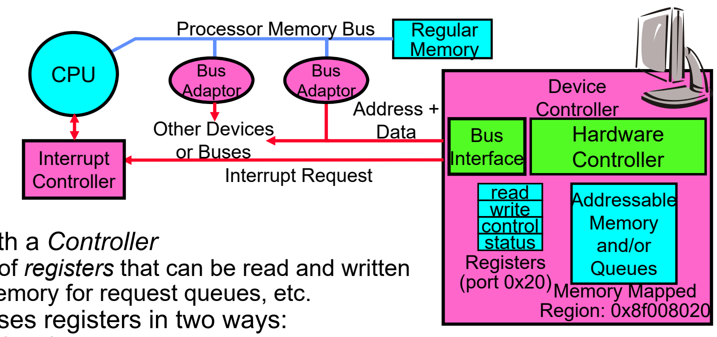
CS162
Operating Systems and Systems Programming
Lecture 20

Device Drivers, Storage Devices, Performance

April 4th, 2024
Prof. John Kubiatowicz
http://cs162.eecs.Berkeley.edu

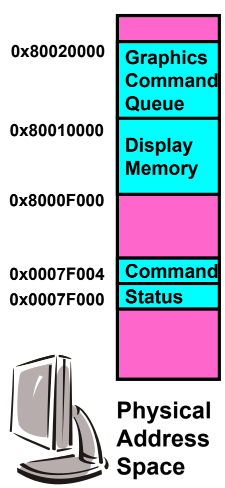
Recall: How does the Processor Talk to the Device?



- 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

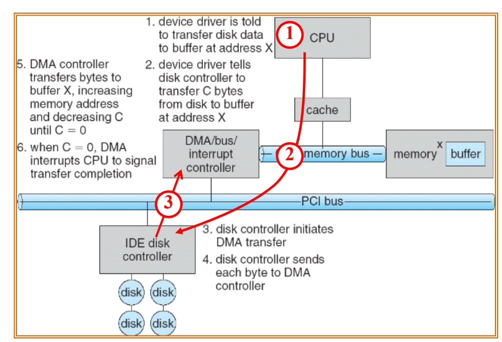
Recall: Example Memory-Mapped Display Controller

- 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):



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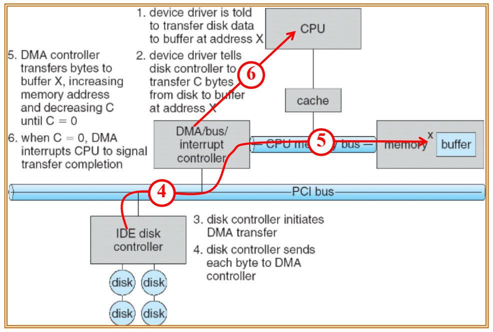
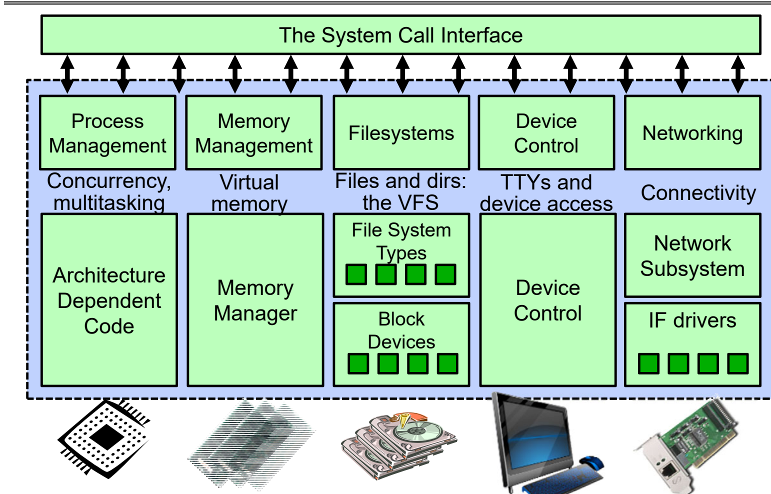


I/O Device Notifying the OS

- 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

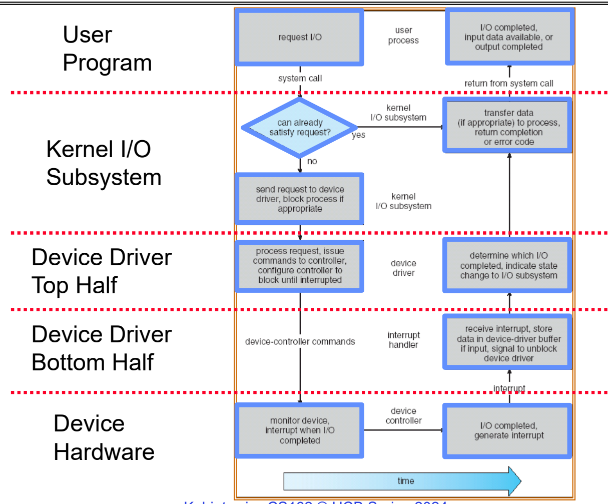
Kernel Device Structure



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

Administrivia

- Sorry about infrastructure disaster yesterday!
  - We extended the HW4 deadline
- HW 5 will have a Rust option!
  - Choose one or the other
- Project 2 still due Friday
- Midterm 3 on April 25
  - All topics up to previous Tuesday (4/23) are in scope
  - Closed book, 3 pages, double-sided handwritten notes.

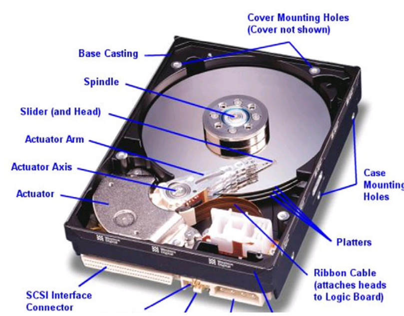
Lecture Attendance EC (4/4/2024)

https://tinyurl.com/yj3976p2

Storage Devices

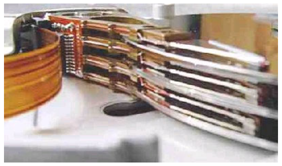
- Magnetic disks
  - Storage that rarely becomes corrupted
  - Large capacity at low cost
  - Block level random access (except for SMR – later!)
  - Slow performance for random access
  - Better performance for sequential access
- Flash memory
  - Storage that rarely becomes corrupted
  - Capacity at 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

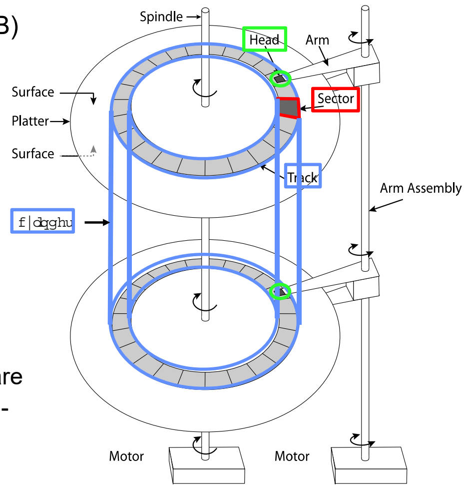


Read/Write Head Side View

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

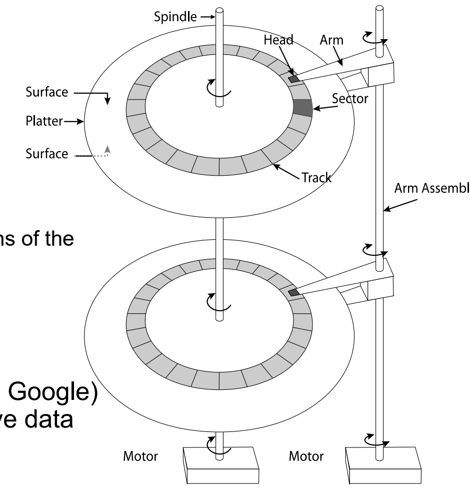
The Amazing Magnetic Disk

- Unit of Transfer: **Sector** (512B or 4096B)
  - 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

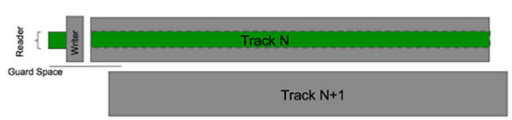
- Track length varies across disk
  - Outside: More sectors per track, higher bandwidth
  - Disk is organized into regions of tracks with same # of sectors/track
  - Only outer half of radius is used
    - » Most of the disk area in the outer regions of the disk
- OS Unit of Transfer: Block
  - Typically more than one Sector
  - Example: 4KB, 16KB
- Disks so big that some companies (like Google) reportedly only use part of disk for active data
  - Rest is archival data



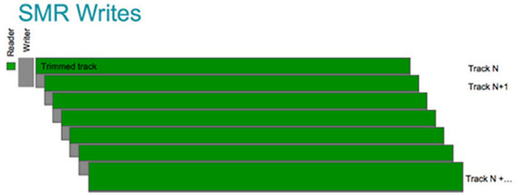
Shingled Magnetic Recording (SMR)

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

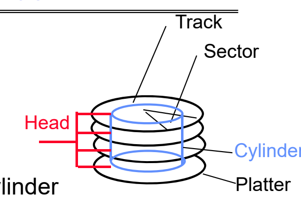
Conventional Writes



SMR Writes

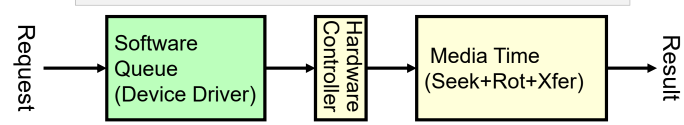


Magnetic Disk Performance



- 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 cylinder
  - 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: 18TB (Seagate), 9 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 270 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
    Avg time to find block = ½ × 8ms = 4ms
  - 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 is to minimize seek and rotational delays

Lots of Intelligence in the Controller

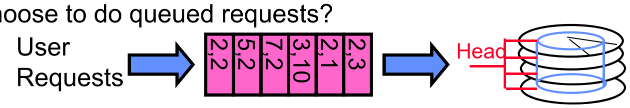
- Sectors contain sophisticated error correcting codes
  - Disk head magnet has a field wider than track
  - Hide corruptions due to neighboring track writes
- Sector sparing
  - Remap bad sectors transparently to spare sectors on the same surface
- Slip sparing
  - Remap all sectors (when there is a 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

When is Disk Performance Highest?

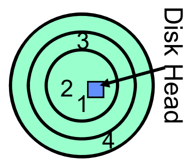
- When there are big sequential reads, or
- When there is so much work to do that they can be piggy backed (reordering queues—one moment)
- It is OK to be inefficient when things are mostly idle
- Bursts are both a threat and an opportunity
- <your idea for optimization goes here>
  - Waste space for speed?
- Other techniques:
  - Reduce overhead through user level drivers
  - Reduce the impact of I/O delays by doing other useful work in the meantime

Disk Scheduling (1/3)

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

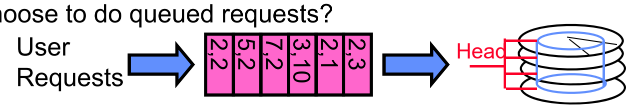


- FIFO Order
  - Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks
- SSTF: Shortest seek time first
  - Pick the request that's closest on the disk
  - Although called SSTF, today must include rotational delay in calculation, since rotation can be as long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

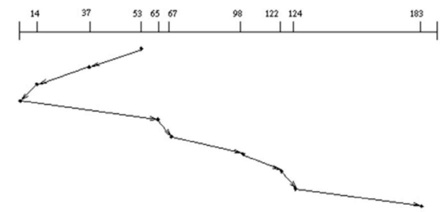


Disk Scheduling (2/3)

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



- SCAN: Implements an Elevator Algorithm: take the closest request in the direction of travel
  - No starvation, but retains flavor of SSTF



Disk Scheduling (3/3)

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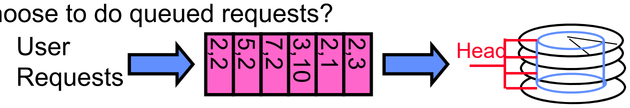
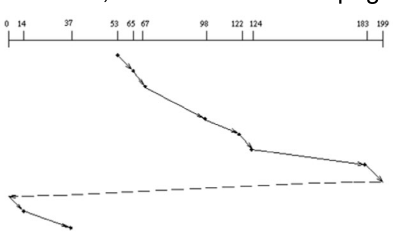


- C-SCAN: Circular-Scan: only goes in one direction
  - Skips any requests on the way back
  - Fairer than SCAN, not biased towards pages in middle



Example of Current HDDs

- Seagate Exos X24 (2023)
  - 24 TB hard disk
    - » 10 platters, 20 heads
    - » 1.26 TB/in^2
    - » Helium filled: reduce friction and power
  - 4.16 ms average seek time
  - 4096 byte physical sectors
  - 7200 RPMs
  - Dual 6 Gbps SATA /12Gbps SAS interface
    - » 285MB/s MAX transfer rate
    - » Cache size: 512MB
  - Price: $ 479 (~ $0.02/GB)
- IBM Personal Computer/AT (1986)
  - 30 MB hard disk
  - 30-40 ms average seek time
  - 0.7-1 MB/s (est.)
  - Price: $500 ($17K/GB)

800K x

10 x

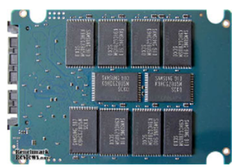
385 x

850K x

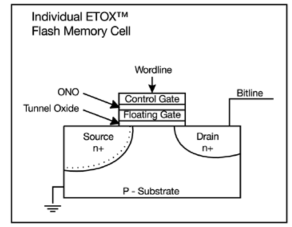
Solid State Disks (SSDs)

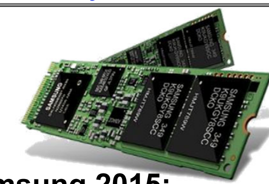
- 1995 – Replace rotating magnetic media with non-volatile memory (battery backed DRAM)
- 2009 – Use NAND Multi-Level Cell (2 or 3-bit/cell) flash memory
  - Sector (4 KB page) addressable, but stores 4-64 “pages” per memory block
  - Trapped electrons distinguish between 1 and 0
- No moving parts (no 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!





FLASH Memory

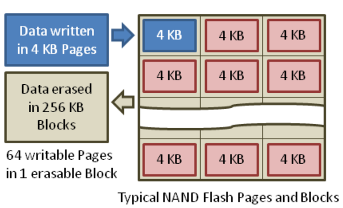


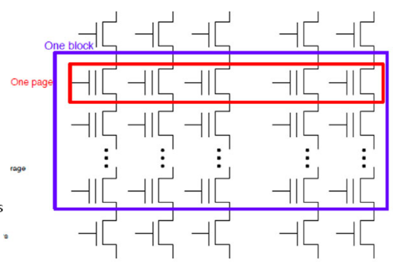


Samsung 2015: 512GB, NAND Flash

- Like a normal transistor but:
  - Has a floating gate that can hold charge
  - To write: raise or lower wordline high enough to cause charges to tunnel
  - To read: turn on wordline as if normal transistor
    - » presence of charge changes threshold and thus measured current
- Two varieties:
  - NAND: denser, must be read and written in blocks
  - NOR: much less dense, fast to read and write
- V-NAND: 3D stacking (Samsung claims 1TB possible in 1 chip)

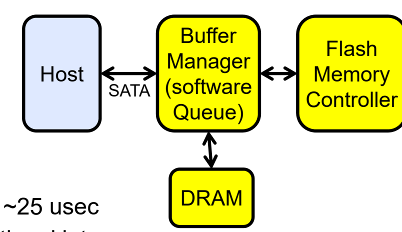
Flash Memory (Con’t)

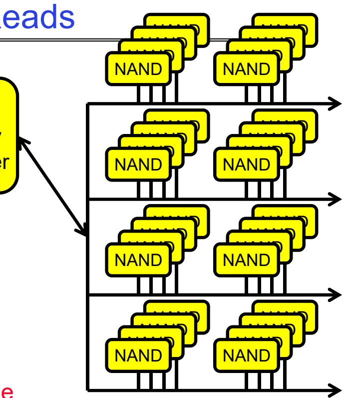




- Data read and written in page-sized chunks (e.g. 4K)
  - Cannot be addressed at byte level
  - Random access at block level for reads (no locality advantage)
  - Writing of new blocks handled in order (kinda like a log)
- Before writing, must be *erased* (256K block at a time)
  - Requires free-list management
  - CANNOT write over existing block (Copy-on-Write is normal case)

SSD Architecture – Reads

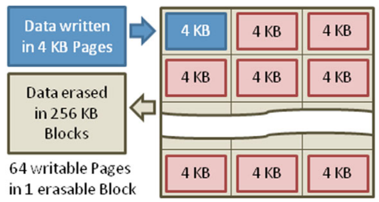




Read 4 KB Page: ~25 usec
- No seek or rotational latency
- Transfer time: transfer a 4KB page
  - » SATA: 300-600MB/s => ~4 x10^3 b / 400 x 10^6 bps => 10 us
- Latency = Queuing Time + Controller time + Xfer Time
- Highest Bandwidth: Sequential OR Random reads

SSD Architecture – Writes

- Writing data to NAND Flash is complex!
  - Can only write empty pages in a block (~ 200μs)
  - 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
- SSDs provide same interface as HDDs: read and write chunk (4KB) 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

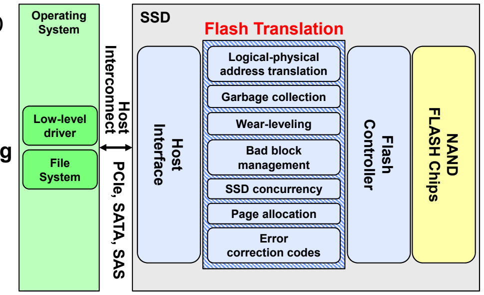


Typical NAND Flash Pages and Blocks

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

Managing Writes: Flash Translation Layer

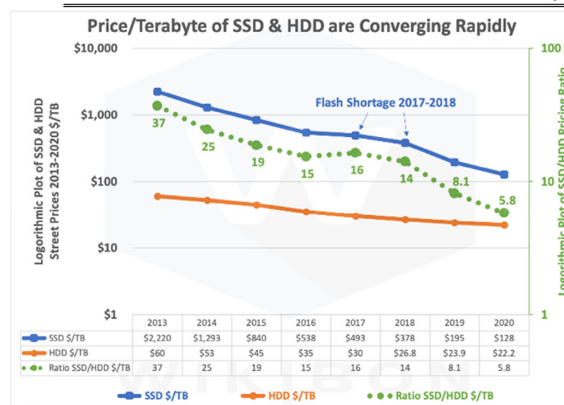
- Maintain *Flash Translation Layer* (*FTL*) in SSD
  - Layer of Indirection between OS and FLASH
  - Map virtual block numbers (which OS uses) to physical page numbers (which flash mem. controller uses)
  - **Can now freely relocate data w/o OS knowing**
- FTL advantages/mechanism:
  - Copy on Write: No need to immediately erase entire 256K block when modifying 4K page
    - » Don't overwrite page when OS updates data
    - » Instead, write new version in a free page
    - » Update FTL mapping to point to new location
  - Wear Levelling: Try to wear out NAND evenly
    - » SSD controller can assign mappings to spread workload across pages
  - What to do with old versions of pages?
    - » *Garbage Collection* in background
    - » Erase blocks with old pages, add to free list



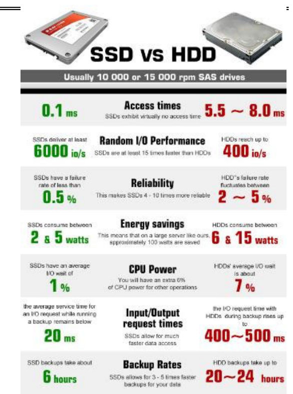
Some "Current" (large) 3.5in SSDs

- 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



	2013	2014	2015	2016	2017	2018	2019	2020
SSD $/TB	$2,220	$1,293	$840	$538	$493	$378	$195	$128
HDD $/TB	$60	$53	$45	$35	$30	$26.8	$23.9	$22.2
Ratio SSD/HDD $/TB	37	25	19	15	16	14	8.1	5.8



SSD prices drop 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

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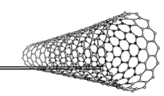
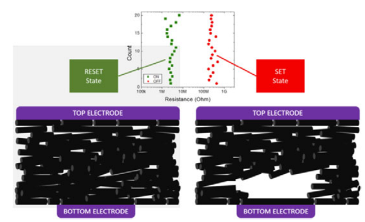
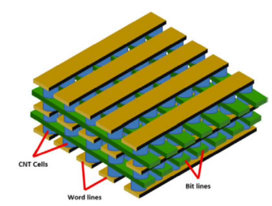
    - » Hybrid alternative: combine small SSD with large HDD
  - Asymmetric block write performance: read pg/erase/write pg
    - » Controller garbage collection (GC) algorithms have major effect on performance
  - Limited drive lifetime
    - » 1-10K writes/page for MLC NAND
    - » Avg failure rate is 6 years, life expectancy is 9–11 years
- These are changing rapidly!

No longer true!

Nano-Tube Memory (NANTERO)







Crosspoint

- 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)

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 $\rightarrow \infty$

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