POSIX - Files and I/O

Introduction

So far, we have seen and used two key virtualization concepts of modern operating systems: the process and the memory address space. Our programs have been mainly built around processes and threads where interactions and data-exchange between those occur within the virtualized memory space, which is typically volatile (e.g., mapped to the RAM memory). Thus, all of our program's data is lost when our programs terminate, either normally or due to unexpected events such as critical errors or system power loss. Additionally, the interaction of our programs with the "outside" world has been restricted to input-output (I/O) transactions on the user's terminal.

In this laboratory work, we will see the concepts and functions provided by modern operating systems for persistent data storage (e.g., files on a hard disk drive) and I/O operations with files and devices. It is divided into 3 parts with the following objectives:

Part A – *Files.*
Part B – *Device driver (kernel space) - two weeks*

At the end there will be an **individual assessment**.

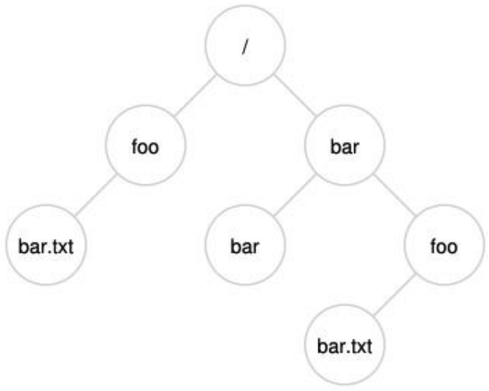
Complementary readings:
- I/O Devices (OSTEP Ch. 36)
- Files and Directories (OSTEP Ch. 39)
- Virtual Machine Monitors (OSTEP Appendix B)

Part A – Files

Files are one of the key abstractions developed over time for the virtualization of storage. A file is nothing more than a simple linear array of bytes, typically on non-volatile storage, that can be read from or written to. The operating system (OS) takes the entire responsibility on knowing how these bytes are accessed and stored in a given media (e.g., magnetic hard disk) so the user does not need to know or worry about low-level details such as cylinders, tracks, sectors, and other pesky (hard-to-deal-with) details!

Files are normally organized into directories, another type of an abstraction provided by the operating system. Directories are treated by most operating systems as special files whose content is essentially a list of files and some metadata (e.g., the kind of file, user permissions, etc.). Both files and directories have associated user-readable names (e.g., foo and bar.txt) and low-level name used and managed by the operating system itself (often known as its inode number). Files and directories can be organized into a hierarchical-tree-like structure - the directory tree (example of the figure below). In Unix-based systems, the root directory under which the directory structure storing all files and directories resides is named "/". In UNIX-like operating systems, users can explore and navigate through the aforementioned file system using a terminal console and commands such as pwd , cd , and ls (try it!).

An example directory tree (from OSTEP ch 39)



Operating systems provide a set of system calls that allow processes to perform multiple operations on files[1] such as opening, reading from, and writing to. For UNIX systems, the most important ones include:

- open() - to open/create files;
- read() - to read from an opened file;
- write() - to write to an opened file;
- fsync() - to force-transfer ("flush") written file data to the disk;
- lseek() - to "navigate" (reposition) within an opened file;
- close() - to close an opened file.

When a process opens an existing file or creates a new one, the OS creates an associated non-negative integer, known as **file descriptor**. This value corresponds

[1] There is a saying related to UNIX that goes "On a UNIX system, everything is a file; if something is not a file, it is a process.". Indeed, many services/entities (e.g., sockets, peripheral devices, etc.) are modeled by the OS as a file, making these system calls also applicable. For now, we focus on regular files.

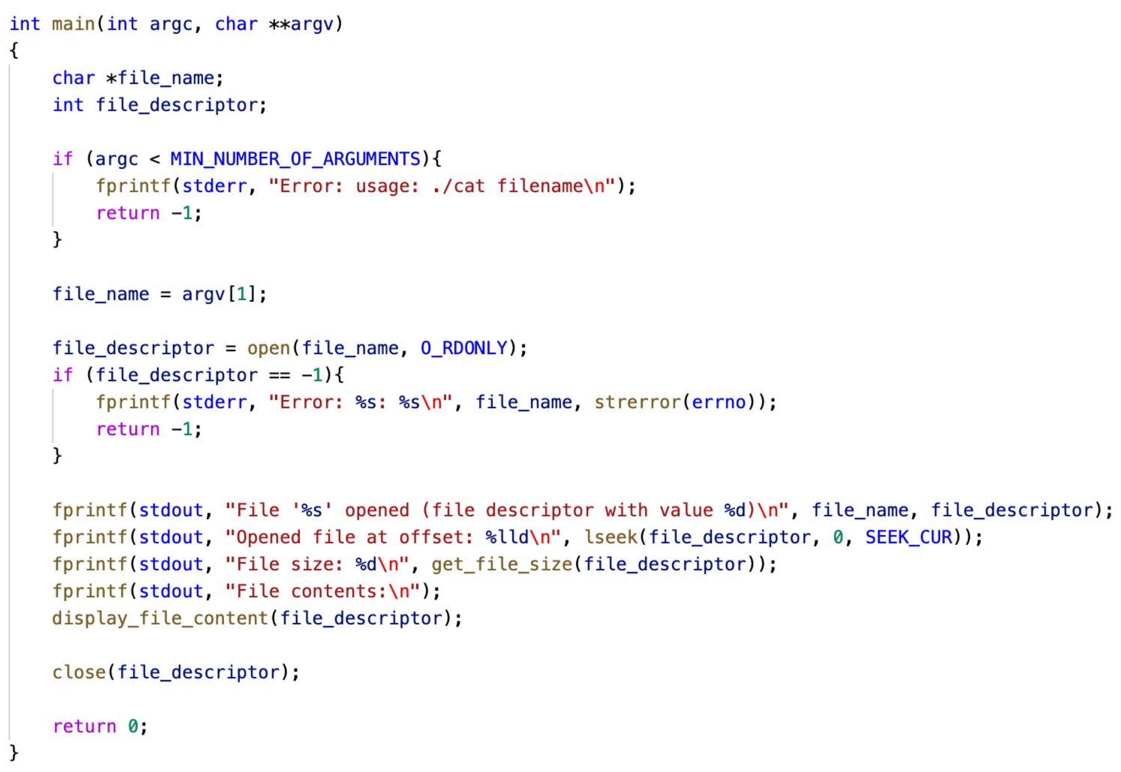
to an entry of the system-wide **open file table**. Each entry in this table tracks which underlying file is being referred to, the current position (offset) within it, and other details such as whether the file is readable or writable. Each process has its own array of file descriptors and it is possible for multiple processes to work on the same file concurrently. By default, the OS opens three **file descriptors**[2] for a newly created process:

- 0, for the standard input, from which the process can read from (typically the keyboard);
- 1, for the standard output, to which the process can dump information to (typically the terminal screen);
- 2, for the standard error, to which the process can dump error messages (typically the terminal screen or a log file).

1. Reading from a file

The code snippet below belongs to a program that displays the file size and contents of a file whose name is passed as a command line argument. Run the program with the name of the provided sample file (fearless_knight.txt) as the argument. Carefully analyze the code and verify if the obtained file descriptor value and file offset are as expected.

Tutorial Program Atp3-1 (full code @Atp3-1.c)



```c
int main(int argc, char **argv)
{
    char *file_name;
    int file_descriptor;

    if (argc < MIN_NUMBER_OF_ARGUMENTS){
        fprintf(stderr, "Error: usage: ./cat filename\n");
        return -1;
    }

    file_name = argv[1];

    file_descriptor = open(file_name, O_RDONLY);
    if (file_descriptor == -1){
        fprintf(stderr, "Error: %s: %s\n", file_name, strerror(errno));
        return -1;
    }

    fprintf(stdout, "File '%s' opened (file descriptor with value %d)\n", file_name, file_descriptor);
    fprintf(stdout, "Opened file at offset: %lld\n", lseek(file_descriptor, 0, SEEK_CUR));
    fprintf(stdout, "File size: %d\n", get_file_size(file_descriptor));
    fprintf(stdout, "File contents:\n");
    display_file_content(file_descriptor);

    close(file_descriptor);

    return 0;
}
```

[2] Instead of memorizing the corresponding integer values, programs can use the constants STDIN_FILENO, STDOUT_FILENO, and STDERR_FILENO from <unistd.h>.

Exercise 1: Using the available system calls to operate on files, complete the display_file_content() function so the entire content of the file "fearless_knight.txt" is displayed on the terminal screen (standard output).

Between consecutive read calls, display the number of read bytes and the current file offset on the screen. Observe how the file offset changes each time and if it is as expected. Experiment changing the size of the buffer and how it affects the output.

When you are done, restore the size of the buffer to 64 and delete/comment the recently introduced offset info printing.

Exercise 2: Making use of the available system calls to operate on files, complete the get_file_size() function so it correctly returns the size, in bytes, of the file "fearless_knight.txt". **Tip:** check the lseek() documentation and try to use it instead of reading through the whole file while counting read sizes.

Exercise 3: By now, you may have noticed that the changes done during the previous exercise "broke" the correct operation of your program (contents are no longer being displayed!!!). Try to understand the issue and fix the display_file_content() function.

2. Using files as Inter-Process Communication (IPC)

Files are a natural mechanism of communication between processes. Given their persistence, files can hold information written by one process and read by another one at a later time. Or one can imagine several processes collaborating in the generation of data that is saved in a common file. Similarly, several processes can collaborate in reading information from a common file and processing it in parallel. In yet another dimension, files can be used to save the outputs of processes but also the configurations that are used by processes in the beginning of their operation.

The code snippet below is part of an application comprising two processes: one producing random numbers and storing those in text format into a file (numbers.txt), and another that reads the stored numbers and splits them into two files, one for odd numbers only and another for even numbers only. In particular, the snippet belongs to the first producer process; for now, we will focus on understanding and completing the source code for the producer process only (Atp3-2-Prod.c).

Tutorial Program Atp3-2-Prod (full code @Atp3-2-Prod.c)

```
void *numbersProducer(void *vargp)
{
    unsigned int number;
    char buffer[BUFFER_SIZE];

    while (1)
    {
        number = rand() % 1000;
        printf("Generated number %u\n", number);
        // Prepare data to be written to file (integer to fixed-size string format)
        snprintf(buffer, BUFFER_SIZE, "%09d\n", number);
        // TODO - Write to file
        sleep(1);
    }

    return NULL;
}

int main()
{
    int file_descriptor = -1;
    pthread_t tid_1;

    // TODO - Open file so that:
    // - only write-only operations are allowed
    // - file is created if not existing
    // - if file exists, append data (don't overwrite file)
    // - set permissions to 0644

    if (file_descriptor == -1)
    {
        fprintf(stderr, "Error: %s: %s\n", PRODUCER_FILE_NAME, strerror(errno));
        return -1;
    }
```

Exercise 4: Complete the main() and numbersProducer() functions so the process operates as intended. First, you should properly open the output file (use the PRODUCER_FILE_NAME constant as the filename) and get a valid file descriptor. Use the same file descriptor in the numbersProducer() thread to write the data to the file. The file should be open such that:

- Only write operations are allowed;
- The file should be created if not already existing;
- If the file exists, it should not be overwritten (data should be appended);
- Set access permissions to 0644 (you can check what this means if you want - we won't cover access permissions in detail here).

With the producer process now (hopefully!) working, let's now have a look at the consumer process (code snippet below).

Tutorial Program Atp3-2-Cons (full code @Atp3-2-Cons.c)

```
int main()
{
    pthread_t tid_1, tid_2;

    // TODO - Open the producer file so that:
    // - only read operations are allowed
    // - file is created if not existing
    // - set permissions to 0644
    // Hint: remember that both threads will read from the same
    // file and how file descriptors track the progress within
    // the file....
    if (file_descriptor == -1)
    {
        fprintf(stderr, "Error: %s: %s\n", PRODUCER_FILE_NAME, strerror(errno));
        return -1;
    }

    pthread_create(&tid_2, NULL, oddNumbersConsumer, /* TODO - Complete me */);
    pthread_create(&tid_2, NULL, evenNumbersConsumer, /* TODO - Complete me */);

    pthread_join(tid_1, NULL);
    pthread_join(tid_2, NULL);

    exit(0);
}
```

Exercise 5: Complete the functions: main(), oddNumbersConsumer() and evenNumbersConsumer() so the process operates as intended. An important detail: both tasks must read from the same file, concurrently, and each of them must process every stored number. That is, if the file contains the sequence [1, 7, 6], both threads should read numbers 1, 7, and 6, and process them accordingly. Recall how file descriptors track the progress within the file in hand, and think of a way to overcome potential issues (Hint: you can open a file multiple times).

3. Locking files for consistent access

When files are shared among multiple processes that execute concurrently, we can run into race conditions. This is very unlikely if the information in the file is accessed with a single read/write command, because of the "block access" nature of the disk[3]. Thus, when a read operation is done it cannot be interrupted by a write operation on the same physical block. This is enforced by the disk controller. However, this is not the case when accessing information with a sequence of read/write operations. In this case, a write operation can be executed in between read operations and corrupt the information being read as a whole.

[3] Generally, devices can be classified in character-oriented (read/write operations are done one byte at a time, e.g., serial port, a text terminal) and block-oriented (read/write operations are done in blocks at a time, e.g., hard disks or solid-state disks).

UNIX-like operating systems define different types of locks that can be semantically attached to files to provide mutually exclusive access, i.e., like mutexes for threads.

Some locks are standardized in POSIX, too, namely the so-called *advisory record locks*. We will now use these locks and apply them to the same producer-consumer problem as before. The locks we will use are defined in `<fcntl.h>`, namely the `struct flock`. Typically, one lock is created in each process that accesses the file. The semantics of these locks is "*single writer, multiple readers*". This means that mutual exclusion is enforced between a writer process and any other process that accesses the file, be it writer or reader. On the other hand, it is not enforced when readers, only, are accessing the file.

Moreover, these locks can protect the whole file or just a block of it, specified in a similar manner as the `lseek()` system call to navigate within the file. This is particularly useful when accessing large files to reduce blocking times.

The following is an example of a record `lock` declared to lock a specified file, as a whole, for writing:

```
#include <fcntl.h>

struct flock lock;  // lock is a file lock (type flock)

lock.l_type = F_WRLCK;
     /* F_WRLCK write lock, F_RDLCK read lock, F_UNLCK unlock */
lock.l_whence = SEEK_SET; /* base for offset of block to be locked */
lock.l_start = 0;         /* start of block to be locked */
lock.l_len = 0;           /* its length (0 means until end of the file) */
lock.l_pid = getpid();    /* pid of process using this lock */
```

The system call that is used to operate these locks is `fcntl()`. This is a powerful function that can be used for multiple purposes. Here we will use it with the following prototype:

```
int fcntl (int fd, // file descriptor of the associated file
           int cmd,       // action to carry out on a file lock
           struct flock *lock);   // the lock attached to the file

// possible commands:

// F_SETLK - try to acquire a lock, non-blocking (returns immediately)

// F_SETlKW - try to acquire a lock and wait if blocked, until success
// F_GETLK - check if a lock can be acquired
```

Assuming that a lock was declared and initialized as above, the typical usage pattern is as follows:

```
// specify the type of lock, for reading F_RDLCK or for writing F_WRLCK
lock.l_type = F_RDLCK; // specify lock for reading
// try acquiring the lock and, if busy, wait until lock is free (F_SETLKW)
if( fcntl( fd, F_SETLKW, &lock ) < 0 )
  exit(-1);  // error in acquiring the lock
// lock was acquired, you can read from the file here

// When done, you can release the lock explicitly
lock.l_type = F_UNLCK;
if (fcntl(fd, F_SETLK, &lock) < 0)   // no need to wait, command F_SETLK
  exit(-1);  // error in releasing the lock
// this lock is released
```

Exercise 6: Using the pattern above, modify the previous producer-consumer application to protect the access to the file with file locks.

Note: File locks (`struct flock` and the `fcntl()` system call) were not made for threads. In particular, it does not provide mutual exclusion among threads. However, in the exercise of part A.2, the two threads are consumers (readers), while the producer (writer) is another process. Thus the mutual exclusion is still enforced between the two processes. In other words, it works. Nevertheless, try modifying exercise 5 to use two consumer processes instead of two threads, and so do it properly !

Check the `fcntl()` man page:
`https://man7.org/linux/man-pages/man2/fcntl.2.html`

Part B – Device driver (kernel space)

Device drivers are pieces of software in the operating system that know, in detail, how a particular device works and how to interact with it (e.g., send/receive data through a network interface card). As low-level interactions with hardware frequently require access to privileged functions, device drivers are typically run within the OS kernel address space.

To implement and add device drivers to the kernel, two approaches can be followed: (i) add the device driver's code to the kernel source tree itself, (ii) load the compiled device driver's code to the kernel while it is running. The former approach is very rigid, requiring the whole system to be brought down and the kernel recompiled every time a new piece of code has to be included. The latter uses **loadable kernel modules** (LKMs) to extend the functionality of the kernel (with the code that we want, i.e., the device driver) during runtime. LKMs can perform a variety of functions, from device and file system drivers to system calls. Indeed, we will use LKMs to develop our own device drivers through the remainder of this lab script.

This part of the script is divided into two phases, each one to be executed within a class session. During the first phase, we will get acquainted on how to program simple LKMs, how to load/unload them, get acquainted with basic kernel API functions, and how to interact with the developed LKMs through user-space. For the second part, we will develop a device driver implementing a "pipe" that can be used for user processes to exchange data between themselves, emulating a communication peripheral device.

NOTE: All development and testing should take place inside a Virtual Machine on your lab or personal computer as LKMs have free run of the system and can easily crash it. Lab computers should already have the utility VMbox with a Linux image ready to be used.

IF YOU HAVE SKIPPED OVER THE PREVIOUS NOTE, READ IT NOW BEFORE CONTINUING!!!

1. Building and using loadable kernel modules

When you boot your Linux machine (or VM), a series of LKMs to control multiple aspects of your system are already probably loaded[4] and running. You can get a list with all modules by executing the lsmod command. Note that all commands to manage LKMs can only be executed using elevated privileges (either by logging in as root or using the sudo command, which is more common, e.g., sudo lsmod). Typically, ordinary users do not have permissions to "mess" with kernel-related stuff.

[4] The compiled LKM modules for most Linux distros are typically found under the /lib/modules/$kernel-version$/ folder.

Let's now have a look on how to build our first LKM; a basic skeleton is shown in the following code snippet.

Tutorial Program Btp3-1 (full code @hello.c)

```c
#include <linux/init.h>
#include <linux/module.h>
#include <linux/kernel.h>

MODULE_LICENSE("Dual BSD/GPL");
MODULE_AUTHOR("I'd rather not say");
MODULE_DESCRIPTION("My first LKM");
MODULE_VERSION("0:0.1");

static int hello_init(void)
{
        printk(KERN_ALERT "Hello, world\n");
        return 0;
}

static void hello_exit(void)
{
        printk(KERN_ALERT "Goodbye, cruel world\n");
}

module_init(hello_init);
module_exit(hello_exit);
```

A kernel module must implement at least two functions: an initialization function, called when the module is loaded into the kernel, and a cleanup function, called upon module unloading. In the example above, we can see the function hello_init() being declared by the pseudo-macro module_init() as the module's initialization function. Similarly, function hello_exit() is declared by module_exit() as the module's cleanup function. Modules can optionally include miscellaneous metadata concerning, for example, the type of license (macro MODULE_LICENSE) and author (MODULE_AUTHOR). Users can use the modinfo command to read this information from compiled modules.

LKM functions are part of the kernel and as such, it is not possible to use the standard C libraries as we have been doing for our previous user-space programs. Hence, we cannot call C library functions like printf(). Instead, modules can only call functions belonging to the kernel API. In the code example above, the printk() kernel function replaces the functionality of printf()[5]. You can also find kernel functions to dynamically allocate memory, write to files, etc.

Due to their nature, LKMs are compiled differently from regular user-space applications (e.g., should not be linked to libraries, must be compiled with the same options as the kernel, etc.). We will not dwell into details on this topic. For each

[5] Note: the information printed by printk() is not typically seen under the user console, but sent to a special kernel buffer that can be consulted, for example, using the dmesg command. Additionally, printk() defines multiple log levels (KERN_EMERG, KERN_ALERT, …, KERN_INFO, KERN_DEBUG) that denote the importance of the message. Consult the printk() documentation for more info.

exercise, a build script (a file named *Makefile*) will be provided that can be used by the make utility command to build the LKM.

The building process of a LKM results in a number of output files, among which, a **.ko** file, the object file with the built kernel module. Built modules can be installed (loaded) using the insmod utility command and the respective **.ko** file. A module can be uninstalled (unloaded) by invoking the rmmod utility with the module's name as command argument (the module name is typically the name of the **.ko** file, without the file extension).

Exercise 1

Download the hello.c and Makefile files to your virtual machine (or shared folder between host OS and virtual machine). Open the Makefile file. At the end you will see the line **obj-m := hello.o** ; this instructs the build tool to create several output files, including **hello.ko,** the object file with the **hello** kernel module. Now, try to build your LKM by invoking the make utility command inside the directory that contains both hello.c and Makefile files.

After successfully building the module, use the modinfo utility to confirm that the metadata is as expected. Next, load the module into the kernel and confirm that it is indeed loaded by executing the command **lsmod | grep hello** (check grep if you want to know what this does). Verify that the "Hello, world" message has been logged. When done, unload the module and confirm that the operation was successful. Confirm that the expected message is logged upon removing the module.

2. Creating a device driver - the echo pseudo device driver

After knowing the basics on how to create an LKM and use it, we will now develop a device driver that just writes to the console what is written to the pseudo device (we call this a pseudo device because it does not control any I/O device, not physical not even virtual).

In Linux systems, devices mostly fall into one of two categories: **character** and **block** devices. Whereas the latter category allows accessing data in independent "blocks", the former allows data to be retrieved only as a stream of characters and bytes. Nevertheless, both device types are accessed through names in the filesystem, corresponding to special files or device files[6]. These device files are conventionally located in the /dev directory. If you issue (try it!) the **ls -l** command for this directory, you will see something akin to the next image snapshot, where device files for character and block devices are identified by a "c" and a "b" in the first column, respectively.

[6] Recall the UNIX saying that goes "On a UNIX system, everything is a file; if something is not a file, it is a process."

```
crw-rw-rw- 1 root   root     1, 3   Feb 23 1999  null
crw------- 1 root   root    10, 1   Feb 23 1999  psaux
crw------- 1 rubini tty      4, 1   Aug 16 22:22 tty1
crw-rw-rw- 1 root   dialout 4, 64   Jun 30 11:19 ttyS0
crw-rw-rw- 1 root   dialout 4, 65   Aug 16 00:00 ttyS1
crw------- 1 root   sys      7, 1   Feb 23 1999  vcs1
crw------- 1 root   sys      7, 129 Feb 23 1999  vcsa1
crw-rw-rw- 1 root   root     1, 5   Feb 23 1999  zero
```

You can also see two numbers separated by a comma. These numbers are known as the **major** (leftmost) and **minor** (rightmost) device numbers, used by the kernel to identify a particular device. The major number identifies the driver associated with the device. In the snapshot above, devices /dev/ttyS0 and /dev/ttyS1 (the virtual consoles) are both managed by driver 4. The kernel uses the major number at *open* time to dispatch execution to the appropriate device driver. The minor number is only used by the driver itself, not by the kernel, and is commonly used to identify a single device out of several (a device driver can control several devices, as shown in the above snapshot).

Note: The kernel also keeps a list with all the currently assigned major device numbers in the **/proc/devices** file; you can run the command **cat /proc/devices** to see its contents.

2.1. Allocation of a device number

When building an LKM for a device driver, users can either request the assignment of pre-defined major/minor device numbers (static assignment) or let the kernel assign them dynamically. Nowadays, major device numbers are commonly assigned dynamically to avoid picking an existing number. For example, device drivers for character devices can request their device numbers from the kernel with the alloc_chrdev_region() function (defined in <linux/fs.h>). The function returns a kernel data structure type **dev_t** (defined in <linux/types.h>) that holds both numbers. The LKM can use the macros MAJOR(dev_t dev) and MINOR(dev_t dev) to obtain the major and minor numbers, respectively. Upon unloading, LKMs should release the allocated device numbers. For character devices, this is done by invoking the unregister_chrdev_region() function.

Exercise 2
The next code snippet belongs to the source code of the device driver we are going to develop throughout the remainder of this section.

Tutorial Program Btp3-2 (full code @echo.c)

```
static int echo_init(void)
{
    int alloc_result = -1;

    // TODO register device driver so that:
    // - Driver name is echo
    // - Major number is dynamically assigned
    // - Minor number starts from 0
    // - Only one device needs to be managed by the driver

    if (alloc_result < 0){
        printk(KERN_ERR "Failed to register echo device driver\n");
        return alloc_result;
    }

    // TODO print "Echo device driver resitered with major number X"
    // to the kernel logging buffer so that:
    // - X is the obtained major number during registration
    // - Message printed using the informational log evel

    return 0;
}
```

Download all the necessary files (echo.c and Makefile), and complete the echo_init() and echo_exit() functions so the device driver is properly registered/unregistered, and the described log messages displayed on the kernel log buffer. Verify that you are able to load and unload the module to the kernel properly, and that the major device number is freed (see the **/proc/devices** file).

2.2. Creation of the device file

So far, we have developed a module that is able to register and obtain a valid device number from the kernel. However, after loading the module, you might have found (if not, try it now) that no device file for our echo driver has been created under the /dev directory! This is normal, as the device file is not created automatically. Indeed, dynamically allocating the major number has a disadvantage: you can't create the device files in advance as the major number assigned to the module can't be guaranteed to always be the same. One way around this problem is to write a script that immediately creates[7] the required device files after loading the device driver. This is possible as the kernel logs all the assigned major device numbers in the **/proc/devices** file; you can run the command **cat /proc/devices** to have a look into it (try it with and without your module loaded). Similarly to the compilation of kernel modules, we will not dwell on the details concerning the development of such scripts; these will also be provided to you throughout the next exercises.

Exercise 3

Download the load_driver.sh and unload_driver.sh scripts. These allow you to load/unload an LKM device driver and create/delete the respective device files. Both scripts take as argument the name of the module to load/unload (without the .ko extension), and must be run with elevated privileges.

[7] Device files can be created using the mknod utility.

First, make sure that the echo driver module has been unloaded since the previous exercises. Then, execute the load_driver.sh script. Verify that the module is indeed loaded and that a device file named “echo” has been created under /dev/ with the correct major and minor numbers. Afterward, run the unload_driver.sh script. Confirm that the module has been unloaded, the device file removed, and that the major number has been released (check /proc/devices).

2.3. Interacting with device files

Now that we have a device file associated with our driver, we can start interacting with it. As you may recall from Part A of this script, we have used a set of system calls such as open(), close(), write(), and read() to perform multiple operations on a file from programs living in user-space. In Linux, these same calls can be used for any kind of file, device files included! However, before these can be used, they must be implemented and registered by the respective device driver in kernel space. In the following section, we will see how a (character) device driver can register its supported system call operations and how they are linked to its implementations by the driver. Afterward, we will see how to implement the most common operations using our driver: open(), close(), write(), and read().

2.3.1. Registering character devices and their operations

Internally, the kernel uses structures of type **struct cdev** (<linux/cdev.h>) to represent a char device and their capabilities. Therefore, before the kernel can be able to invoke the operations of a given device, the driver must allocate and register one (or more) of these structures. A driver can allocate a new **cdev** using the cdev_alloc() function.

A **cdev** structure contains two members: (i) **owner**, used to point to the kernel module to which the driver belongs (always set with the macro THIS_MODULE), (ii) **ops**, a pointer to a structure of type **struct file_operations** (<linux/fs.h>). This last structure specifies the different operations required to implement system calls such as open() and read() supported by the device driver. Essentially, it contains a set of pointers to functions defined by the driver, each of which implements the operations required for the implementation of a given system call. You can find a detailed description of this structure in Ch. 3 of the LDD3 book, page 49 and following.

After creating and initializing the **cdev** structure, the device driver must register it in the kernel by invoking the cdev_add() function. As the main purpose of this device registration is to “tell” the kernel which operations are supported by the device, it should be done within the driver’s initialization function. Similarly, the driver’s cleanup function should remove from the system all **cdev** structures it has previously registered; this can be done by using the cdev_del() function.

Note: As soon as **cdev_add** returns, the device is “live” and its operations can be called by the kernel. Thus, it should only be called when the driver is completely initialized and ready to handle operations on the device.

<u>Exercise 4</u>
Extend the device driver’s echo_init() and echo_exit() functions so the device and its capabilities are registered/deregistered. The structure **file_operations** is already created and filled to indicate the driver’s functions associated with each system call operation, so you need only to allocate, fill and register the **cdev** structure. To test if the registration was successful, load the module and execute **echo 1 > /dev/echo** ; you should see in the kernel log buffer the message “echo_open(): Returning”[8] if everything is correctly done (ignore a potential error message in the user terminal).

2.3.2. Implementing open() and close()

As you may recall from Part A of this script, in Linux, a file (of any kind) must first be opened by an application before performing any operations on it. Likewise, an application must close an opened file once done using it. In this section, we will learn how to implement the necessary functionality in our driver for the support of the open() and close() system calls.

Drivers can implement the **open file operation** to be invoked every time an open() system call is executed. This operation is used to perform any initialization, device-specific procedures in preparation for later operations on the device. In most drivers, the open operation should perform the following tasks:

- Check for device-specific status and errors (e.g., device-not-ready);
- Initialize the device if being opened for the first time;
- Update the reading/writing position, if necessary (recall file offsets from part A in this project script);
- Allocate and fill any auxiliary control data structures (e.g., state information).

The prototype for the open operation is:

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

Note: driver’s operation methods are invoked by the kernel upon certain events such as when a given process invokes a system call. Therefore, the arguments of these methods are used by the kernel to pass relevant information into the driver implementation.

The first order of business is usually to identify which device is being opened (recall that a driver can control multiple devices). As we have seen in the previous section, devices are registered using the **cdev** structure. However, from the open prototype

[8] Why do we see such a message? In summary, the executed command line command tries to write “1” to the file /dev/echo … our device file! Recall that before being able to write to a file, it must first be opened using the system call open(). Well, that’s what happened here! However, since we didn’t implement the support for it in our driver, yet, … the command stops dead there and no write() operation is even tried :)

we see that such structure type is not provided. Instead, two new structures are available:

- **struct inode** - This structure represents a file, a regular or a special file. Note that even though a given file may be opened simultaneously by different processes, the kernel keeps a single struct inode. Among other members, this struct includes the member struct cdev *i_cdev that points to the cdev struct of the corresponding device. This is all you need to know for this project about the inode structure. You can find detailed information on this structure in Ch. 3 of the LDD3 book, on page 55;
- **struct file -** It represents a file descriptor, which is returned on an open system call. Among other members, this struct includes the member **void *private_data** that can be used by a device driver to maintain state information across system calls. For this project, this is all you need to know about the file structure. Detailed description on this structure is available in Ch. 3 of the LDD3 book, on page 53 and following.

Because some operations provided by the device driver, such as **read** and **write**, do not take as argument the address of a **struct inode,** but only the address of a **struct file**, the **private_data** member of the **struct file** is initialized during the **open** method with the address of the corresponding **struct cdev**.

For the close() system call, device drivers implement the **release operation** whose prototype is as follows:

*int release(struct inode *inodep, struct file *filep);*

Here, the arguments are the same as for the open operation, and this operation usually undoes what the open operation has done (e.g., free data structures). Note that not every invocation of the close() system call leads to the invocation of the release operation. If you want some operation to be performed on every invocation of the close() system call, define a **flush** file operation, which is indeed invoked on every close system call. A more detailed discussion of these issues can be found in Ch. 3 of the LDD3 book, on page 59.

Exercise 5

Complete the echo_open() function of the echo device driver. To that end, initialize only the **private_data** member of **struct file** to point to **struct cdev**, and print a short message telling what was just done. Also, change the return code to 0 to signal success. The release operation does not need any changes for now.

Test the module by executing **echo 1 > /dev/echo** . This time, you should see in the kernel log buffer that the **echo_write**() and **echo_release()** functions are invoked as **echo_open()** is now functional.

2.3.3. Implementing read() and write()

A device is usually used for data input/output, therefore we would expect a device driver to provide operations supporting data transfer. In the case of the echo device driver we would like it to support:

- **write** - shows in the user console whatever an application writes to the device;
- **read** - returns how many characters have been written out by all applications to the device since the last time it was loaded.

The prototypes of the aforementioned operations are as follows:

*ssize_t read(struct file *filep, char __user *buff, size_t count, loff_t *offp);*

*ssize_t write(struct file *filep, const char __user *buff, size_t count, loff_t *offp);*

filep is the file pointer, **buff** is a buffer used to transfer data either from user space to the kernel or vice-versa, **count** is the size of the requested transfer, **offp** is a pointer to a long offset type object that indicates the file position the user is accessing. The **offp** argument is needed because device drivers are not aware of the file position: it is maintained by the file system layer. Nevertheless, so that that layer can update the file structure, usually the code should update the file position at ***offp** accordingly after the data transfer.

In the case of the echo device, seeking does not make sense, hence there is no need to keep the file position. Because the default implementation of the operation allows seeking, the **open** operation must invoke the function:

*extern int nonseekable_open(struct inode * inode, struct file * filp);*

This way, the kernel will prevent an lseek() system call from succeeding. In addition, the llseek operation of the struct file_operations should be set to the special helper function **no_llseek** .

Both **read** and **write** should return the number of bytes transferred, if the operation is successful. Otherwise, if no byte is successfully transferred, then they should return a negative number. However, if there is an error after successfully transferring some bytes, both should return the number of bytes transferred, and an error code **in the following call** of the function. This requires the device driver to recall the occurrence of an error from a call to the next. However, the echo device driver needs not worry with partial success because it will always succeed in performing those operations.

Both in read() and in write(), the buff argument is a pointer to user space, and should not be directly dereferenced by kernel code. (An explanation of why this is so can be found in Ch. 3 of the LDD3 book, on pages 63 and 64.) Instead, you can use the following kernel functions, which are defined in <asm/uaccess.h>:

*unsigned long copy_to_user(void __user *to,const void *from,unsigned long count);*

*unsigned long copy_from_user(void *to, const void __user *from, unsigned long count);*

Note that the pages containing the buffer may not be in memory, and the process may be put to sleep while the page is brought in. Therefore functions that invoke them must be **reentrant** and be **able to execute concurrently** with other driver functions.

Exercise 6
Extend the device driver with the following changes:

- Modify the device driver's **open** operation to inform the kernel that the device is non seekable.
- Complete the **write** file operation. It should read the data from the user space buffer to a kernel space buffer, and then print it. Make sure that the last character in the buffer is code 0. Do not forget to free any buffer you allocate in the kernel.
- Implement a small test program to test the system calls open(), close(), lseek(), and write() on the device driver.
- Modify the **write** operation so that it updates the number of characters it echoes.
- Complete the **read** file operation so it returns the total number of characters echoed by the device.
- Change the test program to also test the read operation.

3. Creating a device driver for a *pipe* inter-process communication

In this section we will strengthen our knowledge of the device driver creation process by creating a *pipe* device, i.e., a FIFO that can be written by one process and read by another. Linux already implements what are commonly known as *Unix pipes* represented in the shell input with the character '|'. These pipes are a way of connecting the output of a process to the input of another one, thus allowing their execution in a chain. These are extremely useful in scripting and allow creating powerful sequences of commands.

In our case, we will design a device driver that implements the pipe functionality. In particular, it will implement a circular buffer (see the last exercise of lab assignment two) that can be opened by a producer or a consumer process and allow them to exchange information.

Both system calls for writing and reading should be synchronous and non-blocking, i.e., in the absence of free space (for writing) or new data (for reading) they should return immediately with the appropriate error indication.

Exercise 7
Use as base the device driver you developed in exercise 5 (should have *empty* read and write functions):

- Give it the name "mypipe" and change all functions names accordingly.
- Include `"buff_helper.h"` with the circular buffer definitions and functions.
- Right below this *include*, declare your circular buffer reserving space (in `mypipe_buffer`). Note this will instantiate the buffer as a global variable within the module.

```
#define BUFFER_MAX_SIZE 10

unsigned int data_space[BUFFER_MAX_SIZE];
circ_buff_t mypipe_buffer = {
    data_space,
    BUFFER_MAX_SIZE,
    0,
    0
};
```

- Make sure all functions will return 0, instead of -1, so you can test them without generating errors.
- Replace “echo” with “mypipe” at the end of the Makefile.

At this point, compile the device driver and load it. It will not do any useful function, yet, but you can test if this template is ok. After loading the device driver, try writing to it with `echo AAA > /dev/mypipe`. Similarly, try reading with `cat /dev/mypipe`. None of these operations should do anything expect printing the `printk` messages.

If this is all ok, then let’s proceed to the next exercise, which consists in adding the necessary code to ge the desired functionality.

Exercise 8

Use as base the device driver you developed in exercise 5 (should have *empty* read and write functions):

- Modify the device driver **open** function to inform the kernel that the device is non seekable similarly to Exercise 6.
- Complete the **read** and **write** device functions. Use the circular buffer functions `circ_buff_pop` and `circ_buff_push`, respectively, to access the kernel FIFO buffer `mypipe_buffer`. Note that these functions read/write one byte at a time. Thus, you will need to use them inside an adequate loop to transfer from/to the user *buffer* (argument of the device functions). The number of bytes to transfer is at most *count* (argument of the device functions). The loop should finish if the *pop* function returns *buffer empty*, or if the push function returns buffer full.
- The **return** value of the **read** and **write** functions should be the actual number of bytes read or written. If **no byte** was read or written (FIFO empty or full from the start), the functions should return an error condition (-1).

Note that the circular buffer (the FIFO mypipe_buffer) is implicitly released when the module is unloaded.

Similarly to the previous exercise (7), after compiling and loading, test your device writing to it with `echo AAA > /dev/mypipe`. Then read from it with `cat /dev/mypipe`. You should see what you wrote before.

A better test consists in writing a simple program that launches a producer process and a consumer process, which communicate via this device (pretty much as if it was a file!).

If you feel up to the challenge, you can further complicate the device!

- Instead of doing a static allocation of the circular buffer as with mypipe_buffer, try doing dynamic allocation with kmalloc() when the module is installed. Don't forget to release it when the module is removed.
- You can verify in the open function whether the device is already open and if for writing or reading. You can force an error if more than one process tries to open the device for the same function, either writing or reading. Note that the circular buffer functions, as they are, may not work well with multiple readers or writers.
- You can save the circular buffer in a file when the module is removed and you can load the file contents to the circular buffer in memory upon module insertion.
- The ultimate challenge will be to do blocking read/write operations, so that the device driver waits until it can satisfy the user request (e.g., enough space in the buffer or enough data in the buffer)

Note that all these suggestions are beyond the objectives of this course!