Computer Organization and Structure

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Storage and Other I/O Topics

- I/O Performance Measures
- Types and Characteristics of I/O Devices
- Buses
- Interfacing I/O Devices to the Memory, Processor, and OS
- Designing an I/O System
I/O Design

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

- I/O bus connections
Typical Collection of I/O Devices

- Processor
- Cache
- Main memory
- I/O controller
- Disk
- I/O controller
- Graphics output
- I/O controller
- Network

Interrupts

Memory-I/O bus
# Types and Characteristics of I/O Devices

<table>
<thead>
<tr>
<th>device</th>
<th>behavior</th>
<th>partner</th>
<th>data rate (MB/sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keyboard</td>
<td>input</td>
<td>human</td>
<td>0.0001</td>
</tr>
<tr>
<td>Mouse</td>
<td>input</td>
<td>human</td>
<td>0.0038</td>
</tr>
<tr>
<td>Voice Input</td>
<td>input</td>
<td>human</td>
<td>0.2640</td>
</tr>
<tr>
<td>Sound Input</td>
<td>input</td>
<td>machine</td>
<td>3.0000</td>
</tr>
<tr>
<td>Scanner</td>
<td>input</td>
<td>human</td>
<td>3.2000</td>
</tr>
<tr>
<td>Voice Output</td>
<td>output</td>
<td>human</td>
<td>0.2640</td>
</tr>
<tr>
<td>Sound Output</td>
<td>output</td>
<td>human</td>
<td>8.0000</td>
</tr>
<tr>
<td>Laser Printer</td>
<td>output</td>
<td>human</td>
<td>3.2000</td>
</tr>
<tr>
<td>Graphics Display</td>
<td>output</td>
<td>human</td>
<td>800.0000-8000.0000</td>
</tr>
<tr>
<td>Cable Modem</td>
<td>input or output</td>
<td>machine</td>
<td>0.1280-6.0000</td>
</tr>
<tr>
<td>Network / LAN</td>
<td>input or output</td>
<td>machine</td>
<td>100.0000-10000.0000</td>
</tr>
<tr>
<td>Network / wireless LAN</td>
<td>input or output</td>
<td>machine</td>
<td>11.0000-54.0000</td>
</tr>
<tr>
<td>Optical Disk</td>
<td>storage</td>
<td>machine</td>
<td>80.0000-220.0000</td>
</tr>
<tr>
<td>Magnetic Tape</td>
<td>storage</td>
<td>machine</td>
<td>5.0000-120.0000</td>
</tr>
<tr>
<td>Flash Memory</td>
<td>storage</td>
<td>machine</td>
<td>32.0000-200.0000</td>
</tr>
<tr>
<td>Magnetic Disk</td>
<td>storage</td>
<td>machine</td>
<td>800.0000-3000.0000</td>
</tr>
</tbody>
</table>
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

**Service accomplishment**
- Service delivered as specified

**Service interruption**
- Deviation from specified service

- Restoration
- Failure
Dependability Measures

- Reliability: mean time to failure (MTTF)
- Service interruption: mean time to repair (MTTR)
- Mean time between failures
  - \[ MTBF = MTTF + MTTR \]
- Availability = \( \frac{MTTF}{MTTF + MTTR} \)
- 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
    + $\frac{1}{2} / (15,000/60) = 2$ms rotational latency
    + $512 / 100$MB/s = 0.005ms 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

- Non-volatile 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
  - Used for USB keys, media storage, ...

- Flash bits wears out after 1000’s of accesses
  - Not suitable for direct RAM or disk replacement
  - Wear levelling: remap data to less used blocks
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</td>
<td>PCI-SIG</td>
<td>SATA-IO</td>
<td>INCITS TC T10</td>
</tr>
</tbody>
</table>

Implementers:
- PCI-SIG
- SATA-IO
- INCITS TC T10
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
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

New Data 1. Read 2. Read

1. Write

2. Write

3. Write

4. Write

5. 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
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
Server Computers

- Applications are increasingly run on servers
  - Web search, office apps, virtual worlds, ...

- Requires large data center servers
  - Multiple processors, networks connections, massive storage
  - Space and power constraints

- Server equipment built for 19” racks
  - Multiples of 1.75” (1U) high
Rack-Mounted Servers

Sun Fire x4150 1U server

- 2 Redundant power Supplies
- 3 PCI Express Slots
- System Status LEDs
- Management NIC
- 2 USB Ports
- 4 Gigabit NICs
- Video