Storage - Disks

I/O device

Filesystem

Slides include materials from *Operating System Concepts*, 7th ed., by Silbershatz, Galvin, & Gagne, *Distributed Systems: Principles & Paradigms*, 2nd ed. By Tanenbaum and Van Steen, and *Modern Operating Systems*, 2nd ed., by Tanenbaum

Storage

- **Where is your stuff when you turn your machine off?**
  - In “the cloud”!
- **Where does the cloud store your stuff?**
- **Various storage devices**
  - Magnetic tape
  - “Hard disk”
  - CD-ROM
  - Flash memory
- **What do they have in common? How do they differ?**

Storage characteristics

- ***"Non-volatile"***
  - Write; power-off; read: should return same value
    - *Years* later!
- ***Slow* (compared to RAM)**
  - Milliseconds or seconds instead of nanoseconds Can't execute programs from it (must fetch first)
- ***"Block oriented"***
  - Fetch and store large clumps of data
    - Spinning disk: 512/4096 bytes
    - CD-ROM: 2048 bytes
    - Flash: "hard to say"

Time to fetch 1 byte == time to fetch 1 block

Storage Model

- **Address space**
  - Blocks have numbers
  - Ancient times: (C,H,S) tuple
    - C, H, S were geometric features of old disks
  - Modern: (LBA)
    - “Logical Block Address” runs from 0..N

Storage Model

- **Reading and writing**
  - Read-block(N) ⇒ [huge delay] ⇒ block else failure
    - Sometimes a re-try helps (usually not)
  - Write-block(N) ⇒ [huge delay] ⇒ “ok” else failure
    - Failures usually indicate “obvious” bad things
      - The disk motor stopped
    - “Successful” write doesn't *guarantee* a later read
    - Devices usually contain a power buffer
      - A write operation either completes or has no effect
  - Modern devices support “tagged command queueing”
    - OS can issue multiple requests, each has a “tag”
    - Device can return results in any order, with the OS's tag

Command Queueing In Act

- **Disks serve read requests out of order**
  - OS queues: “read 37”, “read 83”, “read 2”
    - Disk returns 37, 2, 83
      - Great! That's why we buy smart disks and queue multiple requests
- **Disks serve *write* requests out of order, too**
  - OS queues “write 23”, “write 24”, “write 1000”, “read 4-8”, ...
    - Disk writes 24, 23 (!!), gives you 4, 5, 6, 7, 8, writes 1000
    - What if power fails before last write?
    - What if power fails between first two writes?

Command Queueing In Action

- **How can OS ensure data-structure integrity?**
  - Special commands
    - “Flush all pending writes”
      - Think “my disk is 'modern'”, think “disk barrier”
      - Can even queue a flush to apply to all before now
      - Can apply these “barrier” flushes to subsets of requests
      - Rarely used by operating system
    - “Disable write cache”
      - Think “please don't be quite so modern”

Examples

- **“Hard drive”**
  - Parts
  - Execution model
- **NAND flash memory**
  - Challenges
    - Write amplification
    - Wear leveling

Anatomy of a Hard Drive

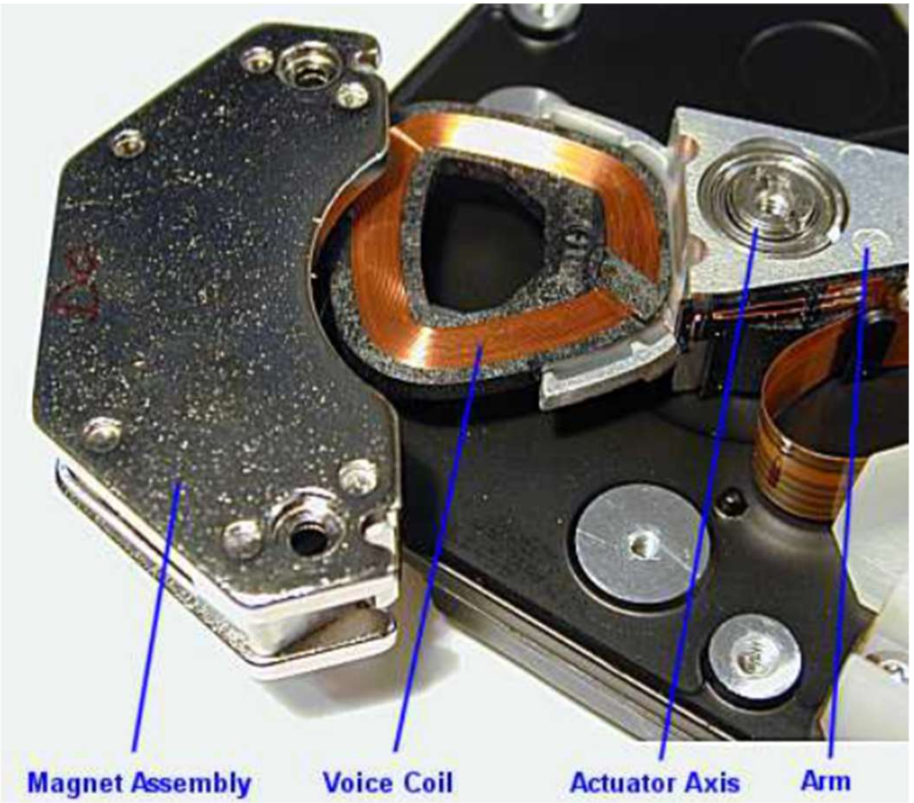
- **Information is written to and read from the platters by the *read/write heads* on the end of the *disk arm***

Taken from "How Hard Disks Work"
http://computer.howstuffworks.com/hard-disk2.htm

https://www.youtube.com/watch?v=NtPc0jI21i0

Anatomy of a Hard Drive

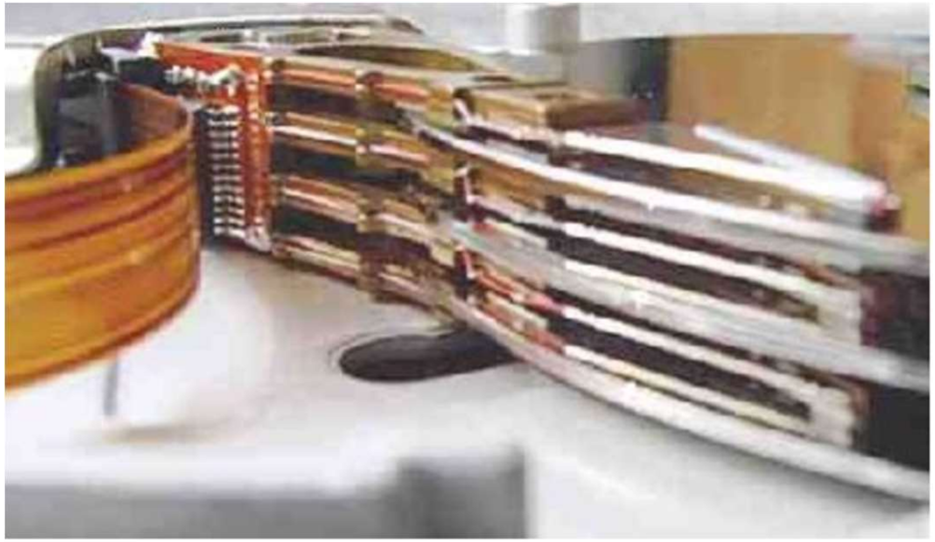
- **The arm is moved by a voice coil actuator**
- **Slow, as computers go**
  - Acceleration time
  - Travel time



Taken from "Hard Disk Drives"
http://www.pcguide.com/ref/hdd

Anatomy of a Hard Drive

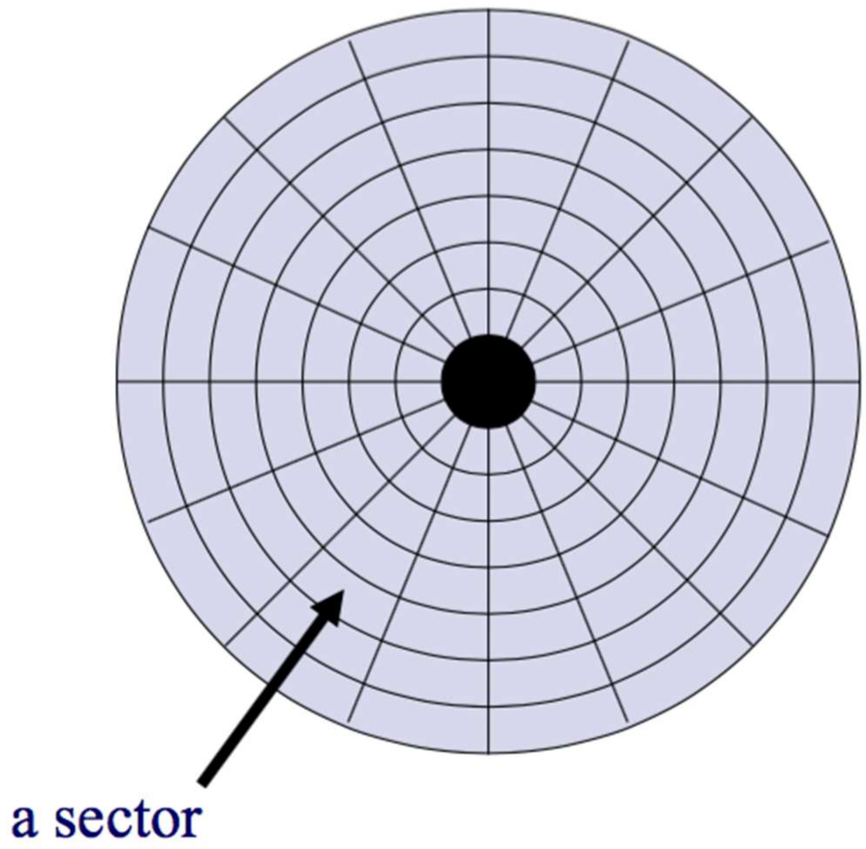
- Both sides of each platter store information
- Each side of a platter is called a *surface*
- Each surface has its own read/write head



Taken from "How Hard Disks Work"
http://computer.howstuffworks.com/hard-disk2.htm

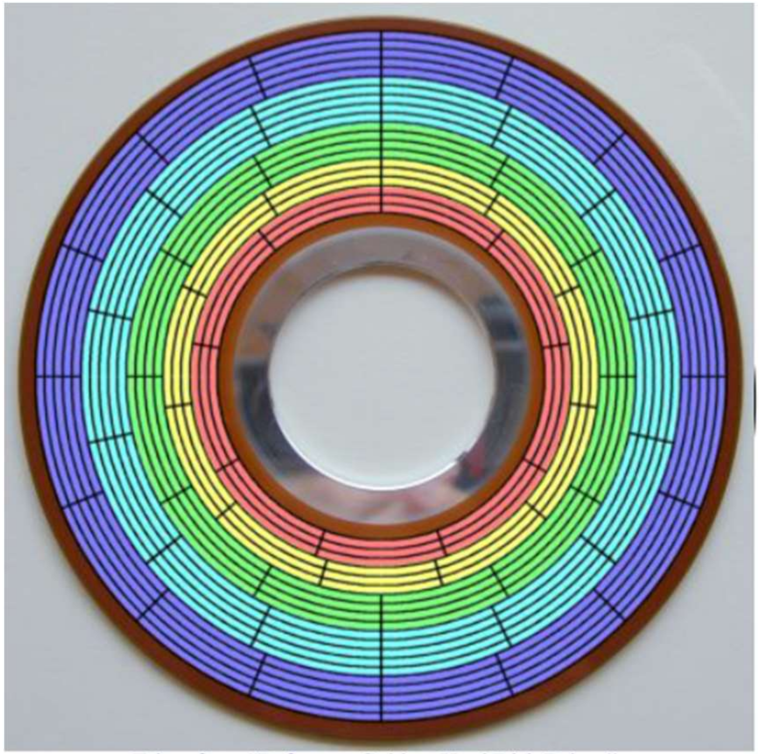
Anatomy of a Hard Drive

- **Each surface is divided by concentric circles, creating *tracks***
- **These tracks are further divided into *sectors***
- **A sector is the smallest unit of data transfer to or from the disk**
  - 512 bytes – traditional disks
  - 2048 bytes – CD-ROMs
  - 4096 bytes – 2010 disks
    - (pretend to be 512!)
- **“Sector address”**
  - “C/H/S”



Anatomy of a Hard Drive, Actual

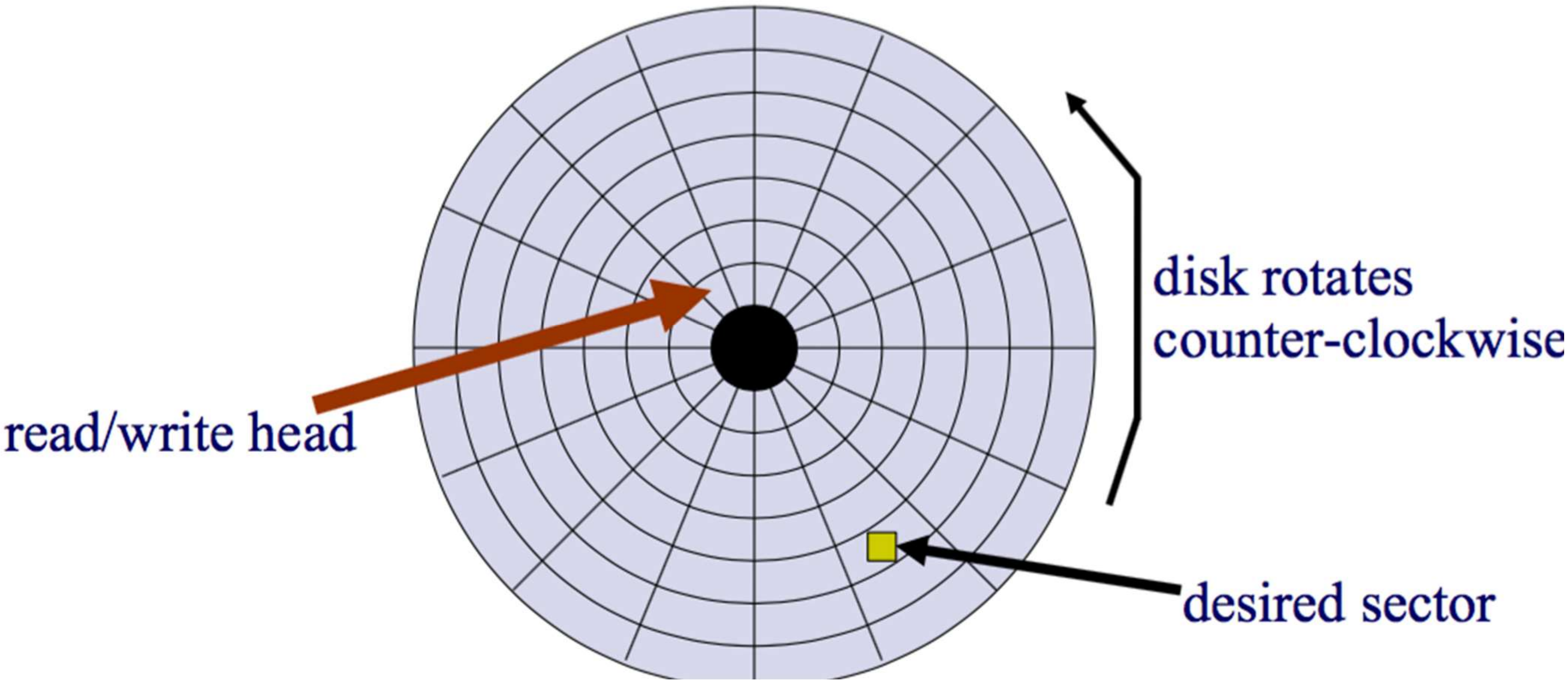
- **Modern hard drives use *zoned bit recording***
  - Disk has tables to map track# to #sectors
  - Sectors are all roughly the same linear length
  - LBA "sector address" names a sector, like "page number" names a frame



Taken from "Reference Guide – Hard Disk Drives"
http://www.storagereview.com/map/lm.cgi/zone

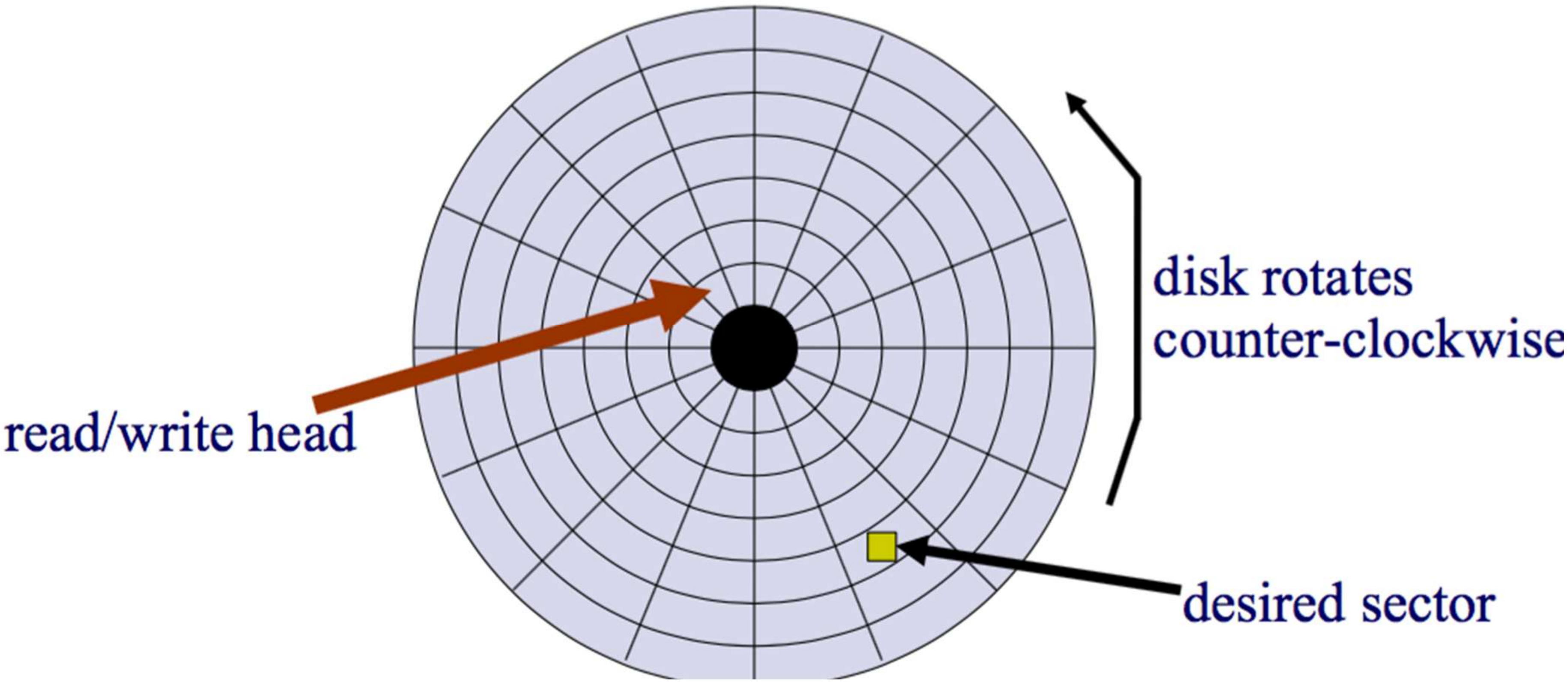
Anatomy of a Hard Drive

- **We need to do two things to transfer a sector**
  1. Move the read/write head to the appropriate track ("seek time")
  2. Wait until the desired sector spins around ("rotational delay"/"rotational latency")



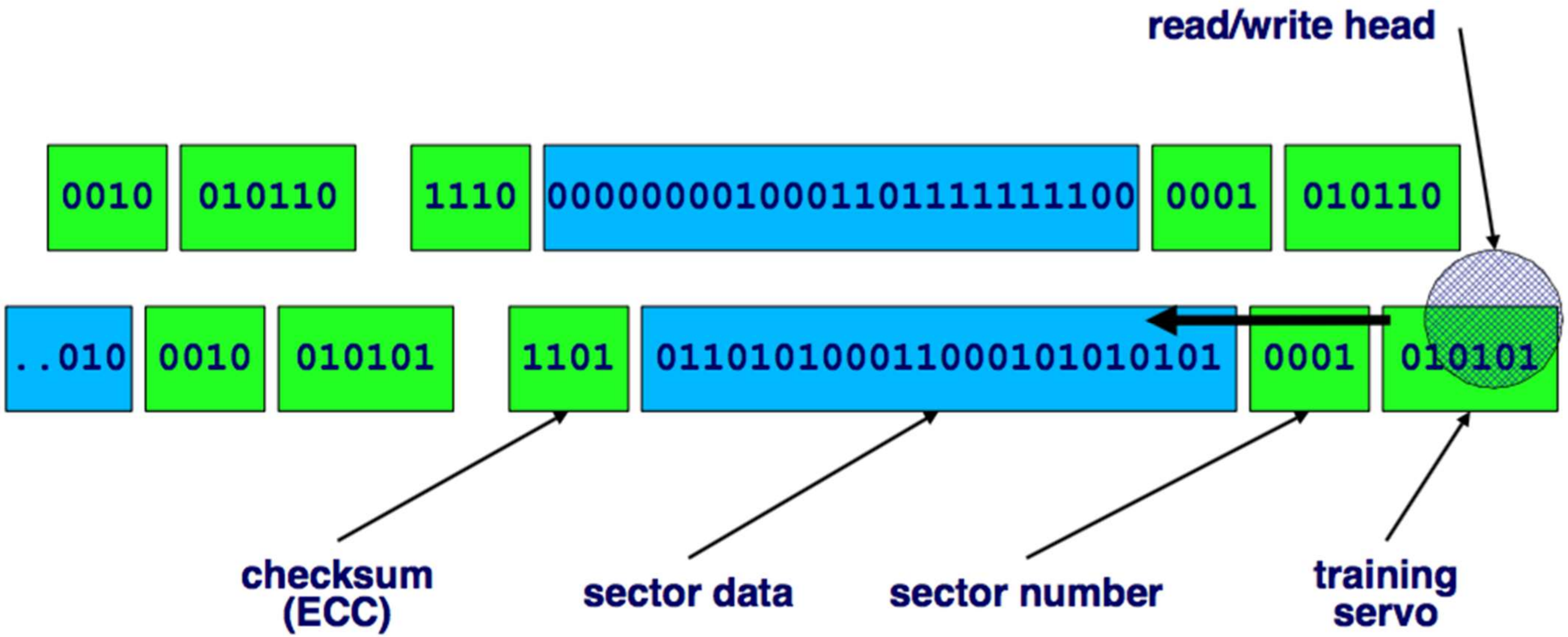
Anatomy of a Hard Drive

- **Observe**
  - Average seeks are 2 – 10 msec
  - Rotation of 5400/7200/10K/15K rpm means rotational delay of 11/8/6/4 msec



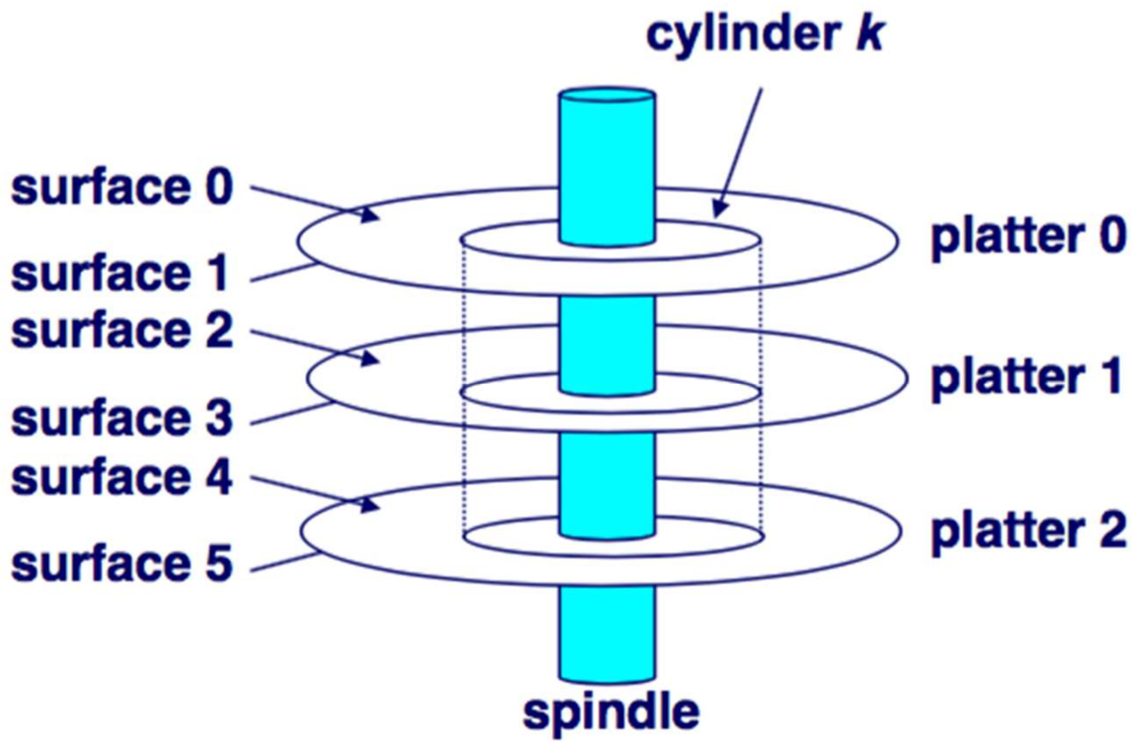
Anatomy of a "Sector"

- **Finding a sector involves real work**
  Locate correct track; scan sector headers for number
- **After sector is read, compare data to checksum**



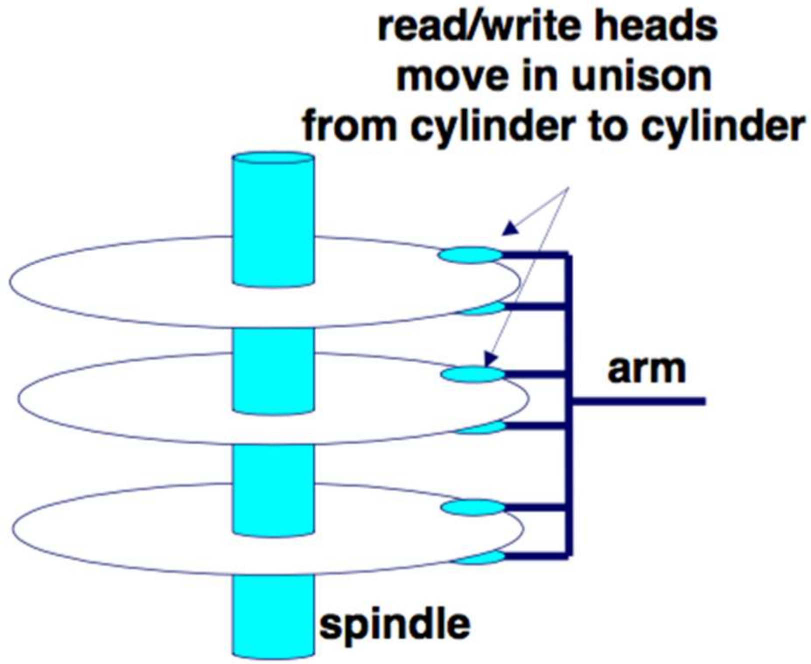
Disk Cylinder

- **Matching tracks across surfaces are collectively called a *cylinder***



Access Within A Cylinder is Faster

- **Heads share one single arm**
  - All heads always on same cylinder
  - Active head is aligned, others are "close"
- **Switching heads is "cheap"**
  - Deactivate head I, activate J
  - Read a few sector headers to fine-tune arm position for J's track
- **Optimal transfer rate?**
  - Transfer all sectors on a track
  - Transfer all tracks on a cylinder
  - *Then* move the arm



Access Time

- **On average, we will have to move the read/write head over one *third* of the tracks**
  - The time to do this is the “average seek time”
    - 5400 rpm: ~10 ms
    - 7200 rpm: ~8.5 ms
- **We will also must wait half a rotation, on average**
  - The time to do this is “average rotational delay”
    - 5400 rpm: ~5.5 ms
    - 7200 rpm: ~4 ms
- **These numbers don't exactly add**
  - While arm moves sideways, disk spins below it

Access Time

- **Total random access time is ~7 to 20 milliseconds**
  - 1000 ms/second, 20 ms/access = 50 accesses/second
  - 50 1⁄2-kilobyte transfers per second = 25 KByte/sec
- **Disks are slow!**
  - But Disk transfer rates are *hundreds of MBytes*/sec!
- **What can we, as OS programmers, do about this?**
  - Read/write more per seek (multi-sector transfers)
    - Disk cache can read ahead and delay/coalesce writes
  - Don't seek so randomly
    - Place data near also-relevant data
    - Re-order requests
      - OS may do "disk scheduling" instead of a FIFO queue
      - **(Disks internally schedule too)**

Solid-State Disks (SSD)

- **What is “solid state”?**
  - Original meaning: “no vacuum tubes”
  - Modern meaning: “no moving parts”
- **What is “solid state” storage?**
  - RAM backed by a battery!
  - “NOR flash”
  - “NAND flash”
  - Newer things

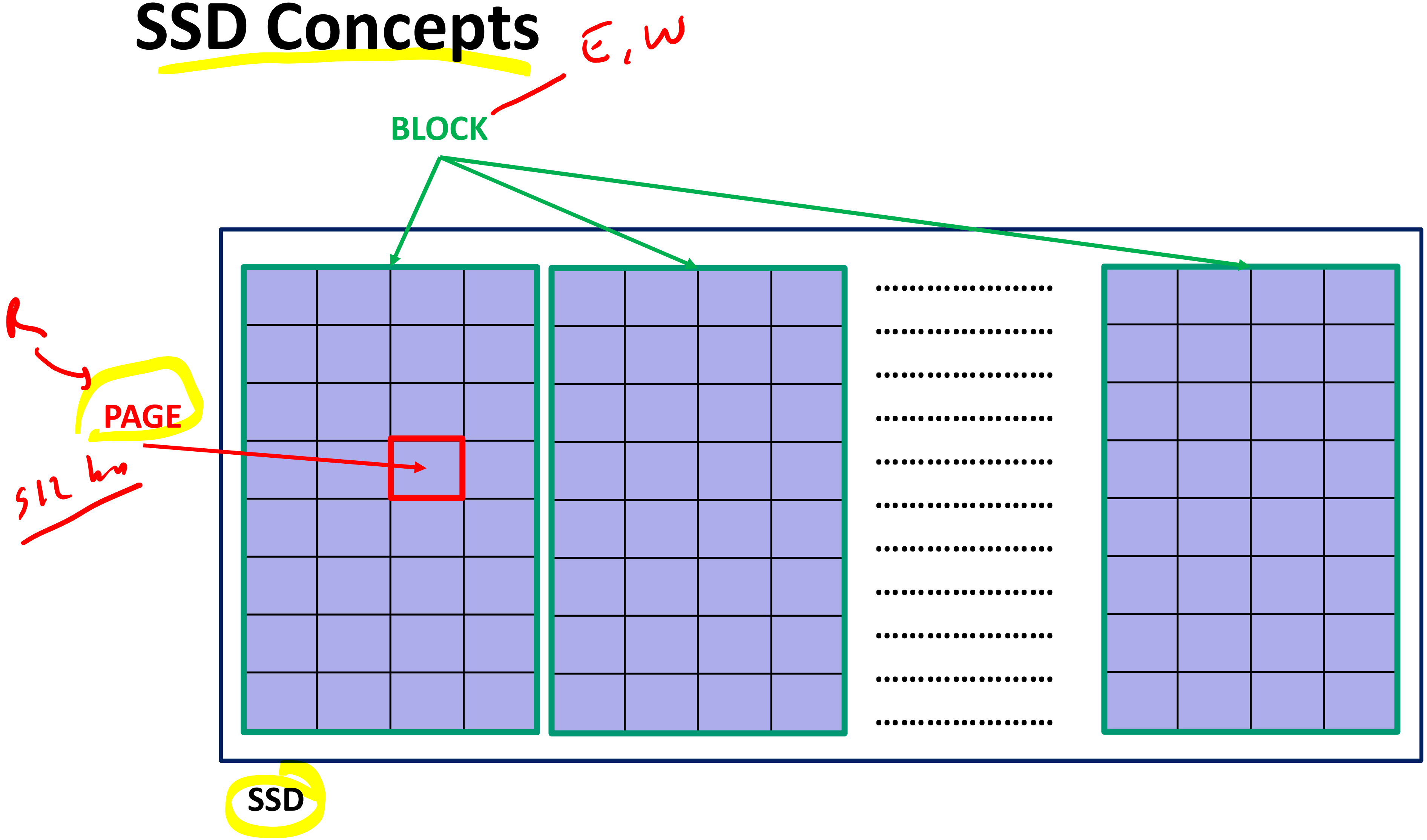
Solid-State Disks (SSD)

- **What is "solid state" storage?**
  - RAM backed by a battery!
    - Fast
- **"NOR flash"**
  - Word-accessible
  - Writes are slow, density is low
  - Used to boot embedded devices, store configuration
- **"NAND flash"**
  - Read/write "pages" (512 B), erase "blocks" (16 KB)
  - Most SSDs today are NAND flash

Solid-State Disks (SSD)

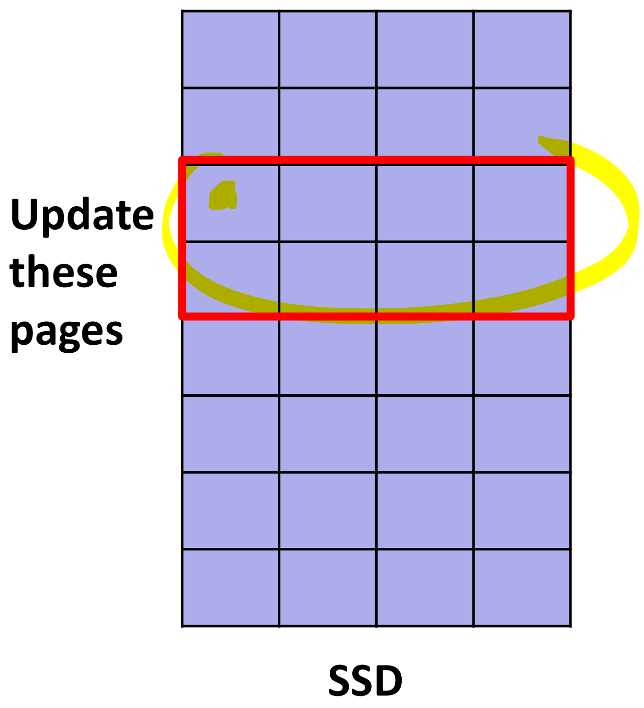
- **Architectural features of NAND flash**
  - No moving parts means no “seek time” / “rotational delay”
  - Read is faster than write
  - Write and “erase” are different
    - A blank page can be written to (once)
    - A written page must be erased before rewriting
    - But pages can't be individually erased!
      - “Erase” works on multi-page *blocks* (16 KB)
      - “Erase” is very slow
      - “Erase” *damages the block* each time
- **Implications**
  - “Write amplification”
  - “Wear leveling”

SSD Concepts



SSD: Updating data via read/erase/write

- Goal: update 8 pages (4 KB) in a block (16 KB)



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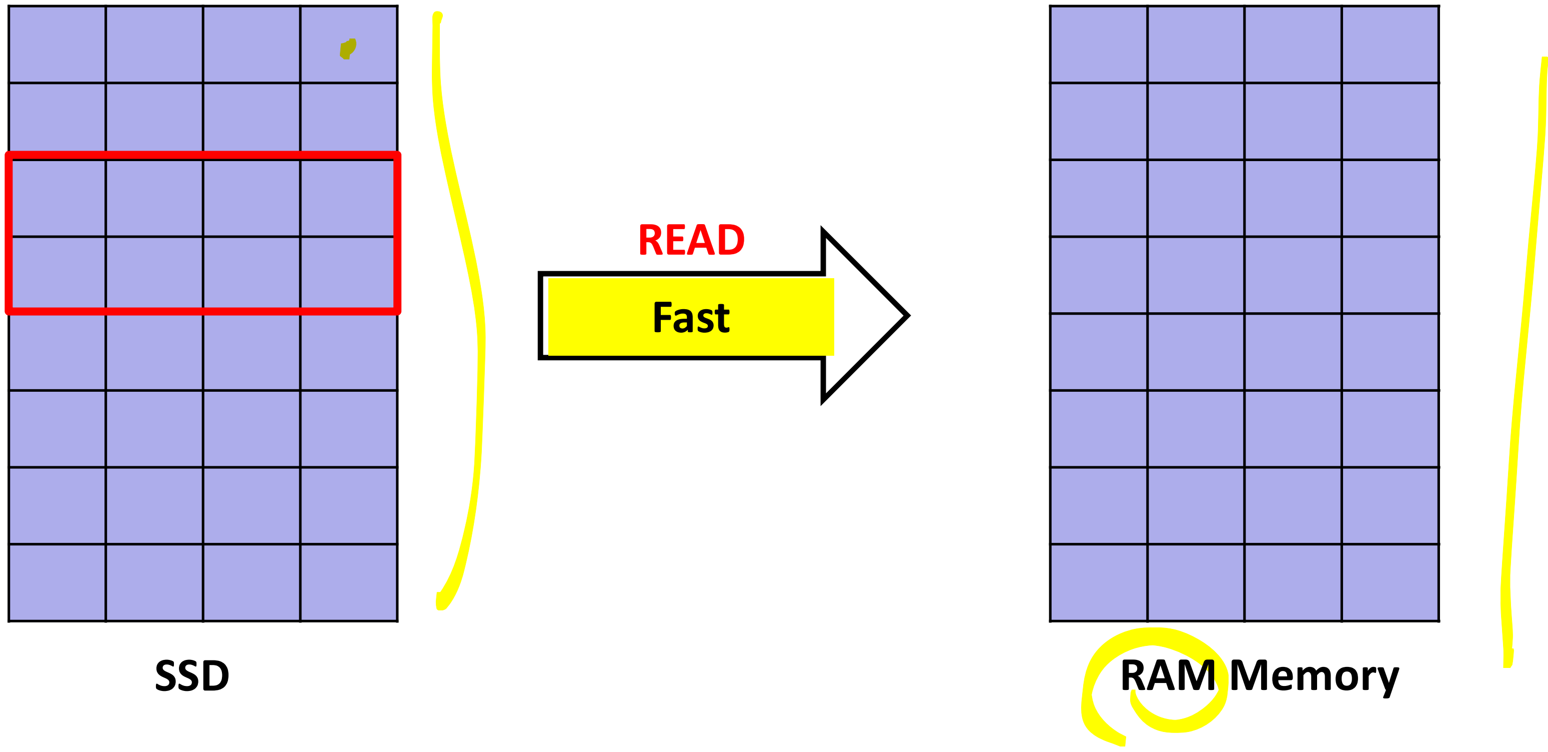

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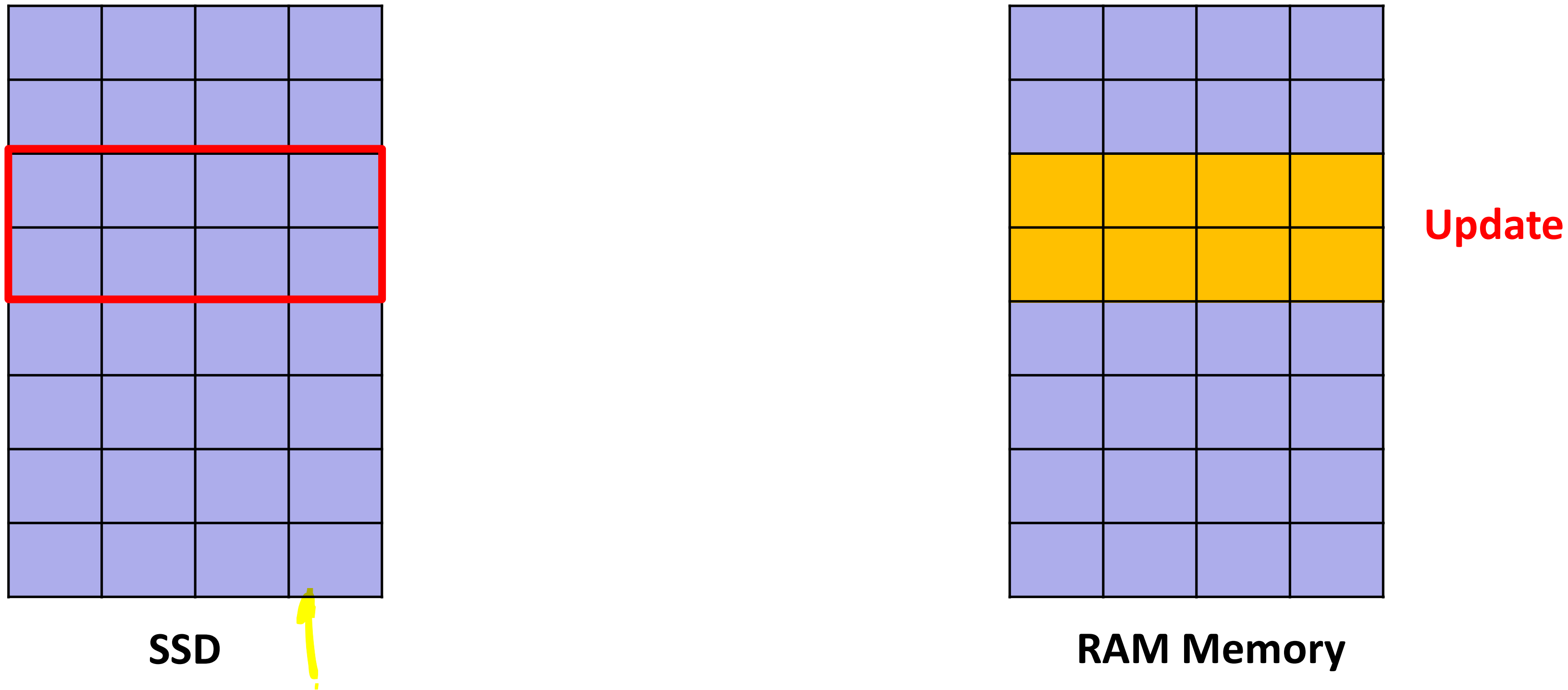

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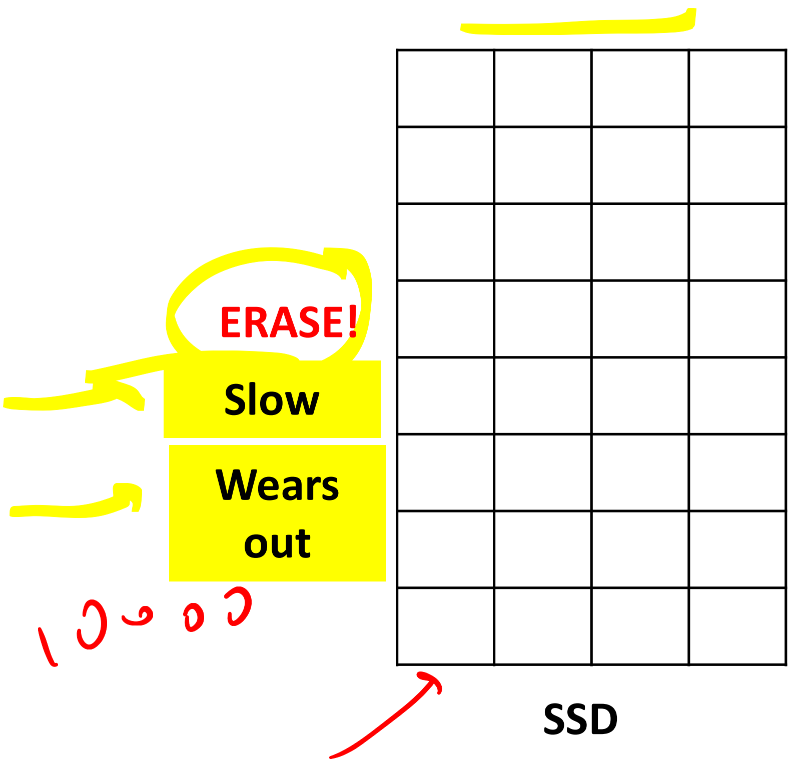
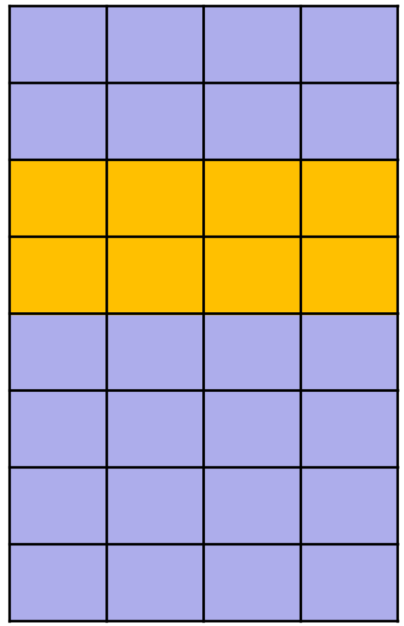


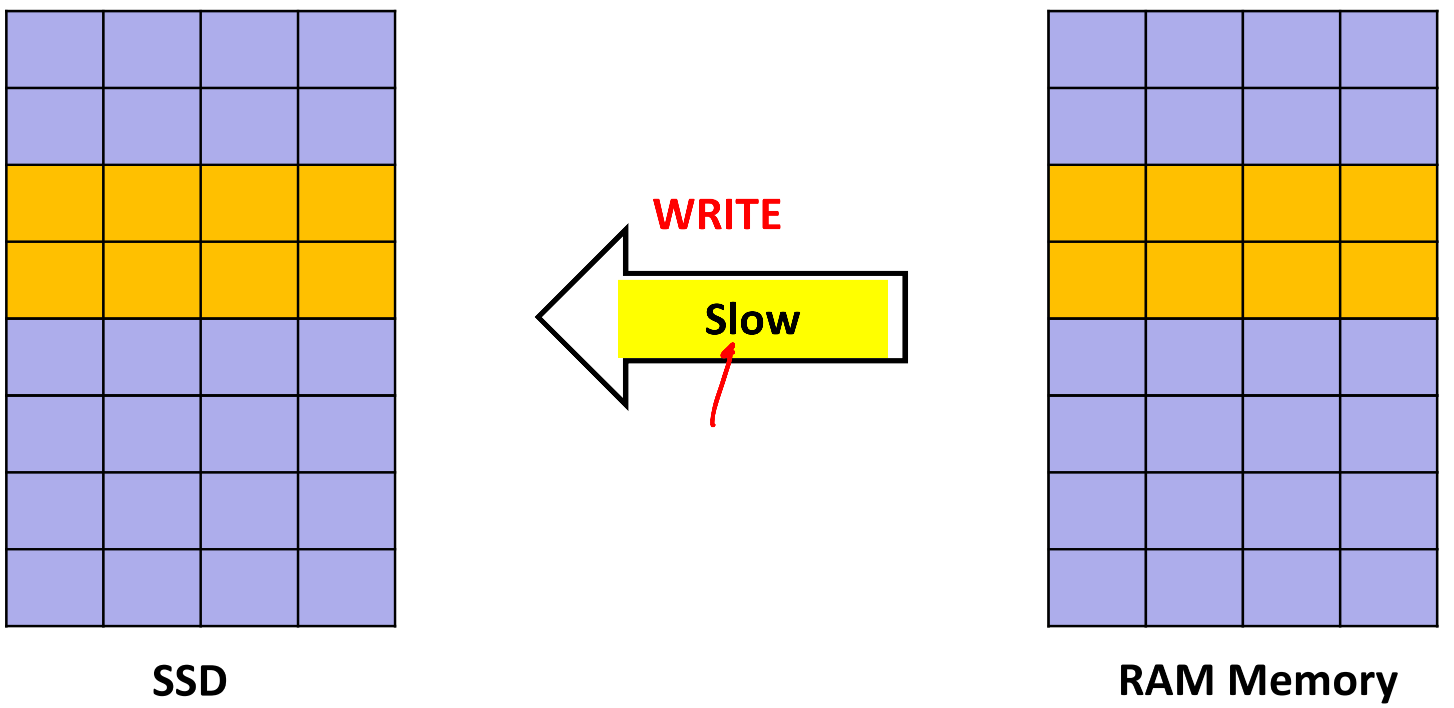
SSD



RAM Memory

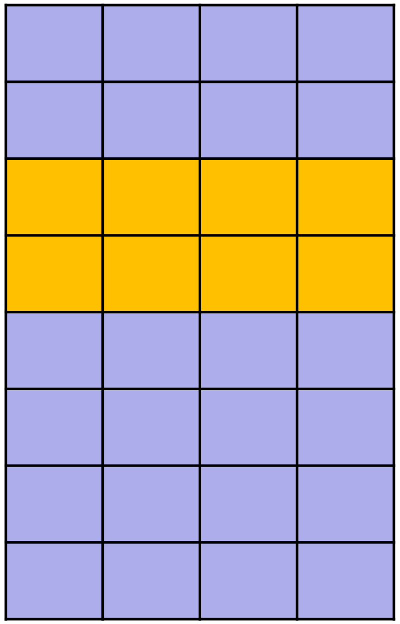
SSD: Updating data via read/erase/write

- Goal: update 8 pages (4 KB) in a block (16 KB)



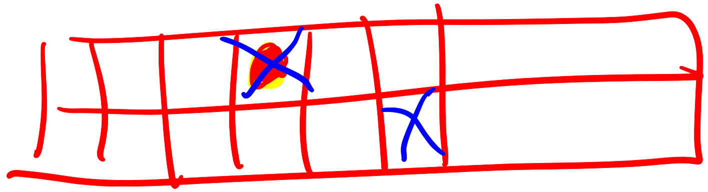
“Write Amplification”

- Goal: update 8 pages (4 KB) in a block (16 KB)

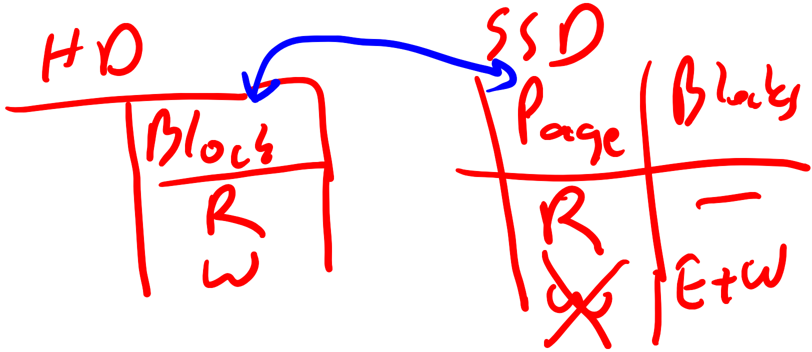


SSD

- Result
  - Logical: wrote 4 KB
  - Physical: erased and write 16 KB
  - “Amplification factor”: 4
    - Why do we care? Device will wear out 4X faster!

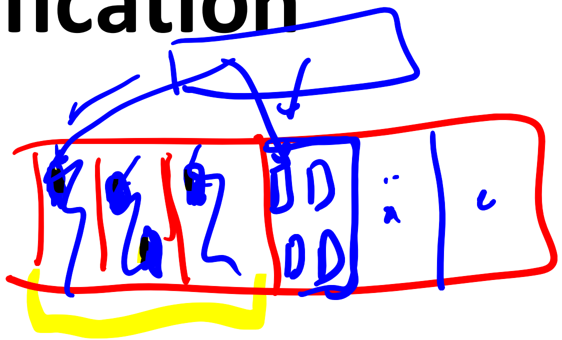


Hot-Spot Wear and Wear Leveling



- **The bad case**
  - File systems like to write the same block repeatedly
  - Erasing damages part of the flash
    - ~10,000 erases destroys a block
- **Strategy: lie to the OS!**
  - Host believes it is writing to specific "disk blocks" - LBA
  - Store the information somewhere else!
    - Secretly re-map host address onto NAND address
    - FTL - "flash translation layer"
- **Each part of the "disk" moves from one part of the flash to another over time**
  - "Over-provision"
    - Advertise less space than there really is
    - Use spare space to replace worn-out blocks
  - Use up overprovisioning as blocks wear out
    - Device eventually gets slower and then fails

Managing - Write Amplification



- **The bad case**
  - Small random writes
- **Strategy: lie to the OS!**
  - Group multiple small writes into full blocks
    - Write at sequential write rates
  - To update a “disk block”, store a new copy *somewhere else*
    - Leaves “holes” in other blocks (stale old block versions)
    - At some point, “clean out” the holes by reading a bunch of old blocks and writing back a smaller number of whole pages
  - Rate of cleaning depends amount of unallocated space
    - Controller reserves X% hidden space (ie. 10, 20, 50%)

SSD vs Disk

- **SSD's implement "regular disk" model**
  - LBA sectors
  - Write-sector, read-sector, "park heads", etc.
- **Read operations are extremely fast (100X faster), no "seek time" or "rotational delay" (every sector is "nearby")**
- **Write operations "vary widely" (maybe 100X faster, maybe not faster at all)**
- **SSD's use less power than actual disks (~1/5?)**
- **SSD's are shock-resistant**
- **Writing to an SSD wears it out much faster than a disk**
- **SSD's are *expensive* (20X or more)**

SSD Drives - Summary

- **Solid State disks have no moving parts and mechanical delays.**
- **SSD's have other problems due to the following characteristics:**
  - Block based read only read access, fast, no restriction.
  - Only empty blocks can be written, slower than read but still fast
  - Non-empty blocks needs to be erased.
  - Erasing has to be done in larger units (segments/clusters). i.e. 512byte vs. 32KByte.
  - Erasing is slow and each segment has a erase cycle limit (i.e. 10000 erases).
- **Single bit update requires:**
  - Erase a whole segment , write all (32K) content with modified bit.

SSD Drives - Summary

- **Erase/write problem solution:**
  - Write modified blocks on already erased segments
  - Logical block number and actual block on disk differs.
  - Keep and internal table for actual block to logical block mapping.
  - OS asks for logical block content, SDD controller returns actual block content.
- **Called Wear Leveling or Write Amplification.**
- **FTL: Flash Translation Layer implemented on Flash hardware does the translation. OS does not know about it.**
- **OS based solution: Use a Log Structured File System.**
  - To be discussed in detail in FileSystems

Disk Management

- **Managing disks on a system gets complicated as space requirement increases by time.**
- **Adding new disks to system, changing failed disks, deleting disks, adjusting partitions with new layout is an issue.**
- **A solution is Logical Volume Management.**
  - A layer in OS maps a group of physical disk partitions into a large contiguous logical volume.
    - E.g. add 5 4T disks to get a 20T as a single partition.
  - LVM helps getting OS independent from underlying disk organization.
- **RAID (Redundant Array of Independent Disks) is another solution which also respects disk failures and efficiency.**
- **Common RAID levels:**
  - 0 stripe (distribute I/O requests on two or more disks for efficiency)
  - 1 mirror (execute same I/O on two or more disks for failure recovery)
  - 5 distributed parity (distribute operation on multiple disk with parity, both efficiency and filure recovery)
- **RAID is best implemented in HW. OS implementation is called Soft RAID**

Further reading

- **Reliably Erasing Data from Flash-based Solid State Drives**
  - Wei et al., UCSD
    FAST '11
    http://www.usenix.org/legacy/events/fast11/tech/full_papers/Wei.pdf
- **A Conversation with Jim Gray**
  - Dave Patterson
  - ACM Queue, June 2003
    http://queue.acm.org/detail.cfm?id=864078
- **Terabyte Territory**
  - Brian Hayes
  - American Scientist, May/June 2002
    http://www.americanscientist.org/issues/pub/terabyte-territory