Operating Systems

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Chapter 8
Mass Storage

Topics in Part 3 (Storage Management)

User Space

KV, Distributed FS, Graph System…

Processes

Operating System Kernel

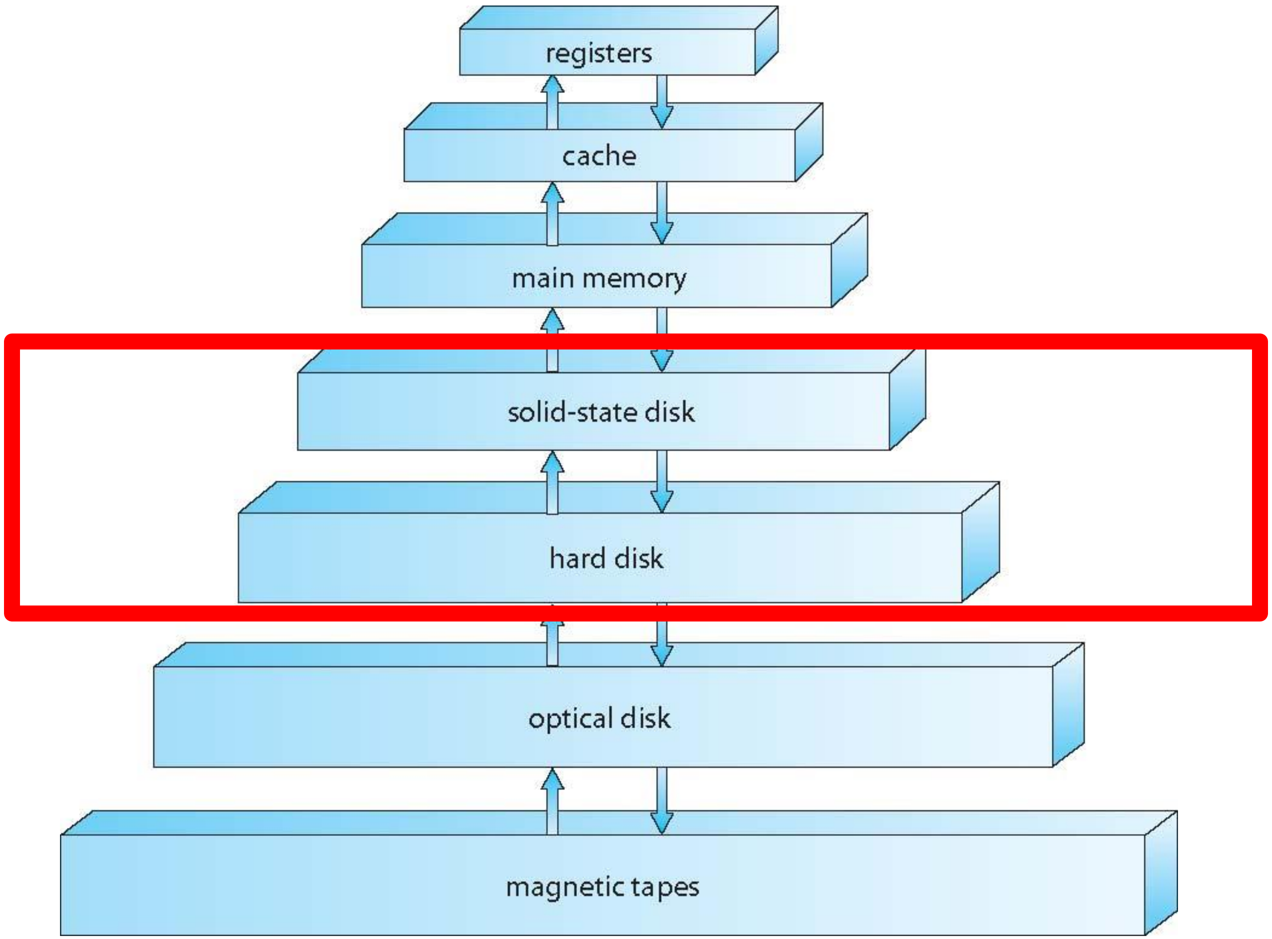
File system Implementation

FAT32, EXT2/3

File System Operations

Devices

Storage Hierarchy



Topics (Mass Storage)

Disk Structure

Disk Scheduling

SSD Structure

SSD Features/Issues

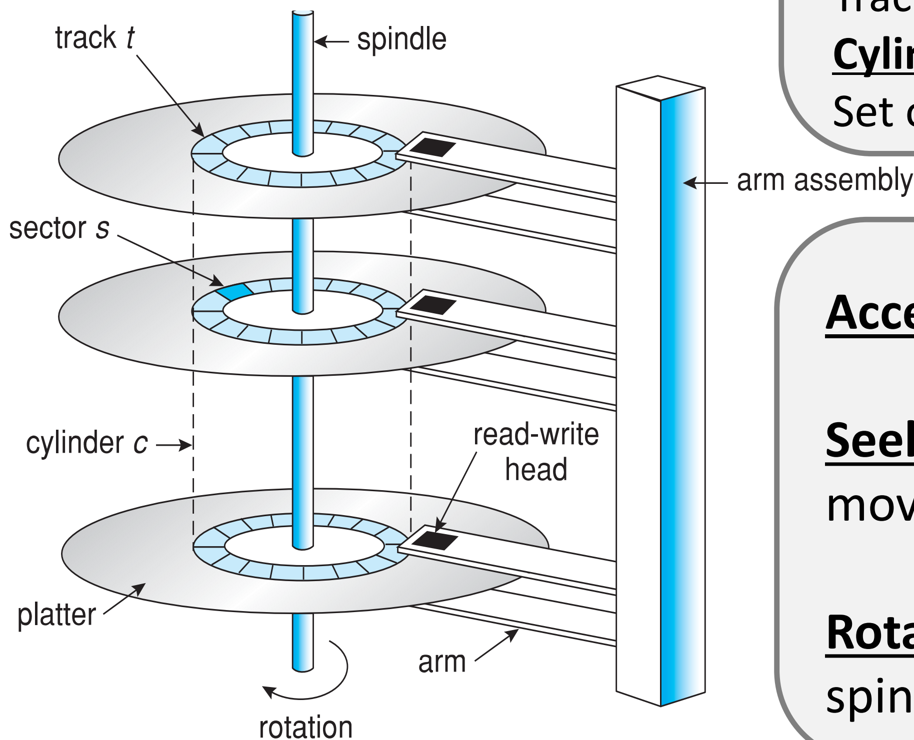
RAID

Erasure Coding

Topics

- **Disk structure**
- Disk scheduling
- Solid-state drives (SSDs)
- RAID & Erasure coding

Hard Disk Structure – Physical view



<u>Physical address (cylinder, track, sector)</u>

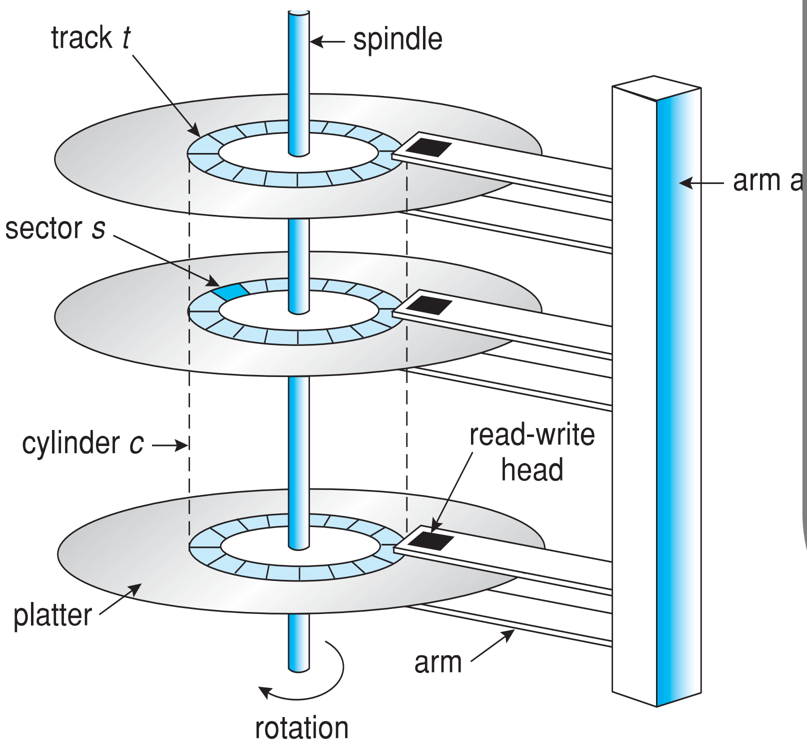
<u>Track:</u>
The surface of a platter is divided into tracks
<u>Sector:</u>
Track is divided into sectors (512B data + ECC)
<u>Cylinder:</u>
Set of tracks that are at one arm position

<u>Access:</u> Seek + Rotate

<u>Seek time:</u>
move disk arm to desired cylinder

<u>Rotational latency</u>:
spin at 5400/7200/10K/15K RPM

Hard Disk Structure – Physical view



<u>Constant liner velocity (CLV)</u>

- Uniform density of bits per track, outer track hold more sectors
- Variable rotation speed to keep the same rate of data moving
- **<u>CD-ROM/DVD-ROM</u>**

<u>Constant angular velocity (CAV)</u>

- Constant rotation speed
- Higher density of bits in inner tracks
- **<u>Hard disks</u>**

Hard Disk Structure – Logical view

How to use?

Large 1-D arrays of logical blocks (usually 512 bytes)

Address mapping

Logical block number -> (cylinder #, track #, sector #)

Disk management is required

- **Disk formatting**
- **Disks are prone to failures: defective sectors are common (bad blocks)**
  - ✓ Need to handle defective sectors: bad block management

Disk Management

Disk Formatting

Step 1: Low-level formatting/physical formatting

- ✓ Divide into sectors so disk controller can read/write
- ✓ Fills the disk with a special data structure for each sector (data area(512B), header and trailer (sector number & ECC))
  - The controller automatically does the ECC processing whenever a sector is read/written
- ✓ Done at factory, used for testing and initializing (e.g., the mapping). It is also possible to set the sector size (256B, 512B, 1K, 4K)

Disk Management

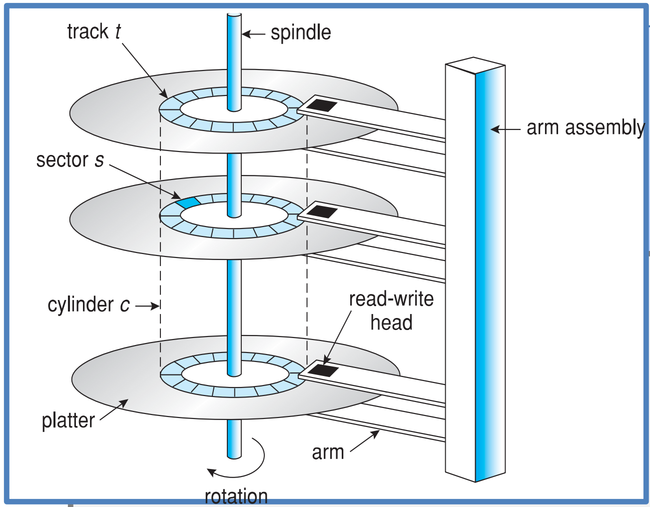
Disk Formatting

Step 2: How to use disks to hold files after shipment?

- ➢ **Choice 1: File system**
- ✓ Partition into one or more groups of cylinders (each as a separate disk)
- ✓ Logical formatting: creating a FS by storing the initial FS data structures
- ✓ I/O optimization: Disk I/O (via blocks) & file system I/O (via clusters), why?
  - More sequential access, fewer random access

- ➢ **Choice 2: Raw disk**
- ✓ Use disk partition as a large sequential array of logical blocks, without FS
- ✓ Raw I/O: bypass all FS services (buffer cache, prefetching…), be able to control exact disk location

Disk Management



Bad Block Management

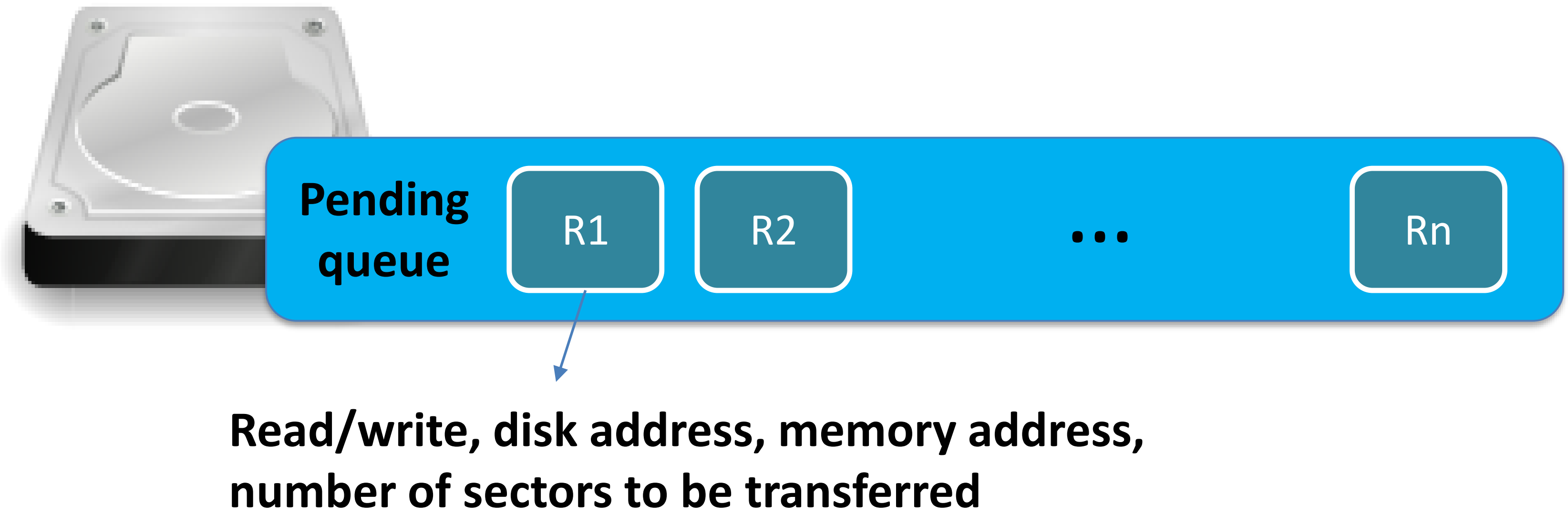
- ✓ Maintain a list of bad blocks (initialized during low-level formatting) and preserve an amount of spare sectors
- ✓ **Sector sparing/forwarding:** replace a bad sector logically with one spare sector
  - Problem: invalidate disk scheduling algorithm
  - Solution: spare sectors in each cylinder + spare cylinder
- ✓ **Sector slipping:** remap to the next sector (data movement is needed)

Topics

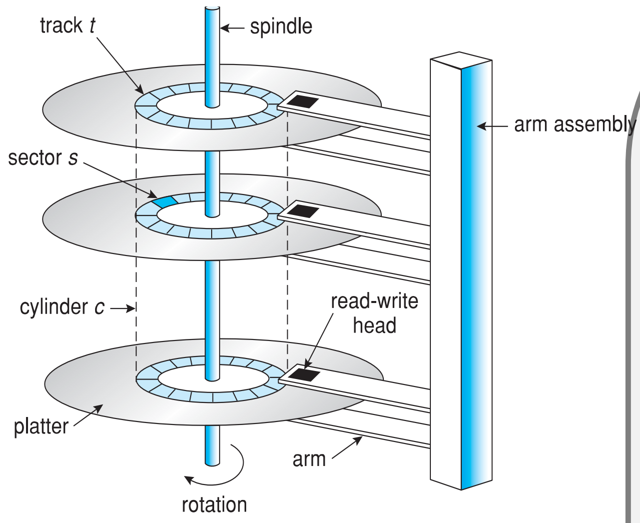
- Disk structure
- **Disk scheduling**
- Solid-state drives (SSDs)
- RAID & Erasure coding

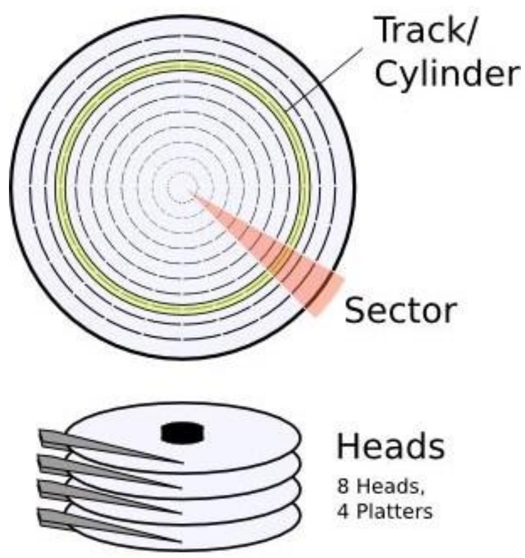
Why needed?

- Requests are placed in the queue of pending requests for that drive if the drive/controller is busy



What is disk scheduling





- I/O access procedure
  - Seek
    - move the head to the desired cylinder
  - Rotate
    - spin to the target sector on the track

Request ordering significantly affects the access performance (seek + rotate), so scheduling is needed

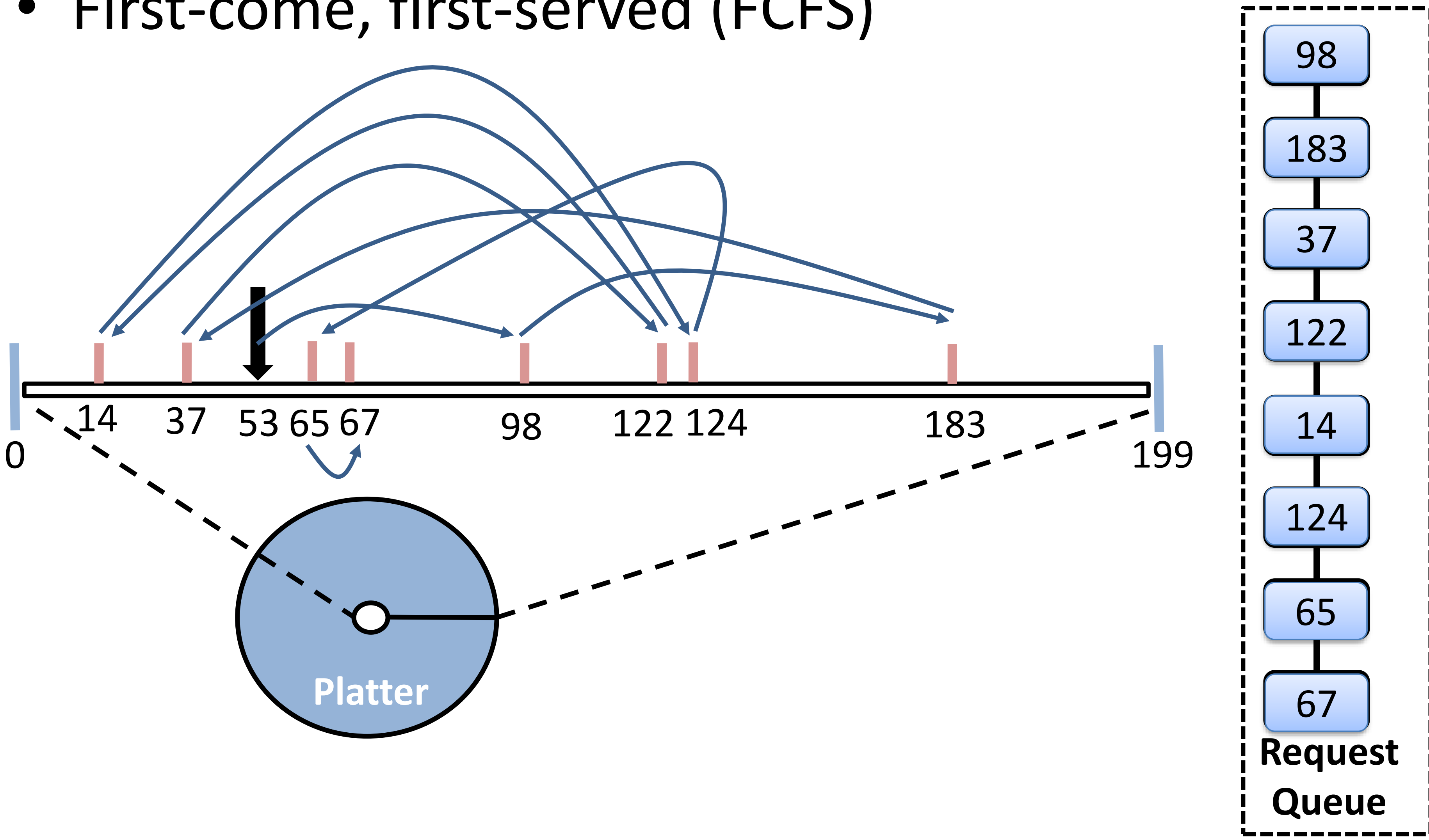
Disk scheduling： Choose the next request in the pending queue to service so as to minimize the seek time (scheduling algorithms)

FCFS Scheduling

- First-come, first-served (FCFS)
  - Intrinsically fair, but does not provide the fastest service

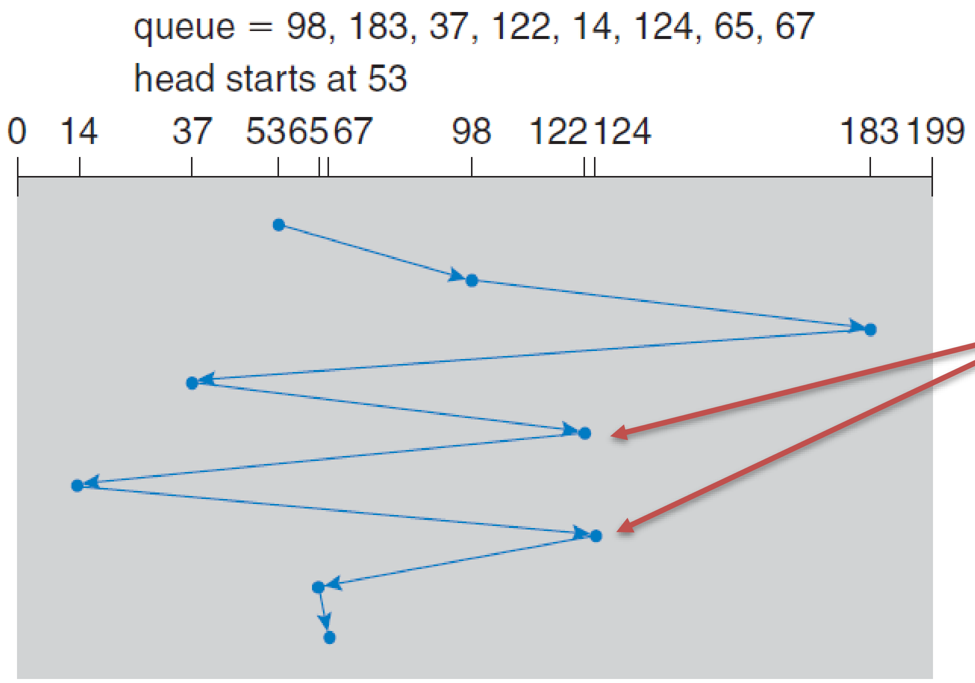
FCFS Scheduling

- First-come, first-served (FCFS)



FCFS Scheduling

- Scheduling diagram



Total head movement

(640 cylinders)

Wild swing is very common

E.g.: 122 to 14, then to 124

How to reduce the head movement?

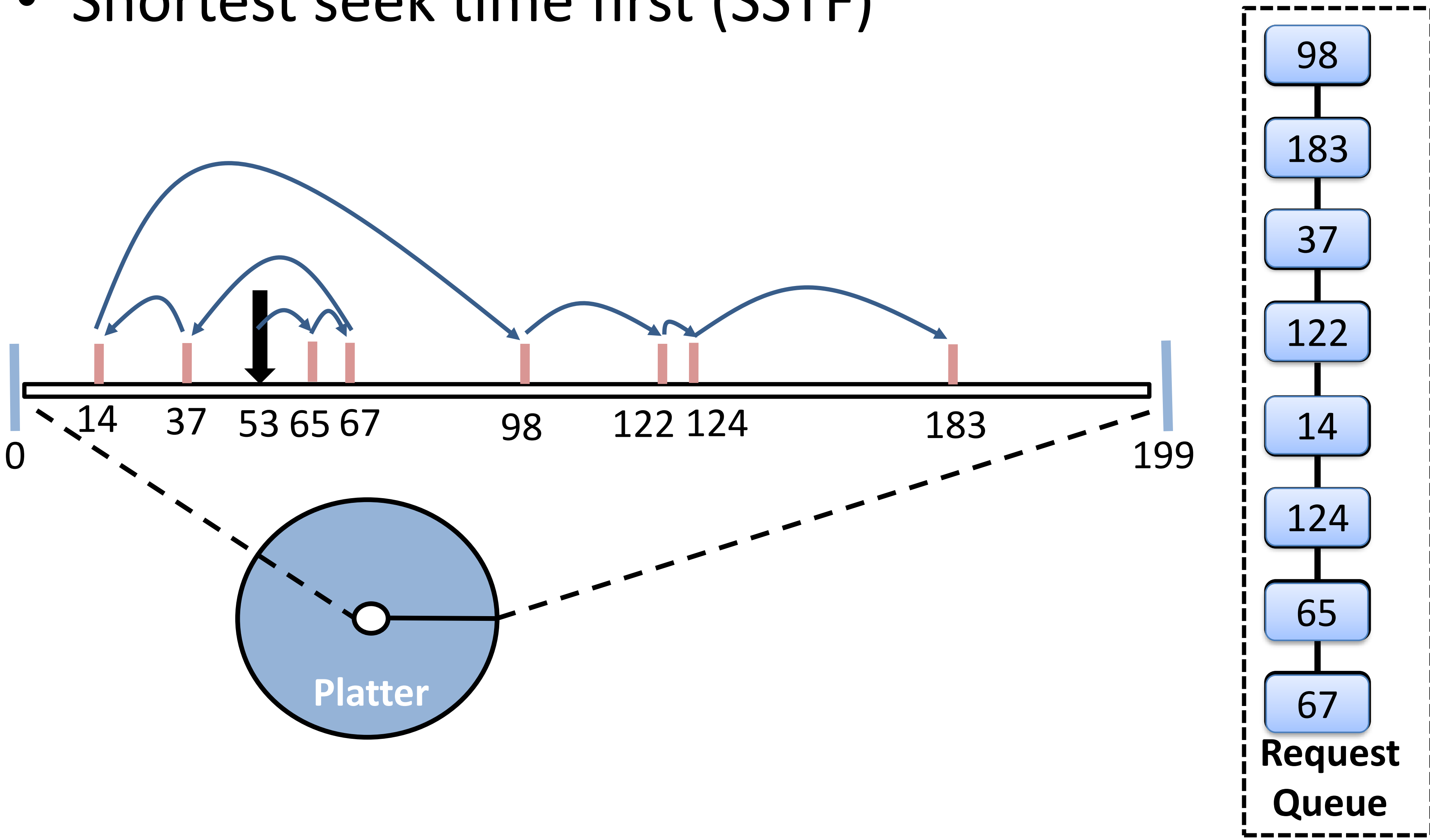
Handle nearby requests first

SSTF Scheduling

- Shortest seek time first (SSTF)
  - Choose the request with the least seek time
  - Choose the request closest to the current head position

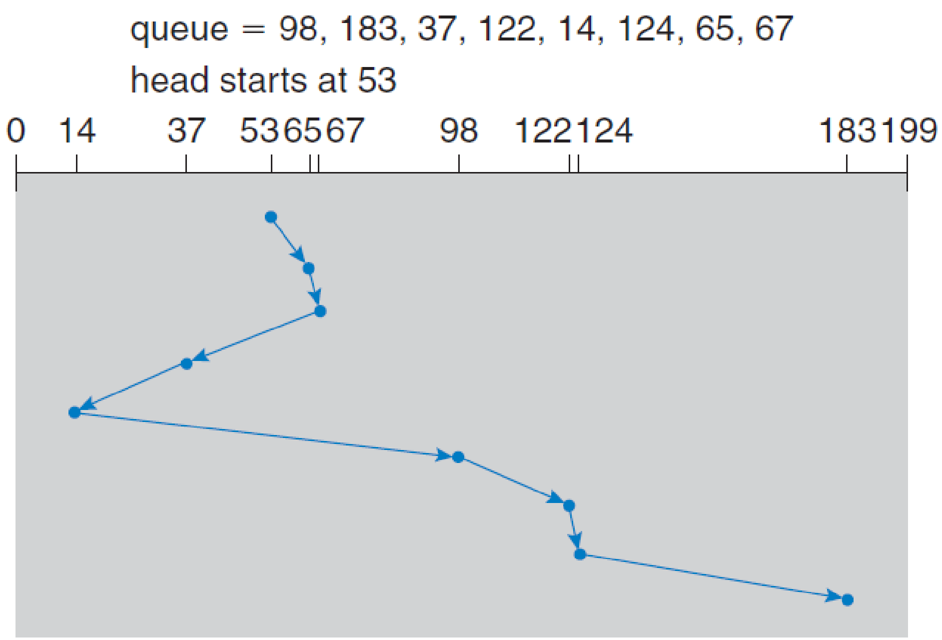
SSTF Scheduling

- Shortest seek time first (SSTF)



SSTF Scheduling

- Scheduling diagram



Total head movement: 236 cylinders (it is 640 for FCFS)

Essentially a form of SJF scheduling

It is not optimal

The sequence of 53-37-14-65… could reduce the head movement to 208

It may cause starvation

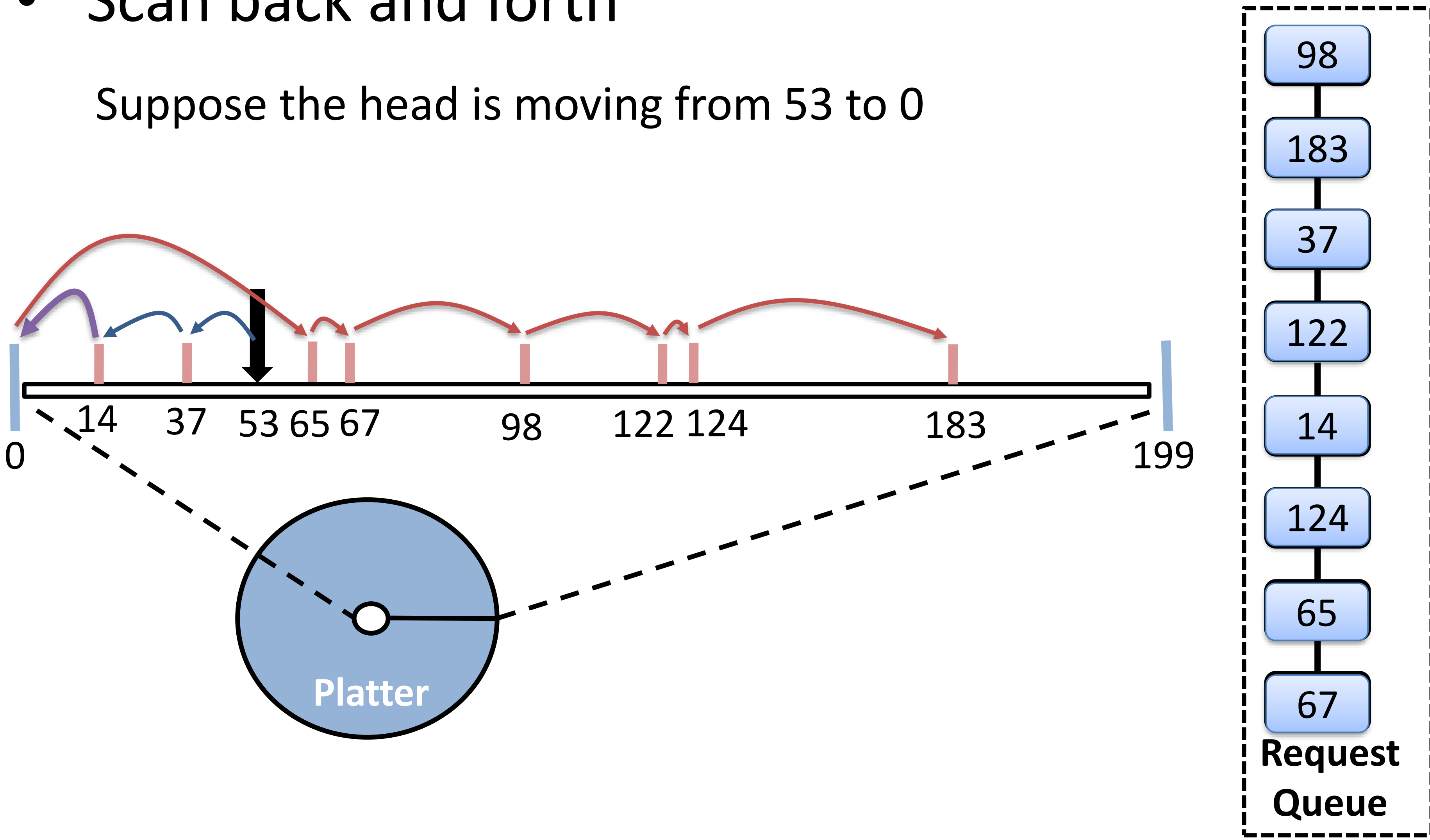
SCAN Scheduling

- Scan back and forth
  - Starts at one end, moves toward the other end
  - Service the requests as it reaches each cylinder
  - Reverse the direction
  - **Elevator algorithm**

SCAN Scheduling

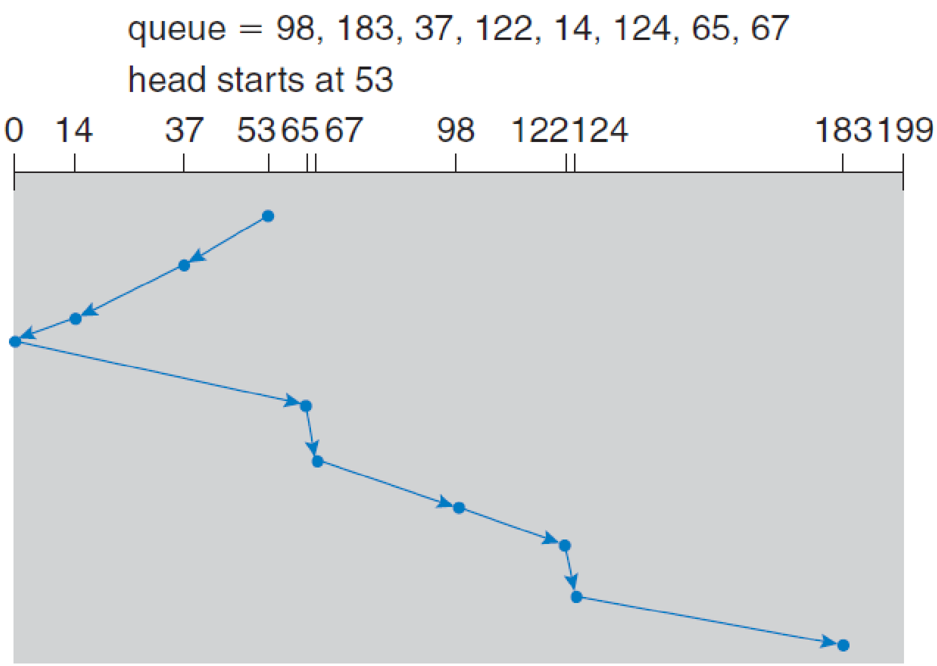
- Scan back and forth

Suppose the head is moving from 53 to 0



SCAN Scheduling

- Scheduling diagram



<u>Any problem?</u>

Assume a uniform request distribution

The heaviest density of requests is at the other end of the disk

They need to wait for a long time

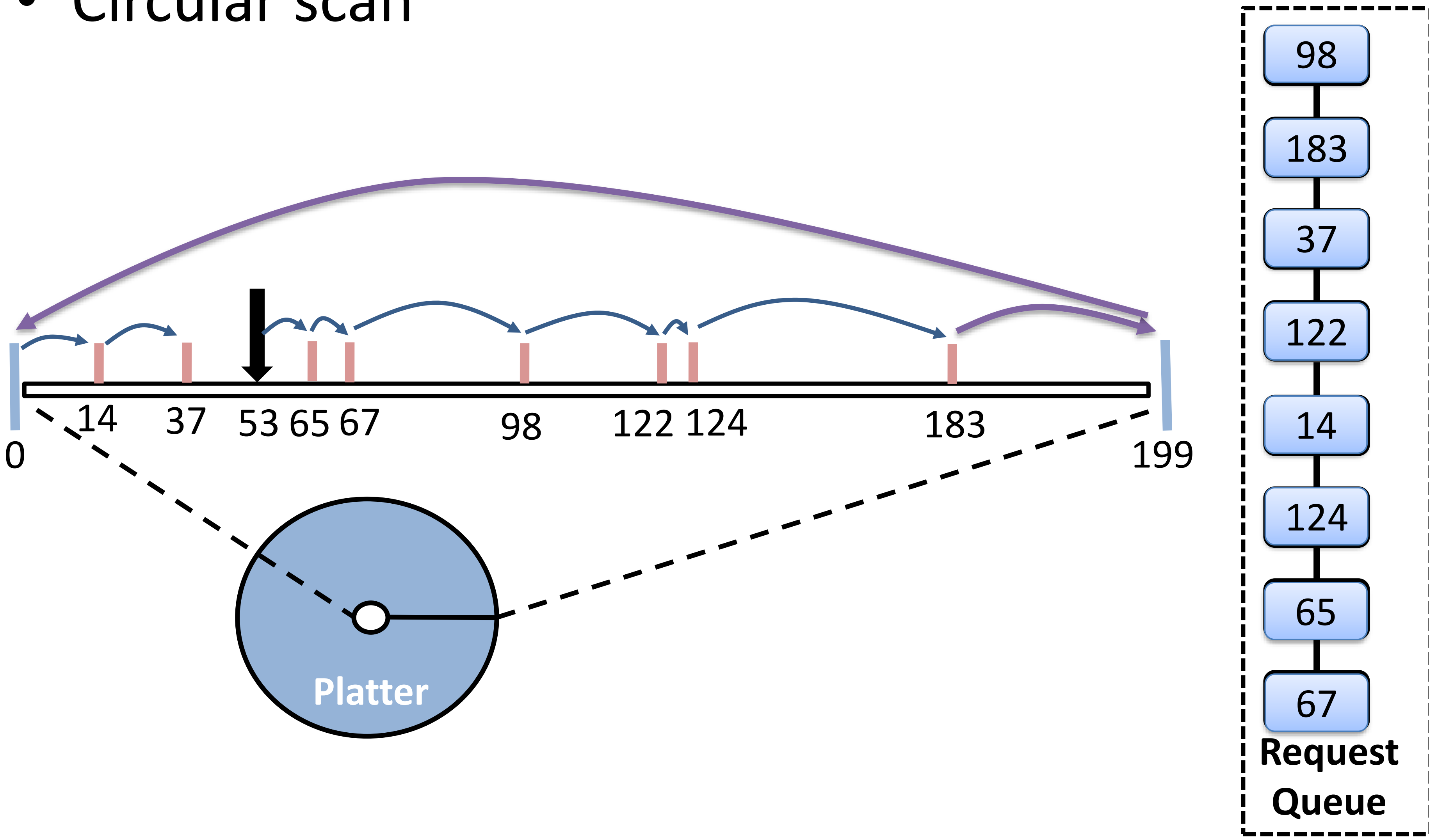
<u>Can we do something about this?</u>

C-SCAN Scheduling

- Circular Scan back and forth
  - A variant of SCAN: immediately return when reaches the end
  - Aim for providing a more uniform wait time

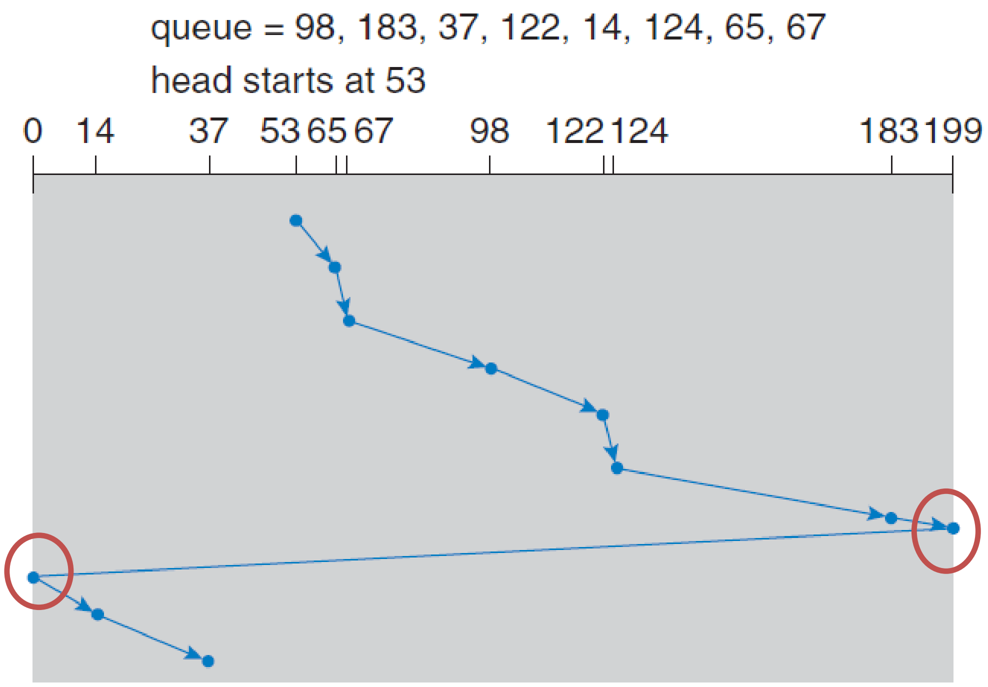
C-SCAN Scheduling

- Circular scan



C-SCAN Scheduling

- Scheduling diagram



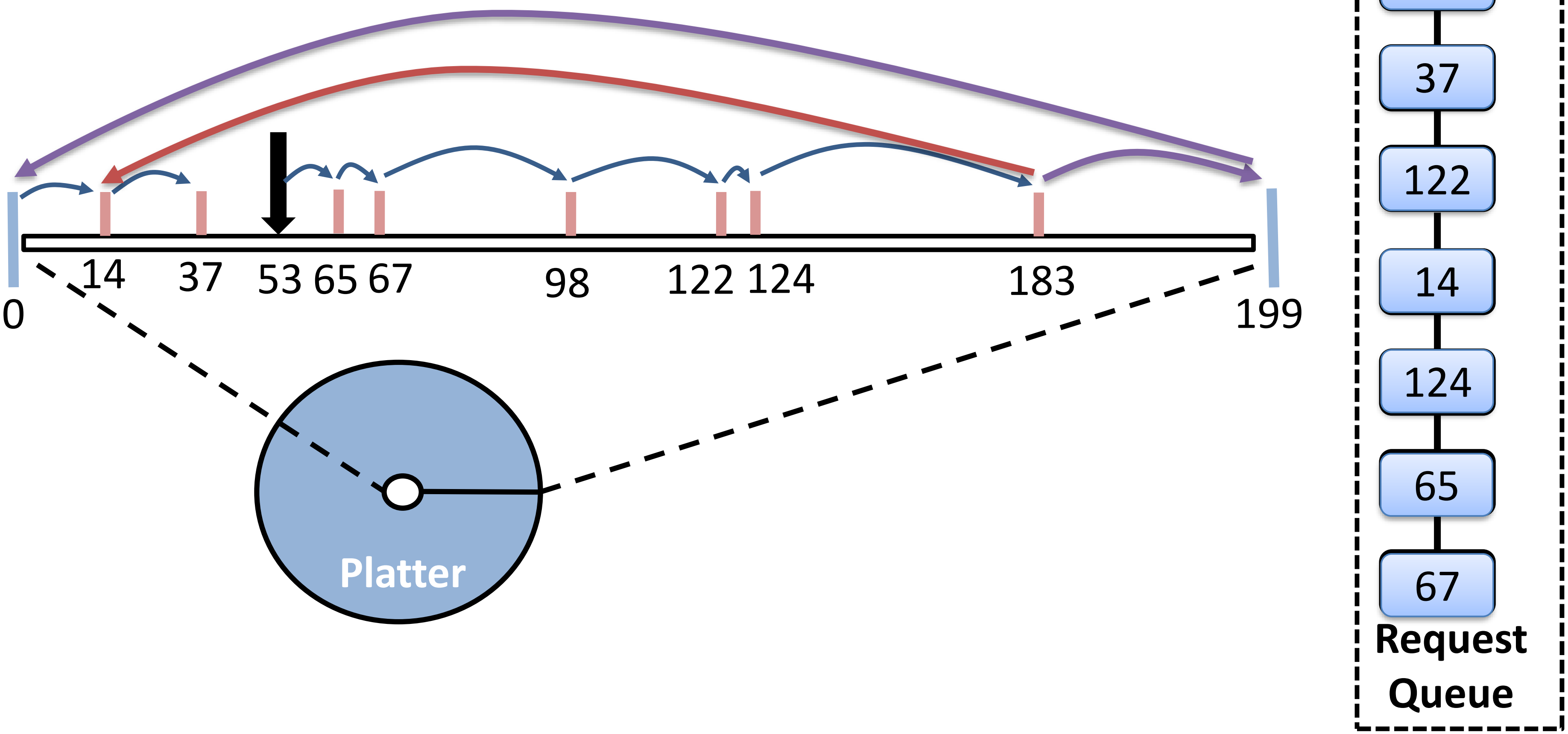
Unnecessary

<u>No need to move across the full width of the disk, but only need to reach the final request</u>

<u>Improved SCAN and C-SCAN: LOOK and C-LOOK</u>

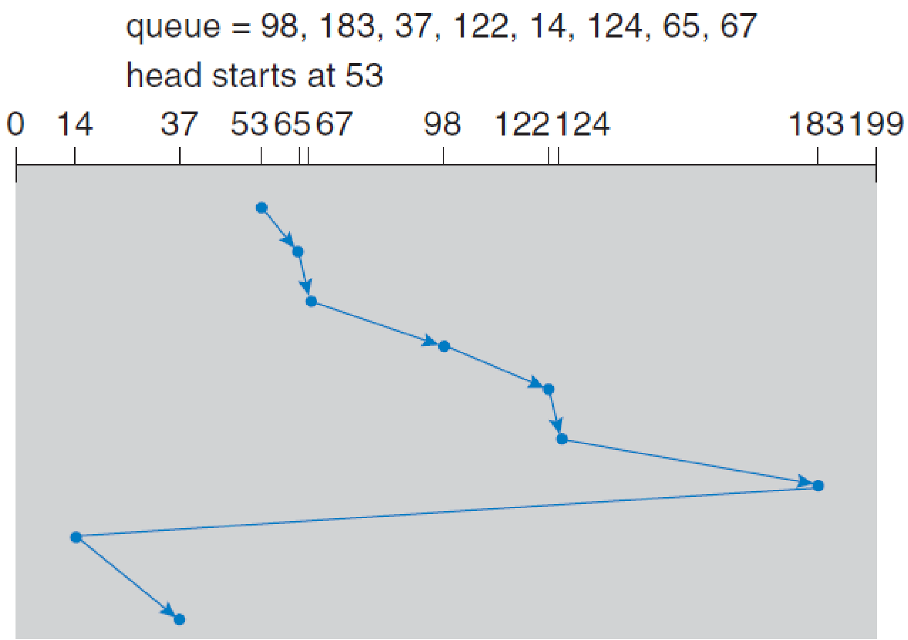
C-LOOK Scheduling

- Goes only as far as the final request
  - Look for a request before moving



C-LOOK Scheduling

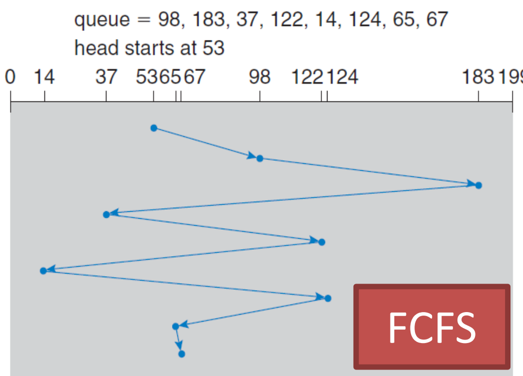
- Scheduling diagram

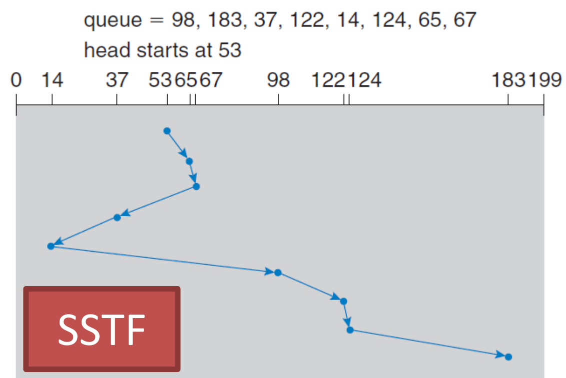


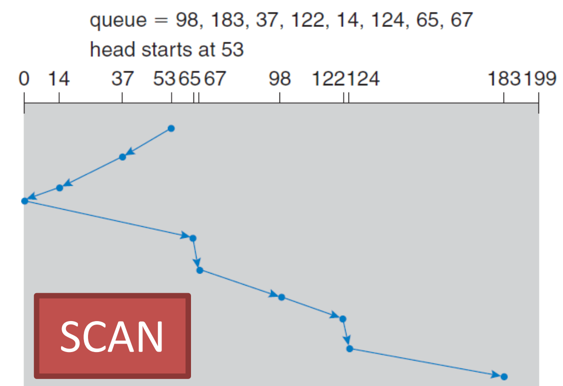
<u>Look for a request before continuing to move in a given direction</u>

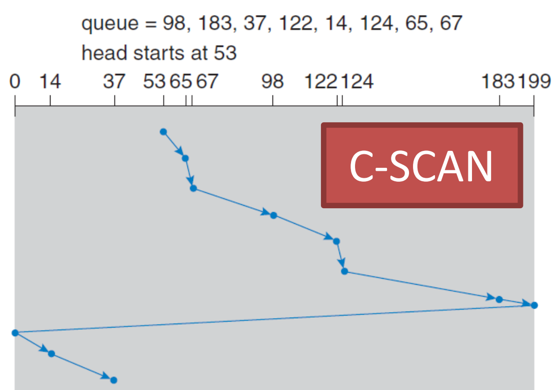
<u>Fewer head movements than SCAN/C-SCAN</u>

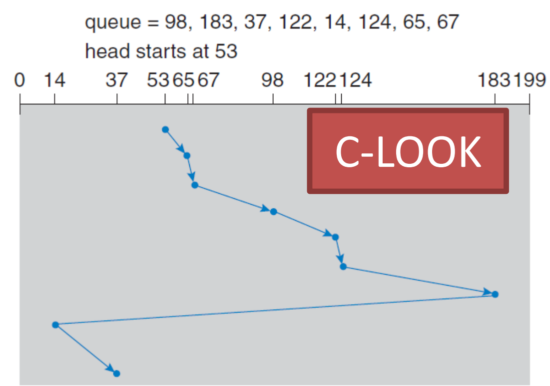
Summary of scheduling algorithms











SSTF outperforms FCFS, but may suffer from starvation

SCAN and C-SCAN perform better for heavy load systems, and they are less likely to cause starvation

Selection of a scheduling algorithm

Disk Performance

Number and types of requests

<u>File allocation method</u>
Large sequential I/O or small random I/O

Location of directories and index blocks (metadata I/O)

Implementing scheduling in OS is necessary to satisfy other constraints (e.g., priority defined by OS)

Write disk scheduling as a separate module of the OS
Can be easily replaced with different alg. (default: SSTF/LOOK).

Topics

- Disk structure
- Disk scheduling
- **Solid-state drives (SSDs)**
- RAID & Erasure coding

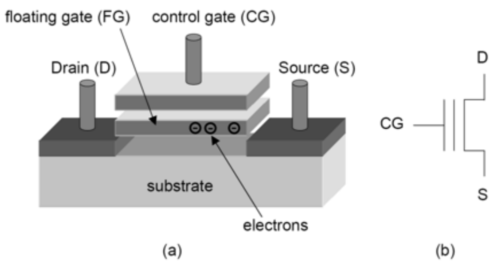
- Solid-state drives (SSDs)
  - SSD architecture
  - SSD operations
  - Flash translation layer

SSDs are widely used

Advantages of flash-based SSDs: non-volatility, shock resistance, high speed and low energy consumption;

Flash Types

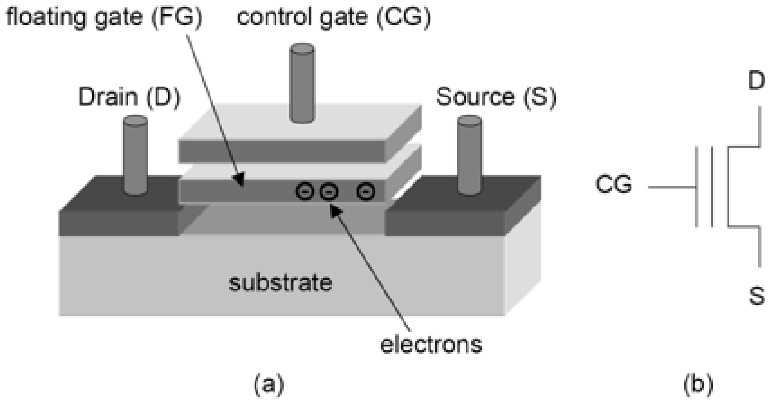
- NAND flash and NOR flash
  - NAND flash: denser capacity, only allow access in units of pages, faster erase operation
  - Most SSD products are based on NAND flash



(a) Floating gate memory cell and (b) its schematic symbol

- NAND flash: SLC and MLC
  - SLC: each cell stores one bit
    - Longer life time, lower access latency, higher cost
  - MLC: each cell stores two (or three) bits
    - Higher capacity

Flash Cell

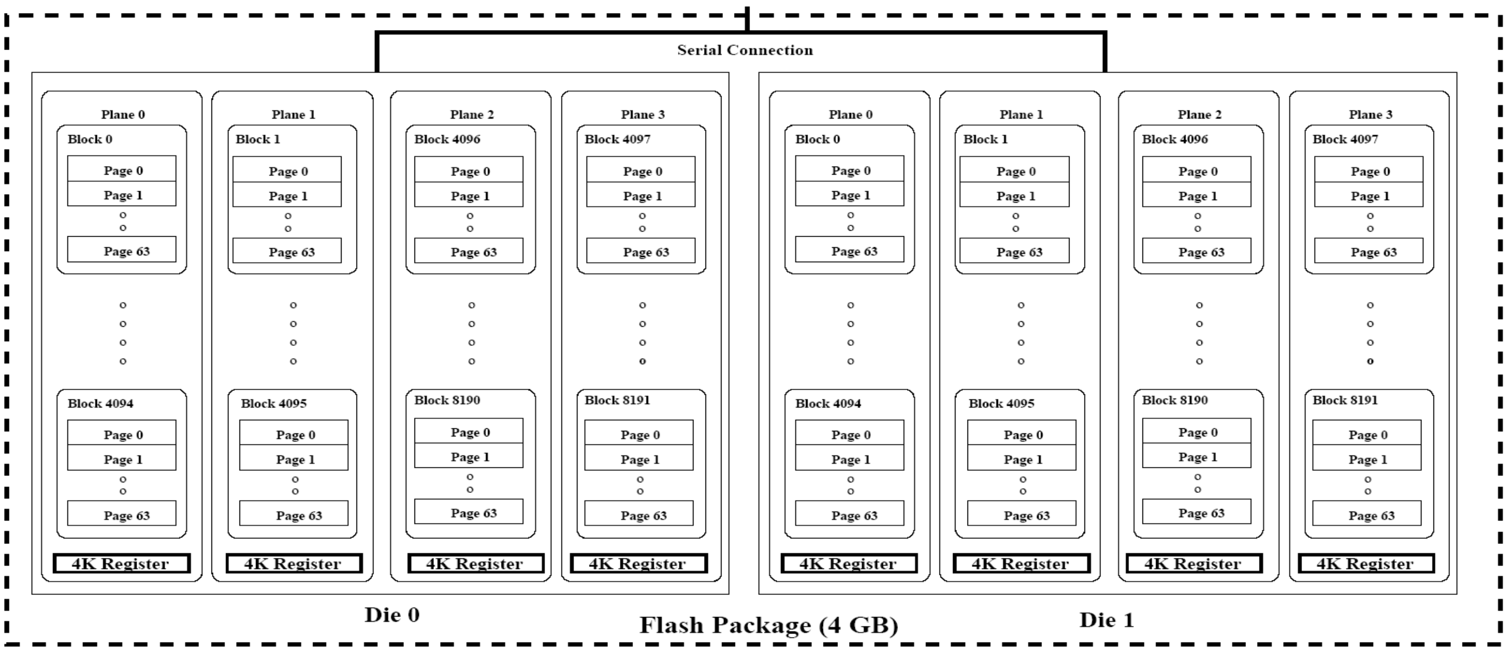


(a) Floating gate memory cell and (b) its schematic symbol

- Program operation can only change the value from 1 to 0 (erase operation changes the value from 0 to 1)
  - **No overwritten**
- The floating gate becomes thinner as the cell undergoes more program-erase cycles
  - **Decreasing reliability**

Flash Package

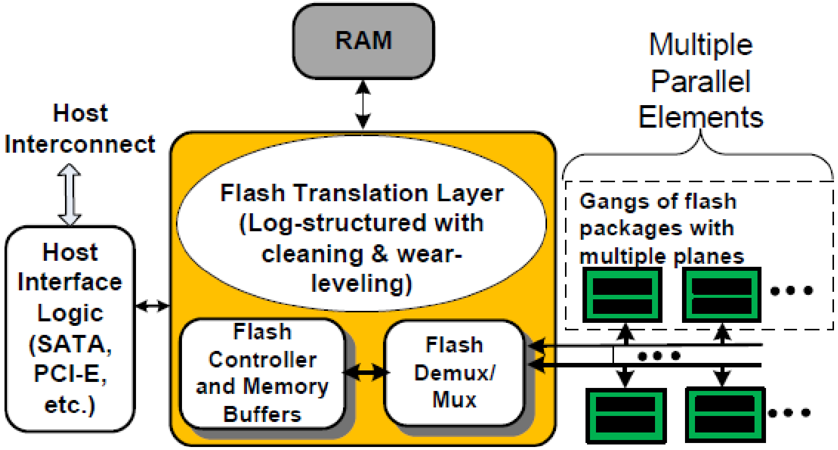
- Package > die/chip > plane > block > page

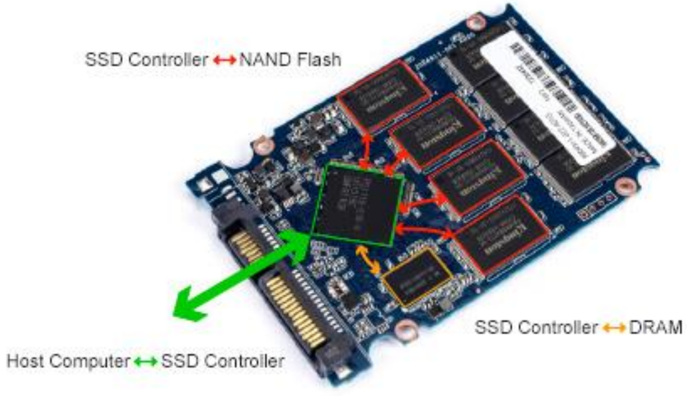


Samsung K9XXG08UXM (SLC) (2 dies, 4 planes, 2048 blocks, 64 pages)

SSD Architecture

- SSD components
  - Multiple flash packages, controller, RAM

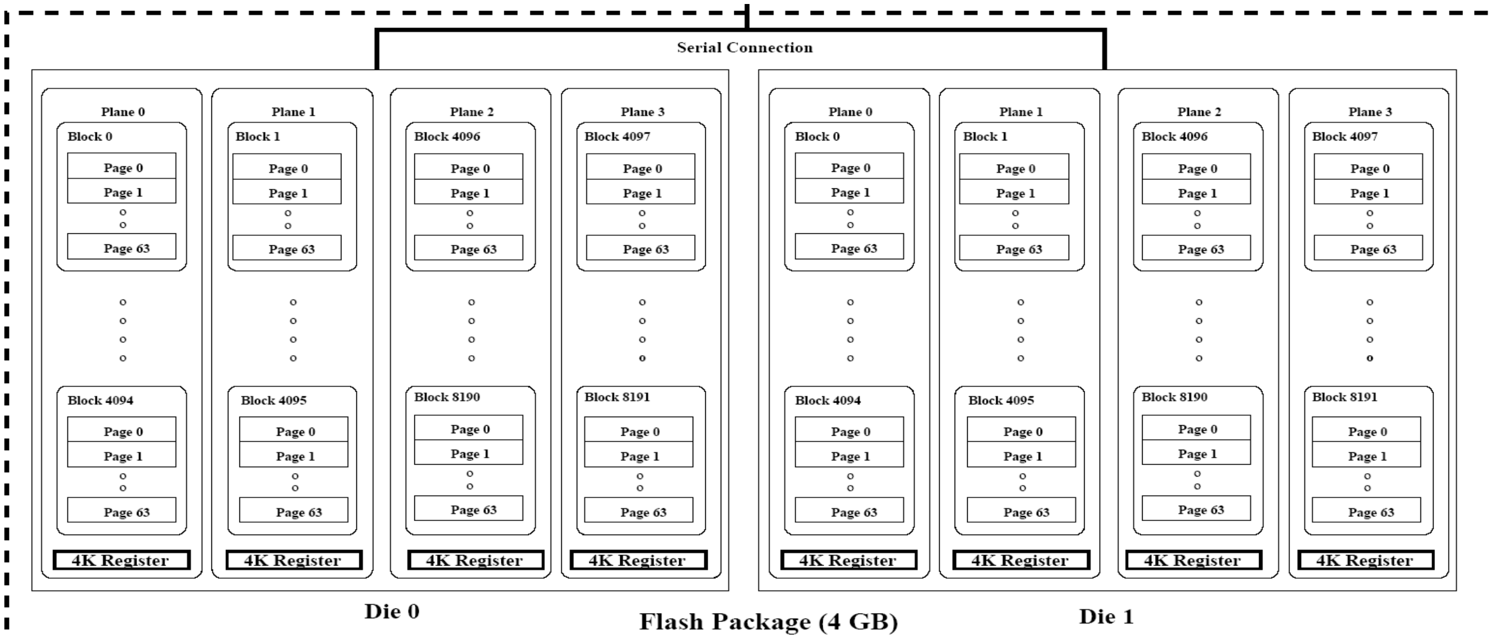




- Solid-state drives (SSDs)
  - SSD architecture
  - SSD operations
  - Flash translation layer

Read

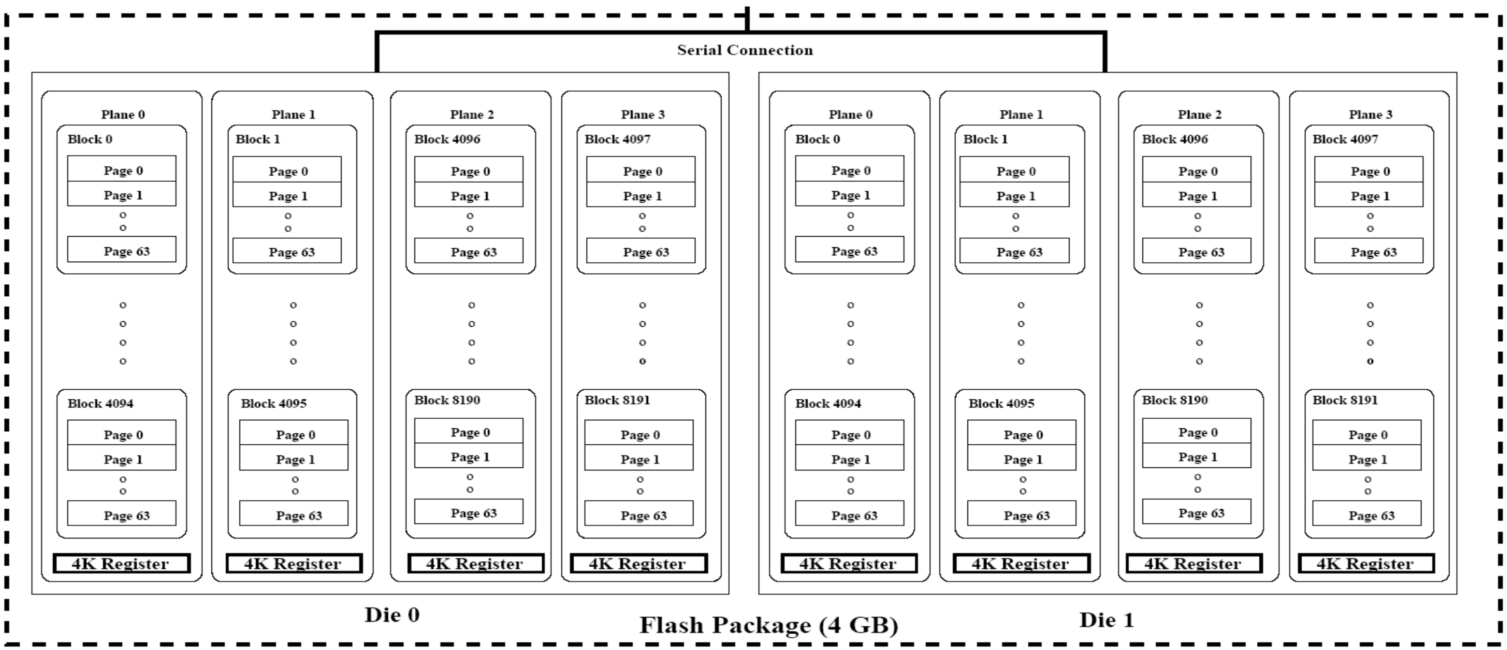
- Read: in unit of pages (4KB)



page $\xrightarrow{\text{data read: 25 µs}}$ register $\xrightarrow{\text{serial bus: 100 µs}}$ controller

Write

- Write: in unit of pages (4KB)



page ← program: 200 µs ← register ← serial bus: 100 µs ← controller

Erase

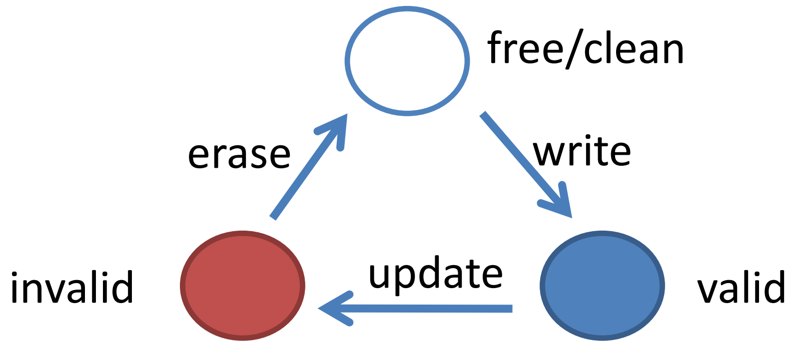
- Erase
  - In unit of blocks (64/128 pages)
  - Change all bits to 1
  - Much slower than read/write: 1.5ms
- Each block can only tolerate limited number of P/E cycles
  - SLC: 100K, MLC: 10K, TLC (several K to several hundred)
- The number of maximum P/E cycles decreases when
  - More bits are stored in one cell
  - The feature size of flash cell decreases (72nm, 34nm, 25nm)

Overwrite & Delete

- Delete
  - Simply mark the page as invalid
- Overwrite/update
  - Does not support in-place overwrite
  - Data can only be programmed to clean pages

Software layer in controller

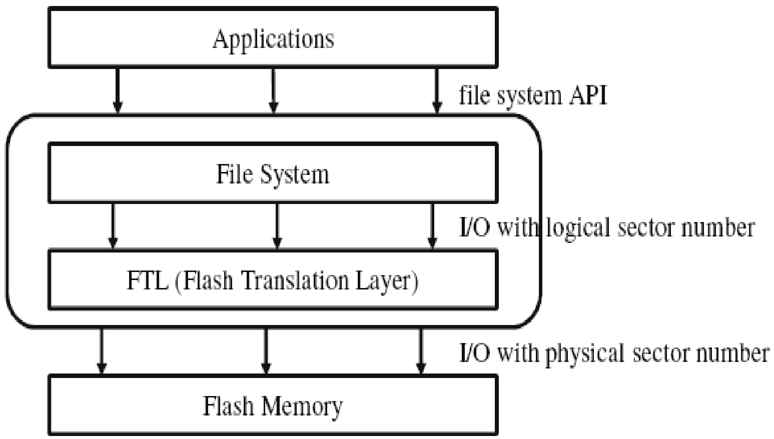
- How to further improve write performance?
  - Address mapping is needed
- Page states
  - Garbage collection is also necessary



- Solid-state drives (SSDs)
  - SSD architecture
  - SSD operations
  - Flash translation layer
  -

Flash Translation Layer

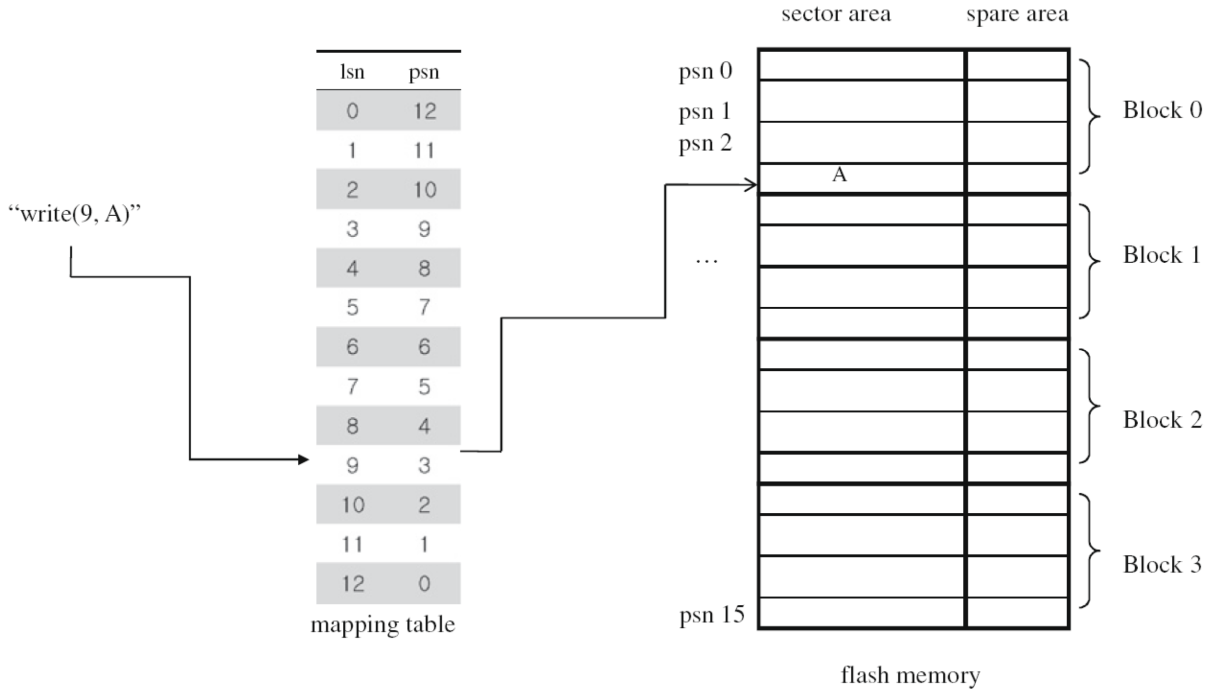
- Three functionalities
  - Address mapping
  - Garbage collection
  - Wear-leveling



Address Mapping

- Sector mapping
- Block mapping
- Hybrid mapping
- Log-structured mapping

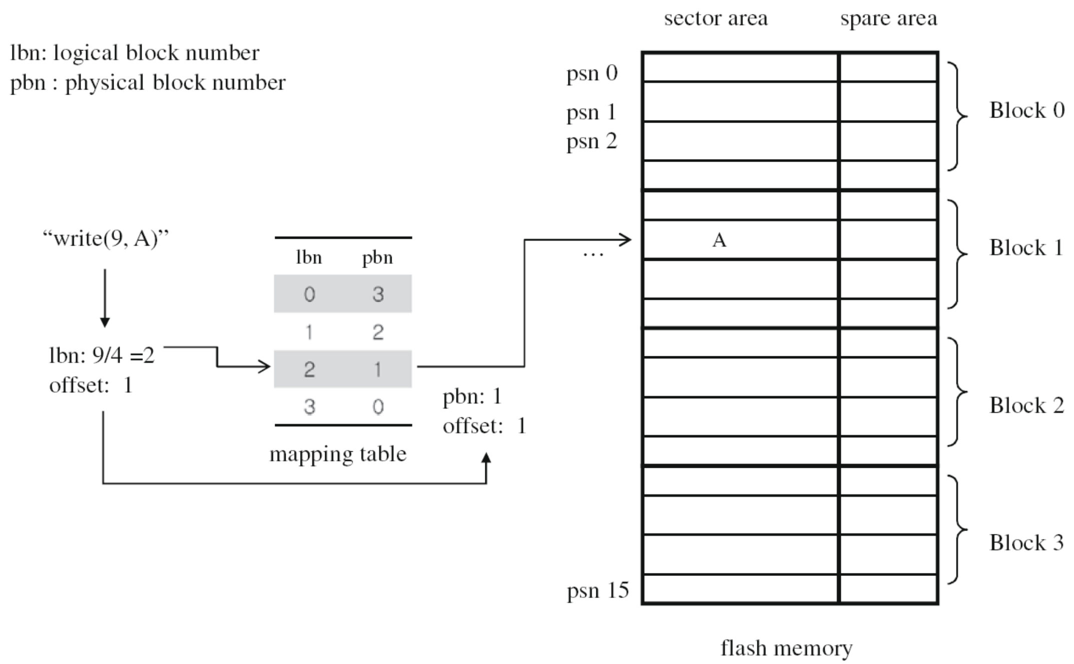
Sector Mapping



Mapping table is large: requires a large amount of RAM

Block Mapping

- The logical sector offset is the same with the physical sector offset

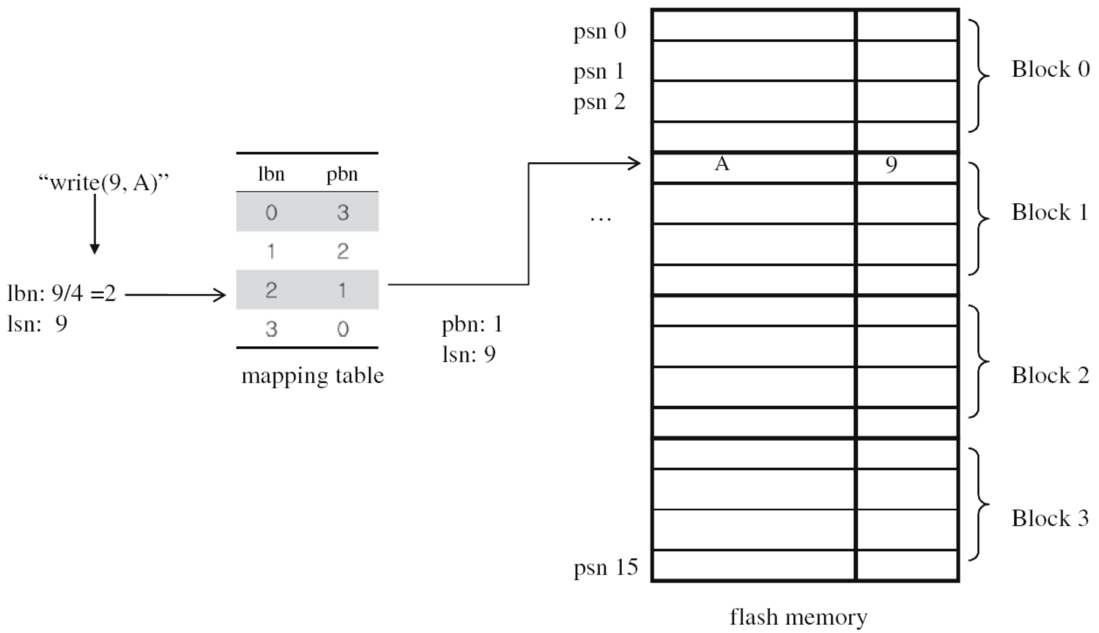


Smaller mapping table

If the FS issues writes with identical lsn, many erases

Hybrid Mapping

- First use block mapping, then use sector mapping in each block

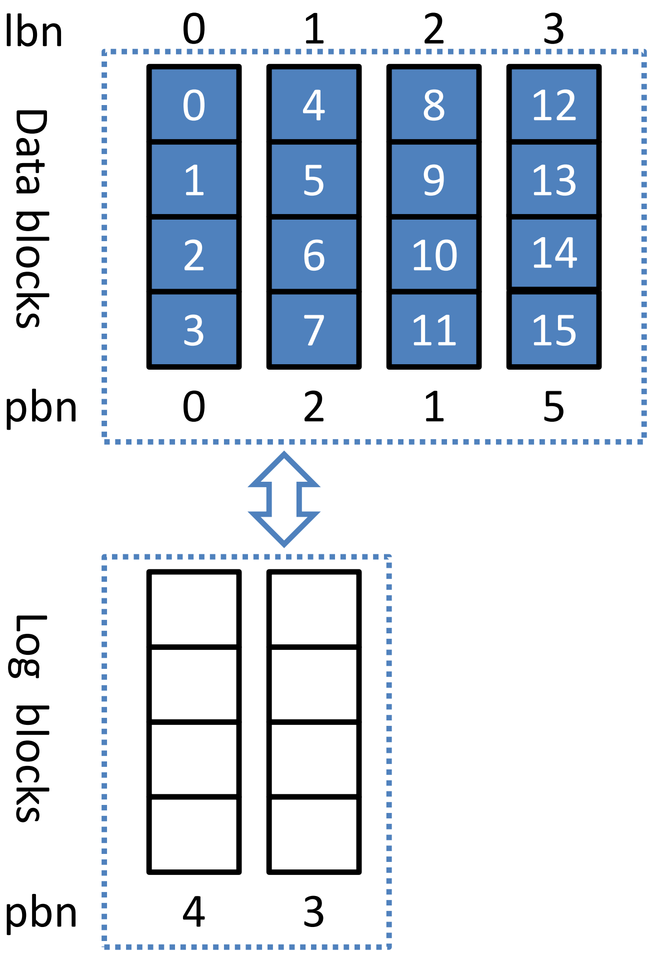


Small mapping table

Avoid a lot of erase operations

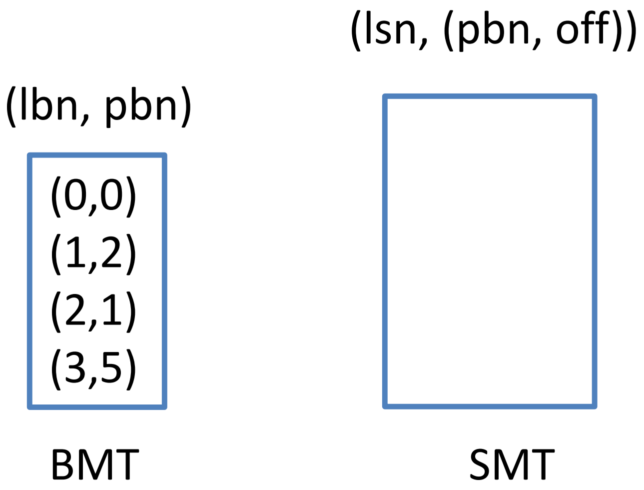
Longer time to identify the location of a page

Log-structured Mapping



Data blocks: block mapping

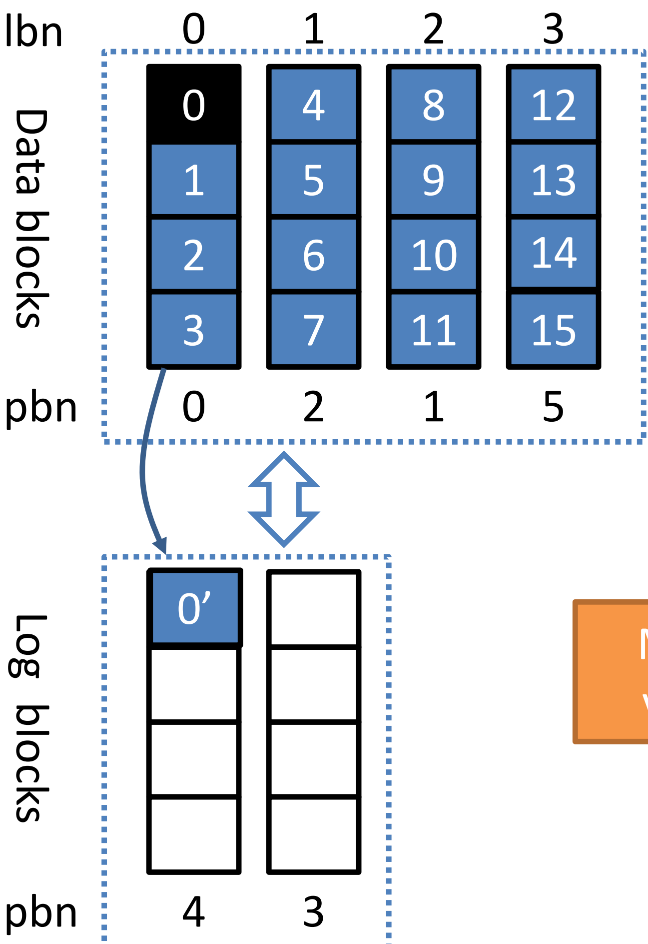
Log blocks: sector mapping



In Flash

In RAM

Log-structured Mapping



Data blocks: block mapping

Log blocks: sector mapping

Multiple variants

(lbn, pbn)

(0,0)
(1,2)
(2,1)
(3,5)

BMT

(lsn, (pbn, off))

(0, (4,0))

SMT

In Flash

In RAM

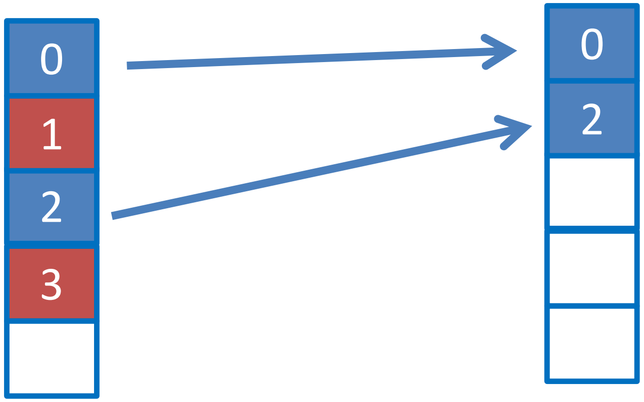
Short summary

- The performance of address mapping is workload dependent
  - Block mapping is suitable for sequential workloads
  - Sector mapping is suitable for random workloads
  - Log-structured mapping is suitable for workloads with large sequential and small random requests

- **Tradeoff exists**

Garbage Collection

- Due to the existence of invalid pages, GC must be called to reclaim storage
  - Choose a candidate block
  - Write valid pages to another free block
  - Erase the original block



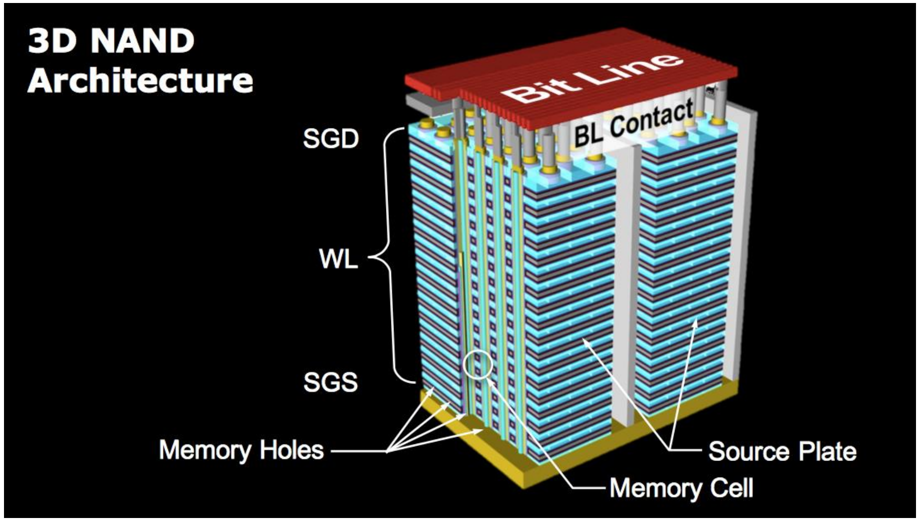
Design Issues of GC Algorithms

- **Tradeoff** in GC design
  - Efficiency: minimize writes
  - Wear-leveling: erase every block as even as possible
  - Tradeoff
  - GC is considered together with wear-leveling

- Algorithms
  - Greedy, random, and their variants
  - Hot/cold identification

Other Technologies

- 3D NAND flash



- Non-volatile memory (NVRAM)
  - PCM, STTRAM, ReRAM, etc…
  - Byte-addressable and non-volatile
  - 3D XPoint

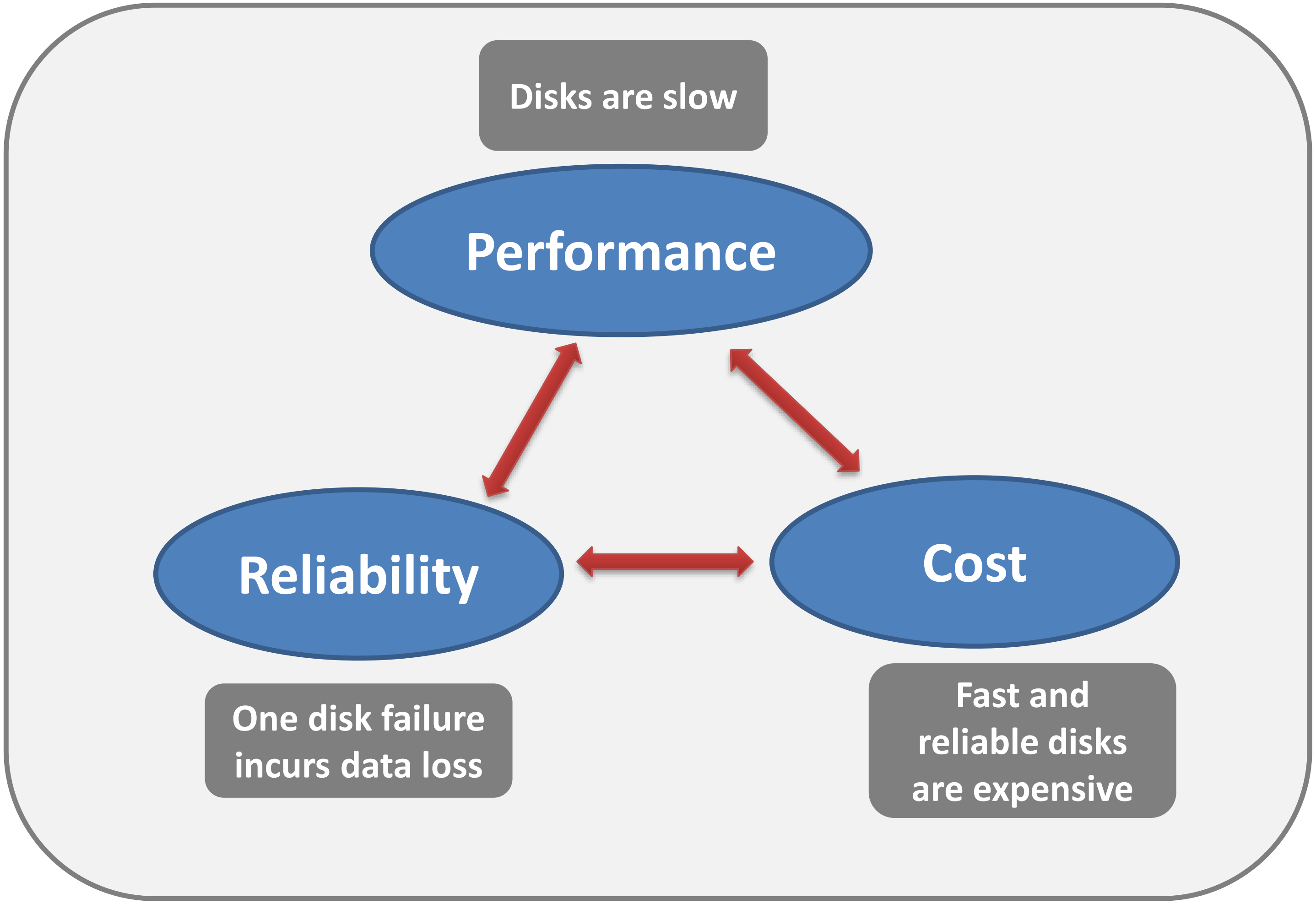
Flash Technology Trend

厂商	东芝、铠侠	Intel、美光	三星	海力士	其他
2014			128Gb，24 层，2Bit		
2015			128Gb，24 层，3Bit		
2016		768Gb，3Bit	256Gb，48 层，3Bit		
2017	512Gb 64 层，3Bit		512Gb，64 层，3Bit		
2018	512Gb 96 层，3Bit		1Tb 64 层，4 代，4Bit		
2019	1.33Tb 96 层 4Bit 512Gb 128 层 3Bit	ReRAM 3.6Mb MRAM 7Mb	512Gb 120+层，6 代，3Bit		
2020	128Gb XL 96 层	1Tb 96 层，4Bit	1Tb 92 层，5 代，4Bit	1Tb 96 层 4Bit	32Mb STT-RAM
2021	1Tb 170 层，3Bit	1Tb 144 层，4Bit	512Gb 7 代，3Bit	512Gb 176 层 3Bit	
2022	1Tb 162 层，4Bit	1Tb 176 层，4Bit	1Tb 8 代，3Bit	1Tb 176 层 4Bit	3D 闪存计算
2023		1.67Tb 192 层，5Bit		1Tb，300 层，3Bit	
2024		1Tb, 2YY 层，3Bit	1Tb，9 代（280 层），4Bit		

Topics

- Disk structure
- Disk scheduling
- Solid-state drives (SSDs)
- **RAID & Erasure coding**

RAID Motivation

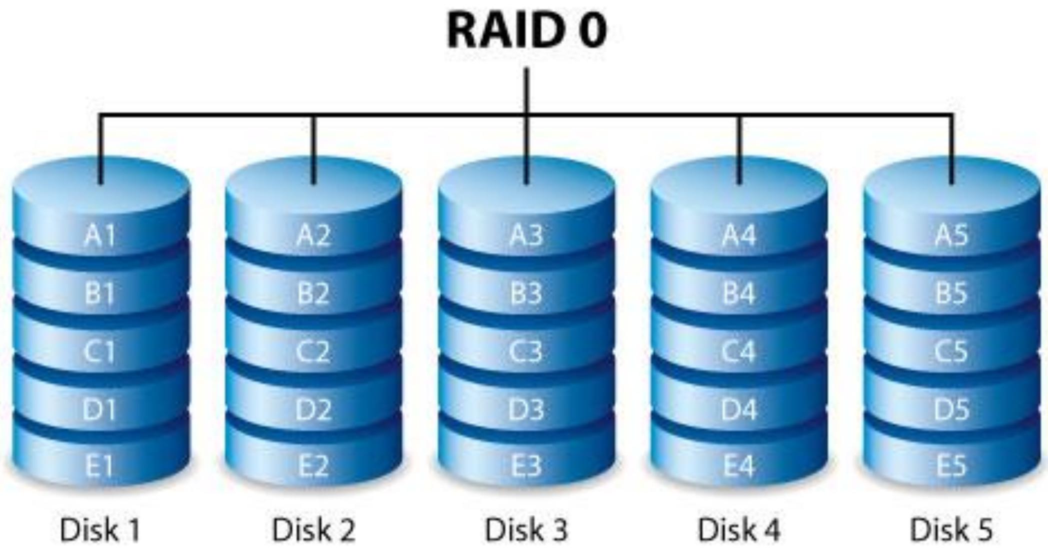


RAID Introduction

RAID: Redundant Array of Inexpensive (independent) Disks

- ✓ In the past
  - ➢ Combine small and cheap disks as a **cost-effective** alternative to large and expensive disks
- ✓ Nowadays
  - ➢ Higher performance
  - ➢ Higher reliability via redundant data
  - ➢ Larger storage capacity
- ✓ Many different levels of RAID systems
  - ➢ Different levels of redundancy, capacity, cost…

RAID 0



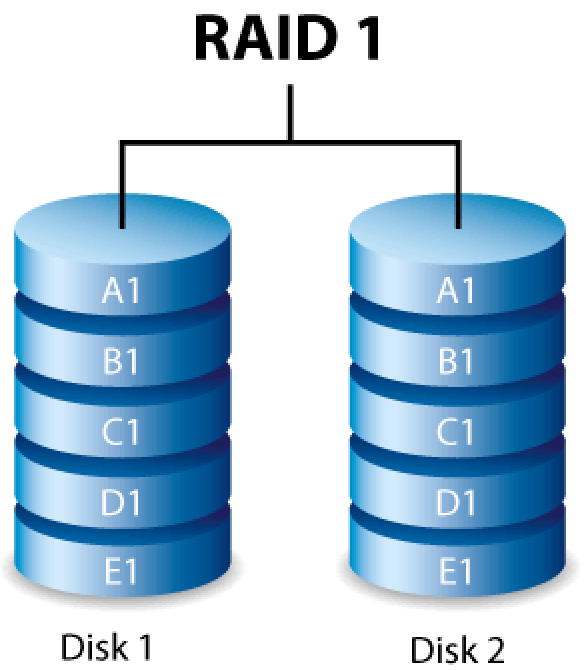
- Block-level striping, no redundancy
- Provides higher data-transfer rate
- Does not improve reliability. **Once a disk fails, data loss may happen (MTTF: mean time to failure)**

RAID 1

- How to improve reliability?

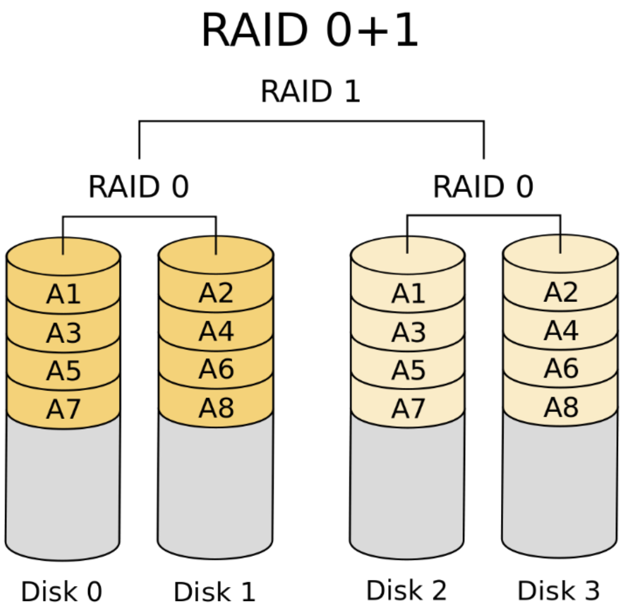
- Data mirroring (RAID1)
  - ✓ Two copies of the data are held on two physical disks, and the data is always identical.
  - ✓ Replication

- High storage cost
  - ✓ Twice as many disks are required to store the same data when compared to RAID 0.
  - ✓ Even worse storage efficiency with more copies



Combinations

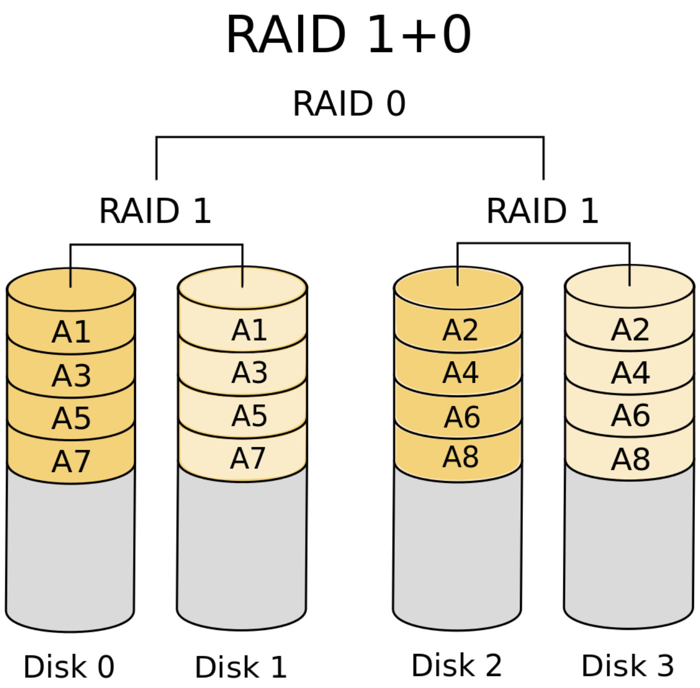
- RAID 0 provides reliability and RAID 1 provides reliability
- RAID 0+1 (RAID01)
  - ✓ First data striping
  - ✓ Then data mirroring



Same storage cost as RAID 1

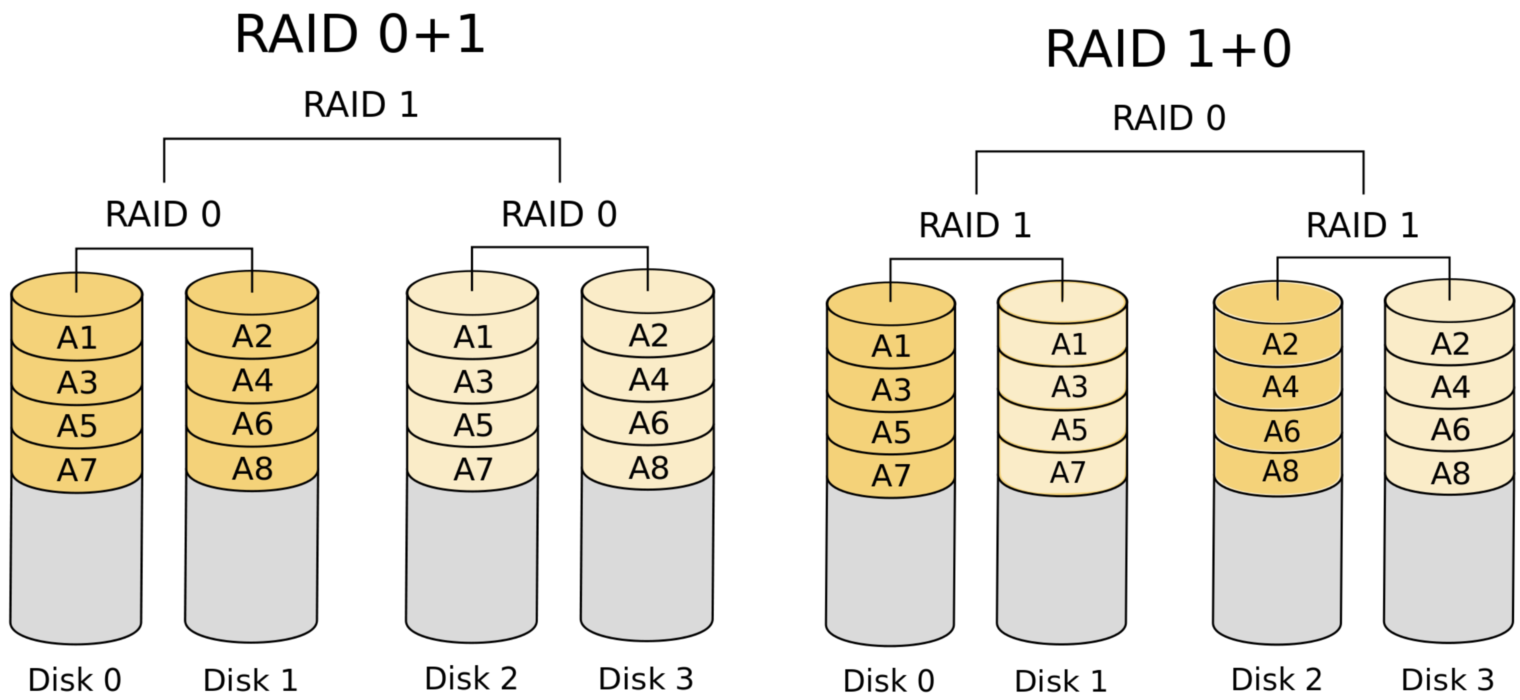
Combinations

- RAID 0 provides reliability and RAID 1 provides reliability
- RAID 0+1 (RAID01)
  - ✓ First data striping
  - ✓ Then data mirroring
- RAID 1+0 (RAID10)
  - ✓ First data mirroring
  - ✓ Then data striping



Same storage cost

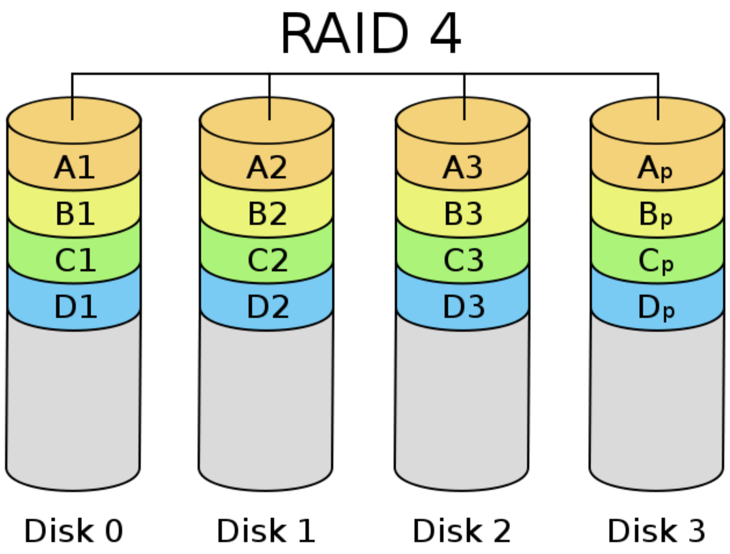
RAID01 vs RAID10



Both suffer from high storage cost

RAID 4

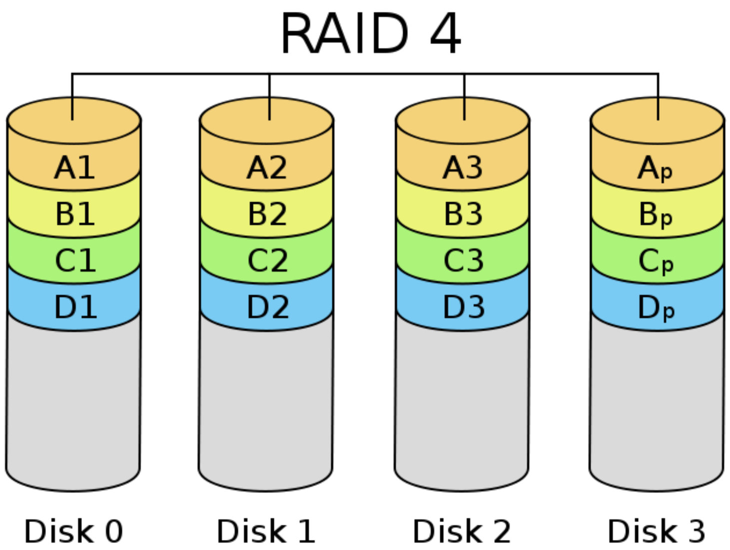
- Balance the tradeoff between reliability and storage cost?
  - Redundancy with parities
- **Parity generation:** Each parity block is the XOR value of the corresponding data disks
- **Block-level data striping**
  - Data and parity blocks are distributed across disks
  - Dedicated parity disk
- Any problem?



$$A_p = A1 \otimes A2 \otimes A3$$

How to update data

- Suppose A1 will be updated to A1'
  - Both A1 and Ap need to be updated
  - Read-modify-write (RMW)



RMW: $A_p' = A_p \otimes A1 \otimes A1'$

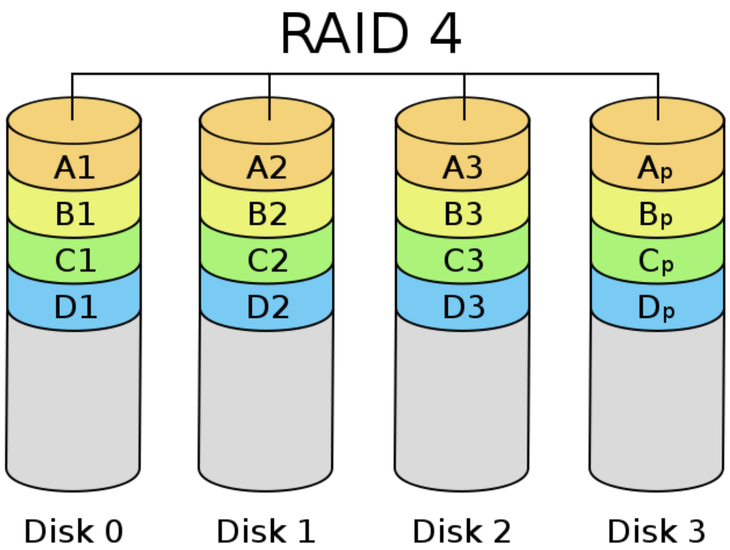
$$A_p{}' = A1 \otimes A2 \otimes A3 \otimes A1 \otimes A1'$$
$$= A2 \otimes A3 \otimes A1'$$

How to update data

- Suppose A1 will be updated to A1'
  - Both A1 and Ap need to be updated
  - Read-modify-write (RMW)

- How about updating both A1 and A2 simultaneously?
  - RMW?
  - Read-reconstruct-write (RRW)

- Selection of RMW/RRW

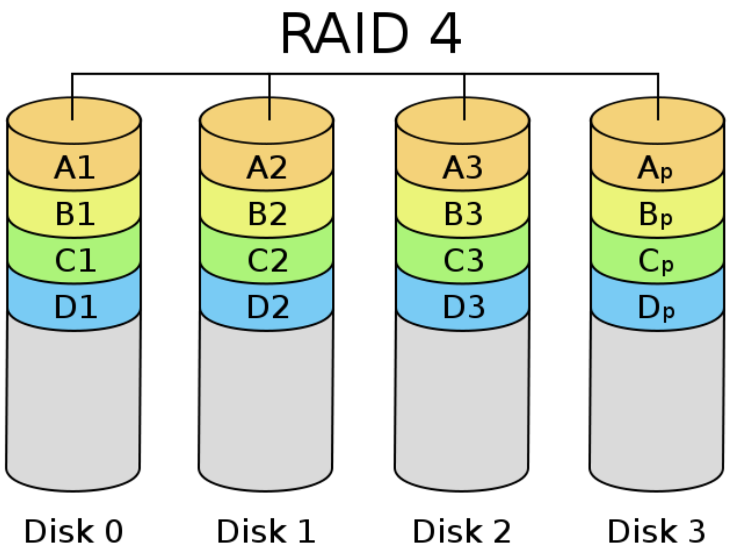


RRW: $A_p' = A3 \otimes A1' \otimes A2'$

Both RMW and RRW incur extra reads and writes

Problems of RAID 4

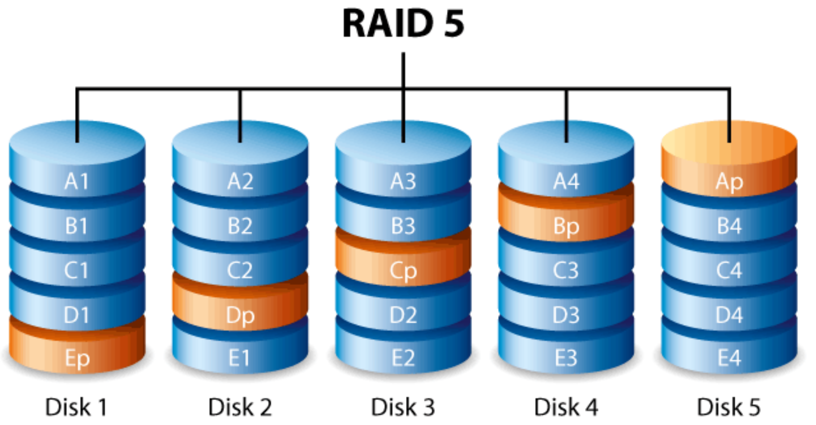
- Problems of RAID 4
- Disk bandwidth are not fully utilized
  - Parity disk will not be accessed under normal mode
- Parity disk may become the bottleneck
  - E.g., updating A1, B2, C3



Read: A1, B2, C3, **Ap, Bp, Cp**
Write: A1’ B2’, C3’, **Ap’, Bp’, Cp’**

RAID 5

- Similar to RAID 4
  - One parity per stripe
- Key difference
  - Uniform parity distribution
- RAID 5 is an ideal combination of
  - good performance
  - good fault tolerance
  - high capacity
  - storage efficiency



$$A_P = A_1 \oplus A_2 \oplus A_3 \oplus A_4$$

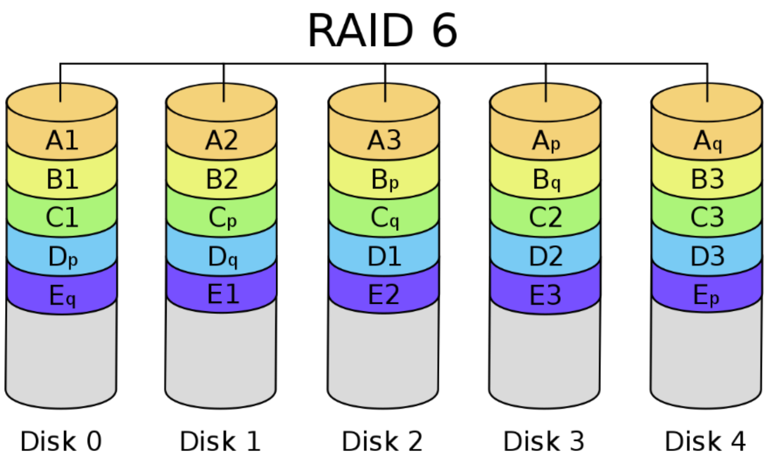
$$\vdots$$

$$E_P = E_1 \oplus E_2 \oplus E_3 \oplus E_4$$

Parity update overhead still exist

RAID 6

- How to tolerate more disk failures?
- RAID-6 protects against two disk failures by maintaining two parities
- Encoding/decoding operations:
  - Based on **Galois field**



$$A_P = A_1 \oplus A_2 \oplus A_3 \oplus A_4$$

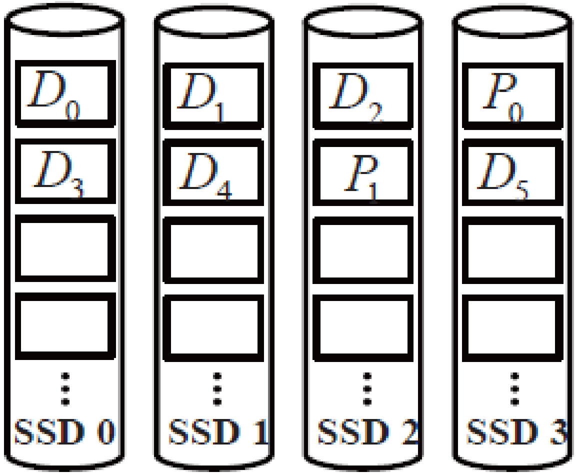
$$A_q = c^0 A_1 \oplus c^1 A_2 \oplus c^2 A_3 \oplus c^3 A_4$$

Parity update overhead becomes larger

Parity Update Overhead

- RAID provides device-level fault tolerance
  - Each stripe contains data and parity

- Limitation: Parity updates
  - Update data -> update parity
    - Update D_1 to D_1'
    - RMW: $P_0' = P_0 \oplus D_1 \oplus D_1'$
    - RRW: $\mathrm{P}_0' = \mathrm{D}_0 \oplus D_1' \oplus D_2$
  - Extra I/Os and GC



Parity chunks:
$P_0 = D_0 \oplus D_1 \oplus D_2$
$P_1 = D_3 \oplus D_4 \oplus D_5$

- SSD RAID
  - Parity update influences both performance and endurance

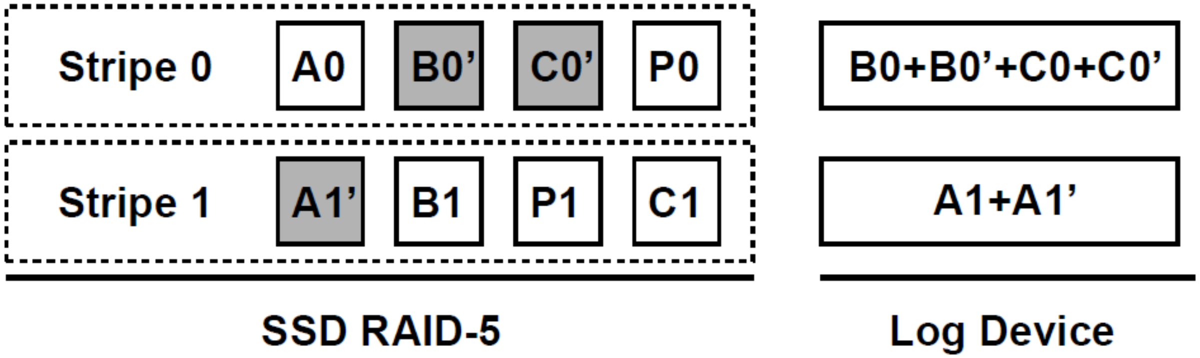
Design tradeoff

- Design trade-off in SSD RAID arrays
  - RAID improves reliability
  - Parity updates incur extra I/Os and GC operations
    - Degrade performance and endurance

How to address the parity update overhead?

Parity Logging

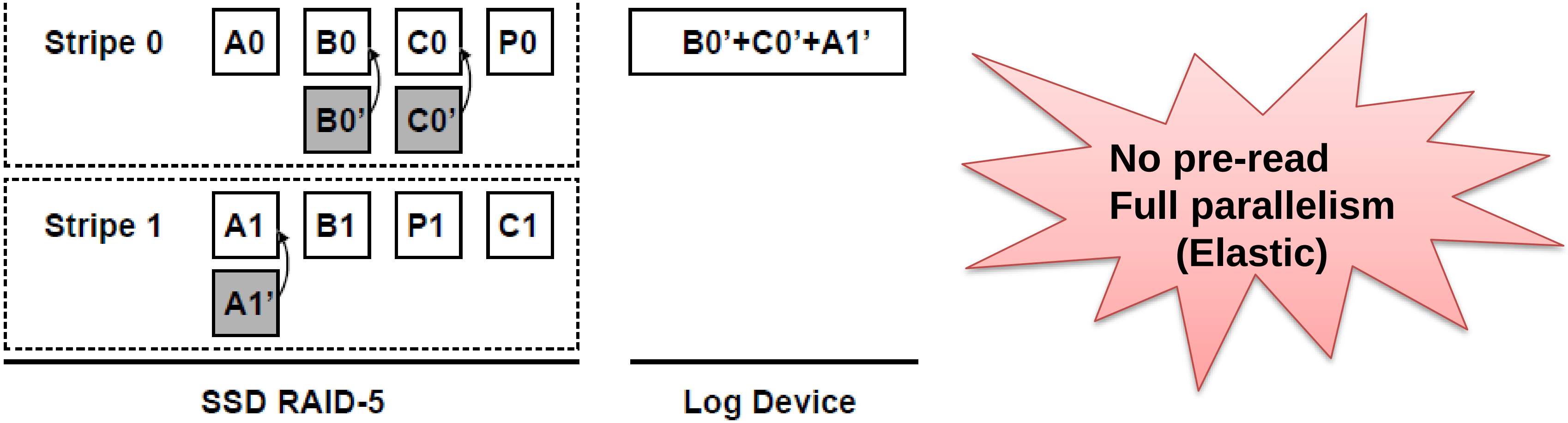
- Original Parity logging
  - Incoming reqs: $\{A_0, B_0, C_0\}$,$\{A_1, B_1, C_1\}$, $\{B_0', C_0', A_1'\}$



- Drawbacks
  - Pre-read: Extra reads
  - Per-stripe basis: Extra log chunks; Partial parallelism

EPLOG

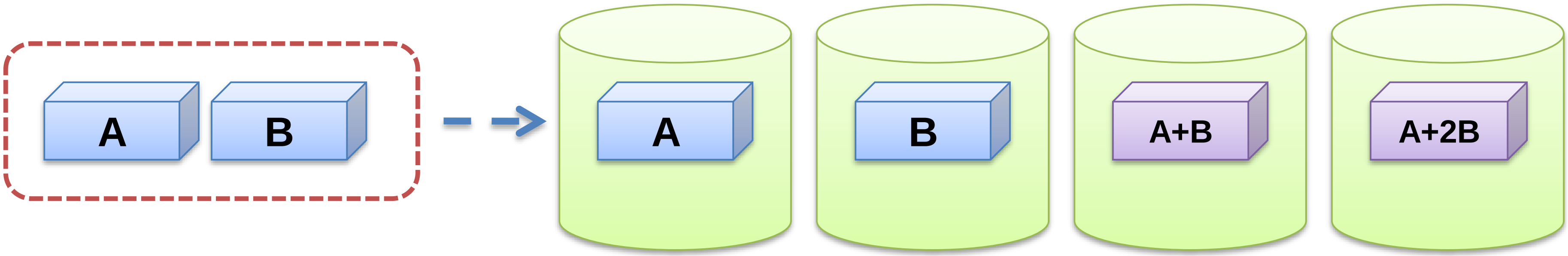
Our solution: New RAID Design via Elastic Parity Logging (EPLOG)



Tolerate any number of failures?

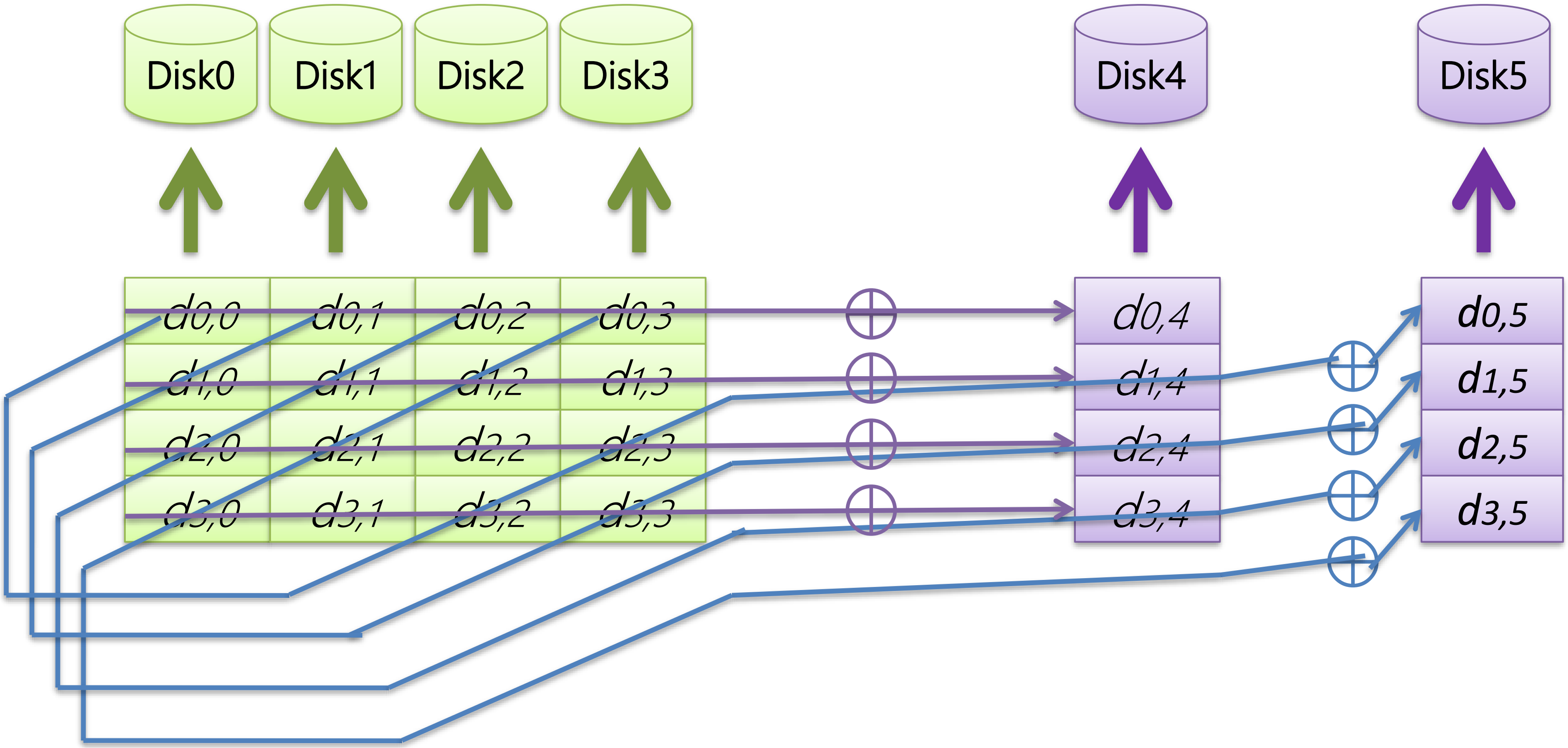
- Erasure codes
  - **General-fault tolerant**: Cauchy Reed-Solomon (CRS)

- Generate **m** code blocks from **k** data blocks, so as to tolerate any **m** disk failures



XOR-based Codes

- **2-fault tolerant**: RDP, EVENODD, X-Code
- An RDP code example with 6 disks



Summary on Erasure Codes

- The motivation to introduce erasure codes in large-scale storage systems

The need to reduce the tremendous cost of storage

- In practice, erasure codes have seen widely deployment in past decade
  - Google File System [Ford, OSDI'10]
  - Windows Azure Storage [Huang, ATC'12]
  - Facebook [Borthakur, Hadoop User Group Meeting 2010]
  - …
- Research topics： wide stripes, EC in disaggregated mem…

Summary of Ch8

Disk Structure

Disk Scheduling

- ✓ Cylinder, Track, Sector: CLV, CAV
- ✓ Access time
- ✓ FCFS, SSTF, SCAN/C-SCAN, LOOK/C-LOOK

SSD Structure

SSD Features/Issues

- ✓ Structure and features
- ✓ Operations (read/write/erase/GC)

RAID

Erasure Coding

- ✓ RAID structures (RAID0, 1, 4, 5, 6)
- ✓ Erasure coded storage