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Device Drivers Demystified
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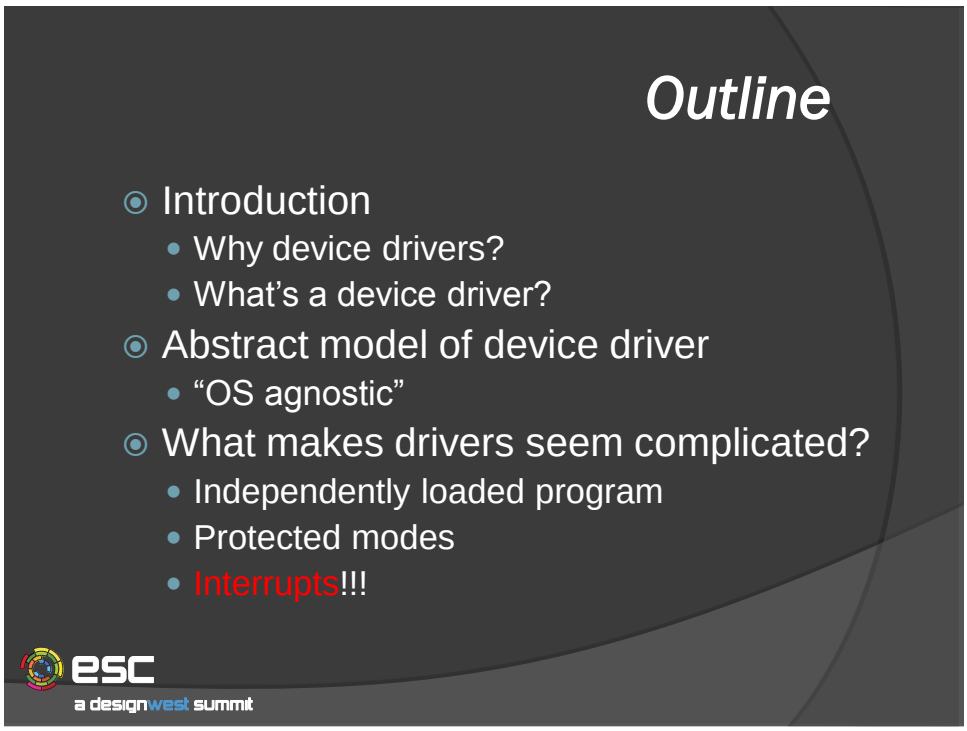
Outline
Introduction
Why device drivers?
What's a device driver?
Abstract model of device driver
"OS agnostic"
What makes drivers seem complicated?
Independently loaded program
Protected modes
Interrupts!!!
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Outline II

- The Linux driver model
  - Kernel loadable modules
  - Character device drivers
  - User space/Kernel space communication
  - Interrupt handling
  - Blocking I/O

Why device drivers?

- It's good programming practice!!!
  - Cleanly separate hardware dependent code from hardware independent code
  - Hides "messy" programming details from application programmer
- I/O access may require higher privilege level

What's a "device driver" anyway?

- A Set of Linkable Functions
- An Independently Loadable Program
- A Separate Task or Set of Tasks
- A Well-defined driver API
- All of the Above??

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Basic APIs

- int read (void *buffer, int length, int *actual);
- int write (void *buffer, int length, int *actual);

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Multiple device types

- read_serial (); write_serial ();
- read_AD (); write_AD();
- read_display (); write_display ();

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Multiple implementations of a device type

- read_serial_8250 () write_serial_8250 ()
- read_serial_68328 () write_serial_68328 ()
- read_serial_atmel () write_serial_atmel ()

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Identifying device with a parameter

- int read (device_t *dev, void *buffer, int length, int *actual);
- int write (device_t *dev, void *buffer, int length, int *actual);

Fill in the dev structure

```
dev->read = read_serial_8250;
dev->write = write_serial_8250;
```

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Connecting to a device

```
device_t dev;

int device_init ()
{
    /* fill in the dev struct */
        .
        .
    device_register ("serial", &dev);

    return 0;          // success
}
```

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Using a device

```
device_t serial_dev;
char command[80];
    .
    .
    .
status = connect ("serial", &serial_dev);
    .
    .
status = read (&serial_dev, command,
   sizeof (command), &actual);
```

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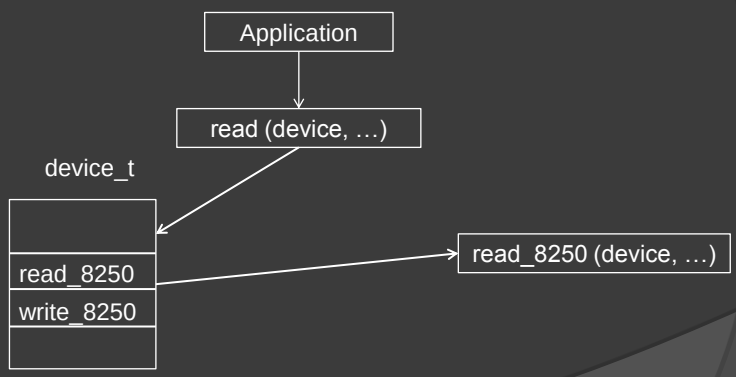
Graphically



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A control function

```
int control (device_t *dev, int command, …);

if (control (&serial_dev, SET_BAUD_RATE,
    115200))
{
    /* Report error */
}
```

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Driver APIs

- int connect (char *name, device_t *dev);
- int read (device_t *dev, void *buffer, int len, int *transferred);
- int write (device_t *dev, void *buffer, int len, int *transferred);
- int control (device_t *dev, int command, …);
- int disconnect (device_t *dev);

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Blocking I/O

- What if…
  - No data available (yet) on read?
  - Buffer full on write?
- Task must "sleep" until condition is satisfied
- Allows another task to run – multitasking
  - Reentrancy!

Blocking methods

- int get_sem (semaphore_t *sem);
- int put_sem (semaphore_t *sem);
  - often called from ISR

```
int read (device_t *dev, void *buffer, int len, int *actual)
{
    prepare to read;

    if (!readable)
        get_sem (&wait);
    do read;
    *actual = bytes read;
    return success;
}
```

Interrupt Service Routine

```
void interrupt_service (void)
{
   determine interrupt source;
   clear interrupt flag;
   put_sem (&wait);
}
```

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Summary

- A device driver is:
  - An abstraction mechanism
  - Set of functions called by application
- Device-independent functions call device-dependent functions
- Usually an independently loaded program file

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The Linux device model

- Everything is a file
  - Peripherals have nodes in file system
  - Device nodes go in /dev directory
- Well, not quite
  - Network devices don't have file system nodes
- Device nodes have *major* and *minor* numbers
  - Major number links to device driver

Device Classes

- Character
  - Stream of bytes
- Block
  - Mass storage
  - Requires file system
- Network
  - Different interface to kernel
  - Responds to packets coming from outside
- Pipe

The /dev directory

```
# ls -l /dev          Major Number        Minor Number
brw-rw----   1 root   disk     3,    0 May  5  1998 hda
brw-rw----   1 root   disk     3,    1 May  5  1998 hda1
brw-rw----   1 root   disk     3,   10 May  5  1998 hda10

lrwxrwxrwx   1 root   root          5 Feb  23  10:00 mouse -> psaux
                .
crw-rw-r--   1 root   root    10,    1 Feb  23  17:14 psaux

crw-------   1 root   root     4,    0 May  5  1998 tty0
crw-------   1 root   tty      4,    1 Feb  23  20:06 tty1
crw-rw----   1 root   uucp    19,    0 Apr  17  1999 ttyC0
```

Links
Owner
Group

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Low-level user space APIs

- int open (const char *path, int oflags);
- size_t read (int file_des, void *data, size_t len);
- size_t write (int file_des, const void *data, size_t len);
- int close (int file_des);
- int ioctl (int file_des, int cmd, …);

Problems

- Data not buffered
- Kernel calls are inefficient

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Standard I/O library, stdio

- FILE *fopen (const char *filename, const char *mode);
- size_t fread (void *buff, size_t size, size_t n, FILE *stream);
- size_t fwrite (const void *buff, size_t size, size_t n, FILE *stream);
- int fclose (FILE *stream);
- getc, putc, and gets families
- Formatted I/O: printf, etc.

Problems

- Non-deterministic
- No control function (ioctl)

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Installable kernel modules are...

- A way to “extend” the kernel
- Dynamically loaded and unloaded
- Executed at Privilege Level 0
- Useful for:
  - Device Drivers
  - File systems

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Installable kernel modules

- **Shell Commands**
  - insmod <module name> [<param>…]
  - rmmod <module name>
- **Required Functions**
  - module initialization
  - module cleanup

Installing a module

Install command

insmod my_module.ko my_int = 1 my_string = “Hello”

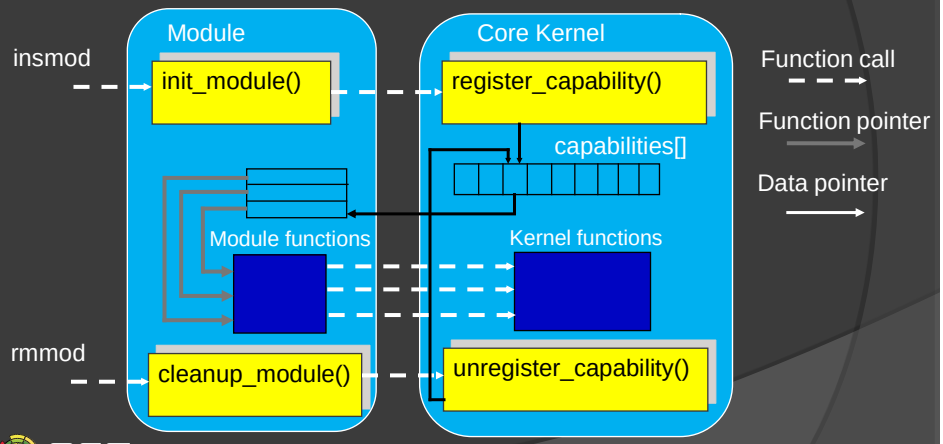
In my_module.c

```
int my_int;
char *my_string;

module_param (my_string, charp, S_IRUGO);
module_param (my_int, int, S_IRUGO);

static int __init my_init (void)
{
     register_capability();
     return 0;
}
module_init (my_init);
```

Linking a module to the kernel



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Building a Module

- **Modules are kernel version specific**
  - Kernel APIs change over time
- **Build in kernel source tree**
  - Need kernel header files
- **Makefile**

```
obj-m := module.o

all:
   make –C /lib/module/$(shell uname -=r)/build
   M=$(shell pwd) modules
```

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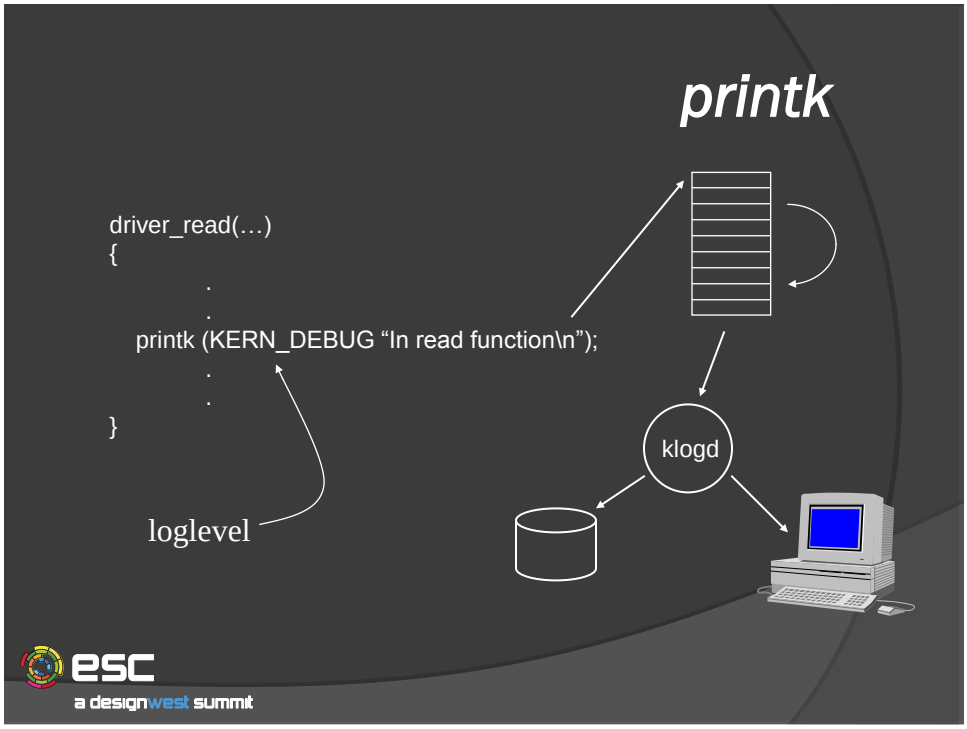
printk
driver_read(…)
{
.
.
printk (KERN_DEBUG “In read function\n”);
.
.
}
loglevel
klogd
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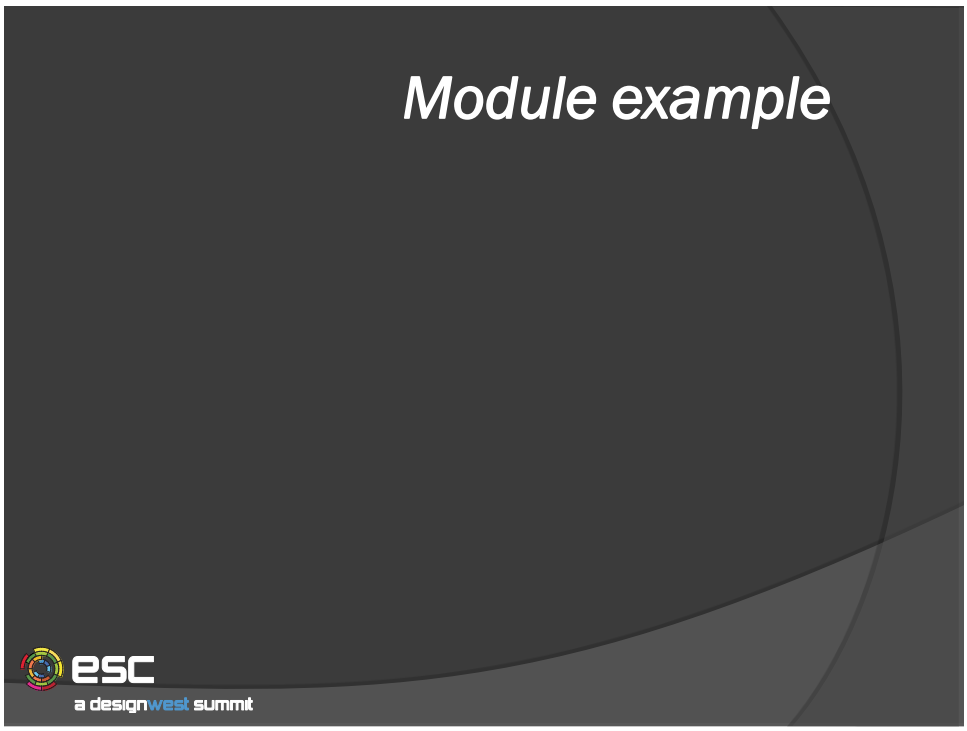
Module example
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Kernel modules and the GPL

- **GPL = Gnu General Public License**
- **Applications in User Space need not be GPL**
- **Kernel is GPL**
  - Any code built into the kernel is GPL
- **Kernel modules need not be GPL**
  - Some developers disagree

File operations table

```
struct file_operations {
    struct module *owner;
    loff_t (*llseek)(struct file *, loff_t, int);
    ssize_t (*read)(struct file *, char __user *, size_t, loff_t *);
    ssize_t (*aio_read)(struct kiocb *, char __user *, size_t, loff_t *);
    ssize_t (*write)(struct file *, const char __user *, size_t, loff _t *);
    ssize_t (*aio_write)(struct kiocb *, const char __user *, size_t, loff _t *);
    int (*readdir)(struct file *, void *, filedir_t);
    unsigned int (*poll)(struct file *, struct poll_table_struct *);
    int (*ioctl)(struct inode *, struct file *, unsigned int, unsigned long);
    int (*mmap)(struct file *, struct vm_area_struct *);
    int (*open)(struct inode *, struct file *);
    int (*flush)(struct file *);
    int (*release)(struct inode *, struct file *);
```

File operations table II

```
        int (*fsync)(struct file *, struct dentry *, int);
        int (*aio_fsync)(struct kiocb *, int);
        int (*fasync)(int, struct file *, int);
        int (*lock)(struct file *, int, struct file_lock *);
        ssize_t (*readv)(struct file *, const struct iovec *, unsigned long, loff_t *);
        ssize_t (*writev)(struct file *, const struct iovec *, unsigned long, loff _t *);
        ssize_t (*sendfile)(struct file *, loff _t *, size_t, read_actor_t, void *);
        ssize_t (*sendpage)(struct file *, struct page *, int, size_t, loff _t *, int);
        unsigned long (*get_unmapped_area )(struct file *, unsigned long,
                        unsigned long, unsigned long, unsigned long);
        int (*check_flags)(int);
        int (*dir_notify )(struct file *, unsigned long);
}
```

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Steps to a device driver

- **Allocate one or more device numbers**
  - dev_t is 32-bit number
  - int register_chrdev_region (dev_t first, unsigned int count, char *name); or…
  - int alloc_chrdev_region (dev_t *dev, unsigned int firstminor, unsigned int count, char *name,);
- **Create nodes in /dev for device numbers**
- **Fill in file operations table**
- **Register driver**

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Allocating device numbers

- dev_t - a 32-bit number in kernel 2.6. Combines major and minor numbers
- MKDEV(int major, int minor) - creates a dev_t
- MAJOR(dev_t dev) – Returns the major part
- MINOR(dev_t dev) – Returns the minor part

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Registering a driver

In init_module()

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

struct cdev *my_cdev = cdev_alloc ( );
my_cdev->ops = &my_fops;
```

or

```
void cdev_init (struct cdev *my_cdev, struct file_operations *my_fops);
```

followed by

```
my_cdev.owner = THIS_MODULE;
int cdev_add (struct cdev *my_cdev, dev_t num, unsigned int count);
```

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Miscellaneous class device

- Creates device nodes for you
  - Uses major device number 10
  - Can dynamically allocate minors

```
struct miscdevice {
    int minor;
    const char *name;
    const struct file_operations *fops;
                .
                .
}

int misc_register (struct miscdevice *);
```


Driver APIs

- int open (struct inode *inodep, struct file *filep);
  - Returns 0 on success.
- int release (struct inode *inodep, struct file *filep);
  - Equivalent to close (). Returns 0 on success.
- ssize_t read (struct file *filep, char __user *buff, size_t count, loff_t *f_pos);
  - Positive return = bytes transferred. Negative is error
- ssize_t write (struct file *filep, char __user *buff, size_t count, loff_t *f_pos);

Important structures

- **file structure**
  - Created before call to open ()
  - Passed to all driver functions
  - May have multiple file structures simultaneously
  - Represented in user space by file descriptor
- **inode structure**
  - One for each file and device entry in the file system
  - Describes the file system entry
  - Passed to open(), release(), and ioctl()

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struct file

```
struct file {
    struct list_head      f_list;
    struct dentry   *f_dentry;
    struct vsfmount       *f_vsfmount;
    struct file_operations *f_op;
          .
          .
    void *private_data;
          .
}
```

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Driver example

The /proc file system

- **Files in /proc don't really exist**
  - Data generated in real time when file is read
- **Window from user space into kernel space**
  - Many utilities get their info from /proc files
  - Numbered subdirectories represent processes
- **Create /proc files as driver debugging tools**

Allocating system resources

- **System resources include:**
  - I/O ports
  - Device numbers
  - Interrupts
- **Must *request* or *register* resources**
  - Resources are allocated exclusively
  - Registration function includes *name* argument that becomes an entry in a /proc file

Registering an interrupt handler

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

int request_irq (unsigned int irq,
        irqreturn_t (*handler) (int, void *),
        unsigned long flags,
        const char *dev_name,
        void *dev_id);

void free_irq (unsigned int irq, void *dev_id);
```

request_irq() flags

- **IRQF_DISABLED** – run ISR with interrupts disabled
- **IRQF_SHARED** – interrupt is shared. Multiple registrations OK.
- **IRQF_SAMPLE_RANDOM** – interrupt can contribute to "entropy pool."

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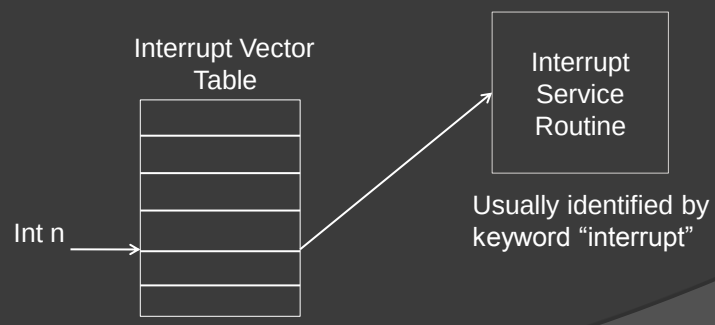
Two approaches to Interrupt handling The "direct" approach



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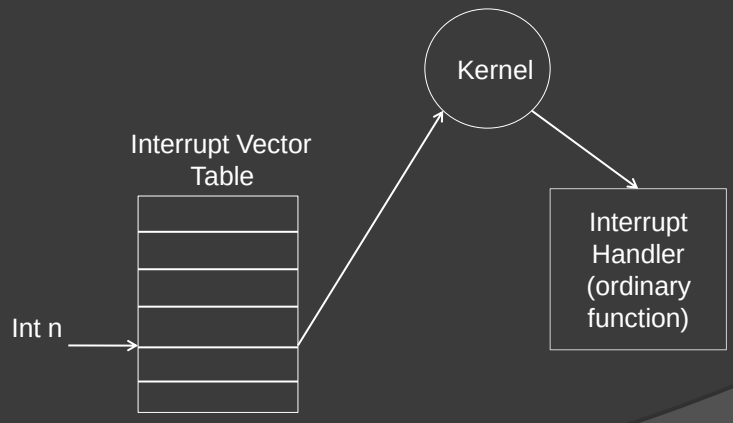
The "indirect" approach Linux does this



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Blocking I/O in Linux – the wait_queue

#include <linux/wait.h>

Create a wait queue

DECLARE_WAIT_QUEUE_HEAD(name);

or

wait_queue_head_t my_queue;
init_waitqueue_head (&my_queue);

Sleep on a queue

wait_event (queue, condition)
wait_event_interruptible (queue, condition)
wait_event_timeout (queue, condition, timeout)
wait_event_interruptible_timeout (queue, condition, timeout)

Wake up a process on a queue

wake_up (&queue);

wake_up_interruptible (&queue);

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Putting a process to sleep

```
DECLARE_WAIT_QUEUE_HEAD(my_wait);
int flag = 0;
int buff_count;

ssize_t sleepy_write (struct file *file, char *buff, int count, loff_t *offset)
{
        copy_from_user (buffer, buff, buff_count = count);
        flag = 1;
        wake_up_interruptible (&my_wait);
        return count;
}
ssize_t sleepy_read (struct file *file, char *buff, int count, loff_t *offset)
{
        wait_event_interruptible (my_wait, flag != 0);
        copy_to_user (buffer, buff, buff_count);
        return buff_count;
}
```


Not that simple – everybody wakes up

```
ssize_t sleepy_read (struct file *file, char *buff, int count,
    loff_t *offset)
{
    while (flag == 0)
        wait_event_interruptible (my_wait, flag != 0);

    copy_to_user (buffer, buff, buff_count);
    return buff_count;
}
```

Accessing hardware

- Where are I/O registers located?
  - Memory space or separate I/O space
- I/O operations may have "side effects"
  - Compiler optimizations can get in the way
    - Caching
    - Reordering
- I/O space must be allocated

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I/O port APIs

Single item transfer

```
unsigned inb (unsigned port);
void outb (unsigned char byte, unsigned port);
unsigned inw (unsigned port);
void outw (unsigned short word, unsigned port);
unsigned inl (unsigned port);
void outl (unsigned longword, unsigned port);
```

"String" transfer

```
void insx (unsigned port, void *addr, unsigned long count);
void outsx (unsigned port, void *addr, unsigned long count);
```

Note: x is "b", "w", or "l".

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I/O memory APIs

```
void *ioremap (unsigned long phys_addr, unsigned long size);
void iounmap (void *address);

unsigned int ioreadn (void *address);
void iowriten (un value, void * address);

unsigned int ioreadn_rep (void *address, void *buf,
        unsigned long count);
void iowriten_rep (void * address , const void *buf,
        unsigned long count);
```

Note: n = 8, 16, or 32

Allocating an I/O region

```
struct resource *request_region (unsigned long first,
        unsigned long n, const char *name);
void release_region (unsigned long start, unsigned long n);

struct resource *request_mem_region (unsigned long first,
        unsigned long n, const char *name);
void release_ mem_ region (unsigned long start,
        unsigned long n);
```

Barriers

Compiler memory barrier

```
#include <linux/kernel.h>
void barrier (void);
```

Hardware barriers

```
#include <asm/system.h>
void rmb (void);
void wmb (void);
void mb (void);
```

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Doing it in User Space

- fd = open (“/dev/mem”, O_RDWR);
- vaddr = mmap (0, size, access, shared, fd, phys_addr);

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Summary

- **Everything is a file – almost**
  - Peripherals are “files” in the /dev directory
  - Except network devices
  - Four device classes
- **Kernel loadable modules**
  - Extend the kernel
  - Dynamically loadable at run time
  - Kernel version specific
- **File Operations Table**
  - Links driver to rest of system

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Summary II

- **Tools**
  - printk() – writes to /var/log/messages
  - /proc file system – window from user space into kernel space
- **Resources**
  - Device numbers, I/O ports, interrupts
  - Must be allocated or registered exclusively
- **Accessing hardware**
  - I/O port space vs. memory space
  - “Side effects” – compiler optimizations
  - Interrupts

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Key takeaway

- Fundamentally, a device driver is just a set of functions that are called on behalf of, and in the context of, a user space process.
- Complexities arise due to:
  - Driver is independently loaded program
  - User space to kernel space transition
- Questions, revised slides/sources
  - www.intellimetrix.us/downloads
  - doug@intellimetrix.us

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