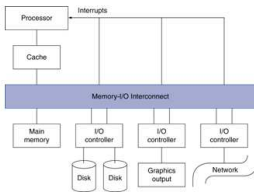


## Introduction

- 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



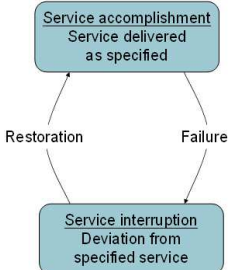
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## I/O System Characteristics

- 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

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## Dependability



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

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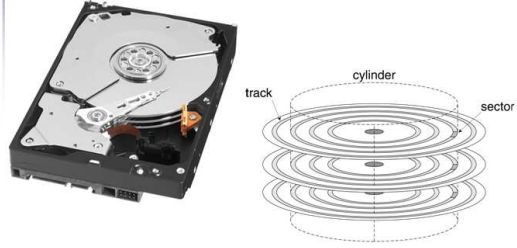
## Dependability Measures

- 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

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## Disk Storage

- Nonvolatile, rotating magnetic storage



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## 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



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## 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



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## 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



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## Flash Storage

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



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## 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 leveling: remap data to less used blocks



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## 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



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## 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

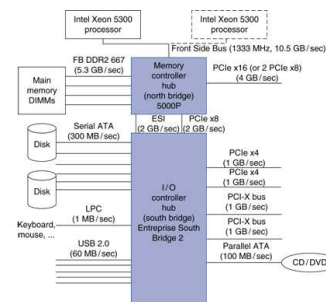


## I/O Bus Examples

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



## Typical x86 PC I/O System



## 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



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## 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**



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## 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



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## 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



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## 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



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## 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



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## 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
  - TPC-C: on-line order entry environment
  - TPC-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

Year	CPU time	I/O time	Elapsed time	% I/O time
now	90s	10s	100s	10%
+2	45s	10s	55s	18%
+4	23s	10s	33s	31%
+6	11s	10s	21s	47%



## 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

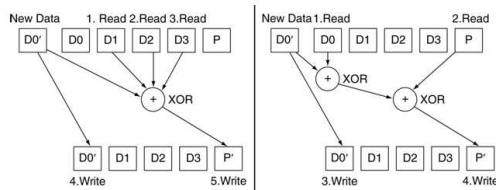


## RAID 4: Block-Interleaved Parity

- 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

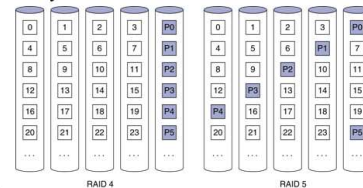


## RAID 3 vs RAID 4



## 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!
- See “Hard Disk Performance, Quality and Reliability”
  - <http://www.pcguides.com/ref/hdd/perf/index.htm>



## 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

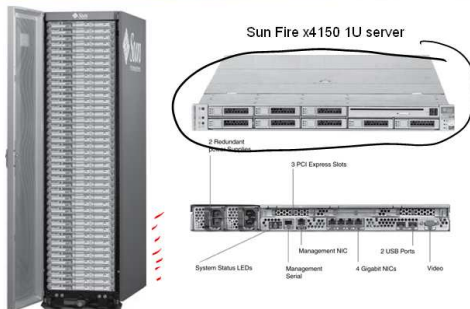


## Server Computers

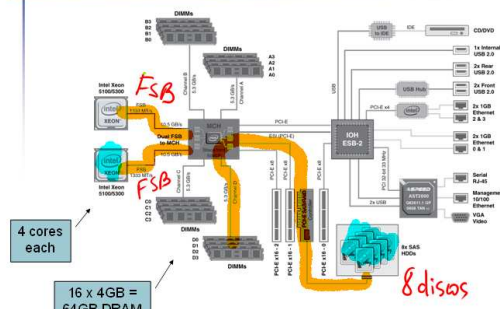
- Applications are increasingly run on servers
  - Web search, office apps, virtual worlds, ...
- Requires large data center servers
  - Multiple processors, networks connections, massive storage
  - Space and power constraints
- Server equipment built for 19" racks
  - Multiples of 1.75" (1U) high



## Rack-Mounted Servers



## Sun Fire x4150 1U server



## I/O System Design Example

- Given a Sun Fire x4150 system with
  - Workload: 64KB disk reads
    - Each I/O op requires 200,000 user-code instructions and 100,000 OS instructions
  - Each CPU:  $10^9$  instructions/sec *Gatgalo?*
  - FSB: 10.6 GB/sec peak
  - DRAM DDR2 667MHz: 5.336 GB/sec
  - PCI-E 8x bus:  $8 \times 250\text{MB/sec} = 2\text{GB/sec}$
  - Disks: 15,000 rpm, 2.9ms avg. seek time, 112MB/sec transfer rate
- What I/O rate can be sustained? *IOPS*
  - For random reads, and for sequential reads



## Design Example (cont)

- I/O rate for CPUs
  - Per core:  $10^9 \times (100,000 + 200,000) = 3,333$  *IOPS*
  - 8 cores: 26,667 ops/sec *x8*
- Random reads, I/O rate for disks
  - Assume actual seek time is average/4
  - Time/op = seek + latency + transfer =  $2.9\text{ms}/4 + 4\text{ms}/2 + 64\text{KB}/(112\text{MB/s}) = 3.3\text{ms}$
  - 303 ops/sec per disk, 2424 ops/sec for 8 disks
- Sequential reads
  - $112\text{MB/s} / 64\text{KB} = 1750$  ops/sec per disk
  - 14,000 ops/sec for 8 disks



## Design Example (cont)

- PCI-E I/O rate
  - 2GB/sec / 64KB = 31,250 ops/sec
- DRAM I/O rate *Mem*
  - 5.336 GB/sec / 64KB = 83,375 ops/sec
- FSB I/O rate
  - Assume we can sustain half the peak rate
  - 5.3 GB/sec / 64KB = 81,540 ops/sec per FSB
  - 163,080 ops/sec for 2 FSBs
- Weakest link: disks
  - 2424 ops/sec random, 14,000 ops/sec sequential
  - Other components have ample headroom to accommodate these rates



## 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, SPECIFS, SPECWeb
- RAID
  - Improves performance and dependability

