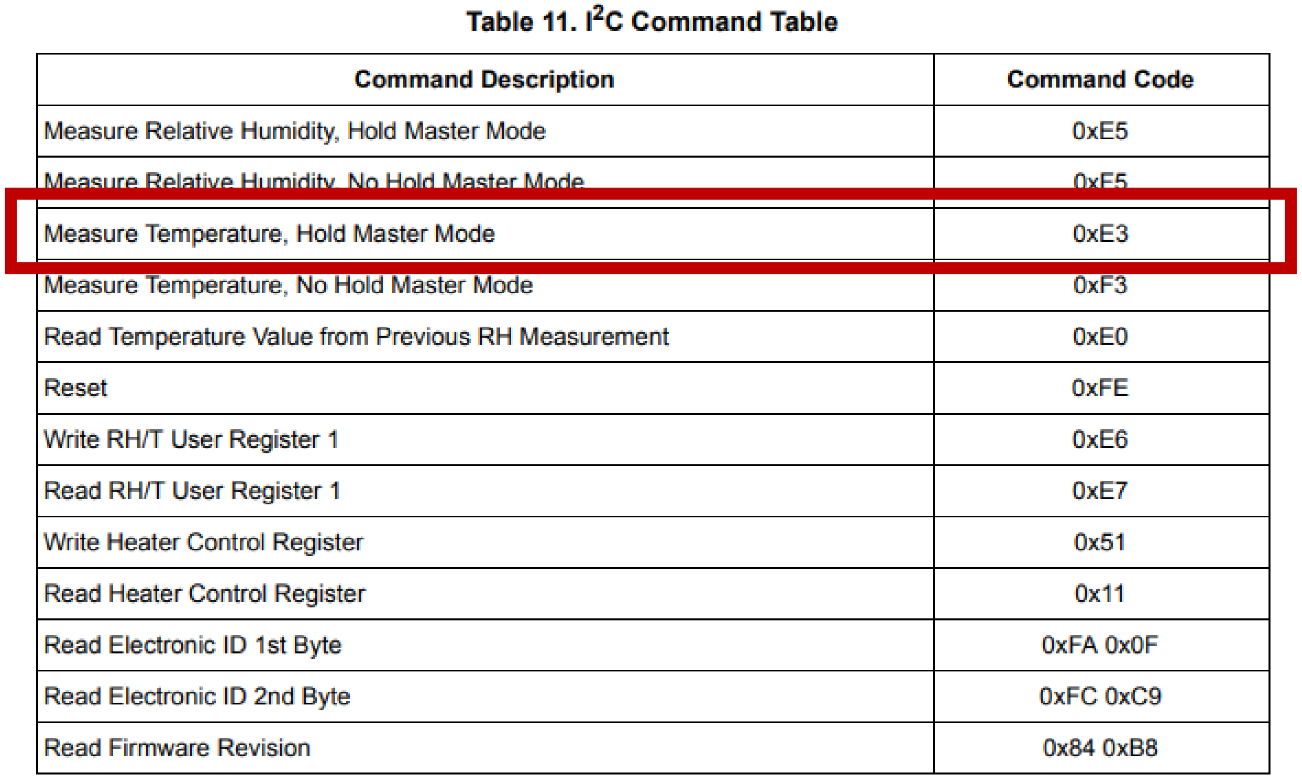


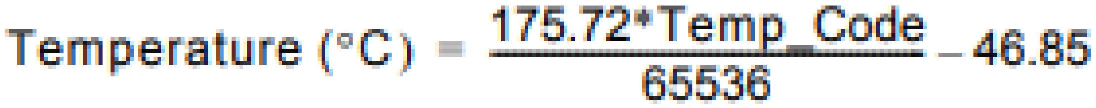
Table 11. I^{2}C Command Table

Command Description	Command Code
Measure Relative Humidity, Hold Master Mode	0xE5
Measure Relative Humidity, No Hold Master Mode	0xF5
Measure Temperature, Hold Master Mode	0xE3
Measure Temperature, No Hold Master Mode	0xF3
Read Temperature Value from Previous RH Measurement	0xE0
Reset	0xFE
Write RH/T User Register 1	0xE6
Read RH/T User Register 1	0xE7
Write Heater Control Register	0x51
Read Heater Control Register	0x11
Read Electronic ID 1st Byte	0xFA 0x0F
Read Electronic ID 2nd Byte	0xFC 0xC9
Read Firmware Revision	0x84 0xB8

What will the driver look like?

- Layer below it will be I^{2}C controller (function calls)

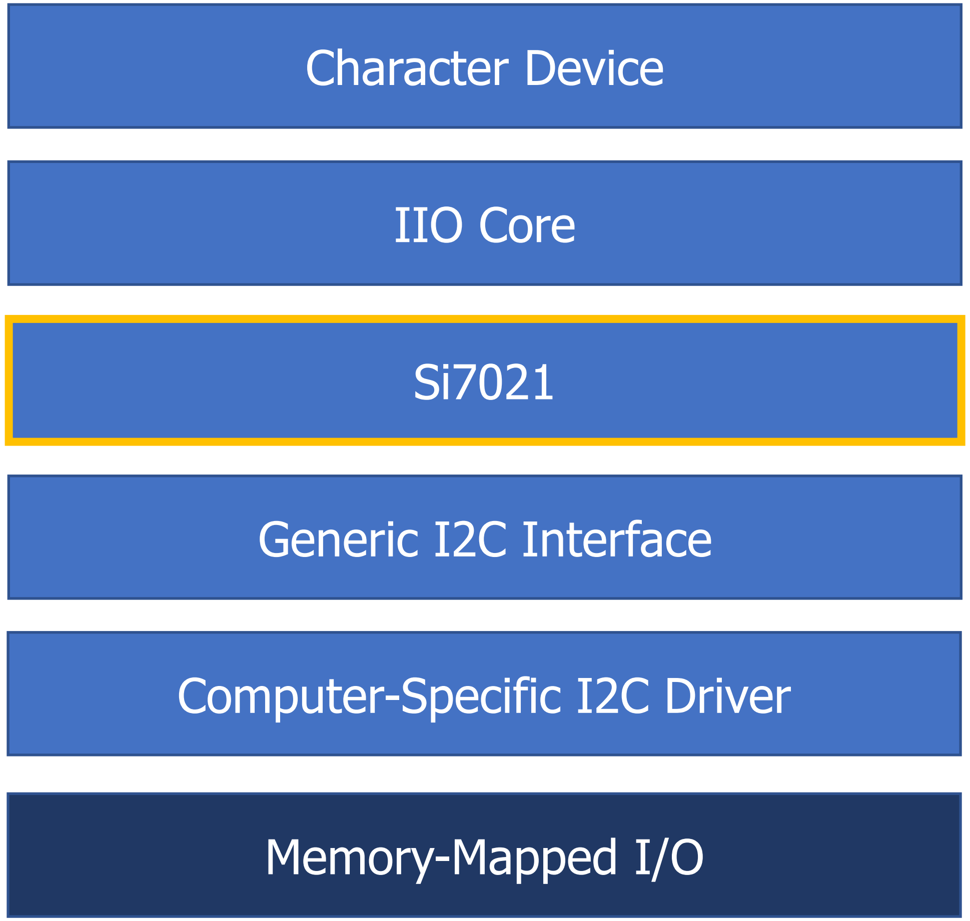
- In the Temperature driver we need to
  - See what the request from the layer above is
  - Perform an I^{2}C write transaction with a command byte (0xE3)
  - Wait until data is ready
  - Perform an I^{2}C read transaction to get the data
  - Translate the data into meaningful units



$$\text{Temperature } (^\circ\text{C}) = \frac{175.72 * \text{Temp\_Code}}{65536} - 46.85$$

What are the driver layers going to be?

- In Linux, some sensors are connected through the Industrial I/O subsystem (IIO)
  - Handles sensor data generically
    - Get raw sample
    - Get scaling value
    - Get offset value
- Lower layers could change and everything would still work
  - USB->I2C converter for example
  - Or a totally different sensor



Demo: Linux device driver code for Si7021

https://github.com/torvalds/linux/blob/master/drivers/iio/humidity/si7020.c

- Linux source code is all on Github!

But if you want to explore Linux code, a better link is:
https://elixir.bootlin.com/linux/latest/source/drivers/iio/humidity/si7020.c

- Creates linked databases for function calls and variable types
    - Lists where it is defined
    - Lists where it is used
- Makes it easy to hop up and down layers

OSes can make design choices about drivers

- Interface does not have to be like a file
  - For example: could have a set of unique syscalls for each device
- Asynchronous model could be enforced
  - Must register callback handlers with lower layer to get response
- Tock embedded operating system does both of these
  - https://www.tockos.org/

Demo: Tock device driver code for Si7021

https://github.com/tock/tock/blob/master/capsules/extra/src/si7021.rs

Outline

- Abstractions

- Device I/O layers
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- Example Driver: Nautilus Character Device

- Example Driver: Temperature Sensor