Disks and RAID

CS 4410
Operating Systems

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

Disk Abstraction

- disk.getsize()
  - returns the #blocks on the disk
- disk.read(offset) → block
  - returns the block at the given offset
- disk.write(offset, block)
  - writes the block at the given offset

What do we want from storage?

- Fast: data is there when you want it
- Reliable: data fetched is what you stored
- Plenty: there should be lots of it
- Affordable: won't break the bank

Storage Devices

- Magnetic disks (HDD)
- Flash drives (SSD)

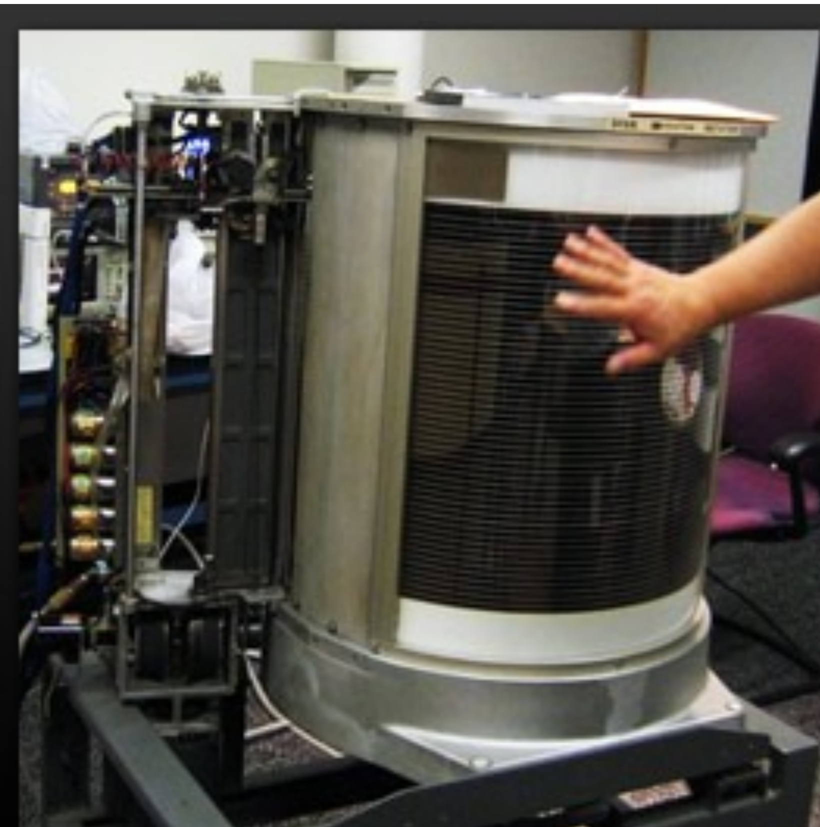
Magnetic Disks are 65 years old!

THAT WAS THEN

- 13th September 1956
- The IBM RAMAC 350
- Total Storage = 5 million characters (about 3.75 MB)

THIS IS NOW

- 2.5-3.5" hard drive
- Example: 500GB Western Digital Scorpio Blue hard drive
- easily up to a few TB



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

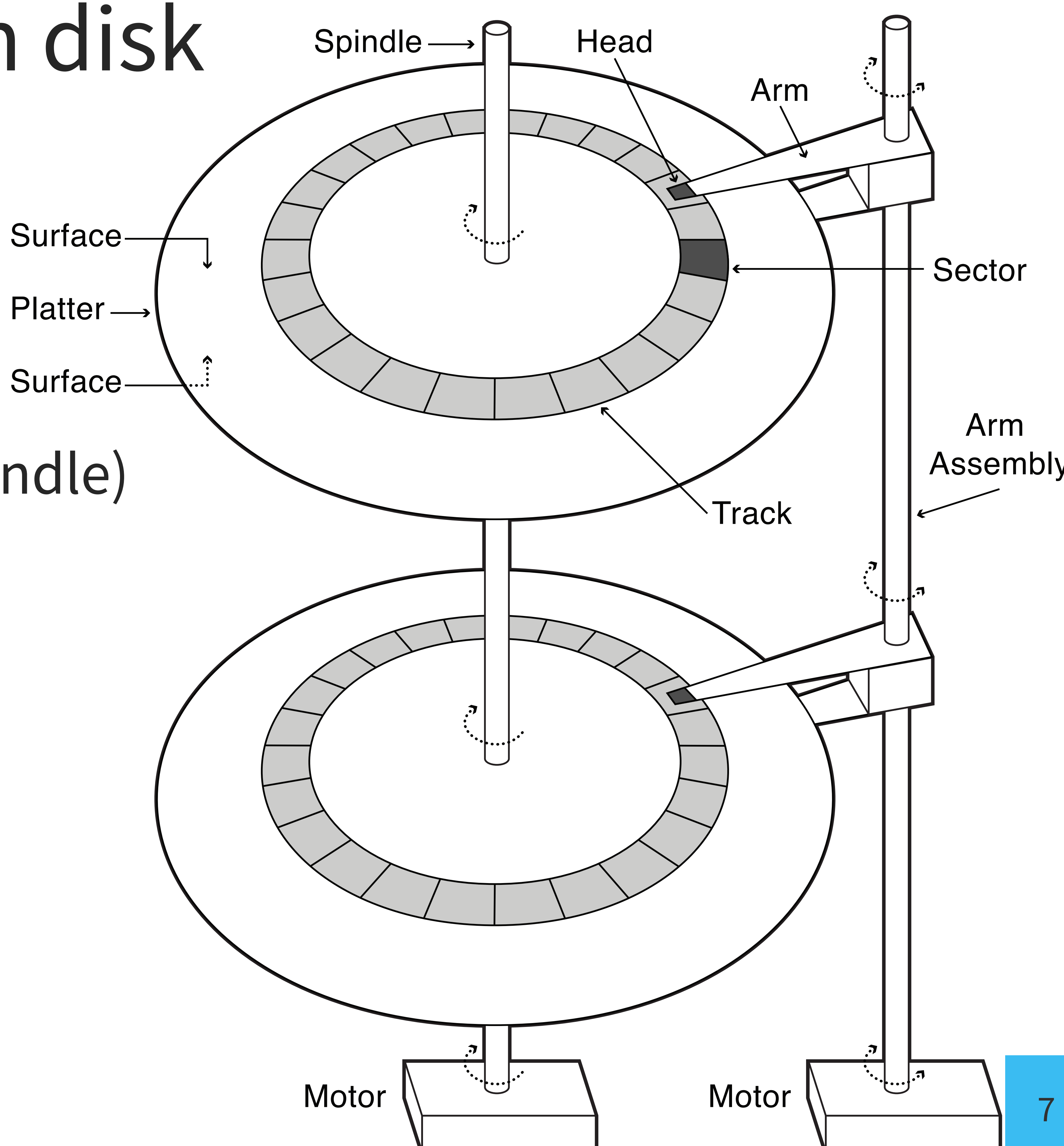
RAM (Memory) vs HDD (Disk) vs SSD, 2020's

	RAM	HDD	SSD
Typical Size	16 GB	1 TB	1TB
Cost	$5-10 per GB	$0.05 per GB	$0.10 per GB
Latency	15 ns	15 ms	1ms
Throughput (Sequential)	8000 MB/s	175 MB/s	500 MB/s
Power Reliance	volatile	non-volatile	non-volatile

Reading from disk

Must specify:

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



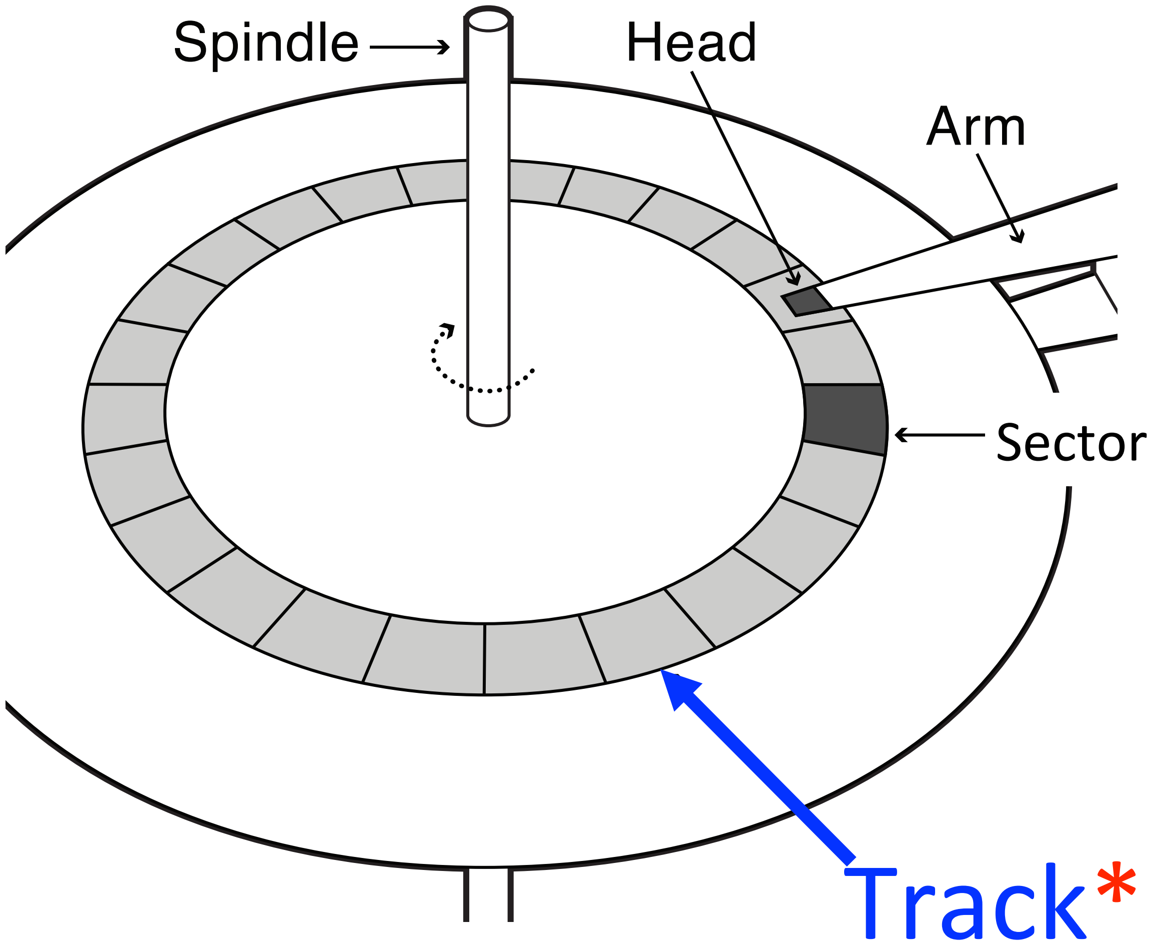
Disk Tracks

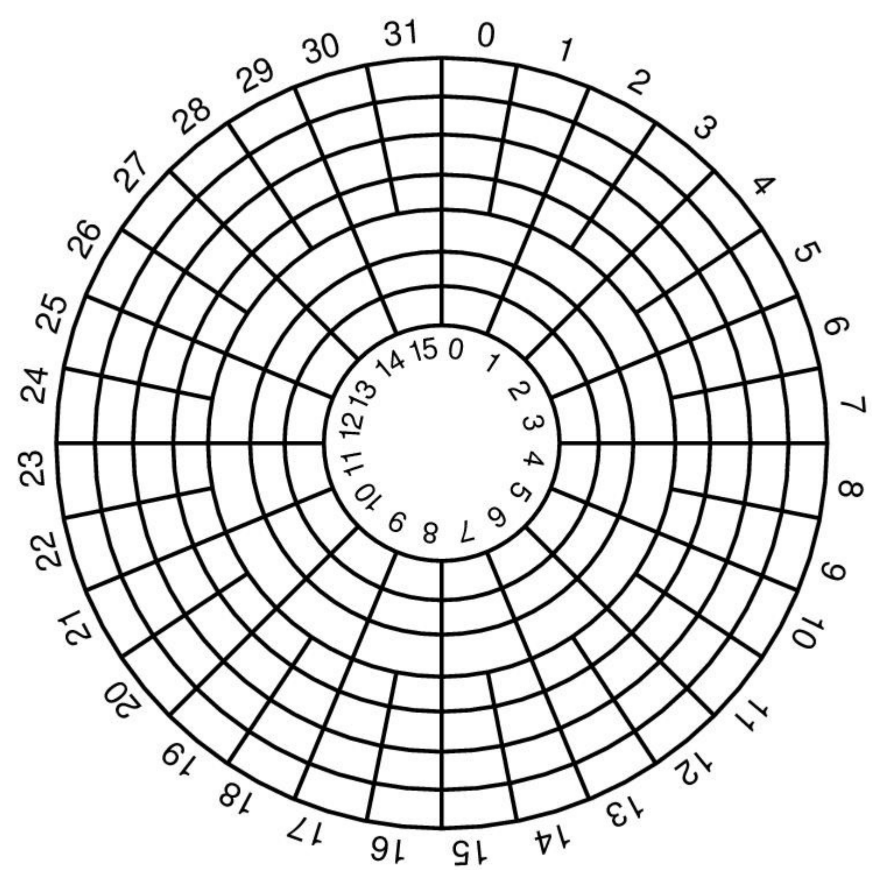
~ 1 micron wide (1000 nm)

- 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



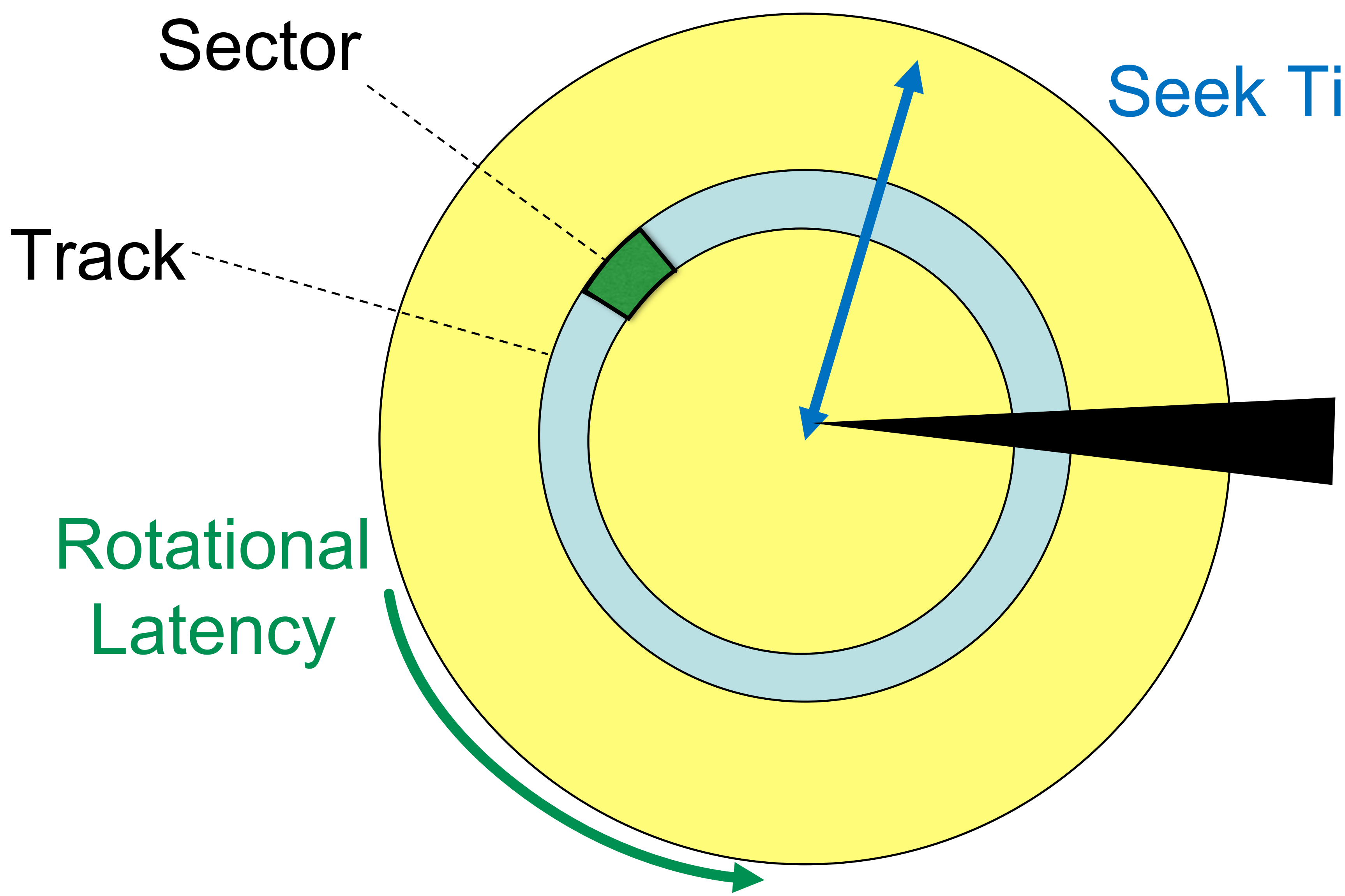


not to scale: head is actually much bigger than a track

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: FIFO

- Schedule disk operations in order they arrive
- Downsides?

FIFO Schedule?
Total head movement?

640 cylinders

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: 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?

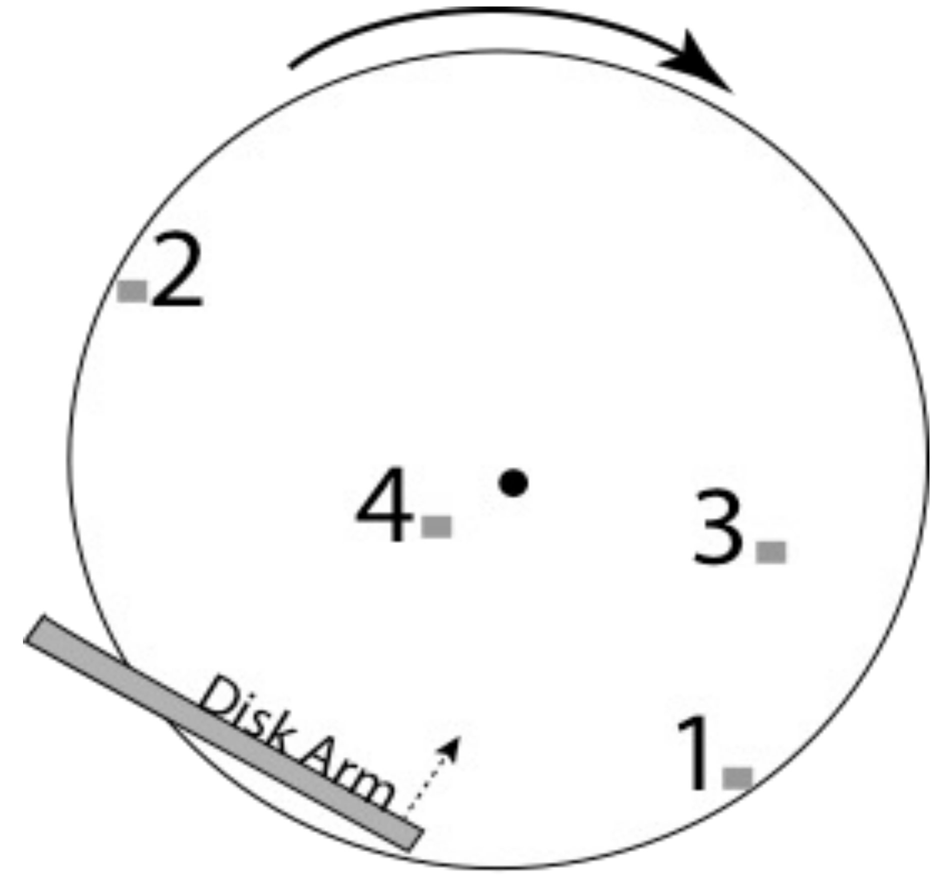
Total head movement? 236 cylinders

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

Disk Scheduling: SCAN

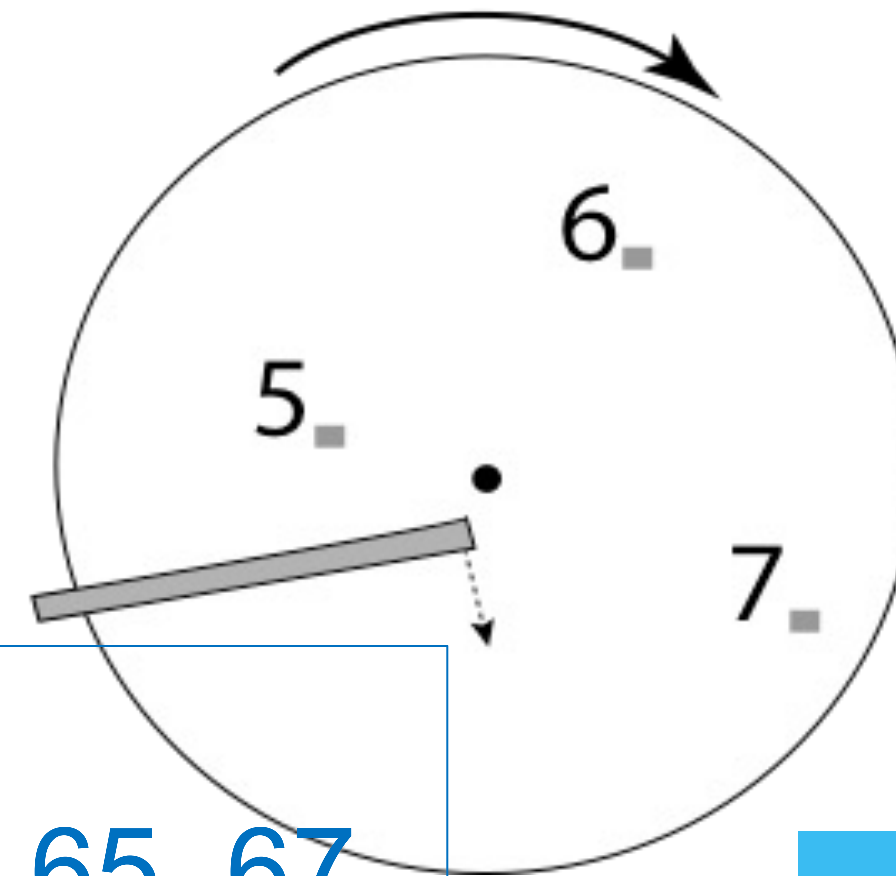
Elevator Algorithm:

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



SCAN Schedule?

Total head movement?



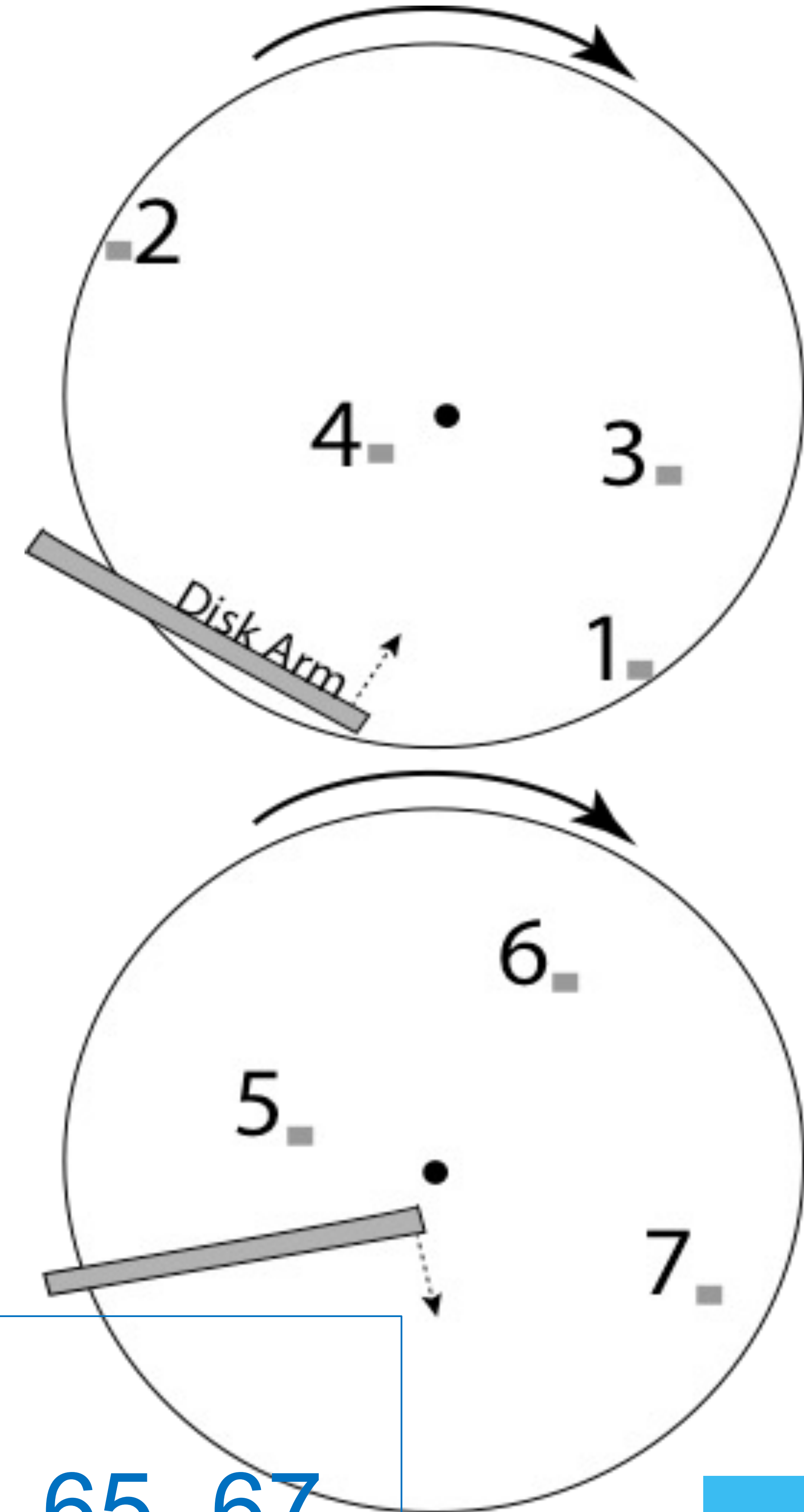
Head pointer @ 53

Queue: 98, 183, 37, 122, 14, 124, 65, 67

Disk Scheduling: 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?

208 cylinders

Head pointer @ 53

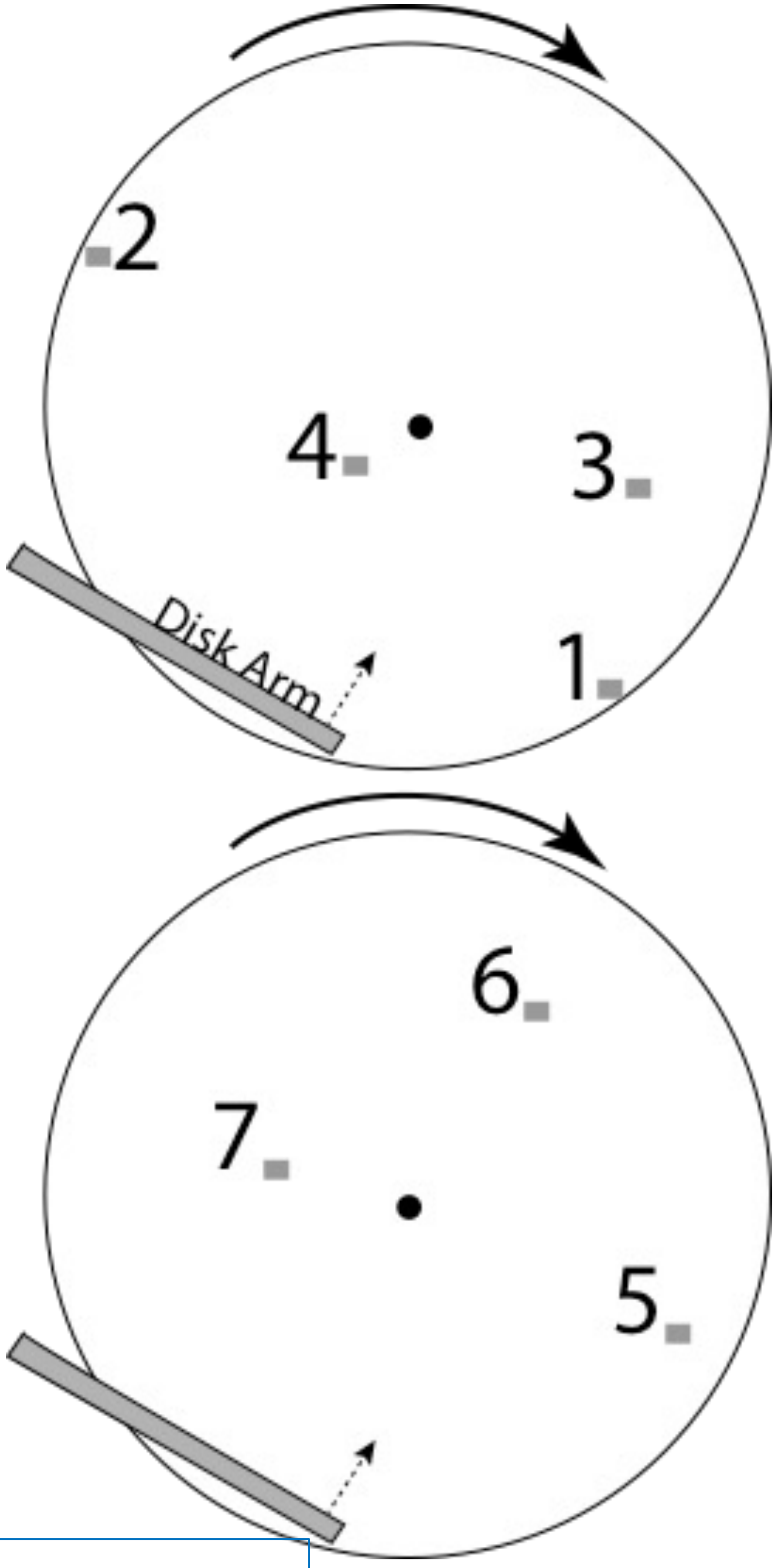
Queue: 98, 183, 37, 122, 14, 124, 65, 67

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

Solid State Drives (Flash)

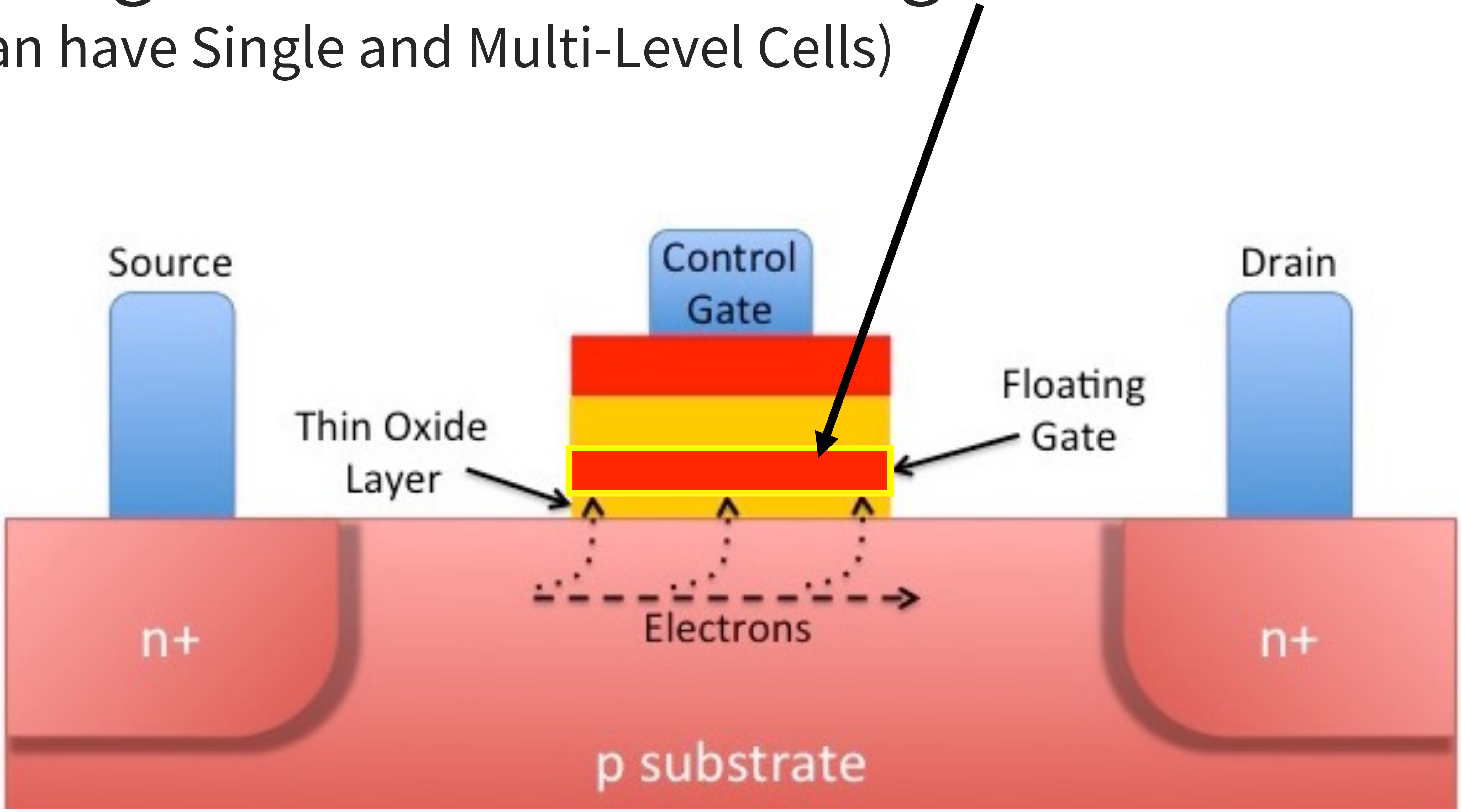
Most SSDs based on NAND-flash

- retains its state for years without power

NAND Flash

Charge is stored in Floating Gate

(can have Single and Multi-Level Cells)



Floating Gate MOSFET (FGMOS)

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

Flash Operations

- **Erase block:** sets each cell to "1"
  - erase granularity = "erasure block" = 128-512 KB
  - time: several ms
- **Write (aka program) page:** can only write erased pages
  - write granularity = 1 page (2-4KBytes)
  - time: 100s of microseconds
- **Read page:**
  - read granularity = 1 page
  - time: 10s of microseconds

- Flash drive consists of several *banks* that can be accessed in parallel
  - Each bank can have thousands of blocks

Flash Limitations

- can't write 1 word or page
  - must first erase whole blocks to write a page
- 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
- Wear-leveling: only write each physical page a limited number of times
- Sector sparing: Remap pages that no longer work

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
- Plenty: there should be lots of it
- Affordable: won’t break the bank

Disks can fail

- Either individual blocks
  - bit flips
  - scratches on hard disk platter
  - wear on SSD
- Or the entire disk
  - damage to hard disk head

- Metrics: MTTF and MTTR
  - Mean Time To Failure
  - Mean Time To Repair

Throughput, Bandwidth, and Latency

- Throughput is usually measured in "number of operations per second"
- Bandwidth is usually measured in "number of bytes per second"
- Latency is usually measured in "seconds"

Throughput and bandwidth are essentially the same thing, as each disk read/write operation transfers a fixed number of bytes ("block size")

Latency vs Throughput

- If you do one operation at a time, then Latency × Throughput = 1.
  - e.g., if it takes 100 ms to do a read or write operation, then you can do 10 operations per second
- But operations can often be pipelined or executed in parallel
  - throughput higher than 1/latency
  - (road analogy)

Sequential vs Random access

- With disks and file systems, sequential access is usually much faster than random access
- Reasons for faster sequential access:
  - “fewer seeks” on the disk
  - blocks can be “prefetched”

RAID

- Redundant Array of Inexpensive Disks
- 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

latency?

throughput?

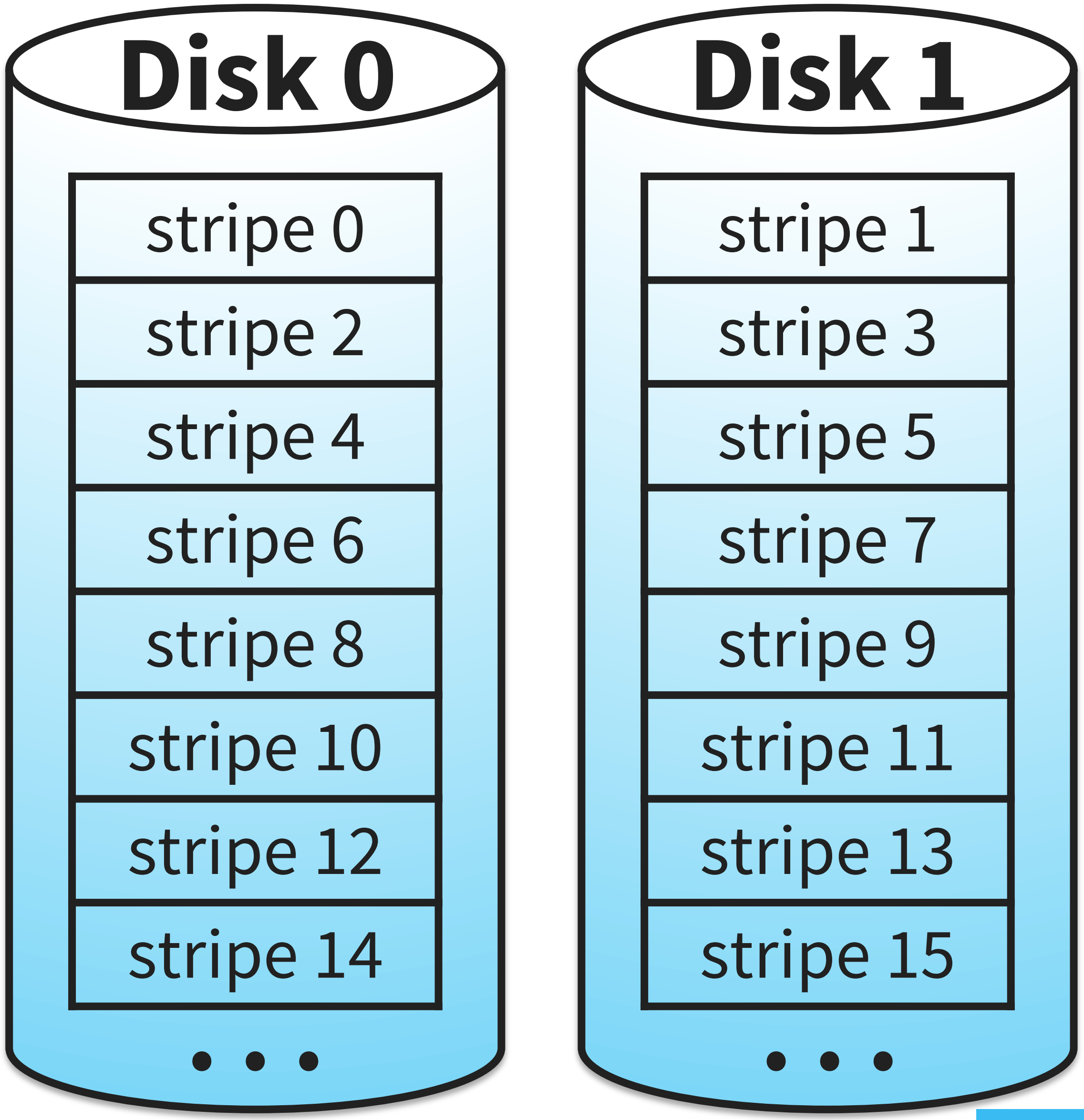
+ Cheap

capacity?

– Unreliable

max #failures?

MTTF?



Striping and Reliability

Striping *reduces* reliability

- More disks ➜ higher probability of some disk failing
- *N* disks: 1/*N*th mean time between failures of 1 disk

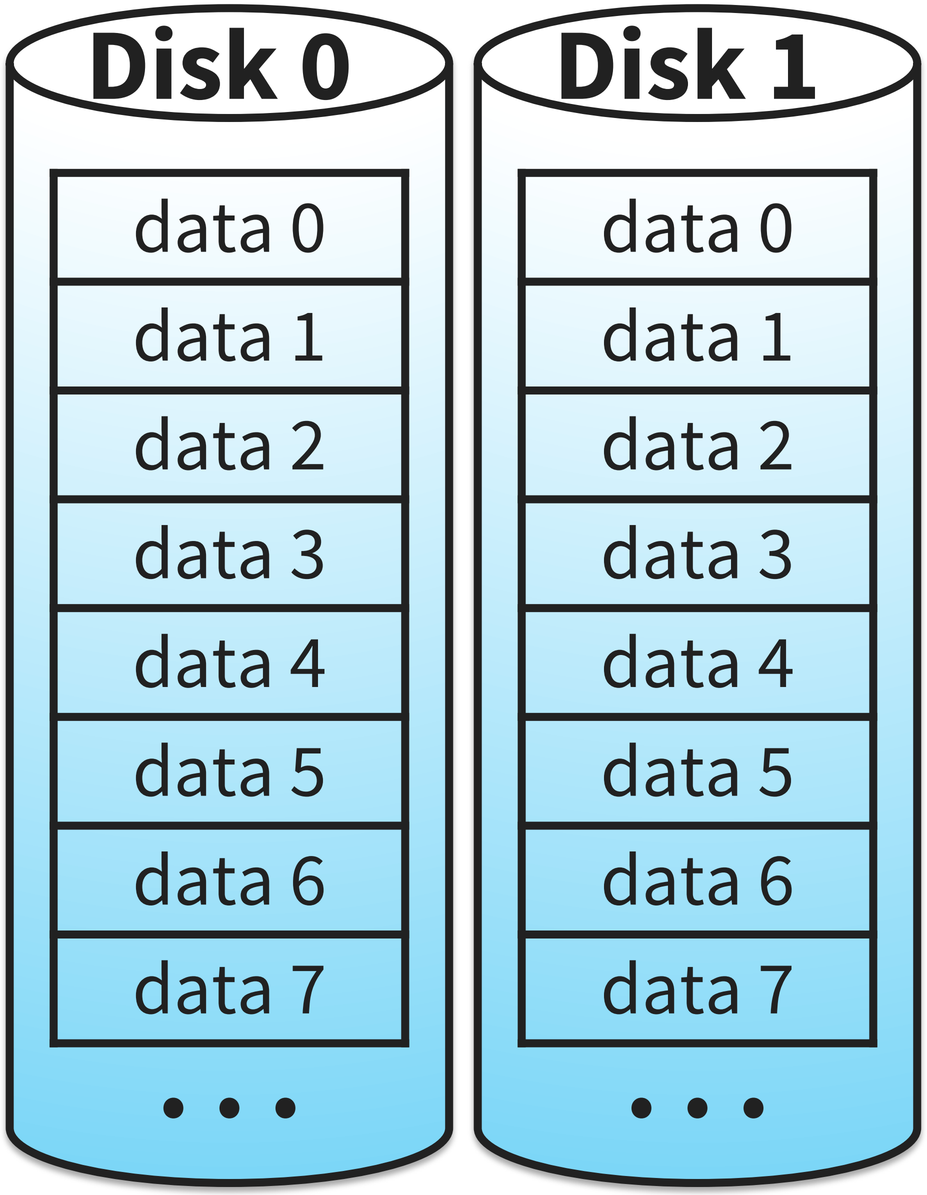
😞

What can we do to improve Disk Reliability?

RAID-1

Disks Mirrored:

data written in 2 places



+ Reliable

deals well with disk loss

but not corruption

(how many needed for that?)

+ Fast

latency?

throughput?

– Expensive

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

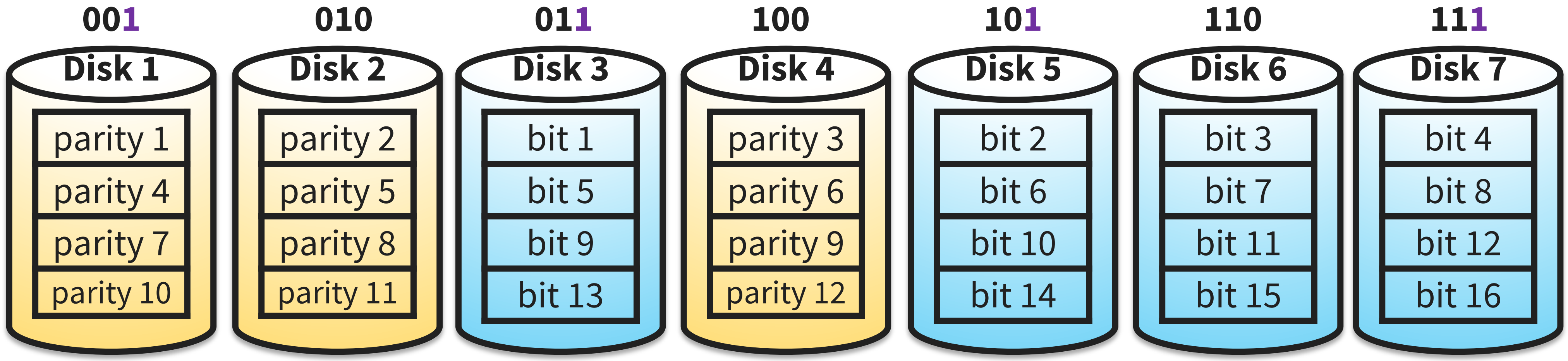
+ Reliable

– Expensive

parity 1 = 3⊕5⊕7

parity 2 = 3⊕6⊕7

parity 4 = 5⊕6⊕7



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

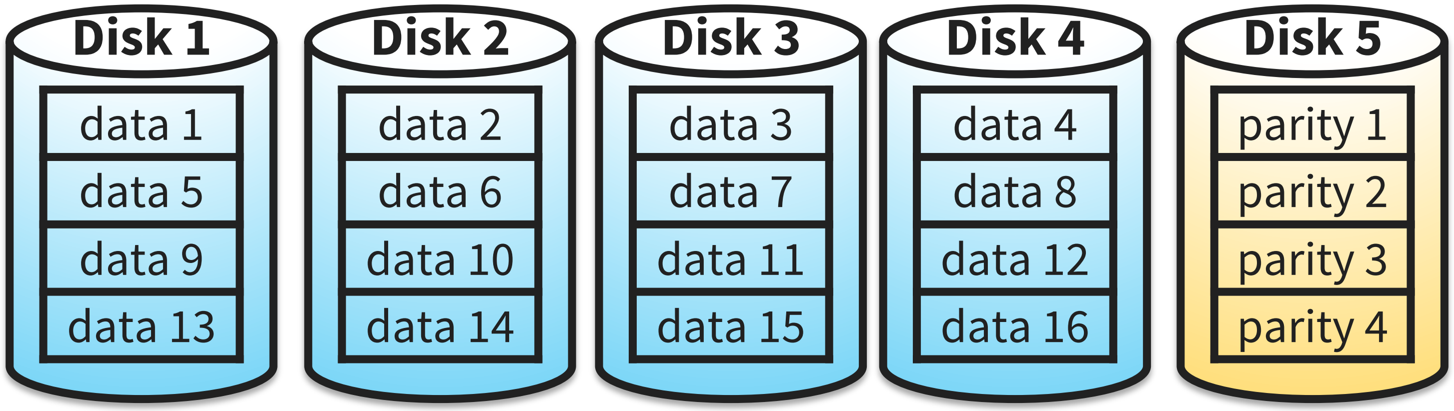
RAID-4: **block**-level striping + parity disk

+ better spatial locality for disk access

+ Cheap

– Slow Writes

– Reliability?



Using a parity disk

- $D_N = D_1 \oplus D_2 \oplus \ldots \oplus D_{N-1}$
  - $\oplus$ = XOR operation
  - therefore $D_1 \oplus D_2 \oplus \ldots \oplus D_N$ = 0
- If one of $D_1 \ldots D_{N-1}$ fails, we can reconstruct its data by XOR-ing all the remaining drives
  - $D_i = D_1 \oplus \ldots \oplus D_{i-1} \oplus D_{i+1} \oplus \ldots \oplus D_N$

Updating a block in RAID-4

- Suppose block lives on disk D_1
- Method 1:
  - read corresponding blocks on $D_2 \ldots D_{N-1}$
  - XOR all with new content of block
  - write disk D_1 and D_N in parallel
- Method 2 (better):
  - read D_1 (old content) and D_N
  - $D_N' = D_N \oplus D_1 \oplus D_1'$

    $= D_1 \oplus D_2 \oplus \ldots \oplus D_{N-1} \oplus D_1 \oplus D_1'$

    $= D_1' \oplus D_2 \oplus \ldots \oplus D_{N-1}$
  - write disk D_1 and D_N in parallel
  - write throughput: ½ of single disk
    - parity disk is the bottleneck
  - write latency: double of single disk

Streaming update in RAID-4

- Save up updates to stripe across $D_1 \ldots D_{N-1}$
  - Batching!
- Compute $D_N = D_1 \oplus D_2 \oplus \ldots \oplus D_{N-1}$
- Write $D_1 \ldots D_N$ in parallel
- Throughput: $(N - 1)$ times single disk

- Note that in all write cases D_N must always be updated

➔ D_N is a write performance bottleneck

➔ and suffers from more wear than the other disks

RAID 5: Rotating Parity w/Striping

+ Reliable

you can lose one disk

+ Fast

$(N-1)$ x seq. write throughput of single disk

N x random read throughput of single disk

$N/4$ x random write throughput of single disk

+ Affordable