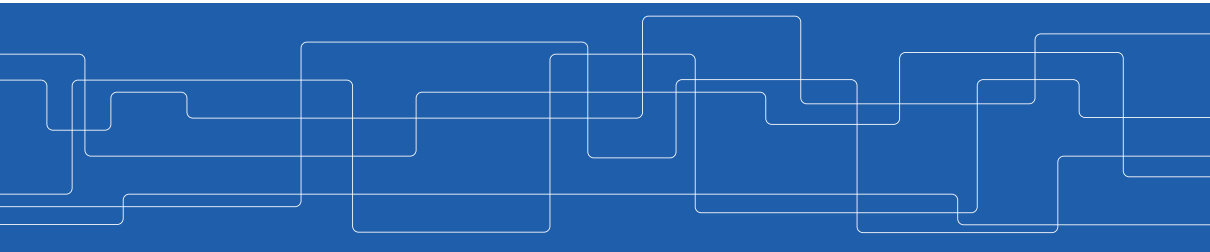
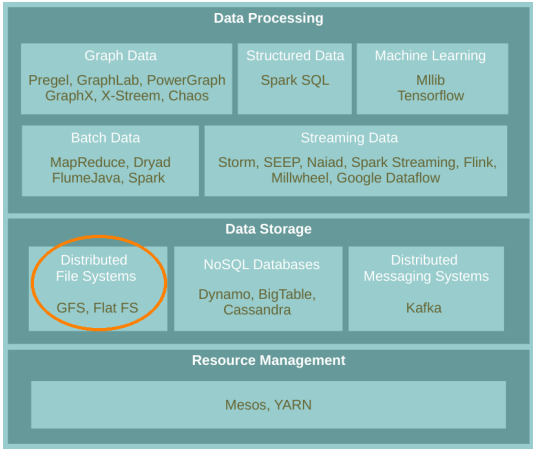
Large Scale File Systems

Amir H. Payberah
payberah@kth.se
2025-08-28

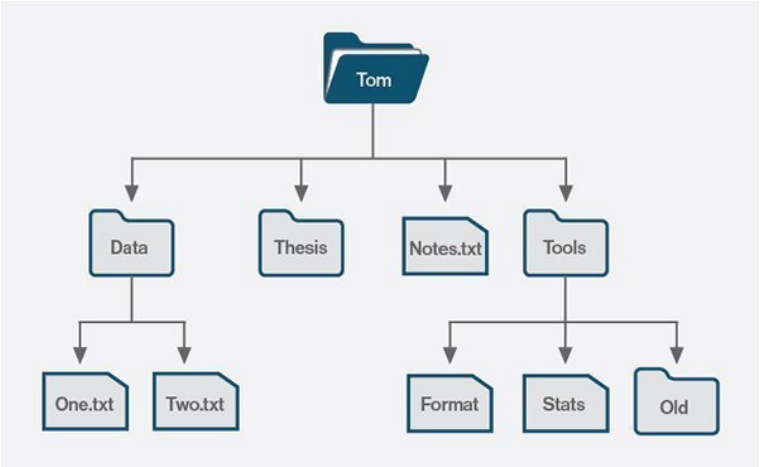


Where Are We?


Data Processing
Graph Data
Pregel, GraphLab, PowerGraph
GraphX, X-Streem, Chaos
Structured Data
Spark SQL
Machine Learning
Mllib
Tensorflow
Batch Data
MapReduce, Dryad
FlumeJava, Spark
Streaming Data
Storm, SEEP, Naiad, Spark Streaming, Flink,
Millwheel, Google Dataflow
Data Storage
Distributed
File Systems
GFS, Flat FS
NoSQL Databases
Dynamo, BigTable,
Cassandra
Distributed
Messaging Systems
Kafka
Resource Management
Mesos, YARN

File System

What is a File System?

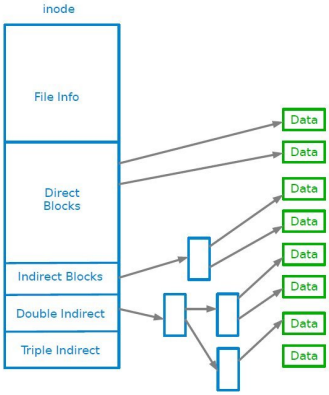


What is a File System?

- Controls how data is stored in and retrieved from storage device.

What is a File System?

- Controls how data is stored in and retrieved from storage device.



Distributed File Systems

- When data outgrows the storage capacity of a single machine: partition it across a number of separate machines.

Distributed File Systems

- When data outgrows the storage capacity of a single machine: partition it across a number of separate machines.
- Distributed file systems: manage the storage across a network of machines.

What Features and Values in Designing a Distributed FS?

https://tinyurl.com/2p8nynct

Google File System (GFS)

Motivation and Assumptions

- Huge files (multi-GB)

Motivation and Assumptions

- Huge files (multi-GB)
- Most files are modified by appending to the end
    - Random writes (and overwrites) are practically non-existent

Motivation and Assumptions

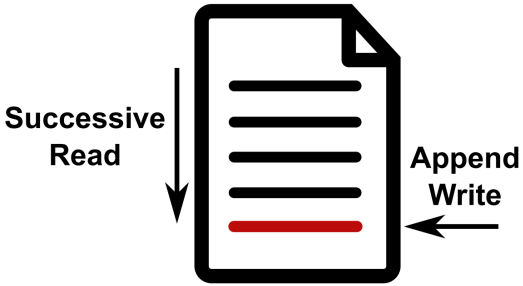
- Huge files (multi-GB)
- Most files are modified by appending to the end
  - Random writes (and overwrites) are practically non-existent
- Optimise for streaming access

Motivation and Assumptions

- Huge files (multi-GB)
- Most files are modified by appending to the end
  - Random writes (and overwrites) are practically non-existent
- Optimise for streaming access
- Node failures happen frequently

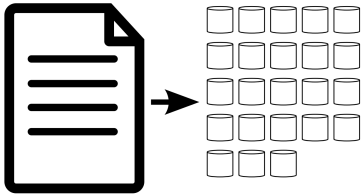
Optimised for Streaming

- Write once, read many.

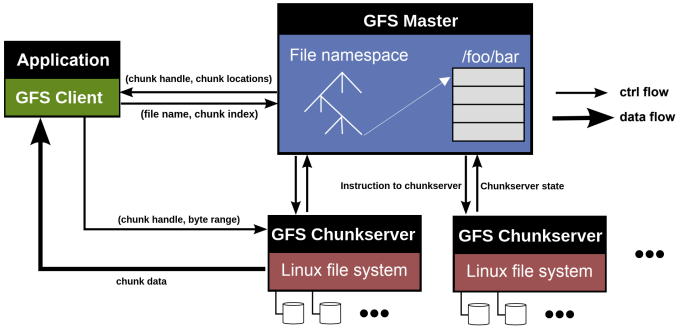


Files and Chunks

- Files are split into chunks.
- Chunk: single unit of storage.
  - Immutable and globally unique chunk handle
  - Transparent to user
  - Each chunk is stored as a plain Linux file

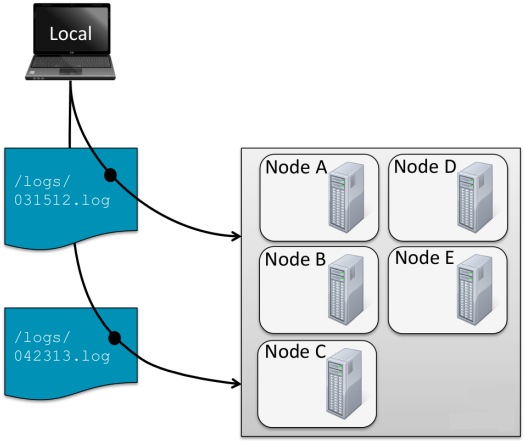


GFS Architecture

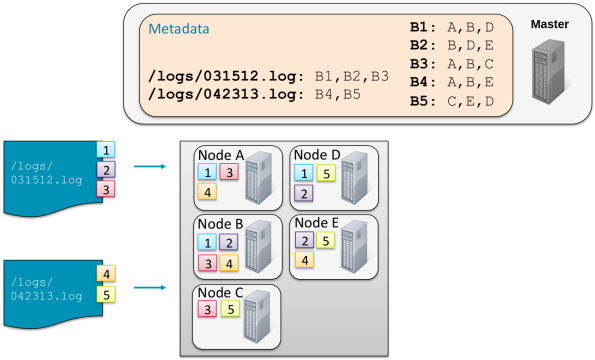


- Main components:
  - GFS master
  - GFS chunkserver
  - GFS client

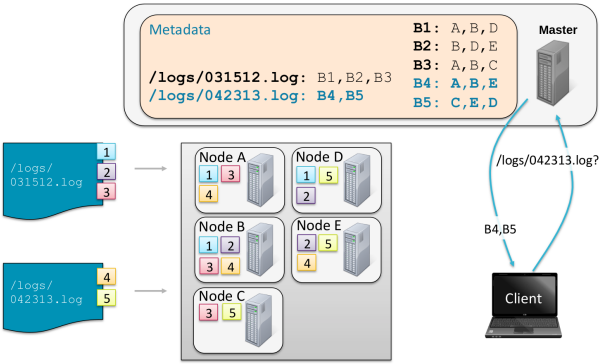
Big Picture - Storing and Retrieving Files (1/4)



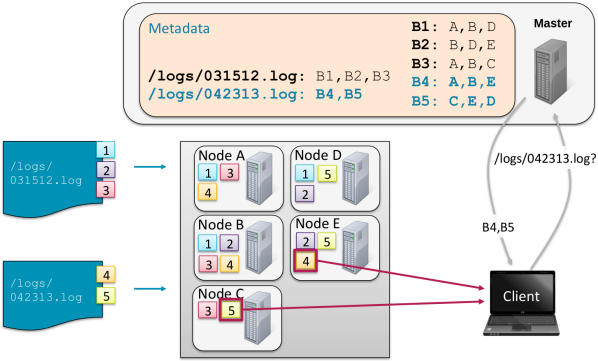
Big Picture - Storing and Retrieving Files (2/4)



Big Picture - Storing and Retrieving Files (3/4)

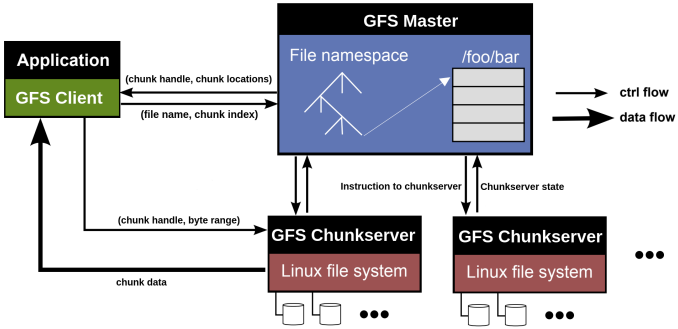


Big Picture - Storing and Retrieving Files (4/4)



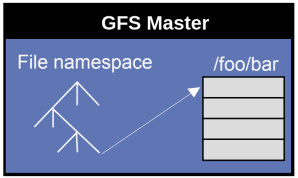
System Architecture Details

GFS Architecture



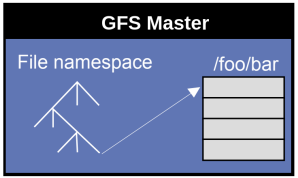
GFS Master

- Responsible for all system-wide activities



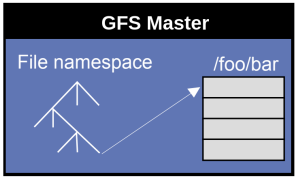
GFS Master

- Responsible for all system-wide activities
- Maintains all file system metadata
  - Namespaces, ACLs, mappings from files to chunks, and current locations of chunks



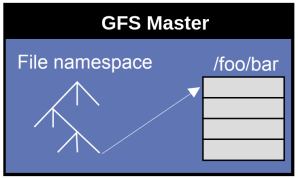
GFS Master

- Responsible for all system-wide activities
- Maintains all file system metadata
  - Namespaces, ACLs, mappings from files to chunks, and current locations of chunks
  - All kept in memory, namespaces and file-to-chunk mappings are also stored persistently in operation log



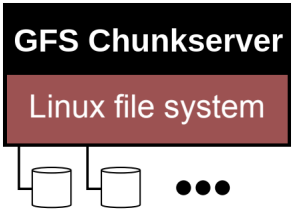
GFS Master

- Responsible for all system-wide activities
- Maintains all file system metadata
  - Namespaces, ACLs, mappings from files to chunks, and current locations of chunks
  - All kept in memory, namespaces and file-to-chunk mappings are also stored persistently in operation log
- Periodically communicates with each chunkserver
  - Determines chunk locations
  - Assesses state of the overall system



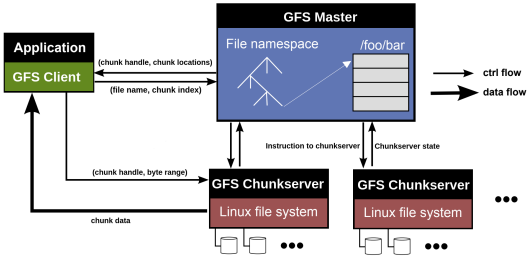
GFS Chunkserver

- Manages chunks
- Tells master what chunks it has
- Stores chunks as files
- Maintains data consistency of chunks



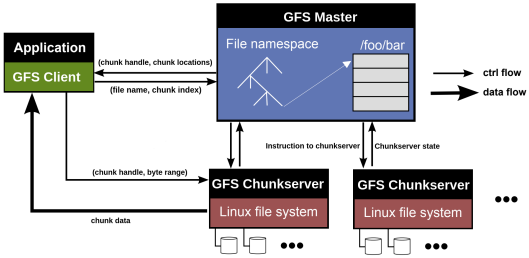
GFS Client

- Issues control requests to master server.
- Issues data requests directly to chunkservers.



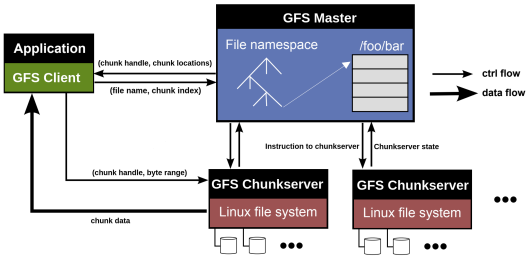
GFS Client

- Issues control requests to master server.
- Issues data requests directly to chunkservers.
- Caches metadata.
- Does not cache data.



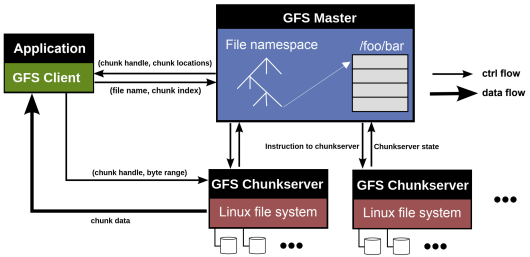
Data Flow and Control Flow

- Data flow is decoupled from control flow



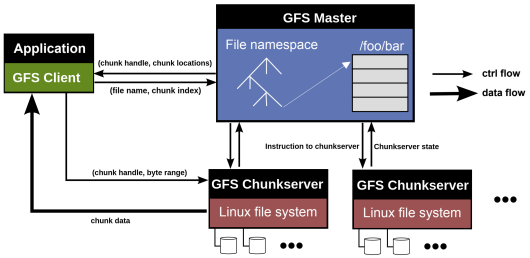
Data Flow and Control Flow

- Data flow is decoupled from control flow
- Clients interact with the master for metadata operations (control flow)



Data Flow and Control Flow

- Data flow is decoupled from control flow
- Clients interact with the master for metadata operations (control flow)
- Clients interact directly with chunkservers for all files operations (data flow)



Why Large Chunks?

- 64MB or 128MB (much larger than most file systems)
- Advantages
- Disadvantages

Why Large Chunks?

- 64MB or 128MB (much larger than most file systems)
- Advantages
  - Reduces the size of the metadata stored in master
  - Reduces clients' need to interact with master
- Disadvantages

Why Large Chunks?

- 64MB or 128MB (much larger than most file systems)
- Advantages
  - Reduces the size of the metadata stored in master
  - Reduces clients' need to interact with master
- Disadvantages
  - Wasted space due to internal fragmentation

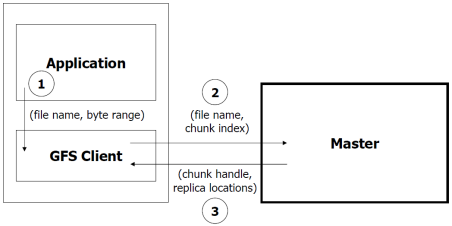
System Interactions

The System Interface

- Not POSIX-compliant, but supports typical file system operations
  - `create`, `delete`, `open`, `close`, `read`, and `write`
- `snapshot`: creates a copy of a file or a directory tree at low cost
- `append`: allow multiple clients to append data to the same file concurrently

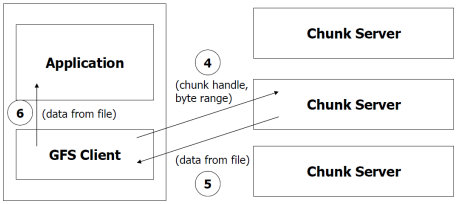
Read Operation (1/2)

- 1. Application originates the read request.
- 2. GFS client translates request and sends it to the master.
- 3. The master responds with chunk handle and replica locations.



Read Operation (2/2)

- 4. The client picks a location and sends the request.
- 5. The chunkserver sends requested data to the client.
- 6. The client forwards the data to the application.



Update Order (1/2)

- Update (mutation): an operation that changes the content or metadata of a chunk.

Update Order (1/2)

- Update (mutation): an operation that changes the content or metadata of a chunk.
- For consistency, updates to each chunk must be ordered in the same way at the different chunk replicas.
- Consistency means that replicas will end up with the same version of the data and not diverge.

Update Order (2/2)

- For this reason, for each chunk, one replica is designated as the primary.
- The other replicas are designated as secondaries.
- Primary defines the update order.
- All secondaries follow this order.

Primary Leases (1/2)

- For correctness there needs to be one single primary for each chunk.

Primary Leases (1/2)

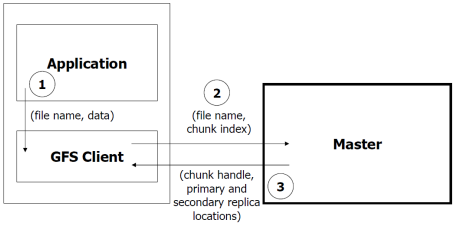
- For correctness there needs to be one single primary for each chunk.
- At any time, at most one server is primary for each chunk.
- Master selects a chunkserver and grants it lease for a chunk.

Primary Leases (2/2)

- The chunkserver holds the lease for a period T after it gets it, and behaves as primary during this period.
- If master does not hear from primary chunkserver for a period, it gives the lease to someone else.

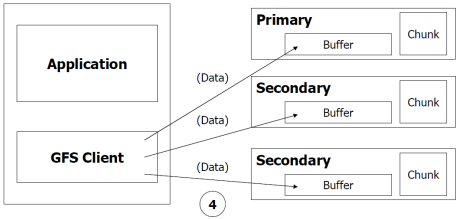
Write Operation (1/3)

- 1. Application originates the request.
- 2. The GFS client translates request and sends it to the master.
- 3. The master responds with chunk handle and replica locations.



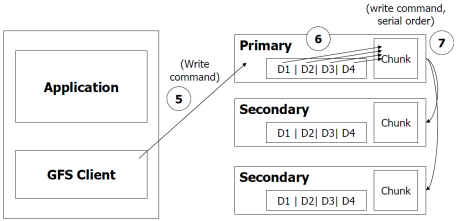
Write Operation (2/3)

- 4. The client pushes write data to all locations. Data is stored in chunkserver's internal buffers.



Write Operation (3/3)

- 5. The client sends write command to the primary.
- 6. The primary determines serial order for data instances in its buffer and writes the instances in that order to the chunk.
- 7. The primary sends the serial order to the secondaries and tells them to perform the write.



Write Consistency

- Primary enforces one update order across all replicas for concurrent writes.
- It also waits until a write finishes at the other replicas before it replies.

Write Consistency

- Primary enforces one update order across all replicas for concurrent writes.
- It also waits until a write finishes at the other replicas before it replies.
- Therefore:
  - We will have identical replicas.
  - But, file region may end up containing mingled fragments from different clients: e.g., writes to different chunks may be ordered differently by their different primary chunkservers
  - Thus, writes are consistent but undefined state in GFS.

Delete Operation

- Metadata operation.
- Renames file to special name.
- After certain time, deletes the actual chunks.
- Supports undelete for limited time.
- Actual lazy garbage collection.

The Master Operations

A Single Master

- The master has a global knowledge of the whole system
- It simplifies the design
- The master is (hopefully) never the bottleneck

A Single Master

- The master has a global knowledge of the whole system
- It simplifies the design
- The master is (hopefully) never the bottleneck
  - Clients never read and write file data through the master
  - Client only requests from master which chunkservers to talk to
  - Further reads of the same chunk do not involve the master

The Master Operations

- Namespace management and locking
- Replica placement
- Creating, re-replicating and re-balancing replicas
- Garbage collection
- Stale replica detection

Namespace Management and Locking (1/2)

- Represents its namespace as a lookup table mapping pathnames to metadata.

Namespace Management and Locking (1/2)

- Represents its namespace as a lookup table mapping pathnames to metadata.
- Each master operation acquires a set of locks before it runs.
- Read lock on internal nodes, and read/write lock on the leaf.

Namespace Management and Locking (1/2)

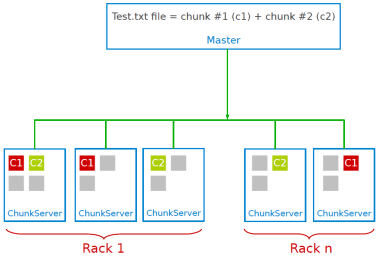
- Represents its namespace as a lookup table mapping pathnames to metadata.
- Each master operation acquires a set of locks before it runs.
- Read lock on internal nodes, and read/write lock on the leaf.
- Example: creating multiple files (`f1` and `f2`) in the same directory (`/home/user/`).
  - Each operation acquires a read lock on the directory name `/home/user/`
  - Each operation acquires a write lock on the file name `f1` and `f2`

Namespace Management and Locking (2/2)

- Read lock on directory (e.g., `/home/user/`) prevents its deletion, renaming or snapshot
- Allows concurrent mutations in the same directory

Replica Placement

- Maximize data reliability, availability and bandwidth utilization.
- Replicas spread across machines and racks, for example:
  - 1st replica on the local rack.
  - 2nd replica on the local rack but different machine.
  - 3rd replica on a different rack.
- The master determines replica placement.



Creation, Re-replication and Re-balancing

- Creation
  - Place new replicas on chunkservers with below-average disk usage.
  - Limit number of recent creations on each chunkserver.

Creation, Re-replication and Re-balancing

- Creation
  - Place new replicas on chunkservers with below-average disk usage.
  - Limit number of recent creations on each chunkserver.
- Re-replication
  - When number of available replicas falls below a user-specified goal.

Creation, Re-replication and Re-balancing

- Creation
  - Place new replicas on chunkservers with below-average disk usage.
  - Limit number of recent creations on each chunkserver.
- Re-replication
  - When number of available replicas falls below a user-specified goal.
- Rebalancing
  - Periodically, for better disk utilization and load balancing.
  - Distribution of replicas is analyzed.

Garbage Collection

- File deletion logged by master.
- File renamed to a hidden name with deletion timestamp.

Garbage Collection

- File deletion logged by master.
- File renamed to a hidden name with deletion timestamp.
- Master regularly removes hidden files older than 3 days (configurable).
- Until then, hidden files can be read and undeleted.

Garbage Collection

- File deletion logged by master.
- File renamed to a hidden name with deletion timestamp.
- Master regularly removes hidden files older than 3 days (configurable).
- Until then, hidden files can be read and undeleted.
- When a hidden file is removed, its in-memory metadata is erased.

Stale Replica Detection

- Chunk replicas may become stale: if a chunkserver fails and misses mutations to the chunk while it is down.

Stale Replica Detection

- Chunk replicas may become stale: if a chunkserver fails and misses mutations to the chunk while it is down.
- Need to distinguish between up-to-date and stale replicas.

Stale Replica Detection

- Chunk replicas may become stale: if a chunkserver fails and misses mutations to the chunk while it is down.
- Need to distinguish between up-to-date and stale replicas.
- Chunk version number:
  - Increased when master grants new lease on the chunk.
  - Not increased if replica is unavailable.

Stale Replica Detection

- Chunk replicas may become stale: if a chunkserver fails and misses mutations to the chunk while it is down.
- Need to distinguish between up-to-date and stale replicas.
- Chunk version number:
  - Increased when master grants new lease on the chunk.
  - Not increased if replica is unavailable.
- Stale replicas deleted by master in regular garbage collection.

Fault Tolerance

Fault Tolerance for Chunks

- Chunks replication (re-replication and re-balancing)
- Data integrity
  - Checksum for each chunk divided into 64KB blocks.
  - Checksum is checked every time an application reads the data.

Fault Tolerance for Chunkserver

- All chunks are versioned.
- Version number updated when a new lease is granted.
- Chunks with old versions are not served and are deleted.

Fault Tolerance for Master

- Master state replicated for reliability on multiple machines.
- When master fails:
  - It can restart almost instantly.
  - A new master process is started elsewhere.
- Shadow (not mirror) master provides only read-only access to file system when primary master is down.

GFS and HDFS

GFS vs. HDFS

GFS	HDFS
Master	Namenode
Chunkserver	DataNode
Operation Log	Journal, Edit Log
Chunk	Block
Random file writes possible	Only append is possible
Multiple write/reader model	Single write/multiple reader model
Default chunk size: 64MB	Default chunk size: 128MB

DFS Through a Data Feminism Lens

- Who do they serve?

DFS Through a Data Feminism Lens

- Who do they serve?
  - For large-scale industrial use.
  - Not designed for local data sovereignty.

DFS Through a Data Feminism Lens

- Who do they serve?
  - For large-scale industrial use.
  - Not designed for local data sovereignty.
- Design philosophy

DFS Through a Data Feminism Lens

- Who do they serve?
  - For large-scale industrial use.
  - Not designed for local data sovereignty.
- Design philosophy
  - Business-first: speed, cost, scale.
  - Missing: participatory governance, equitable access, ecological accountability.

DFS Through a Data Feminism Lens

- Who do they serve?
  - For large-scale industrial use.
  - Not designed for local data sovereignty.
- Design philosophy
  - Business-first: speed, cost, scale.
  - Missing: participatory governance, equitable access, ecological accountability.
- Environmental impact

DFS Through a Data Feminism Lens

- Who do they serve?
  - For large-scale industrial use.
  - Not designed for local data sovereignty.
- Design philosophy
  - Business-first: speed, cost, scale.
  - Missing: participatory governance, equitable access, ecological accountability.
- Environmental impact
  - Triple replication = high energy, water, and carbon footprint.

Questions

- DFS, like GFS and HDFS, were built for speed and scale in corporate settings, not for local control or sustainability.
  If you are to design a DFS for a small community or NGO, how would you change the architecture, governance, and replication strategy to align with principles like equity, inclusion, and environmental responsibility?

Possible Answers

- Architecture

Possible Answers

- Architecture
  - Lightweight, runs on modest hardware
  - Local-first storage (keep data near community)
  - Energy-efficient design; prioritize renewable-powered nodes

Possible Answers

- Architecture
  - Lightweight, runs on modest hardware
  - Local-first storage (keep data near community)
  - Energy-efficient design; prioritize renewable-powered nodes
- Governance

Possible Answers

- Architecture
  - Lightweight, runs on modest hardware
  - Local-first storage (keep data near community)
  - Energy-efficient design; prioritize renewable-powered nodes
- Governance
  - Community-owned and operated
  - Transparent decision-making on data use and access
  - Respect cultural and legal data sovereignty

Possible Answers

- Architecture
  - Lightweight, runs on modest hardware
  - Local-first storage (keep data near community)
  - Energy-efficient design; prioritize renewable-powered nodes
- Governance
  - Community-owned and operated
  - Transparent decision-making on data use and access
  - Respect cultural and legal data sovereignty
- Replication Strategy

Possible Answers

- Architecture
  - Lightweight, runs on modest hardware
  - Local-first storage (keep data near community)
  - Energy-efficient design; prioritize renewable-powered nodes
- Governance
  - Community-owned and operated
  - Transparent decision-making on data use and access
  - Respect cultural and legal data sovereignty
- Replication Strategy
  - Adaptive replication: balance resilience with energy use
  - Choose replica locations with community input
  - Use erasure coding or low-energy redundancy methods

Feminist-Aligned Alternative Systems

- Tahoe-LAFS
  - Decentralized, least-authority model; only the data owner has full access.
  - Community-driven; supports privacy, resilience, and user control.

Feminist-Aligned Alternative Systems

- Tahoe-LAFS
  - Decentralized, least-authority model; only the data owner has full access.
  - Community-driven; supports privacy, resilience, and user control.
- IPFS
  - Peer-to-peer, content-addressed storage.
  - Avoids dependence on centralized hyperscalers; supports local, renewable-powered nodes.

Feminist-Aligned Alternative Systems

- Tahoe-LAFS
  - Decentralized, least-authority model; only the data owner has full access.
  - Community-driven; supports privacy, resilience, and user control.
- IPFS
  - Peer-to-peer, content-addressed storage.
  - Avoids dependence on centralized hyperscalers; supports local, renewable-powered nodes.
- Ceph
  - Flexible replication to keep data in local or community-controlled infrastructure.
  - Can be adapted for jurisdictional compliance and reduced environmental impact.

Summary

Summary

- Google File System (GFS)
- Files and chunks
- GFS architecture: master, chunk servers, client
- GFS interactions and master operations
- Alternative systems, e.g., Tahoe-LAFS, IPFS, Ceph

References

- S. Ghemawat et al., The Google File System, Vol. 37. No. 5. ACM, 2003.
- Z. Wilcox-OHearn et al., Tahoe: The Least-Authority Filesystem, ACM StorageSS 2008.
- J. Benet, IPFS: Content Addressed, Versioned, P2P File System, arXiv preprint arXiv:1407.3561, 2014.
- S.A. Weil, Ceph: A Scalable, High-Performance Distributed File System. USENIX OSDI, 2006.

Questions?