Device Drivers

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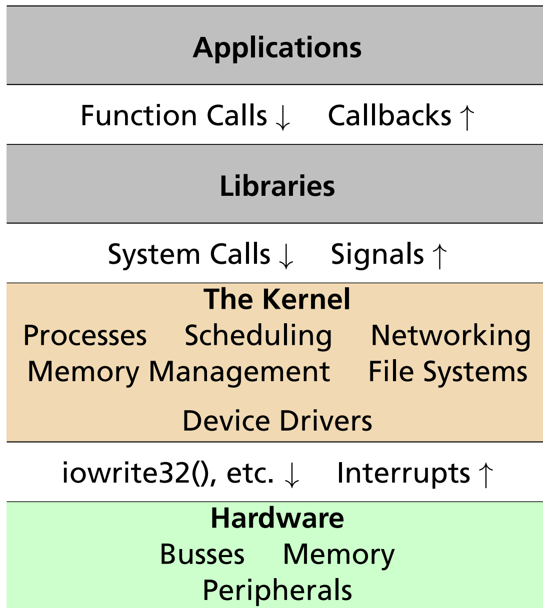
Linux Operating System Structure



User Space vs. Kernel Space

User Space

Process abstraction central to most OSes

Independent PC, registers, and memory

Virtual memory hardware isolates processes, OS

Processes run in limited-resource “user mode”

Bug in a process only affects the process

Kernel Space

Kernel runs in “supervisor mode” with no access limitations

Bugs in kernel code take down the whole system

Unix Device Driver Model

"Everything is a file"

By convention, special "device" files stored in /dev

Created by the `mknod` command or dynamically

```
# ls -Ggl --time-style=+ \
   /dev/sd{a,a1,a2,b} /dev/tty{,1,2} \
   /dev/ttyUSB0

brw-rw---- 1   8,  0  /dev/sda
brw-rw---- 1   8,  1  /dev/sda1
brw-rw---- 1   8,  2  /dev/sda2
brw-rw---- 1   8, 16  /dev/sdb
crw-rw-rw- 1   5,  0  /dev/tty
crw-rw---- 1   4,  1  /dev/tty1
crw-rw---- 1   4,  2  /dev/tty2
crw-rw---- 1 188,  0  /dev/ttyUSB0
```


https://www.cs.columbia.edu/~smb/classes/s06-4118/l23.pdf

/proc/devices

Virtual file with a list of device drivers by major number

```
# cat /proc/devices
Character devices:
  4 /dev/vc/0
  4 tty
  4 ttyS
  5 /dev/tty
 10 misc
188 ttyUSB

Block devices:
  8 sd
```

More virtual files and directories:

```
# ls /sys/bus
amba         cpu           hid  mdio_bus  platform  sdio   soc  usb
clocksource  event_source  i2c  mmc       scsi      serio  spi

# ls /sys/class/misc
cpu_dma_latency  network_latency  network_throughput  psaux  vga_ball
```

Kernel Modules

Device drivers can be compiled into the kernel

Really annoying for, e.g., “hotplug” USB devices

Solution: dynamically linked kernel modules

Similar to shared libraries/DLLs

```
# lsmod
Module                  Size  Used by
# insmod vga_ball.ko
# lsmod
Module                  Size  Used by
vga_ball               16384  0
# rmmod vga_ball
```

4K stack limit (don’t use recursion)

No standard library; many equivalent functions available

init and *exit* functions compulsory; called when loaded/unloaded

Our First Driver

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

static int __init ofd_init(void)
{
        pr_info("ofd registered");
        return 0;
}

static void __exit ofd_exit(void)
{
        pr_info("ofd unregistered");
}

module_init(ofd_init);
module_exit(ofd_exit);

MODULE_LICENSE("GPL");
MODULE_AUTHOR("Stephen Edwards <sedwards@cs.columbia.edu>");
MODULE_DESCRIPTION("Our First Driver: Nothing");
```

http://www.linuxforu.com/2010/12/writing-your-first-linux-driver/

Debugging: pr_info and friends

In the kernel, there's no *printf* (no stdio.h)

printk the traditional replacement:

```
printk(KERN_ERR "something went wrong, return code: %d\n", ret);
```

KERN_ERR just the string "<3>"

Now deprecated in favor of equivalent

```
pr_info("Information\n");
pr_err("Error\n");
pr_alert("Really big problem\n");
pr_emerg("Life as we know it is over\n");
```

Kernel Logging

How do you see the output of *printk* et al.?

Send kernel logging to the console:

```
# echo 8 > /proc/sys/kernel/printk
# insmod vga_ball.ko
[ 1533.730421] vga_ball: init
```

Diagnostic messages from dmesg:

```
# dmesg | tail -4
[  990.780462] vga_ball: init
[ 1530.230146] vga_ball: exit
[ 1533.730421] vga_ball: init
```

Copying to/from user memory

```
#include <linux/uaccess.h>

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

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

Checks that pointers are valid before copying memory between user and kernel space

Return number of bytes remaining to transfer (0 on success)

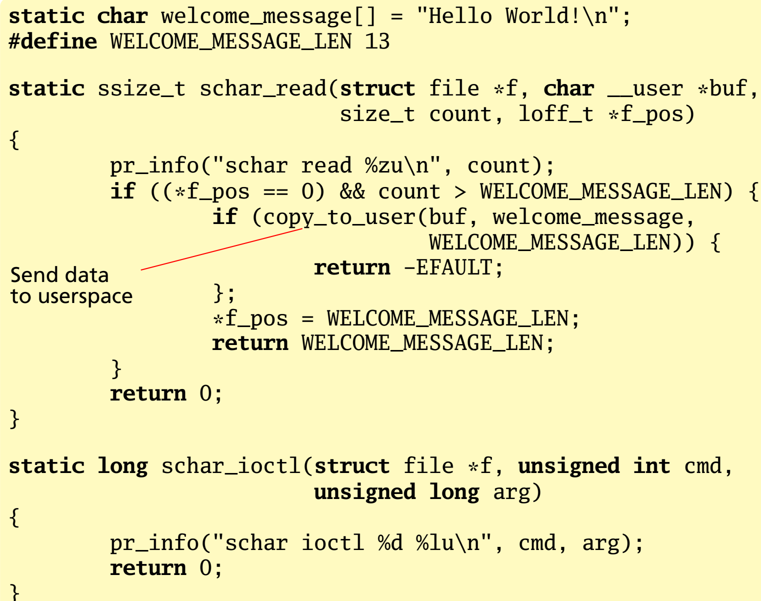
A Very Simple Character Device

```c
#include <linux/module.h>
#include <linux/printk.h>
#include <linux/fs.h>
#include <linux/cdev.h>
#include <linux/uaccess.h>

#define MY_MAJOR 60
#define MY_MINOR 0

static int schar_open(struct inode *inode, struct file *file)
{
        pr_info("schar open\n");
        return 0;
}
static int schar_release(struct inode *inode, struct file *f)
{
        pr_info("schar release\n");
        return 0;
}
static ssize_t schar_write(struct file *f, const char __user *buf,
                           size_t count, loff_t *f_pos)
{
        pr_info("schar write %zu\n", count);
        return 0;
}
```

A Very Simple Character Device: Read



```c
static char welcome_message[] = "Hello World!\n";
#define WELCOME_MESSAGE_LEN 13

static ssize_t schar_read(struct file *f, char __user *buf,
                          size_t count, loff_t *f_pos)
{
        pr_info("schar read %zu\n", count);
        if ((*f_pos == 0) && count > WELCOME_MESSAGE_LEN) {
                if (copy_to_user(buf, welcome_message,
                                 WELCOME_MESSAGE_LEN)) {
                        return -EFAULT;
                };
                *f_pos = WELCOME_MESSAGE_LEN;
                return WELCOME_MESSAGE_LEN;
        }
        return 0;
}

static long schar_ioctl(struct file *f, unsigned int cmd,
                        unsigned long arg)
{
        pr_info("schar ioctl %d %lu\n", cmd, arg);
        return 0;
}
```

A Very Simple Character Device: Init

```
static struct file_operations schar_fops = {
        .owner          = THIS_MODULE,
        .open           = schar_open,
        .release        = schar_release,
        .read           = schar_read,
        .write          = schar_write,
        .unlocked_ioctl = schar_ioctl };

static struct cdev schar_cdev = { .owner = THIS_MODULE,
                                  .ops   = &schar_fops };
static int __init schar_init(void) {
        int result;
        dev_t dev = MKDEV(MY_MAJOR, 0);
        pr_info("schar init\n");
        result = register_chrdev_region(dev, 2, "schar");
        if (result < 0) {
                pr_warn("schar: unable to get major %d\n", MY_MAJOR);
                return result;  }
        cdev_init(&schar_cdev, &schar_fops);
        result = cdev_add(&schar_cdev, dev, 1);
        if (result < 0) {
                unregister_chrdev_region(dev, 2);
                pr_notice("schar: unable to add cdev\n");
                return result; }
```

Function pointer called by each operation

Request minor numbers 0–1

A Very Simple Character Device: Exit

```
static void __exit schar_exit(void)
{
        cdev_del(&schar_cdev);
        unregister_chrdev_region(MKDEV(MY_MAJOR, 0), 2);
        pr_info("schar unregistered\n");
}

module_init(schar_init);
module_exit(schar_exit);

MODULE_LICENSE("GPL");
MODULE_AUTHOR("Stephen Edwards <sedwards@cs.columbia.edu>");
MODULE_DESCRIPTION("Really Simple Character Driver");
```

Simple Char Driver: Behavior

```
# echo 8 > /proc/sys/kernel/printk
# cd /dev
# mknod schar c 60 0
# ls -Ggl --time-style=+ schar
crw-r--r-- 1 60, 0  schar
# cd ~/schar
# insmod schar.ko
schar init
# cat /dev/schar > foo
schar open
schar read 65536
schar read 65536
schar release
# cat foo
Hello World!
# rmmod schar.ko
schar unregistered
```

The ioctl() System Call

```
#include <sys/ioctl.h>

int ioctl(int fd, int request, void *argp);
```

A catch-all for "out-of-band" communication with a device

E.g., setting the baud rate of a serial port, reading and setting a real-time clock

Ultimately passes a number and a userspace pointer to a device driver

ioctl requests include some "magic numbers" to prevent accidental invocation. Macros do the encoding:

```
_IO(magic, number)          /* No argument */
_IOW(magic, number, type)   /* Data sent to driver */
_IOR(magic, number, type)   /* Data returned by driver */
_IOWR(magic, number, type)  /* Data sent and returned */
```

The Misc Class

Thin layer around character devices

Major number 10; minor numbers assigned dynamically

Subsystem automatically creates special file in */dev* directory

```
#include <linux/miscdevice.h>

struct miscdevice {
  int minor; /* MISC_DYNAMIC_MINOR assigns it dynamically */
  const char name; /* e.g., vga_ball */
  struct struct file_operations *fops;
};

int misc_register(struct miscdevice *misc);
int misc_deregister(struct miscdevice *misc);
```

```
# ls -Ggl --time-style=+ /dev/vga_ball
crw------- 1 10, 60  /dev/vga_ball
# cat /proc/misc
 60 vga_ball
 61 network_throughput
 62 network_latency
 63 cpu_dma_latency
  1 psaux
```

The Platform Bus

Modern busses can discover their devices (`lsusb`, `lspci`, etc.); subsystems exist to deal with these

"Platform Bus" is for everything else

```c
#include <linux/platform_device.h>

struct platform_driver {
        int (*probe)(struct platform_device *);
        int (*remove)(struct platform_device *);
        void (*shutdown)(struct platform_device *);
        int (*suspend)(struct platform_device *, pm_message_t state);
        int (*resume)(struct platform_device *);
        struct device_driver driver;
        const struct platform_device_id *id_table;
    };

int platform_driver_register(struct platform_driver *driver);
/* Or, for non hot-pluggable devices */
int platform_driver_probe(struct platform_driver *driver,
                          int (*probe)(struct platform_device *));

void platform_driver_unregister(struct platform_driver *driver);
```

http://lwn.net/Articles/448499/

Device Tree

Where are our device's registers?

```
#define PARPORT_BASE 0x378
```

Compiling this into the kernel is too fragile: different kernel for each system?

Alternative: a standard data structure holding a description of the hardware platform.

Device Tree: Standard derived from Open Firmware, originally from Sun

http://devicetree.org/

http://devicetree.org/Device_Tree_Usage

http://elinux.org/images/a/a3/Elce2013-petazzoni-devicetree-for-dummies.pdf

http://lwn.net/Articles/572692/

http://xillybus.com/tutorials/device-tree-zynq-1

Raspberry Pi DTS Excerpt

The Raspberry Pi uses a Broadcom BCM2835 SoC with a 700 MHz ARM processor.

```
/ {
    compatible = "brcm,bcm2835";
    model = "BCM2835";
    interrupt-parent = <&intc>;

    soc {
        compatible = "simple-bus";
        #address-cells = <1>;
        #size-cells = <1>;
        ranges = <0x7e000000 0x20000000 0x02000000>;


        uart@20191000 {
            compatible = "brcm,bcm2835-pl011",
                         "arm,pl011", "arm,primecell";

            reg = <0x7e201000 0x1000>;

            interrupts = <2 25>;
            clock-frequency = <3000000>;
        };
    };
```

Vga_ball in the soc_system DTS

Connected through the "lightweight AXI bridge"

Avalon bus address 0 appears to the ARM at 0xff200000

```
sopc0: sopc@0 {
   device_type = "soc";

   hps_0_bridges: bridge@0xc0000000 {
      compatible = "altr,bridge-18.1", "simple-bus";
      reg = <0xc0000000 0x20000000>,
        <0xff200000 0x00200000>;
      reg-names = "axi_h2f", "axi_h2f_lw";
      clocks = <&clk_0 &clk_0>;
      clock-names = "h2f_axi_clock", "h2f_lw_axi_clock";
      #address-cells = <2>;
      #size-cells = <1>;
      ranges = <0x00000001 0x00000000 0xff200000 0x00000008>;

      vga_ball_0: vga@0x100000000 {
        compatible = "csee4840,vga_ball-1.0";
        reg = <0x00000001 0x00000000 0x00000008>;
        clocks = <&clk_0>;
      };
   };
```

Accessing the Device Tree

```
#include <linux/of.h>  /* "Open Firmware" */
#include <linux/of_address.h>

/* Table of "compatible" values to search for */
static const struct of_device_id vga_ball_of_match[] = {
        { .compatible = "csee4840,vga_ball-1.0" },
        {},
};
MODULE_DEVICE_TABLE(of, vga_ball_of_match);

/* Platform device info */
static struct platform_driver vga_ball_driver = {
        .driver = {
                .name   = "vga_ball",
                .owner  = THIS_MODULE,
                .of_match_table = of_match_ptr(vga_ball_of_match),
        },
        .remove = __exit_p(vga_ball_remove),
};

/* Locate a device's registers, return a pointer to their base */
void __iomem *of_iomap(struct device_node *node, int index);
```

I/O Memory Management

Resource allocation a central OS facility

Interface for requesting/releasing memory regions:

```
#include <linux/ioport.h>

struct resource *request_mem_region(unsigned long start,
                                    unsigned long extent,
                                    const char *name);

void release_mem_region(unsigned long start, unsigned long extent);
```

I/O Memory Access

Mapping I/O regions in memory; accessing them:

```
#include <linux/io.h>

void *ioremap(unsigned long offset, unsigned long size);
void iounmap(void *addr);

u8  ioread8( const __iomem *addr);
u16 ioread16(const __iomem *addr);
u32 ioread32(const __iomem *addr);

void iowrite8( u8 val,  void __iomem *addr);
void iowrite16(u16 val, void __iomem *addr);
void iowrite32(u32 val, void __iomem *addr);
```

/proc/iomem

```
# insmod vga_ball.ko
vga_ball: init
# cat /proc/iomem
00000000-3fffffff : System RAM
  00008000-00bfffff : Kernel code
  00d00000-00da24ff : Kernel data
ff200000-ff200007 : vga_ball
ff702000-ff703fff : ethernet@0xff702000
ff704000-ff704fff : flash@0xff704000
ff706000-ff706fff : axi_slave0
ff708000-ff7080ff : gpio@0xff708000
ff709000-ff7090ff : gpio@0xff709000
ff70a000-ff70a0ff : gpio@0xff70a000
ffb40000-ffb7ffff : usb@0xffb40000
ffb90000-ffb900ff : axi_slave1
ffc02000-ffc0201f : serial
ffc04000-ffc040ff : i2c@0xffc04000
```

The Vga_ball Driver: Header File

```
#ifndef _VGA_BALL_H
#define _VGA_BALL_H

#include <linux/ioctl.h>

typedef struct {
        unsigned char red, green, blue;
} vga_ball_color_t;


typedef struct {
  vga_ball_color_t background;
} vga_ball_arg_t;

#define VGA_BALL_MAGIC 'q'

/* ioctls and their arguments */
#define VGA_BALL_WRITE_BACKGROUND \
  _IOW(VGA_BALL_MAGIC, 1, vga_ball_arg_t *)
#define VGA_BALL_READ_BACKGROUND  \
  _IOR(VGA_BALL_MAGIC, 2, vga_ball_arg_t *)

#endif
```

The Vga_ball Driver: write_background

```
#include <linux/module.h>
/* ... many more #includes ... */
#include <linux/uaccess.h>
#include "vga_ball.h"
#define DRIVER_NAME "vga_ball"

/* Device registers */
#define BG_RED(x) (x)
#define BG_GREEN(x) ((x)+1)
#define BG_BLUE(x) ((x)+2)

struct vga_ball_dev {
        struct resource res; /* Resource: our registers */
        void __iomem *virtbase; /* Where registers are in memory */
        vga_ball_color_t background;
} dev;

static void write_background(vga_ball_color_t *background)
{
        iowrite8(background->red, BG_RED(dev.virtbase) );
        iowrite8(background->green, BG_GREEN(dev.virtbase) );
        iowrite8(background->blue, BG_BLUE(dev.virtbase) );
        dev.background = *background;
}
```

The Vga_ball Driver: Ioctl

```
static long vga_ball_ioctl(struct file *f, unsigned int cmd,
                           unsigned long arg)
{
        vga_ball_arg_t vla;

        switch (cmd) {
        case VGA_BALL_WRITE_BACKGROUND:
                if (copy_from_user(&vla, (vga_ball_arg_t *) arg,
                                   sizeof(vga_ball_arg_t)))
                        return -EACCES;
                write_background(&vla.background);
                break;

        case VGA_BALL_READ_BACKGROUND:
                vla.background = dev.background;
                if (copy_to_user((vga_ball_arg_t *) arg, &vla,
                                 sizeof(vga_ball_arg_t)))
                        return -EACCES;
                break;

        default:
                return -EINVAL;
        }

        return 0;
```

The Vga_ball Driver: file_operations

```
static const struct file_operations vga_ball_fops = {
        .owner          = THIS_MODULE,
        .unlocked_ioctl = vga_ball_ioctl,
};

static struct miscdevice vga_ball_misc_device = {
        .minor          = MISC_DYNAMIC_MINOR,
        .name           = DRIVER_NAME,
        .fops           = &vga_ball_fops,
};
```

The Vga_ball Driver: vga_ball_probe

```
static int __init vga_ball_probe(struct platform_device *pdev)
{
        vga_ball_color_t beige = { 0xf9, 0xe4, 0xb7 };
        int ret;

        /* Register ourselves as a misc device: creates /dev/vga_ball */
        ret = misc_register(&vga_ball_misc_device);

        /* Get the address of our registers from the device tree */
        ret = of_address_to_resource(pdev->dev.of_node, 0, &dev.res);
        if (ret) {
                ret = -ENOENT;
                goto out_deregister;
        }

        /* Make sure we can use these registers */
        if (request_mem_region(dev.res.start, resource_size(&dev.res),
                               DRIVER_NAME) == NULL) {
                ret = -EBUSY;
                goto out_deregister;
        }
```

The Vga_ball Driver: probe (cont) & remove

```
        /* Arrange access to our registers */
        dev.virtbase = of_iomap(pdev->dev.of_node, 0);
        if (dev.virtbase == NULL) {
                ret = -ENOMEM;
                goto out_release_mem_region;
        }

        /* Set an initial color */
        write_background(&beige);

        return 0;

out_release_mem_region:
        release_mem_region(dev.res.start, resource_size(&dev.res));
out_deregister:
        misc_deregister(&vga_ball_misc_device);
        return ret;
}

static int vga_ball_remove(struct platform_device *pdev)
{
        iounmap(dev.virtbase);
        release_mem_region(dev.res.start, resource_size(&dev.res));
        misc_deregister(&vga_ball_misc_device);
        return 0;
```

The Vga_ball Driver: init and exit

```
static const struct of_device_id vga_ball_of_match[] = {
        { .compatible = "csee4840,vga_ball-1.0" },
        {},
};
MODULE_DEVICE_TABLE(of, vga_ball_of_match);

static struct platform_driver vga_ball_driver = {
        .driver = {
                .name    = DRIVER_NAME,
                .owner   = THIS_MODULE,
                .of_match_table = of_match_ptr(vga_ball_of_match),
        },
        .remove = __exit_p(vga_ball_remove),
};

static int __init vga_ball_init(void)
{
        pr_info(DRIVER_NAME ": init\n");
        return platform_driver_probe(&vga_ball_driver, vga_ball_probe);
}
static void __exit vga_ball_exit(void)
{
        platform_driver_unregister(&vga_ball_driver);
        pr_info(DRIVER_NAME ": exit\n");
}
```

The Vga_ball Driver

```
module_init(vga_ball_init);
module_exit(vga_ball_exit);

MODULE_LICENSE("GPL");
MODULE_AUTHOR("Stephen A. Edwards, Columbia University");
MODULE_DESCRIPTION("VGA ball driver");
```

References

http://free-electrons.com/

http://www.opersys.com/training/linux-device-drivers

Rubini, Corbet, and Kroah-Hartman, *Linux Device Drivers*, 3ed, O'Reilly
https://lwn.net/Kernel/LDD3/

The Linux Kernel Source, and its Documentation/driver-model directory.