Imperial College London

Operating Systems

Device Management

Course 211
Spring Term 2016-2017

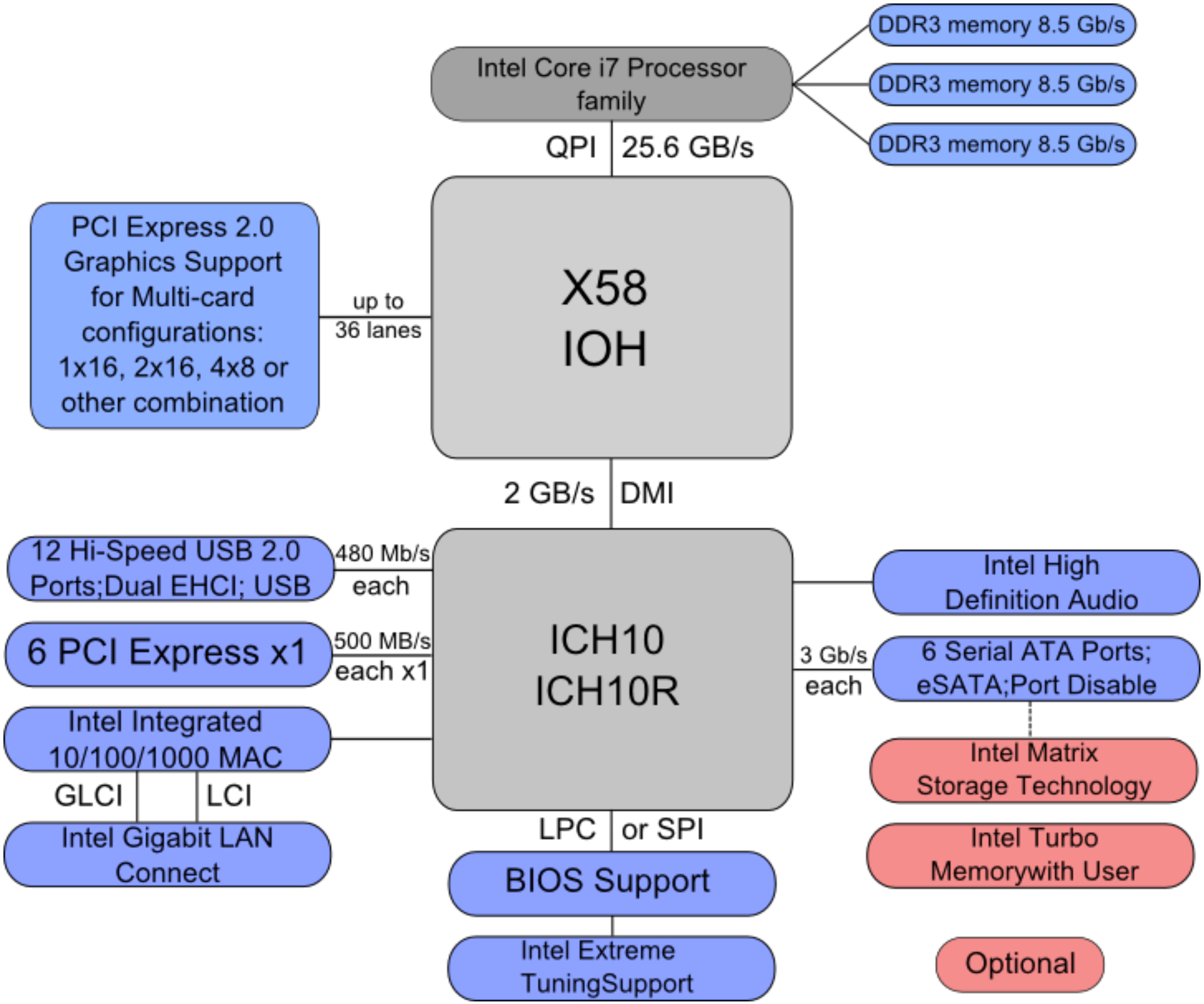
http://www.imperial.ac.uk/computing/current-students/courses/211/calendar/

Based on slides by Daniel Rueckert

Peter Pietzuch

prp@doc.ic.ac.uk
http://www.doc.ic.ac.uk/~prp

Example: Intel Architecture



I/O Device Management

Objectives

- Fair access to shared devices
  - Allocation of dedicated devices
- Exploit parallelism of I/O devices for multiprogramming
- Provide uniform simple view of I/O
  - Hide complexity of device handling
  - Give uniform naming and error handling

Device Independence

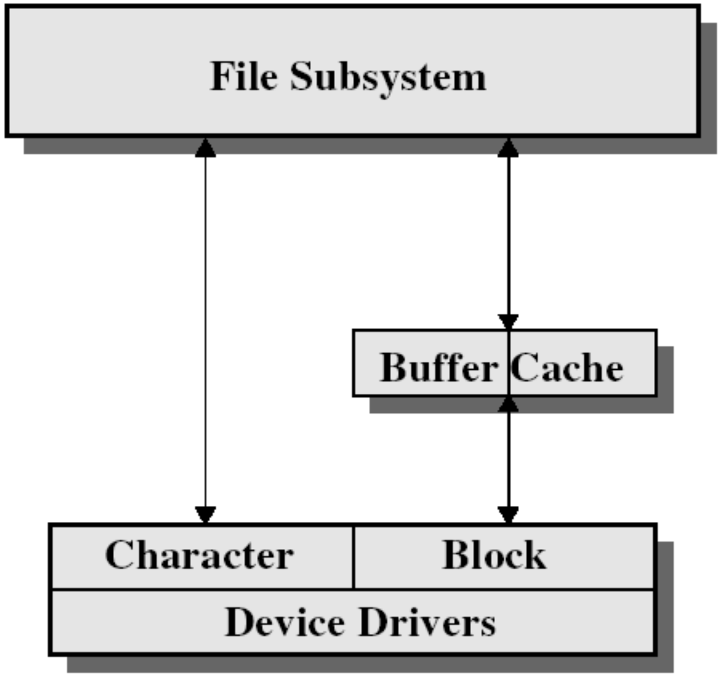
Device independence from

- Device type (e.g. terminal, disk or DVD drive)
- Device instance (e.g. which disk)

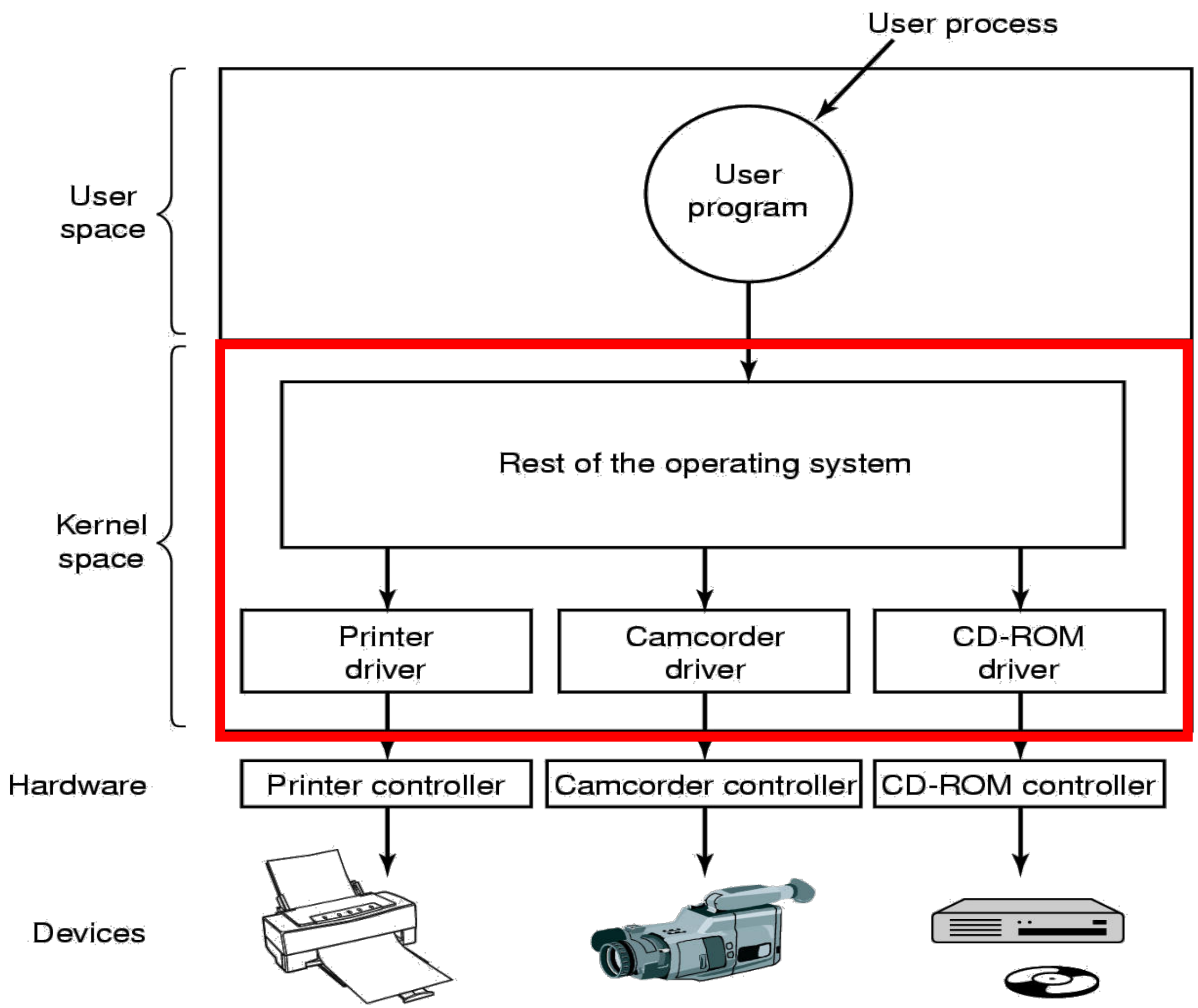
Device variations

- Unit of data transfer: character or block
- Supported operations: e.g. read, write, seek
- Synchronous or asynchronous operation
- Speed differences
- Sharable (e.g. disks) or single user (e.g. printer, DVD-RW)
- Types of error conditions

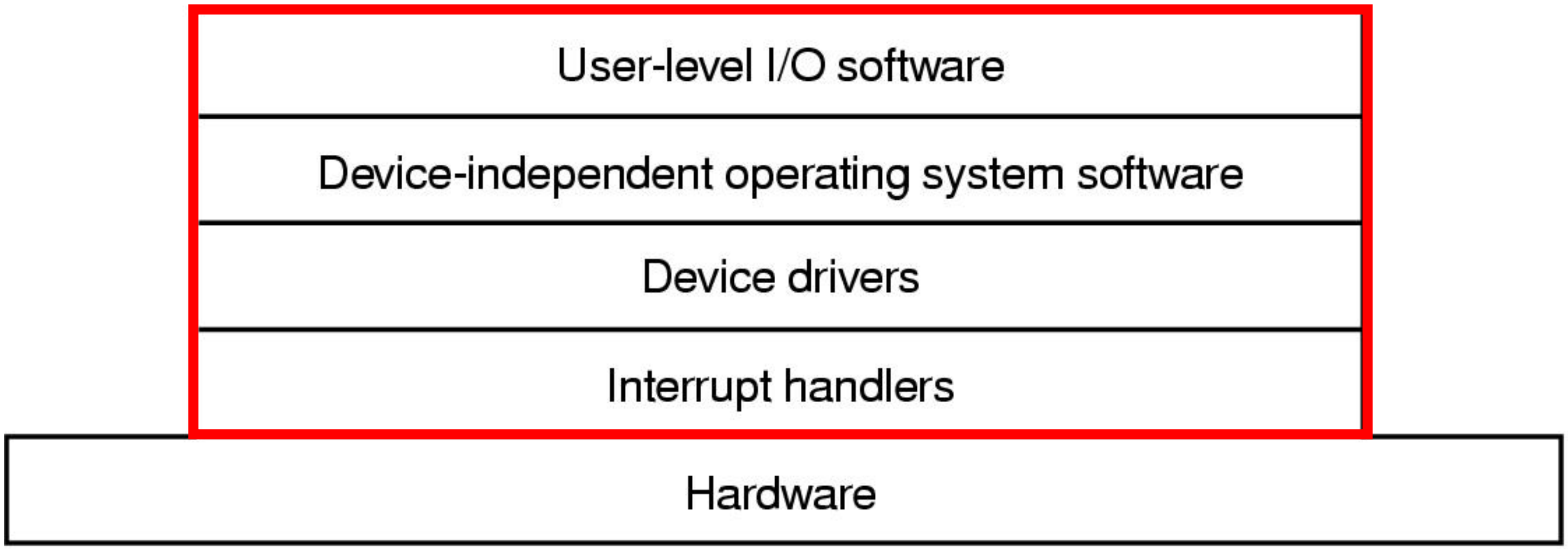
Device Variations: Character vs. Block



I/O Layering


User process
User space
User program
Kernel space
Rest of the operating system
Printer driver
Camcorder driver
CD-ROM driver
Hardware
Printer controller
Camcorder controller
CD-ROM controller
Devices

I/O Layers: Overview



Interrupt Handler

Interrupt handler

- Process each interrupt

- For block devices:
  - on transfer completion, signal device handler
- For character devices
  - when character transferred, process next character

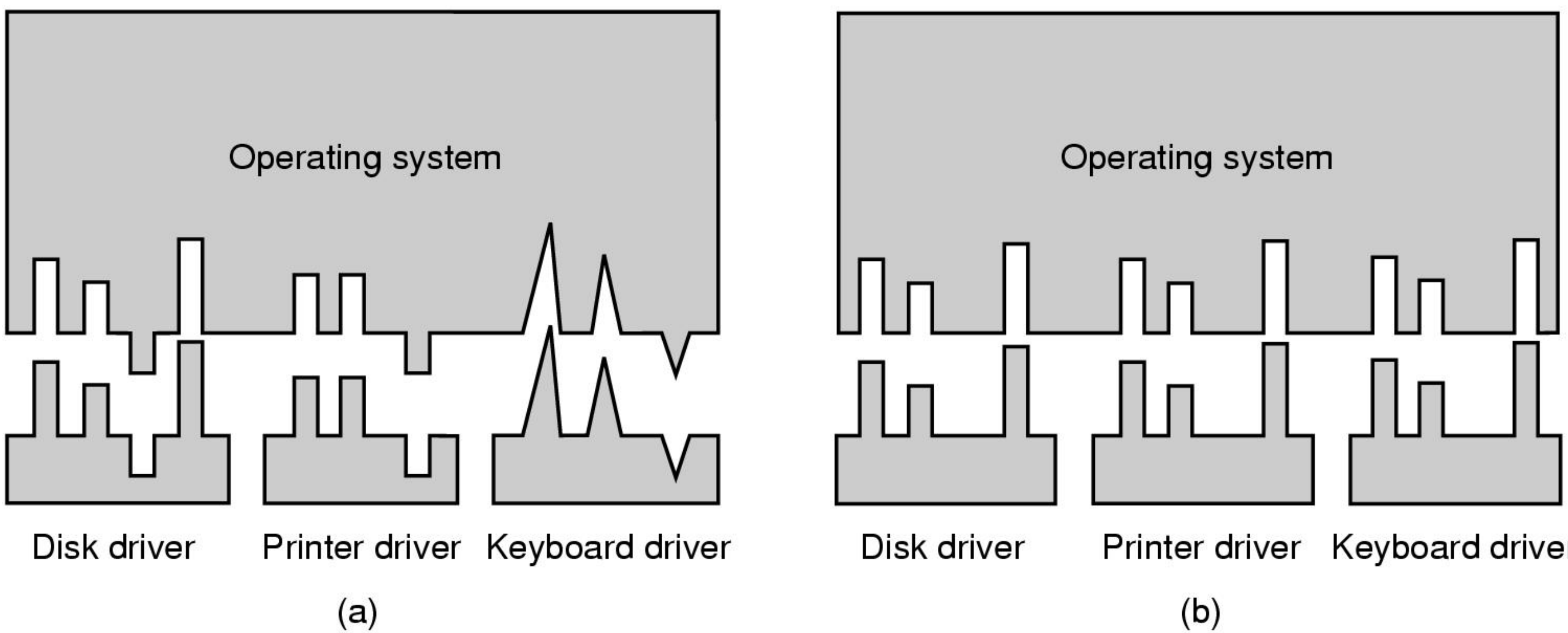
Device Driver

Device handler/driver

- Handles one device type
  - but may control multiple devices of same type

- Implements block read or write
- Access device registers
- Initiate operations
- Schedule requests
- Handle errors

Device Independent OS Layer I



(a) without standard driver interface
(b) with standard driver interface

Device Independent OS Layer II

Device independent layer provides device independence

- Mapping logical to physical devices (naming and switching)
- Request validation against device characteristics
- Allocation of dedicated devices
- Protection/user access validation
- Buffering for performance and block size independence
- Error reporting

Dedicated vs. Shared Device Allocation

Dedicated device (e.g. DVD writer, terminal, printer, ...)

- Simple policy:
  - Open fails if already opened
  - Alternatively, queue open requests
- Allocated for long periods
- Only allocated to authorised processes

Shared device (e.g. disks, window terminals, ...)

- OS provides file system for disks

Device Allocation: Spooling

Blocking user access to allocated, nonsharable devices?

- Causes delays and bottlenecks

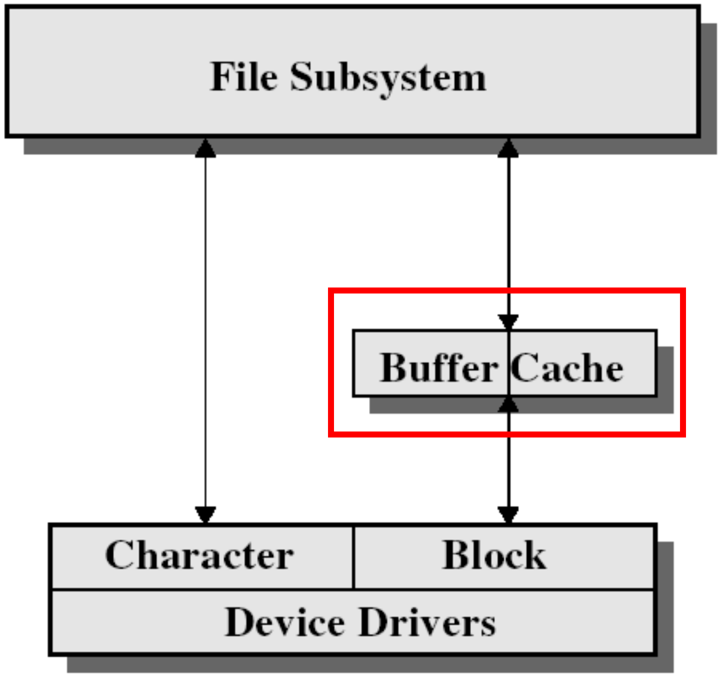
☛ Spool to intermediate medium (disk file)

Spooled devices (e.g. printers)

1. Printer output saved to disk file
2. File printed later by **spooler daemon**
   - Printer only allocated to spooler daemon
   - No normal process allowed direct access

- Provides sharing of nonsharable devices
- Reduces I/O time ➔ gives greater throughput

Buffering


File Subsystem
Buffer Cache
Character
Block
Device Drivers

Buffered vs. Unbuffered I/O

Buffered I/O

<u>Output</u>: User data transferred to OS output buffer
Process continues and only suspends when buffer full

<u>Input</u>: OS reads ahead; reads normally satisfied from buffer
Process blocks when buffer empty

- Used to smooth peaks in I/O traffic
- Caters for differences in data transfer units between devices

Unbuffered I/O

- Data transferred directly from user space to/from device
  - Each read/write causes <u>physical I/O</u>
  - Implies device handler used for each transfer
- High process switching overhead (e.g. per character)

User-Level I/O Interface

User interface

- I/O operations: open, close, read, write, seek
- OS I/O library procedures to set up parameters
  - Must be device independent

- Synchronous or asynchronous
- Blocking or non-blocking

- Unix: Access virtual devices as files

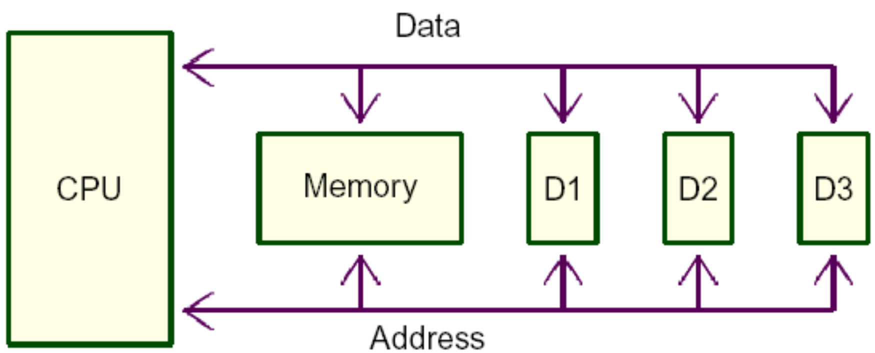
Device Drivers

Memory-Mapped I/O

Device addressed as memory location

Example: Disabling the I2S clock on Raspberry PI:

```
*(clk+0x26) = 0x5A000000;
*(clk+0x27) = 0x5A000000;
```



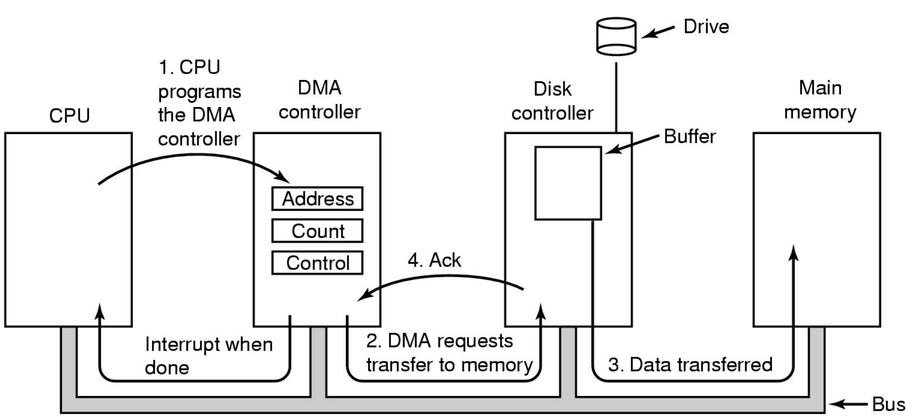
More flexible

Ways to do I/O

1. Programmed I/O

2. Interrupt-Driven I/O

3. I/O using Direct Memory Access (DMA)



Linux: Loadable Kernel Module (LKM)

Loadable kernel modules provide device drivers

- Contain object code, loaded **on-demand**
  - Dynamically linked to running kernel
  - Provided by hardware vendors or independent developers
- Require **binary compatibility**
  - Modules written for different kernel versions may not work

Kmod

- Kernel subsystem managing modules without user intervention
- Determines module dependencies
- Load modules on demand

Linux: Basic LKM module

Every LKM consists of two basic functions (minimum):

```
int init_module(void)  /* used for all initialisation code */
{
...
}
void cleanup_module(void)  /* used for clean shutdown */
{
...
}
```

Load module by issuing following command:

```
insmod module.o
```

– Normally restricted to root

Linux I/O Management

Linux I/O Management

Kernel provides common interface for I/O system calls

Devices grouped into **device classes**

- Members of each device class perform similar functions
- Allows kernel to address performance needs of certain devices (or classes of devices) individually

Major and **minor** identification numbers

- Used by device drivers to identify their devices
- Devices with same major num controlled by same driver
- Minor nums enable system to distinguish between devices of same class

Linux: Device Drivers

Device special files

- Most devices represented by device special files
- Entries in **`/dev`** directory that provide access to devices
- List of devices in system can be obtained by reading contents of **`/proc/devices`:**

Character devices:

```
  1 mem
  2 pty
  4 ttyS
  5 cua
 10 misc
 13 input
109 lvm
136 pts
162 raw
180 usb
```

Block devices:

```
 1 ramdisk
 2 fd
 3 ide0
 7 loop
 8 sd
 9 md
58 lvm
65 sd
66 sd
```

Linux: /dev

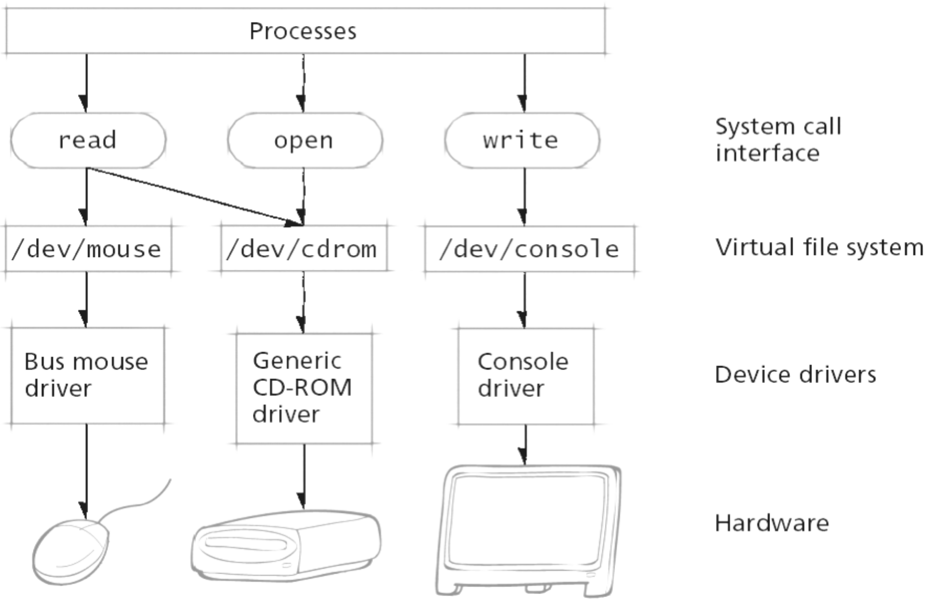
c/b major minor file name

```
crw-------    1 root     root      5,   1 Dec 27 16:09 console
brw-rw-rw-    1 root     disk      2,   0 May 21  2001 fd0
brw-rw-rw-    1 root     disk      2,   4 May 21  2001 fd0d360
brw-rw-rw-    1 root     disk      2,   8 May 21  2001 fd0h1200
brw-rw-rw-    1 root     disk      2,  40 May 21  2001 fd0h1440
crw-rw----    1 root     lp        6,   0 May 21  2001 lp0
crw-rw----    1 root     lp        6,   1 May 21  2001 lp1
crw-rw----    1 root     lp        6,   2 May 21  2001 lp2
crw-rw----    1 root     lp      180,   0 May 21  2001 usblp0
crw-rw----    1 root     lp      180,   1 May 21  2001 usblp1
crw-rw----    1 root     lp      180,   2 May 21  2001 usblp2
lrwxrwxrwx    1 root     root          10 Dec  6 06:53 mouse -> /dev/psaux
crw-rw-r--    1 root     root     10,   1 May 21  2001 psaux
lrwxrwxrwx    1 root     root           3 Nov 30  2001 cdrom -> hdc
brw-rw-rw-    1 root     disk      3,   0 May 21  2001 hda
brw-rw-rw-    1 root     disk      3,  16 May 21  2001 hdb
brw-rw-rw-    1 root     disk      3,  32 May 21  2001 hdc
```

Linux: Device Access

Device files accessed via **virtual file system (VFS)**

- System calls pass to VFS, which in turn issues calls to device drivers
- Most drivers implement common file operations
  - e.g. read, write, seek



I/O subsystem overview

Linux provides **ioctl** system call

- Supports special tasks:
  - Ejecting CD-ROM tray
    `ioctl(cdrom, CDROMEJECT, 0)`
  - Retrieving status information from printer

Linux: Character Device I/O I

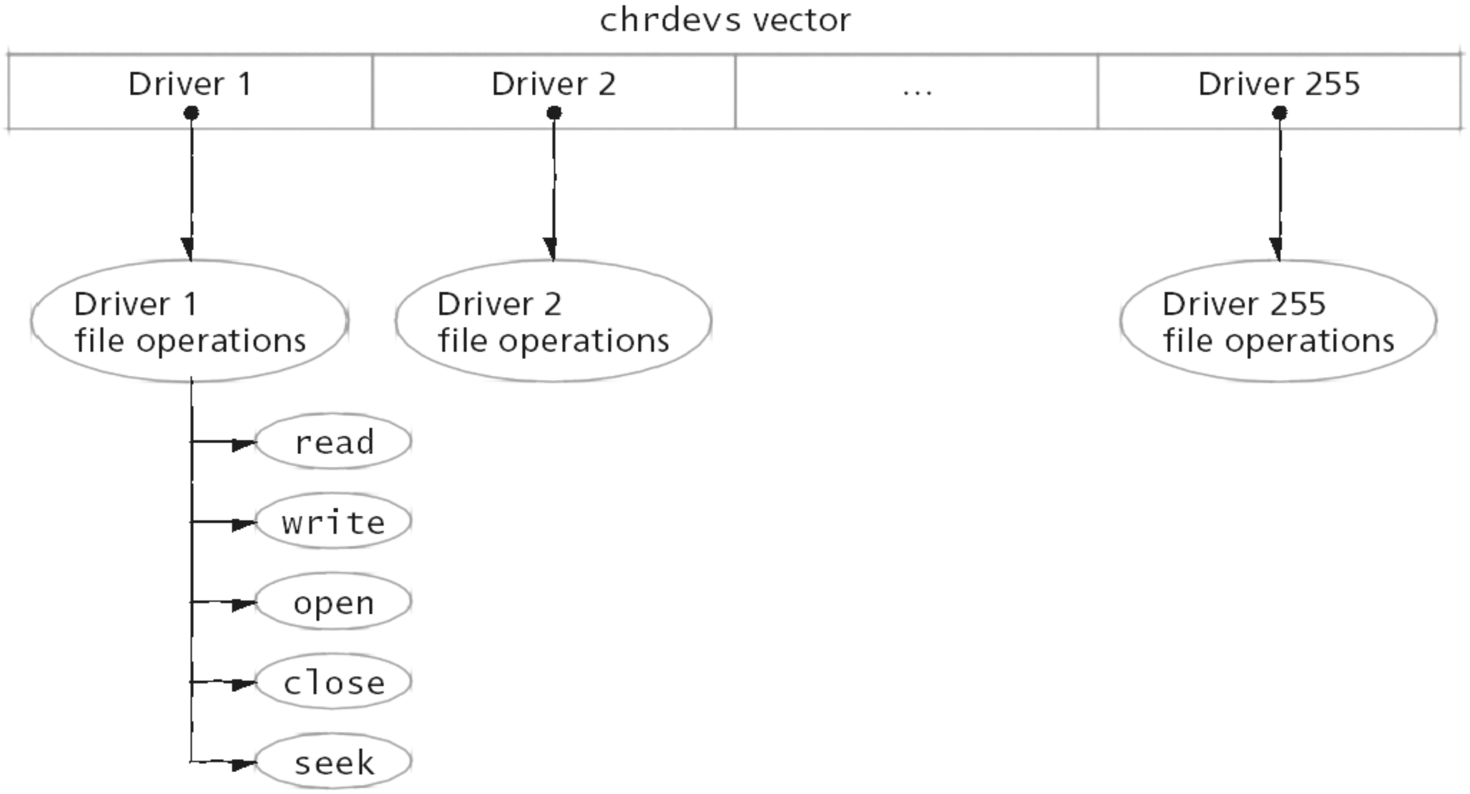
Character device

- Transmits data as **stream of bytes**
- Represented by `device_struct` structure contains:
  - Driver name
  - Pointer to driver's `file_operations` structure
- All registered drivers referenced by `chrdevs` vector

`file_operations` structure

- Maintains operations supported by device driver
- Stores functions called by VFS when system call accesses device special file

Linux: Character Device I/O II



Linux: Block Device I/O

Block I/O subsystem

- Kernel's block I/O subsystem contains number of layers
- Modularise block I/O operations by placing common code in each layer

Two primary strategies used by kernel to minimise amount of time spent accessing block devices:

- Caching data
- Clustering I/O operations

Linux: Block Device Caching

When data from block device requested, kernel first searches **cache**

- If found, data copied to process's address space
- Otherwise, typically added to request queue

Direct I/O

- Driver bypasses kernel cache when accessing device
- Important for databases and other applications
  - Kernel caching inappropriate and may reduce performance/consistency

Linux I/O API

Linux: I/O API I

I/O classes

Character (unstructured):	Files and devices
Block (structured):	Devices
Pipes (message):	Interprocess communication
Socket (message):	Network interface

I/O calls

`fd = create(filename, permission)`

Opens file for reading/writing; **`fd`** is index to file descriptor, permission is used for access control

`fd = open(filename, mode)`

Mode is 0, 1, 2 for read, write, read/write

Linux: I/O API II

`close(fd)`

Close file or device

`numbytesread = read(fd, buffer, numbytes)`

read **`numbytes`** from file or device referenced by **`fd`** into memory buffer; returns number of bytes actually read in **`numbytesread`**

`numbyteswritten = write(fd, buffer, numbytes)`

write **`numbytes`** to file referenced by **`fd`** from memory buffer; returns number of bytes actually written in **`numbyteswritten`**

Linux: I/O User Interface API III

`pipe(&fd[0])`

Creates pipe; **`fd`** is an array of two integers: **`fd[0]`** is for reading, **`fd[1]`** for writing

`newfd = dup(oldfd), dup2(oldfd, newfd)`

Duplicate file descriptor

`ioctl(fd, operation, &termios)`

Used to control devices; e.g. **`&termios`** is array of control chars

`fd = mknod(filename, permission, dev)`

Creates new special file e.g. character or block device

Linux: File Descriptors

Each process has its own **file descriptor table**

- Each process has 3 file descriptors when created:

file descriptor	input/output
0	stdin
1	stdout
2	stderr

- By default, all three file descriptors refer to terminal from which program was started

Linux: I/O Example I

```
#include <stdlib.h>
#define BUFSIZE 512

int main( int argc, char ** argv){

  int fd, n, stdin, stdout, stderr;
  char buffer[BUFSIZE];

  /* Standard input always corresponds to fd = 0 */
  stdin = 0;

  /* Standard output always corresponds to fd = 1 */
  stdout = 1;

  /* Standard error always corresponds to fd = 2 */
  stderr = 2;

  /* Open file */
  fd = open(argv[1], O_RDONLY);
```

Linux: I/O Example II

```
  if (fd < 0) {

    write(stderr, "Can't open file", 15);

  } else {

    do {
       n = read(fd, buffer, BUFSIZE);
       if (n < 0) {
          write(stderr, "Error while reading", 19);
       } else {
          write(stdout, buffer, n);
       }
    } while (n > 0);

  }

  /* Close file */
  close(fd);
}
```

Blocking vs. Non-blocking I/O

Blocking I/O

- I/O call returns when operation completed
- Process suspended ➔ I/O appears "instantaneous"
- Easy to understand but leads to multi-threaded code

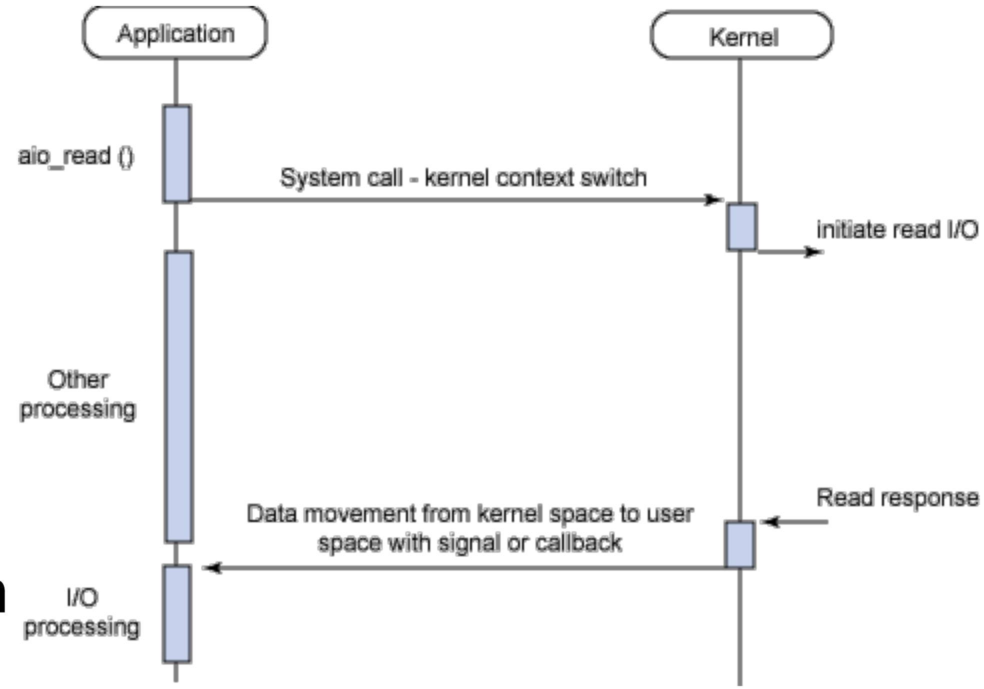
Non-blocking I/O

- I/O call returns as much as available
  (e.g. **`read`** with 0 bytes)
- Turn on for file descriptor using **`fcntl`** system call
- Provides application-level polling for I/O (how?)

Asynchronous I/O

Asynchronous I/O

- Process executes <u>in parallel</u> with I/O operation
  - No blocking in interface procedure
- I/O subsystems notifies process upon completion
  - Callback function, process signal, ...



Source: IBM Developerworks

- Supports check/wait if I/O operation completed
- Very flexible and efficient
- Harder to use and potentially less secure (why?)

Linux: AIO Example I

AIO: Support for asynchronous I/O in Linux 2.6

```
#include <aio.h>
...
  int fd, ret;
  struct aiocb my_aiocb;

  fd = open("myfile", O_RDONLY );

  /* Allocate buffer for aio request */
  my_aiocb.aio_buf = malloc(BUFSIZE + 1);

 /* Initialise aio control structure */
  my_aiocb.aio_fildes = fd;
  my_aiocb.aio_nbytes = BUFSIZE;
  my_aiocb.aio_offset = 0;
```

Linux: AIO Example II

```
/* Initiate read request */
ret = aio_read(&my_aiocb);

/* Wait for read to finish (more usefully do something else)
   Also possible to register signal notification or thread callback */
while (aio_error(&my_aiocb) == EINPROGRESS);

/* Check result from read */
if ((ret = aio_return(&my_iocb)) > 0) {
    /* Successfully read ret bytes */
} else {
    /* Read failed, check errno*/
}
```