I/O Devices and Disks
I/O Devices

• Input and output (I/O) is critical part of computer systems

• Issues:
  • How should I/O be integrated into systems?
  • What are the general mechanisms?
  • How can we make I/O efficient?
Structure of input/output (I/O) device

• Buses
  • Data paths that provided to enable information between CPU(s), RAM, and I/O devices

• I/O bus
  • Data path that connects a CPU to an I/O device
  • I/O bus is connected to I/O device by three hardware components:
    • I/O ports
    • Interfaces
    • Device controllers
Canonical Device

- Canonical Devices has two important components
  - **Hardware interface** allows the system software to control its operation
  - **Internals** which is implementation specific

- Registers
  - **status register**
    - See the current status of the device
  - **command register**
    - Tell the device to perform a certain task
  - **data register**
    - Pass data to the device, or get data from the device
    - These registers are typically only a few bytes wide

- By reading and writing these registers, the OS can control device behavior
The Canonical Protocol

• Example of programmed I/O (PIO)
  • CPU is involved with the data movement

• Operating system waits until the device is ready by repeatedly reading the status register
  • Simple and correct
  • Wastes CPU time just waiting for the device
    • Switching to another ready process would utilize the CPU more

While ( STATUS == BUSY)
  ; //wait until device is not busy
Write data to DATA register
Write command to COMMAND register
  Doing so starts the device and executes the command
While ( STATUS == BUSY)
  ; //wait until device is done with your request

Diagram of CPU utilization by polling
Interrupts

• Put the I/O request process to sleep and context switch to another
• When the device is finished, wake the process waiting for the I/O by interrupt
  • Allows for the CPU and the disk to be properly utilized

Diagram of CPU utilization by interrupt
Polling vs. interrupts

- Interrupts are not always the best solution
  - If a device performs very quickly interrupts slow down the system
    - Context switches are expensive

- If a device is fast, polling is preferred

- If the device is slow, interrupts are better
Data movement with PIO

- The CPU wastes time copying data from memory to the device
  - CPU copies one word at a time to the device
  - After data is copied to the device, then it can be written to disk

```
<table>
<thead>
<tr>
<th></th>
<th>task 1</th>
<th>task 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU</td>
<td>1 1 1 1</td>
<td>C C C 2 2 2 2 2 1 1 1</td>
</tr>
<tr>
<td>Disk</td>
<td>1 1 1 1</td>
<td></td>
</tr>
</tbody>
</table>
```

Diagram of CPU utilization
DMA (Direct Memory Access)

- Copy data in memory by knowing “where the data lives in memory, how much data to copy”
- When completed, DMA raises an interrupt, I/O begins on Disk
  - Transfers between devices and main memory without much CPU intervention

Diagram of CPU utilization by DMA
Device interaction

• Two main ways to communicate with devices

• **I/O instructions**: a way for the OS to send data to specific device registers
  • E.g., `in` and `out` instructions on x86
  • Typically, this a privileged instruction – why?

• **Memory-mapped I/O**
  • Device registers available as if they were memory locations
  • The OS loads (to read) or stores (to write) to the device instead of main memory
  • No new instructions, same as a memory read or write
The OS interface: the device driver

• How does the OS interact with different specific hardware interfaces?
  • E.g., we would like to build a single file system interface that works with:
    • SCSI disks
    • SATA disks
    • USB disks and so on

• **Abstraction** encapsulates any specifics of device interaction
  • At the lowest level, the OS must know how the hardware works
  • We call this software a device driver
  • Provides a higher-level interface to the rest of the system
Example Driver: File system Abstraction

- Application is unaware of the type of filesystem
- File system is unaware of which type of disk it is using
  - Issues block read/write requests to a generic block layer
- Many drivers expose a raw interface to allow for special applications
Problems With Device Driver Abstraction

• If there is a device with special capabilities, these capabilities will go unused in the generic interface layer

• Over 70% of Linux code is found in device drivers
  • Need a device driver for any piece of hardware you might plug into your system
  • Often not written by full-time kernel developers
    • Especially true for non commodity hardware
    • They are primary contributor to kernel crashes!
A Simple IDE Disk Driver: Registers

• Control Register:
  • Address 0x3F6: set to enable interrupts

• Command Block Registers:
  • Address 0x1F0: Data Port
  • Address 0x1F1: Error
  • Address 0x1F2: Sector Count
  • Address 0x1F3: LBA low byte
  • Address 0x1F4: LBA mid byte
  • Address 0x1F5: LBA hi byte
  • Address 0x1F6: 1B1D TOP4LBA: B=LBA, D=drive
  • Address 0x1F7 = Command/status

• Status Register (Address 0x1F7):

<table>
<thead>
<tr>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUSY</td>
<td>READY</td>
<td>FAULT</td>
<td>SEEK</td>
<td>DRQ</td>
<td>CORR</td>
<td>IDDEX</td>
<td>ERROR</td>
</tr>
</tbody>
</table>

• Error Register (Address 0x1F1): (check when Status ERROR==1)

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<tr>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
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<tbody>
<tr>
<td>BBK</td>
<td>UNC</td>
<td>MC</td>
<td>IDNF</td>
<td>MCR</td>
<td>ABRT</td>
<td>T0NF</td>
<td>AMNF</td>
</tr>
</tbody>
</table>

BBK = Bad Block
UNC = Uncorrectable data error
MC = Media Changed
IDNF = ID mark Not Found
MCR = Media Change Requested
ABRT = Command aborted
T0NF = Track 0 Not Found
AMNF = Address Mark Not Found
Basic IDE Protocol

• Wait for drive to be ready
  • Read Status Register (0x1F7) until drive is not BUSY and READY

• Write parameters to command registers
  • Write the sector count, logical block address (LBA) of the sectors to be accessed, and drive number to command registers (0x1F2-0x1F6)

• Start the I/O
  • Write the READ/WRITE command to command register (0x1F7)

• Data transfer (for writes)
  • Wait until drive status is READY and DRQ (drive request for data)
  • Write data to data port

• Handle interrupts
  • In the simplest case, handle an interrupt for each sector transferred
  • DMA allows for batching and a final interrupt when the entire transfer is complete

• Error handling
  • After each operation, read the status register
  • If the ERROR bit is on, read the error register for details
I/O Summary

• For efficiency we use:
  • Interrupts: allow process to sleep while slow I/O takes place
  • DMA: Allow transfer between memory and a device with little CPU intervention

• Accessing Hardware
  • Explicit I/O instructions (\texttt{inb} \texttt{outb})
  • Memory mapped I/O (register access looks like a memory read or write)

• Drivers
  • Encapsulate low-level details of the hardware
  • Makes it easier to build the rest of the OS in a device-neutral fashion
Hard Disk Drives

• Hard disk drives have been the main form of persistent data storage in computer systems for decades
  • The drive consists of many sectors (e.g., 512-byte blocks)
    • Arranged in circular tracks around the disk
    • The only guarantee is that a single 512-byte write is atomic
  • Address Space
    • We can view a disk with n sectors as an array of sectors, 0 to n-1

• Multi-sector operations are possible
  • Many file systems will read or write 4KB at a time (common page size)
  • Torn write
    • If an untimely power loss or error occurs, only a portion of a larger write may complete

• Accessing blocks in a contiguous chunk is the fastest access mode
  • A sequential read or write
  • Much faster than a more random access pattern
Basic Geometry

- **Platter** (Aluminum coated with a thin magnetic layer)
  - A circular hard surface
  - Data is stored persistently by inducing magnetic changes to it
  - Each platter has 2 sides, each of which is called a **surface**

- **Spindle**
  - Spindle is connected to a motor that spins the platters around
  - The rate of rotations is measured in **RPM** (Rotations Per Minute)
    - Typical modern values: 7,200 RPM to 15,000 RPM
    - E.g., 10,000 RPM: A single rotation takes about 6 ms

- **Track**
  - Concentric circles of sectors
  - Data is encoded on each surface in a track
  - A single surface contains many thousands and thousands of tracks
A Simple Disk Drive

- Disk head (one head per surface of the drive)
  - The process of reading and writing is accomplished by the disk head
  - Attached to a single disk arm, which moves across the surface
Example of a Disk

![Diagram of a disk drive showing track, sector, cylinder, platter, arm assembly, read-write head, and rotation]
Single-track Latency: The Rotational Delay

- Rotational delay: Time for the desired sector to rotate
  - E.g., full rotational delay is \( R \) and we start at sector 6
    - Read sector 0: Rotational delay = \( \frac{R}{2} \) (average case)
    - Read sector 5: Rotational delay = \( R \) (worst case)
Multiple Tracks: Seek Time

- E.g., move to sector 11
  - Seek: move the disk arm to the correct track
    - One of the costliest disk operations
  - Seek time: time to move head to the track contain the desired sector
Phases of Seek

• Acceleration → Coasting → Deceleration → Settling

  • **Acceleration**: The disk arm gets moving
  
  • **Coasting**: The arm is moving at full speed
  
  • **Deceleration**: The arm slows down
  
  • **Settling**: The head is *carefully positioned* over the correct track
    
    • The settling time is often quite significant, e.g., 0.5 to 2ms
Transfer

• The final phase of I/O
  • Data is either *read from* or *written* to the surface

• Complete I/O time:
  • Seek
  • Waiting for the *rotational delay*
  • Transfer
Track Skew

- Make sure that sequential reads can be properly serviced **even when crossing track boundaries**

  - Example:
    - Moving from 23 to 24

- **Without track skew**, the head would be moved to the next track, but the desired next block would have already rotated under the head
Cache (Track Buffer)

- Disk cache holds data read from or written to the disk
  - Allow the drive to quickly respond to requests
  - Small amount of memory (usually around 8 or 16 MB)

- Write back (Immediate reporting)
  - Acknowledge a write has completed when it has put the data in its memory
  - Faster but dangerous

- Write through
  - Acknowledge a write has completed only after the write has been written to disk
  - Slower but safer
I/O Time: Fun With Math

- I/O time ($T_{I/O}$):

$$T_{I/O} = T_{\text{seek}} + T_{\text{rotation}} + T_{\text{transfer}}$$

- The rate of I/O ($R_{I/O}$):

$$R_{I/O} = \frac{\text{Size}_{\text{Transfer}}}{T_{I/O}}$$

<table>
<thead>
<tr>
<th></th>
<th>Cheetah 15K.5</th>
<th>Barracuda</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>300 GB</td>
<td>1 TB</td>
</tr>
<tr>
<td>RPM</td>
<td>15,000</td>
<td>7,200</td>
</tr>
<tr>
<td>Average Seek</td>
<td>4 ms</td>
<td>9 ms</td>
</tr>
<tr>
<td>Max Transfer</td>
<td>125 MB/s</td>
<td>105 MB/s</td>
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<tr>
<td>Platters</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Cache</td>
<td>16 MB</td>
<td>16/32 MB</td>
</tr>
<tr>
<td>Connects Via</td>
<td>SCSI</td>
<td>SATA</td>
</tr>
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**Disk Drive Specs: SCSI Versus SATA**
I/O Time Example

- **Random workload**: Issue 4KB read to random locations on the disk
- **Sequential workload**: Read 100MB consecutively from the disk

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<tr>
<th></th>
<th>Cheetah 15K.5</th>
<th>Barracuda</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{seek}}$</td>
<td>4 ms</td>
<td>9 ms</td>
</tr>
<tr>
<td>$T_{\text{rotation}}$</td>
<td>2 ms</td>
<td>4.2 ms</td>
</tr>
<tr>
<td>$T_{\text{transfer}}$</td>
<td>30 microsecs</td>
<td>38 microsecs</td>
</tr>
<tr>
<td>$T_{I/O}$</td>
<td>6 ms</td>
<td>13.2 ms</td>
</tr>
<tr>
<td>$R_{I/O}$</td>
<td>0.66 MB/s</td>
<td>0.31 MB/s</td>
</tr>
<tr>
<td>$T_{\text{transfer}}$</td>
<td>800 ms</td>
<td>950 ms</td>
</tr>
<tr>
<td>$T_{I/O}$</td>
<td>806 ms</td>
<td>963.2 ms</td>
</tr>
<tr>
<td>$R_{I/O}$</td>
<td>125 MB/s</td>
<td>105 MB/s</td>
</tr>
</tbody>
</table>

**Disk Drive Performance: SCSI Versus SATA**

There is a huge gap in drive performance between random and sequential workloads.
Disk Scheduling

- **Disk Scheduler** decides which I/O request to schedule next
- **SSTF** (Shortest Seek Time First)
  - Order the queue of I/O request by track
  - Pick requests on the nearest track to complete first

SSTF: Scheduling Request 21 and 2

Issue the request to 21 → issue the request to 2
SSTF is not a panacea

- **Problem 1**: The drive geometry is not available to the host OS
  - Solution: OS can simply implement **Nearest-block-first (NBF)**

- **Problem 2**: Starvation
  - If there were a steady stream of request to the inner track, request to other tracks would then be ignored completely
Elevator (a.k.a. SCAN or C-SCAN)

- Move across the disk servicing requests in order across the tracks
  - **Sweep**: A single pass across the disk
    - If a request comes for a block on a track that has already been serviced on this sweep of the disk, it is queued until the next sweep

- **F-SCAN**
  - Freeze the queue to be serviced when it is doing a sweep
  - Avoid starvation of far-away requests by nearer by late coming requests

- **C-SCAN** (Circular SCAN)
  - Sweep from outer-to-inner, and then inner-to-outer, etc.
How to account for Disk rotation costs?

- If rotation is faster than seek: request 16 $\rightarrow$ request 8
- If seek is faster than rotation: request 8 $\rightarrow$ request 16

On modern drives, both seek and rotation are roughly equivalent: Thus, SPTF (Shortest Positioning Time First) is useful
Where is disk scheduling performed?

- Older systems:
  - OS did all the scheduling

- Newer systems:
  - Disks can handle multiple outstanding requests
  - Disks have sophisticated internal schedulers
    - Exact head position is available
    - Can implement SPTF accurately
  - OS issues a small number of disk requests (e.g., 16) and issues them all at once
    - Disk calculates the best possible SPTF order
Other scheduling issues

• I/O Merging
  • Reduce the number of request sent to the disk and lowers overhead
  • E.g., read blocks 33, then 8, then 34:
    • The scheduler merge the request for blocks 33 and 34 into a single two-block request

• How long to wait before issuing an I/O request?
  • **Work-conserving** – Issue I/O request right away
    • Disk will never be idle if there are requests to serve
  • Non-work-conserving – wait a little bit before issuing I/O request
    • A new and better request might arrive at the disk, increasing efficiency