I/O and Disk Storage

COMP375 Computer Architecture and Organization
“Back up my hard drive? How do I put it in reverse?”
Homework

• An assignment on disk systems has been posted on Blackboard
• Upload your solutions to Blackboard or bring your answers on paper to class by 1:00pm on Monday, November 11, 2019
Goals

• Understand the purpose and operation of I/O controllers
• Understand how information is stored on a disk drive
• Be able to calculate how long it will take to read data from a disk
• Understand how data is stored on a CD and how this impacts its use
Internal & External

• The CPU, memory and bus are internal components of a computer
• Everything else is an input or output device
I/O Devices

Disk       Keyboard
  hard     Speakers
  floppy   Printer
 CD        Mouse
  DVD      Scanner
Monitor    Game controller
Network    USB drive

Many, many more
Device Speed

- Gigabit Ethernet
- Graphics display
- Hard disk
- Ethernet
- Optical disk
- Scanner
- Laser printer
- Floppy disk
- Modem
- Mouse
- Keyboard

Data Rate (bps)
Many Different Devices

• I/O devices differ in
  – Speed
  – Granularity
  – Control

• I/O controllers interface between the many different devices and the internal system components; CPU, memory and bus
Basic Computer Components

- CPU
- cache
- I/O Controller
- I/O Device
- Bus
- Memory
Basic Computer Components

CPU

cache

I/O Controller

I/O Devices

I/O Device

I/O Controller

Bus

Memory
Processor’s View Of I/O

• A processor does not access external devices directly.
• Instead, the processor uses a programming interface to pass requests to an I/O controller, which translates the requests into the appropriate external signals.
I/O Controller

- Connects the I/O devices to the system
- Communicates with the CPU and the RAM over the bus
- A single I/O controller may control multiple devices
- Most computers have several I/O controllers
- Actions are initiated by the CPU
I/O Controller Functionality

• Interface translation
  – connection, voltage
  – protocol
  – clocking
• Addressing
• Multiplexing
• Buffering
• Error detection and correction
• Control of multiple steps
How many I/O controllers do most computers have?

A. 1
B. 3
C. 1 for each device
D. 1 for each type of device
I/O Addressing

• The CPU communicates with the I/O controllers over the bus using the same fetch and store protocol as memory
• Each I/O controller has a unique address, possibly several addresses
• I/O addresses can be
  – independent of memory addresses
  – in the same as memory, but not overlapping with memory. This is memory mapped I/O.
I/O Address Range

- Some system have a separate address space for program data and instructions and another address space for I/O devices.
Memory Mapped I/O

• Some systems use the same address space for memory and I/O devices
Control and Status Registers

• I/O controller addresses provide
  – Data transfer
  – Control
    • Device address
    • Read or Write or other operation
  – Status
    • Device ready
    • Operation complete

• Respond to *fetch* or *store* operation
Example I/O

```
checkio
MOV EAX, DeviceStatus
AND EAX, IOreadyBit
JZ checkio
MOV EBX, databyte
MOV DeviceData, EBX
```

`DeviceStatus` addr of I/O status register
`IOreadyBit` bit indicating device ready
`DeviceData` addr of I/O data register
Buffering

• Some I/O controllers store and analyze incoming data in controller memory

• An Ethernet controller will receive the data into local memory on the controller card. The data will only be transferred to RAM if it was received correctly and has the machines address

• Controllers may perform many transformations on the data
Compared to the speed of the bus, most I/O devices are

A. Faster
B. Slower
C. Same speed
D. None of the above
Latency And Throughput

- The **latency** of an interface is a measure of the time required to perform a transfer.
- The **throughput** of an interface is a measure of the data that can be transferred per unit time.
Multiple Step Control

- Operating a device may involve many separate steps. An I/O controller can specify the individual steps to a device to carry out a function specified by the CPU.
- The controller can detect errors in the operation of a device. It may also attempt to recover from errors.
Dumb Controller Example

• Processor performs all the work
• Example of interaction
  – Processor starts the floppy disk spinning
  – Disk interrupts when it reaches full speed
  – Processor starts disk arm moving to the desired location
  – Disk interrupts when arm is in position
  – Processor starts a read operation to transfer data to memory
  – Disk interrupts when the transfer completes
Smart Controller Example

• Device contains embedded processor
• Offloads work from CPU
• Allows each device to operate independently
• Improves I/O and CPU performance

Smart Device Example

– Processor requests a read operation by specifying the location on the disk and the location in memory
– Disk performs all steps of the operation and interrupts when the operation completes
Direct Memory Access (DMA)

- Important optimization
- Needed for high-speed I/O
- Device moves data across the bus to and from memory without using processor
- Requires smart controller
Buffer Chaining

• Handles multiple transfers without the processor
• Device given linked list of buffers
• Device hardware uses next buffer on list automatically
Scatter Read and Gather Write

• Special case of buffer chaining
• Large data transfer formed from separate blocks
• *Example*: to write a network packet, combine packet header from buffer 1 and packet data from buffer 2
• Eliminates OS from copying data into single, large buffer
Operation Chaining

• Further optimization for smart device
• Processor gives series of commands to device, sometimes called a channel program
• Device carries out successive commands automatically
## Internal Memory Summary

<table>
<thead>
<tr>
<th>Type</th>
<th>Category</th>
<th>Erasure</th>
<th>Byte alterable</th>
<th>Volatile</th>
<th>Typical use</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRAM</td>
<td>Read/write</td>
<td>Electrical</td>
<td>Yes</td>
<td>Yes</td>
<td>Level 2 cache</td>
</tr>
<tr>
<td>DRAM</td>
<td>Read/write</td>
<td>Electrical</td>
<td>Yes</td>
<td>Yes</td>
<td>Main memory</td>
</tr>
<tr>
<td>ROM</td>
<td>Read-only</td>
<td>Not possible</td>
<td>NO</td>
<td>NO</td>
<td>Large volume appliances</td>
</tr>
<tr>
<td>PROM</td>
<td>Read-only</td>
<td>Not possible</td>
<td>NO</td>
<td>NO</td>
<td>Small volume equipment</td>
</tr>
<tr>
<td>EPROM</td>
<td>Read-only</td>
<td>UV light</td>
<td>NO</td>
<td>NO</td>
<td>Device prototyping</td>
</tr>
<tr>
<td>EEPROM</td>
<td>Read-mostly</td>
<td>Electrical</td>
<td>Yes</td>
<td>NO</td>
<td>BIOS</td>
</tr>
<tr>
<td>Flash</td>
<td>Read/write</td>
<td>Electrical</td>
<td>NO</td>
<td>NO</td>
<td>mobile device disks</td>
</tr>
</tbody>
</table>
Core Memory

Long ago, small iron rings were magnetized in either clockwise or counter-clockwise direction to store a bit.
Disk Drives

• There are several types of rotating media storage devices
  – Hard drives
    • 36 GB to 2 TB
  – Floppy disk
    • 1.4 MB
  – CD ROM
    • 600 MB to 750 MB
  – DVD
    • 4.7 GB to 8.5 GB
Hard Drive Storage

- A hard drive contains several flat platters covered with a smooth iron coating like that of a tape cassette.
- Data can be stored by magnetizing small areas of the iron coating.
- The disk surface is polished to be very flat.
- The disk head floats over the platter spinning at 4.3 million inches/sec or 70 mph.
Disk Read/Write Head

Magnetizing current

Magnetic yoke

Air gap

Magnetic thin film

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Disk Tracks

• Data is written on the disk drive in concentric circles called tracks
• A track is composed of blocks of data called sectors. Each sector has a header including address and checksum
• An arm containing the read/write head can move closer or farther from the center of the disk
• All of the tracks on both sides of all platters that can be read without moving the heads is called a cylinder
Cylinder, Heads and Sectors
Terminology

• **Sector** or **Block** – the smallest unit that can be read or written. Often 512 bytes although 4096 in newer drives

• **Track** – all blocks that form a ring on a disk surface that can be read without moving the head

• **Cylinder** – all tracks on all surfaces, one on top of another, that can be read without moving the head
4K Disk Sectors

- Newer disk drives now have 4K sectors instead of 512 sectors
- Allows more data to be stored
Disk Operation

To read (or write) data to the disk:

• The arm containing the read/write heads must be moved to the proper radius from the center
• The system must wait for the data to rotate under the read head
• The data is read as it passes under the read head
• The data is checked and then passed to the I/O controller
The head is at the end of the arm
If a disk has 4 platters and 16K tracks per surface, how many tracks are on the disk?

A. 4
B. 16K
C. 64K
D. 128K
E. 256K
Disk Performance Parameters

Disk read or write involves three factors

1. **Seek time**
   - time it takes to position the head at the desired track

2. **Rotational delay** or rotational latency
   - time it takes for the beginning of the sector to reach the head

3. **Transfer time**
   - time required for the data to move under the head
Seek Time

• Seek Time is fixed by the design of the disk.
• Manufacturers will usually tell you the
  – average seek time
  – maximum seek time (*from center to edge*)
  – time to seek to the next adjacent track
Rotational Delay

• If you know the rotational speed, you can calculate the time per revolution

\[
\frac{60 \text{ sec/min} \times 1000 \text{ ms/sec}}{\text{rev/min}} = \text{ms/rev}
\]

• Best case is when the data comes under the head just as it is needed (delay is zero)

• Worst case is you just missed it and have to wait a whole revolution.

• Average delay is half a revolution or above/2
How many sectors?

- Files are stored in sectors or blocks on the disk
- A whole sector is read or written. Never a fraction of a sector
- The number of bytes in a sector varies per disk but is often 512 bytes/sector or 4K / sector

\[
\text{sectors} = \left\lfloor \frac{\text{FileSize}}{\text{bytes/sector}} \right\rfloor
\]
If a disk drive has 4096 byte sectors, how many sectors are required to hold a 15K file?

A. 3.66
B. 3.75
C. 4.00
D. 273.3
Transfer Time

• The transfer time is determined by how long it takes the data to travel under the head
• The fraction of sectors on the track that are being read times the rotation time gives the transfer time

\[
\frac{\text{sectors}_{\text{read}}}{\text{sectors/rev}} \times \text{ms/rev} = \text{transfer time}
\]
<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational Speed</td>
<td>7,200 RPM</td>
</tr>
<tr>
<td>Average Read Seek Time</td>
<td>8.9 ms</td>
</tr>
<tr>
<td>Track-To-Track Seek Time</td>
<td>2.0 ms (average)</td>
</tr>
<tr>
<td>Full Stroke Seek</td>
<td>21.0 ms (average)</td>
</tr>
<tr>
<td>Cylinders</td>
<td>16,383</td>
</tr>
<tr>
<td>Number of Heads (Physical)</td>
<td>6</td>
</tr>
<tr>
<td>Sectors Per Track</td>
<td>63</td>
</tr>
<tr>
<td>Bytes Per Sector</td>
<td>512</td>
</tr>
</tbody>
</table>
### Performance Example

How long does it take to read a 512 byte block from the disk?

**Rotation Time**

\[ 8.33 \text{ms} = \frac{60 \text{sec/min} \times 1000 \text{ms/sec}}{7200 \text{rev/min}} \]

<table>
<thead>
<tr>
<th>Average Seek time</th>
<th>8.9 ms</th>
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<tbody>
<tr>
<td>Average Rotational Delay</td>
<td>8.33 ms / 2 = 4.17 ms</td>
</tr>
<tr>
<td>Transfer time</td>
<td>( \frac{1 \text{sector}}{63 \text{sectors/rev}} \times 8.33 \text{ms} = 0.13 \text{ms} )</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>13.2 ms</strong></td>
</tr>
</tbody>
</table>
Performance Example

How long does it take to read two 512 byte blocks from the disk?

Rotation Time

\[
8.33\text{ms} = \frac{60\text{sec/min} \times 1000\text{ms/sec}}{7200\text{rev/min}}
\]

<p>| | | |</p>
<table>
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<td></td>
</tr>
<tr>
<td>Transfer time</td>
<td>( \frac{2\text{sector}}{63\text{sectors/rev}} \times 8.33\text{ms} = 0.26\text{ms} )</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>13.3 ms</td>
<td></td>
</tr>
</tbody>
</table>
Performance Notes

• For small files, the largest component of the time to read a file is the seek time
• Spinning the disk faster reduces the rotational delay and transfer time
• It is very advantageous to be able to read data without moving the heads
• Disk fragmentation causes a significant reduction in speed
  – 2 consecutive blocks takes 13.3 ms
  – 2 randomly located blocks takes 26.4 ms
How long does it take to read a 10K file?

| **Sectors / file** | 20 sectors/file = \( \frac{10\text{Kbytes/file}}{512\text{bytes/sector}} \) |
| **Rotation Time** | 8.33ms = \( \frac{60\text{sec/min} \times 1000\text{ms/sec}}{7200\text{rev/min}} \) |

| **Average Seek time** | 8.9 ms |
| **Average Rotational Delay** | 8.33ms / 2 = 4.17 ms |
| **Transfer time** | \( \frac{20\text{ sectors}}{63\text{ sectors/rev}} \times 8.33\text{ms} = 2.64\text{ms} \) |
| **Total** | 15.7 ms |
How long does it take to read a 14KB file on the average?

Rotational Speed 10,000 RPM
Average Seek Time 4.5 ms
Bytes / sector 4096
Sectors / track 63

A. 7.7 ms
B. 7.8 ms
C. 7.9 ms
D. 11.2 ms
E. 8.3*10^{42} seconds
Logical vs. Physical

• Many disks present the OS with a logical layout that is different from the physical layout
• Most modern disks use Logical Block Addressing (LBA) to hide the physical layout
• LBA represents the disk as a sequential list of blocks
Disk Regions

• The tracks on an actual disk drive are grouped into regions
• The tracks closer to the center of the disk are shorter than the tracks at the far edge of the disk
• Tracks on the far edge can hold more data than tracks close to the center
• Different regions have a different number of blocks per track
Solid State Drives

- Solid state drives (SSD) use flash memory chips to store the data instead of rotating magnetic disks
- No seek time or rotational delay
- Low power and quiet
- Less vulnerable to vibration
- Short life spans
- Writes longer than reads
Fragmentation on a SSD is

A. More of a concern than on rotating drives
B. Less of a concern than on rotating drives
C. Same concern as rotating drives
D. All the above
E. None of the above
Flash Memory Degradation

• When flash memory is written, it must first be erased or "flashed"
• A memory block is only good for about 100,000 flashes
• The OS creates a queue of available blocks
• Recently used blocks are put on the end of the queue
• When updating a file, new blocks are used
SSD Performance

• Some SSD can read 41K blocks of 4K per second
• An SSD can read up to 540 MB per second
• A hard drive can read about 200 MB per second
High Performance Rotating Disk

- Average seek time of 2.6 ms
- Disk rotation of 15,000 rpm
- 98 sectors of 4K per track
- To read on 4K block
  - seek: 2.6 ms
  - rotation: 2.0 ms
  - transfer: 0.04 ms
  - total time: 4.64 ms
If a disk can read random blocks in 4.64 ms, how many reads can it do in a second?

A. 22
B. 216
C. 278
D. 4640
E. cannot be calculated
CD ROM

Early *Laserdisk* and current DVD
CD ROM

• A CD contains an aluminum layer sandwiched between layers of clear plastic
• An infrared laser is used to read the CD
• Bits are recorded as pits or spots in the aluminum. These affect the reflectance of the laser light
• Each pit is approximately 100 nm deep by 500 nm wide, and varies from 850 nm to 3.5 \( \mu \text{m} \) in length
• The data on a CD is written as one long 5.38 km spiral
A. Polycarbonate disc layer has the data encoded by using bumps

B. A shiny layer reflects the laser

C. A layer of lacquer protects the shiny layer

D. Artwork label

E. Laser beam
CD Data Format

A CD contains 2352 byte blocks with:

• 2048 bytes of data
• 16 byte header containing the address
• 288 bytes of error correcting codes

Music CDs

• 16 bit samples
• 44,100 samples per second
CD Performance

• The “X” of CD speed claims represents the number of times faster the CD spins than music CD players. 1X = 75 blocks/sec
• CDs are written in a long spiral instead of concentric tracks. This is good for music
• The average seek time for a CD is 90 ms (compare to 9 ms for a hard drive)
• CDs are efficient reading large files but slow reading small files
How long does it take to read 20K from a 24X CD?

24 * 75 Blocks per sec
2K blocks
90 ms seek time
3.0 ms rotational delay

A. 93.1 ms
B. 98.6 ms
C. 102.5 ms
D. 13.6 ms
Writing a CD

• Prerecorded CDs have bumps pressed into the aluminum before being embedded in the plastic
• CD-Recordables burn spots in an organic dye on the aluminum. The spots do not reflect as well
• CD-Rewritables use two different temperatures to melt or crystallize the metal layer. High heat makes it opaque. Low heat makes it transparent
## Optical Disks

<table>
<thead>
<tr>
<th>Optical Disk</th>
<th>Wavelength</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>780 nm infrared</td>
<td>750 MB</td>
</tr>
<tr>
<td>DVD</td>
<td>650 nm red</td>
<td>4.7 GB</td>
</tr>
<tr>
<td>Blu-Ray</td>
<td>405 nm blue-violet</td>
<td>25 GB</td>
</tr>
</tbody>
</table>
Thumb Drives

1. Connector
2. Controller
4. Flash memory
5. Clock
6. LED
7. Read-only switch
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