Disks and RAID

(Chapter 12, 14.2)

CS 4410
Operating Systems

[R. Agarwal, L. Alvisi, A. Bracy, E. Sirer, R. Van Renesse]

Storage Devices

- Magnetic disks
  - Storage that rarely becomes corrupted
  - Large capacity at low cost
  - Block level random access
  - Slow performance for random access
  - Better performance for streaming access
- Flash memory
  - Storage that rarely becomes corrupted
  - Capacity at intermediate cost (50x disk)
  - Block level random access
  - Good performance for reads; worse for random writes

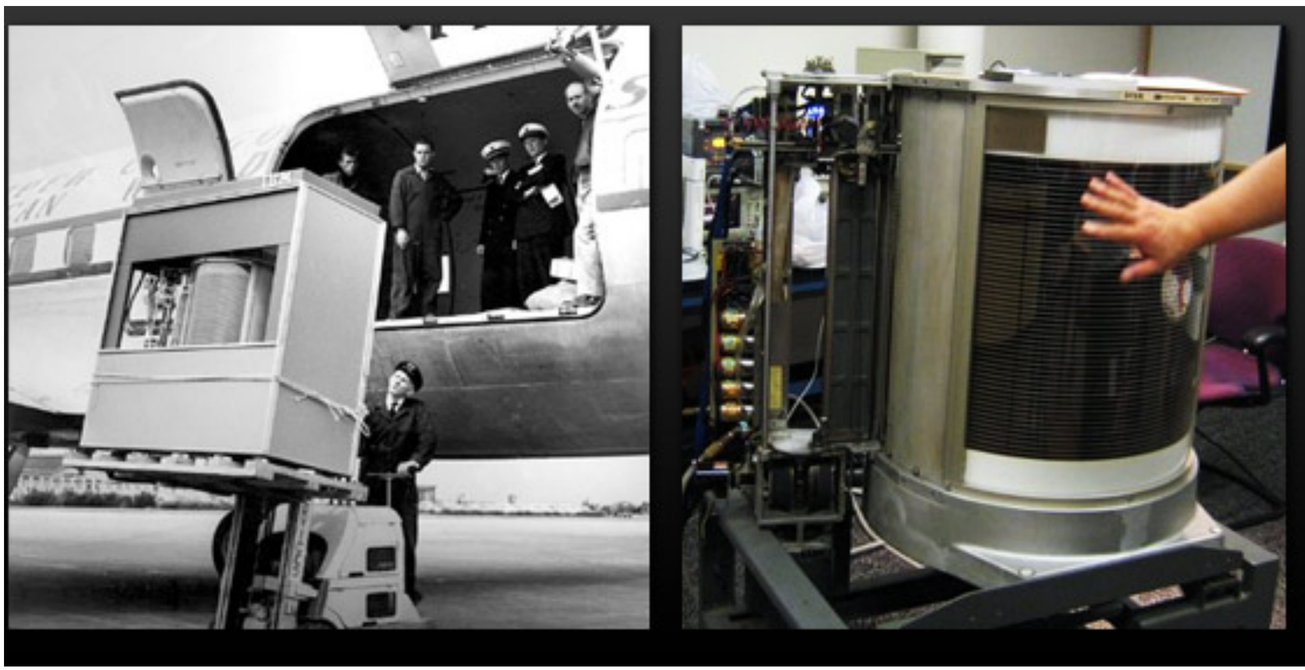
Magnetic Disks are 60 years old!

THAT WAS THEN

- 13th September 1956
- The IBM RAMAC 350
- Total Storage = 5 million characters (just under 5 MB)

THIS IS NOW

- 2.5-3.5” hard drive
- Example: 500GB Western Digital Scorpio Blue hard drive
- easily up to 1 TB



http://royal.pingdom.com/2008/04/08/the-history-of-computer-data-storage-in-pictures/

RAM (Memory) vs. HDD (Disk), 2018

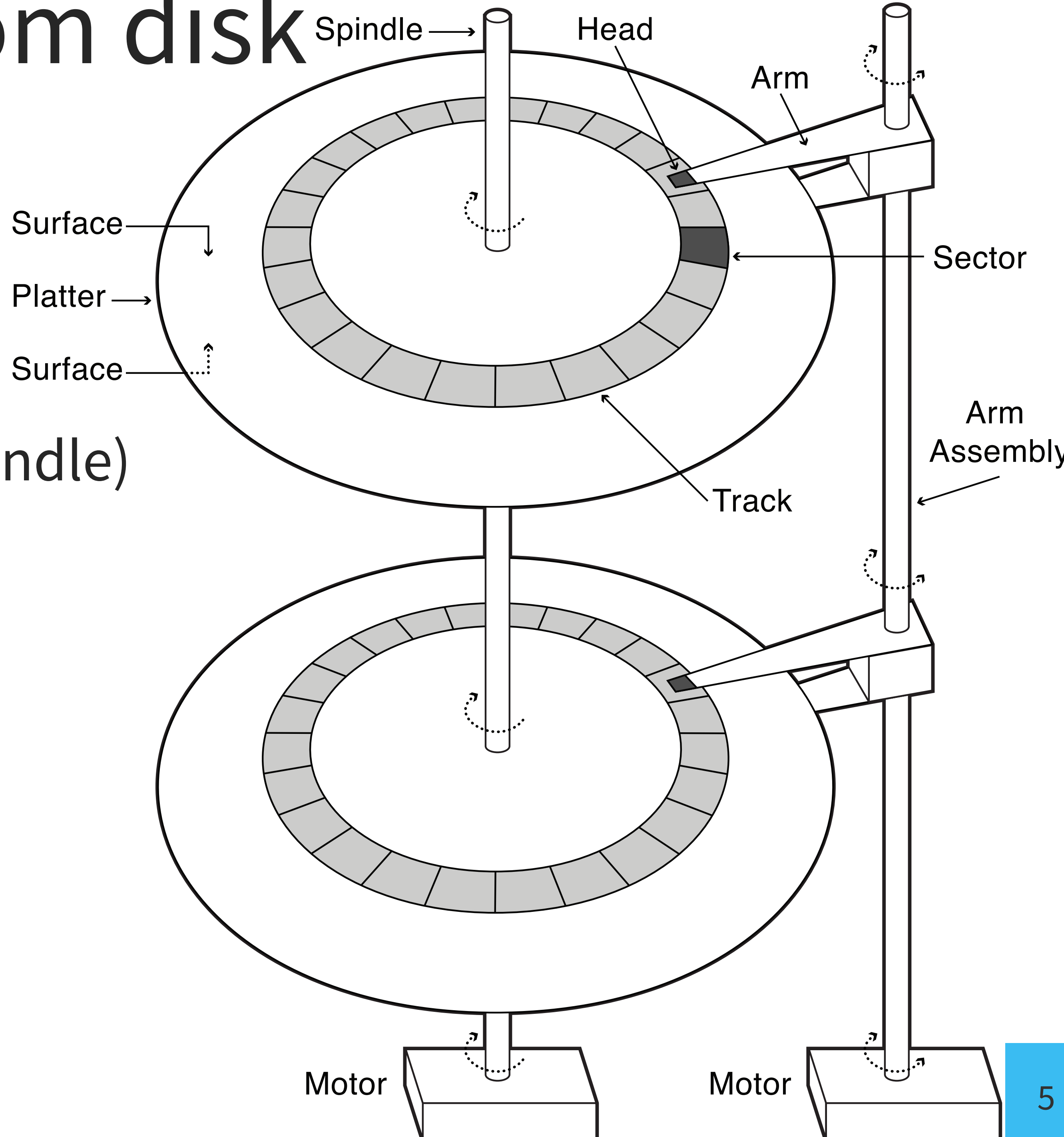
	RAM	HDD
Typical Size	8 GB	1 TB
Cost	$10 per GB	$0.05 per GB
Power	3 W	2.5 W
Read Latency	15 ns	15 ms
Read Speed (Sequential)	8000 MB/s	175 MB/s
Write Speed (Sequential)	10000 MB/s	150 MB/s
Read/Write Granularity	word	sector
Power Reliance	volatile	non-volatile

[C. Tan, buildcomputers.net, codecapsule.com, crucial.com, wikipedia]

Reading from disk

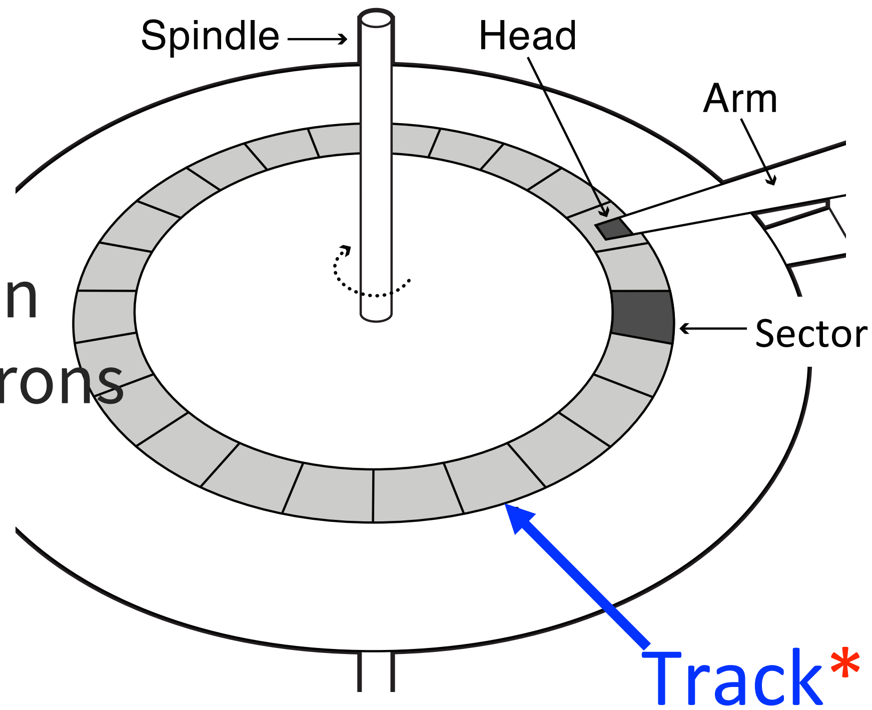
Must specify:

- cylinder #
  (distance from spindle)
- surface #
- sector #
- transfer size
- memory address

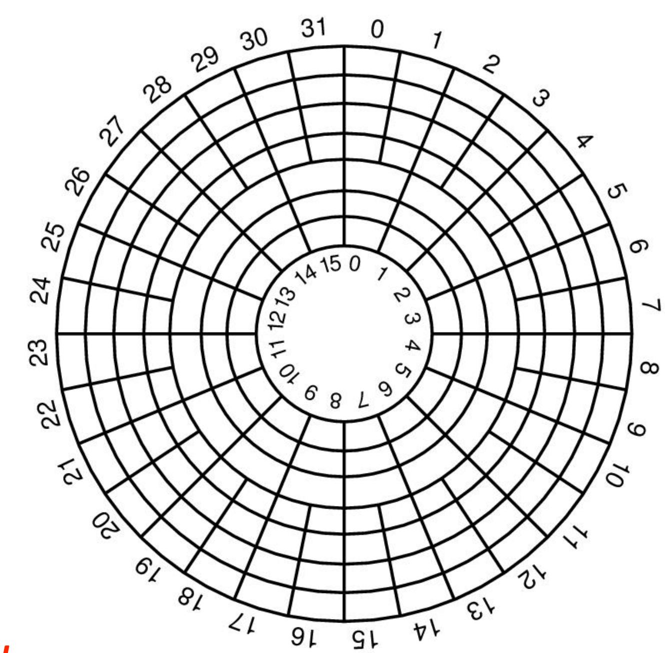


Disk Tracks

~ 1 micron wide (1000 nm)
- Wavelength of light is ~ 0.5 micron
- Resolution of human eye: 50 microns
- 100K tracks on a typical 2.5” disk



Track length varies across disk
- Outside:
  - More sectors per track
  - Higher bandwidth
- Most of disk area in outer regions

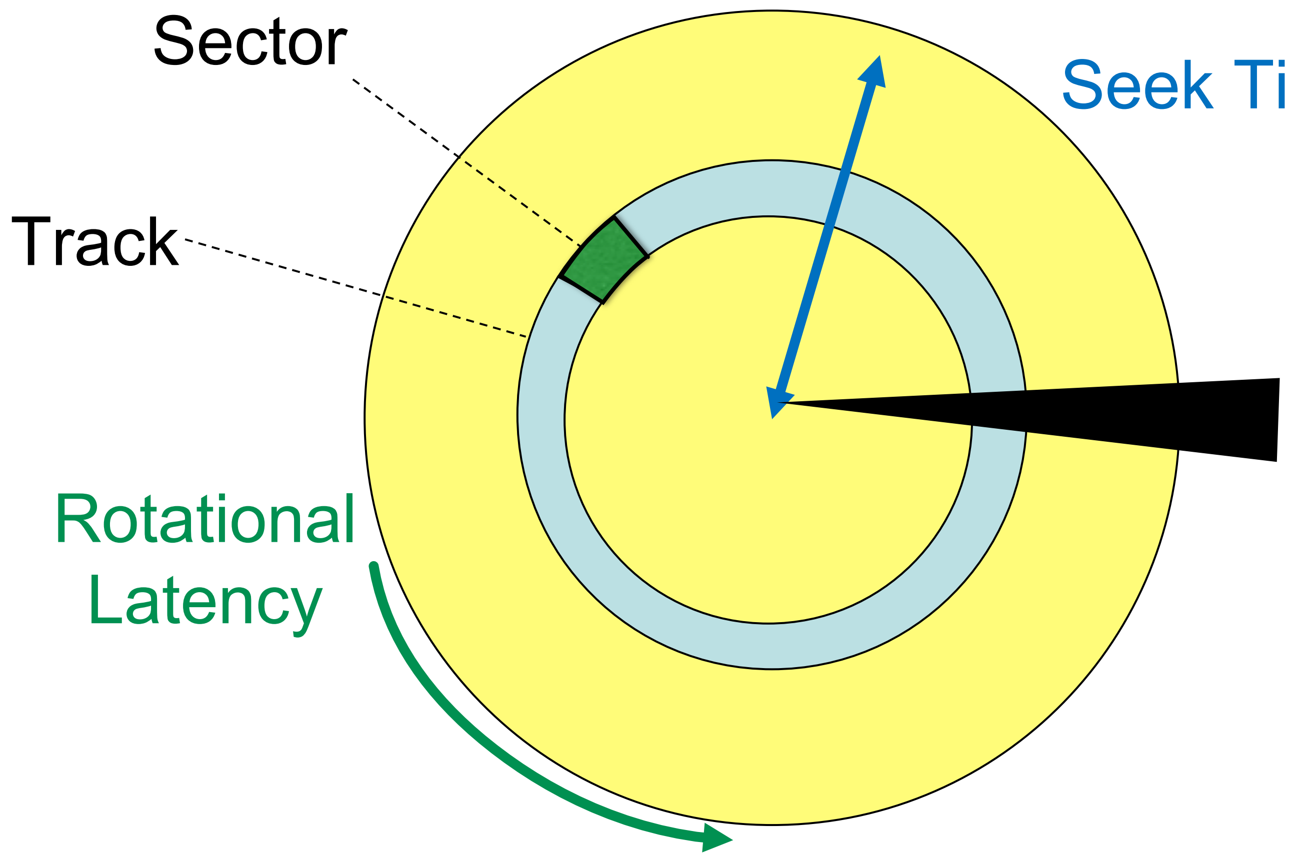


*not to scale: head is actually much bigger than a track

Disk overheads

*Disk Latency = **Seek Time** + **Rotation Time** + Transfer Time*

- **Seek:** to get to the track (5-15 millisecs (ms))
- **Rotational Latency:** to get to the sector (4-8 millisecs (ms))
  (on average, only need to wait half a rotation)
- **Transfer:** get bits off the disk (25-50 microsecs (μs)



Disk Scheduling

Objective: minimize seek time

Context: a queue of cylinder numbers (#0-199)

Head pointer @ 53
Queue: 98, 183, 37, 122, 14, 124, 65, 67

Metric: how many cylinders traversed?

Disk Scheduling: **FIFO**

- Schedule disk operations in order they arrive
- Downsides?

FIFO Schedule?
Total head movement?

Head pointer @ 53
Queue: 98, 183, 37, 122, 14, 124, 65, 67

Disk Scheduling: Shortest Seek Time First

- Select request with minimum seek time from current head position
- A form of Shortest Job First (SJF) scheduling
- Not optimal: suppose cluster of requests at far end of disk → starvation!

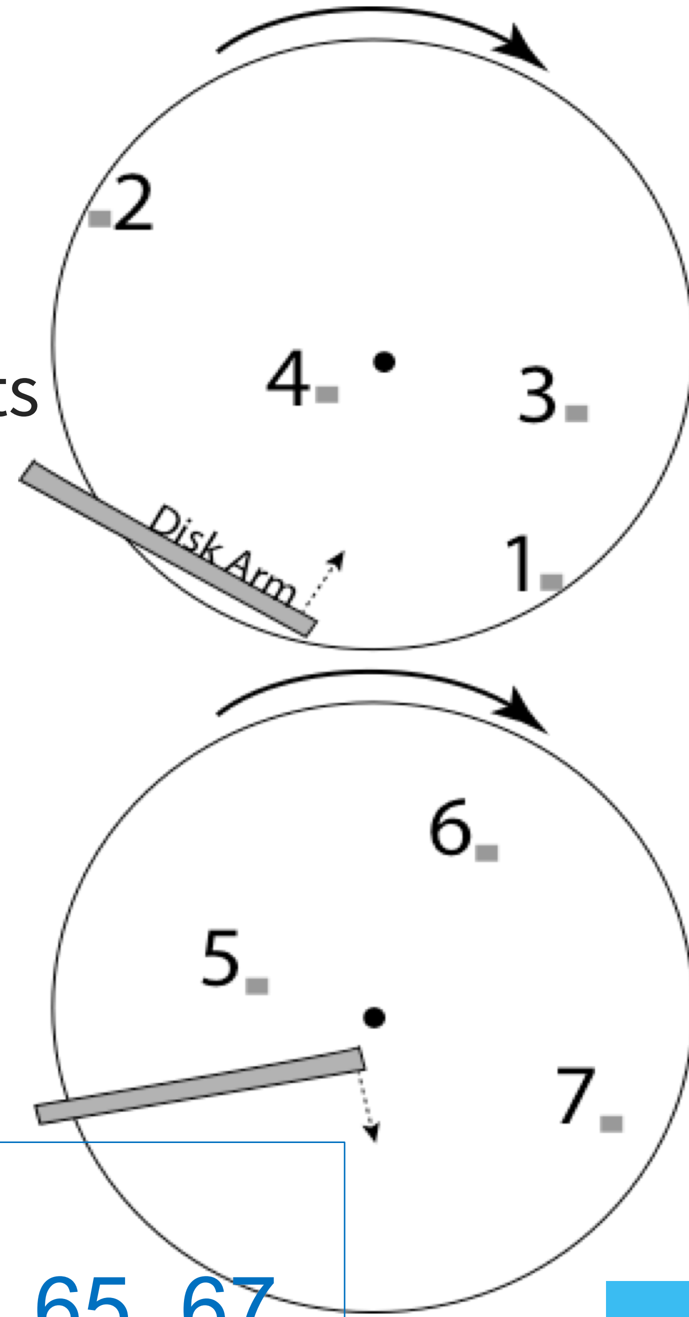
SSTF Schedule?
Total head movement?

Head pointer @ 53
Queue: 98, 183, 37, 122, 14, 124, 65, 67

Disk Scheduling: SCAN

Elevator Algorithm:

- arm starts at one end of disk
- moves to other end, servicing requests
- movement reversed @ end of disk
- repeat



SCAN Schedule?

Total head movement?

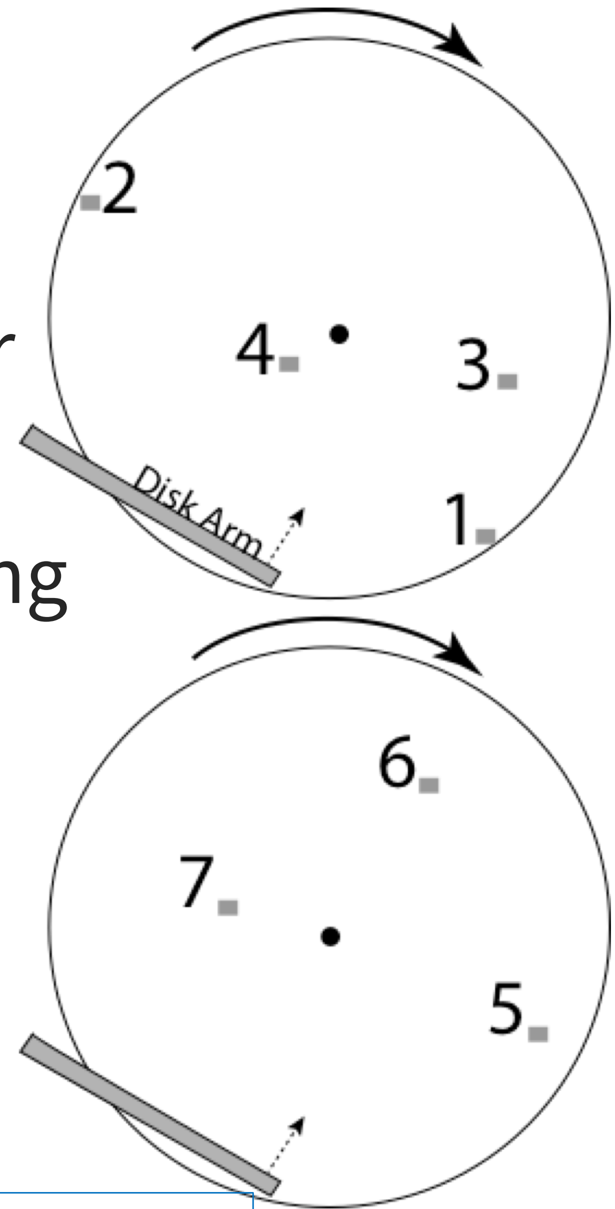
Head pointer @ 53
Queue: 98, 183, 37, 122, 14, 124, 65, 67

Disk Scheduling: C-SCAN

Circular list treatment:

- head moves from one end to other
- servicing requests as it goes
- reaches the end, returns to beginning
- no requests serviced on return trip

+ More uniform wait time than SCAN



C-SCAN Schedule?

Total Head movement?(?)

Head pointer @ 53
Queue: 98, 183, 37, 122, 14, 124, 65, 67

RAM vs. HDD vs Flash, 2018

	RAM	HDD	Flash
Typical Size	8 GB	1 TB	250 GB
Cost	$10 per GB	$0.05 per GB	$0.32 per GB
Power	3 W	2.5 W	1.5 W
Read Latency	15 ns	15 ms	30 μs
Read Speed (Seq.)	8000 MB/s	175 MB/s	550 MB/s
Write Speed (Seq.)	10000 MB/s	150 MB/s	500 MB/s
Read/Write Granularity	word	sector	page*
Power Reliance	volatile	non-volatile	non-volatile
Write Endurance	*	**	100 TB

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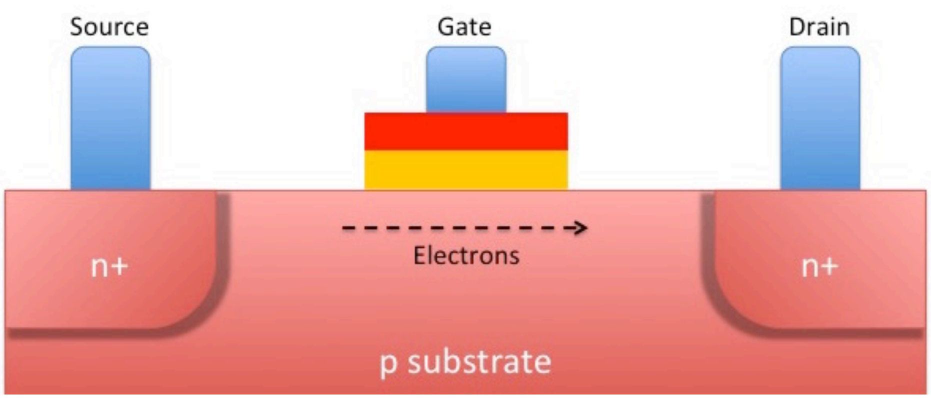
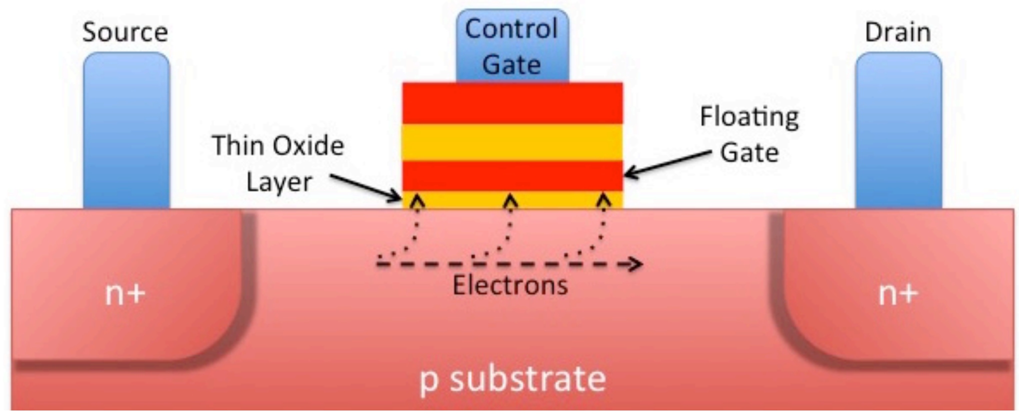
Solid State Drives (Flash)

Most SSDs based on NAND-flash

- retains its state for months to years without power



Metal Oxide Semiconductor Field Effect **Transistor** (MOSFET)



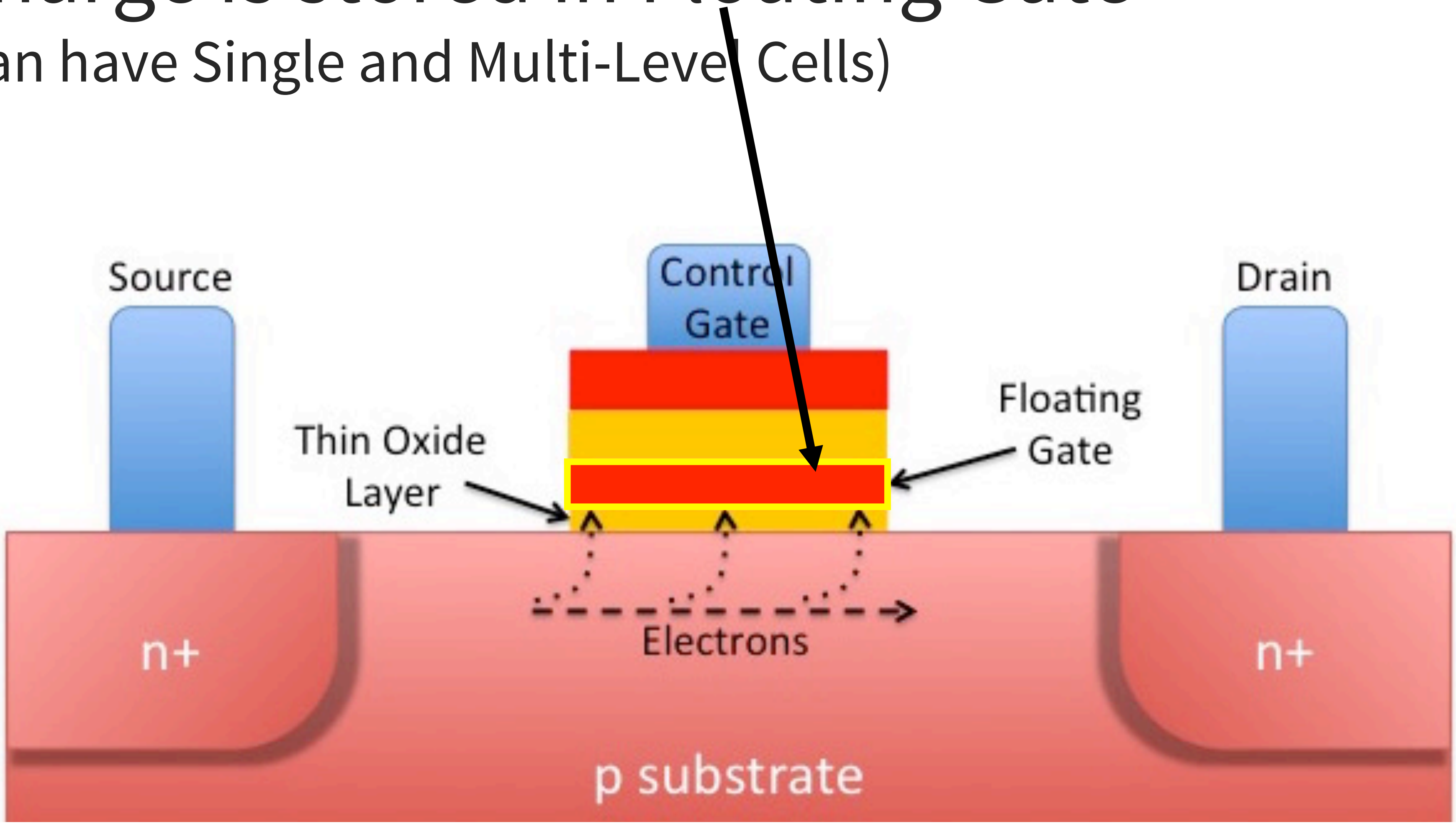
Floating Gate MOSFET (FGMOS)

https://flashdba.com/2015/01/09/understanding-flash-floating-gates-and-wear/

NAND Flash

Charge is stored in Floating Gate

(can have Single and Multi-Level Cells)



Floating Gate MOSFET (FGMOS)

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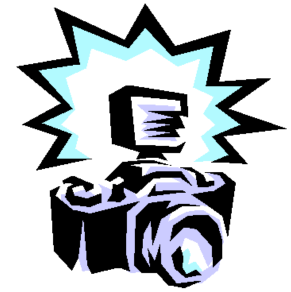
Flash Operations



- **Erase block:** sets each cell to “1”
  - erase granularity = “erasure block” = 128-512 KB
  - time: several ms
- **Write page:** can only write erased pages
  - write granularity = 1 page = 2-4KBytes
  - time: 10s of ms
- **Read page:**
  - read granularity = 1 page = 2-4KBytes
  - time: 10s of ms

Flash Limitations

- can’t write 1 byte/word (must write whole blocks)
- limited # of erase cycles per block (memory wear)
  - 10^3-10^6 erases and the cell wears out
  - reads can “disturb” nearby words and overwrite them with garbage

- **Lots of techniques to compensate:**
  - error correcting codes
  - bad page/erasure block management
  - wear leveling: trying to distribute erasures across the entire driver

Flash Translation Layer

Flash device firmware maps logical page # to a physical location

- Garbage collect erasure block by copying live pages to new location, then erase
  - More efficient if blocks stored at same time are deleted at same time (e.g., keep blocks of a file together)
- Wear-levelling: only write each physical page a limited number of times
- Remap pages that no longer work (sector sparing)

Transparent to the device user

What do we want from storage?

- Fast: data is there when you want it
- Reliable: data fetched is what you stored
- Affordable: won’t break the bank

Enter: Redundant Array of Inexpensive Disks (RAID)

- In industry, “I” is for “Independent”
- The alternative is SLED, single large expensive disk
- RAID + RAID controller looks just like SLED to computer (*yay, abstraction!*)

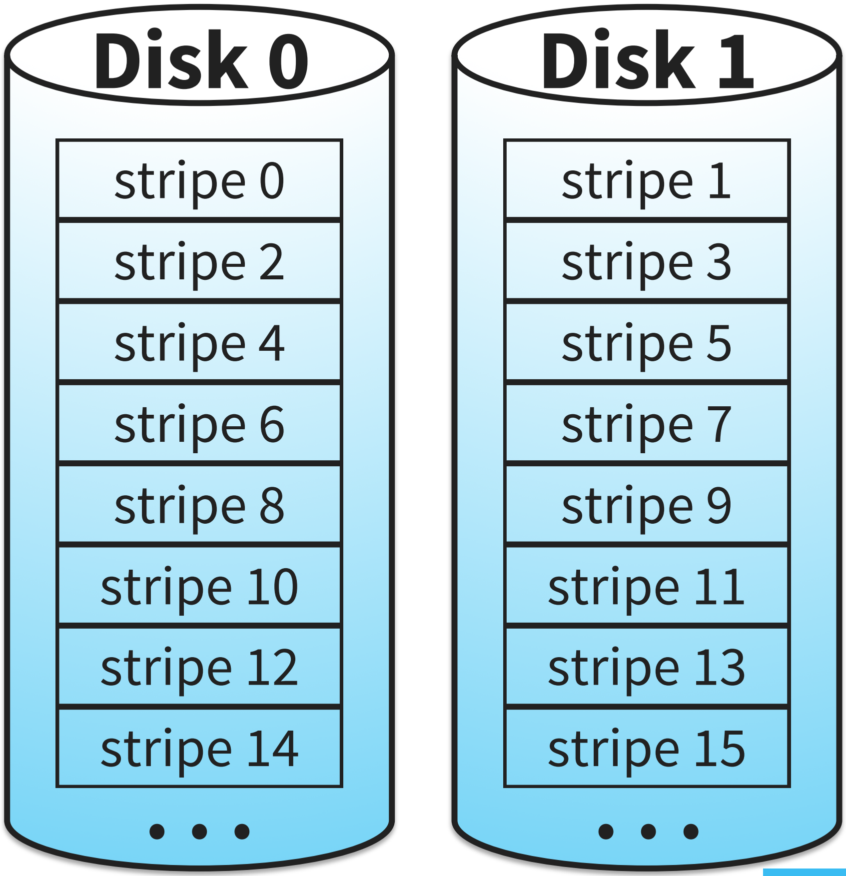
RAID-0

Files striped across disks

+ Fast

+ Cheap

– Unreliable



Failure Cases

(1) Isolated Disk Sectors (1+ sectors down, rest OK)

Permanent: physical malfunction (magnetic coating, scratches, contaminants)

Transient: data corrupted but new data can be successfully written to / read from sector

(2) Entire Device Failure

- Damage to disk head, electronic failure, wear out
- Detected by device driver, accesses return error codes
- Annual failure rates or Mean Time To Failure (MTTF)

Striping and Reliability

Striping *reduces* reliability

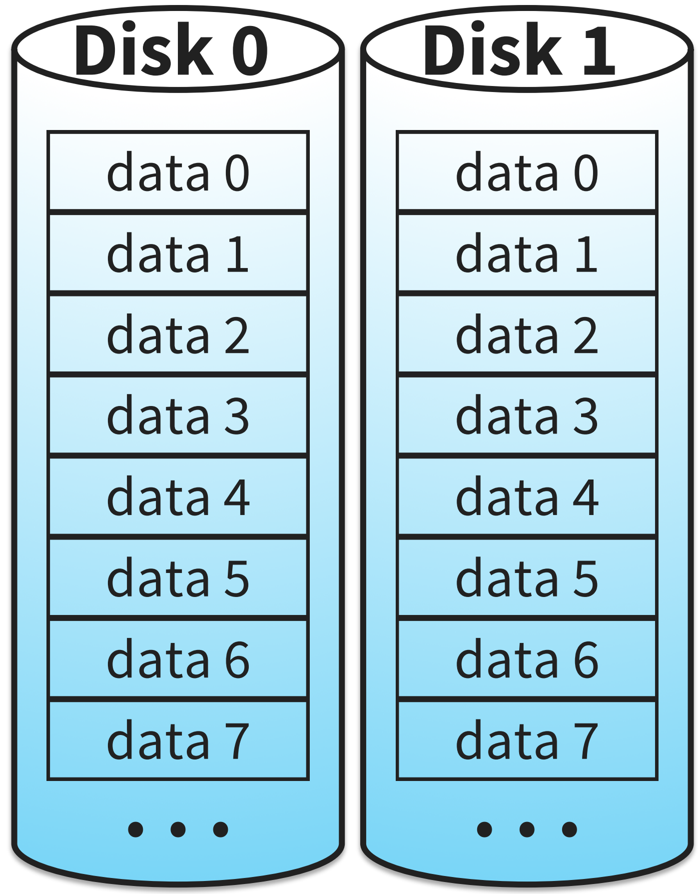
- More disks → higher probability of some disk failing
- N disks: 1/Nth mean time between failures of 1 disk

What can we do to improve Disk Reliability?

Hint #1: When CPUs stopped being reliable, we also did this…

RAID-1

Disks Mirrored:
data written in 2 places



+ Reliable

+ Fast

– Expensive

Example: Google File System replicates data across multiple disks

RAID-2

bit-level striping with ECC codes

- 7 disk arms synchronized, move in unison
- Complicated controller (→ very unpopular)
- Detect & Correct 1 error with no performance degradation

+ Reliable

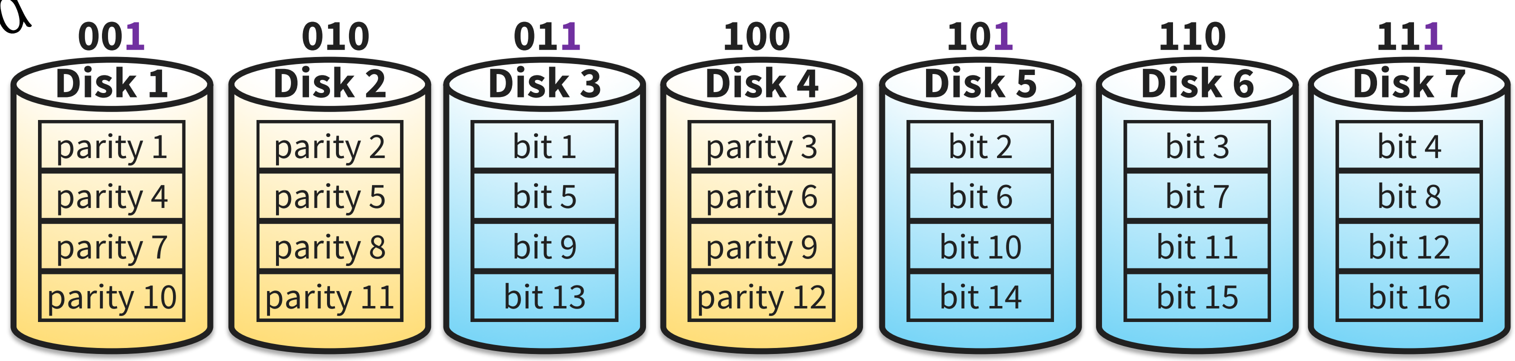
– Expensive

parity 1 = 3⊕5⊕7 (all disks whose # has 1 in LSB, xx1)

parity 2 = 3⊕6⊕7 (all disks whose # has 1 in 2^{nd} bit, x1x)

parity 4 = 5⊕6⊕7 (all disks whose # has 1 in MSB, 1xx)

do we really need to detect?

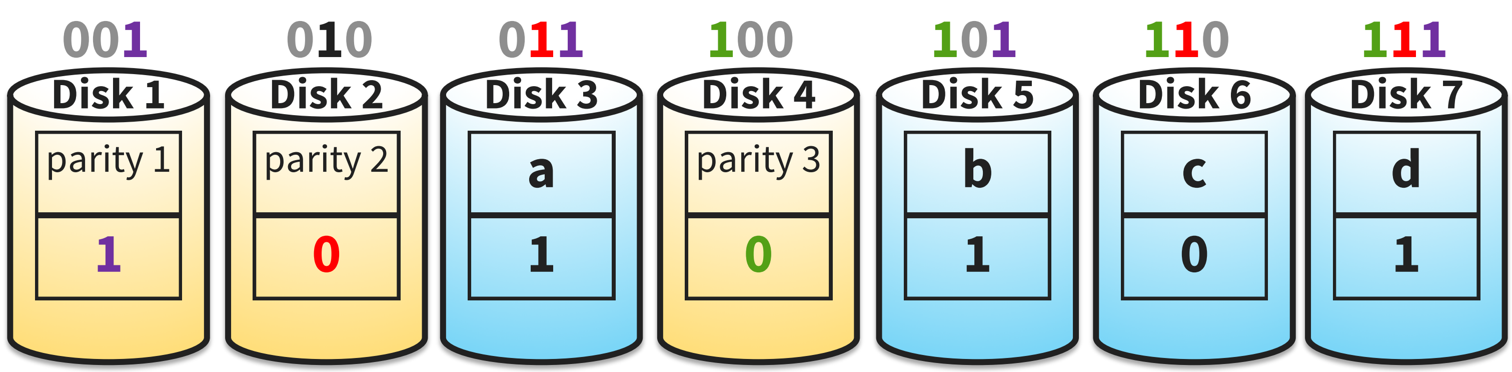


RAID-2 Generating Parity

parity 1 = 3⊕5⊕7 (all disks whose # has 1 in LSB, xx**1**)
= a⊕b⊕d = 1⊕1⊕1 = **1**

parity 2 = 3⊕6⊕7 (all disks whose # has 1 in 2nd bit, x**1**x)
= a⊕c⊕d = 1⊕0⊕1 = **0**

parity 4 = 5⊕6⊕7 (all disks whose # has 1 in MSB, **1**xx)
= b⊕c⊕d = 1⊕0⊕1 = **0**



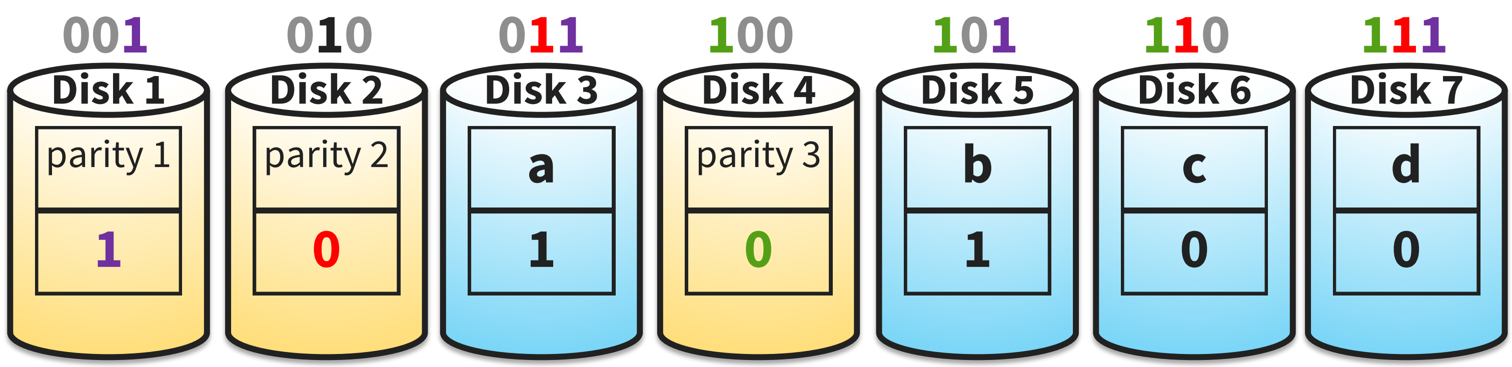
RAID-2 Detect and Correct

I flipped a bit. Which one?

parity 1 = $3 \oplus 5 \oplus 7$ (all disks whose # has 1 in LSB, xx**1**)
= $a \oplus b \oplus d = 1 \oplus 1 \oplus 0 =$ **0** ← **problem**

parity 2 = $3 \oplus 6 \oplus 7$ (all disks whose # has 1 in 2nd bit, x**1**x)
= $a \oplus c \oplus d = 1 \oplus 0 \oplus 0 =$ **1** ← **problem**

parity 4 = $5 \oplus 6 \oplus 7$ (all disks whose # has 1 in MSB, **1**xx)
= $b \oplus c \oplus d = 1 \oplus 0 \oplus 0 =$ **1** ← **problem**



Problem @ xx1, x1x, 1xx → 111, d was flipped

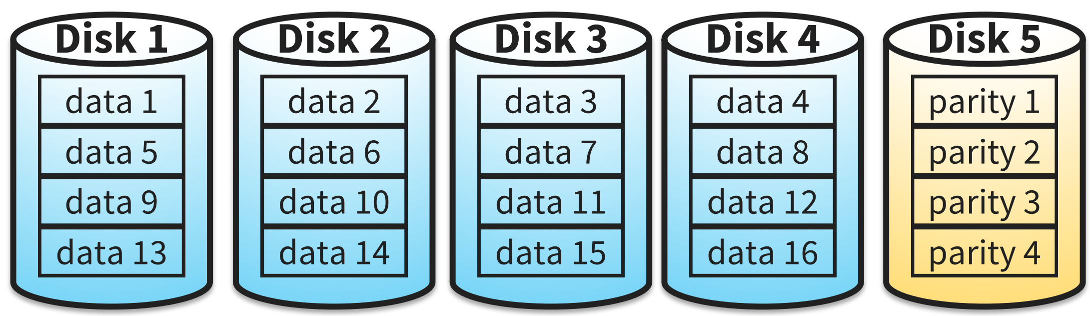
2 more rarely-used RAIDS

RAID-3: **byte**-level striping + parity disk

- read accesses all data disks
- write accesses all data disks + parity disk
- On disk failure: read parity disk, compute missing data

RAID-4: **block**-level striping + parity disk

+ better spatial locality for disk access



+ Cheap

– Slow Writes

– Unreliable

parity disk is write bottleneck and wears out faster

A word about Granularity

Bit-level → byte-level → block level

fine-grained: stripe a file across all disks

- \+ high throughput for the file
- \- wasted disk seek time
- \- limits to transfer of 1 file at a time

coarse-grained: stripe a file over a few disks

- \- limits throughput for 1 file
- \+ better use of spatial locality (for disk seek)
- \+ allows more parallel file access

RAID 5: Rotating Parity w/Striping

+ Reliable

+ Fast

+ Affordable