CS 423
Operating System Design:
Introduction to Linux Kernel Programming
(MP1 Walkthrough)

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(Some content taken from a previous year's walkthrough
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MP1 Goals

- Learn the basics of Linux kernel programming
- Learn the kernel implementation of linked lists
- Learn how to set up communication between the kernel and user space through *procfs*
- Also learn timers, interrupts, concurrency, etc.

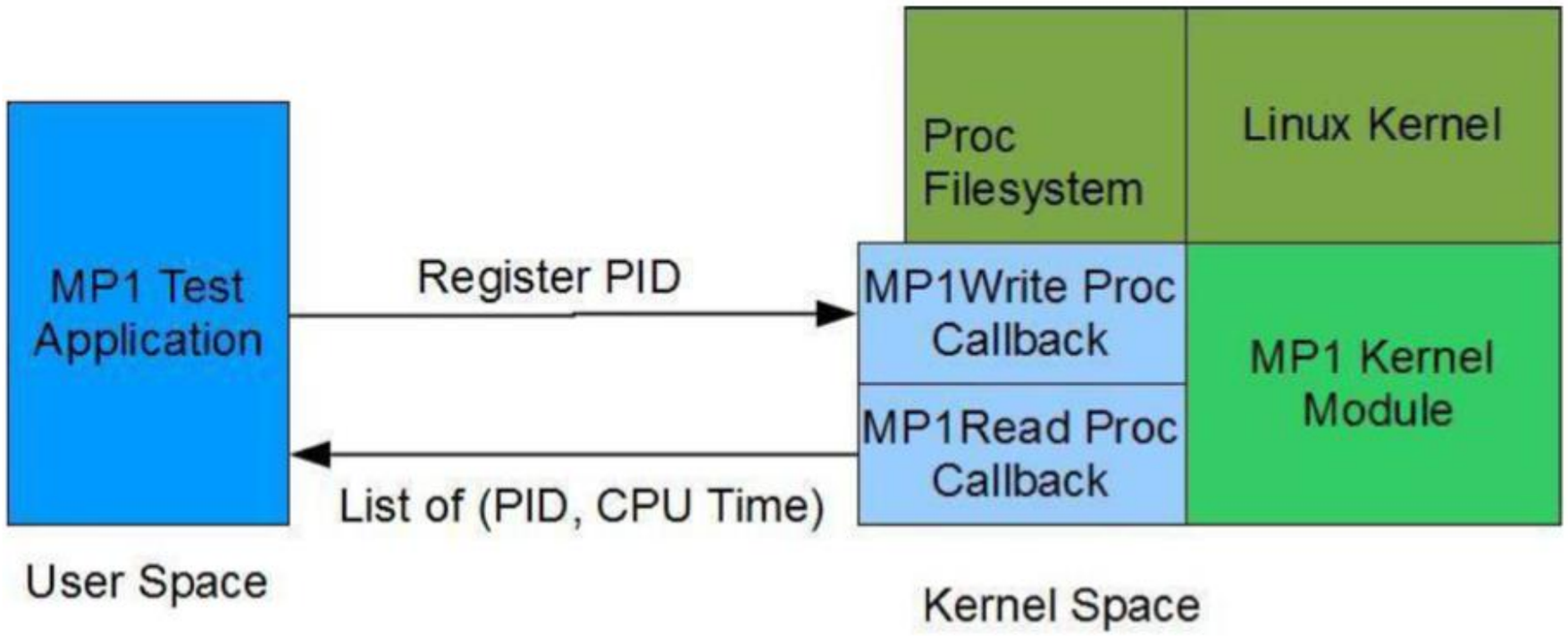
Kernel Programming

- No memory protection
  - Driver, modules, and kernel threads all share same space
  - Don't crash your system!!
  - Don't corrupt your system!!
- Less reliable preemption
  - Deadlocks? CPU hogging? Concurrency = headache?
- Lack of user space libraries
- No floating point support
- No signals or security descriptors

Be Careful

- If your VMs fail, instructors are happy to help
- HOWEVER, you should try to avoid these problems
  - It can cost you valuable time
- Three ways:
  - Regularly snapshot your VM, but not too much
  - Push to your repository (basically no limit)
  - Keep track of your logs in /var

MP1 Overview



- Kernel module that measures CPU time of process
- Simple application that uses this service
- Proc filesystem to create a communication line between user space and kernel
  - /proc/mp1/status
- Two halves interrupt
  - Top half – Interrupt handler
  - Bottom half – Worker thread

Linux Kernel Module (LKM)

- LKM is code that is loaded and unloaded into the kernel on demand
  - Not necessary to change kernel source code
- Entry and exit functions
- Compilation and runtime linkage different

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

int __init mp1_init(void){
    printk(KERN_ALERT "Hello, World\n");
    return 0;
}

void __exit mp1_exit(void){
    printk(KERN_ALERT "Goodbye, World\n");
}

module_init(myinit);
module_exit(myexit);
MODULE_LICENSE("GPL");
```

LKM "Hello World"

```c
#define LINUX

#include <linux/module.h>
#include <linux/kernel.h>
#include "mp1_given.h"

MODULE_LICENSE("GPL");
MODULE_AUTHOR("Group_ID");
MODULE_DESCRIPTION("CS-423 MP1");

#define DEBUG 1

// mp1_init - Called when module is loaded
int __init mp1_init(void)
{
   printk(KERN_ALERT "Hello, World\n");
   return 0;
}

// mp1_exit - Called when module is unloaded
void __exit mp1_exit(void)
{
   printk(KERN_ALERT "Goodbye, World\n");
}

// Register init and exit funtions
module_init(mp1_init);
module_exit(mp1_exit);
```

- Edit source file as above
- Makefile is provided for MP1 (can be reused for MP2 and MP3)

LKM "Hello World"

```
abyoo2@sp20-cs423-005:~/mp1/demo$ make
rm -f userapp *~ *.ko *.o *.mod.c Module.symvers modules.order
make -C /lib/modules/4.4.0-abyoo2/build M=/home/abyoo2/mp1/demo modules
make[1]: Entering directory '/usr/src/linux-headers-4.4.0-abyoo2'
  CC [M]  /home/abyoo2/mp1/demo/mp1.o
  Building modules, stage 2.
  MODPOST 1 modules
  CC      /home/abyoo2/mp1/demo/mp1.mod.o
  LD [M]  /home/abyoo2/mp1/demo/mp1.ko
make[1]: Leaving directory '/usr/src/linux-headers-4.4.0-abyoo2'
gcc -o userapp userapp.c
abyoo2@sp20-cs423-005:~/mp1/demo$ ls
Makefile  modules.order  Module.symvers  mp1.c  mp1_given.h  mp1.ko  mp1.mod.c  mp1.mod.o  mp1.o  userapp  userapp.c  userapp.h
abyoo2@sp20-cs423-005:~/mp1/demo$
```

LKM “Hello World”

```
abyoo2@sp20-cs423-005:~/mp1/demo$ ls
Makefile  modules.order  Module.symvers  mp1.c  mp1_given.h  mp1.ko  mp1.mod.c  mp1.mod.o  mp1.o  userapp  userapp.c  userapp.h
abyoo2@sp20-cs423-005:~/mp1/demo$ sudo insmod mp1.ko
[sudo] password for abyoo2:
abyoo2@sp20-cs423-005:~/mp1/demo$ lsmod
Module                  Size  Used by
mp1                    1259  0
```

- sudo insmod hello.ko
  - "Installs" the module
- lsmod
  - Shows installed modules, including mp1

LKM “Hello World”

```
abyoo2@sp20-cs423-005:~/mp1/demo$ modinfo mp1.ko
filename:       /home/abyoo2/mp1/demo/mp1.ko
description:    CS-423 MP1
author:         Group_ID
license:        GPL
srcversion:     CFC9C46D984AA03A4699A82
depends:
vermagic:       4.4.0-abyoo2 SMP mod_unload
abyoo2@sp20-cs423-005:~/mp1/demo$
```

- modinfo
  - Lists the modules information

LKM “Hello World”

```
abyoo2@sp20-cs423-005:~/mp1/demo$ sudo rmmod mp1
abyoo2@sp20-cs423-005:~/mp1/demo$ lsmod
Module                  Size  Used by
st                     49357  0
lp                     10271  0
```

- sudo rmmod mp1
  - Uninstalls the module

LKM “Hello World”

```
abyoo2@sp20-cs423-005:~/mp1/demo$ dmesg | tail -2
[595856.856798] Hello, World
[596179.876272] Goodbye, World
abyoo2@sp20-cs423-005:~/mp1/demo$
```

- dmesg | tail -n
  - dmesg checks kernel messages
  - tail -n prints the last n lines
  - Use these to debug

Kernel vs. Application Programming

Kernel Module (LKM)

- Starts with module_init()
- Runs in kernel space
- Does nothing until the kernel explicitly calls a module function
- Finishes with module_exit()

Application

- Start with main()
- Runs in user space
- Executes through each lines
- Terminates

Functions available to LKM

- Applications have access to library functions
  - printf(), malloc(), free()
- Kernel modules need to use library functions provided by kernel:
  - printk(), kmalloc(), kfree(), vmalloc()
  - /proc/kallsyms lists kernel provided functions
- Linux Kernel Programming Guide page and references on the MP1 page

The /proc file system

- Virtual file system
- Allows communication between kernel and user space
- Does not contain 'real' files
- Contains runtime system information
- System memory, hardware configuration, etc.

http://www.tldp.org/LDP/Linux-Filesystem-Hierarchy/html/proc.html

The /proc file system

```
abyoo2@sp20-cs423-005:/proc$ ls
1     1038  1206  1346  13782  1465  15159  205  215  224  236  246  257  266  2880  31     39   461  478  616  813  848  861  911  acpi         dma          kallsyms     mdstat      sched_debug  sysvipc
10    107   1209  1350  13821  14651 15161  206  216  225  237  247  258  267  2881  32     392  462  546  617  815  849  862  92   buddyinfo    driver       kcore        meminfo     schedstat    thread-self
100   1092  121   13566 13822  14661 16     207  217  227  238  248  259  268  29    32027  417  47   558  7    816  850  87   93   bus          execdomains  keys         misc        scsi         timer_list
1009  11    122   1357  1409   14664 17     208  218  228  239  249  26   269  3     322    419  471  559  8    819  854  874  94   cgroups      fb           key-users    modules     self         tty
1012  11624 1239  1358  14314  14808 18     209  219  23   240  250  260  27   30    33     430  472  571  807  821  855  88   95   cmdline      filesystems  kmsg         mounts      slabinfo     uptime
1017  1199  1252  13593 1444   15147 182    21   22   230  241  251  261  28   300   34     431  473  592  808  831  856  89   96   consoles     fs           kpagecgroup  mpt         softirqs     version
1019  12    13    13769 1454   15148 183    210  220  231  242  252  262  2876 301   35     44   474  594  809  844  857  9    97   cpuinfo      interrupts   kpagecount   mtrr        stat         vmallocinfo
1026  1201  1321  13773 1455   15150 184    212  221  233  243  253  263  2877 302   36     440  475  595  810  845  858  90   98   crypto       iomem        kpageflags   net         swaps        vmstat
1032  1202  1337  13776 1456   15152 2      213  222  234  244  254  264  2878 304   37     45   476  596  811  846  859  907  9891 devices      ioports      loadavg      pagetypeinfo sys          zoneinfo
1036  1205  1338  13778 1463   15156 20     214  223  235  245  256  265  2879 306   38     46   477  614  812  847  860  91   99   diskstats    irq          locks        partitions  sysrq-trigger
abyoo2@sp20-cs423-005:/proc$
```

The /proc file system

```
abyoo2@sp20-cs423-005:/proc$ cat cpuinfo
processor       : 0
vendor_id       : GenuineIntel
cpu family      : 6
model           : 63
model name      : Intel(R) Xeon(R) CPU E5-2670 v3 @ 2.30GHz
stepping        : 2
microcode       : 0x43
cpu MHz         : 2299.998
cache size      : 30720 KB
physical id     : 0
siblings        : 1
core id         : 0
cpu cores       : 1
apicid          : 0
initial apicid  : 0
fpu             : yes
fpu_exception   : yes
cpuid level     : 15
wp              : yes
flags           : fpu vme de pse tsc msr pae mce cx8 apic sep mtrr pge mca cmov pat
```

Using /proc in MP1

- Create a directory using proc_mkdir()
  - Arguments: name and parent (proc_dir_entry*)
  - Returns proc_dir_entry*
- Create a file using proc_create
  - Arguments: name, mode (permissions), parent, pointer to file operations
  - returns proc_dir_entry*

Using /proc in MP1

```
1486 struct file_operations {
1487         struct module *owner;
1488         loff_t (*llseek) (struct file *, loff_t, int);
1489         ssize_t (*read) (struct file *, char __user *, size_t, loff_t *);
1490         ssize_t (*write) (struct file *, const char __user *, size_t, loff_t *);
1491         ssize_t (*aio_read) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
1492         ssize_t (*aio_write) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
1493         ssize_t (*read_iter) (struct kiocb *, struct iov_iter *);
1494         ssize_t (*write_iter) (struct kiocb *, struct iov_iter *);
1495         int (*iterate) (struct file *, struct dir_context *);
1496         unsigned int (*poll) (struct file *, struct poll_table_struct *);
1497         long (*unlocked_ioctl) (struct file *, unsigned int, unsigned long);
1498         long (*compat_ioctl) (struct file *, unsigned int, unsigned long);
1499         int (*mmap) (struct file *, struct vm_area_struct *);
1500         int (*open) (struct inode *, struct file *);
1501         int (*flush) (struct file *, fl_owner_t id);
1502         int (*release) (struct inode *, struct file *);
1503         int (*fsync) (struct file *, loff_t, loff_t, int datasync);
1504         int (*aio_fsync) (struct kiocb *, int datasync);
1505         int (*fasync) (int, struct file *, int);
1506         int (*lock) (struct file *, int, struct file_lock *);
1507         ssize_t (*sendpage) (struct file *, struct page *, int, size_t, loff_t *, int);
1508         unsigned long (*get_unmapped_area)(struct file *, unsigned long, unsigned long, unsigned long, unsig
1509         int (*check_flags)(int);
1510         int (*flock) (struct file *, int, struct file_lock *);
1511         ssize_t (*splice_write)(struct pipe_inode_info *, struct file *, loff_t *, size_t, unsigned int);
1512         ssize_t (*splice_read)(struct file *, loff_t *, struct pipe_inode_info *, size_t, unsigned int);
1513         int (*setlease)(struct file *, long, struct file_lock **, void **);
1514         long (*fallocate)(struct file *file, int mode, loff_t offset,
1515                           loff_t len);
1516         int (*show_fdinfo)(struct seq_file *m, struct file *f);
1517 };
```

Using /proc in MP1

Sample code:

```
#define FILENAME "status"
#define DIRECTORY "mp1"
static struct proc_dir_entry *proc_dir;
static struct proc_dir_entry *proc_entry;
static ssize_t mp1_read (struct file *file, char __user *buffer, size_t count, loff_t
*data){
    // implementation goes here...
}
static ssize_t mp1_write (struct file *file, const char __user *buffer, size_t count, loff_t
*data){
    // implementation goes here...
}
static const struct file_operations mp1_file = {
    .owner = THIS_MODULE,
    .read  = mp1_read,
    .write = mp1_write,
};
int __init mp1_init(void){
    proc_dir = proc_mkdir(DIRECTORY, NULL);
    proc_entry = proc_create(FILENAME, 0666, proc_dir, & mp1_file);
}
```

Using /proc in MP1

- Within MP1_read/mp1_write, you may need to move data between kernel/user space
  - copy_from_user()
  - copy_to_user()

Sample code (There are other ways of implementing it):

```
static ssize_t mp1_read (struct file *file, char __user *buffer, size_t count, loff_t
*data){
    // implementation goes here...
    int copied;
    char * buf;
    buf = (char *) kmalloc(count,GFP_KERNEL);
    copied = 0;
    //… put something into the buf, updated copied
    copy_to_user(buffer, buf, copied);
    kfree(buf);
    return copied ;
}
```

Linux Kernel Lists

- You will use Linux list to store all registered user processes
- Linux kernel list is a widely used data structure in Linux kernel
  - Defined in <linux/linux.h>
  - You MUST get familiar of how to use it

```
struct list_head{
    struct list_head *next;
    struct list_head *prev;
};
```

```
struct my_cool_list{
    struct list_head list; /* kernel's list structure */
    int my_cool_data;
    void* my_cool_void;
};
```

Linux Kernel Lists

- Some useful API calls:

```
LIST_HEAD(new_list)
list_add(struct list_head *new, struct list_head *head)
list_for_each_safe(pos, n, head)
list_entry(ptr, type, member)
list_del(pos)
list_for_each_entry(pos, head, member)
list_empty(ptr)
```

Kernel Timer

- Operate in units called `jiffies', not seconds
  - msec_to_jiffies() converts ms to jiffies
  - jiffies_to_msec() converts jiffies to ms

```
struct timer_list {
        /* ... */
        unsigned long expires;
        void (*function)(unsigned long);
        unsigned long data;
};
```

Kernel Timer

- Some useful API calls:

```
void setup_timer(struct timer_list *timer,
void(*function)(unsigned long), unsigned long data)

int mod_timer(struct timer_list *timer, unsigned long
expires)

void del_timer(struct timer_list *timer)

void init_timer(struct timer_list *timer);

struct timer_list TIMER_INITIALIZER(_function, _expires,
_data);

void add_timer(struct timer_list * timer);
```

Work queues

- Request a function to be called at some time
  - Workqueue functions can sleep
  - Can be used to implement bottom half
- Some useful API calls:

```
INIT_WORK (struct work_struct *work, void (*function) (void
*),void *data)

void flush_workqueue (struct workqueue_struct *queue)

void destroy_workqueue (struct workqueue_struct *queue)

int queue_work (struct workqueue_struct *queue, struct
work_struct *work)
```

Questions??

Don’t forget about Office hours & Piazza!