File Systems 1: Storage Devices and FAT

Lecture 16

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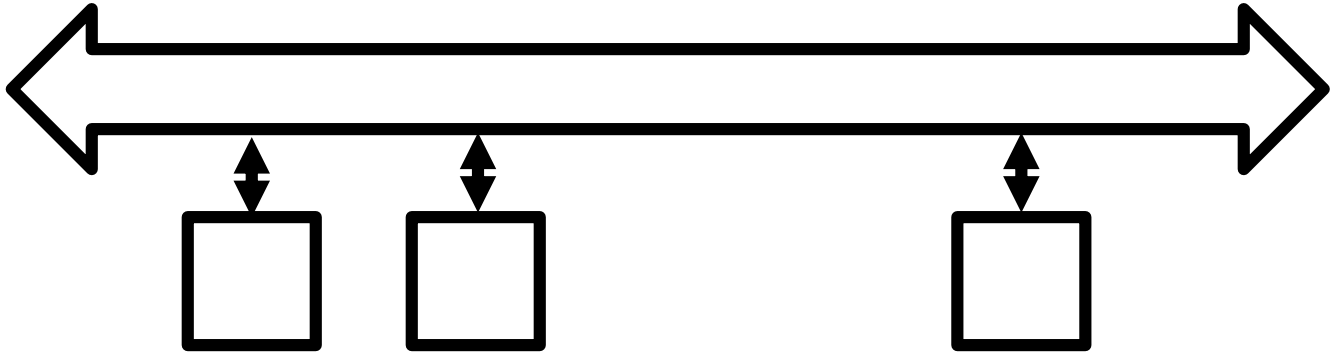
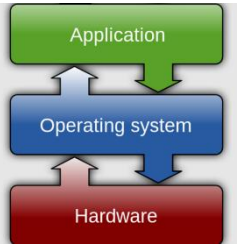
https://teaching.hkaiser.org/spring2026/csc4103/

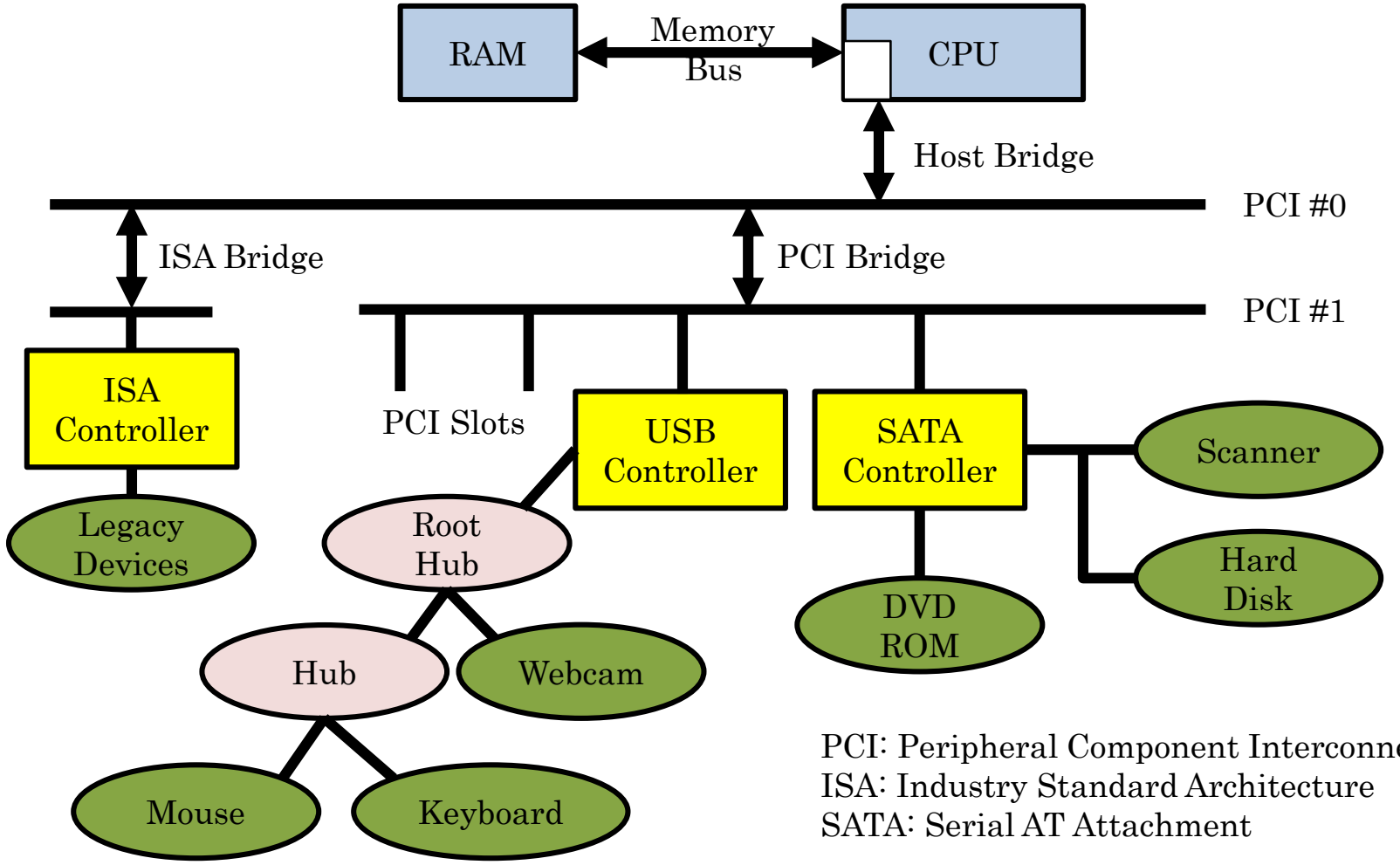
What's a Bus?

- Common set of wires for communication among hardware devices plus protocols for carrying out data transfer transactions
  - Operations: e.g., Read, Write
  - Control lines, Address lines, Data lines
- Protocol: initiator requests access, arbitration to grant, identification of recipient, handshake to convey address, length, data
- Very high BW close to processor (wide, fast, and inflexible), low BW with high flexibility out in I/O subsystem

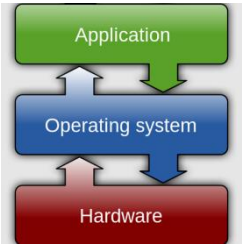




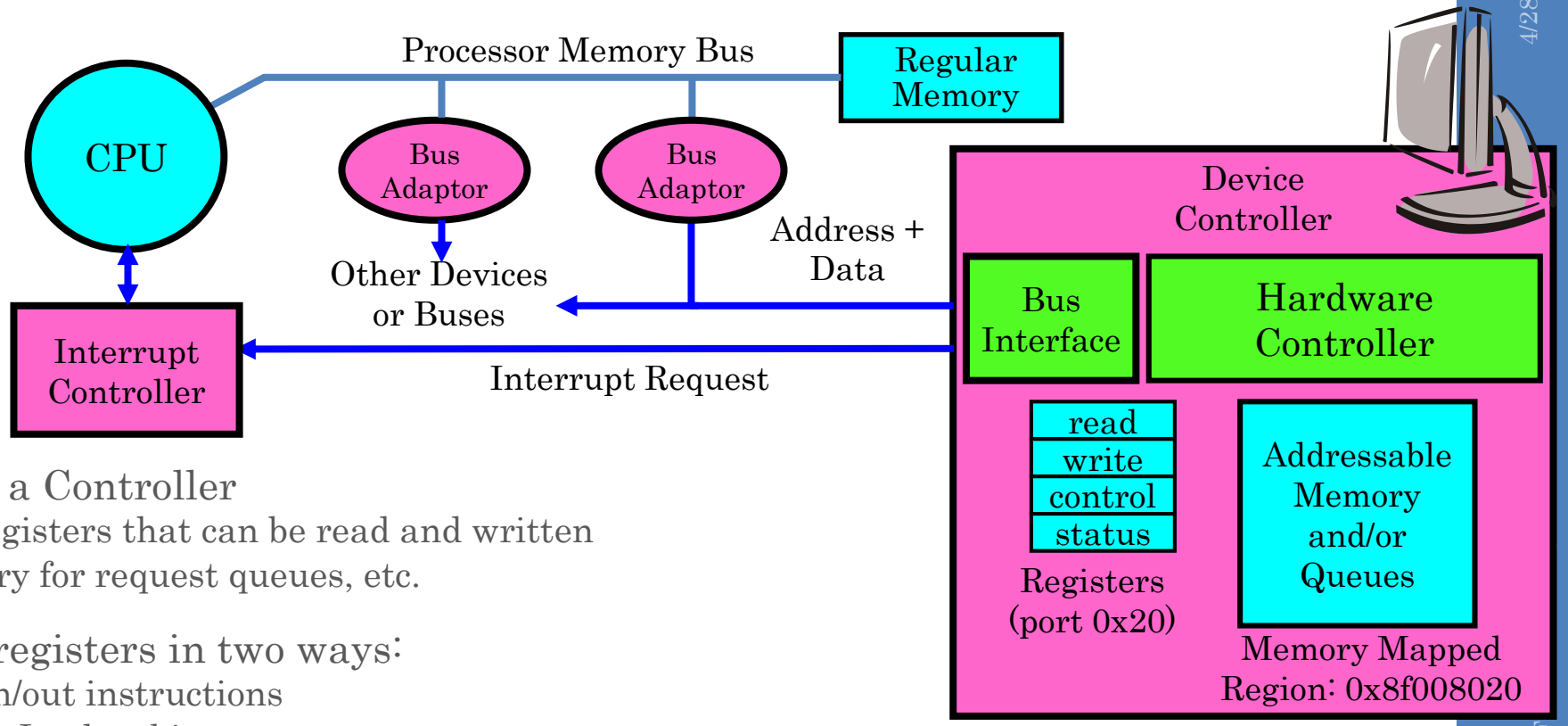
Typical PCI Architecture



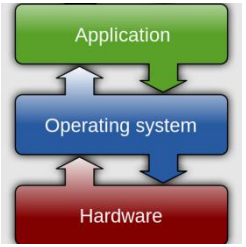
PCI: Peripheral Component Interconnect
ISA: Industry Standard Architecture
SATA: Serial AT Attachment



How does the Processor Talk to the Device?

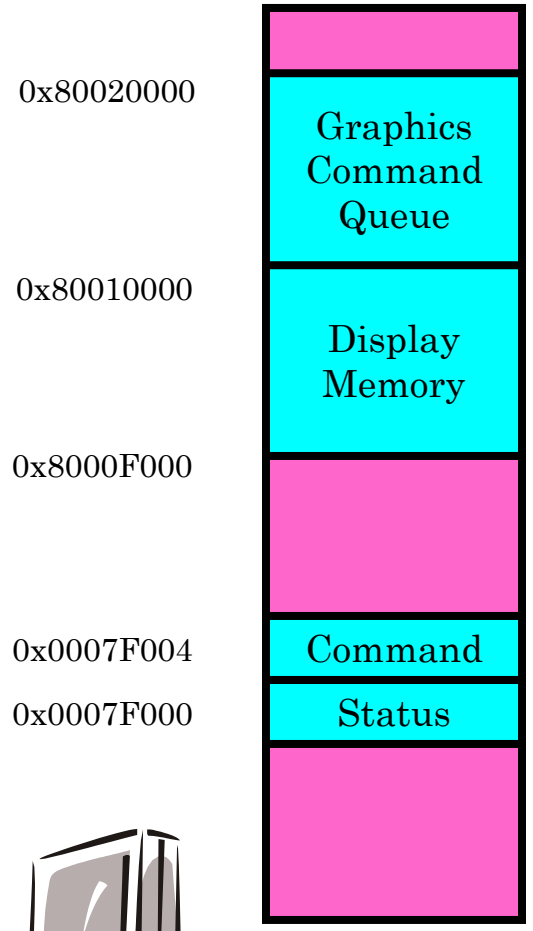


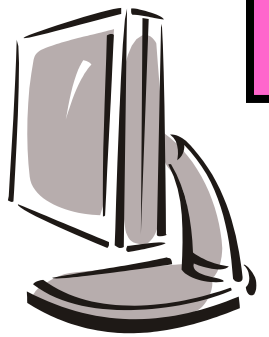
- CPU interacts with a Controller
  - Contains a set of registers that can be read and written
  - May contain memory for request queues, etc.
- Processor accesses registers in two ways:
  - Port-Mapped I/O: in/out instructions
    - Example from the Intel architecture: `out 0x21,AL`
  - Memory-mapped I/O: load/store instructions
    - Registers/memory appear in physical address space
    - I/O accomplished with load and store instructions



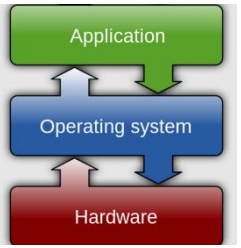
Memory-Mapped Display Controller

- 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 be protected with address translation

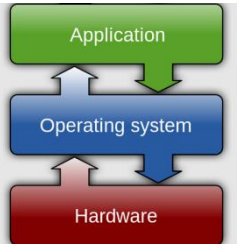




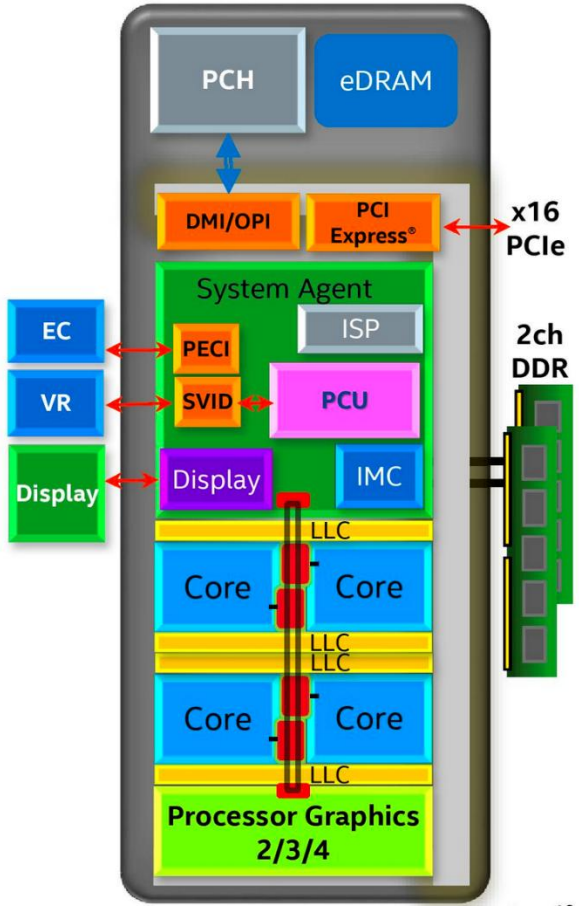
Physical Address Space



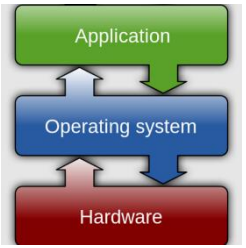
There's more than just a CPU in there!



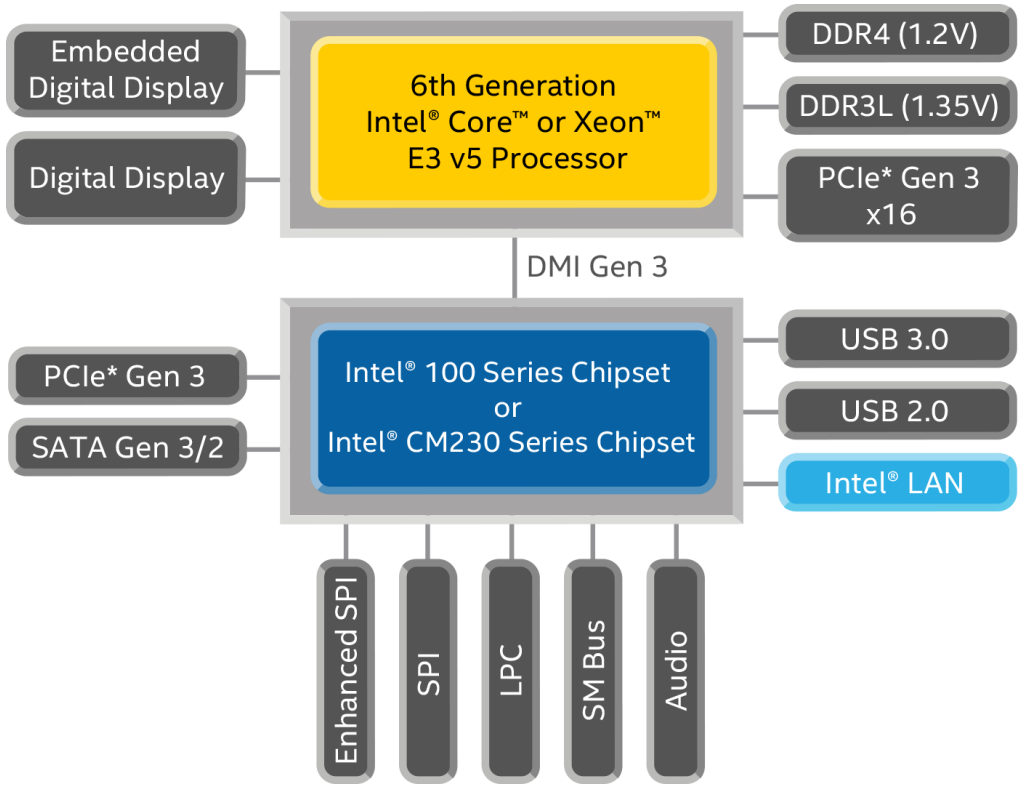
Chip-Scale Features of Skylake (x86 in 2015)



- Significant pieces:
  - Four OOO (out-of-order) cores with deeper buffers
  - Integrated GPU, System Agent (Mem, Fast I/O)
  - Large shared L3 cache with on-chip ring bus
    - 2 MB/core instead of 1.5 MB/core
    - High-BW access to L3 Cache
- Integrated I/O
  - Integrated memory controller (IMC)
    - Two independent channels of DRAM
  - High-speed PCI-Express (for Graphics cards)
  - Direct Media Interface (DMI) Connection to PCH (Platform Control Hub)

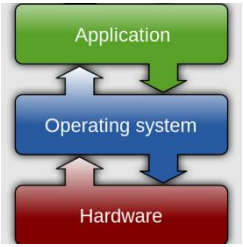


Skylake I/O: Platform Controller Hub (PCH)



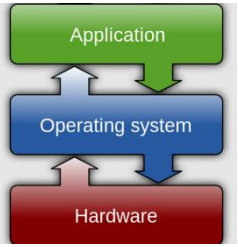
Sky Lake
System Configuration

- Platform Controller Hub
  - Connected to processor with proprietary bus
    - Direct Media Interface
- Types of I/O on PCH:
  - USB, Ethernet
  - Thunderbolt 3
  - Audio, BIOS support
  - More PCI Express (lower speed than on Processor)
  - SATA (for Disks)



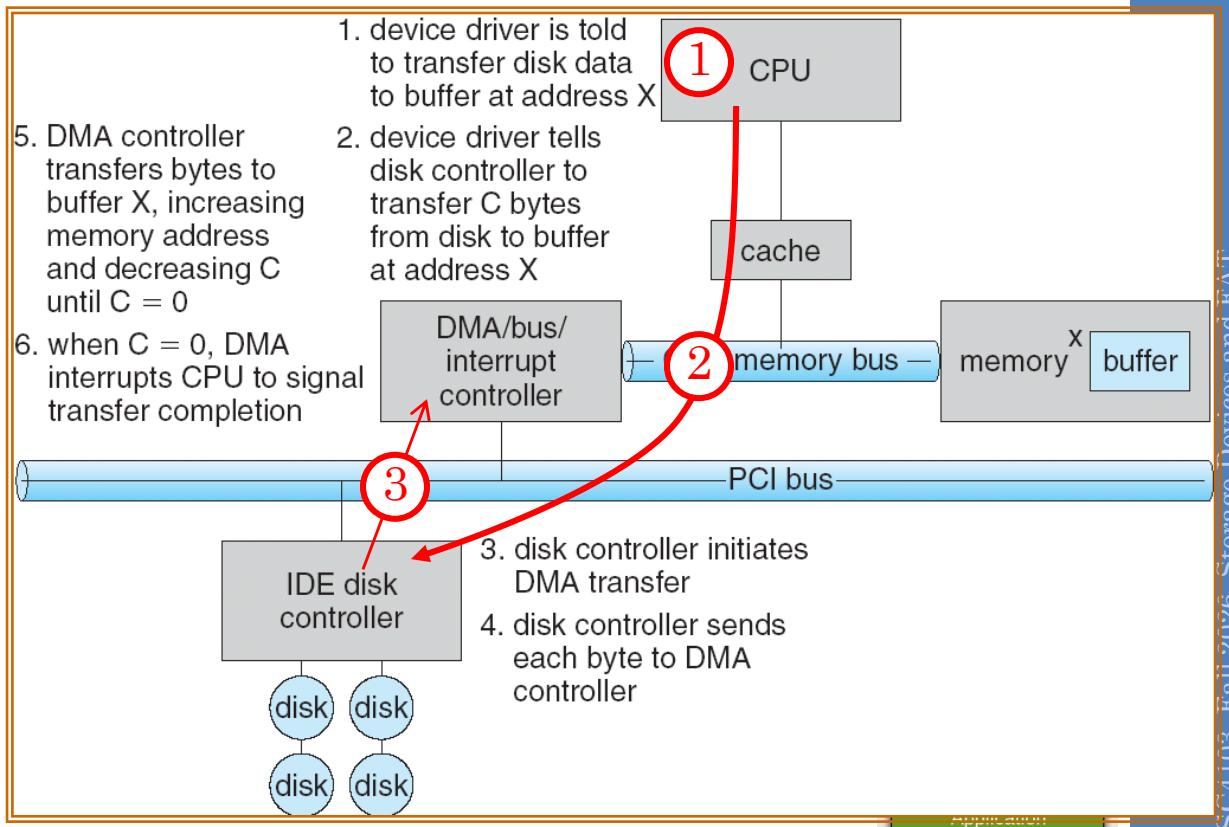
Operational Parameters for I/O

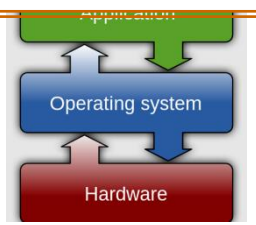
- Data granularity: Byte vs. Block
  - Some devices provide single byte at a time (e.g., keyboard)
  - Others provide whole blocks (e.g., disks, networks, etc.)
- Access pattern: Sequential vs. Random
  - Some devices must be accessed sequentially (e.g., tape)
  - Others can be accessed "randomly" (e.g., disk, CD, etc.)
    - Fixed overhead to start transfers
  - Some devices require continual monitoring (polling)
  - Others generate interrupts when they need service
- Transfer Mechanism: Programmed I/O and DMA



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
- Interaction with DMA controller





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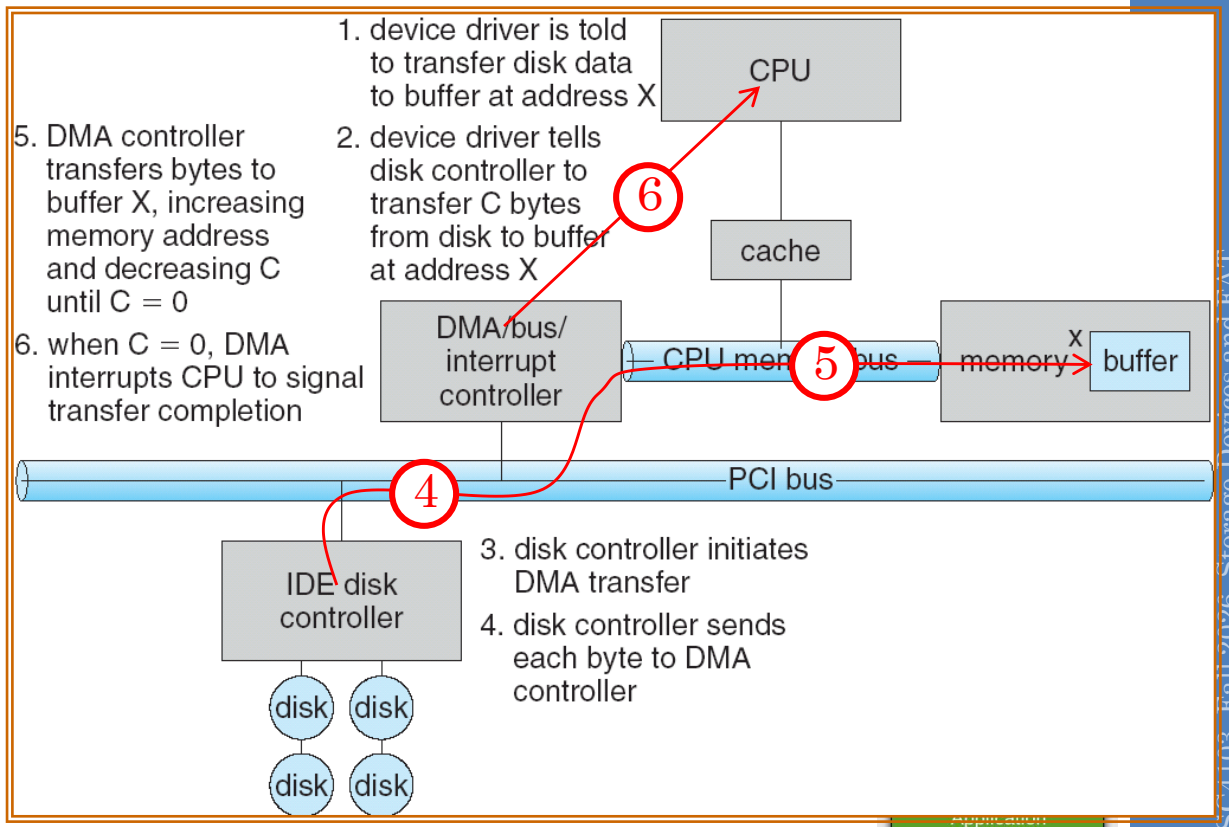
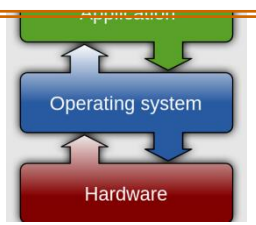
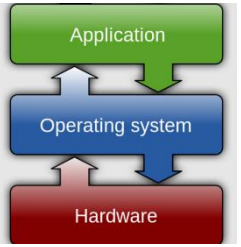


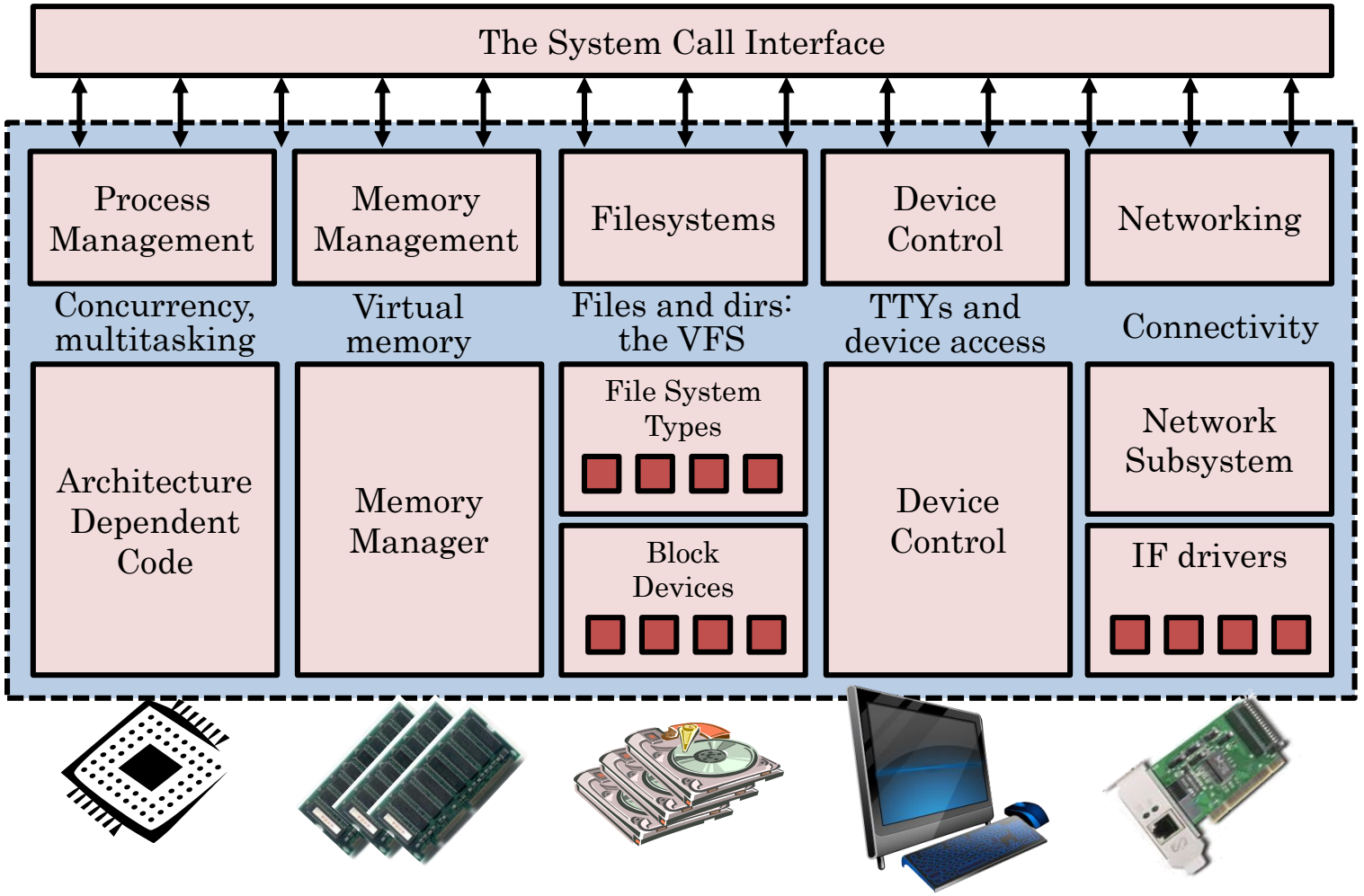


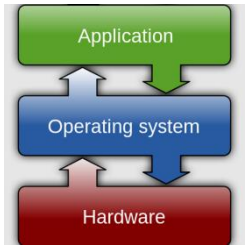
I/O Device Notifying the OS

- 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 interrupt when it needs service
  - Handles unpredictable events well, but high overhead
- Polling: OS periodically checks device-specific status register
  - Low overhead, but may waste cycles for infrequent or unpredictable I/O
- Actual devices combine both polling and interrupts
  - E.g., high-bandwidth network adapter



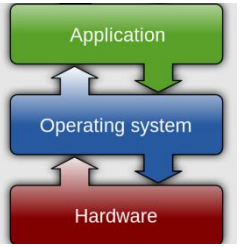
Kernel Device Structure



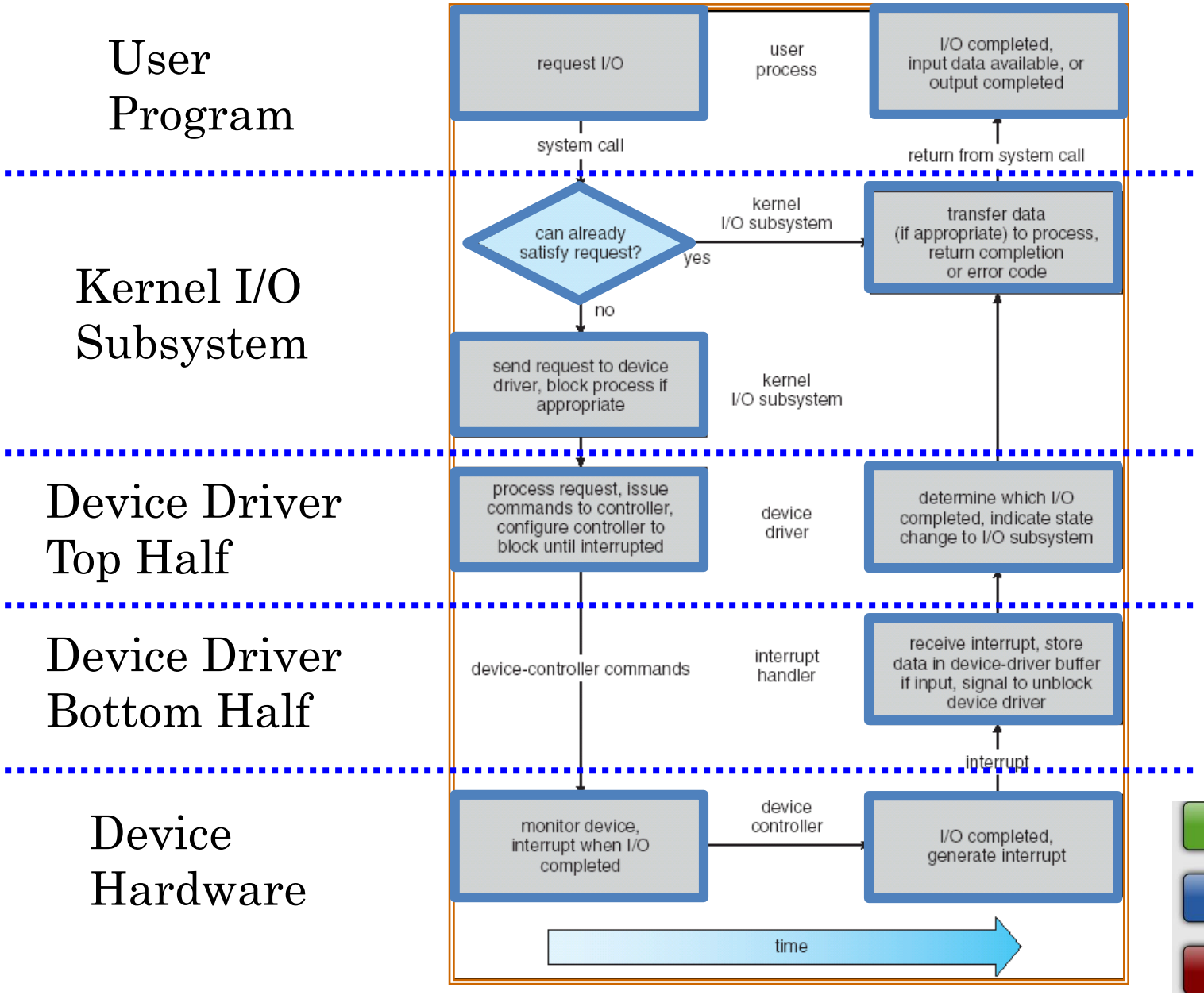


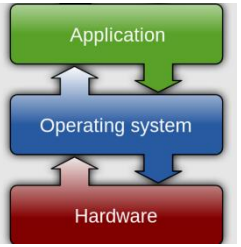
Device Drivers

- 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()
      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



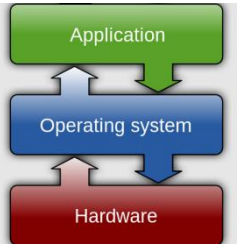


The Goal of the I/O Subsystem

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

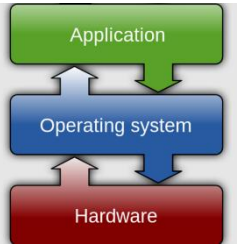
```
FILE fd = fopen("/dev/something", "rw");
for (int i = 0; i < 10; i++) {
    fprintf(fd, "Count %d\n", i);
}
close(fd);
```

  - 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!



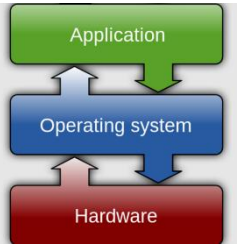
Want Standard Interface to Devices

- 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
  - May not be buffered like block devices
  - Libraries layered on top allow line editing
- Network Devices: e.g. Ethernet, Wireless, Bluetooth
  - Different enough from block/character devices to have an extended 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 I/O Timing?

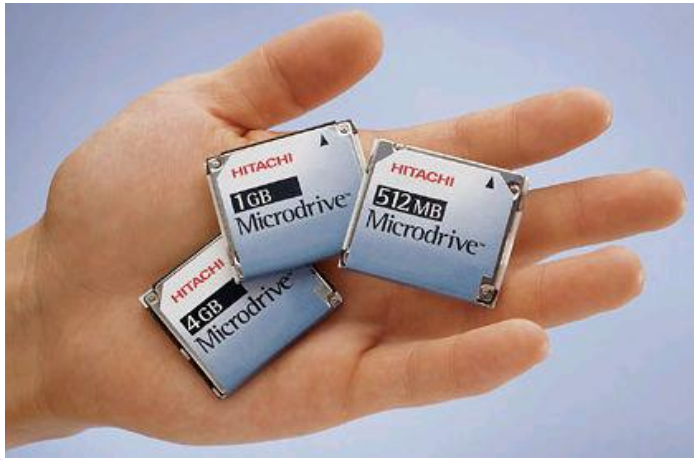
- Blocking Interface: "Wait"
  - When request data (e.g. read syscall), put process to sleep until data is ready
  - When write data (e.g. write syscall), put process to sleep until device is ready for data
- Non-blocking Interface: "Don't Wait"
  - Returns quickly from read or write request with count 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



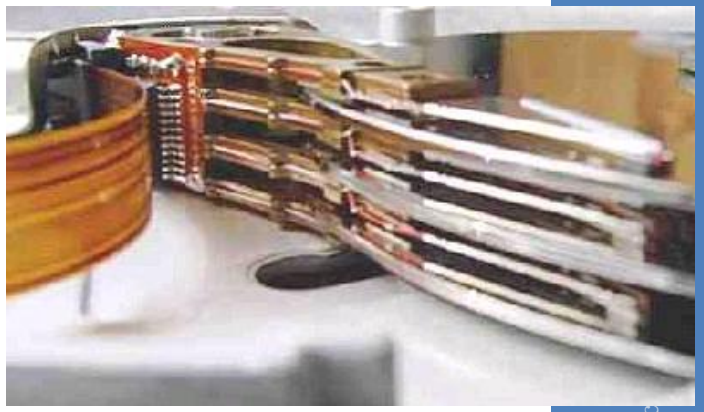
Storage Devices

Hard Disk Drives (HDDs)

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

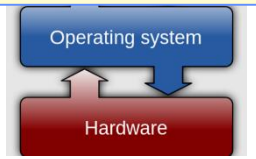


IBM/Hitachi Microdrive



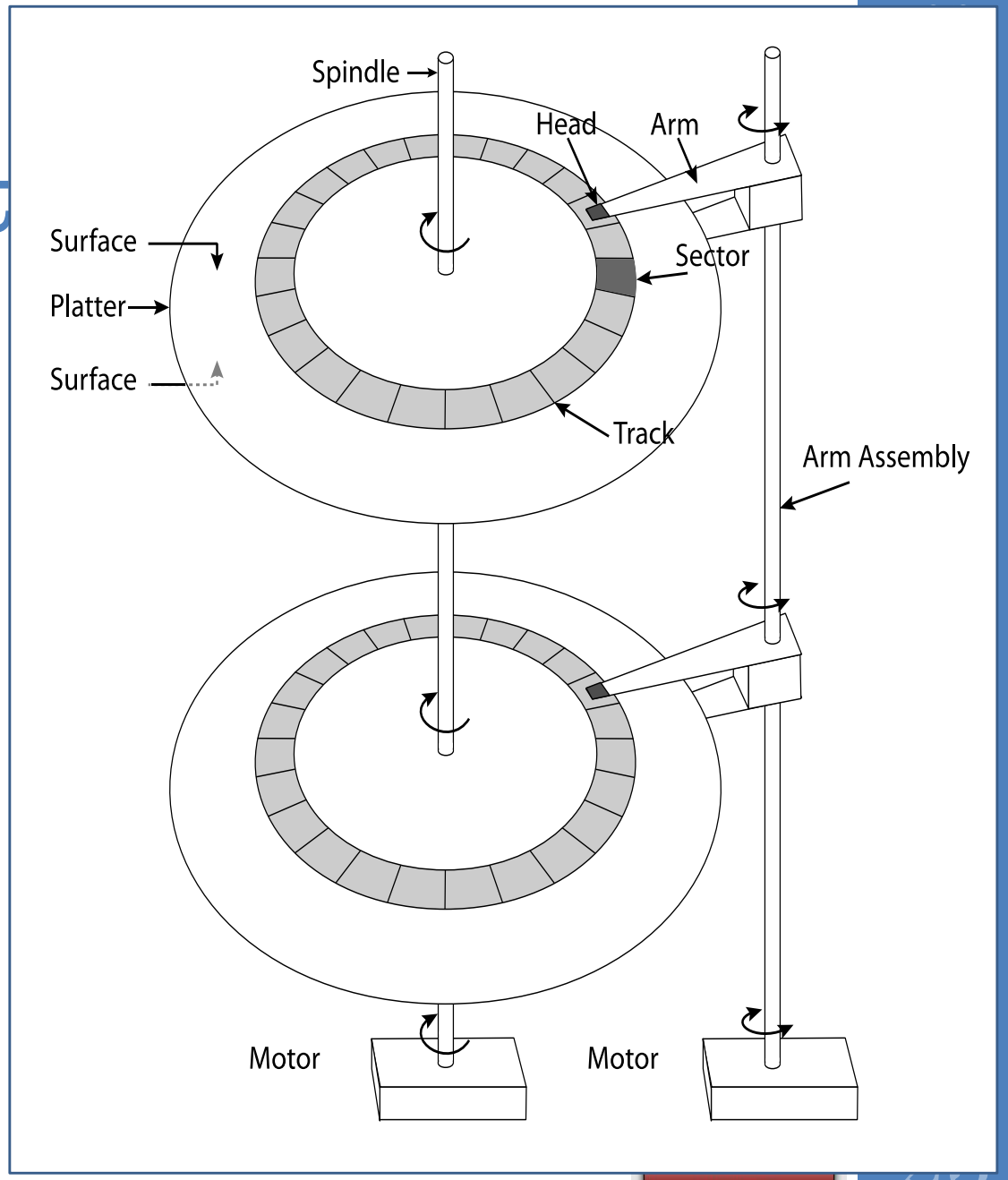
Read/Write Head
Side View

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



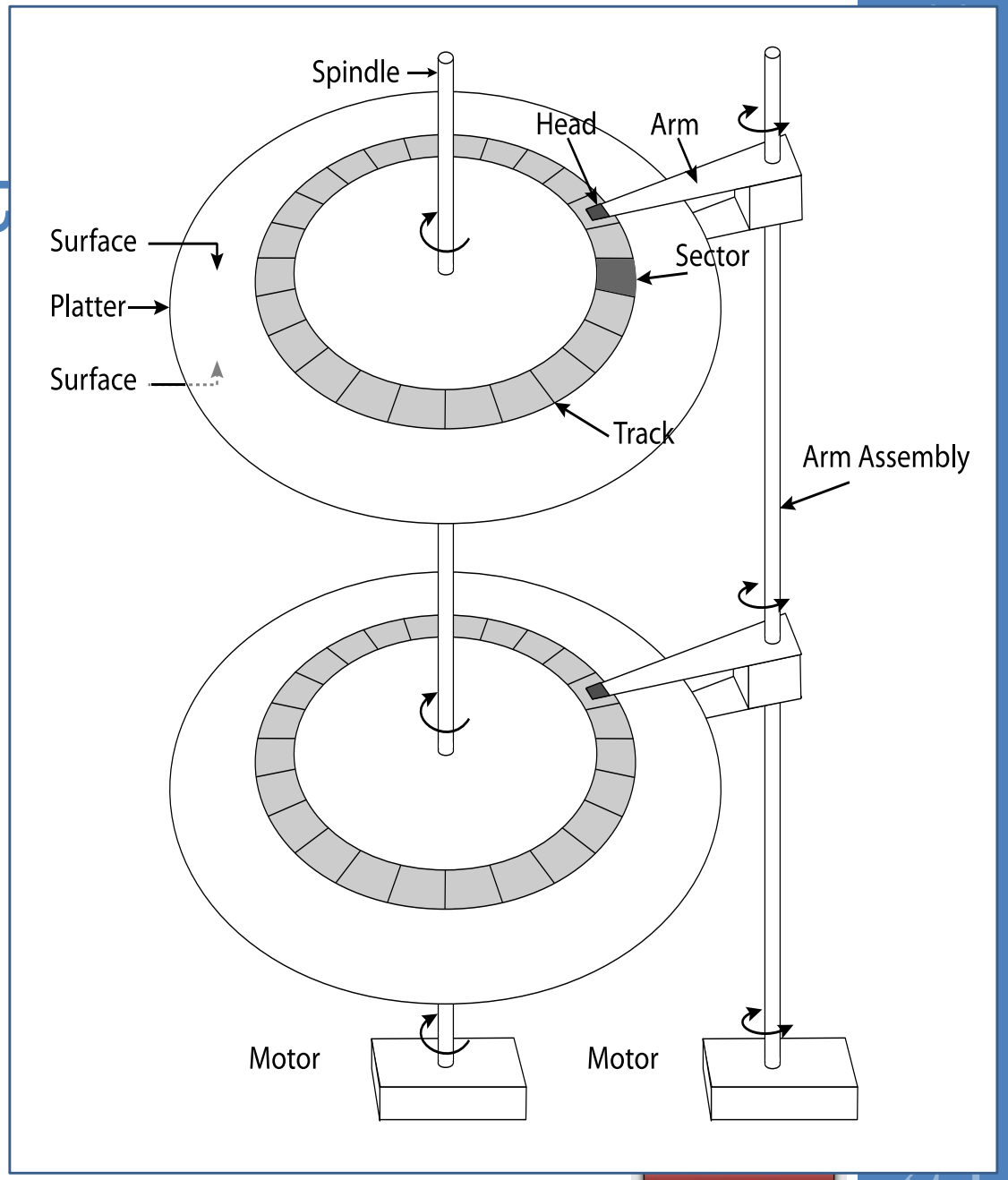
The Amazing Magnet

- 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)



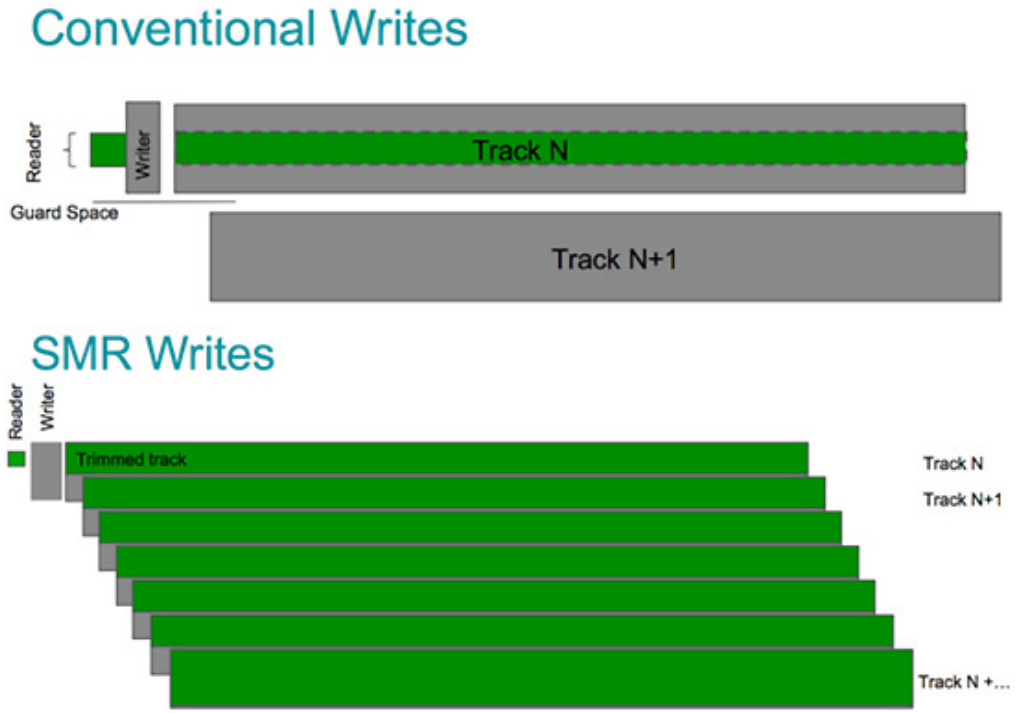
The Amazing Magnet

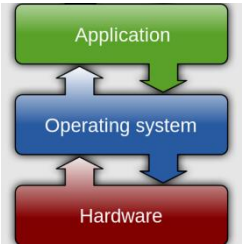
- Track length varies across disk
  - Outside: More sectors per track, higher bandwidth
  - Disk is organized into regions of tracks with same # of sectors/track
  - Only outer half of radius is used
    - Most of the disk area in the outer regions of the disk
- Disks so big that some companies (like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



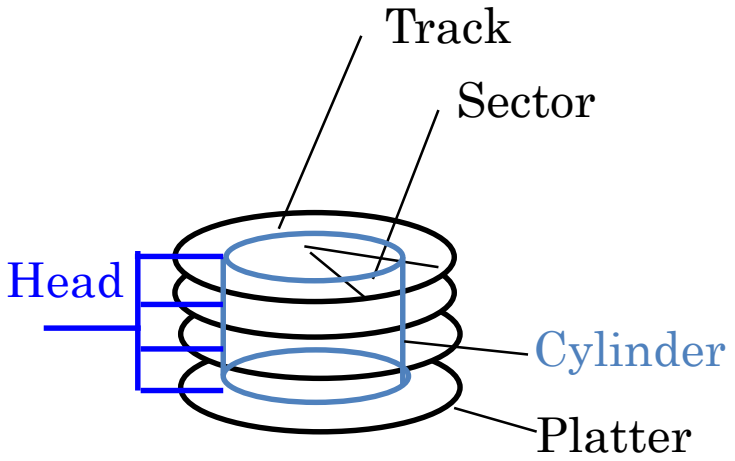
Shingled Magnetic Recording (SMR)

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



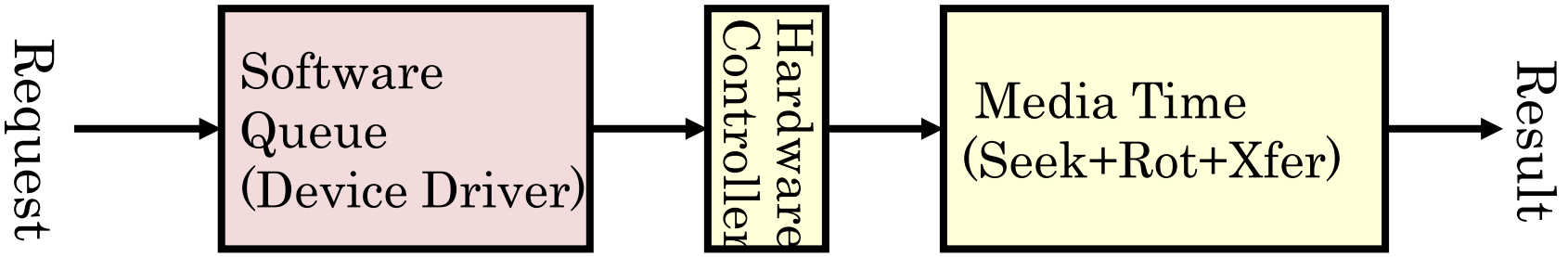


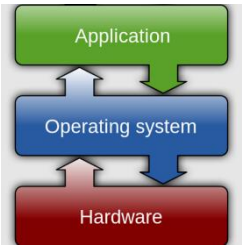
Magnetic Disks



- 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

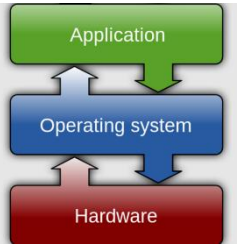
Disk Latency = Queueing Time + Controller time + Seek Time + Rotation Time + Xfer Time





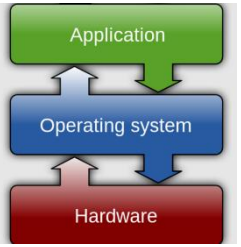
Disk Performance Example

- 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



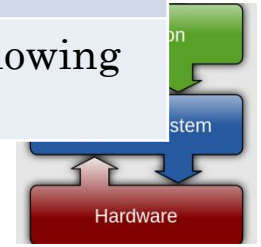
Lots of Intelligence in the Controller

- 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

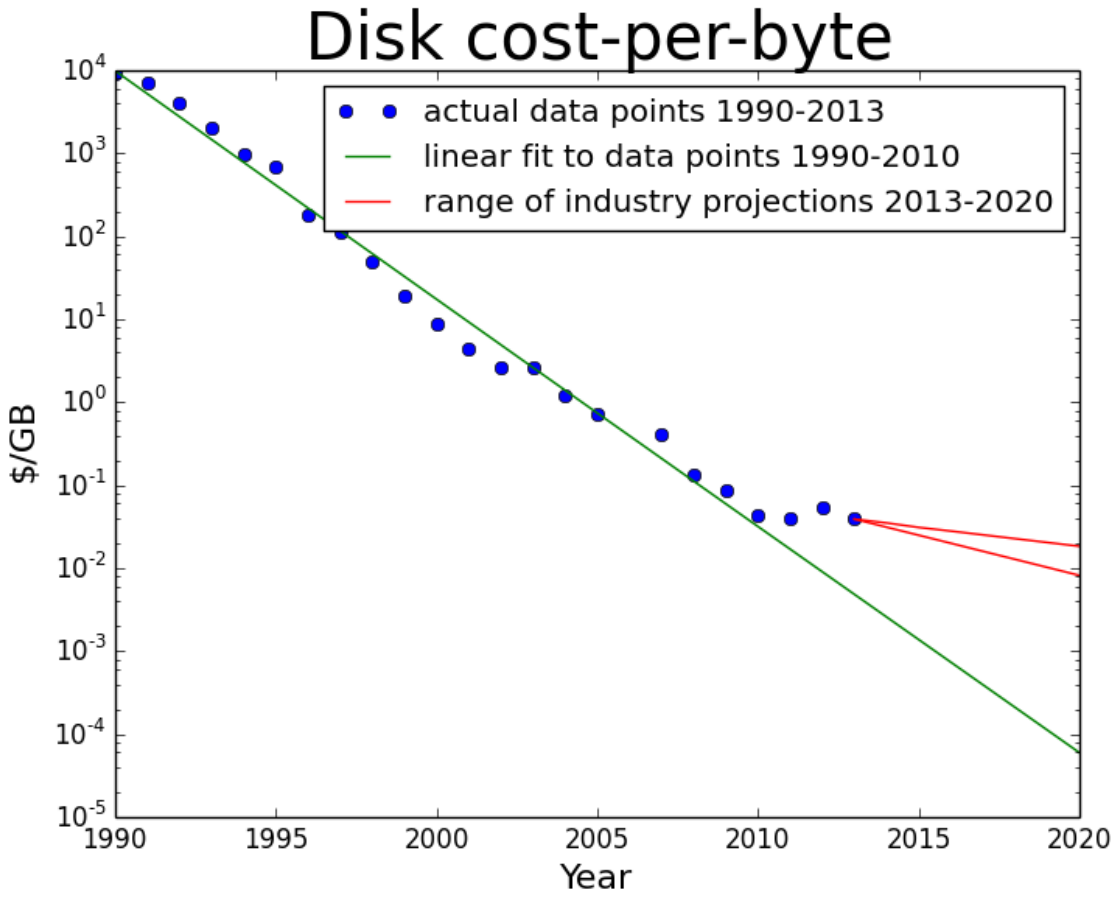


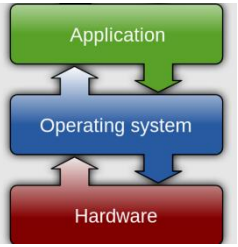
Typical Numbers for Magnetic Disk

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



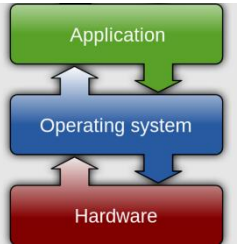
Hard Drive Prices over Time





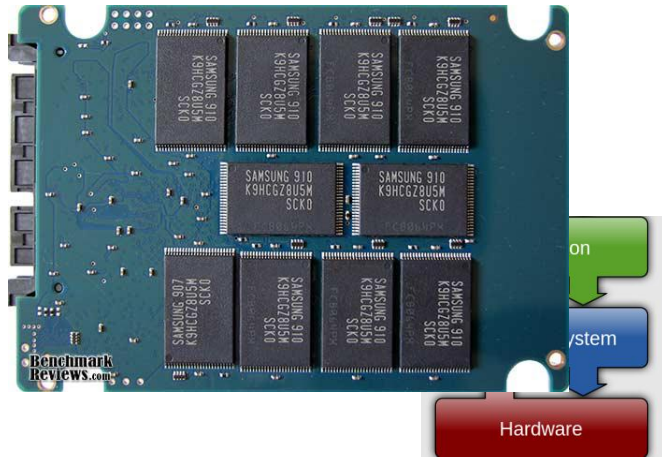
Example of Current HDDs

- Seagate Exos X14 (2018)
  - 14 TB hard disk
    - 8 platters, 16 heads
    - Helium filled: reduce friction and power
  - 4.16ms average seek time
  - 4096 byte physical sectors
  - 7200 RPMs
  - 6 Gbps SATA /12Gbps SAS interface
    - 261MB/s MAX transfer rate
    - Cache size: 256MB
  - Price: $615 (< $0.05/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 !!)

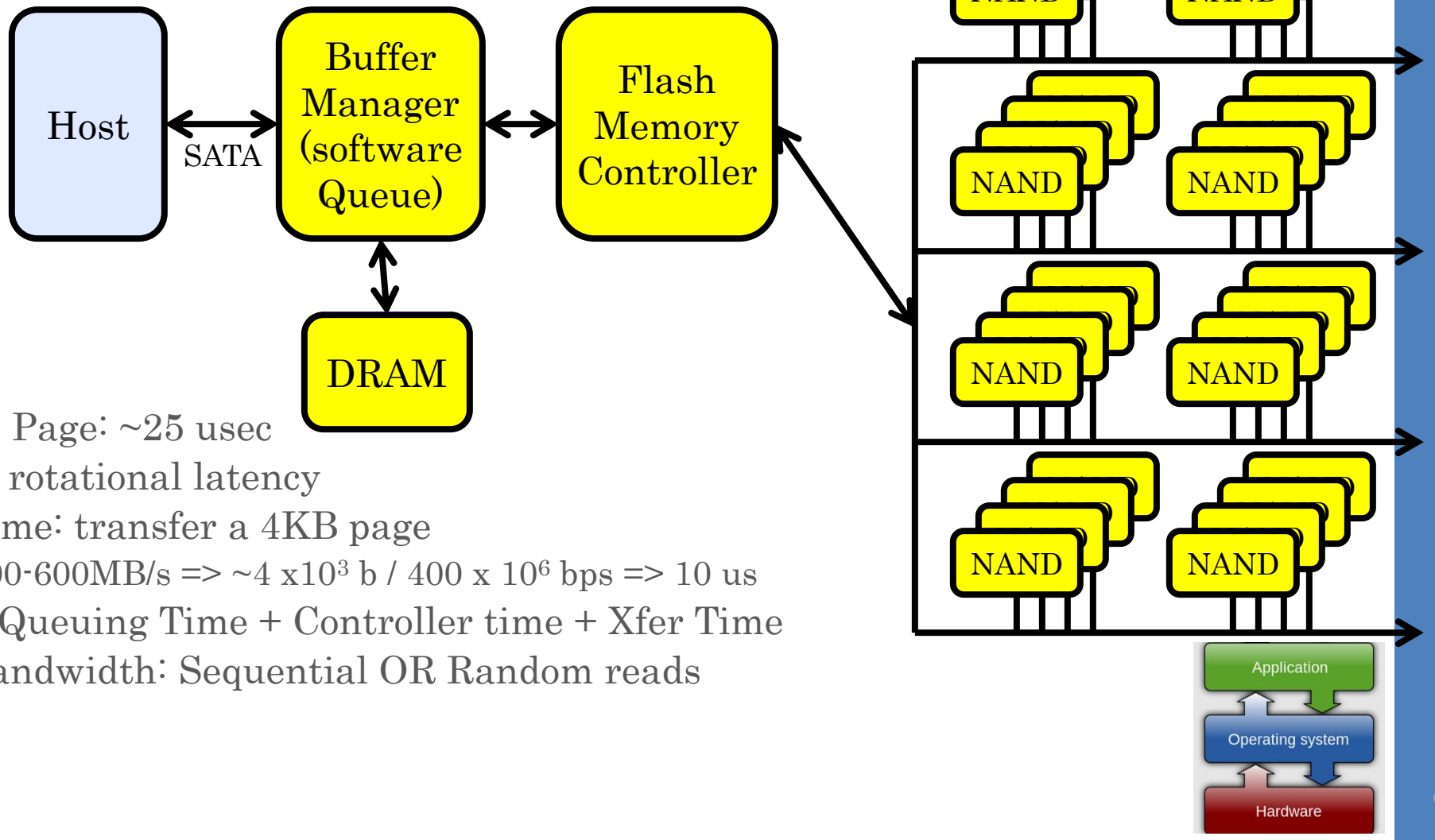


Solid State Disks (SSDs)

- 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!



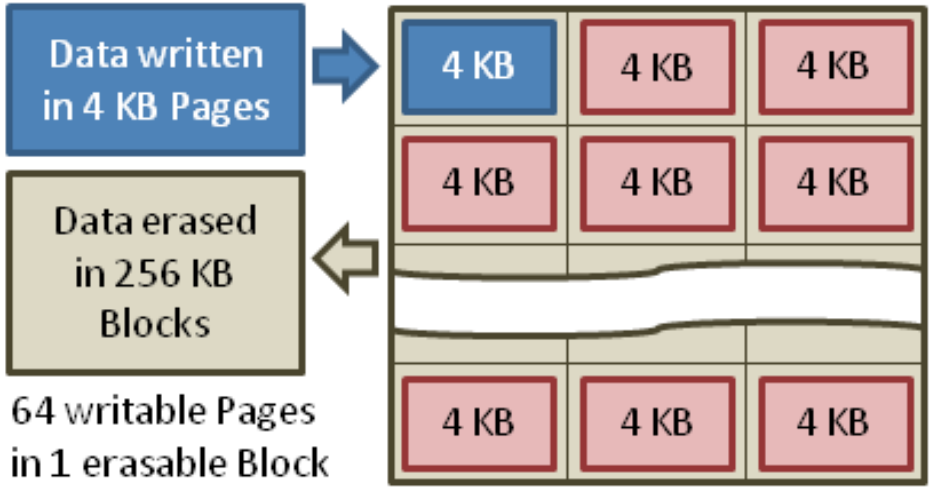
SSD Architecture – Reads



- 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

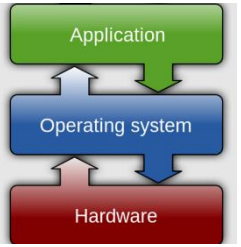
SSD Architecture – Writes

- Writing data is complex! (~200µs – 1.7ms)
  - Can only write to 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 slower than reads
  - erasure 10x slower than writes



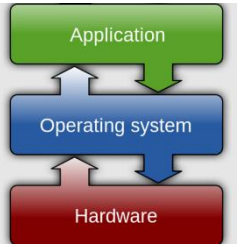
Typical NAND Flash Pages and Blocks

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



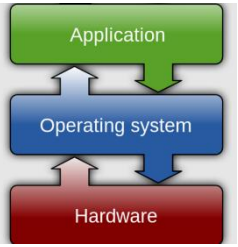
SSD Architecture – Writes

- 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



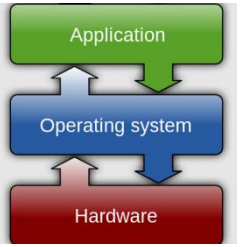
Solution – Two Systems Principles

- 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
- 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

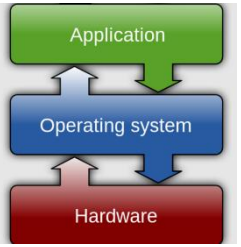
- No need to erase and rewrite entire 256KB block when making small modifications
- SSD controller can assign mappings to spread workload across pages
  - Wear Levelling
- What to do with old versions of pages?
  - Garbage Collection in background
  - Erase blocks with old pages, add to free list



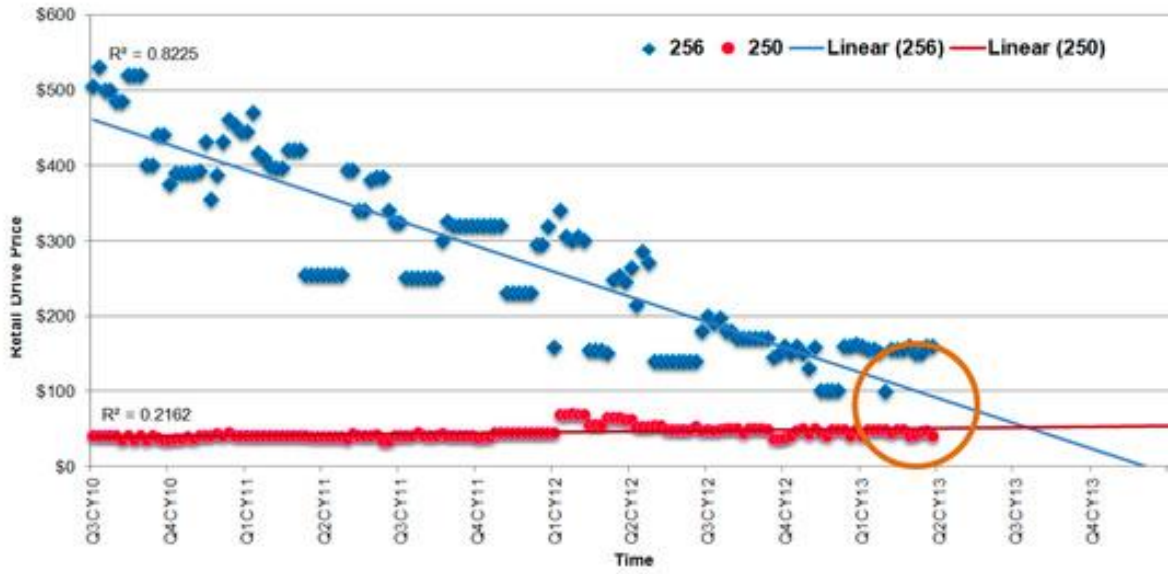
Some "Current" 3.5in SSDs

- Seagate Nytro SSD: 15TB (2017)
  - Dual 12Gb/s interface
  - Seq reads 860MB/s
  - Seq writes 920MB/s
  - Random Reads (IOPS): 102K
  - Random Writes (IOPS): 15K
  - Price (Amazon): $6325 ($0.41/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: ~ $50K? ($0.50/GB)

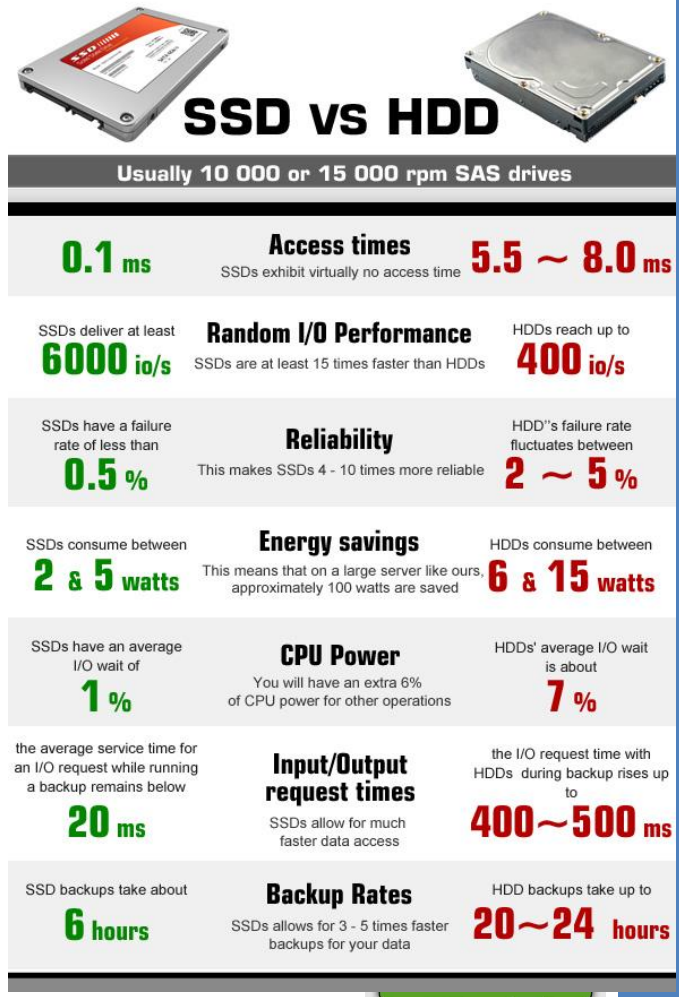


HDD vs. SSD Comparison

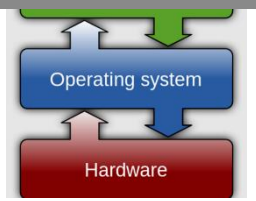


Price Crossover Point for HDD and SSD

	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

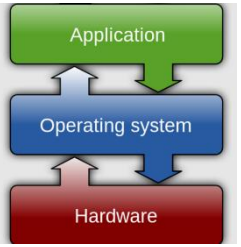


SSD prices drop much faster than HDD



SSD Summary

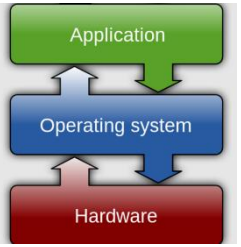
- Pros (vs. hard disk drives):
  - Low latency, high throughput (eliminate seek/rotational delay)
  - No moving parts:
    - Very light weight, low power, silent, very shock insensitive
  - Read at memory speeds (limited by controller and I/O bus)
- Cons
  - Small storage (0.1-0.5x disk)
  - Hybrid alternative: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



A Bit of I/O Performance

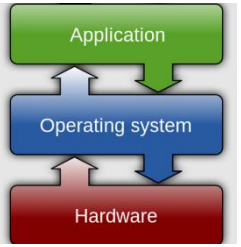
Recall: Times (s) and Rates (op/s)

- 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, GLOP/s)
- Performance???
  - Operation time (4 mins to run a mile…)
  - Rate (mph, mpg, …)



Basic Performance Concepts

- Response Time or Latency: Time to perform an operation(s)
- Bandwidth or Throughput: Rate at which operations are performed (op/s)
  - Files: MB/s, Networks: Mb/s, Arithmetic: 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

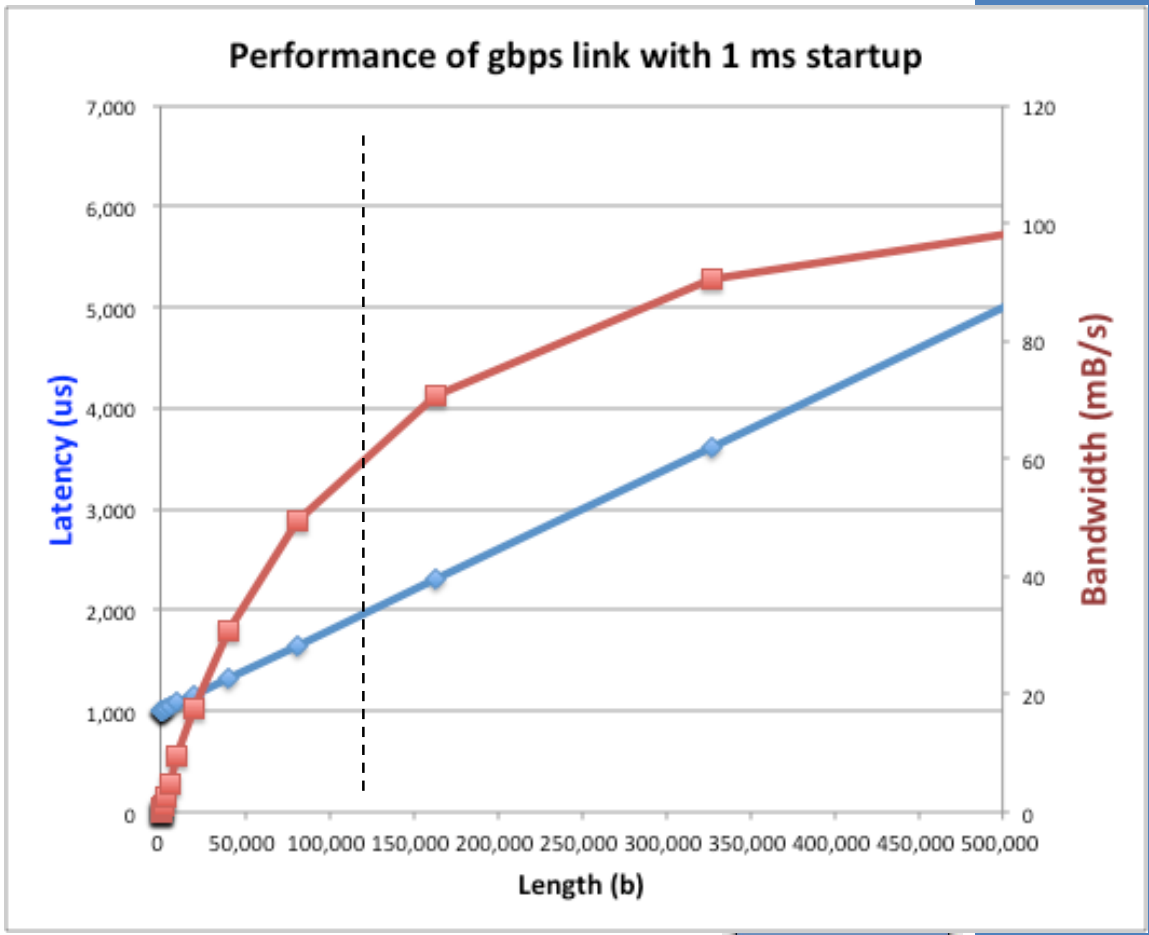


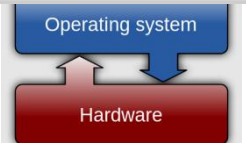
Example (Fast Network)

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

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

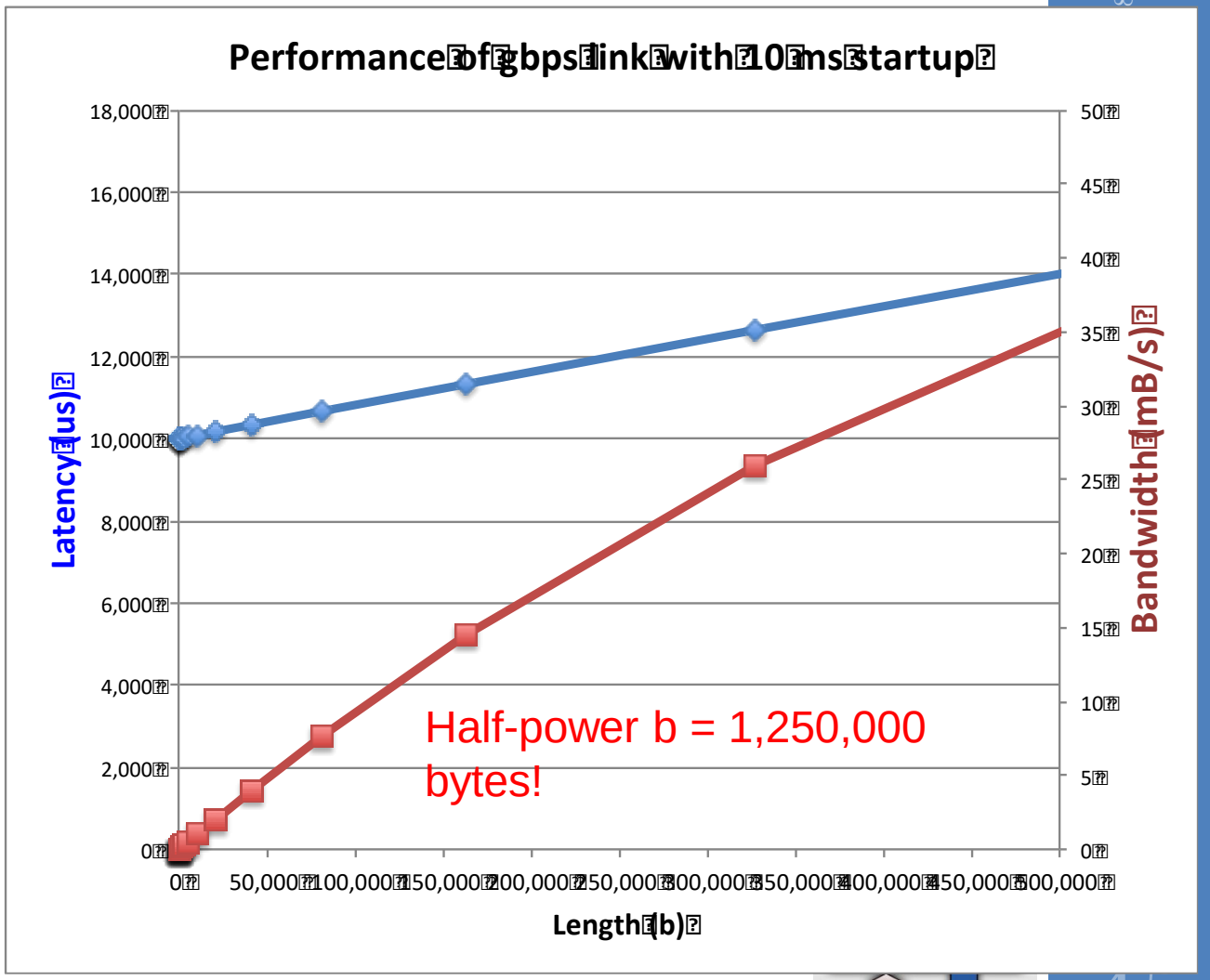
- Half-power Bandwidth: $E(b) = \frac{B}{2}$
- For this example, half-power bandwidth occurs at $b = 125$ KB





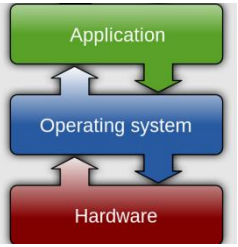
Example: 10 ms Startup Cost (e.g., Disk)

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



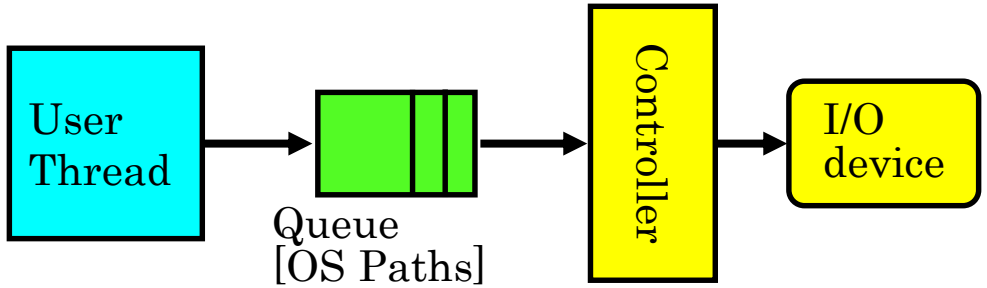
What Determines Peak BW for I/O?

- 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…

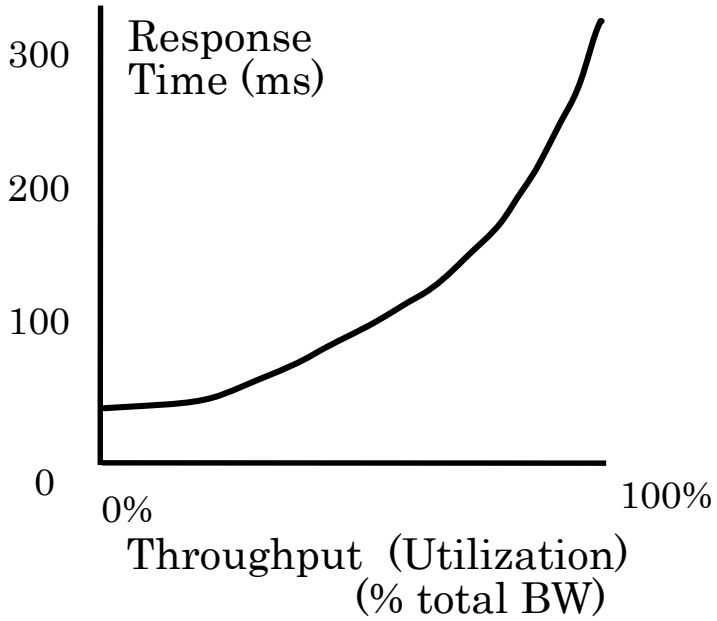


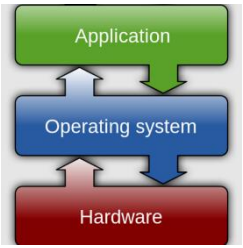
Overall I/O performance

- 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



Response Time = Queue + I/O device service time





Recall: I/O and Storage Layers

Application / Service

High Level I/O — *Streams*

Low Level I/O — *File Descriptors*

Syscall — *open(), read(), write(), close(), …*

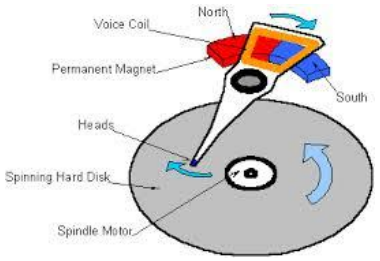
What we covered before

File System — *Files/Directories/Indexes*

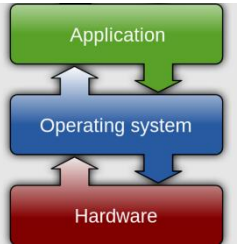
What we will cover next…

I/O Driver — *Commands and Data Transfers*

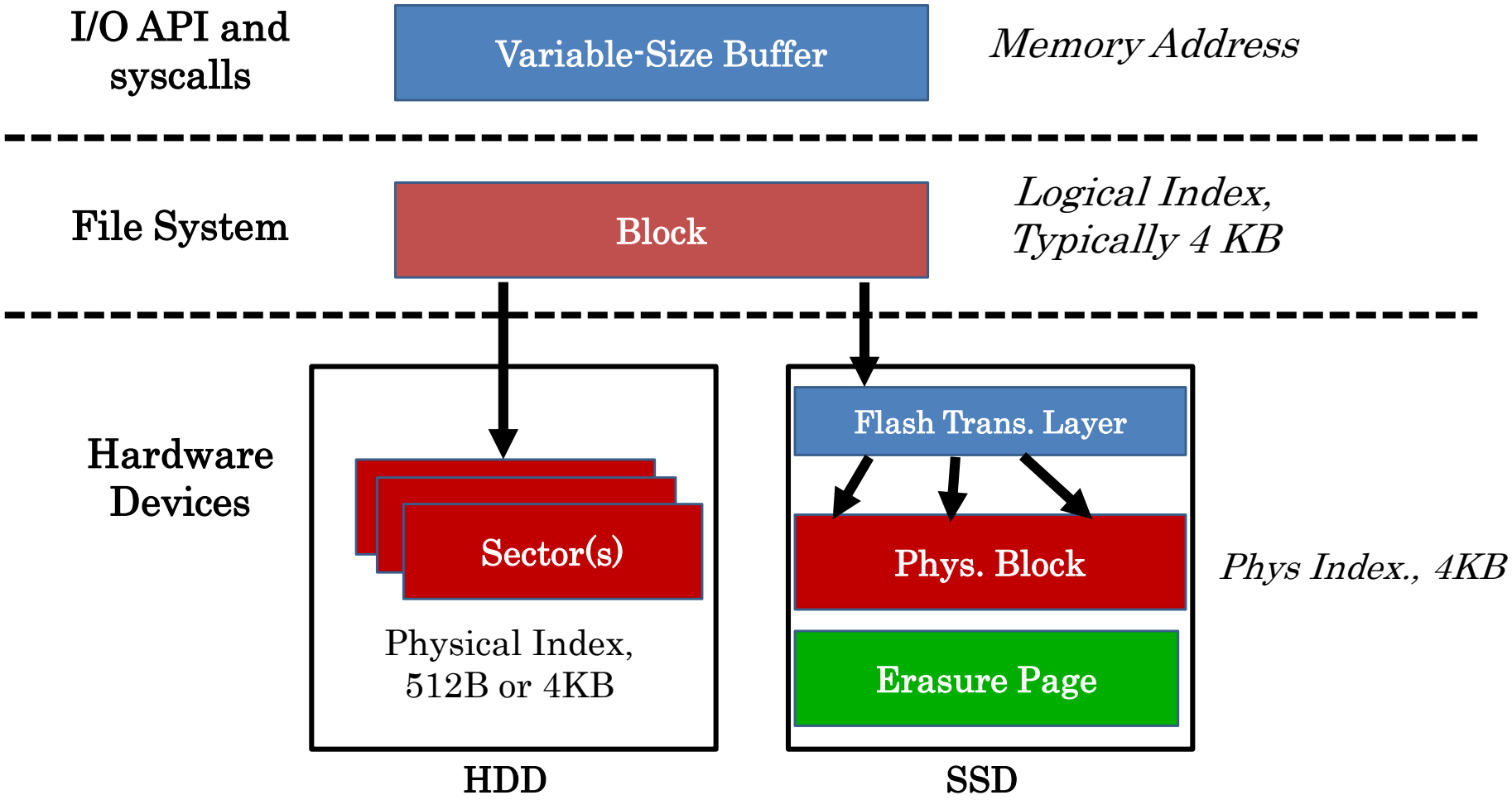
Disks, Flash, Controllers, DMA

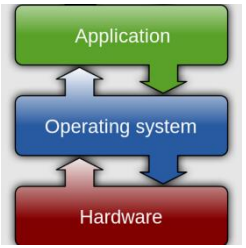


What we just covered…



From Storage to File Systems





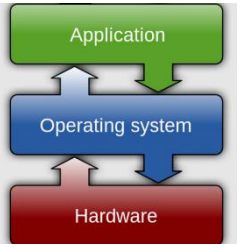
Building a File System

Classic OS situation

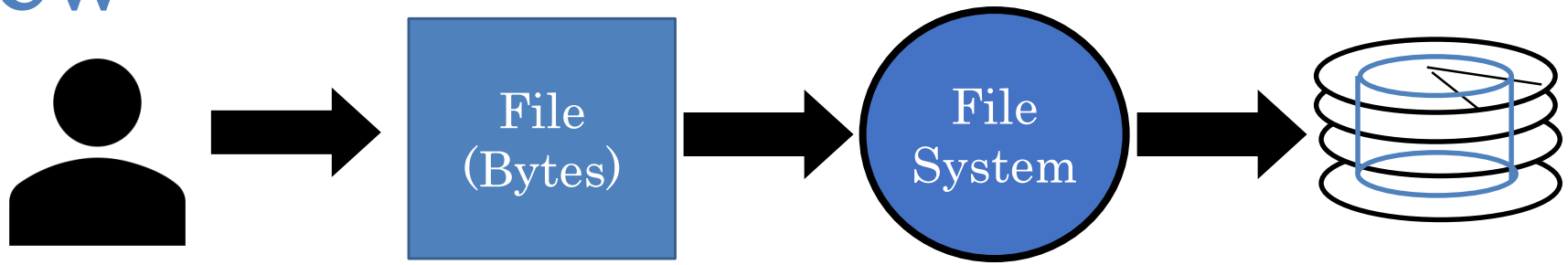
Take limited hardware interface (array of blocks) and provide a more convenient/useful interface with:

- Naming: Find file by name, not block numbers
- Organize file names with directories

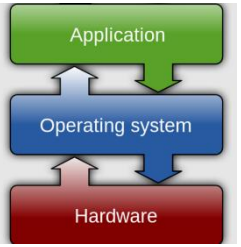
- Organization: Map files to blocks
- Protection: Enforce access restrictions
- Reliability: Keep files intact despite crashes, hardware failures, etc.



Translation from User to System View

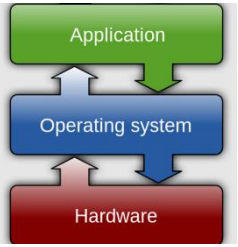


- What happens if user says: "give me bytes 2 – 12?"
  - Fetch block corresponding to those bytes
  - Return just the correct portion of the block
- What about writing bytes 2 – 12?
  - Fetch block, modify relevant portion, write out block
- Everything inside file system is in terms of whole-size blocks
  - Actual disk I/O happens in blocks
  - read/write smaller than block size needs to translate and buffer



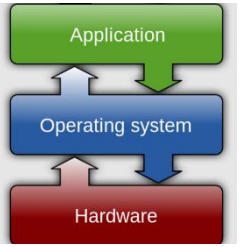
Disk Management

- The disk is accessed as a linear array of sectors.
- How to identify a sector?
  - Physical position
    - Sector is a vector [cylinder, surface, sector]
    - Not used anymore
    - OS/BIOS must deal with bad sectors
  - Logical Block Addressing (LBA)
    - Every sector has an integer address
    - Controller translates from address to physical position
    - Shields OS from disk structure



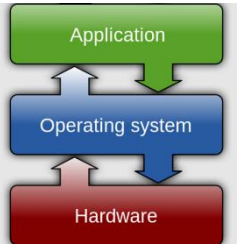
What Does the File System Need?

- Track free disk blocks
  - Need to know where to put newly written data
- Track which blocks contain data for which files
  - Need to know where to read a file from
- Track files in a directory
  - Find list of file's blocks given its name
- Where do we maintain all of this?
  - **Somewhere on disk**



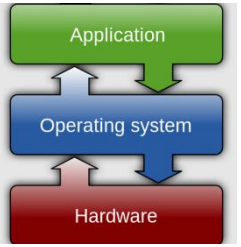
Data Structures on Disk

- Bit different than data structures in memory
- Access a block at a time
  - Can't efficiently read/write a single word
  - Have to read/write full block containing it
  - Ideally want **sequential** access patterns
- Durability
  - Ideally, file system is in meaningful state upon shutdown
  - This obviously isn't always the case…



Critical Factors in File System Design

- (Hard) Disks Performance !!!
  - Maximize sequential access, minimize seeks
- Open before Read/Write
  - Can perform protection checks and look up where the actual file resource are, in advance
- Size is determined as they are used !!!
  - Can write (or read zeros) to expand the file
  - Start small and grow, need to make room
- Organized into directories
  - What data structure (on disk) for that?
- Need to carefully allocate / free blocks
  - Such that access remains efficient



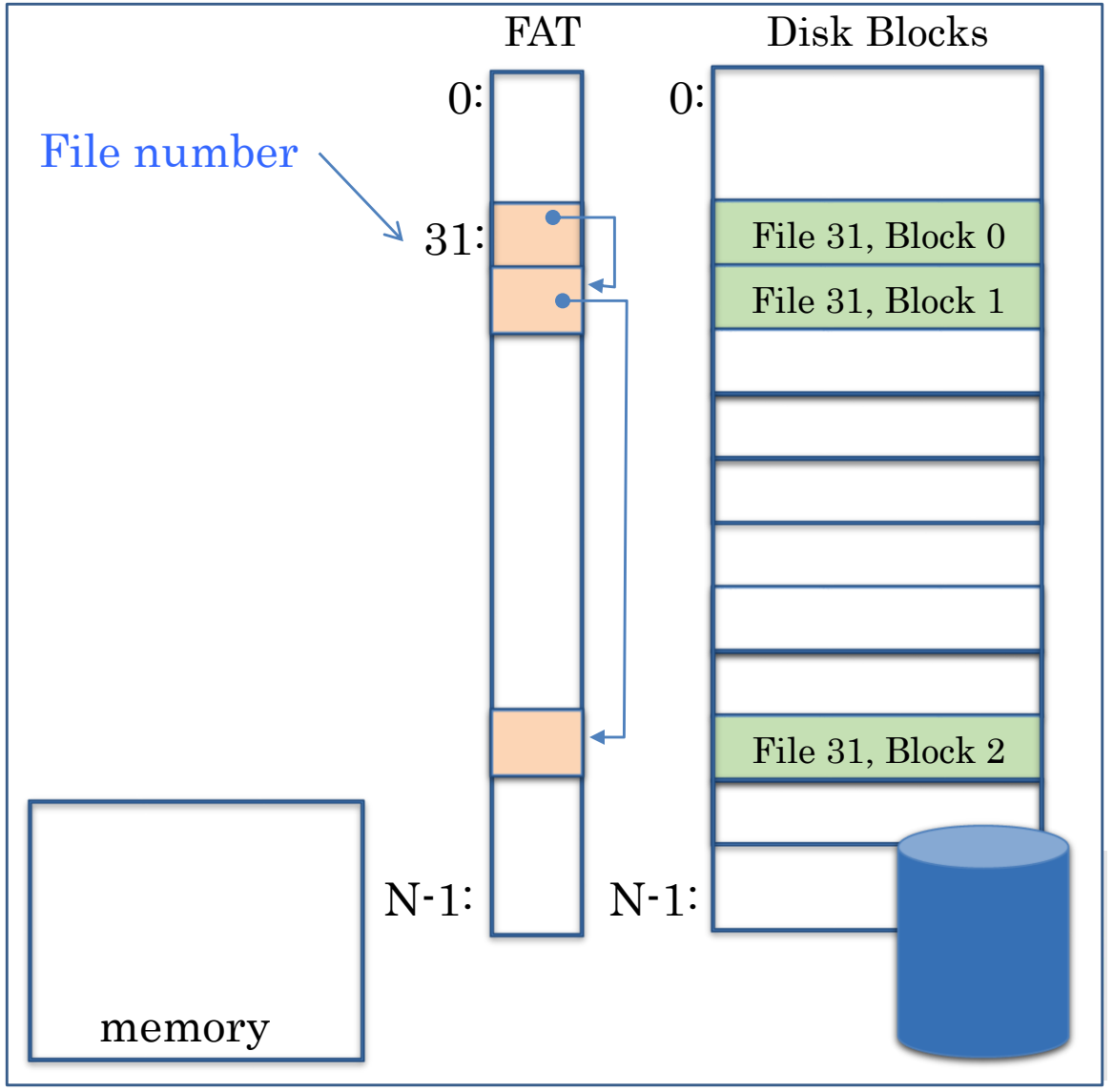
FAT: File Allocation Table

MS-DOS, 1977

Still widely used!

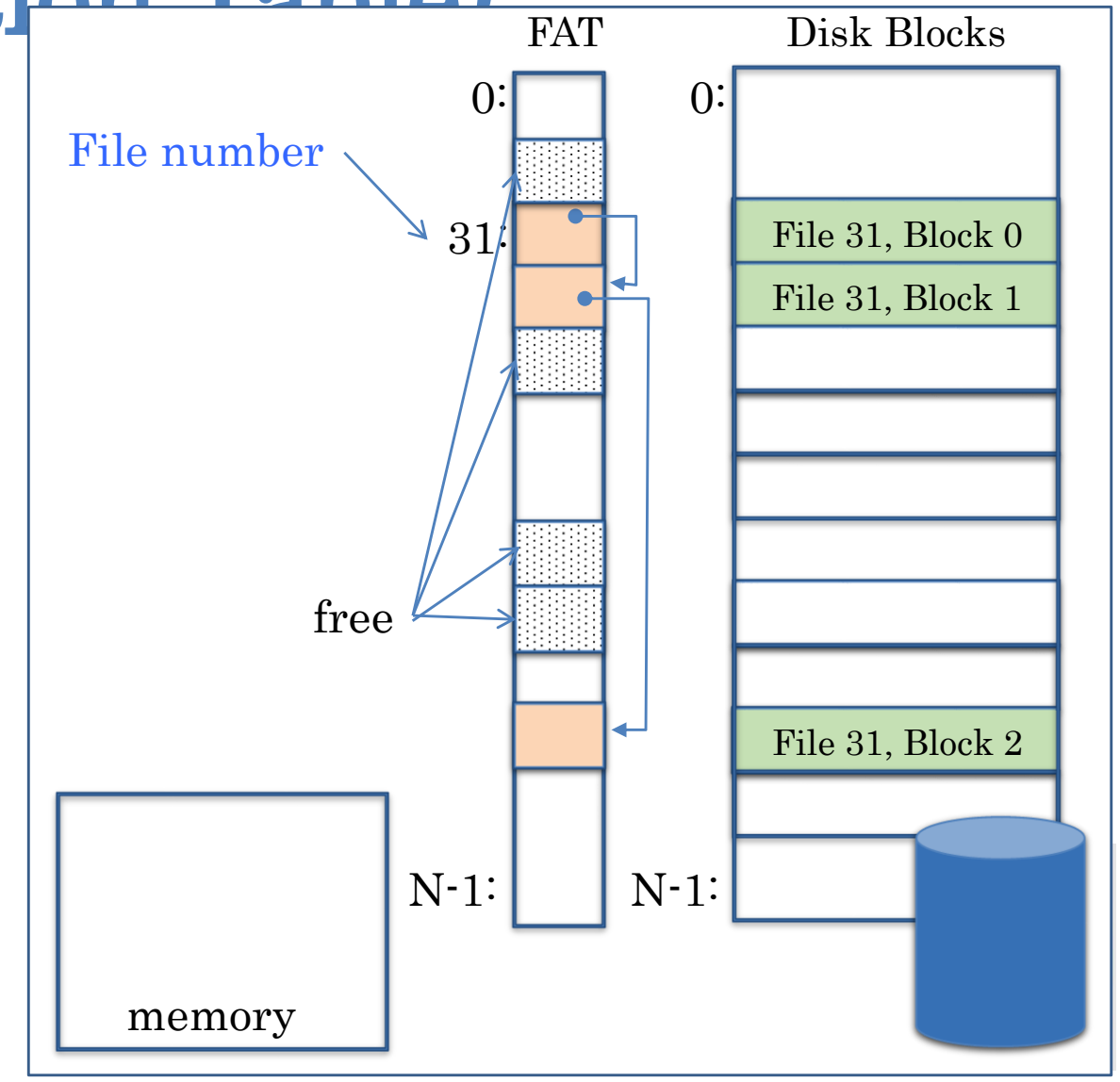
FAT (File Allocation Table)

- Assume (for now) we have a way to translate a path to a "file number"
  - i.e., a directory structure
- Disk Storage is a collection of Blocks
  - Just hold file data (offset o = <B, x>)
- Example: file_read 31, <2, x>
  - Index into FAT with file number
  - Follow linked list to block
  - Read the block from disk into memory



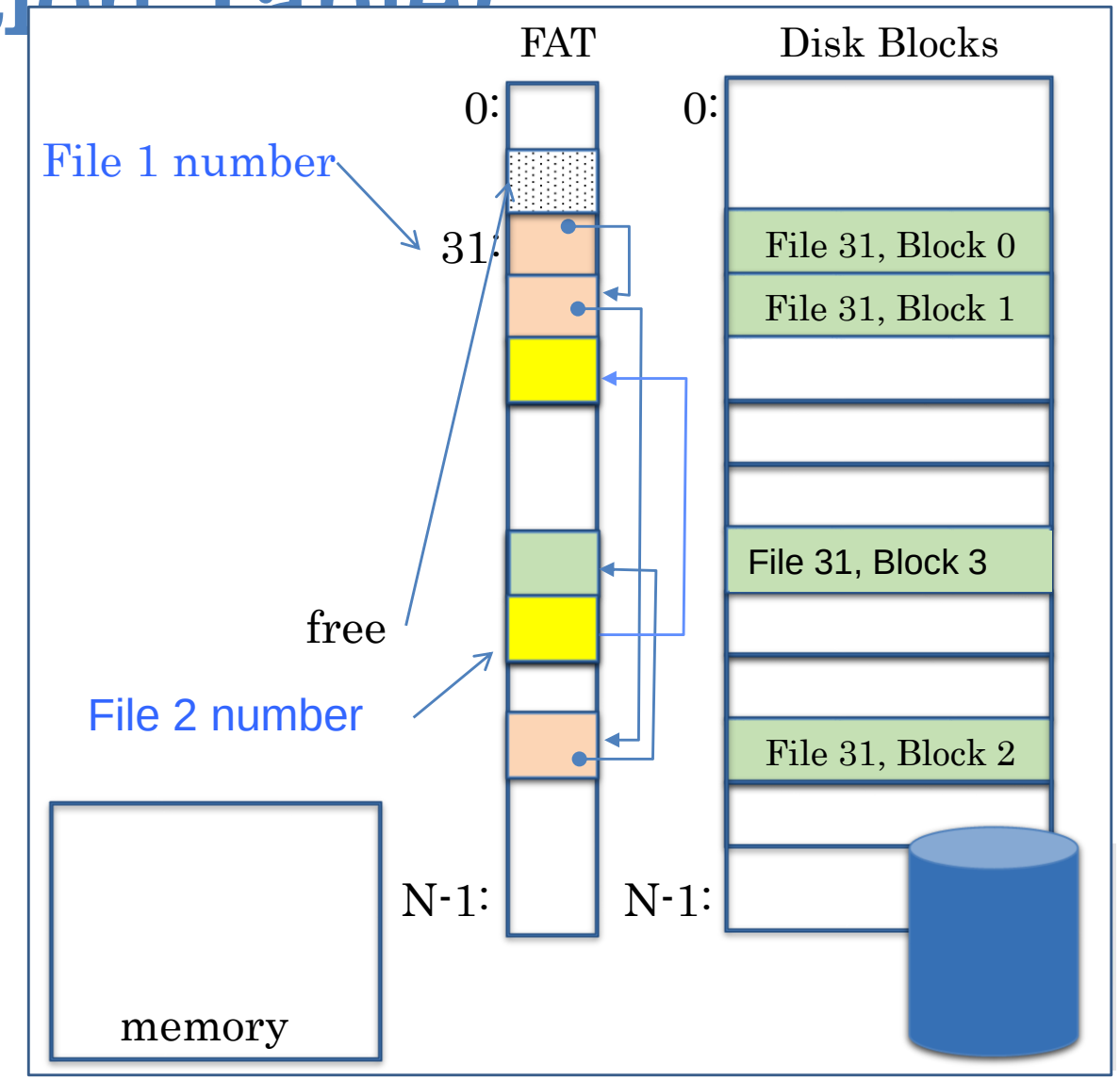
FAT (File Allocation Table)

- File is a collection of disk blocks
- FAT is linked list 1-1 with blocks
- File number is index of root of block list for the file
- File offset: block number and offset within block
- Follow list to get block number
- Unused blocks marked free
  - Could require scan to find
  - Or, could use a free list



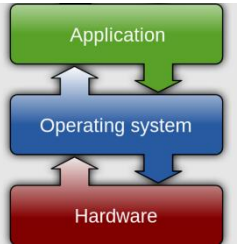
FAT (File Allocation Table)

- Where is FAT stored?
  - On disk
- How to format a disk?
  - Zero the blocks, mark FAT entries "free"
- How to quick format a disk?
  - Mark FAT entries "free"
- Simple: can be implemented in device firmware

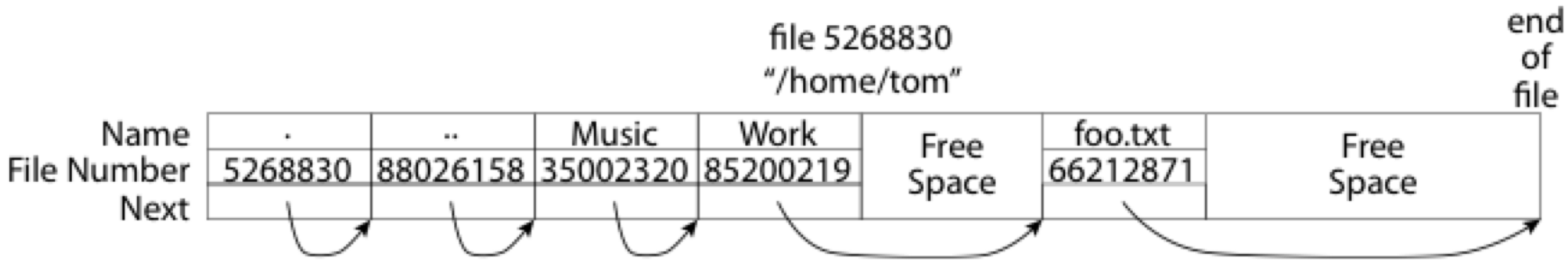


How to get the File Number?

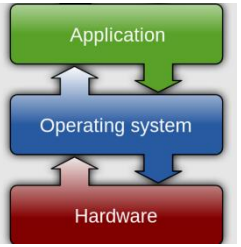
- Look up in directory structure
- A directory is a file containing <file_name : file_number> mappings
  - File number could be a file or another directory
  - Operating system stores the mapping in the directory in a format it interprets
  - Each <file_name : file_number> mapping is called a directory entry
- Process isn't allowed to read the raw bytes of a directory
  - The read function doesn't work on a directory
  - Instead, see `readdir`, which iterates over the map without revealing the raw bytes
- Why shouldn't the OS let processes read/write the bytes of a directory?



FAT: Directories

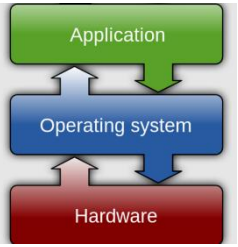


- A directory is a file containing <file_name: file_number> mappings
- Free space for new entries
- In FAT: file attributes are kept in directory (!!!)
- Each directory a linked list of entries
- Where do you find root directory ("/")?



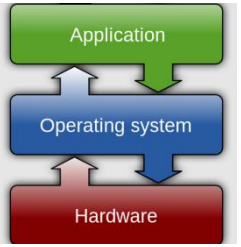
FAT Directory Structure

- How many disk accesses to resolve "/my/book/count"?
  - Read in file header for root (fixed spot on disk)
  - Read in first data block for root
    - Table of file name/index pairs. Search linearly – ok since directories typically very small
  - Read in file header for "my"
  - Read in first data block for "my"; search for "book"
  - Read in file header for "book"
  - Read in first data block for "book"; search for "count"
  - Read in file header for "count"
- Current working directory: Per-address-space pointer to a directory used for resolving file names
  - Allows user to specify relative filename instead of absolute path (say CWD="/my/book" can resolve "count")



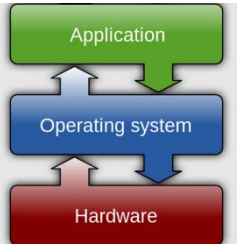
Many Huge FAT Security Holes!

- FAT has no access rights
- FAT has no header in the file blocks
- Just gives an index into the FAT
  - (file number = block number)



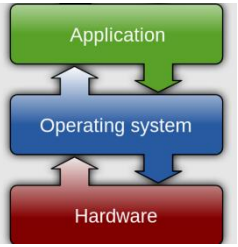
Conclusion: I/O Devices

- I/O Devices Types:
  - Many different speeds (0.1 bytes/sec to GBytes/sec)
  - Different Access Patterns:
    - Block Devices, Character Devices, Network Devices
  - Different Access Timing:
    - Blocking, Non-blocking, Asynchronous
- I/O Controllers: Hardware that controls actual device
  - Processor Accesses through I/O instructions, load/store to special physical memory
- 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



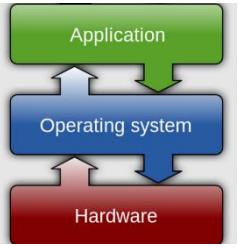
Conclusion: Storage Devices

- 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
  - SDD: Queuing time + controller + transfer (erasure & wear)
- Systems (e.g., file system) designed to optimize performance and reliability
  - Relative to performance characteristics of underlying device
- Bursts & High Utilization introduce queuing delays



Conclusion: File Systems

- File System:
  - Transforms blocks into Files and Directories
  - Optimize for size, access and usage patterns
  - Maximize sequential access, allow efficient random access
  - Projects the OS protection and security regime (UGO vs ACL)
- Naming: translating from user-visible names to actual sys resources
  - Directories provide naming for local file systems
  - Linked or tree structure stored in files
- Components: directory, index, storage blocks, free list
- File Allocation Table (FAT) – simple and primitive
  - I-number = FAT index, FAT 1-1 with disk blocks, file is singly-link list of FAT=Blocks, directory is essentially file of <name, index, attributes> at known location
  - Linear search – for block, for i-number



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