Persistent Storage

Persistent storage

just like memory, only different

- Just like diamonds
  - last forever (?)
    - memory is volatile
  - very dense
    - 10 TBytes of storage fit here 
- ...but much cheaper
  - 10 TByte NAS drive is $ 300 on Amazon
    - way cheaper than 

A new abstraction

File System

An OS abstraction that provides persistent, named data

How persistent storage affects File System design

Goal	Physical Characteristics	Design Implication
High performance		
Named data		
Controlled Sharing		
Reliability		

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Reliability	Crash can occur during updates Storage devices can fail Flash memory wears out	Use transactions to atomically update multiple blocks of persistent storage Use redundancy to detect and correct failures Migrate data to even the wear

Understanding how File Systems work matters

- Example: Word processor with auto-save feature
- If file is large and application is naive in using the file system
  - poor performance
    - may have to overwrite entire file to insert a few bytes!
      - clever doc format may transform updates in appends
  - corrupt file
    - crash while overwriting may leave file in inconsistent state
  - lost file
    - Say we write update to a new file; delete original file; copy new file to old file location…untimely crash could leave us with no file!

Storage Devices

- We focus on two types of persistent storage
  - magnetic disks
    - servers, workstations, laptops
  - flash memory
    - smart phones, tablets, cameras, laptops
- Other exist(ed)
  - tapes
  - drums
  - clay tablets

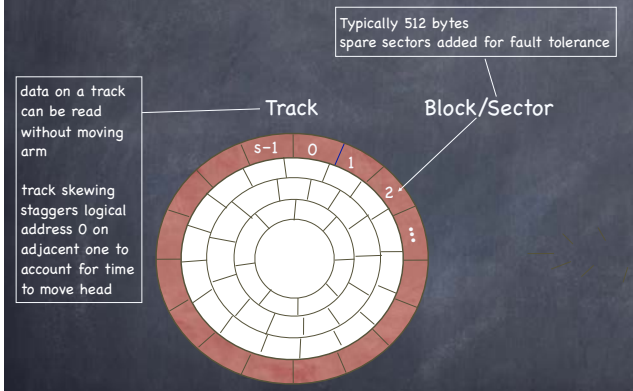
Storage Devices

- Magnetic Disks
  - Rarely becomes corrupted
  - Large capacity at low cost
  - Block level random access
  - Slow performance for random access
  - Better performance for sequential access
- Flash Memory
  - Rarely becomes corrupted
  - Capacity at intermediate cost (8x disk)
  - Block level random access
  - Good performance for reads; worse for random reads

Magnetic disk

- Store data magnetically on thin metallic film bonded to rotating disk of glass, ceramic, or aluminum

Disk Drive Schematic



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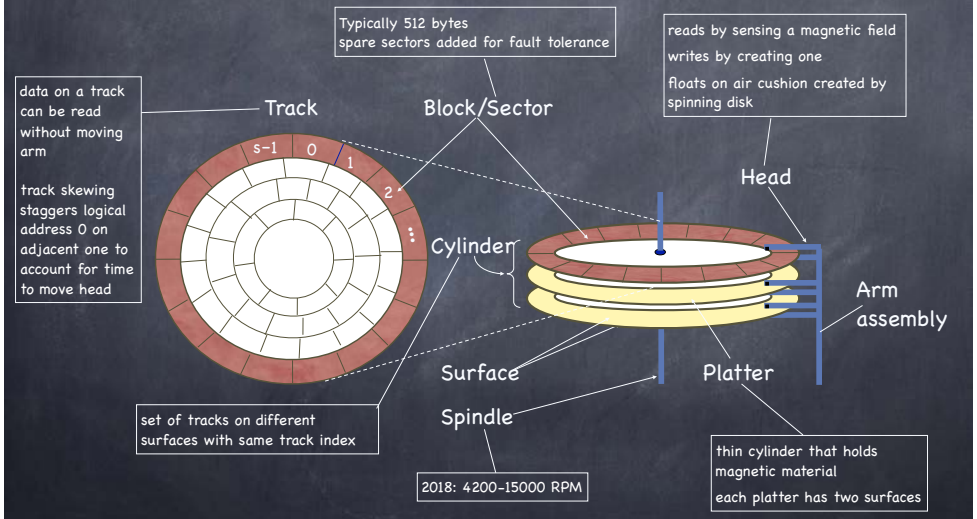
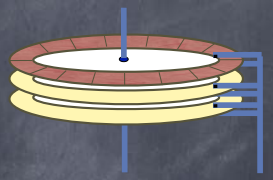


Disk Read/Write

- Present disk with a sector address
  - Old: CHS = (cylinder, head, sector)
  - New abstraction: Logical Block Address (LBA)
    - linear addressing 0…N-1
- Heads move to appropriate track
  - seek
  - settle
- Appropriate head is enabled
- Wait for sector to appear under head
  - rotational latency
- Read/Write sector
  - transfer time



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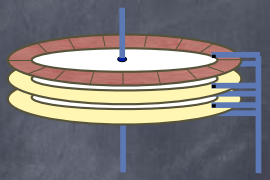

Disk access time:

seek time +

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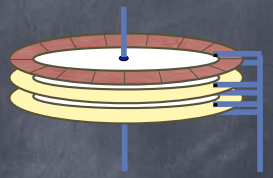

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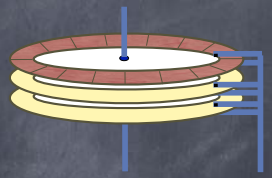

Disk access time:

seek time +

rotation time +

transfer time

A closer look: seek time

- Minimum: time to go from one track to the next
  - 0.3-1.5 ms
- Maximum: time to go from innermost to outermost track
  - more than 10ms; up to over 20ms
- Average: average across seeks between each possible pair of tracks
  - approximately time to seek 1/3 of the way across disk
- Head switch time: time to move from track i on one surface to the same track on a different surface
  - range similar to minimum seek time

A closer look: rotation time

- Today most disk rotate at 4200 to 15,000 RPM
  - 15ms to 4ms per rotation
  - good estimate for rotational latency is half that amount
- Head starts reading as soon as it settles on a track
  - track buffering to avoid "shoulda coulda" if any of the sectors flying under the head turn out to be needed

A closer look: transfer time

- Surface transfer time
  - Time to transfer one or more sequential sectors to/ from surface after head reads/writes first sector
  - Much smaller that seek time or rotational latency
    - 512 bytes at 100MB/s ≈ 5μs (0.005 ms)
  - Lower for outer tracks than inner ones
    - same RPM, but more sectors/track
- Host transfer time
  - time to transfer data between host memory and disk buffer
    - 60MB/s (USB 2.0) to 2.5GB/s (Fibre Channel 20GFC)

Example: Toshiba MK3254GSY (2008)

Size	
Platters/Heads	2/4
Capacity	320GB
Performance	
Spindle speed	7200 RPM
Avg. seek time R/W	10.5/12.0 ms
Max. seek time R/W	19 ms
Track-to-track	1 ms
Surface transfer time	54-128 MB/s
Host transfer time	375 MB/s
Buffer memory	16MB
Power	
Typical	16.35 W
Idle	11.68 W

500 Random Reads

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- Workload
  - 500 read requests, randomly chosen sector
  - served in FIFO order
- How long to service them?
  - 500 times (seek + rotation + transfer)
  - seek time: 10.5 ms (avg)
  - rotation time:
    - 7200 RPM = 120 RPS
    - rotation time 8.3 ms
    - on average, half of that: 4.15 ms
  - transfer time
    - at least 54 MB/s
    - 512 bytes transferred in (.5/54,000) seconds = 9.25μs
  - Total time:
    - 500 x (10.5 + 4.15 + 0.009) ≈ 7.33 sec

500 Sequential Reads

Size	
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Performance	
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Avg. seek time R/W	10.5/12.0 ms
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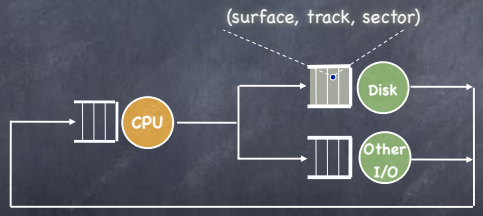
Surface transfer time	54-128 MB/s
Host transfer time	375 MB/s
Buffer memory	16MB
Power	
Typical	16.35 W
Idle	11.68 W

- Workload
  - 500 read requests for sequential sectors on the same track
  - served in FIFO order
- How long to service them?
  - seek + rotation + 500 times transfer
  - seek time: 10.5 ms (avg, since don't know where we are starting from)
  - rotation time:
    - 4.15 ms, as in previous example
  - transfer time
    - outer track: 500 x (.5/128000) ≈ 2ms
    - inner track: 500 x (.5/54000) seconds ≈ 4.6ms
  - Total time is between:
    - outer track: (2 + 4.15 + 10.5) ms ≈ 16.65 ms
    - inner track: (4.6 + 4.15 + 10.5) ms ≈ 19.25 ms

Disk Head Scheduling

- Ina multiprogramming/time sharing environment, a queue of disk I/Os can form



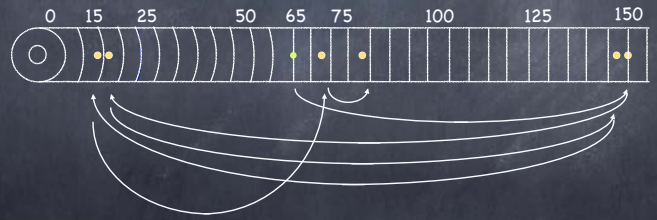
- OS maximizes disk I/O throughput by minimizing head movement through disk head scheduling

FCFS

- Assume a queue of request exists to read/write tracks

83	72	14	147	16	150

and the head is on track 65



FCFS scheduling results in the head moving 550 tracks

SSTF: Shortest Seek Time First

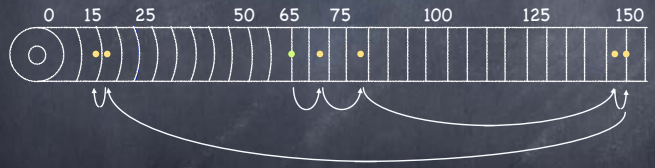
- Greedy scheduling

Rearrange queue from:

83	72	14	147	16	150

to:

14	16	150	147	83	72



SSTF scheduling results in the head moving 221 tracks

SCAN Scheduling "Elevator"

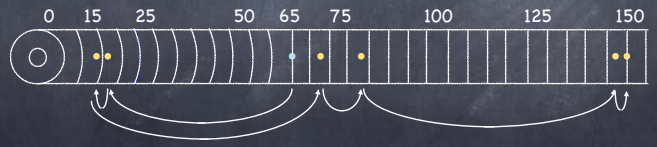
- Move the head in one direction until all requests have been serviced, and then reverse

Rearrange queue from:

83	72	14	147	16	150

to:

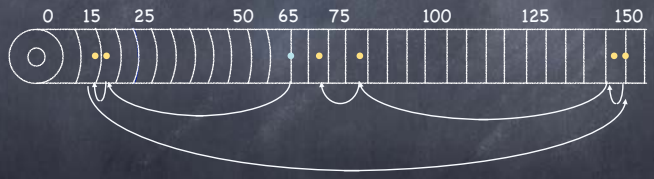
150	147	83	72	14	16



Head moves 187 tracks.

C-SCAN scheduling

- Circular SCAN
  - move the head in one direction until an edge of the disk is reached and then reset to the opposite edge



- More uniform wait time than SCAN
  - moves head to serve requests that are likely to have waited longer

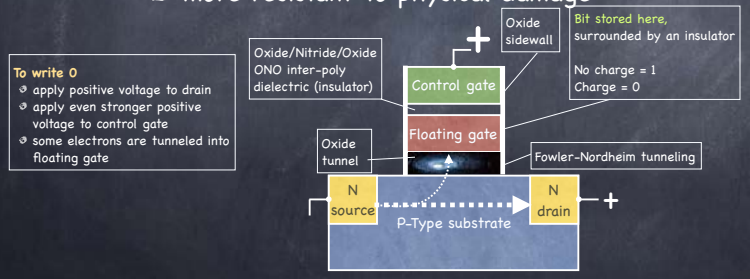
RAM vs. HDD vs. SSD, 2018

	RAM	HDD	SSD
Typical Size	8GB	1TB	256GB
Cost	$10/GB	$0.05/GB	$0.32/GB
Power	3W	2.5W	1.5W
Read Latency	15ns	15ms	30μs
Read Speed (seq)	8000MB/s	175MB/s	550MB/s
Read/Write granularity	byte	sector	page
Power Reliance	volatile	non-volatile	non-volatile
Write Endurance	N/A	N/A	450TB

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

Flash Storage

- No moving parts
  - better random access performance
  - less power
  - more resistant to physical damage



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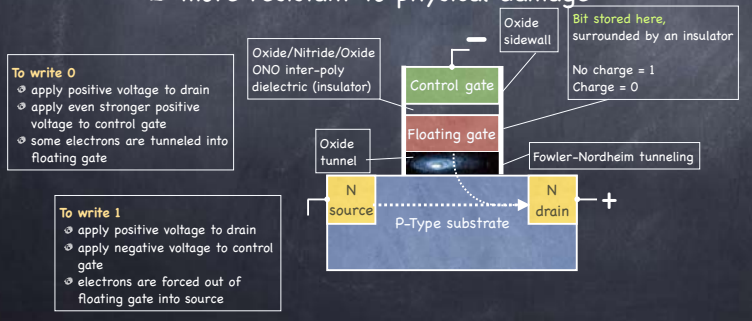

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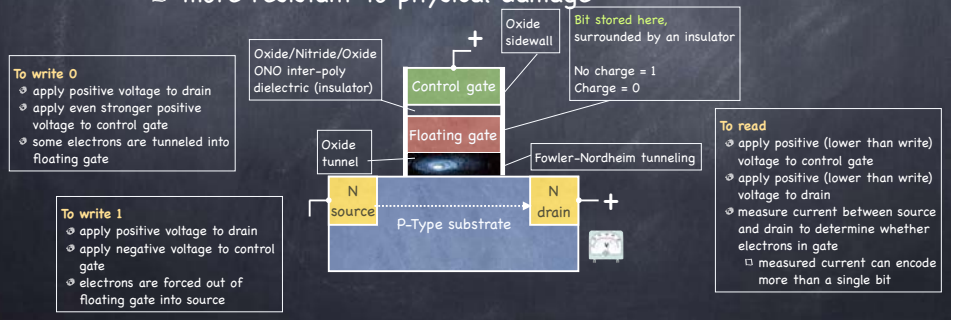
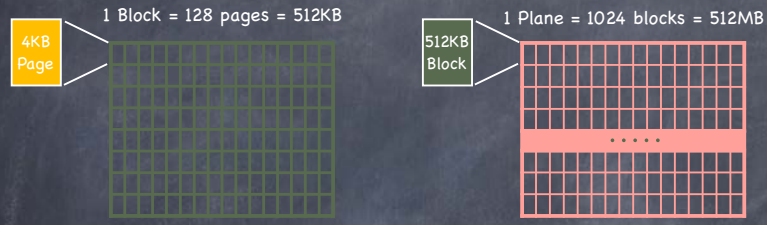


NAND Flash Units



- Operations
  - Erase "erasure block"
    - before a block can be written, it needs to be set to logical "1"
    - operation takes several ms
    - Flash Translation Layer maps logical page to several physical pages; logical page is written to already erased physical page and mapping is adjusted
  - Write page
    - tens of μs
  - Read page
    - tens of μs
- Flash devices can have multiple independent data paths
  - OS can issue multiple concurrent requests to maximize bandwidth

Example: Remapping Flash Drives

- Flash drive specs
  - 4 KB page
  - 3ms to erase erasure block
  - 512KB erasure block
  - 50μs read page/write page
- How long to naively read/erase/and write each page?
  - 128 x (50 x 10^{-3}) + 3 + 128 x (50 x 10^{-3}) = 15.8ms per write

read block; erase; write entire block

- Suppose we use remapping, and we always have a free erasure block available. How long now?
  - 3/128 + 50 x 10^{-3} = 73.4μs

erasure cost amortized over 128 writes

Flash durability

- Flash memory stops reliably storing a bit
  - after many erasures (in the order of 10^3 to 10^6)
  - after a few years without power
  - after nearby cell is read many times (read disturb)
- To improve durability
  - error correcting codes
    - extra bytes in every page
  - management of defective pages/erasure blocks
    - firmware marks them as bad
  - wear leveling
    - spreads updates to hot logical pages to many physical pages
  - spares (pages and erasure blocks)
    - for both wear leveling and managing bad pages and blocks
- Transparent to the device user