Start: 8:01

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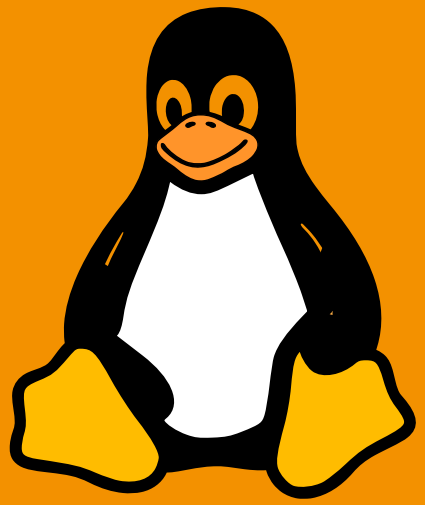
Prof. Dr. Florian Künzner

Technical University of Applied Sciences Rosenheim, Computer Science

OS 16 – Drivers



source: iconspng.com

The lecture is based on the work and the documents of Prof. Dr. Ludwig Frank

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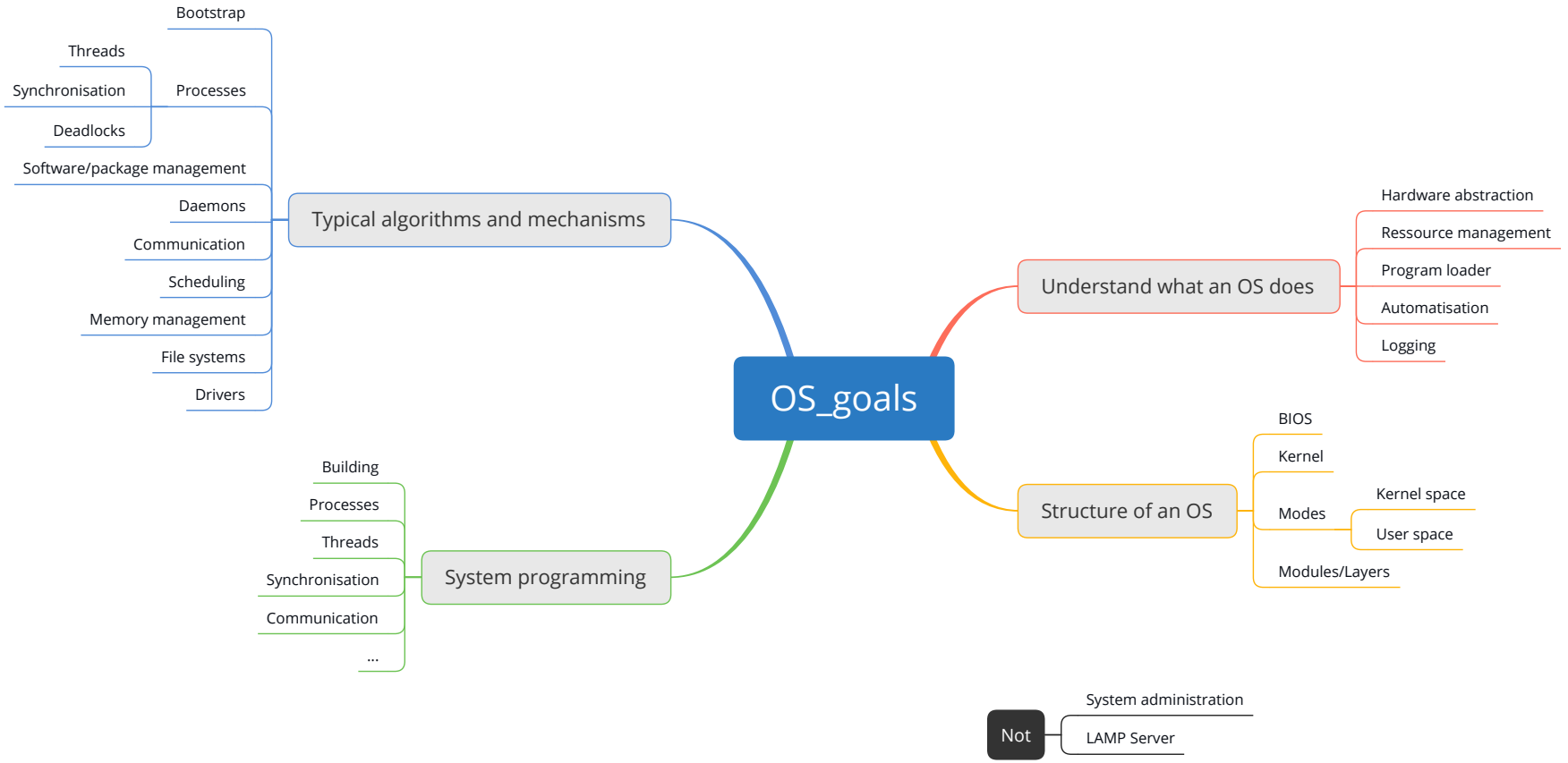
Goal



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Goal

OS::Drivers

- Design goals
- Structure of I/O systems
- Linux device files
- Kernel modules
- Linux device driver development

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Intro

What is a **device driver**?

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Intro

A **device driver** is a piece of software that **controls** the **interaction** with an connected, built-in, or virtual device.

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Static vs dynamic driver

A **static** driver is **built-in** into the kernel.

A **dynamic** driver can be **loaded and unloaded at runtime**.

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Device classes

- Character device
- Block device
- USB
- Network
- Bluetooth
- FireWire (IEEE1394)
- SCSI
- IrDA (Infrared Data Association)
- Cardbus and PCMCIA
- Parallelport
- I2C
- ...

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Design goals

User programs should be device independent

The type of the device or the position on the bus shouldn't be visible to the user application.

- Different hardware vendors
- Different device types: hard drive, SSD, USB stick, network drive, ...

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Design goals

Uniform device names

Devices are in the /dev folder and should be independent of a hardware connection.

Example 1:

```
cat file > /dev/lp1  #sends file to printer on /dev/lp1
```

Example 2:

```
int main(void){
    int fd = open("/dev/device", O_RDWR, 0666);

    char buffer[LEN] = {"Hello\n"};
    ssize_t bytes_written = write(fd, buffer, LEN);
    ssize_t bytes_read    = read(fd, buffer, LEN);

    close(fd);

    return EXIT_SUCCESS;
}
```

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Design goals

Error handling

- Localisation and report of errors
- Error logging
- Correction of transient errors (e.g. read again)
- Automatic notification of the maintenance service

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Design goals

Support for synchronous and asynchronous data transfer

Synchronous
Process waits until the I/O operation completes.

Asynchronous
Process can proceed while the OS transfers the data.

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Design goals

Device management

- Exclusive or shared access
- Locking mechanism (`fcntl()`)
- Deadlock monitoring (e.g. banker's algorithm)

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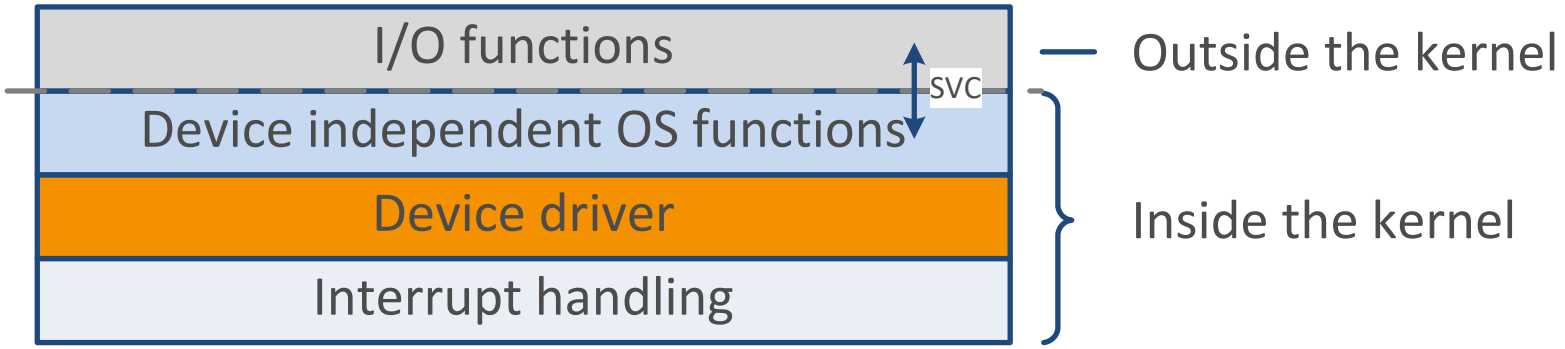
Structure of I/O systems



Device independent OS functions

- Naming of device files (e.g. `/dev/fd0`)
- Access control
- Caching
- Locking mechanism
- Device allocation management
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Device driver

- Knows the HW properties of the devices
- Provides a HW independent interface

Interrupt handling

- Handling of interrupts
- Assignment to the waiting process

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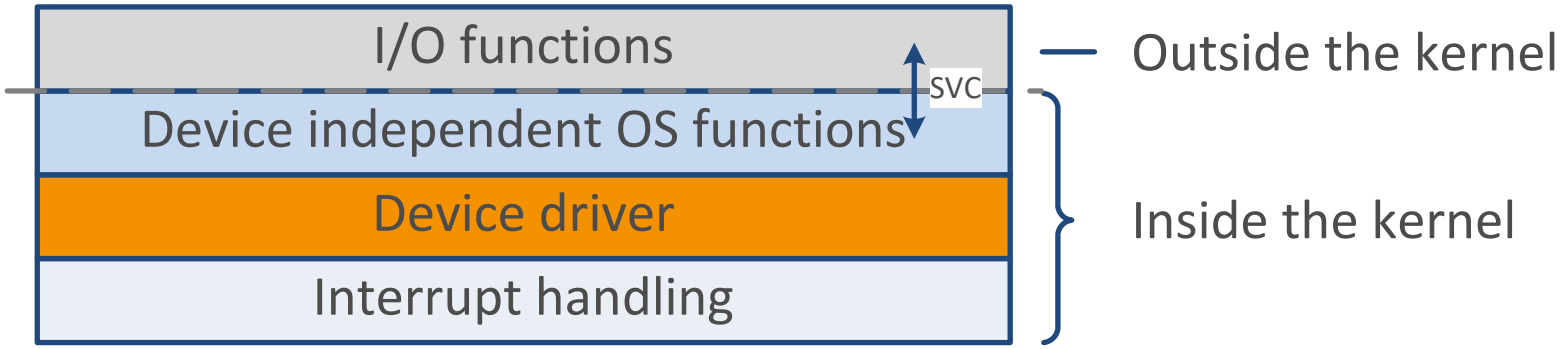

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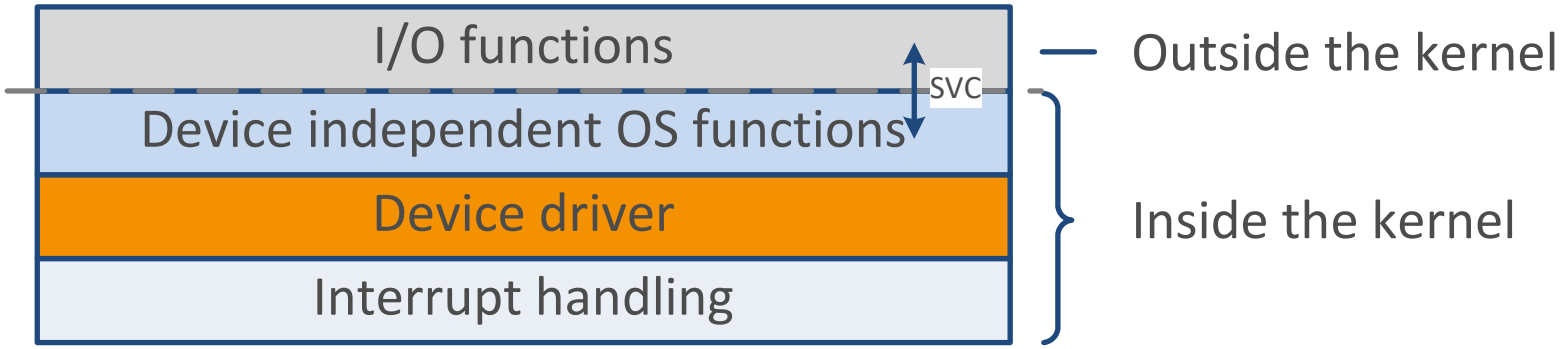

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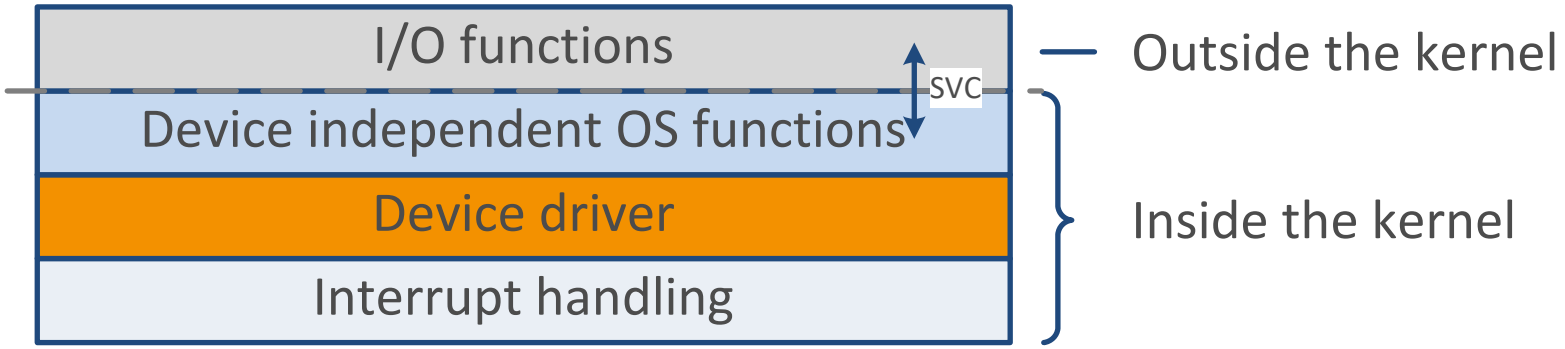

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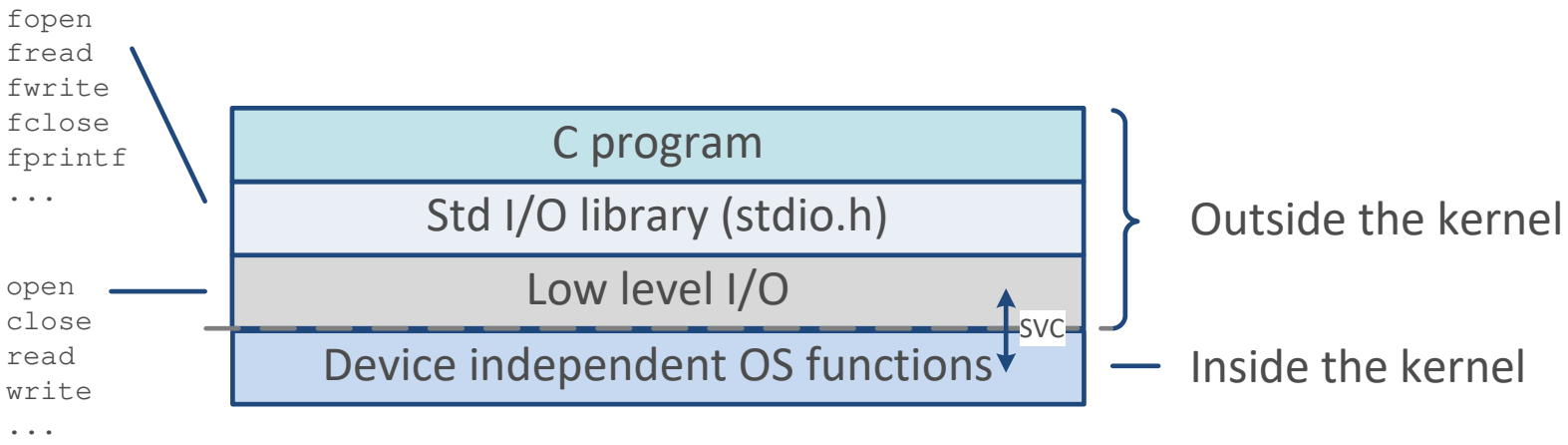
I/O layers



Functions of `stdio.h`

- Buffering
- Formatting
- Format conversion
- Higher level of abstraction (easier to use)

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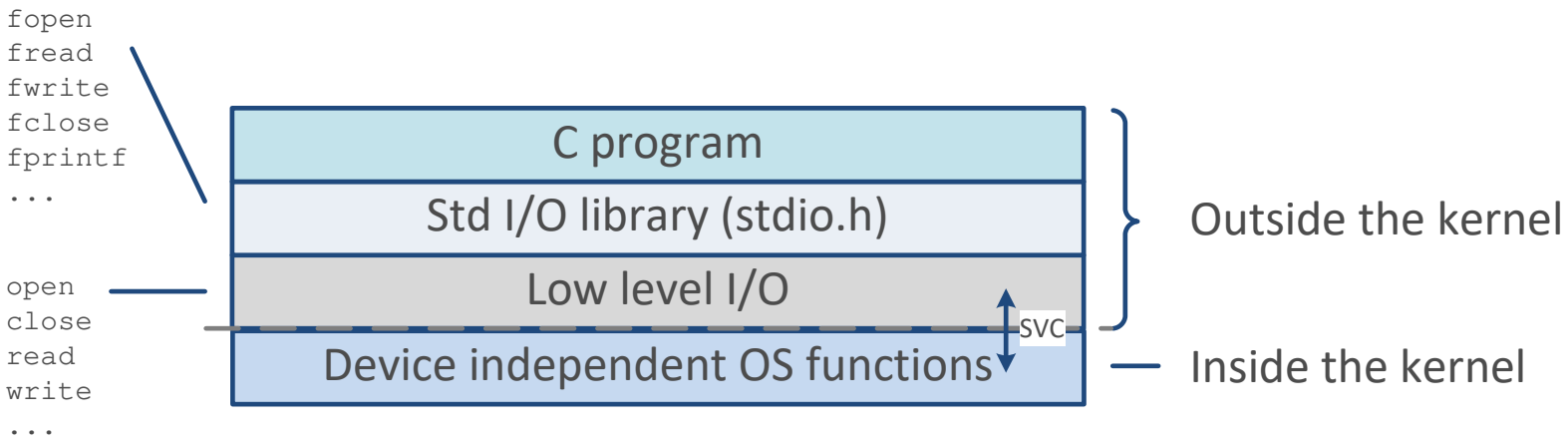

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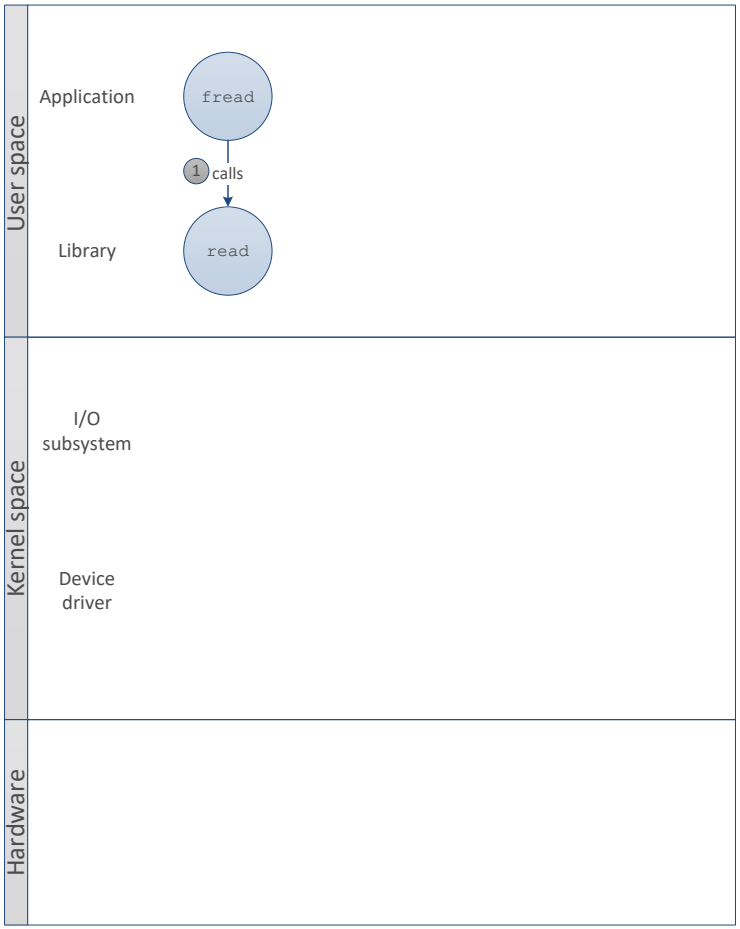
Example operation: read data



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2. `read()` starts a SVC (supervisor call)
3. The HW independent I/O read calls the driver
4. The driver starts the read on the HW and sets the calling process into waiting state.
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11. The data is processed in `fread()` and finally returned to the application.

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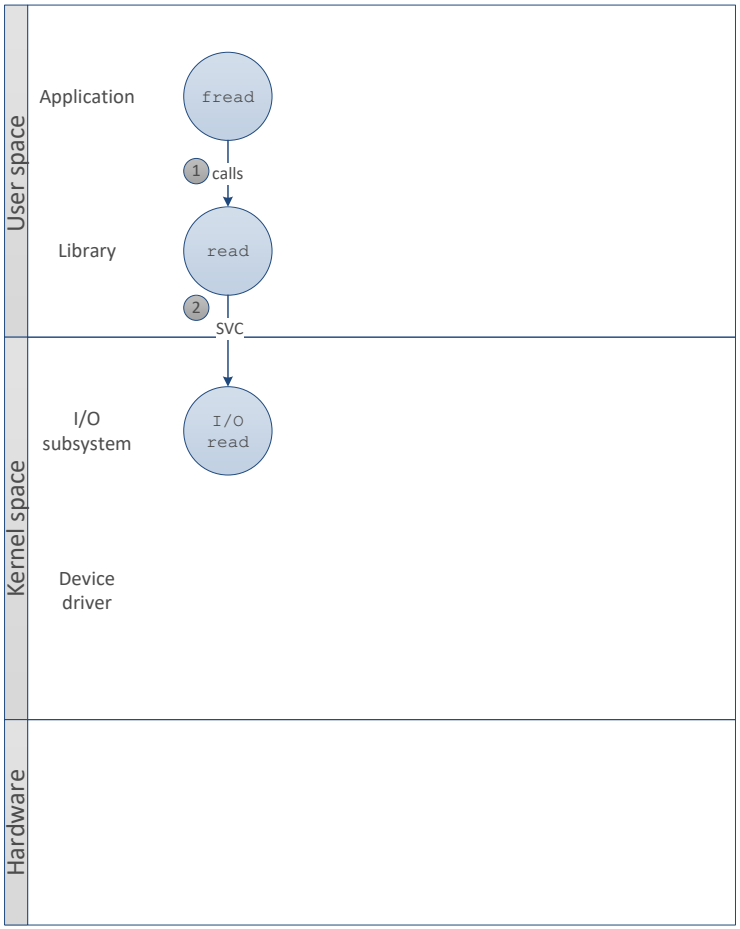

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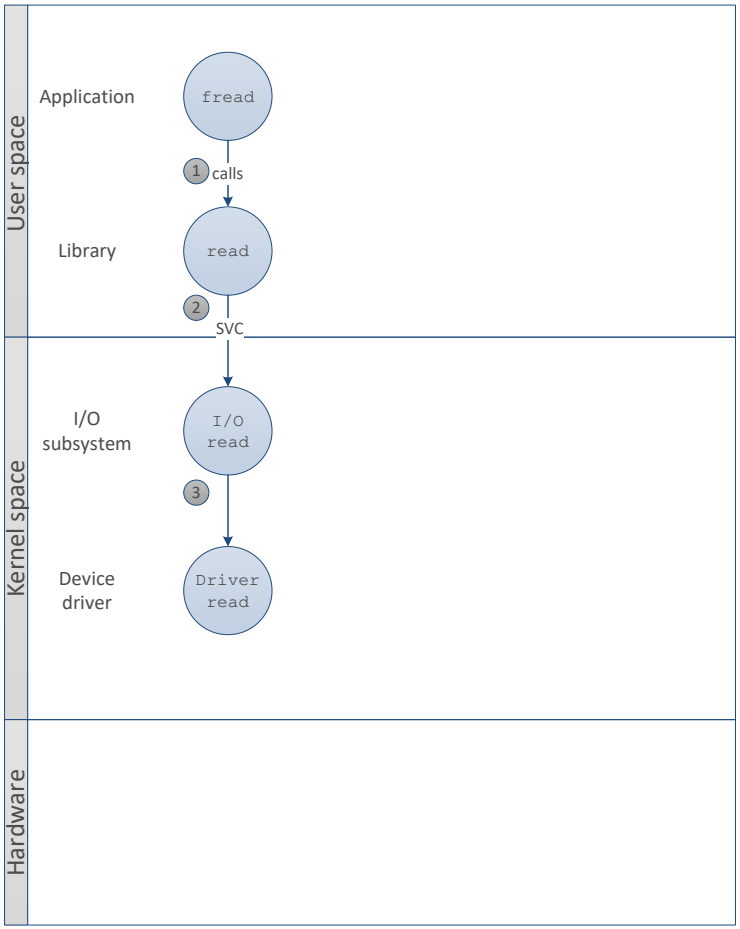

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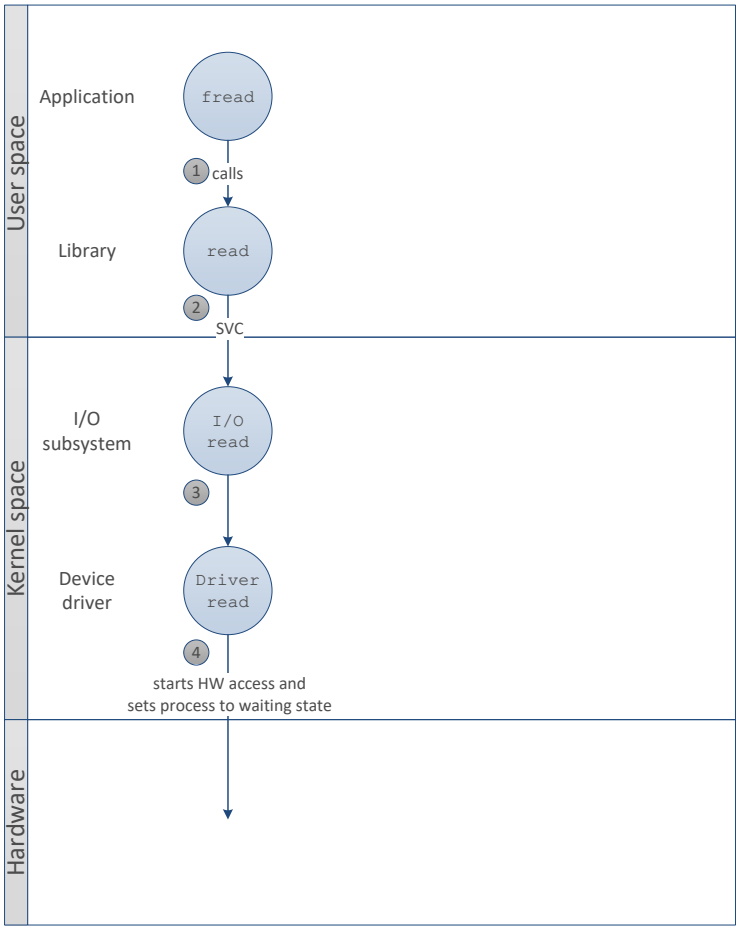

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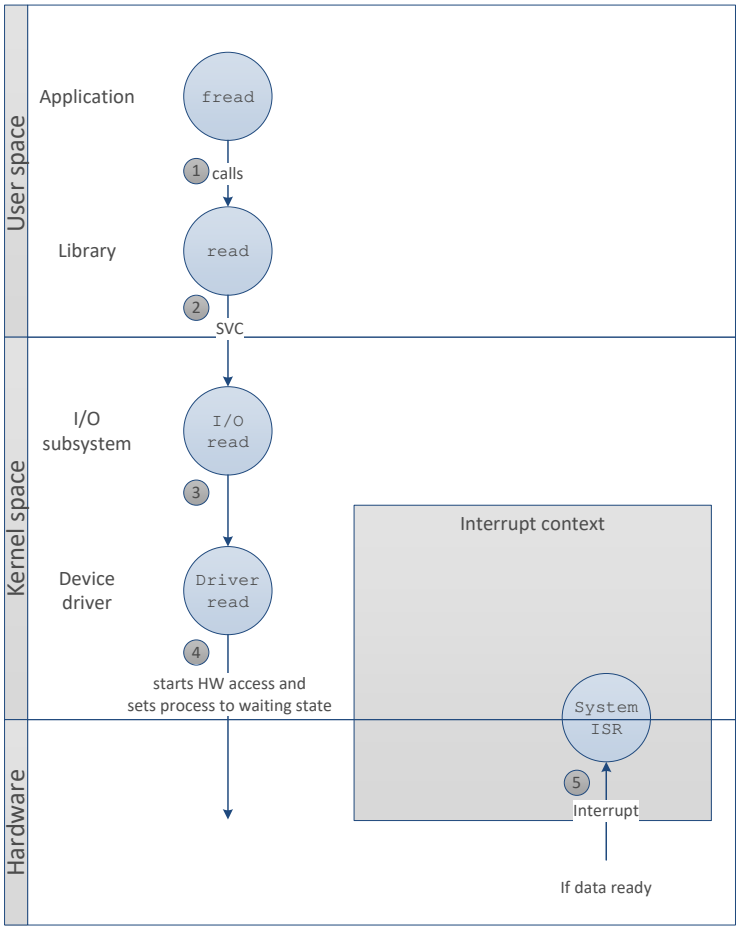

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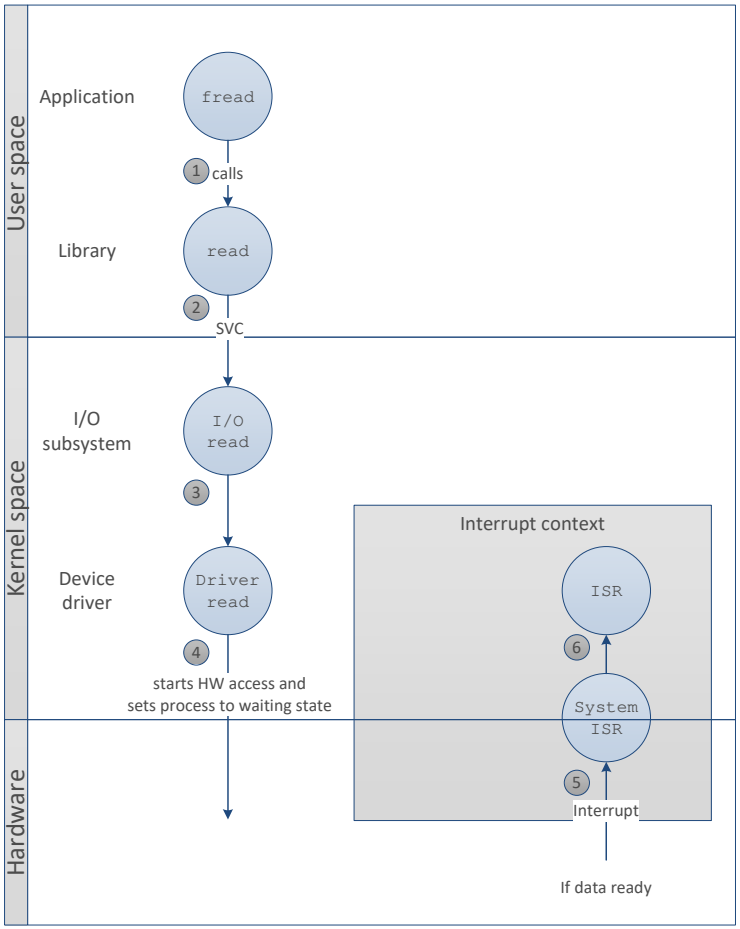

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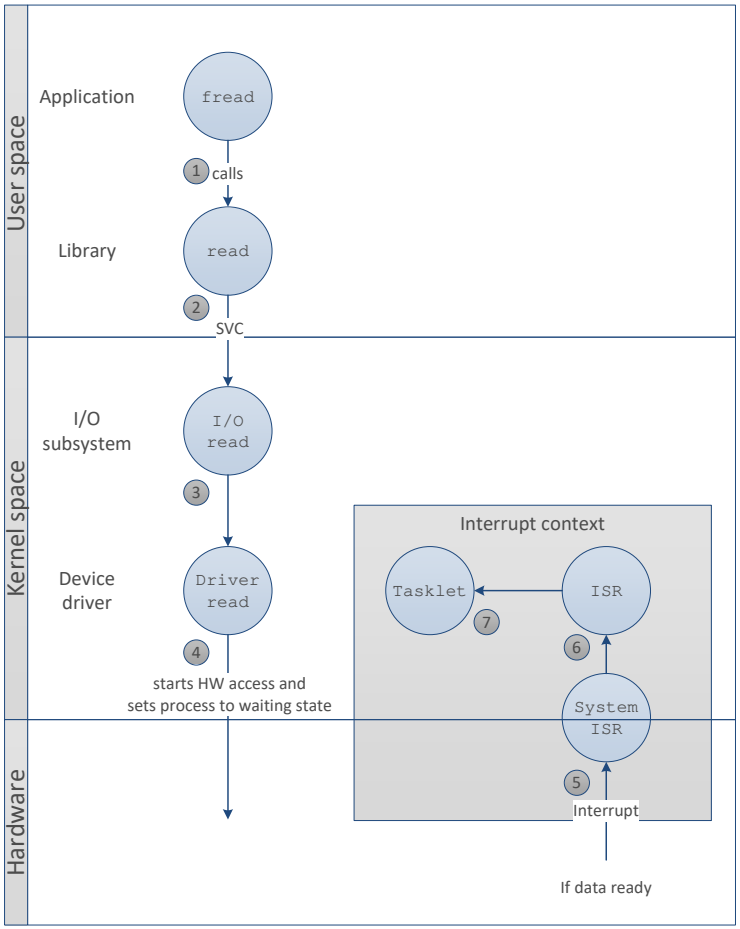

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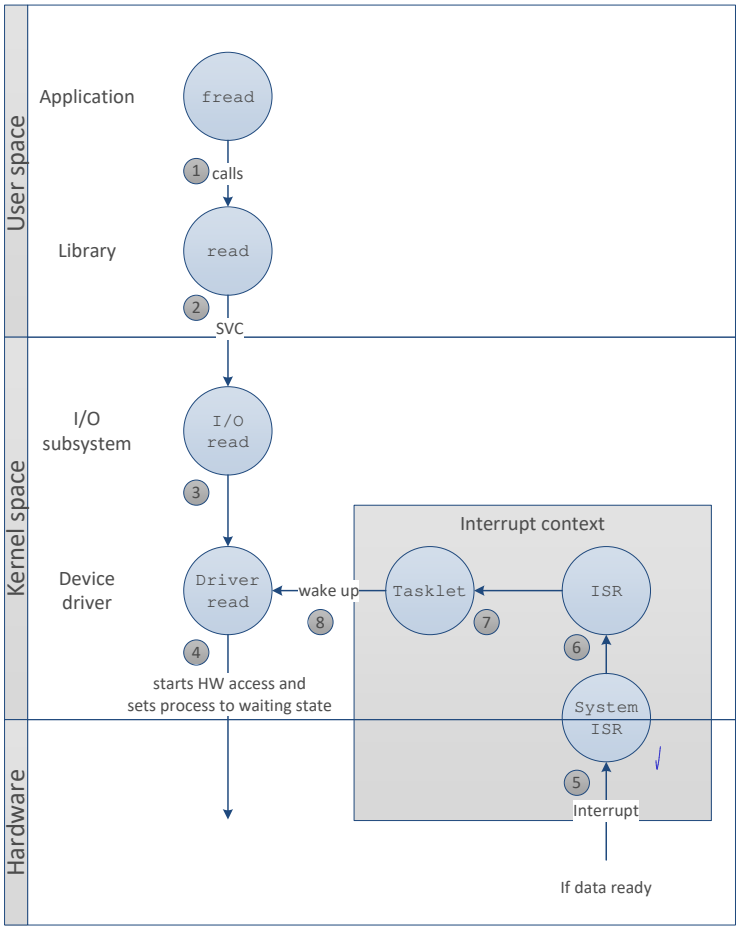

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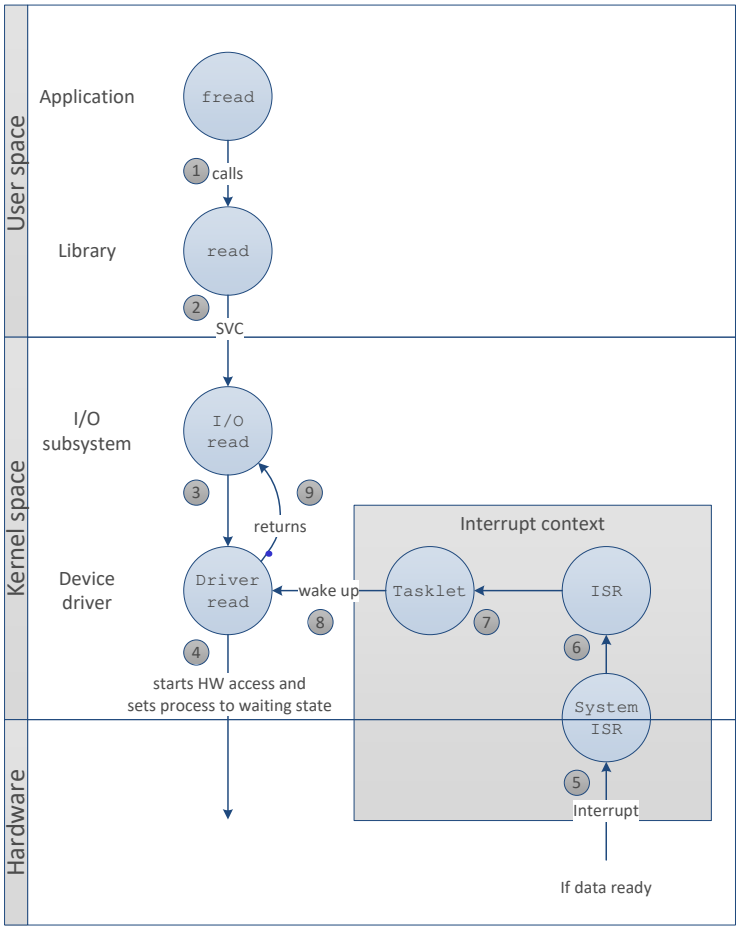

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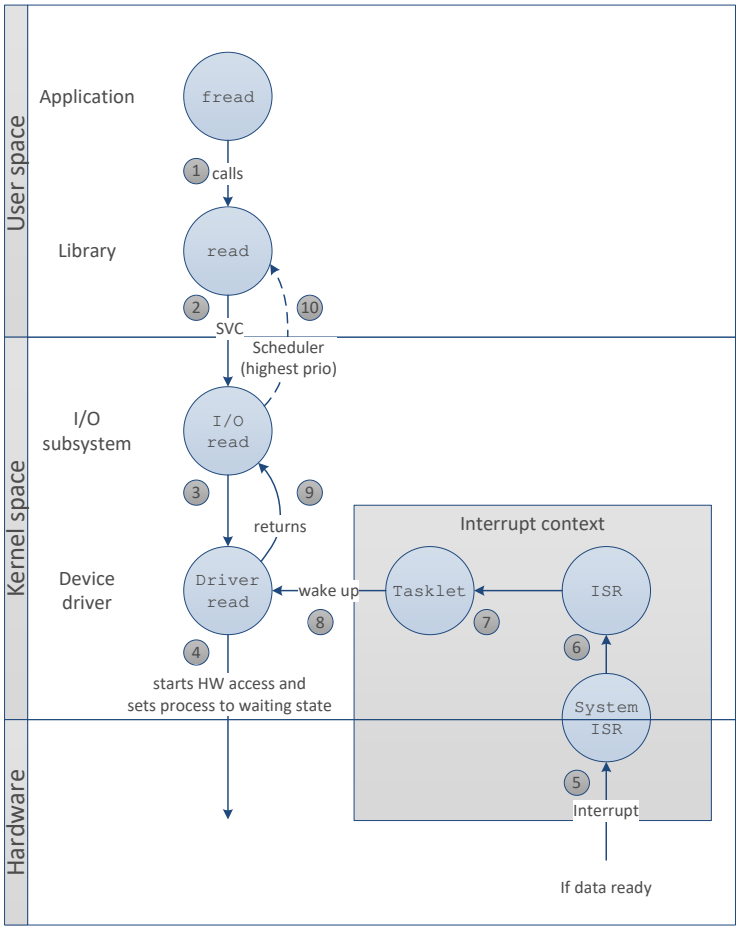
Example operation: read data



1. Application calls `fread()`
2. `read()` starts a SVC (supervisor call)
3. The HW independent I/O read calls the driver
4. The driver starts the read on the HW and sets the calling process into waiting state.
5. The HW triggers an interrupt if the data is ready. The kernel first handles the interrupt in its system ISR (interrupt service routine)
6. The system ISR calls the ISR of the driver
7. The ISR of the driver starts a tasklet (its like a thread in the kernel but more lightweight)
8. The tasklet wakes up the driver
9. The driver read function continuous: fetches and copies the data into user space.
10. The I/O read function continuous and the SVC is now finished. If the process has the highest prio it can run on the CPU.
11. The data is processed in `fread()` and finally returned to the application.

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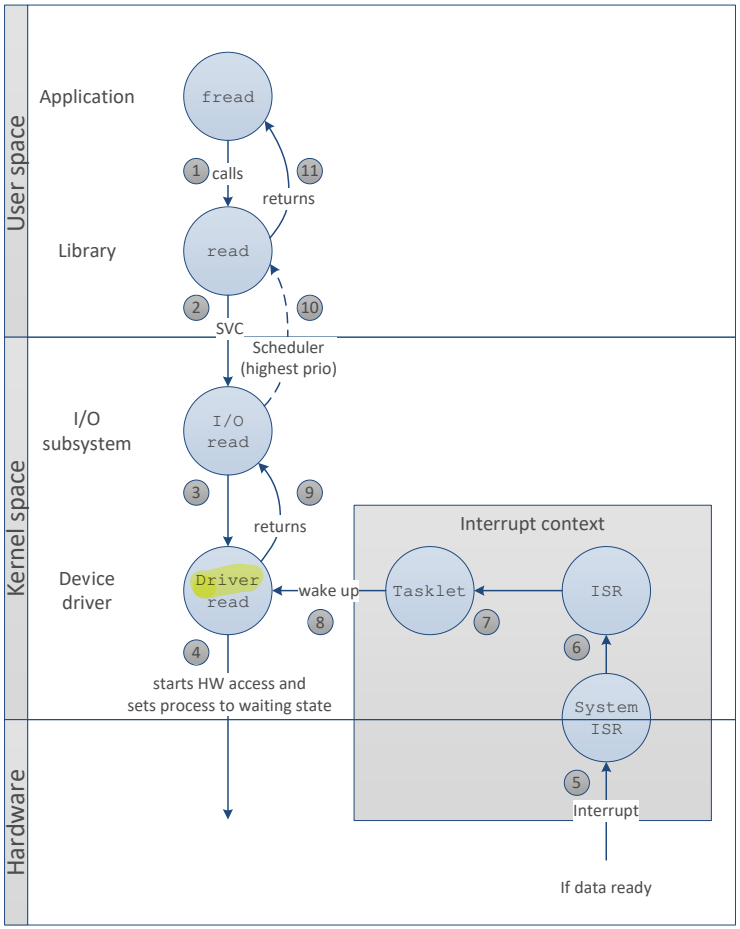

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Linux device files

- One **device file** per device
- **Device examples**: mouse, harddisk, keyboard, display, terminal, ...
- **Device file examples**: `/dev/sda`, `/dev/tty0`, `/dev/cdrom`
- Talk to device → `open()`/`close()`/`read()`/`write()` with device file
- Application uses the device file to communicate with a device
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Device types

Device type	File type	Example	Description
character device	c	Terminal, printers, ...	Sending and receiving single characters (bytes).
block device	b	Harddisks, USB, CD, ...	Sending and receiving of entire data blocks.

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Create a Linux device file

Create a device file

```
1 mknod /dev/device_file TYPE MAJOR MINOR
2
3 #TYPE  = c (character) or b (block)
4 #MAJOR = device type and the corresponding driver
5 #MINOR = device within the driver (major_device_number)
```

Delete a device file

```
1 #delete device file
2 rm /dev/device_file
```

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Inode device file example

An inode on a device files contains the device type (c/b), the **major**, and the **minor** number.

```
1  ls -l -i /dev
2      type                        major  minor
3  328 brw-rw----  1 root disk     259,    1      Jan 14 22:37 nvme0n1p1
4  329 brw-rw----  1 root disk     259,    2      Jan 14 22:37 nvme0n1p2
5  330 brw-rw----  1 root disk     259,    3      Jan 14 22:37 nvme0n1p3
6  ...
7    6 crw-rw-rw-  1 root root       1,    3      Dez 27 10:42 null
8  ...
9   15 crw--w----  1 root tty        4,    0      Dez 27 10:42 tty0
10  20 crw--w----  1 root tty        4,    1      Dez 27 10:42 tty1
11 ...
```

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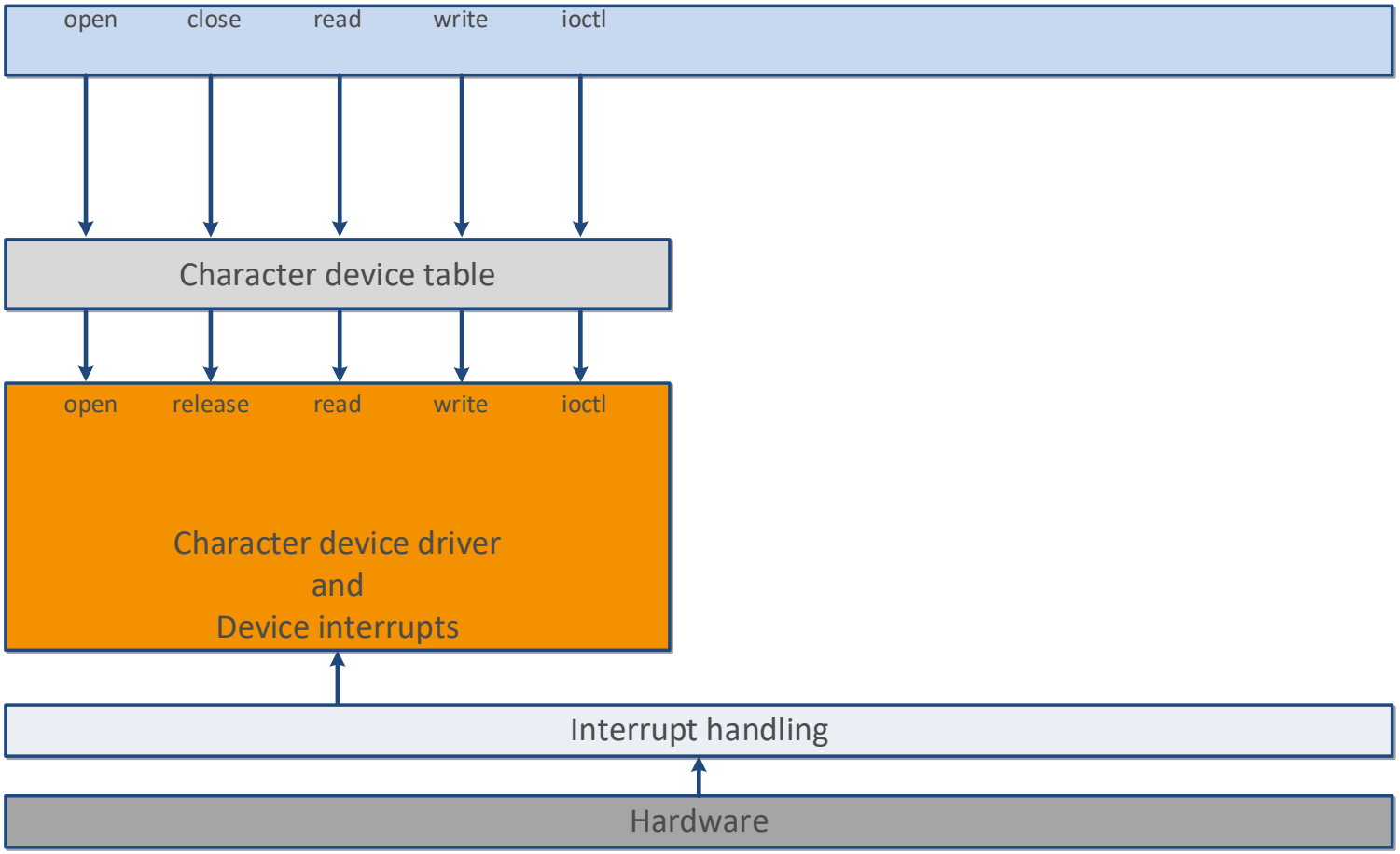
Integration of the device drivers



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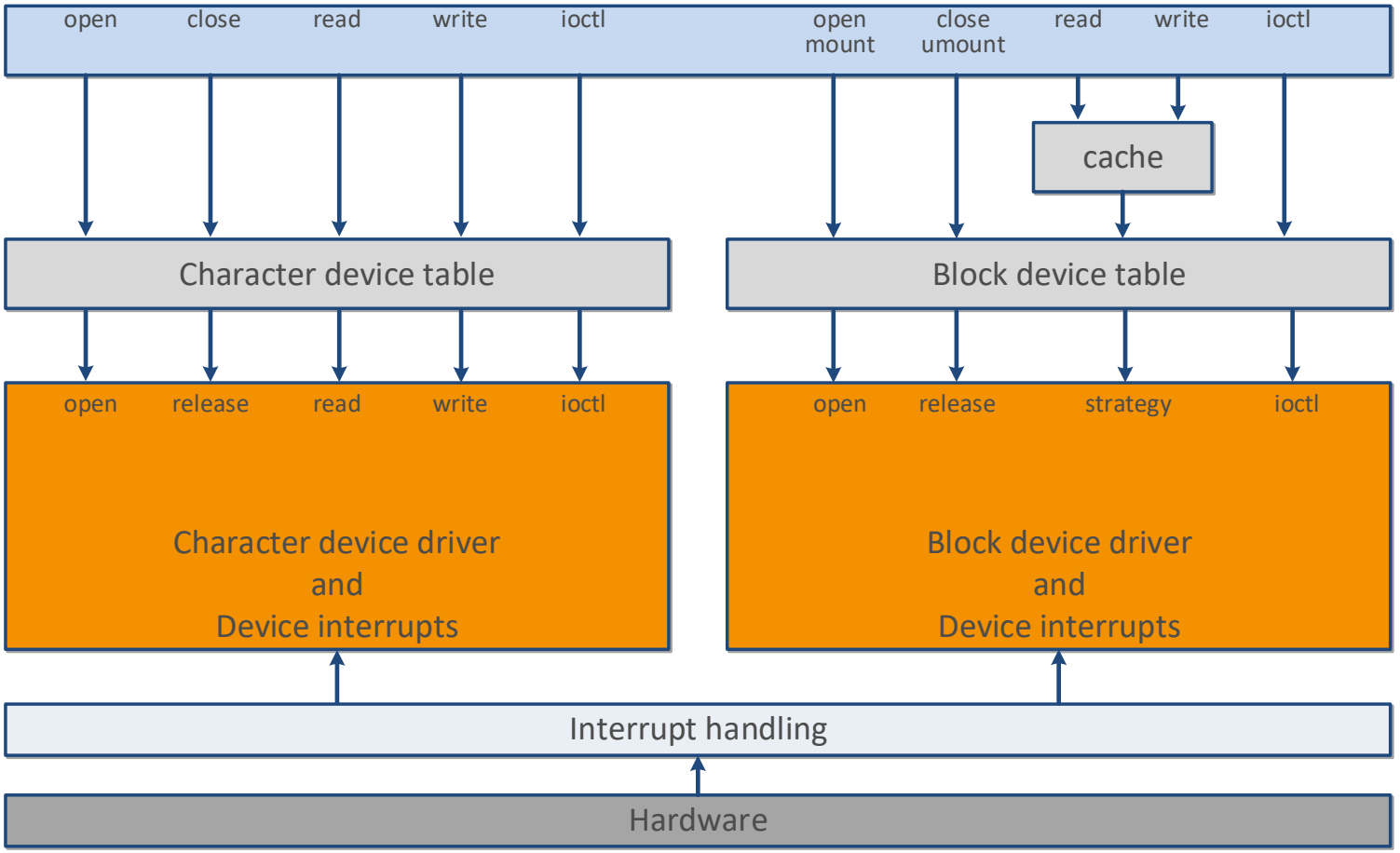

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Linux device driver tables

Character device table*

MAJOR	open	release	read	write	ioctl	Example
1	ram_open	ram_release	ram_read	ram_write	ram_ioctl	Memory
3	ser_open	ser_release	ser_read	ser_write	ser_ioctl	Serial
4	tty_open	tty_release	tty_read	tty_write	tty_ioctl	Terminal
...						

Block device table*

MAJOR	open	release	ioctl	...	Example
1	hd_open	hd_release	hd_ioctl	hd_...	Harddisk
2	fd_open	fd_release	fd_ioctl	fd_...	Floppy disk
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* Simplified visualisation of device table with sample data.

List of MAJOR device numbers: https://www.kernel.org/doc/html/latest/admin-guide/devices.html

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Kernel modules

A **kernel module** is a piece of compiled code that is dynamically loaded into the kernel.

- Filetype: `*.ko` (kernel object)
- Place: `/lib/modules` btw. `/lib/modules/$(uname -r)/`
- Executed in the context of the kernel (kernel space).
- Can be loaded and unloaded at runtime (without reboot).

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Kernel module: C template

```c
#include <linux/module.h>   //needed by all modules
#include <linux/kernel.h>   //needed for KERN_INFO
#include <linux/init.h>     //needed for the macros

//this is called when the module is loaded
static int __init exmod_init(void) {
    printk(KERN_INFO "Hello, exmod\n");
    //register functions and initialise the module
    return 0;
}

//this is called when the module is unloaded
static void __exit exmod_exit(void) {
    printk(KERN_INFO "Goodbye, exmod\n");
    //unregister functions and cleanup the module
}

module_init(exmod_init); //register the exmod_init to be called on load
module_exit(exmod_exit); //register the exmod_exit to be called on unload

//module meta data
MODULE_LICENSE("GPL");
MODULE_AUTHOR("Florian Künzner");
MODULE_DESCRIPTION("Exmod is an example module");
MODULE_VERSION("1.0");
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Kernel modules: Linux kernel API

Inside the kernel you can **only** use the **Linux kernel API**. The `glibc` is not available there.

Linux kernel API examples:

Function	Description

Linux kernel API https://linux-kernel-labs.github.io/refs/heads/master/labs/kernel_api.html#linux-kernel-api

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Compile a kernel module

Makefile

```
1 obj-m += module_name.o
2
3 all:
4     make -C /lib/modules/$(shell uname -r)/build M=$(PWD) modules
5
6 clean:
7     make -C /lib/modules/$(shell uname -r)/build M=$(PWD) clean
```

On shell:

```
dev@dev ~/module$  make
```

Kernel Makefile doc: `https://elixir.bootlin.com/linux/latest/source/Documentation/kbuild/makefiles.rst`

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Kernel modules: Linux commands

Command	Description

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`modinfo module`	**Show** information about a `module`.
`insmod module.ko`	**Load** a `module.ko` file into the kernel.

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`depmod`	**Update** `/lib/module/$(uname -r)/modules.dep`

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`depmod`	**Update** `/lib/module/$(uname -r)/modules.dep`
`rmmod module`	**Unload** a `module`

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`depmod`	**Update** `/lib/module/$(uname -r)/modules.dep`
`rmmod module`	**Unload** a `module`
`modprobe -r module`	**Unload** a `module` and handle dependencies.

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Device driver development

The developer has to implement

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- register itself at the I/O management in the OS
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Functions that have to be implemented

Functions to load the module into the kernel

- `module_init()` → `driver_init()`
- `module_exit()` → `driver_exit()`

Functions triggered through applications

- `open()` → `driver_open()`/`close()` → `driver_release()`
- `read()` → `driver_read()`/`write()` → `driver_write()`
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Functions triggered through OS or hardware

- ISR (Interrupt Service Routine)
- Kernel threads
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Device driver: C template

```
6  #define MAJOR_NR 236
7  static int __init driver_init(void) {      //called on modprobe
8      register_chrdev(MAJOR_NR, "driver" , &fops);
9      //...
10     return 0;
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Low level function usage

User space program:

```
1  #include <stdlib.h> //EXIT_SUCCESS
2  #include <fcntl.h>  //flags O_RDWR, ...
3  #include <unistd.h> //open, close, read, write...
4  #include <stdio.h>  //printf
5
6  #define LEN 10
7
8  int main(void){
9      int fd = open("/dev/device", O_RDWR, 0666);
10
11     char buffer[LEN] = {"Hello\n"};
12     ssize_t bytes_written = write(fd, buffer, LEN);
13     ssize_t bytes_read    = read(fd, buffer, LEN);
14
15     close(fd);
16
17     return EXIT_SUCCESS;
18 }
```

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Summary

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- Design goals
- Structure of I/O systems
- Linux device files
- Kernel modules
- Linux device driver development

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The end

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