Operating Systems Design
11. Devices

Paul Krzyzanowski
pxk@cs.rutgers.edu

1

Categories of devices

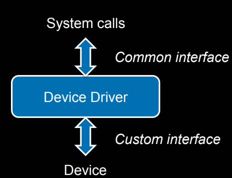
- Block devices (can hold a file system)
- Network (sockets)
- Character devices (everything else)

- Devices as files:
  - Character & block devices appear in the file system name space
  - Use open/close/read/write operations
  - Extra controls may be needed for device-specific functions (*ioctl*)

2

Device driver

Software in the kernel that interfaces with devices



3

Device System

Contains:

- Buffer cache & I/O scheduler
- Generic device driver code
- Drivers for specific devices (including bus drivers)

4

Device Drivers

- Device Drivers
  - Implement mechanism, *not* policy
  - Mechanism: ways to interact with the device
  - Policy: who can access and control the device

- Device drivers may be compiled into the kernel or loaded as modules

5

Kernel Modules

- Chunks of code that can be loaded & unloaded into the kernel on demand
- Dynamic loader
  - Links unresolved symbols to the symbol table of the running kernel
- Linux
  - `insmod` to add a module and `rmmod` commands to remove a module
  - *`module_init`*
    - Each module has a function that the kernel calls to initialize the module and register each facility that the module offers
  - *`delete_module`*: system call calls a *`module_exit`* function in the module
  - Reference counting
    - Kernel keeps a use count for each device in use
    - *get()*: increment – called from *open* when opening the device file
    - *put()*: decrement – called from *close*
  - You can remove only when the use count is 0

6

Example: Linux Kernel Module ELF sections

ELF: Executable & Linkable Format object file

Section	Description
.text	Instructions
.fixup	Runtime modifications
.init.text	Module initialization instructions
.exit.text	Module exit instructions
.rodatastr1.1	Read-only strings
.modinfo	Module information (license, author, description)
__versions	Module version data
.data	Initialized data
.bss	Uninitialized data

7

Device Driver Initialization

- All modules have to register themselves
  - *How else would the kernel know what they do?*
- Device drivers register themselves as devices
  - Character drivers
    Initialize & register a `cdev` structure & implement `file_operations`
  - Block drivers
    Initialize & register a `gendisk` structure & implement `block_device_operations`
  - Network drivers
    Initialize & register a `net_device` structure & implement `net_device_ops`

8

Block Devices

- Structured access to the underlying hardware
- Something that can host a file system
- Supports only block-oriented I/O
- Convert the user abstraction of the disk being an array of bytes to the underlying structure
- Examples
  - USB memory keys, disks, CDs, DVDs

9

Buffered vs. Unbuffered I/O

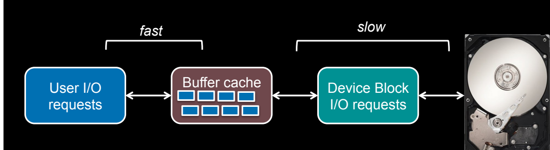
Buffered I/O:
- Kernel copies the *write* data to a block of memory (buffer):
  - Allow the process to write bytes to the buffer and continue processing
  - Buffer does not need to be written to the disk … yet
- Read operation:
  - When the device is ready, the kernel places the data in the buffer

- Why is buffering important?
  - Deals with device burstiness (*leaky bucket*)
  - Allows user data to be modified without affecting the data that's read or written to the device
  - Caching (for block devices)
  - Alignment (for block devices)

10

Buffer Cache

- Pool of kernel memory to hold frequently used blocks from block devices
- Minimizes the number of I/O requests that require device I/O
- Allows applications to read/write from/to the device as a stream of bytes or arbitrary-sized blocks



11

Blocking & Non-blocking I/O

- Buffer cache deals with the device level
- Options at the system call level
- Blocking I/O (aka synchronous I/O):
  - user process waits until I/O is complete
- Non-blocking I/O (aka asynchronous I/O):
  - Schedule output but don't wait for it to complete
  - Poll if data is ready for input (e.g., *select* system call)

12

Asynchronous I/O

- Request returns immediately but the I/O is scheduled and the process will be signaled when it is ready
  - Differs from non-blocking because the I/O will be performed in its entirety … just later
- If the system crashes or is shut off before modified blocks are written, that data is lost and the user will not realize it
- To minimize data loss
  - Perform periodic flushes (especially when there is no other disk I/O)
    - On BSD: a user process, *update*, calls *sync* to flush data
    - On Linux: *kupdated*, a kernel update daemon does the work
  - Or force synchronous writes (but performance suffers!)

13

File systems

- Determine how data is organized on a block device
- A file system is ***NOT*** a device driver
  - But file systems are implemented on top of block devices
- It is a software driver
  - Maps low-level to high-level data structures
- *More on this later…*

14

Network Devices

- Packet, not stream, oriented device
- Not visible in the file system
- Accessible through the *socket* interface
- May be hardware or software devices
  - Software is agnostic
  - E.g., ethernet or loopback devices
- *More on this later…*

15

Character Devices

- Unstructured access to underlying hardware
- Different types (anything that's not a block or network device):
  - Streams of characters: *Terminal multiplexor, serial port*
  - Frame buffer: *Has its own buffer management policies and custom interfaces*
  - Sound devices, I²C controllers, etc.
- Higher-level software provides line-oriented I/O
  - tty driver that interacts with the character driver
  - Raw vs. cooked I/O: *line buffering, eof, erase, kill character processing*
- Character access to block devices (disks, USB memory keys, …)
  - Character interface is the unstructured (raw) interface
  - I/O does NOT go through buffer cache
  - Operates directly between the device and buffers in user's address space
  - I/O must be a multiple of the disk's block size

16

All objects get a common file interface

Key to supporting a "devices look like files" model of interaction

All devices support generic "file" operations. File systems will call these functions when using the device.

```
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 (*write) (struct file *, const char __user *, size_t, loff_t *);
 ssize_t (*aio_read) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
 ssize_t (*aio_write) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
 int (*readdir) (struct file *, void *, filldir_t); NULL for device files
 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 *, fl_owner_t id);
 int (*release) (struct inode *, struct file *);
 int (*fsync) (struct file *, struct dentry *, int datasync);
 int (*fasync) (int, struct file *, int);
 int (*flock) (struct file *, int, struct file_lock *);
 ...
}
```

17

Device driver entry points

- Each device driver provides a fixed set of entry points
  - Define whether the device has a block or character interface
  - Block device interfaces appear in a block device table
  - Character device interfaces: character device table
- Identifying a device in the kernel
  - Major number
    - Identifies device: index into the device table (block or char)
  - Minor number
    - Interpreted within the device driver
    - Instance of a specific device
    - E.g., Major = SATA disk driver, Minor = specific disk
- Unique device ID = { type, major #, minor # }

18

How do you locate devices?

- Explicit namespace (MS-DOS approach)
  - `C:`, `D:`, `LPT1:`, `COM1:`, etc.
- Big idea!
  - *Use the file system interface as an abstract interface for both file and device I/O*
  - Device: file with no contents but with metadata:
    - Device file
    - Type of device (block or character)
    - Major & minor numbers (index into device table & instance)
  - Devices are traditionally located in `/dev`
  - Created by the *mknod* system call (or `mknod` command)

19

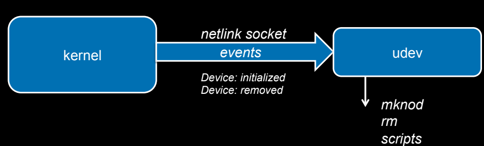
Device names: Windows

- Windows NT architecture (XP, 2000, Vista, Win 7, …)
  - When a device driver is loaded
    - It is registered by name with the Object Manager
  - Names have a hierarchical namespace maintained by Object Manager
    `\Device\Serial0`
    `\Device\CDRom0`
  - (Linux sort of did this with devfs and devtmpfs)
- Win32 API requires support for MS-DOS names
  - `C:`, `D:`, `LPT1:`, `COM1:`, etc.
  - These names are in the `\??` Directory in the Object Manager's namespace
  - Visible to Win32 programs
  - Symbolic links to corresponding Windows NT device names

20

Linux: Creating devices in /dev

- Static devices (mknod)
- udev – kernel device manager
  - udev runs as a user-level process



21

Character device entry points

Character (and raw block) devices include these entry points:

open: open the device
close: close the device
ioctl: do an I/O control operation
mmap: map the device offset to a memory location
read: do an input operation
reset: reinitialize the device
select: poll the device for I/O readiness
stop: stop output on the device
write: do an output operation

22

Block device entry points

Block devices include these entry points:

open: prepare for I/O
Called for each open system call on a block device (e.g. on mount)

strategy: schedule I/O to read/write blocks
Called by the buffer cache. The kernel makes *bread()* and *bwrite()* requests to the buffer cache. If the block isn't there then it contacts the device.

close: called after the final client using the device terminates

psize: get partition size

23

Kernel execution contexts

- Interrupt context
  - Unable to block because there's no process to reschedule
    nothing to put to sleep and nothing to wake up
- User context
  - Invoked by a user thread in synchronous function
  - May block on a semaphore, I/O, or copying to user memory
  - E.g., *read* invoked by the *read* system call
  - (Linux) Driver can access global variable `context`
    - Pointer to `struct task_struct`: tells driver who invoked the call
- Kernel context
  - Scheduled by kernel scheduler (just like any process)
  - No relation to any user threads
  - May block on a semaphore, I/O, or copying to user memory

24

Interrupt Handler

- Device drivers register themselves with the interrupt handler
  - *Hooks* registered at initialization: call code when an event happens
- Operations of the interrupt hander
  - Switch to kernel stack (if not using it already)
  - Save all registers
  - Update interrupt statistics: counts & timers
  - Call interrupt service routine in driver with the appropriate unit number (ID of device that generated the interrupt)
  - Restore registers, including original stack pointer
  - Return from interrupt
- The driver itself does not have to deal with saving/restoring registers

25

Handling interrupts quickly

- Processing results of an interrupt may take time
- We want interrupt handlers to finish quickly
  - Don't keep interrupts blocked

26

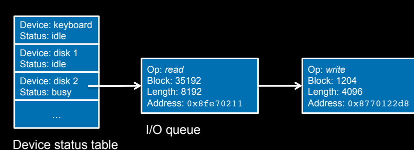
Delegation: top half → bottom half

- Split interrupt handling into two parts:
  - Top half (interrupt handler)
    - Part that's registered with *request_irq* and is called whenever an interrupt is detected.
    - Saves data in a buffer/queue, schedules bottom half, exits
  - Bottom half (work queue – kernel thread)
    - Scheduled by top half for later execution
    - Interrupts enabled
    - This is where there real work is done
    - Linux 2.6 provides tasklets & work queues for dispatching bottom halves
- Bottom halves are handled in a *kernel context*
  - Work queues are handled by kernel threads
  - One thread per processor (`events/0`, `events/1`)

27

I/O Queues

- When I/O request is received
  - Request is placed on a per-device queue for processing
- Device Status Table
  - List of devices and the current status of the device
  - Each device has an I/O queue attached to it



28

I/O Queues

- Primary means of communication between top & bottom halves
- I/O queues are shared among asynchronous functions
  - Access to them must be synchronized (critical sections)

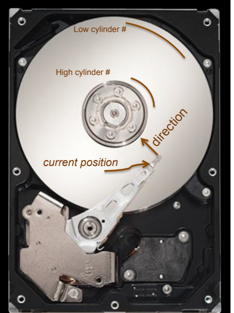
29

I/O Scheduling for Block Devices (disks)

30

Elevator Algorithms

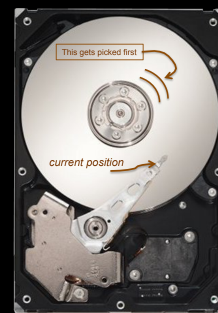
- Elevator algorithm (SCAN)
  - Know: head position & direction
  - Schedule pending I/O in the sequence of the current direction
  - When the head reaches the end, switch the direction
- LOOK
  - When there are no more blocks to read/write in the current direction, switch direction
- Circular SCAN (C-SCAN)
  - Like SCAN, but: when you reach the end of the disk, seek to the beginning without servicing I/O
  - Provides more uniform wait time
- C-LOOK
  - Like C-SCAN but seek to the lowest track with scheduled I/O



31

Shortest Seek Time First (SSTF)

- Know: head position
- Schedule the next I/O that is closest to the current head position
- Analogous to shortest job first scheduling
- Distant cylinders may get starved (or experience long latency)



32

Scheduling I/O: Linux options

- Completely Fair Queuing (CFQ)
  - default scheduler
  - distribute I/O equally among all I/O requests
  - Synchronous requests
    - Go to per-process queues
    - Time slices allocated per queue
  - Asynchronous requests
    - Batched into queues by priority levels
- Deadline
  - Each request has a deadline
  - Service them using C-SCAN
  - If a deadline is threatened, skip to that request
  - Helps with real-time performance
  - Gives priority to real-time processes. Otherwise, it's fair

33

Scheduling I/O: Linux options

- NOOP
  - Simple FIFO queue - minimal CPU overhead
  - Assumes that the block device is intelligent
- Anticipatory
  - introduce a delay before dispatching I/O to try to aggregate and/or reorder requests to improve locality and reduce disk seek.
  - After issuing a request, wait (even if there's work to be done)
  - If a request for nearby blocks occurs, issue it.
  - If no request, then C-SCAN
  - Fair
  - No support for real time
  - May result in higher I/O latency
  - Works surprisingly well in benchmarks!!

34

Smarter Disks

- Disks are smarter than in the past
  - E.g.: WD Caviar Black drives: dual processors, 64 MB cache
- Logical Block Addressing (LBA)
  - Versus Cylinder, Head, Sector
- Automatic bad block mapping (can mess up algorithms!)
  - Leave spare sectors on a track for remapping
- Native Command Queuing (SATA & SCSI)
  - Allow drive to queue and re-prioritize disk requests
  - Queue up to 256 commands with SCSI
- Cached data
  - Volatile memory; improves read time
- Read-ahead caching for sequential I/O
- Hybrid Hard Drives (HDD)
  - Non-volatile RAM (NVRAM)

35

Solid State Disks

- NAND Flash
  - NOR Flash: random access bytes; suitable for execution; lower density
  - NAND Flash: block access
- No seek latency
- Asynchronous random I/O is efficient
  - Sequential I/O less so
- Writes are less efficient: erase-on-write needed
- Limited re-writes
  - Wear leveling becomes important (~ 100K-1M program/erase cycles)

36

Back to drivers

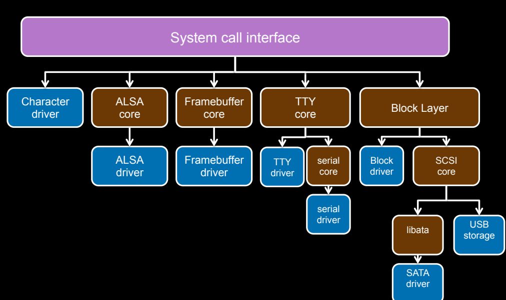
Device Model Framework

- Most drivers are not individual character or block drivers
  - Implemented under a framework for a device type
  - Goal: create a set of standard interfaces
  - e.g., ALSA core, TTY serial, SCSI core, framebuffer devices

ALSA = Advanced Linux Sound Architecture

- Define common parts for the same kinds of devices
  - Still seen as normal devices to users
  - Each framework defines a set of operations that the device must implement
    - e.g., framebuffer operations, ALSA audio operations
- Device model framework provides a common interface
  - ioctl numbering for custom functions, semantics, etc.

Example of the device model framework



Example: Framebuffer

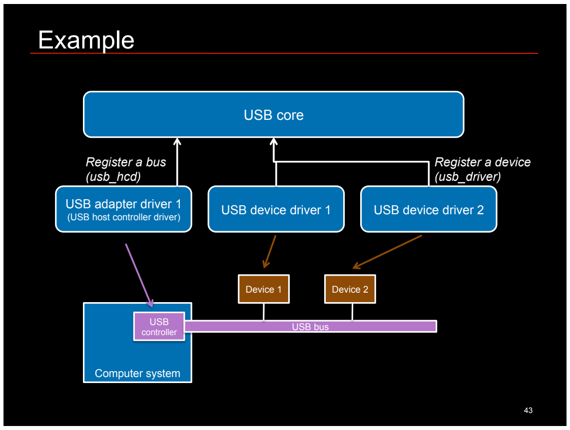
- Must implement functions defined in `struct fb_ops`
  - These are framebuffer-specific operations
  - `xxx_open()`, `xxx_read()`, `xxx_write()`, `xxx_release()`, `xxx_checkvar()`, `xxx_setpar()`, `xxx_setcolreg()`, `xxx_blank()`, `xxx_pan_display()`, `xxx_fillrect()`, `xxx_copyarea()`, `xxx_imageblit()`, `xxx_cursor()`, `xxx_rotate()`, `xxx_sync()`, `xxx_get_caps()`, etc.
- Also must:
  - allocate a `fb_info` structure with `framebuffer_alloc()`
  - set the `->fbops` field to the operation structure
  - register the framebuffer device with `register_framebuffer()`

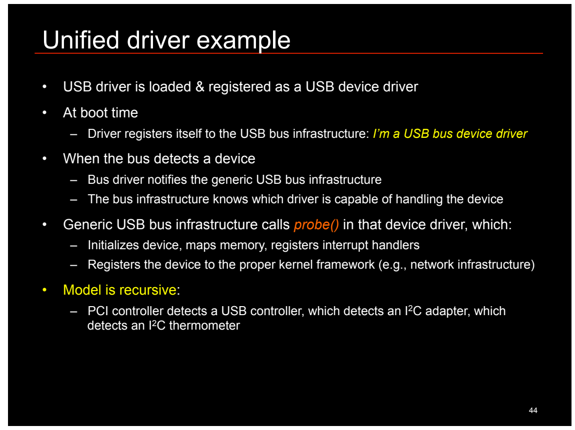
Linux 2.6 Unified device/driver model

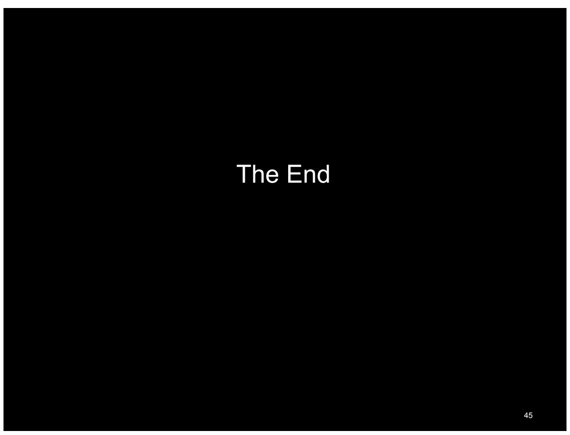
- Goal: unify the relationship between:
  devices, buses, and device classes
- Bus driver
  - Interacts with each communication bus that supports devices (USB, PCI, SPI, MMC, I^2C, etc.)
  - Responsible for:
    - Registering bus type
    - Registering adapter/interface drivers (USB controllers, SPI controllers, etc.): devices capable of detecting & providing access to devices connected to the bus
    - Allow registration of device drivers (USB, I^2C, SPI devices)
    - Match device drivers against devices

Linux 2.6 Unified device/driver model

- Devices
  - Connected to a parent (typically a bus or host controller)
  - Identification on the bus
  - Reference to the device driver for the device
  - Registration/unregistration functions
  - *release* method when the last reference to the device is removed
- Classes
  - High-level view of a device
    - E.g., Disk instead of an eSATA disk or a SCSI disk
  - Presents the device under /sys/class/<category>
  - No need for explicit driver support


Example
USB core
Register a bus
(usb_hcd)
Register a device
(usb_driver)
USB adapter driver 1
(USB host controller driver)
USB device driver 1
USB device driver 2
Device 1
Device 2
USB controller
USB bus
Computer system
43


Unified driver example
• USB driver is loaded & registered as a USB device driver
• At boot time
– Driver registers itself to the USB bus infrastructure: *I'm a USB bus device driver*
• When the bus detects a device
– Bus driver notifies the generic USB bus infrastructure
– The bus infrastructure knows which driver is capable of handling the device
• Generic USB bus infrastructure calls *probe()* in that device driver, which:
– Initializes device, maps memory, registers interrupt handlers
– Registers the device to the proper kernel framework (e.g., network infrastructure)
• Model is recursive:
– PCI controller detects a USB controller, which detects an I^2C adapter, which detects an I^2C thermometer
44


The End
45