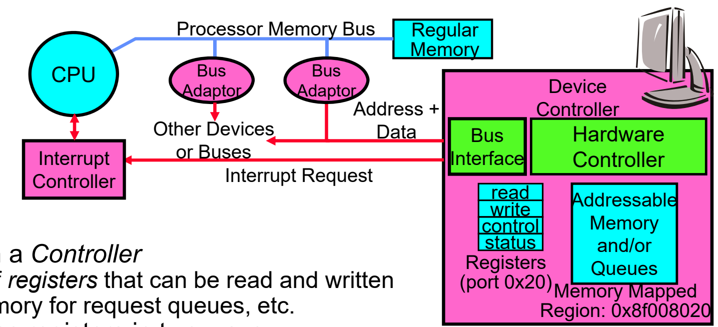
CS162
Operating Systems and Systems Programming
Lecture 18

General I/O (Con't), Storage Devices, Performance

October 28th, 2020

Prof. John Kubiatowicz
http://cs162.eecs.Berkeley.edu

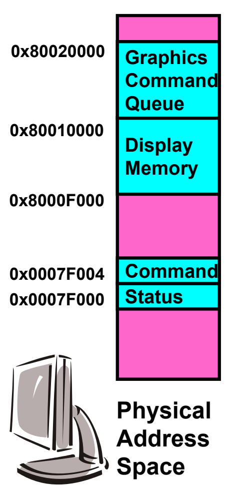
Recall: How does the Processor Talk to the Device?



- CPU interacts with a *Controller*
  – Contains a set of *registers* that can be read and written
  – May contain memory for request queues, etc.
- Processor accesses registers in two ways:
  – Port-Mapped I/O: 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

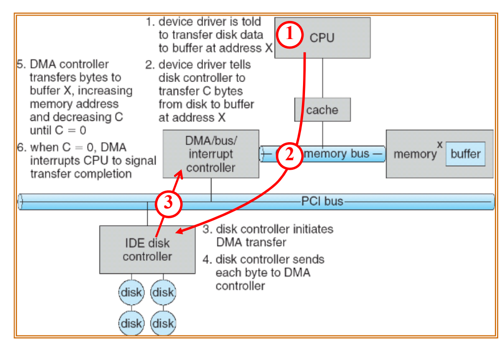
Recall: Memory-Mapped Display Controller

- Memory-Mapped:
  – Hardware maps control registers and display memory into physical address space
    » Addresses set by HW jumpers or at boot time
  – Simply writing to display memory (also called the "frame buffer") changes image on screen
    » Addr: 0x8000F000 — 0x8000FFFF
  – Writing graphics description to cmd queue
    » Say enter a set of triangles describing 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 address translation



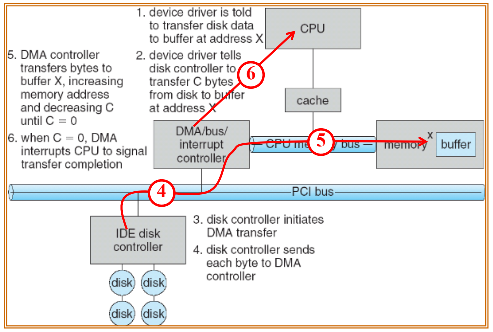
Transferring Data To/From Controller

- 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 blocks to/from memory directly
- Sample interaction with DMA controller (from OSC book):



Transferring Data To/From Controller

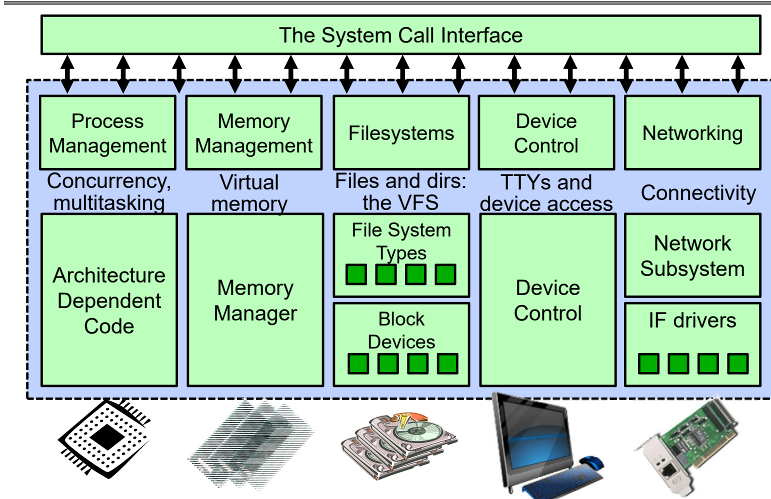
- Programmed I/O:
  - Each byte transferred via processor in/out or load/store
  - Pro: Simple hardware, easy to program
  - Con: Consumes processor cycles proportional to data size
- Direct Memory Access:
  - Give controller access to memory bus
  - Ask it to transfer data blocks to/from memory directly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



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
  - 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
  - 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 adapter:
    - » Interrupt for first incoming packet
    - » Poll for following packets until hardware queues are empty

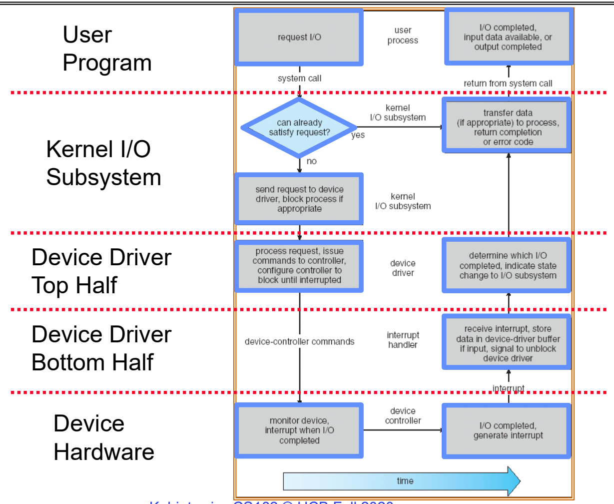
Kernel Device Structure



Recall: 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

Recall: Life Cycle of An I/O Request



The Goal of the I/O Subsystem

- Provide Uniform Interfaces, Despite Wide Range of Different Devices
  - This code works on many different devices:

```
FILE fd = fopen("/dev/something", "rw");
for (int i = 0; i < 10; i++) {
  fprintf(fd, "Count %d\n", i);
}
close(fd);
```

  - Why? Because code that controls devices ("device driver") implements standard interface
- We will try to get a flavor for what is involved in actually controlling devices in rest of lecture
  - Can only scratch surface!

Want Standard Interfaces to Devices

- Block Devices: *e.g.* disk drives, tape drives, DVD-ROM
  - 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

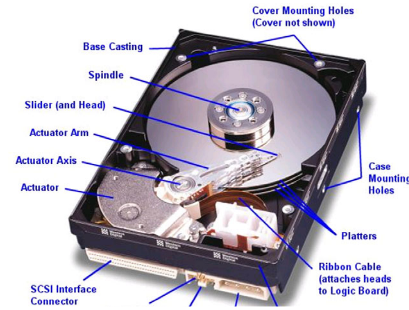
How Does User Deal with Timing?

- 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

Storage Devices

- Magnetic disks
  - Storage that rarely becomes corrupted
  - Large capacity at low cost
  - Block level random access (except for SMR – later!)
  - Slow performance for random access
  - Better performance for sequential access
- Flash memory
  - Storage that rarely becomes corrupted
  - Capacity at intermediate cost (5-20x disk)
  - Block level random access
  - Good performance for reads; worse for random writes
  - Erasure requirement in large blocks
  - Wear patterns issue

Hard Disk Drives (HDDs)



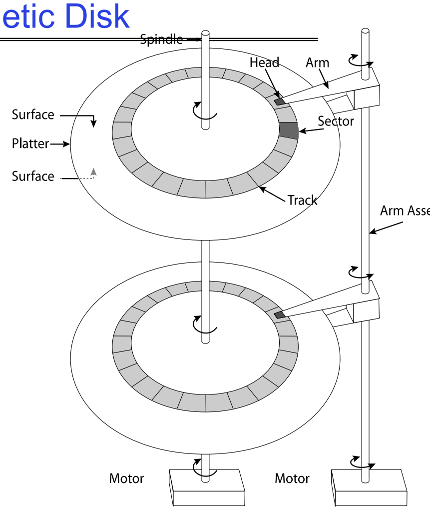
Western Digital Drive
http://www.storagereview.com/guide/

IBM/Hitachi Microdrive

Read/Write Head Side View

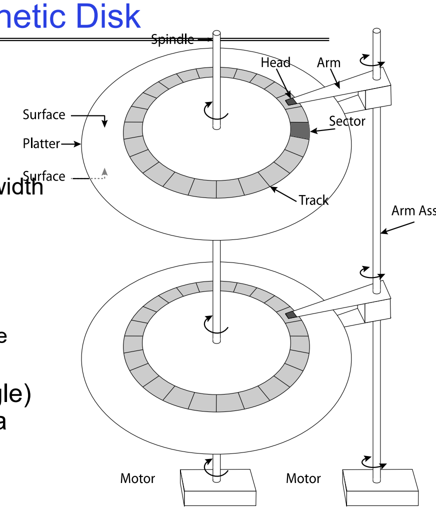
IBM Personal Computer/AT (1986)
30 MB hard disk - $500
30-40ms seek time
0.7-1 MB/s (est.)

The Amazing Magnetic Disk



- Unit of Transfer: Sector
  - Ring of sectors form a track
  - Stack of tracks form a cylinder
  - Heads position on cylinders
- Disk Tracks ~ 1µm (micron) wide
  - Wavelength of light is ~ 0.5µm
  - Resolution of human eye: 50µm
  - 100K tracks on a typical 2.5" disk
- Separated by unused guard regions
  - Reduces likelihood neighboring tracks are corrupted during writes (still a small non-zero chance)

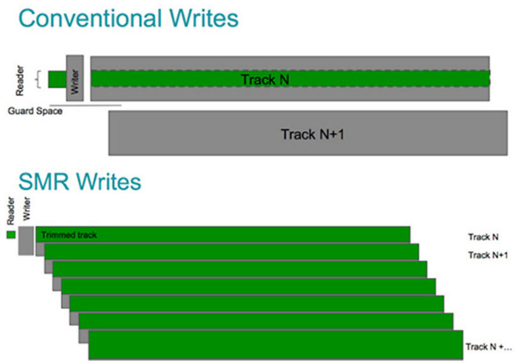
The Amazing Magnetic Disk



- Track length varies across disk
  - Outside: More sectors per track, higher bandwidth
  - Disk is organized into regions of tracks with same # of sectors/track
  - Only outer half of radius is used
    - » Most of the disk area in the outer regions of the disk
- Disks so big that some companies (like Google) reportedly only use part of disk for active data
  - Rest is archival data

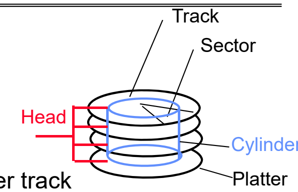
Shingled Magnetic Recording (SMR)

- Overlapping tracks yields greater density, capacity
- Restrictions on writing, complex DSP for reading

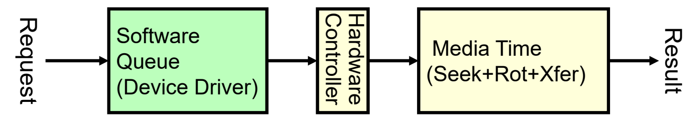


Review: Magnetic Disks

- Cylinders: all the tracks under the head at a given point on all surfaces
- Read/write data is a three-stage process:
  - Seek time: position the head/arm over the proper track
  - Rotational latency: wait for desired sector to rotate under r/w head
  - Transfer time: transfer a block of bits (sector) under r/w head



Disk Latency = Queueing Time + Controller time + Seek Time + Rotation Time + Xfer Time



Typical Numbers for Magnetic Disk

Parameter	Info/Range
Space/Density	Space: 14TB (Seagate), 8 platters, in 3½ inch form factor! **Areal Density: ≥ 1 Terabit/square inch! (PMR, Helium, …)**
Average Seek Time	Typically 4-6 milliseconds
Average Rotational Latency	Most laptop/desktop disks rotate at 3600-7200 RPM (16-8 ms/rotation). Server disks up to 15,000 RPM. Average latency is halfway around disk so 4-8 milliseconds
Controller Time	Depends on controller hardware
Transfer Time	Typically 50 to 250 MB/s. Depends on: • 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
Cost	Used to drop by a factor of two every 1.5 years (or faster), now slowing down

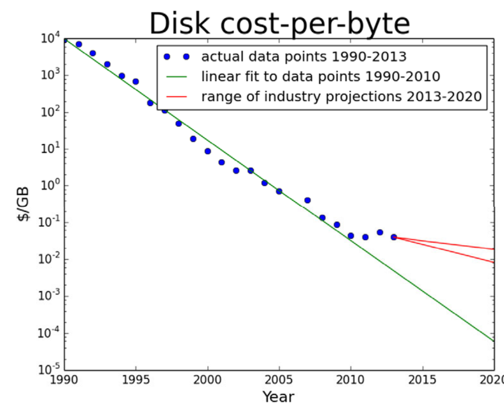
Disk Performance Example

- Assumptions:
  - Ignoring queuing and controller times for now
  - Avg seek time of 5ms,
  - 7200RPM ⇒ Time for rotation: 60000 (ms/min) / 7200(rev/min) ~= 8ms
  - Transfer rate of 50MByte/s, block size of 4Kbyte ⇒ 4096 bytes/50×10^6 (bytes/s) = 81.92 × 10^{-6} sec ≅ 0.082 ms for 1 sector
- Read block from random place on disk:
  - Seek (5ms) + Rot. Delay (4ms) + Transfer (0.082ms) = 9.082ms
  - Approx 9ms to fetch/put data: 4096 bytes/9.082×10^{-3} s ≅ 451KB/s
- Read block from random place in same cylinder:
  - Rot. Delay (4ms) + Transfer (0.082ms) = 4.082ms
  - Approx 4ms to fetch/put data: 4096 bytes/4.082×10^{-3} s ≅ 1.03MB/s
- Read next block on same track:
  - Transfer (0.082ms): 4096 bytes/0.082×10^{-3} s ≅ 50MB/sec
- Key to using disk effectively (especially for file systems) is to minimize seek and rotational delays

Lots of Intelligence in the Controller

- Sectors contain sophisticated error correcting codes
  - Disk head magnet has a field wider than track
  - Hide corruptions due to neighboring track writes
- Sector sparing
  - Remap bad sectors transparently to spare sectors on the same surface
- Slip sparing
  - Remap all sectors (when there is a bad sector) to preserve sequential behavior
- Track skewing
  - Sector numbers offset from one track to the next, to allow for disk head movement for sequential ops

Hard Drive Prices over Time



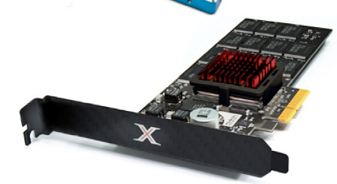
Example of Current HDDs

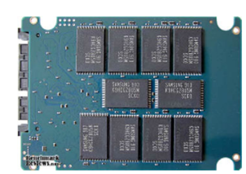
- Seagate Exos X18 (2020)
  - 18 TB hard disk
    - » 9 platters, 18 heads
    - » Helium filled: reduce friction and power
  - 4.16ms average seek time
  - 4096 byte physical sectors
  - 7200 RPMs
  - Dual 6 Gbps SATA /12Gbps SAS interface
    - » 270MB/s MAX transfer rate
    - » Cache size: 256MB
  - Price: $ 562 (~ $0.03/GB)

- IBM Personal Computer/AT (1986)
  - 30 MB hard disk
  - 30-40ms seek time
  - 0.7-1 MB/s (est.)
  - Price: $500 ($17K/GB, 340,000x more expensive !!)

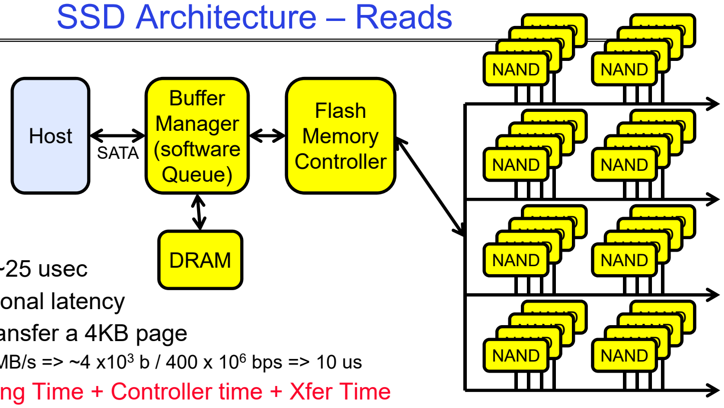
Solid State Disks (SSDs)

- 1995 – Replace rotating magnetic media with non-volatile memory (battery backed DRAM)
- 2009 – Use NAND Multi-Level Cell (2 or 3-bit/cell) flash memory
  - Sector (4 KB page) addressable, but stores 4-64 "pages" per memory block
  - Trapped electrons distinguish between 1 and 0
- No moving parts (no rotate/seek motors)
  - Eliminates seek and rotational delay (0.1-0.2ms access time)
  - Very low power and lightweight
  - Limited "write cycles"
- Rapid advances in capacity and cost ever since!





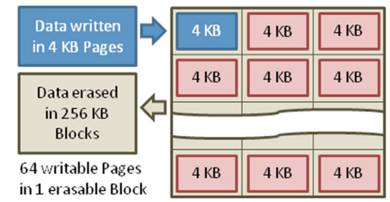
SSD Architecture – Reads



Read 4 KB Page: ~25 usec
- No seek or rotational latency
- Transfer time: transfer a 4KB page
  - » SATA: 300-600MB/s => ~4 x10^3 b / 400 x 10^6 bps => 10 us
- Latency = Queuing Time + Controller time + Xfer Time
- Highest Bandwidth: Sequential OR Random reads

SSD Architecture – Writes

- Writing data is complex! (~200μs – 1.7ms)
  - Can only write empty pages in a block
  - Erasing a block takes ~1.5ms
  - Controller maintains pool of empty blocks by coalescing used pages (read, erase, write), also reserves some % of capacity
- Rule of thumb: writes 10x reads, erasure 10x writes



Typical NAND Flash Pages and Blocks

https://en.wikipedia.org/wiki/Solid-state_drive

SSD Architecture – Writes

- SSDs provide same interface as HDDs to OS – read and write chunk (4KB) at a time
- But can only overwrite data 256KB at a time!
- Why not just erase and rewrite new version of entire 256KB block?
  - Erasure is very slow (milliseconds)
  - Each block has a finite lifetime, can only be erased and rewritten about 10K times
  - Heavily used blocks likely to wear out quickly

Solution – Two Systems Principles

1. Layer of Indirection
   - Maintain a *Flash Translation Layer (FTL)* in SSD
   - Map virtual block numbers (which OS uses) to physical page numbers (which flash mem. controller uses)
   - **Can now freely relocate data w/o OS knowing**
2. Copy on Write
   - Don't overwrite a page when OS updates its data
   - Instead, write new version in a free page
   - Update FTL mapping to point to new location

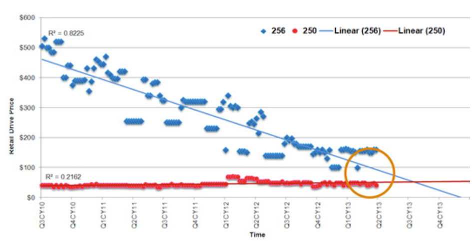
Flash Translation Layer

- No need to erase and rewrite entire 256KB block when making small modifications
- SSD controller can assign mappings to spread workload across pages
  - *Wear Levelling*
- What to do with old versions of pages?
  - *Garbage Collection* in background
  - Erase blocks with old pages, add to free list

Some "Current" (large) 3.5in SSDs

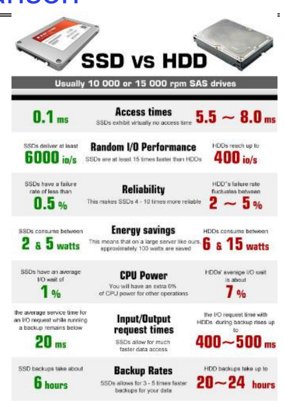
- Seagate Exos SSD: 15.36TB (2017)
  - Dual 12Gb/s interface
  - Seq reads 860MB/s
  - Seq writes 920MB/s
  - Random Reads (IOPS): 102K
  - Random Writes (IOPS): 15K
  - Price (Amazon): $5495 ($0.36/GB)
- Nimbus SSD: 100TB (2019)
  - Dual port: 12Gb/s interface
  - Seq reads/writes: 500MB/s
  - Random Read Ops (IOPS): 100K
  - *Unlimited writes for 5 years!*
  - Price: ~ $40K? ($0.4/GB)
    - » However, 50TB drive costs $12500 ($0.25/GB)

HDD vs. SSD Comparison



Price Crossover Point for HDD and SSD

	2012	2013	2014	2015E	2016F	2017F
HDD	0.09	0.08	0.07	0.06	0.06	0.06
2.5" SSD	0.99	0.68	0.55	0.39	0.24	0.17



SSD prices drop much faster than HDD

Amusing calculation: Is a full Kindle heavier than an empty one?

- Actually, "Yes", but not by much
- Flash works by trapping electrons:
  - So, erased state lower energy than written state
- Assuming that:
  - Kindle has 4GB flash
  - ½ of all bits in full Kindle are in high-energy state
  - High-energy state about 10^{-15} joules higher
  - Then: Full Kindle is 1 attogram (10^{-18}gram) heavier (Using $E = mc^2$)
- Of course, this is less than most sensitive scale can measure (it can measure 10^{-9} grams)
- Of course, this weight difference overwhelmed by battery discharge, weight from getting warm, ….
- Source: John Kubiatowicz (New York Times, Oct 24, 2011)

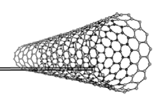
SSD Summary

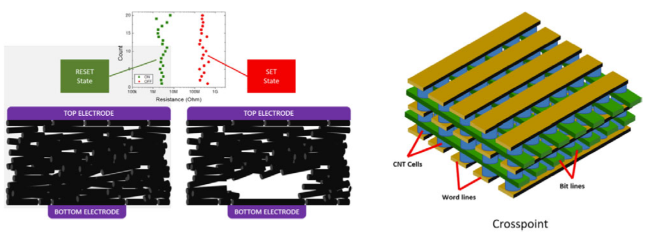
- Pros (vs. hard disk drives):
  - Low latency, high throughput (eliminate seek/rotational delay)
  - No moving parts:
    - » Very light weight, low power, silent, very shock insensitive
  - Read at memory speeds (limited by controller and I/O bus)
- Cons
  - Small storage (0.1-0.5x disk), expensive (3-20x disk)
    - » Hybrid alternative: combine small SSD with large HDD

SSD Summary

- Pros (vs. hard disk drives):
  - Low latency, high throughput (eliminate seek/rotational delay)
  - No moving parts:
    - » Very light weight, low power, silent, very shock insensitive
  - Read at memory speeds (limited by controller and I/O bus)
- Cons
  - ~~Small storage (0.1-0.5x disk), expensive (3-20x disk)~~ No longer true!
    - » Hybrid alternative: combine small SSD with large HDD
  - Asymmetric block write performance: read pg/erase/write pg
    - » Controller garbage collection (GC) algorithms have major effect on performance
  - Limited drive lifetime
    - » 1-10K writes/page for MLC NAND
    - » Avg failure rate is 6 years, life expectancy is 9–11 years
- These are changing rapidly!

Nano-Tube Memory (NANTERO)





- Yet another possibility: Nanotube memory
  - NanoTubes between two electrodes, slight conductivity difference between ones and zeros
  - No wearout!
- Better than DRAM?
  - Speed of DRAM, no wearout, non-volatile!
  - Nantero promises 512Gb/dice for 8Tb/chip! (with 16 die stacking)

Ways of Measuring Performance: Times (s) and Rates (op/s)

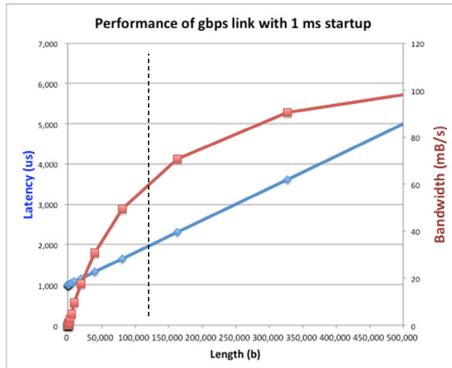
- ***Latency*** – time to complete a task
  - Measured in units of time (s, ms, us, …, hours, years)
- ***Response Time*** - time to initiate and operation and get its response
  - Able to issue one that *depends* on the result
  - Know that it is done (anti-dependence, resource usage)
- ***Throughput*** or ***Bandwidth*** – rate at which tasks are performed
  - Measured in units of things per unit time (ops/s, GFLOP/s)
- ***Start up or "Overhead"*** **–** time to initiate an operation
- Most I/O operations are roughly linear in *b* bytes
  - Latency(b) = Overhead + b/TransferCapacity
- Performance???
  - Operation time (4 mins to run a mile…)
  - Rate (mph, mpg, …)

Example: Overhead in Fast Network

- Consider a $1\ \mathrm{Gb/s}$ link ($B = 125\ \mathrm{MB/s}$) with startup cost $S = 1\ \mathrm{ms}$
- Latency: $L(b) = S + \frac{b}{B}$
- Effective Bandwidth:

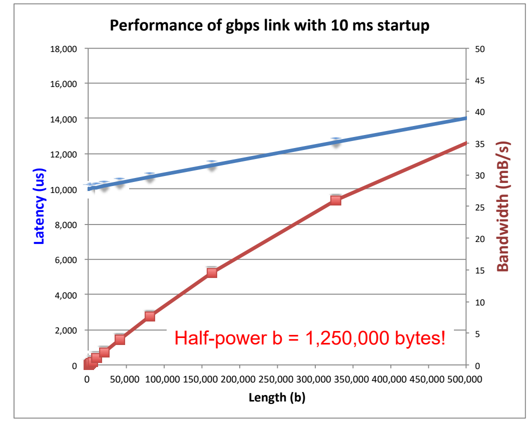
$$E(b) = \frac{b}{S + \frac{b}{B}} = \frac{B \cdot b}{B \cdot S + b} = \frac{B}{\frac{B \cdot S}{b} + 1}$$

- Half-power Bandwidth: $E(b) = \frac{B}{2}$
- For this example, half-power bandwidth occurs at $b = 125\ \mathrm{KB}$



Example: 10 ms Startup Cost (e.g., Disk)

- Half-power bandwidth at $b = 1.25\ \mathrm{MB}$
- Large startup cost can degrade effective bandwidth
- Amortize it by performing I/O in larger blocks

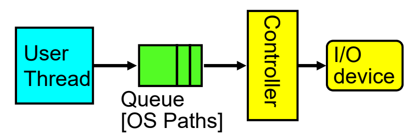


What Determines Peak BW for I/O?

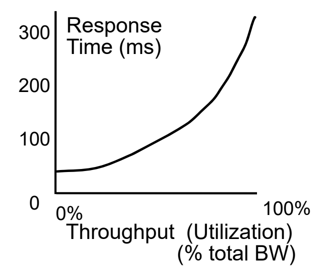
- Bus Speed
  - PCI-X: 1064 MB/s = 133 MHz x 64 bit (per lane)
  - ULTRA WIDE SCSI: 40 MB/s
  - Serial Attached SCSI & Serial ATA & IEEE 1394 (firewire): 1.6 Gb/s full duplex (200 MB/s)
  - USB 3.0 – 5 Gb/s
  - Thunderbolt 3 – 40 Gb/s
- Device Transfer Bandwidth
  - Rotational speed of disk
  - Write / Read rate of NAND flash
  - Signaling rate of network link
- Whatever is the bottleneck in the path…

Overall Performance for I/O Path

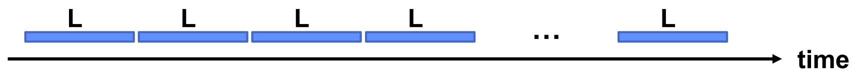
- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW = transfer size / response time
  - Contributing factors to latency:
    - » Software paths (can be loosely modeled by a queue)
    - » Hardware controller
    - » I/O device service time
- Queuing behavior:
  - Can lead to big increases of latency as utilization increases
  - Solutions?



Response Time = Queue + I/O device service time

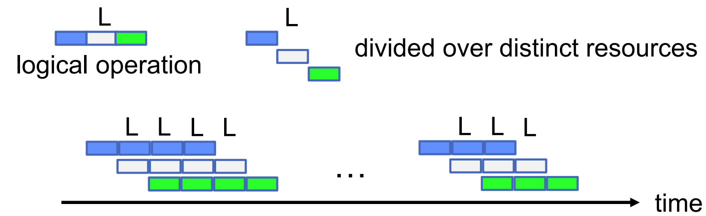


Sequential Server Performance



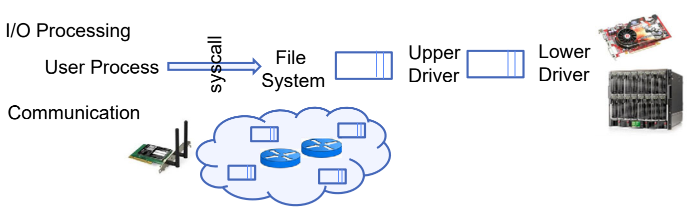
- Single sequential "server" that can deliver a task in time L operates at rate $\leq \frac{1}{L}$ (on average, in steady state, …)
  - $L = 10$ ms $\rightarrow B = 100$ $^{\text{op}}/_{\text{s}}$
  - $L = 2$ yr $\rightarrow B = 0.5$ $^{\text{op}}/_{\text{yr}}$
- Applies to a processor, a disk drive, a person, a TA, …

Single Pipelined Server



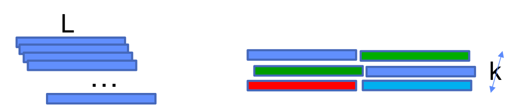
- Single pipelined server of k stages for tasks of length L (i.e., time $^{L}/_{k}$ per stage) delivers at rate $\leq$ $^{k}/_{L}$.
  - $L = 10$ ms, $k = 4 \rightarrow B = 400$ $^{\text{op}}/_{\text{s}}$
  - $L = 2$ yr, $k = 2 \rightarrow B = 1$ $^{\text{op}}/_{\text{yr}}$

Example Systems "Pipelines"



- Anything with queues between operational process behaves roughly "pipeline like"
- Important difference is that "initiations" are decoupled from processing
  - May have to queue up a burst of operations
  - Not synchronous and deterministic like in 61C

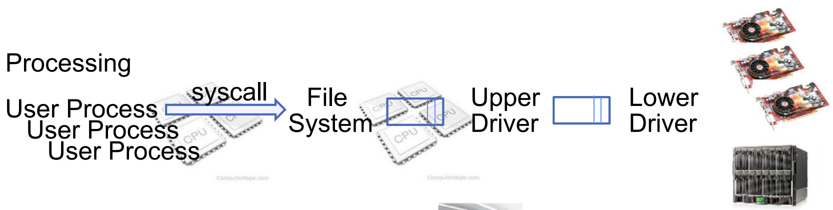
Multiple Servers



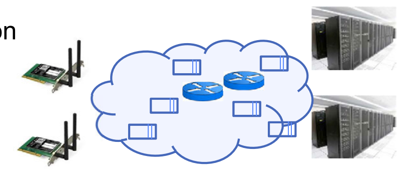
- k servers handling tasks of length L delivers at rate $\leq$ $^{k}/_{L}$.
  - $L = 10$ ms, $k = 4 \rightarrow B = 400$ $^{\text{op}}/_{\text{s}}$
  - $L = 2$ yr, $k = 2 \rightarrow B = 1$ $^{\text{op}}/_{\text{yr}}$
- In 61C you saw multiple processors (cores)
  - Systems present lots of multiple parallel servers
  - Often with lots of queues

Example Systems "Parallelism"

I/O Processing



Communication



Parallel Computation, Databases, …

Conclusion (1/2)

- Notification mechanisms
  - Interrupts
  - Polling: Report results through status register that processor looks at periodically
- Device drivers interface to I/O devices
  - Provide clean Read/Write interface to OS above
  - Manipulate devices through PIO, DMA & interrupt handling
  - Three types: block, character, and network
- Direct Memory Access (DMA)
  - Permit devices to directly access memory
  - Free up processor from transferring every byte

Conclusion (2/2)

- 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
- Devices have complex interaction and performance characteristics
  - Response time (Latency) = Queue + Overhead + Transfer
    - » Effective BW = BW * T/(S+T)
  - HDD: Queuing time + controller + seek + rotation + transfer
  - SSD: Queuing time + controller + transfer (erasure & wear)
- Systems (e.g., file system) designed to optimize performance and reliability
  - Relative to performance characteristics of underlying device
- Next time: Bursts & High Utilization introduce queuing delays
- Next time: Queuing Latency:
  - M/M/1 and M/G/1 queues: simplest to analyze
  - As utilization approaches 100%, latency $\rightarrow \infty$

$$T_q = T_{ser} \times ½(1+C) \times \rho/(1 - \rho))$$