Chapter 10:
Mass-Storage Systems

Zhi Wang
Florida State University

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Overview

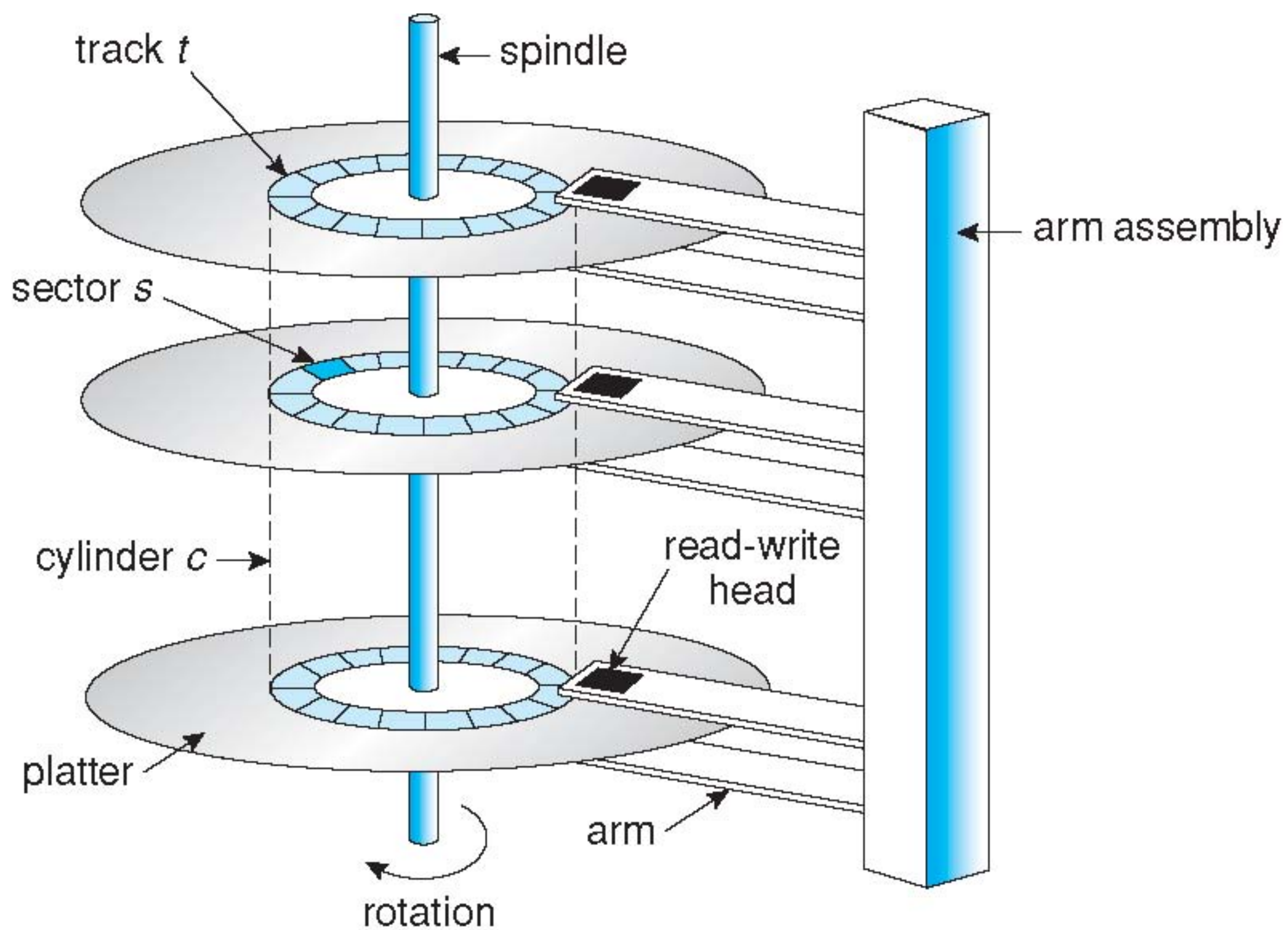
- Magnetic disks provide bulk of secondary storage of computer system
  - hard disk is most popular; some magnetic disks could be removable
  - driver attached to computer via I/O buses (e.g., USB, SCSI, EIDE, SATA…)
  - drives rotate at 60 to 250 times per second (7000rpm = 117rps)
- Magnetic disks has platters, range from .85” to 14” (historically)
  - 3.5”, 2.5”, and 1.8” are common nowadays
- Capacity ranges from 30GB to 3TB per drive

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

Moving-head Magnetic Disk



Magnetic Disks

- **Positioning time** is time to move disk arm to desired sector
  - positioning time includes **seek time** and **rotational latency**
    - seek time: move disk to the target cylinder
    - rotational latency: for the target sector to rotate under the disk head
  - positioning time is also called random-access time
- Performance
  - **transfer rate**: theoretical 6 Gb/sec; effective (real) about 1Gb/sec
    - Transfer rate is rate at which data flow between drive and computer
  - **seek time** from 3ms to 12ms (9ms common for desktop drives)
  - latency based on spindle speed: 1/rpm * 60
    - average latency = ½ latency

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

Magnetic Disk

- **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 + (data to transfer / transfer rate) + controller overhead
  - e.g., to transfer a 4KB block on a 7200 RPM disk; 5ms average seek time, 1Gb/sec transfer rate with a .1ms controller overhead:

5ms + 4.17ms + 4KB / 1Gb/sec + 0.1ms = 9.39ms (4.17 is average latency)

Magnetic Tape

- Tape was early type of secondary storage, now mostly for backup
  - large capacity: 200GB to 1.5 TB
  - slow access time, especially for random access
    - seek time is much higher than disks
    - once data under head, transfer rates comparable to disk (140 MB/s)
    - need to wind/rewind tape for random access
  - data stored on the tape are relatively permanent

Disk Structure

- Disk drives are addressed as a 1-dimensional arrays of logical blocks,
  - logical block is the smallest unit of transfer
- Logical blocks are mapped into **sectors** of the disk sequentially
  - sector 0 is the first sector of the first track on the outermost cylinder
  - mapping proceeds in order
    - first through that **track**
    - then the rest of the tracks in that **cylinder**
    - then through the rest of the cylinders from outermost to innermost
  - logical to physical address should be easy
    - except for bad sectors

Disk Attachment

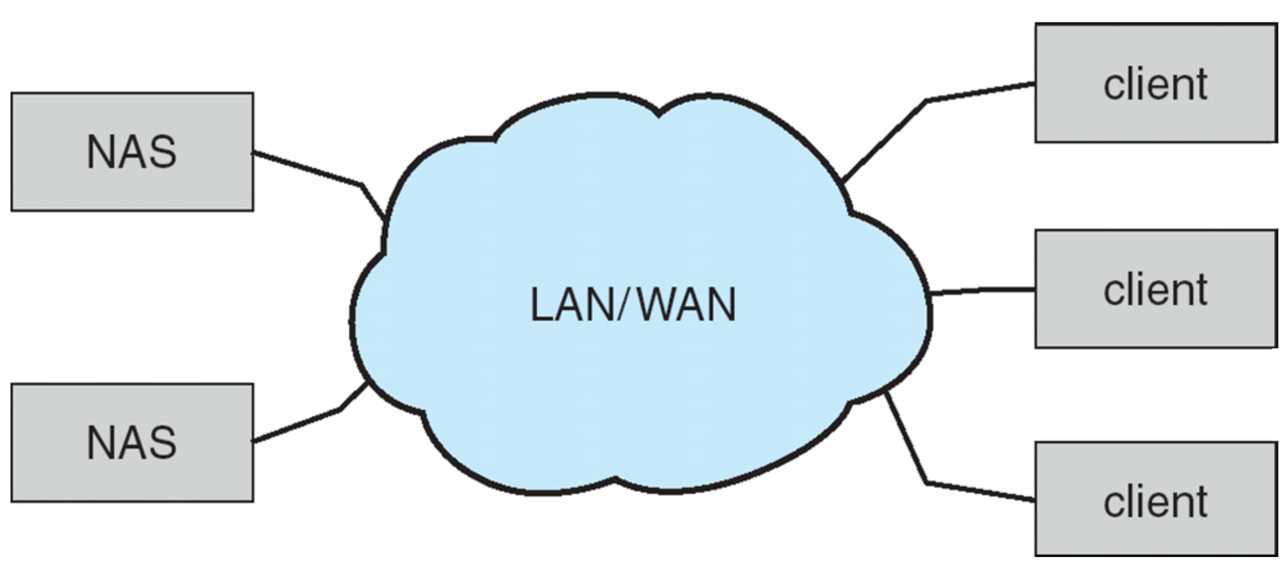
- Disks can be attached to the computer as:
  - **host-attached** storage
    - hard disk, RAID arrays, CD, DVD, tape…
  - **network-attached** storage
  - **storage area network**

Host-Attached Storage

- Disks can be attached to the computers directly via an **I/O bus**
  - e.g., SCSI is a bus architecture, up to 16 devices on one cable,
    - SCSI initiator requests operations; SCSI targets(e.g., disk) perform tasks
    - each target can have up to 8 logical units
  - e.g., Fiber Channel is high-speed serial bus
    - can be switched fabric with 24-bit address space
    - most common storage area networks (SANs) interconnection

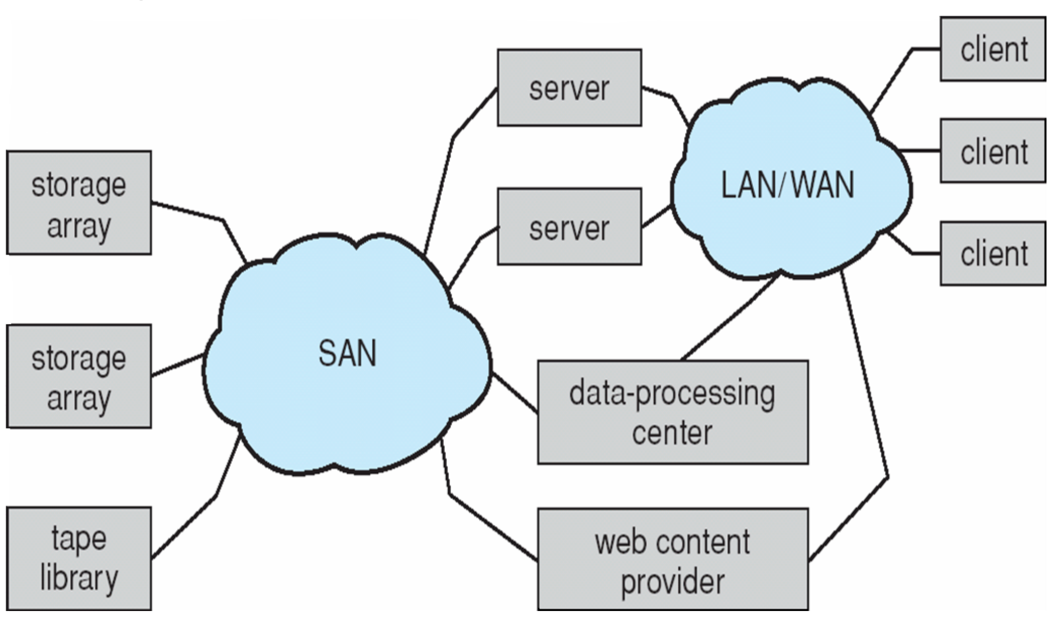
Network-Attached Storage

- **NAS** is storage made available over a network instead of a local bus
  - client can remotely attach to file systems on the server
  - NFS, CIFS, and iSCSI are common protocols
  - usually implemented via remote procedure calls (RPCs)
  - typically over TCP or UDP on IP network
    - iSCSI protocol uses IP network to carry the SCSI protocol



Storage Area Network

- **SAN** is a private network connecting servers and storage units
  - SAN consumes high bandwidth on the data network, separation is needed
  - TCP/IP stack less efficient for storage access
    - SAN uses high speed interconnection and efficient protocols
    - FC (Infiniband) is the most common SAN interconnection
  - multiple hosts and storage arrays can attach to the same SAN
    - a *cluster* of servers can share the same storage
  - storage can be *dynamically* allocated to hosts



Disk Scheduling

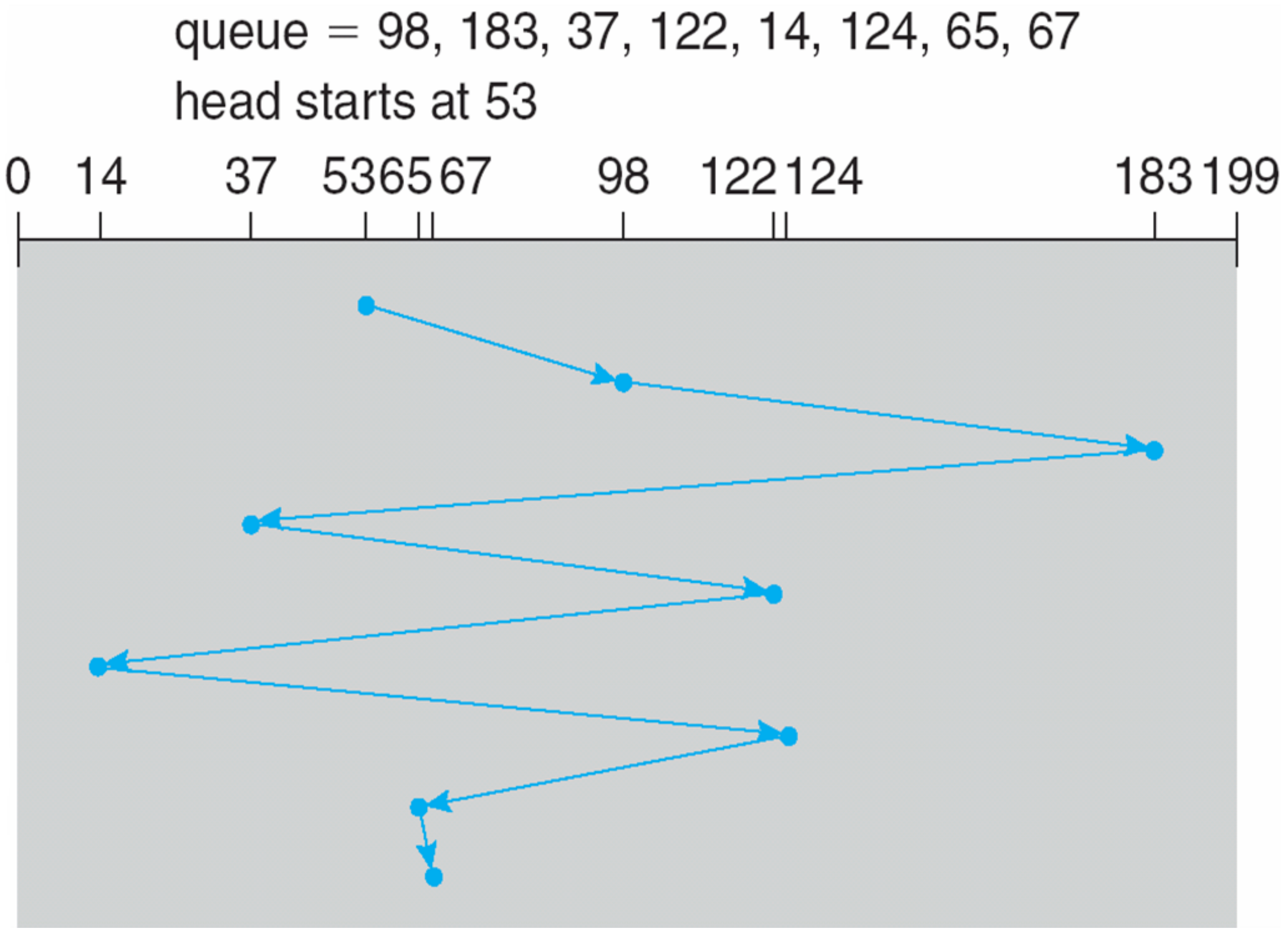
- OS is responsible for using hardware efficiently
  - for the disk drives: a fast access time and high disk bandwidth
  - **access time**: seek time (roughly linear to seek distance) + rotational latency
  - **disk bandwidth** is the speed of data transfer, data /time
    - data: total number of bytes transferred
    - time: between the first request and completion of the last transfer
- **Disk scheduling** chooses which pending disk request to service next
  - concurrent sources of disk I/O requests include OS, system/user processes
  - idle disk can immediately work on a request, otherwise os queues requests
    - each request provide I/O mode, disk & memory address, and # of sectors
    - OS maintains a queue of requests, per disk or device
    - optimization algorithms only make sense when a queue exists

Disk Scheduling

- Disk scheduling usually tries to minimize **seek time**
  - rotational latency is difficult for OS to calculate
- There are many disk scheduling algorithms
  - FCFS
  - SSTF
  - SCAN
  - C-SCAN
  - C-LOOK
- We use a request queue of “**98, 183, 37, 122, 14, 124, 65, 67**” (**[0, 199]**), and initial head position **53** as the example

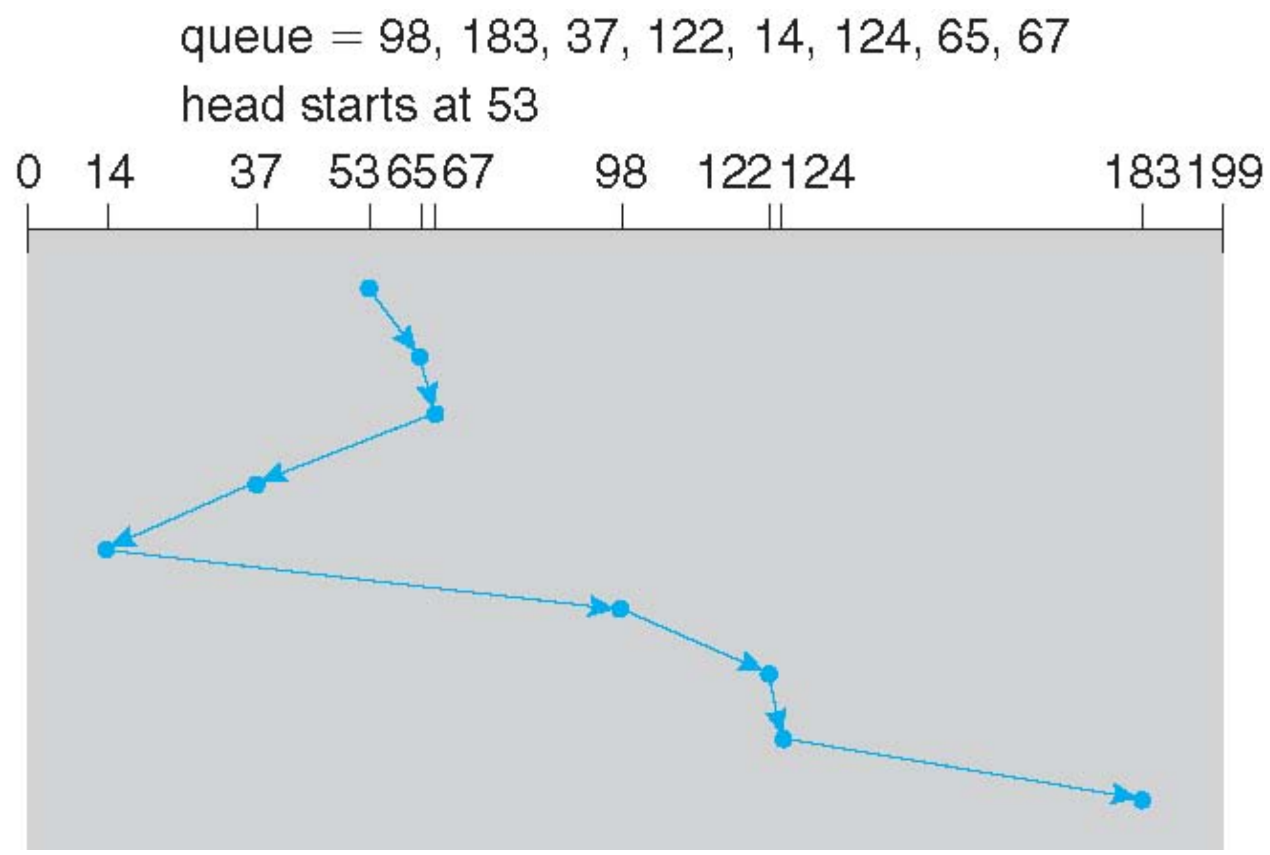
FCFS

- First-come first-served, simplest scheduling algorithm
- Total head movements of *640* cylinders



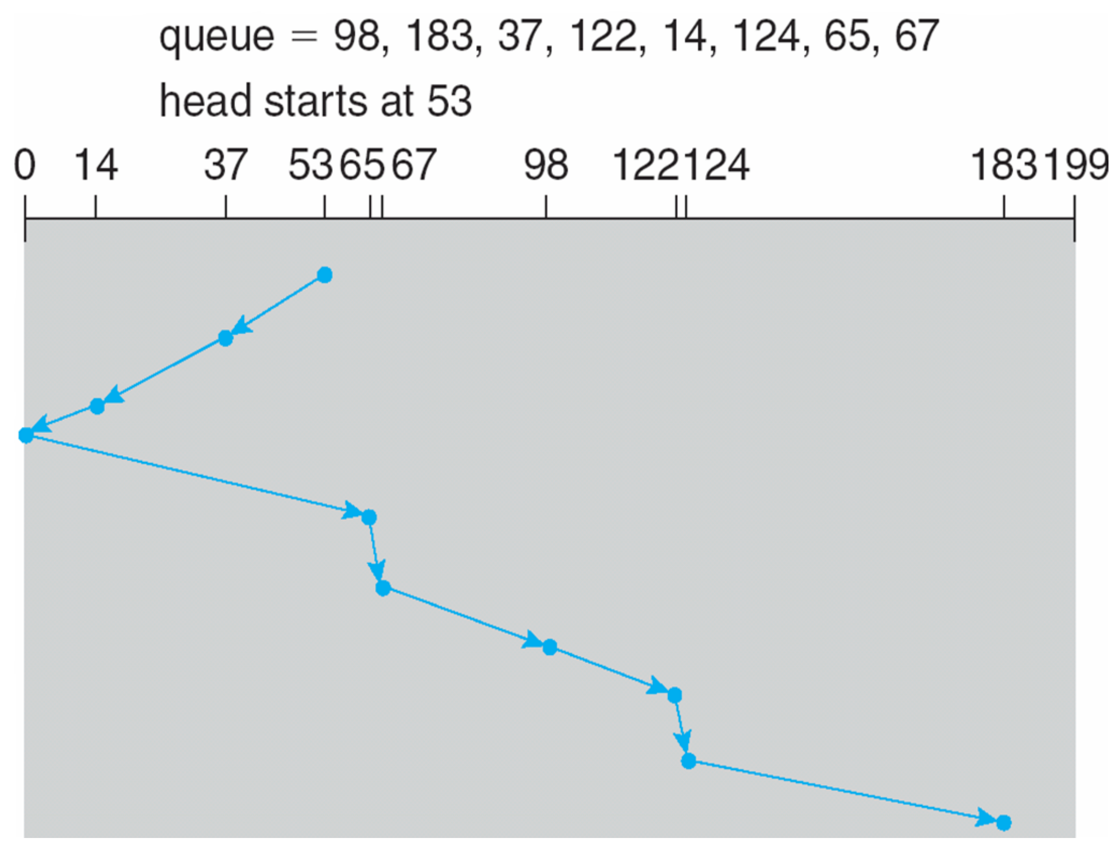
SSTF

- SSTF: shortest seek time first
  - selects the request with minimum seek time from the **current** head position
  - SSTF scheduling is a form of SJF scheduling, **starvation** may exist
    - unlike SJF, SSTF **may not** be **optimal** (why?)
- Total head movement of *236* cylinders



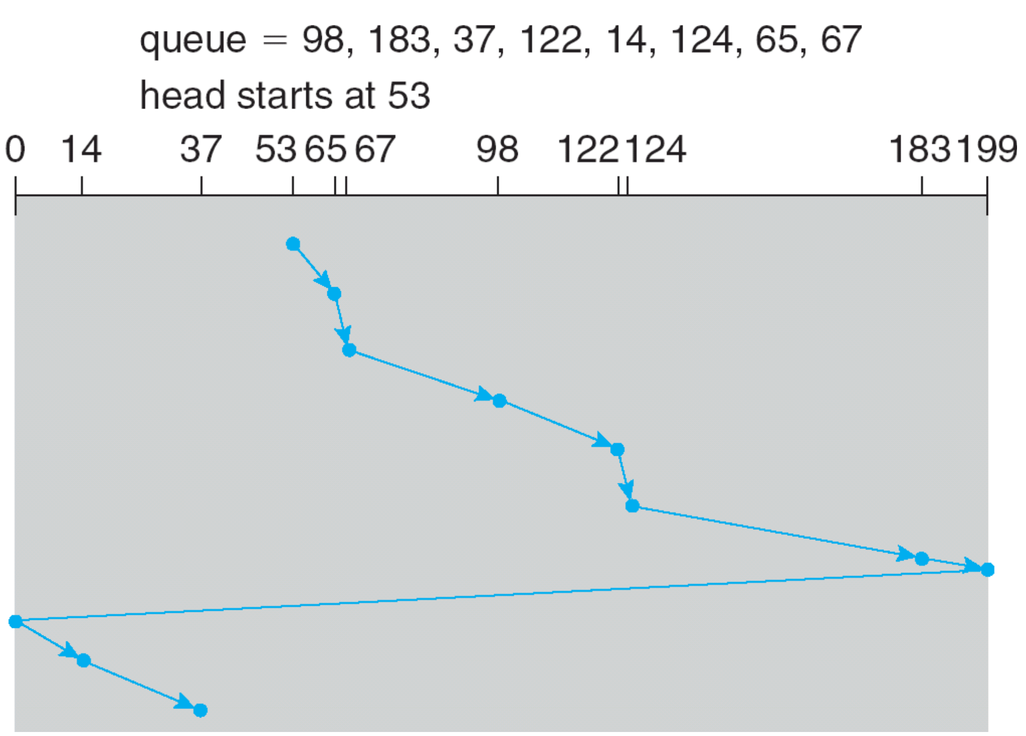
SCAN

- SCAN algorithm sometimes is called the **elevator** algorithm
  - disk arm starts at one **end** of the disk, and moves toward the **other end**
  - service requests during the movement until it gets to the other end
  - then, the head movement is reversed and servicing continues.
- Total head movement of *236* cylinders



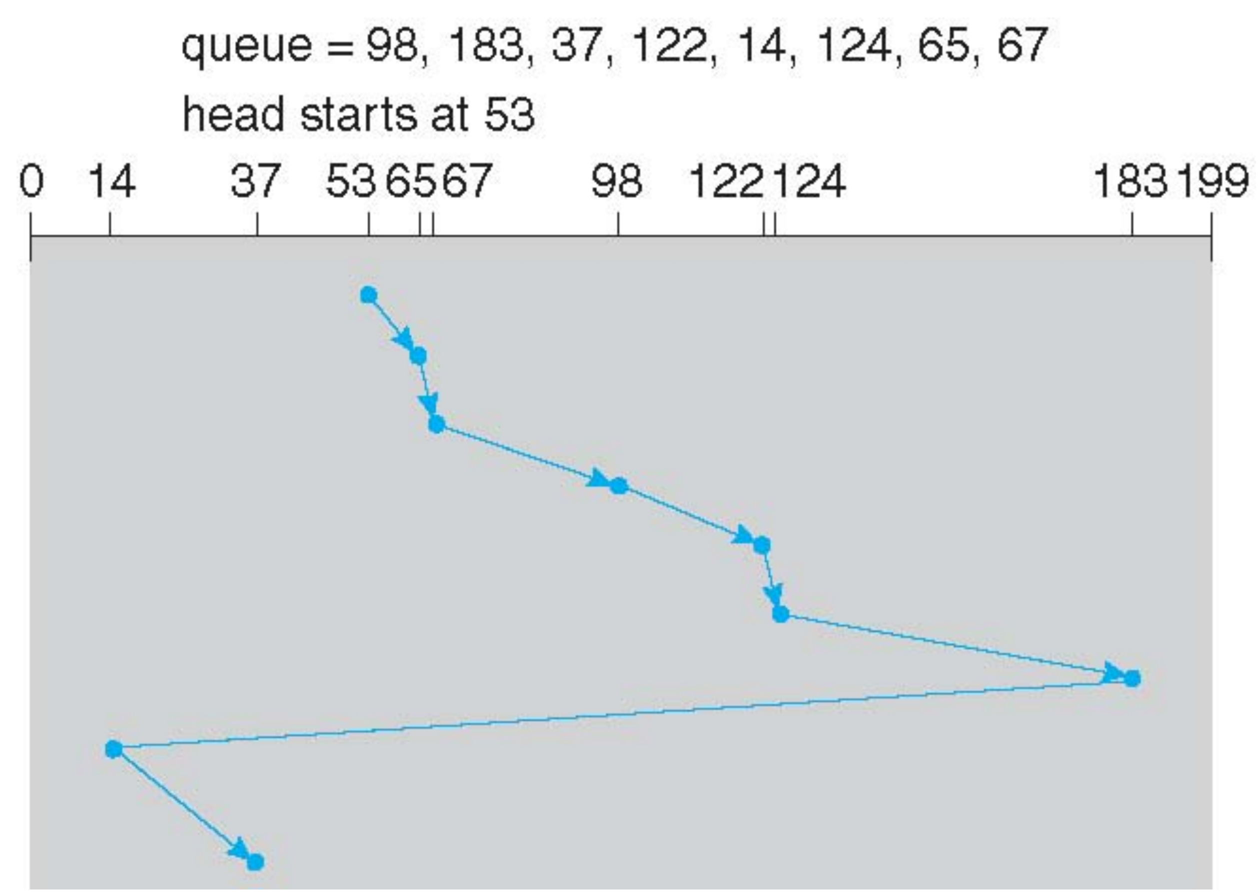
C-SCAN

- Circular-SCAN is designed to provides a more uniform wait time
  - head moves from **one end** to **the other**, servicing requests while going
  - when the head reaches the end, it immediately returns to the beginning
    - **without** servicing any requests on the return trip
  - it essentially treats the cylinders as a circular list
- Total number of cylinders?



LOOK/C-LOOK

- SCAN and C-SCAN moves head end to end, even no I/O in between
    - in implementation, head only goes as far as **last request** in each direction
    - **LOOK** is a version of **SCAN**, **C-LOOK** is a version of **C-SCAN**
- Total number of cylinders?



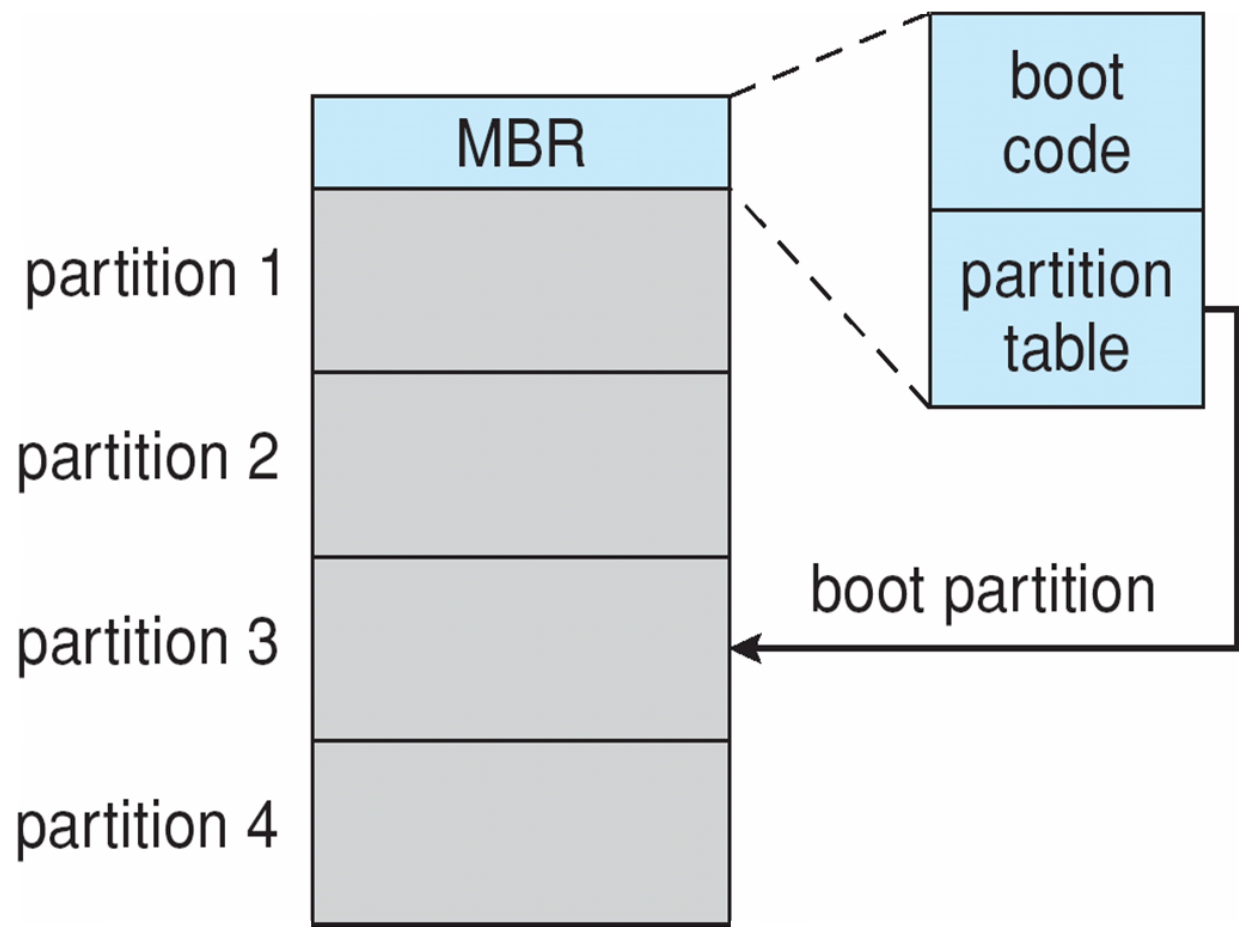
Selecting Disk-Scheduling Algorithm

- Disk scheduling performance depends on the # and types of requests
  - disk-scheduling should be written as a separate, replaceable, module
    - SSTF is common and is a reasonable choice for the default algorithm
    - LOOK and C-LOOK perform better for systems that have heavy I/O load
  - disk performance can be influenced by file-allocation and metadata layout
    - file systems spend great deal of efforts to increase spatial locality

Disk Management

- **Physical formatting**: divide disk into sectors for controller to read/write
  - each sector is usually 512 bytes of data but can be selectable
- OS records its own data structures on the disk
  - **partition disk** into groups of cylinders, each treated as a logical disk
  - **logical formatting** partitions to make a file system on it
    - some FS has spare sectors reserved to handle bad blocks
    - FS can further group blocks into clusters to improve performance
  - initialize the boot sector if the partition contains OS image

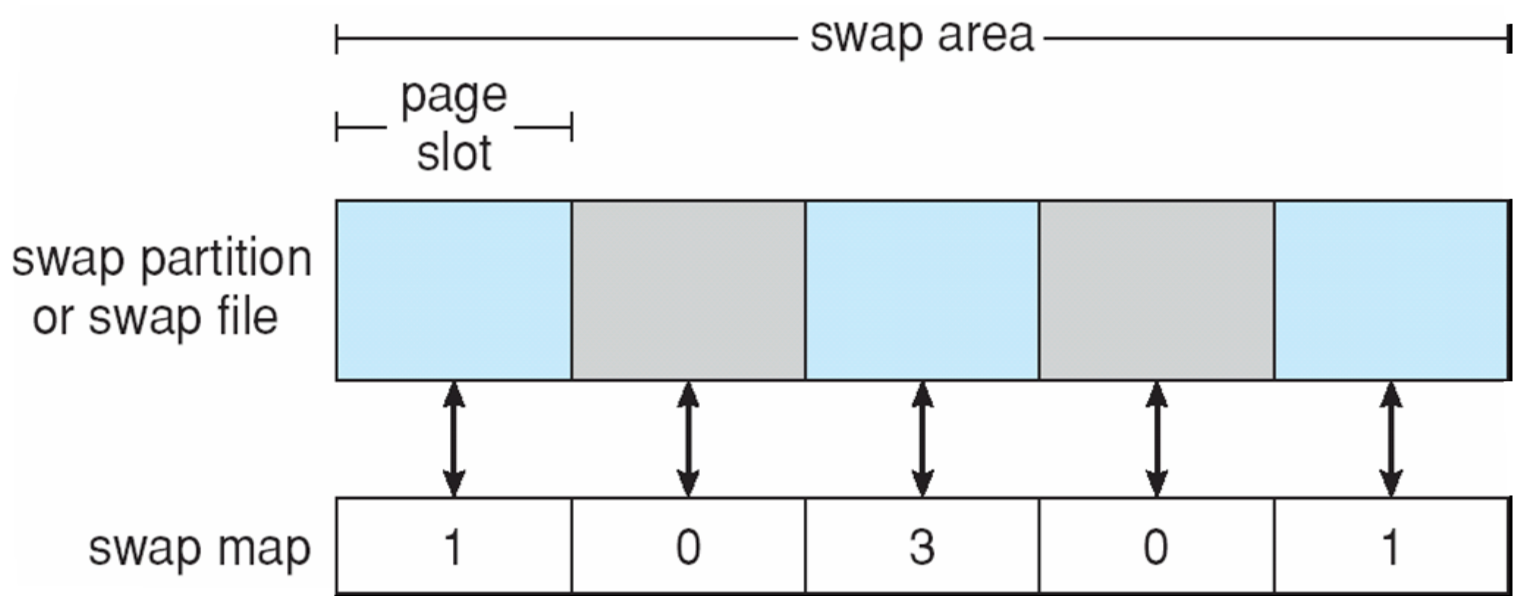
Windows 2000 Disk Layout



Swap Space Management

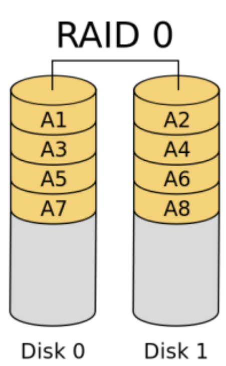
- **Swap space**: disk space used by virtual memory as an extension of the main memory
  - swap space can be carved out of normal FS, or a separate partition (raw)
  - less common now due to increased memory capacity
- Swap space management varies among OS
  - usually, kernel uses swap maps to track swap-space use
  - 4.3BSD allocates swap space when process starts
    - to hold text segment (the program) and data segment
  - Solaris 2 allocates it only when a dirty page is to be paged out
    - 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

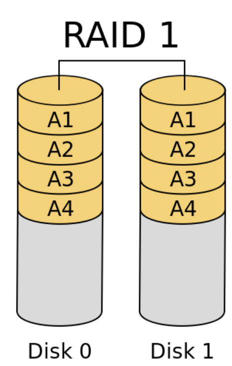
Linux Swap Space Management

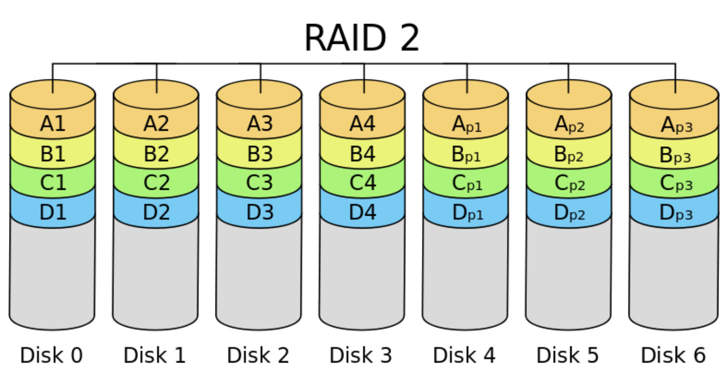


RAID

- RAID: use multiple disk drives to provide performance/reliability
  - reliability via mirroring or error correction code
  - performance via **disk striping**
    - segmenting logically sequential data, such as a file, and
    - store consecutive segments on different physical storage devices
- RAID is arranged into **six** different levels
  - **RAID 0**: splits data evenly across two or more disks without parity bits
    - aka. striped volume, it improves performance, but decrease MTTF
  - **RAID 1**: an exact copy (or mirror) of a set of data on two disks
  - **RAID 2**: stripes data at the bit-level; uses Hamming code for error correction (not used)
    - hamming code (4bit data+3bit parity) allows 7 disks to be used

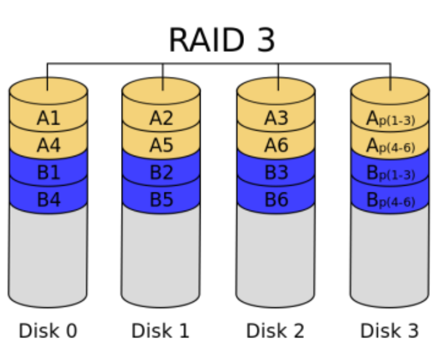


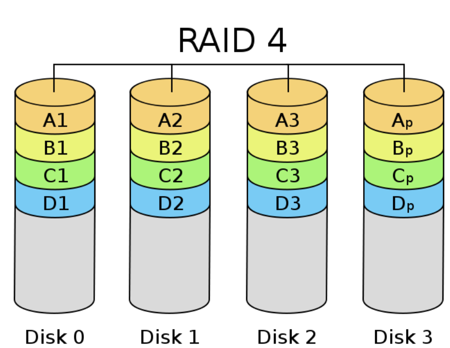


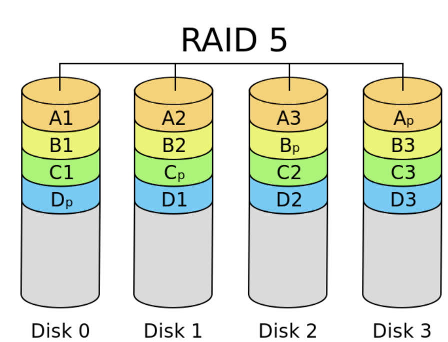


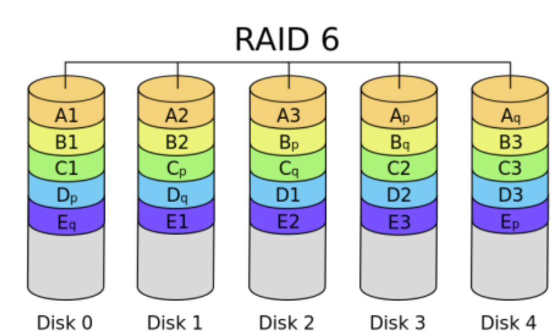
RAID

- **RAID 3**: byte-level striping with a dedicated parity disk (not used)
  - require synchronized disk spinning (RAID 3 is usually not used)
- **RAID 4**: block-level striping with a dedicated parity disk
  - a single block request can be fulfilled by one disk
  - different disk can fulfill different block requests
- **RAID 5**: block-level striping with parity data distributed across all disks
- **RAID 6**: extends RAID 5 by adding an additional parity block
  - RAID 6 has block-level striping with 2 parity blocks

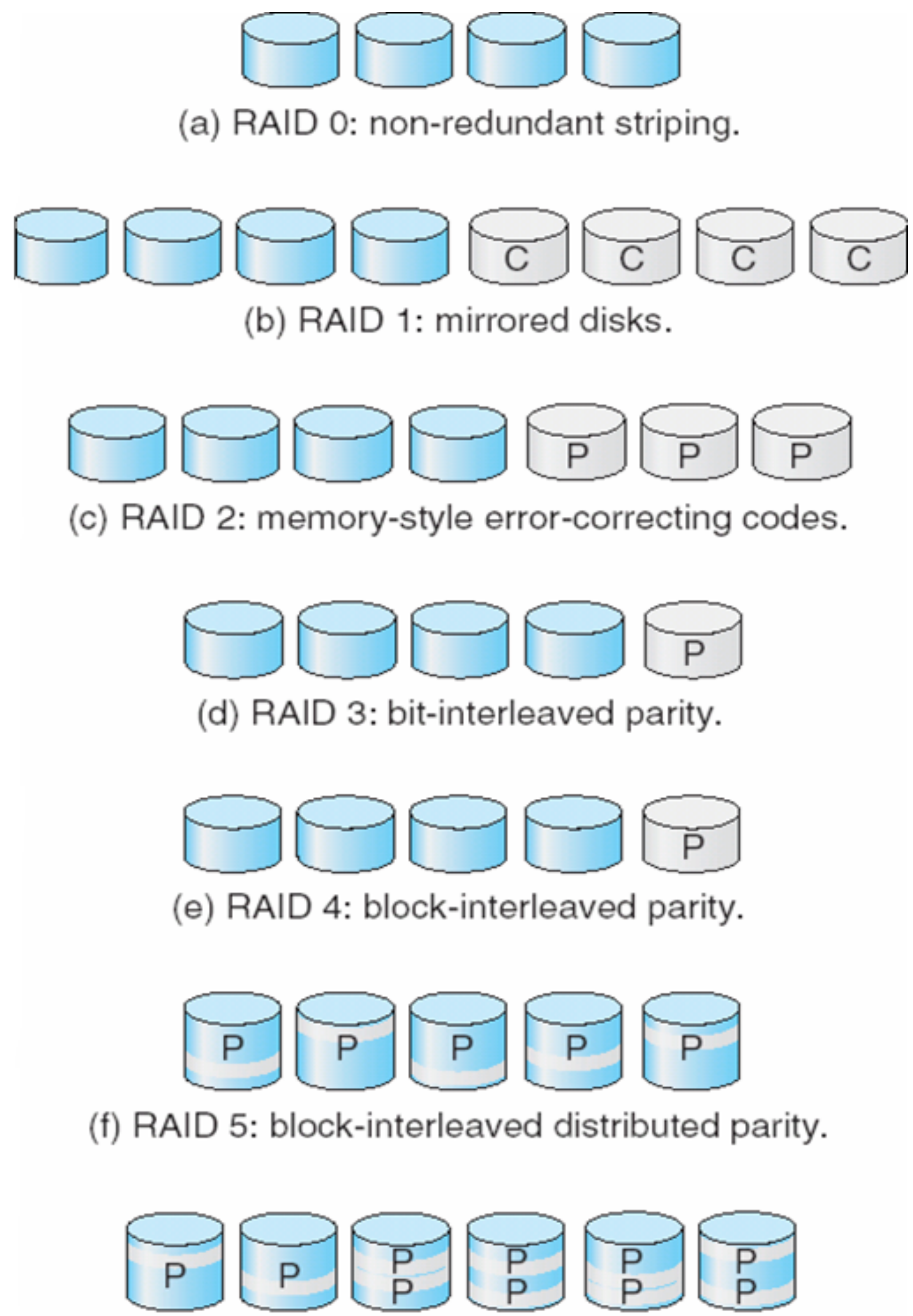








RAID Levels



(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.

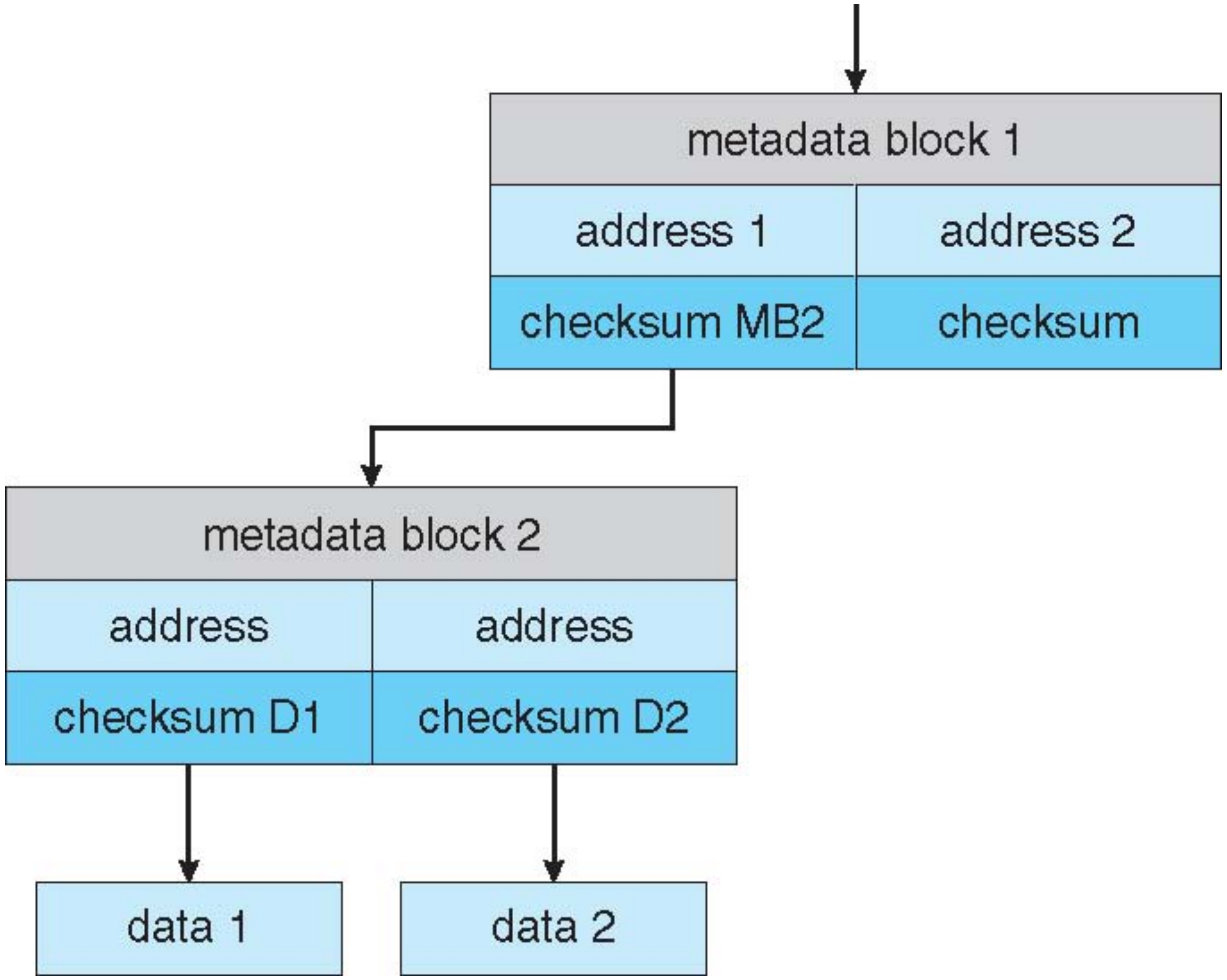
(f) RAID 5: block-interleaved distributed parity.

(g) RAID 6: P + Q redundancy.

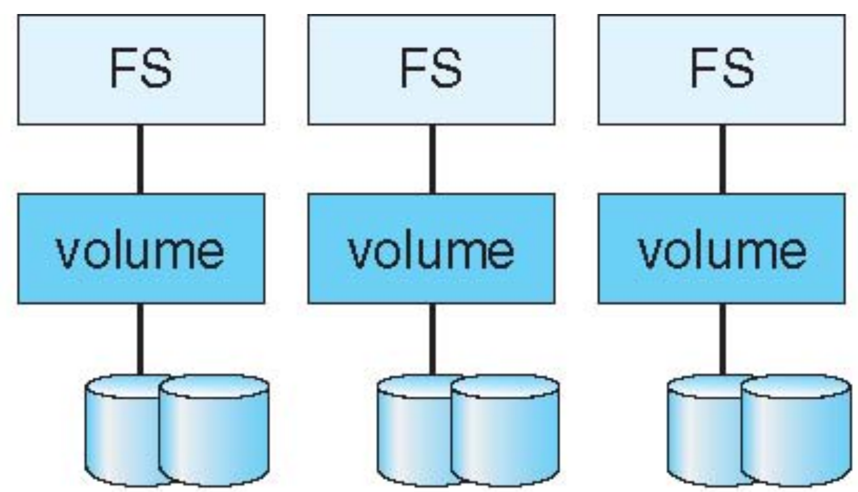
RAID and File Systems

- RAID can only detect/recover from **disk failures**
  - it does not prevent or detect data corruption or other errors
- File systems like Solaris ZFS add additional checks to detect errors
  - ZFS adds checksums to all FS data and metadata
    - checksum is collocated with pointer to the data/metadata
    - can detect and correct data and metadata corruption
  - ZFS allocates disks in pools, instead of volumes or partitions
    - file systems within a pool share that pool, allocate/free space from/to pool

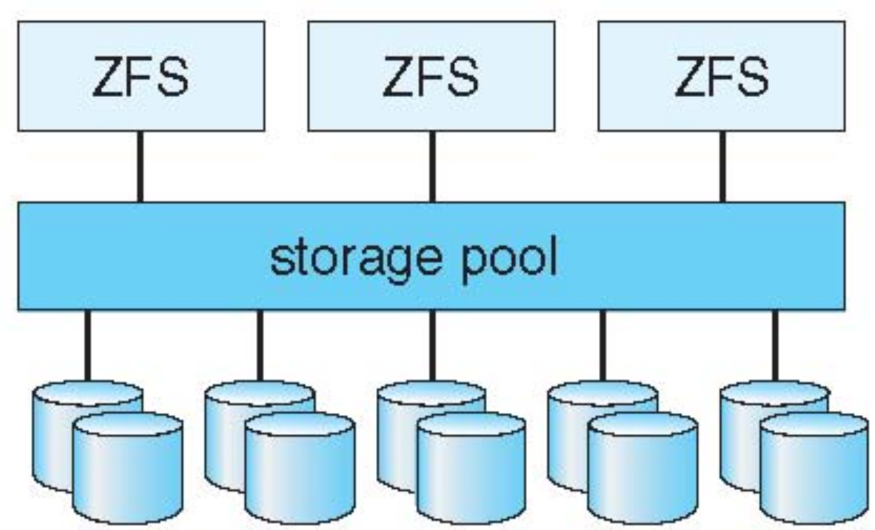
ZFS Checksums



Traditional and Pooled Storage



(a) Traditional volumes and file systems.



(b) ZFS and pooled storage.

Tertiary Storage Devices

- Tertiary storage: being third-level after memory and magnetic disks
  - e.g., floppy disks, CD-ROMs, DVDs…
  - usually removable
  - low cost

Magneto-optic Disks

- MO disk records data on a rigid platter coated with magnetic material
  - laser is used to record and read data
  - larger distance between head and disk surface (to shot the laser)
  - optical disks don't use magnetism; employs materials changeable by laser
- MO disk usually can be written many times

WORM Disks

- WORM disks can be written only once
  - WORM: write once, read many time (e.g., CD-ROM, DVD-ROM…)
  - usually a thin aluminum film sandwiched between two glass/plastic platters
  - to write a bit, drive uses laser to burn a small hole through the aluminum
    - information can be destroyed by not altered
  - relatively durable and reliable

Tapes

- Tape is less expensive and has higher capacity than disk
  - many cheap cartridges share a few expensive drives
    - e.g., dell PowerVault LTO-3: $2,056
- Tape is best for **sequential access**, random access is much slower
  - mostly used for backup or transfer of large volumes of data
  - large tape installation automates tape change and storage with robotic arms

OS-support for Tape

- Tapes are usually presented as a **raw** storage medium
  - normal disks can be accessed as either as raw media or with file systems
  - no file system on the tape, just array of blocks
  - tape drive is usually reserved for exclusive use of the application
  - the application decides how to use the array of blocks
    - other applications usually do not understand the format of it
- Tape drives are "**append-only**" devices
  - an EOT mark is placed after a block that is written
  - updating a block in the middle effectively erases everything beyond it

Speed of Tertiary Storage

- Two aspects of speed in tertiary storage are bandwidth and latency
- **Bandwidth** is measured in bytes per second.
  - **sustained bandwidth**: average data rate during a large transfer
    - data rate when the data stream is actually flowing
  - **effective bandwidth**: average over the entire I/O time
    - including seek time or locate time, and cartridge switching
    - drive's overall data rate
- **Access latency**: amount of time needed to locate data
  - access time for a disk: seek time + rotational latency; < 35 milliseconds
  - access time for tape: tens or hundreds seconds to wind the tape
    - thousands times slower than disk

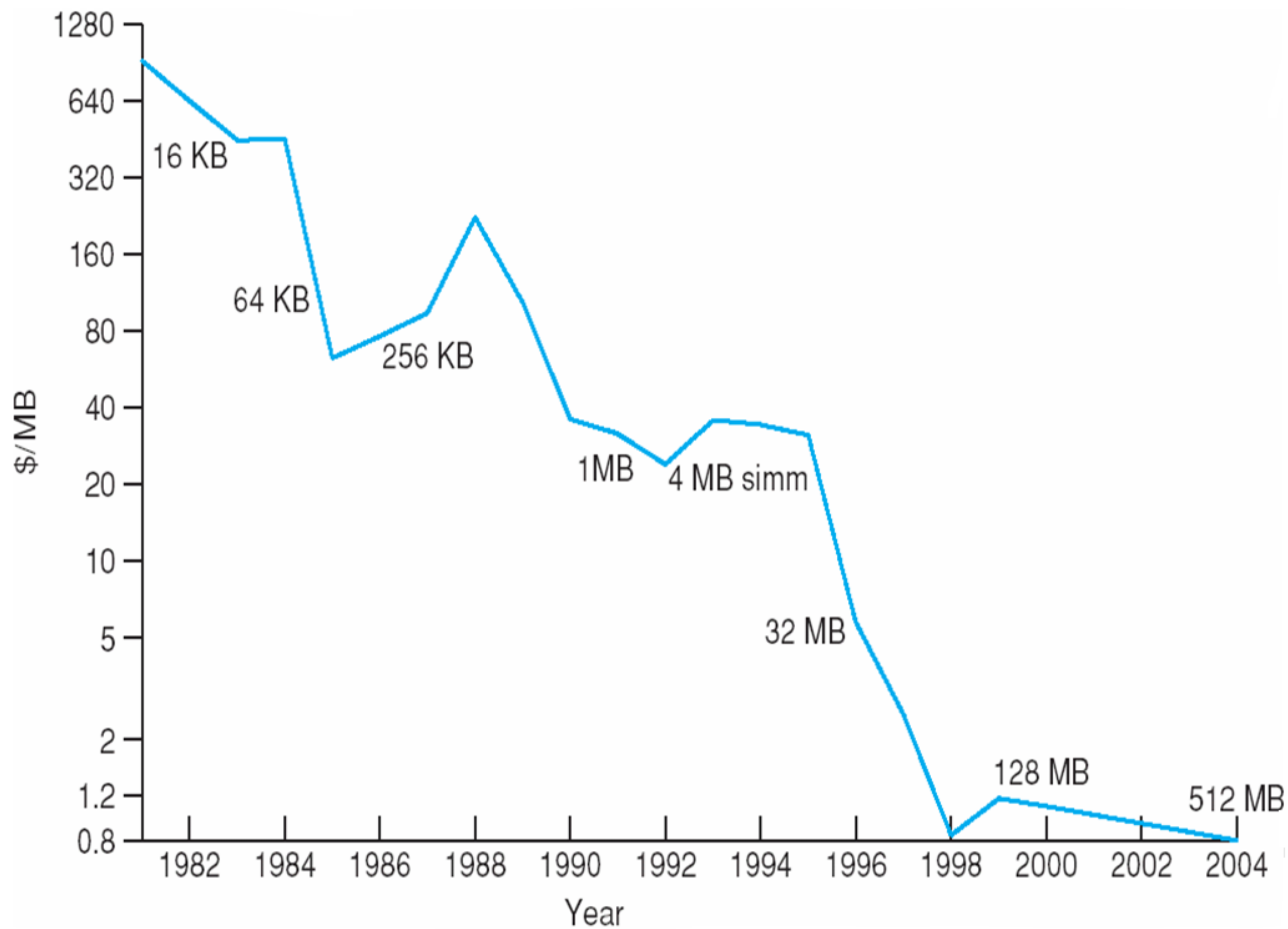
Relative Reliability

- A fixed disk is likely to be more reliable than a removable disk or tape
  - flash device is even more reliable as there are no moving parts
  - though a head crash in a fixed hard disk generally destroys the data
  - failure of tape drive or optical disk drive often leaves data undamaged
- An optical cartridge normally more reliable than magnetic disk or tape

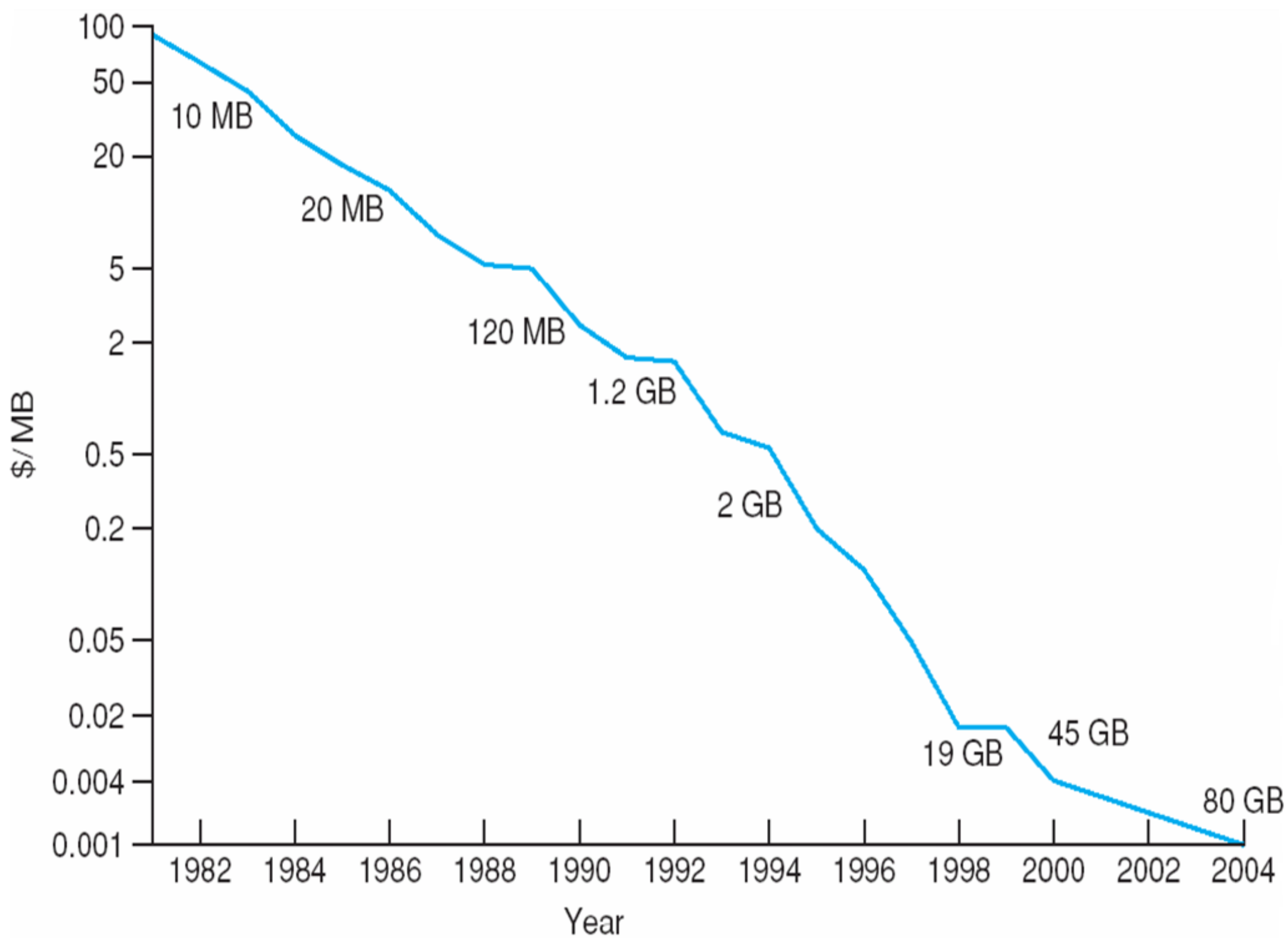
Cost

- Main memory is much more expensive than disk storage
- Cost per megabyte of hard disk is comparable to tape if only one tape is used per drive
  - but tape drive is expensive and tape is cheap
  - cheap tape and hard disk have about same storage capacity

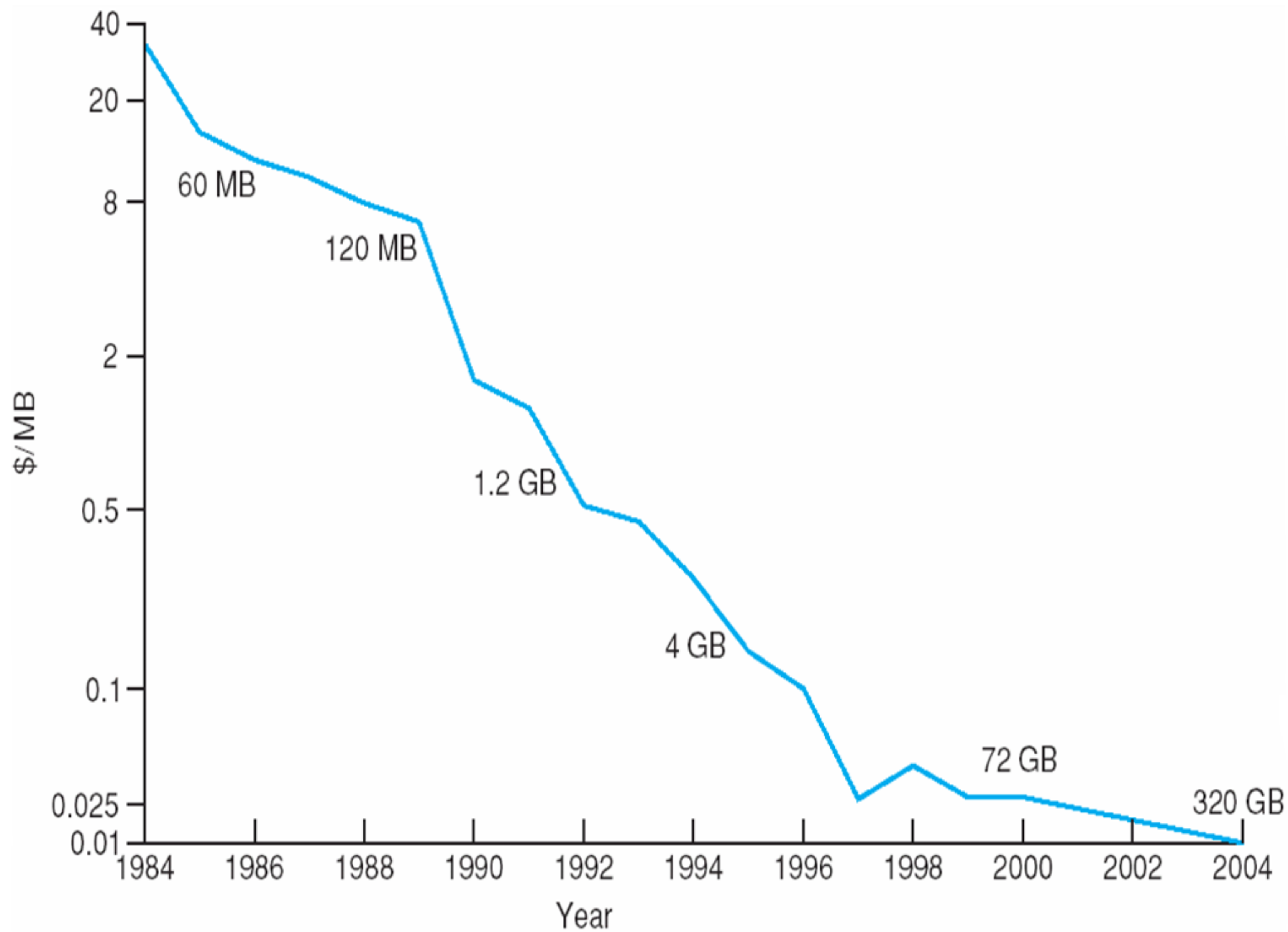
Cost Per Megabyte of DRAM



Cost Per Megabyte of Hard Disk



Cost Per Megabyte of Tape



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