Hard Disk Drives (HDDs)

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Three Pieces

• Virtualization
  – Virtual CPUs
  – Virtual memory

• Concurrency
  – Threads
  – Synchronization

• Persistence
  – How to make information persist, despite computer crashes, disk failures, or power outages?
  – Storage
  – File systems
Modern System Architecture

- 4 Memory Channels DDR4 / Up to 2400 MHz
- PCIe* 3.0 Up to 40 Ports
- "Broadwell" Intel® Xeon® Processor E5-2600 v4 Product Family Up to 22 cores
- 4.8 GHz 2 Intel® QPI Links
- 19.2 GB/s per channel
- Up to 1536 GB
- Up to 400 MB/s
- 6 USB 3.0 Ports
- 8 USB 2.0 Ports
- 10 SATA Gen 3 Ports (6 Gb/s)
- Up to 600 MB/s
- x4 DMI 2.0 Up to 2 GB/s
- Intel® C612 Chipset
- 19.2 GB/s per link
- 1 GB/s per lane
- Up to 400 MB/s
- 8 PCIe* 2.0 Ports
- 500 MB/s per lane
- Intel® Ethernet Controller XL710 Family
- Up to 600 MB/s
- 19.2 GB/s per channel
- 1 GB/s per lane
- Up to 400 MB/s
- 8 PCIe* 2.0 Ports
- 500 MB/s per lane
- Intel® Ethernet Controller XL710 Family
- Up to 40 GbE
- 1 GB/s per lane
- Up to 400 MB/s
- 8 PCIe* 2.0 Ports
- 500 MB/s per lane
- Intel® Ethernet Controller XL710 Family
- Up to 40 GbE
A Typical I/O Device

- **Control:** Special instructions (e.g. *in* & *out* in x86) vs. memory-mapped I/O (e.g. *load* & *store*)
- **Data transfer:** Programmed I/O (PIO) vs. DMA
- **Status check:** Polling vs. Interrupts
Classifying I/O Devices

• Block device
  – Stores information in fixed-size blocks, each one with its own address
  – Typically, 512B or 4KB per block
  – Can read or write each block independently
  – Disks, tapes, etc.

• Character device
  – Delivers or accepts a stream of characters
  – Not addressable and no seek operation supported
  – Printers, networks, mouse, keyboard, etc.
I/O Stack

Make I/O call, format I/O, spooling

Naming, protection, blocking, buffering, allocation

Set up device registers, check status

Wake up driver when I/O completed

Perform I/O operation
Device Drivers

• Device-specific code to control each I/O device
  – Require to define a well-defined model and a standard interface

• Implementation
  – Statically linked with the kernel
  – Selectively loaded into the system during boot time
  – Dynamically loaded into the system during execution (especially for hot pluggable devices)

• Variety is a challenge
  – Many, many devices
  – Each has its own protocol
OS Reliability
OS Reliability and Device Drivers

• Reliability remains a crucial, but unresolved problem
  – 5% of Windows systems crash every day
  – Huge cost of failures: stock exchange, e-commerce, etc.
  – Growing “unmanaged systems”: digital appliances, CE devices

• OS extensions are increasingly prevalent
  – 70% of Linux kernel code
  – Over 35,000 drivers with over 120,000 versions on WinXP
  – Written by less experienced programmer

• Extensions are a leading cause of OS failure
  – Drivers cause 85% of WinXP crashes
  – Drivers are 7 times buggier than the kernel in Linux
Secondary Storage

• Anything that is outside of “primary memory”
  – Does not permit direct execution of instructions or data retrieval via machine load/instructions
  – Abstracted as an array of sectors
  – Each sector is typically 512 bytes or 4096 bytes

• HDD (Hard Disk Drive) Characteristics
  – It’s large: 100 GB or more
  – It’s cheap: 3TB SATA3 hard disk costs 100,000won
  – It’s persistent: data survives power loss
  – It’s slow: milliseconds to access
HDD Architecture

Electromechanical
- Rotating disks
- Arm assembly

Electronics
- Disk controller
- Buffer
- Host interface
A Modern HDD

- Seagate Barracuda ST5000DM000 (5TB)
  - 8 Heads, 4 Discs
  - 63 sectors/track, 16,383 cylinders
  - Avg. track density: 455K TPI (tracks/inch)
  - Avg. areal density: 826 Gbits/sq.inch
  - Spindle speed: 7200 rpm (8.3 ms/rotation)
  - Internal cache buffer: 128 MB
  - Average seek time: < 12.0 ms
  - Max. I/O data transfer rate: 600 MB/s (SATA3)
  - Max. sustained data transfer rate: 160 MB/s
  - Max power-on to ready: < 22.0 sec
HDD Internals

- Our Boeing 747 will fly at the altitude of only a few mm at the speed of approximately 65mph periodically landing and taking off
- And still the surface of the runway, which consists of a few mm-think layers, will stay intact for years
Interfacing with HDDs

• Cylinder-Head-Sector (CHS) scheme
  – Each block is addressed by \(<\text{Cylinder #, Head #, Sector #}>\)
  – The OS needs to know all disk “geometry” parameters

• Logical block addressing (LBA) scheme
  – First introduced in SCSI
  – Disk is abstracted as a logical array of blocks \([0, \ldots, N-1]\)
  – Address a block with a “logical block address (LBA)”
  – Disk maps an LBA to its physical location
  – Physical parameters of a disk are hidden from OS
HDD Performance Factors

• **Seek time** ($T_{\text{seek}}$)
  - Moving the disk arm to the correct cylinder
  - Depends on the cylinder distance (not purely linear cost)
  - Average seek time is roughly one-third of the full seek time

• **Rotational delay** ($T_{\text{rotation}}$)
  - Waiting for the sector to rotate under head
  - Depends on rotations per minute (RPM)
  - 5400, 7200 RPM is common, 10K or 15K RPM for servers

• **Transfer time** ($T_{\text{transfer}}$)
  - Transferring data from surface into disk controller, sending it back to the host
## HDD Performance Comparison

<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>Avg. 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>
</tr>
<tr>
<td>Platters</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Cache</td>
<td>16MB</td>
<td>16/32 MB</td>
</tr>
<tr>
<td>Interface</td>
<td>SCSI</td>
<td>SATA</td>
</tr>
</tbody>
</table>

### Random Read (4 KB)

\[
T_{\text{seek}} = 4\text{ms} \\
T_{\text{rotation}} = \frac{60}{15000} / 2 = 2\text{ms} \\
T_{\text{transfer}} = \frac{4\text{KB}}{125\text{MB}} = 32\mu\text{s} \\
R_{I/O} \approx \frac{4\text{KB}}{6\text{ms}} = 0.66\text{ MB/s}
\]

\[
T_{\text{seek}} = 9\text{ms}, \\
T_{\text{rotation}} = \frac{60}{7200} / 2 = 4.2\text{ms} \\
T_{\text{transfer}} = \frac{4\text{KB}}{105\text{MB}} = 37\mu\text{s} \\
R_{I/O} \approx \frac{4\text{KB}}{13.2\text{ms}} = 0.31\text{ MB/s}
\]

### Sequential Read (100 MB)

\[
T_{\text{transfer}} = \frac{100\text{MB}}{125\text{MB}} = 0.8\text{s} \\
R_{I/O} \approx \frac{100\text{MB}}{0.8\text{s}} = 125\text{ MB/s}
\]

\[
T_{\text{transfer}} = \frac{100\text{MB}}{105\text{MB}} = 0.95\text{s} \\
R_{I/O} \approx \frac{100\text{MB}}{0.95\text{s}} = 105\text{ MB/s}
\]
Disk Scheduling

• Given a stream of I/O requests, in what order should they be served?
  – Much different than CPU scheduling
  – Seeks are so expensive
  – Position of disk head relative to request position matters more than length of a job

• Work conserving schedulers
  – Always try to do work if there’s work to be done

• Non-work-conserving schedulers
  – Sometimes, it’s better to wait instead if system anticipates another request will arrive
FCFS

• First-Come First-Served (= do nothing)
  – Reasonable when load is low
  – Long waiting times
    for long request queues
SSTF

- Shortest Seek Time First
  - Minimizes arm movement (seek time)
  - Unfairly favors middle blocks
  - May cause starvation

- Nearest-Block-First (NBF) when the drive geometry is not available to the host OS
SCAN

• SCAN
  – Service requests in one direction until done, then reverse
  – Skews wait times non-uniformly
  – Favors middle blocks

• F-SCAN
  – Freezes the queue when it is doing a sweep
  – Avoids starvation of far-away requests
C-SCAN

• Circular SCAN
  – Like SCAN, but only goes in one direction (e.g. typewriter)
  – Uniform wait times

• SCAN and C-SCAN are referred to as the “elevator” algorithm
  – Both do not consider rotation
Modern Disk Scheduling

• I/O scheduler in the host OS
  – Improve overall disk throughput
    • Merge requests to reduce the number of requests
    • Sort requests to reduce disk seek time
  – Prevent starvation
  – Provide fairness among different processes

• Disk drive
  – Disk has multiple outstanding requests
    • e.g. SATA NCQ (Native Command Queueing): up to 32 requests
  – Disk schedules requests using its knowledge of head position and track layout
    • e.g. SPTF (Shortest Positioning Time First): consider rotation as well