Chapter 6

Storage and Other I/O Topics
Introduction

- I/O devices can be characterized by
  - Behaviour: input, output, storage
  - Partner: human or machine
  - Data rate: bytes/sec, transfers/sec

- I/O bus connections

![Diagram of I/O bus connections]

- Processor
- Cache
- Memory-I/O Interconnect
  - Main memory
  - I/O controller
  - I/O controller
  - I/O controller
  - Disk
  - Disk
  - Graphics output
  - Network
  - Interrupts
I/O System Characteristics

- **Dependability is important**
  - Particularly for storage devices

- **Performance measures**
  - Latency (response time)
  - Throughput (bandwidth)
  - Desktops & embedded systems
    - Mainly interested in response time & diversity of devices
  - Servers
    - Mainly interested in throughput & expandability of devices
Dependability

- Fault: failure of a component
  - May or may not lead to system failure
Dependability Measures

- Reliability: mean time to failure (MTTF)
- Service interruption: mean time to repair (MTTR)
- Mean time between failures
  - MTBF = MTTF + MTTR
- Availability = MTTF / (MTTF + MTTR)
- Improving Availability
  - Increase MTTF:
    fault avoidance, fault tolerance, fault forecasting
  - Reduce MTTR:
    improved tools and processes for diagnosis and repair
Disk Storage

- Nonvolatile, rotating magnetic storage
Disk Sectors and Access

- Each sector records
  - Sector ID
  - Data (512 bytes, 4096 bytes proposed)
  - Error correcting code (ECC)
    - Used to hide defects and recording errors
  - Synchronization fields and gaps

- Access to a sector involves
  - Queuing delay if other accesses are pending
  - Seek: move the heads
  - Rotational latency
  - Data transfer
  - Controller overhead
Disk Access Example

- **Given**
  - 512B sector, 15,000rpm, 4ms average seek time, 100MB/s transfer rate, 0.2ms controller overhead, idle disk

- **Average read time**
  - 4ms seek time
    + $\frac{1}{2} / (15,000/60) = 2\text{ms}$ rotational latency
    + $512 / 100\text{MB/s} = 0.005\text{ms}$ transfer time
    + 0.2ms controller delay
    = 6.2ms

- **If actual average seek time is 1ms**
  - Average read time = 3.2ms
Disk Performance Issues

- Manufacturers quote average seek time
  - Based on all possible seeks
  - Locality and OS scheduling lead to smaller actual average seek times

- Smart disk controller allocate physical sectors on disk
  - Present logical sector interface to host
  - SCSI, ATA, SATA

- Disk drives include caches
  - Prefetch sectors in anticipation of access
  - Avoid seek and rotational delay
Flash Storage

- Nonvolatile semiconductor storage
  - 100× – 1000× faster than disk
  - Smaller, lower power, more robust
  - But more $/GB (between disk and DRAM)
Flash Types

- **NOR flash: bit cell like a NOR gate**
  - Random read/write access
  - Used for instruction memory in embedded systems

- **NAND flash: bit cell like a NAND gate**
  - Denser (bits/area), but block-at-a-time access
  - Cheaper per GB
  - MLC vs SLC
  - Used for USB keys, media storage, …

- **Flash bits wears out after 1000’s of accesses**
  - Not suitable for direct RAM or disk replacement
  - Wear leveling: remap data to less used blocks
Flash Translation Layer

- **Erase before write (not inplace update)**
  - Erase at block granularity
  - Write at page granularity

- **Wear-leveling**

- **Solution: FTL (Flash Translation Layer)**
Hybrid Storage

Host
- Disk Driver
- Disk Interface

Hybrid Storage
- Disk Interface
- Micro-tiering Controller
  - Hard Disk Media
  - Flash Media
Hybrid Storage

- **Conceptual Benefit**
  - Large capacity of HDDs with high performance of SSDs
  - Low power at most of time

- **Reality**
  - What to put in each media?
  - When? At what granularity?
  - Complex metadata management
Flash Cache

Application
- File System
- Block Layer

Cache Manager

Disks

SSC

OS
Interconnecting Components

- Need interconnections between
  - CPU, memory, I/O controllers

- Bus: shared communication channel
  - Parallel set of wires for data and synchronization of data transfer
  - Can become a bottleneck

- Performance limited by physical factors
  - Wire length, number of connections

- More recent alternative: high-speed serial connections with switches
  - Like networks
Bus Types

- Processor-Memory buses
  - Short, high speed
  - Design is matched to memory organization

- I/O buses
  - Longer, allowing multiple connections
  - Specified by standards for interoperability
  - Connect to processor-memory bus through a bridge
Bus Signals and Synchronization

- **Data lines**
  - Carry address and data
  - Multiplexed or separate

- **Control lines**
  - Indicate data type, synchronize transactions

- **Synchronous**
  - Uses a bus clock

- **Asynchronous**
  - Uses request/acknowledge control lines for handshaking
# I/O Bus Examples

<table>
<thead>
<tr>
<th></th>
<th>Firewire</th>
<th>USB 2.0</th>
<th>PCI Express</th>
<th>Serial ATA</th>
<th>Serial Attached SCSI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intended use</strong></td>
<td>External</td>
<td>External</td>
<td>Internal</td>
<td>Internal</td>
<td>External</td>
</tr>
<tr>
<td><strong>Devices per channel</strong></td>
<td>63</td>
<td>127</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td><strong>Data width</strong></td>
<td>4</td>
<td>2</td>
<td>2/lane</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>Peak bandwidth</strong></td>
<td>50MB/s or 100MB/s</td>
<td>0.2MB/s, 1.5MB/s, or 60MB/s</td>
<td>250MB/s/lane 1×, 2×, 4×, 8×, 16×, 32×</td>
<td>300MB/s</td>
<td>300MB/s</td>
</tr>
<tr>
<td><strong>Hot pluggable</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Depends</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Max length</strong></td>
<td>4.5m</td>
<td>5m</td>
<td>0.5m</td>
<td>1m</td>
<td>8m</td>
</tr>
<tr>
<td><strong>Standard</strong></td>
<td>IEEE 1394</td>
<td>USB Implementers Forum</td>
<td>PCI-SIG</td>
<td>SATA-IO</td>
<td>INCITS TC T10</td>
</tr>
</tbody>
</table>
Typical x86 PC I/O System

- Intel Xeon 5300 processor
- Main memory DIMMs
- Memory controller hub (north bridge) 5000P
  - FB DDR2 667 (5.3 GB/sec)
  - Serial ATA (300 MB/sec)
  - LPC (1 MB/sec)
  - USB 2.0 (60 MB/sec)
  - ESI (2 GB/sec)
  - PCIe x8 (2 GB/sec)
- Intel Xeon 5300 processor
- Front Side Bus (1333 MHz, 10.5 GB/sec)
- PCIe x16 (or 2 PCIe x8) (4 GB/sec)
- PCIe controller hub (south bridge) Entreprise South Bridge 2
  - PCIe x4 (1 GB/sec)
  - PCIe x4 (1 GB/sec)
  - PCI-X bus (1 GB/sec)
  - PCI-X bus (1 GB/sec)
  - Parallel ATA (100 MB/sec)
  - CD/DVD
I/O Management

- I/O is mediated by the OS
  - Multiple programs share I/O resources
    - Need protection and scheduling
  - I/O causes asynchronous interrupts
    - Same mechanism as exceptions
  - I/O programming is fiddly
    - OS provides abstractions to programs
I/O Commands

- I/O devices are managed by I/O controller hardware
  - Transfers data to/from device
  - Synchronizes operations with software

- Command registers
  - Cause device to do something

- Status registers
  - Indicate what the device is doing and occurrence of errors

- Data registers
  - Write: transfer data to a device
  - Read: transfer data from a device
I/O Register Mapping

- **Memory mapped I/O**
  - Registers are addressed in same space as memory
  - Address decoder distinguishes between them
  - OS uses address translation mechanism to make them only accessible to kernel

- **I/O instructions**
  - Separate instructions to access I/O registers
  - Can only be executed in kernel mode
  - Example: x86
Polling

- Periodically check I/O status register
  - If device ready, do operation
  - If error, take action

- Common in small or low-performance real-time embedded systems
  - Predictable timing
  - Low hardware cost

- In other systems, wastes CPU time
Interrupts

- When a device is ready or error occurs
  - Controller interrupts CPU

- Interrupt is like an exception
  - But not synchronized to instruction execution
  - Can invoke handler between instructions
  - Cause information often identifies the interrupting device

- Priority interrupts
  - Devices needing more urgent attention get higher priority
  - Can interrupt handler for a lower priority interrupt
I/O Data Transfer

- **Polling and interrupt-driven I/O**
  - CPU transfers data between memory and I/O data registers
  - Time consuming for high-speed devices

- **Direct memory access (DMA)**
  - OS provides starting address in memory
  - I/O controller transfers to/from memory autonomously
  - Controller interrupts on completion or error
DMA/Cache Interaction

- If DMA writes to a memory block that is cached
  - Cached copy becomes stale
- If write-back cache has dirty block, and DMA reads memory block
  - Reads stale data
- Need to ensure cache coherence
  - Flush blocks from cache if they will be used for DMA
  - Or use non-cacheable memory locations for I/O
DMA/VM Interaction

- **OS uses virtual addresses for memory**
  - DMA blocks may not be contiguous in physical memory

- **Should DMA use virtual addresses?**
  - Would require controller to do translation

- **If DMA uses physical addresses**
  - May need to break transfers into page-sized chunks
  - Or chain multiple transfers
  - Or allocate contiguous physical pages for DMA
Measuring I/O Performance

- I/O performance depends on
  - Hardware: CPU, memory, controllers, buses
  - Software: operating system, database management system, application
  - Workload: request rates and patterns

- I/O system design can trade-off between response time and throughput
  - Measurements of throughput often done with constrained response-time
Transaction Processing Benchmarks

- **Transactions**
  - Small data accesses to a DBMS
  - Interested in I/O rate, not data rate

- **Measure throughput**
  - Subject to response time limits and failure handling
  - ACID (Atomicity, Consistency, Isolation, Durability)
  - Overall cost per transaction

- **Transaction Processing Council (TPC) benchmarks** ([www.tpc.org](http://www.tpc.org))
  - TPC-APP: B2B application server and web services
  - TCP-C: on-line order entry environment
  - TCP-E: on-line transaction processing for brokerage firm
  - TPC-H: decision support — business oriented ad-hoc queries
File System & Web Benchmarks

- **SPEC System File System (SFS)**
  - Synthetic workload for NFS server, based on monitoring real systems
  - Results
    - Throughput (operations/sec)
    - Response time (average ms/operation)

- **SPEC Web Server benchmark**
  - Measures simultaneous user sessions, subject to required throughput/session
  - Three workloads: Banking, Ecommerce, and Support
I/O vs. CPU Performance

- **Amdahl’s Law**
  - Don’t neglect I/O performance as parallelism increases compute performance

- **Example**
  - Benchmark takes 90s CPU time, 10s I/O time
  - Double the number of CPUs/2 years
    - I/O unchanged

<table>
<thead>
<tr>
<th>Year</th>
<th>CPU time</th>
<th>I/O time</th>
<th>Elapsed time</th>
<th>% I/O time</th>
</tr>
</thead>
<tbody>
<tr>
<td>now</td>
<td>90s</td>
<td>10s</td>
<td>100s</td>
<td>10%</td>
</tr>
<tr>
<td>+2</td>
<td>45s</td>
<td>10s</td>
<td>55s</td>
<td>18%</td>
</tr>
<tr>
<td>+4</td>
<td>23s</td>
<td>10s</td>
<td>33s</td>
<td>31%</td>
</tr>
<tr>
<td>+6</td>
<td>11s</td>
<td>10s</td>
<td>21s</td>
<td>47%</td>
</tr>
</tbody>
</table>
RAID

- **Redundant Array of Inexpensive (Independent) Disks**
  - Use multiple smaller disks (c.f. one large disk)
  - Parallelism improves performance
  - Plus extra disk(s) for redundant data storage

- **Provides fault tolerant storage system**
  - Especially if failed disks can be “hot swapped”

- **RAID 0**
  - No redundancy ("AID"?)
    - Just stripe data over multiple disks
  - But it does improve performance
RAID 1 & 2

- **RAID 1: Mirroring**
  - N + N disks, replicate data
    - Write data to both data disk and mirror disk
    - On disk failure, read from mirror

- **RAID 2: Error correcting code (ECC)**
  - N + E disks (e.g., 10 + 4)
  - Split data at bit level across N disks
  - Generate E-bit ECC
  - Too complex, not used in practice
RAID 3: Bit-Interleaved Parity

- **N + 1 disks**
  - Data striped across N disks at byte level
  - Redundant disk stores parity
  - Read access
    - Read all disks
  - Write access
    - Generate new parity and update all disks
  - On failure
    - Use parity to reconstruct missing data

- **Not widely used**
RAID 4: Block-Interleaved Parity

- **N + 1 disks**
  - Data striped across N disks at block level
  - Redundant disk stores parity for a group of blocks
  - Read access
    - Read only the disk holding the required block
  - Write access
    - Just read disk containing modified block, and parity disk
    - Calculate new parity, update data disk and parity disk
  - On failure
    - Use parity to reconstruct missing data

- **Not widely used**
RAID 3 vs RAID 4

New Data 1. Read 2. Read 3. Read
D0’ D0 D1 D2 D3 P

+ XOR

D0’ D1 D2 D3 P’
4. Write 5. Write

New Data 1. Read
D0’ D0 D1 D2 D3 P

+ XOR

D0’ D1 D2 D3 P’
2. Read

+ XOR

D0’ D1 D2 D3 P’
3. Write 4. Write
RAID 5: Distributed Parity

- N + 1 disks
  - Like RAID 4, but parity blocks distributed across disks
    - Avoids parity disk being a bottleneck

- Widely used
RAID 6: P + Q Redundancy

- **N + 2 disks**
  - Like RAID 5, but two lots of parity
  - Greater fault tolerance through more redundancy

- **Multiple RAID**
  - More advanced systems give similar fault tolerance with better performance
RAID Summary

- RAID can improve performance and availability
  - High availability requires hot swapping
- Assumes independent disk failures
  - Too bad if the building burns down!
- JBOD (Just a Bunch of Disks)
  - An alternative solution to RAID
I/O System Design

- Satisfying latency requirements
  - For time-critical operations
  - If system is unloaded
    - Add up latency of components

- Maximizing throughput
  - Find “weakest link” (lowest-bandwidth component)
  - Configure to operate at its maximum bandwidth
  - Balance remaining components in the system

- If system is loaded, simple analysis is insufficient
  - Need to use queuing models or simulation
Fallacy: Disk Dependability

- If a disk manufacturer quotes MTTF as 1,200,000hr (140yr)
  - A disk will work that long
- **Wrong:** this is the mean time to failure
  - What is the distribution of failures?
  - What if you have 1000 disks
    - How many will fail per year?

Annual Failure Rate (AFR) = \( \frac{1000 \text{ disks} \times 8760 \text{ hrs/disk}}{1200000 \text{ hrs/failure}} \) = 0.73%
Fallacies

- Disk failure rates are as specified
  - Studies of failure rates in the field
    - Schroeder and Gibson: 2% to 4% vs. 0.6% to 0.8%
    - Pinheiro, *et al.*: 1.7% (first year) to 8.6% (third year) vs. 1.5%
  - Why?

- A 1GB/s interconnect transfers 1GB in one sec
  - But what’s a GB?
  - For bandwidth, use $1\text{GB} = 10^9 \text{B}$
  - For storage, use $1\text{GB} = 2^{30} \text{B} = 1.075 \times 10^9 \text{B}$
  - So 1GB/sec is 0.93GB in one second
    - About 7% error
Pitfall: Offloading to I/O Processors

- Overhead of managing I/O processor request may dominate
  - Quicker to do small operation on the CPU
  - But I/O architecture may prevent that

- I/O processor may be slower
  - Since it’s supposed to be simpler

- Making it faster makes it into a major system component
  - Might need its own coprocessors!
Pitfall: Backing Up to Tape

- Magnetic tape used to have advantages
  - Removable, high capacity
- Advantages eroded by disk technology developments
- Makes better sense to replicate data
  - E.g, RAID, remote mirroring
Fallacy: Disk Scheduling

- Best to let the OS schedule disk accesses
  - But modern drives deal with logical block addresses
    - Map to physical track, cylinder, sector locations
    - Also, blocks are cached by the drive
  - OS is unaware of physical locations
    - Reordering can reduce performance
    - Depending on placement and caching
Pitfall: Peak Performance

- Peak I/O rates are nearly impossible to achieve
  - Usually, some other system component limits performance
  - E.g., transfers to memory over a bus
    - Collision with DRAM refresh
    - Arbitration contention with other bus masters
  - E.g., PCI bus: peak bandwidth ~133 MB/sec
    - In practice, max 80MB/sec sustainable
Concluding Remarks

- **I/O performance measures**
  - Throughput, response time
  - Dependability and cost also important

- **Buses used to connect CPU, memory, I/O controllers**
  - Polling, interrupts, DMA

- **I/O benchmarks**
  - TPC, SPECSFS, SPECWeb

- **RAID**
  - Improves performance and dependability