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I/O and peripherals

Advanced Operating Systems

Vittorio Zaccaria | Politecnico di Milano | '25/26

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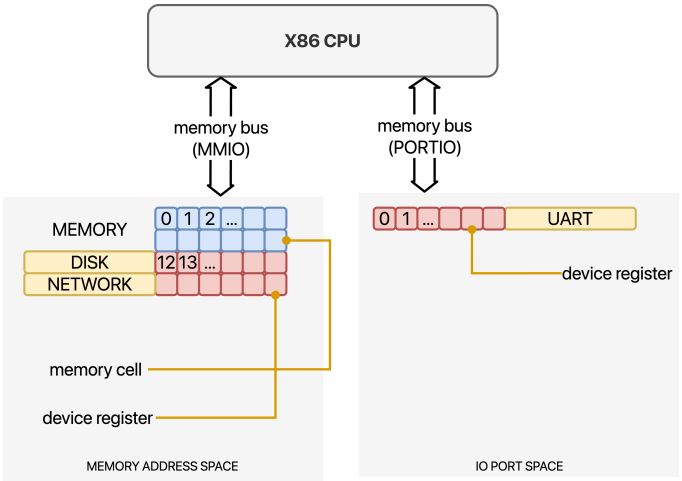
System architecture and IO

Introduction

A **bus** is a connection channel between the CPU and the peripherals.

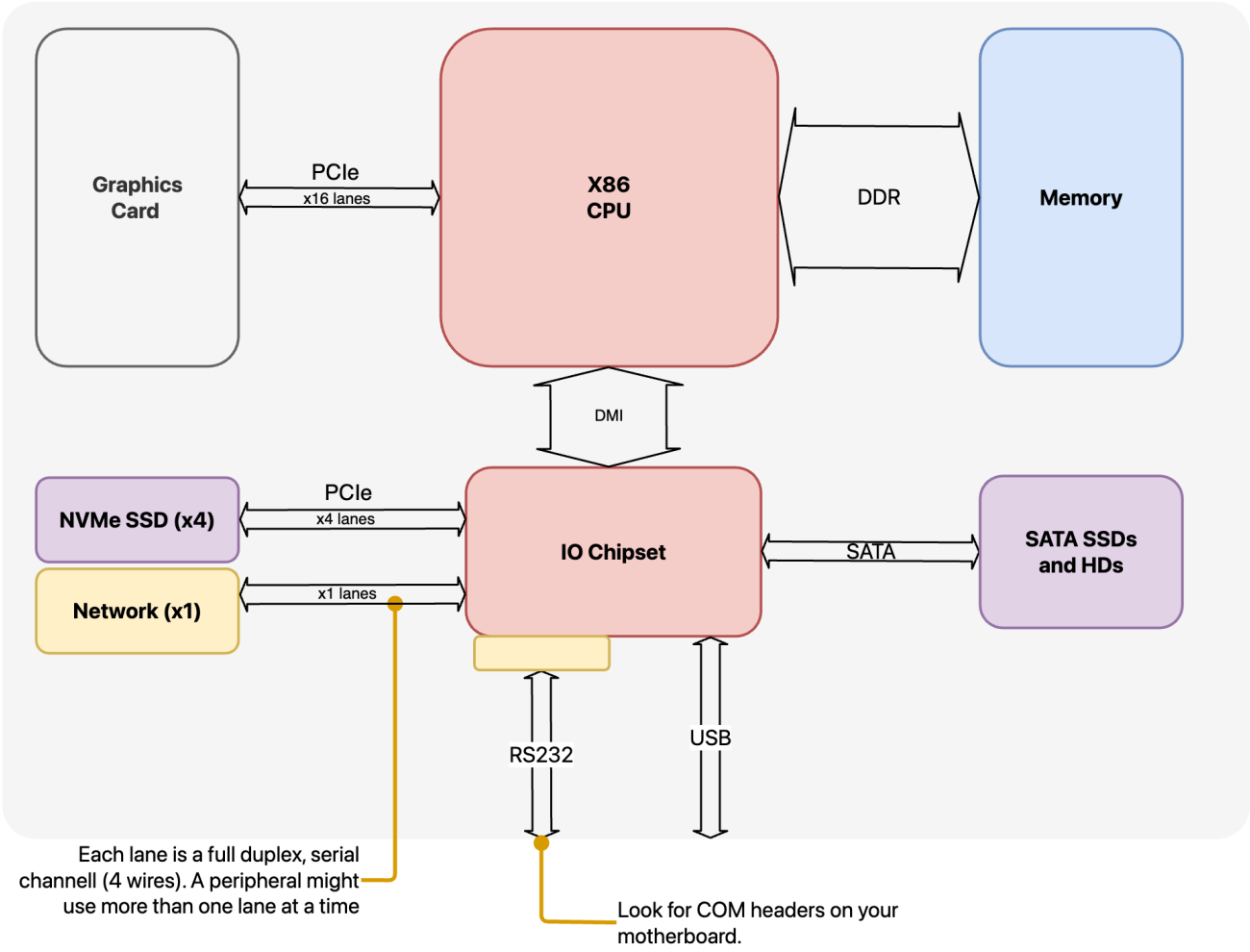
Communication between the CPU and devices can happen over two buses, the **memory bus** and the **port bus**.

- **Memory bus**: Communication happens through loads and stores; here device registers to send/receive data are exposed as memory addresses on the address space of the CPU. This is also called **Memory-mapped IO**.
- **Port bus**: Uses special instructions and special addressing modes (*port indices*). This is called **Port-based IO**.



Introduction

Modern system device architecture (intel Z270 motherboard)



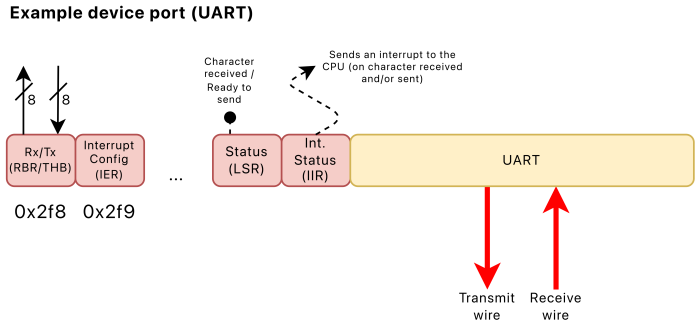
CPU to device communication

Port I/O Instructions

- Port bus I/O operations are done through **special I/O instructions**.
- Some devices are assigned a `port` number in the I/O address space which names the device and must be used with the instructions
- For example on `intel` you use the `in` and `out` (**privileged**)

Port I/O Instructions

Example: legacy x86 systems have a universal asynchronous receiver-transmitter (UART) whose register indices start on the port bus at 0x2f8.



To read a character received through the receive wire, you would use the following assembly code.

```
in RBR, %al   ;; RBR = 0x2f8
```

Port I/O Instructions » Available ports

```
% cat /proc/ioports
0000-0cf7 : PCI Bus 0000:00
  0000-001f : dma1
  0020-0021 : pic1
  0040-0043 : timer0
  0050-0053 : timer1
  0060-0060 : keyboard
  0064-0064 : keyboard
  0070-0071 : rtc0
  0080-008f : dma page reg
  00a0-00a1 : pic2
  00c0-00df : dma2
  ...
  03f8-03ff : serial
```

Memory-mapped IO

- I/O operations done implicitly through loads/stores
- Hardware makes device registers available as if they were memory locations.

Memory-mapped IO

Gained importance as `in` / `out` instructions are inefficient and limited in their use of registers. Additionally, there is a restriction of only 2^{16} port numbers.

In fact, devices registers can operated on with loads/stores to specific physical addresses (also called memory mapped registers).

Here we are writing `0x80` into a device register positioned at address `0xc0100`:

```
volatile int32_t *device_control
        = (int32_t *) (0xc0100);
*device_control = 0x80;
```

Memory-mapped IO » Available mapped devices

Example, the ethernet device e1000

```
% cat /proc/iomem
...
08000000-febfffff : PCI Bus 0000:00
  ...
  feb80000-feb9ffff : 0000:00:03.0
    feb80000-feb9ffff : e1000
...
```

Device to CPU communication

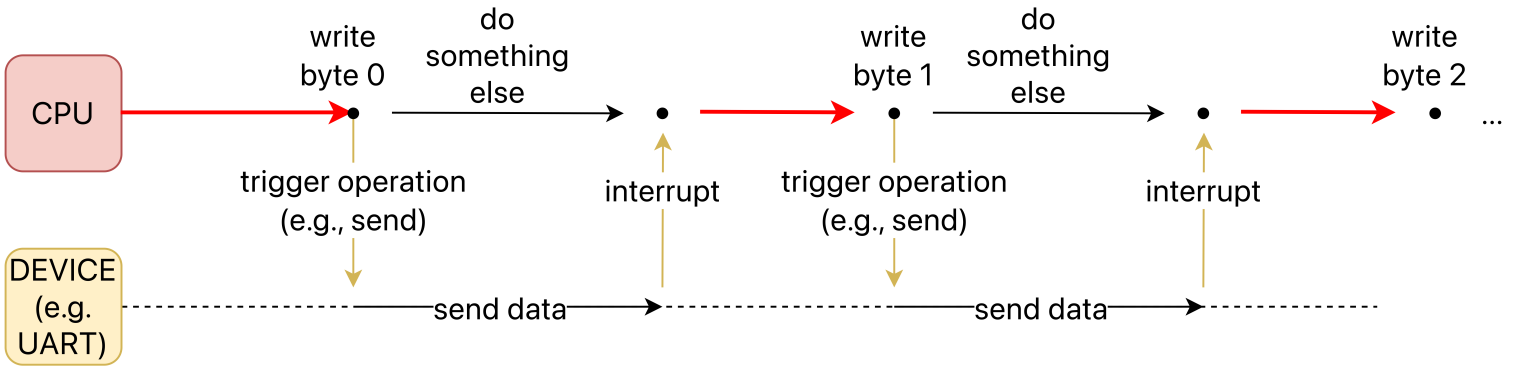
Polling

- Polling is a method of interaction with devices where the processor waits until the device requires attention.
- This can result in wasted processor cycles if the device is slow, but it is inexpensive if the device is fast.

```
// Here we are using in/out instructions
// to wait until the UART is ready to send;
while((inb(LSR) & RDY)==0) ;
outb(c, THR); // send character
```

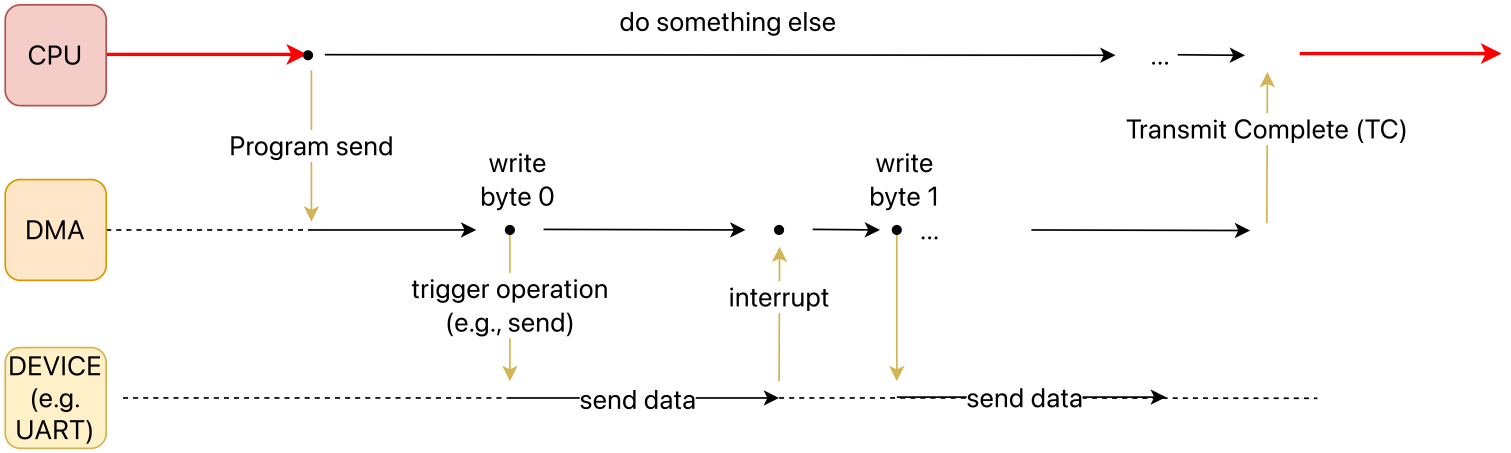
Interrupts

- Instead of polling the device repeatedly, the OS can issue a request, put the calling process to sleep, and context switch to another task.
- When the device is finally finished with the operation, it will raise a **hardware interrupt**, causing the CPU to jump into the OS at a predetermined **interrupt service routine (ISR)** or more simply an **interrupt handler**.



DMA

The fundamental concept behind DMA is the introduction of an additional device (DMA controller) that can manage transfers between different devices and memory autonomously, without requiring the CPU's involvement.



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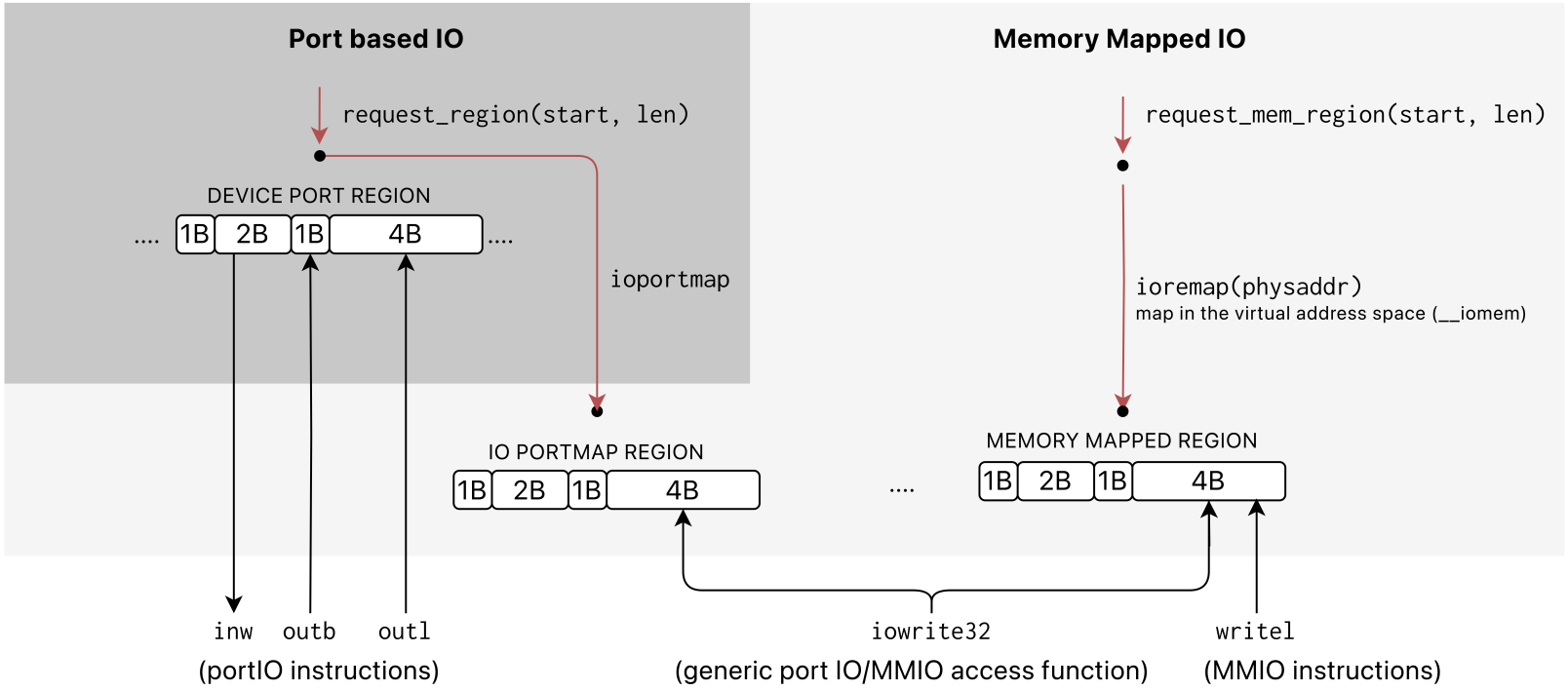
Linux low level programming

Low level IO

Requesting access to devices



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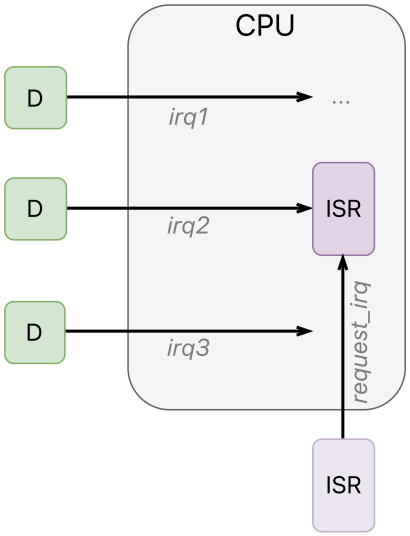
Interrupt management

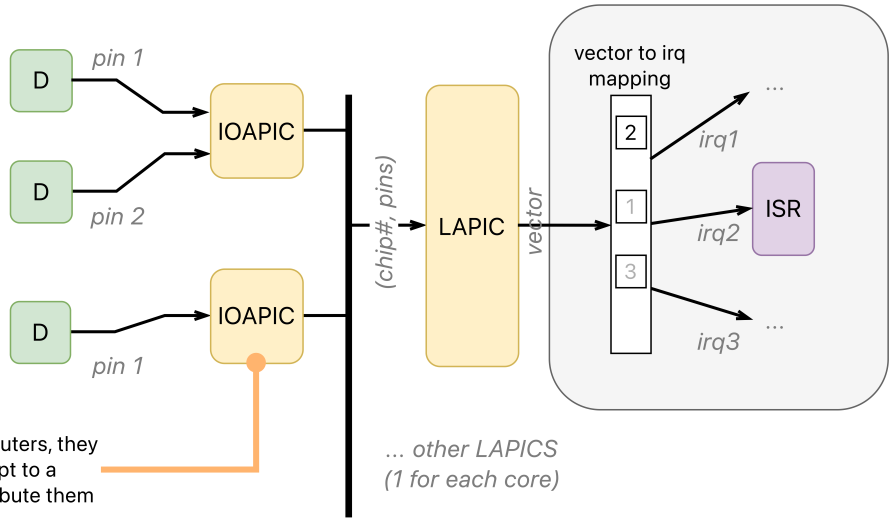
Interrupt flow

Ideal



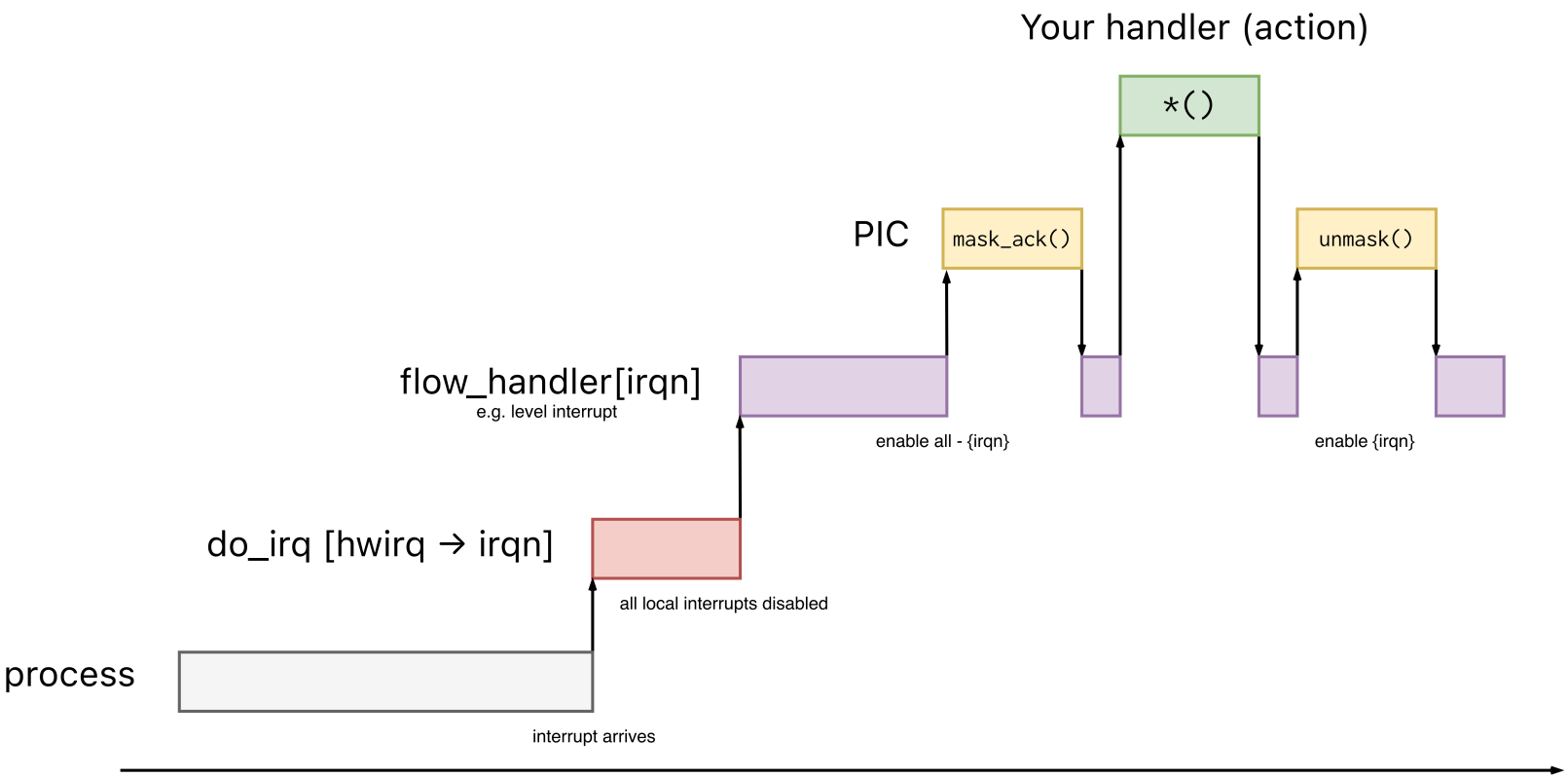
IRQs belong to a global Linux namespace. They are assigned by Linux to each interrupt in the system.

Real (x86)



Linux must configure intermediate interrupt controllers which know only their own numbering of interrupts so that it knows which ISR to invoke as soon as possible

Interrupt flow



Interrupt flow » Registering an action

```
static irqreturn_t handler(int irq, void *mydata) {
  ...
  // acquire locks on shared data
  // read/write from peripherals through MMIO
  // defer work
  // release lock
  return IRQ_HANDLED;
}

static int __init mydriver_init_module(void) {
  ret = request_irq(MY_IRQN, handler, 0, NULL);
  ...
}
```

Interrupt management » Deferring work

Idea

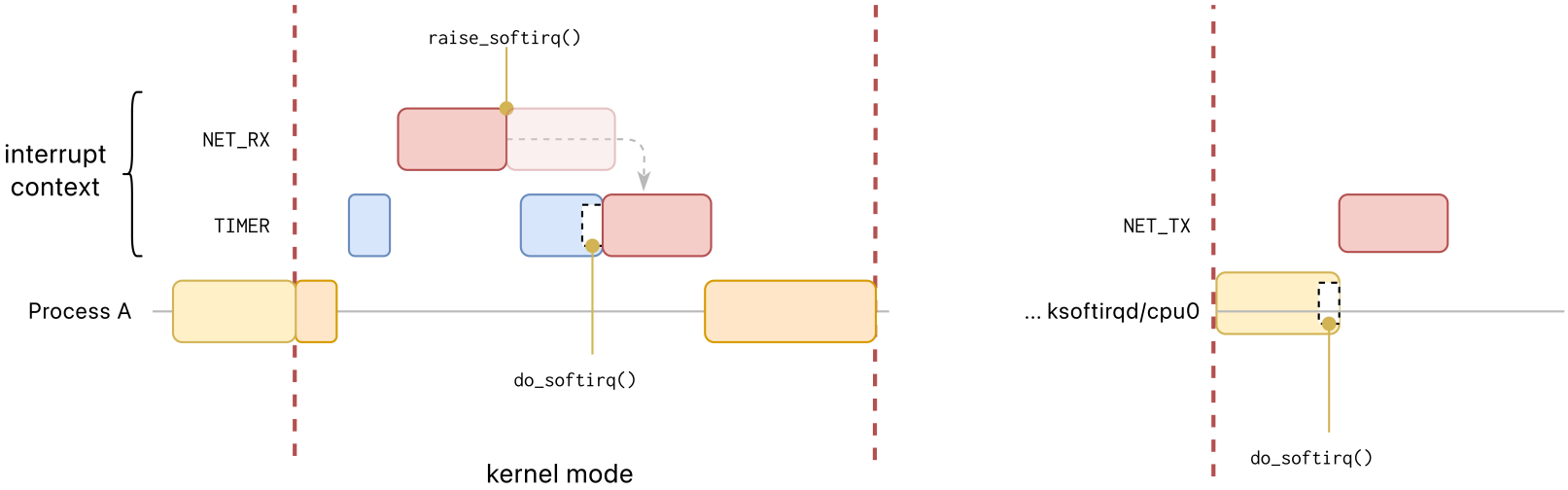
Move the non-critical management of interrupts to a later time to

- Improve responsiveness
- Benefit from aggregation (many small operations merged into a single one)

Implemented by splitting interrupts into two parts:

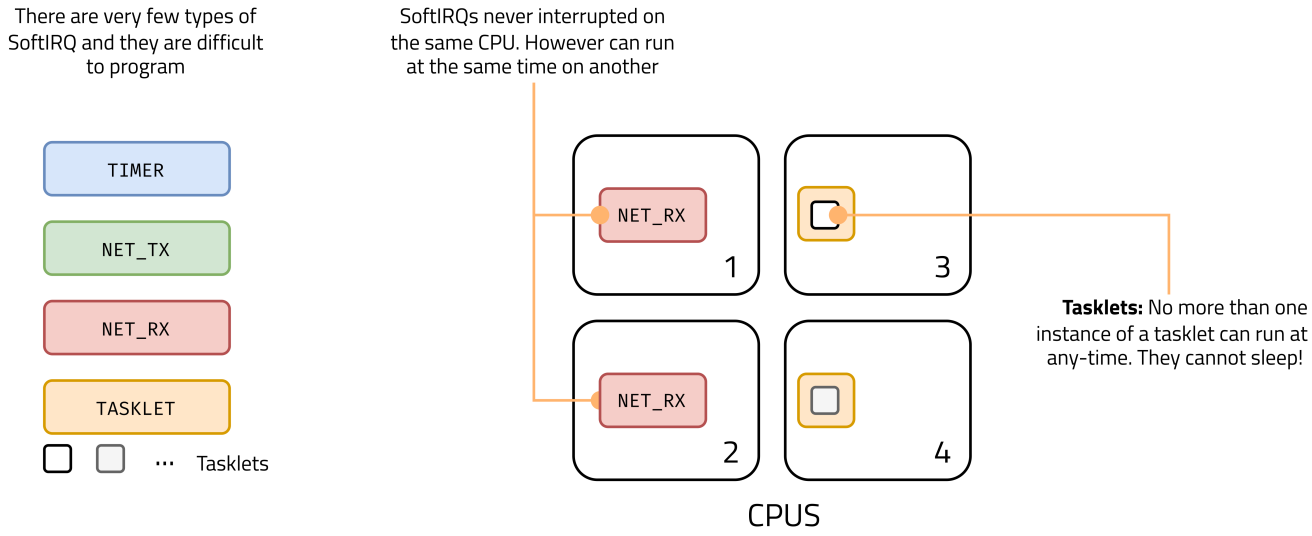
- **Top half**: executes a minimal amount of work which is mandatory to later finalize the whole interrupt management.
  - Works in a **non-interruptible** context.
  - Schedules some deferred work (**deferred functions**) through the SoftIRQs infrastructure.
- **Bottom half**: Finalizes the work specified by the SoftIRQs at particular **reconciliation points** in time.

SoftIRQs


raise_softirq()
interrupt context
NET_RX
TIMER
Process A
do_softirq()
kernel mode
NET_TX
... ksoftirqd/cpu0
do_softirq()

Tasklets

Tasklets are a way to exploit SoftIRQs with ease. They have a simpler interface and kernel ensures no more than one instance of them is running concurrently. It is a a one-shot deferral scheme: If you schedule two, only one is ran.



Tasklets

A tasklet is a pointer to a function plus some data; it is represented by the kernel with a list of `tasklet_struct`

```
struct tasklet_struct {
  struct tasklet_struct *next;
  unsigned long state; /* 0, scheduled or running */
  ...
  void (*func)(unsigned long);
  unsigned long data;
};
...
DECLARE_TASKLET(my_tasklet, my_tasklet_handler, my_data);
...
tasklet_schedule(&my_tasklet); // this is invoked by the interrupt handler to
```

Work queues

- What if your deferred action must block? I.e., allocate a lot of memory, obtain a semaphore, or perform block I/O.
- Use a **work queue** which is a schedulable entity that runs in process context to execute your bottom half.
- General mechanism to submit work to a **worker kernel thread** (`events/n`)

To create work for the `events/n` thread:

```
DECLARE_WORK(work, void (*func)(void *), void *data);
```

To enqueue it:

```
schedule_work(&work);
```

Timers

The `hrtimer` subsystem provides precise, high-resolution software timers for kernel use. It enables sub-millisecond timing, suitable for real-time tasks.

```
struct hrtimer my_timer;
static enum hrtimer_restart my_timer_callback(struct hrtimer *timer) {
        // Optional if you want to repeat it
        hrtimer_forward_now(timer, ms_to_ktime(100));
        return HRTIMER_RESTART;
        // otherwise
        // return HRTIMER_NORESTART;

}

my_timer.function = my_timer_callback;
hrtimer_init(&my_timer, CLOCK_MONOTONIC, HRTIMER_MODE_REL);
hrtimer_start(&my_timer, ms_to_ktime(50), HRTIMER_MODE_REL);
```

Flags:

- `HRTIMER_MODE_REL/ABS` Timer expires after a *relative* interval from the moment it's started or at an absolute time
- `CLOCK_REALTIME / CLOCK_MONOTONIC` Choose between wallclock time or a monotonic time reference.

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Linux Device management

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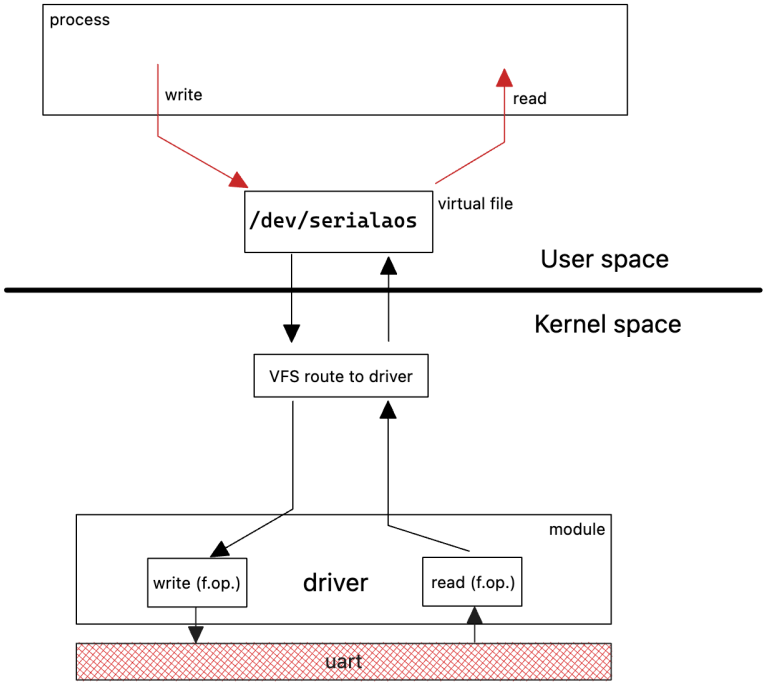
Introduction to devices in Linux

Device categories

- Devices are divided into three categories:
  - A **character device** is characterized by a **character stream**. Writing or reading from the file has **direct impact on the device itself**; no buffering is performed
  - A **block device** is seen as a sequence of numbered blocks. Each block can be individually addressed and accessed through a cache (random access).
  - A **network device**, essentially a sequence of packets.

Device special files

- Linux integrates devices into the file system as **special files**
- Each device is assigned a path name, usually in `/dev`. For example, if you had a uart device named 'serialaos' 🙂, this would be assigned the file `/dev/serialaos`.



Device major and minor numbers

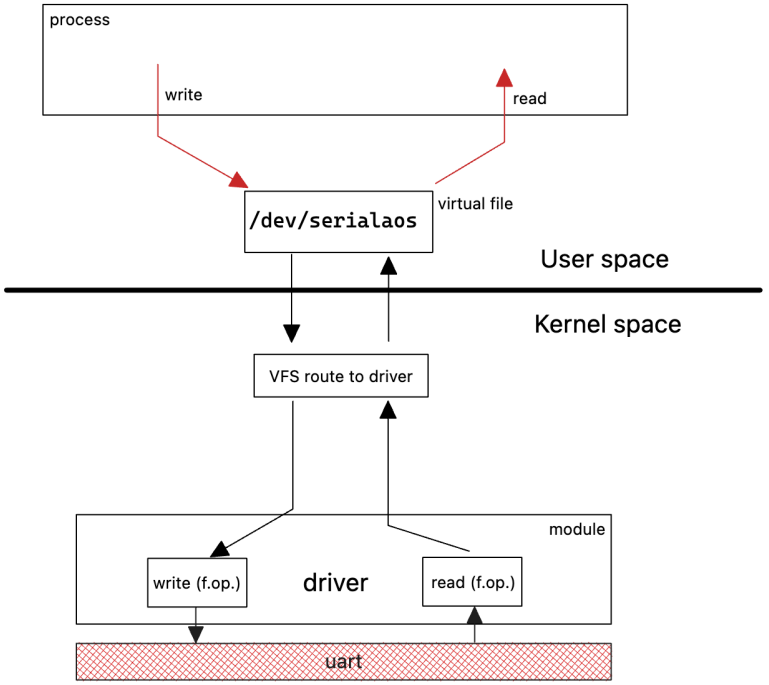
- Each driver has what is called a **major device number** that serves to identify it.
- If a driver supports multiple devices, say, two disks of the same type, each disk has a **minor device** number that identifies it.
- Example (same driver, different disks or partitions)

```
ls -l /dev/sd*
#                     +--- major
#                     V  V--- minor
brw-rw---- 1 root disk 8, 1  9 apr 09.31 /dev/sda1
brw-rw---- 1 root disk 8, 2  9 apr 09.31 /dev/sda2
```

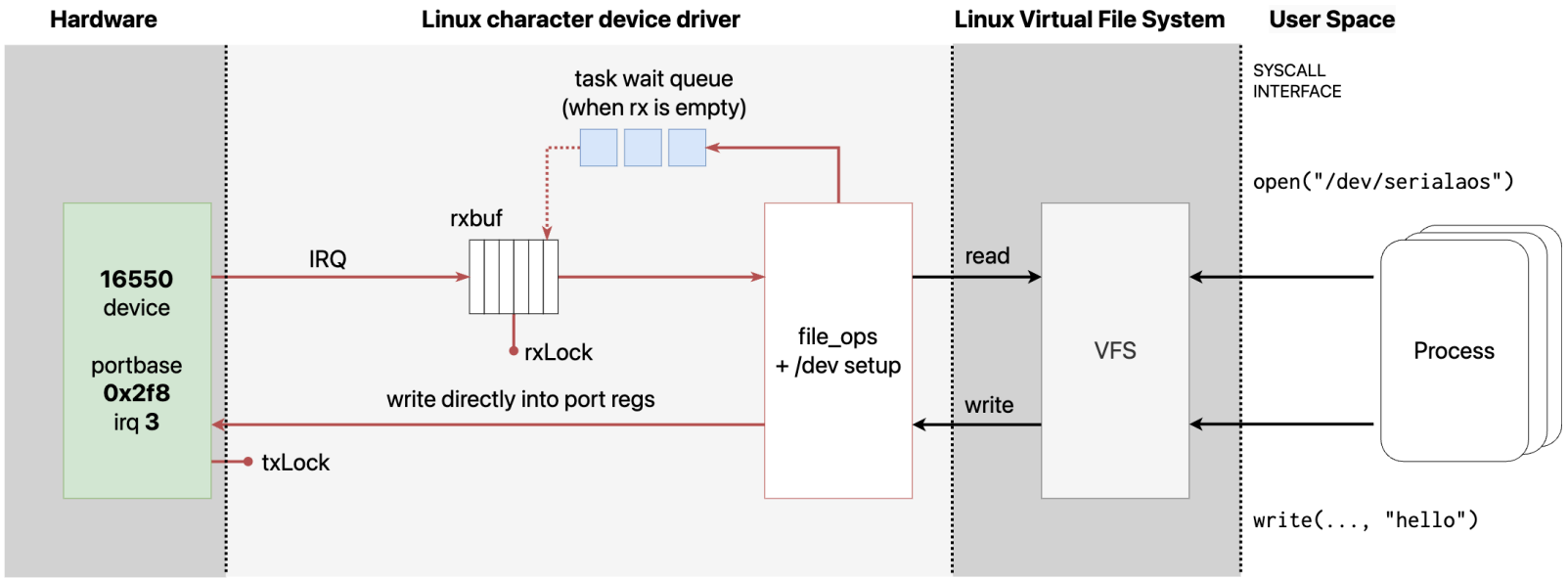
Low level device management » Char devices

Low level driver interface

```
struct file_operations {
 ...

 ssize_t (*read)
    (struct file *, char *,...);

 ssize_t (*write)
    (struct file *, char *,...);

 int (*open)
    (struct inode *, struct file *);

 ...
}
```



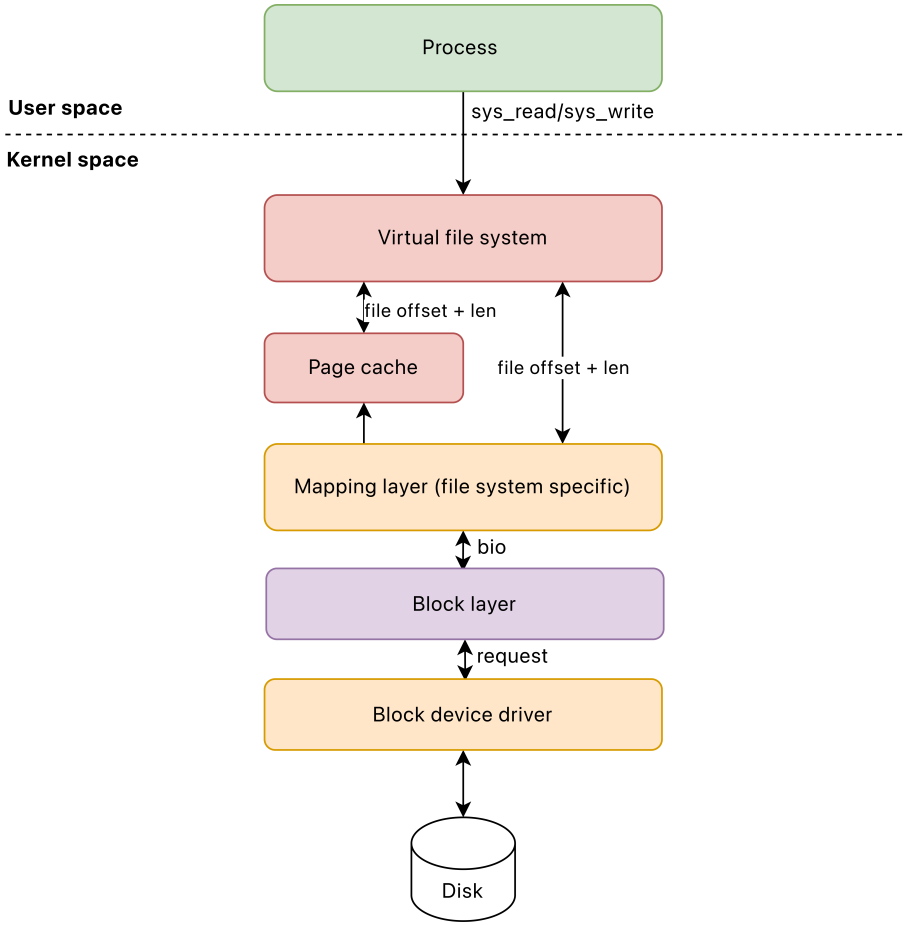
Low level driver interface » Hands-on lab topics



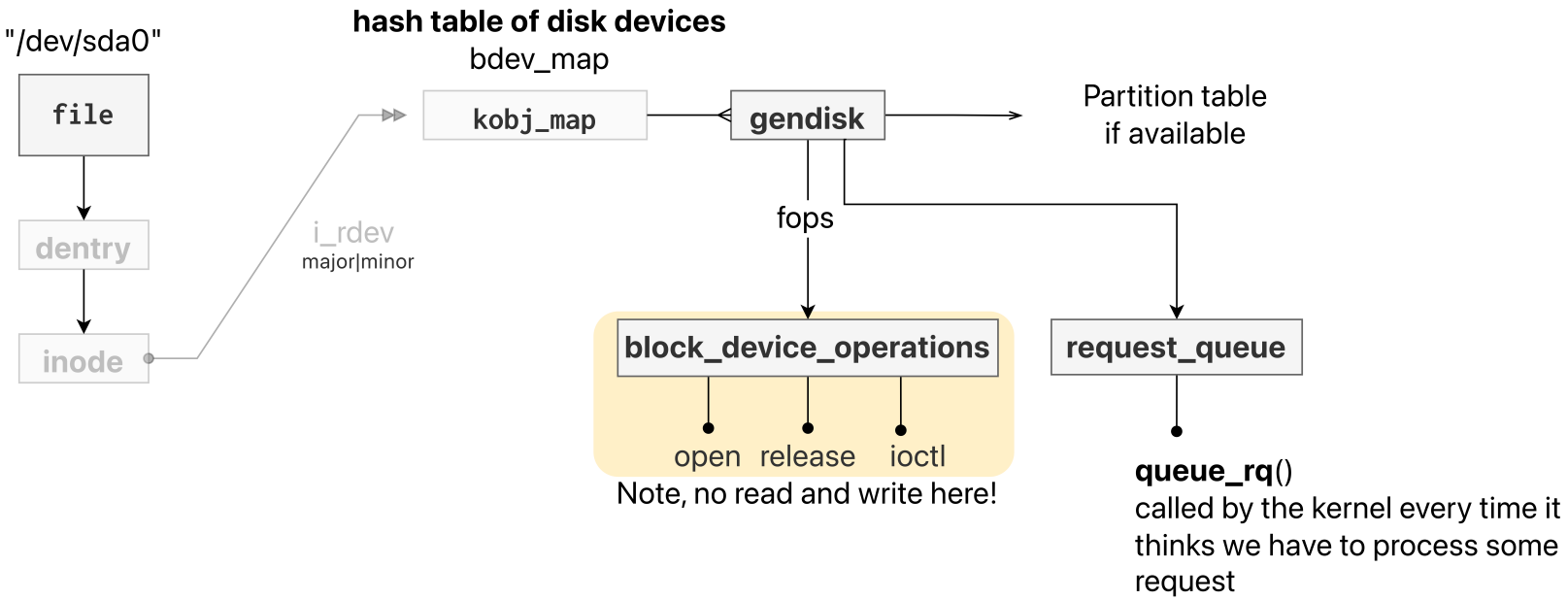
Serialaos driver as implemented during the lab, using only low-level character device primitives

Low level device management » Block devices

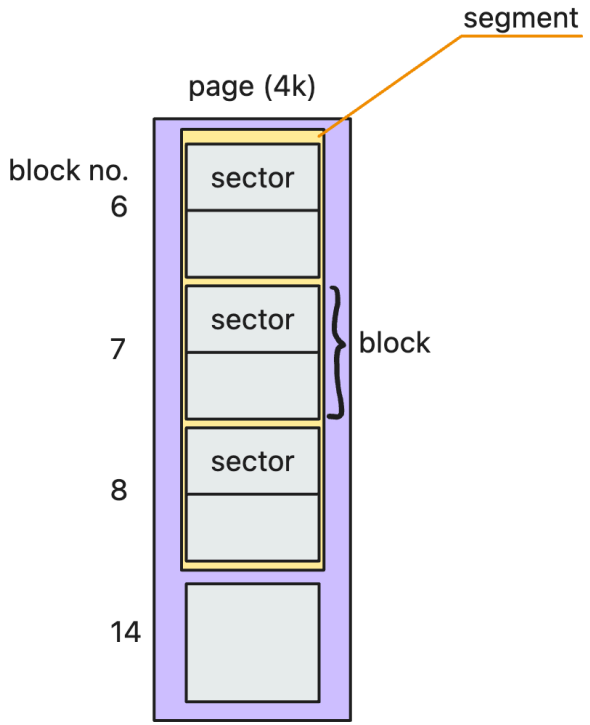
Introduction



Low level driver interface



Page cache to Block requests



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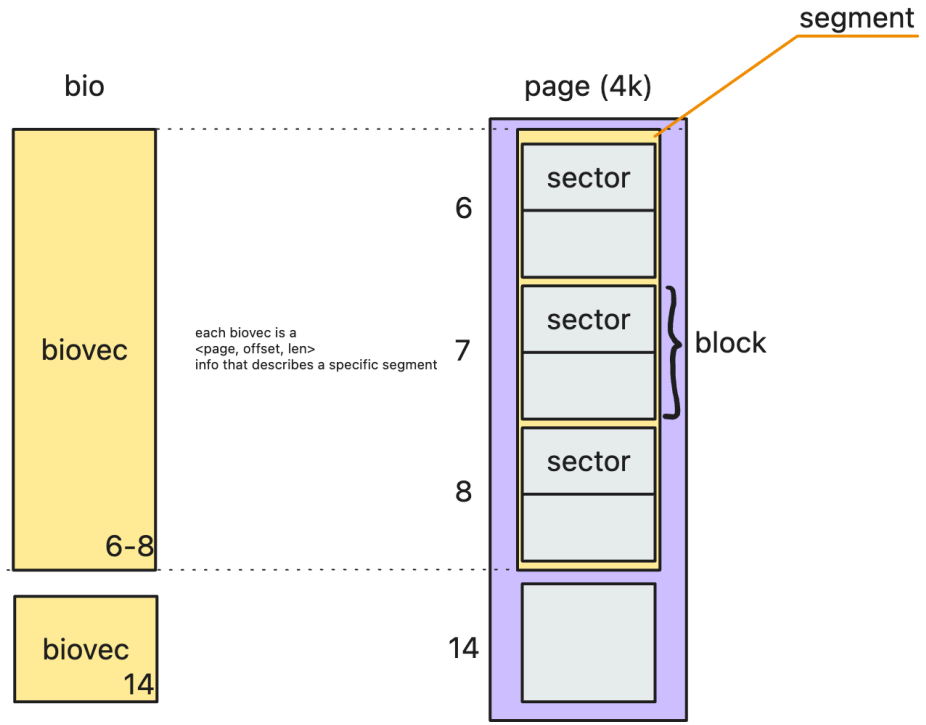
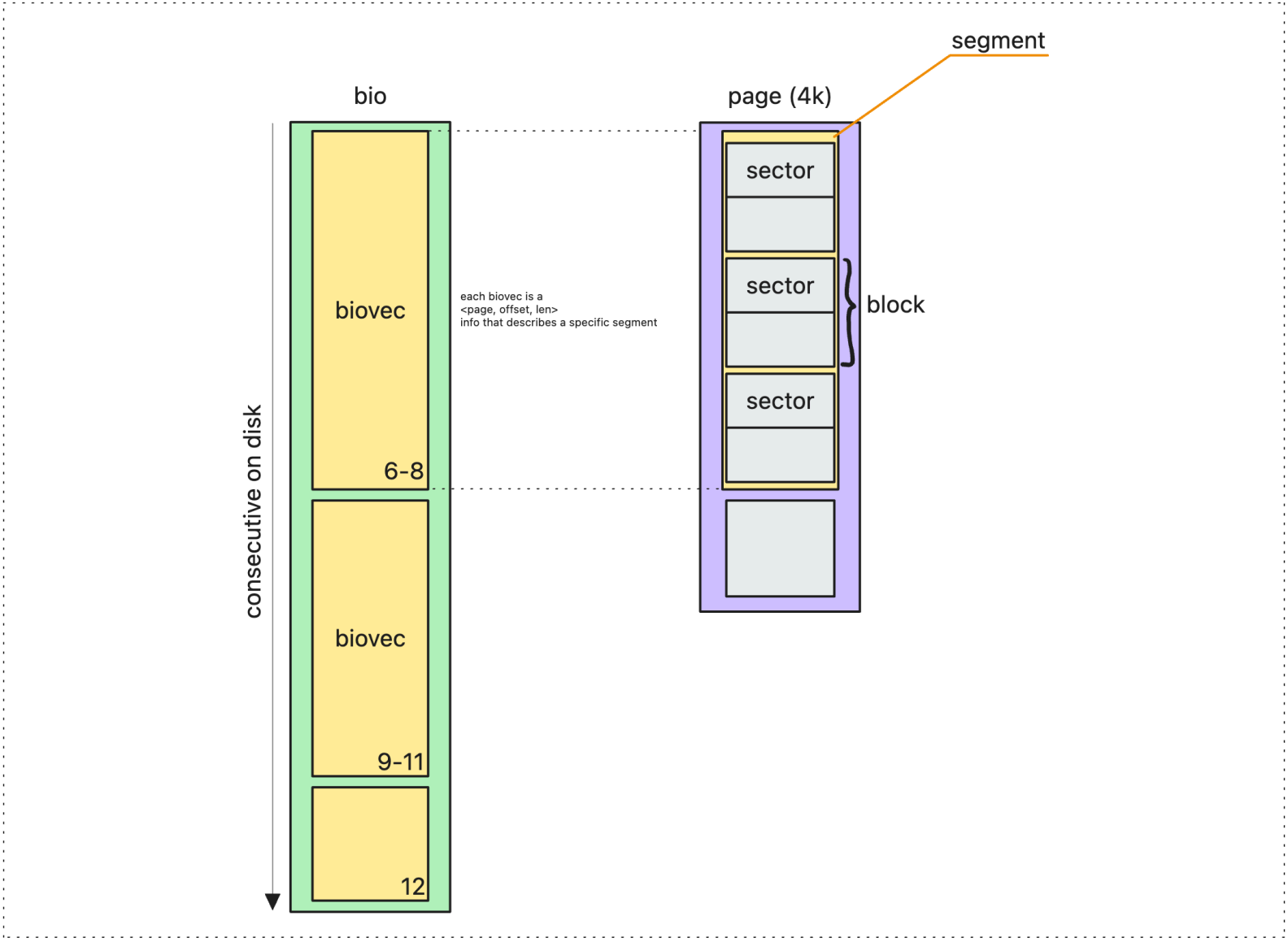
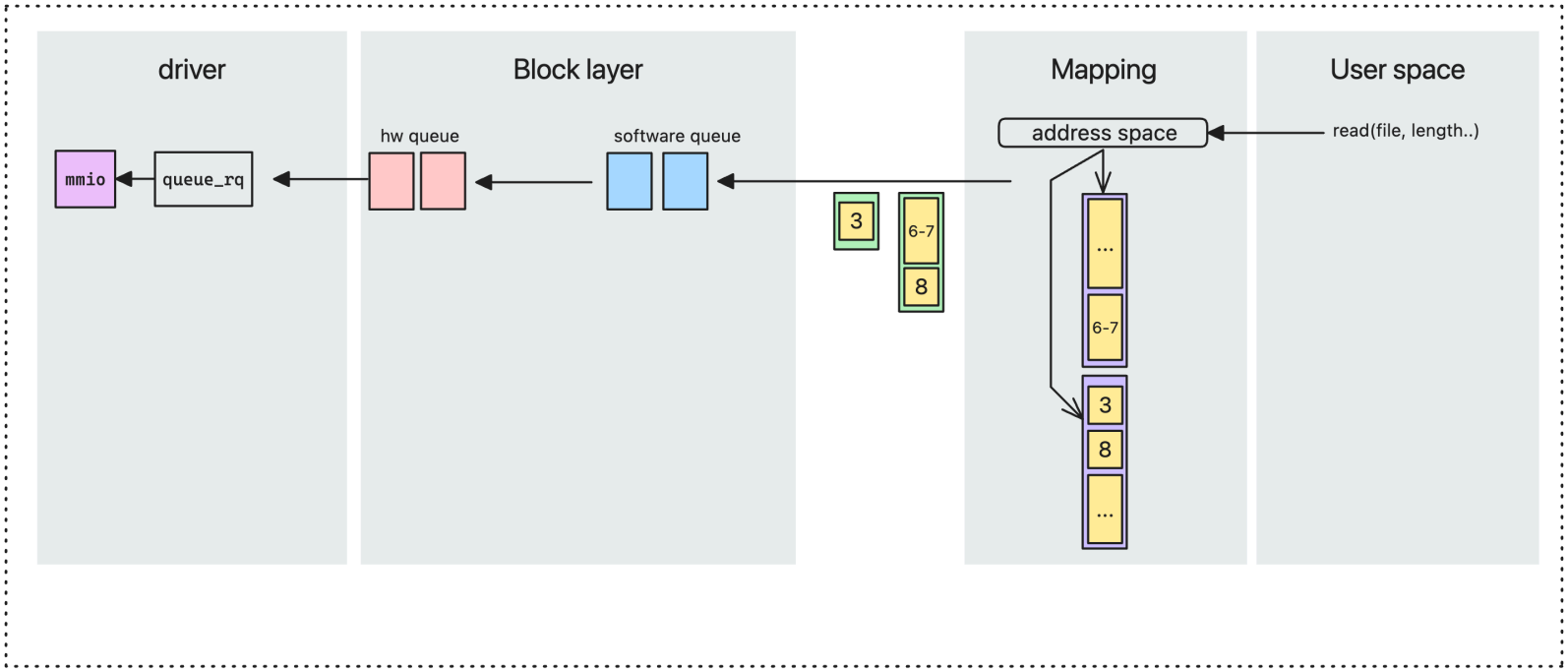


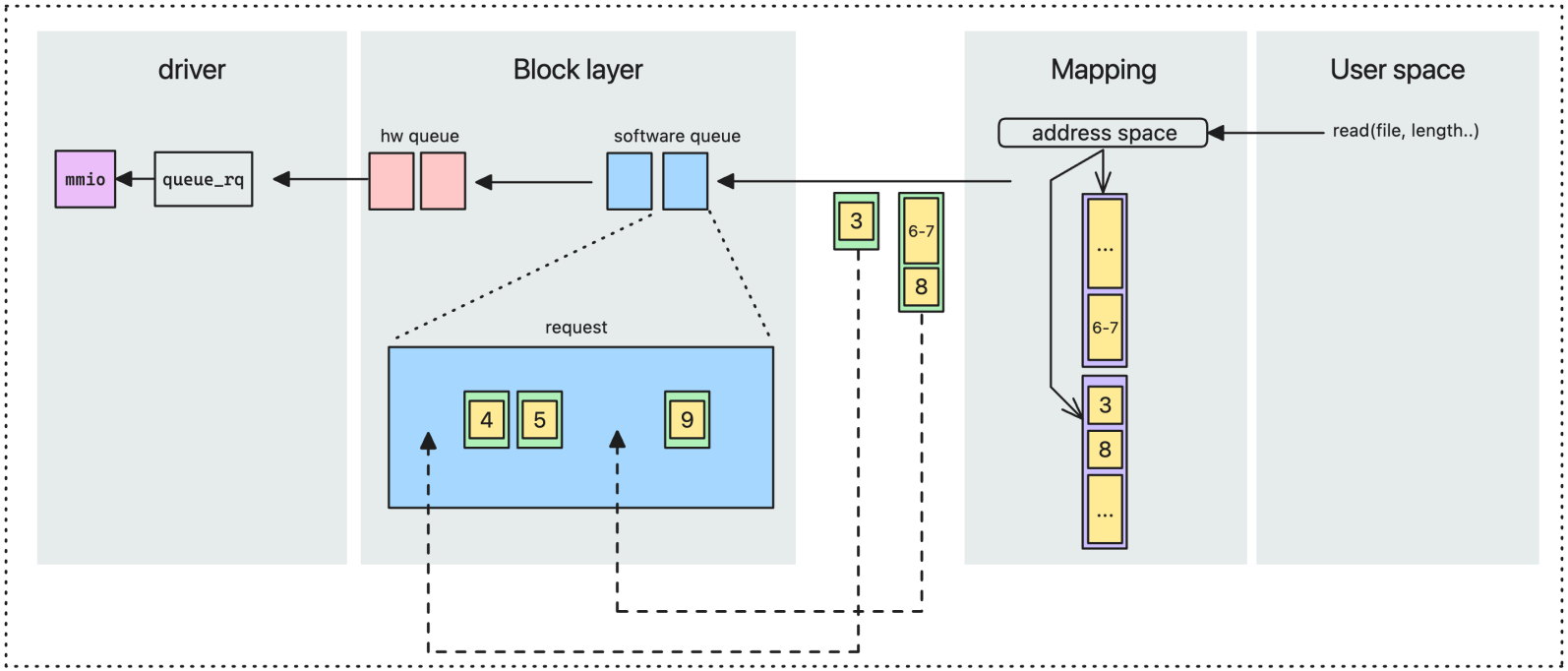
Page cache to Block requests



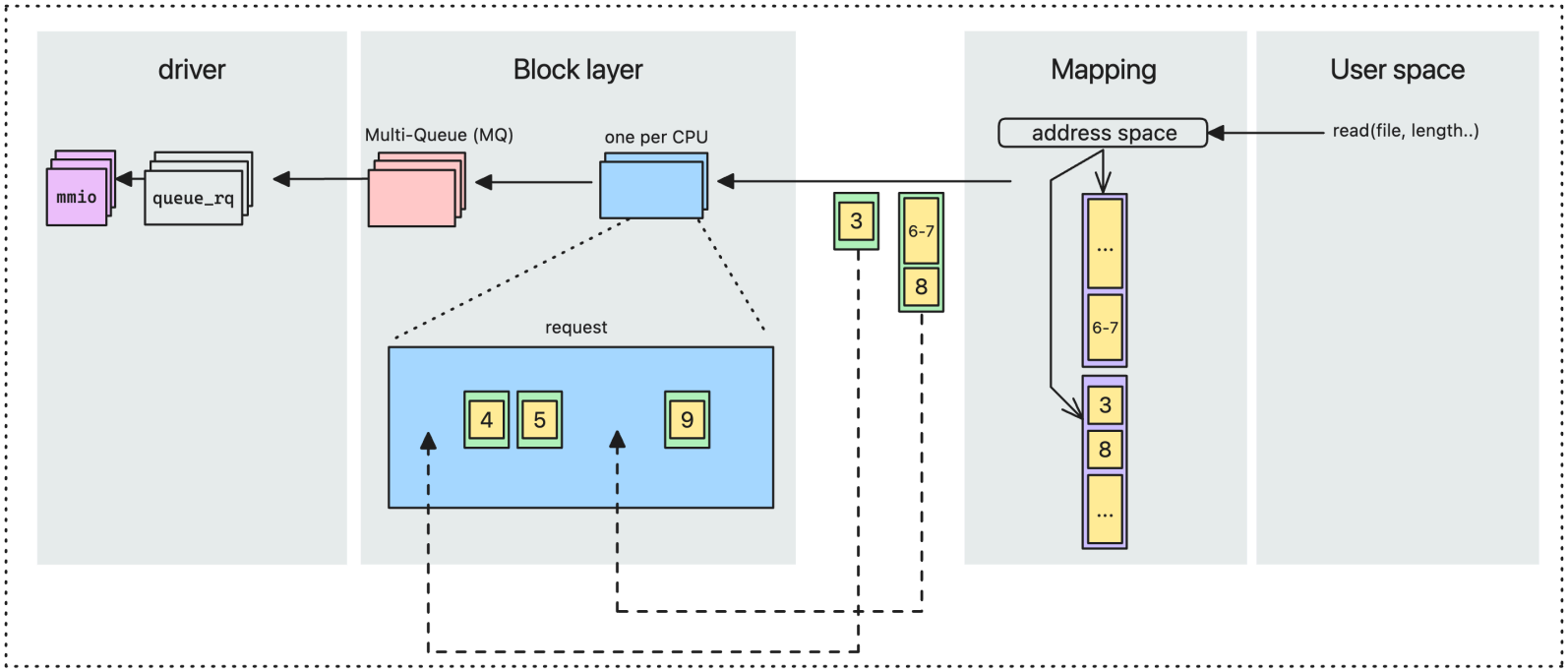
Block requests' management



Block requests' management



Block requests' management



Low level device management » Block devices » IO Schedulers

Introduction

I/O schedulers can have many purposes depending on the goals; common purposes include the following:

- To minimize time wasted by hard disk seeks (still relevant in some cases).
- To prioritize a certain processes' I/O requests.
- To give a share of the disk bandwidth to each running process.
- To guarantee that certain requests will be issued before a particular deadline.

Introduction

History of IO Schedulers

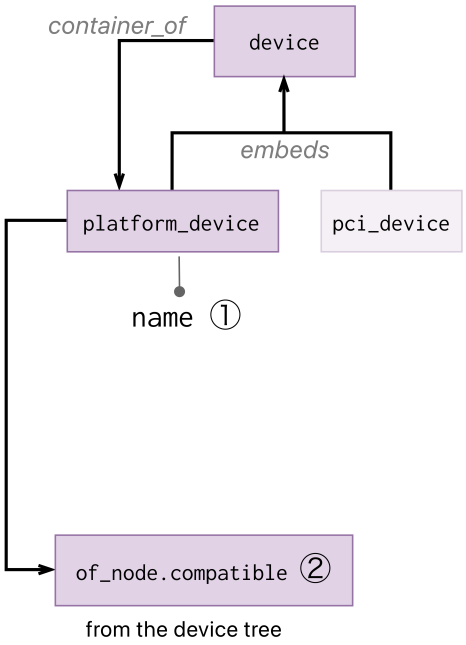
- Linux 2.4: Linus Elevator
- Linux 2.6: Deadline, Anticipatory (removed in 2.6.33), CFQ (Complete Fairness Queueing), Noop (No operation).
- Linux 3.0: Deadline, CFQ, Noop.
- Linux 4.12: MQ-Deadline, CFQ, BFQ (Budget Fair Queueing), Kyber, Noop.
- Linux 4.11: MQ-Deadline, CFQ, Noop (note, first introduction of blk-mq ca 2013)
- Linux 5.0: **MQ-Deadline, BFQ (Budget Fair Queueing), Kyber, Noop.**

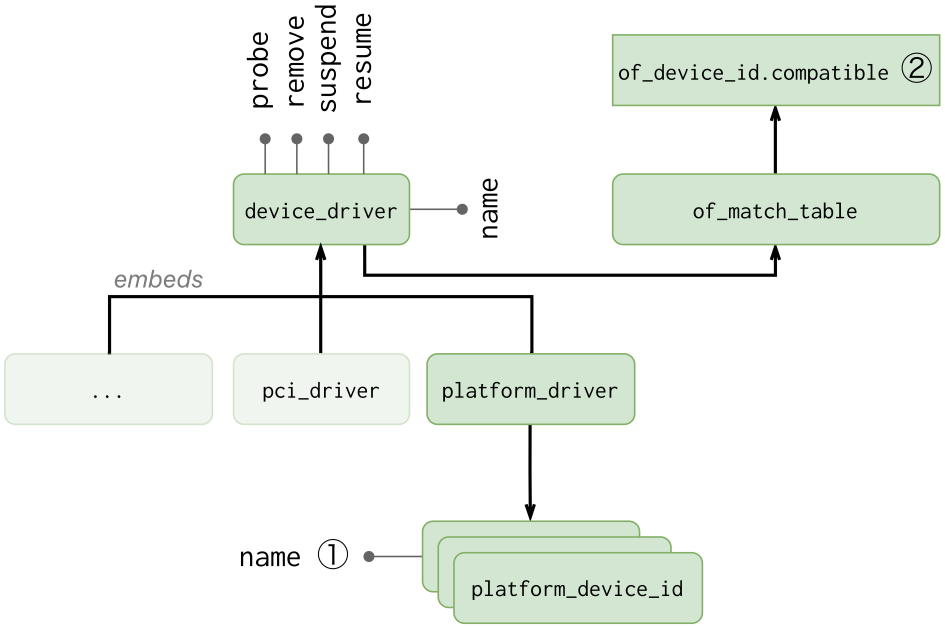
High level device management » The device model

What is a device model?

- The Linux kernel runs on several architectures and hardware platforms
- How maximize the reusability of code between platforms?
  - Example: the same USB device driver to be usable on a x86 PC, or an ARM platform, even though the USB controllers used on these platforms are different.
- How to manage device lifetime (new device plugged in for example) without reinventing the wheel?
- This requires a clean organization of the code which is enforced by the kernel through an appropriate API based on a **framework/bus** matrix

What is a device model?

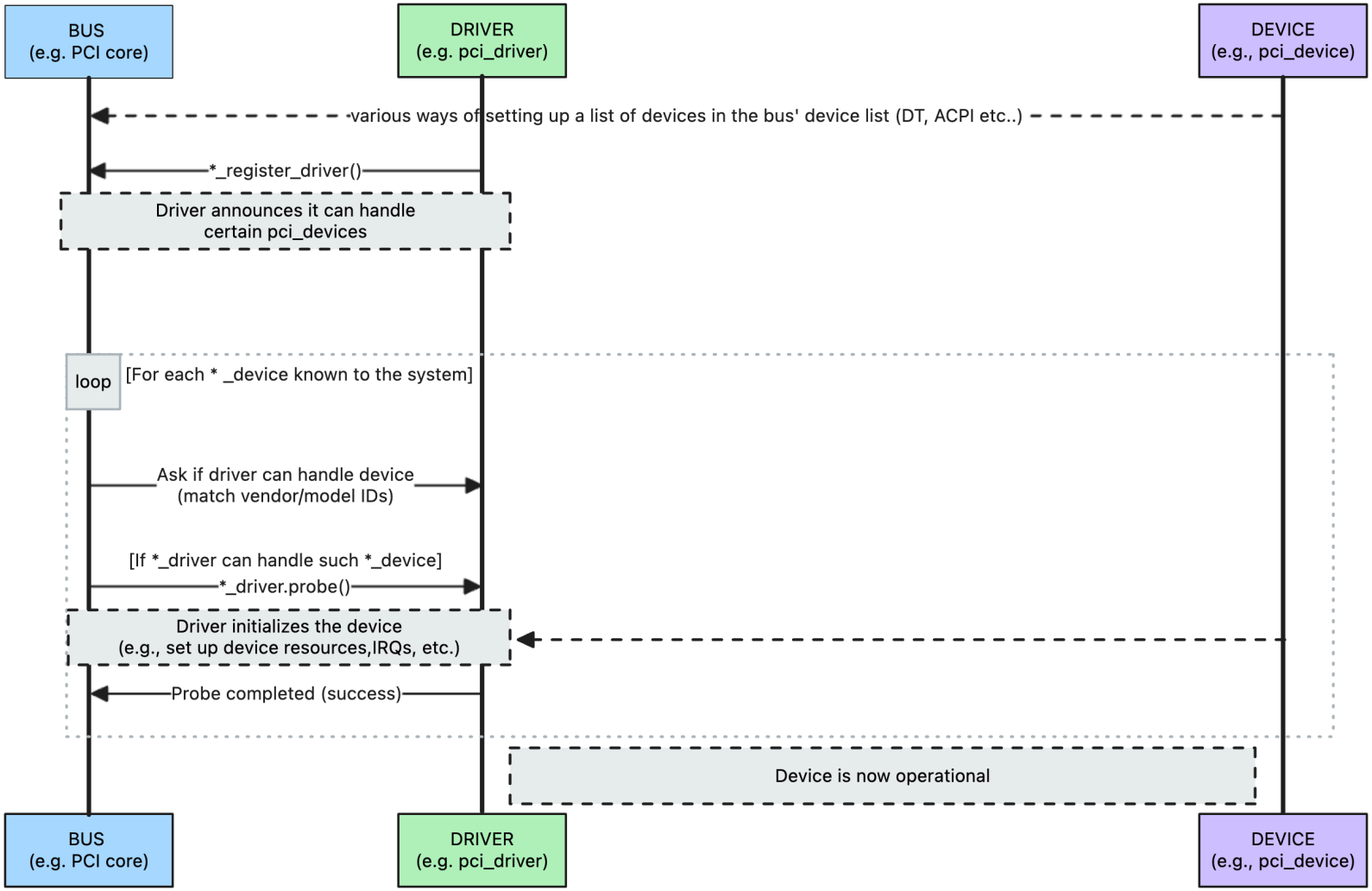




① Matching done through names between supported device_ids and device names

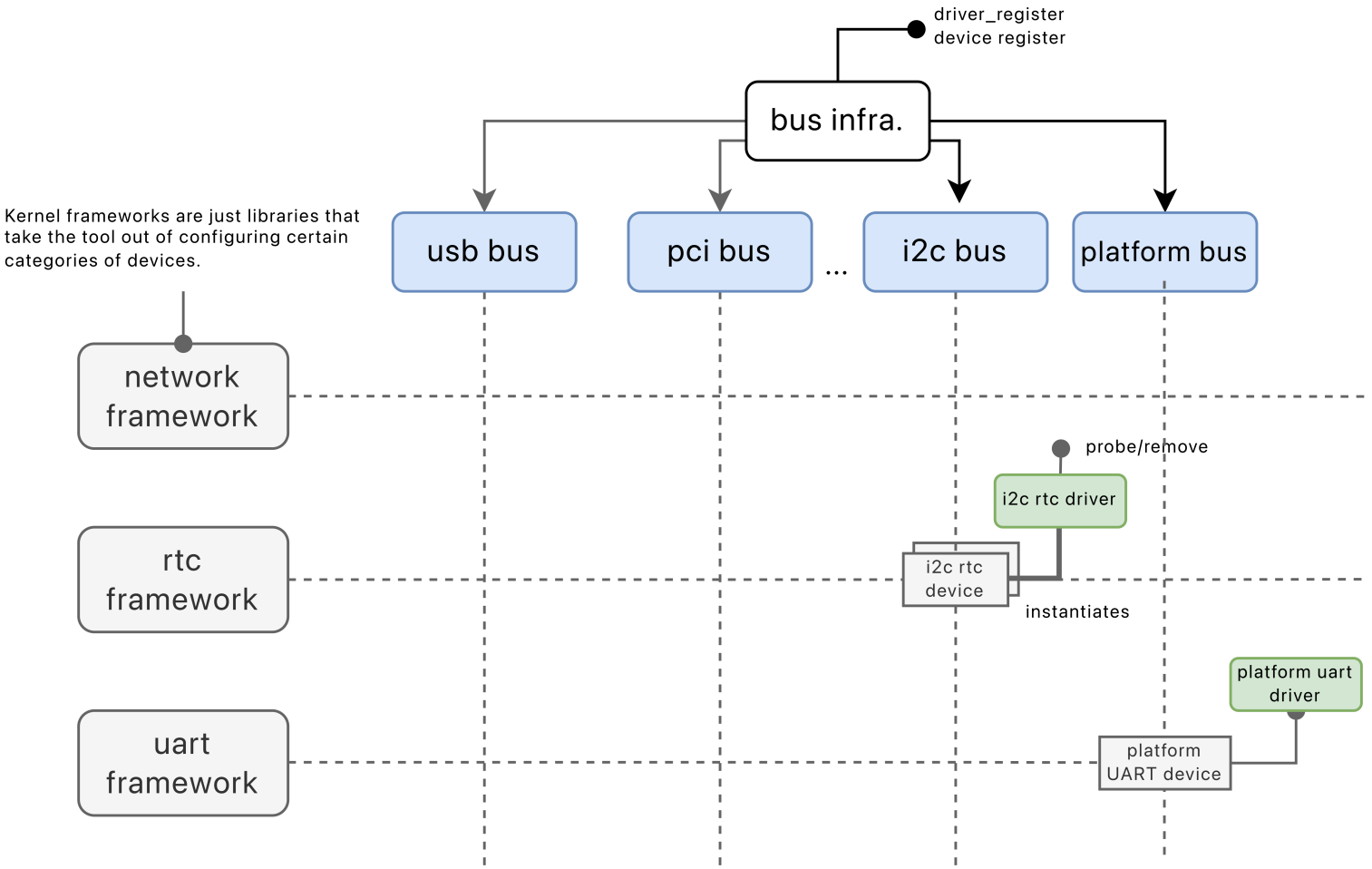
② Matching done through the device tree (of_node) compatible string of the device and the of_device_id.compatible property of the driver

What is a device model?

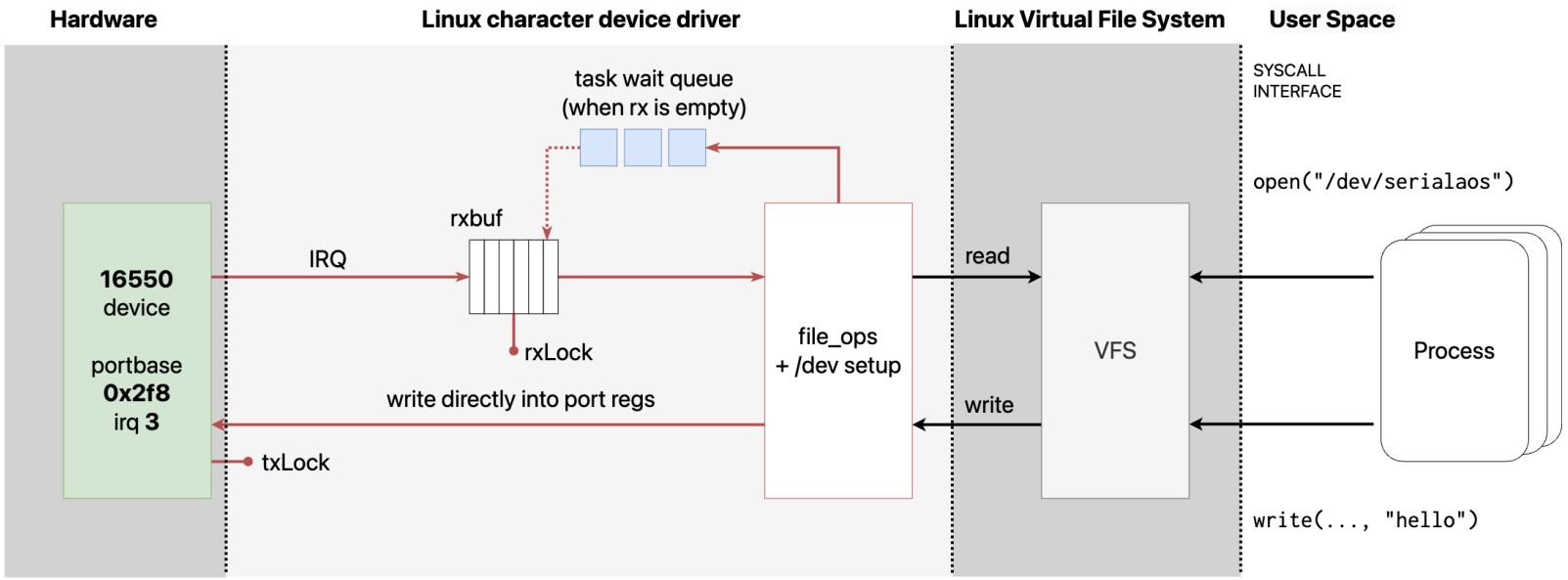


High level device management » The device model » Kernel driver frameworks

Introduction

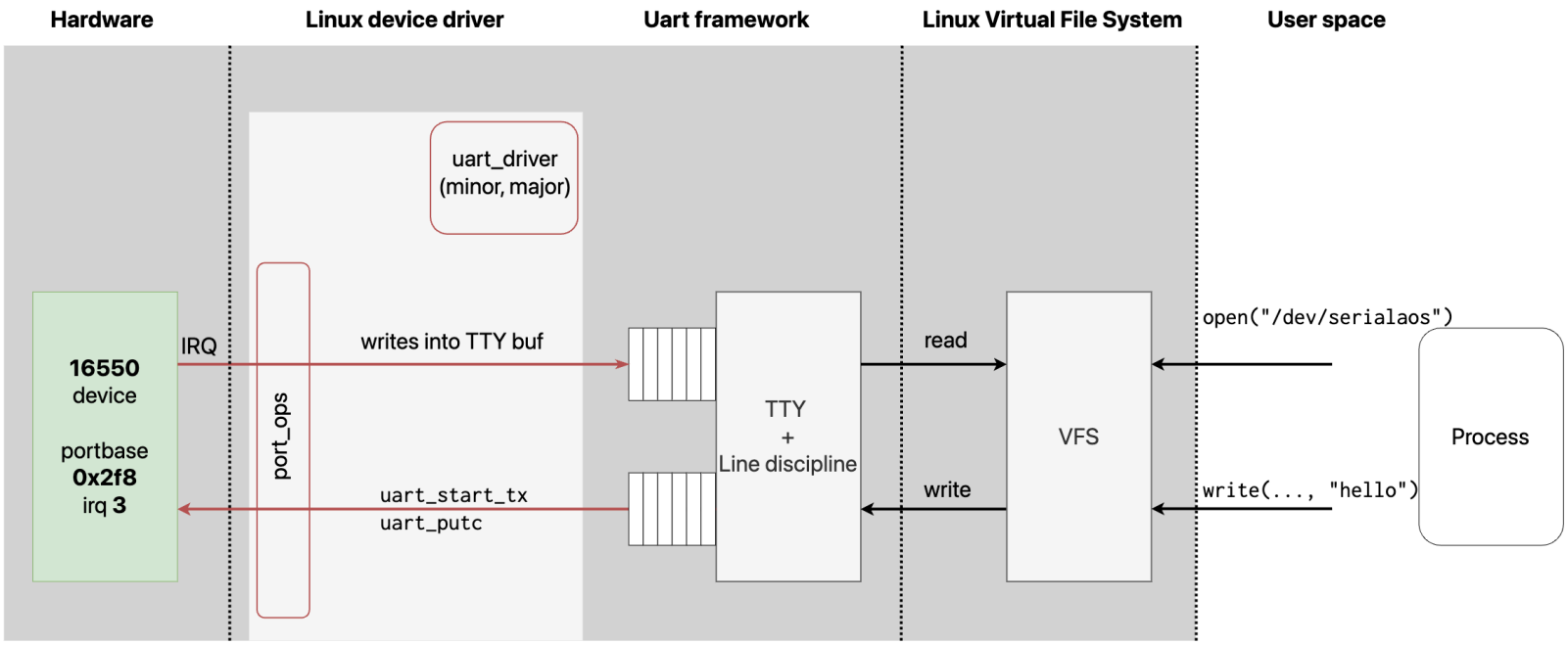


The uart framework



Serialaos driver as implemented during the lab, using only low-level character device primitives

The uart framework



Serialaos driver could be implemented with uart framework by writing much less code

High level device management » The device model » Bus frameworks

The Platform bus framework

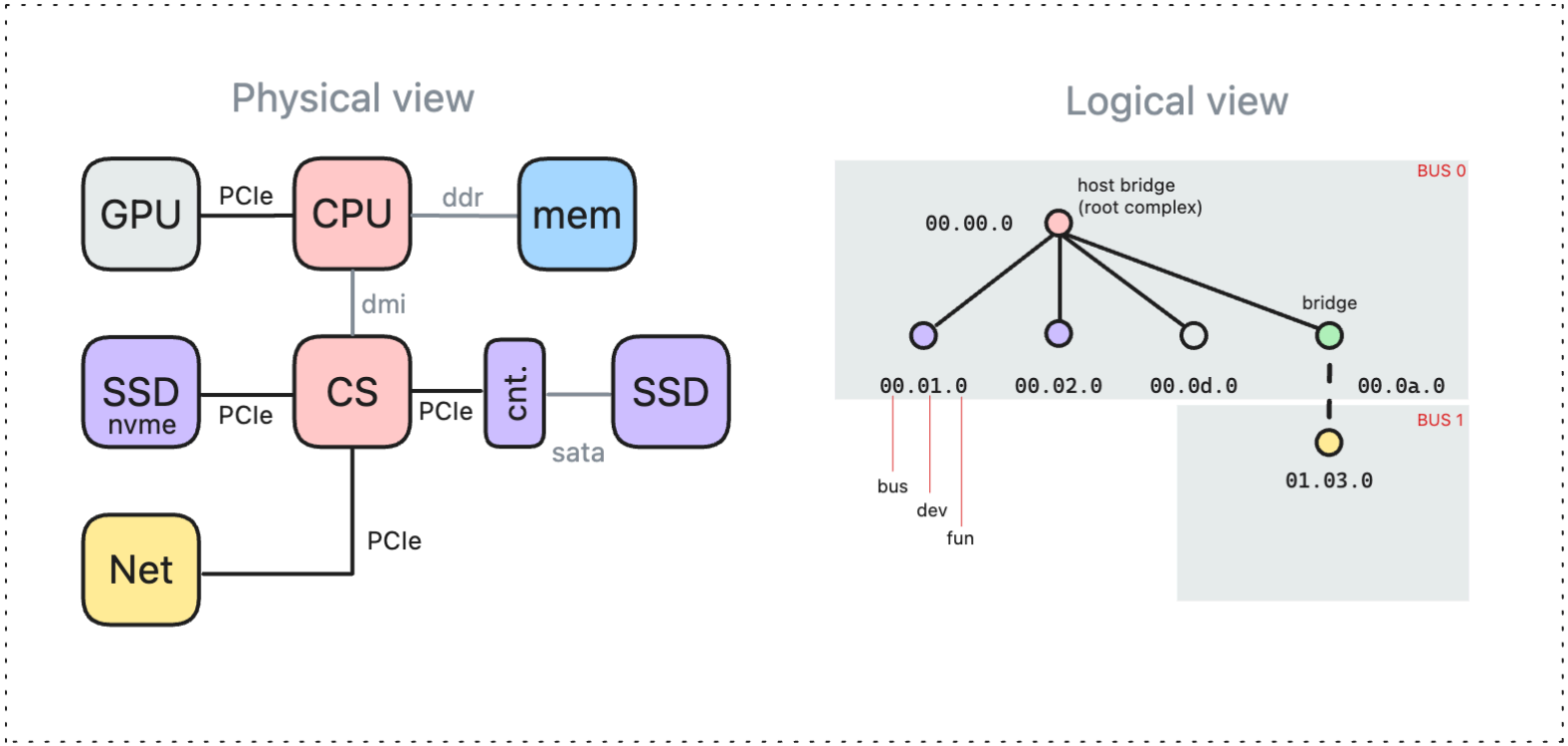
What is it

- Designed for system-on-chip (SoC) and embedded devices
- Manages non-easily-discoverable hardware components
- Represent fixed hardware resources
- Defined in board-specific code or Device Tree

Key Advantages

- Simplifies driver development for embedded systems
- Encourages code reusability
- Maintains clean and maintainable codebase for board-specific logic

The PCI bus framework

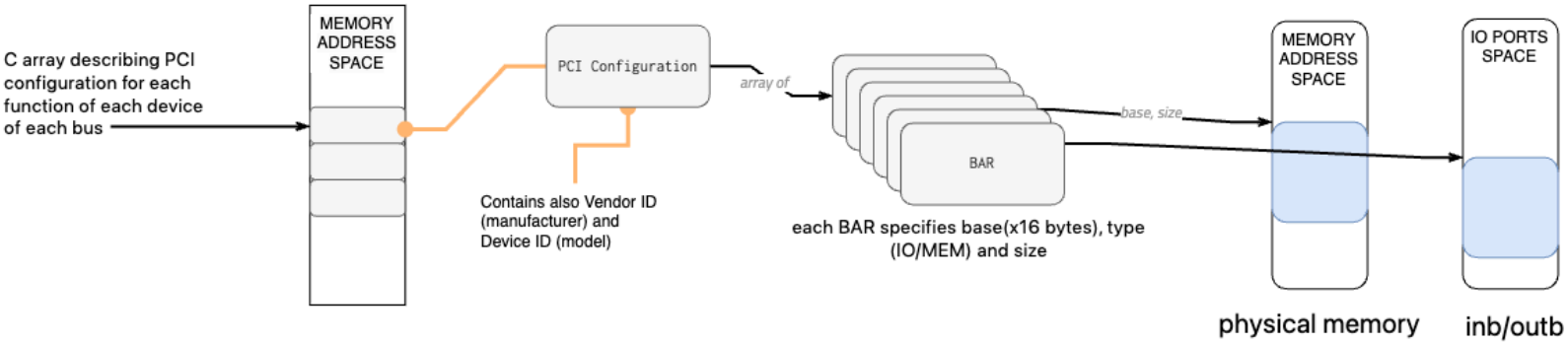


The PCI bus framework

```
root@e43fd856ef30:/scripts# lspci
+---- bus number
|  +---- device number
V  V  V---- function
00:00.0 Host bridge: Intel Corporation ...
...
00:0a.0 PCI bridge: Intel Corporation 8
00:0d.0 SATA controller: Intel Corporation ...
...
01:03.0 Ethernet controller: Intel Corporation 82540EM
```

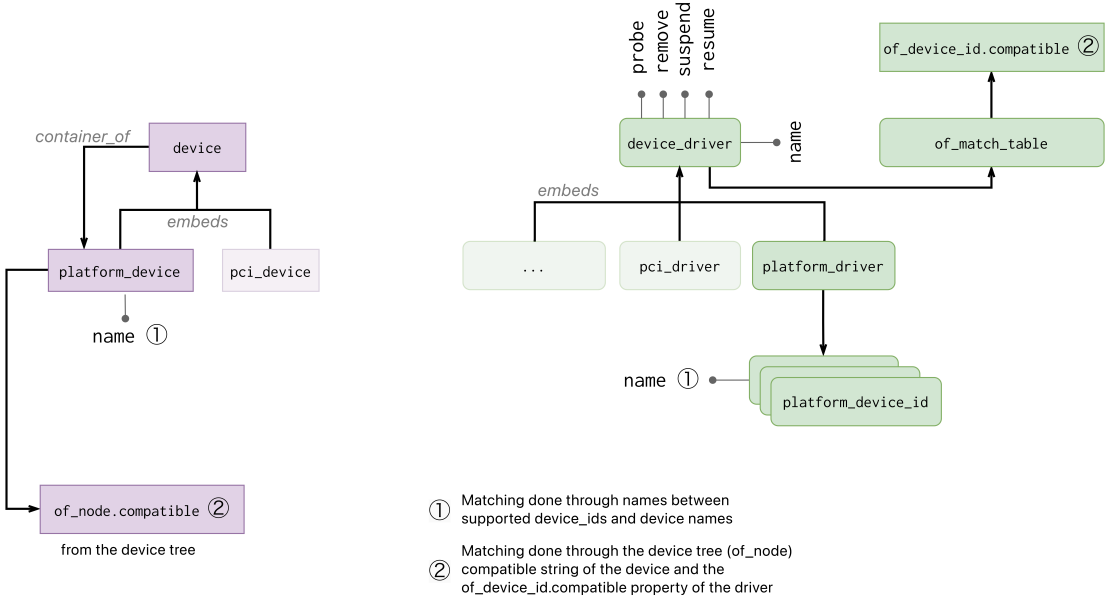
The PCI bus framework

Extended configuration access mechanism (PCIe)



The PCI bus framework

```
$ dmesg
...
pci 0000:00:01.3: [4431:2212] type 00 class 0x040000
pci 0000:00:01.3: quirk: [io  0x0600-0x063f] claimed by PIIX4 ACPI
pci 0000:00:01.3: quirk: [io  0x0700-0x070f] claimed by PIIX4 SMB
...
...              # [VID : DID]
pci 0000:00:02.0: [1234:1111] type 00 class 0x030000
pci 0000:00:02.0: reg 0x10: [mem 0xfd000000-0xfdffffff pref]
pci 0000:00:02.0: reg 0x18: [mem 0xfebb0000-0xfebb0fff]
pci 0000:00:02.0: reg 0x30: [mem 0xfeba0000-0xfebaffff pref]
```



Other » Sysfs and Kobjects

- Kobjects are the **underlying foundation of the device model**
- Represent kernel objects such as **bus, devices, drivers**, and modules
- kobjects have fields (or attributes) and are exposed to user space via the `sysfs` virtual filesystem (kobject → directory, attributes → file)
- kobjects belong to **ksets**, and the corresponding hierarchy is useful for mimicking real hardware topology
- **kobjects emit uevents** to notify user-space tools like udev of changes
- Example: inserting a usb pen drive, creates entries in `/sys/usb/devices`, `/sys/class/block` and `/dev/sdb` (through udev).