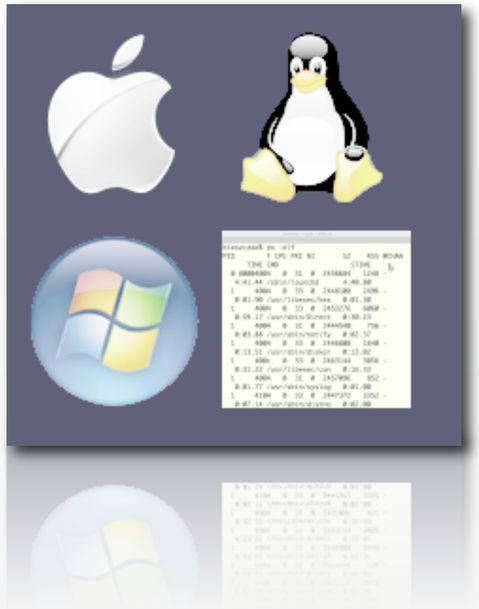


Lecture 13: Mass-Storage Systems

COMP362 Operating Systems
Prof. AJ Bieszczad

Outline

- Location of Mass-Storage Media
- Magnetic Disks
  - Structure
  - Scheduling
- Solid State Drives
- Performance Issues
- Trends in Costs
- RAID Structure

Classification of Storage

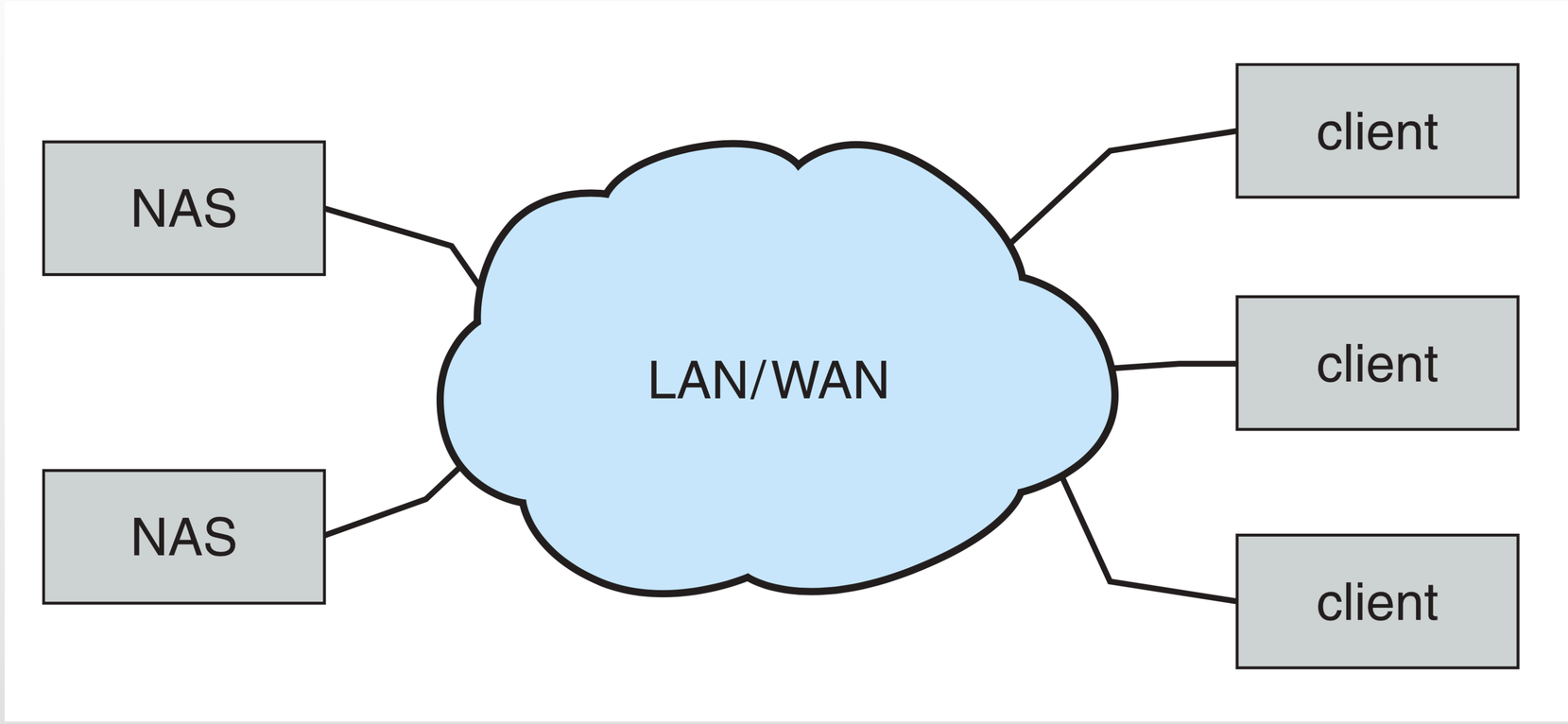
- Function
  - **primary** - computer memory directly accessed by CPU during computation
  - **secondary** - memory indirectly accessible to CPU by copying to and from the primary storage
  - **tertiary** - backup; accessible to CPU (still indirectly) after loading to secondary storage
- Access
  - **online** - available at once
  - **nearline** - available after some automated action executed
    - e.g. a robot arm inserts a tape into a reader
  - **offline** - available only after human intervention
- Location
  - **directly-attached** (**DAS**)
    - a.k.a. **host-attached**
  - **network-attached** (**NAS**)
  - **storage area network** (**SAN**)
    - attached through a switching fabric
  - **cloud**
    - managed at the application rather than OS level
    - some OS “hooks” needed for advanced features like automatic syncing

Directly Attached Storage (DAS)

- Host-attached storage accessed through **I/O ports** and **I/O buses**
- **ATA** (**Advanced Technology Attachment**) is older parallel interface
  - also called **IDE** (Integrated Drive Electronics)
  - also **ATAPI** (**ATA Packet Interface**) for non-HD devices
    - e.g., add eject command
- **SATA** is newer serial interface (**Serial ATA**)
  - also external **eSATA**
- **USB** (**Universal Serial Bus**)
  - **USB-C** increasingly popular
  - v3.1 up to 10 Gbps
- **SCSI** (pronounced scuzzy) **Small Computer System Interface**
  - a bus, up to 16 devices on one cable (initially parallel; recently serial; iSCSI uses IP)
  - uniform interface
  - mostly on high end systems, servers
- **FC** (**fiber channel**) is high-speed serial architecture
  - can be attached to a switched fabric with 24-bit address space
    - the basis of storage area networks (SANs) in which many hosts attach to many storage units
  - can also be attached to an **arbitrated loop** (**FC-AL**) of 126 devices
- **Thunderbolt**
  - daisy-chain up to 6 devices
  - up to 3 m copper and 100 m optical
  - originally optical; switched to copper for cost and ability to supply power

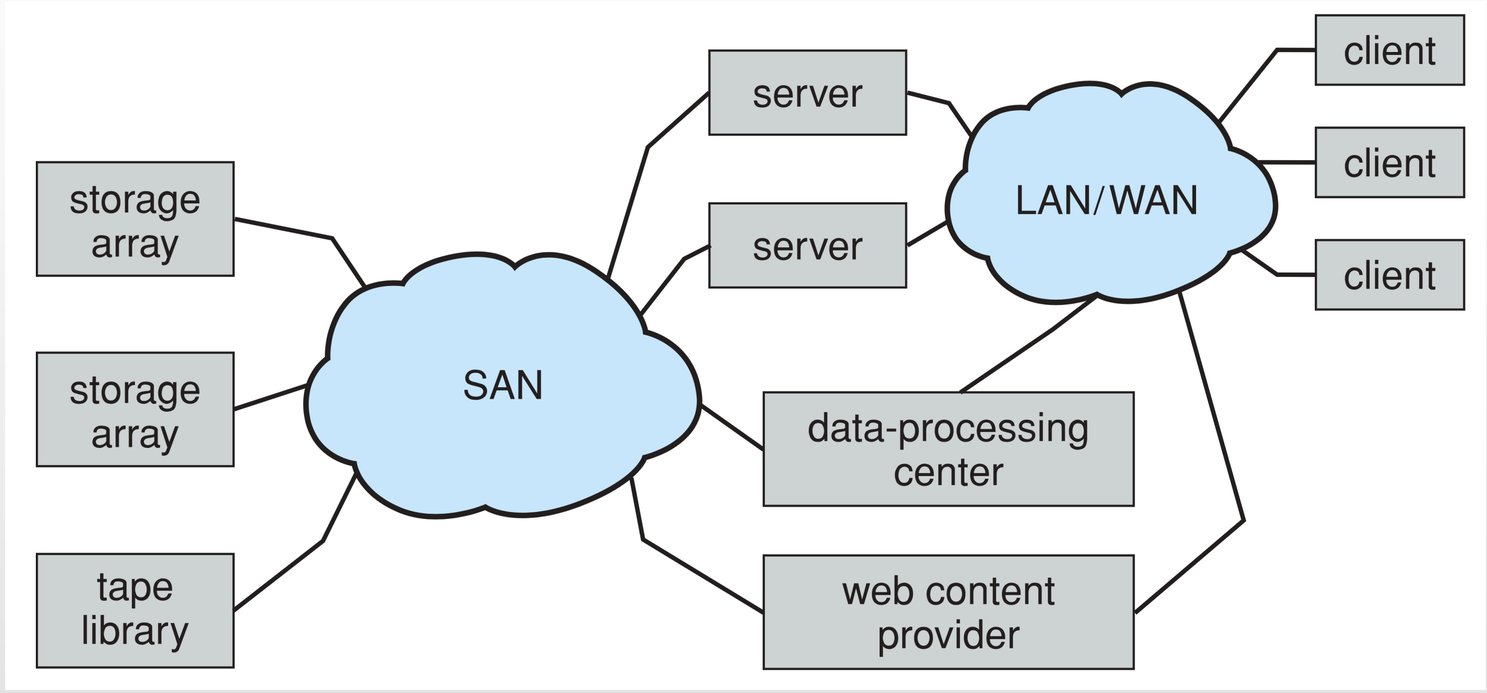
Network-Attached Storage (NAS)

- File-level storage made available over a network rather than over a local connection (such as a bus)
  - clients read/write files on remote computers
- Uses network access protocols
  - **NFS** historical
  - **CIFS/SMB** are common protocols
  - **AFP** in Mac world
- Implemented via **remote procedure calls** (**RPCs**) between local host and storage host
- **iSCSI** protocol uses IP network to carry the SCSI protocol



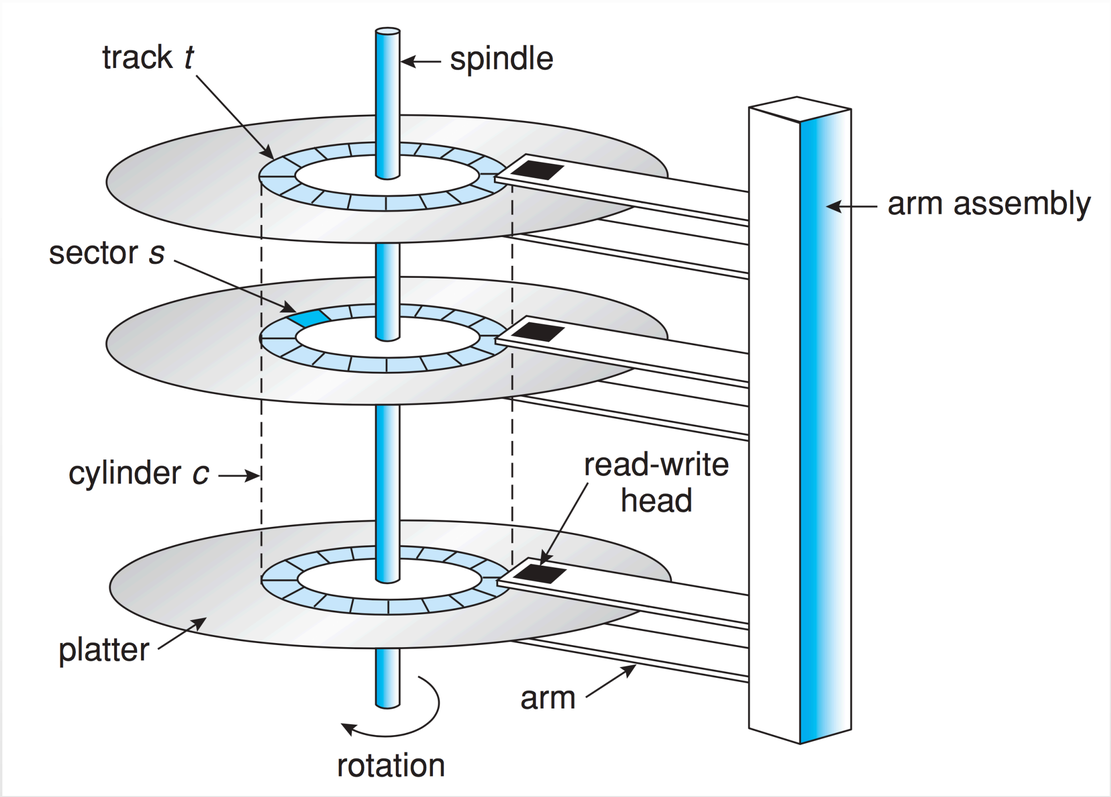
Storage Area Network (SAN)

- Block-level storage common in large storage environments
  - blocks are read/written rather than files
- Multiple hosts attached to multiple storage arrays
  - very flexible
    - for example, can provide storage utility (storage on-demand)
- Attached devices appear as local
  - uses local rather than network access protocols



Magnetic Disks

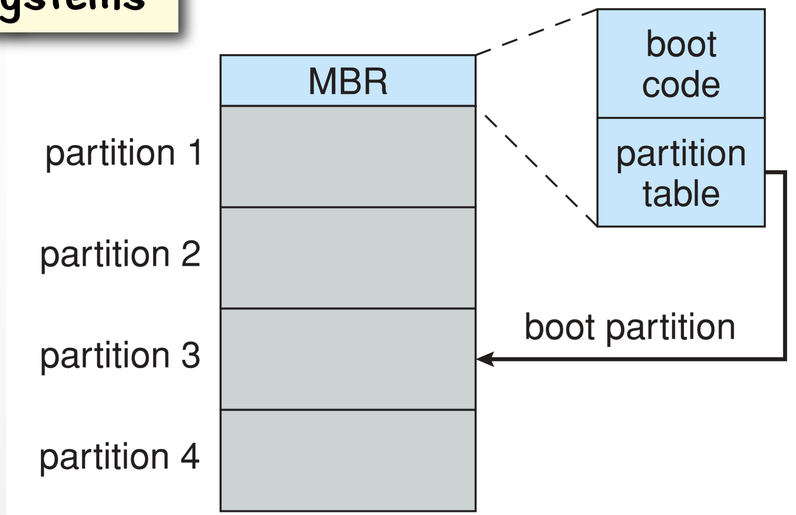
- Although solid state memory is becoming more common, magnetic disks still provide bulk of secondary storage of modern computers
  - drives rotate at 60 to 200 times per second
    - 5400 rpm, 7200 rpm, 10,000 rpm, etc.
  - **transfer rate** is rate at which data flow between drive and computer
  - **positioning time** (random-access time)
    - time to move disk arm to desired cylinder (**seek time**) and
    - time for desired sector to rotate under the disk head (**rotational latency**)
  - head crash may occur as a result of disk head making contact with the disk surface
- Disks can be removable
- Drive attached to computer via I/O bus
  - buses vary, including EIDE, ATA, SATA, USB, Thunderbolt, Fiber Channel, SCSI
  - host controller in computer uses bus to talk to disk controller built into drive or storage array



Disk Management

- Physical/Low-level formatting
  - dividing a disk into blocks that the disk controller can read and write
  - usually a block is the size of a sector
- To use a disk to hold files, the operating system still needs to record its own data structures on the disk
  - divide the disk into one or more partitions
  - logical formatting or “making a file system”

Non-EFI Systems



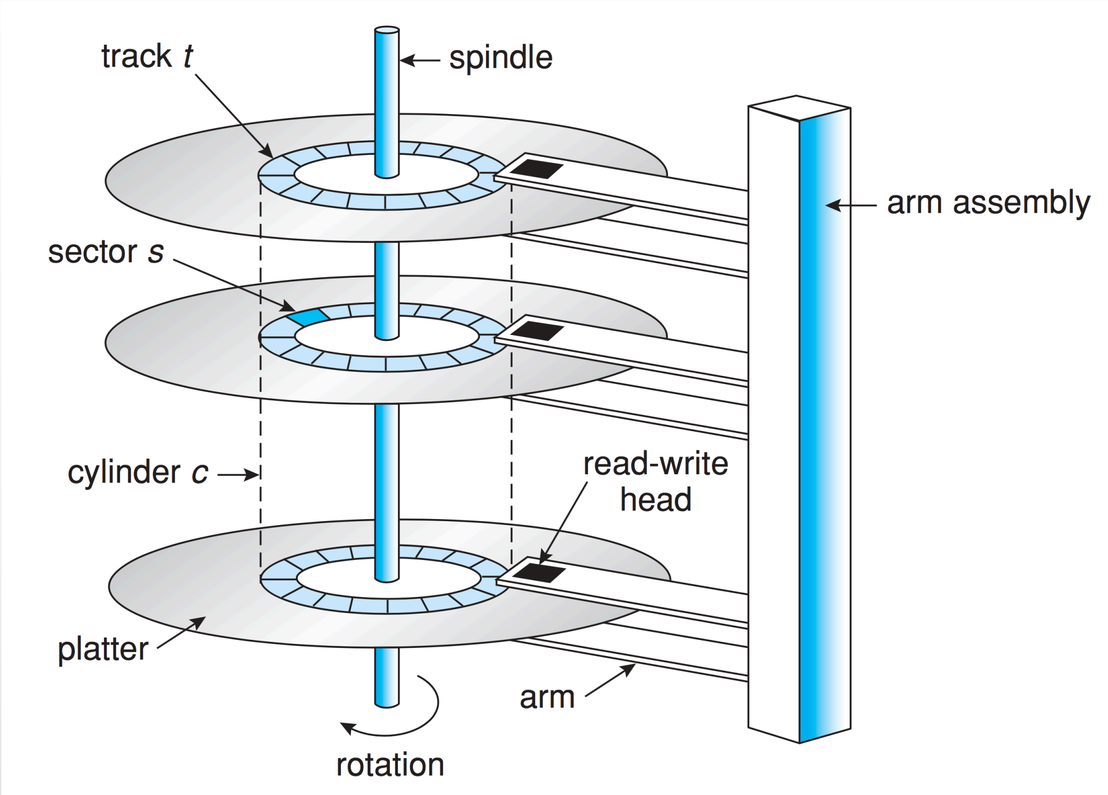
- Boot block holds code that initializes system
  - bootstrap loader is stored in ROM,
    - loads actual bootstrap from disk

Similar ideas at a cell level in SSDs

- Methods such as sector sparing or sector slipping used to handle bad blocks:
  - **sparring** replaces bad sectors with pre-arranged spares
  - **slipping** rewrites (slips) chunks of disk to create spares adjacent to bad sectors

Disk Structure

- **Cylinder-head-sector** (**CHS**)
  - historical organization of discs that reflected internal disk structure
  - originally built into system architecture (BIOS), and still used in some utilities
  - does not map well onto new media
- **Logical block addressing** (**LBA**)
  - since ATA-6 disk drives are addressed as large one-dimensional arrays of logical blocks, where the logical block is the smallest unit of transfer.
  - no guarantees, but the block-to-CHS mapping tends to be sequential



Disk Structure

- The one-dimensional array of logical blocks is mapped into the sectors of the disk sequentially.
  - sector 0 is the first sector of the first track on the outermost cylinder
  - mapping proceeds in order through that track, then the rest of the tracks in that cylinder, and then through the rest of the cylinders from outermost to innermost
    - not necessarily in order, as tagging sequential numbers sparsely may speed up access

	72	73	74	75	76	77	78	79
0	1	2	3	4	5	6	7	
8	9	10	11	12	13	14	15	
16	...							
24	...							
32	...							
40	...							
48	...							
56	...							
64	...							

Simplified!

cylinders

May not be as regular as shown, since blocks might be assigned in a variety of ways; e.g., to deal with bad sectors, sector density, etc. Also, sectors in outer cylinders might have more capacity.

Disk Scheduling

- The operating system is responsible for using hardware efficiently
  - for the disk drives, this means having a fast access time and high disk bandwidth
- Maximizing **disk bandwidth** is one of the objectives
  - this is the total amount of data transferred, divided by the total time between the first request for service and the completion of the last transfer.
- OS tries to minimize seek time
  - seek time ≈ seek distance (is proportional)
  - OS aggregates requests and reorders them to optimize disk access

As we already discussed, access time has two major components: seek time and rotational latency.
The rotational latency is determined by the disk manufacturer and cannot be controlled by the OS

- A number of algorithms exist to schedule the servicing of disk I/O requests.
- On the following slides, we illustrate the algorithms with a request queue for a disk with 200 tracks (0-199).

Disk Scheduling: First Come First Serve (FCFS)

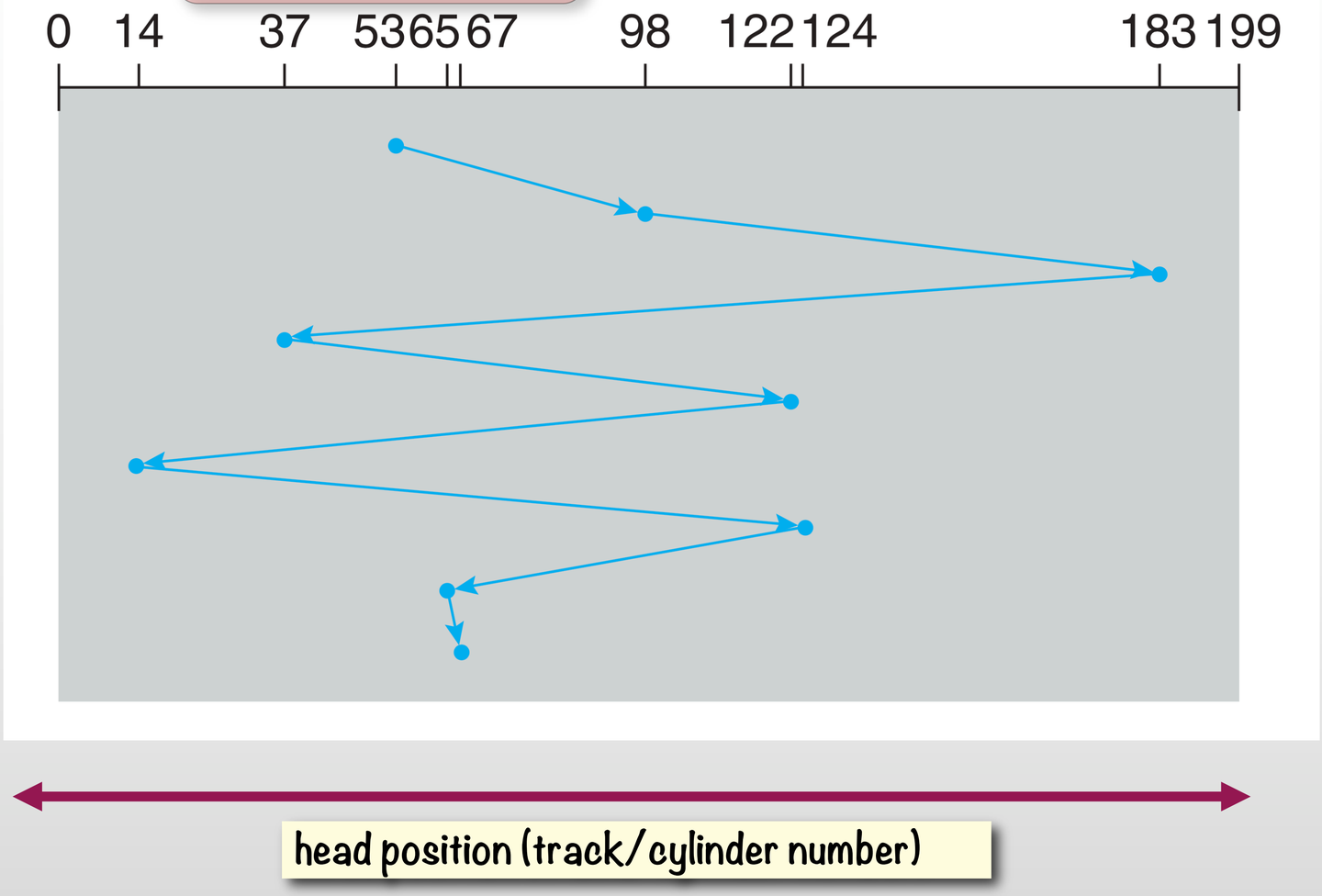
the OS received the following aggregated list of disk access requests

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

head starts at 53

- Illustration shows total head movement of 640 cylinders.

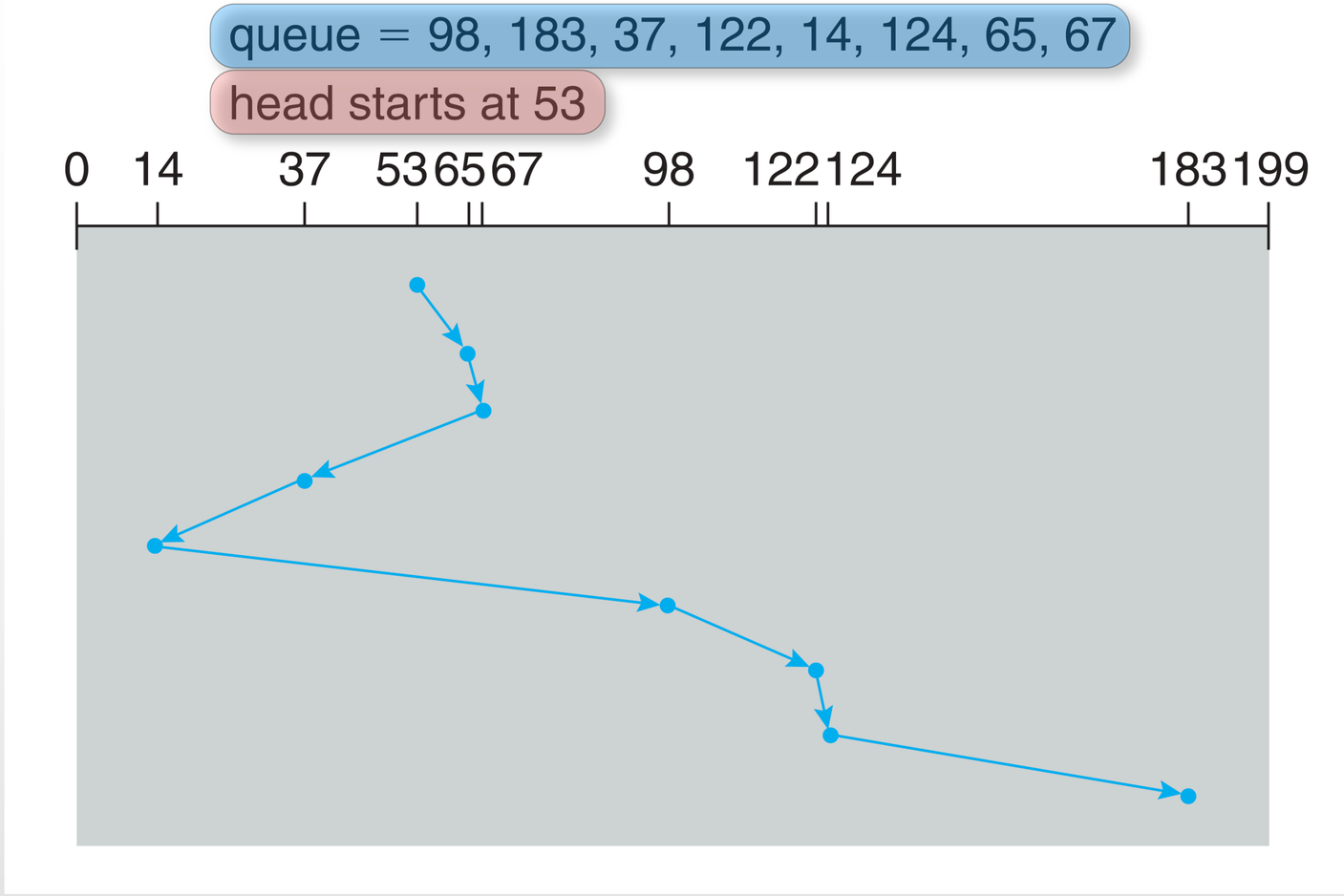
a measure of movement efficiency



- a.k.a. FIFO
- a.k.a. NOOP

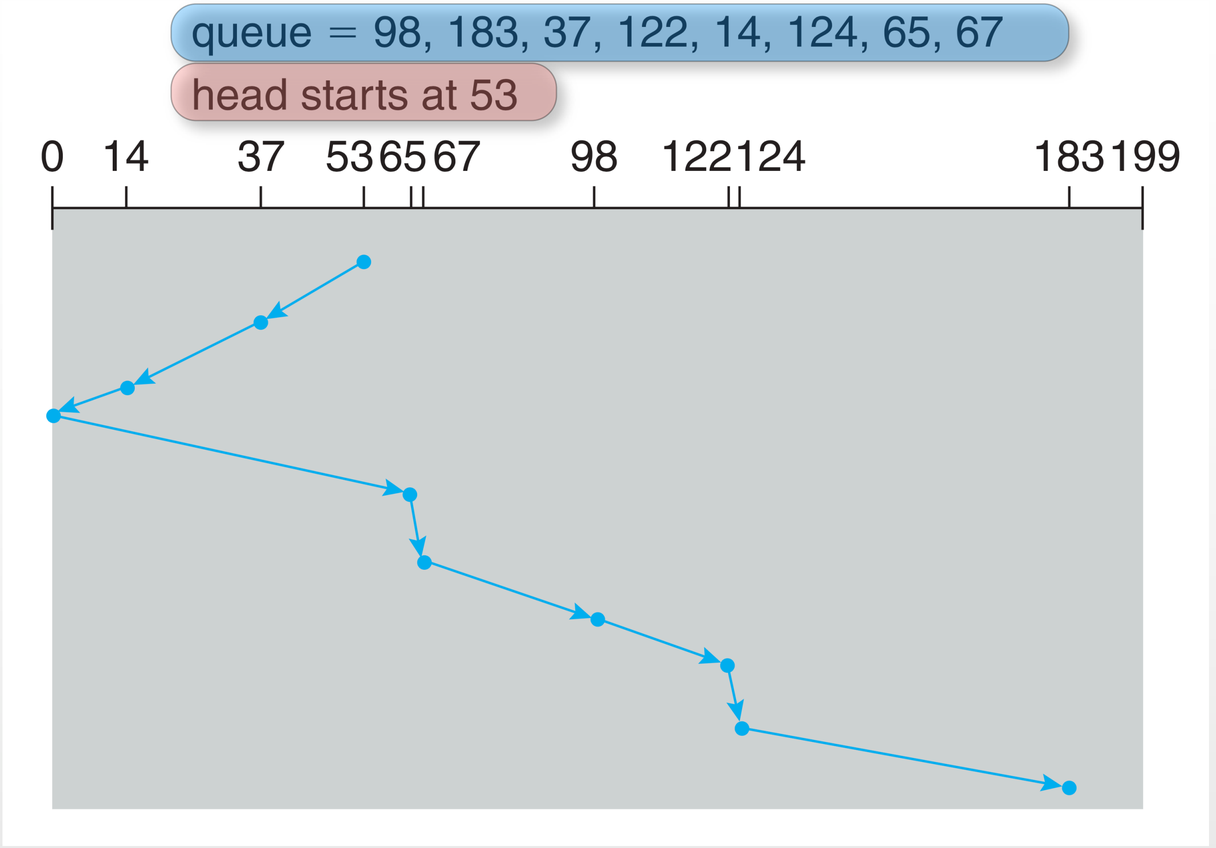
Disk Scheduling: Shortest Seek Time First (SSTF)

- Selects the request with the minimum seek time from the current head position.
- SSTF scheduling is a form of shortest job first (SJF) scheduling
  - this is a greedy algorithm, so it may cause starvation of some requests.
- Illustration shows total head movement of 236 cylinders.



Disk Scheduling: SCAN (a.k.a. Elevator Algorithm)

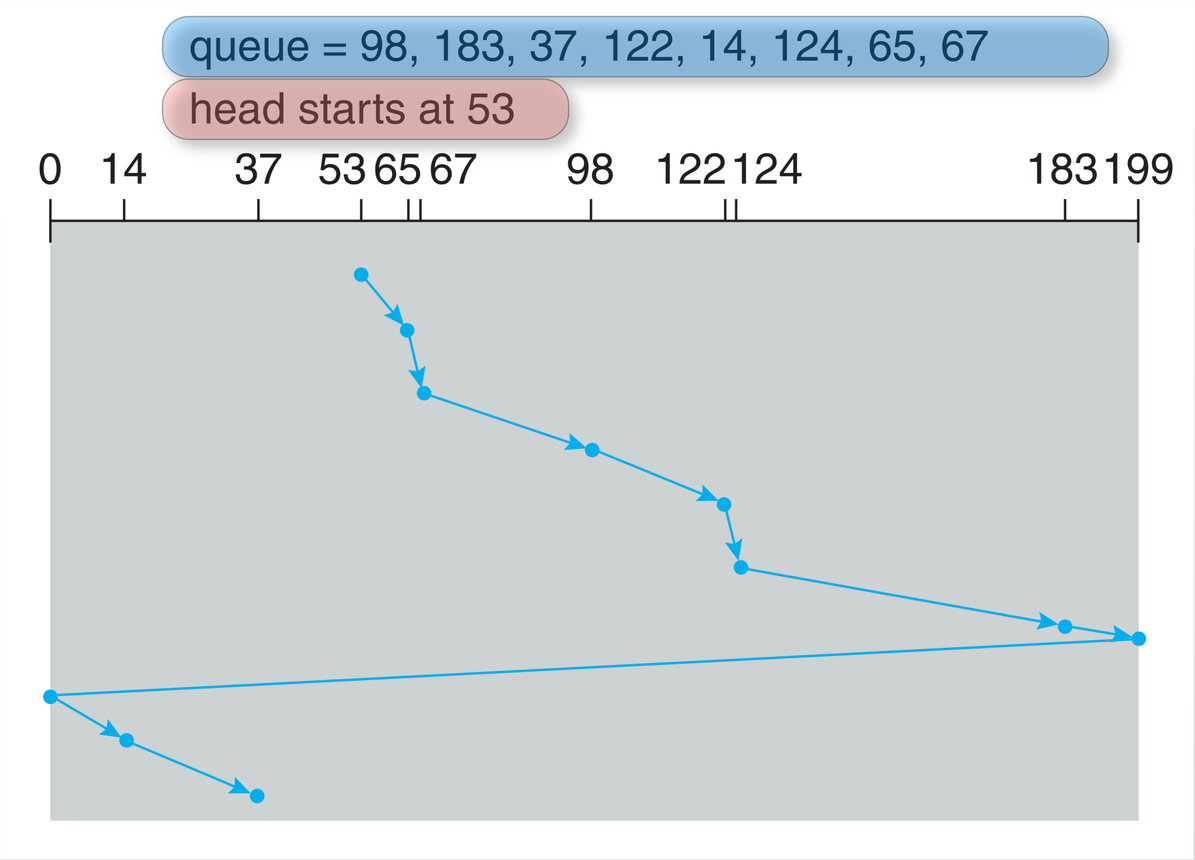
- SCAN -- acronym from scanning tracks
- The idea is to minimize changes of direction
  - sweep one way, then the other, and so on
- The disk arm starts at one end of the disk, and moves toward the other end, servicing requests until it gets to the other end of the disk, where the head movement is reversed, and servicing continues.
- A.k.a. elevator algorithm.
  - why?
- Illustration shows total head movement of 236 cylinders



- Favors recently “visited” sectors
  - usually not the best approach as it checks for the requests at the end that was just recently checked

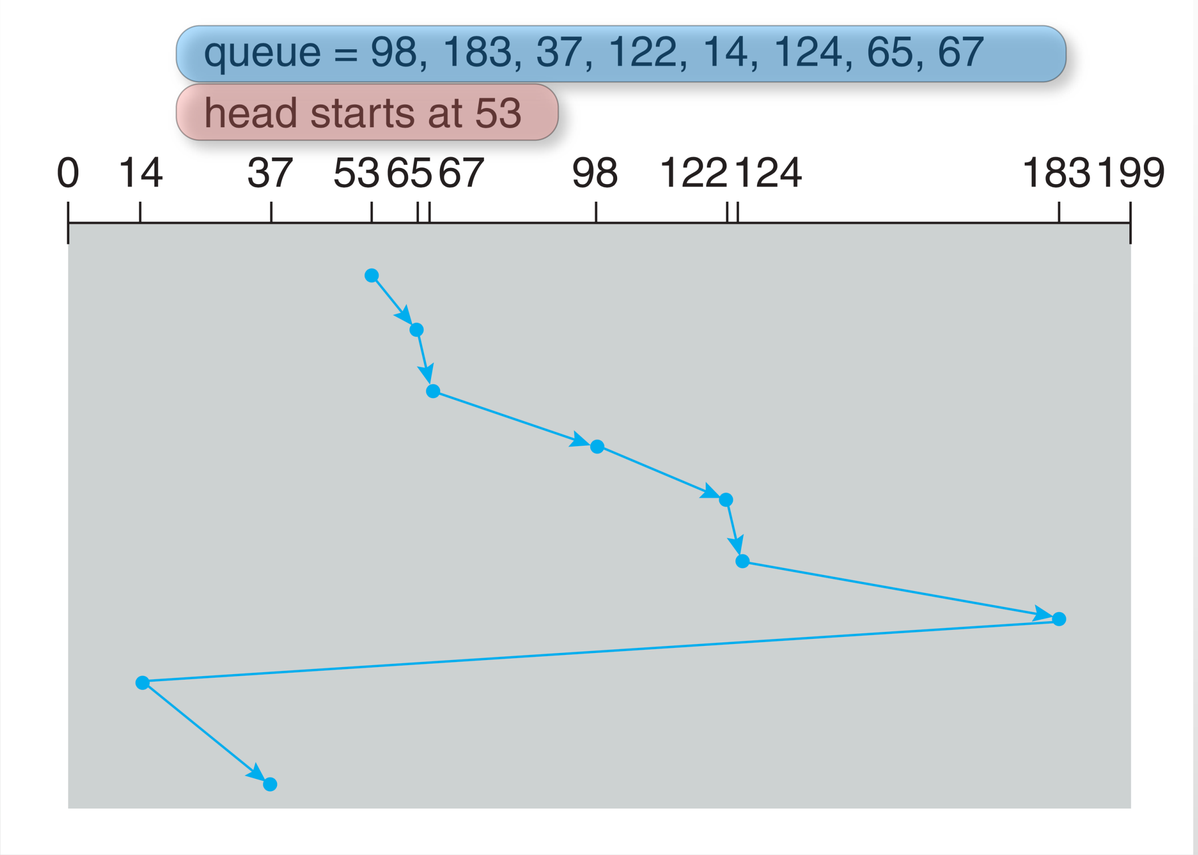
Disk Scheduling: Circular SCAN (C-SCAN)

- The head moves from one end of the disk to the other servicing requests as it goes. When it reaches the other end, however, it immediately returns to the beginning of the disk, without servicing any requests on the return trip.
  - this technique provides a more uniform wait time than SCAN
- Treats the cylinders as a circular list that wraps around from the last cylinder to the first one.
- Illustration shows total head movement of 183 cylinders.
  - without counting the return



Disk Scheduling: LOOK and C-LOOK

- LOOK is a version of SCAN in which the arm only goes as far as the last request in each direction, then reverses direction immediately, without first going all the way to the end of the disk.
  - improvement from 236 to 208 cylinders
- C-LOOK is a version of C-SCAN with similar scanning border policy
  - Illustration shows total head movement of 153 cylinders (C-LOOK).



OS Disk Scheduling vs. Disk Controller Scheduling

- **Q:** Why not have driver controller do all the scheduling?
  - e.g., could be more efficient; some controllers do exactly that
  - however…
- **A:** OS knows about constraints that the disk doesn't
  - for example:
    - demand paging takes priority over application I/O
    - writing is more important than reading if the cache is almost full
    - OS may need guaranteed write ordering
      - e.g. journaling, data flushing

- Hard to address rotational latency from the OS
  - disk controllers perform some optimization
    - e.g., request ordering, coalescing (aggregating), sector numbering schemes

Linux I/O Schedulers

- **NOOP**
  - no optimization (**none**); all is FCFS
  - good for non-rotational media
- **Linus Elevator** (default in 2.4 kernel)
  - merges adjacent requests and sorts request queue by block (sector) number
  - may lead to starvation of requests with large block numbers
- **Deadline**
  - employs multiple queues to minimize seeks while ensuring requests don't starve
    - adds expiration timer to requests
    - expired requests move from elevator to expired queue
    - process requests from the deadline queue sorted by expiration time
    - if deadline queue empty, then use the elevator queue sorted (still sorted by block numbers)
- **Anticipatory**
  - acts like deadline scheduler, but pauses for a few milliseconds after a read request to see if another request is made from nearby blocks
    - addresses the deceptive idleness syndrome
      - a program may be processing the read data before asking for more reads from following sectors
    - if prediction is correct, the gain in efficiency is substantial, while the loss is small
- **Completely Fair Queueing** (**CFQ**)
  - maintains a queue for each process
  - queues are serviced round-robin, usually picking 4 requests from each queue at a time
- **mq-deadline**
  - deadline specialized for multi-core
  - the only no-noop option in Linux kernel 5.x

```
root@aj:/home/aj# cd /sys/block/sda/queue/
root@aj:/sys/block/sda/queue# cat scheduler
[mq-deadline] none
```

- When to use which?
  - Deadline - good for lots of seeks, critical workloads
  - Anticipatory - good for servers
  - CFQ - good for desktops, multimedia (e.g., ensuring audio buffers are full)
- Used to be fairly easy to change a scheduler, but it is quite complicated now:

https://wiki.ubuntu.com/Kernel/Reference/IOSchedulers

Sorting I/O Requests

- Sorting can be done by:
  - name/path
    - usually, blocks (sectors) allocated for a file are close to each other
    - fast, but approximate
  - inode (a.k.a. file descriptor)
    - usually: for **i** < **j**, data block numbers of a file with inode **i** are smaller than data block numbers of a file with inode **j**
    - faster; still approximate
  - block number
    - obtain all blocks of a file, and then group I/O operations for contiguous sequences
    - accurate, but slowest

```
fstat (fd, &buf);
// use buf.st_ino for sorting
```

```
fstat (fd, &buf);
// number of file blocks buf.st_blocks
// get block number for each subsequent
// block in the file
for (int i = 0; i < buf.st_blocks; i++) {
  int block_num = i;
// block_num is an in-out parameter
// FIBMAP requests FIle Block MAPping
  ioctl (fd, FIBMAP, &block_num);
// then, use the use block_num for sorting
}
```

Solid State Drives

- Utilize the solid-state memory
  - use non-volatile flash memory
    - flash drives have usually some small DRAM that is used for caching, swap file, etc.
- Emulate interface to hard drives
  - can be accessed through “standard” hard drive interfaces (e.g., SATA)
- Use similar logical organizational structures to hard drives
  - e.g., paging, RAID (see later slides)
- Good
  - faster to start, read and write
    - with DRAM cache
  - no noise, spin
  - mechanical reliability (SLC better than MLC; single- vs. multi-level cell)
  - file fragmentation not a problem due to the direct access to any location
  - problems usually happen on writes, so writes can be repeated in good cells
  - less power usually
    - higher power consumption on SSDs with DRAM caches
- Bad
  - still expensive
  - still relatively low capacity
  - limited write cycles (up to 10,000 for MLC, and 100,000 for SLC)

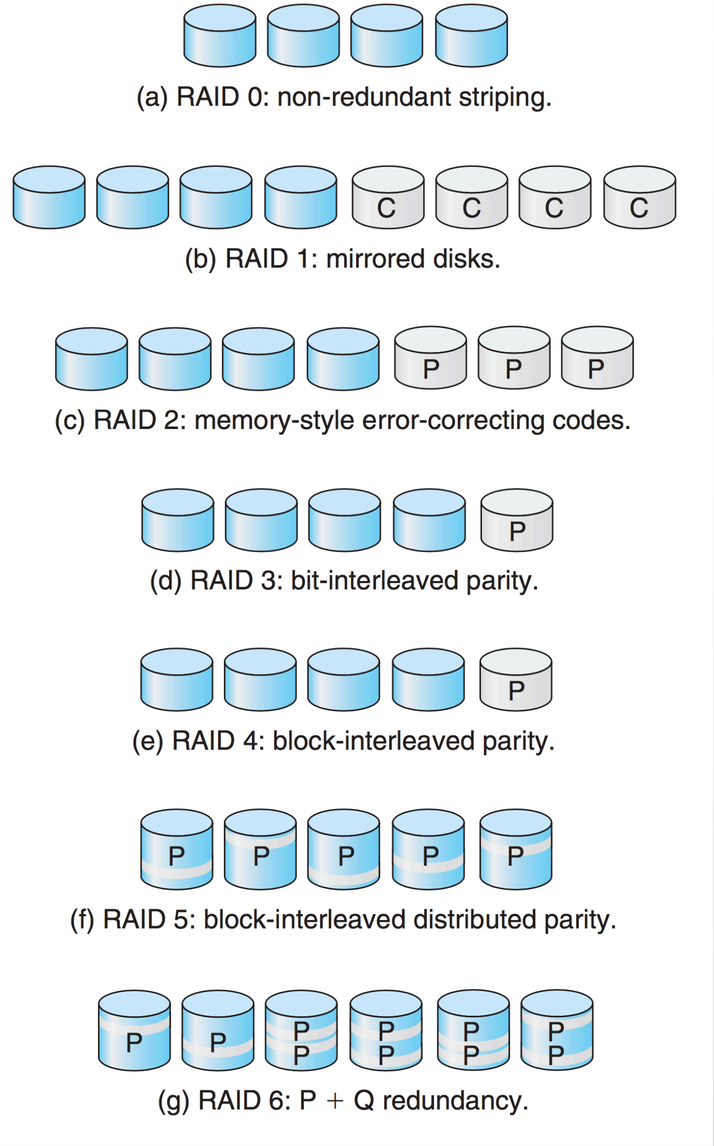
one bit per cell
⇛ 0 or 1

usually 4 levels
⇛ equivalent of two bits
⇛ lower cost per bit

⇛ **LESS RELIABLE!**

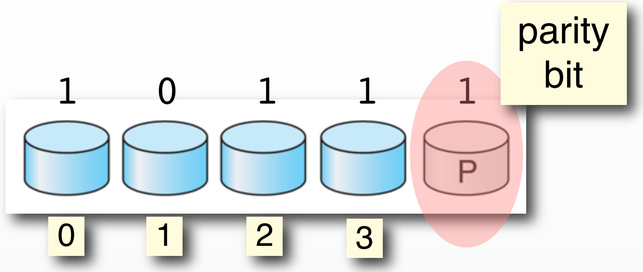
Improving Efficiency and Reliability of Storage

- **RAID** (**Redundant Array of Independent Disks**)
- RAID schemes improve performance and improve the reliability of the storage system by storing redundant data
  - mirroring or shadowing keeps a duplicate of each disk
  - block interleaved parity uses much less redundancy, but still may allow for recovery from errors
- RAID specifies six ways to arrange multiple disks
  - disk striping uses a group of disks as one storage unit
    - improves disk usage (balancing)
    - improves efficiency (concurrent access)
- RAID can be implemented by the OS or as a hardware controller



Error Correcting Codes (ECC)

- Bit striping distributes data among a number of disks. Why bother?
- Let's say we want to store 1011
  - we compute the even parity for the four bits ➔ 1
    - could also use odd parity
  - we store each bit on a separate disk



- If - let's say - disk 2 fails, we read: 10x11
- Since we know what the parity is, we compute that x must be 1
  - if x was 0, then the parity would be 0 and not 1

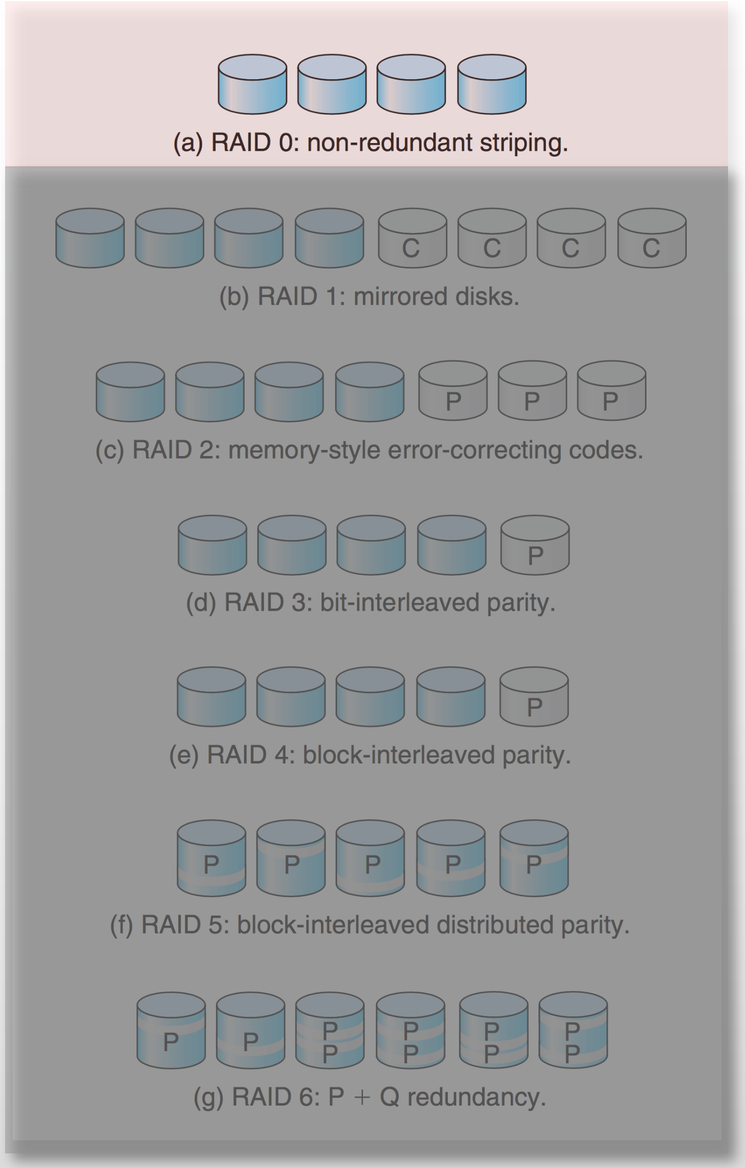
- This is an example of an **error-correcting code** (**ECC**)
  - extremely important in any data communication
- This ECC can correct only 1-bit errors

- More bits can be used for better correction capabilities
  - multidimensional parity, for example

RAID Level 0

- Block (rather than bit) **striping** between several disks
  - block 0 ➔ disk 0
  - block 1 ➔ disk 1
  - …
  - block k - 1 ➔ disk k - 1
  - block k ➔ disk 0
  - block k + 1 ➔ disk 1
  - …
  - block n ➔ disk n % k
  - …

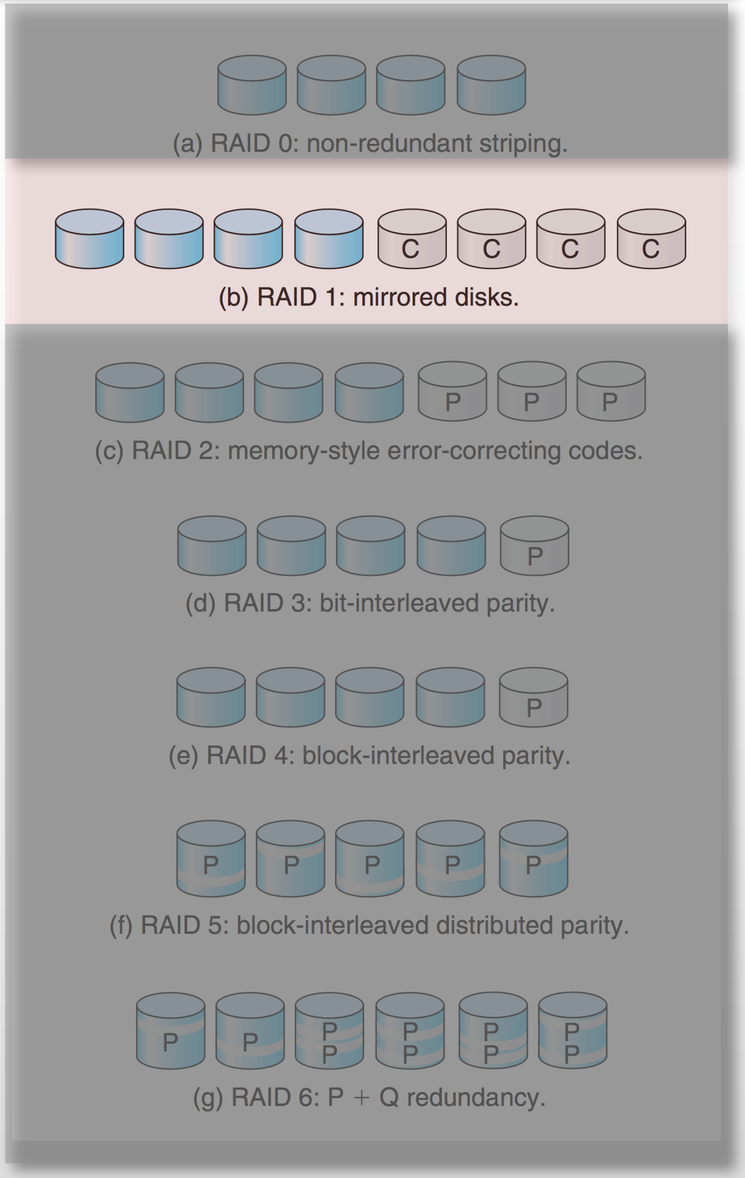
- No redundancy
- No error recovery (so: back up!)
- But... fast access
  - can read k blocks concurrently in parallel



RAID Level 1

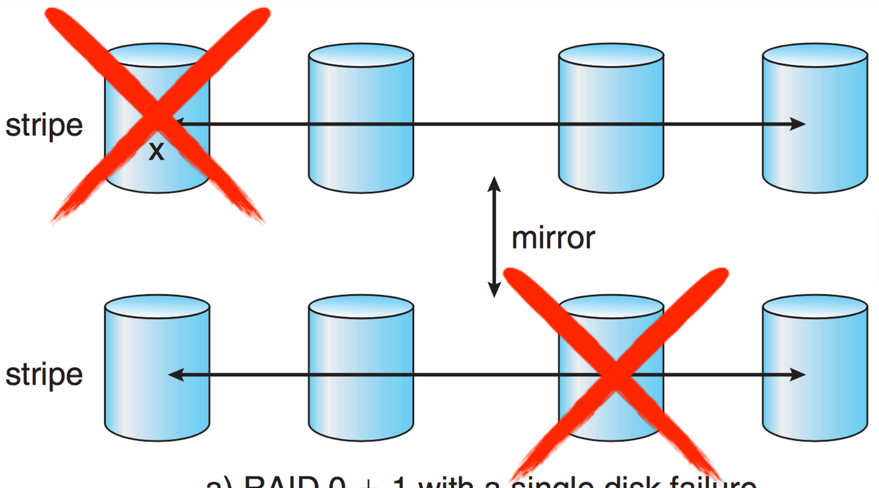
- Complete **mirroring**
- Best redundancy
  - for failures, and not mistakes!
    - if you delete, then it's deleted from both disks: the main and the mirror
  - but
    - if one of the two shadows fails, then the other has a complete mirror
  - to recover
    - replace the broken disk
    - replication process restores the data
- Can be combined with striping
  - 0 + 1
  - 1 + 0
  - see next slide

hot swappable controllers available



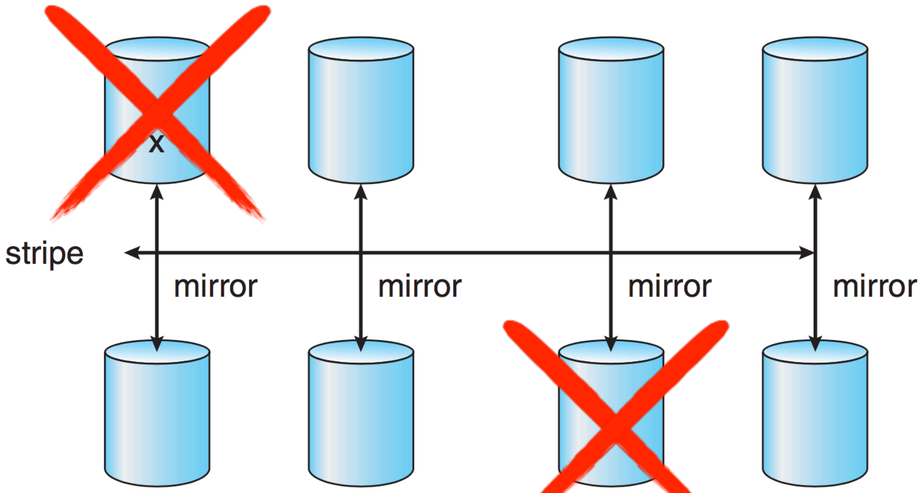
RAID (0 + 1) and (1 + 0)

- RAID (0 + 1)
  - stripe, then mirror
- RAID (1 + 0)
  - mirror, then stripe
- RAID (1 + 0) a bit better when a disk fails
  - the whole stripe is still available, since each of its elements works as a pair
    - replication to a new disk might be done with disk array online
    - resistant to some-two disk failures
  - in RAID (0 + 1) if a disk fails, then the whole stripe is unusable
    - it will be usable after replication to a new disk
    - the whole RAID lost if two disks fail on each side of the mirror



FAILED

a) RAID 0 + 1 with a single disk failure.

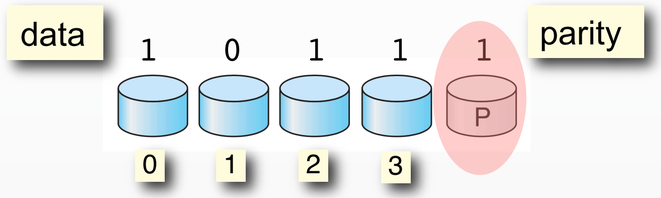


OK

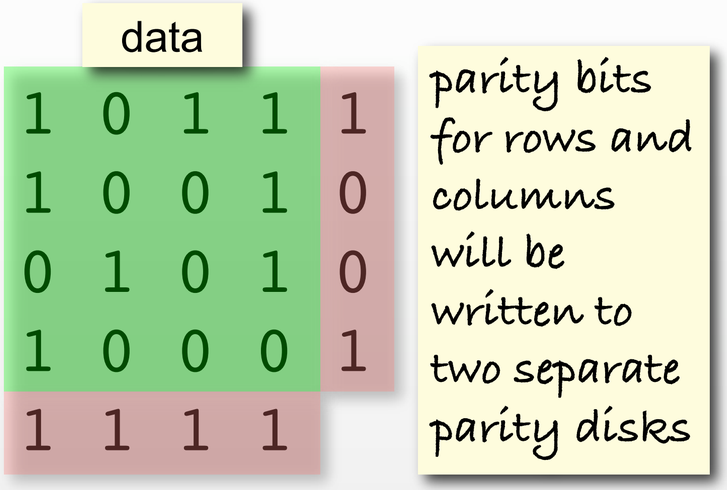
b) RAID 1 + 0 with a single disk failure.

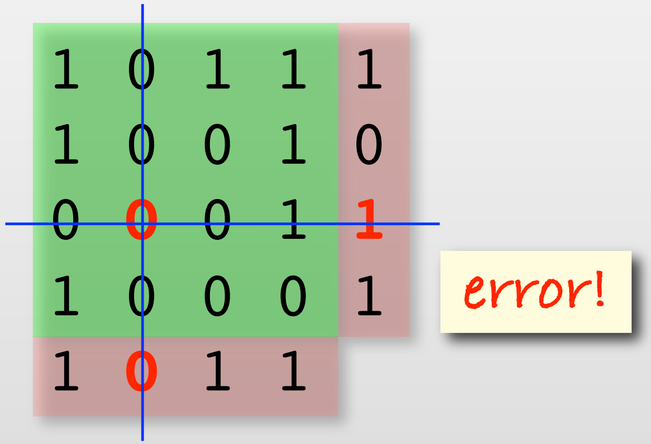
RAID Level 2 *(obsolete)*

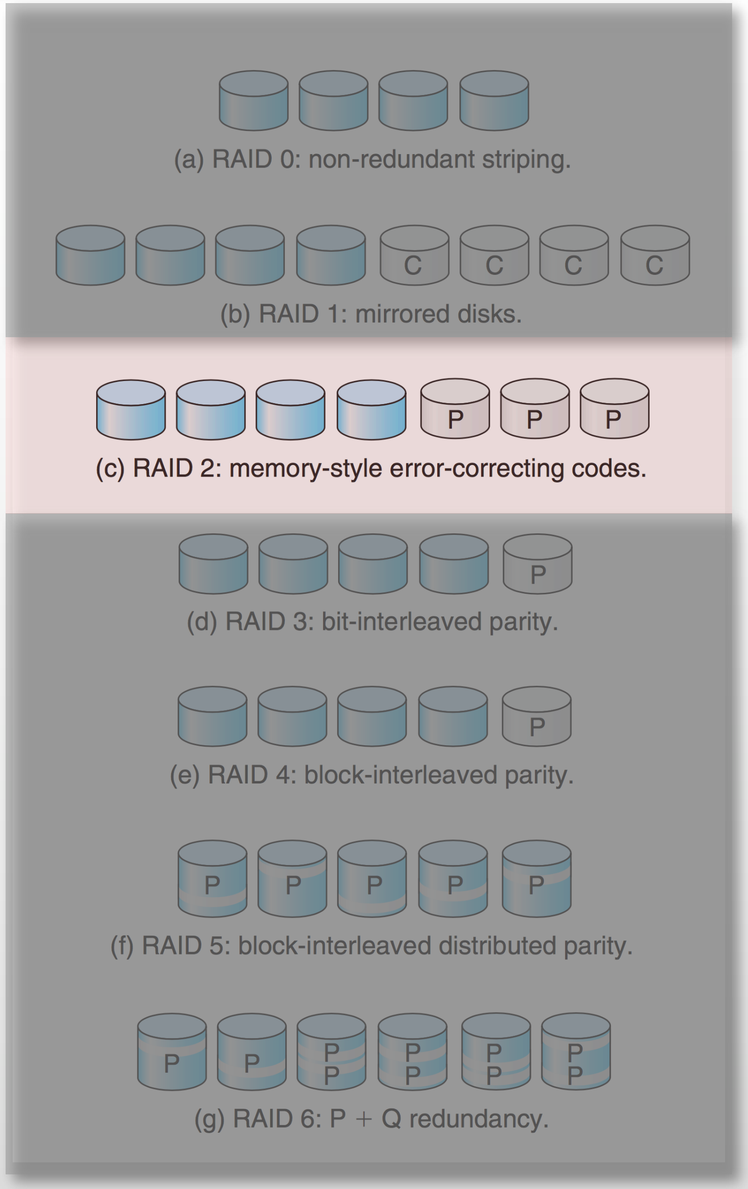
- Bit-level striping



- Uses **multi-dimensional ECCs**
  - like if it was memory
  - If a disk fails, then we can detect where and correct to some degree
- No redundancy
- Slower access
  - computing plus more writing
- Needs synchronized spindles

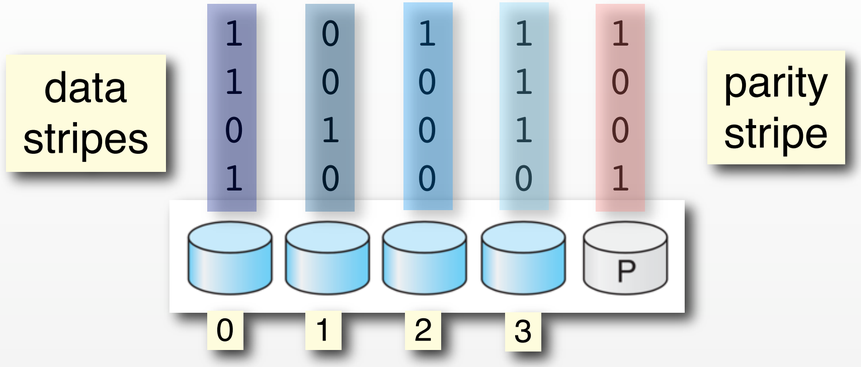




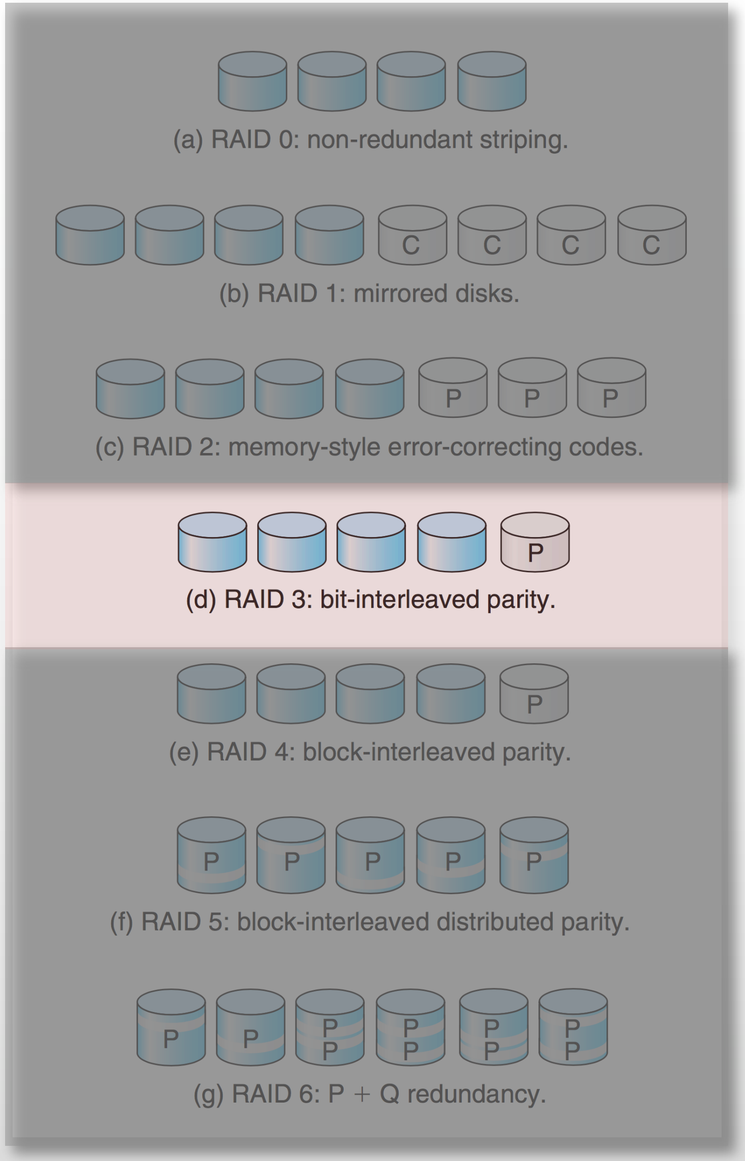


RAID Level 3 *(obsolete)*

- Byte-level striping
- RAID 3 uses just one disk for parities

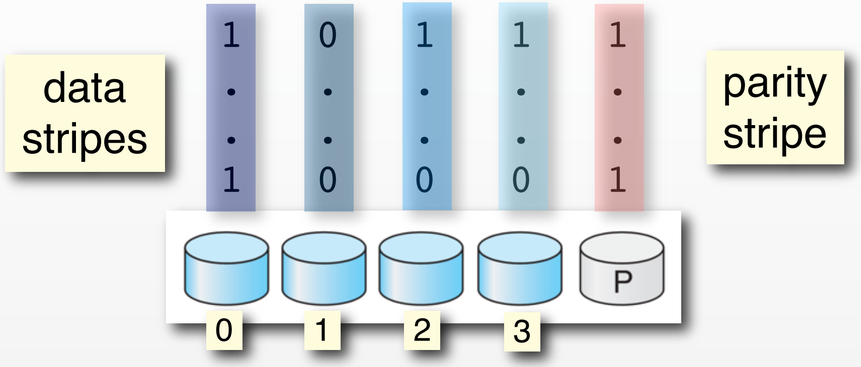


- No redundancy, but recovery from 1-bit errors
  - detection is not necessary for disks, since I/O controllers tell the OS if there was a disk error
    - i.e., reading is fine, but one of the disks will show error
- Fast access for sequential reads/writes
  - parallel byte-level reads/writes to disks
  - not so good for random writes (of blocks)
- Needs synchronized spindles

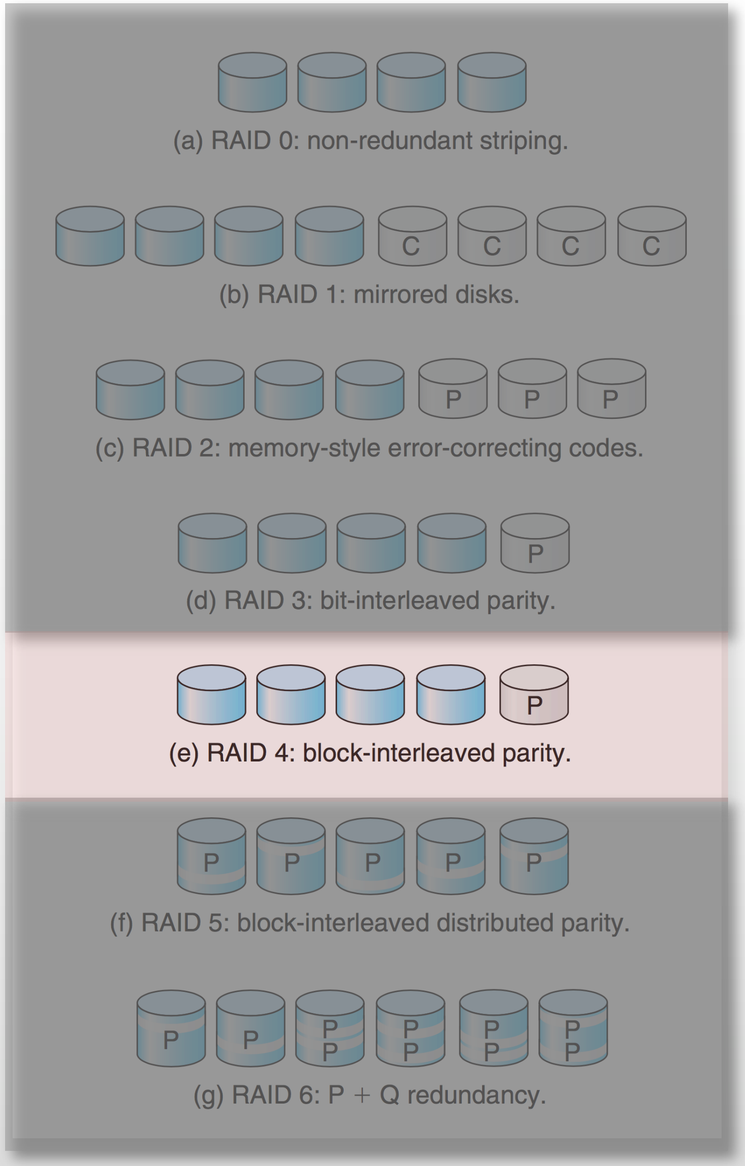


RAID Level 4

- Similar in concept to RAID 3, but striping blocks (stripes) rather than bytes; e.g., 128-byte sectors

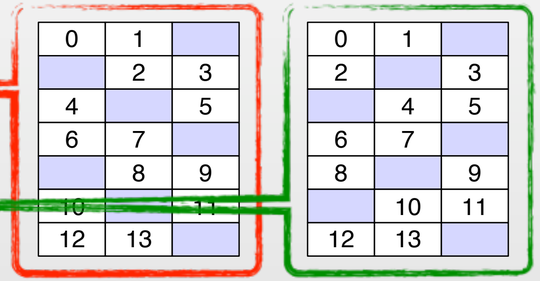


- No redundancy, but again 1-bit error recovery
  - parity disk may be overloaded
- Fast access
  - can read a number of blocks in parallel
  - multiple processes can use the disk array at the same time
- Problem: bottleneck at the parity disk
  - written for every write on any other disk

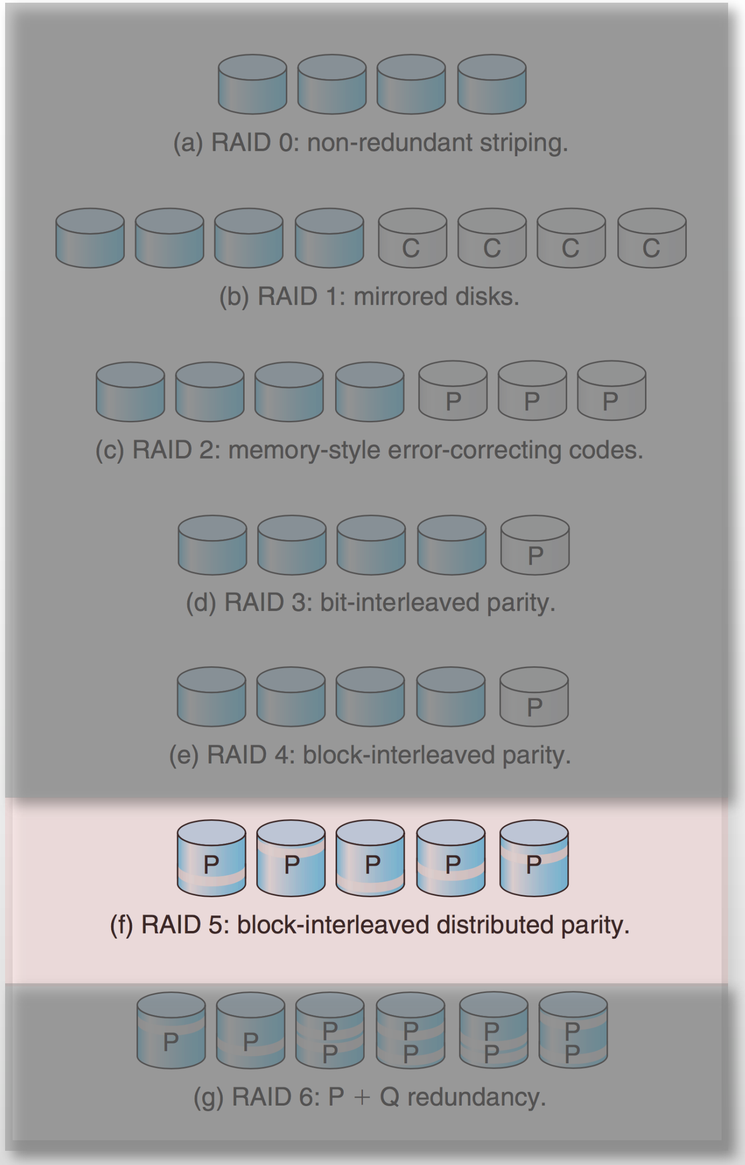


RAID Level 5

- Just like RAID 4 except that parity blocks (stripes) are distributed among all disks
  - prevents “overheating” of one disk that holds only parities
- No redundancy, but 1-bit error recovery
- Fast access
  - can read k blocks in parallel
- Even distribution of load between all disks
  - need a **parity distribution algorithm**
    - e.g.,
      - forward rotation
      - backward rotation

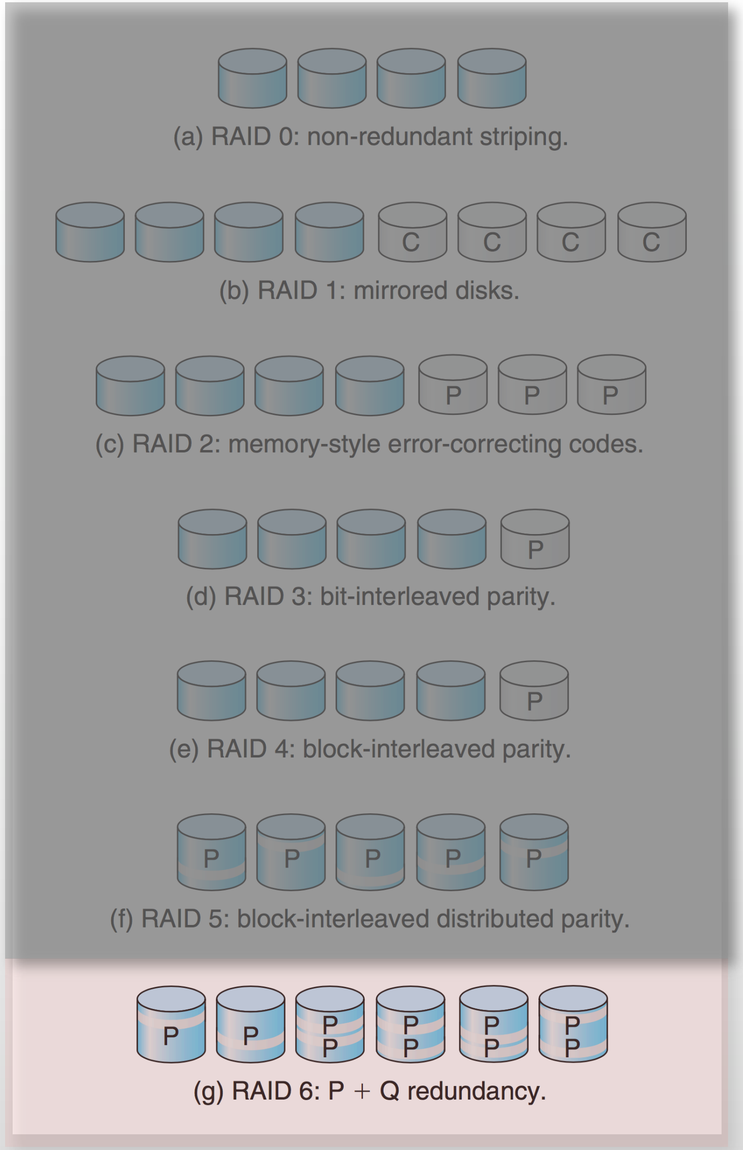


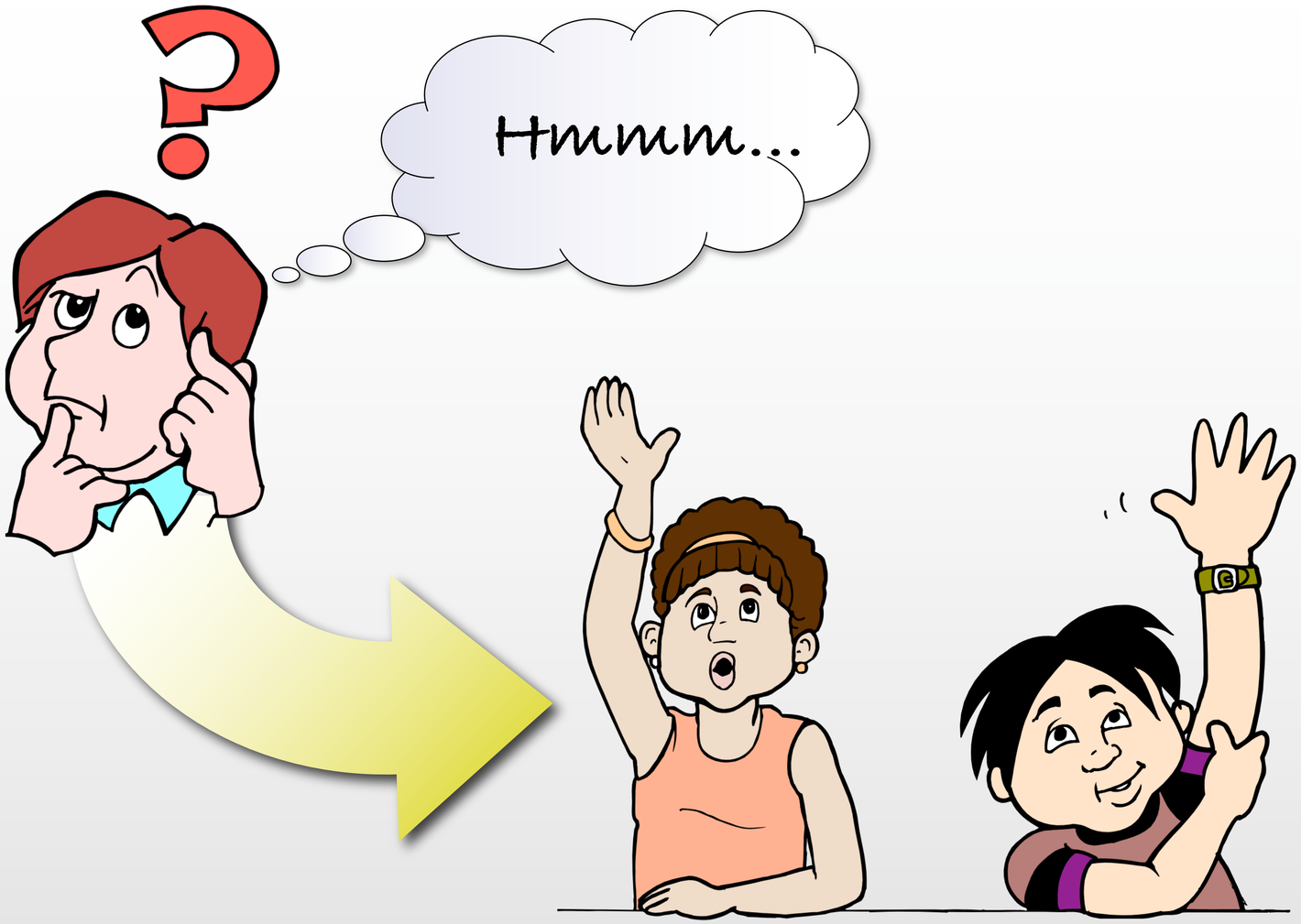
    - if we know sector number, then we can compute the stripe number, and in turn, the parity location



RAID Level 6

- Just like RAID 5, but with more complex error correction coding
  - e.g., two-dimensional
    - i.e., two parity bits used
      - as we saw on an earlier slide
    - parities distributed on all disks





COMP362 Operating Systems

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