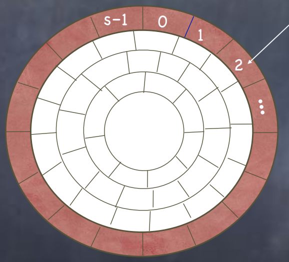
Disk Drive Schematic

data on a track can be read without moving arm

track skewing staggers logical address 0 on adjacent one to account for time to move head

Typically 512 bytes
spare sectors added for fault tolerance



Disk Drive Schematic

data on a track can be read without moving arm

track skewing staggers logical address 0 on adjacent one to account for time to move head

Typically 512 bytes
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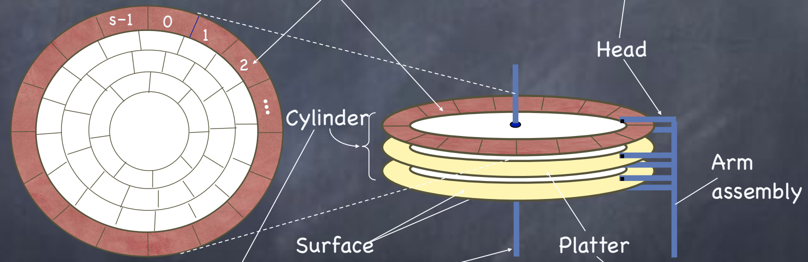
reads by sensing a magnetic field
writes by creating one
floats on air cushion created by spinning disk



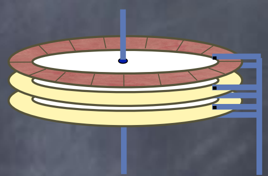
set of tracks on different surfaces with same track index

2018: 4200-15000 RPM

thin cylinder that holds magnetic material
each platter has two surfaces

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



Disk access time:

Disk Read/Write

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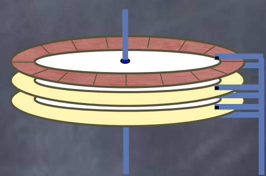

Disk access time:

seek time +

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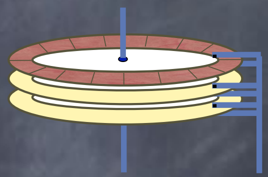

Disk access time:

seek time +

rotation time +

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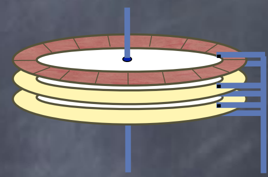

Disk access time:

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

How did we get that?

- To compute average seek time, add distance between every possible pair of tracks and divide by total number of pairs
  - assuming N tracks, N^2 pairs, and sum of distances is $\sum_{x=0}^{N}\sum_{y=0}^{N}|x-y|$ which we compute as $\int_{x=0}^{N}\int_{y=0}^{N}|x-y|\,dy\,dx$

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  - The inner integral expands to $\int_{y=0}^{x}(x-y)dy + \int_{y=x}^{N}(y-x)dy$

    which evaluates to $x^2/2 + (N^2/2 - xn + x^2/2)$

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    which evaluates to $x^2/2 + (N^2/2 - xn + x^2/2)$
  - The outer integral becomes $\int_{x=0}^{N}(x^2 + N^2/2 - xn) = N^3/3$

    which we divide by the number of pairs to obtain $N/3$

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: higher bandwidth!
- 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)

Buffer Memory

- Small cache (8 to 16 MB) that holds data
  - read from disk
  - about to be written to disk
- On write
  - write back (return from write as soon as data is cached)
  - write through (return once it is on disk)

Computing I/O time

$$T_{I/O} = T_{seek} + T_{rotation} + T_{transfer}$$

- The rate of I/O is computed as

$$R_{I/O} = \frac{Size_{Transfer}}{T_{I/0}}$$

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 = 9.26µs
  - Total time:
    - 500 x (10.5 + 4.15 + 0.009) ≈ 7.33 sec

$$R_{I/O} = \frac{500 \times .5 \times 10^{-3} MB}{7.33\, s} = 0.034\, MB/s$$

500 Sequential Reads

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

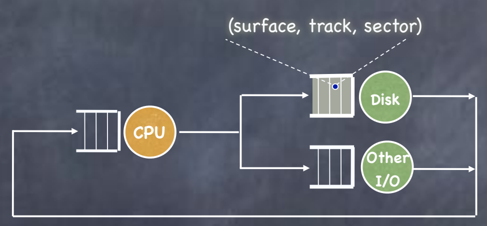
- Workload
  - 500 read requests for sequential sectors on the same track
  - served in FIFO order
- How long to service them?
  - seek + rotation + 500 times transfer
  - seek time: 10.5 ms (avg)
  - rotation time:
    - 4.15 ms, as before
  - transfer time
    - outer track: 500 x (.5/128000) ≈ 2ms
    - inner track: 500 x (.5/54000) seconds ≈ 4.6ms
  - Total time is between:
    - outer track: (2 + 4.15 + 10.5) ms ≈ 16.65 ms

      $R_{I/O} = \frac{500 \times .5 \times 10^{-3} MB}{16.65\, ms} = 15.02\, MB/s$
    - inner track: (4.6 + 4.15 + 10.5) ms ≈ 19.25 ms

      $R_{I/O} = \frac{500 \times .5 \times 10^{-3} MB}{19.25\, ms} = 12.99\, MB/s$

Disk Head Scheduling

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

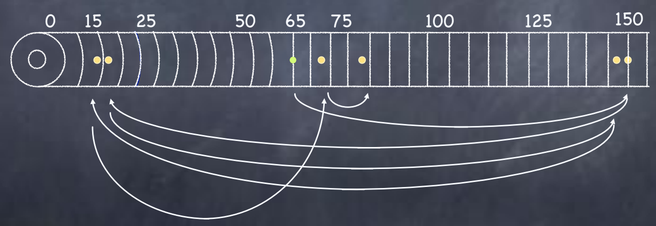


- OS maximizes disk I/O throughput by minimizing head movement through disk head scheduling
  - and this time we have a good sense of the length of the task!

FCFS

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

and the head is on track 65



FCFS scheduling results in disk head moving 550 tracks

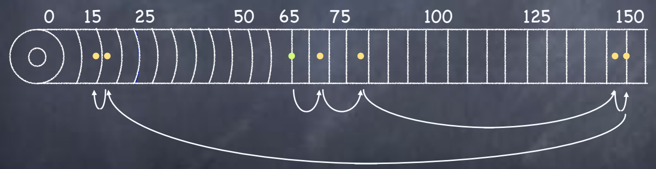
and makes no use of what we know about the length of the tasks!

SSTF: Shortest Seek Time First

- Greedy scheduling

  Rearrange queue from: .... | 83 | 72 | 14 | 147 | 16 | 150 |

  to: .... | 14 | 16 | 150 | 147 | 83 | 72 |



Head moves 221 tracks BUT

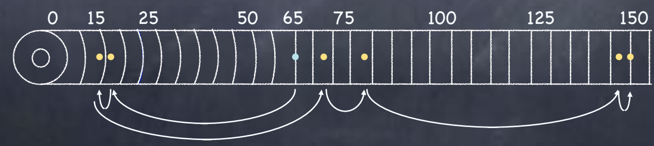
- OS knows blocks, not tracks (easily fixed)
- starvation

SCAN Scheduling "Elevator"

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

  Rearrange queue from: .... | 83 | 72 | 14 | 147 | 16 | 150 |

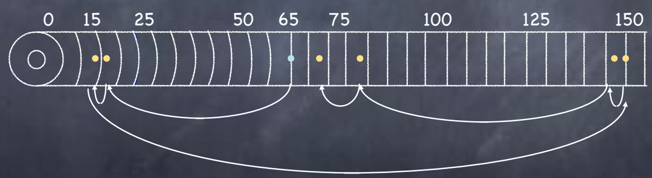
  to: .... | 150 | 147 | 83 | 72 | 14 | 16 |



Head moves 187 tracks.

C-SCAN scheduling

- Circular SCAN
  - sweeps disk in one direction (from outer to inner track), then resets to outer track and repeats e



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

Outsourcing Scheduling Decisions

- Selecting which track to serve next should include rotation time (not just seek time!)
  - SPTF: Shortest Positioning Time First
- Hard for the OS to estimate rotation time accurately
  - Hierarchical decision process
    - OS sends disk controller a batch of "reasonable" requests
    - disk controller makes final scheduling decisions

RAID

Redundant Array of Inexpensive* Disks

* In industry, "inexpensive" has been replaced by "independent" :-)

E Pluribus Unum

- Implement the abstraction of a faster, bigger and more reliable disk using a collection of slower, smaller, and more likely to fail disks
  - different configurations offer different tradeoffs
- Key feature: transparency
  - to the OS looks like a single, large, highly performant and highly reliable single disk
    - a linear array of blocks
    - mapping needed to get to actual disk
    - cost: one logical I/O may translate into multiple physical I/Os
- In the box:
  - microcontroller, DRAM (to buffer blocks) [sometimes non-volatile memory, parity logic]

Failure Model

- RAIDs can detect and recover from certain kinds of failures
- Adopt the strong, somewhat unrealistic Fail-Stop failure model
  - component works correctly until it crashes, permanently
    - disk is either working: all sectors can be read and written
    - or has failed: it is permanently lost
  - failure of the component is immediately detected
    - RAID controller can immediately observe when a disk has failed

How to Evaluate a RAID

- Capacity
  - what fraction of the sum of the storage of its constituent disks does the RAID make available?
- Reliability
  - How many disk fault can a specific RAID configuration tolerate?
- Performance
  - Workload dependent

RAID-0: Striping

Spread blocks across disks using round robin

Stripe	0	1	2	3
Stripe	4	5	6	7
Stripe	8	9	10	11
Stripe	12	13	14	15

\+ Excellent parallelism — high positioning time

RAID-0: Striping

Spread blocks across disks using round robin

Stripe	0	2	4	6
	1	3	5	7
Stripe	8	10	12	14
	9	11	13	15

\+ lower positioning time — lower parallelism

RAID-0: Evaluation

- Capacity
  - Excellent: N disks of B blocks: RAID-0 exports NxB blocks
- Reliability
  - Poor: Any disk failure causes data loss
- Performance
  - Workload dependent, of course
  - We'll consider two
    - Sequential: single disk transfers S MB/s
    - Random: single disk transfer R MB/s
    - S >> R (50 times higher in your textbook example!)

RAID-0: Performance

- Single-block read/write throughput
  - about the same as accessing a single disk
- Latency
  - Read: T ms (latency of one I/O op to disk)
  - Write: T ms
- Steady-state read/write throughput
  - Sequential: N x S MB/s
  - Random: N x R MB/s

RAID-1: Mirroring

Each block is replicated twice

0	0	1	1
2	2	3	3
4	4	5	5
6	6	7	7

Read from any

Write to both

RAID-1: Evaluation

- Capacity
  - Poor: N disks of B blocks yield (N x B)/2 blocks
- Reliability
  - Good: Can tolerate the failure of any one disk
    - and if you can pick who fails, can tolerate up to N/2 disk failures [NOT ROBUST!]
- Performance
  - Fine for reads: can choose any disk
  - Poor for writes: every logical write requires writing to both disks
    - suffers worst seek+rotational delay of the two writes

RAID-1: Performance

- Steady-state throughput
  - Sequential Writes: N/2 x S MB/s
    - Each logical W involves two physical W
  - Sequential Reads: N/2 x S MB/s
    -

0	0	1	1
2	2	3	3
4	4	5	5
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Suppose we want to read
0, 1, 2, 3, 4, 5, 6, 7

RAID-1: Performance

- Steady-state throughput
  - Sequential Writes: N/2 x S MB/s
    - Each logical Write involves two physical Writes
  - Sequential Reads: N/2 x S MB/s

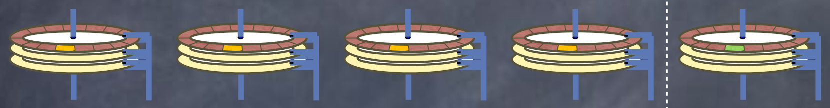
0	0	1	1
2	2	3	3
4	4	5	5
6	6	7	7

Suppose we want to read
0, 1, 2, 3, 4, 5, 6, 7

Each disk only delivers half of his bandwidth

  - Random Writes: N/2 x R MB/s
    - Each logical Write involves two physical Writes
  - Random Reads: N x R MB/s
    - Reads can be distributed across all disks
- Latency for Reads and Writes: T ms

RAID-4: Block Striped, with Parity



Stripe 0	1	2	3	P0
Stripe 4	5	6	7	P1
Stripe 8	9	10	11	P2
Stripe 12	13	14	15	P3

1	1	0
0	1	0
0	0	1

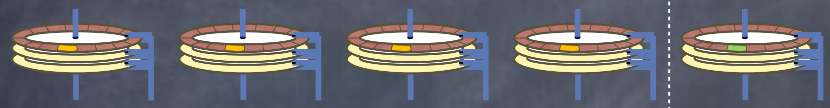
1	0	0
1	1	0
0	1	1

1	0	0
0	1	0
1	0	1

1	1	0
1	1	1
0	0	1

0	0	0
0	0	1
1	1	0

RAID-4: Block Striped, with Parity



Stripe 0	1	2	3	P0
Stripe 4	5	6	7	P1
Stripe 8	9	10	11	P2
Stripe 12	13	14	15	P3

1	1	0
0	1	0
0	0	1

1	0	0
1	1	0
0	1	1

1	0	0
0	1	0
1	0	1

1	1	0
1	1	1
0	0	1

0	0	0
0	0	1
1	1	0

Disk controller can identify faulty disk

- single parity disk can detect and correct errors

RAID-4: Evaluation

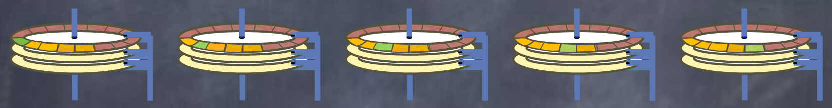
- Capacity
  - Pretty good: N disks of B blocks yield (N-1) x B blocks
- Reliability
  - Pretty Good: Can tolerate the failure of any one disk
- Performance
  - Fine for sequential read/write accesses and random reads
  - Random writes are a problem!

RAID-4: Performance

- Sequential Reads: (N-1) x S MB/s
- Sequential Writes: (N-1) x S MB/s
  - compute & write parity block once for the full stripe
- Random Read: (N-1) x R MB/s
- Random Writes: R/2 MB/s (Yikes!)
  - need to read block from disk and parity block
  - Compute P_{new} = (B_{old} XOR B_{new}) XOR P_{old}
  - Write back B_{new} and P_{new}
  - Every logical I/O requires two physical I/Os: every disk can at most achieve 1/2 of its random transfer rate (i.e. R/2)
  - Every write must go through parity disk, eliminating any chance of parallelism — and we are stuck with R/2!
- Latency: Reads: T ms; Writes: 2T m

RAID-5: Rotating Parity

Parity and Data distributed across all disks



0	1	2	3	P0
5	6	7	P1	4
10	11	P2	8	9
15	P3	12	13	14
P4	16	17	18	19

RAID-5: Evaluation

- Capacity & Reliability
  - As in Raid-4
- Performance
  - Sequential read/write accesses as in RAID-4
  - Random Reads are slightly better
    - N x R MB/s (instead of (N-1) x R MB/s)
  - Random Writes much better than RAID-4: R/2 x N/2
    - as in RAID-4 writes involve two operation at every disk: each disk can achieve at most R/2
    - but, without a bottleneck parity disk, we can issue up to N/2 writes in parallel (each involving 2 disks)