Hand-on Exercise 0ne

This assignment will involve designing two kernel two kernel modules in C. You can do this assignment on a computer running on Linux (Ubuntu or CentOS, or others on VM VirtualBox) only.

You need to submit three files for this assignment: *hello.c*, *jiffies.c* and *second.c*. At the beginning of this program, put the comment including the information: author, student id, date, function requirements. Refer to Rubrics for the grading criteria.

Introduction to Linux Kernel Modules

In this project, you will learn how to create a kernel module and load it into the Linux kernel. You will then modify the kernel module so that it creates an entry in the */proc* file system. The project can be completed using the Linux virtual machine that is available with this text. Although you may use any text editor to write these C programs, you will have to use the ***terminal*** application to compile the programs, and you will have to enter commands on the command line to manage the modules in the kernel.

As you'll discover, the advantage of developing kernel modules is that it is a relatively easy method of interacting with the kernel, thus allowing you to write programs that directly invoke kernel functions. It is important for you to keep in mind that you are indeed writing ***kernel code*** that directly interacts with the kernel. That normally means that any errors in the code could crash the system! However, since you will be using a virtual machine, any failures will at worst require rebooting the system only.

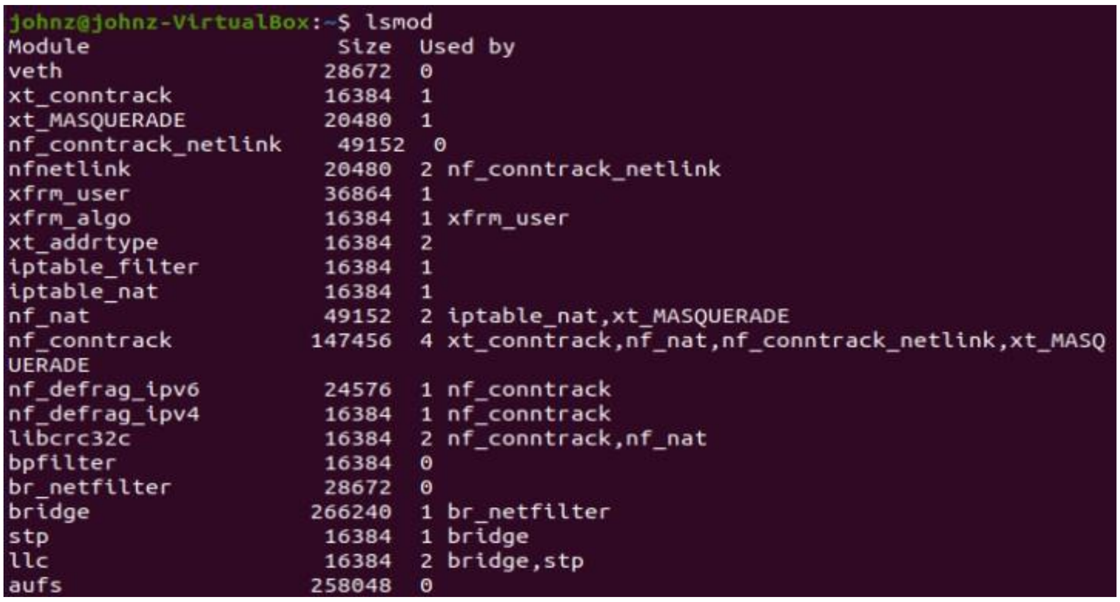
I. Kernel Modules Overview

The first part of this project involves following a series of steps for creating and inserting a module into the Linux kernel.

You can list all kernel modules that are currently loaded by entering the command

```
lsmod
```

This command will list the current kernel modules in three columns: name, size, and where the module is being used.



```
johnz@johnz-VirtualBox:~$ lsmod
Module                  Size  Used by
veth                   28672  0
xt_conntrack           16384  1
xt_MASQUERADE          20480  1
nf_conntrack_netlink    49152  0
nfnetlink              20480  2 nf_conntrack_netlink
xfrm_user              36864  1
xfrm_algo              16384  1 xfrm_user
xt_addrtype            16384  2
iptable_filter         16384  1
iptable_nat            16384  1
nf_nat                 49152  2 iptable_nat,xt_MASQUERADE
nf_conntrack          147456  4 xt_conntrack,nf_nat,nf_conntrack_netlink,xt_MASQ
UERADE
nf_defrag_ipv6         24576  1 nf_conntrack
nf_defrag_ipv4         16384  1 nf_conntrack
libcrc32c              16384  2 nf_conntrack,nf_nat
bpfilter               16384  0
br_netfilter           28672  0
bridge                266240  1 br_netfilter
stp                    16384  1 bridge
llc                    16384  2 bridge,stp
aufs                  258048  0
```

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

/* This function is called when the module is loaded. */
int simple_init(void)
{
        printk(KERN_INFO "Loading Kernel Module\n");
        return 0;
}

/* This function is called when the module is removed. */
void simple_exit(void)
{
        printk(KERN_INFO "Removing Kernel Module\n");
}

/* Macros for registering module entry and exit points.*/
module_init(simple_init);
module_exit(simple_exit);
MODULE_LICENSE("GPL");
MODULE_DESCRIPTION("Simple Module");MODULE_AUTHOR("SGG");
```

Kernel module **simple.c**.

The above program illustrates a very basic kernel module that prints appropriate messages when it is loaded and unloaded.

The function *simple_init()* is the module entry point, which represents the function that is invoked when the module is loaded into the kernel. Similarly, the *simple_exit()* function is the module exit point - the function that is called when the module is removed from the kernel.

The module *entry* point function must return an integer value, with 0 representing success and any other value representing failure. The module *exit* point function returns *void*. Neither the module entry point nor the module *exit* point is passed any parameters. The two following macros are used for registering the module entry and exit points with the kernel:

```
module_init(simple_init)
module_exit(simple_exit)
```

Notice in the above code how the module *entry* and *exit* point functions make calls to the *printk()* function. *printk()* is the kernel equivalent of *printf()*, but its output is sent to a kernel log buffer whose contents can be read by the ***dmesg*** command. One difference between *printf()* and *printk()* is that *printk()* allows us to specify a priority flag, whose values are given in the <linux/printk.h> *include* file. In this instance, the priority is KERN_INFO, which is defined as an ***informational*** message.

The final lines - *MODULE_LICENSE()*, *MODULE_DESCRIPTION()*, and *MODULE_AUTHOR()* - represent details regarding the software license, description of the module, and author. For our purposes, we do not require this information, but we include it because it is standard practice in developing kernel modules.

This kernel module *simple.c* is compiled using the *Makefile* (can be found in this exercise package). To compile the module, enter the following on the command line:

```
make
```

The compilation produces several files. The file *simple.ko* represents the compiled kernel module. The following step illustrates inserting this module into the Linux kernel.

II. Loading and Removing Kernel Modules

Kernel modules are loaded using the ***insmod*** command, which is run as follows:

```
sudo insmod simple.ko
```

To check whether the module has loaded, enter the ***lsmod*** command and search for the module simple. Recall that the module entry point is invoked when the module is inserted into the kernel. To check the contents of this message in the kernel log buffer, enter the command

```
dmesg
```

You should see the message "Loading Module."

Removing the kernel module involves invoking the ***rmmod*** command (notice that the *.ko* suffix is unnecessary):

```
sudo rmmod simple
```

Be sure to use the ***dmesg*** command to check and ensure the module has been removed.

Because the kernel log buffer can fill up quickly, it oftens make sense to clear the buffer periodically. This can be accomplished as follows:

```
sudo dmesg -c
```

Proceed through the steps described above to create the kernel module and to load and unload the module. Be sure to check the contents of the kernel log buffer using ***dmesg*** to ensure that you have followed the steps properly.

As kernel modules are running within the kernel, it is possible to obtain values and call functions that are available only in the kernel and not to regular user applications. For example, the Linux include file <linux/hash.h> defines several hash functions for use within the kernel. This file also defines the constant value *GOLDEN_RATIO_PRIME* (which is defined as an *unsigned long*). This value can be printed out as follows:

```
printk(KERN_INFO "%lu\n", GOLDEN_RATIO_PRIME);
```

As another example, the include file <linux/gcd.h> defines the following function

```
unsigned long gcd(unsigned long a, unsigned b)
```

which returns the greatest common divisor of the parameters *a* and *b*.

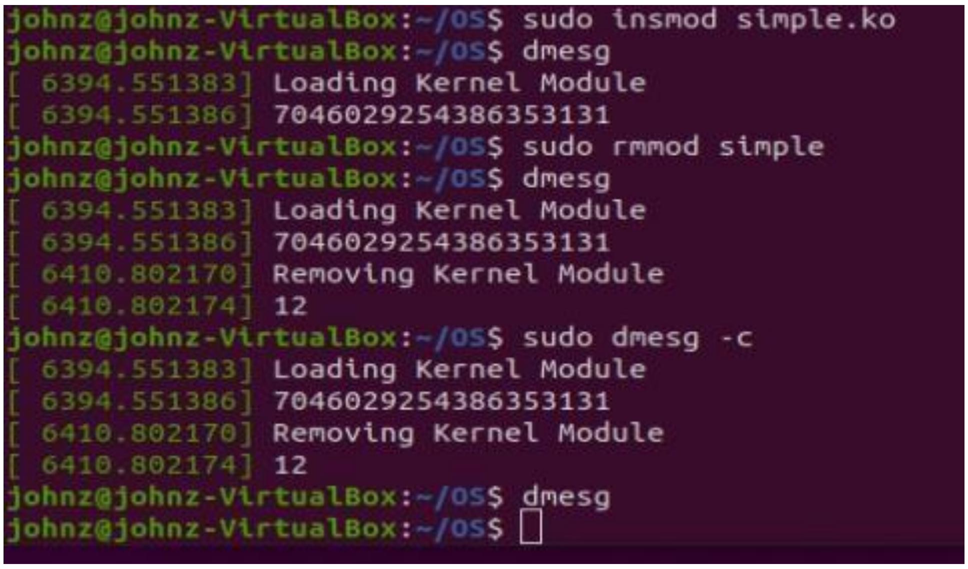
Once you are able to correctly load and unload your module,complete the following additional steps:

1. Print out the value of GOLDEN_RATIO_PRIME in the simple *init()* function.
2. Print out the greatest common divisor of 3,300 and 24 in the *simple_exit()* function.

The code is modified as follows:

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

/* This function is called when the module is loaded. */
int simple_init(void)
{
    printk(KERN_INFO "Loading Kernel Module\n");
    printk(KERN_INFO "%lu\n", GOLDEN_RATIO_PRIME);
    return 0;
}

/* This function is called when the module is removed. */
void simple_exit(void)
{
     printk(KERN_INFO "Removing Kernel Module\n");
     printk(KERN_INFO "%ld\n", gcd(3300, 24));
}

/* Macros for registering module entry and exit points.*/
module_init(simple_init);
module_exit(simple_exit);
MODULE_LICENSE("GPL");
MODULE_DESCRIPTION("Simple Module");
MODULE_AUTHOR("SGG");
```

Updated **simple.c**



```
johnz@johnz-VirtualBox:~/OS$ sudo insmod simple.ko
johnz@johnz-VirtualBox:~/OS$ dmesg
[ 6394.551383] Loading Kernel Module
[ 6394.551386] 7046029254386353131
johnz@johnz-VirtualBox:~/OS$ sudo rmmod simple
johnz@johnz-VirtualBox:~/OS$ dmesg
[ 6394.551383] Loading Kernel Module
[ 6394.551386] 7046029254386353131
[ 6410.802170] Removing Kernel Module
[ 6410.802174] 12
johnz@johnz-VirtualBox:~/OS$ sudo dmesg -c
[ 6394.551383] Loading Kernel Module
[ 6394.551386] 7046029254386353131
[ 6410.802170] Removing Kernel Module
[ 6410.802174] 12
johnz@johnz-VirtualBox:~/OS$ dmesg
johnz@johnz-VirtualBox:~/OS$ 
```

As compiler errors are not often helpful when performing kernel development, it is important to compile your program often by running ***make*** regularly. Be sure to load and remove the kernel module and check the kernel log buffer using ***dmesg*** to ensure that your changes to *simple.c* are working properly.

In Section 1.5.2 of textbook (9th version), the role of the timer as well as the timer interrupt handler are described. In Linux, the rate at which the timer ticks (the **tick rate**) is the value ***HZ*** defined in <asm/param.h>. The value of *HZ* determines the frequency of the timer interrupt, and its value varies by machine type and architecture.

For example, if the value of ***HZ*** is 100, a timer interrupt occurs 100 times per second, or every 10 milliseconds. Additionally, the kernel keeps track of the global variable jiffies, which maintains the number of timer interrupts that have occurred since the system was booted. The *jiffies* variableis declared in the file <linux/jiffies.h>.

1. Print out the values of *jiffies* and *HZ* in the *simple_init()* function.
2. Print out the value of *jiffies* in the *simple_exit()* function.

Here is the solution code:

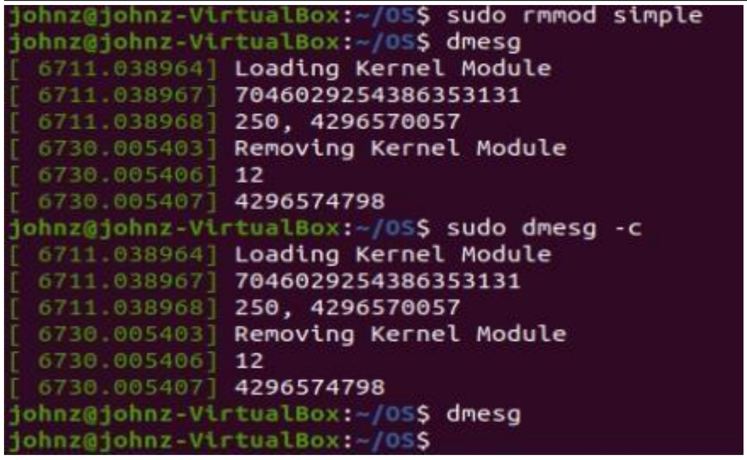
```
#include <linux/init.h>
#include <linux/kernel.h>
#include <linux/module.h>
#include <linux/hash.h>
#include <linux/gcd.h>
#include <asm/param.h>
#include <linux/jiffies.h>

/* This function is called when the module is loaded. */
int simple_init(void)
{
	printk(KERN_INFO "Loading Kernel Module\n");
	printk(KERN_INFO "%lu\n", GOLDEN_RATIO_PRIME);
	printk(KERN_INFO "%d, %ld\n", HZ, jiffies);
	return 0;
}

/* This function is called when the module is removed. */
void simple_exit(void)
{
	printk(KERN_INFO "Removing Kernel Module\n");
	printk(KERN_INFO "%ld\n", gcd(3300, 24));
	printk(KERN_INFO "%ld\n", jiffies);

}

/* Macros for registering module entry and exit points.*/
module_init(simple_init);
module_exit(simple_exit);
MODULE_LICENSE("GPL");
MODULE_DESCRIPTION("Simple Module");
MODULE_AUTHOR("SGG");
```

Updated **simple.c** to print out jiffies

Before proceeding to the next set of exercises, consider how you can use the different values of *jiffies* in *simple_init()* and *simple_exit()* to determine the number of *seconds* that have elapsed since the time the kernel module was loaded and then removed. One possible solution could be as follows:

```
#include <linux/init.h>
#include <linux/kernel.h>
#include <linux/module.h>
#include <linux/hash.h>
#include <linux/gcd.h>
#include <asm/param.h>
#include <linux/jiffies.h>

long int old_jiffies;

/* This function is called when the module is loaded. */
  int simple_init(void)
{
       printk(KERN_INFO "Loading Kernel Module\n");
       printk(KERN_INFO "%lu\n", GOLDEN_RATIO_PRIME);
       printk(KERN_INFO "%d, %ld\n", HZ, jiffies);
       old_jiffies = jiffies;
     return 0;
}

/* This function is called when the module is removed. */
void simple_exit(void)
{
       printk(KERN_INFO "Removing Kernel Module\n");
       printk(KERN_INFO "%ld\n", gcd(3300, 24));
       printk(KERN_INFO "%ld\n", jiffies);
       printk(KERN_INFO "%ld\n", (jiffies-old_jiffies)/HZ);
}

/* Macros for registering module entry and exit points.*/
module_init(simple_init);
module_exit(simple_exit);
MODULE_LICENSE("GPL");
MODULE_DESCRIPTION("Simple Module");
MODULE_AUTHOR("SGG");
```

Updated **simple.c** to print out seconds


```
johnz@johnz-VirtualBox:~/OS$ sudo rmmod simple
johnz@johnz-VirtualBox:~/OS$ dmesg
[ 6711.038964] Loading Kernel Module
[ 6711.038967] 7046029254386353131
[ 6711.038968] 250, 4296570057
[ 6730.005403] Removing Kernel Module
[ 6730.005406] 12
[ 6730.005407] 4296574798
johnz@johnz-VirtualBox:~/OS$ sudo dmesg -c
[ 6711.038964] Loading Kernel Module
[ 6711.038967] 7046029254386353131
[ 6711.038968] 250, 4296570057
[ 6730.005403] Removing Kernel Module
[ 6730.005406] 12
[ 6730.005407] 4296574798
johnz@johnz-VirtualBox:~/OS$ dmesg
johnz@johnz-VirtualBox:~/OS$
```

III. The /proc File System

The */proc* file system is a “pseudo” file system that exists onlyin kernel memory and is used primarily for querying various kernel and per-process statistics.

We begin by describing how to create a new entry in the */proc* file system. The following program example (named *hello.c*, available in this exercise package) creates a */proc* entry named */proc/hello*. If a user enters the command

```
cat /proc/hello
```

The infamous Hello World message is returned.

```
#include <linux/init.h>
#include <linux/kernel.h>
#include <linux/module.h>
#include <linux/proc_fs.h>
#include <asm/uaccess.h>

#define BUFFER_SIZE 128
#define PROC_NAME "hello"

//for kernel version (5.6.0) or above
//find your Linux system kernel version:
//$ sudo uname -a or $ cat /proc/version
#define HAVE_PROC_OPS

ssize_t proc_read(struct file *file, char   *usr_buf,size_t count, loff_t *pos);

#ifdef HAVE_PROC_OPS
static struct proc_ops ops = {
  .proc_read = proc_read,
  };
#else
static struct file_operations ops = {
    .owner = THIS_MODULE,
    .read = proc_read,
};
#endif

/* This function is called when the module is loaded. */
int proc_init(void)
{
    /* creates the /proc/hello entry */ proc_create(PROC_NAME, 0666, NULL, &ops);
    return 0;
}
/* This function is called when the module is removed. */
void proc_exit(void)
{
      /* removes the /proc/hello entry */
      remove_proc_entry(PROC_NAME, NULL);
}

/* This function is called each time /proc/hello is read */
ssize_t proc_read(struct file *file, char *usr_buf, size_t count, loff_t *pos)
{
    int rv = 0;
    char buffer[BUFFER_SIZE];
    static int completed = 0;
    if (completed) {
        completed = 0;
        return 0;
    }
    completed = 1;
    rv = sprintf(buffer, "Hello World\n");
    /* copies kernel space buffer to user space usr buf */
    raw_copy_to_user(usr_buf, buffer, rv);
    return rv;
}
module_init(proc_init);
module_exit(proc_exit);
```

```
MODULE_LICENSE("GPL");
MODULE_DESCRIPTION("Hello Module");
MODULE_AUTHOR("SGG");
```

Hello.c

In the module entry point *proc_init()*, we create the new */proc/hello* entry using the *proc_create()* function. This function is passed *proc_ops*, which contains a reference to a struct *file_operations*. This *struct* initializes the *.owner* and *.read* members. The value of *.read* is the name of the function *proc_read()* that is to be called whenever */proc/hello* is read.

Examining this *proc_read()* function, we see that the string "Hello World\n" is written to the variable buffer where buffer exists in kernel memory. Since */proc/hello* can be accessed fromuser space, we must copy the contents of the buffer to user space using the kernel function *raw_copy_to_user()*. This function copies the contents of kernel memory buffer to the variable *usr_buf*, which exists in user space.

Each time the */proc/hello* file is read, the *proc_read()* function is called repeatedly until it returns 0, so there mustbe logic to ensure that this function returns 0 once it has collected the data (in this case, the string "Hello World\n") that is to go into the corresponding */proc/hello* file.

Finally, notice that the */proc/hello* file is removed in the module exit point *proc_exit()* using the function *remove_proc_entry()*. In order to compile the above *hello.c* file, you need to change ***Makefile***: from *simple.o* to *hello.o*.

```
obj-m += hello.o
all:
   make -C /lib/modules/$(shell uname -r)/build M=$(PWD) modules
clean:
   make -C /lib/modules/$(shell uname -r)/build M=$(PWD) clean
```

Enter the following on the command line:

```
make
```

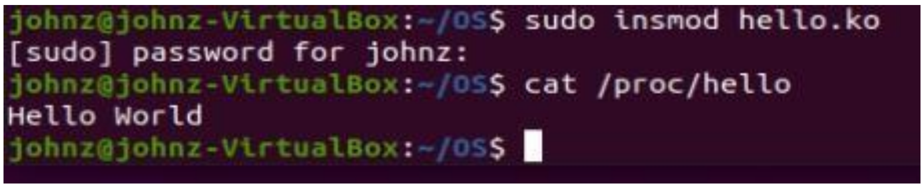
you will get *hello.ko* in your current directory. Insert this module into kernel

```
sudo insmod hello.ko
```

check the hello module:

```
cat /proc/hello
```

it will display a message *Hello World*.



```
johnz@johnz-VirtualBox:~/OS$ sudo insmod hello.ko
[sudo] password for johnz:
johnz@johnz-VirtualBox:~/OS$ cat /proc/hello
Hello World
johnz@johnz-VirtualBox:~/OS$ 
```

IV. Assignment

This assignment will do the following work:

1. Make changes to ***hello.c*** in this document so that it will print out your student ID. Submit the updated one into iSpace.
2. Design a kernel module that creates a */proc* file named */proc/jiffies* that reports the current value of jiffies when the */proc/jiffies* file is read, such as with the command

   cat /proc/jiffies

   Be sure to remove */proc/jiffies* when the module is removed. Submit ***jiffies.c*** into iSpace.
3. Design a kernel module that creates a proc file named */proc/seconds* that reports the number of elapsed seconds since the kernel module was loaded. This will involve using the value of *jiffies* as well as the *HZ* rate. When a user enters the command

   cat /proc/seconds

   Your kernel module will report the number of seconds that have elapsed since the kernel module was first loaded. Besure to remove */proc/seconds* when the module is removed. Submit ***seconds.c*** into iSpace.

In order to compile the ***jiffies.c*** and ***seconds.c*** modules separately, you have to change ***Makefile*** every time you compile one of them, as done for compiling ***hello.c***.