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Implementation of Linux GPIO Device Driver on Raspberry Pi Platform

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The project was aimed at implementing a General Purpose Input/Output (GPIO) device driver for the Raspberry Pi model B rev 2.0 platform. Specific attention was given to implement the device driver based on the Linux character device driver.

Each of the GPIO pins on Raspberry Pi is exposed to userspace for use by a device file in the */dev* directory. While a dynamically assigned major number was used to identify the device driver associated with the GPIO device, a minor number was used by the kernel to differentiate between GPIO pins that the device driver controls. Four entry points were implemented to handle low-level hardware GPIO resources on behalf of system calls requested by a userspace application. Besides, interrupt handling was implemented as an experimental feature to see how a device driver supports interrupt in an embedded Linux system.

The GPIO device driver could be used on the Raspberry Pi platform by loading it either as a kernel module or as an integral component of the Linux kernel. One or more userspace processes could open a device file for reading the logic level of a GPIO pin, controlling the direction of a GPIO pin, and setting its logic level to high state or low state. Besides, interrupt handling feature was tested; the result showed that more than one process could share an interrupt resource on a GPIO pin and could disable interrupt on that GPIO pin.

There still remain, however, some limitations to the features offered by the driver. Interrupt handling is still an experimental feature. More work needs to be done to make the feature useful for use. Furthermore, the GPIO character device driver is deprecated with a newer version of the Linux kernel by the gpio-sysfs driver.

Keywords	Linux GPIO driver, Raspberry Pi, Linux character driver, GPIO kernel module

Contents

List of Abbreviations

API	Application programming interface
DHCP	Dynamic host configuration protocol
DMM	Digital multimeter
DNS	Domain name system
FAT	File allocation table
GCC	GNU compiler collection
GND	Ground
GPIO	General-purpose input/output
GPU	Graphics processing unit
I2C	Inter-integrated circuit
IC	Integrated circuit
IDE	Integrated development environment
IO	Input/ouput
IP	Internet protocol
IPC	Inter-process communication
LAN	Local area network
LED	Light-emitting diode
LTS	Long term support
MAC	Media access control
PC	Personal computer
PLD	Programmable logic device
PWM	Pulse-width modulation
SD	Secure digital
SoC	System on chip
SPI	Serial peripheral interface
SSH	Secure shell
UART	Universal asynchronous receiver/transmitter
USB	Universal serial bus
UTP	Unshielded twisted pair
VFS	Virtual filesystem

1 Introduction

Nowadays Linux is an operating system of choice for many computing systems ranging from personal computers (PC), servers, mainframe computers and supercomputers to electronic devices known as embedded systems. An embedded system is a computing system which is specifically designed to carry out a set of dedicated tasks, and it typically uses a custom microcontroller as its main processing unit. Linux is a highly portable operating system; it can run on a variety of hardware architectures such as x86, PowerPC, MIPS, H8, SPARC, or ARM, to name just a few.

This portability also comes with limitations, however. It is no doubt that while the modular architecture of Linux makes it easy when porting to different types of architectures, a great deal of effort is required to build new kernel components in order to support a target platform. The real hard work of these efforts is to develop device drivers for a particular target platform. A device driver (kernel module) is a piece of software that consists of a set of low-level interfaces, and is designed to control a hardware device. The Raspberry Pi platform is an example of a target device that Linux can be ported to run on it. GPIO device driver is one of the kernel components that can be developed to support the Raspberry Pi platform. The goal of this project was to implement a GPIO device driver for Raspberry Pi.

Specifically, attention was given to the implementation of the GPIO device driver based on Linux character device drivers. The intended result of this work was to give a deeper understanding on the Raspberry Pi platform, to learn what a Linux device driver does and how it works, and finally to implement a GPIO character device driver for the Raspberry Pi platform from scratch.

2 Theoretical Background on the Embedded Linux System of the Project

2.1 Raspberry Pi Model B Rev 2.0 Platform

The Raspberry Pi model B rev 2.0 platform was chosen for the project to implement the Linux GPIO device driver. This is due to the fact that Raspberry Pi is a low-cost Linux computer which costs approximately $35 from the Farnell distributor. The platform is widely used by hobbyists and professional embedded developers around the world. Therefore, there is a large support from the community when it comes to getting help or information. For convenience, Raspberry Pi will be used when referring to the Raspberry Pi model B rev 2.0 platform throughout this report. Figure 1 shows the Raspberry Pi platform used in the project.

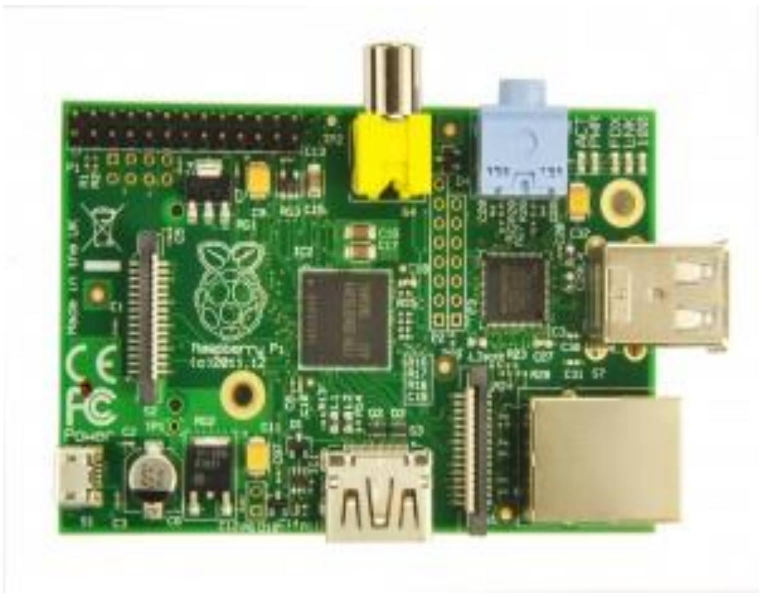
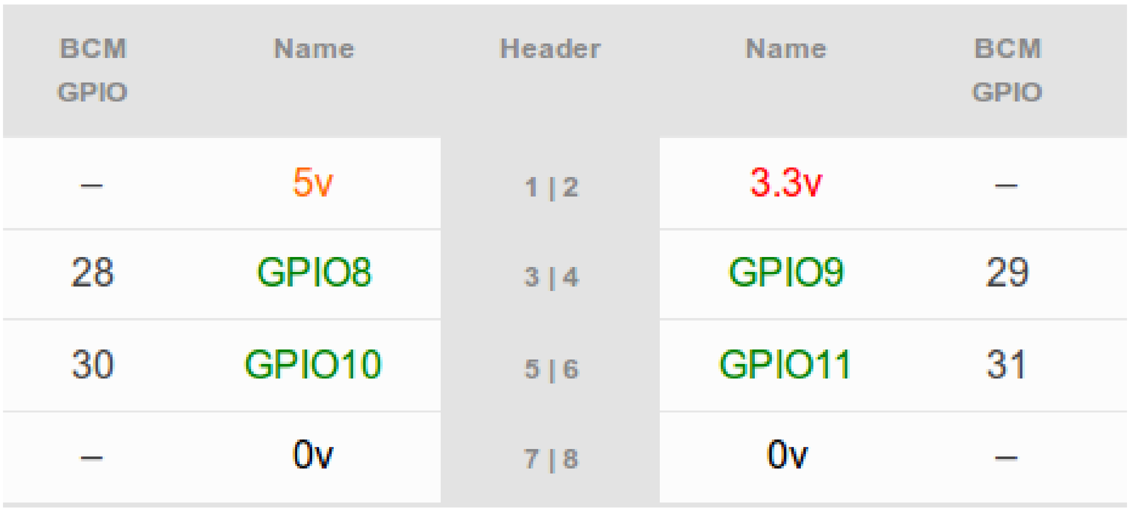


Figure 1. Raspberry Pi model B rev 2.0 platform
Reprinted from Raspberry Pi Wiki (2014) [1]

Raspberry Pi is a fan-less embedded computer which is equipped with a wide range of peripherals such as Universal Serial Bus (USB), Ethernet, Universal Asynchronous Receiver/Transmitter (UART), High-Definition Multimedia Interface (HDMI), Serial Peripheral Interface (SPI), Inter-Integrated Circuit (I2C), audio codec and so on. The heart of the platform is a Broadcom BCM2835 System on Chip (SoC) that has an ARM1176JZF-S 700 MHz core processor, an integrated graphics processor VideoCore IV Graphic Processing Unit (GPU), 512MB of RAM for model B rev 2.0, and an SD card in place of a hard disk drive [2]. The platform is powered from an external power supply via a USB micro connector. It is recommended from the official Raspberry Pi website that the board be powered from a good-quality power supply that gives at least 700mA at 5V [3]. This is because if the board is powered by a USB micro connector, there will not be enough current and, as a result, the board my reboot sometimes when it draws too much power.

2.2 Overview of Raspberry Pi GPIO Pins

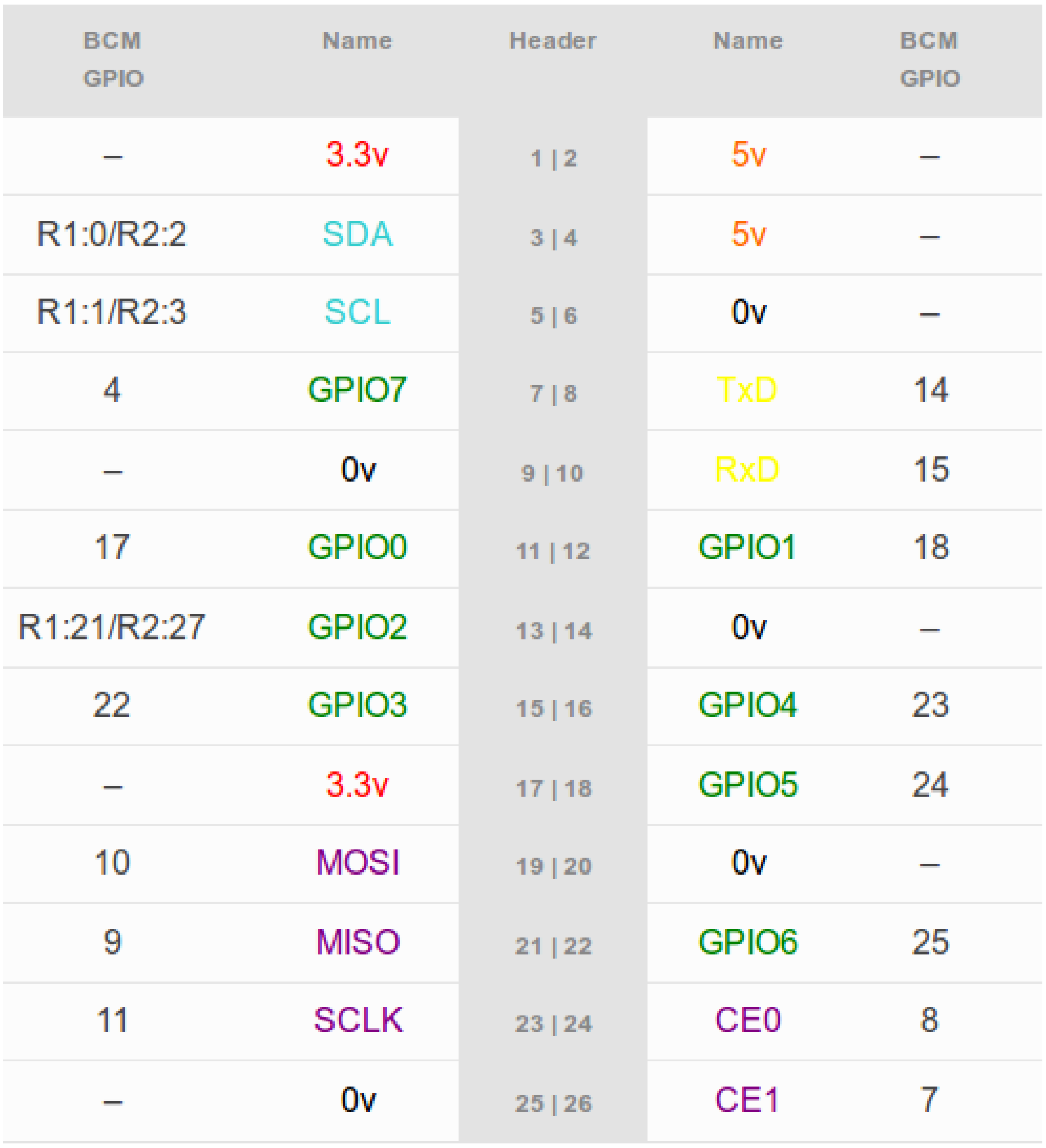
Raspberry Pi comes with a 26-pin connector called P1 and an 8-pin connector called P5. The pins on these connectors expose to users a set of buses such as I2C, SPI, Pulse Width Modulation (PWM), and signals. There are eight GPIO pins on P1 connector and four GPIO pins on P5 connector. In addition, the P1 connector has an I2C interface which consists of two pins, a 5-wire SPI interface, and a serial interface with two pins. These pins can be configured to be GPIO pins, thus making the total number of GPIO pins on Raspberry Pi to be 21 pins. A point worth mentioning here is that four GPIO pins on the P5 connector are available only on the Raspberry Pi model B rev 2.0 platform.



BCM GPIO	Name	Header	Name	BCM GPIO
–	5v	1 | 2	3.3v	–
28	GPIO8	3 | 4	GPIO9	29
30	GPIO10	5 | 6	GPIO11	31
–	0v	7 | 8	0v	–

Figure 2. Mapping between BCM2835 GPIO pins and Raspberry Pi P5 connector Modified from Henderson (2013) [4]

Figure 2 shows the mapping between Broadcom BCM2835 SoC's GPIO pins and the Raspberry Pi P5 connector. The P5 connector which consists of eight pins as seen in figure 2 is viewed from the bottom side of the board. Since Raspberry Pi was originally shipped without any header on P5 connector, a double sided 2.54mm header has to be soldered either on top or at the bottom of the board for use.



BCM GPIO	Name	Header	Name	BCM GPIO
–	3.3v	1 | 2	5v	–
R1:0/R2:2	SDA	3 | 4	5v	–
R1:1/R2:3	SCL	5 | 6	0v	–
4	GPIO7	7 | 8	TxD	14
–	0v	9 | 10	RxD	15
17	GPIO0	11 | 12	GPIO1	18
R1:21/R2:27	GPIO2	13 | 14	0v	–
22	GPIO3	15 | 16	GPIO4	23
–	3.3v	17 | 18	GPIO5	24
10	MOSI	19 | 20	0v	–
9	MISO	21 | 22	GPIO6	25
11	SCLK	23 | 24	CE0	8
–	0v	25 | 26	CE1	7

Figure 3. Mapping between BCM2835 GPIO pins and Raspberry Pi P1 connectors Modified from Henderson (2013) [4]

As can be seen from figure 3, the pins on the P1 connector, on the other hand, are viewed looking at the platform from above with the USB micro connector at the top-left to the Raspberry Pi and P1 connector to the top-right of the platform.

As the name implies, GPIO is a general-purpose pin on a chip which, whether configured as input or output, can be controlled on the fly by means of software. By default, a GPIO pin has no defined special purpose, and is not used. GPIO pins may be used in situations where there is a need to have multiple digital control lines so that no additional circuitry is required [5]. A GPIO pin is capable of performing the following:

- Can be configured as an input pin or an output pin
- Can be set low or high for output GPIO pin
- Can be set as input for reading digital logic level
- Can be set to enable interrupt. [5.]

Due to the flexibility of GPIO pins, they are often used in a wide range of integrated circuits (IC), SoC, embedded platforms such as Arduino, BeagleBoard, Stellaris Launchpad, and Raspberry Pi, multiple function chips, for example audio codes and video cards, or Programmable Logic Devices (PLD) [5]. It should be noted that GPIO pins 2 and 3 on Raspberry Pi are initially configured as I2C interfaces with 1.8KΩ pull-up resistors, and pin 15 being configured as a serial UART receive pin. When Raspberry Pi is booting, these pins must be left unused. Otherwise, the board will not be able to boot successfully.

2.3 Raspbian Linux Distribution

The Raspberry Pi platform includes hardware resources such as CPU, memory, Input/Output (I/O) peripherals, networking, and many other resources. In order to manage those hardware resources, a Linux kernel was utilized in the project. The Linux kernel is one of the components of an embedded Linux system which was created by a Finnish student named Linus Torvalds in 1991 as a hobby project. The announcement was made by Linus in 1991 on the newsgroups comp.os.minix. Since then Linux has made its way into a robust, reliable, and high-end operating system that can be considered to be a strong rival of closed-source operating systems. Nowadays, over 50% of Internet services on the Internet are being run on Linux servers. [6,65.] The Linux kernel is the heart of an embedded Linux system just like a processor is the heart of an embedded system. In particular, the Linux kernel is responsible for the following tasks:

- To manage and control a system's hardware resources (e.g. I/O, CPU, memory)
- To offer set Application Programming Interfaces (API) so that application programs and libraries can use hardware devices
- To handle concurrent accesses and usage of hardware devices from application programs. [6,5.]

All of the above mentioned tasks mean that having the Linux kernel to manage system resources abstracts away all of the low-level hardware details that are hard to use from a userspace application's point of view. An application must make a request to the kernel via system calls when it needs to use a certain hardware resource. The kernel in turn evaluates the request and manages the hardware resource on behalf of the userspace application. By doing so, it is easier and safer for userspace applications to make use of a system's hardware resources as opposed to bare-metal programming when an application has total rights to access hardware resources.

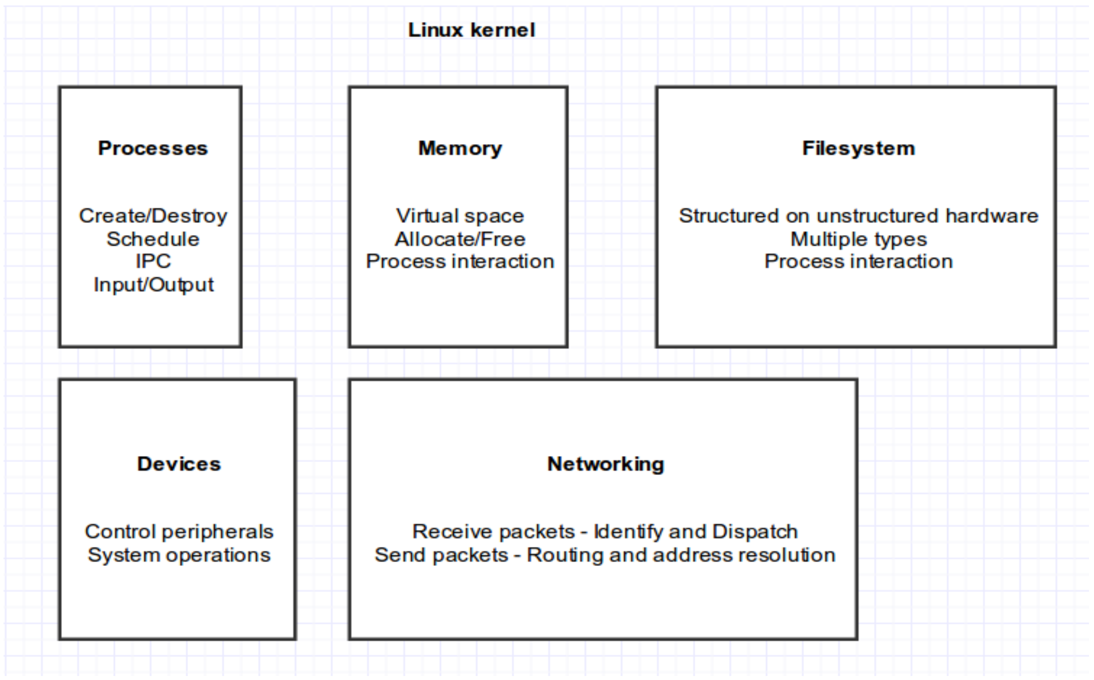


Figure 4. Main tasks of the Linux kernel
Data gathered from Cooperstein (2009) [7,68]

Figure 4 illustrates the main tasks that a Linux kernel performs. Typically, the Linux kernel components consist of process management, memory management, filesystems, device management, and networking. The process management component takes care of creating and terminating processes, providing input and output to processes, offering inter-process communication (IPC), signals and pipes so that processes are able to communicate with each other, and scheduling to share processor time slice between multiple processes. The second component is the memory management which is responsible for managing process address spaces, allocating and freeing memory spaces. The next component called filesystems builds structured filesystems, for instance FAT filesystem, on top of a unstructured hardware resource. An example is a flash memory secure digital (SD) card that the Linux kernel can make it a structured FAT filesystem. It also helps processes to interact with filesystems. Following the filesystems component is the networking component. All of the networking operations must be managed by the kernel since certain network operations are not process-specific, such as processing an incoming packet. Since the arrival of packets to an Ethernet port is not known by a process in advance, they have to be gathered, identified and forwarded before a process can handle them. The last one and also the focus of the project is the device management component. This component is sometimes called a device driver component because it is responsible for abstracting away hardware devices and allowing userspace applications to access them. It is at the lowest abstraction level of the kernel and is the largest component in terms of code size. This is due to the fact that the world is full of many different types of hardware devices. [7,67-69.]

A distribution of Linux called Raspbian was used in this project. Raspbian is a Debian-based operating system. Raspbian is optimized and adjusted with its compilation settings so that it can be run on Raspberry Pi. By optimization, the operating system is actually adjusted to produce optimized hard float code. Thanks to this adjustment, this provides a much faster performance for userspace applications that use floating point arithmetic operations. Raspbian also comes with more than 35,000 packages and pre-compiled software. [8.] Instead of using an official Linux kernel from *www.kernel.org*, I decided to use Raspbian. This decision was because Raspbian is a widely used, free operating system. It also supports many features necessary in the project, and is familiar to the Debian-based Ubuntu distribution which I am using now. Besides, the official kernel offers very limited support for the Raspberry Pi platform. It has basic interrupt management, resource definitions, basic definitions and register address and timers.

2.4 Linux Character Device Driver

In Linux there are essentially three kinds of devices: network devices, block devices and, character devices. Network devices are represented as network interfaces and are visible when issuing *ifconfig* command from userspace. Block devices provide userspace applications with access to raw storage hardware devices (e.g. hard disks). These are visible to userspace as device files in */dev* directory. The last type is character devices. They provide userspace applications with access to other types of devices such as input, serial, graphics, or sound, to name just a few. The design of the Linux GPIO device driver for Raspberry Pi was based on the Linux character device driver. For that reason, this section will look at the internals of the Linux character device driver.

Linux character device drivers are byte-oriented operations or character-oriented operations in the C lingo. Because a large number of hardware devices are character-oriented, a majority of Linux device drivers are character device drivers. Linux character device drivers are the kernel code that gets access to data from a hardware device sequentially. They are capable of capturing raw data from several kinds of devices such as serial ports, mice, tapes, or memory. [9,120].

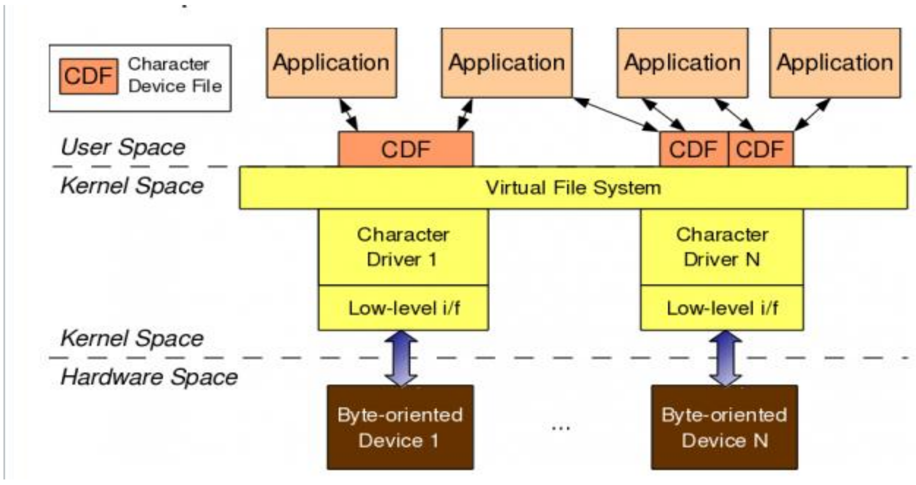
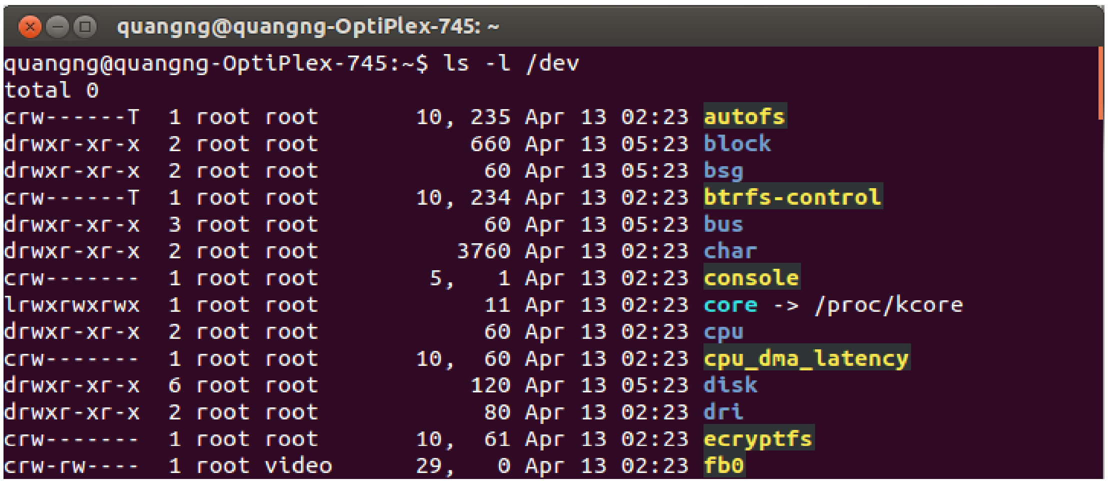


Figure 5. Overview of Linux character device driver
Reprinted from Pugalia (2011) [10]

As illustrated by figure 5, in order for a userspace application to use a character-oriented device in hardware space, it must use a corresponding character device driver in kernel space. A character device file appeared in */dev* directory acts as a communication channel between a userspace application and a character device driver. A userspace application performs usual file operations (e.g. open, read, write, close) on the character device file. Those operations are then mapped into the entry points in the linked character device driver by the virtual filesystem (VFS). Those entry points finally perform low-level accesses to the actual device to get the desired results. [10.]

To access a device file exported by a character device driver, the */dev* directory should be listed. Figure 6 shows the device files that are exported to userspace by Linux device drivers including character device drivers and block device drivers.



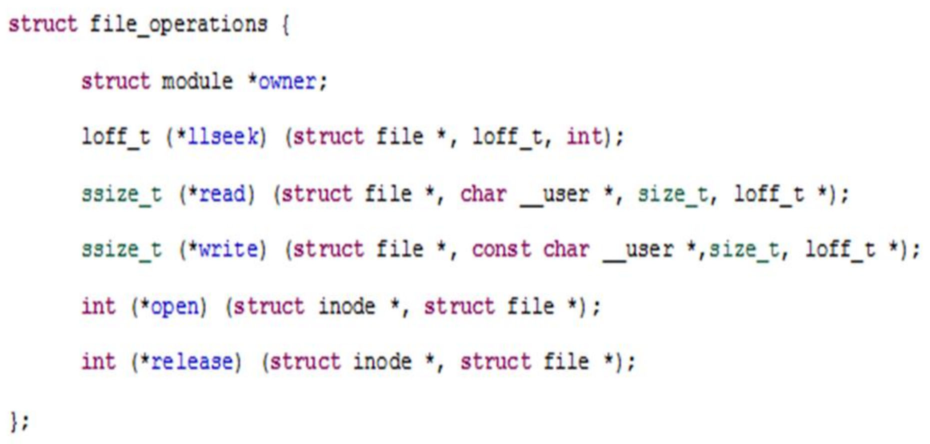
```
quangng@quangng-OptiPlex-745: ~
quangng@quangng-OptiPlex-745:~$ ls -l /dev
total 0
crw------T  1 root root      10, 235 Apr 13 02:23 autofs
drwxr-xr-x  2 root root          660 Apr 13 05:23 block
drwxr-xr-x  2 root root           60 Apr 13 05:23 bsg
crw------T  1 root root      10, 234 Apr 13 02:23 btrfs-control
drwxr-xr-x  3 root root           60 Apr 13 05:23 bus
drwxr-xr-x  2 root root         3760 Apr 13 02:23 char
crw-------  1 root root       5,   1 Apr 13 02:23 console
lrwxrwxrwx  1 root root           11 Apr 13 02:23 core -> /proc/kcore
drwxr-xr-x  2 root root           60 Apr 13 02:23 cpu
crw-------  1 root root      10,  60 Apr 13 02:23 cpu_dma_latency
drwxr-xr-x  6 root root          120 Apr 13 05:23 disk
drwxr-xr-x  2 root root           80 Apr 13 02:23 dri
crw-------  1 root root      10,  61 Apr 13 02:23 ecryptfs
crw-rw----  1 root video     29,   0 Apr 13 02:23 fb0
```

Figure 6. Device files exported by device driver on */dev* directory

Network interfaces are, however, not exported on the */dev* directory since they do not have mapping on the filesystem. The first character of the first column in figure 6 identifies the type of a device. Device files for character drivers are identified by a “c” which stands for character. Block devices are identified by a “b” which stands for block. The reason that device drivers export their device files to the /dev directory to the userspace is because Linux inherits many features from the Unix operating system. In the Unix design philosophy, everything is a file. This allows the system to represent system objects as files, and applications manipulate all system objects with files by means of normal file APIs, for example, open, read, write, and close. Linux inherits this feature from Unix, so the devices are represented as files to the userspace.

When a device driver is registered to a running kernel, a major number will be used to assign to it. The kernel uses this major number to distinguish between different device drivers, not by the names of the device drivers, however. A device driver may have many instances, and minor numbers are used by the kernel assign to these device driver instances. As can be seen from figure 6, the fifth column indicates the major number of a device driver, and the sixth row indicates the minor number. We can have the same major number but cannot have the same minor number.

Since the GPIO device driver is a character device driver, it must therefore implement and register entry points or methods that enable userspace applications to manipulate the device as a file. These entry points are described in the *struct file_operations* structure which is defined in <*linux/fs.h*> header file in Linux. Some of the most important entry points for a character device driver are shown in listing 1 below.



```
struct file_operations {

      struct module *owner;

      loff_t (*llseek) (struct file *, loff_t, int);

      ssize_t (*read) (struct file *, char __user *, size_t, loff_t *);

      ssize_t (*write) (struct file *, const char __user *,size_t, loff_t *);

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

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

};
```

Listing 1. Entry points for the GPIO device driver

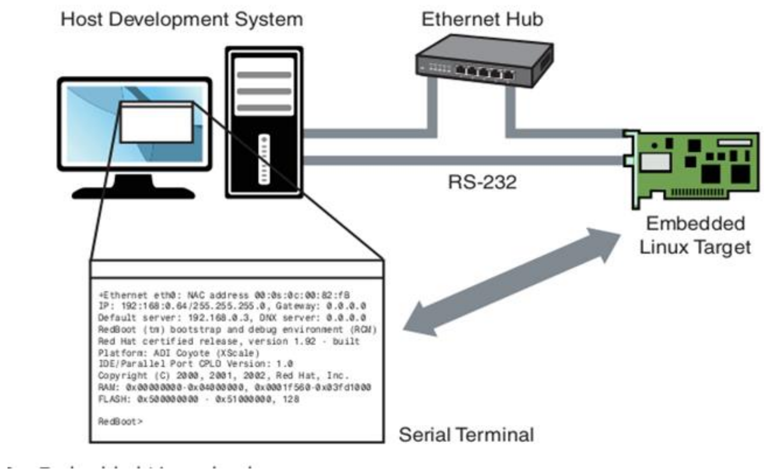
Implementing the entry points and registering them is not sufficient when writing a character device driver. Several other steps have to been taken, and they can be generalized from two perspectives: code-flow perspective and data-flow perspective. From the perspective of code-flow, character device drivers possess an initialization function, called *raspi_gpio_init()* in this project, that takes care of initializing the character device driver and registering the device driver to the kernel by using registration functions (e.g. *cdev_add*). The next is a collection of methods such as the ones mentioned in listing 1 which directly map to system calls. The last is bottom halves, timer handlers, interrupt service routines and other support infrastructure. From a data-flow perspective, character device drivers have at first a driver-specific data structure to keep track of the state of the device driver itself. Secondly, it has a *struct cdev* structure. The Linux kernel uses this structure as an abstraction for character device drivers, and this is often nested inside the driver-specific data structure. Thirdly, it has a *struct file_opentations* structure which has already been mentioned in listing 1. The last one is a *struct file* structure that holds information about the associated */dev* device file. [9,121.] By now, it is believed that the reader should have a basic knowledge of what constitutes a Linux character device driver and the relation between userspace applications, device files, system calls, entry points and character device drivers. Detailed implementation of the GPIO character device driver will be discussed in chapter 4.

One important point worth mentioning here is that the subject of interrupt handling in Linux was studied during the design of the project, and I did not really understand to a large degree about interrupt handling in Linux. As a result, interrupt handling can be considered to be an experimental feature in the design of the device driver.

3 Design of the GPIO Device Driver

3.1 Project Setup

The first step in the design of the GPIO device driver in this project was to set up a proper embedded Linux development environment. Figure 7 shows the development setup used in the project. On the left-hand side of the figure is a host development system which runs on my favorite Ubuntu 12.04 Long Term Support (LTS) Linux distribution. To the right of the figure is an embedded Linux target which, in this case, is the Raspberry Pi platform. Communication between the host development system and the embedded Linux target is done via Ethernet. The platform's Ethernet interface and the Ethernet hub's socket is connected using an RJ45 Unshielded twisted pair (UTP) cable. Similarly, the host development system's Ethernet interface is connected to the Ethernet hub's socket using an RJ45 UTP cable. The serial connection RS-232 was not used in the project since host-target communication was done using Secure Shell (SSH) protocol. In order to use the SSH protocol as a means of communication between the host and the target, an SSH daemon was installed in Raspberry Pi, which makes the target become a server, whereas an SSH client was installed in the host development system, thus making the host a client.



```
+Ethernet eth0: NAC address 00:0s:0c:00:82:f8
IP: 192:168:0.64/255.255.255.0, Gateway: 0.0.0.0
Default server: 192.168.0.3, DNX server: 0.0.0.0
RedBoot (tm) bootstrap and debug environment (RCM)
Red Hat certified release, version 1.92 - built
Platform: ADI Coyote (XScale)
IDE/Parallel Port CPLD Version: 1.0
Copyright (C) 2000, 2001, 2002, Red Hat, Inc.
RAM: 0x00000000-0x04000000, 0x0001f560-0x03fd1000
FLASH: 0x500000000 - 0x51000000, 128

RedBoot>
```

Figure 7. Project development setup
Reprinted from Hallinan (2010) [6,14]

After the target has been booted successfully, it will receive a dynamic Internet Protocol (IP) address. This IP address is assigned dynamically from the Dynamic Host Configuration Protocol (DHCP) server. Given the Media Access Control (MAC) address of the target, the dynamic IP address assigned to the target can be found by using the following command from the host:

$ arp -a

This command lists MAC and IP addresses of all the devices available on a Local Area Network (LAN). By doing so, the assigned IP address is found and the host can make a connection to the target by using the SSH protocol. At the initial stage of the design, it was realized that it is time-consuming and not convenient to find out the dynamic IP address assigned to the target after each time the target is rebooted. The solution to solve this inconvenience was to install a Domain Name System (DNS) client on Raspberry Pi and to sign up a domain name from a DNS hosting website. In this project, a DNS client called *ddclient* was installed on Raspberry Pi and a domain name was registered from a free DNS hosting website from the link *http://freedns.afraid.org*. For security reasons, in this thesis report a domain name called *vunguyen.fyp.org* and a user name “pi” will be used when referring to the actual domain name that was registered from the DNS hosting website mentioned just before and the user name from the target, respectively. After all the networking had been set up properly, communication between the host and the target was tested. Apparently, the procedure became much simpler and faster by simply using the following command from the host:

```
$ ssh pi@vunguyen.fyp.org
```

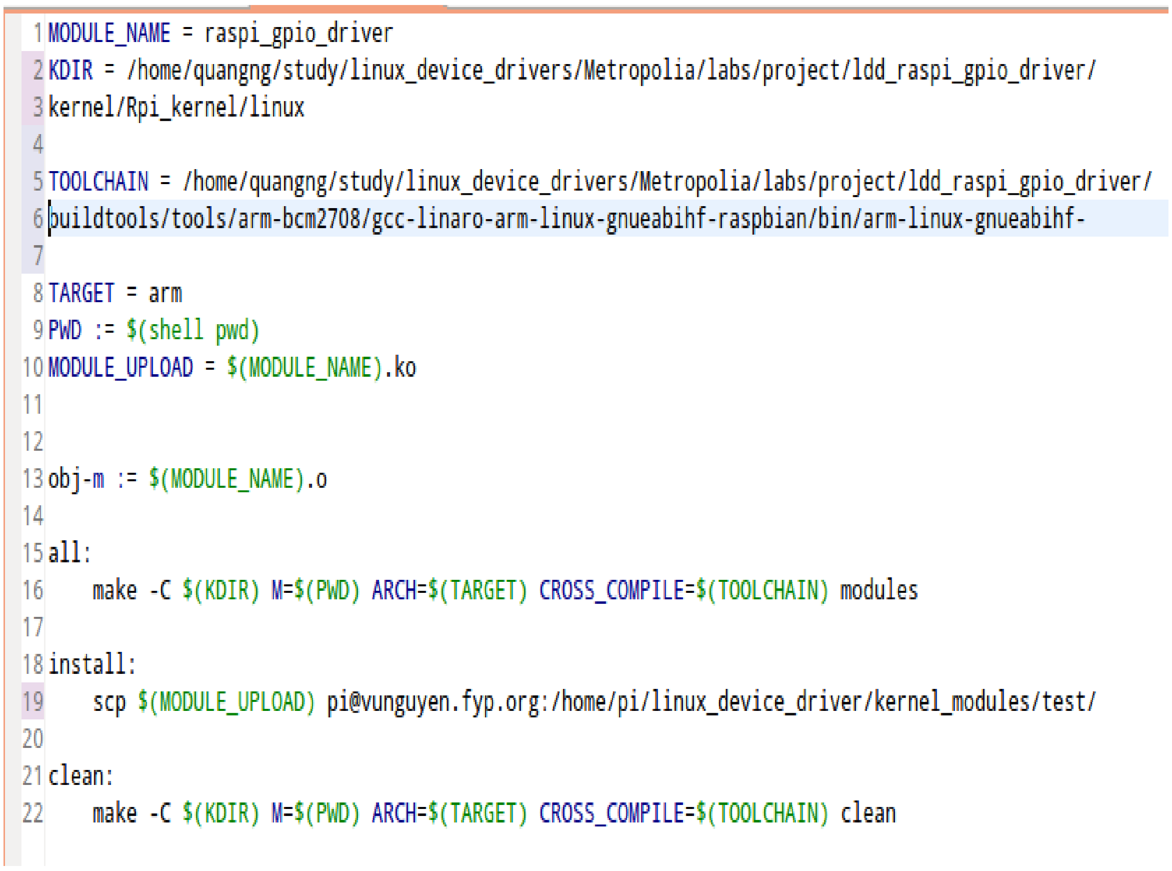
A password required by the ssh server which is the target was entered for checking authentication. After that, the host could interact with the target board as if it was working on the local host machine. Further information about the development environment setup can be referenced from my personal blog page at *http://e-linux-note.blogspot.fi/*. The physical setup of the development environment has been covered by now. The following paragraphs will discuss the software aspects the host development system needed in the project.

Regarding a programming tool, an Eclipse Indigo version 3.7.2 Integrated Development Environment (IDE) was chosen to be installed in the development host. The Eclipse IDE is an open source programming tool which has a base workspace and a plug-in system for customizing the programming environment. Eclipse was chosen as a programming tool because it offers a C/C++ Development Tools plug-in which supports programming in the C language. What's more, it contains many nice features such as syntax highlighting, on-the-fly syntax check, auto-completion, code folding, code navigation, and so on. These features can help speed up the coding process, thus reducing the project time allocated for the implementation phase. In order to develop application programs and Linux device drivers, the Eclipse IDE alone is not sufficient. Since the target platform runs on the ARM1176JZF-S processor, a toolchain was needed to cross-compile the source code so that it could run on the target. It should be noted that the native GNU C Compiler (GCC) compiler on the host is targeted to build source code for Intel x86 family processors, not for other processor architectures. The toolchain used in the project was *gcc-linaro-arm-linux-gnueabihf-raspbian*. This toolchain was downloaded from the link *https://github.com/raspberrypi/tools*. The last software component needed in the development host was the source code for the Linux kernel. It was obtained from the Raspberry Pi kernel source code repository at *https://github.com/raspberrypi/linux*. To ease the management of the toolchain, the Linux kernel source code, application programs, Linux device drivers, final report, and other project related documents, I proceeded to set up the layout for a project workspace. The process of organizing the layout could be compared to making the layout for the thesis report which is being worked on now. At the top of the project workspace tree is *ldd_raspi_gpio_driver* directory inside which other subdirectories are created. Table 1 shows the layout of the project workspace with parent directories and their subdirectories as well as the contents of each directory.

Table 1. Project workspace layout

Directory	Level-1 subdirectories	Level-2 Subdirectories	Content
ldd_raspi_gpio_driver	app	input_test	- Executable for testing GPIO input - Source code for testing GPIO input
		output_test	- Executable for testing GPIO output - Source code for testing GPIO output
	buildtools	Tools	Cross toolchain for ARM processor
	documentation		All documentation needed for the project
	drivers	rpi_gpio	Linux GPIO device driver version 1
		rpi_gpio_v2	Linux GPIO device driver version 2
	kernel	Linux	The vanilla Linux kernel source code
		Rpi_kernel	Rapberry Pi Linux kernel source code
	report	report_figures	Normal figures included in the thesis report
		testing_figures	Figures from testing phase of the project

The *Rpi_kernel* directory contains two subdirectories: *linux* directory and *modules* directory. The *linux* directory holds the Raspberry Pi source code from which the Linux kernel build system uses for building a kernel image for Raspberry Pi. The *modules* directory contains kernel modules which Raspberry Pi will install when it is booting. It is, undoubtedly, impossible to compile a Linux device driver without a Makefile file. Therefore, inside the *rpi_gpio* and *rpi_gpio_v2* subdirectories are Makefile files used by the Eclipse IDE during Linux device driver compilation process. The Makefile file is shown in listing 2.



```makefile
MODULE_NAME = raspi_gpio_driver
KDIR = /home/quangng/study/linux_device_drivers/Metropolia/labs/project/ldd_raspi_gpio_driver/
kernel/Rpi_kernel/linux

TOOLCHAIN = /home/quangng/study/linux_device_drivers/Metropolia/labs/project/ldd_raspi_gpio_driver/
buildtools/tools/arm-bcm2708/gcc-linaro-arm-linux-gnueabihf-raspbian/bin/arm-linux-gnueabihf-

TARGET = arm
PWD := $(shell pwd)
MODULE_UPLOAD = $(MODULE_NAME).ko


obj-m := $(MODULE_NAME).o

all:
	make -C $(KDIR) M=$(PWD) ARCH=$(TARGET) CROSS_COMPILE=$(TOOLCHAIN) modules

install:
	scp $(MODULE_UPLOAD) pi@vunguyen.fyp.org:/home/pi/linux_device_driver/kernel_modules/test/

clean:
	make -C $(KDIR) M=$(PWD) ARCH=$(TARGET) CROSS_COMPILE=$(TOOLCHAIN) clean
```

Listing 2. Makefile file for Linux device driver compilation

Finally, a note about the vanilla Linux kernel. This is an official Linux kernel which is hosted at the main Linux kernel website *https://www.kernel.org/*. This kernel is located in the kernel level-1 subdirectory for future experiments when the project has been completed.

3.2 Design of Per-device Structure and Initialization and Exit Routines

Since the per-device structure (driver-specific data structure) is the information repository which the GPIO character device driver instantiates and revolves, it was designed first. The structure consists of the following data elements:

- A *cdev* kernel abstraction element for character device drivers
- An instance of *struct gpio* structure describing a GPIO pin with configuration
- A variable indicating the state of a GPIO pin (low or high)
- A variable indicating the direction of a GPIO pin (input or output)
- A boolean variable used to enable or disable interrupt on a GPIO pin
- A flag indicating rising or falling edge trigger on a GPIO pin
- A counter for keeping track of the number of requests for interrupt
- A spinlock used for synchronization.

The per-device data structure plays the role of representing a GPIO pin on the Raspberry Pi platform. There are, in total, 21 GPIO pins on Raspberry Pi; therefore, 21 instances of the per-device data structure were created to represent these GPIO pins.

After the per-device structure had been created, the design of driver initialization routine and driver exit routine took place. The driver initialization routine is the one which is called first when the kernel installs the GPIO device driver. The driver exit routine, in contrast, is the last one called by the kernel when being unloaded from the system. In this thesis report, device driver and kernel module will be used interchangeably. Because the driver initialization routine is the bedrock for registering the GPIO character device driver to the kernel, it will be responsible for doing the following steps:

- Register a range of character device numbers
- Create a device class in */sys* directory
- Claim GPIO pin resources
- Allocate memory for the per-device structure
- Initialize a spinlock to be used for synchronization
- Register character device to the kernel
- Create device nodes to expose GPIO resources to userspace
- Get current timestamp used for contact debouncing.

A feature in the design of the GPIO character device driver was to let a userspace policy daemon *udevd* to dynamically create device nodes in the */dev* directory. That is why step 2 and step 7 were added to the initialization routine. It should be kept in mind that the implementation of the GPIO device driver followed the steps of driver initialization in the order mentioned above. Handling errors was the responsibility in the implementation phase. As a rule, if there is an error when calling kernel APIs, it must log error information to the kernel log system, release any previously allocated resources, and exit without any further processing. Doing the opposite of what the driver initialization routine is supposed to do is the driver exit routine. When the system is rebooted or when a userspace user issues a command, for example *rmmod*, the exit routine takes action. Firstly, it unregisters a range of character device numbers. After that, it frees all the per-device structures allocated previously during the initialization routine. Next, it releases all the device nodes in the */dev* directory, frees all GPIO pin resources, and sets the direction of all the GPIO pins to output and sets their logic levels low. Finally, it destroys the device class registered in the virtual filesystem mounted at */sys* directory. It is a good practice to set the direction of all GPIO pins to output and their logic levels low. This is because sometimes a user of the GPIO device driver might make mistakes by accidentally short-circuiting a certain GPIO pin, thus playing havoc with the processor of Raspberry Pi. It cannot prevent Raspberry Pi from damaging when a user applies a high voltage to a GPIO pin, however.

3.3 Design of the Entry Points for the GPIO Device Driver

The GPIO character device driver consists of four entry points which handle requests from userspace applications on behalf of system calls. The open entry point went first when designing entry points of the GPIO character device driver. This order of design was followed based on the theory of code-flow perspective discussed in section 2.4.

Although the open entry point is the first operation exercised on the device file, this is not compulsory for a character device driver to declare. Opening a device file always returns success even if this entry point is NULL. [11,51.] The open entry point was designed for the device driver, however. The reason for this is that it is needed for registering interrupt resources and keeping track of how many times an interrupt is requested by userspace applications. Moreover, it is recommended that an interrupt request be called when a device file is first open [11,261]. Clearly, this means that a request for an interrupt should be handled in the open entry point. Figure 8 illustrates the flowchart for the open entry point of the GPIO device driver.

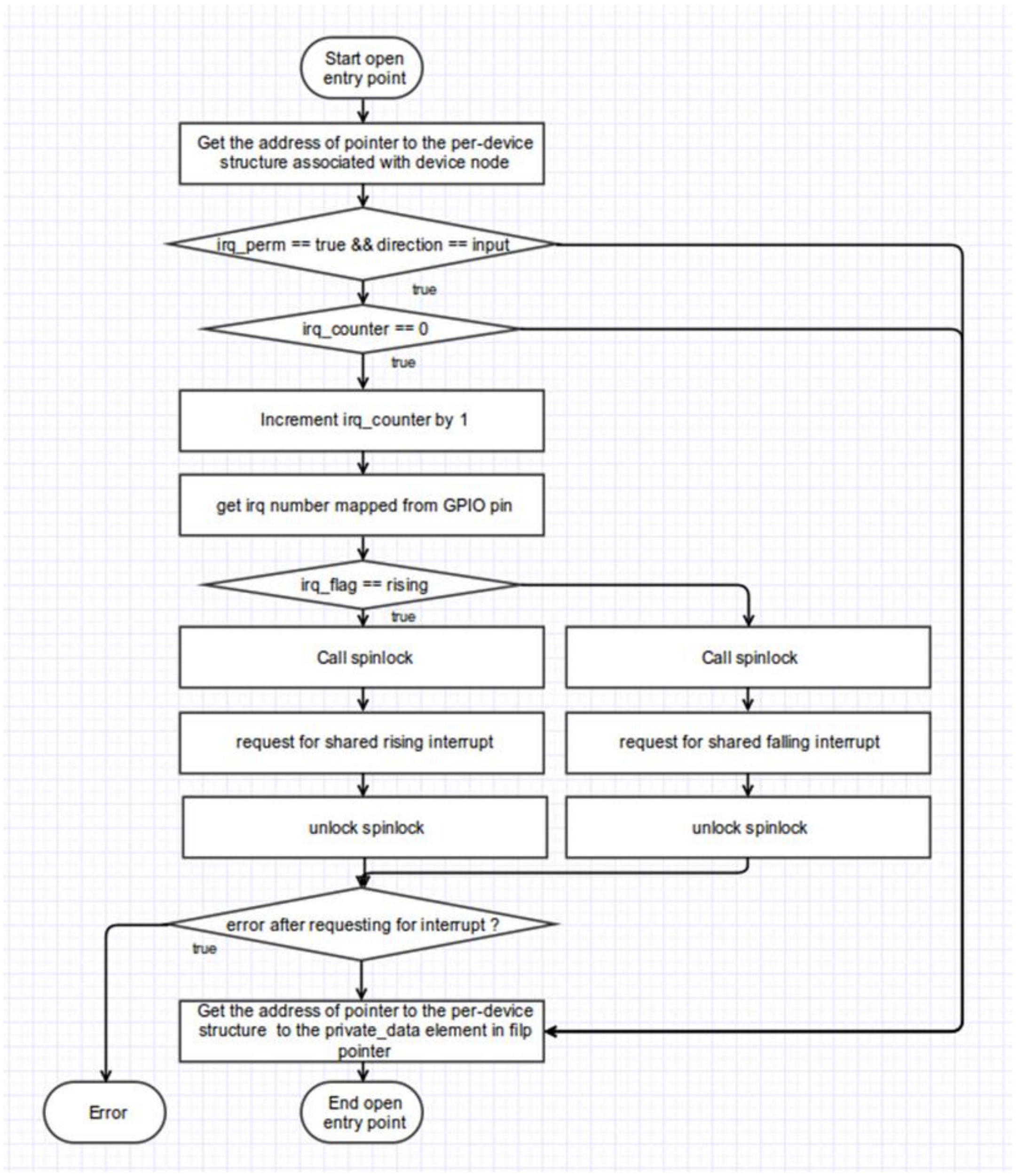

Start open entry point
Get the address of pointer to the per-device structure associated with device node
irq_perm == true && direction == input
true
irq_counter == 0
true
Increment irq_counter by 1
get irq number mapped from GPIO pin
irq_flag == rising
true
Call spinlock
Call spinlock
request for shared rising interrupt
request for shared falling interrupt
unlock spinlock
unlock spinlock
error after requesting for interrupt ?
true
Get the address of pointer to the per-device structure to the private_data element in filp pointer
Error
End open entry point

Figure 8. Flowchart of open entry point for GPIO device driver

The open entry point of the GPIO character device driver is called *raspi_gpio_open*. This function allocates GPIO interrupt resources when requested on the condition that the interrupt flag is enabled and the direction of a GPIO pin is set to input. Based on the *irq_flag* variable in the per-device structure, this open entry point allows a userspace application to request for a rising edge trigger interrupt or a falling edge trigger interrupt. The last feature which was designed for the *raspi_gpio_open* entry point was that an interrupt line could be shared by multiple userspace applications.

When a userspace application closes a device file, the kernel invokes the release entry point. Like the open entry point, the release entry point is not needed and can be NULL. For the GPIO device driver, the release entry point was designed. The design of this release entry point followed after the design of the open entry point. The release entry point, when being called, is responsible for releasing the GPIO interrupt resource that has been requested before. It only releases the interrupt resource when the device is last closed. To do this, there is a counter called *irq_counter* inside the per-device structure which keeps track of how many times an interrupt has been requested. The design philosophy of the GPIO character device driver was defined so that multiple userspace applications could share the same interrupt resource on a certain GPIO pin. In addition to that feature, the release entry point also controls enabling and disabling of an interrupt upon request regardless of how many devices are using the interrupt. A spinlock used for synchronization is also part of the code-flow in the release entry point. The last two entry points for the GPIO character device driver are read entry point and write entry point.

Perhaps, the read entry point was the easiest part during the design phase of the device driver. This entry point is called, by design, *raspi_gpio_read*. This function allows userspace applications to read the logic state of input GPIO pins and of output GPIO pins. Since multiple processes are allowed to read the logic state of a GPIO pin simultaneously, it was not designed to use a spinlock for protecting atomic sections of code or synchronization or whatsoever.

The last and also the most important entry point is the write entry point. This entry point is responsible for exchanging data between userspace and a hardware device. The write entry point does the opposite to the read entry point. Instead of reading from the hardware device, it receives bytes of data from the userspace and then writes what has been received directly to the device. Finally it returns the number of bytes that it has successfully written. That is the mechanism how the write entry point works. For the GPIO character device driver, the write entry point accepts a set of defined commands received from the userspace and takes action accordingly. In particular, it was designed to accept a set of seven defined commands from userspace. The commands are, in fact, a string of characters sent to the device file by a userspace application. Those commands are listed in table 2.

The description in table 2 should be descriptive enough to understand what a command asks the write entry point to perform. If a userspace application needs to set, for example, GPIO pin 2 to output and set it to logic level low, it will need to do the following commands based on the description from table 2.

```
$ echo out > /dev/raspiGpio2
$ echo 1 > /dev/raspiGpio2
```

Table 2. Command set for GPIO character device driver

Command	Description
“out”	Set GPIO direction to output
“in”	Set GPIO direction to input
“1”	Set GPIO pin's logic level to high
“0”	Set GPIO pin's logic level to low
“rising”	Enable rising edge trigger
“falling”	Enable falling edge trigger
“disable-irq”	Disable interrupt on a GPIO pin

After that the GPIO pin 2 will be set to output with high logic level. What the first command does is that it first opened the device file */dev/raspiGpio2* and sent to the device file the string “out”. The string “out” or command “out” in this case was then read by the write entry point. It then processed if a correct command was received. If so, it sets the direction of GPIO pin 2 to output. Otherwise, error will be printed on the console. In the demonstration above, there was no error reported. Therefore, it means that the command “out” was processed successfully by the write entry point, and the direction of GPIO pin 2 was set to output. The same process happens when the command “1” was written to the */dev/raspiGpio2* device file. Again, there was no error and it was measured from the GPIO pin 2 by a Digial Multimeter (DMM) that the voltage of the pin was about 3.287 V. It is easy to use from the userspace application's point of view. However, there are many low-level details that require the job of the GPIO device driver’s write entry point.

Figure 9 shows the flowchart for the write entry point. The design of the write entry point was based on the switch case statement.

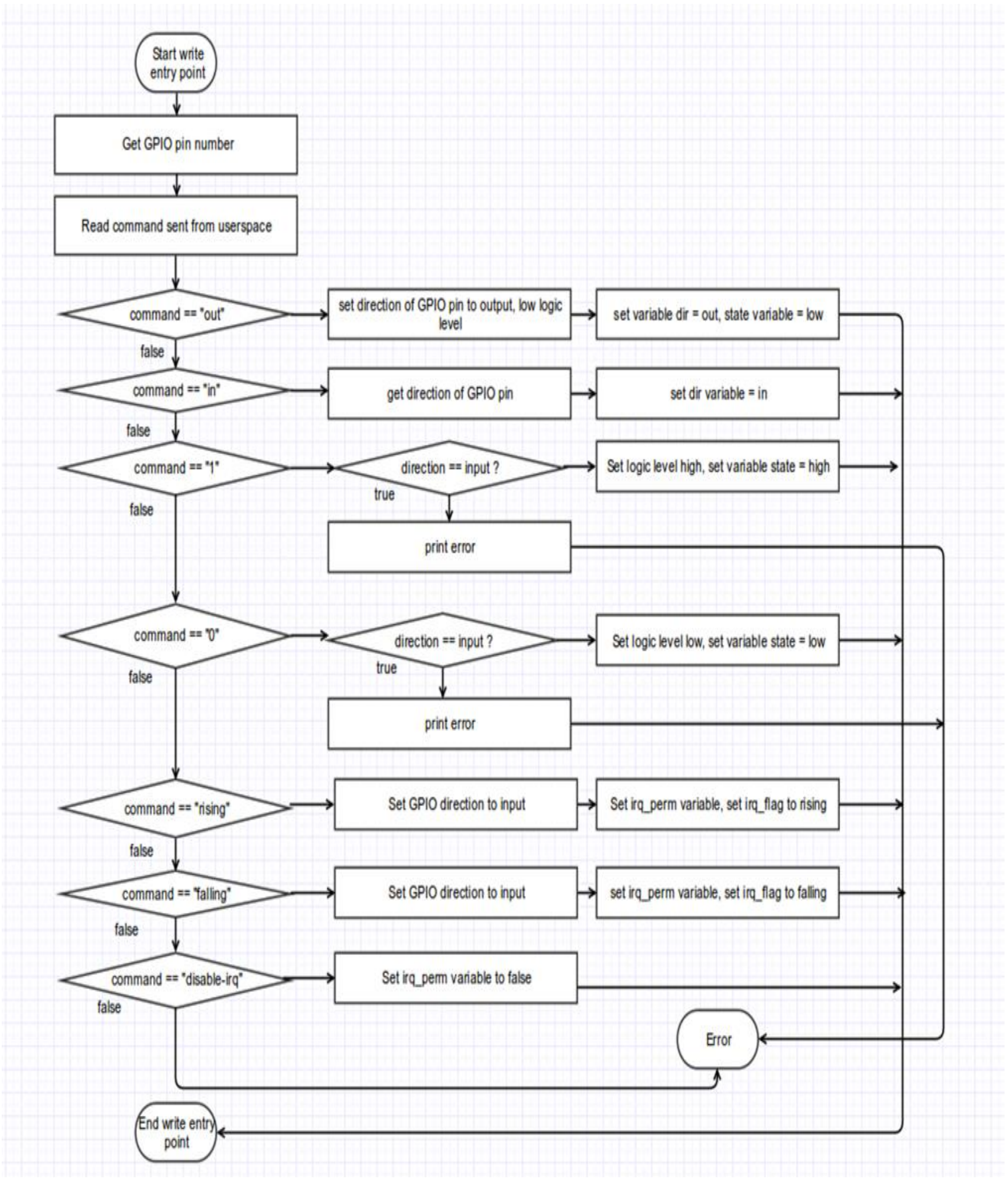

Start write entry point
Get GPIO pin number
Read command sent from userspace
command == "out"
set direction of GPIO pin to output, low logic level
set variable dir = out, state variable = low
false
command == "in"
get direction of GPIO pin
set dir variable = in
false
command == "1"
direction == input ?
Set logic level high, set variable state = high
true
print error
false
command == "0"
direction == input ?
Set logic level low, set variable state = low
true
print error
false
command == "rising"
Set GPIO direction to input
Set irq_perm variable, set irq_flag to rising
false
command == "falling"
Set GPIO direction to input
set irq_perm variable, set irq_flag to falling
false
command == "disable-irq"
Set irq_perm variable to false
false
Error
End write entry point

Figure 9. Flowchart of write entry point for the GPIO device driver

The write entry point first reads a command sent from userspace and stores the command into a buffer. Based on the content of the buffer, it makes a decision on whether or not to go forward. If there is no match between the buffer and a specified command shown in table 2, an error will be returned indicating an invalid value was received. When a request for an interrupt such as falling or rising is received, it will be processed by the write entry point as a high priority task, thus overriding the setting of the GPIO pin’s direction and the permission flag in the per-device structure. Other commands are just trivial commands for setting the direction and logic level of a GPIO pin. For sections of code which require to be atomic, the implementation for the write operation entry point should be able to decide suitable places for inserting a spinlock.

3.4 Design of Interrupt Handling Functions

Interrupt handling is a feature that was decided to be added to the GPIO device driver later when the first version of the driver had been finished. This was due to some changes in the requirements of the project. The subject of interrupt handling was studied during the design phase, and was not really understood thoroughly. For that reason, this feature was designed in the second version of the GPIO device driver, and is considered to be experimental. To make this feature useful for userspace applications, more work needs to be done.

Requesting for interrupt resources and releasing them were already mentioned in section 3.2. This section will look at the design of an interrupt handler that is called by the kernel when a hardware interrupt signal arrives. In addition, a simple timing function was designed so that it solves a problem known as contact bouncing. Contact bouncing is the problem which is caused by mechanical switches when they are pressed and released. This problem causes the processor to misinterpret when the signal from the switch oscillates several times, going from logic level low to high and vice versa. In other words, when a switch is pressed and released only one time, it will be interpreted by the processor as several switch presses.

Basically, when called by the kernel, the interrupt handler starts taking a timestamp right at the moment it was started. It will then compare the current time with the last timestamp when it was called. If the time duration between successive calls is less than 200 milliseconds, it will consider the interrupt signal that has just arrived as a signal pulse caused by contact bouncing. Otherwise, it will be interpreted as an interrupt signal; the handler takes proper actions that userspace applications desire. In the GPIO device driver, the interrupt handler simply displays some information to the kernel logging system to signify that an interrupt signal has been received. In order to avoid being interrupted by another interrupt signal when the interrupt handler is busy, functions *local_irq_save* and *local_irq_restore* were used to disable interrupt signals temporarily and then resume them as before.

The timing function was designed in quite a simple way. This function is named *millis* which means milliseconds. It takes no argument and returns the current system time in milliseconds. The data type of the return value was designed to be *unsigned int*. It takes the current system time by calling *do_gettimeofday(struct timeval *tv)* function which is defined in <*linux/time.h*> header file.

4 Implementation of the GPIO Device Driver

4.1 Linux Kernel Compilation and Installation

In order to see how the Linux kernel was compiled and installed for Raspberry Pi in this project, it is necessary to understand how Raspberry Pi boots up. The Broadcom BCM2385 SoC consists of two processors; one is a VideoCore IV GPU and the other is an ARM1176JZF-S 700 MHz core which runs the Linux kernel. A small RISC core on the GPU starts running first at power-up, and this core runs the first stage bootloader which has been preprogrammed into the SoC to mount the FAT32 boot partition on the SD card. Next the GPU looks for the second stage bootloader called *bootcode.bin* and loads it into the system memory and starts executing that code. Then the second stage bootloader searches for a file called *config.txt* from the SD card and searches again for the *kernel.img* file which is the Linux kernel image. Finally, the kernel image is loaded into memory at the address (0X8000), and this in turn starts the ARM processor executing at that memory location. The GPU is ready and the ARM will start using the code in *kernel.img*. [12.]

In a nutshell, the following components are needed for booting the Raspberry Pi platform:

- A second stage bootloader file called *bootcode.bin*
- A *config.txt* file used for kernel settings
- A *kernel.img* file

- Linux kernel modules
- Other files: *start.elf*, *fixup.dat*, *.config* configuration file.

The *bootcode.bin* second stage bootloader, the *start.elf* and *fixup.dat* files were downloaded for the project from the Raspberry Pi main repository at *https://github.com/raspberrypi/firmware/tree/master/boot*
The *config.txt* file already exists in the running Raspberry Pi platform at */boot* directory. So, it was copied from there. If that file is not available, it can be downloaded from *https://github.com/Evilpaul/RPi-config/blob/master/config.txt*
The *kernel.img* kernel image and the Linux kernel modules were cross-compiled from the development host. All of the preparation steps were done as follows:

- Get the Raspberry Pi Linux kernel source code
- Get a *gcc-linaro-arm-linux-gnueabihf-raspbian* toolchain for cross compilation
- Get an existing *.config* configuration file.

The first step in compiling the kernel image for Raspberry Pi was to have the Raspberry Pi Linux kernel source code. It was obtained from *https://github.com/raspberrypi/linux.git* by using the following git command:

```
git clone https://github.com/raspberrypi/linux.git
```

The kernel source code was then stored in the *Rpi_kernel* workspace directory as shown in table 1. The next step was to get a toolchain in order to cross-compile for the target. The toolchain is stored in the *tools* level-2 subdirectory in the workspace. It was downloaded by using the following command:

```
git clone https://github.com/raspberrypi/tools
```

The Raspberry Pi *tools* directory contains several toolchain versions. *gcc-linaro-arm-linux-gnueabihf-raspbian* was chosen since it contains linaro patches. The last one needed was a configuration file for kernel compilation. In order save time, an existing configuration file from a running Raspberry Pi system was retrieved. This configuration file is stored in */proc/config.gz* directory. This file was copied, unzipped, renamed to *.config* and saved into the top tree of the Raspberry Pi kernel. Next the compilation process took place. The following commands were run to compile the Linux kernel image. It should be noted that they were executed in the following order:

```
make oldconfig ARCH=arm CROSS_COMPILE=${CCPREFIX}
make ARCH=arm CROSS_COMPILE=${CCPREFIX}
make modules_install ARCH=arm CROSS_COMPILE=${CCPREFIX}
```

The result after a successful compilation was a kernel image and a folder containing kernel modules. The new kernel image was stored in the */linux/arch/arm/boot/* directory of the kernel source tree. It was a compressed file called *zImage*, so it was uncompressed to be used on Raspberry Pi. The tool for uncompressing *zImage* kernel image comes from the *tools/mkimage* directory in the workspace. This tool is called imagetool-uncompressed.py which is a kind of Python script. The following commands were used to uncompress and upload the *zImage* kernel image to Raspberry Pi:

```
./imagetool-uncompressed.py zImage
scp kernel.img pi@vunguyen.fyp.org:/tmp
```

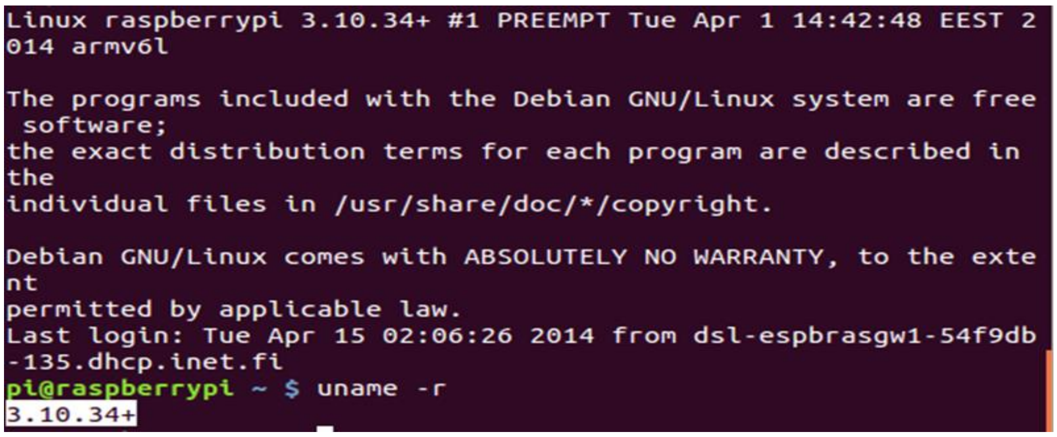
Another component needed for booting the Raspberry Pi platform is kernel modules. These modules were stored in my development host's directory at the path */home/quangng/study/linux_device_drivers/Metropolia/labs/project/ldd_raspi_gpio_driver/kernel/Rpi_kernel/modules*. Since this directory contains quite a large number of modules, it was compressed before uploading to Raspberry Pi to save uploading time. It was done as follows:

```
cd ./Rpi_kernel/module
tar czf modules.tgz *
scp modules.tgz pi@vunguyen.fyp.org:/tmp
```

Finally, the kernel image and the kernel modules were installed for Raspberry Pi using the command as follows:

```
cd /
sudo mv /tmp/kernel.img /boot/
sudo tar xzf /tmp/modules.tgz
rm /tmp/modules.tgz
```

After Raspberry Pi were rebooted and connected to the development host over SSH, the command *uname -r* was used to verify that the new kernel image that had been built before was booted successfully.



```
Linux raspberrypi 3.10.34+ #1 PREEMPT Tue Apr  1 14:42:48 EEST 2
014 armv6l

The programs included with the Debian GNU/Linux system are free
 software;
the exact distribution terms for each program are described in
the
individual files in /usr/share/doc/*/copyright.

Debian GNU/Linux comes with ABSOLUTELY NO WARRANTY, to the exte
nt
permitted by applicable law.
Last login: Tue Apr 15 02:06:26 2014 from dsl-espbrasgw1-54f9db
-135.dhcp.inet.fi
pi@raspberrypi ~ $ uname -r
3.10.34+
```

Figure 10. Successful result after building a new Linux kernel

Figure 10 shows the result from a successful boot from Raspberry Pi with the new kernel version 3.10.34+. After the successful compilation of the new kernel, the target was ready for the implementation and testing later on during the project.

4.2 Implementation of Per-device Structure and Initialization and Exit Routines

The design of the per-device structure, the initialization routine and the exit routine was discussed in section 3.2. This section gives more details on how each of them was implemented by analyzing their source code. Listing 3 shows a snippet of code that was implemented for the per-device data structure.

```
struct raspi_gpio_dev {
        struct cdev cdev;
        struct gpio pin;
        enum state state;
        enum direction dir;
        bool irq_perm;
        unsigned long irq_flag;
        unsigned int irq_counter;
        spinlock_t lock;
};
```

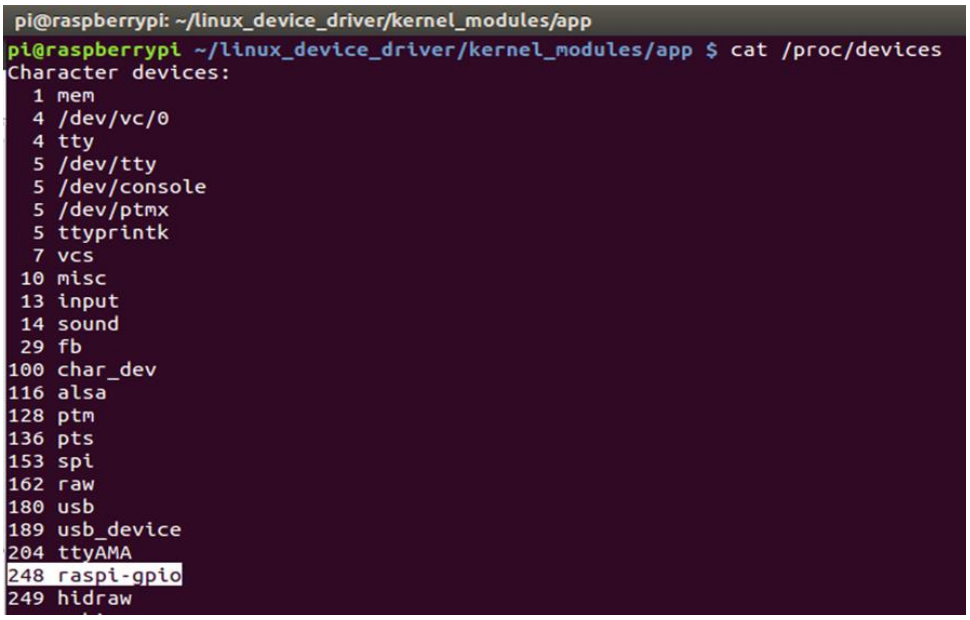
Listing 3. Per-device data structure for the GPIO device driver

The very first pieces of code implemented for the GPIO device driver were the per-device data structure. This data structure is named *raspi_gpio_dev*. In the project, almost every name of variables, structures, and functions were named beginning with the prefix *raspi_gpio_*. Each instance of the per-device data structure represents a GPIO pin. The first element of the structure is an instance of *struct cdev* structure. This is the internal structure of the Linux kernel that represents character devices. This structure is defined in <*linux/cdev.h*> header file. The next element is an instance of *struct gpio* structure. As the name implies, this element is used to store such information as GPIO pin number, flags to define the status of a GPIO pin when it is first claimed, and a pointer to the *const char* data type called label. The *struct gpio* structure encapsulates all the three fields just mentioned; hence, when using this structure to represent a GPIO pin, it will be much easier to handle. The next two elements in the per-device structure are *state* and *dir* elements which are of user-defined data types. The user-defined data type for the *state* data element has two values: low or high. Likewise, the data type of *dir* data element has two discrete values: in or out. To support the interrupt feature, three more data elements were added to the *raspi_gpio_dev* structure. They are *irq_perm, irq_flag*, and *irq_counter*. The *irq_perm* is of *bool* data type, so it has two values, either true or false. The *irq_flag* is of data type *unsigned long* which is used to determine the triggering type for an interrupt. The *irq_counter* is of data type *unsigned int* which keeps track of the number of requests for interrupt from userspace applications. The last element is a *lock* that is of system data type *spinlock_t*. This data element is used for synchronization purposes.

When the GPIO kernel module is loaded by the kernel upon request, the initialization routine will be called. First of all, *raspi_gpio_init ()* invokes *alloc_chrdev_region()* to dynamically request a range of unused character device numbers. Variable *first* of data type *dev_t* contains the allocated major number if the call is successful. The second and third arguments passed into *alloc_chrdev_region()* require the function to allocate NUM_GPIO_PINS number of minor devices starting from zero. The last argument is the device name which will appear in */proc/devices* when the device driver is registered successfully. This argument is defined using a macro called DEVICE_NAME. Figure 11 shows the output from *cat /proc/devices* command.

When the Raspberry Pi GPIO kernel module has been registered successfully, displaying the content of */proc/devices* directory shows the major number allotted for the device which, as shown in figure 11, is 248 in the first column. After that, the initialization routine creates a class under the virtual filesystem which is mounted at */sys* by using function *class_create()*. Together with function *class_create()*, the function *de-*

vice_create() results in the generation of 21 *uevents*. Since there are, in total, 21 GPIO pins on Raspberry Pi, the *raspi_gpio_init()* loops 21 times. With each iteration, it requests the kernel to allocate memory dynamically for the per-device structure using kernel API function *kmalloc()*. It should be noted that the *cdev* is embedded inside each per-device structure. When the kernel allocates memory for the per-device structure, *cdev* will also be allocated. If successful, the initialization routine will continue by claiming resource for a GPIO pin with initial status of a GPIO pin set to output and low logic level. Since initial values and states should be set at the beginning when the kernel module is first loaded, the initialization routine is responsible for doing that. In particular, it sets the direction of all GPIO pins to output and initial states of GPIO pins to low level, disables the *irq_perm* flag in each per-device structure, sets the *irq_flag* flag to rising edge triggering, initializes the *irq_counter* to be zero since there is no interrupt request at the beginning, and finally sets the owner of the module to THIS_MODULE. In order to protect atomic sections of code, a spinlock is used. Hence, it is initialized for each per-device structure. Finally, *cdev_init()* associates the file operations in *raspi_gpio_fops* structure with the *cdev*. It is also responsible for connecting major and minor numbers previously allocated to the *cdev*. If everything goes smoothly without any error, the initialization process completes and prints out a message "RaspberryPi GPIO driver initialized" indicating its happiness.



```
pi@raspberrypi: ~/linux_device_driver/kernel_modules/app
pi@raspberrypi ~/linux_device_driver/kernel_modules/app $ cat /proc/devices
Character devices:
  1 mem
  4 /dev/vc/0
  4 tty
  5 /dev/tty
  5 /dev/console
  5 /dev/ptmx
  5 ttyprintk
  7 vcs
 10 misc
 13 input
 14 sound
 29 fb
100 char_dev
116 alsa
128 ptm
136 pts
153 spi
162 raw
180 usb
189 usb_device
204 ttyAMA
248 raspi-gpio
249 hidraw
```

Figure 11. Output shown from *cat /proc/devices* command

Listing 4 shows the implementation of the exit routine. When a kernel module is being unloaded from the system, the kernel calls this function to take care of that job. The exit function of the GPIO device driver is called *raspi_gpio_exit().* Basically, its job is to de-allocate resources that were requested from the initialization routine. Firstly, it unregisters from the system a range of NUM_GPIO_PINS device numbers. To be specific, the value of NUM_GPIO_PINS is defined to be 21. There are 21 per-device structures representing each GPIO pin. These structures were allocated dynamically by the kernel. In order to de-allocate those, the kernel API function *kfree()* is used.

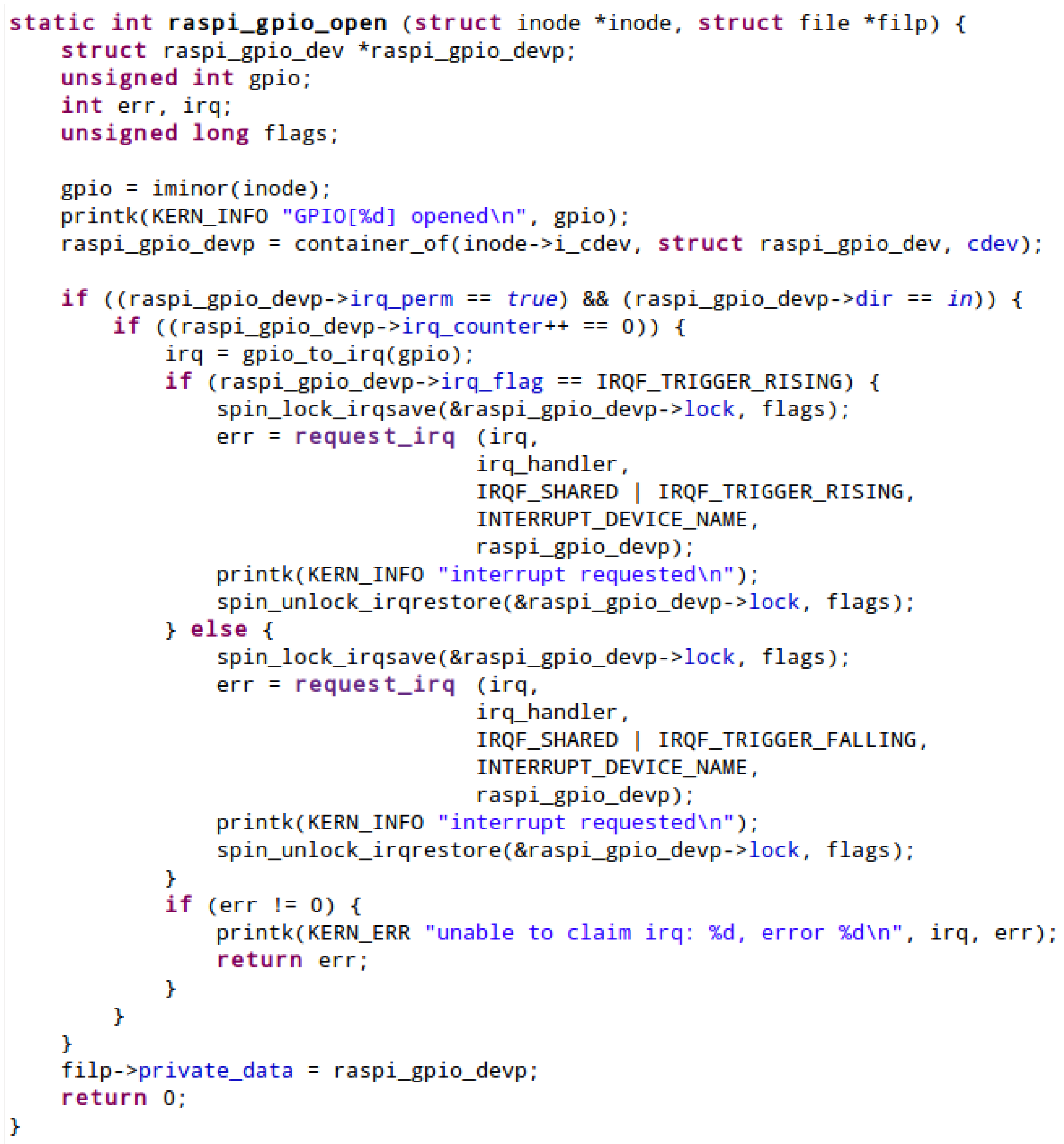
```
static void __exit
raspi_gpio_exit(void)
{
    int i = 0;

    unregister_chrdev_region(first, NUM_GPIO_PINS);

    for (i = 0; i < NUM_GPIO_PINS; i++)
        kfree(raspi_gpio_devp[i]);

    for (i = 0; i < MAX_GPIO_NUMBER; i++) {
        if (i != 0 && i != 1 && i != 5 && i != 6 &&
            i != 12 && i != 13 && i != 16 && i != 19 &&
            i != 20 && i != 21 && i != 26) {
            gpio_direction_output(i, 0);
            device_destroy (raspi_gpio_class,
                            MKDEV(MAJOR(first), MINOR(first) + i));
            gpio_free(i);
        }
    }

    class_destroy(raspi_gpio_class);

    printk(KERN_INFO "RaspberryPi GPIO driver removed\n");
}
```

Listing 4. Implementation of exit routine

As explained in section 3.2, the exit routine should set the direction of all GPIO pins to output and their logic levels to low. For that reason, *gpio_direction_output()* is called. This function is defined in <*linux/gpio.h*> Linux header file. The resource for GPIO pins were requested by *gpio_request_one()* before, so *gpio_free()* will take care of releasing those resources. Finally, all the information that populates the virtual filesystem mounted at */sys* directory and all the *uevents* created by *device_create()* are destroyed by *class_destroy()* and *device_destroy()*, respectively.

4.3 Implementation of the Entry Points for the GPIO Device Driver

When a user space application opens a corresponding device file, the *raspi_gpio_open()* entry point will be invoked by the kernel. Listing 5 shows the implementation of the *raspi_gpio_open()* entry point.



```
static int raspi_gpio_open (struct inode *inode, struct file *filp) {
    struct raspi_gpio_dev *raspi_gpio_devp;
    unsigned int gpio;
    int err, irq;
    unsigned long flags;

    gpio = iminor(inode);
    printk(KERN_INFO "GPIO[%d] opened\n", gpio);
    raspi_gpio_devp = container_of(inode->i_cdev, struct raspi_gpio_dev, cdev);

    if ((raspi_gpio_devp->irq_perm == true) && (raspi_gpio_devp->dir == in)) {
        if ((raspi_gpio_devp->irq_counter++ == 0)) {
            irq = gpio_to_irq(gpio);
            if (raspi_gpio_devp->irq_flag == IRQF_TRIGGER_RISING) {
                spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
                err = request_irq (irq,
                                    irq_handler,
                                    IRQF_SHARED | IRQF_TRIGGER_RISING,
                                    INTERRUPT_DEVICE_NAME,
                                    raspi_gpio_devp);
                printk(KERN_INFO "interrupt requested\n");
                spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
            } else {
                spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
                err = request_irq (irq,
                                    irq_handler,
                                    IRQF_SHARED | IRQF_TRIGGER_FALLING,
                                    INTERRUPT_DEVICE_NAME,
                                    raspi_gpio_devp);
                printk(KERN_INFO "interrupt requested\n");
                spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
            }
            if (err != 0) {
                printk(KERN_ERR "unable to claim irq: %d, error %d\n", irq, err);
                return err;
            }
        }
    }
    filp->private_data = raspi_gpio_devp;
    return 0;
}
```

Listing 5. Implementation of *raspi_gpio_open* entry point

The implementation of the open entry point was first started by obtaining a minor number that corresponds to a GPIO pin number. Mapping between a minor number and a GPIO pin number was specified by design. The inode which is passed as an argument to *raspi_gpio_open()* holds the address of the cdev structure allocated during initialization. Since *struct cdev* structure is nested inside the *raspi_gpio_dev* per-device structure as show in listing 3, the *raspi_gpio_dev* structure is the container of the *struct cdev* structure. In order to access data elements of the per-device structure, the address of it needs to be elicited. The open entry point uses the kernel helper function *container_of()* to do this. The address of *raspi_gpio_dev* structure is needed not only in the open entry point but also in other entry points including release, read, and write. Hence, this address is assigned to the *private_data* data field that is part of the *struct file* structure, the second argument. The *raspi_gpio_open()* entry point is also responsible for requesting interrupt resources upon request from userspace applications. The open entry point which was implemented based on the flowchart shown in figure 8 checks the status of the interrupt request permission variable *irq_perm* and the GPIO pin direction variable *dir*. If the interrupt permission variable *irq_perm* is set and the direction of the GPIO pin is set as input, the entry point will continue by checking the value of *irq_counter*. Otherwise, it will return zero indicating everything is fine. The *irq_counter* is used to keep track of how many times an interrupt is requested. If the value of the *irq_counter* is equal to zero, it means that an interrupt resource has not been acquired. As a result, the entry point will request for an interrupt resource from the GPIO pin and increment the value of the *irq_counter* by one. Since requesting for an interrupt resource must be atomic, *spin_lock_irqsave()* and *spin_unlock_irqrestore()* are used to protect this section of code. If requesting for an interrupt is successful, the open entry point will return zero. If there is an error due to interrupt request, the entry point will log the string "unable to claim irq: %d, error %d\n" to the kernel logging system and exit with an error code. Next the release entry point was implemented.

When a device file is closed by a userspace application, the kernel invokes the release entry point. The release entry point for the Raspberry Pi GPIO device driver is called *raspio_gpio_release*. Two arguments are passed into the *raspi_gpio_release* entry point, namely *inode* and *filp*. The entry point does not make use of the *filp* pointer; only the *inode* is used to get the address of the per-device structure. It can, of course, elicit the per-device structure's address from the *private_data* filed inside the *struct file* structure as an alternative. A GPIO pin number is obtained by using the inline function *iminor()*. This number is needed when the release entry point de-allocates an interrupt resource from a GPIO pin. There are two cases in which the release entry point is supposed handle. The first case is when an interrupt is enabled. In such a case, the release entry point keeps track of the value of the *irq_counter*. When the device is last closed, the value of the *irq_counter* should be zero after being decremented and the interrupt will be released by the entry point. On the other hand, if the interrupt is still enabled and the value of the *irq_counter* is not equal to zero after being decremented, this means that some userspace applications are still using the interrupt, and therefore, the release entry point will just return zero indicating the device file is closed successfully. The second case is when interrupt is asked to be disabled. The release entry point will respond to the request by checking the value of the *irq_counter*. If this value is equal to zero, it means that the interrupt resource has already been released, thus no need to do anything else. If the *irq_counter* value is larger than zero, some userspace applications are still using the interrupt. Since the interrupt is asked to be disabled, the release entry point will force the *irq_counter* value to be zero and then release interrupt resource. Accessing the *irq_counter* and releasing the interrupt resource should be atomic. As a result, the spinlock is utilized to protect these critical sections of code.

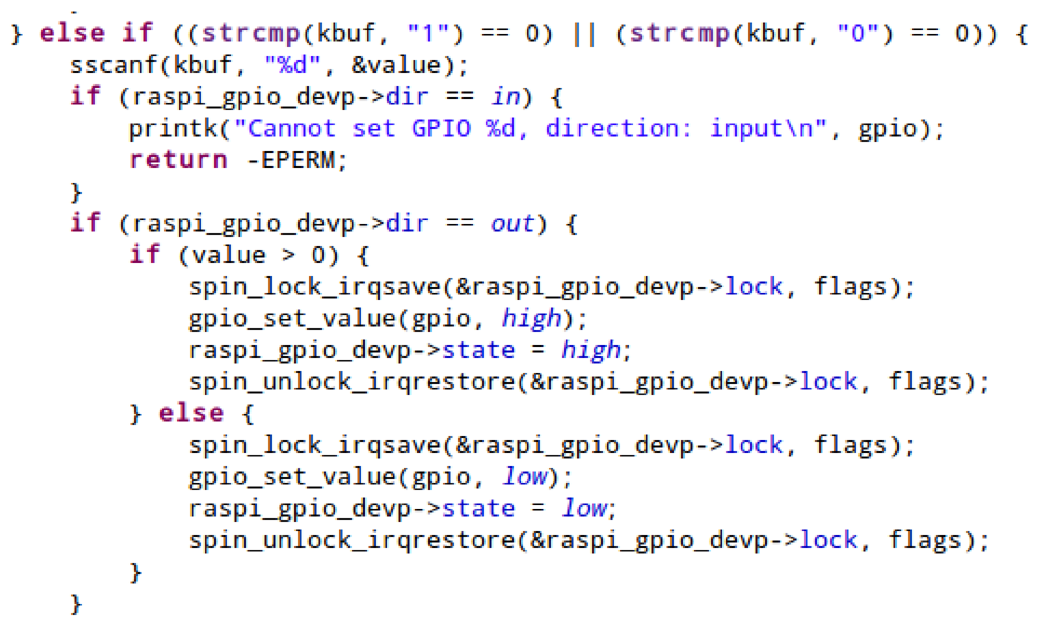
```
static ssize_t
raspi_gpio_read   (struct file *filp,
                   char *buf,
                   size_t count,
                   loff_t *f_pos)
{
    unsigned int gpio;
    ssize_t retval;
    char byte;

    gpio = iminor(filp->f_path.dentry->d_inode);
    for (retval = 0; retval < count; ++retval) {
        byte = '0' + gpio_get_value(gpio);
        if(put_user(byte, buf+retval))
            break;
    }

    return retval;
}
```

Listing 6. Implementation of *raspi_gpio_read* entry point

The last two entry points for the GPIO device driver are *raspi_gpio_read* entry point and *raspi_gpio_write* entry point. Listing 6 shows the implementation of the *raspi_gpio_read* entry point. This entry point was the easiest and simplest part of the device driver implementation, so it will be explained briefly. The *raspi_gpio_read* entry point first obtains a GPIO pin number from a device file by using the inline function *iminor()*. After that it gets the state of the GPIO pin with the help of the kernel function *gpio_get_value()*. This function returns either zero or one. Then the value returned from *gpio_get_value()* function will be converted into a character and saved to a temporary variable called *byte*. Finally this value will be copied to the userspace by using the kernel API function *put_user()*. It should be noted that copying from kernel space to userspace cannot be done by using normal C library functions. Instead, this has to be done by using kernel API functions such as *put_user()* or *copy_to_user()* functions. Upon completion of copying, the *raspi_gpio_read* entry point exits and returns the number of bytes copied to the userspace buffer pointed to by the *buf* pointer, the second argument passed into the *raspi_gpio_read()* entry point.

Similarly, the write entry point performs the task of copying data between a kernel space and a userspace. The last implementation of entry points for the GPIO device driver was the *raspi_gpio_write()* entry point. The *struct file* structure is passed as an argument into the *raspi_gpio_write* entry point. The *private_data* field contained in this *struct file* structure holds the address of the per-device structure which will be needed in this entry point. This is due to the fact that the address of the per-device structure was assigned to the *private_data* filed when the *raspi_gpio_open* entry point was called. This assignment can be seen from the third to last line in listing 5. Passed as the third argument to the write entry point is a *count* which indicates the number of bytes a userspace application has written into the buffer which is pointed to by the *buf* pointer, the second argument. Based on this information, the *raspi_gpio_open* entry point then reads *count* numbers of bytes from the buffer pointer to by *buf* pointer into its own temporary buffer in the kernel space called *kbuf*. Once the reading process has been completed and *kbuf* contains what has been read, the *raspi_gpio_open* entry point will compare the value of the *kbuf* with a set of commands specified in the design phase. These commands can be referenced from table 2. If the *kbuf* buffer contains commands “in” or “out”, the direction of the GPIO pin will be set by using *gpio_direction_in()* or *gpio_direction_out()*, respectively. Besides, the data elements in the per-device structure will be accessed and updated. For output direction setting, the data field *dir* will be set to *out*, and the data field state will be set to *low*. The default logic level when setting output direction is to set it *low*. For the input direction setting, only the data field *dir* needs to be updated and is set to *in*.

Listing 7 shows a code snippet implemented for the *raspi_gpio_write* entry point. When the content of the *kbuf* buffer is “1” or “0”, it will be understood by the write entry point that a userspace application requests for setting the logic level of a GPIO pin. The value is first converted into integer data type and stored in the temporary *value* variable. If the GPIO pin has been configured as an input pin, the write entry point will ignore this request and return an error code because an input GPIO pin cannot be set low or high. If the GPIO pin has been configured as an output pin, the content of the *value* variable will be checked. If the value of *value* variable is larger than zero, the GPIO pin's logic level will be set high and the *state* data field in the per-device structure will be updated accordingly – that is, it will be updated to *high*. If it is not larger than zero, the GPIO pin's logic level will be set low and the *state* data field will be updated to *low*. The practice of setting GPIO pin direction and updating the *state* data field should be atomic; therefore, a spinlock is used to protect these critical sections of code.



```
} else if ((strcmp(kbuf, "1") == 0) || (strcmp(kbuf, "0") == 0)) {
    sscanf(kbuf, "%d", &value);
    if (raspi_gpio_devp->dir == in) {
        printk("Cannot set GPIO %d, direction: input\n", gpio);
        return -EPERM;
    }
    if (raspi_gpio_devp->dir == out) {
        if (value > 0) {
            spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
            gpio_set_value(gpio, high);
            raspi_gpio_devp->state = high;
            spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
        } else {
            spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
            gpio_set_value(gpio, low);
            raspi_gpio_devp->state = low;
            spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
        }
    }
```

Listing 7. Code snippet for *raspi_gpio_write* entry point

The last part of code implemented for the *raspi_gpio_write* entry point was interrupt handling. Requesting for an interrupt resource by a userspace application means that either the string “rising” or “falling” is received. The following actions will be performed by the *raspi_gpio_write* entry point upon receiving a valid string command:

- Lock a spinlock to protect a critical section of code
- Set GPIO pin's direction to input
- Update the *dir* data field in the per-device structure to *in*
- Update the *irq_perm* data field in the per-device structure to *true*

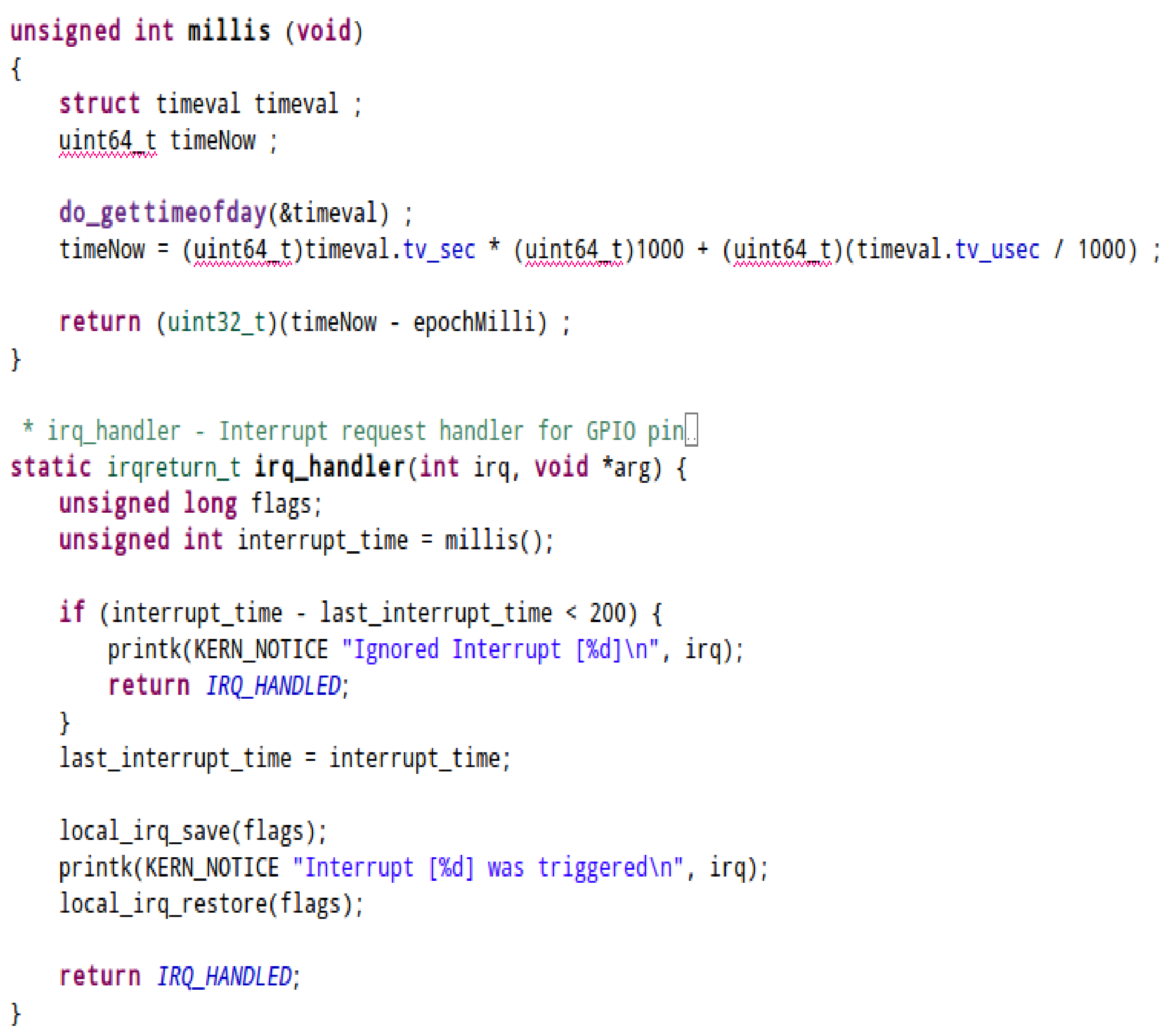
- Set *irq_flag* data field in the per-device structure to IRQF_TRIGGER_RISING if “rising” command is received
- Set *irq_flag* data field in the per-device structure to IRQF_TRIGGER_FALLING if “falling” command is received
- Unlock a spinlock.

When a userspace application asks to disable interrupt on a GPIO pin, it will send “disable-irq” command. This command simply means “disable interrupt request” in plain English. Upon receiving this command, the write entry point will set the *irq_perm* data field in the per-device structure to *false* indicating that the request for interrupt is not permitted. Any command received by the *raspi_gpio_write* entry point other than the ones specified in table 2 will be ignored, and EINVAL error code will be returned. Finally, the entry point will update the current position of the *f_pos* pointer by *count* positions and return the number of bytes received.

4.4 Implementation of Interrupt Handling Functions

The interrupt handling feature in the project was experimental, so the implementation for it was quite short and simple. Listing 8 shows the source code for interrupt handling functions. The interrupt handling of the GPIO device driver consists of two functions: *millis()* and *irq_handler*. While *millis()* is a normal function which returns the current system time to the caller, the *irq_hanlder* is a special function which is called only when a hardware interrupt signal arrives. As for the *millis()* function, it gets the current system time by calling the kernel API function *do_gettimeofday()*. This function returns the current system time and stores it in the *timeval* variable of type *struct timeval*. After that, it converts the time stored in *timeval* variable to milliseconds. What is returned from the *millis()* function is the current system time.

Regarding the interrupt handling function *irq_handler()*, this function will be called when an interrupt occurs. Due to the nature of interrupt handling, this function was implemented in such a way that it is fast and it does not contain any blocking functions. The interrupt handler first gets the current time and compares it with the last timestamp when an interrupt occurred. By trial and error, it was determined that a time duration of 200 milliseconds is good enough to avoid voltage glitches caused by contact bouncing. The timestamp when the interrupt handler was called is stored in *last_interrupt_time* global variable as a reference timestamp for the next interrupt. Since an interrupt handler can be interrupted by another interrupt, functions *local_irq_save()* and *local_irq_restore()* are used to prevent that problem from happening. The *irq_handler* interrupt handle is not of practical use since this feature is still experimental. It simply logs the string “Interrupt [%d] was triggered\n” into the kernel logging system.



```
unsigned int millis (void)
{
    struct timeval timeval ;
    uint64_t timeNow ;

    do_gettimeofday(&timeval) ;
    timeNow = (uint64_t)timeval.tv_sec * (uint64_t)1000 + (uint64_t)(timeval.tv_usec / 1000) ;

    return (uint32_t)(timeNow - epochMilli) ;
}

 * irq_handler - Interrupt request handler for GPIO pin
static irqreturn_t irq_handler(int irq, void *arg) {
    unsigned long flags;
    unsigned int interrupt_time = millis();

    if (interrupt_time - last_interrupt_time < 200) {
        printk(KERN_NOTICE "Ignored Interrupt [%d]\n", irq);
        return IRQ_HANDLED;
    }
    last_interrupt_time = interrupt_time;

    local_irq_save(flags);
    printk(KERN_NOTICE "Interrupt [%d] was triggered\n", irq);
    local_irq_restore(flags);

    return IRQ_HANDLED;
}
```

Listing 8. Implementation of interrupt handling functions for the GPIO device driver

That was the last part in the implementation of the GPIO character device driver. Chapter 5 will discuss how the device driver was tested.

5 Testing of the GPIO Device Driver

5.1 Testing Preparation

Testing was the final phase in the development of the GPIO character device driver for Raspberry Pi. The purpose of the testing was to verify that the GPIO device driver worked according to a set of defined test cases. The testing of the device driver was based on black-box testing. In other words, the functionalities offered by the device driver were examined case by case. There were three test cases applied to test the device driver, namely output functionality test case, input functionality test case, and interrupt functionality test case.

The hardware needed for the testing included 7 white light-emitting diodes (LED), 17 resistors with a resistance of 100Ω, 19 male to female electrical wires, 2 100KΩ resistors, a switch, and 2 breadboards. Each 100Ω resistor was used to limit the current flowing through each white LED. The switch was used for testing interrupt functionality.

The test software used for testing the GPIO device driver is located at *ldd_raspi_gpio_driver/app* directory where *ldd_raspi_gpio_driver* is the workspace root directory. Two application programs were developed for testing, and they were written in the C programming language. The first application program, called *output_test.c*, is located at *ldd_raspi_gpio_driver/app/output_test* and is provided in appendix 2. This was used for testing output functionality of the device driver. The second application, called *input_test.c*, is located at *ldd_raspi_gpio_driver/app/input_test* and is provided in appendix 3. This was used for testing input functionality of the device driver. The GPIO device driver had been loaded into the running kernel before performing each test case.

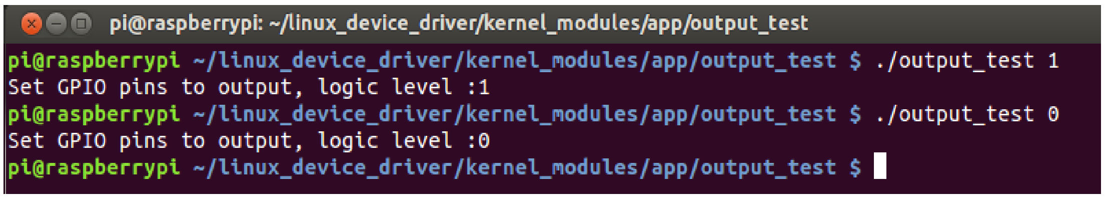
5.2 Testing of Output Functionality

The first test case was carried out to verify the output functionality offered by the GPIO device driver. An application program called *output_test* was run in the userspace to test the driver, and it has the following syntax:

```
./output_test <logic_level>
```

where *<logic_level>* refers to the logic state that is passed as an argument to the program for setting a GPIO pin low or high. If *<logic_level>* is “1”, the application will set the logic level of all GPIO pins high, whereas passing “0” as an argument to the application program will set all the logic level of all GPIO pins low.

A simple circuit was constructed on a breadboard for testing the output functionality. Each of the 17 100Ω resistors was connected in series with each of the 17 white LEDs in order to limit the current flowing through the LEDs. The output from each GPIO pin was wired to the anode terminal of an LED. The cathode terminal of the LED was connected in series with a 100Ω resistor which in turn was connected to a GND pin from the breadboard. Below is the output of the application program when invoked from the command line with arguments ”1” and ”0”, respectively.


pi@raspberrypi: ~/linux_device_driver/kernel_modules/app/output_test

```
pi@raspberrypi ~/linux_device_driver/kernel_modules/app/output_test $ ./output_test 1
Set GPIO pins to output, logic level :1
pi@raspberrypi ~/linux_device_driver/kernel_modules/app/output_test $ ./output_test 0
Set GPIO pins to output, logic level :0
pi@raspberrypi ~/linux_device_driver/kernel_modules/app/output_test $
```

Figure 12. Output of the application program output_test with arguments ”0” and ”1”

The results of the output functionality test case are shown in figure 13 and figure 14. Figure 13 shows that the LEDs connected to the Raspberry Pi P1 header were lit when the application program was executed with argument “1” being passed into the program.

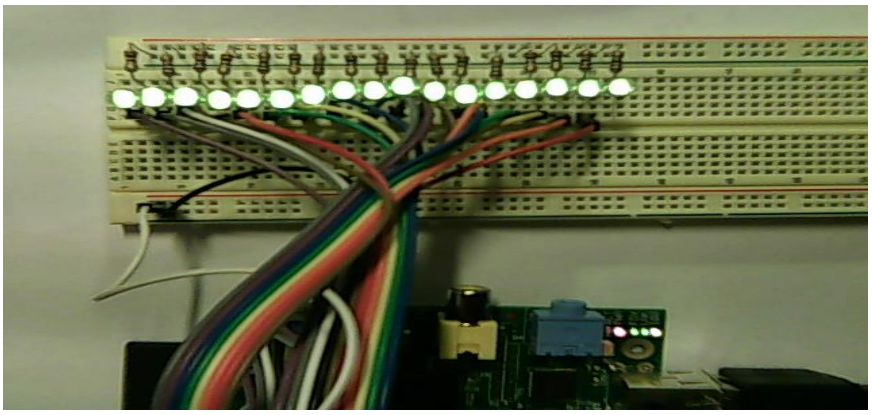


Figure 13. Output functionality testing result with all GPIO pins set high

Figure 14 shows that all the white LEDs went off when the application program was executed with argument “0” being passed into the program. In fact, four GPIO pins from the Raspberry Pi P5 connector were also set high. Because I did not solder any header into the P5 connector, these four GPIO pins were not tested using LEDs. I did, however, measure the voltages from each of the four GPIO pins from the P5 connector. The voltage values were about 3V when GPIO pins were set high, and about 0V with GPIO pins being set low.

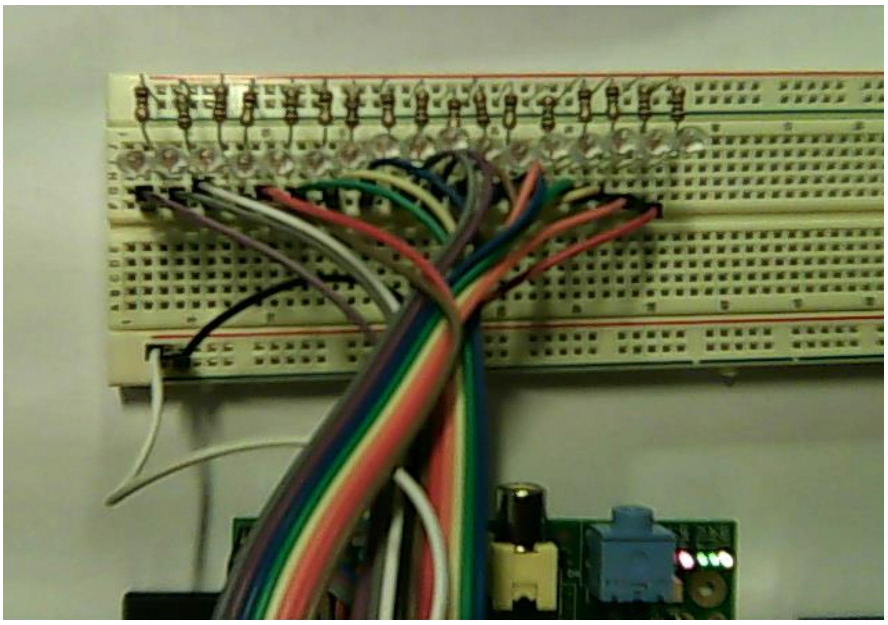


Figure 14. Output functionality testing result with all GPIO pins set low

The next section will show the test setup, testing procedures as well as testing results from the input functionality test case of the GPIO device driver.

5.3 Testing of Input Functionality

Input functionality test case was performed to verify the input functionality offered by the GPIO device driver. An application program called *input_test* was run in the userspace to test the driver. When invoked from the userspace, the application program first sets all the GPIO pins on Raspberry Pi to input. After that it reads the logic levels of all the GPIO pins and prints these values to the terminal.

Figure 15 shows a circuit that was constructed on a breadboard for testing input functionality of the GPIO device driver when all GPIO pins were connected to the ground

(GND). Each of the 17 GPIO pins was connected in series with one terminal of a 100Ω resistor. The other end of each resistor was connected to the GND of the breadboard.

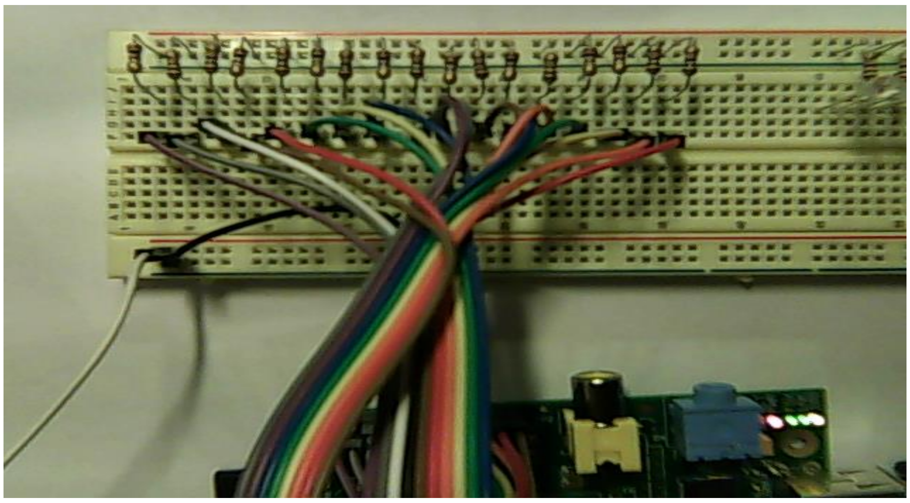


Figure 15. Test setup for input functionality testing with GPIO pins connected to ground

In a similar fashion, the circuit in figure 16 was built to test the input functionality of the device driver. However, in this circuit all the other ends of each resistor were connected to a 3.3V power supply from the breadboard.

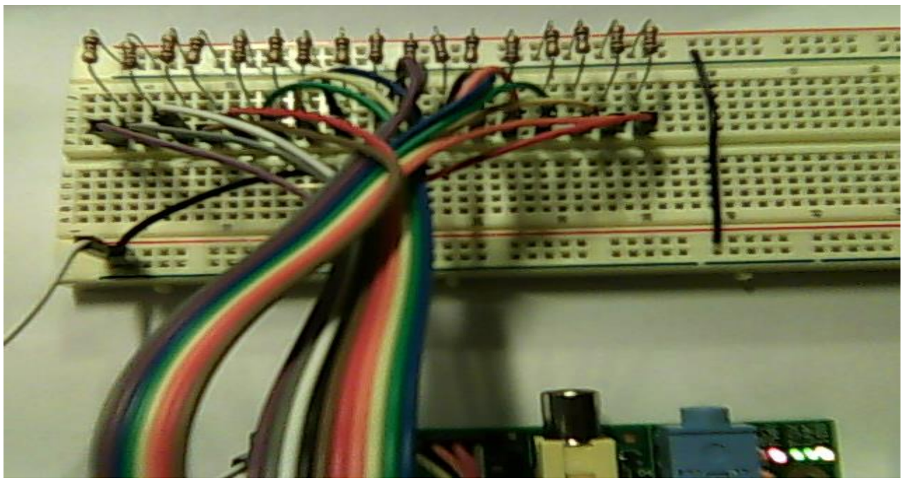
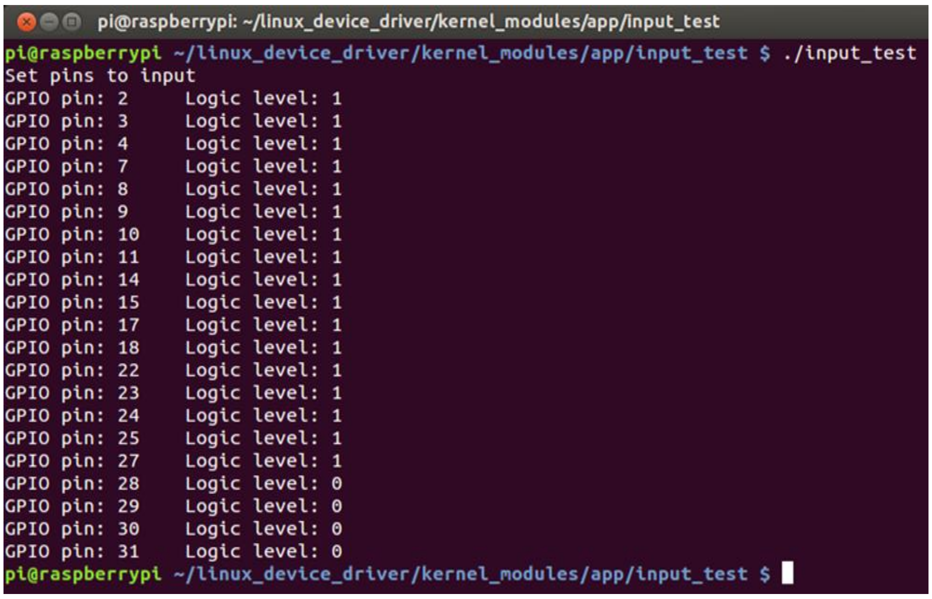


Figure 16. Test setup for input functionality testing with GPIO pins connected to 3.3V

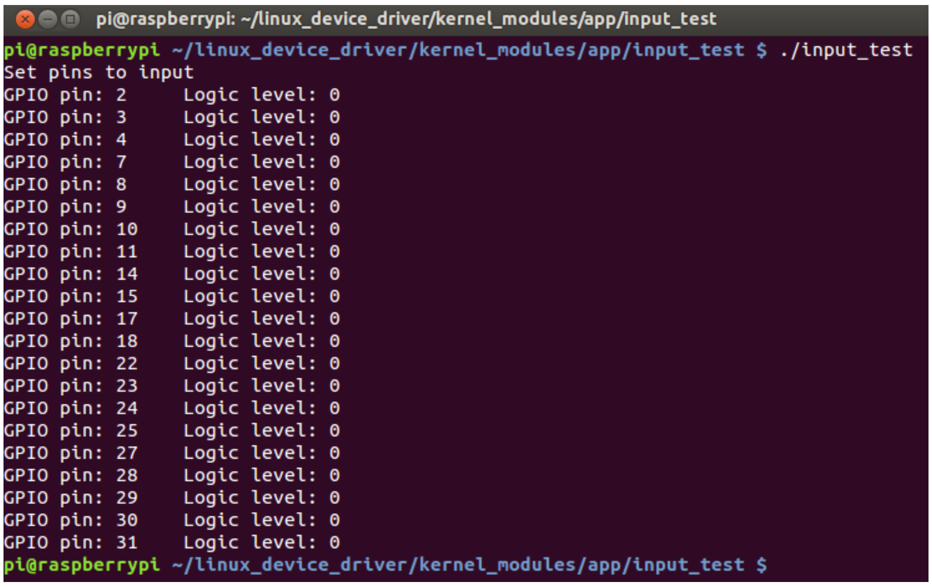
Figure 17 shows the output of the application program *input_test* when the GPIO pins were connected to a 3.3 V power supply. All 21 GPIO pins were read by the program as high logic level except for the last four GPIO pins. This is because these GPIO pins come from the P5 header of Raspberry Pi, and they were left floating. Therefore, their logic levels are usually low when being set as input.



```
pi@raspberrypi: ~/linux_device_driver/kernel_modules/app/input_test
pi@raspberrypi ~/linux_device_driver/kernel_modules/app/input_test $ ./input_test
Set pins to input
GPIO pin: 2     Logic level: 1
GPIO pin: 3     Logic level: 1
GPIO pin: 4     Logic level: 1
GPIO pin: 7     Logic level: 1
GPIO pin: 8     Logic level: 1
GPIO pin: 9     Logic level: 1
GPIO pin: 10    Logic level: 1
GPIO pin: 11    Logic level: 1
GPIO pin: 14    Logic level: 1
GPIO pin: 15    Logic level: 1
GPIO pin: 17    Logic level: 1
GPIO pin: 18    Logic level: 1
GPIO pin: 22    Logic level: 1
GPIO pin: 23    Logic level: 1
GPIO pin: 24    Logic level: 1
GPIO pin: 25    Logic level: 1
GPIO pin: 27    Logic level: 1
GPIO pin: 28    Logic level: 0
GPIO pin: 29    Logic level: 0
GPIO pin: 30    Logic level: 0
GPIO pin: 31    Logic level: 0
pi@raspberrypi ~/linux_device_driver/kernel_modules/app/input_test $
```

Figure 17. Input functionality testing result with all GPIO pins connected to 3.3 V

When all GPIO pins were connected to the ground of the breadboard, the application program was executed again. The logic levels of all GPIO pins were read as “0” as shown in figure 18.



```
pi@raspberrypi: ~/linux_device_driver/kernel_modules/app/input_test
pi@raspberrypi ~/linux_device_driver/kernel_modules/app/input_test $ ./input_test
Set pins to input
GPIO pin: 2     Logic level: 0
GPIO pin: 3     Logic level: 0
GPIO pin: 4     Logic level: 0
GPIO pin: 7     Logic level: 0
GPIO pin: 8     Logic level: 0
GPIO pin: 9     Logic level: 0
GPIO pin: 10    Logic level: 0
GPIO pin: 11    Logic level: 0
GPIO pin: 14    Logic level: 0
GPIO pin: 15    Logic level: 0
GPIO pin: 17    Logic level: 0
GPIO pin: 18    Logic level: 0
GPIO pin: 22    Logic level: 0
GPIO pin: 23    Logic level: 0
GPIO pin: 24    Logic level: 0
GPIO pin: 25    Logic level: 0
GPIO pin: 27    Logic level: 0
GPIO pin: 28    Logic level: 0
GPIO pin: 29    Logic level: 0
GPIO pin: 30    Logic level: 0
GPIO pin: 31    Logic level: 0
pi@raspberrypi ~/linux_device_driver/kernel_modules/app/input_test $
```

Figure 18. Input functionality testing result with all GPIO pins connected to GND

The next section will discuss the testing of interrupt handling feature of the device driver. Another circuit was built to interface with a GPIO pin of Raspberry Pi.

5.4 Testing of Interrupt Functionality

Testing of interrupt functionality is called interrupt functionality test case. The aim of this test case was to verify interrupt functionality of the GPIO device driver. To make it clearer, when a userspace application makes a request for interrupt on a certain GPIO pin, the device driver will act accordingly by allocating an interrupt resource on that GPIO pin. Then when a hardware interrupt signal arrives at the GPIO pin, interrupt on that GPIO pin will be triggered. Below are commands used to enable interrupt on GPIO pin 27. An interrupt can be rising edge triggering or falling edge triggering.

```
echo <triggering_type> > /dev/raspiGPIO27
cat /dev/raspiGPIO27
```

where <triggering_type> can be rising or falling.

When asked by a userspace application to disable an interrupt, the device driver will force to free an interrupt resource regardless of how many userspace applications are still using a GPIO pin for the interrupt. Below is a sample command which is used to disable the interrupt from GPIO pin 27.

```
echo disable-irq > /dev/raspiGpio27
```

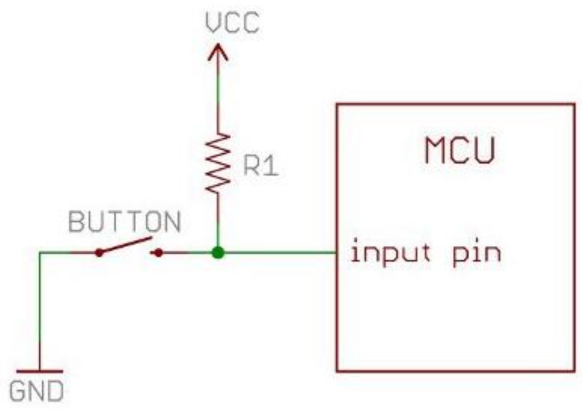
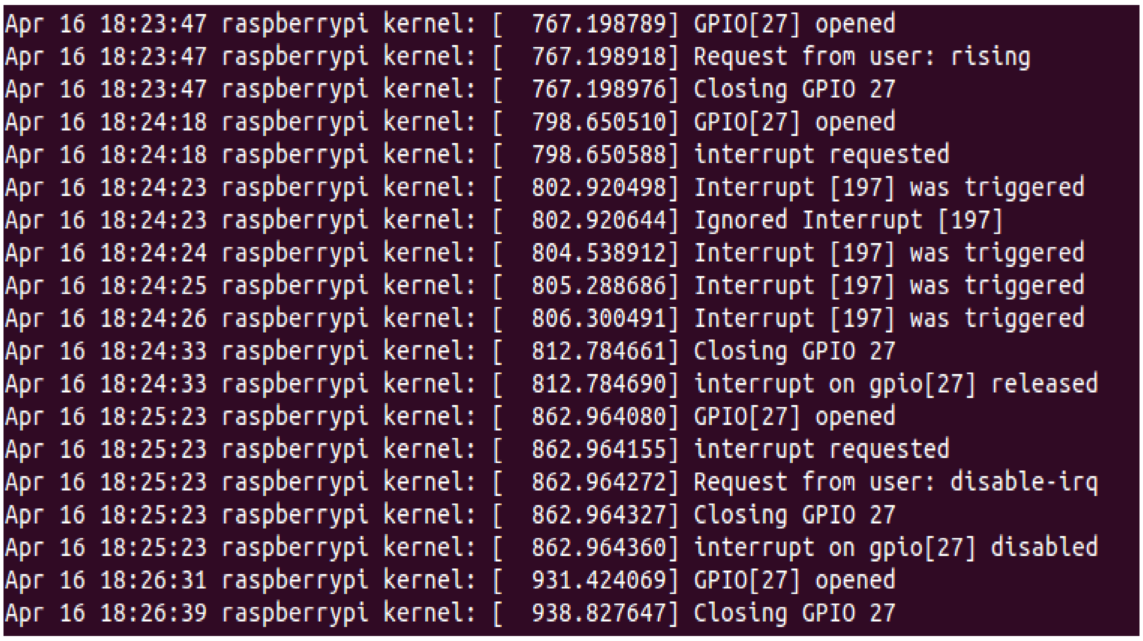


Figure 19. External pull-up-resistor circuit diagram
Reprinted from Mando [13]

Figure 19 shows a circuit diagram built for testing an interrupt. The circuit consists of a switch (button) and a 10KΩ pull-up-resistor. When the switch is not pressed, the input pin will read a high logic state because a small amount of current flows between the power supply VCC and the input pin. When the switch is pressed, the current will flow directly to the ground via the 10KΩ resistor. As a result, the input pin reads a low logic state.



```
Apr 16 18:23:47 raspberrypi kernel: [  767.198789] GPIO[27] opened
Apr 16 18:23:47 raspberrypi kernel: [  767.198918] Request from user: rising
Apr 16 18:23:47 raspberrypi kernel: [  767.198976] Closing GPIO 27
Apr 16 18:24:18 raspberrypi kernel: [  798.650510] GPIO[27] opened
Apr 16 18:24:18 raspberrypi kernel: [  798.650588] interrupt requested
Apr 16 18:24:23 raspberrypi kernel: [  802.920498] Interrupt [197] was triggered
Apr 16 18:24:23 raspberrypi kernel: [  802.920644] Ignored Interrupt [197]
Apr 16 18:24:24 raspberrypi kernel: [  804.538912] Interrupt [197] was triggered
Apr 16 18:24:25 raspberrypi kernel: [  805.288686] Interrupt [197] was triggered
Apr 16 18:24:26 raspberrypi kernel: [  806.300491] Interrupt [197] was triggered
Apr 16 18:24:33 raspberrypi kernel: [  812.784661] Closing GPIO 27
Apr 16 18:24:33 raspberrypi kernel: [  812.784690] interrupt on gpio[27] released
Apr 16 18:25:23 raspberrypi kernel: [  862.964080] GPIO[27] opened
Apr 16 18:25:23 raspberrypi kernel: [  862.964155] interrupt requested
Apr 16 18:25:23 raspberrypi kernel: [  862.964272] Request from user: disable-irq
Apr 16 18:25:23 raspberrypi kernel: [  862.964327] Closing GPIO 27
Apr 16 18:25:23 raspberrypi kernel: [  862.964360] interrupt on gpio[27] disabled
Apr 16 18:26:31 raspberrypi kernel: [  931.424069] GPIO[27] opened
Apr 16 18:26:39 raspberrypi kernel: [  938.827647] Closing GPIO 27
```

Figure 20. Result of interrupt testing

Figure 20 shows the result of interrupt testing displayed on the kernel log. It was displayed by using the following command:

tailf /var/log/messages

Table 3 shows commands issued on the terminal together with actions from the external circuit and their corresponding results shown in figure 20. Firstly, an interrupt was requested from the userspace by issuing the command *echo rising > /dev/raspiGpio27*. It should be kept in mind that allocating an interrupt resource actually took place until the device file */dev/raspiGpio27* was opened again. Lines 4 and 5 in figure 20 show that when the device file */dev/raspiGpio27* was opened by using cat */dev/raspiGpio27*, an interrupted was requested for GPIO pin 27. While reading from the device file, the switch was pressed four times and the interrupt was triggered as shown from lines 6 to 10. Line 7 in figure 20 shows that the interrupt was ignored. The reason for this is that the mechanical switch causes a phenomenon known as contact bouncing when pressed and released. Contact bouncing is undesirable, and therefore, it was ignored since the switch was pressed only four times. When the userspace closed the device file, a message “Closing GPIO 27” showed up on line 11 indicating that the device file was being closed. After that, the interrupt was released as shown on line 12 because only one userspace process used the GPIO pin 27 for the interrupt at the time.

Table 3. Commands issued together with actions from external circuit and their corresponding results

Commands issued on terminal and actions from external circuit	Corresponding result shown in figure 20
echo rising > /dev/raspiGpio27	lines 1 – 3
cat /dev/raspiGpio27 Switch pressed	Lines 4 – 12
echo disable-irq > /dev/raspiGpio27	Lines 13 – 17
cat /dev/raspiGpio27 Switch pressed	Lines 18 – 19

Another interrupt handling feature tested in this test case was to disable the interrupt on a GPIO pin and to verify if the interrupt was really disabled. Below is the command used to disable the interrupt on GPIO pin 27.

```
echo disable-irq > /dev/raspiGpio27
```

Lines 13 to 17 in figure 20 show the output of the kernel logging system when the device file */dev/raspiGpio27* was opened to disable the interrupt and closed. To test if the interrupt on GPIO pin 27 was disabled, the device file was opened again and the switch was pressed and released several times. No logging messages indicating the interrupt triggering were displayed on the terminal as shown on lines 18 and line 19 in figure 20. This means that the interrupt on GPIO pin 27 was successfully disabled.

6 Results and Discussion

A complete GPIO character device driver for Raspberry Pi was designed and implemented from scratch. It was also tested in the form of black-box testing during the testing phase of the project. The results of the testing phase show that the device driver does what it is supposed to function. By and large, the objective of the final year project was met.

Regarding the output functionality feature, the direction of all GPIO pins on Raspberry Pi could be set to output. These GPIO pins can also be set to a high logic level or a low logic level. The input functionality was verified to be working normally. When all the GPIO pins were grounded, the logic level values read from them were all zero. Likewise, the logic level values were read high or one when all the GPIO pins were connected to a 3.3V power supply. Finally the interrupt handling feature was tested in the interrupt handling test case. One or more processes were able to share an interrupt on a GPIO pin, and an external signal could invoke an interrupt on that GPIO pin.

However, there still remain several limitations. First of all, interrupt handling offered by the device driver is rather an experimental feature. When a hardware interrupt signal arrives, the kernel will simply call the interrupt handler and display a message to its logging system. Therefore, it is not practically useful when a userspace application needs interrupt from a GPIO pin. In addition to that, the time duration for contact debouncing of a switch was determined based on trial and error. A time duration of 200 milliseconds was effective to avoid the contact bouncing problem in the case of this project. Each button or switch possesses its own characteristics; the bouncing time duration of each type of switch is different. Therefore, the debouncing solution implemented in the device driver will not be effective if another type of switch is used.

Secondly, GPIO character device driver is deprecated with a newer version of the Linux kernel by the gpio-sysfs driver. This implies that for a newer Linux kernel version a GPIO device driver could be implemented so that the driver exposes interfaces for userspace to use in the virtual filesystem mounted at */sys* directory.

Finally, there are about 500 lines of code implemented for the GPIO device driver. This is due to repetitions of code implemented for the *raspi_gpio_write* and *raspi_gpio_release* entry points. In my opinion, 500 lines of code for the GPIO device driver is still a rather long snippet of code.

7 Conclusion

The goal of the project was to design and implement a GPIO device driver from scratch based on Linux character device drivers. The final result was a working GPIO character device driver for the Raspberry Pi platform.

Three drawbacks and limiations were drawn, and these could be improved in the future. With reference to the contact boucing problem discussed in chapter 6, it is recommend that a Schmitt trigger circuit, for example, be built when interfacing a switch circuit to a GPIO pin of Raspberry Pi. As for the code size implemented for the device driver, the repetitions of code could be reduced by breaking them into several small functions. By doing this, the code would not only be reduced in terms of code size but also be easier to maintain and debug. Lastly, a newer method for implementing a GPIO device driver could be used – that is, interfaces exposed by a GPIO device driver to the userspace are in the virtual filesystem mounted at */sys* directory.

The GPIO character device driver implemented for Raspberry Pi in this project could be further modified and implemented for other platforms such as BeagleBone, BeagleBone Black, Beagleboard, PandaBoard and so on. This is due to the fact that the GPIO device driver was designed and implemented using the GPIO APIs offered by the Linux kernel.

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Source code for GPIO Linux device driver

```
/*
 * raspi_gpio_driver.c - GPIO Linux device driver for Raspberry Pi B
 * rev 2.0 platform
 * Author:    Vu Nguyen <quangngmetro@gmail.com>
 * Version:   0.2
 * License:   GPL
 */
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/types.h>
#include <linux/kdev_t.h>
#include <linux/fs.h>
#include <linux/device.h>
#include <linux/cdev.h>
#include <asm/uaccess.h>
#include <linux/gpio.h>
#include <linux/slab.h>
#include <linux/errno.h>
#include <uapi/asm-generic/errno-base.h>
#include <linux/string.h>
#include <linux/spinlock.h>
#include <linux/interrupt.h>
#include <linux/time.h>

/* User-defined macros */
#define NUM_GPIO_PINS             21
#define MAX_GPIO_NUMBER           32
#define DEVICE_NAME               "raspi-gpio"
#define BUF_SIZE                  512
#define INTERRUPT_DEVICE_NAME     "gpio interrupt"

/* User-defined data types */
enum state    {low, high};
enum direction{in, out};

/*
```

```
 * struct raspi_gpio_dev - Per gpio pin data structure
 * @cdev:      instance of struct cdev
 * @pin:       instance of struct gpio
 * @state:     logic state (low, high) of a GPIO pin
 * @dir:       direction of a GPIO pin
 * @irq_perm:  used to enable/disable interrupt on GPIO pin
 * @irq_flag:  used to indicate rising/falling edge trigger
 * @lock:      used to protect atomic code section
 */
struct raspi_gpio_dev {
  struct cdev cdev;
  struct gpio pin;
  enum state state;
  enum direction dir;
  bool irq_perm;
  unsigned long irq_flag;
  unsigned int irq_counter;
  spinlock_t lock;
};

/* Declaration of entry points */
static int raspi_gpio_open(struct inode *inode, struct file *filp);
static ssize_t raspi_gpio_read ( struct file *filp,
                                 char *buf,
                                 size_t count,
                                 loff_t *f_pos);
static ssize_t raspi_gpio_write (struct file *filp,
                                 const char *buf,
                                 size_t count,
                                 loff_t *f_pos);
static int raspi_gpio_release(struct inode *inode, struct file *filp);

/* File operation structure */
static struct file_operations raspi_gpio_fops = {
  .owner    = THIS_MODULE,
  .open     = raspi_gpio_open,
  .release  = raspi_gpio_release,
  .read     = raspi_gpio_read,
  .write    = raspi_gpio_write,
};

/* Forward declaration of functions */
static int raspi_gpio_init(void);
static void raspi_gpio_exit(void);
unsigned int millis (void);
static irqreturn_t irq_handler(int irq, void *arg);

/* Global varibles for GPIO driver */
struct raspi_gpio_dev *raspi_gpio_devp[NUM_GPIO_PINS];
static dev_t first;
static struct class *raspi_gpio_class;
static unsigned int last_interrupt_time = 0;
static uint64_t epochMilli;

/*
 * millis - Get current time
 *
 * This function returns current time in ms. It is primarily used for
 * debouncing
 */
unsigned int millis (void)
{
  struct timeval timeval ;
  uint64_t timeNow ;

  do_gettimeofday(&timeval) ;
  timeNow = (uint64_t)timeval.tv_sec * (uint64_t)1000 +
            (uint64_t)(timeval.tv_usec/1000);

  return (uint32_t)(timeNow - epochMilli) ;
}

/*
 * irq_handler - Interrupt request handler for GPIO pin
 *
 * This feature is pretty experiment, so more work needs to
 * be done to make the feature useful for application
 */
```

```
static irqreturn_t irq_handler(int irq, void *arg) {
  unsigned long flags;
  unsigned int interrupt_time = millis();

  if (interrupt_time - last_interrupt_time < 200) {
    printk(KERN_NOTICE "Ignored Interrupt [%d]\n", irq);
    return IRQ_HANDLED;
  }
  last_interrupt_time = interrupt_time;

  local_irq_save(flags);
  printk(KERN_NOTICE "Interrupt [%d] was triggered\n", irq);
  local_irq_restore(flags);

  return IRQ_HANDLED;
}

/*
 * raspi_gpio_open - Open GPIO device node in /dev
 *
 * This function allocates GPIO interrupt resource when requested
 * on the condition that interrupt flag is enabled and pin direction
 * set to input, then allow the specified GPIO pin to set interrupt.
 */
static int raspi_gpio_open (struct inode *inode, struct file *filp) {
  struct raspi_gpio_dev *raspi_gpio_devp;
  unsigned int gpio;
  int err, irq;
  unsigned long flags;

  gpio = iminor(inode);
  printk(KERN_INFO "GPIO[%d] opened\n", gpio);
  raspi_gpio_devp = container_of(inode->i_cdev,
                                 struct raspi_gpio_dev,
                                 cdev);

  if ((raspi_gpio_devp->irq_perm == true) &&
      (raspi_gpio_devp->dir == in)) {
    if ((raspi_gpio_devp->irq_counter++ == 0)) {
      irq = gpio_to_irq(gpio);
      if (raspi_gpio_devp->irq_flag == IRQF_TRIGGER_RISING) {
        spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
        err = request_irq  ( irq,
                             irq_handler,
                             IRQF_SHARED | IRQF_TRIGGER_RISING,
                             INTERRUPT_DEVICE_NAME,
                             raspi_gpio_devp);
        printk(KERN_INFO "interrupt requested\n");
        spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
      } else {
        spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
        err = request_irq  ( irq,
                             irq_handler,
                             IRQF_SHARED | IRQF_TRIGGER_FALLING,
                             INTERRUPT_DEVICE_NAME,
                             raspi_gpio_devp);
        printk(KERN_INFO "interrupt requested\n");
        spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
      }
      if (err != 0) {
        printk(KERN_ERR "unable to claim irq: %d, error %d\n", irq,
                                                              err);
        return err;
      }
    }
  }
  filp->private_data = raspi_gpio_devp;
  return 0;
}

/*
 * raspi_gpio_release - Release GPIO pin
 *
 * This functions releases GPIO interrupt resource when the device is
 * last closed. When requested to disable interrupt, it releases GPIO
 * interrupt resource regardless of how many devices are using
 * interrupt.
 */
```

```
static int
raspi_gpio_release (struct inode *inode, struct file *filp)
{
  unsigned int gpio;
  struct raspi_gpio_dev *raspi_gpio_devp;

  raspi_gpio_devp = container_of(inode->i_cdev,
                                 struct raspi_gpio_dev,
                                 cdev);
  gpio = iminor(inode);
  printk(KERN_INFO "Closing GPIO %d\n", gpio);

  spin_lock(&raspi_gpio_devp->lock);
  if (raspi_gpio_devp->irq_perm == true) {
    if (raspi_gpio_devp->irq_counter > 0) {
      raspi_gpio_devp->irq_counter--;
      if (raspi_gpio_devp->irq_counter == 0) {
        printk(KERN_INFO "interrupt on gpio[%d] released\n", gpio);
        free_irq(gpio_to_irq(gpio), raspi_gpio_devp);
      }
    }
  }
  spin_unlock(&raspi_gpio_devp->lock);

  if ( raspi_gpio_devp->irq_perm == false &&
      raspi_gpio_devp->irq_counter > 0) {
    spin_lock(&raspi_gpio_devp->lock);
    free_irq(gpio_to_irq(gpio), raspi_gpio_devp);
    raspi_gpio_devp->irq_counter = 0;
    spin_unlock(&raspi_gpio_devp->lock);
    printk(KERN_INFO "interrupt on gpio[%d] disabled\n", gpio);
  }

  return 0;
}

/*
 * raspi_gpio_read - Read the state of GPIO pins
 *
 * This functions allows to read the logic state of input GPIO pins
 * and output GPIO pins. Since it multiple processes can read the
 * logic state of the GPIO, spin lock is not used here.
 */
static ssize_t
raspi_gpio_read  ( struct file *filp,
                   char *buf,
                   size_t count,
                   loff_t *f_pos)
{
  unsigned int gpio;
  ssize_t retval;
  char byte;

  gpio = iminor(filp->f_path.dentry->d_inode);
  for (retval = 0; retval < count; ++retval) {
    byte = '0' + gpio_get_value(gpio);
    if(put_user(byte, buf+retval))
      break;
  }

  return retval;
}

/*
 * raspi_gpio_write - Write to GPIO pin
 *
 * This function allows to set GPIO pin direction (input/out),
 * to set GPIO pin logic level (high/low), and to enable/disable
 * edge-triggered interrupt on a GPIO pin (rising/falling)
 * Set logic level (high/low) to an input GPIO pin is not permitted
 * The command set for setting GPIO pins is as follows
 * Command       Description
 * "out"      Set GPIO direction to output via gpio_direction_ouput
 * "in"       Set GPIO direction to input via gpio_direction_input
 * "1"        Set GPIO pin logic level to high
 * "0"        Set GPIO pin logic level to low
 * "rising"      Enable rising edge trigger
 * "falling"     Enable falling edge trigger
 * "disable-irq" Disable interrupt on a GPIO pin
 */
static ssize_t
raspi_gpio_write ( struct file *filp,
                   const char *buf,
                   size_t count,
                   loff_t *f_pos)
{
  unsigned int gpio, len = 0, value = 0;
  char kbuf[BUF_SIZE];
  struct raspi_gpio_dev *raspi_gpio_devp = filp->private_data;
  unsigned long flags;

  gpio = iminor(filp->f_path.dentry->d_inode);

  len = count < BUF_SIZE ? count-1 : BUF_SIZE-1;
  if(copy_from_user(kbuf, buf, len) != 0)
    return -EFAULT;
  kbuf[len] = '\0';

  printk(KERN_INFO "Request from user: %s\n", kbuf);

  // Check the content of kbuf and set GPIO pin accordingly
  if (strcmp(kbuf, "out") == 0) {
    printk(KERN_ALERT "gpio[%d] direction set to ouput\n", gpio);
    if (raspi_gpio_devp->dir != out) {
      spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
      gpio_direction_output(gpio, low);
      raspi_gpio_devp->dir = out;
      raspi_gpio_devp->state = low;
      spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
    }
  } else if (strcmp(kbuf, "in") == 0) {
    if (raspi_gpio_devp->dir != in) {
      printk(KERN_INFO "Set gpio[%d] direction: input\n", gpio);
      spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
      gpio_direction_input(gpio);
      raspi_gpio_devp->dir = in;
      spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
```

```
        }
    } else if ((strcmp(kbuf, "1") == 0) || (strcmp(kbuf, "0") == 0)) {
        sscanf(kbuf, "%d", &value);
        if (raspi_gpio_devp->dir == in) {
            printk("Cannot set GPIO %d, direction: input\n", gpio);
            return -EPERM;
        }
        if (raspi_gpio_devp->dir == out) {
            if (value > 0) {
                spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
                gpio_set_value(gpio, high);
                raspi_gpio_devp->state = high;
                spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
            } else {
                spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
                gpio_set_value(gpio, low);
                raspi_gpio_devp->state = low;
                spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
            }
        }
    } else if ( (strcmp(kbuf, "rising") == 0) ||
                (strcmp(kbuf, "falling") == 0)) {
        spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
        gpio_direction_input(gpio);
        raspi_gpio_devp->dir = in;
        raspi_gpio_devp->irq_perm = true;
        if (strcmp(kbuf, "rising") == 0)
            raspi_gpio_devp->irq_flag = IRQF_TRIGGER_RISING;
        else
            raspi_gpio_devp->irq_flag = IRQF_TRIGGER_FALLING;
        spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
    } else if (strcmp(kbuf, "disable-irq") == 0){
        spin_lock_irqsave(&raspi_gpio_devp->lock, flags);
        raspi_gpio_devp->irq_perm = false;
        spin_unlock_irqrestore(&raspi_gpio_devp->lock, flags);
    } else {
        printk(KERN_ERR "Invalid value\n");
        return -EINVAL;
    }
```

```
   *f_pos += count;
   return count;
}



/*
 * raspi_gpio_init - Initialize GPIO device driver
 *
 * This function performs the following tasks:
 * Dynamically register a character device major
 * Create "raspi-gpio" class
 * Claim GPIO resource
 * Initialize the per-device data structure raspi_gpio_dev
 * Initialize spin lock used for synchronization
 * Register character device to the kernel
 * Create device nodes to expose GPIO resource
 */
static int __init
raspi_gpio_init(void)
{
    int i, ret, index = 0;
    struct timeval tv ;

    if (alloc_chrdev_region(&first,
                            0,
                            NUM_GPIO_PINS,
                            DEVICE_NAME) < 0) {
        printk(KERN_DEBUG "Cannot register device\n");
        return -1;
    }

    if ((raspi_gpio_class = class_create( THIS_MODULE,
                                          DEVICE_NAME)) == NULL) {
     printk(KERN_DEBUG "Cannot create class %s\n", DEVICE_NAME);
     unregister_chrdev_region(first, NUM_GPIO_PINS);
     return -EINVAL;
    }
```

```
for (i = 0; i < MAX_GPIO_NUMBER; i++) {
 if ( i != 0 && i != 1 && i != 5 && i != 6 &&
      i != 12 && i != 13 && i != 16 && i != 19 &&
      i != 20 && i != 21 && i != 26) {
   raspi_gpio_devp[index] = kmalloc(sizeof(struct raspi_gpio_dev),
                                           GFP_KERNEL);

   if (!raspi_gpio_devp[index]) {
     printk("Bad kmalloc\n");
     return -ENOMEM;
   }

   if (gpio_request_one(i, GPIOF_OUT_INIT_LOW, NULL) < 0) {
     printk(KERN_ALERT "Error requesting GPIO %d\n", i);
     return -ENODEV;
   }
   raspi_gpio_devp[index]->dir = out;
   raspi_gpio_devp[index]->state = low;
   raspi_gpio_devp[index]->irq_perm = false;
   raspi_gpio_devp[index]->irq_flag = IRQF_TRIGGER_RISING;
   raspi_gpio_devp[index]->irq_counter = 0;
   raspi_gpio_devp[index]->cdev.owner = THIS_MODULE;

   spin_lock_init(&raspi_gpio_devp[index]->lock);

   cdev_init(&raspi_gpio_devp[index]->cdev, &raspi_gpio_fops);

   if ((ret = cdev_add( &raspi_gpio_devp[index]->cdev,
                        (first + i),
                        1))) {
     printk (KERN_ALERT "Error %d adding cdev\n", ret);
     for (i = 0; i < MAX_GPIO_NUMBER; i++) {
       if ( i != 0 && i != 1 && i != 5 && i != 6 &&
            i != 12 && i != 13 && i != 16 && i != 19 &&
            i != 20 && i != 21 && i != 26) {
         device_destroy (raspi_gpio_class,
                         MKDEV(MAJOR(first),
                         MINOR(first) + i));
       }
```

```
          }
          class_destroy(raspi_gpio_class);
          unregister_chrdev_region(first, NUM_GPIO_PINS);

          return ret;
        }

        if (device_create( raspi_gpio_class,
                           NULL,
                           MKDEV(MAJOR(first), MINOR(first)+i),
                           NULL,
                           "raspiGpio%d",
                           i) == NULL) {
          class_destroy(raspi_gpio_class);
          unregister_chrdev_region(first, NUM_GPIO_PINS);

          return -1;
        }
        index++;
      }
     }

    // Configure interrupt
    do_gettimeofday(&tv) ;
    epochMilli = (uint64_t)tv.tv_sec *(uint64_t)1000 +
                (uint64_t)(tv.tv_usec/1000);

    printk("RaspberryPi GPIO driver initialized\n");

    return 0;
}

/*
 * raspi_gpio_exit - Clean up GPIO device driver when unloaded
 *
 * This functions performs the following tasks:
 * Release major number
 * Release device nodes in /dev
 * Release per-device structure arrays
 * Detroy class in /sys
 * Set all GPIO pins to output, low level
 */
static void __exit
raspi_gpio_exit(void)
{
    int i = 0;

    unregister_chrdev_region(first, NUM_GPIO_PINS);

    for (i = 0; i < NUM_GPIO_PINS; i++)
     kfree(raspi_gpio_devp[i]);

    for (i = 0; i < MAX_GPIO_NUMBER; i++) {
     if ( i != 0 && i != 1 && i != 5 && i != 6 &&
          i != 12 && i != 13 && i != 16 && i != 19 &&
          i != 20 && i != 21 && i != 26) {
       gpio_direction_output(i, 0);
       device_destroy ( raspi_gpio_class,
                        MKDEV(MAJOR(first), MINOR(first) + i));
       gpio_free(i);
     }
    }

    class_destroy(raspi_gpio_class);

    printk(KERN_INFO "RaspberryPi GPIO driver removed\n");
}

module_init(raspi_gpio_init);
module_exit(raspi_gpio_exit);

MODULE_LICENSE("GPL");
MODULE_AUTHOR("Vu Nguyen <quangngmetro@gmail.com>");
MODULE_DESCRIPTION("GPIO device driver for Raspberry Pi B rev2
                   platform);
```

Source code for output testing of GPIO device driver

```
/*
 * Name         :   output_test.c
 * Author       :   Vu Nguyen <quangngmetro@gmail.com>
 * Version      :   0.1
 * Copyright    :   GPL
 * Description : This is a test application which is used for testing
 * GPIO output functionality of the raspi-gpio Linux device driver
 * implemented for Raspberry Pi revision B platform. The test
 * application first sets all the GPIO pins on the Raspberry Pi to
 * output, then it sets all the GPIO pins to "high"/"low" logic
 * level based on the options passed to the program from the command
 * line
 * Usage example:
 *   ./output_test 1    // Set all GPIO pins to output, high state
 *   ./output_test 0    // Set all GPIO pins to output, low state
 */
#include <unistd.h>
#include <stdlib.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <stdio.h>
#include <string.h>

#define NUM_GPIO_PINS       21
#define MAX_GPIO_NUMBER     32
#define BUF_SIZE            4
#define PATH_SIZE           20

int main(int argc, char **argv)
{
  int i = 0, index = 0, value;
  int fd[NUM_GPIO_PINS];
  char path[PATH_SIZE];
  char buf[BUF_SIZE];

  if (argc != 2) {
```

```
  printf("Option low/high must be used\n");
  exit(EXIT_FAILURE);
}

// Open all GPIO pins
for (i = 0; i < MAX_GPIO_NUMBER; i++) {
  if (i != 0 && i != 1 && i != 5 && i != 6 &&
    i != 12 && i != 13 && i != 16 && i != 19 &&
    i != 20 && i != 21 && i != 26) {
    snprintf(path, sizeof(path), "/dev/raspiGpio%d", i);
    fd[index] = open(path, O_WRONLY);
    if (fd[index] < 0) {
      perror("Error opening GPIO pin");
      exit(EXIT_FAILURE);
    }
    index++;
  }
}

// Set direction of GPIO pins to output
printf("Set GPIO pins to output, logic level :%s\n", argv[1]);
strncpy(buf, "out", 3);
buf[3] = '\0';
for (index = 0; index < NUM_GPIO_PINS; index++) {
  if (write(fd[index], buf, sizeof(buf)) < 0) {
    perror("write, set pin output");
    exit(EXIT_FAILURE);
  }
}

// Set logic state of GPIO pins low/high
value = atoi(argv[1]);
if (value == 1) {
  strncpy(buf, "1", 1);
  buf[1] = '\0';
} else if (value == 0) {
  strncpy(buf, "0", 1);
  buf[1] = '\0';
} else {
        printf("Invalid logic value\n");
        exit(EXIT_FAILURE);
    }

    for (index = 0; index < NUM_GPIO_PINS; index++) {
        if (write(fd[index], buf, sizeof(buf)) < 0) {
            perror("write, set GPIO state of GPIO pins");
            exit(EXIT_FAILURE);
        }
    }

    return EXIT_SUCCESS;
}
```

Source code for input testing of GPIO device driver

```
/*
 * Name        : input_test.c
 * Author      : Vu Nguyen <quangngmetro@gmail.com>
 * Version     : 0.1
 * Copyright   : GPL
 * Description : This is a test application which is used for testing
 * GPIO input functionality of the raspi-gpio Linux device driver
 * implemented for Raspberry Pi revision B platform. The test
 * application first sets all the GPIO pins on the Raspberry Pi to
 * input, then it reads all the GPIO pins logic level and print these
 * value to the terminal.
 */
#include <unistd.h>
#include <stdlib.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <stdio.h>
#include <string.h>

#define NUM_GPIO_PINS     21
#define MAX_GPIO_NUMBER   32
#define BUF_SIZE          3
#define PATH_SIZE         20

int main(int argc, char **argv)
{
  int i = 0, index = 0;
  int fd[NUM_GPIO_PINS];
  char path[PATH_SIZE];
  char buf[BUF_SIZE];
  char readBuf[2];

  // Open all GPIO pins
  for (i = 0; i < MAX_GPIO_NUMBER; i++) {
    if (i != 0 && i != 1 && i != 5 && i != 6 &&
      i != 12 && i != 13 && i != 16 && i != 19 &&
            i != 20 && i != 21 && i != 26) {
            snprintf(path, sizeof(path), "/dev/raspiGpio%d", i);
            fd[index] = open(path, O_RDWR);
            if (fd[index] < 0) {
                perror("Error opening GPIO pin");
                exit(EXIT_FAILURE);
            }
            index++;
        }
    }

    // Set direction of GPIO pins to input
    printf("Set pins to input\n");
    strncpy(buf, "in", 2);
    buf[2] = '\0';
    for (index = 0; index < NUM_GPIO_PINS; index++) {
        if (write(fd[index], buf, sizeof(buf)) < 0) {
            perror("write, set pin input");
            exit(EXIT_FAILURE);
        }
    }

    // Read logic level of GPIO pins and display them to the terminal
    index = 0;
    for (i = 0; i < MAX_GPIO_NUMBER; i++) {
        if (i != 0 && i != 1 && i != 5 && i != 6 &&
            i != 12 && i != 13 && i != 16 && i != 19 &&
            i != 20 && i != 21 && i != 26) {
            if (read(fd[index], readBuf, 1) < 1) {
                perror("write, set pin input");
                exit(EXIT_FAILURE);
            }
            readBuf[1] = '\0';
            printf("GPIO pin: %d  Logic level: %s\n", i, readBuf);
            index++;
        }
    }
    return EXIT_SUCCESS;
}
```