Device Drivers

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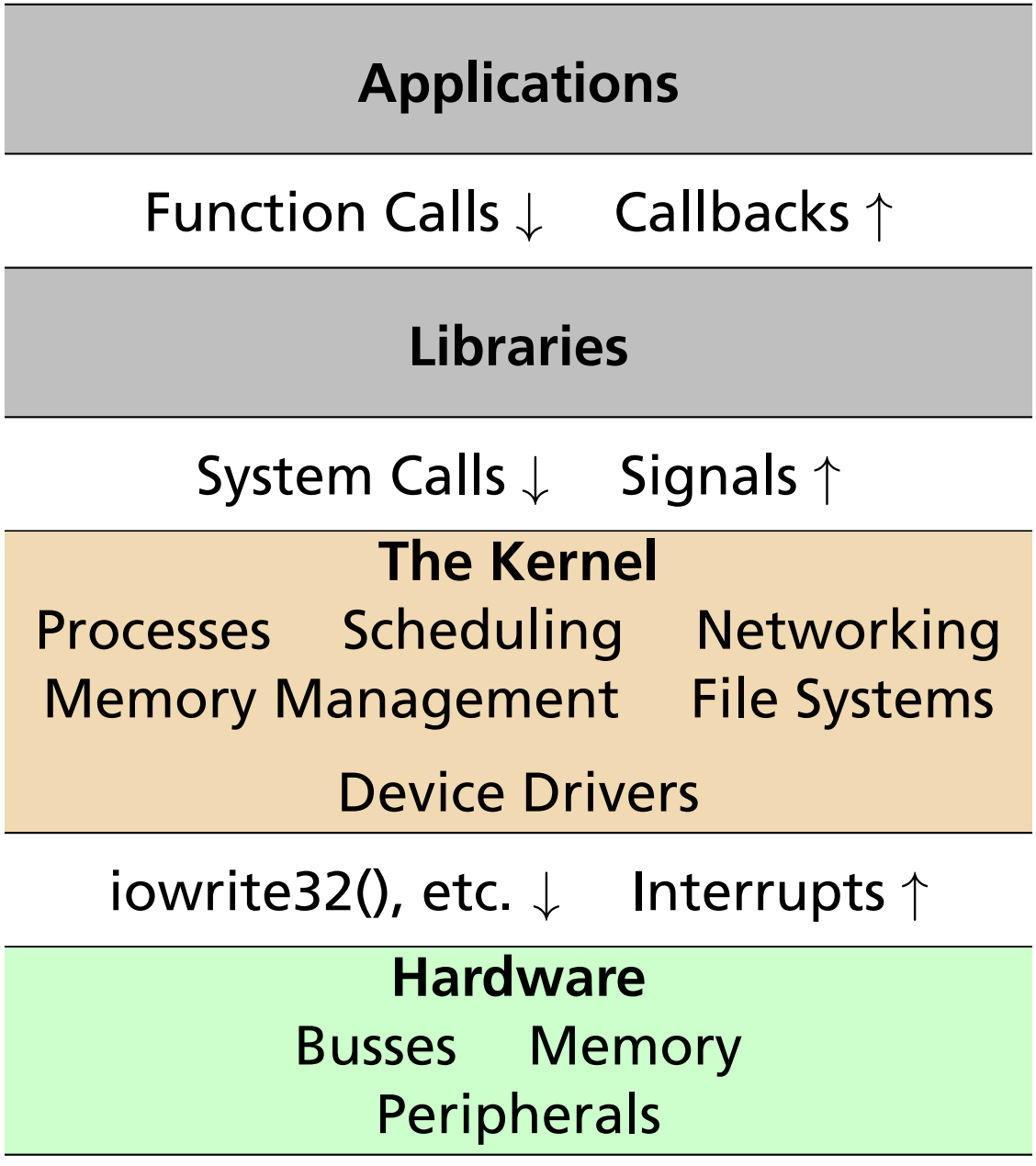
Linux Operating System Structure



User Space vs. Kernel Space

Process abstraction central to most OSes

Independent PC, registers, and memory

Virtual memory hardware isolates processes, OS

Processes run in limited-resourse “user mode”

Bug in a process takes down the process only

Kernel runs in “supervisor mode” with no access limitations

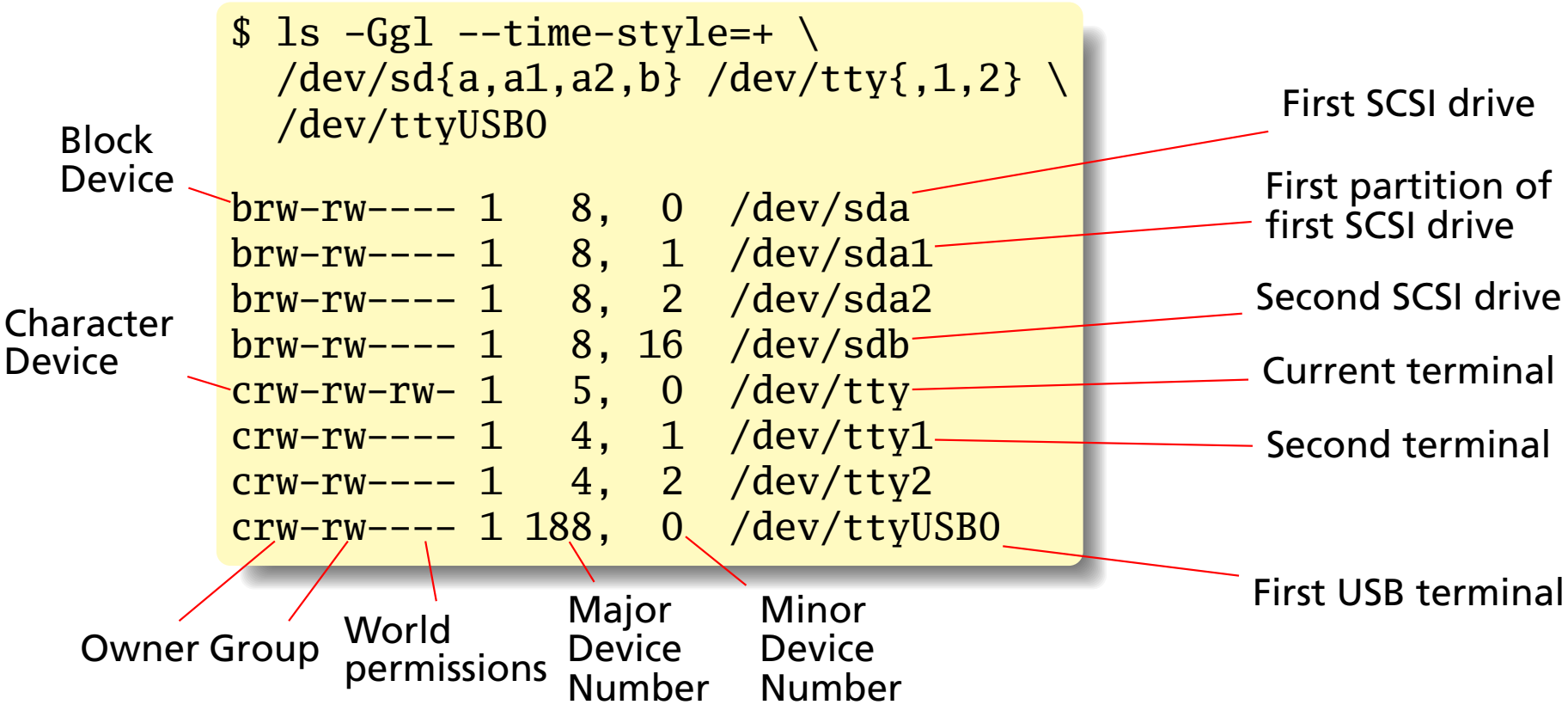
Bugs in kernel code take down the whole system

Unix Device Driver Model

"Everything is a file"

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

Created by the `mknod` command or dynamically



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
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_led
```

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_led.ko
# lsmod
Module                  Size  Used by
vga_led                 1814  0
# rmmod vga_led
```

4K stack limit (don’t use recursion)

No standard library; many replacements 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");
```

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
```

Diagnostic messages from dmesg:

```
# dmesg | tail -4
init: tty1 main process (933) killed by TERM signal
vga_led: init
vga_led: exit
vga_led: init
```

/var/log/syslog

```
# tail -3 /var/log/syslog
Jan  1 07:28:11 linaro-nano kernel: vga_led: init
Jan  1 07:49:57 linaro-nano kernel: vga_led: exit
Jan  1 07:51:06 linaro-nano kernel: vga_led: 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 left to transfer (0 on success)

A Very Simple Character Device

```
#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

```
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

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; }
        return 0;
}
```

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_led */
  struct struct file_operations *fops;
};

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

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

http://www.linuxjournal.com/article/2920

The Platform Bus

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

"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);
```

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@20201000 {
            compatible = "brcm,bcm2835-pl011",
                         "arm,pl011", "arm,primecell";

            reg = <0x7e201000 0x1000>;

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

from address

to address

size

Search key

base address

size

DTS for the VGA_LED

Connected through the “lightweight AXI bridge”
Avalon bus address 0 appears to the ARM at 0xff200000

```
lightweight_bridge: bridge@0xff200000 {
   compatible = "simple-bus";

   #address-cells = <1>;
   #size-cells = <1>;
   ranges = < 0x0 0xff200000 0x200000 >;

   vga_led: vga_led@0 {
      compatible = "altr,vga_led";
      reg = <0x0 0x8>;
   };
};
```

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_led_of_match[] = {
        { .compatible = "altr,vga_led" },
        {},
};
MODULE_DEVICE_TABLE(of, vga_led_of_match);

/* Platform device info */
static struct platform_driver vga_led_driver = {
        .driver = {
                .name   = "vga_led",
                .owner  = THIS_MODULE,
                .of_match_table = of_match_ptr(vga_led_of_match),
        },
        .remove = __exit_p(vga_led_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_led.ko
vga_led: init
# cat /proc/iomem
00000000-3fffffff : System RAM
  00008000-0052262f : Kernel code
  00552000-005bd72b : Kernel data
ff200000-ff200007 : vga_led
ff702000-ff703fff : /soc/ethernet@ff702000
ff704000-ff704fff : /soc/dwmmc0@ff704000
ff705000-ff705fff : ff705000.spi
ffa00000-ffa00fff : ff705000.spi
ffb40000-ffb4fffe : dwc_otg
ffc02000-ffc0201f : serial
ffc03000-ffc0301f : serial
ffc04000-ffc04fff : ffc04000.i2c
fff00000-fff00fff : fff00000.spi
fff01000-fff01fff : fff01000.spi
```

The VGA_LED Driver: Header File

```
#ifndef _VGA_LED_H
#define _VGA_LED_H

#include <linux/ioctl.h>

#define VGA_LED_DIGITS 8

typedef struct {
  unsigned char digit;    /* 0, 1, .. , VGA_LED_DIGITS - 1 */
  unsigned char segments; /* LSB: segment a; MSB: decimal point */
} vga_led_arg_t;

#define VGA_LED_MAGIC 'q'

/* ioctls and their arguments */
#define VGA_LED_WRITE_DIGIT _IOW(VGA_LED_MAGIC, 1, vga_led_arg_t *)
#define VGA_LED_READ_DIGIT  _IOWR(VGA_LED_MAGIC, 2, vga_led_arg_t *)

#endif
```

The VGA_LED Driver: write_digit

```
#include <linux/module.h>
#include <linux/init.h>
#include <linux/errno.h>
#include <linux/version.h>
#include <linux/platform_device.h>
#include <linux/miscdevice.h>
#include <linux/io.h>
#include <linux/of.h>
#include <linux/of_address.h>
#include <linux/fs.h>
#include <linux/uaccess.h>
#include "vga_led.h"
#define DRIVER_NAME "vga_led"

struct vga_led_dev {
        struct resource res;    /* Resource: our registers */
        void __iomem *virtbase; /* Pointer to registers */
        u8 segments[VGA_LED_DIGITS];
} dev;

static void write_digit(int digit, u8 segments)
{
        iowrite8(segments, dev.virtbase + digit);
        dev.segments[digit] = segments;
}
```

The VGA_LED Driver: Ioctl

```
static long vga_led_ioctl(struct file *f, unsigned int cmd,
                          unsigned long arg)
{
        vga_led_arg_t vla;
        switch (cmd) {
        case VGA_LED_WRITE_DIGIT:
                if (copy_from_user(&vla, (vga_led_arg_t *) arg,
                                   sizeof(vga_led_arg_t)))
                        return -EACCES;
                if (vla.digit > 8)
                        return -EINVAL;
                write_digit(vla.digit, vla.segments);
                break;
        case VGA_LED_READ_DIGIT:
                if (copy_from_user(&vla, (vga_led_arg_t *) arg,
                                   sizeof(vga_led_arg_t)))
                        return -EACCES;
                if (vla.digit > 8)
                        return -EINVAL;
                vla.segments = dev.segments[vla.digit];
                if (copy_to_user((vga_led_arg_t *) arg, &vla,
                                 sizeof(vga_led_arg_t)))
                        return -EACCES;
                break;
        default: return -EINVAL;
        }
```

The VGA_LED Driver: file_operations

```
static const struct file_operations vga_led_fops = {
        .owner          = THIS_MODULE,
        .unlocked_ioctl = vga_led_ioctl,
};

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

The VGA_LED Driver: vga_led_probe

```
static int __init vga_led_probe(struct platform_device *pdev)
{
        static unsigned char welcome_message[VGA_LED_DIGITS] = {
                0x3E, 0x7D, 0x77, 0x08, 0x38, 0x79, 0x5E, 0x00};
        int i, ret;

        /* Register ourselves as a misc device: creates /dev/vga_led
        ret = misc_register(&vga_led_misc_device);
        /* Find our registers in device tree; verify availability */
        ret = of_address_to_resource(pdev->dev.of_node, 0, &dev.res);
        if (ret) {
                ret = -ENOENT;
                goto out_deregister;
        }
        if (request_mem_region(dev.res.start, resource_size(&dev.res)
                               DRIVER_NAME) == NULL) {
                ret = -EBUSY;
                goto out_deregister;
        }

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

The VGA_LED Driver: probe (cont) & remove

```
        /* Display a welcome message */
        for (i = 0; i < VGA_LED_DIGITS; i++)
                write_digit(i, welcome_message[i]);

        return 0;

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

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

The VGA_LED Driver: init and exit

```
static const struct of_device_id vga_led_of_match[] = {
        { .compatible = "altr,vga_led" },
        {},
};
MODULE_DEVICE_TABLE(of, vga_led_of_match);

static struct platform_driver vga_led_driver = {
        .driver = {
                .name   = DRIVER_NAME,
                .owner  = THIS_MODULE,
                .of_match_table = of_match_ptr(vga_led_of_match),
        },
        .remove = __exit_p(vga_led_remove),
};

static int __init vga_led_init(void)
{
        pr_info(DRIVER_NAME ": init\n");
        return platform_driver_probe(&vga_led_driver, vga_led_probe);
}
static void __exit vga_led_exit(void)
{
        platform_driver_unregister(&vga_led_driver);
        pr_info(DRIVER_NAME ": exit\n");
}
```

The VGA_LED Driver

```
module_init(vga_led_init);
module_exit(vga_led_exit);

MODULE_LICENSE("GPL");
MODULE_AUTHOR("Stephen A. Edwards, Columbia University");
MODULE_DESCRIPTION("VGA 7-segment LED Emulator");
```

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.