The Google File System

Definition -DFS

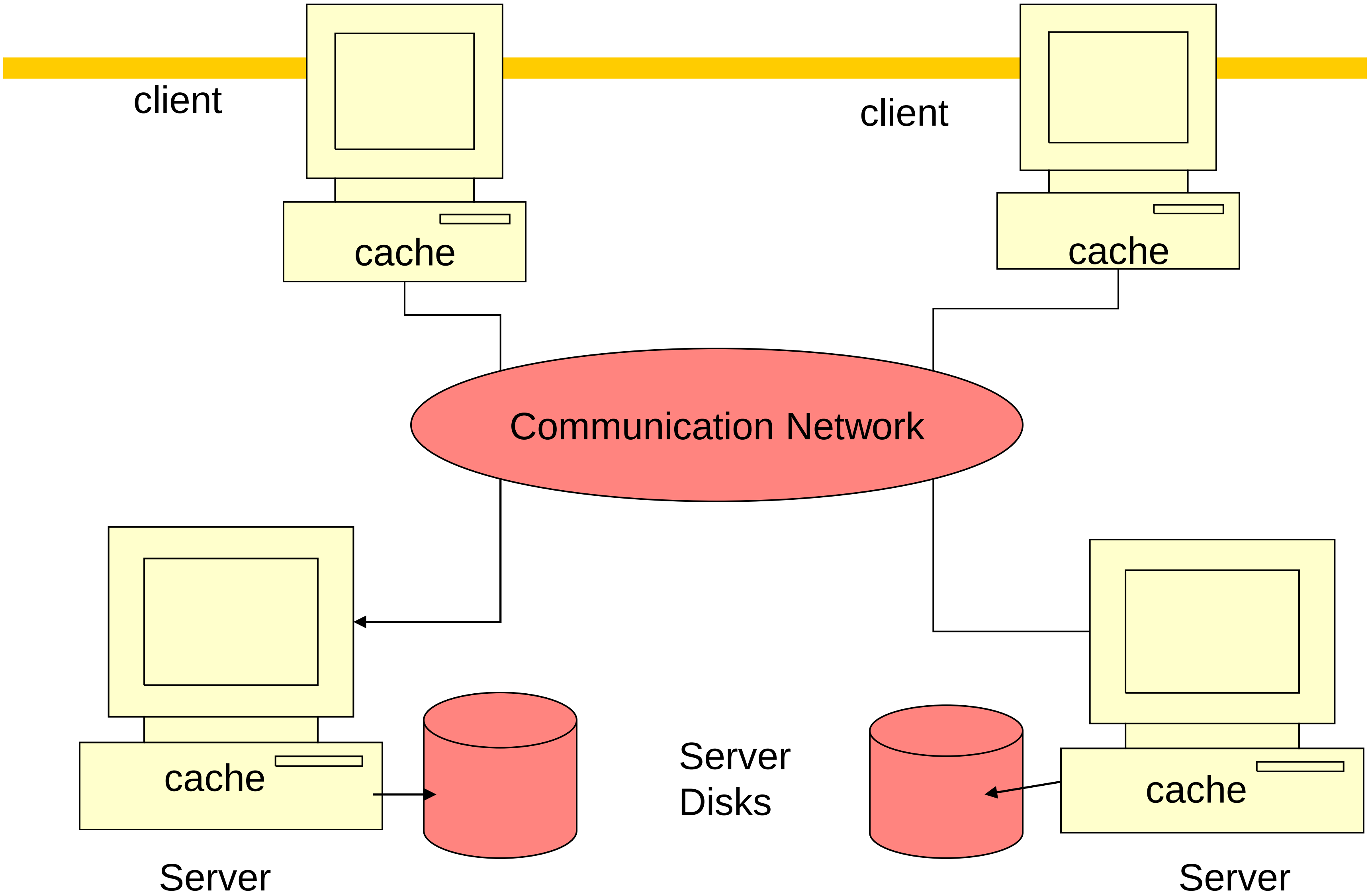
- DFS: multiple users, multiple sites, and (possibly) distributed storage of files.
- Benefits
  - File sharing
  - Uniform view of system from different clients
  - Centralized administration
- Goals of a distributed file system
  - **Network Transparency** (access transparency)
  - **Availability-** files should be easily and quickly accessible.

Architectures

- Client-Server
  - Traditional; e.g. Sun Microsystems Network File System (NFS)
  - Cluster-Based Client-Server; e.g., Google File System (GFS)
- Symmetric
  - Fully decentralized; based on peer-to-peer technology
    e.g., Ivy (uses a Chord DHT approach)

Client-Server Architecture

- One or more machines (file servers) manage the file system.
- Files are stored on disks at the servers
- Requests for file operations are made from clients to the servers.
- Client-server systems centralize storage and management; P2P systems decentralize it.



Architecture of a distributed file system: client-server model

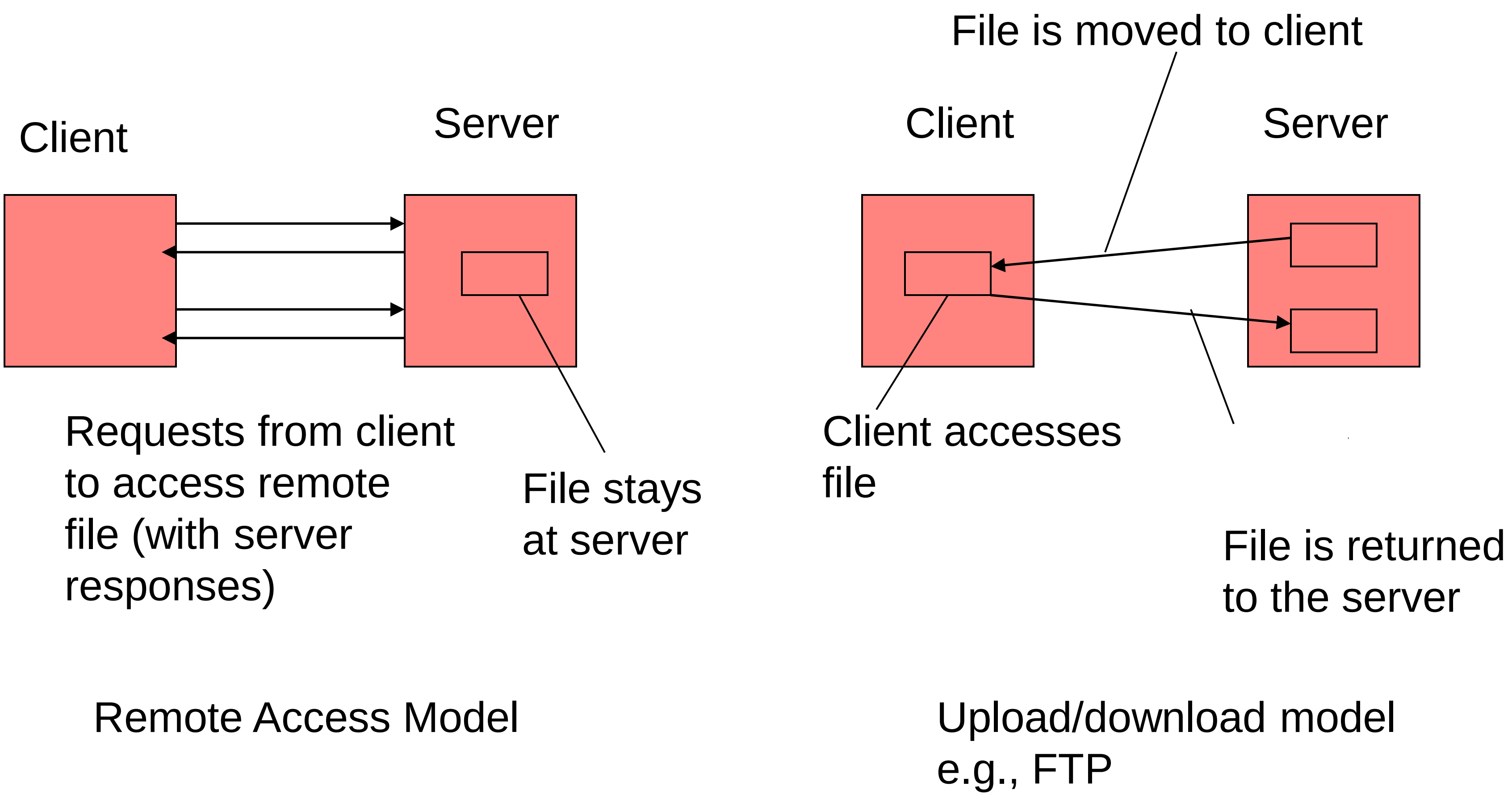
Sun’s Network File System

- Sun’s NFS for many years was the most widely used distributed file system.
  - NFSv3: version three, used for many years
  - NFSv4: introduced in 2003
    - Version 4 made significant changes

Overview

- NFS goals:
  - Each file server presents a standard view of its local file system
  - transparent access to remote files
  - compatibility with multiple operating systems and platforms.
  - easy crash recovery at server
- Originally UNIX based; now available for most operating systems.
- NFS communication protocols lets processes running in different environments share a file system.

NFS Implements Remote Access



Access Models

- Most distributed file systems use the remote access model
  - Client-side caching may be used to save time and network traffic
  - Access is transparent to user; the interface resembles the interface to the local file system
- FTP implements the upload/download model for read-write files.

NFS as a Stateless Server

- NFS servers historically did not retain any information about past requests.
- Consequence: crashes weren’t too painful
  – If server crashed, it had no tables to rebuild – just reboot and go
- Disadvantage: client has to maintain all state information; messages are longer than they would be otherwise.
- NFSv4 is stateful

Advantages/Disadvantages

- Stateless Servers
  - Fault tolerant
  - No open/close RPC required
  - No need for server to waste time or space maintaining tables of state information
  - Quick recovery from server crashes
- Stateful Servers
  - Messages to server are shorter (no need to transmit state information)
  - Supports file locking
  - Supports idempotency (don’t repeat actions if they have been done)

File System Model

- NFS implements a file system model that is almost identical to a UNIX system.
  - Files are structured as a sequence of bytes
  - File system is hierarchically structured
  - Supports hard links and symbolic links
  - Implements most file operations that UNIX supports

Cluster-based or Clustered File System

- A distributed file system that consists of several servers that share the responsibilities of the system, as opposed to a single server (possibly replicated).
- The design decisions for a cluster-based systems are mostly related to how the data is distributed across the cluster and how it is managed.

Cluster-Based DFS

- Some cluster-based systems organize the clusters in an application specific manner
- For file systems used primarily for parallel applications, the data in a file might be striped across several servers so it can be read in parallel.
- Or, it might make more sense to partition the file system itself – some portion of the total number of files are stored on each server.
- For systems that process huge numbers of requests; e.g., large data centers, reliability and management issues take precedence.

    e.g., Google File System

Google File System (GFS) Concepts(Assumptions)

- GFS uses a cluster-based approach implemented on ordinary commodity Linux boxes (not high-end servers).
- Component failures are the norm rather than the exception.
  - File System consists of hundreds or even thousands of storage machines built from inexpensive commodity parts.
- Files are Huge. Multi-GB Files are common.
  - Each file typically contains many application objects such as web documents.
- Append, Append, Append.
  - Most files are mutated by appending new data rather than overwriting existing data.
- Co-Designing
  - Co-designing applications and file system API benefits overall system by increasing flexibility

The Google File System

- GFS stores a huge number of files, totaling many terabytes of data
- Individual file characteristics
  - Very large, multiple gigabytes per file
  - Files are updated by appending new entries to the end (faster than overwriting existing data)
  - Files are virtually never modified (other than by appends) and virtually never deleted.
  - Files are mostly read-only

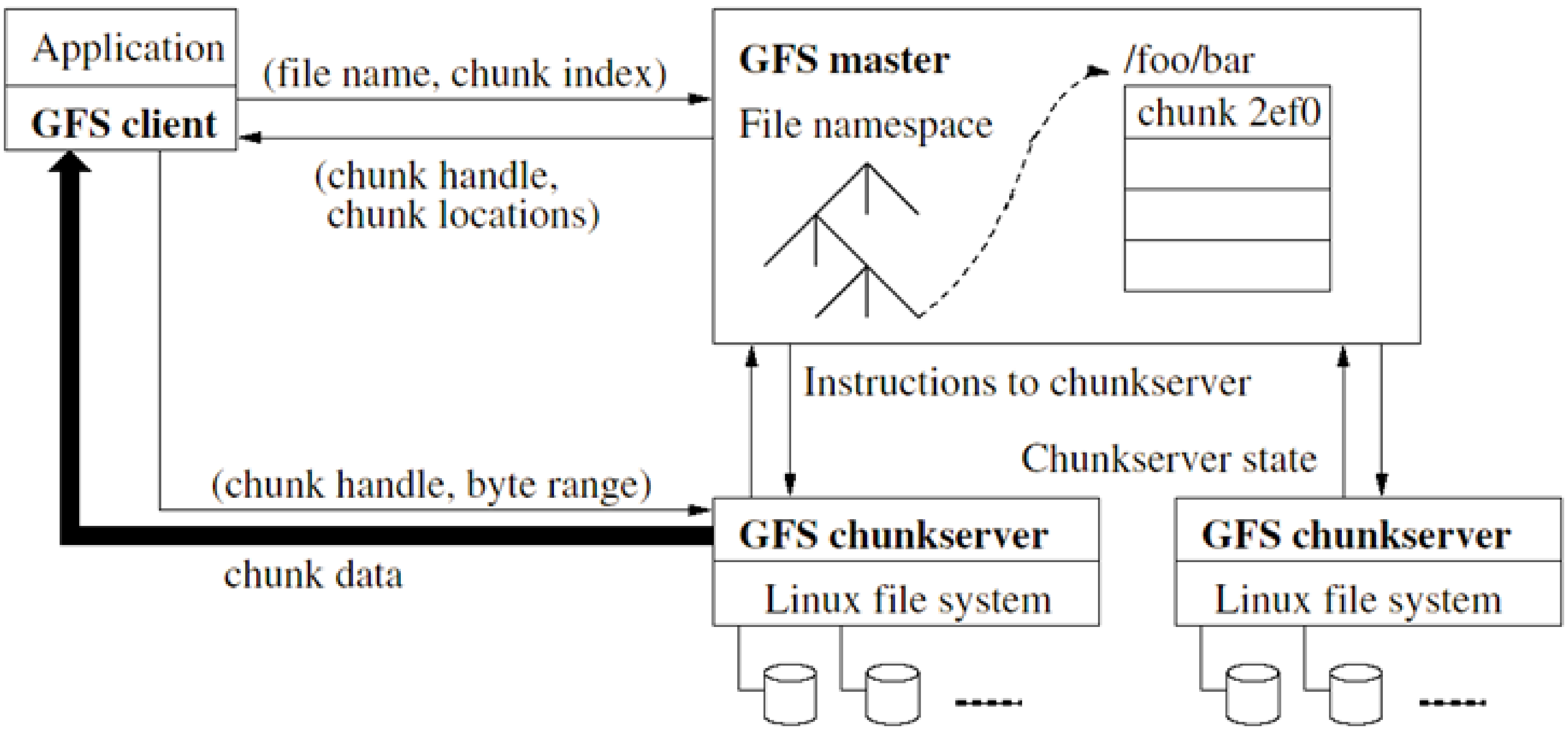
Architecture

- A GFS cluster consists of Single master & multiple chunkservers.
- Files divided into fixed-size chunks (64MB).
  - Immutable and globally unique 64 bit chunk handle assigned at creation
  - Chunks stored by chunkservers on local disks as Linux files
  - R or W chunk data specified by chunk handle and byte range
  - Each chunk replicated on multiple chunkservers – default is 3
- The master knows (more or less) where chunks are stored
  - Maintains a mapping from file name to chunks & chunks to chunk servers
- Clients contact the master to find where a particular chunk is located.

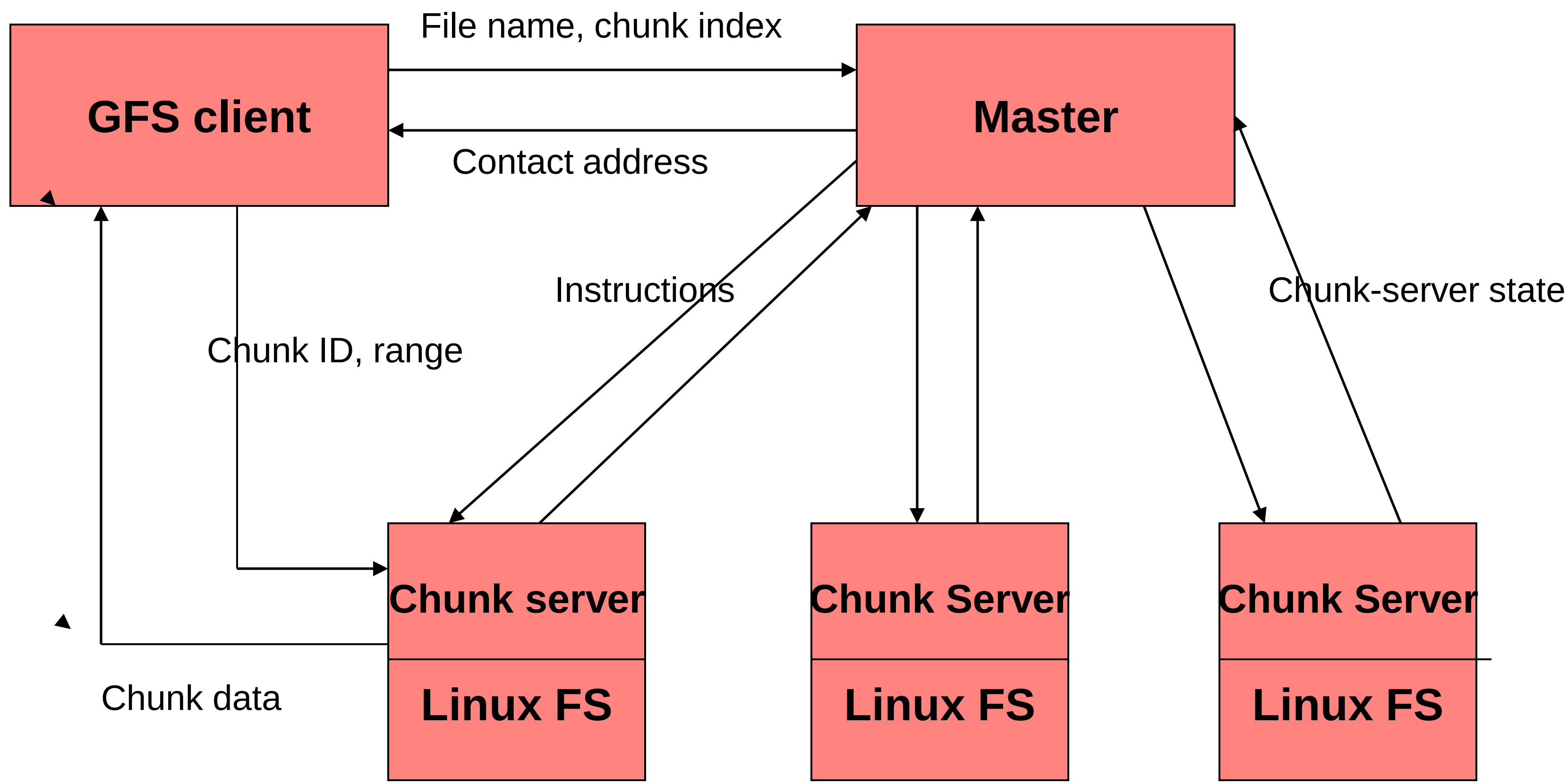
Architecture

- Master maintains all file system metadata
  - Namespace, access control info, mapping from files to chunks, location of chunks
  - Controls garbage collection of chunks
  - Communicates with each chunkserver through HeartBeat messages
  - Clients interact with master for metadata, chunksevers do the rest, e.g. R/W on behalf of applications
- Periodically the master polls all its chunk servers to find out which chunks each one stores
  - This means the master doesn't need to know each time a new server comes on board, when servers crash, etc.
- Polling occurs often enough to guarantee that master's information is "good enough".

Architecture



Architecture



The organization of a Google cluster of servers

Master

- Single Master –
  - Simplifies design
  - Placement, replication decisions made with global knowledge
  - Doesn’t R/W, so not a bottleneck
  - Client asks master which chunkservers to contact

Client

- Client translate file name/offset into chunk index within file
- Send master request with file name/chunk index
- Master replies with chunk handle and location of replicas
- Client caches info using file name/chunk index as key
- Client sends request to one of the replicas (closest)
- Further reads of same chunk require no interaction
- Can ask for multiple chunks in same request

Operation Log

- Historical record of critical metadata changes
- Log replicated on remote machines
- Log kept small – checkpoint when > size
- New checkpoint built without delaying mutations (takes about 1 min for 2 M files)
- Only keep latest checkpoint and subsequent logs

Consistency Model

<table>
<tr><th></th><th>Write</th><th>Record Append</th></tr>
<tr><td>Serial success</td><td>defined</td><td rowspan="2">defined interspersed with inconsistent</td></tr>
<tr><td>Concurrent successes</td><td>consistent but undefined</td></tr>
<tr><td>Failure</td><td colspan="2">inconsistent</td></tr>
</table>

Table 1: File Region State After Mutation

- File namespace mutations are atomic
  - Relatively simple, since just a single master.
- Data mutations may be writes or record appends
- Various file region states after mutations:
  - Consistent - All clients see the same data, regardless of replicas
  - Defined – Clients see what mutation writes in entirety
  - Inconsistent – Different clients see different data

Leases and Mutation Order

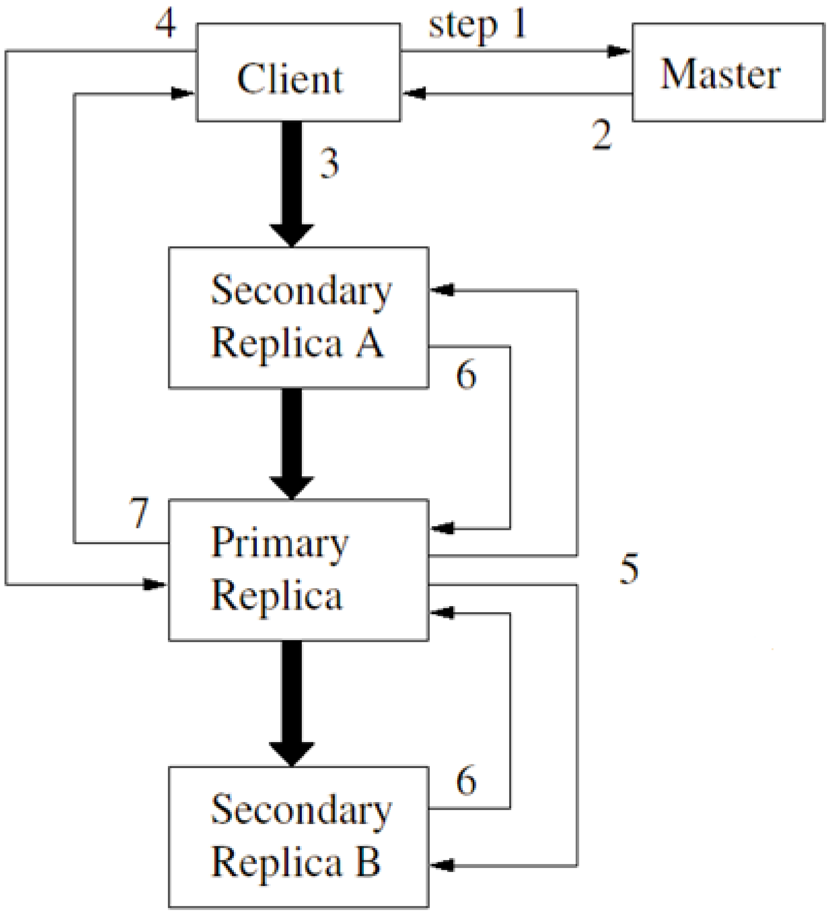
- A mutation is an operation that changes the contents or metadata of a chunk such as a write or an append operation. Each mutation is performed at all the chunk’s replicas.

- We use leases to maintain a consistent mutation order across replicas.

- The master grants a chunklease to one of the replicas, which we call the primary. The primary picks a serial order for all mutations to the chunk.

- A lease has an initial timeoutof 60 seconds.

Control flow of a write operation



1. Client asks master for all replicas.
2. Master replies with primary and secondary. Client caches.
3. Client pushes the data to all replicas.
4. After all replicas acknowledge, client sends write request to primary.
5. Primary forwards write request to all replicas.
6. Secondaries reply to primary indicating operation completion.
7. Primary replies to client. Errors handled by retrying.

Data Flow

- Fully utilize each machine's network bandwidth
  - Data pushed along chain chunkservers
- Avoid bottlenecks and high-latency
  - Machine forwards to closest machine in topology
- Minimize latency
  - Pipeline data transfer over TCP connections

Atomic Record Appends

- Client pushes data to all replicas of last chunk of the file
- Sends request to primary
- Primary checks if will exceed 64MB, if so send message to retry on next chunk, else primary appends, tells 2ndary to write, send reply to client
- If append fails, retries
  - Replicas of same chunk may contain different data, including duplication of same record in part or whole
  - Does not guarantee all replicas bytewise identical
  - Guarantees **data written at least once as atomic unit**
  - Data must have been written at same offset on all replicas of same chunk, but not same offset in file

Replica Placement

- GFS cluster distributed across many machine racks
- Need communication across several network switches
- Challenge to distribute data
- Chunk replica
  - Maximize data reliability
  - Maximize network bandwidth utilization
- Spread replicas across racks (survive even if entire rack offline)

Creation, Re-replication, and Rebalancing

- Replicas created for three reasons:

1. **Creation**
   - Balance disk utilization
   - Balance creation events
     - After a creation, lots of traffic
   - Spread replicas across racks
2. **Re-replication**
   - Occurs when number of replicas falls below a watermark.
     - Replica corrupted, chunkserver down, watermark increased.
   - Replicate based on priority (fewest replicas)
3. **Rebalancing**
   - Periodically moves replicas for better disk space and load balancing
   - Gradually fills up new chunkserver

Garbage Collection

- Storage reclaimed lazily by GC.
- File first renamed to a hidden name.
- Hidden files removes if more than three days old.
- When hidden file removed, in-memory metadata is removed.
- Regularly scans chunk namespace, identifying orphaned chunks. These are removed.
- Chunkservers periodically report chunks they have. If not “live”, master replies.

Fault Tolerance

- Fast Recovery
  - Master/chunkservers restore state and start in seconds regardless of how terminated
    - Abnormal or normal
- Chunk Replication

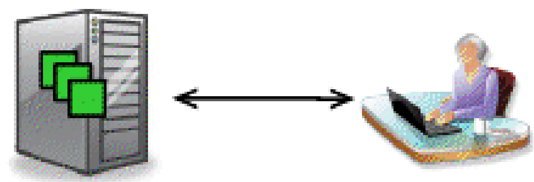
Shadow Master

- Master Replication
  - Replicated for reliability
  - One master remains in charge of all mutations and background activities
  - If fails, start instantly
  - If machine or disk mails, monitor outside GFS starts new master with replicated log
  - Clients only use canonical name of master

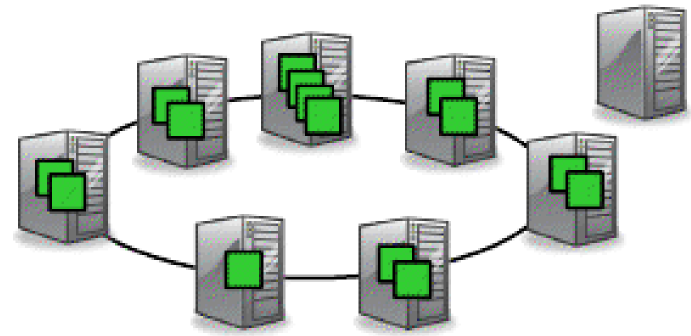
Shadow Master

- Shadow Master
  - Read-only access to file systems even when primary master down
  - Not mirrors, so may lag primary slightly (fractions of second)
  - Enhance read availability for files not actively mutated or if stale OK, e.g. metadata, access control info ???
  - Shadow master read replica of operation log, applies same sequence of changes to data structures as the primary does
  - Polls chunkserver at startup,monitors their status, etc.
  - Depends only on primary for replica location updates

GFS versus NFS



Network File System (NFS)



Google File System (HDFS)

- Single machine makes part of its file system available to other machines
- Sequential or random access
- PRO: Simplicity, generality, transparency
- CON: Storage capacity and throughput limited by single server

- Single virtual file system spread over many machines
- Optimized for sequential read and local accesses
- PRO: High throughput, high capacity
- "CON": Specialized for particular types of applications