Google File System (GFS)

Ashvin Goel

Electrical and Computer Engineering
University of Toronto

ECE1724

Authors: Sanjay Ghemawat, Howard Gobioff, and Shun-Tak Leung

Why Build GFS?

- Need a scalable, distributed file system that targets Google's workloads
  - Need to support much bigger (GB+) files
  - On 100/1000s of commodity servers that fail regularly
- Workloads process bulk multi-GB/TB datasets
  - High throughput more important than low latency accesses
  - Mostly sequential reads
    - Read sizes are bimodal, between 1-64K, or larger than 512KB
  - Most writes are file appends
    - Multiple clients perform concurrent file appends, e.g., producer-consumer queues, many-way merge operations, etc.
    - Overwrites are practically non-existent

GFS Interface

- Google co-designs its applications
  - Applications don't require POSIX compliance
  - Weaker consistency for higher throughput is acceptable
- Supports typical file system operations
  - E.g., create, delete, open, close, read, and write
- record append: allows multiple concurrent clients to append data to the same file
  - At-least once semantics
- snapshot: create copy of file/directory tree at low cost
  - Enables backup, experimentation
  - Similar to some modern file systems, e.g., btrfs, zfs

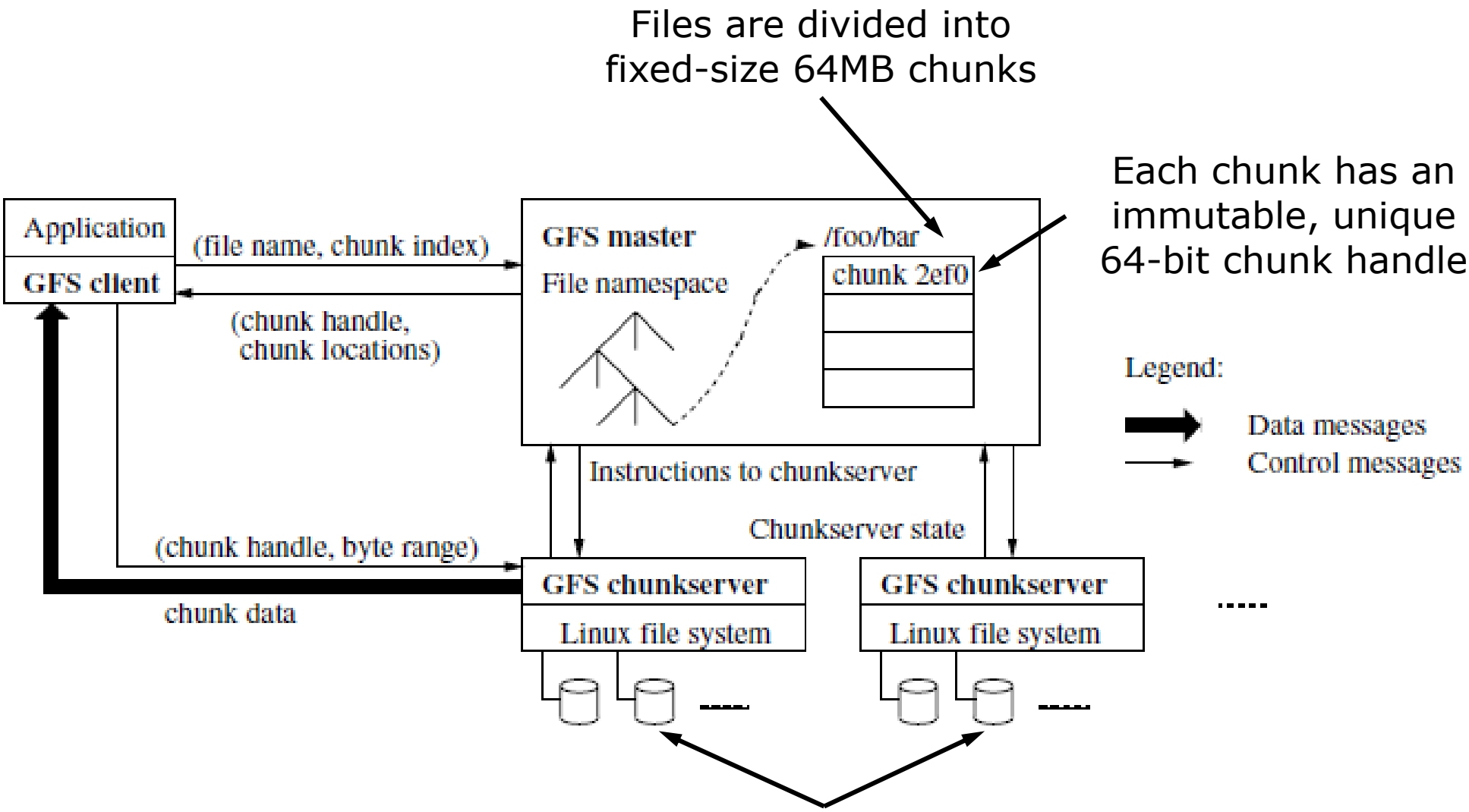
Key Design Ideas

- Use a cluster of inexpensive, commodity machines
  - Separate metadata and data operations for scalability
  - Node failures are common, so need fault tolerance
- Single metadata server
  - Simplifies design of overall system
  - Serializes metadata operations using a metadata log
  - Replicates metadata log for fault tolerance
  - Manages data replication
    - Data consistency, replica placement, load balancing, etc.
  - Avoids performing any data operations
- Data servers …

Key Design Ideas

- Use a cluster of inexpensive, commodity machines
  - Separate metadata and data operations for scalability
  - Node failures are common, so need fault tolerance
- Single metadata server …
- Data servers
  - Store replicas of chunks (fixed-size partitions) of files
  - Chunk size is relatively large (64MB)
    - Allows efficiently accessing large files
  - Support file appends efficiently

GFS Architecture



Master

- Maintains file system metadata in memory:
  - Chunk namespace, i.e., all chunk handles in the system
    - For each chunk: reference count (for copy-on-write snapshots), version number (for detecting stale chunk replicas)
  - File namespace, i.e., all file paths
    - For each file path: acl, file->chunk_handle mappings
- This metadata is stored persistently for failure recovery
  - All metadata changes are ordered and logged to disk
  - Log is replicated to backup master nodes
  - Then changes are applied to in-memory structures
  - In-memory structures are periodically checkpointed to reduce recovery time

Master

- Manages chunks and their replicas
  - Creates new chunks on chunkservers
  - Tracks chunk replicas by caching chunk locations, i.e., chunkservers on which a chunk is stored
  - Makes chunk replica placement decisions
- Ensures that concurrent metadata operations are performed atomically with per-filepath read-write locks
  - To modify /a/b/c,
    acquire read locks on /a, /a/b,
    write lock on /a/b/c
- This data is not stored persistently

Chunkserver

- A chunkserver stores
  - Chunks as Linux files on local disks
  - Chunk handle is Linux filename
  - Checksums for each 64KB block within chunk
- Each chunk is replicated across three chunkservers
- Application may read chunk from any replica
- Chunkservers report chunks they store to master
  - Master controls chunk placement but chunkservers serve as authorities for chunks

Master <-> Chunkserver

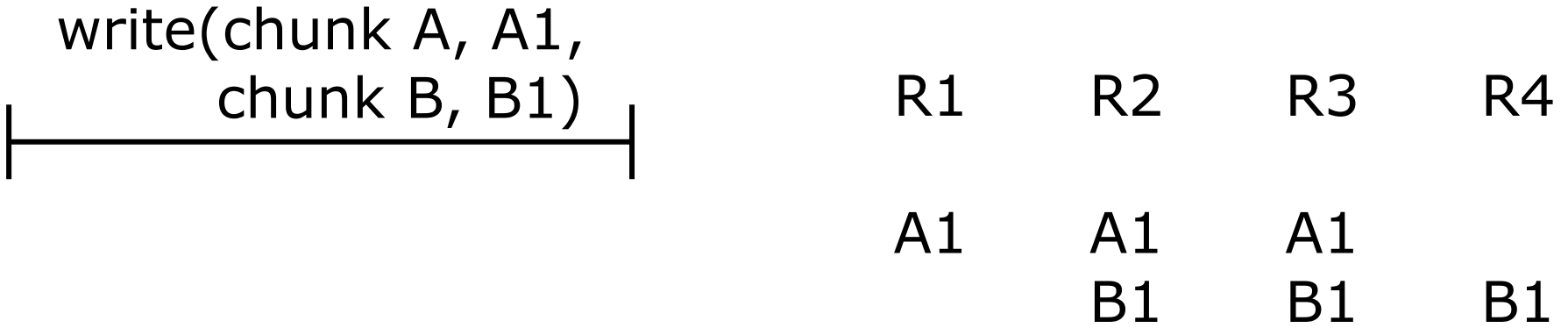
- Master periodically communicates with each chunkserver using HeartBeat messages
- Enables master to:
  - Know about chunk locations
  - Perform lease management, i.e., maintain primary for a chunk
  - Determine stale chunk servers
  - Garbage collect orphaned and stale chunks, etc.

Weak Consistency Model

- Definitions:
  - consistent: for a file region, all replicas store the same data
  - defined: after a write to a file region, the region is consistent and has the entire write (same as linearizable write)
- Complicated guarantees
  - Serial write: defined regions
  - Failed write: inconsistent regions
  - Concurrent writes within a chunk: defined regions
  - Concurrent writes that cross chunks: consistent but not defined regions
  - Record append: defined region, possibly interspersed with inconsistent regions

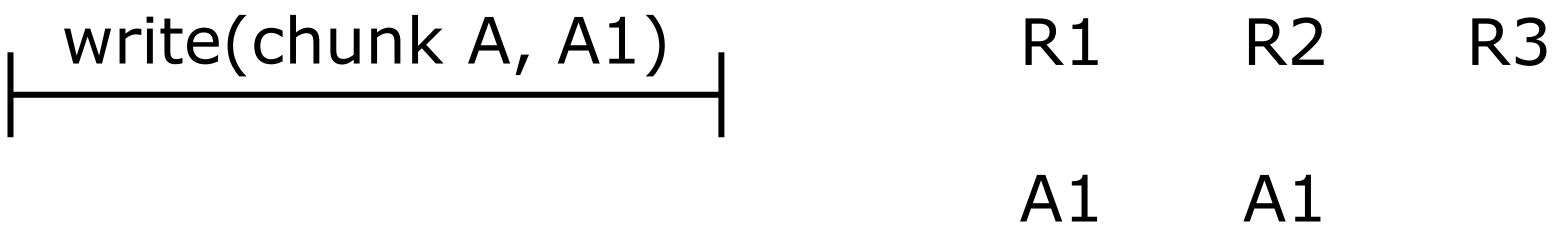
Understanding Consistency Model

- Clients perform writes at chunk granularity
  - For each chunk, writes are applied to all replicas
    - Ensures consistent file regions
- With serial writes, file region has full write
    - Ensures defined regions



Understanding Consistency Model

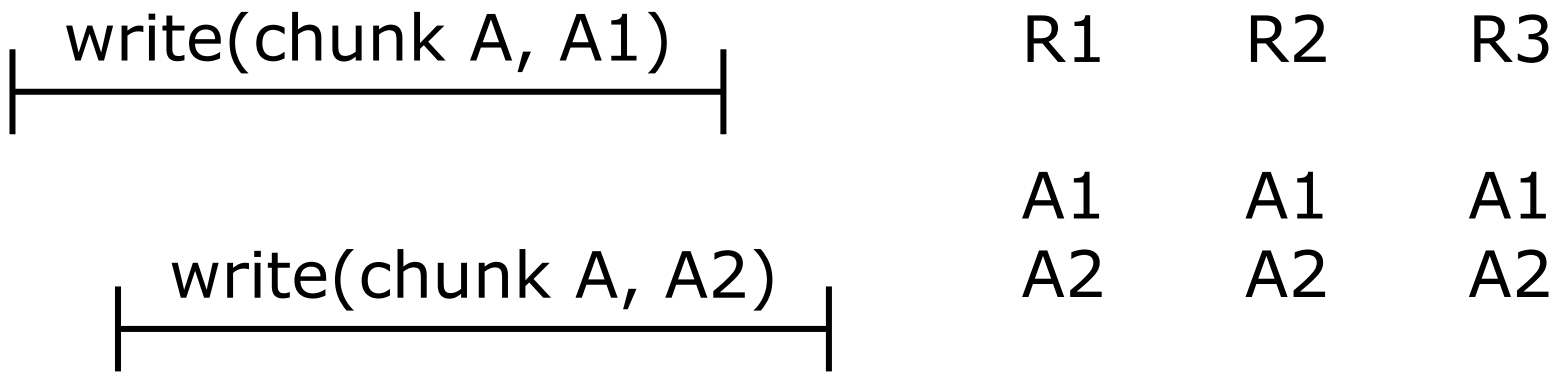
- Failed write
  - All replicas must respond with success or else a write is considered failed
  - In this case, the region may have different data at the different replicas, i.e., inconsistent region



- Application needs to handle failure by retrying write

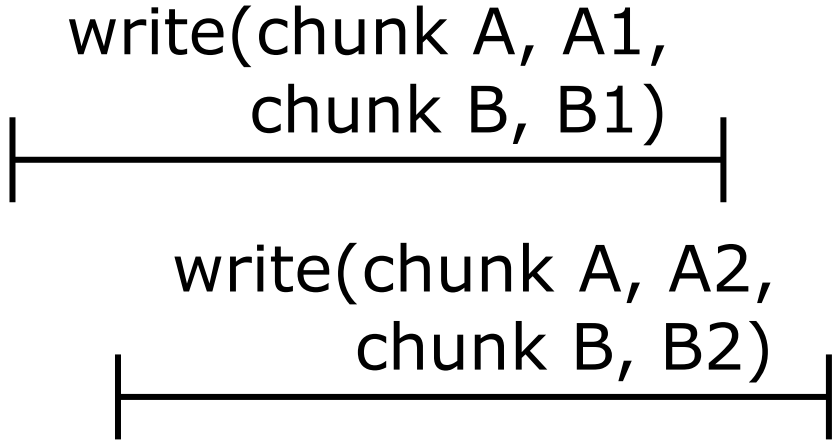
Understanding Consistency Model

- Concurrent writes within a chunk
- Writes to a chunk are applied in the same order at all replicas, so writes produce defined regions



Understanding Consistency Model

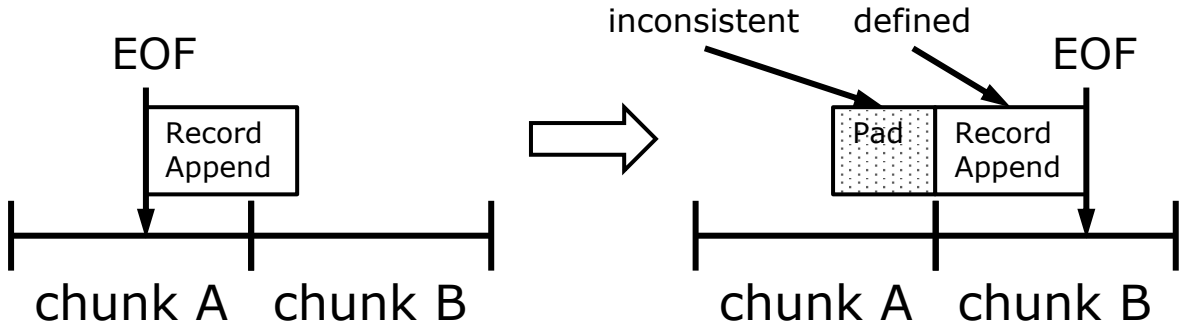
- Concurrent writes that cross chunks
- Writes to different chunks may be serialized in different order
  - e.g., final state is consistent (A=A2, B=B1), but not defined



R1	R2	R3	R4
A1	A1	A1	
A2	B2	A2	B2
	A2	B2	B1
	B1	B1	

Understanding Consistency Model

- Record append
- Need to ensure that record append yields a defined region, i.e., these write operations are linearizable
- Key idea: force append to lie within chunk with padding

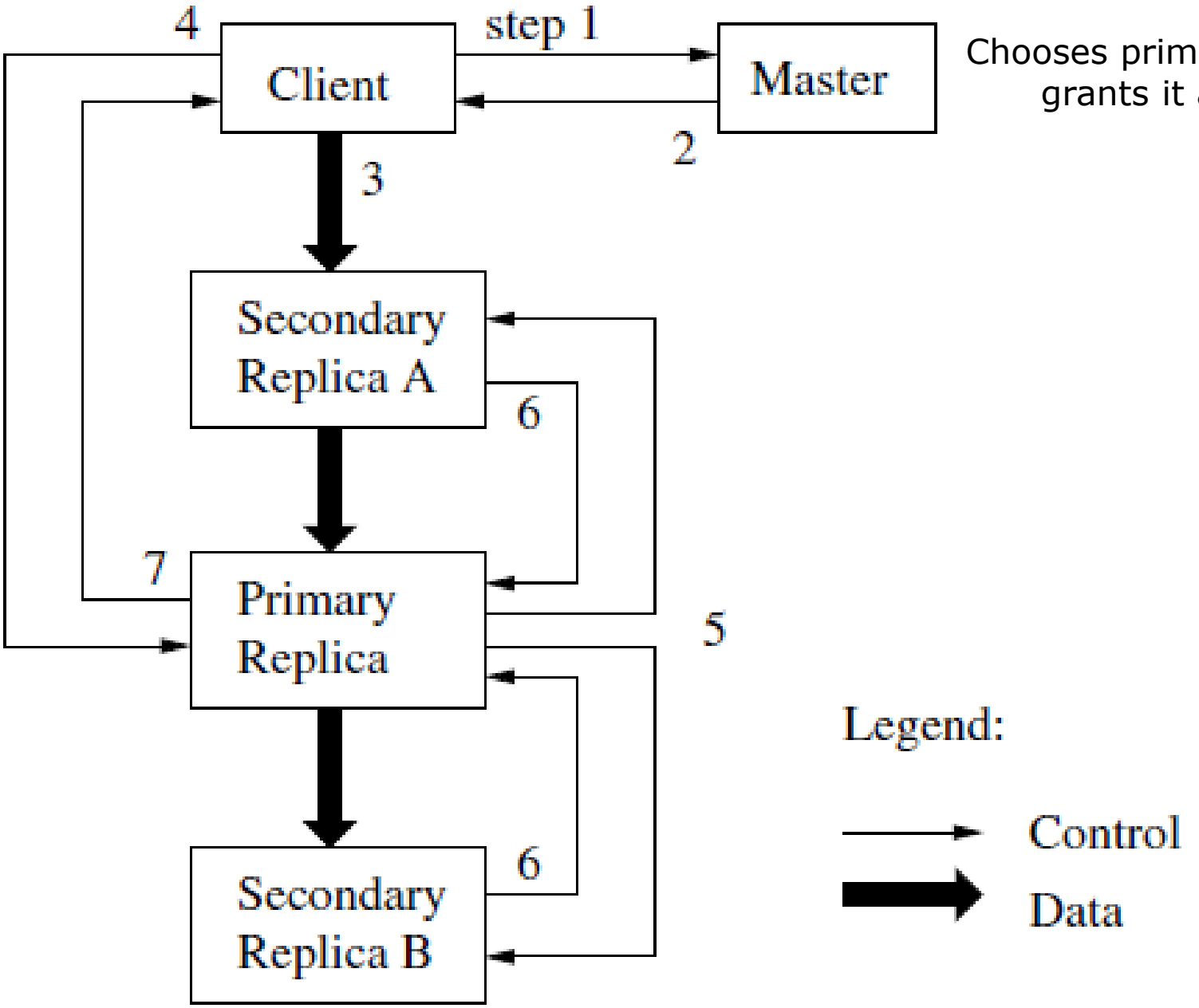


- Padding is an inconsistent region
- If record append fails, it creates an inconsistent region
  - A retry may lead to duplicate record appends

Implementing Consistency Model

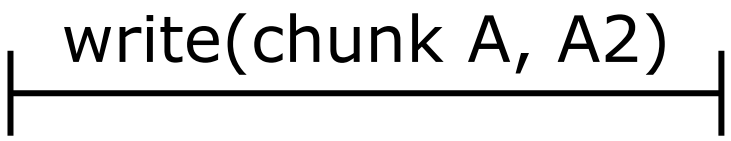
- Use lease mechanism to ensure consistency
  - Master grants a chunk lease to one of replicas (primary)
  - Primary picks a serial order for all mutations to the chunk
  - All replicas follow this order when applying mutations
  - Global mutation order defined by
    - Lease grant order chosen by the master
    - Serial numbers assigned by the primary within lease
- If master doesn't hear from primary, it grant lease to another replica after lease expires

Chunk Write Implementation



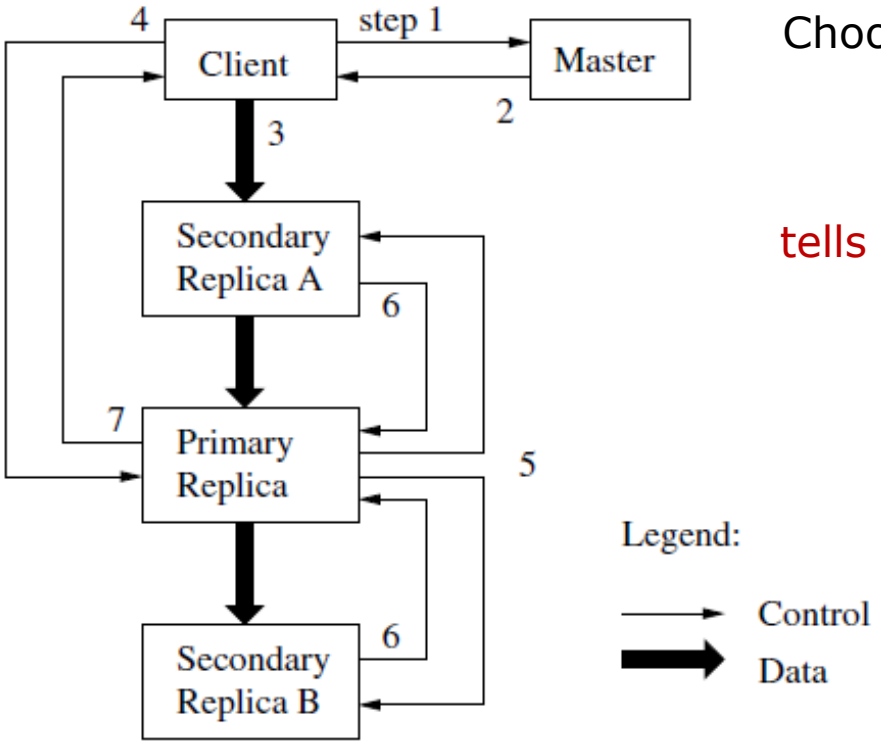
Stale Replicas

- What would happen if a replica is stale, i.e., doesn't have recent writes, and a write is attempted?



- Assume A1 and A2 do not overlap within Chunk A
  - Writing A2 to the three replicas will make them inconsistent
  - Reading from R3 will not return the A1 update

Detecting Stale Replicas with Chunk Versions



Chooses primary replica, grants it a lease,

increases chunk version number,
stores it persistently,
tells all up-to-date replicas to do the same.

write(chunk A, A2)

R1	R2	R3
A1	A1	
A2	A2	

Master Failures

- Master replicates metadata operation log and checkpoints to backup masters
- An external service detects master failure and promotes a backup to primary
  - Updates DNS so clients can access new master
- Backup applies operation log to its most recent checkpoint before starting operation

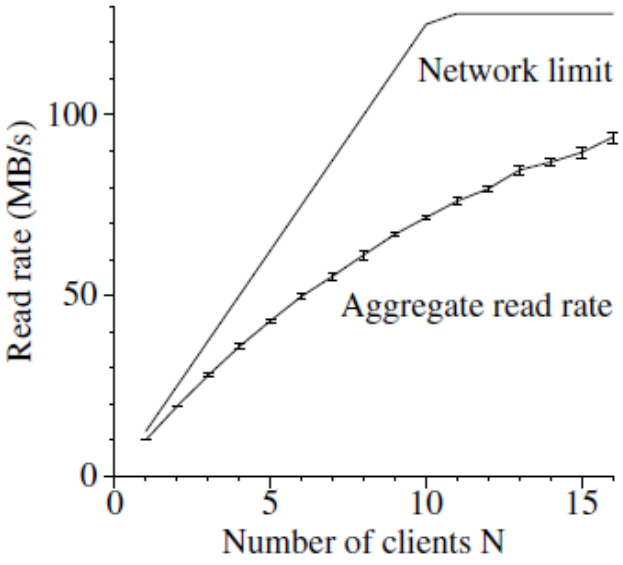
Chunkserver Failures

- Master uses HeartBeat messages to determine chunkserver status, enables master to:
  - Learn about failed chunkserver
  - Switch primary for chunks stored on chunkserver
  - Clone chunks that have fewer than 3 replicas to other chunkservers

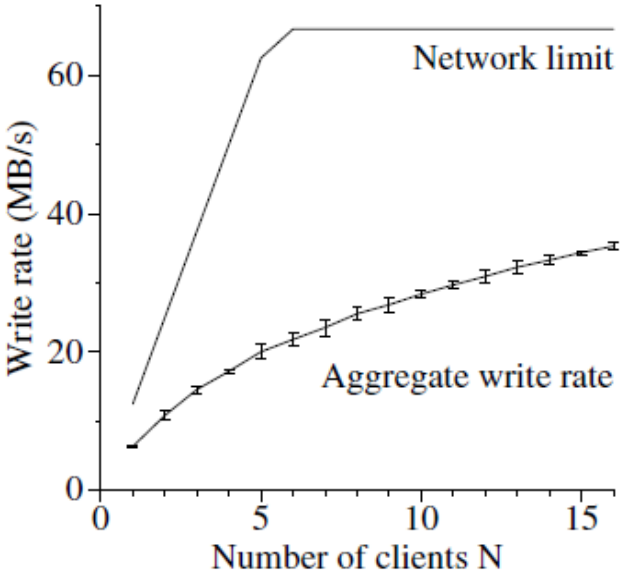
Evaluation

- Performance measured on test cluster with:
  - 1 master, 2 master backups
  - 16 chunkservers (store 3 replicas for each chunk)
  - 16 client machines
- Server machines connected to 100 Mbps switch
- Client machines connected to second 100 Mbps switch
- Switches connected with 1 Gbps link

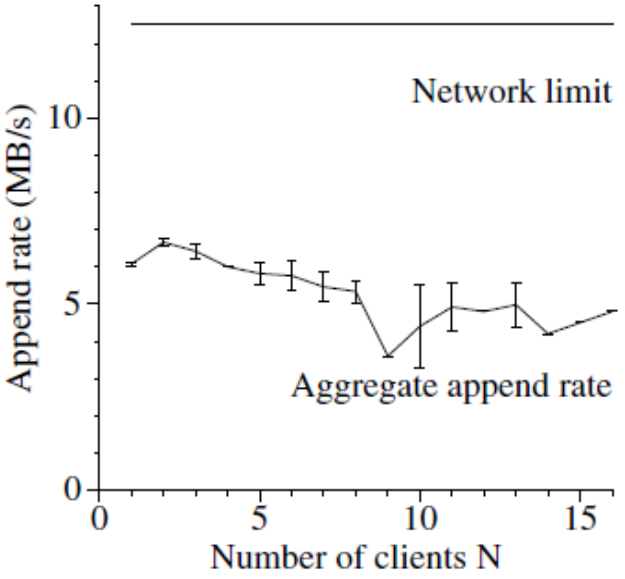
Performance



(a) Reads



(b) Writes



(c) Record appends

Conclusions

- Single master can dramatically simplify design
  - However, need to carefully design it to ensure it doesn't become a CPU, memory, disk, etc., bottleneck
- Decoupling metadata and data operations in file systems enables optimizing for them separately
- Targeting important use cases (e.g., concurrent appends) allows focusing on correct abstractions
  - Enables scaling with weaker consistency guarantees
- Very influential
  - Apache HDFS based on GFS design

GFS: Pros, Cons

- Pros
  - Can handle massive data and massive objects scalably
  - Works well for large sequential reads, appends
  - Simple, robust reliability model
- Cons
  - Metadata server can be bottleneck, single point of failure
    - However, sharding the namespace or replicating the server is feasible
  - Weak consistency guarantees
    - Linearizability for single chunk writes (not for cross-chunk writes)
    - Stale chunk reads possible
    - Duplicate and inconsistent data can be read
  - Small reads, overwrites are expensive

Q1

- Traditional file systems use small block sizes, e.g., 4KB, while GFS uses a large chunk size (64MB). Why does it use such a large chunk size? What are the tradeoffs?

Q2

- What are the most important differences between GFS and Zookeeper in terms of functionality?

Q3

- Zookeeper and RAFT ensures linearizable writes using a quorum-based protocol. How does GFS ensure linearizable metadata and data operations without using a similar protocol?

Q4

- When a chunk write fails at any chunkserver, GFS
  1. Exposes the failure to the client, and
  2. May update the chunk at some chunkservers (inconsistent region)
- Why is this done? How does this approach compare with writes to Zookeeper?

Q5

- Why are stale reads possible in GFS? Why does GFS allow them?