COS 318: Operating Systems

Storage Devices

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(http://www.cs.princeton.edu/courses/cos318/)

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Where Are We?

- Covered:
  - Management of CPU & concurrency
  - Management of main memory & virtual memory
- Currently --- "Management of I/O devices"
  - Last lecture: Interacting with I/O devices, device drivers
  - This lecture: storage devices
- Then, file systems
  - File system structure
  - Naming and directories
  - Efficiency and performance
  - Reliability and protection

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Storage Devices

- Magnetic disks
- Disk arrays
- Flash memory
- The devices provide
  - Storage that (usually) survives across machine crashes
  - Block level (random) access
  - Large capacity at low cost
  - Relatively slow performance
    - Magnetic disk read takes 10-20M processor instructions
- Users typically access via file system, which provides a very different interface and translates to blocks

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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

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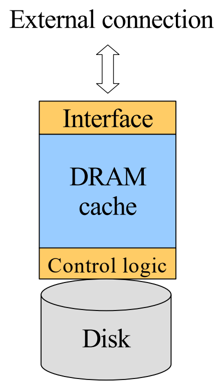
A Typical Magnetic Disk Controller

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



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Caching in a Disk Controller

- Method
  - Disk controller has DRAM to cache recently accessed blocks
    - e.g. Hitachi disk has 16MB
    - Some of the RAM space stores “firmware” (an embedded OS)
  - Blocks are replaced usually in an LRU order + “tracks”
  - Disk and Flash devices have CPU in them
- Pros
  - Good for reads if accesses have locality
- Cons
  - Expensive
  - Doesn’t really help with writes since they need to be reliable

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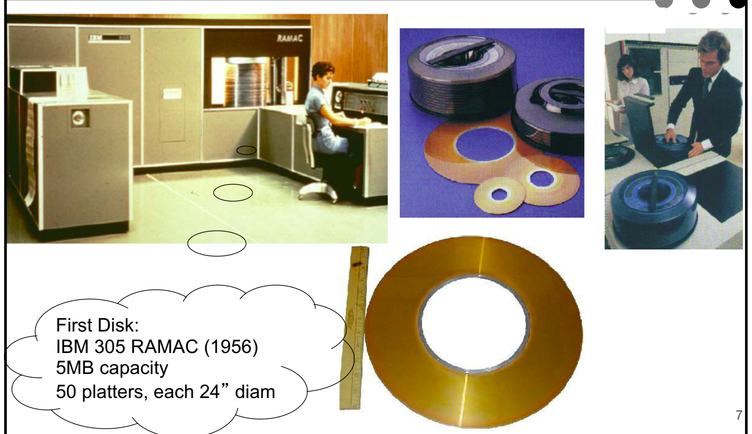
Disks Were Large



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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: 1-2TB

Form factor: PCI card
Storage: 0.5-10TB

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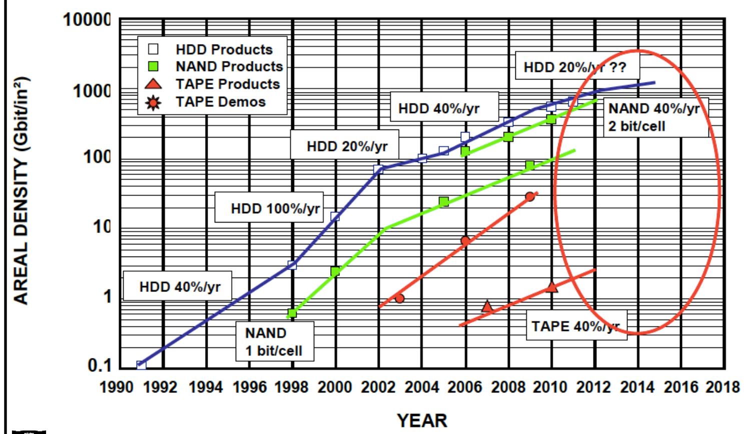
Areal Density vs. Moore's Law



(Fontana, Decad, Hetzler, 2012)

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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

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Magnetic disk

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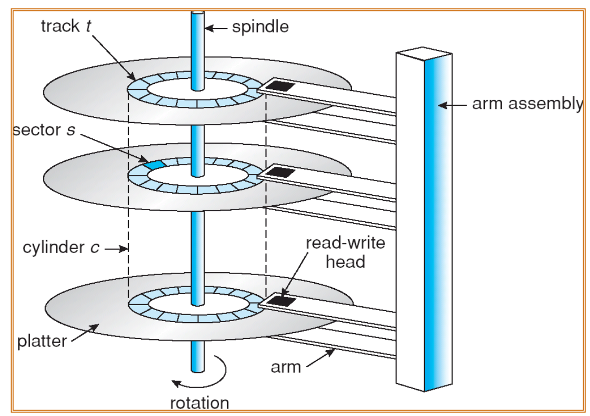
Moving-head Disk Mechanism



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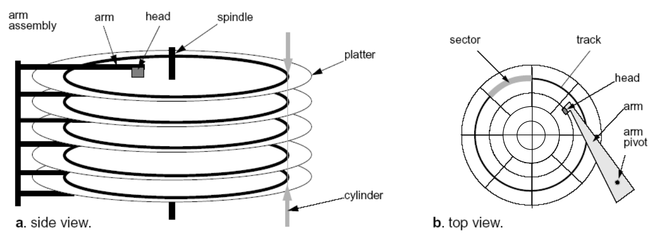
Tracks, Cylinders, Sectors



- 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
- Sector
  - Arc of track holding some min # of bytes, variable # sectors/track

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Disk Tracks

- ~1 micron wide
  - Wavelength of light is ~0.5 micron
  - Resolution of human eye is 50 microns
  - 100K tracks on a typical 2.5" disk
- Tracks separated by unused guard regions
  - Reduces likelihood of corrupting nearby tracks during write
- Track length varies across disk
  - Outer tracks have more sectors per track, higher bandwidth
  - Disk organized into "zones" of tracks, each with same no. of sectors per track
  - Only outer half of disk radius is typically used

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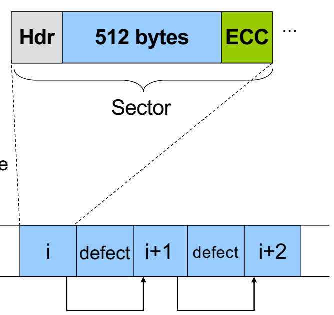
Disk Sectors

- What is a sector?
  - Header (ID, defect flag, …)
  - Real space (e.g. 512 bytes)
  - Trailer (ECC code)
- Skewed from one track to next
  - Accommodate head movement for sequential operations
- Logically addressed (usually)
- Have sophisticated ECC
  - If not recoverable, replace with a spare
- Sector sparing
  - When bad sector, remap it to spare sectors on same surface
  - Skip bad sectors in the future
- Slip sparing
  - When bad sector, remap all sectors to preserve sequential behavior



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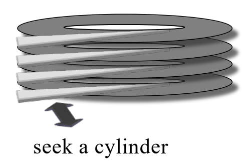
How Data are Read/Written

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



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Disk Performance

- Disk latency = seek + rotation + transfer (time)
- Seek time
  - Position heads over cylinder, typically 1-20 ms
- Rotation time
  - Wait for a sector to rotate underneath the heads
  - Disk rotation time is yypically 4-15 ms
  - On average, need to wait half a rotation
- Transfer time
  - 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?

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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

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Question

- How long to complete 500 random disk reads, in FIFO order?

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Question

- How long to complete 500 random disk reads, in FIFO order?
  - Seek: average 10.5 msec
  - Rotation: average 4.15 msec
  - Transfer: 5-10 usec
- 500 * (10.5 + 4.15 + 0.01)/1000 = 7.3 seconds

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Question

- How long to complete 500 sequential disk reads?
  - Seek Time: 10.5 ms (to reach first sector)
  - Rotation Time: 4.15 ms (to reach first sector)
  - Transfer Time: (outer track)

    500 sectors * 512 bytes / 128MB/sec = 2ms

Total: 10.5 + 4.15 + 2 = 16.7 ms

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Disk Performance

- Seek and rotational times dominate the cost of small accesses
  - Disk transfer bandwidth iswasted
  - Need algorithms to reduce seek time
- Let's look at some disk scheduling algorithms

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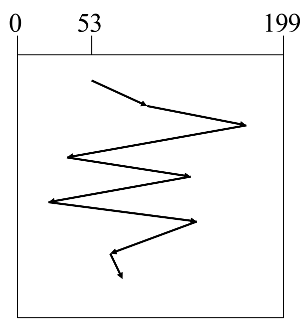
FIFO (FCFS) order

- 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 swings can happen
  - Low throughput, esp with small transfers



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

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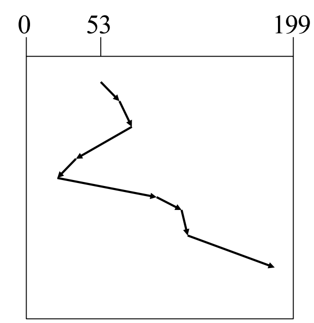
SSTF (Shortest Seek Time First)

- Method
  - Pick the one closest on disk
  - Can include rotational delay in calculation
- Pros
  - Try to minimize seek (and rotation) 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)

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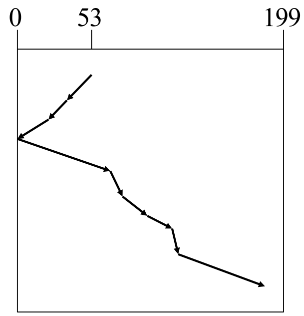
Elevator (SCAN)

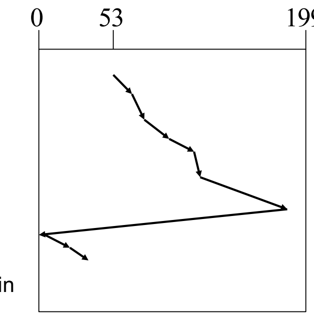
- Method
  - Take the closest request in the direction of travel
  - Real implementations do not go to the end (called LOOK)
- Pros
  - Bounded time for each request
- Cons
  - Request at the other end will take a while



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 bound regardless of where on disk
- Cons
  - Do nothing on the return, so the bound can be larger than in Elevator



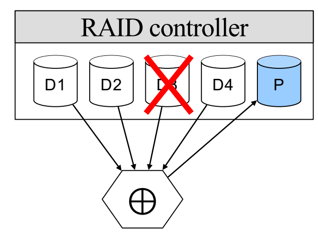
98, 183, 37, 122, 14, 124, 65, 67
(65, 67, 98, 122, 124, 183, 14, 37)

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)

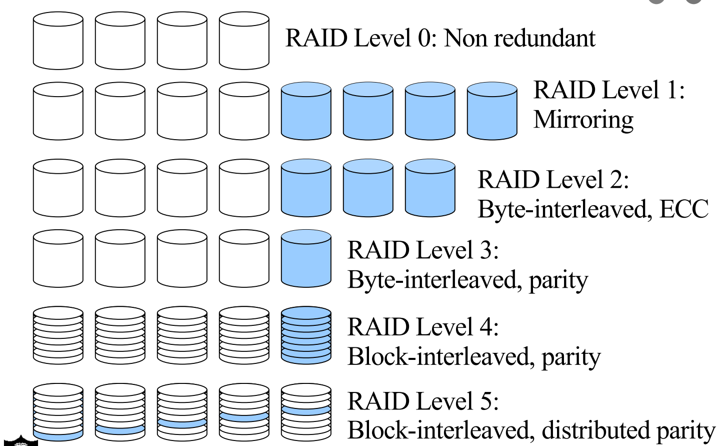
- Main idea
  - Compute XORs and store parity on disk P
  - Upon any failure, one can recover the block from using P and other disks
- Pros
  - Reliability
  - High bandwidth?
- Cons
  - Cost
  - The controller is complex



P = D1 ⊕ D2 ⊕ D3 ⊕ D4

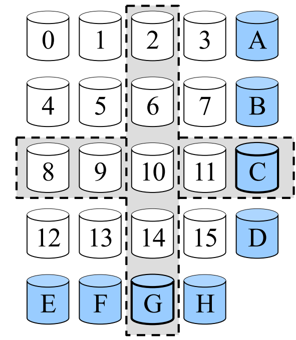
D3 = D1 ⊕ D2 ⊕ P ⊕ D4

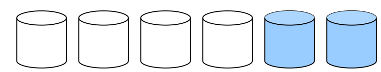
Synopsis of RAID Levels



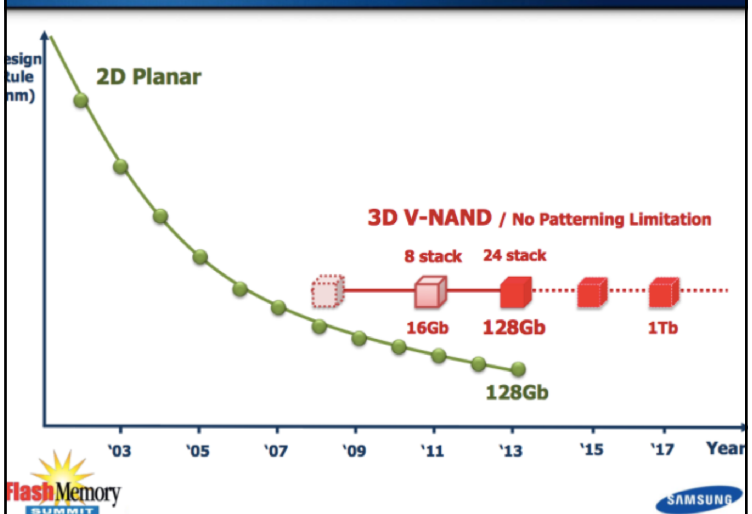
RAID Level 6 and Beyond

- Goals
  - Less computation and fewer updates per random write
  - Small amount of extra disk space
- Extended 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



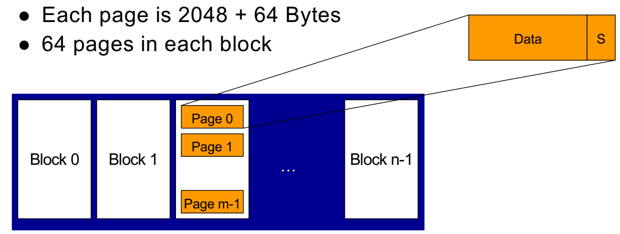


V-NAND Era for the Future



NAND Flash Memory

- High capacity
  - Single cell (more expensive, durable) vs. multiple cell
- Small block
  - Each page 512 + 16 Bytes (data + ECC etc)
  - 32 pages in each block
- Large block
  - Each page is 2048 + 64 Bytes
  - 64 pages in each block



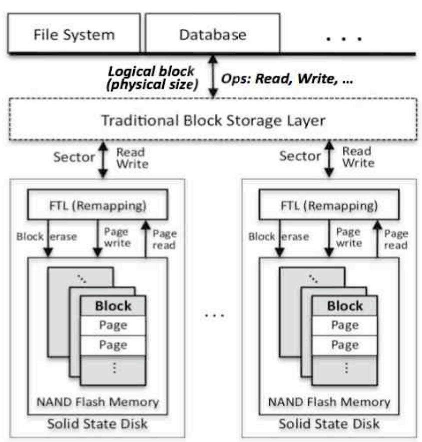
NAND Flash Memory Operations

- 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
  - Erasure blocks of 128-512KB are written into
- Solution: Flash Translation Layer (FTL)
  - Map virtual page to physical page address in flash controller
  - Keep erasing unused blocks
  - Garbage collect by copying live pages to new locations, and erasing large blocks
  - Remap to currently erased block to reduce latency

NAND Flash Lifetime

- Wear out limitations
  - ~50k to 100k writes / page (SLC – single level cell)
  - ~15k to 60k writes / page (MLC – multi-level cell)
- Wear Leveling:
  - Spread erases evenly across blocks, rather than using same block repeatedly
  - Remap pages that no longer work (like sector sparing on magnetic disks)
  - 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 device controller
  - 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