Operating Systems

15. Storage: Mass storage device

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- Overview of Mass Storage Structure
  - HDDs, SSDs, and Magnetic tapes
  - Abstraction of storage devices
- Disk Structures
  - Disk Attachment
  - Structures: Storage array, RAID Structure, SAN and NAS
- Disk Scheduling
- Others
  - Disk Management
  - Swap-Space Management
  - Stable-Storage Implementation

Objectives

- To describe the physical structure of secondary storage devices and its effects on the uses of the devices
- To explain the performance characteristics of mass-storage devices
- To evaluate disk scheduling algorithms
- To discuss operating-system services provided for mass storage, including RAID

Overview of Mass Storage Structure

- Magnetic disks provide bulk of secondary storage of modern computers
  - Drives rotate at 60 to 250 times per second (5400, 7200, 15000 RPM)
  - Transfer rate is rate at which data flow between drive and computer
  - Positioning time (random-access time) is 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 results from disk head making contact with the disk surface -- That's bad
- SSD and Tapes
- Drive attached to computer via I/O bus
  - Busses vary, including EIDE, ATA, SATA, USB, Fibre Channel, SCSI, SAS, Firewire
  - Host controller in computer uses bus to talk to disk controller built into drive or storage array

The First Commercial Disk Drive

1956
IBM RAMDAC computer included the IBM Model 350 disk storage system

5M (7 bit) characters
50 x 24” platters
Access time = < 1 second

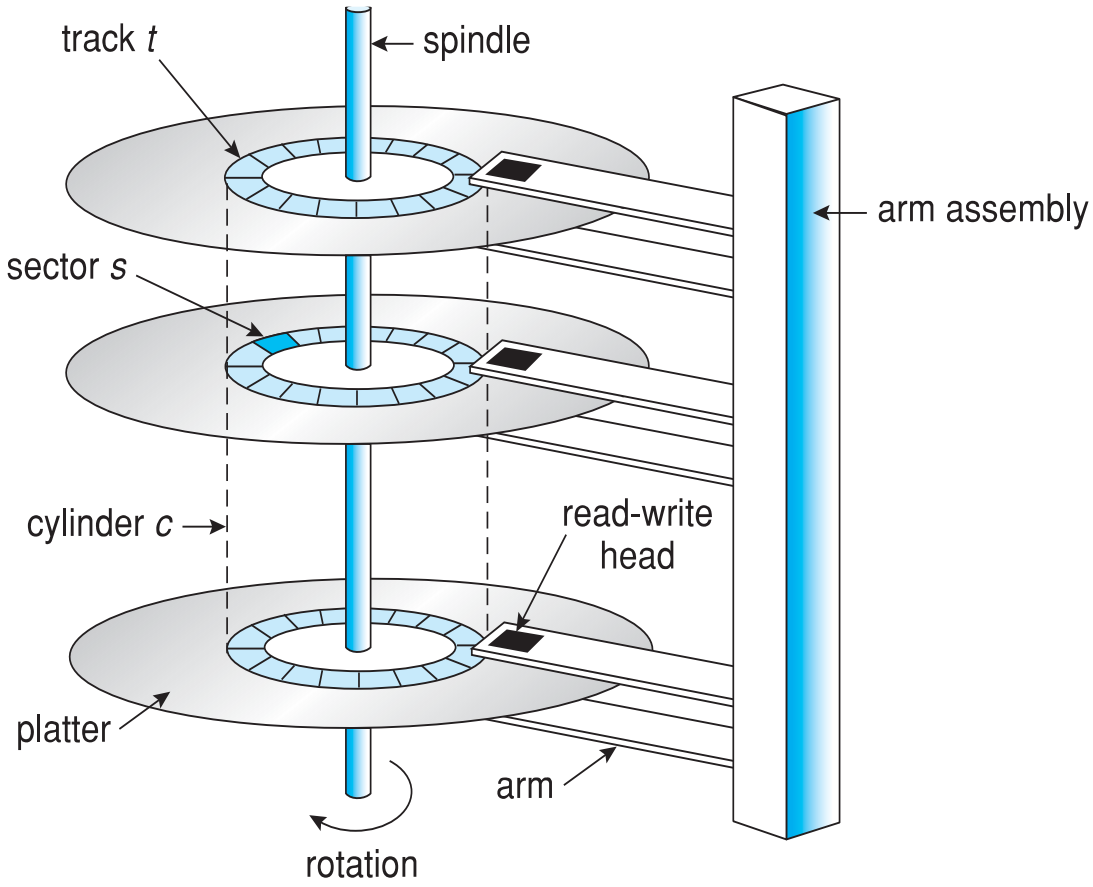
Recently: NVMe SSD

- More than terabytes

Intel SSD 730, 750		
Drive	Intel 730	Intel 750
NAND	**Intel 20nm MLC NAND**	
연속 읽기	550MB/s	2,200MB/s
연속 쓰기	520MB/s	900MB/s
4KB 랜덤 읽기	89K IOPS	430K IOPS
4KB 랜덤 쓰기	74K IOPS	230K IOPS
인터페이스	SATA3 6GB/s	PCIe Gen3 * 4

	Read [MB/s]	Write [MB/s]
Seq	6002	8561
512K	5708	7753
4K	448.7	419.8
4K QD32	438.6	403.3

Moving-head Disk Mechanism



Hard Disks

- Platters range from .85” to 14” (historically)
  - Commonly 3.5”, 2.5”, and 1.8”
- Range from 30GB to 3TB per drive
- Performance
  - Transfer Rate – theoretical – 6 Gb/sec
    - Effective Transfer Rate – real – 1Gb/sec
  - Seek time from 3ms to 12ms – 9ms common for desktop drives
    - Average seek time measured or calculated based on 1/3 of tracks
  - Latency based on spindle speed (i.e. rotation delay)
    - 1 / (RPM / 60) = 60 / RPM
    - Average latency = ½ latency

(From Wikipedia)

Spindle [rpm]	Average latency [ms]
4200	7.14
5400	5.56
7200	4.17
10000	3
15000	2

Hard Disk Performance

- Average access time = average seek time + average latency
  - For fastest disk 3ms + 2ms = 5ms
  - For slow disk 9ms + 5.56ms = 14.56ms
- Average I/O time = **average access time** + (amount to transfer / transfer rate) + controller overhead
- For example to transfer a 4KB block on a 7200 RPM disk with a 5ms average seek time, 1Gb/sec transfer rate with a .1ms controller overhead =
  - 5ms + 4.17ms + 0.1ms + transfer time
    - 4.17 ms = 60/7200/2 seconds
  - Transfer time = 4KB / 128 MB/s = 0.031 ms
  - Average I/O time for 4KB block = 9.27ms + .031ms = 9.301ms

Solid-State Disks

- Nonvolatile memory used like a hard drive
  - Many technology variations
- Can be more reliable than HDDs
- More expensive per MB
- Maybe have shorter life span
- Less capacity
- But much faster
- Busses can be too slow -> connect directly to PCI for example
- No moving parts, so no seek time or rotational latency

Magnetic Tape

- Was early secondary-storage medium
  - Evolved from open spools to cartridges
- Relatively permanent and holds large quantities of data
- Access time slow
- Random access ~1000 times slower than disk
- Mainly used for backup, storage of infrequently-used data, transfer medium between systems
- Kept in spool and wound or rewound past read-write head
- Once data under head, transfer rates comparable to disk
  - 140MB/sec and greater
- 200GB to 1.5TB typical storage
- Common technologies are LTO-{3,4,5} and T10000

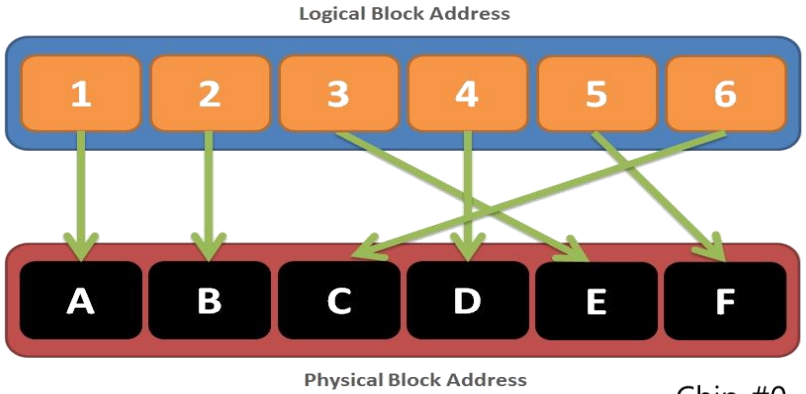
Abstraction of Block Storage Device

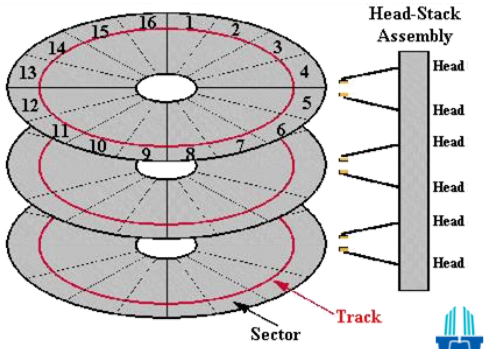
	Hard disk drives	Solid state drives
Material	Magnetic rotating disk	NAND Flash memory chip
Architecture	Platters, tracks, sectors	Channels, banks, blocks, pages
Characteristic	Spindle motors and disk head	Several cores and large cache

Abstraction level 1: a block storage

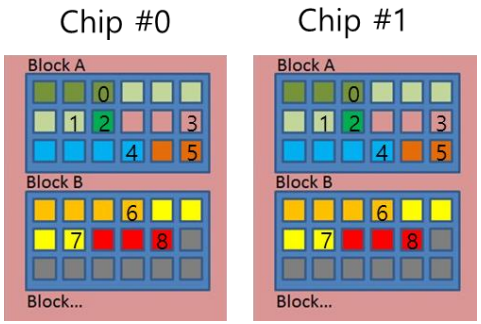
- Different addressing methods of HDD and SSD
  - HDD: Cylinder #, head #, sector #
  - SSD: Channel #, bank #, block #, page #
- How to use in common way?
  - LBA: logical block addressing → becomes a block storage device

It is the abstraction!





<HDD>



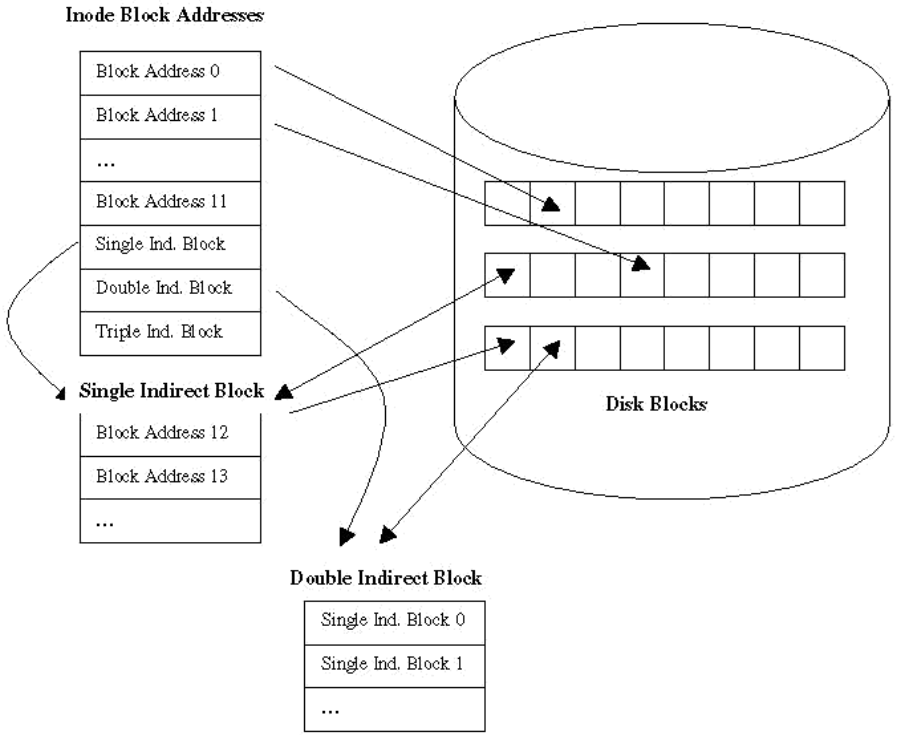
<SSD>

Abstraction level 2: a file system

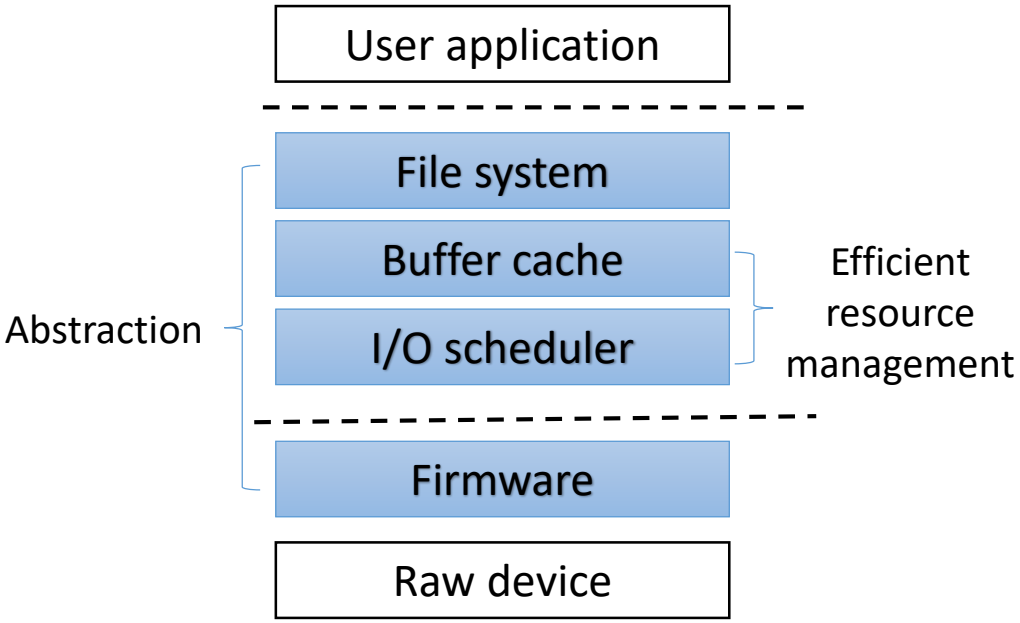
- What is the "*File?*"
  - Several definitions:
    - Named collection of bytes (or linear array of bytes)
    - Collection of data with some properties; name, size, owner, and etc.
  - Apps usually use *File* for storing data, not the block storage directly
  - File system provides *File* and other abstractions
    - Directories, pseudo file, links, types, access controls, and etc.
- Benefits
  - Apps do not consider about the block storage
    - "I don't know the LBA, but I can store and access my data in a file"
  - Convenient access and management of user data
    - By naming and hierarchical structure

Abstraction level 2: a file system

- File implementation in Unix: i-node
  - Pointers to (logical) block numbers
  - And other properties: name, access date, owner, i-node number, and etc.



Complete storage stack in OS



- Provide abstraction
  - Firmware: LBA
  - File system: File
- Provide efficiency
  - Buffer cache
  - I/O scheduler

Disk Scheduling

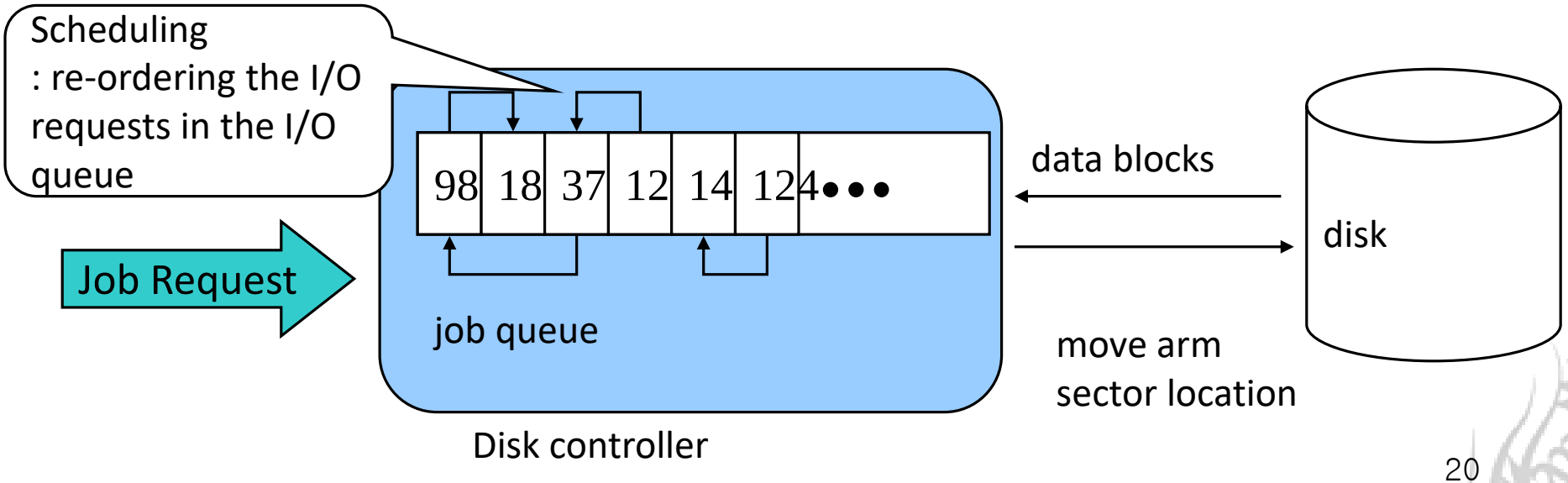
Disk Scheduling

- The operating system is responsible for using hardware efficiently — for the disk drives, this means having a fast access time and disk bandwidth
- Minimize seek time
- Seek time ≈ seek distance
- Disk bandwidth is the total number of bytes transferred, divided by the total time between the first request for service and the completion of the last transfer

Disk Scheduling (Cont.)

- There are many sources of disk I/O request
  - OS
  - System processes
  - Users processes
- I/O request includes input or output mode, disk address, memory address, number of sectors to transfer
- OS maintains queue of requests, per disk or device
- Idle disk can immediately work on I/O request, busy disk means work must queue
  - Optimization algorithms only make sense when a queue exists

Disk Scheduling (Cont.)

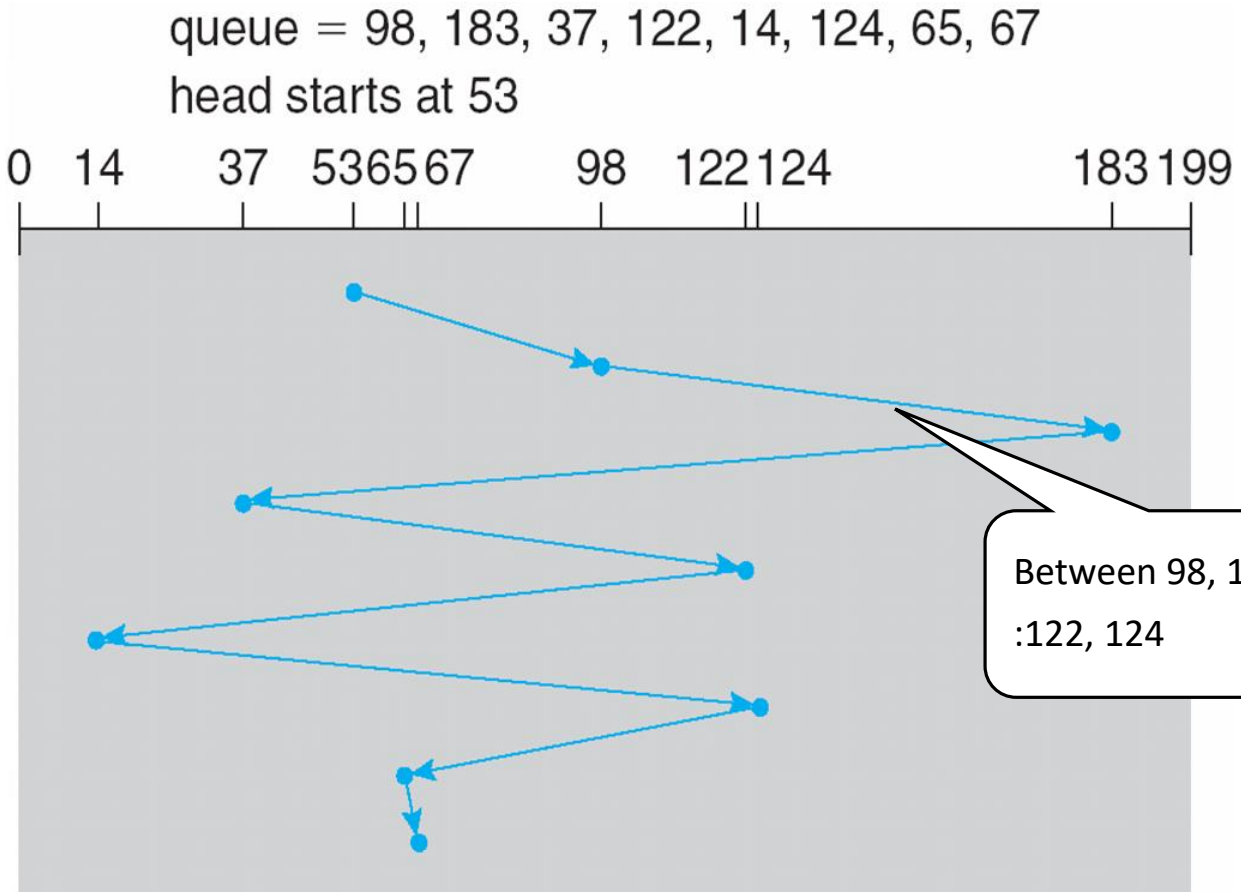


Disk Scheduling (Cont.)

- Note that drive controllers have small buffers and can manage a queue of I/O requests (of varying “depth”)
- Several algorithms exist to schedule the servicing of disk I/O requests
- The analysis is true for one or many platters
- We illustrate scheduling algorithms with a request queue (0-199)
- 98, 183, 37, 122, 14, 124, 65, 67
- Head pointer 53

FCFS

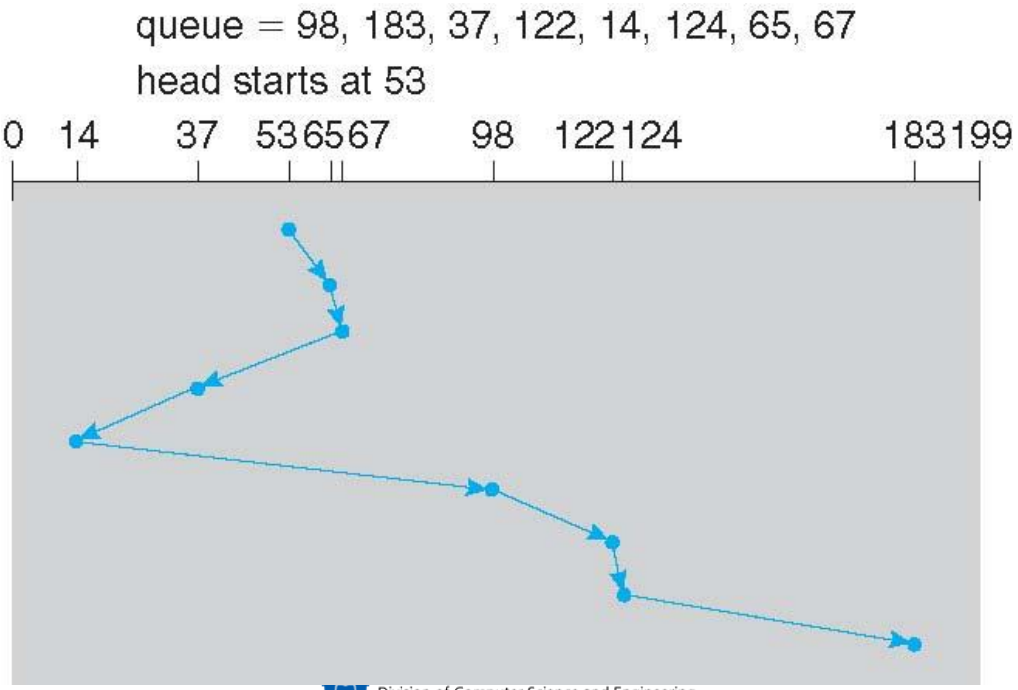
Illustration shows total head movement of 640 cylinders



= (98-53) + (183-98) + (199-183) + (199-37) + (122-37) + (122-14) + (124 – 14) + (124 – 65) + (67 – 65) = 640

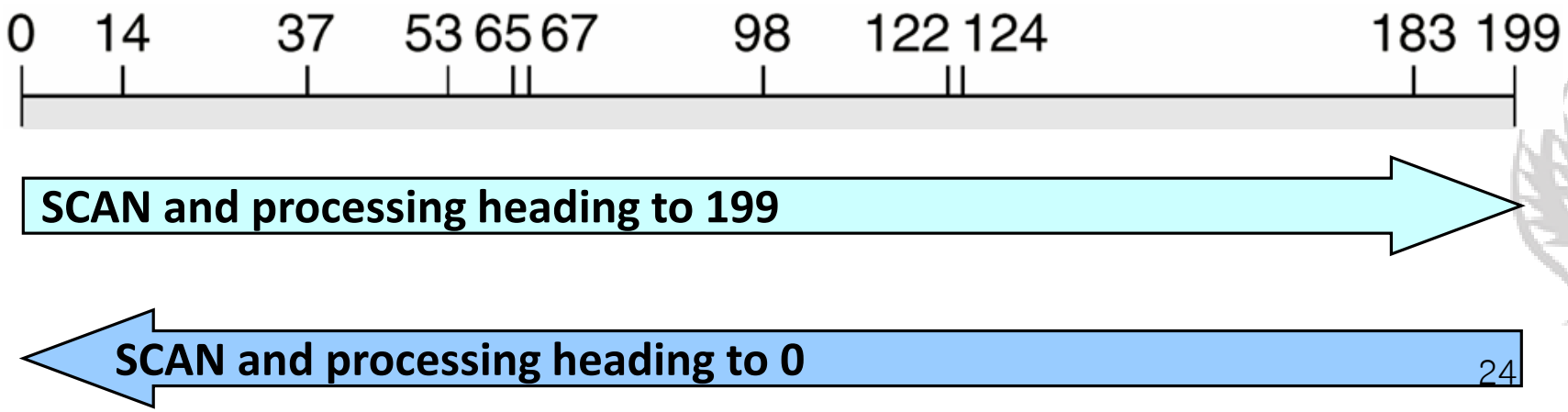
SSTF

- Shortest Seek Time First selects the request with the minimum seek time from the current head position
- SSTF scheduling is a form of SJF scheduling; may cause starvation of some requests
- Illustration shows total head movement of 236 cylinders

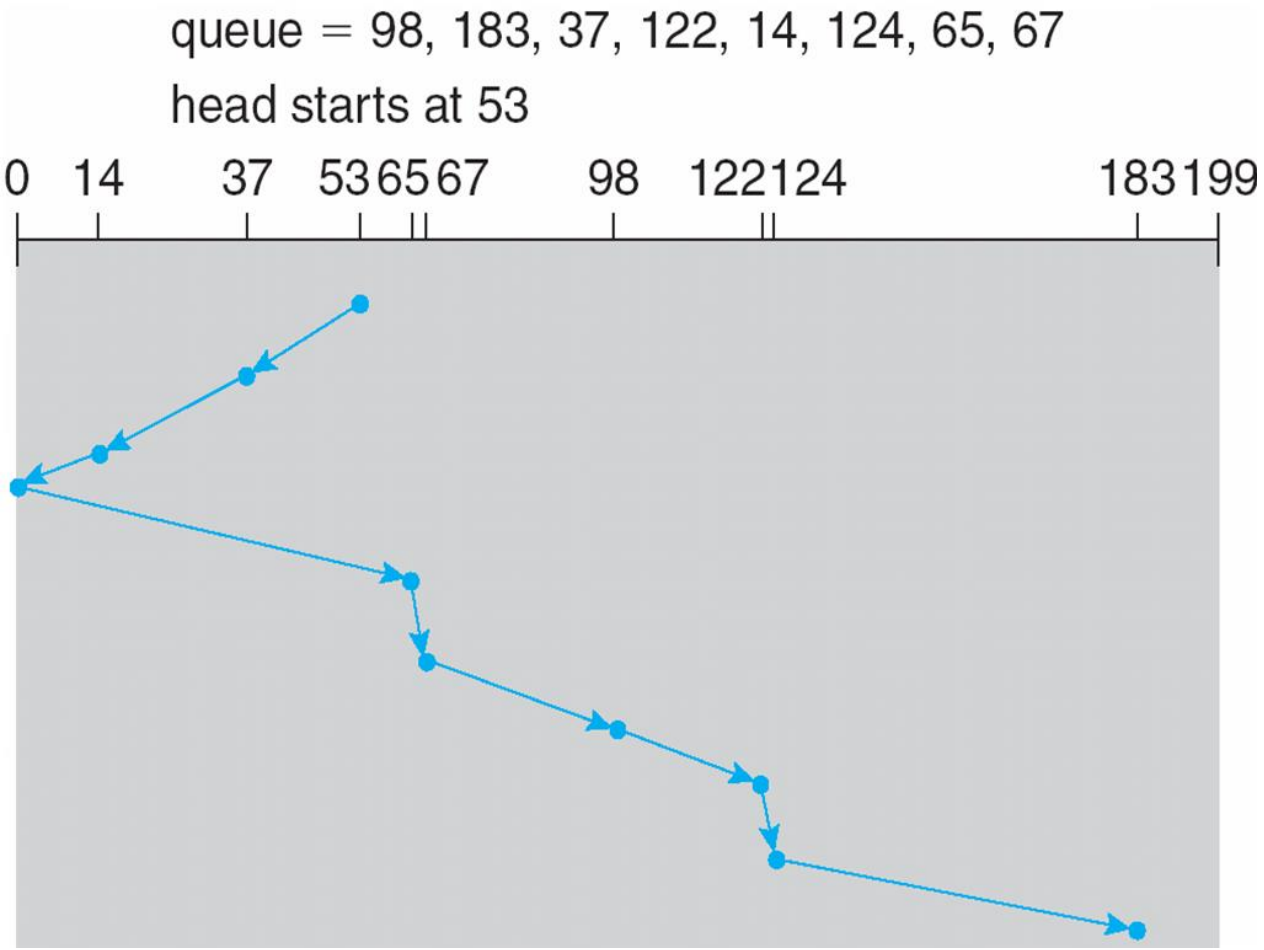


SCAN

- 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.
- SCAN algorithm Sometimes called the elevator algorithm
- Illustration shows total head movement of 208 cylinders
- Cons: Non-uniform waiting time

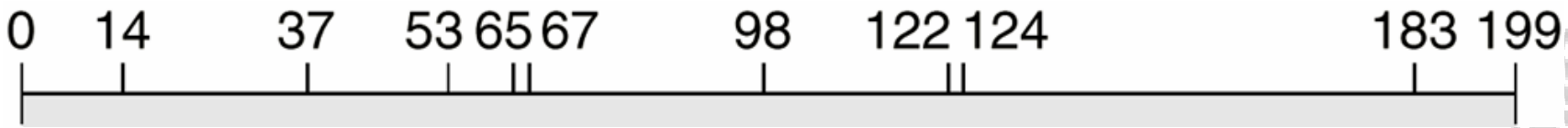


SCAN (Cont.)


queue = 98, 183, 37, 122, 14, 124, 65, 67
head starts at 53
0
14
37
53
65
67
98
122
124
183
199

C-SCAN

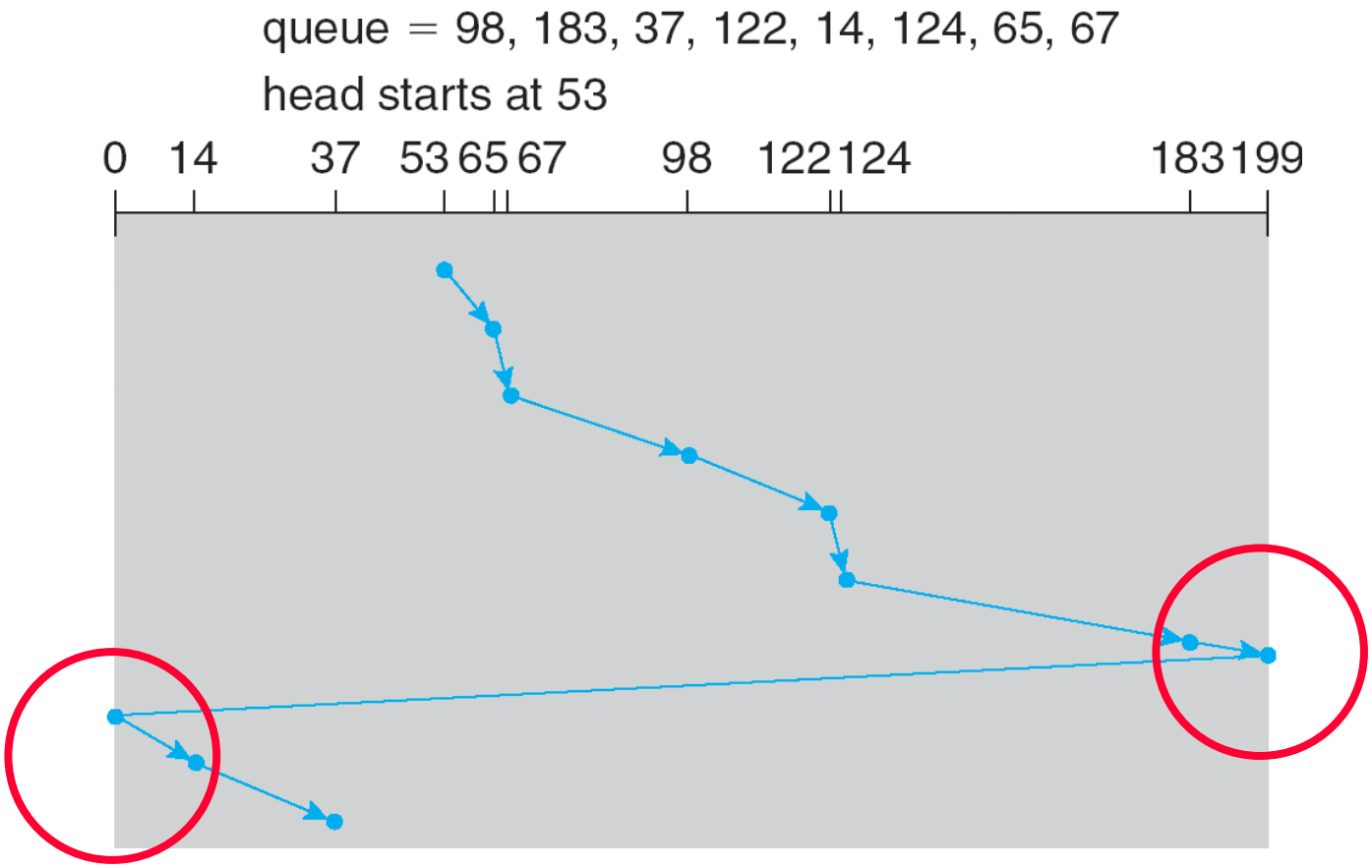
- Provides a more uniform wait time than SCAN
- The head moves from one end of the disk to the other, servicing requests as it goes
  - When it reaches the other end, however, it immediately returns to the beginning of the disk, without servicing any requests on the return trip
- Treats the cylinders as a circular list that wraps around from the last cylinder to the first one
- Total number of cylinders?



SCAN and processing heading to 199

SCAN and processing heading to 199

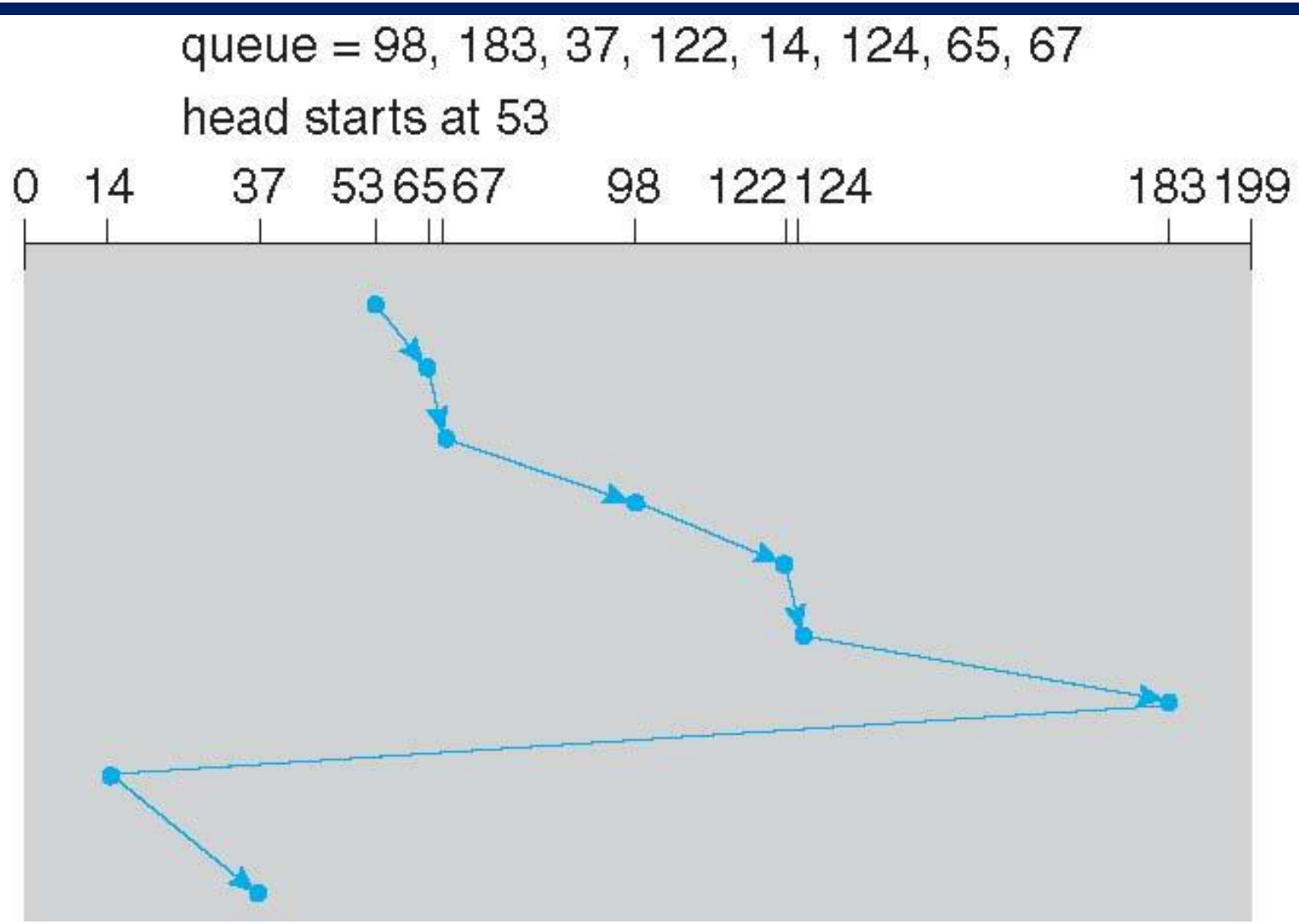
C-SCAN (Cont.)


queue = 98, 183, 37, 122, 14, 124, 65, 67
head starts at 53
0
14
37
53
65
67
98
122
124
183
199

C-LOOK

- LOOK a version of SCAN, C-LOOK a version of C-SCAN
- 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
- Total number of cylinders?

C-LOOK (Cont.)


queue = 98, 183, 37, 122, 14, 124, 65, 67
head starts at 53
0
14
37
53
65
67
98
122
124
183
199

Selecting a Disk-Scheduling Algorithm

- SSTF is common and has a natural appeal
- SCAN and C-SCAN perform better for systems that place a heavy load on the disk
  - Less starvation
- Performance depends on the number and types of requests
- Requests for disk service can be influenced by the file-allocation method
  - And metadata layout
- The disk-scheduling algorithm should be written as a separate module of the operating system, allowing it to be replaced with a different algorithm if necessary
- Either SSTF or LOOK is a reasonable choice for the default algorithm
- What about rotational latency?
  - Difficult for OS to calculate
- How does disk-based queueing effect OS queue ordering efforts?

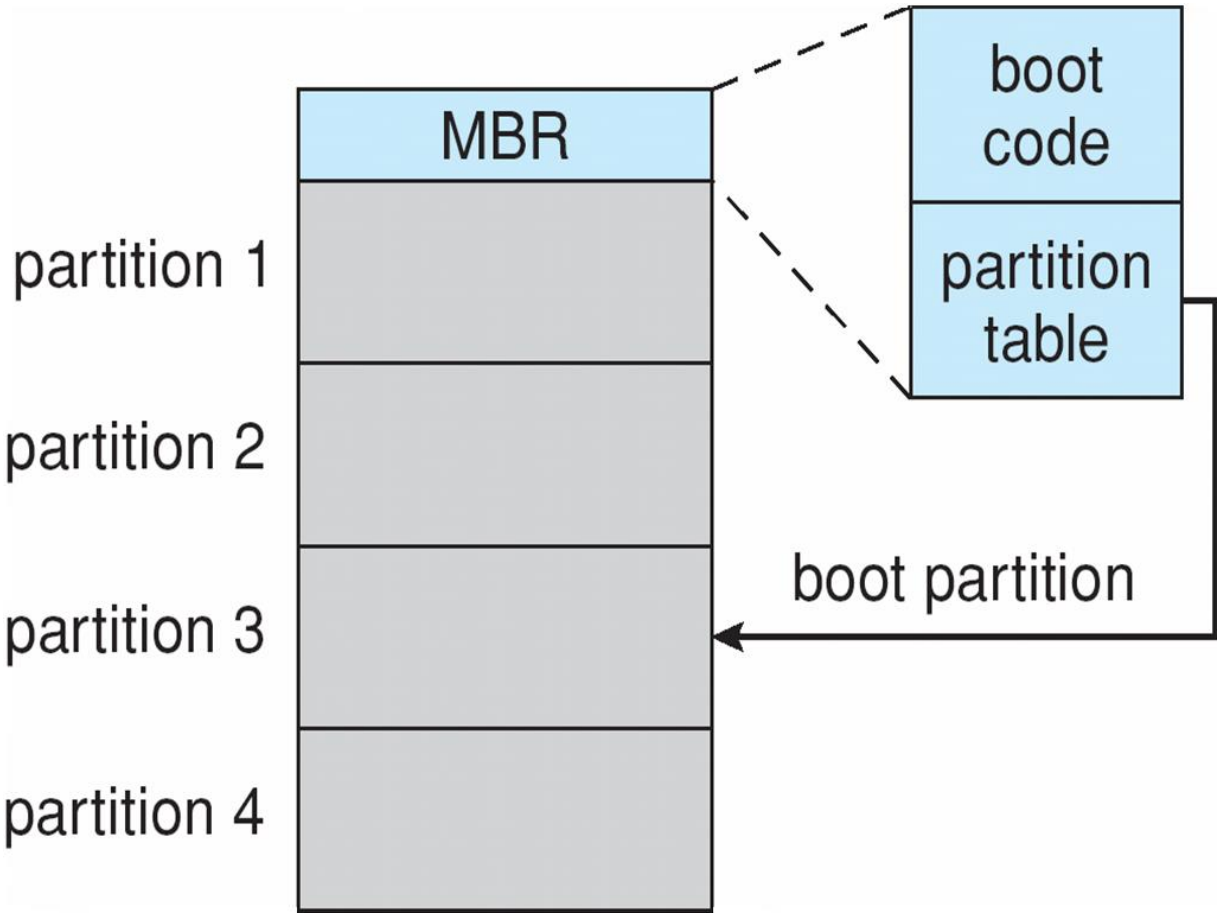
Disk Management

- Low-level formatting, or physical formatting — Dividing a disk into sectors that the disk controller can read and write
  - Each sector can hold header information, plus data, plus error correction code (ECC)
  - Usually 512 bytes of data but can be selectable
- To use a disk to hold files, the operating system still needs to record its own data structures on the disk
  - Partition the disk into one or more groups of cylinders, each treated as a logical disk
  - Logical formatting or “making a file system”
  - To increase efficiency most file systems group blocks into clusters
    - Disk I/O done in blocks
    - File I/O done in clusters

Disk Management (Cont.)

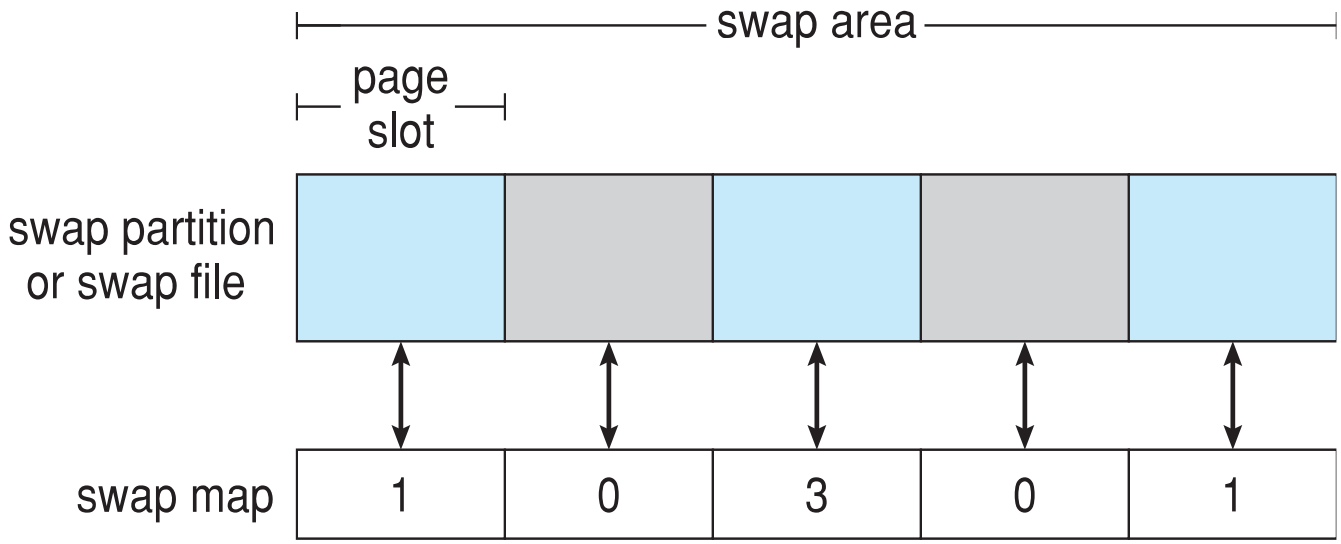
- Raw disk access for apps that want to do their own block management, keep OS out of the way (databases for example)
- Boot block initializes system
  - The bootstrap is stored in ROM
  - Bootstrap loader program stored in boot blocks of boot partition
- Methods such as sector sparing used to handle bad blocks

Booting from a Disk in Windows



Swap-Space Management

- Swap-space — Virtual memory uses disk space as an extension of main memory
  - Less common now due to memory capacity increases
- Swap-space can be carved out of the normal file system, or, more commonly, it can be in a separate disk partition (raw)



Data Structures for Swapping on Linux Systems

Swap-Space Management

- Swap-space management
  - 4.3BSD allocates swap space when process starts; holds text segment (the program) and data segment
  - Kernel uses swap maps to track swap-space use
  - Solaris 2 allocates swap space only when a dirty page is forced out of physical memory, not when the virtual memory page is first created
    - File data written to swap space until write to file system requested
    - Other dirty pages go to swap space due to no other home
    - Text segment pages thrown out and reread from the file system as needed
- What if a system runs out of swap space?
- Some systems allow multiple swap spaces

Stable-Storage Implementation

- Stable storage means data is never lost (due to failure, etc)
- To implement stable storage:
  - Replicate information on more than one nonvolatile storage media with independent failure modes
  - Update information in a controlled manner to ensure that we can recover the stable data after any failure during data transfer or recovery
- Disk write has 1 of 3 outcomes
  - Successful completion - The data were written correctly on disk
  - Partial failure - A failure occurred in the midst of transfer, so only some of the sectors were written with the new data, and the sector being written during the failure may have been corrupted
  - Total failure - The failure occurred before the disk write started, so the previous data values on the disk remain intact

Stable-Storage Implementation (Cont.)

- If failure occurs during block write, recovery procedure restores block to consistent state
  - System maintains 2 physical blocks per logical block and does the following:
    - Write to 1st physical
    - When successful, write to 2nd physical
    - Declare complete only after second write completes successfully
  - Systems frequently use NVRAM as one physical to accelerate

Disk Structures

Disk Structure

- Disk drives are addressed as large 1-dimensional arrays of logical blocks, where the logical block is the smallest unit of transfer
  - Low-level formatting creates logical blocks on physical media
- The 1-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
  - Logical to physical address should be easy
    - Except for bad sectors
    - Non-constant # of sectors per track via constant angular velocity

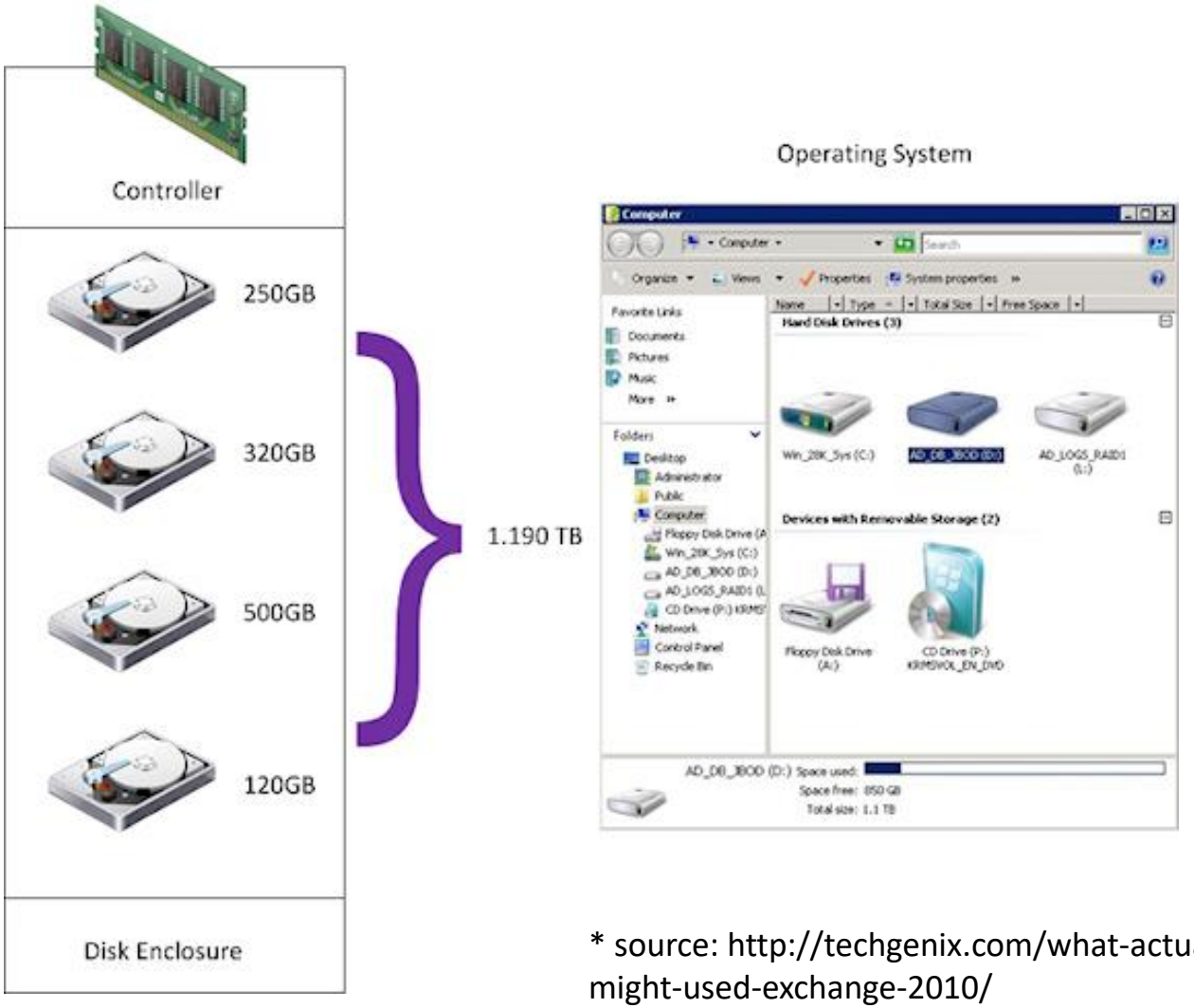
Disk Attachment

- Host-attached storage accessed through I/O ports talking to I/O busses
- SCSI itself is a bus, up to 16 devices on one cable, SCSI initiator requests operation and SCSI targets perform tasks
  - Each target can have up to 8 logical units (disks attached to device controller)
- FC is high-speed serial architecture
  - Can be switched fabric with 24-bit address space – the basis of storage area networks (SANs) in which many hosts attach to many storage units
- I/O directed to bus ID, device ID, logical unit (LUN)

Storage Array

- Can just attach disks, or arrays of disks
  - JBOD: just bunch of disks
- Storage Array has controller(s), provides features to attached host(s)
  - Ports to connect hosts to array
  - Memory, controlling software (sometimes NVRAM, etc)
  - A few to thousands of disks
  - RAID, hot spares, hot swap
  - Shared storage -> more efficiency
  - Features found in some file systems
    - Snaphots, clones, thin provisioning, replication, deduplication, etc

JBOD and Storage Array



* source: http://techgenix.com/what-actually-is-jbod-how-might-used-exchange-2010/

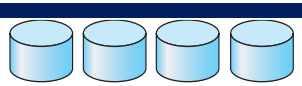
RAID Structure

- RAID – redundant array of inexpensive disks
  - multiple disk drives provides reliability via redundancy
- Increases the mean time between failure (MTBF)
- Mean time to repair – exposure time when another failure could cause data loss
- Mean time to data loss based on above factors
- Frequently combined with NVRAM to improve write performance
- Several improvements in disk-use techniques involve the use of multiple disks working cooperatively

RAID (Cont.)

- Disk striping uses a group of disks as one storage unit
- RAID is arranged into six different levels
- RAID schemes improve performance and improve the reliability of the storage system by storing redundant data
  - Mirroring or shadowing (RAID 1) keeps duplicate of each disk
  - Striped mirrors (RAID 1+0) or mirrored stripes (RAID 0+1) provides high performance and high reliability
  - Block interleaved parity (RAID 4, 5, 6) uses much less redundancy
- RAID within a storage array can still fail if the array fails, so automatic replication of the data between arrays is common
- Frequently, a small number of hot-spare disks are left unallocated, automatically replacing a failed disk and having data rebuilt onto them

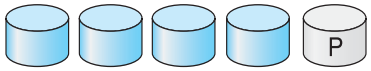
RAID Levels



(a) RAID 0: non-redundant striping.

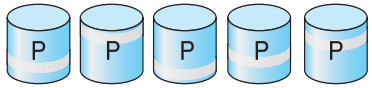
(b) RAID 1: mirrored disks.

(c) RAID 2: memory-style error-correcting codes.



(d) RAID 3: bit-interleaved parity.

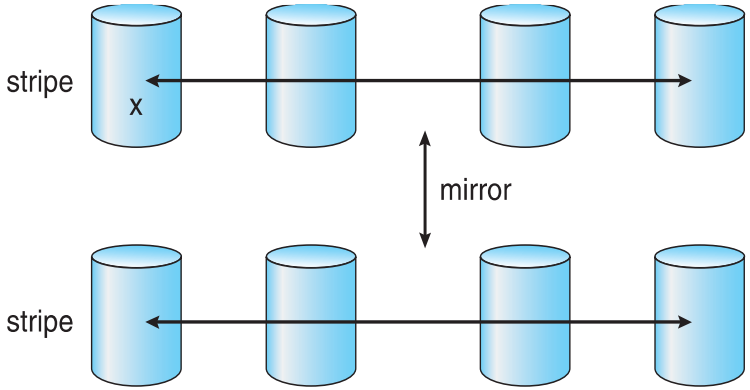
(e) RAID 4: block-interleaved parity.



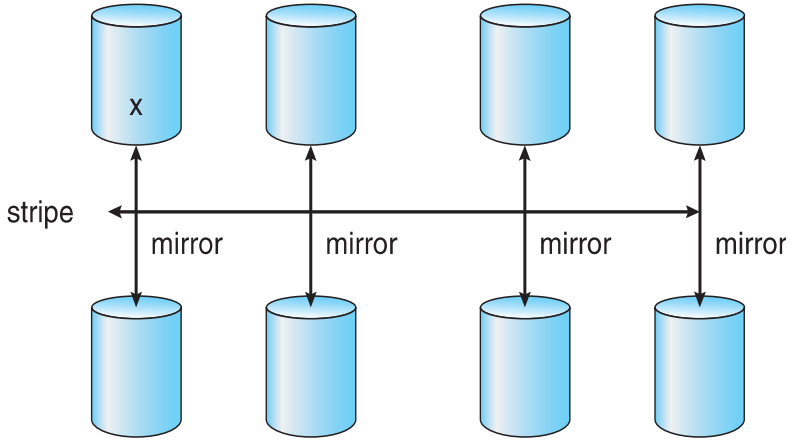
(f) RAID 5: block-interleaved distributed parity.

(g) RAID 6: P + Q redundancy.

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



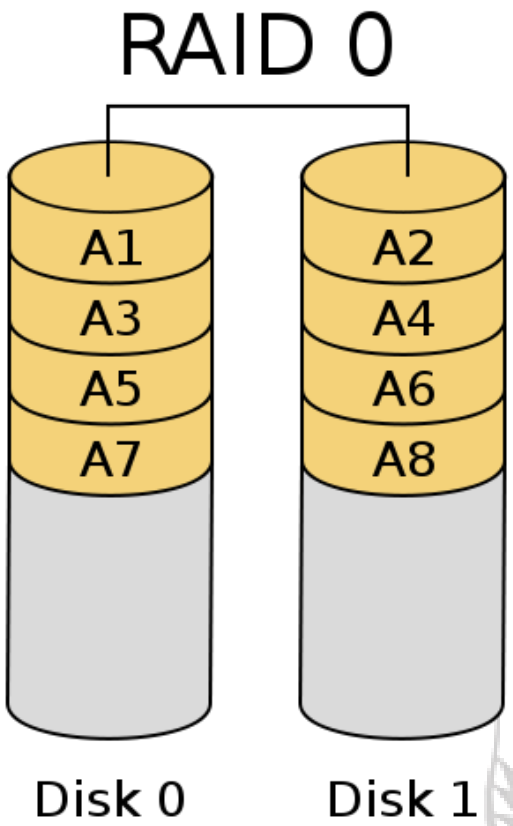
a) RAID 0 + 1 with a single disk failure.



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

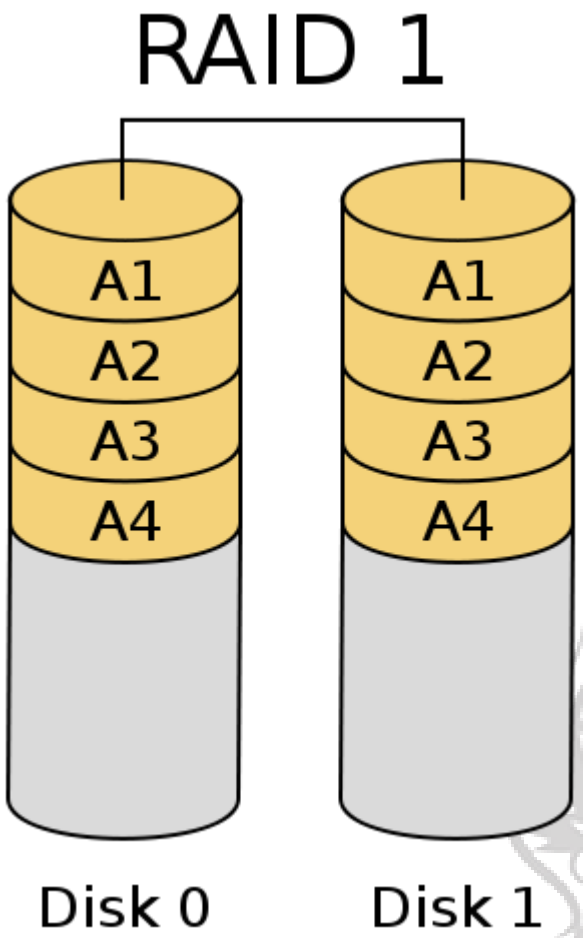
RAID Level – RAID0

- 구성
  - 여러 디스크를 하나로 묶음(strip)
  - Redundancy와 parity bit를 제공하지 않음
- 그림 설명
  - 마치 두 개의 디스크를 하나로 쓰는 것과 같음
- 단점
  - Disk0의 fail은 남아있는 Disk1의 데이터 까지 쓸모가 없어짐



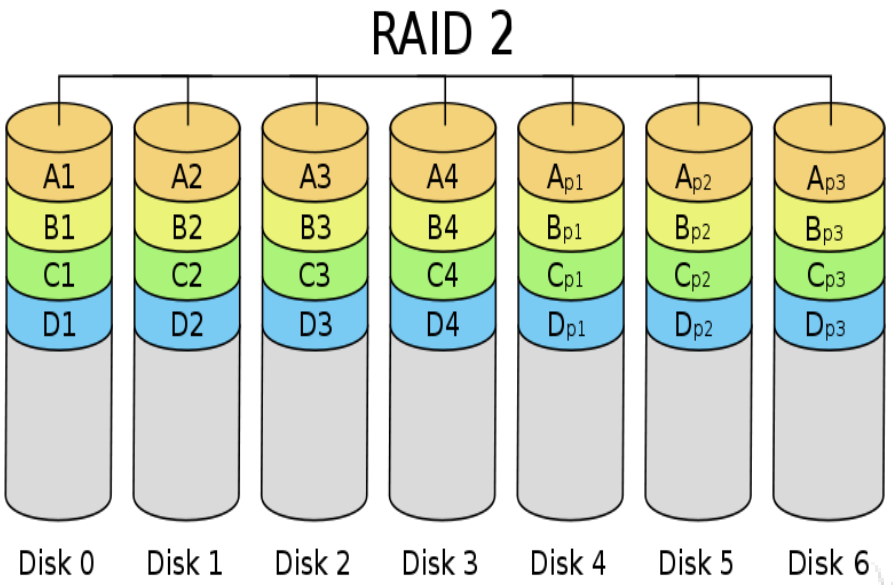
RAID Level – RAID1

- 구성
  - 두 개의 disk에 같은 내용을 복사하여 저장
  - RAID1을 통해서 확보할 수 있는 공간은 n개의 디스크 에서 n/2로 줄어듦
- 그림 설명
  - 디스크 2개씩 짝을 지어 하나의 내용을 복제(mirroring)하도록 설정
  - Disk0에서 fail이 발생하더라도 Disk1의 내용을 이용하여 복구 가능
- 단점
  - Diks0의 일부 bit가 오류로 인해 잘못 저장될 경우, Disk0 과 Disk1의 내용 중 어느 것이 올바른 것인지 알 수 없음



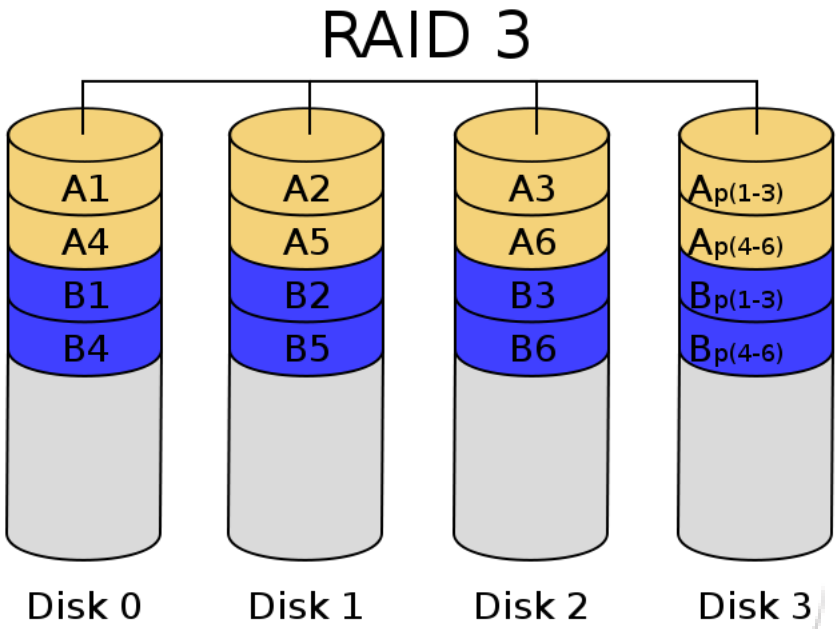
RAID Level – RAID2

- 구성
  - Bit-level strip 구성
  - 에러 체크 및 복구를 위한 humming code parity를 제공
- 그림 설명
  - 네 개의 디스크를 묶어 하나의 디스크에 쓰는 것처럼 데이터를 기록
  - 패리티를 저장하는 별도의 디스크를 통해 데이터의 소실 시 복구
- 단점
  - 4 data bit마다 3 parity bit가 필요하여 저장 공간 소모가 큼



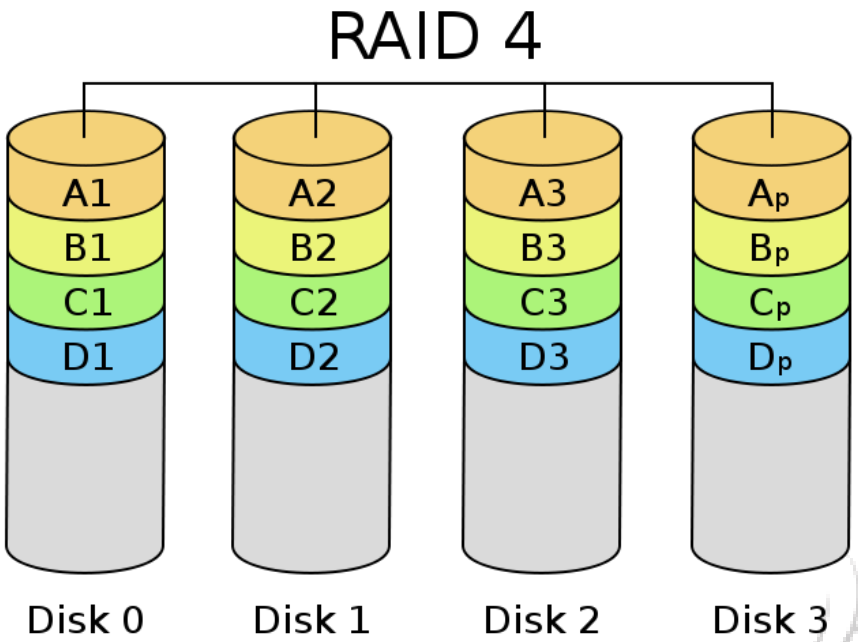
RAID Level – RAID3

- 구성
  - Byte-level strip 구성
  - XOR ECC(error-correcting) codes
    - 별도의 디스크에 parity 저장
- 그림 설명
  - Disk0~Disk2의 한 바이트마다 Disk 3에 XOR ECC 기록
  - (Disk 3 = Disk 0 ^ (Disk 1 ^ Disk 2))
- 단점
  - Byte 단위로 저장하므로 성능 하락
  - Parity 디스크 접근에 병목 발생
  - Parity를 저장한 디스크가 손상될 경우 복구할 수 없음



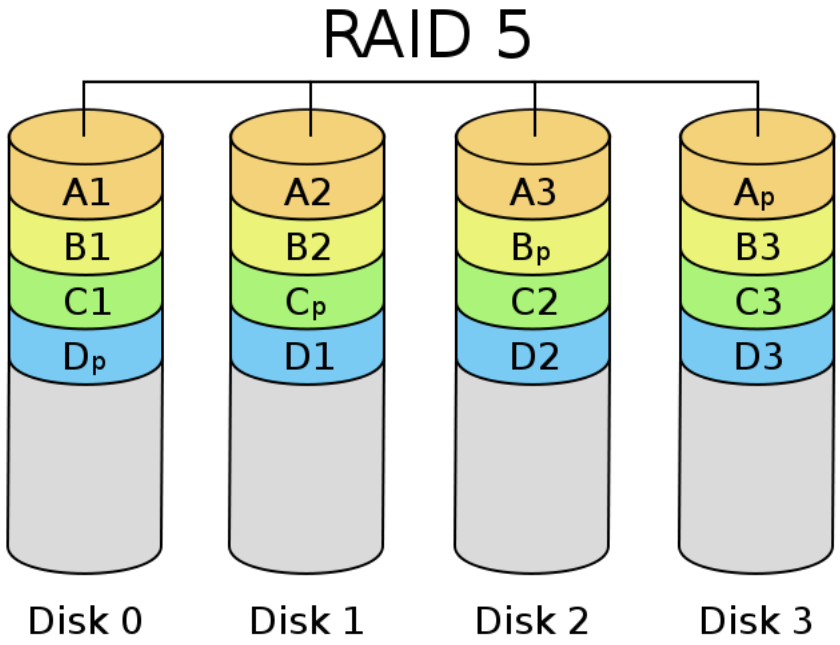
RAID Level – RAID4

- 구성
  - Block level strip 구성
  - XOR ECC codes
    - 별도의 디스크에 parity 저장
- 그림 설명
  - Disk0~Disk2의 한 블록마다 Disk 3에 XOR ECC 기록
  - (Disk 3 = Disk 0 ^ (Disk 1 ^ Disk 2))
- 단점
  - Parity 디스크 접근에 병목 발생
  - Parity를 저장한 디스크가 손상될 경우 복구할 수 없음



RAID Level – RAID5

- 구성
  - Block level strip 구성
  - XOR ECC(error-correcting) codes
    - 별도의 parity 디스크 대신 데이터 디스크에 parity를 분산 저장
- 그림 설명
  - Disk 0~Disk 3중 3개의 디스크 블록에 데이터를 저장하고, 나머지 디스크 블록에 XOR ECC 저장
- 단점
  - 분산된 Parity에 의한 RAID 0보다 낮은 읽기 성능
  - Parity 저장에 따른 RAID 1보다 낮은 쓰기 성능



RAID: Other Features

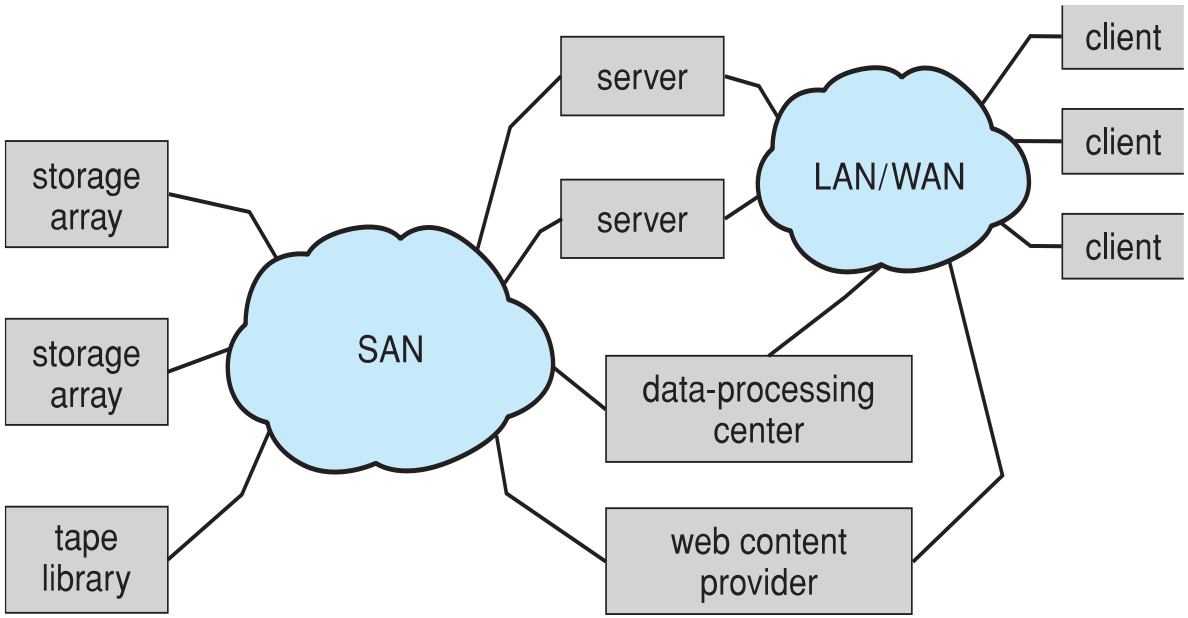
- Regardless of where RAID implemented, other useful features can be added
- Snapshot is a view of file system before a set of changes take place (i.e. at a point in time)
  - More in Ch 12
- Replication is automatic duplication of writes between separate sites
  - For redundancy and disaster recovery
  - Can be synchronous or asynchronous
- Hot spare disk is unused, automatically used by RAID production if a disk fails to replace the failed disk and rebuild the RAID set if possible
  - Decreases mean time to repair

RAID: Extensions

- RAID alone does not prevent or detect data corruption or other errors, just disk failures
- Solaris ZFS adds checksums of all data and metadata
- Checksums kept with pointer to object, to detect if object is the right one and whether it changed
- Can detect and correct data and metadata corruption
- ZFS also removes volumes, partitions
  - Disks allocated in pools
  - Filesystems with a pool share that pool, use and release space like malloc() and free() memory allocate / release calls

Storage Area Network

- Common in large storage environments
- Multiple hosts attached to multiple storage arrays - flexible



Storage Area Network (Cont.)

- SAN is one or more storage arrays
  - Connected to one or more Fibre Channel switches
- Hosts also attach to the switches
- Storage made available via LUN Masking from specific arrays to specific servers
- Easy to add or remove storage, add new host and allocate it storage
  - Over low-latency Fibre Channel fabric
- Why have separate storage networks and communications networks?
  - Consider iSCSI, FCOE

Network-Attached Storage

- Network-attached storage (NAS) is storage made available over a network rather than over a local connection (such as a bus)
  - Remotely attaching to file systems
- NFS and CIFS are common protocols
- Implemented via remote procedure calls (RPCs) between host and storage over typically TCP or UDP on IP network
- iSCSI protocol uses IP network to carry the SCSI protocol
  - Remotely attaching to devices (blocks)