CS370 Operating Systems

Colorado State University

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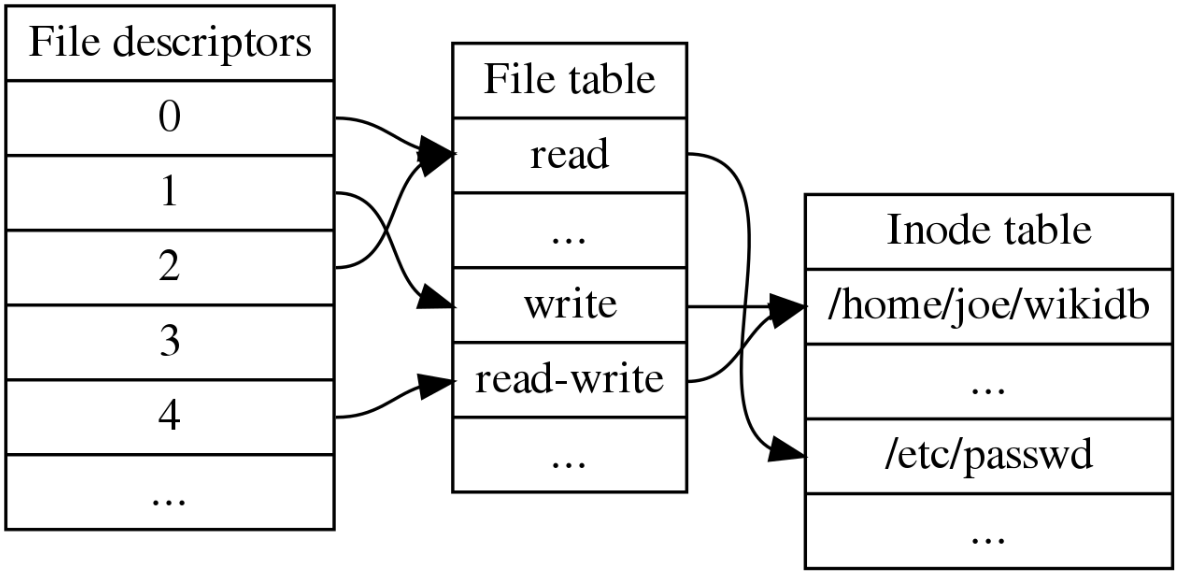
Fall 2024 L22

File-system Implementation

Slides based on

- Text by Silberschatz, Galvin, Gagne
- Various sources

Process, System, Files



- **File descriptor table for a process:** File descriptor (FD int), pointer
- **System wide open File Table in memory:** r/w status, offset, open count, inode number
- **Inode table for all files/dirs:** indexed by inode numbers on the disk **(unix: ls – ia)**
  - **Inode for a file:** file/dir metadata (attributes etc), pointers to blocks

On-disk File-System Structures

1. **Boot control block** contains info needed by system to boot OS from that volume
   – Needed if volume contains OS, usually first block of volume

> Volume: logical disk drive, perhaps a partition

2. **Volume control block** (**superblock** ext **or master file table** NTFS) contains volume details
   – Total # of blocks, # of free blocks, block size, free block pointers or array
3. Directory structure organizes the files
   – File Names and inode numbers UFS, master file table NTFS

Boot block	Super block	FCBs	File data blocks

When a file is created

When a new file is created n a directory, the OS

- Allocates a new FCB.
- Update directory
  - Reads the appropriate directory into memory, in unix a directory is a file with special type field
  - updates it with the new file name and FCB,
  - writes it back to the disk.

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Block Allocation Methods

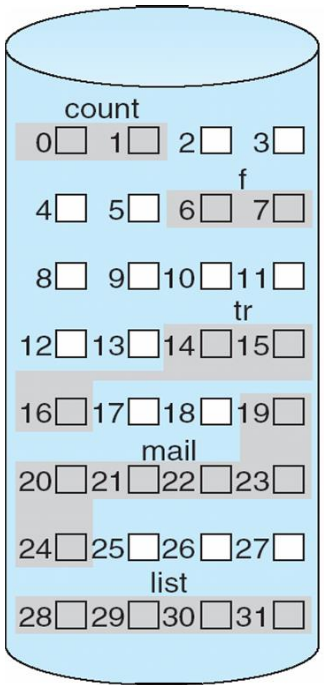
An allocation method refers to how disk blocks are allocated for files:

- Contiguous (not common, except for DVDs etc.)
- Linked blocks, Linked guide (e.g., FAT32)
- Indexed (e.g., ex4)

A disk block can be a physical sector. They ae numbered using a linear sequence.

Actual implementations are more complex than the simple ones examined here.
Contrast these with allocation for processes in memory

Contiguous Allocation

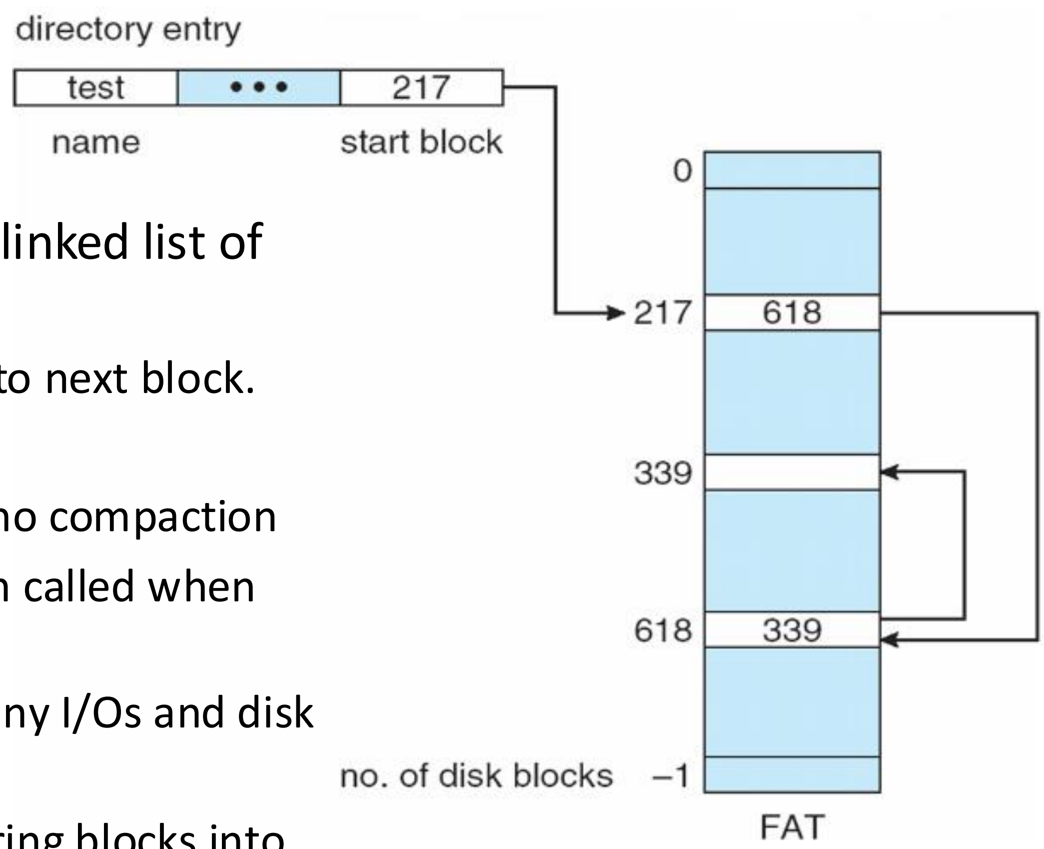


directory

file	start	length
count	0	2
tr	14	3
mail	19	6
list	28	4
f	6	2

File **tr**: 3 blocks
Starting at block 14

Allocation Methods - Linked



ii. Linked allocation – each file a linked list of blocks

- Each block contains pointer to next block.
- File ends at null pointer
- No external fragmentation, no compaction

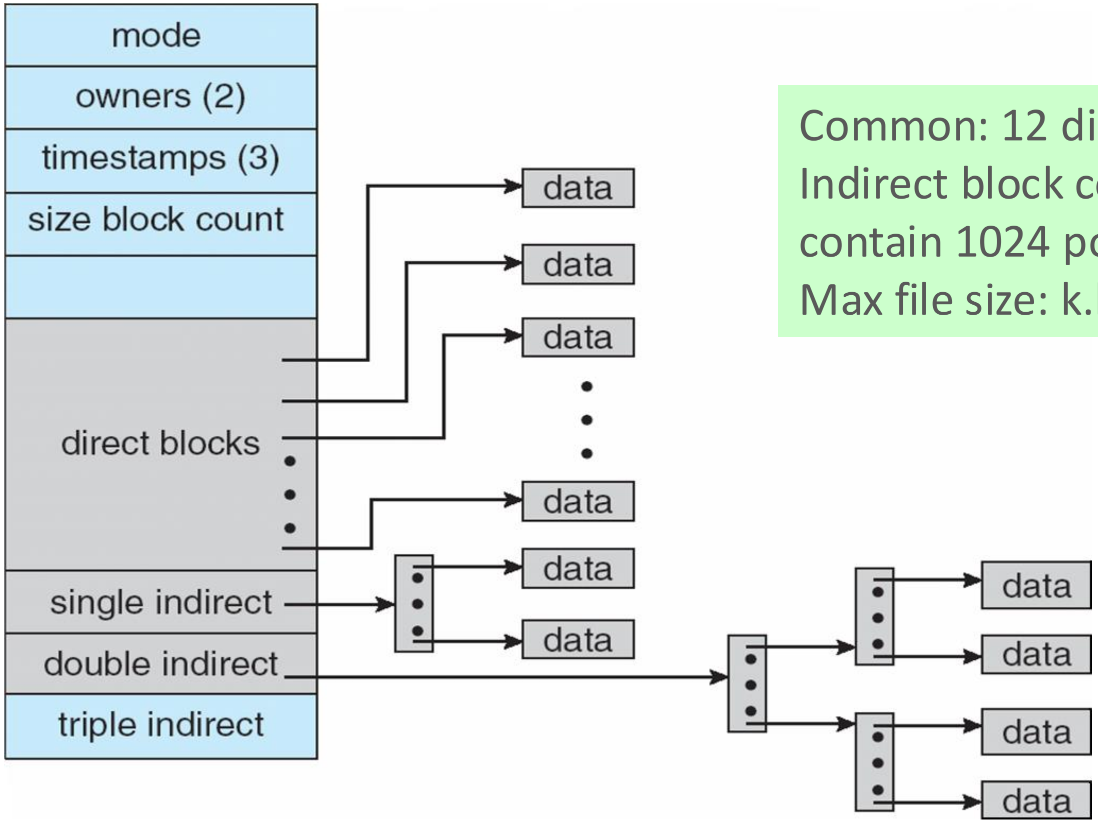
Free space management system called when new block needed

- Locating a block can take many I/Os and disk seeks.
- Improve efficiency by clustering blocks into groups but increases internal fragmentation
- Reliability can be a problem, since every block in a file is linked.

Indexed Scheme: UNIX inodes

Assume 4K bytes per block, 32-bit addresses. Ext3 example.

Volume block:
Table with file names
Points to this inode
(file control block)



Common: 12 direct+3.
Indirect block could
contain 1024 pointers.
Max file size: k.k.k.4k (triple)+

Ext4: uses extents
(pointer+ length)

More index blocks than can be addressed with 32-bit file pointer

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Performance

- Best method depends on file access type
  - Contiguous: OK when files don't change much
  - Linked: used for smaller file systems of the past: FAT, FAT32
  - Indexed more complex, modern
    - Single block access could require 0-3 index block reads then data block read
    - Clustering or disk caching can help improve throughput, reduce CPU overhead
    - Ex: Ext3, Ext4

Cluster: set of contiguous sectors

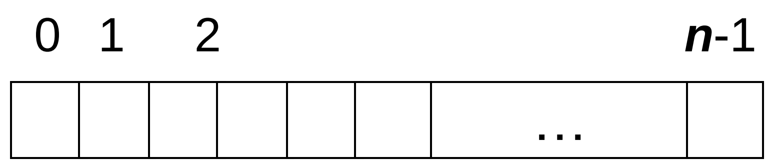
Performance (Cont.)

- Is adding instructions to the execution path to save one disk I/O is reasonable?
  - AMD Ryzen Threadripper 3990X (2020) 2,356,230 MIPS
    - http://en.wikipedia.org/wiki/Instructions_per_second
  - Typical disk drive at 250 I/Os per second
    - 2,356,230 MIPS / 250 = 9425 million instructions during one disk I/O
  - Fast SSD drives provide 60,000 IOPS
    - 2,356,230 MIPS / 60,000 = 39.3 millions instructions during one disk I/O

Free-Space Management

- File system maintains **free-space list** to track available blocks/clusters
  - (Using term "block" for simplicity)
  - **Approaches: i. Bit vector ii. Linked list iii. Grouping iv. Counting**

i. Bit vector or **bit map** (***n*** blocks)



$$\text{bit}[i] = \begin{cases} 1 \Rightarrow \text{block}[i] \text{ free} \\ 0 \Rightarrow \text{block}[i] \text{ occupied} \end{cases}$$

Block number calculation for first free block

(number of bits per word) *(number of 0-value words) + offset of first 1 bit

00000000
00000000
00111110
..

CPUs may have instructions to return offset within word of first "1" bit

Free-Space Management (Cont.)

Bit map requires extra space

- Example:

  block size = 4KB = 2^{12} bytes

  disk size = 2^{40} bytes (1 terabyte)

  blocks: $\boldsymbol{n} = 2^{40}/2^{12} = 2^{28}$

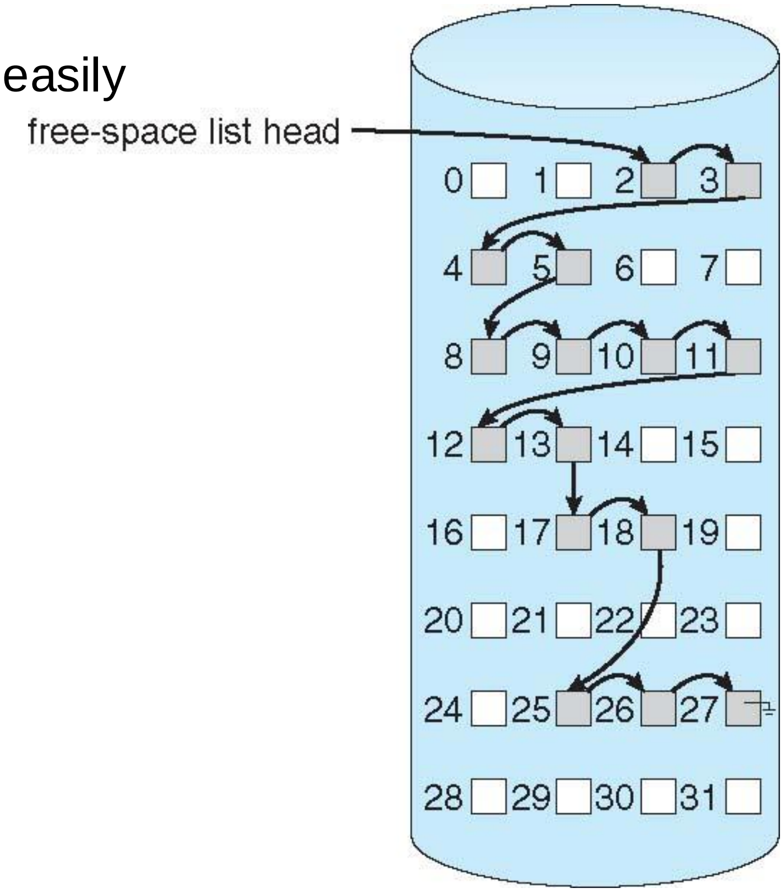
  Need 2^{28} bits or 32MB for map

  if clusters of 4 blocks -> 8MB of memory

Bit map makes it easy to get contiguous files if desired

Linked Free Space List on Disk

- ii. Linked list (free list)
  - Cannot get contiguous space easily
  - No waste of space



Superblock Can hold pointer to head of linked list

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Free-Space Management (Cont.)

- iii. Grouping
  - Modify **linked list** to store address of next *n-1* free blocks in first free block, plus a pointer to next block that contains free-block-pointers free block pointer blocks in a linked list.
- iv. Counting
  - Because space is frequently contiguously used and freed, with contiguous-allocation allocation, extents, or clustering
    - Keep address of first free block and count of following free contiguous blocks
    - Free space list then has entries containing **addresses and counts**

UNIX directory structure

- Contains only file names and the corresponding inode numbers an inode uniquely identifies a file
- Use **ls – i** to retrieve inode numbers of the files in the directory
- Looking up path names in UNIX

  Example: /usr/tom/mbox

  – Lookup inode for /, then for usr, then for tom, then for mbox

Advantages of directory entries that have name and inode information

- Changing filename only requires changing the directory entry
- Only 1 physical copy of file needs to be on disk
  - File may have several names (or the same name) in different directories
- Directory entries are small
  - Most file info is kept in the inode

Hard and symbolic links

Hard Links:

- Both file names refer to the same inode (and hence same file)
  - Directory entry in /dirA

    ..[12345 filename1]..
  - Directory entry in /dirB

    ..[12345 filename2]..
- To create a hard link

  ln /dirA/filename1 /dirB/filename2
- Symbolic link *shortcut* in windows
  - To create a symbolic link

    ln -s /dirA/filenmame1 /dirB/filename3

    File filename3 just contains a pointer

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File system based on inodes

Limitations

- File **must fit** in a single disk partition
- Partition size and number of files are **fixed** when system is set up

inode preallocation and distribution

- inodes are **preallocated** on a volume
  - Even on empty disks % of space lost to inodes
- Preallocating inodes
  - Improves performance
- Keep file's data block **close** to its inode
  - Reduce seek times

Checking up on the inodes

Command: df -i (df is for disk filesystem)

Gives inode statistics for the file systems: total, free and used nodes

```
Filesystem                   Inodes   IUsed    IFree IUse% Mounted on
devtmpfs                    2045460     484  2044976    1% /dev
tmpfs                       2053722       1  2053721    1% /dev/shm
tmpfs                       2053722     695  2053027    1% /run
tmpfs                       2053722      16  2053706    1% /sys/fs/cgroup
```

Command: ls –i (lists inodes of the files in current directory_

```
13320302                diskusage.txt
2408538                 Documents/
680003                  downloads/
```

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Fall 2024. Ch 11

Mass Storage

Slides based on
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- Various sources

Chapter 11: Mass-Storage Systems

- Overview of Mass Storage
- Technologies, performance
- Disk Scheduling
- Disk Management
- RAID Structure

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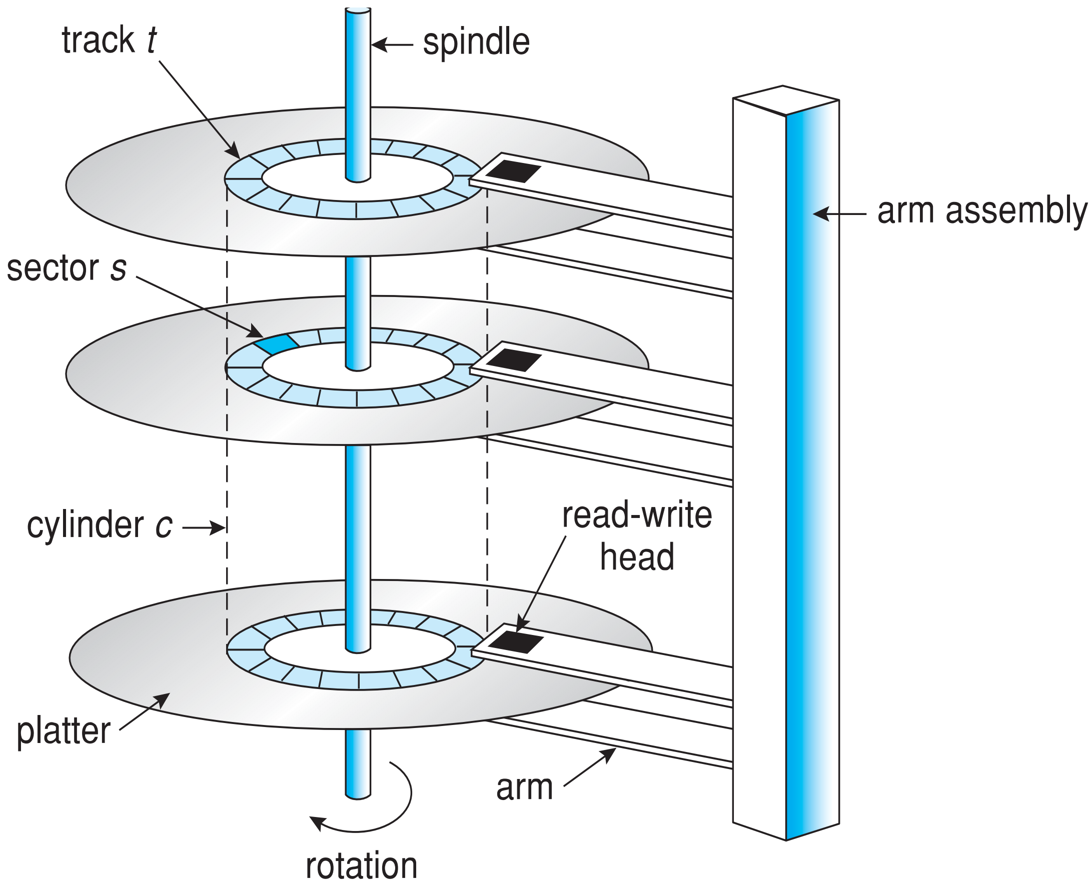
Objectives

- 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
  - **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
- Disks can be removable
- 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

Moving-head Disk Mechanism



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Hard Disks

- Platters range from 0.85" to 14" (historically)
  - Commonly 3.5", 2.5", and 1.8"
- Range from 16GB to **12TB** per drive
- Performance
  - Transfer Rate – theoretical – 6 G**b**/sec
  - Effective Transfer Rate – real – 1G**b**/sec (about 150 M**B**/s)
  - Seek time from 2ms to 12ms – 9ms common for desktop drives
  - Average seek time measured or calculated based on 1/3 of tracks
  - Latency based on spindle speed
    - 1 / (RPM / 60) = 60 / RPM
  - Average latency = ½ latency

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

(From Wikipedia)

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
- Example: Find expected I/O time to transfer a 4KB block on a 7200 RPM disk with a 5ms average seek time, 1Gb/sec transfer rate with a 0.1ms controller overhead.

Av latency =60/(7200*2)

= (5ms + 4.17ms) + 0.1ms + transfer time

- Transfer time = 4KB / 1Gb/s = 4x8K/G = 0.031 ms
- Average I/O time for 4KB block = 9.27ms + .031ms = 9.301ms

Strategy: memorize formula or understand how it works?

Interfaces for HDD/SSD

Actual data rates (not raw)

Serial ATA (SATA): Serial: 4 Pin + grounds

- SATA-I: 125 MB/s
- SATA-II: 250 MB/s
- SATA-III: 500 MB/s

PCI Express (PCIe) v5.0

- 32 GB/s per lane, Up to 16 lanes
- Very low power and broad hardware support
- Very expensive, extremely high-performance applications

USB 3.2

- 610MB/s

Thunderbolt 3

- 4.88 GB/s

The First Commercial Disk Drive

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

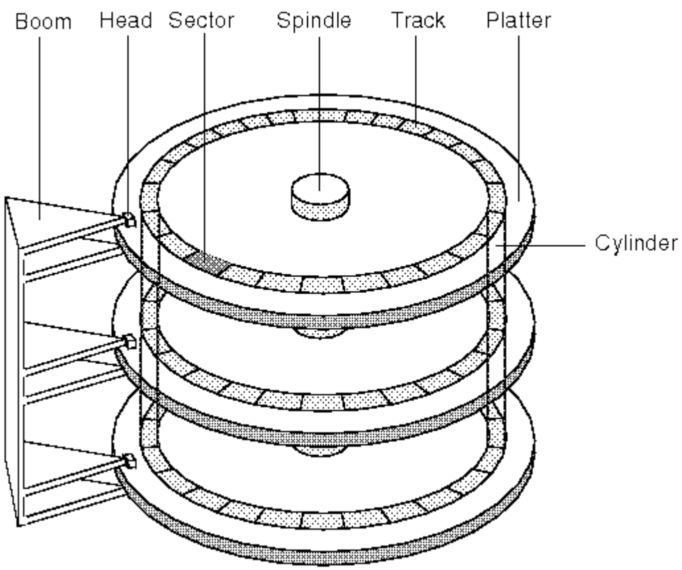
5M (7 bit) characters
50 x 24" platters
Access time = < 1 second

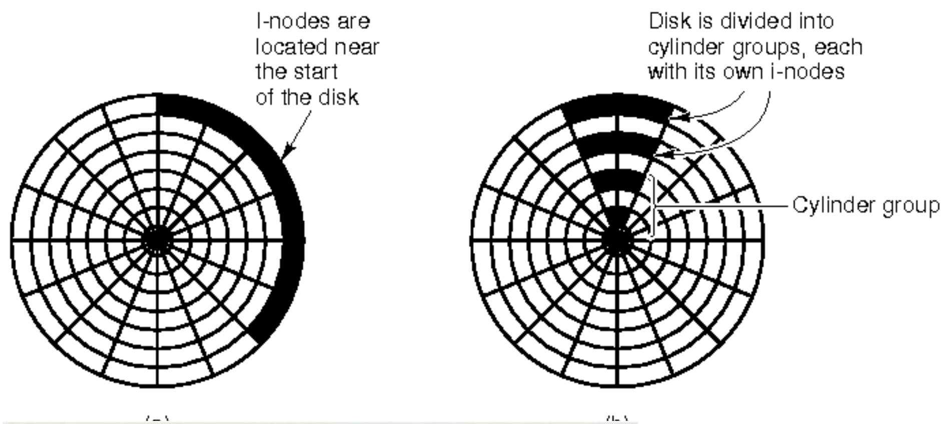
Disk Structure

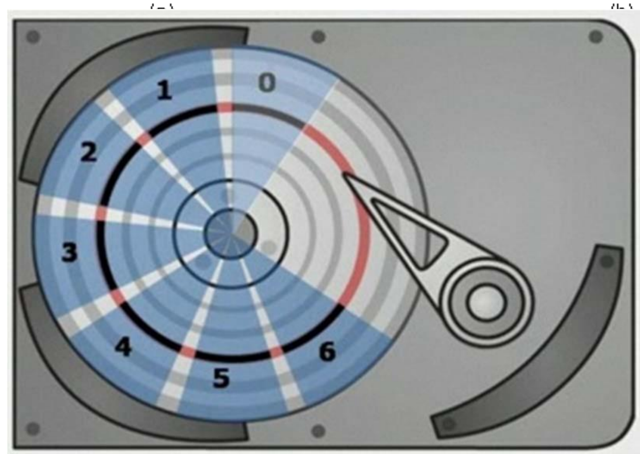
- Disk drives are addressed as large 1-dimensional arrays of **logical blocks**, where the logical block is the smallest unit of transfer
  - Low-level formatting creates **sectors** on physical media (typically 512 bytes)
- The 1-dimensional array of logical blocks is mapped into the sectors of the 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

FAQ

- Physical: Drive, Cylinder, Head, sector
- Logical Block Addressing (LBA): blocks addressed by numbers.
- Inodes: where?







Disk Formatting

- Low-level formatting marks the surfaces of the disks with markers indicating the start of a recording block (sector markers) and other information by the disk controller to read or write data.
- Partitioning divides a disk into one or more regions, writing data structures to the disk to indicate the beginning and end of the regions. Often includes checking for defective tracks/sectors.
- High-level formatting creates the file system format within a disk partition or a logical volume. This formatting includes the data structures used by the OS to identify the logical drive or partition's contents.

Solid-State Disks

- Nonvolatile memory used like a hard drive
  - Many technology variations
  - Same physical sizes, same interfaces (SATA, PCIe, SCSI)
- Can be more reliable than HDDs
- More expensive per MB ($0.30/GB vs $0.05 for HD)
- Life span (1-5 million write cycles) shorter/longer?
- Capacity ? (up to 16 TB vs 8 TB for HD)
- faster (access time <0.1 millisec, transfer rate 100MB-GB/s)
  - No moving parts, so no seek time or rotational latency
- Lower power consumption
- 3D Xpoint: 10x faster, 3x endurance, 4x denser than NAND flash


CARTOONSTOCK
.com
Search ID: bfrn431
" MY DOG ATE THE FLASH DRIVE WITH MY HOMEWORK ON IT...BUT I'M HOPING TO GET IT BACK REAL SOON! "

SSD Architecture

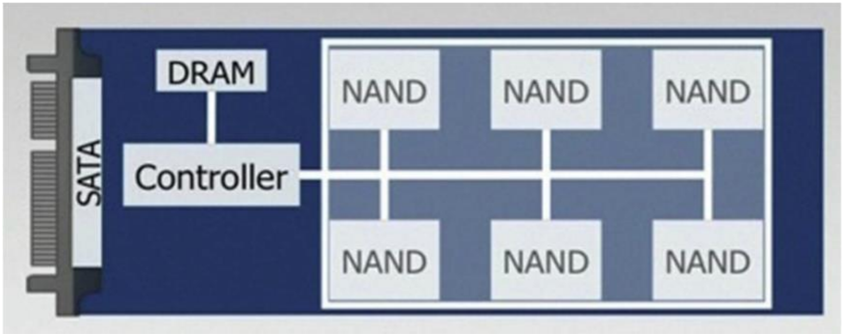
Controller

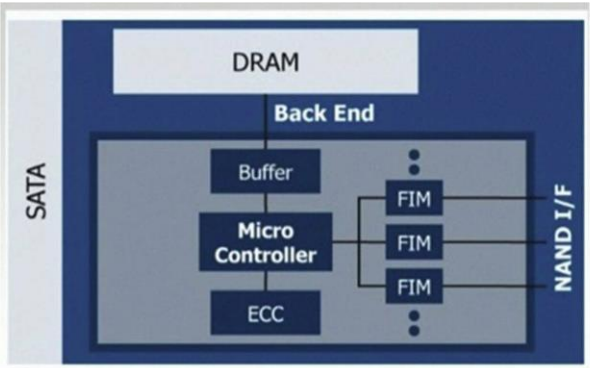
- Takes the raw data storage in the NAND flash and makes it look and act like hard disk drive
- Contains the micro controller, buffer, error correction, and flash interface modules

Micro Controller – a processor inside the controller that takes the incoming data and manipulates it

- Correcting errors
- Manages mapping
- Putting data into the flash or retrieving it from the flash

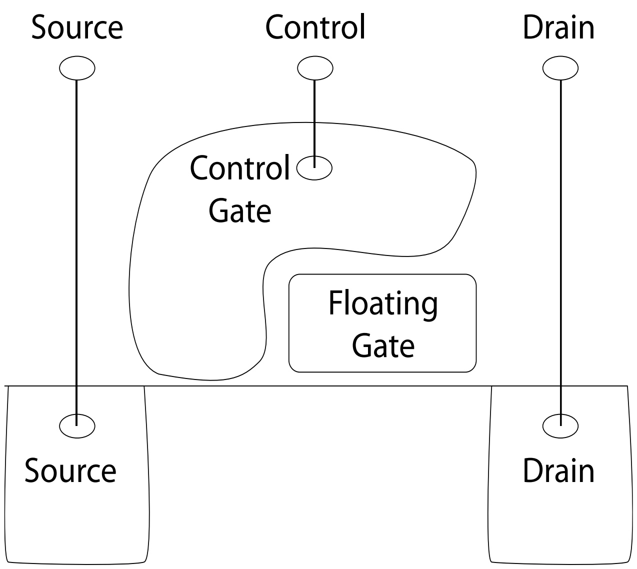
DRAM Cache – Reasonable amount of very low latency



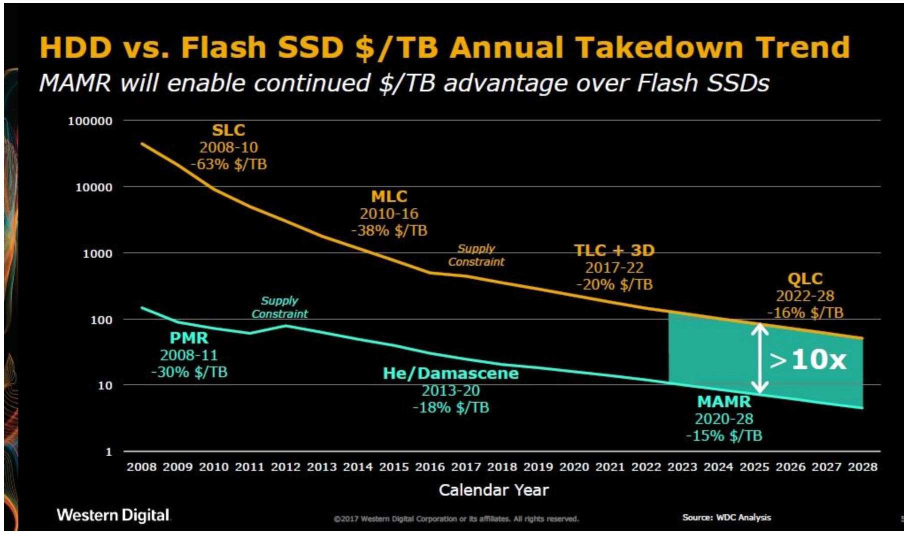


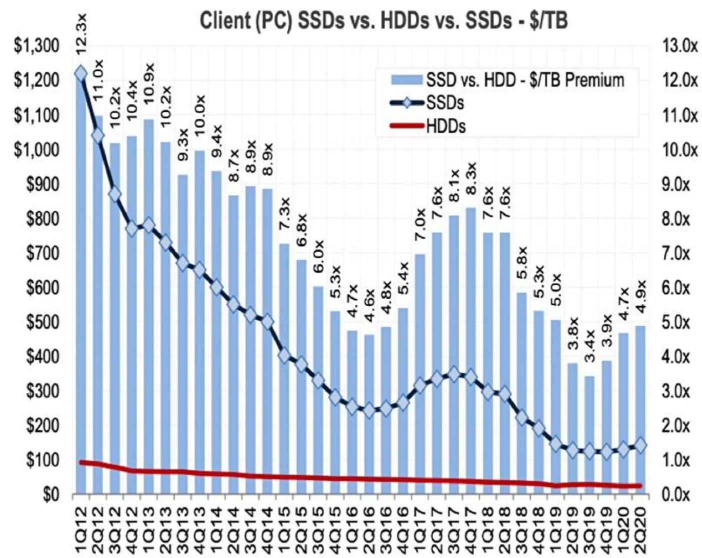
Flash Memory

- Writes must be to "clean" cells; no update in place
  - Large block erasure required before write
  - Erasure block: 128 – 512 KB
  - Erasure time: Several milliseconds
- Write/read page (2-4KB)
  - 50-100 usec

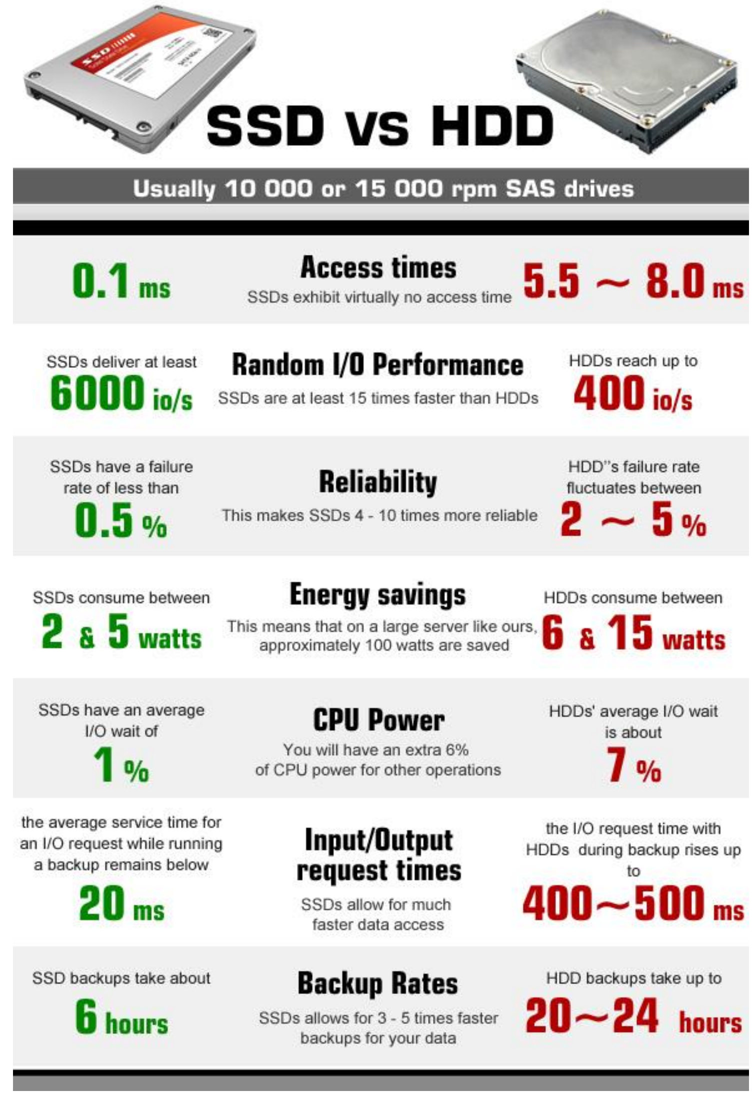


SSD vs HDD





Source: IDC Worldwide Quarterly SSD Results; TrendFocus; Wells Fargo Securities, LLC



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HDD vs SSD

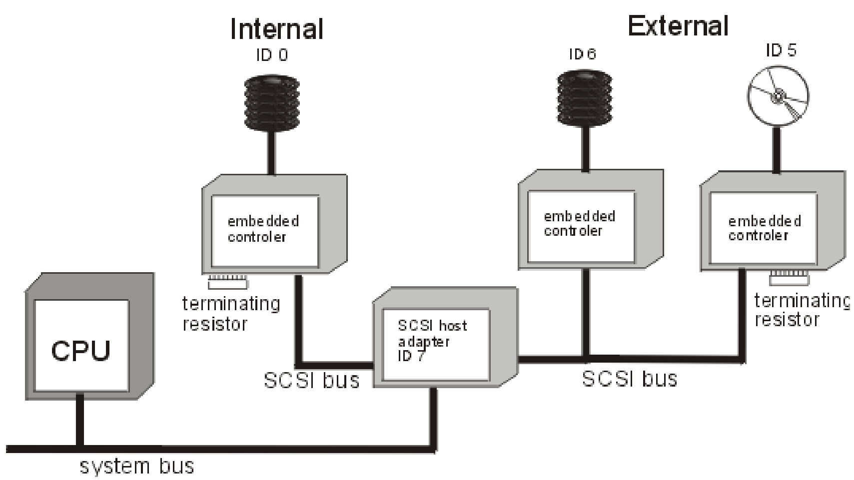
	HDD	SSD
	WD VelociRaptor	OCZ Vertex 3
Storage Capacity	600GB	120GB-360GB
Price for storage	48¢/ GB	2.08$/GB x4
Seek Time/Rotational Speed	7ms/157 MB/s	
MTBF	1.4 million hours?	2 million hours?
Sequential Read/Write	1 MB/s	413.5/371.4 MB/s
Random Read	1 MB/s	68.8 MB/s
Random Write	1 MB/s	332.5 MB/s
IOPS	905	60,000 x60

Magnetic Tape

- Was early secondary-storage medium (now tertiary)
  - 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 Sony: New 185 TB

Disk Attachment: I/O busses

- 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** (adapter) requests operation and **SCSI targets** (controller) perform tasks
  - Each target can have up to 8 **logical units** (disks attached to device controller)
- FC (fibre channel) 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

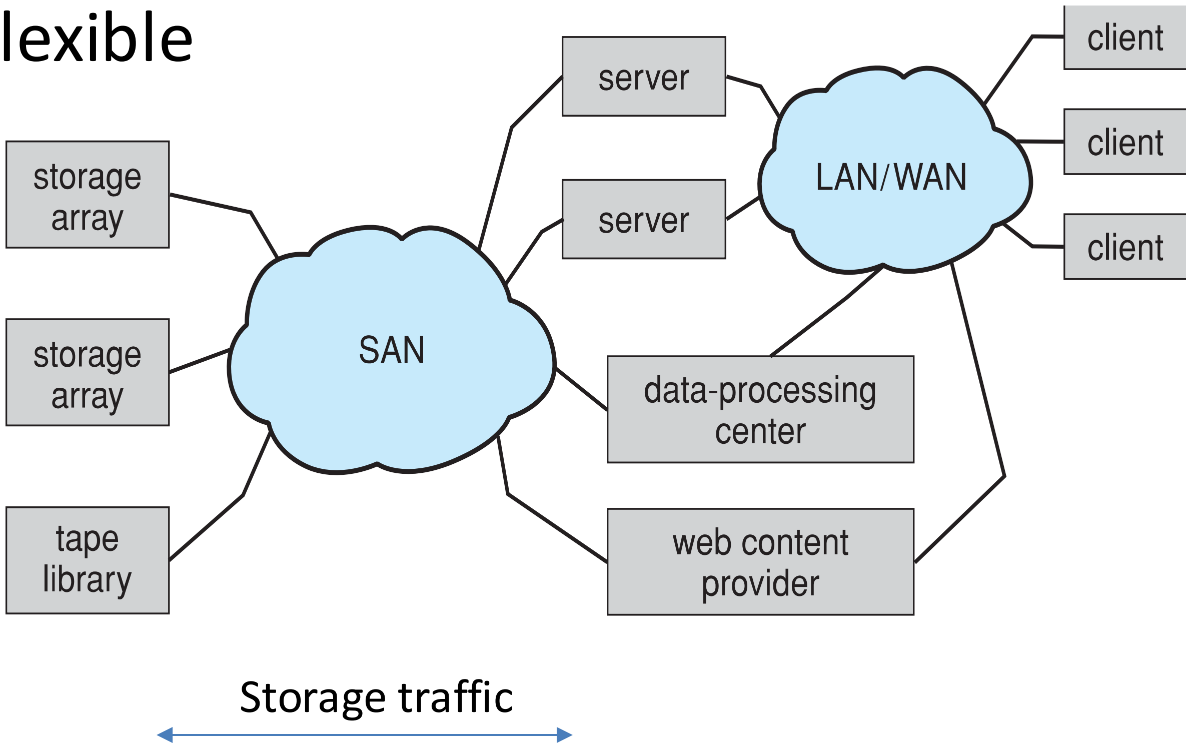


Storage Array

- Can just attach disks, or arrays of disks to an I/O port
- Storage Array has controller(s), provides features to attached host(s)
  - Ports to connect hosts to array
  - Memory, controlling software
  - A few to thousands of disks
  - RAID, hot spares, hot swap
  - Shared storage -> more efficiency

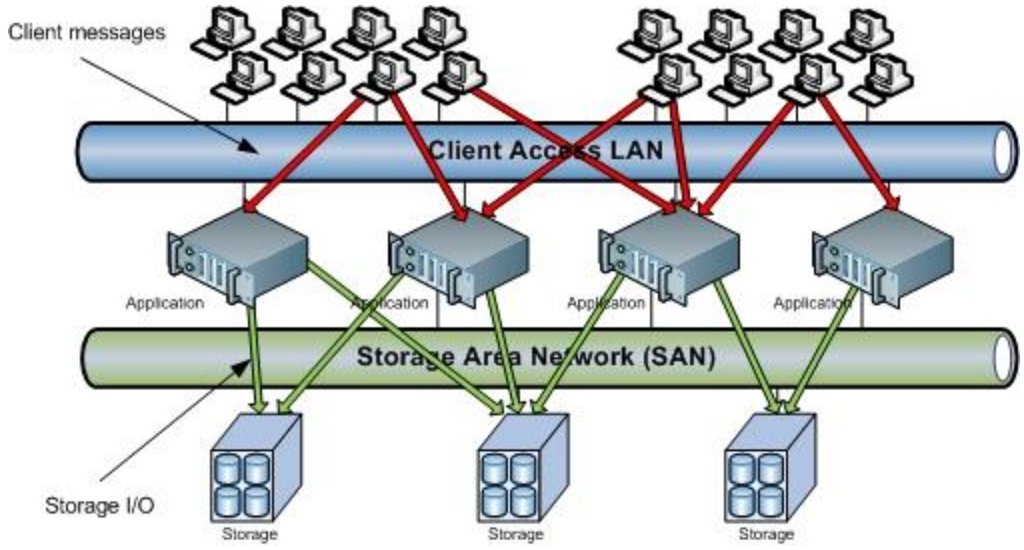
Storage Area Network

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



Storage Area Network (Cont.)

- SAN is one or more storage arrays
- Hosts also attach to the switches
- Storage made available 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



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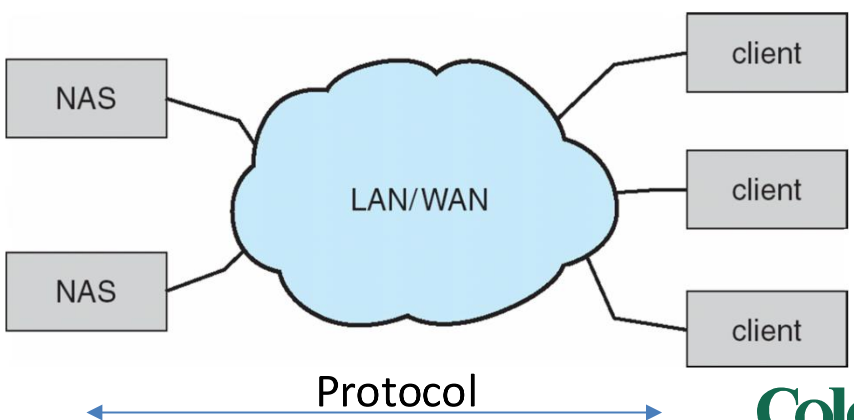
Network-Attached Storage

- 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 (windows) 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)



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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 $\approx \propto$ seek distance (between cylinders)
- 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.)

- 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 (cylinders 0-199)

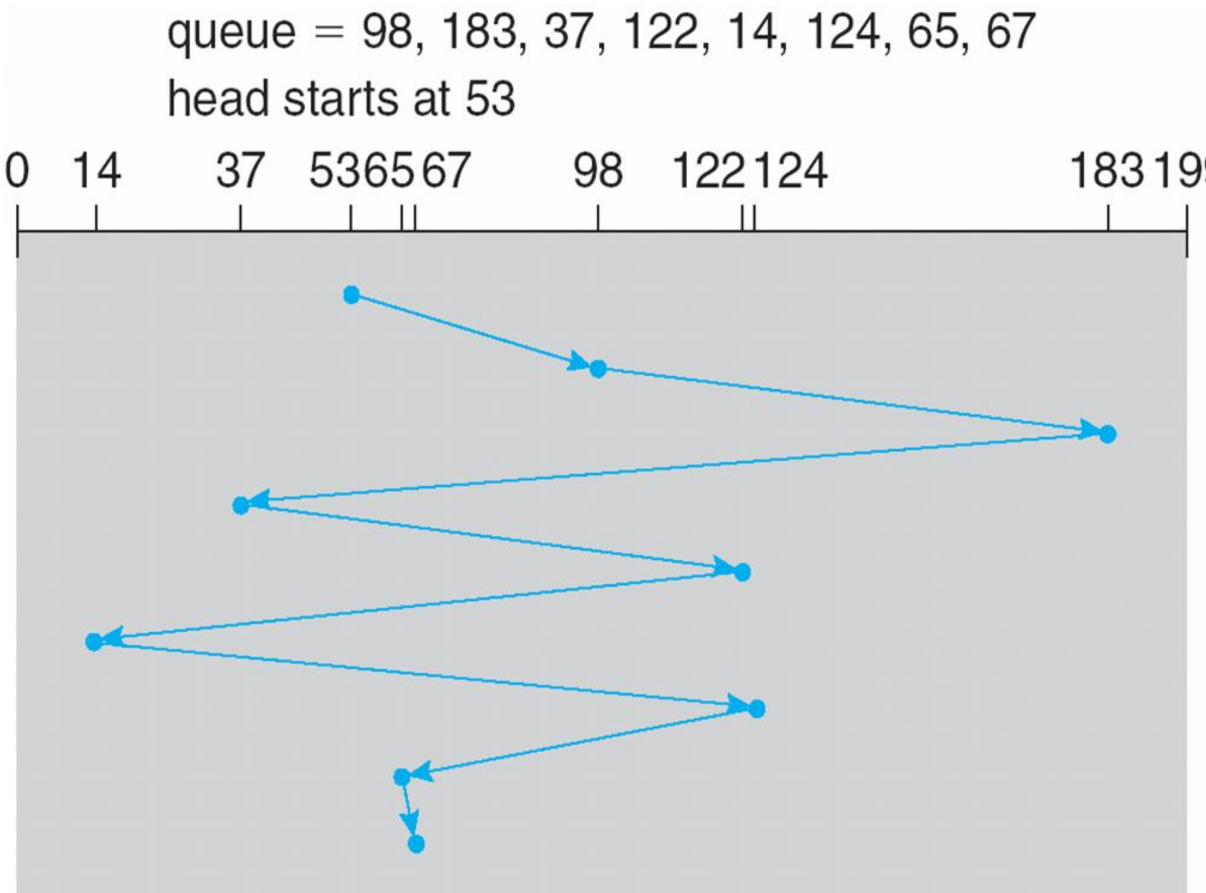
  98, 183, 37, 122, 14, 124, 65, 67

  Head pointer 53 (head is at cylinder 53)

Similar problems: limousine pickup/dropoff, elevator etc.

FCFS (First come first served)

Illustration shows total head movement. Cylinder 0 is outermost



Total seek time = (98-53) + …..= **640** cylinders

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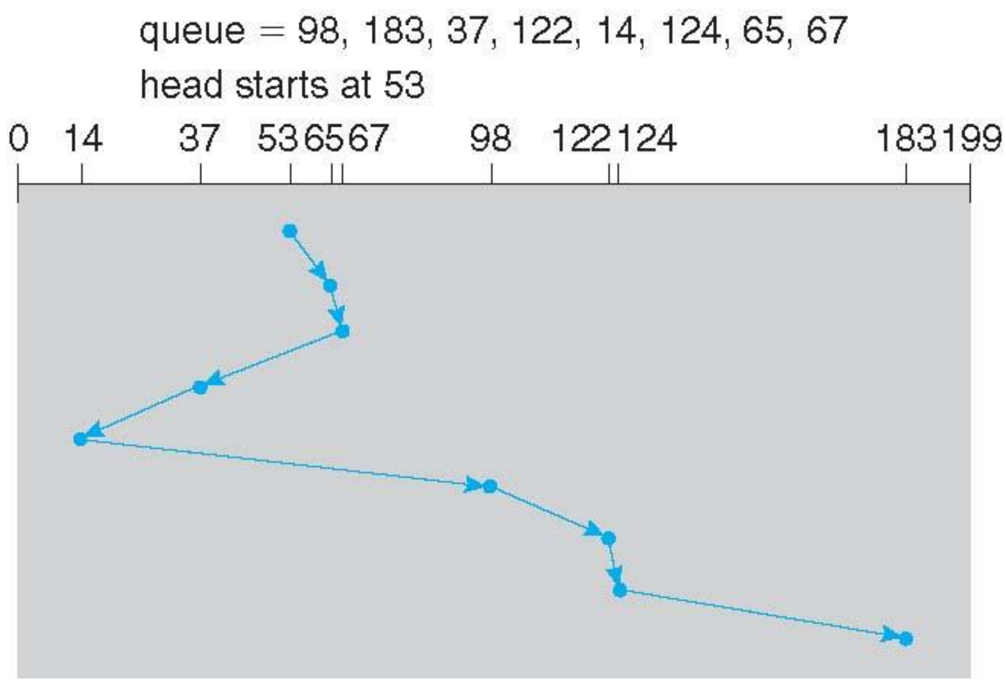
SSTF Shortest Seek Time First

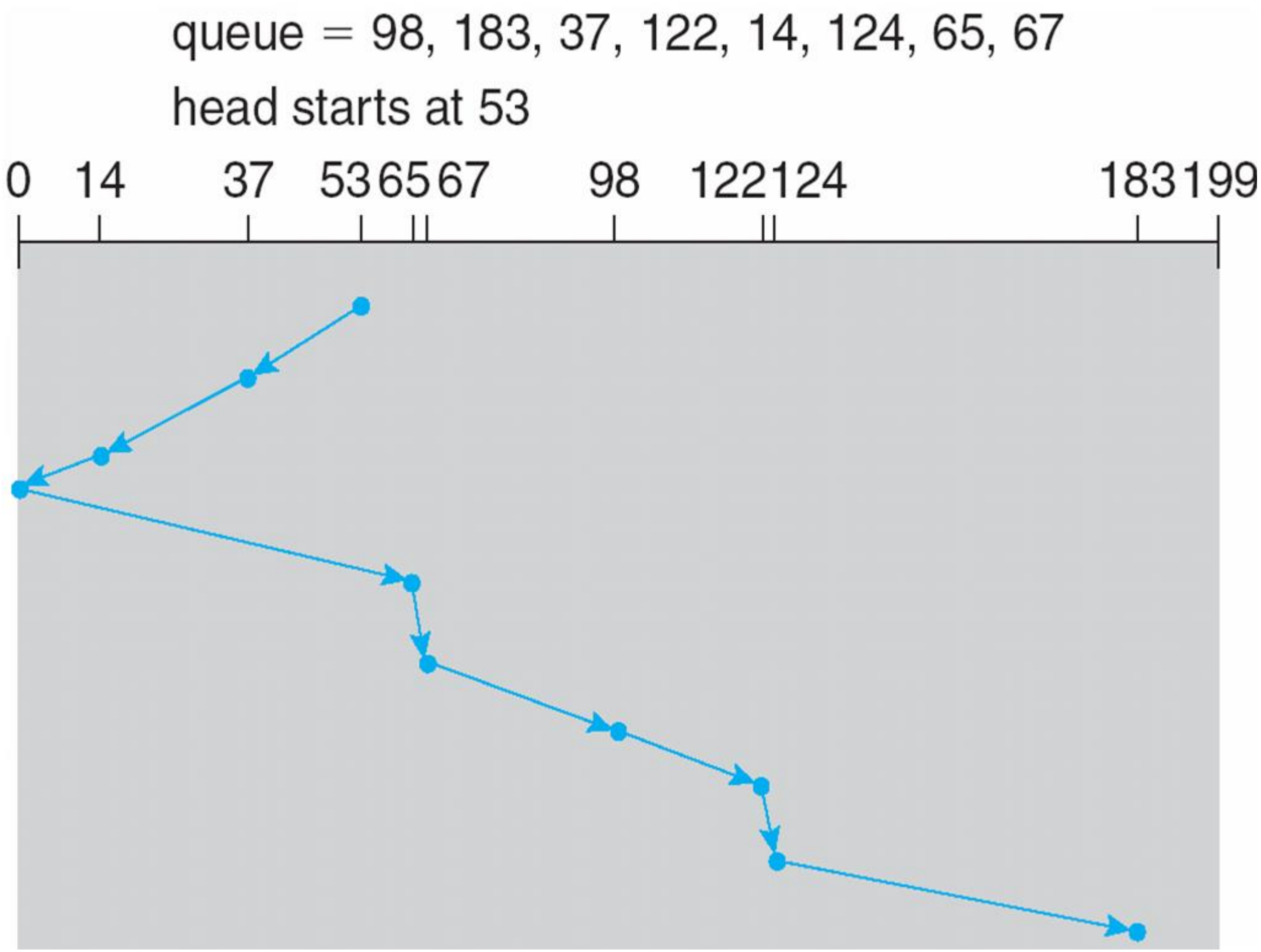
- **Shortest Seek Time First** selects the request with the minimum seek time from the current head position
- SSTF scheduling is a form of SJF scheduling; may cause starvation of some requests
- total head movement of **236** cylinders



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**
- But note that if requests are uniformly dense, largest density at the other end of disk and those wait the longest
- Variation: **Look**: may not go to the very edge

SCAN (Cont.)



LOOK will not go to 0

Total 53+ 183= **236** cylinders

FAQ

- LAN: local area network
- WAN: wide area network consisting of many LANs
- Page$_{memory}$ vs blocks/sectors$_{disk}$
- Difference among a file, its inode, and inode number?
  - inode number is the index of the inode in the inode table
- Hard links vs symbolic links:
  - Hard links refer to the same inode
  - Symbol link file is a pointer