CS162
Operating Systems and Systems Programming
Lecture 17

I/O Systems (Con't)
Disk Performance and Queueing Models

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Review: Want Standard Interfaces to Devices

- **Block Devices:** *e.g.* disk drives, tape drives, Cdrom
  - Access blocks of data
  - Commands include `open()`, `read()`, `write()`, `seek()`
  - Raw I/O or file-system access
  - Memory-mapped file access possible
- **Character Devices:** *e.g.* keyboards, mice, serial ports, some USB devices
  - Single characters at a time
  - Commands include `get()`, `put()`
  - Libraries layered on top allow line editing
- **Network Devices:** *e.g.* Ethernet, Wireless, Bluetooth
  - Different enough from block/character to have own interface
  - Unix and Windows include socket interface
    - » Separates network protocol from network operation
    - » Includes `select()` functionality
  - Usage: pipes, FIFOs, streams, queues, mailboxes

Review: How Does User Deal with Timing?

- **Blocking Interface:** "Wait"
  - When request data (e.g. `read()` system call), put process to sleep until data is ready
  - When write data (e.g. `write()` system call), put process to sleep until device is ready for data
- **Non-blocking Interface:** "Don't Wait"
  - Returns quickly from read or write request with count of bytes successfully transferred
  - Read may return nothing, write may write nothing
- **Asynchronous Interface:** "Tell Me Later"
  - When request data, take pointer to user's buffer, return immediately; later kernel fills buffer and notifies user
  - When send data, take pointer to user's buffer, return immediately; later kernel takes data and notifies user

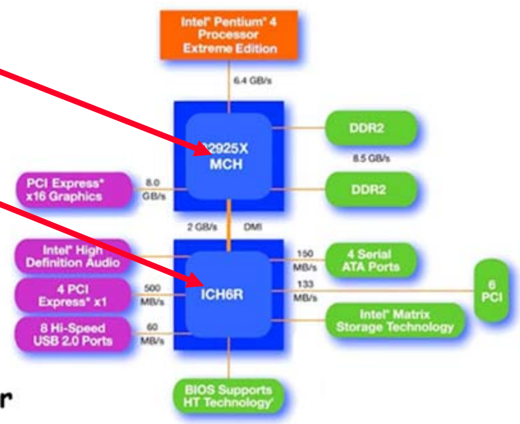
Goals for Today

- Finish Discussing I/O Systems
  - Hardware Access
  - Device Drivers
- Disk Performance
  - Hardware performance parameters
  - Queuing Theory
- File Systems
  - Structure, Naming, Directories, and Caching

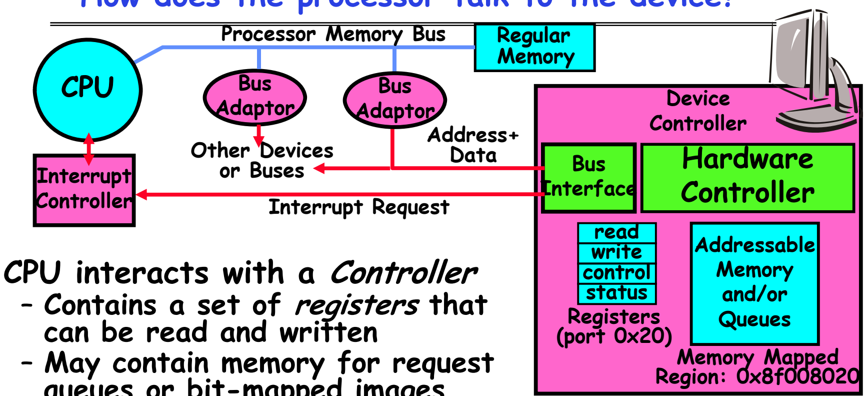
Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Many slides generated from my lecture notes by Kubiatowicz.

Main components of Intel Chipset: Pentium 4

- Northbridge:
  - Handles memory
  - Graphics
- Southbridge: I/O
  - PCI bus
  - Disk controllers
  - USB controllers
  - Audio
  - Serial I/O
  - Interrupt controller
  - Timers



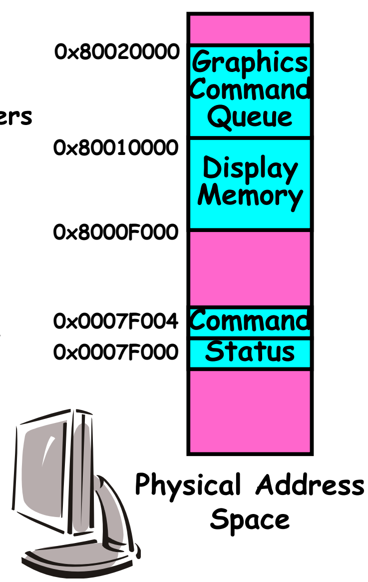
How does the processor talk to the device?



- CPU interacts with a *Controller*
  - Contains a set of *registers* that can be read and written
  - May contain memory for request queues or bit-mapped images
- Regardless of the complexity of the connections and buses, processor accesses registers in two ways:
  - I/O instructions: in/out instructions
    - » Example from the Intel architecture: `out 0x21,AL`
  - Memory mapped I/O: load/store instructions
    - » Registers/memory appear in physical address space
    - » I/O accomplished with load and store instructions

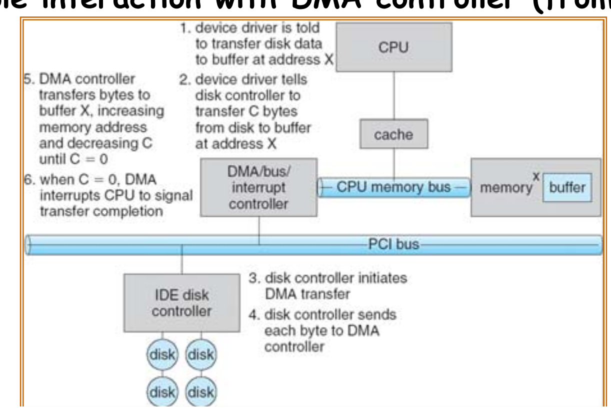
Memory-Mapped Display Controller Example

- Memory-Mapped:
  - Hardware maps control registers and display memory to physical address space
    - » Addresses set by hardware jumpers or programming at boot time
  - Simply writing to display memory (also called the "frame buffer") changes image on screen
    - » Addr: 0x8000F000—0x8000FFFF
  - Writing graphics description to command-queue area
    - » Say enter a set of triangles that describe some scene
    - » Addr: 0x80010000—0x8001FFFF
  - Writing to the command register may cause on-board graphics hardware to do something
    - » Say render the above scene
    - » Addr: 0x0007F004
- Can protect with page tables

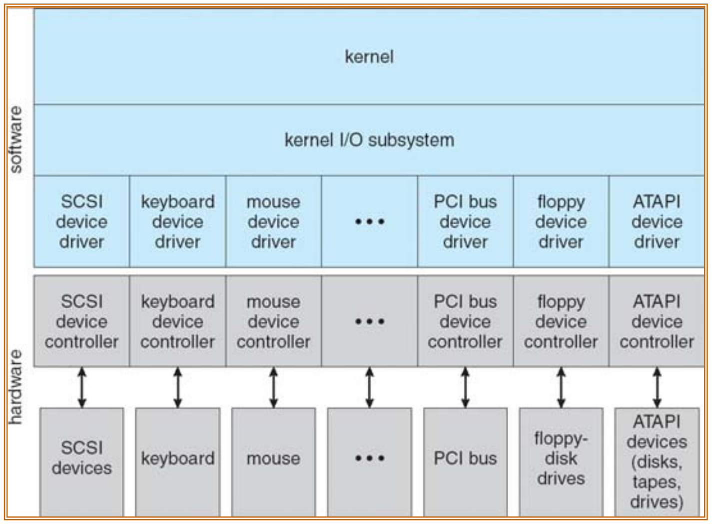


Transferring Data To/From Controller

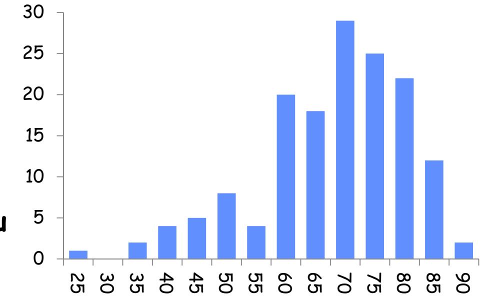
- Programmed I/O:
  - Each byte transferred via processor in/out or load/store
  - Pro: Simple hardware, easy to program
  - Con: Consumes processor cycles proportional to data size
- Direct Memory Access:
  - Give controller access to memory bus
  - Ask it to transfer data to/from memory directly
- Sample interaction with DMA controller (from book):



A Kernel I/O Structure



Administrivia

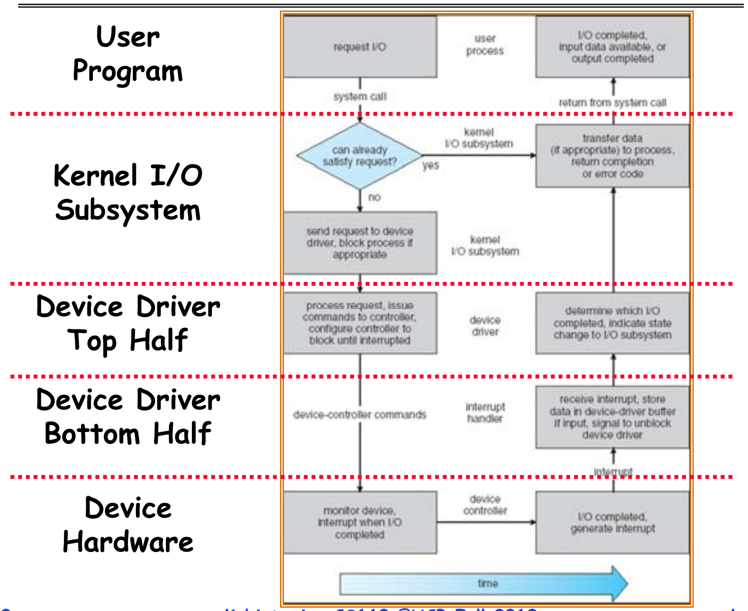


- Midterm I results:
  - Mean: 69.9, STD: 12.3
  - Min: 27.5, Max: 90.5
- Group Evaluations (Both Projects 1 and 2)
  - These MUST be done: you will get ZERO if you don't fill them out
  - Fill them out honestly (you may be asked about them)
- Projects are a zero-sum game
  - If you don't contribute (and help in the debugging) you can end up with a ZERO for the projects!
- Other things
  - Group problems? Don't wait.
  - Talk to TA/talk to me: Let's get things fixed!
- Midterm II. Well, we have a room and interest. So…

Device Drivers

- **Device Driver:** Device-specific code in the kernel that interacts directly with the device hardware
  - Supports a standard, internal interface
  - Same kernel I/O system can interact easily with different device drivers
  - Special device-specific configuration supported with the `ioctl()` system call
- Device Drivers typically divided into two pieces:
  - Top half: accessed in call path from system calls
    - » implements a set of **standard, cross-device calls** like `open()`, `close()`, `read()`, `write()`, `ioctl()`, `strategy()`
    - » This is the kernel's interface to the device driver
    - » Top half will *start* I/O to device, may put thread to sleep until finished
  - Bottom half: run as interrupt routine
    - » Gets input or transfers next block of output
    - » May wake sleeping threads if I/O now complete

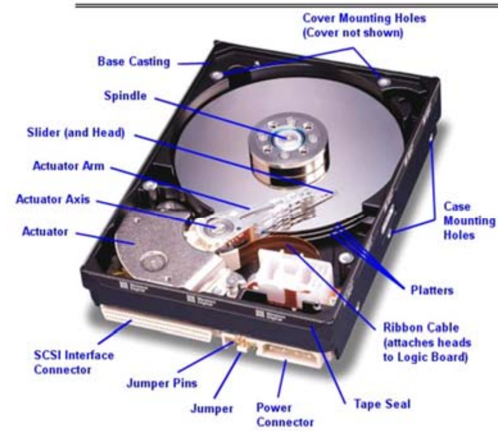
Life Cycle of An I/O Request



I/O Device Notifying the OS

- The OS needs to know when:
  - The I/O device has completed an operation
  - The I/O operation has encountered an error
- **I/O Interrupt:**
  - Device generates an interrupt whenever it needs service
  - Handled in bottom half of device driver
    - » Often run on special kernel-level stack
  - Pro: handles unpredictable events well
  - Con: interrupts relatively high overhead
- **Polling:**
  - OS periodically checks a device-specific status register
    - » I/O device puts completion information in status register
    - » Could use timer to invoke lower half of drivers occasionally
  - Pro: low overhead
  - Con: may waste many cycles on polling if infrequent or unpredictable I/O operations
- Actual devices combine both polling and interrupts
  - For instance: High-bandwidth network device:
    - » Interrupt for first incoming packet
    - » Poll for following packets until hardware empty

Hard Disk Drives

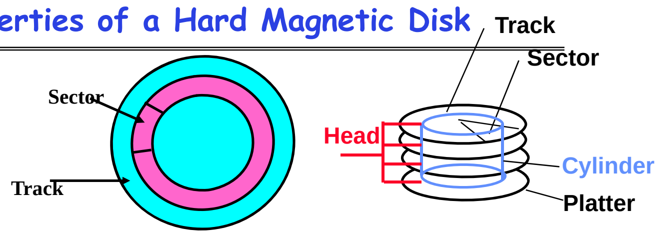


Western Digital Drive
http://www.storagereview.com/guide/

Read/Write Head Side View

IBM/Hitachi Microdrive

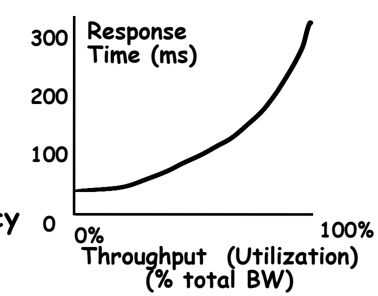
Properties of a Hard Magnetic Disk



- Properties
  - Head moves in to address circular **track** of information
  - Independently addressable element: **sector**
    - » OS always transfers groups of sectors together—"**blocks**"
  - Items addressable without moving head: **cylinder**
  - A disk can be rewritten in place: it is possible to read/modify/write a block from the disk
- Typical numbers (depending on the disk size):
  - 500 to more than 20,000 tracks per surface
  - 32 to 800 sectors per track
- Zoned bit recording
  - Constant bit density: more sectors on outer tracks
  - Speed varies with track location

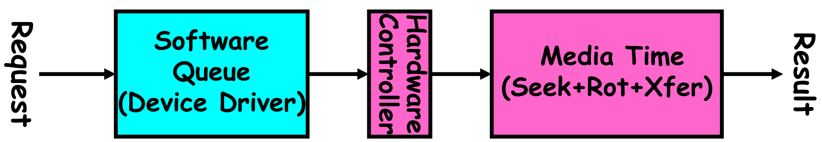
Properties of Magnetic Disk (Con't)

- Performance of disk drive/file system
  - Metrics: Response Time, Throughput
  - Contributing factors to latency:
    - » Software paths (can be loosely modeled by a queue)
    - » Hardware controller
    - » Physical disk media
- Queuing behavior:
  - Leads to big increases of latency as utilization approaches 100%



Performance Model

- Read/write data is a three-stage process:
  - Seek time: position the head/arm over the proper track (into proper cylinder)
  - Rotational latency: wait for the desired sector to rotate under the read/write head
  - Transfer time: transfer a block of bits (sector) under the read-write head
- Disk Latency = Queueing Time + Controller time + Seek Time + Rotation Time + Xfer Time



- Highest Bandwidth:
  - Transfer large group of blocks sequentially from one track

Typical Numbers of a Magnetic Disk

- Specs for modern drives
  - Space: 2TB in 3½ form factor (several manufacturers)
  - Area Density: up around 340 GB/square Inch for 2TB
- Average seek time as reported by the industry:
  - Typically in the range of 5 ms to 12 ms
  - Locality of reference may only be 25% to 33% of the advertised number
- Rotational Latency:
  - *Most* disks rotate at 3,600 to 7200 RPM (Up to 15,000RPM or more)
  - Approximately 16 ms to 8 ms per revolution, respectively
  - An average latency to the desired information is halfway around the disk: 8 ms at 3600 RPM, 4 ms at 7200 RPM
- Transfer Time is a function of:
  - Transfer size (usually a sector): 512B – 1KB per sector
  - Rotation speed: 3600 RPM to 15000 RPM
  - Recording density: bits per inch on a track
  - Diameter: ranges from 1 in to 5.25 in
  - Typical values: 2 to 50 MB per second
- Controller time depends on controller hardware

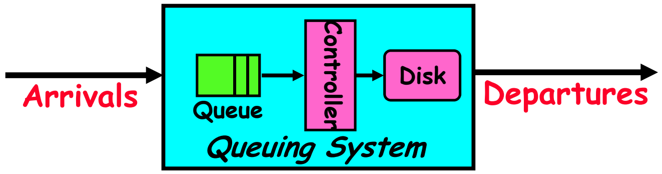
Disk Performance

- Assumptions:
  - Ignoring queuing and controller times for now
  - Avg seek time of 5ms, avg rotational delay of 4ms
  - Transfer rate of 4MByte/s, sector size of 1 KByte
- Random place on disk:
  - Seek (5ms) + Rot. Delay (4ms) + Transfer (0.25ms)
  - Roughly 10ms to fetch/put data: 100 KByte/sec
- Random place in same cylinder:
  - Rot. Delay (4ms) + Transfer (0.25ms)
  - Roughly 5ms to fetch/put data: 200 KByte/sec
- Next sector on same track:
  - Transfer (0.25ms): 4 MByte/sec
- Key to using disk effectively (esp. for filesystems) is to minimize seek and rotational delays

Disk Tradeoffs

- How do manufacturers choose disk sector sizes?
  - Need 100-1000 bits between each sector to allow system to measure how fast disk is spinning and to tolerate small (thermal) changes in track length
- What if sector was 1 byte?
  - Space efficiency – only 1% of disk has useful space
  - Time efficiency – each seek takes 10 ms, transfer rate of 50 – 100 Bytes/sec
- What if sector was 1 KByte?
  - Space efficiency – only 90% of disk has useful space
  - Time efficiency – transfer rate of 100 KByte/sec
- What if sector was 1 MByte?
  - Space efficiency – almost all of disk has useful space
  - Time efficiency – transfer rate of 4 MByte/sec

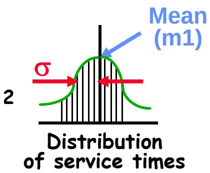
Introduction to Queuing Theory



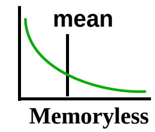
- What about queuing time??
  - Let's apply some queuing theory
  - Queuing Theory applies to long term, steady state behavior ⇒ Arrival rate = Departure rate
- Little's Law:
  Mean # tasks in system = arrival rate x mean response time
  - Observed by many, Little was first to prove
  - Simple interpretation: you should see the same number of tasks in queue when entering as when leaving.
- Applies to any system in equilibrium, as long as nothing in black box is creating or destroying tasks
  - Typical queuing theory doesn't deal with transient behavior, only steady-state behavior

Background: Use of random distributions

- Server spends variable time with customers
  - Mean (Average) m1 = $\Sigma p(T)\times T$
  - Variance $\sigma^2 = \Sigma p(T)\times(T-m1)^2 = \Sigma p(T)\times T^2-m1^2$
  - Squared coefficient of variance: $C = \sigma^2/m1^2$
    Aggregate description of the distribution.

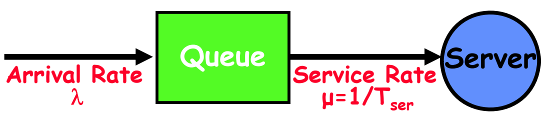


- Important values of C:
  - No variance or deterministic ⇒ C=0
  - "memoryless" or exponential ⇒ C=1
    - » Past tells nothing about future
    - » Many complex systems (or aggregates) well described as memoryless
  - Disk response times $C \approx 1.5$ (majority seeks < avg)



A Little Queuing Theory: Some Results

- Assumptions:
  - System in equilibrium; No limit to the queue
  - Time between successive arrivals is random and memoryless



- Parameters that describe our system:
  - λ: mean number of arriving customers/second
  - T_{ser}: mean time to service a customer ("m1")
  - C: squared coefficient of variance = $\sigma^2/m1^2$
  - μ: service rate = $1/T_{ser}$
  - u: server utilization ($0\le u\le 1$): $u = \lambda/\mu = \lambda \times T_{ser}$
- Parameters we wish to compute:
  - T_q: Time spent in queue
  - L_q: Length of queue = $\lambda \times T_q$ (by Little's law)
- Results:
  - Memoryless service distribution ($C = 1$):
    - » Called M/M/1 queue: $T_q = T_{ser} \times u/(1 - u)$
  - General service distribution (no restrictions), 1 server:
    - » Called M/G/1 queue: $T_q = T_{ser} \times \frac{1}{2}(1+C) \times u/(1 - u)$

A Little Queuing Theory: An Example

- Example Usage Statistics:
  - User requests 10 x 8KB disk I/Os per second
  - Requests & service exponentially distributed (C=1.0)
  - Avg. service = 20 ms (From controller+seek+rot+trans)
- Questions:
  - How utilized is the disk?
    - » Ans: server utilization, $u = \lambda T_{ser}$
  - What is the average time spent in the queue?
    - » Ans: T_q
  - What is the number of requests in the queue?
    - » Ans: L_q
  - What is the avg response time for disk request?
    - » Ans: $T_{sys} = T_q + T_{ser}$
- Computation:

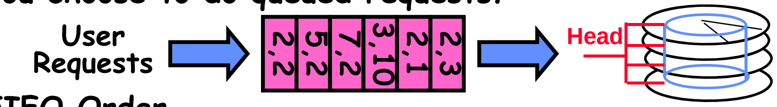
λ (avg # arriving customers/s) = 10/s
T_{ser} (avg time to service customer) = 20 ms (0.02s)
u (server utilization) = $\lambda \times T_{ser}$ = 10/s x .02s = 0.2
T_q (avg time/customer in queue) = $T_{ser} \times u/(1 - u)$
= 20 x 0.2/(1-0.2) = 20 x 0.25 = 5 ms (0 .005s)
L_q (avg length of queue) = $\lambda \times T_q$=10/s x .005s = 0.05
T_{sys} (avg time/customer in system) =$T_q + T_{ser}$= 25 ms

Queuing Theory Resources

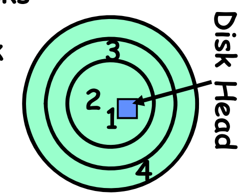
- Handouts page contains Queueing Theory Resources:
  - Scanned pages from Patterson and Hennesey book that gives further discussion and simple proof for general eq.
  - A complete website full of resources
- Midterms with queueing theory questions:
  - Midterm IIs from previous years that I've taught
- Assume that Queueing theory is fair game for Midterm II and/or the final!

Disk Scheduling

- Disk can do only one request at a time; What order do you choose to do queued requests?



- FIFO Order
  - Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks
- SSTF: Shortest seek time first
  - Pick the request that's closest on the disk
  - Although called SSTF, today must include rotational delay in calculation, since rotation can be as long as seek
  - Con: SSTF good at reducing seeks, but may lead to starvation



- SCAN: Implements an Elevator Algorithm: take the closest request in the direction of travel
  - No starvation, but retains flavor of SSTF
- C-SCAN: Circular-Scan: only goes in one direction
  - Skips any requests on the way back
  - Fairer than SCAN, not biased towards pages in middle

Summary

- I/O Controllers: Hardware that controls actual device
  - Processor Accesses through I/O instructions or load/store to special physical memory
- Notification mechanisms
  - Interrupts
  - Polling: Report results through status register that processor looks at periodically
- Disk Performance:
  - Queuing time + Controller + Seek + Rotational + Transfer
  - Rotational latency: on average ½ rotation
  - Transfer time: spec of disk depends on rotation speed and bit storage density
- Queuing Latency:
  - M/M/1 and M/G/1 queues: simplest to analyze
  - As utilization approaches 100%, latency → ∞

$$T_q = T_{ser} \times \frac{1}{2}(1+C) \times u/(1 - u))$$