

Device Drivers

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Linux Operating System Structure

Applications

Function Calls ↓ Callbacks ↑

Libraries

System Calls ↓ Signals ↑

The Kernel

Processes Scheduling Networking
Memory Management File Systems
Device Drivers

iowrite32(), etc. ↓ Interrupts ↑

Hardware

Busses Memory
Peripherals

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					First SCSI drive	
Block Device	brw-rw----	1	8, 0	/dev/sda		
	brw-rw----	1	8, 1	/dev/sda1	First partition of first SCSI drive	
	brw-rw----	1	8, 2	/dev/sda2	Second SCSI drive	
Character Device	brw-rw----	1	8, 16	/dev/sdb		
	crw-rw-rw-	1	5, 0	/dev/tty	Current terminal	
	crw-rw----	1	4, 1	/dev/tty1	Second terminal	
	crw-rw----	1	4, 2	/dev/tty2		
	crw-rw----	1	188, 0	/dev/ttyUSB0	First USB terminal	
Owner Group		World permissions	Major Device Number	Minor Device Number		

/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

```
#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");
```

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)

```
#include <linux/module.h>  // A Very Simple Character Device
#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;
}
```

```
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;
}
```

Send data
to userspace



```
static struct file_operations schar_fops = {  
    .owner          = THIS_MODULE,           Function  
    .open           = schar_open,           pointer  
    .release        = schar_release,        called  
    .read           = schar_read,           by each  
    .write          = schar_write,          operation  
    .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);          Request  
                                              minor numbers 0-1  
    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; }  
    return 0;
```

```
}
```

```
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");

// End of the Very Simple Character Device
```

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 file_operations *fops;
};

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

```
# ls -Gls --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

Linux has subsystems for busses that know their devices (lsusb, lspci, etc.)
The “Platform Bus” is for everything else

```
#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);
```

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

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>;  
        };  
    };  
};
```

Diagram annotations:

- Search key points to `uart@20191000`
- base address points to `uart@20191000`
- from address points to `0x7e000000`
- to address points to `0x20000000`
- size points to `0x02000000`
- size points to `0x1000`

Vga_ball in the soc_system DTS

Connected through the "lightweight AXI bridge"

Avalon bus address 0 appears to the ARM at 0xff200000

```
sopc0: socp@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
```

```
00008000-00bfffffff : 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@0xfffc04000
```

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;
}
```

```
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;
    }

    // continued on next slide...
}
```

```
/* 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;
```

```
}
```

```
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.