Disk Scheduling and Raid

CPSC 457: Principles of Operating Systems
Winter 2024

Contains slides from Pavol Federl, Mea Wang, Andrew Tanenbaum and Herbert Bos, Silberschatz, Galvin and Gagne

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UNIVERSITY OF CALGARY

Overview

- Magnetic disks
- Disk structure
- Disk scheduling
- RAID
- I/O hardware - block and character devices

Spinning disk - based on old idea

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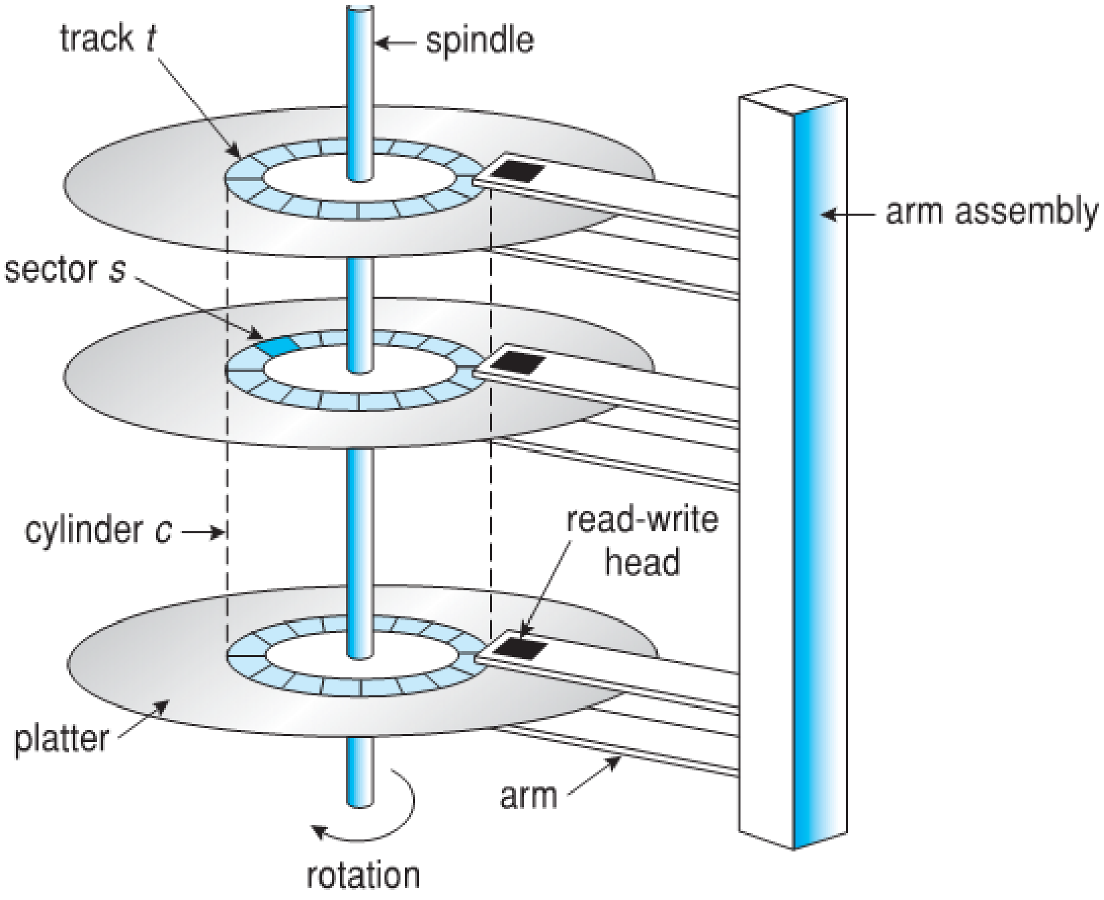
Magnetic Disks

Magnetic disks

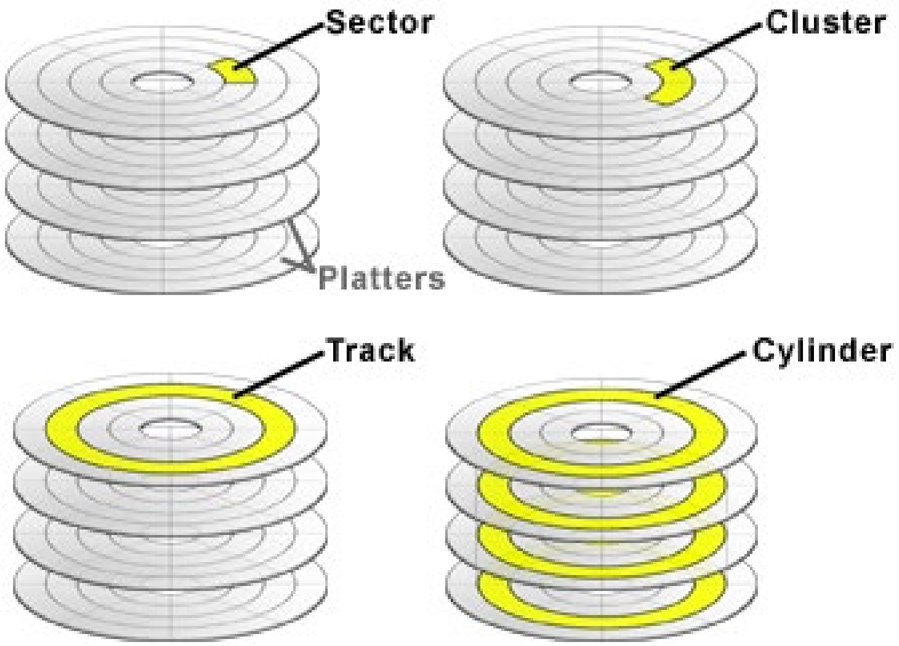


Physical description:

- each disk platter has a flat circular shape (1.8” < diameter < 5.25”)
- platters rotate (5,400 - 15,000 RPMs)
- the read-write heads *fly* just above the surface of each platter
- head crash: the head makes contact with the disk surface, causing permanent damage to the disk
- each head is attached to a disk arm that moves all heads at the same time

Disk Structure

Disk space



Logical representation:

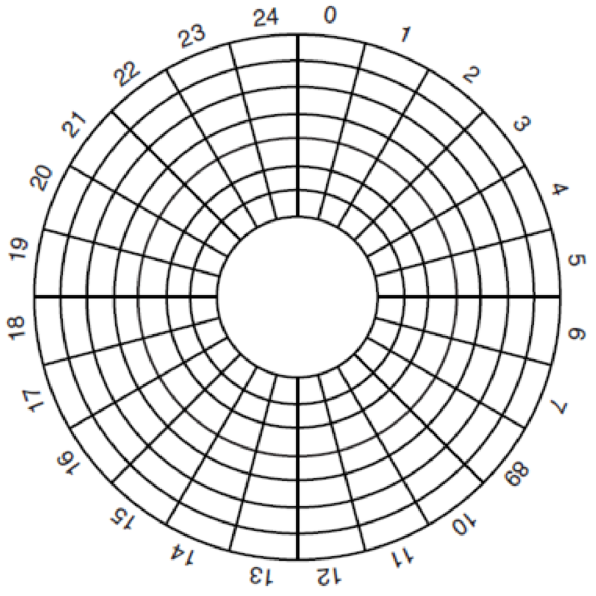
- the surface of a platter is logically divided into circular tracks
- each track is further divided into sectors
- the set of tracks that are at the same arm position make up a cylinder

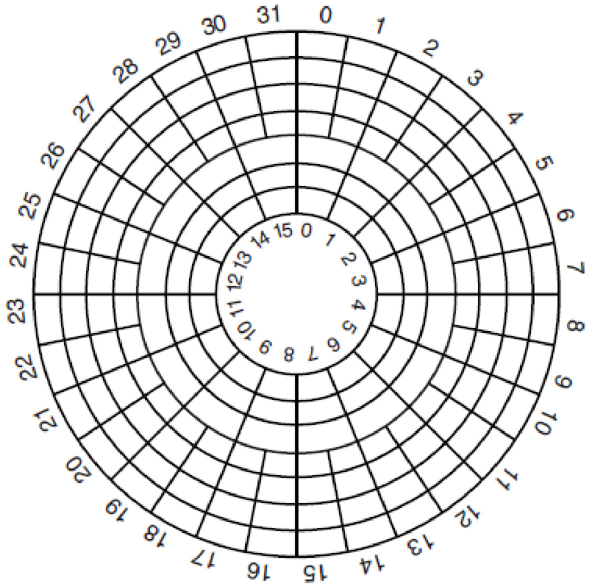
Mapping

- a logical block is the smallest unit of transfer between the disk and the memory, e.g., 512 bytes

- software accesses data on disks only using `write(block_num)` and `read(block_num)`

- mapping: converting a logical block number into physical disk address that consists of a cylinder number, a head number, and a sector number

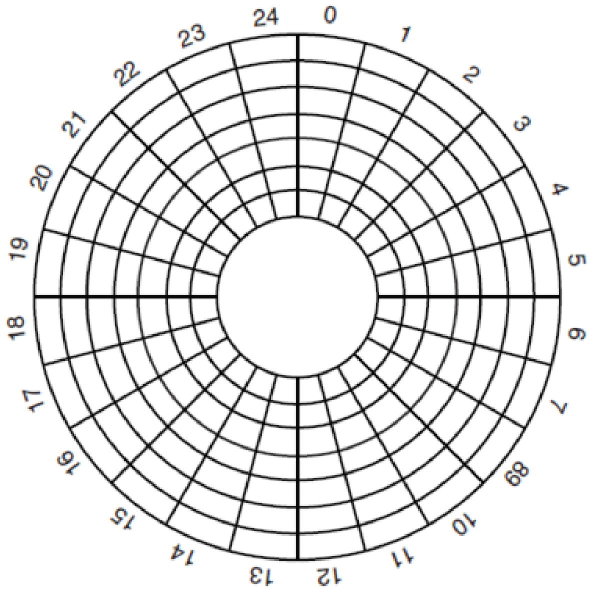


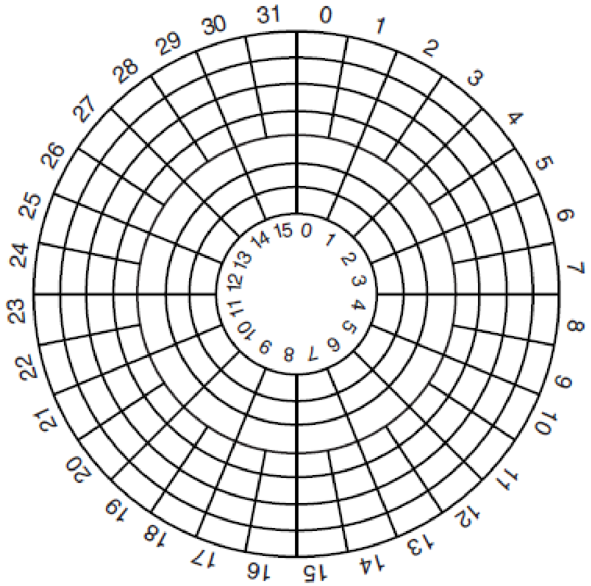


Mapping

- the sectors on disk are mapped to large one-dimensional arrays of logical blocks, numbered consecutively

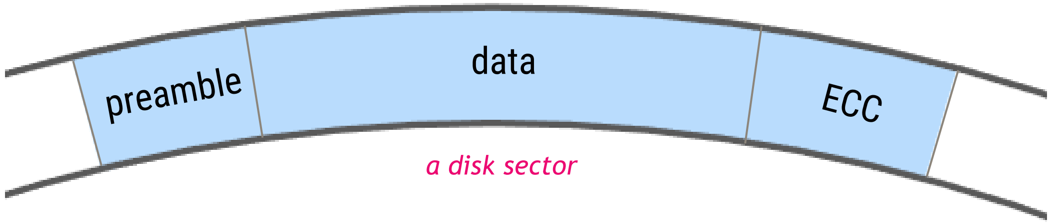
- on modern disks this mapping is done by an embedded controller because geometry is quite complicated





Low level format

- low-level format or physical format: writes low level information to the disk, dividing it into series of tracks, each containing some number of sectors, with small gaps between the sectors
- components of a sector:



a disk sector

  - preamble: starts with a special bit sequence, cylinder number, sector number, etc.
  - data: depends on the format (eg. 512 bytes)
  - Error Correction Code - redundant information to detect read errors
- the formatted capacity is about 20% lower than the unformatted capacity

Disk management

- in order to use a disk to hold files, the OS needs to record its own data structures on the disk
  - partition the disk into one or more regions, each treated as a logical disk
  - logical formatting or “making a file system” on a partition
    - abstracting blocks into files and directories

- OS can allow raw disk access for applications that want to do their own block management, and want to keep OS out of the way (databases for example which have own disk format)

- methods such as sector sparing can be used to handle bad blocks
  - either at OS level, or at lower level

Disk Scheduling

Disk scheduling

- the time required for reading or writing a disk block is determined by several factors

- the most important one, and the one we'll focus on is the seek time
    - seek time — the time to move the heads to the correct cylinder (avg ~10ms)

Disk scheduling

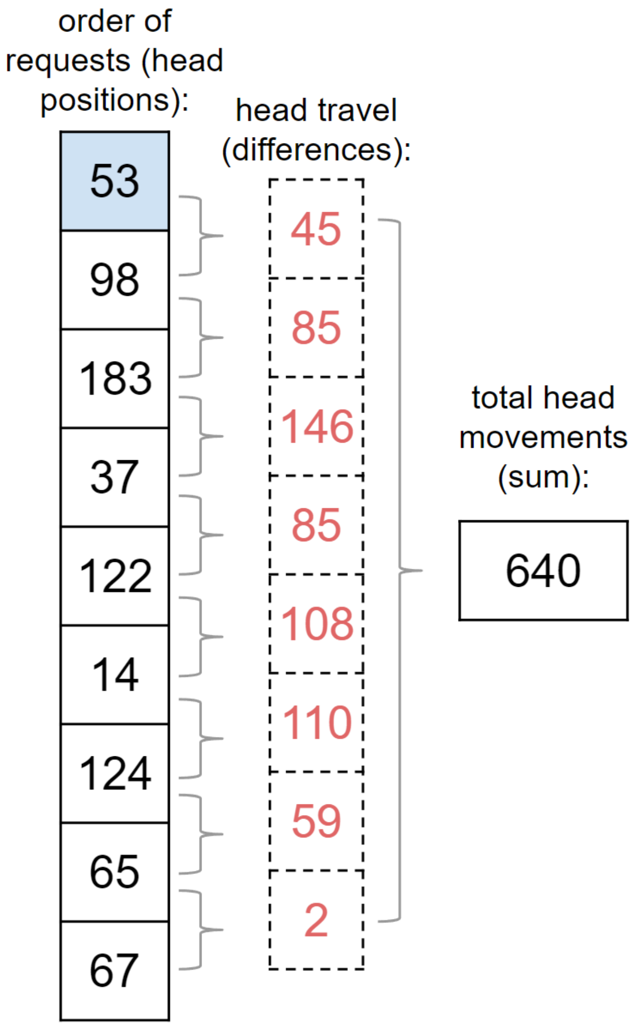
- other factors that we will not discuss include:
  - rotational delay — the time for the correct sector to rotate under the head
  - power consumption — eg. reducing rotation speed, parking heads, etc.
  - noise management — slowing down head movement
  - request processing time — speed of the electronics on the drive
  - connection bandwidth — how fast the drive can communicate with the computer
  - ...

Disk scheduling

- the requests for disk I/O are appended to the **disk queue**
- OS maintains separate queues of requests for each disk
- OS can improve the overall I/O performance by reordering disk I/O requests, with the goal of minimizing the total head movement
- we will look at 6 different algorithms:
    - FCFS scheduling
    - SSTF scheduling
    - elevator scheduling
        - SCAN, C-SCAN, LOOK, C-LOOK

FCFS scheduling

- First-Come-First-Served scheduling
- requests are processed in the same order they are received
- FCFS is intrinsically fair
- but it generally does not provide the fastest overall service
- example:
    - head starts at cylinder 53
    - queue = 98, 183, 37, 122, 14, 124, 65, 67



order of requests (head positions):

53
98
183
37
122
14
124
65
67

head travel (differences):

45
85
146
85
108
110
59
2

total head movements (sum):

640

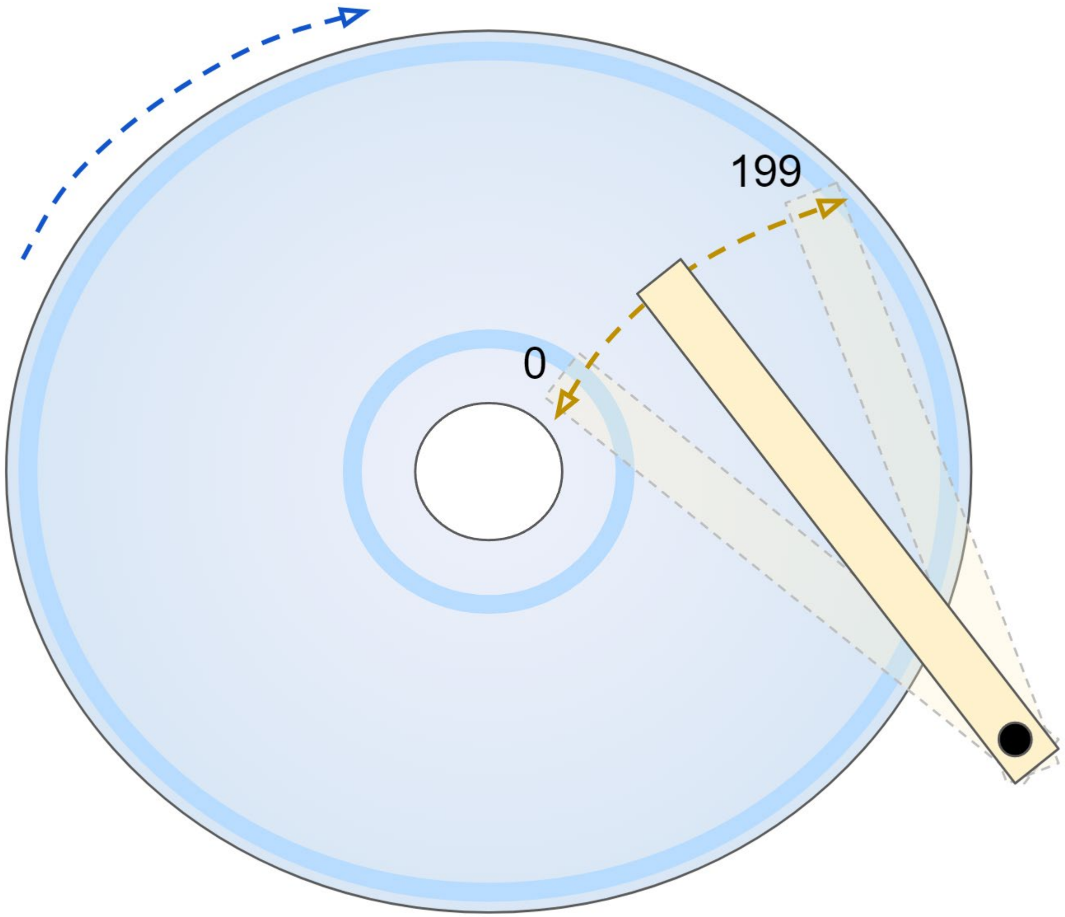
FCFS scheduling

Example:

disk with 200 cylinders, numbered 0 .. 199

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

head starts at 53

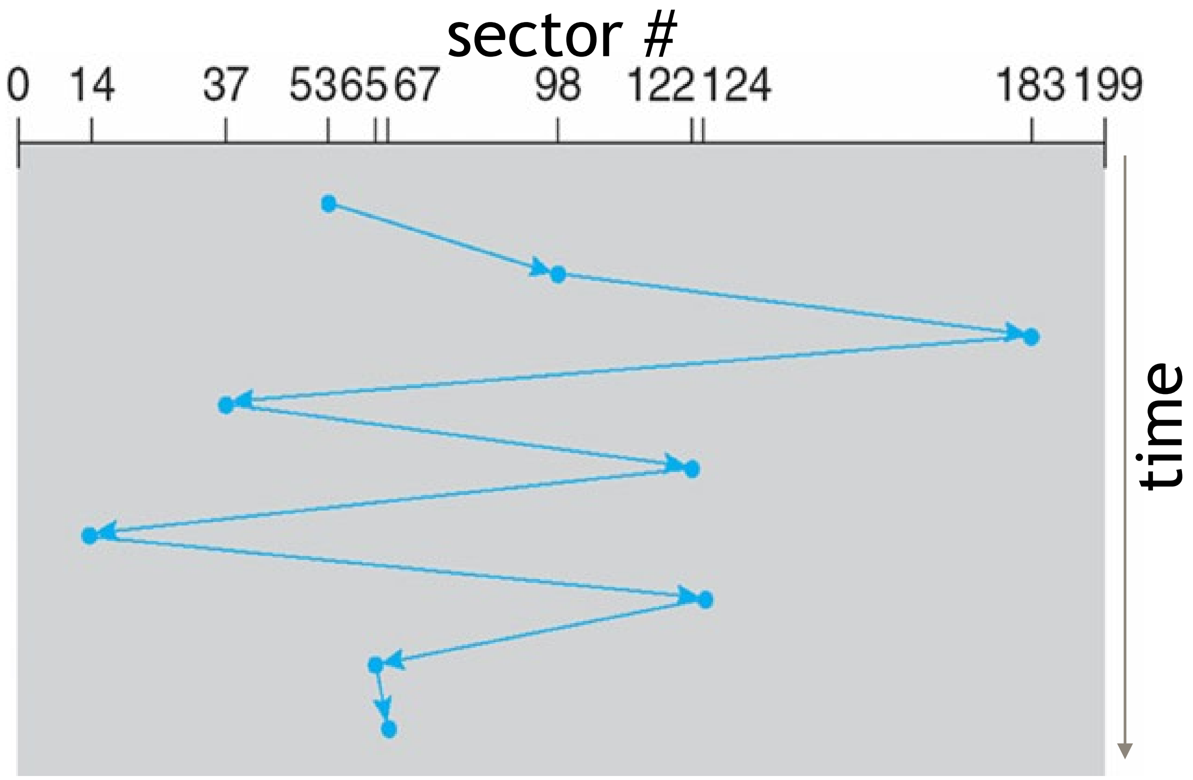


FCFS scheduling

Example:

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

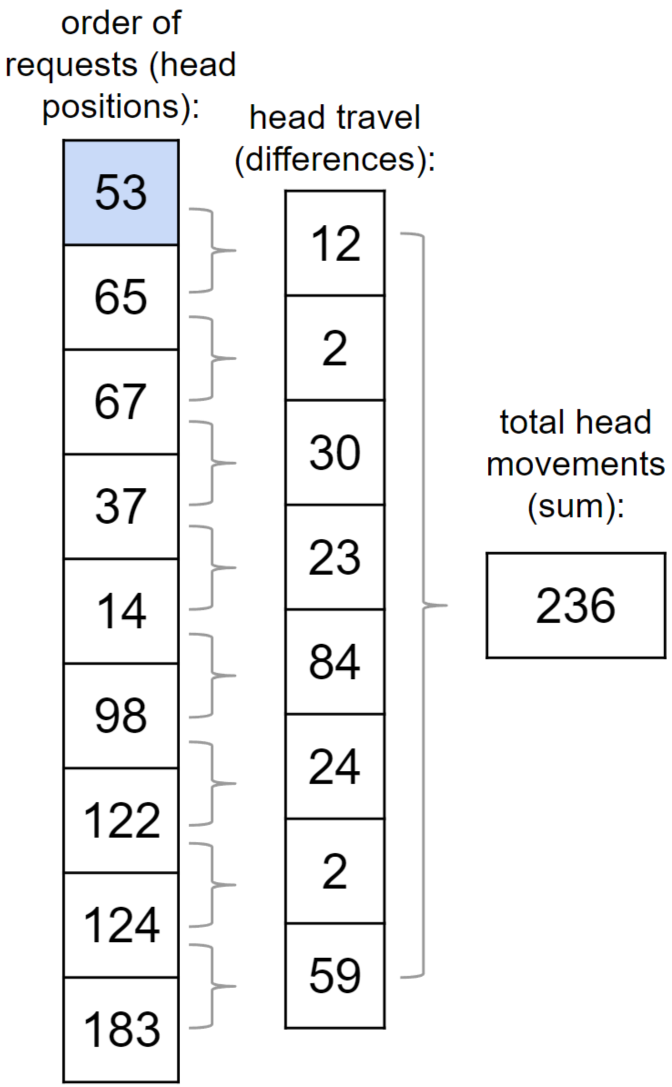
head starts at 53



640 head moves

SSTF scheduling

- Shortest-Seek-Time-First
- selects the next request that would result in the shortest seek time from the current head position, i.e. picks the 'closest' request next
- seek time = distance to move the heads
- may cause starvation of some requests
- Example:
  - head starts at 53
  - queue = 98, 183, 37, 122, 14, 124, 65, 67



order of requests (head positions):

53
65
67
37
14
98
122
124
183

head travel (differences):

12
2
30
23
84
24
2
59

total head movements (sum):

236

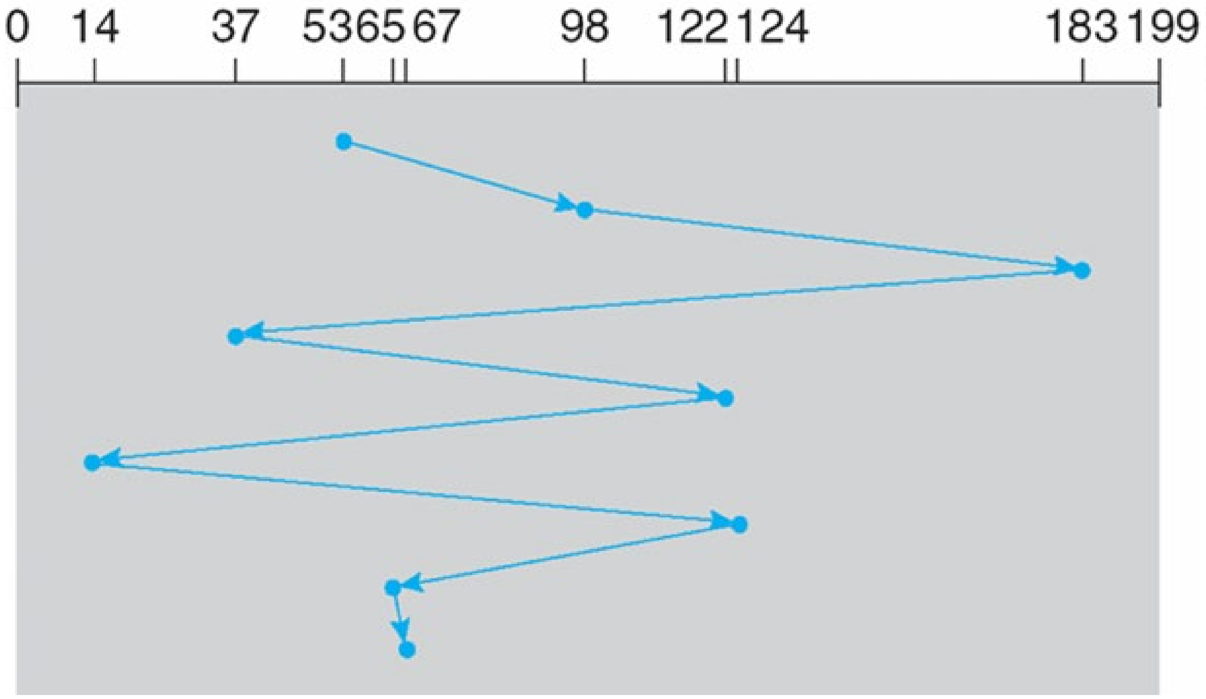
SSTF scheduling

Example:

head starts at 53

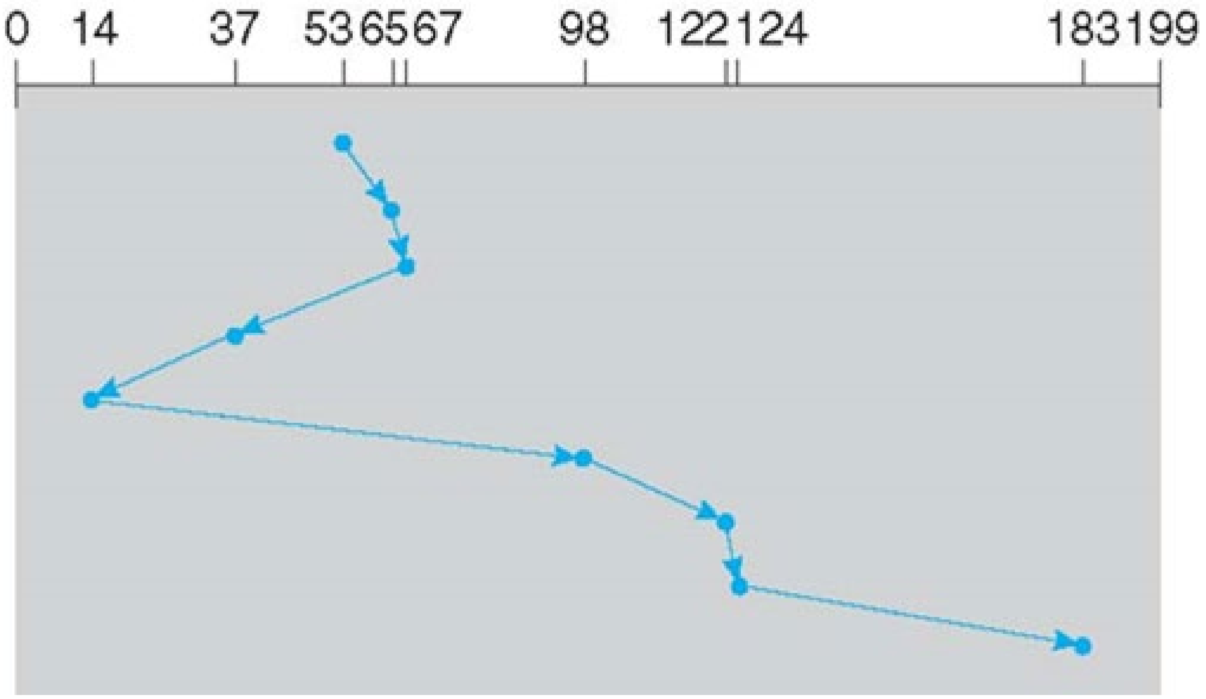
queue = 98, 183, 37, 122, 14, 124, 65, 67

FCFS



640 head moves

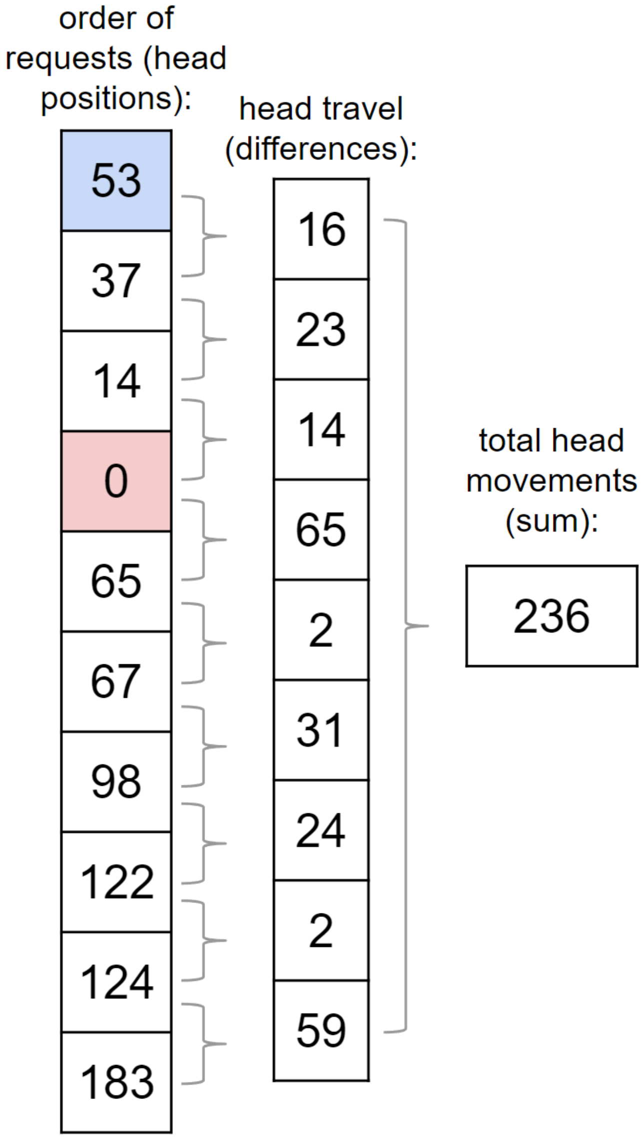
SSTF



236 cylinder moves

SCAN (elevator) scheduling

- the head continuously scans back and forth across the disk and serves the requests as it reaches each cylinder
- head moves all the way to first/last cylinder before turning back
- requests at either end tend to wait the longest
- Example:
  - head starts at 53, direction is downwards
  - queue = 98, 183, 37, 122, 14, 124, 65, 67



order of requests (head positions):

53
37
14
0
65
67
98
122
124
183

head travel (differences):

16
23
14
65
2
31
24
2
59

total head movements (sum):

236

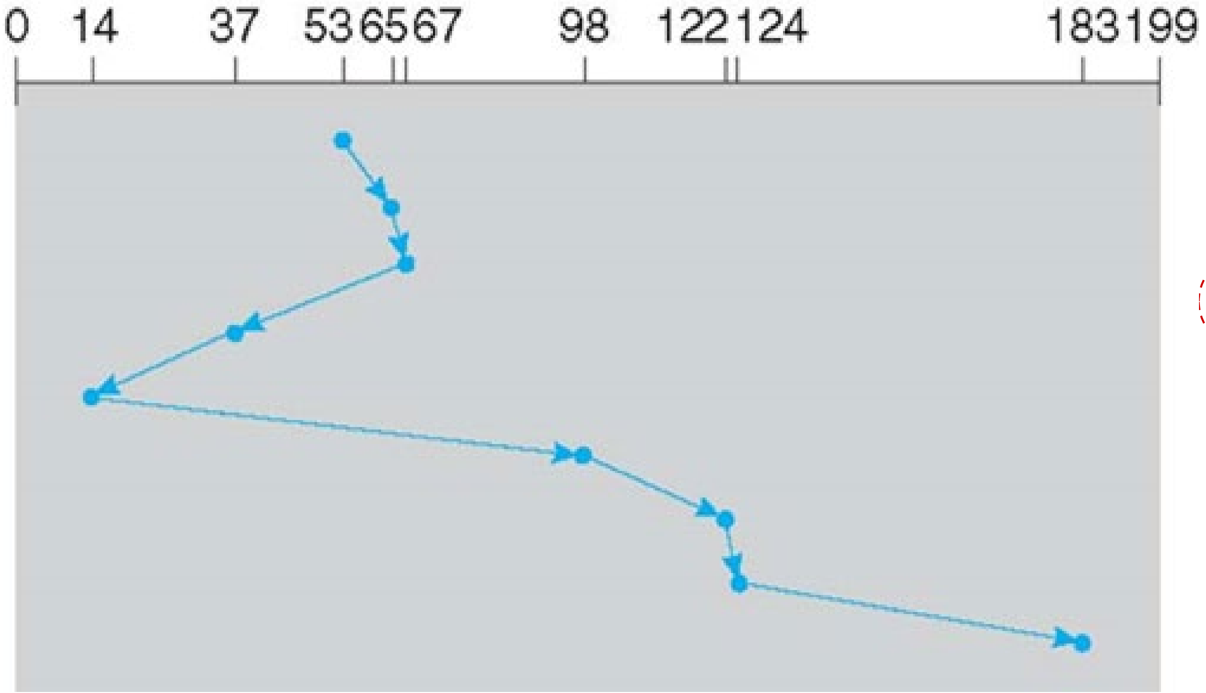
SCAN (elevator) scheduling

Example:

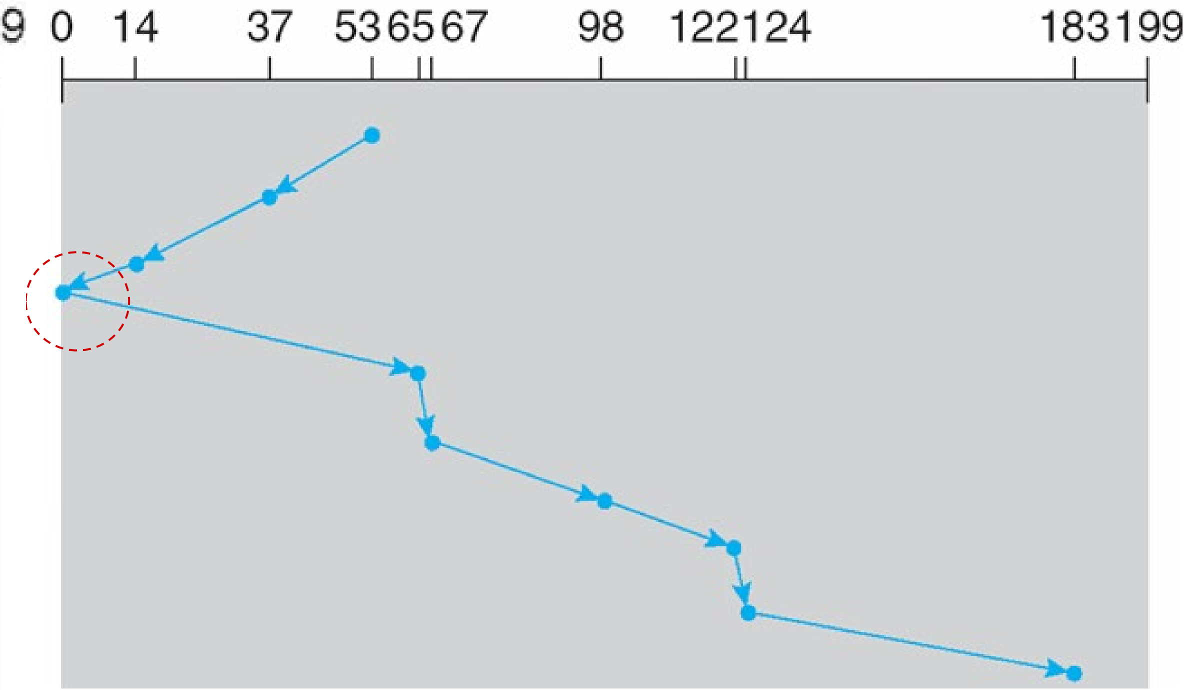
head starts at 53, direction is downwards

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

SSTF	SCAN



236 cylinder moves



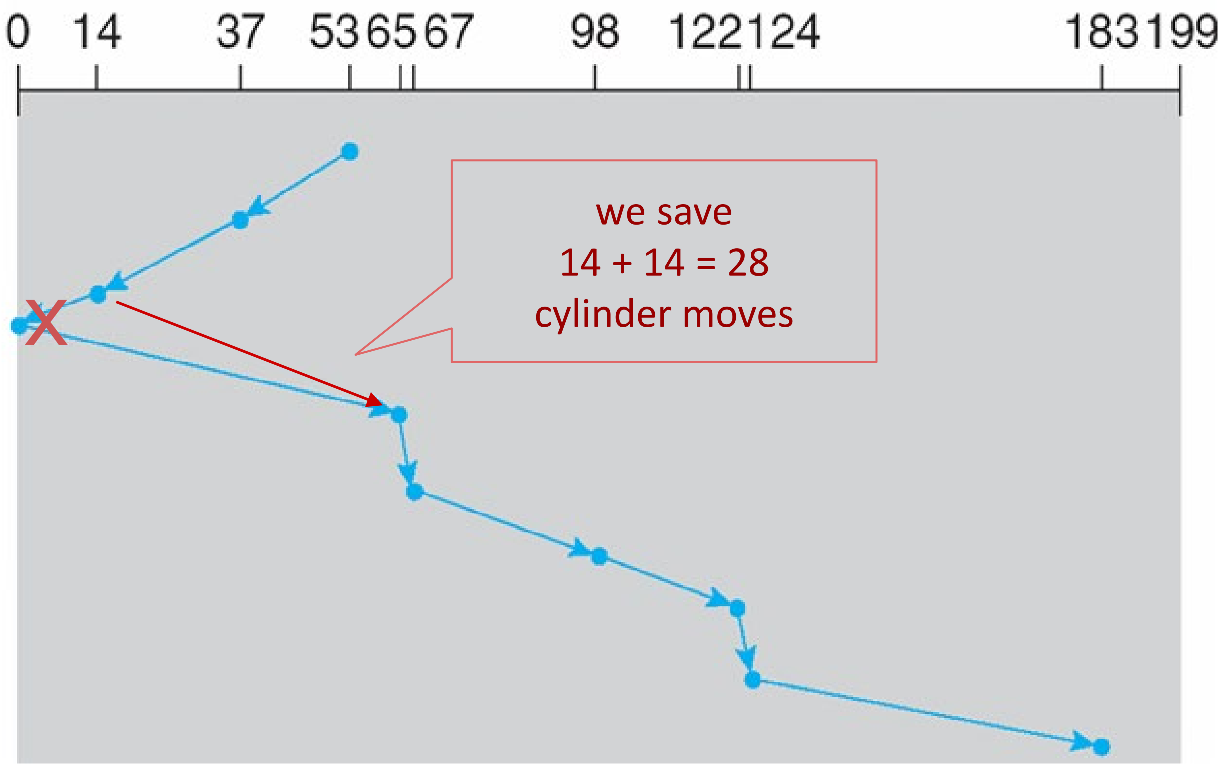
236 cylinder moves

LOOK scheduling

- nearly identical to SCAN, but head does not move all the way to first/last cylinder before turning back
- instead it only goes as far as necessary
- results in the same request order as SCAN
- but less overall head movement

Example:

- queue = 98, 183, 37, 122, 14, 124, 65, 67
- head starts at 53, direction is downwards



we save
14 + 14 = 28
cylinder moves

208 cylinder moves

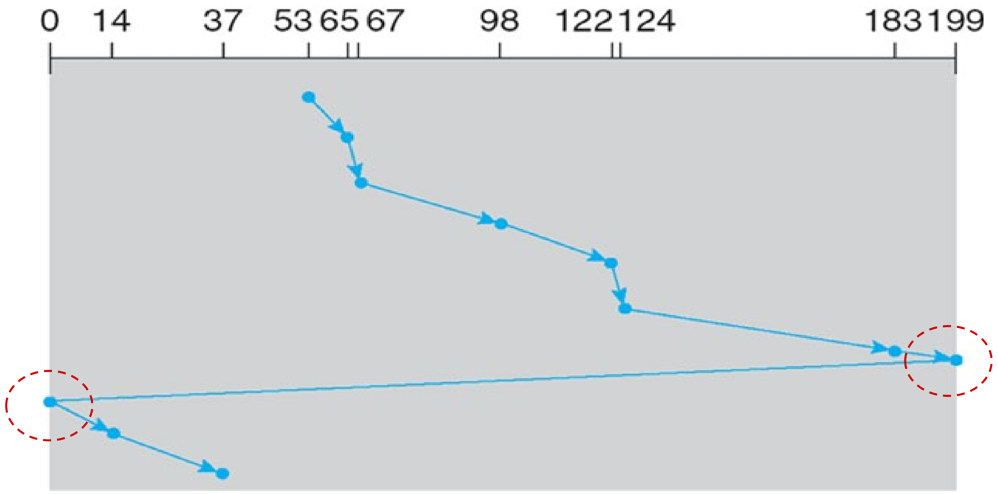
C-SCAN scheduling

- same as SCAN in one direction
- but after reaching last cylinder, head repositions to the first cylinder, and no requests are processed during this time
- achieves more uniform wait time than SCAN

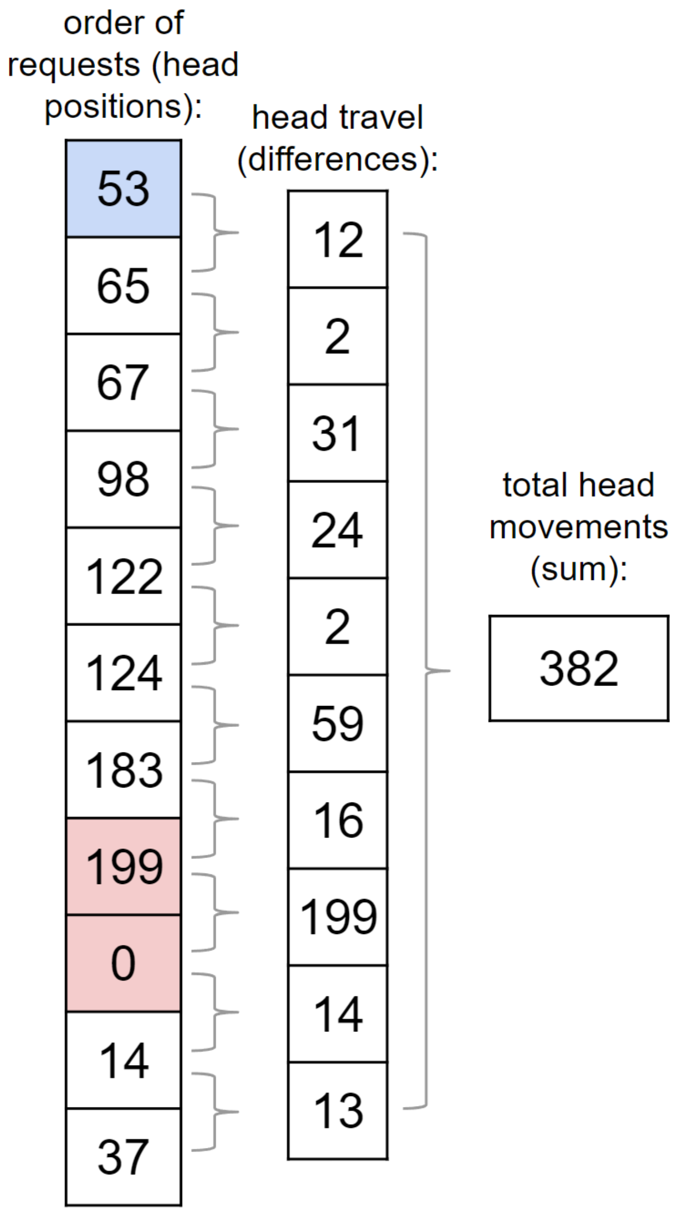
Example:

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

head starts at 53, direction is upwards



382 cylinder moves



order of requests (head positions):

53
65
67
98
122
124
183
199
0
14
37

head travel (differences):

12
2
31
24
2
59
16
199
14
13

total head movements (sum):

382

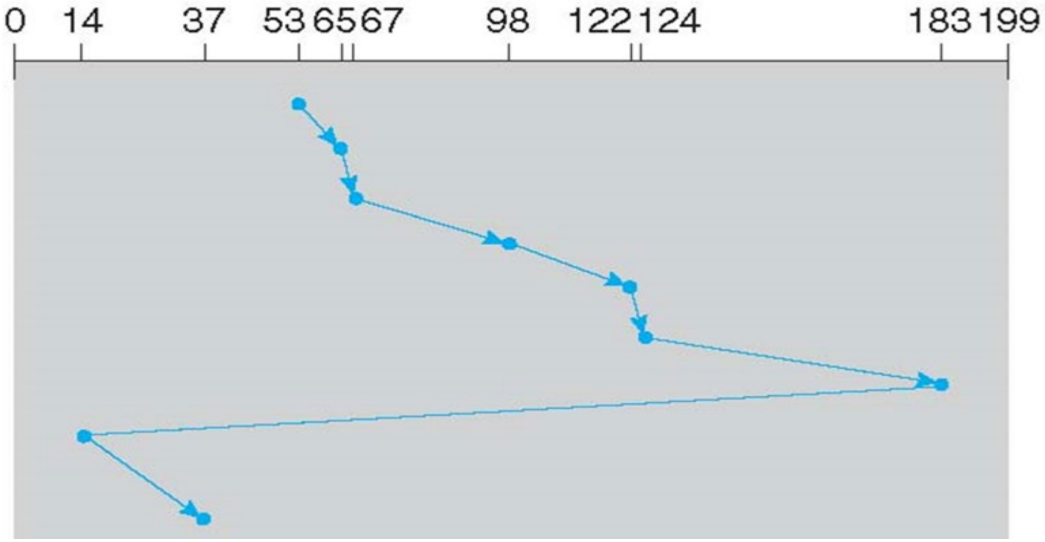
C-LOOK scheduling

- small optimization of C-SCAN, head only goes as far as needed by the next request (same optimization as SCAN → LOOK)

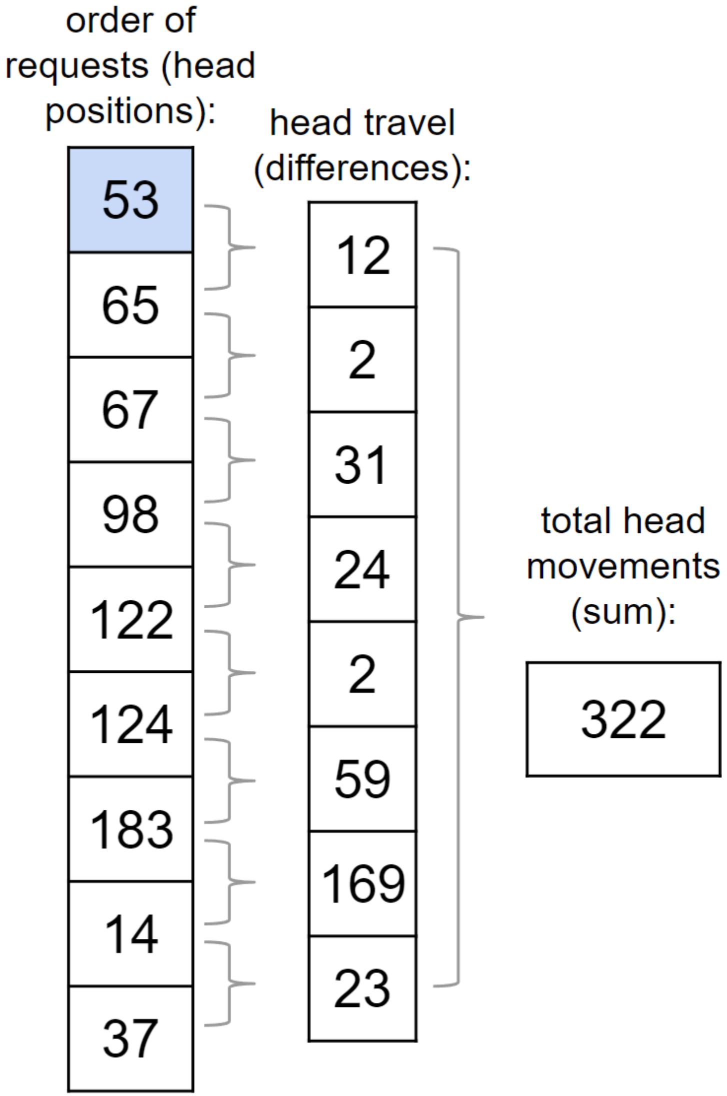
Example:

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

head starts at 53, direction is upwards



322 cylinder moves



order of requests (head positions):

53
65
67
98
122
124
183
14
37

head travel (differences):

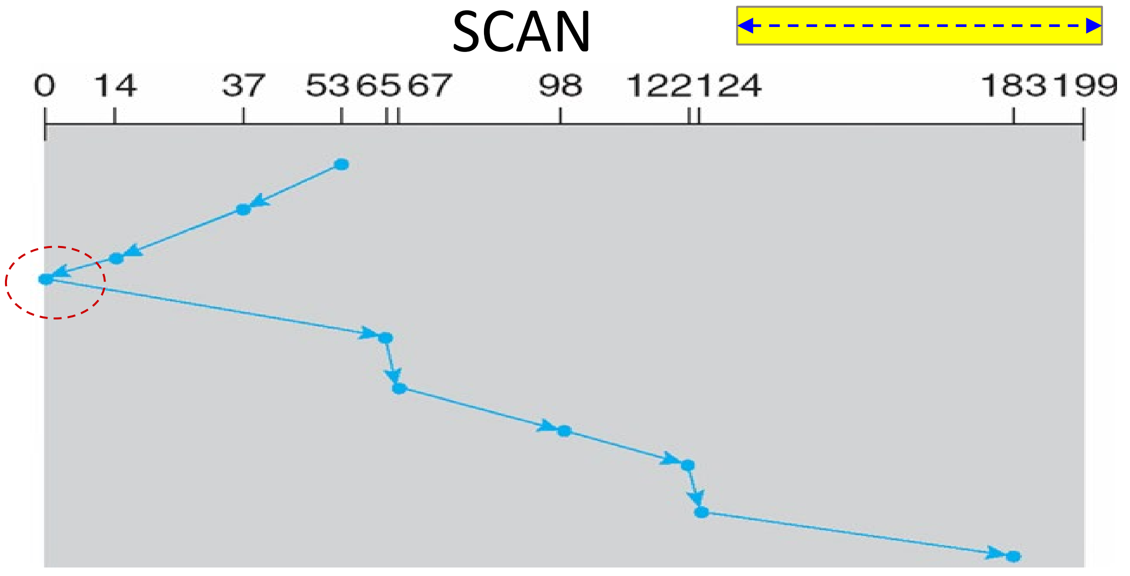
12
2
31
24
2
59
169
23

total head movements (sum):

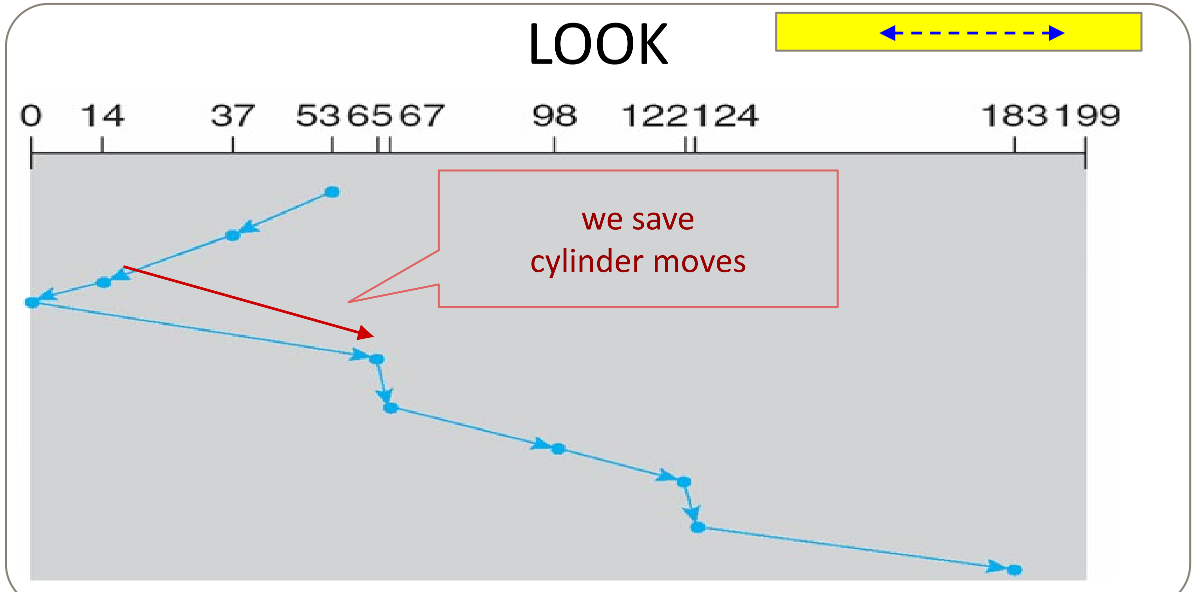
322

Elevator scheduling

SCAN

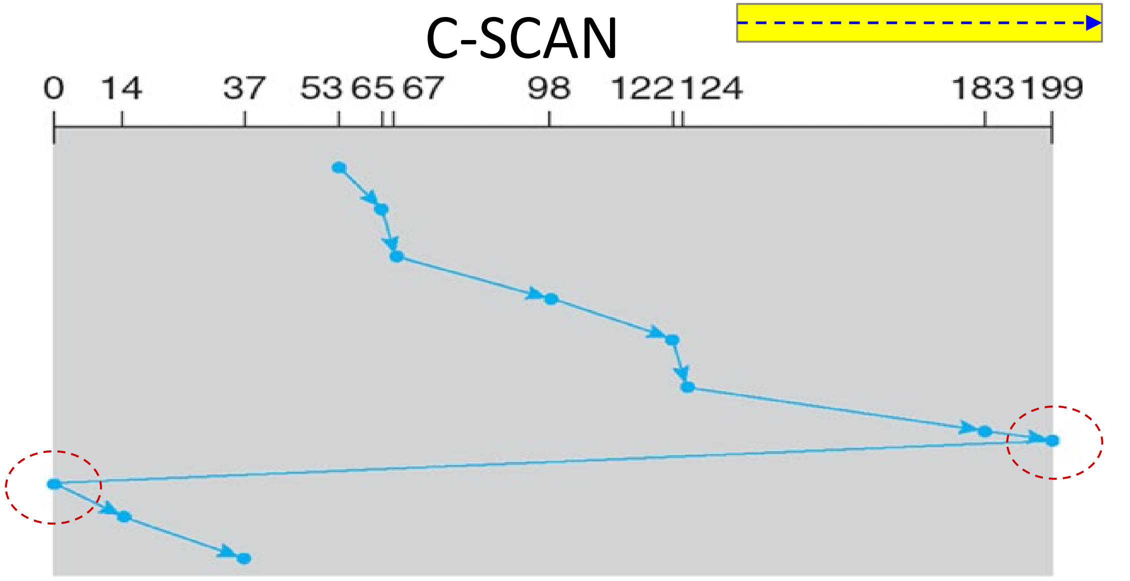


LOOK

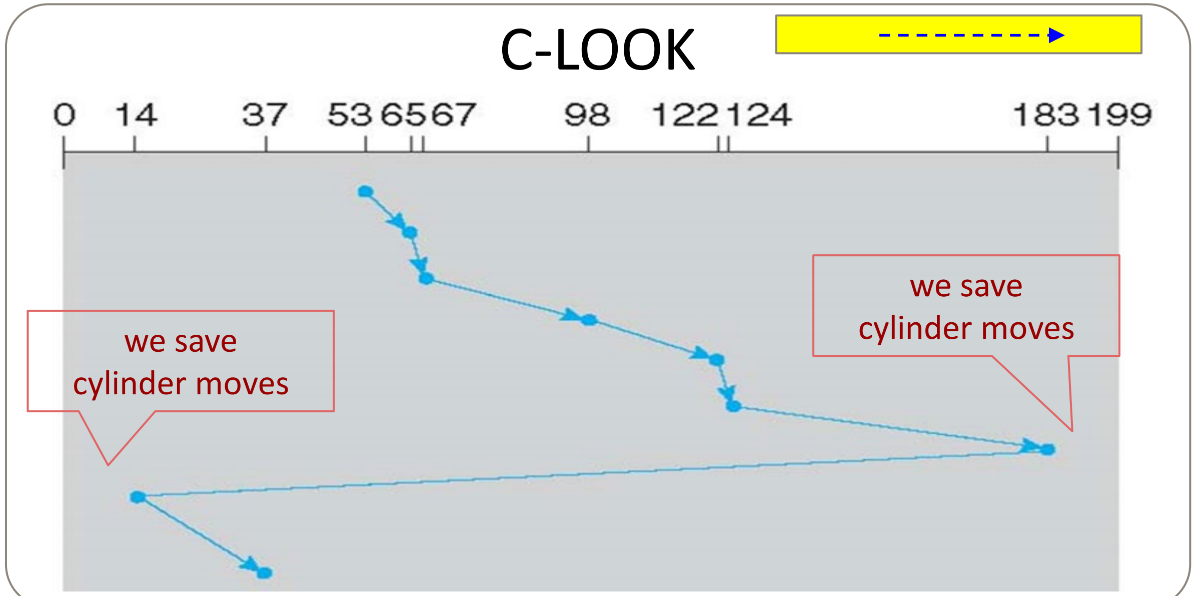


we save cylinder moves

C-SCAN



C-LOOK



we save cylinder moves

we save cylinder moves

Disk scheduling

- the performance of a scheduling algorithm depends on:
    1. the number and types of requests
    2. the file-allocation method
    3. the location of directories and index blocks

- either SSTF or LOOK is a reasonable choice for a default algorithm
    - C-LOOK if we need more consistent wait times on Linux

Disk scheduling

- other scheduling algorithms also consider:
  - rotational latency
  - priority of the task - requests belonging to higher priority process receive higher priority eg. requests related to demand paging should receive higher priority
  - prioritize read over write, since read requests usually block processes
  - examples: completely fair queuing (CFQ) & deadline scheduler on Linux

RAID

RAID

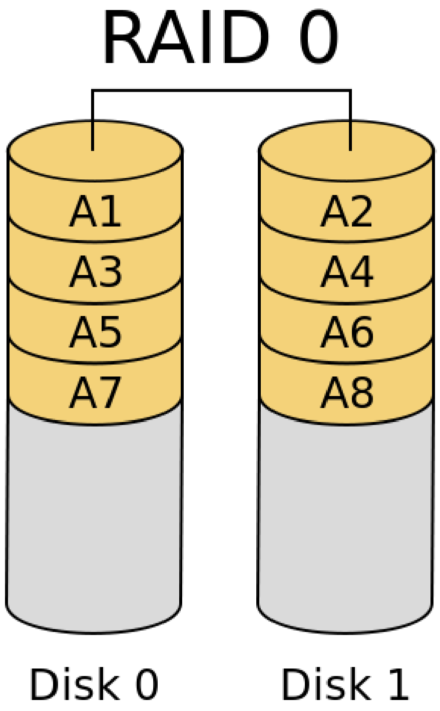
- RAID – Redundant Array of I~~nexpensive~~ Independent Disks
- multiple disk drives provide reliability via redundancy, increasing the mean time to failure
- can also improve performance through parallelization of requests
- accessed as one big disk (increased capacity for over one disk)
- can be implemented via dedicated hardware, or in software, or a combination
- can think of it as an abstraction of multiple disks, presented as a single disk (opposite of partitioning)

RAID 0 – striped volume

- uses a group of disks as one unit
- purpose: highest performance for read & write
- consecutive logical blocks distributed across all disks, ideally contents of every file are evenly distributed over all disks

- offers no redundancy — a single disk failure leads to entire RAID failure actually reduces reliability
- with N disks, read & write performance can be up to N times higher than with a single disk, because both read & write requests can be parallelized

- often used for high-performance temporary storage, where data loss is tolerable, eg: for storing temporary data, `/tmp` or `/scratch`

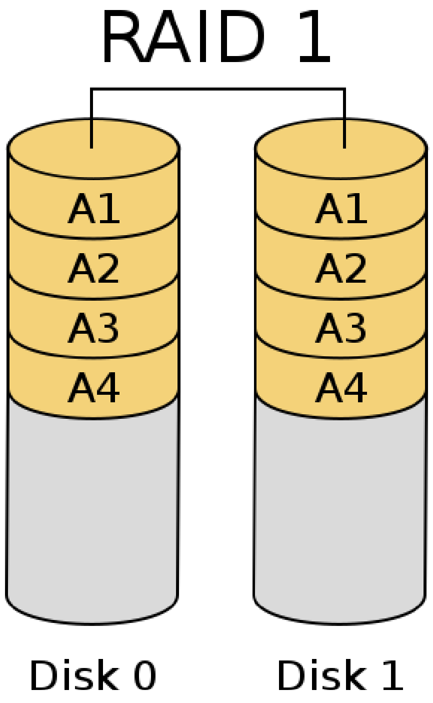


Images from:
https://en.wikipedia.org/wiki/Standard_RAID_levels

RAID 1 – mirrored disks

- keeps 1 or more duplicates of a disk
- purpose: very high reliability & fast read performance

- with N disks, it is tolerant to N-1 simultaneous disk failures
  - RAID continues to work in degraded mode
  - RAID software usually notifies the operator
  - failed disk can be removed & rebuilt from the surviving disks
- with N disks, read performance can be up to N times higher than with a single disk
- write performance is that of a single disk
- with N disks, only 1 disk worth of space used to store data!!!



Images from:
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RAID so far

- Raid 0 (striped) – fast but one big disk that all goes down at once
- Raid 1 (mirrored) – no speed but reliability super scaled

- Raid next (reliability like raid 1 but some speed of raid 0) parity!

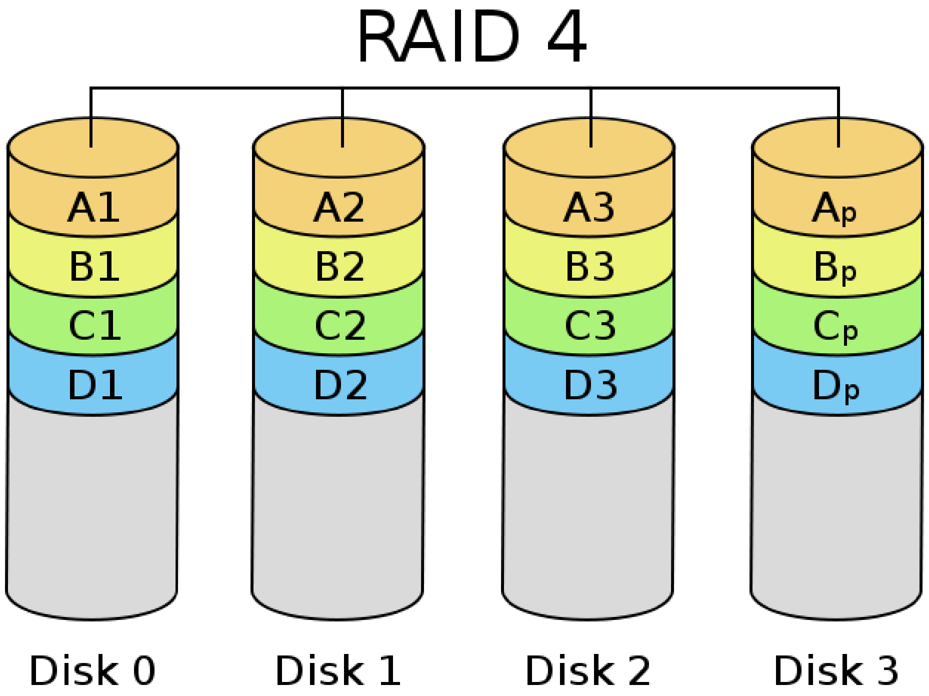
Images from:
https://en.wikipedia.org/wiki/Standard_RAID_levels

RAID 4 – striping with dedicated parity

- one disk dedicated to contain parity information, computed eg. using XOR
- purpose: reliability & fast read performance

- tolerant of a single disk failure
- with N disks, only N-1 are used for data

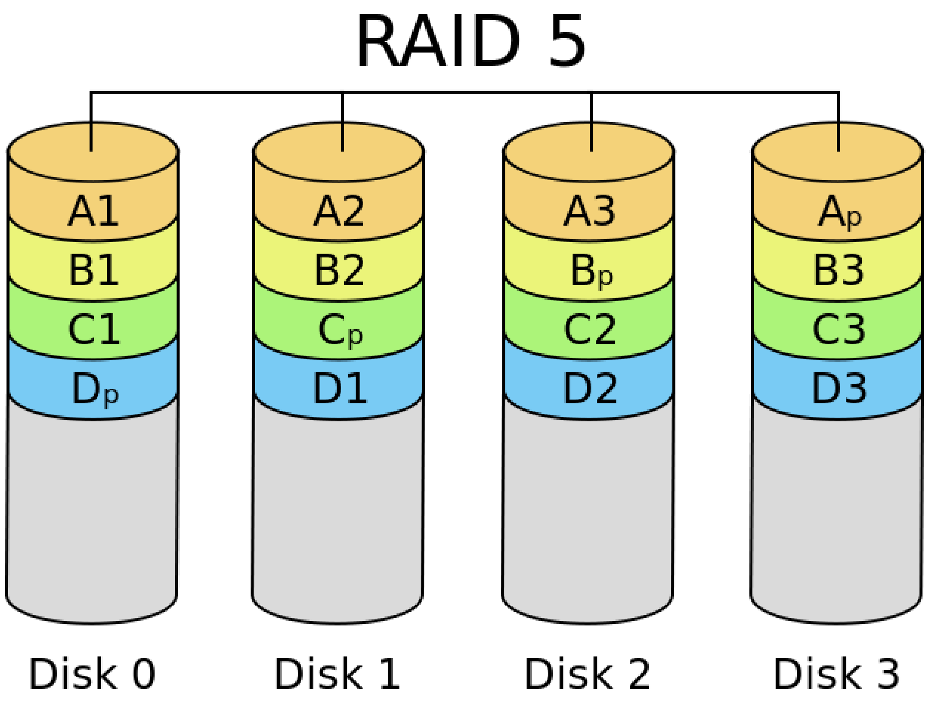
- not very common
  - write is slow, since parity disk is a bottleneck
  - parity disk also wears out faster than the other disks in the array



Images from:
https://en.wikipedia.org/wiki/Standard_RAID_levels

RAID 5 – striping with distributed parity

- similar to RAID 4, but parity information is distributed among all disks
- purpose: reliability, fast read and write performance, although not as fast as RAID 0
- tolerant of a single disk failure
- with N disks, only N-1 space is used for data
- quite common when we need both performance and basic redundancy



Images from:
https://en.wikipedia.org/wiki/Standard_RAID_levels

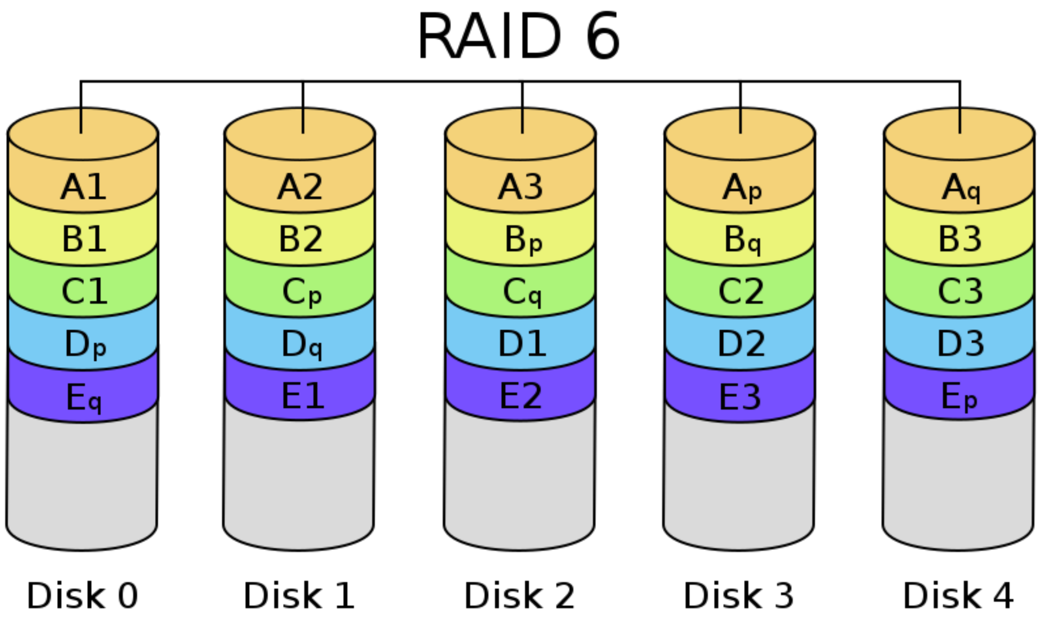
RAID 6 – striping with double distributed parity

- similar to RAID 5, but doubles the amount of parity
  - (parity computation more complicated)
- purpose: reliability, fast read/write performance

- tolerant of 2 simultaneous disk failures
- with N disks, only N-2 space is used for data

- usage: same as RAID 5, but data is very important

- what about RAID 2 and RAID 3?
  - not used, obsolete



Images from:
https://en.wikipedia.org/wiki/Standard_RAID_levels

RAID so far

- Raid 0 (striped) – fast but one big disk that all goes down at once
- Raid 1 (mirrored) – no speed and no more space, but reliability super scaled

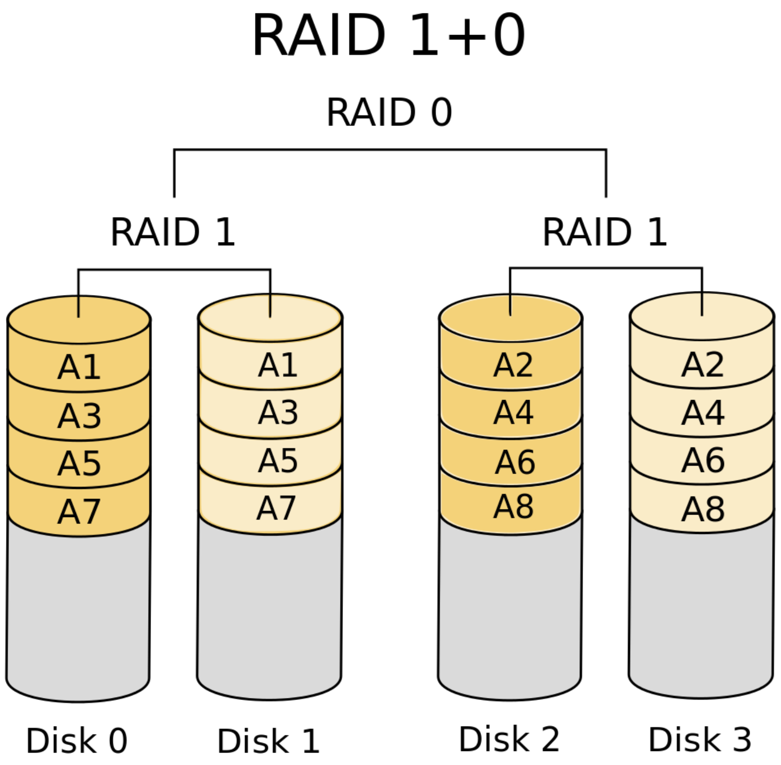
- Raid 4 (one disk parity) – reliability at cost of 1 disk, but 1 parity disk is bottleneck
- Raid 5 (one disk parity) – distributed parity so faster but can still only lose 1 disk
- Raid 6 (two disk parity) – same as raid 5 but can lose 2 disks (now lose 2 disks of space)

- Raid next (hybrid raid)

Images from:
https://en.wikipedia.org/wiki/Standard_RAID_levels

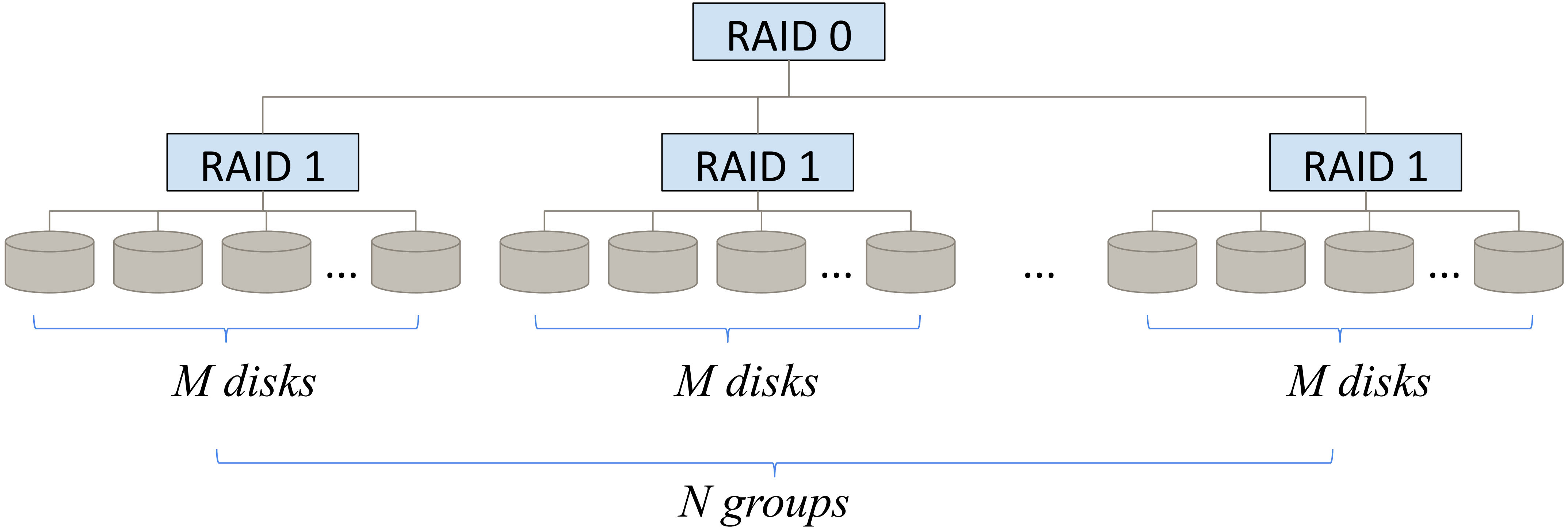
RAID 1+0 (RAID 10) – striped mirrors

- aka RAID 10, is an example of a hybrid/nested RAID
  - nests RAID 1 in RAID 0 configuration
  - simplest form: 4 disks, 2 groups of 2
- purpose: very fast & very reliable
  - combines advantages of RAID 0 and RAID 1
- in simplest form (4 disks), it can survive at least 1 disk failure, and if lucky 2 failures
- common for high-performance uses where data cannot be lost, eg. databases, email server
- can tune redundancy to 3, 4, 5 … simultaneous failures



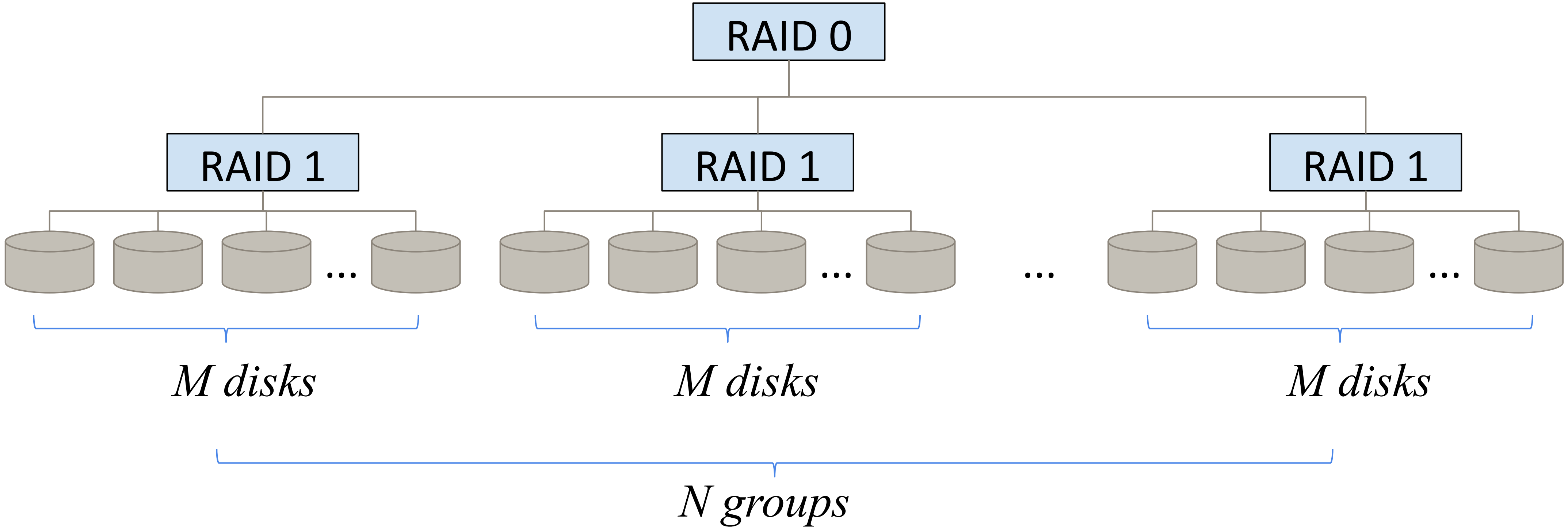
Images from:
https://en.wikipedia.org/wiki/Nested_RAID_levels

RAID 10 – striped mirrors



- consider RAID 10 that has N groups of RAID 1, and each group has M disks i.e. total number disks = M * N
- can survive at least M - 1 simultaneous disk failures, but potentially up to N*(M-1) failures

RAID 10 – striped mirrors



- read performance potentially up to N * M of a single disk, write performance is N times higher
- only N disks worth of space used for data out of N * M, so it is a very expensive RAID configuration
- note: other nested RAIDs are also possible,eg. RAID 5+0, RAID 6+0, RAID 10+0

RAID so far

- Raid 0 (striped) – fast but one big disk that all goes down at once
- Raid 1 (mirrored) – no speed and no more space, but reliability super scaled

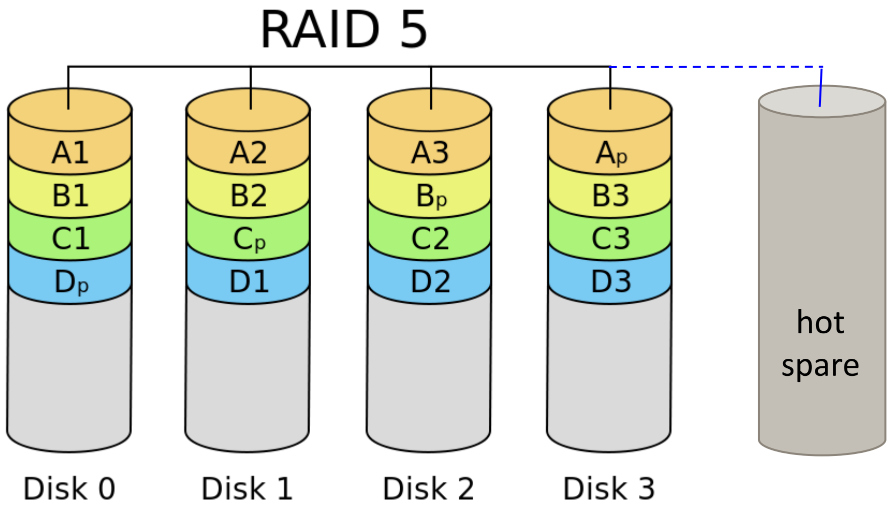
- Raid 4 (one disk parity) – reliability at cost of 1 disk, but 1 parity disk is bottleneck
- Raid 5 (one disk parity) – distributed parity so faster but can still only lose 1 disk
- Raid 6 (two disk parity) – same as raid 5 but can lose 2 disks (now lose 2 disks of space)

- Raid 10 (striped mirrors) – at cost of many more disks you can have cake and eat it to of RAID 1 and 0

Images from:
https://en.wikipedia.org/wiki/Standard_RAID_levels

Hot Spares

- a small number of hot-spare disks can be left unallocated
- these automatically replace a failed disk
  - data is rebuilt onto them
  - time spent in degraded mode is minimized
- hot-spares are not used until failure occurs
- can be added to any RAID that supports redundancy



Images from:
https://en.wikipedia.org/wiki/Standard_RAID_levels

Other I/O Devices

Solid State Drives (SSDs)

- drives with no moving parts (other than electrons)

- some pros compared to spinning disks:
  - no moving parts → theoretically less prone to damage
  - nearly 0 latency (seek time and rotational latency non-existent)
  - often much higher transfer speeds
  - quieter, need less power, lighter, not sensitive to temperature or pressure changes

- some cons compared to spinning disks:
  - more expensive, usually smaller capacity
  - performance degrades over time (more writes → slower performance)
  - can have quite inconsistent performance with mixed read/write workloads
    - write block size usually very large

- SSDs are not (yet) a clear winner in every situation

I/O Devices

- block devices:
  - store information in fixed-size blocks (eg.512 bytes to 32KB)
  - each block has its own address
  - data transferred in units of one or more entire blocks
  - read or write can be done in any order
  - e.g., hard disk, CD-ROMs, USB
- character devices:
  - delivers or accepts a stream of characters, without regard to any block structure
  - not addressable, and no seek operations
  - e.g., printer, network interface, mouse, keyboard
- other devices:
  - clocks (also known as timers)

Review

Review

- Which one of the following disk scheduling algorithms could lead to starvation among requests?
  - FCFS
  - SSTF
  - SCAN

- Which RAID configuration cannot survive a single disk failure?
  - RAID 0
  - RAID 1
  - RAID 5
  - RAID 10
- Keyboard is a character device.
  - True or False

Review

If we build a

RAID 0
RAID 1
RAID 5
RAID 6
RAID 10

with

2
3
4
5
10

disks, each with capacity of **x** TB

what is

... the capacity of the array?

... the maximum/minimum number of simultaneous failures the raid can tolerate?

... the read/write performance?

Done!

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