CS370 Operating Systems

Colorado State University

Yashwant K Malaiya

Fall 2025 L22

Mass Storage

Slides based on

- Text by Silberschatz, Galvin, Gagne
- Various sources

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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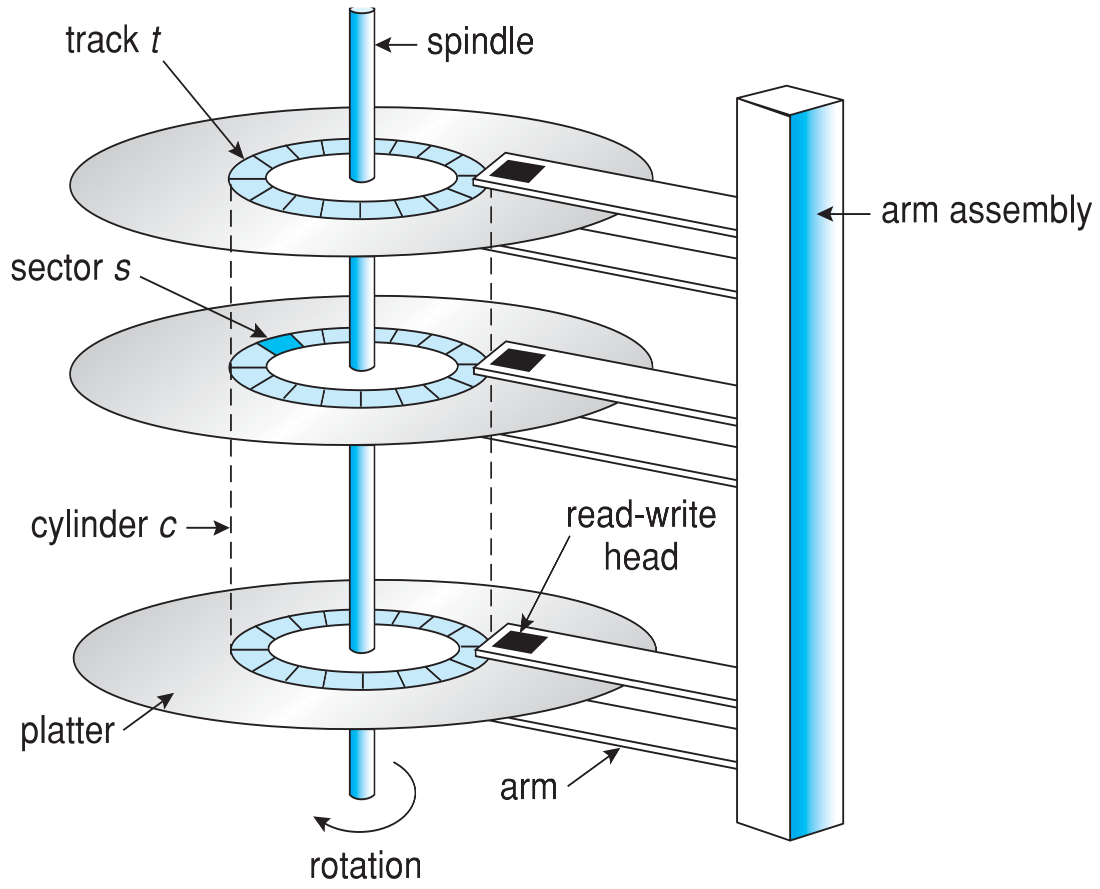
Moving-head Disk Mechanism



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?

Research Project

- Proper two column IEEE/ACM conference format
- Digging out the information from news reports, industrial articles/publications, research articles etc. All sources need to be properly cited.
- Connecting the information found and preparing a coherent, well focused report. **Non-text information needed: Diagrams, plots, data, tables, flow-charts etc**.

  Cite the sources.
- Readers (students/TAs/Prof) should find the presentation and report interesting and informative.

Use of Generative AI

- Emergence of generative AI is an exciting development. That has created a challenge in academics.
- Use of AI (or copying-and-pasting text) is not permitted in CS370. You must do your own research and write/organize your own report.
- We will check using automated and manual approaches and act as needed.
- A few students have expressed their concern about people in their team using AI generated text, since the responsibility is collective.
- Send me any thoughts privately.

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

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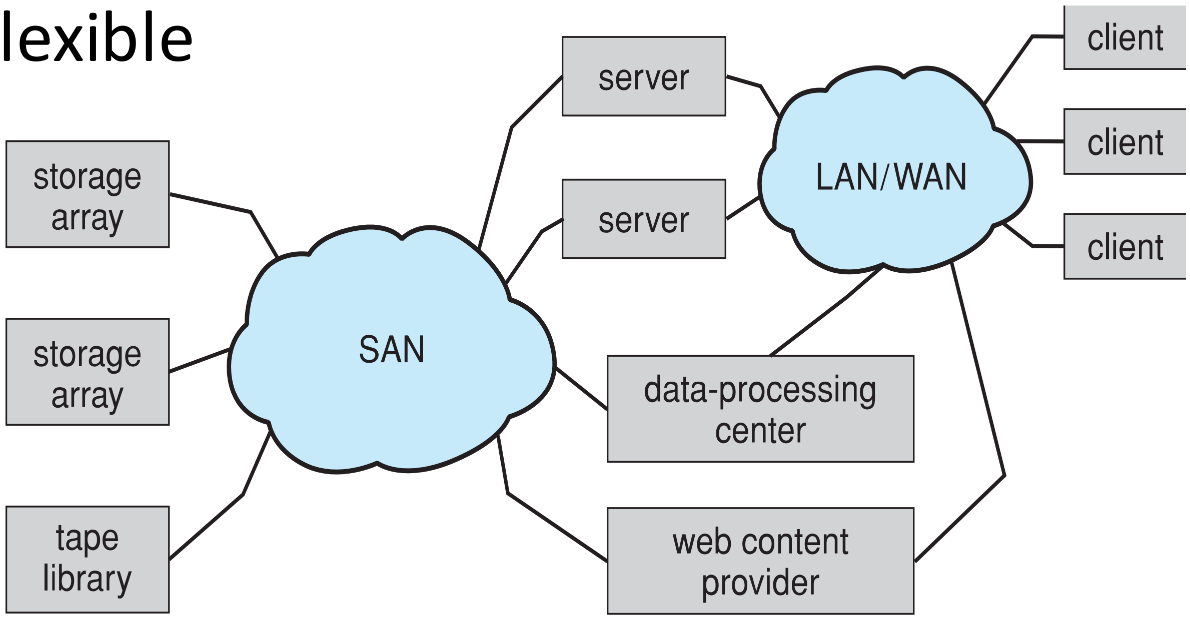
Storage Area Network

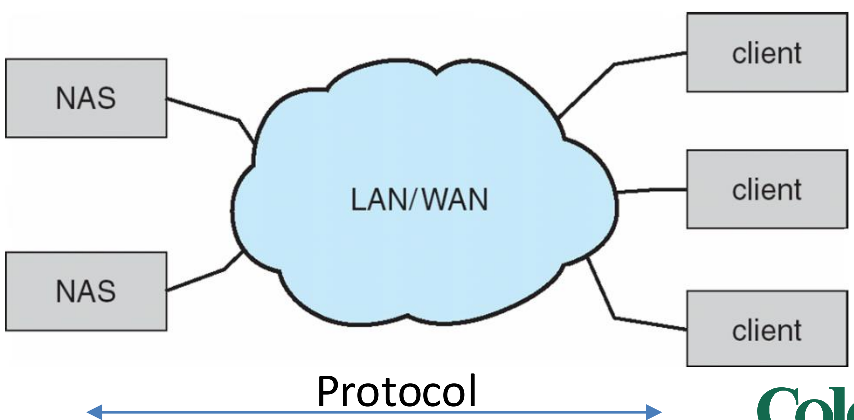
- Common in large storage environments
- Multiple hosts attached to multiple storage arrays - flexible



Storage traffic

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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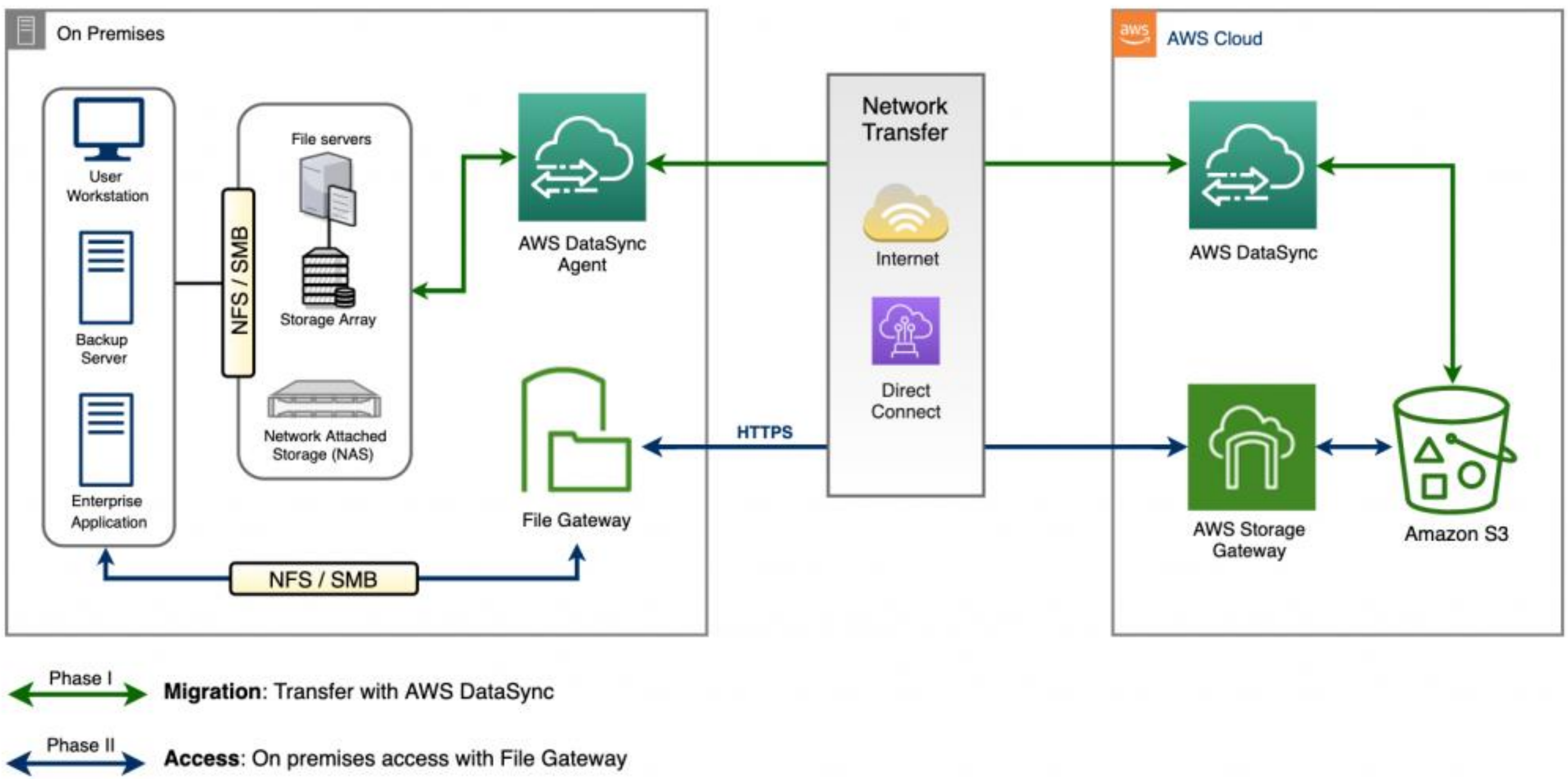
Cloud Storage

AWS DataSync and Storage Gateway



Amazon S3 (Simple Storage Service)

Issues: Delay, security, availability, cost

https://aws.amazon.com/blogs/storage/from-on-premises-to-aws-hybrid-cloud-architecture-for-network-file-shares/

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.)

- 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)

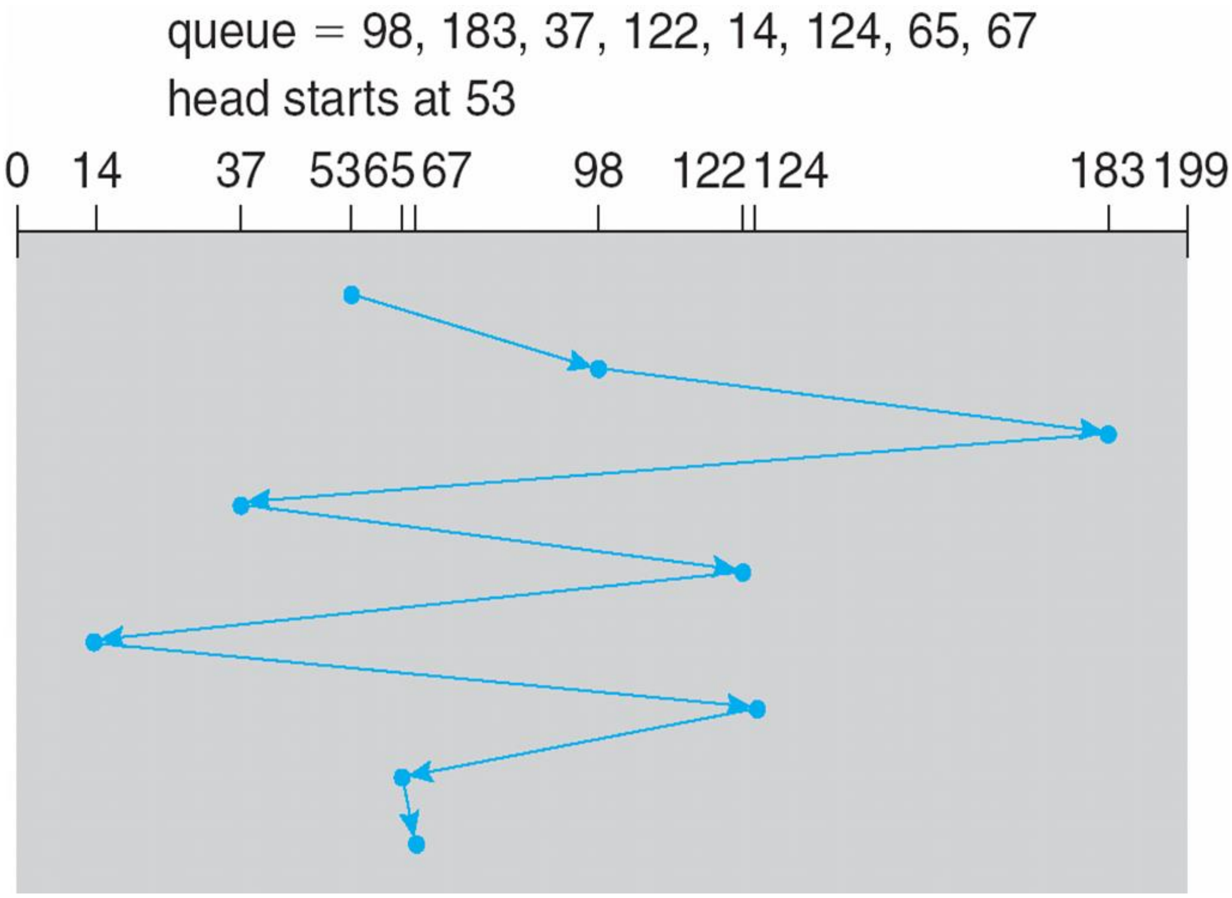
  98, 183, 37, 122, 14, 124, 65, 67

  Head pointer 53 (head is at cylinder 53)

Similar problems: limousine pickup/dropoff, elevator etc.

FCFS (First come first served)

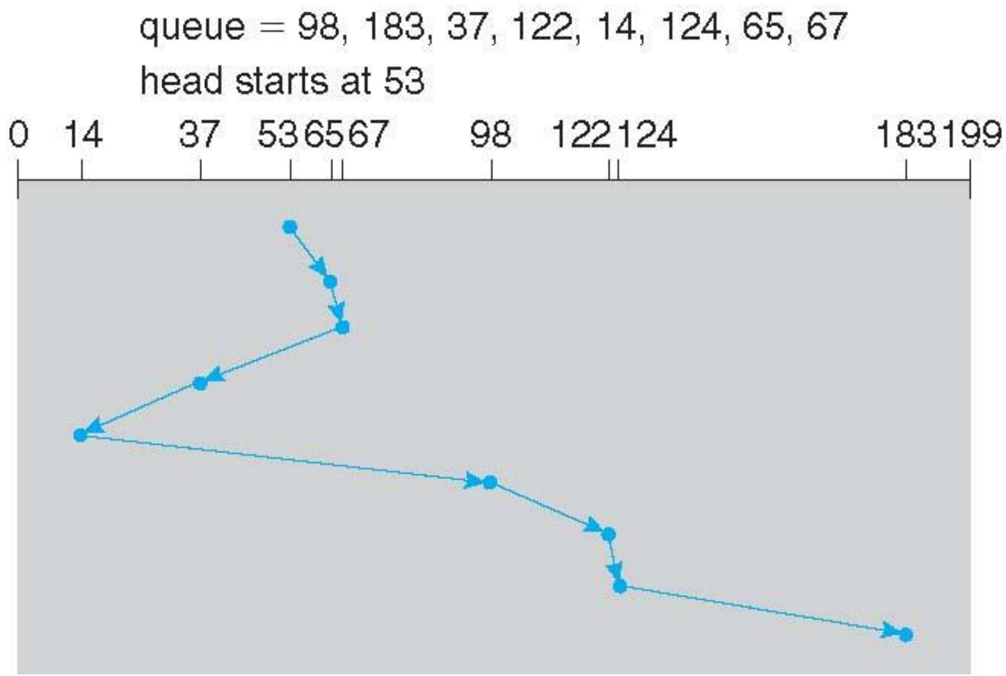
Illustration shows total head movement. Cylinder 0 is outermost



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

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



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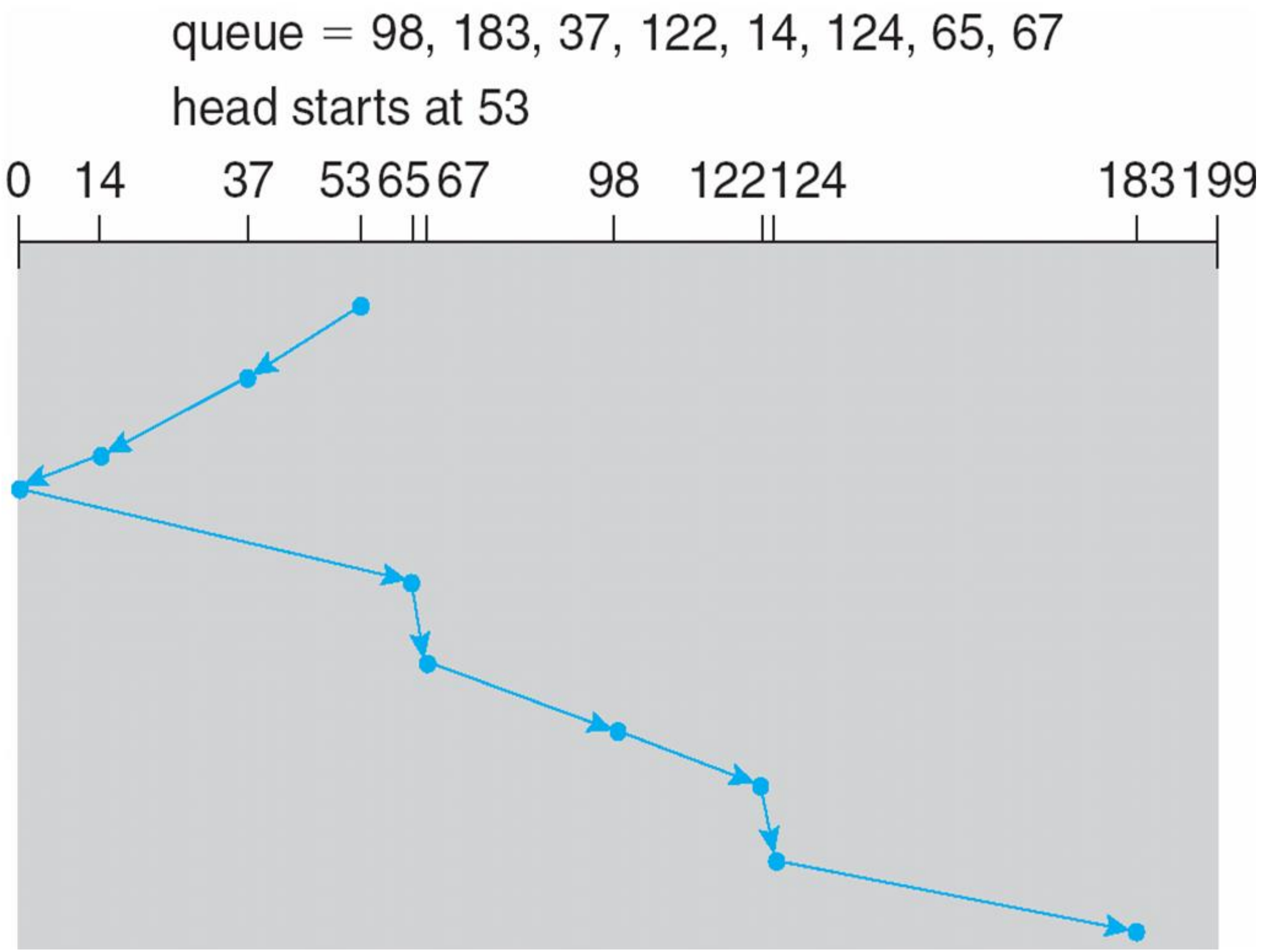
SCAN

- 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

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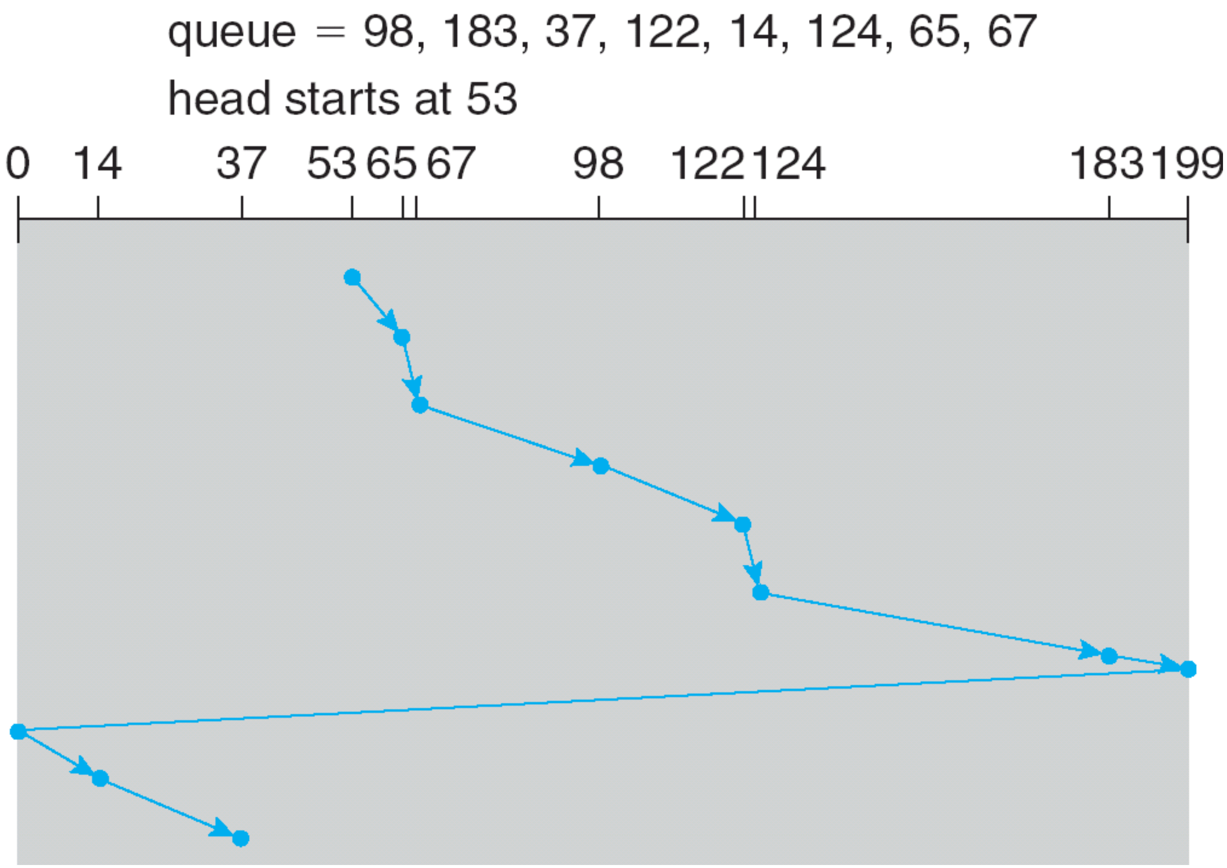
C-SCAN

- 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?

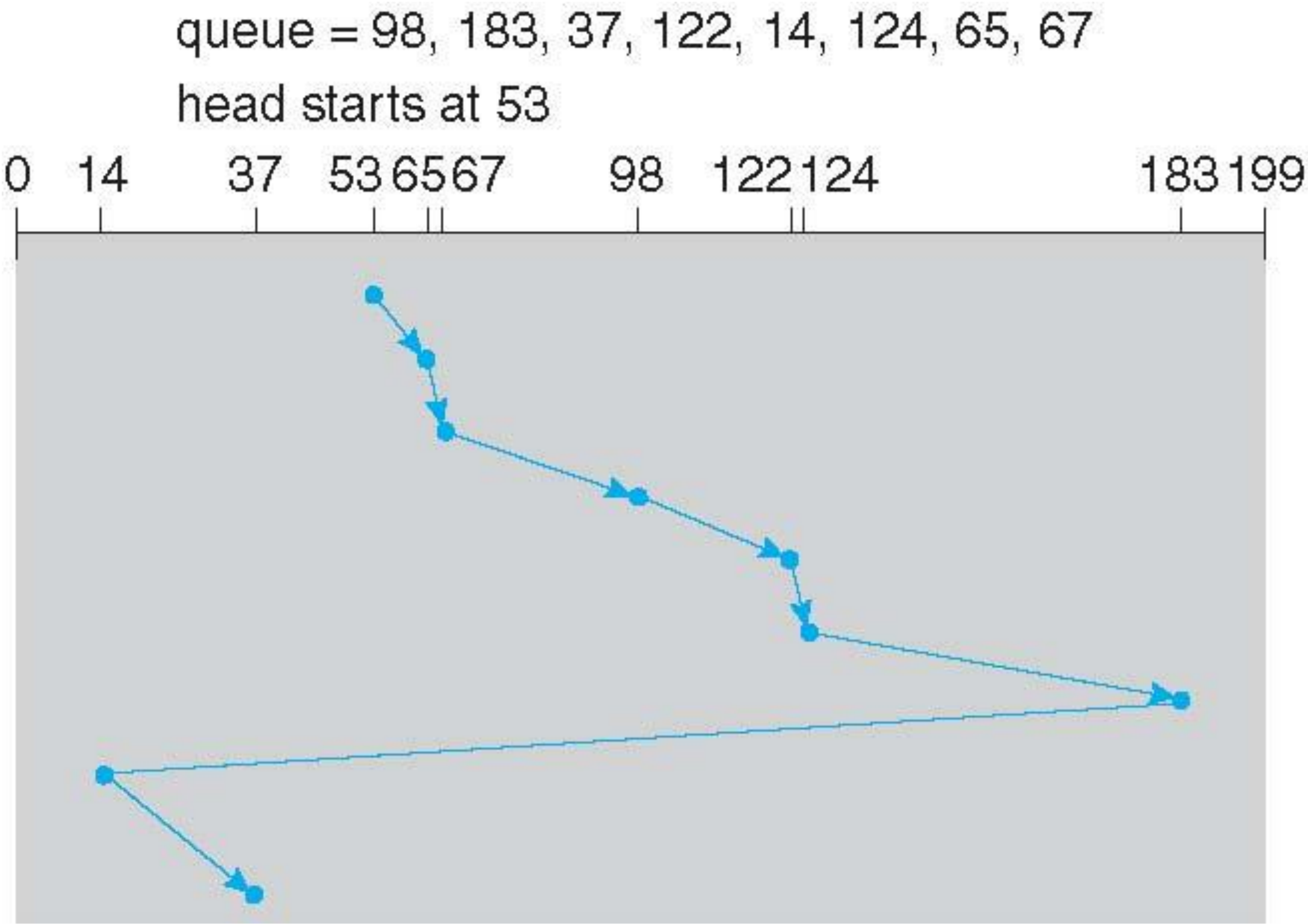
C-SCAN (Cont.)


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.)



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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

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Reliability & RAIDs

- Various sources

RAID Techniques

- **Striping** uses multiple disks in parallel by splitting data: higher performance (ex. RAID 0)
- **Mirroring** keeps duplicate of each disk: higher reliability (ex. RAID 1)
- **Block parity: One Disk hold** parity block for other disks. A failed disk can be rebuilt using parity. Wear leveling if interleaved (RAID 5, double parity RAID 6).
- Ideas that did not work: Bit or byte level level striping (RAID 2, 3) Bit level Coding (RAID 2), dedicated parity disk (RAID 4).
- Nested Combinations:
  - RAID 01: Mirror RAID 0
  - RAID 10: Multiple RAID 1, striping
  - RAID 50: Multiple RAID 5, striping
  - others

Ch 11 + external

RAID Structure

- RAID – redundant array of inexpensive disks
  - multiple disk drives provides reliability via **redundancy**
  - can increases the **mean time to failure**
- **Mean time to repair –** exposure time when another failure could cause data loss.
  - Can be many hours based on size of the disk.
- **Mean time to data loss** based on above factors. Date is lost if an additional failure makes it impossible to restore the data.

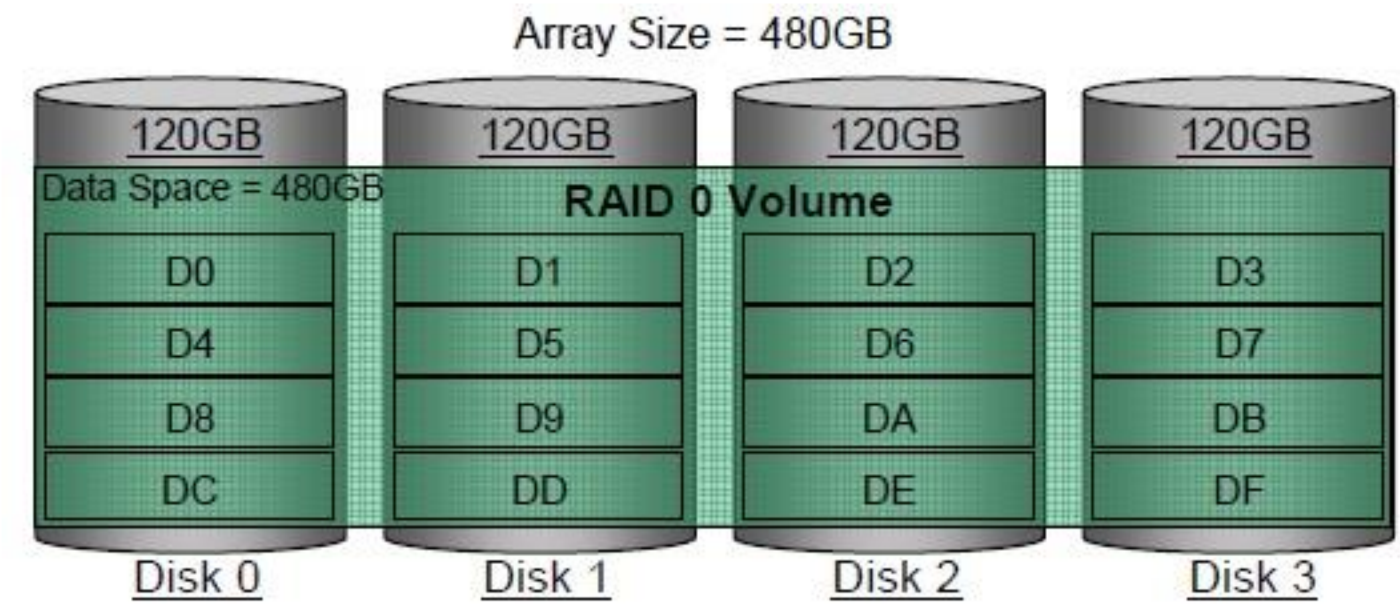
RAID

- Replicate data for availability
  - RAID 0: no replication, data split across disks
  - RAID 1: mirror data across two or more disks
    - Google File System replicated its data on three disks, spread across multiple racks
  - RAID 5: split data across disks, with redundancy to recover from a single disk failure
  - RAID 6: RAID 5, with extra redundancy to recover from two disk failures

Failures and repairs

- If a disk has *mean time to failure (MTTF) of* 100,000 hour.
  - Failure rate is 1/100,000 per hour.
- May be estimated using historical data
- If a disk has a bad data, it may be repaired
  - Copy data from a backup
  - Reconstruct data using available data and some invariant property.
- If data cannot be repaired, it is lost.

RAID 0: Striping



- Additional disks provide additional storage
- No redundancy

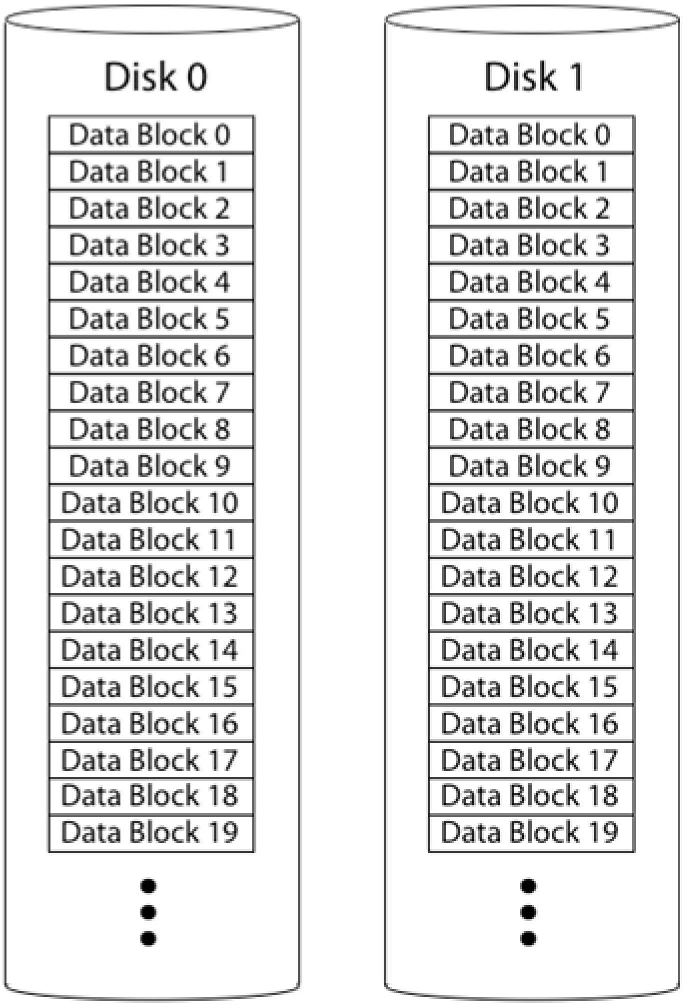
RAID 1: Mirroring

- Replicate writes to both disks
- Reads can go to either disk
- If they fail independently, consider disk with 100,000 hour *mean time to failure* and 10 hour *mean time to repair*
  - probability that two will fail within 10 hours =

    $(2\times10)\ \ /100{,}000^2$
  - *Mean time to data loss* is

    $100{,}000^2/(2\times10) = 500\times10^6$

    hours, or 57,000 years!



Parity bit, Parity block

- **Parity bit(s):** Extra bits obtained using data bits. Used for error detection/correction.
- **Ex:** Parity bit_i = $word_0$ $bit_i \oplus .. \oplus$ $word_n$ bit_i

  = bit needed make 1's even
  - Block parity: bit-by-bit parity for all disks
  - RAID 4: extra disk to hold parity blocks (not used anymore)
  - RAID 5: Parity blocks are distributed among the disks
  - RAID 6: Double the number of parity blocks

Parity

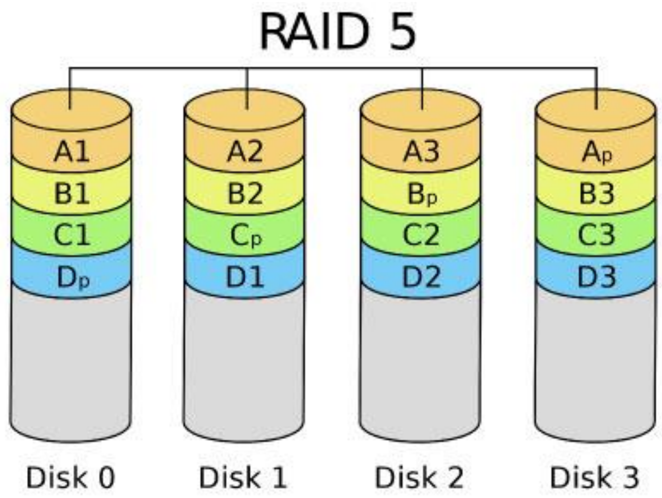
- Data blocks: Block1, block2, block3, ...
- Parity block: Block1 xor block2 xor block3 …

10001101	block1
01101100	block2
11000110	block3

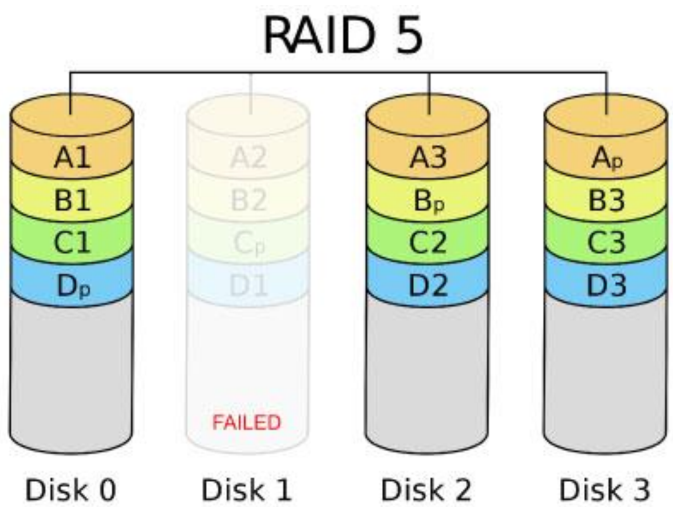
00100111	parity block (*ensures even number of 1s*)

- Can reconstruct any missing block from the others Error-control coding identifies that a block is bad.

RAID 5: Rotating Parity



Parity blocks Ap, Bp, Cp, Dp distributed across disks.



Time to rebuild depends on disk capacity and data transfer rate

Parity bit, Parity block

- RAID recovery:
  - RAID 1: Copy info from good mirror
  - RAID 5,6: rebuild using available data, parity info
- How do we know a disk is corrupted? Use of CRC redundancy at a lower level.

Read Errors and RAID recovery

- Example: RAID 5
  - Each bit has 10^{-15} probability of being bad.
  - 10 one-TB disks, and 1 disk fails
  - Read remaining disks to reconstruct missing data
- Probability of an error in reading 9 TB disks =

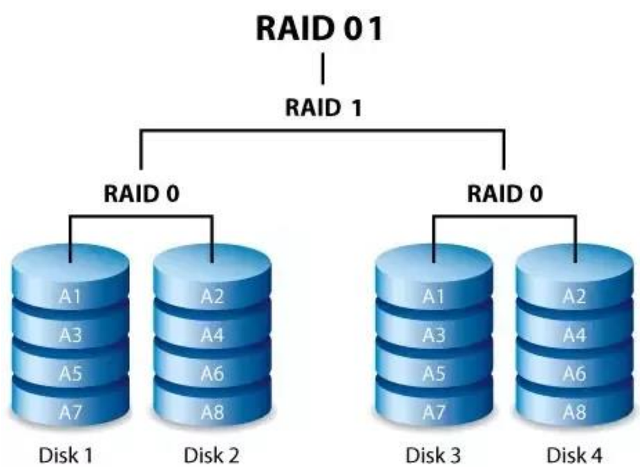
  10^{-15}*total bits =10^{-15}* (9 disks * 8 bits * 10^{12} bytes/disk)

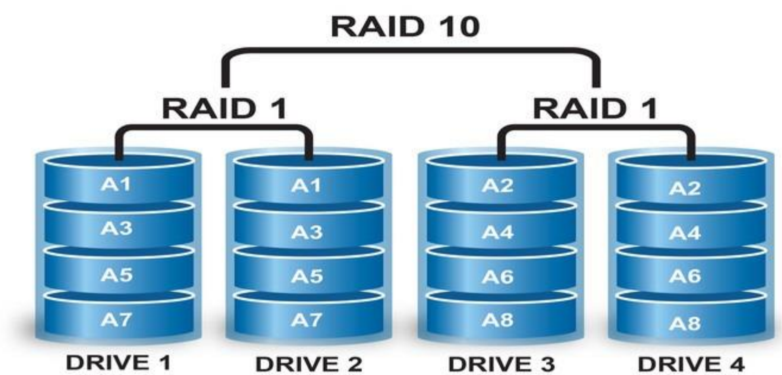
  = 7.2%   Thus recovery probability = 92.8%
- Even better:
  - RAID-6: two redundant disk blocks parity plus Reed-Solomon code
  - Can work even in presence of one bad disk, can recover from 2 disk failures
  - Scrubbing: read disk sectors in background to find and fix latent errors

RAIDs: Nested systems

Nested systems: combine striping with mirroring/parity

- RAID 01: Two RAID 0 systems (with striping) mirrored
- RAID 10: Multiple RAID 1 systems (with mirroring) striped.





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Big Data: HDFS and map-reduce

- Various sources, mostly external

Hadoop: Distributed Framework for Big Data

Big Data attributes:

- Large volume: TB -> PB varies with Kryder's law: disk density doubles / 13 months
- Geographically Distributed: minimize data movement
- Needs: reliability, analytic approaches

History:

- Google file system 2003 and Map Reduce 2004 programming lang
- Hadoop to support distribution for the Yahoo search engine project '05, given to Apache Software Foundation '06
- Hadoop ecosystem evolves with Yarn '13 resource management, Pig '10 scripting, Spark '14 distributed computing engine. etc.

- *The Google file system* by Sanjay Ghemawat, Howard Gobioff, and Shun-Tak Leung (2003)
- *MapReduce: Simplified Data Processing on Large Clusters.* by Jeffrey Dean and Sanjay Ghemawat (2004)

Hadoop: Distributed Framework for Big Data

Recent development.

- Big data: multi-terabyte or more data for an app
- Distributed file system
  - Reliability through replication (Fault tolerance)
- Distributed execution
  - Parallel execution for higher performance

Hadoop: Core components

Hadoop (originally): HDFS + MapReduce

- HDFS: A **d**istributed **f**ile **s**ystem designed to efficiently allocate data across multiple commodity machines, and provide self-healing functions when some of them go down
- MapReduce: A programming framework for processing parallelizable problems across huge datasets using a large number of commodity machines.

> - Commodity machines: lower performance per machine, lower cost, perhaps lower reliability compared with special high-performance machines.

Challenges in Distributed Big Data

Common Challenges in Distributed Systems

- **Node Failure**: Individual computer nodes may overheat, crash, have hard drive failures, or run out of memory or disk space.
- **Network issues**: Congestion/delays (large data volumes)**,** Communication Failures.
- **Bad data**: Data may be corrupted, or maliciously or improperly transmitted.
- **Other issues**: Multiple versions of client software may use slightly different protocols from one another.
- **Security**

HDFS Architecture

Hadoop Distributed File System (HDFS):

- HDFS Block size: 64-128 MB ext4: 4KB
- HDFS file size: "Big"
- Single HDFS FS cluster can span many nodes possibly geographically distributed. datacenters-racks-blades
- Node: system with CPU and memory

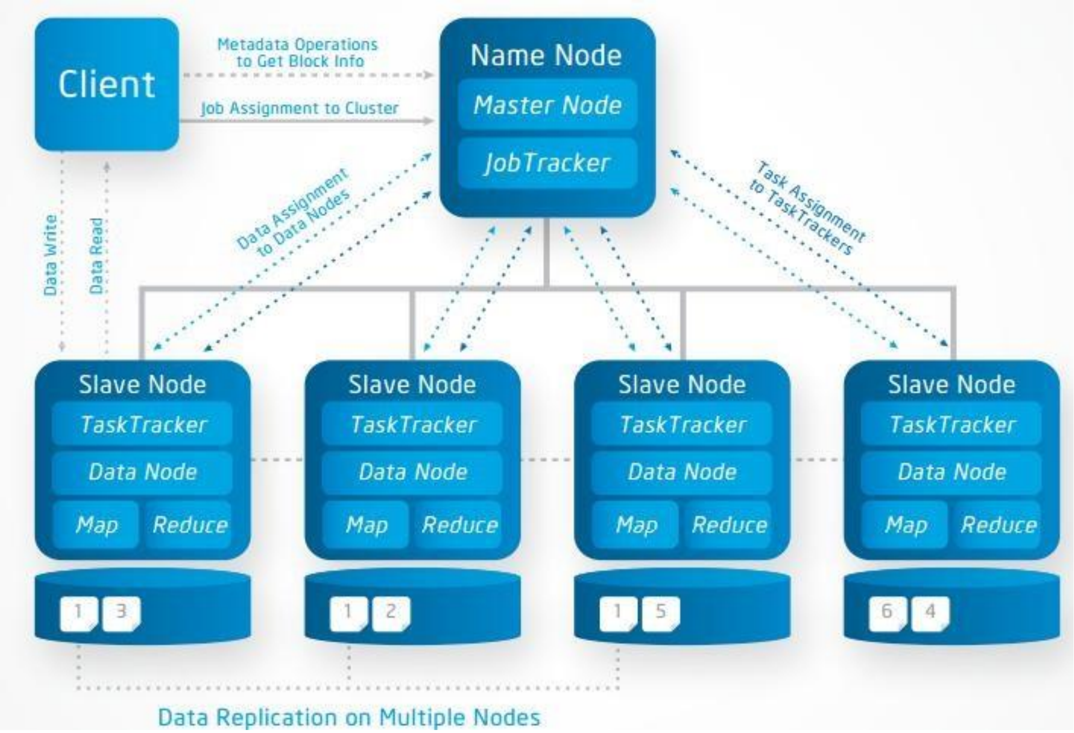
Metadata (corresponding to superblocks, Inodes)

- Name Node: metadata giving where blocks are physically located

Data (files blocks)

- Data Nodes: hold blocks of files (files are distributed)

HDFS Architecture



http://a4academics.com/images/hadoop/Hadoop-Architecture-Read-Write.jpg

Secondary Name node
If primary fails.

Data is distributed and replicated.

Name Node: metadata giving where blocks are physically located
Data Nodes: hold blocks of files (files are distributed

Q. What do I need to know? motivation, approaches, concepts

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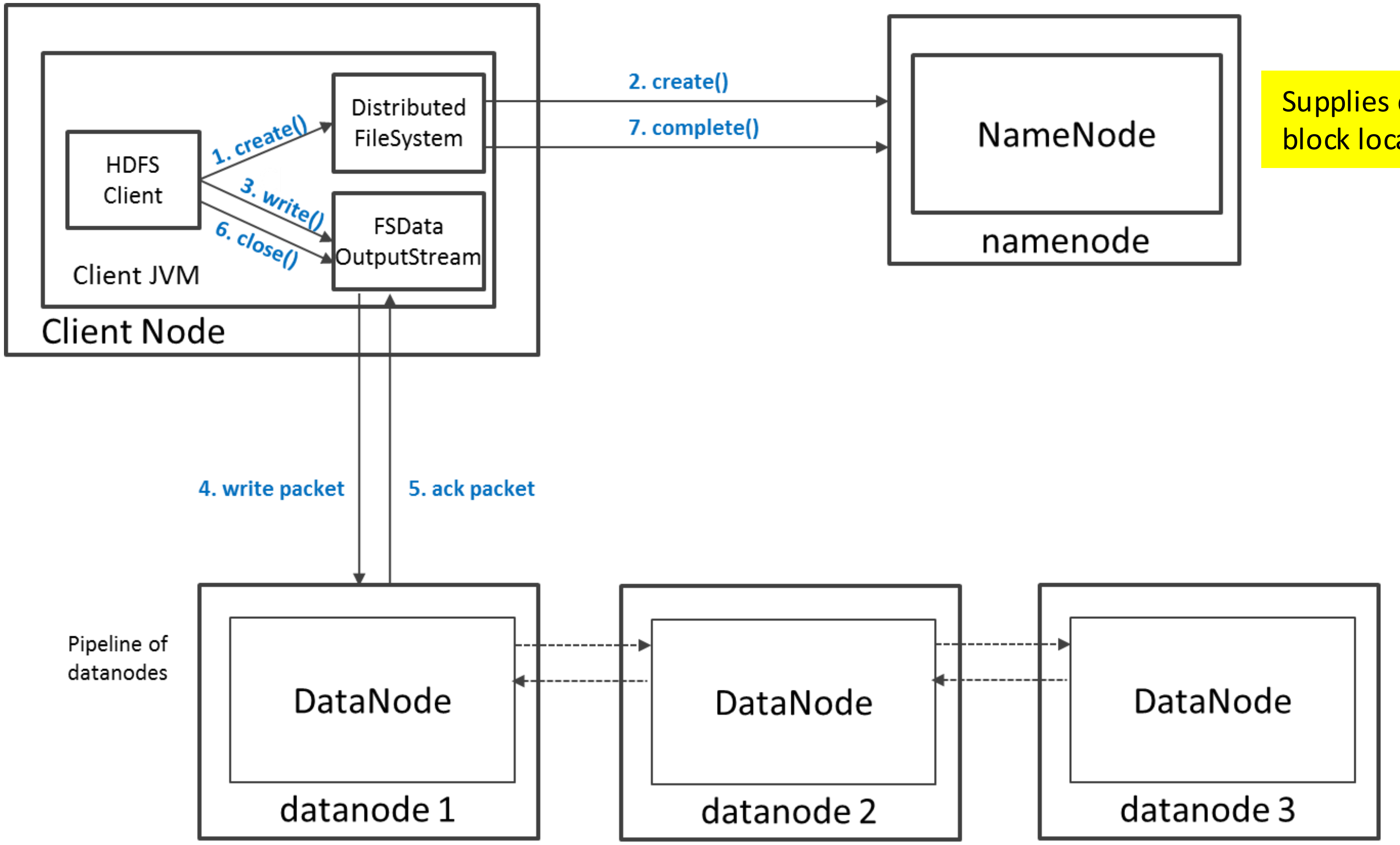
HDFS Write operation



Supplies data block locations

https://indico.cern.ch/event/404527/contributions/968835/attachments/1123385/1603232/Introduction_to_HDFS.pdf

CERN

HDFS Fault-tolerance

- Disks use error detecting codes to detect corruption.
- Individual node/rack may fail.
- Data Nodes (on slave nodes):
  - data is replicated. Default is 3 times. Keep a copy far away.
  - Send periodic heartbeat (I'm OK) to Name Nodes. Perhaps once every 10 minutes.
  - Name node creates another copy if no heartbeat.

HDFS Fault-tolerance

Name Node (on master node) Protection:

- Transaction log for file deletes/adds, etc. Creation of more replica blocks, when necessary, after a Data Node failure
- Standby name node: namespace backup
  - In the event of a failover, the Standby will ensure that it has read all of the edits from the Journal Nodes and then promotes itself to the Active state
  - Implementation/delay version dependent

Name Node metadata is in RAM as well as checkpointed on disk.
On disk the state is stored in two files:

- fsimage: Snapshot of file system metadata
- editlog: Changes since last snapshot

HDFS Command line interface

- hadoop fs –help
- hadoop fs –ls : List a directory
- hadoop fs mkdir : makes a directory in HDFS
- hadoop fs –rm : Deletes a file in HDFS
- copyFromLocal : Copies data to HDFS from local filesystem
- copyToLocal : Copies data to local filesystem
- Java code can read or write HDFS files (URI) directly

HDFS is on top of a local file system

https://hadoop.apache.org/docs/r2.4.1/hadoop-project-dist/hadoop-common/FileSystemShell.html

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Distributing Tasks

MapReduce Engine:

- JobTracker splits up the job into smaller tasks(“Map”) and sends it to the TaskTracker process in each node.
- TaskTracker reports back to the JobTracker node and reports on job progress, sends partial results (“Reduce”) or requests new jobs.
- Tasks are run on local data, thus avoiding movement of bulk data.
- Originally developed for search engine implementation.

Hadoop Ecosystem Evolution

- Hadoop YARN: A framework for job scheduling and cluster resource management, can run on top of Windows Azure or Amazon S3.
- Apache spark is more general, faster and easier to program than MapReduce.
  - Resilient Distributed Datasets: A Fault-Tolerant Abstraction for In-Memory Cluster Computing, Berkeley, 2012

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Fall 2022

Virtualization & Containerization

Slides based on

- Various sources

Virtualization

- Why we need virtualization?
- The concepts and terms
- Brief history of virtualization
- Types of virtualization
- Implementation Issues
- Containers

Ch 18 + external

We will skip implementation specific details. Please consult the documentation and watch related videos.

Isolation and resource allocation

Isolation levels:

- **Process**: Isolated address space
- **Container**: Isolated set of processes, files and network
- **Virtual Machines** (VM): Isolated OSs
- **Physically isolated** machines

Resource allocation:

- Resources need to be allocated to
  - processes
  - Containers
  - VMs and
- managed to serve needs best.

Virtualization in Virtual machines

- A Virtual scheme provides a simpler perspective of a Physical scheme. Needs mapping.
  - Example: each process a separate virtual address space.
  - OS allocates physical memory and disk space and handles mapping.
- System ("machine") virtualization
  - A machine needs its own CPU, memory, storage, I/O to run its OS and apps. "Machine" = {CPU, memory, storage, I/O, OS, apps}
  - Needs to be isolated from other machines.
  - "Virtual machines" allocated part of resources from physical machine (hardware) with allocation done by a Virtual Machine Monitor (VMM) or hypervisor.
  - A single physical machine can run multiple virtual machines.
  - A virtual machine can be "migrated" from one physical system to another.

Virtualization

"Tell that intern that you can't migrate physical machines."

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Virtualization

- Processors have gradually become very powerful
- Dedicated servers can be very underutilized (5-15%)
- Virtualization allow a single server to support several virtualized servers: typical consolidation ratio 6:1
- Power cost a major expense for data centers
  - Companies frequently locate their data centers in the middle of nowhere where power cost is low
- If a hardware server crashes, would be nice to migrate the load to another one.
- A key component of cloud computing

Virtual Machines (VM)

- **Virtualization** technology enables a single PC/server to simultaneously run multiple Virtual Machines,
  - with different operating systems or multiple sessions of a single OS.
- A machine with virtualization can host many applications, including those that run on different operating systems, on a single platform.
- The host operating system can support a number of virtual machines, each of which has the characteristics of a specific OS.
- The software that enables virtualization is a **virtual machine monitor (VMM),** or **hypervisor.**