# COS 318: Operating Systems

# Storage Devices

Kai Li and Andy Bavier
Computer Science Department
Princeton University

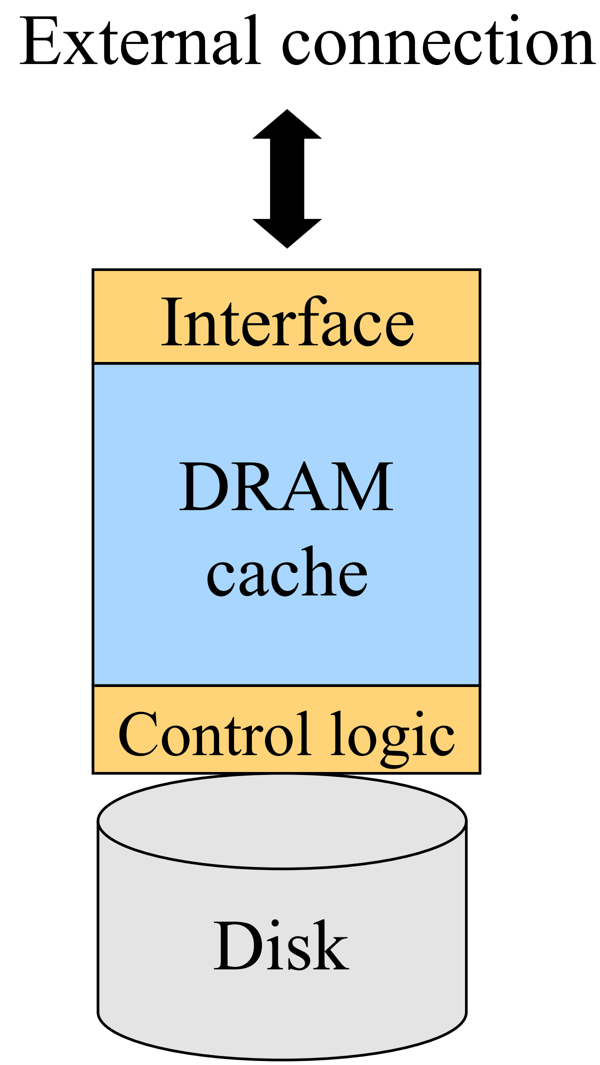
http://www.cs.princeton.edu/courses/archive/fall13/cos318/

# Today’s Topics

- Magnetic disks
- Magnetic disk performance
- Disk arrays
- Flash memory

# A Typical Magnetic Disk Controller

- External interfaces
  - IDE/ATA, **SATA(1.0, 2.0, 3.0)**
  - SCSI (1, 2, 3),
    Ultra-(160, 320, 640) SCSI
  - Fibre channel
- Cache
  - Buffer data between disk and interface
- Control logic
  - Read/write operation
  - Cache replacement
  - Failure detection and recovery

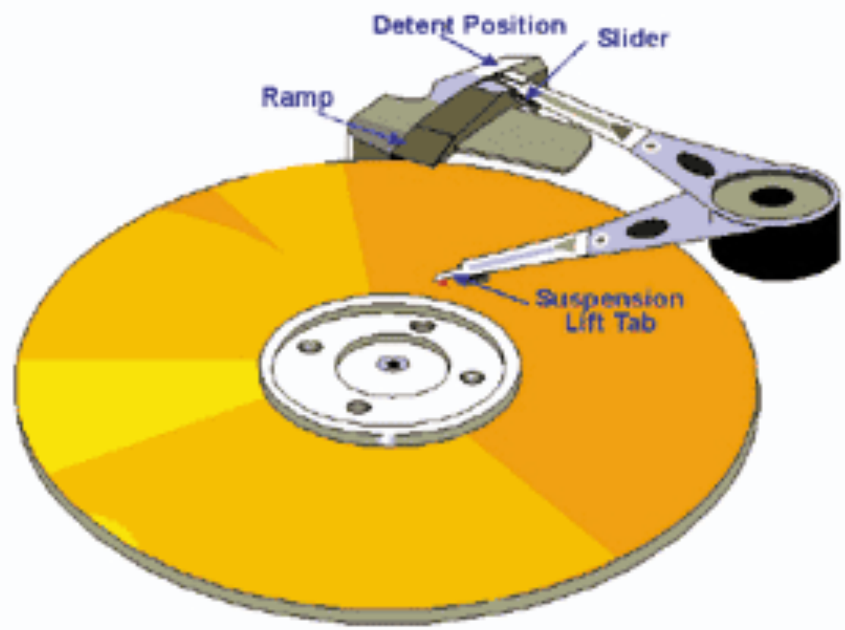


# Disk Caching

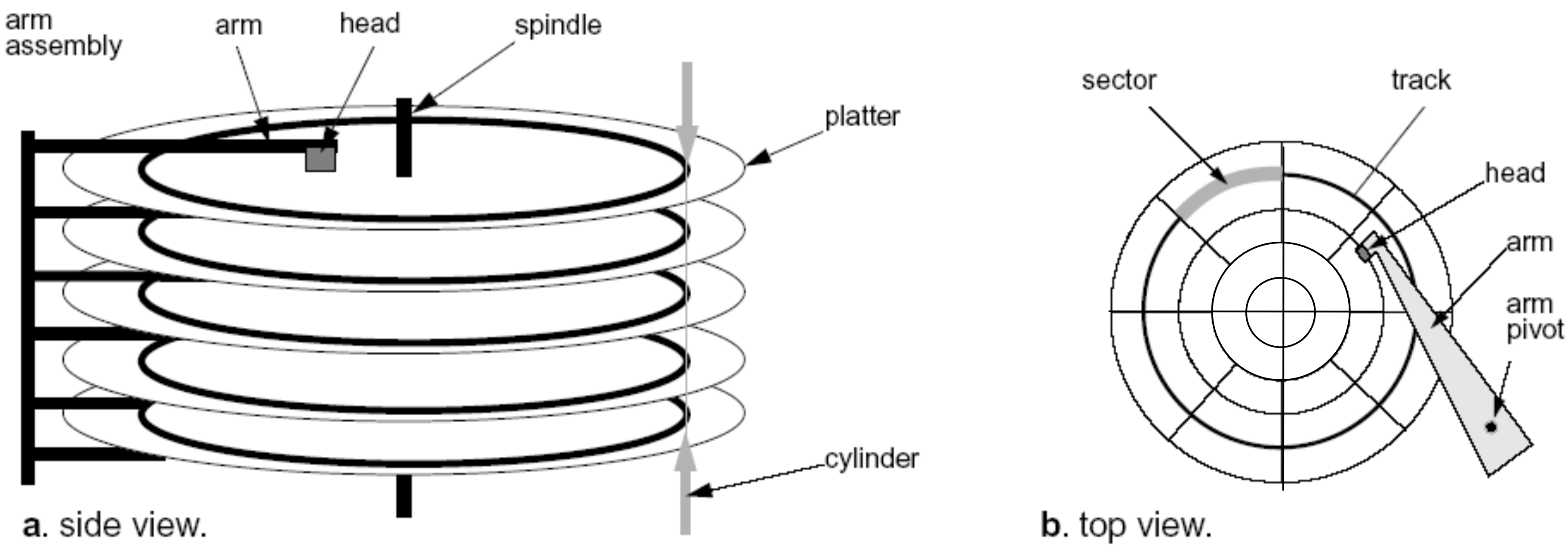
- Method
  - Use DRAM to cache recently accessed blocks
    - Typically a disk has 64-128 MB
    - Some of the RAM space stores “firmware” (an embedded OS)
  - Blocks are replaced usually in an LRU order + “tracks”
- Pros
  - Good for reads if accesses have locality
- Cons
  - Need to deal with reliable writes

# Disk Arm and Head

- Disk arm
  - A disk arm carries disk heads
- Disk head
  - Mounted on an actuator
  - Read/write on disk surface
- Read/write operation
  - Read/write with (track, sector)
  - Seek the right cylinder (tracks)
  - Wait until the sector comes
  - Perform read/write



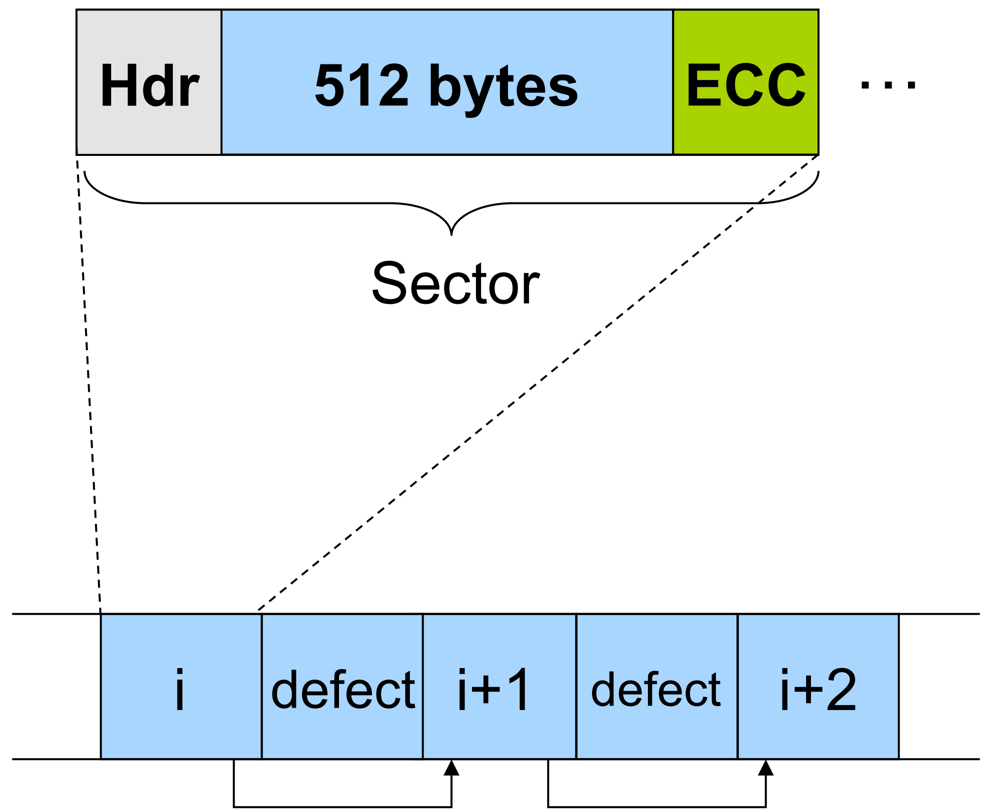
# Mechanical Component of A Disk Drive



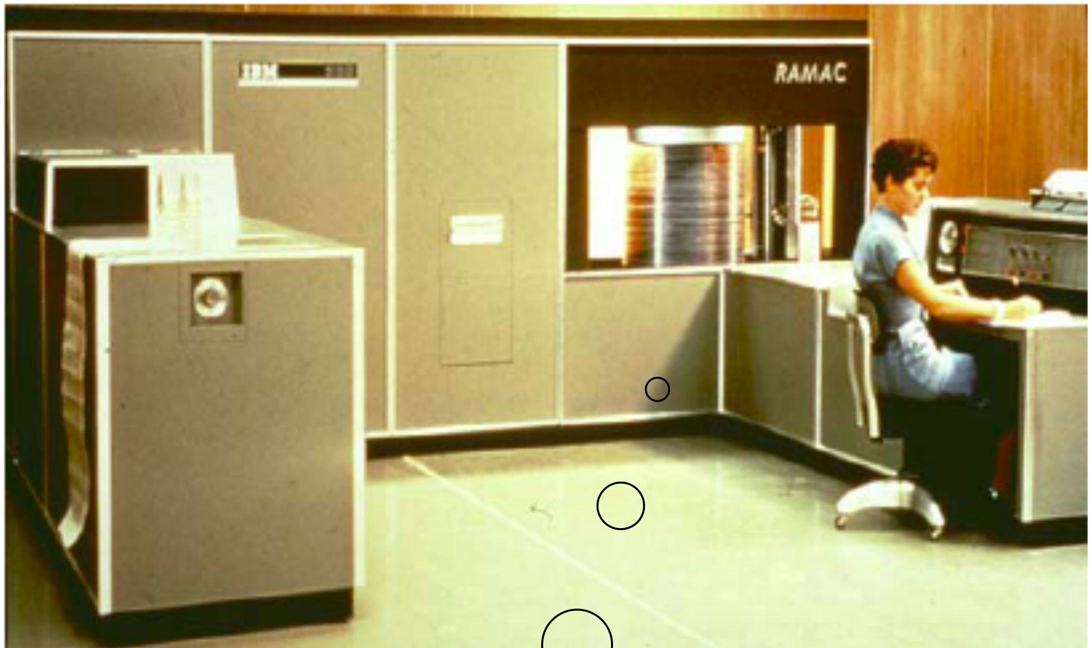

- Tracks
  - Concentric rings around disk surface, bits laid out serially along each track
- Cylinder
  - A track of the platter, 1000-5000 cylinders per zone, 1 spare per zone
- Sectors
  - Arc of track holding some min # of bytes, variable # sectors/track

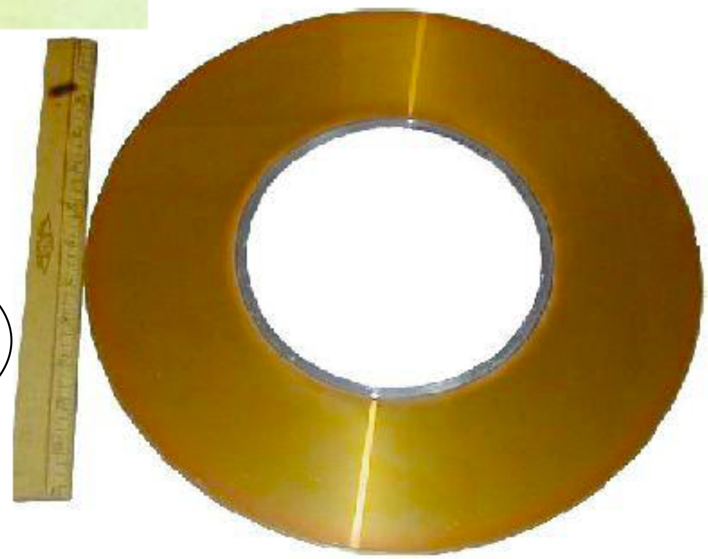
# Disk Sectors

- Where do they come from?
  - Formatting process
  - Logical maps to physical
- What is a sector?
  - Header (ID, defect flag, …)
  - Real space (e.g. 512 bytes)
  - Trailer (ECC code)
- What about errors?
  - Detect errors in a sector
  - Correct them with ECC
  - If not recoverable, replace it with a spare
  - Skip bad sectors in the future



# Disks Were Large



First Disk:
IBM 305 RAMAC (1956)
5MB capacity
50 disks, each 24”

# Storage Form Factors Are Changing

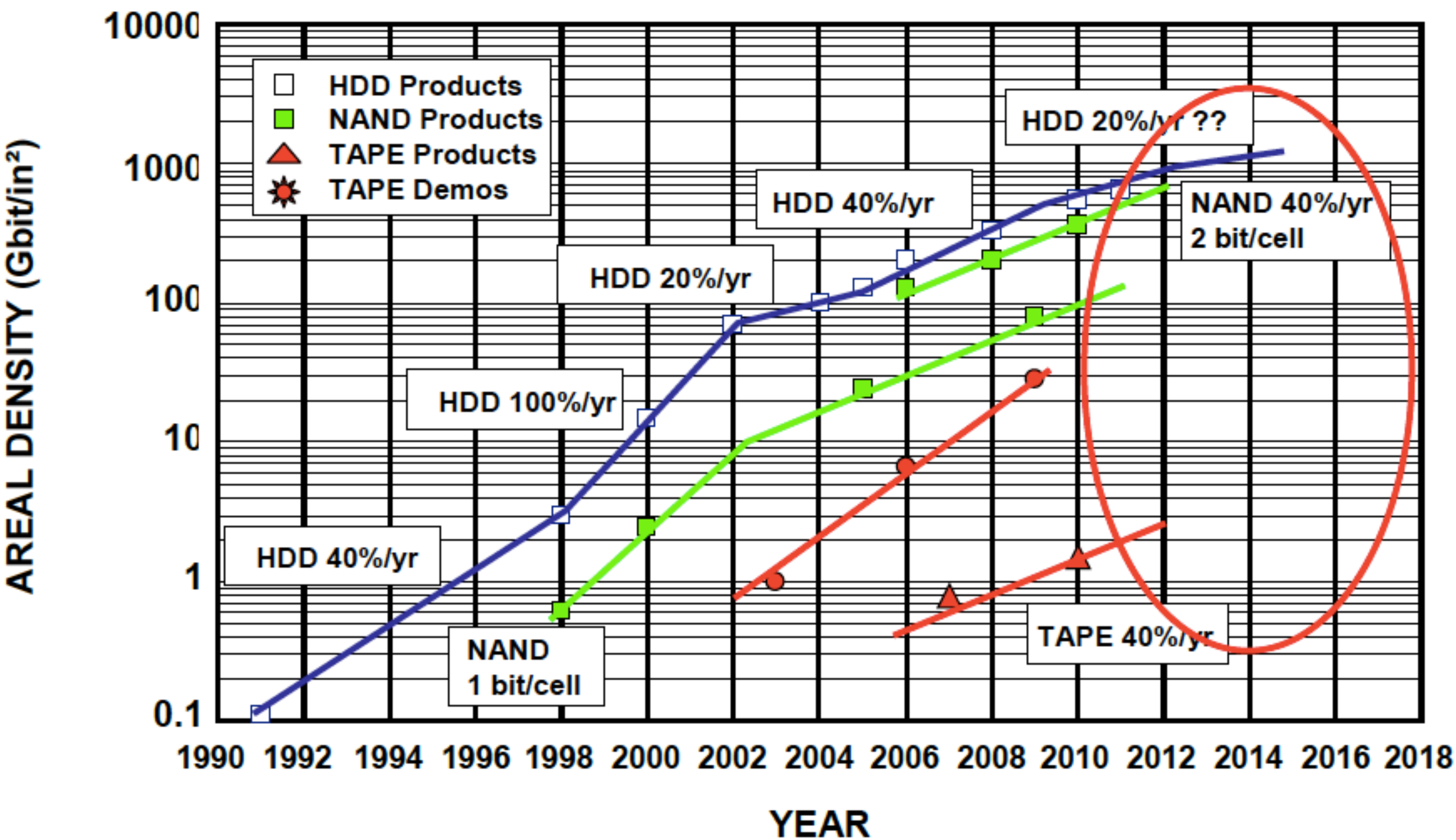
Form factor:
.5-1”× 4”× 5.7”
Storage:
0.5-6TB

Form factor:
.4-.7” × 2.7” × 3.9”
Storage:
0.5-2TB


Form factor: 24mm × 32mm × 2.1mm
Storage: 1-256GB

Form factor: PCI card
Storage: 0.5-10TB

# Areal Density vs. Moore's Law




(Fontana, Decad, Hetzler, 2012)

# 50 Years (Mark Kryder at SNW 2006)

| | IBM RAMAC (1956) | Seagate Momentus (2006) | Difference |
|---|---|---|---|
| **Capacity** | 5MB | 160GB | 32,000 |
| **Areal Density** | 2K bits/in$^2$ | 130 Gbits/in$^2$ | 65,000,000 |
| **Disks** | 50 @ 24” diameter | 2 @ 2.5” diameter | 1 / 2,300 |
| **Price/MB** | $1,000 | $0.01 | 1 / 100,000 |
| **Spindle Speed** | 1,200 RPM | 5,400 RPM | 5 |
| **Seek Time** | 600 ms | 10 ms | 1 / 60 |
| **Data Rate** | 10 KB/s | 44 MB/s | 4,400 |
| **Power** | 5000 W | 2 W | 1 / 2,500 |
| **Weight** | ~ 1 ton | 4 oz | 1 / 9,000 |

# Sample Disk Specs (from Seagate)

| | Enterprise Performance | Desktop HDD |
|---|---|---|
| **Capacity** | | |
| Formatted capacity (GB) | 600 | **4096** |
| Discs / heads | 3 / 6 | 4 / 8 |
| Sector size (bytes) | 512 | 512 |
| **Performance** | | |
| External interface | STA | SATA |
| Spindle speed (RPM) | 15,000 | 7,200 |
| Average latency (msec) | **2.0** | 4.16 |
| Seek time, read/write (ms) | **3.5/3.9** | 8.5/9.5 |
| Track-to-track read/write (ms) | **0.2-0.4** | 0.8/1.0 |
| Transfer rate (MB/sec) | **138-258** | 146 |
| Cache size (MB) | 128 | 64 |
| **Power** | | |
| Average / Idle / Sleep | 8.5 / 6 / NA | 7.5 / **5 / 0.75** |
| **Reliability** | | |
| Recoverable read errors | 1 per $10^{12}$ bits read | 1 per $10^{10}$ bits read |
| Non-recoverable read errors | **1 per $10^{16}$ bits read** | 1 per $10^{14}$ bits read |

# Disk Performance

- Seek
  - Position heads over cylinder, typically 3.5-9.5 ms
- Rotational delay
  - Wait for a sector to rotate underneath the heads
  - Typically 8 - 4 ms (7,200 – 15,000RPM)
- Transfer bytes
  - Transfer bandwidth is typically 70 -250 Mbytes/sec
- Example:
  - Performance of transfer 1 Kbytes of Desktop HDD, assuming BW = 100MB/sec, seek = 5ms, rotation = 4ms
  - Total time = 5ms + 4ms + 0.01ms = 9.01ms
  - What is the effective bandwidth?

# More on Performance

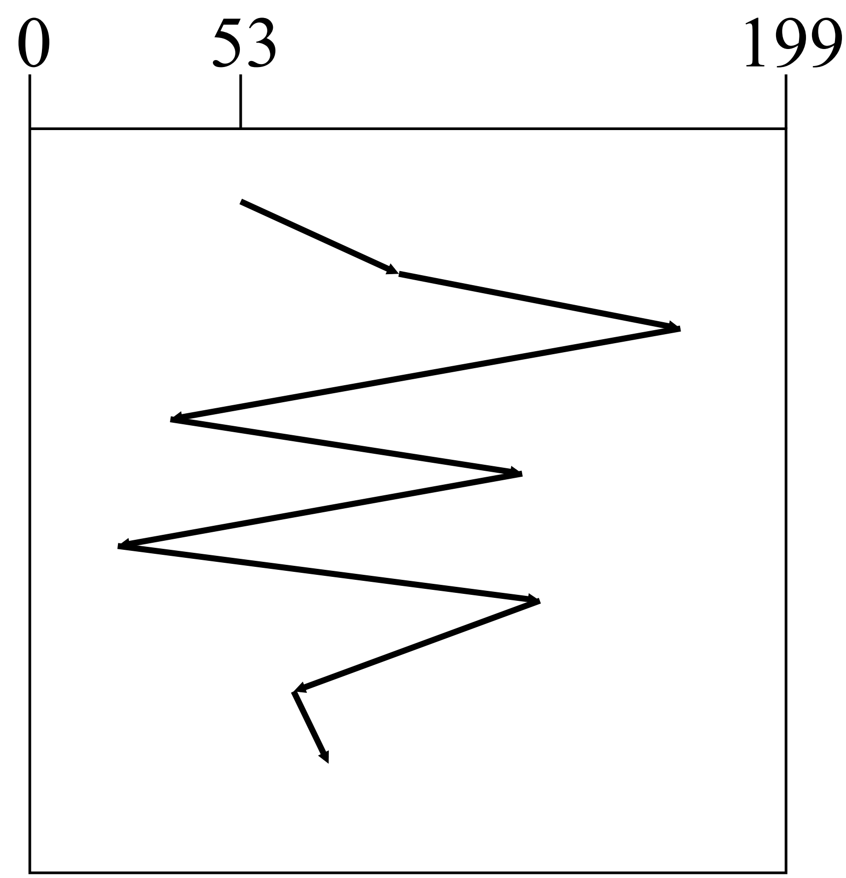
- What transfer size can get 90% of the disk bandwidth?
  - Assume Disk BW = 100MB/sec, avg rotation = 4ms, avg seek = 5ms
  - BW * 90% = size / (size/BW + rotation + seek)
  - size = BW * (rotation + seek) * 0.9 / (1 – 0.9)
    = 100MB * 0.009 * 0.9 / 0.1 = 8.1MB

| Block Size (Kbytes) | % of Disk Transfer Bandwidth |
|---|---|
| 9Kbytes | 1% |
| 100Kbytes | 10% |
| 0.9Mbytes | 50% |
| 8.1Mbytes | 90% |

- Seek and rotational times dominate the cost of small accesses
  - Disk transfer bandwidth are wasted
  - Need algorithms to reduce seek time

# FIFO (FCFS) order

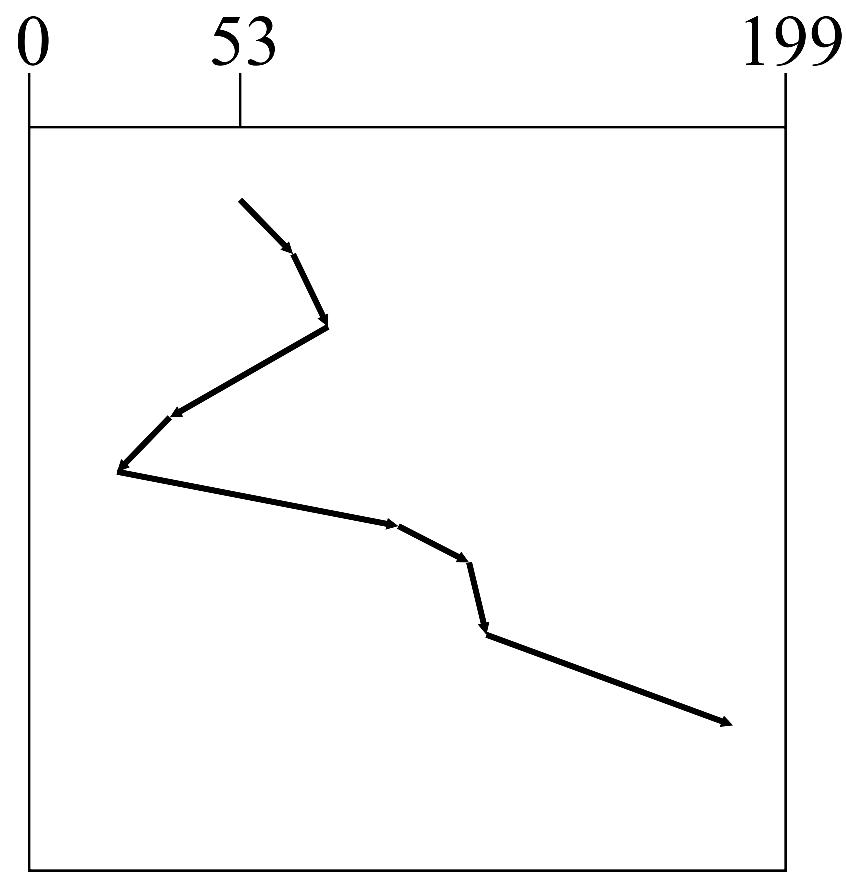
- Method
  - First come first serve
- Pros
  - Fairness among requests
  - In the order applications expect
- Cons
  - Arrival may be on random spots on the disk (long seeks)
  - Wild swing can happen




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

# SSTF (Shortest Seek Time First)

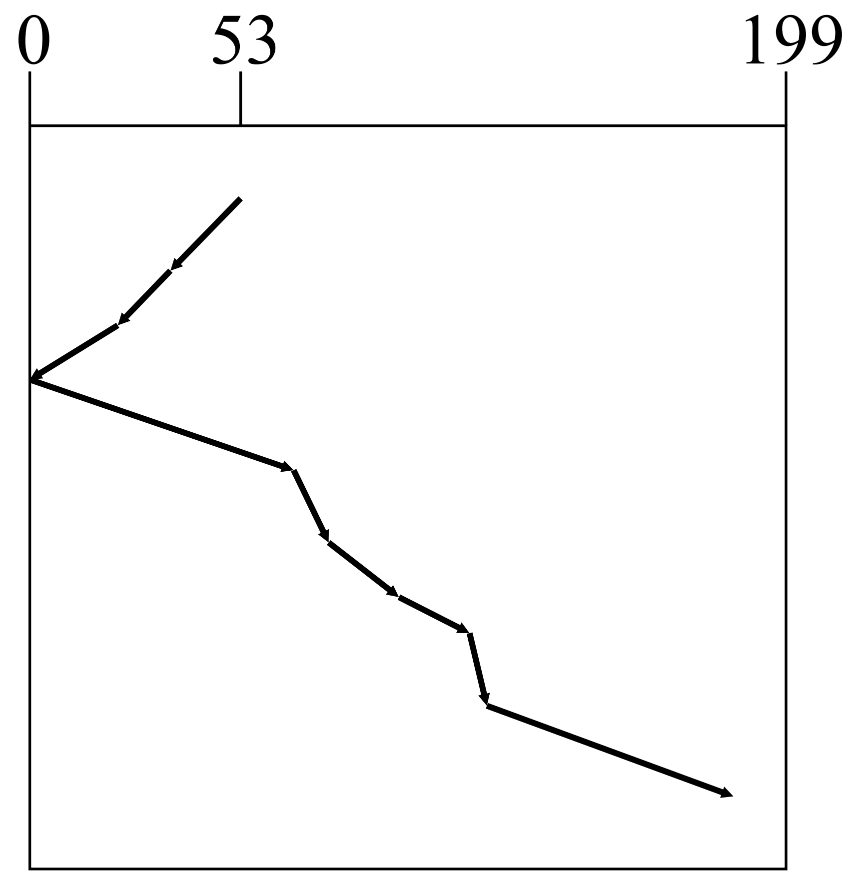
- Method
  - Pick the one closest on disk
  - Rotational delay is in calculation
- Pros
  - Try to minimize seek time
- Cons
  - Starvation
- Question
  - Is SSTF optimal?
  - Can we avoid the starvation?




98, 183, 37, 122, 14, 124, 65, 67
(65, 67, 37, 14, 98, 122, 124, 183)

# Elevator (SCAN)

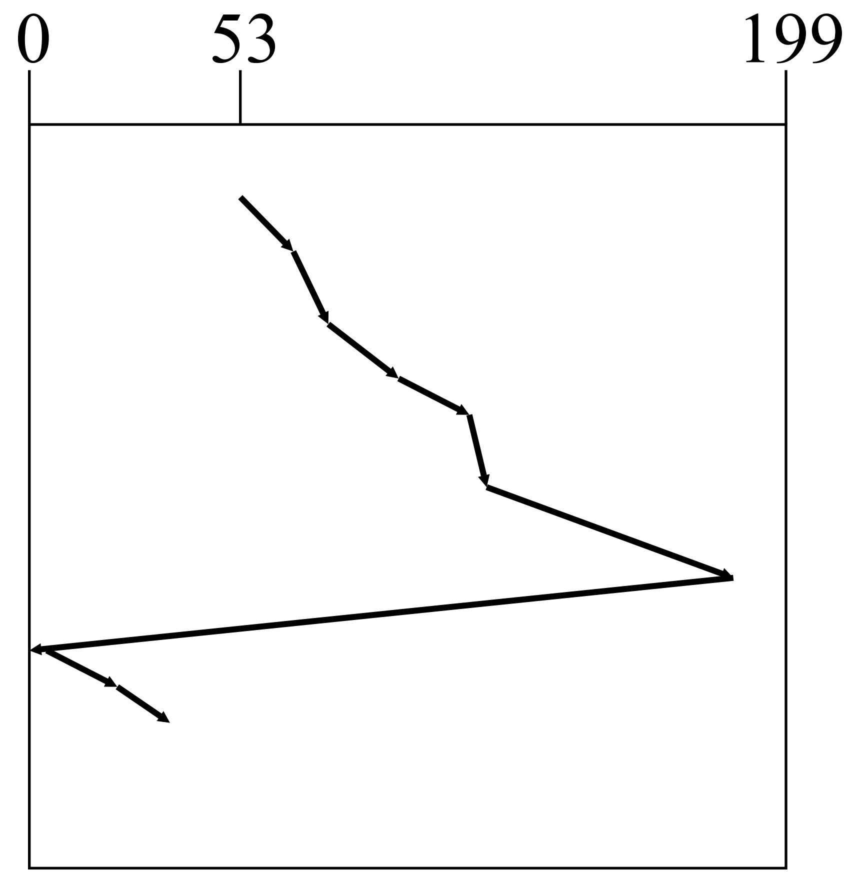
- Method
  - Take the closest request in the direction of travel
  - Real implementations do not go to the end (called LOOK)
- Pros
  - Bounded time for each request
- Cons
  - Request at the other end will take a while




98, 183, 37, 122, 14, 124, 65, 67
(37, 14, 65, 67, 98, 122, 124, 183)

# C-SCAN (Circular SCAN)

- Method
  - Like SCAN
  - But, wrap around
  - Real implementation doesn't go to the end (C-LOOK)
- Pros
  - Uniform service time
- Cons
  - Do nothing on the return



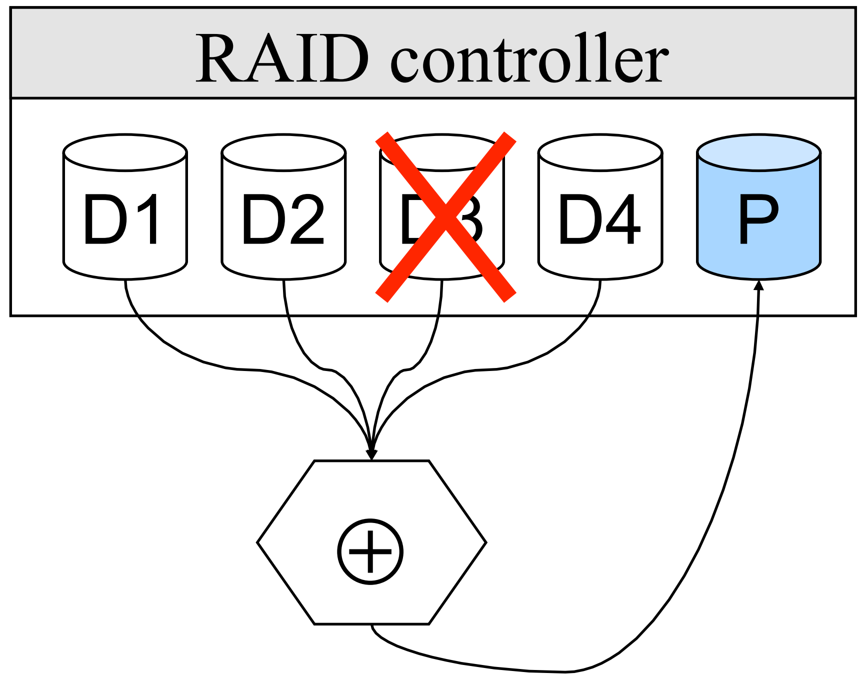

98, 183, 37, 122, 14, 124, 65, 67
(65, 67, 98, 122, 124, 183, 14, 37)

# Discussions

- Which is your favorite?
  - FIFO
  - SSTF
  - SCAN
  - C-SCAN
- Disk I/O request buffering
  - Where would you buffer requests?
  - How long would you buffer requests?
- More advanced issues
  - Can the scheduling algorithm minimize both seek and rotational delays?

# RAID (Redundant Array of Independent Disks)

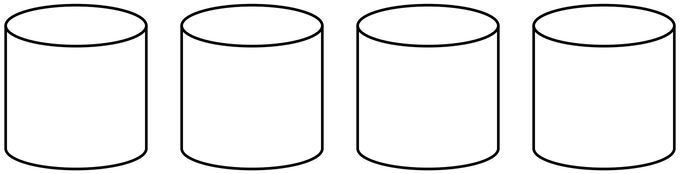
- Main idea
  - Compute XORs and store parity on disk P
  - Upon any failure, one can recover the block from using P and other disks
- Pros
  - Reliability
  - High bandwidth?
- Cons
  - Cost
  - The controller is complex



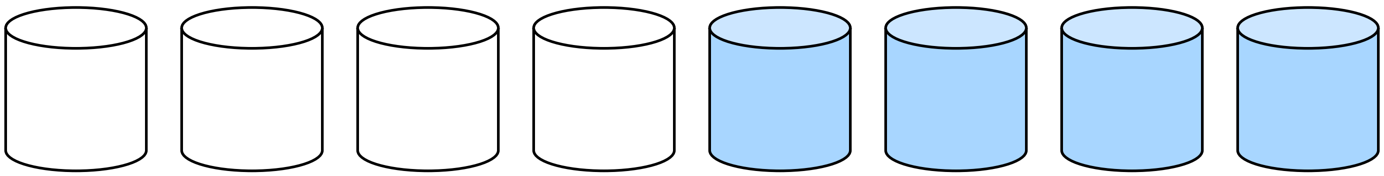

$P = D1 \oplus D2 \oplus D3 \oplus D4$

$D3 = D1 \oplus D2 \oplus P \oplus D4$

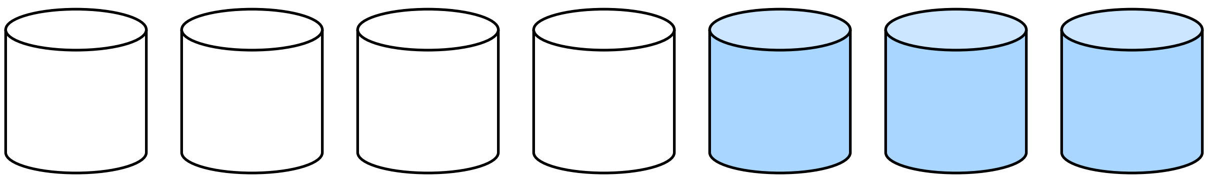
# Synopsis of RAID Levels



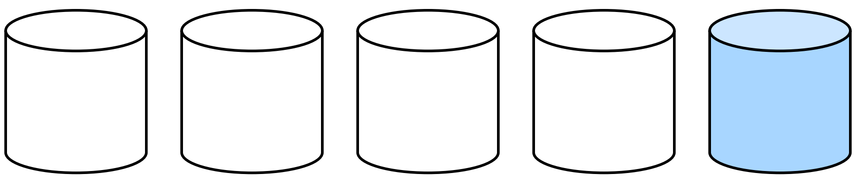
RAID Level 0: Non redundant



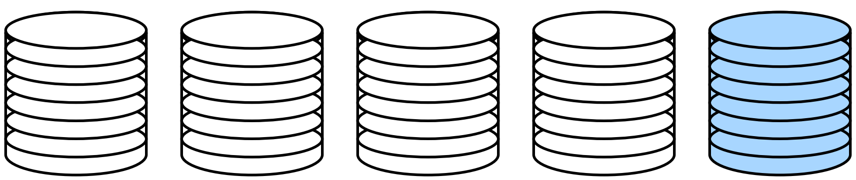
RAID Level 1:
Mirroring



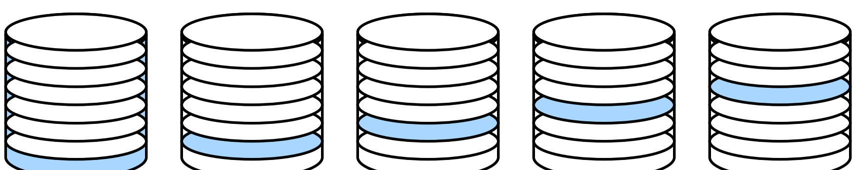
RAID Level 2:
Byte-interleaved, ECC



RAID Level 3:
Byte-interleaved, parity



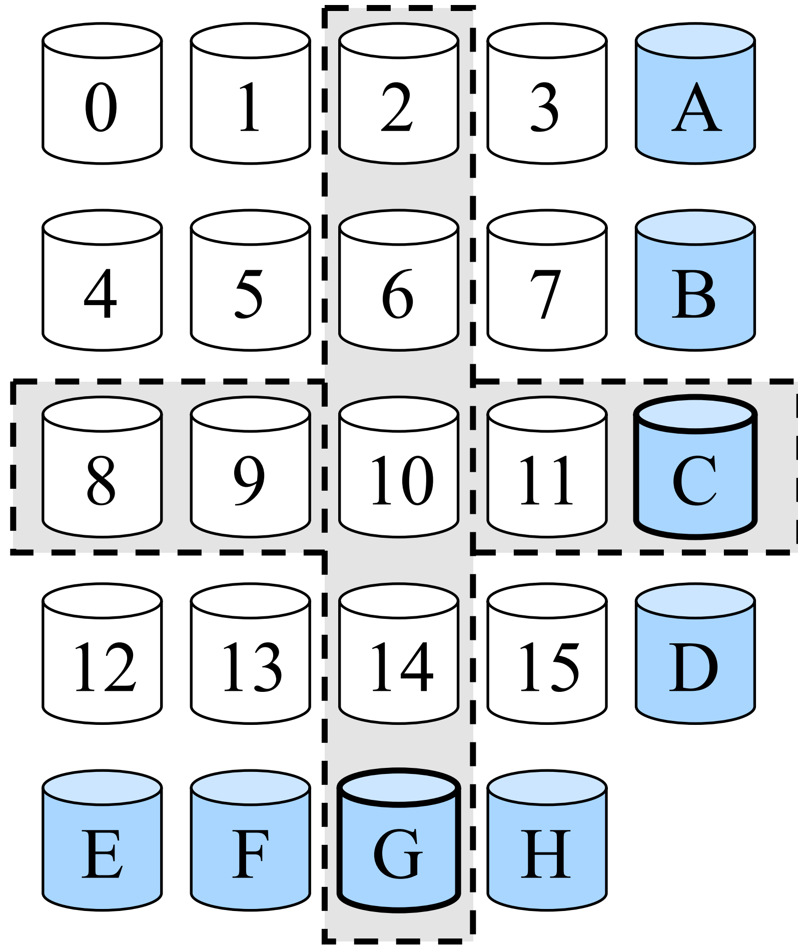
RAID Level 4:
Block-interleaved, parity

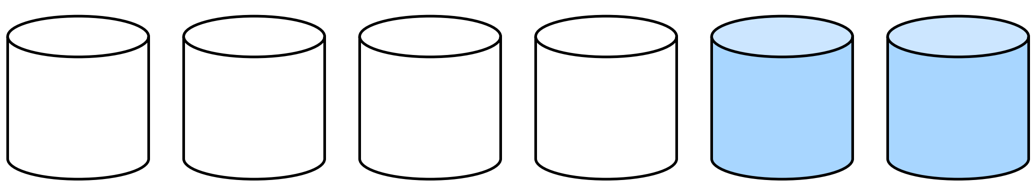


RAID Level 5:
Block-interleaved, distributed parity

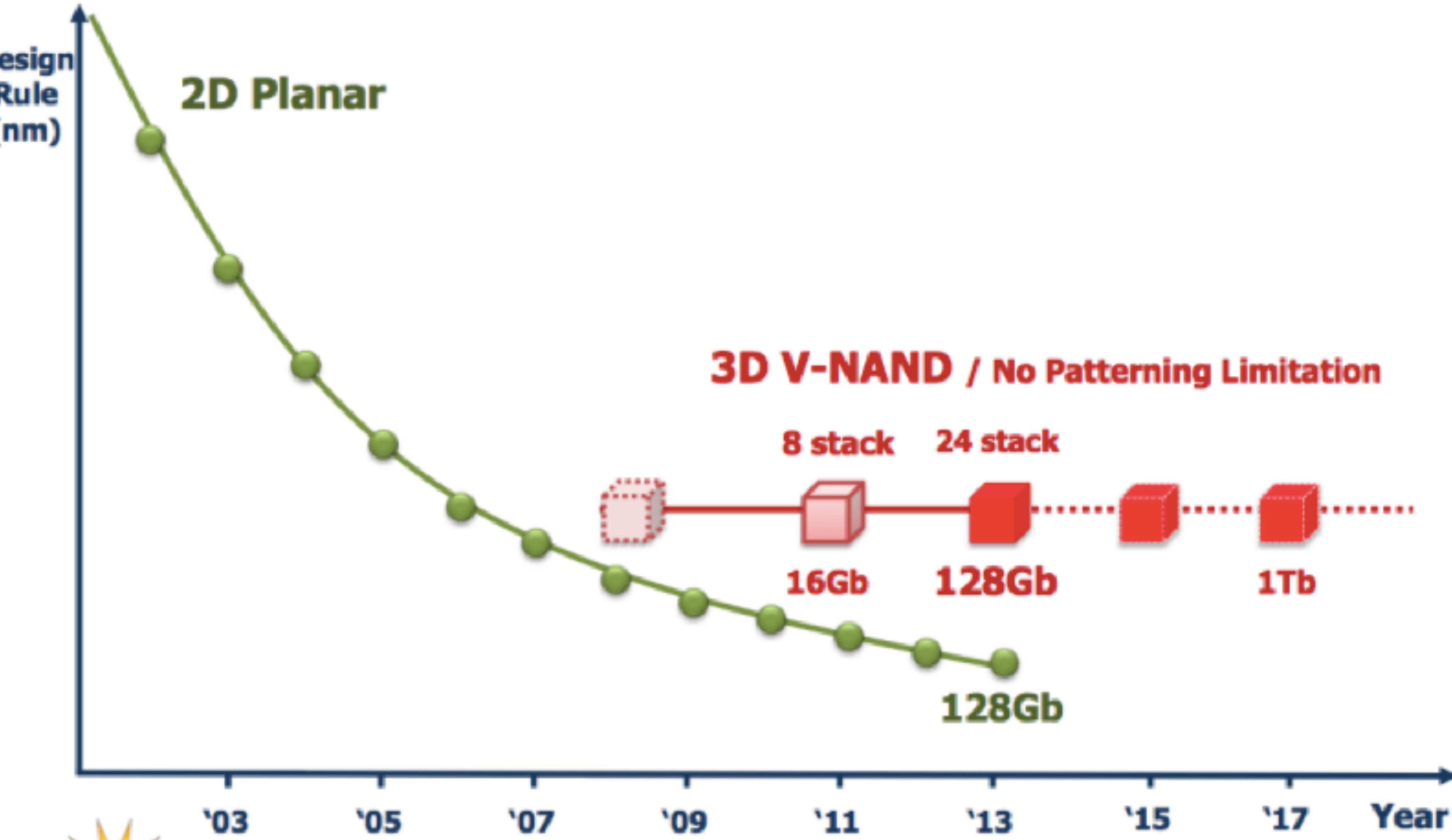
# RAID Level 6 and Beyond

- Goals
  - Less computation and fewer updates per random writes
  - Small amount of extra disk space
- Extended Hamming code
  - Remember Hamming code?
- Specialized Eraser Codes
  - IBM Even-Odd, NetApp RAID-DP, …
- Beyond RAID-6
  - Reed-Solomon codes, using MOD 4 equations
  - Can be generalized to deal with k (>2) disk failures



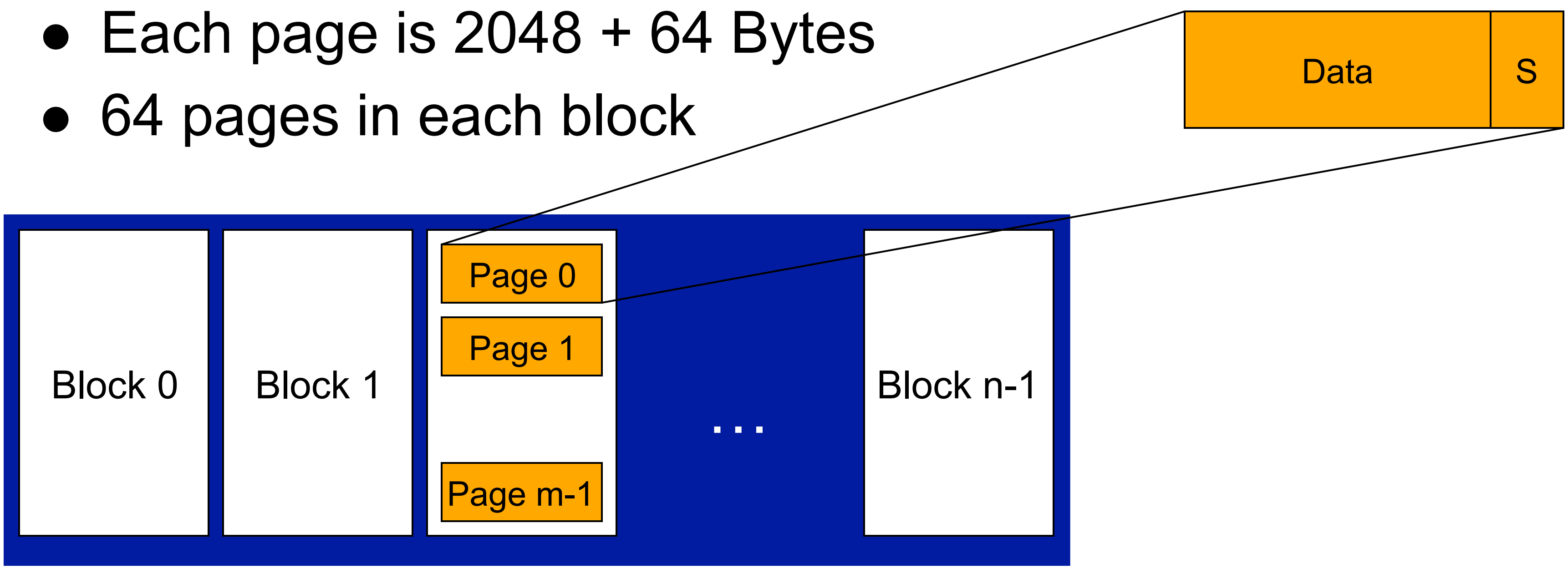



# V-NAND Era for the Future



# NAND Flash Memory

- High capacity
  - Single cell vs. multiple cell
- Small block
  - Each page 512 + 16 Bytes
  - 32 pages in each block
- Large block
  - Each page is 2048 + 64 Bytes
  - 64 pages in each block



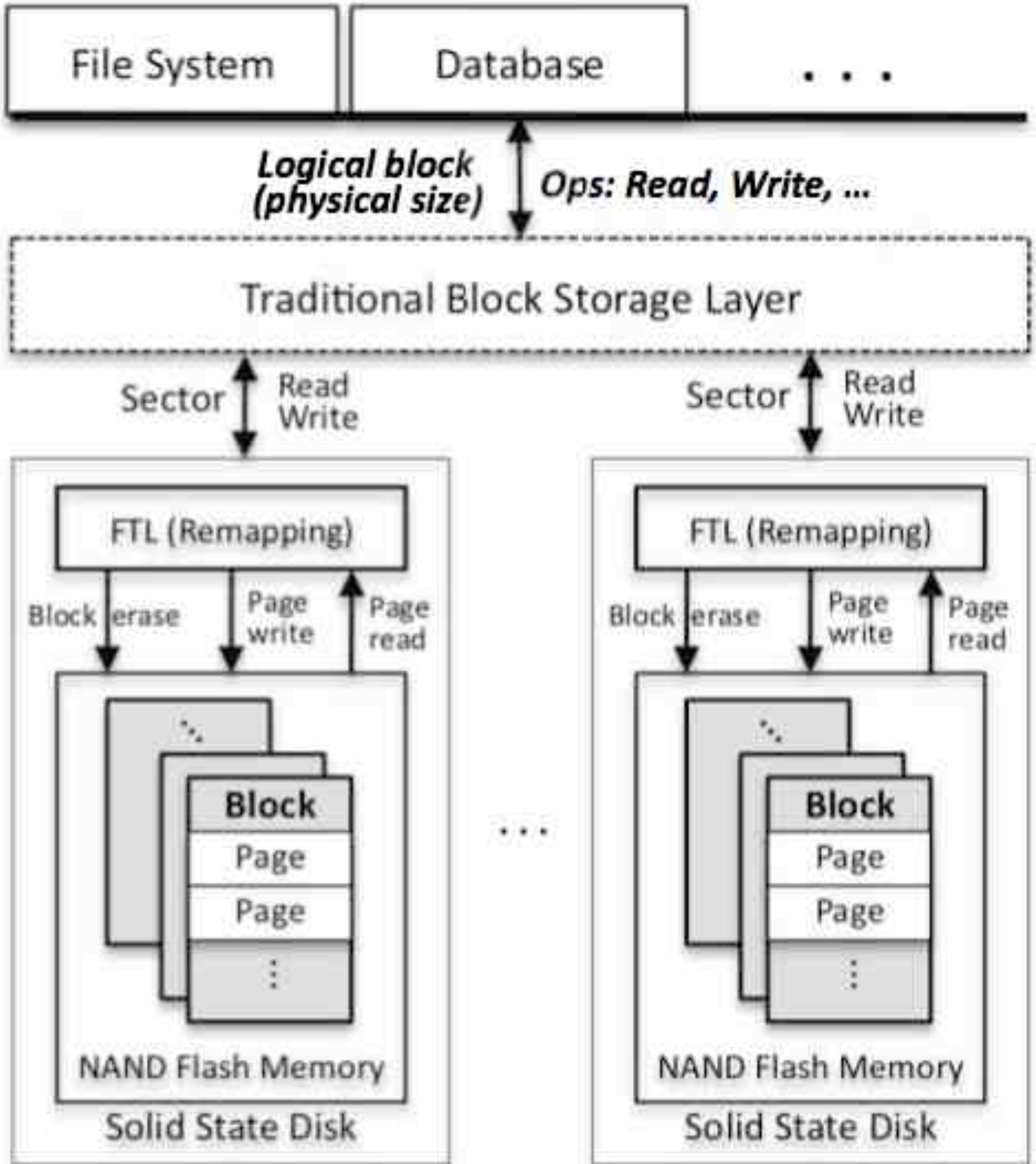
# NAND Flash Memory Operations

- Speed
  - Read page: ~10-20 us
  - Write page: 20-200 us
  - Erase block: ~1-2 ms
- Limited performance
  - Can only write 0's, so erase (set all 1) then write
- Solution: Flash Translation Layer (FTL)
  - Map virtual page address to physical page address in flash controller
  - Keep erasing unused blocks
  - Remap to currently erased block to reduce latency

# NAND Flash Lifetime

- Wear out limitations
  - ~50k to 100k writes / page (SLC)
  - ~15k to 60k writes / page (MLC)
  - Question
    - Suppose write to cells evenly and 200,000 writes/sec, how long does it take to wear out 1,000M pages on SLC flash (50k/page)?
- Who does "wear leveling?"
  - Flash translation layer
  - File system design (later)

# Flash Translation Layer



# Example: Fusion I/O Flash Memory

- Flash Translation Layer (FTL) in driver
  - Remapping
  - Wear-leveling
  - Write buffering
  - Log-structured file system (later)
- Performance
  - Fusion-IO Octal
  - 10TB
  - 6.7GB/s read
  - 3.9GB/s write
  - 45µs latency

# Summary

- Disk is complex
- Disk real density has been on Moore’s law curve
- Need large disk blocks to achieve good throughput
- System needs to perform disk scheduling
- RAID improves reliability and high throughput at a cost
- Flash memory has emerged at low and high ends