Big Data Storage I: Distributed File System, Google File System(GFS) & Colossus(GSF 2)

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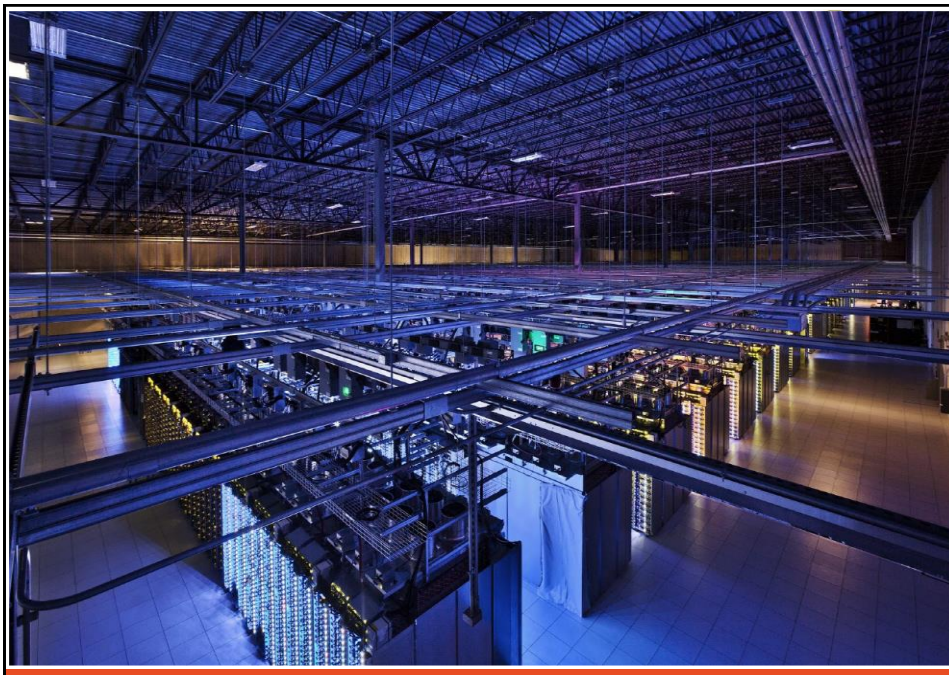
Lecture material is mostly home-grown, partly taken with permission and courtesy from Professor Shih-Wei Liao of NTU.

Outline

- Big data storage overview
- File systems overview
- Distributed File Systems (DFS)
- Google File System (GFS)
  - Motivations
  - Architecture
  - System Interactions
  - Fault Tolerance
  - Conclusion
- Colossus (GFS 2)

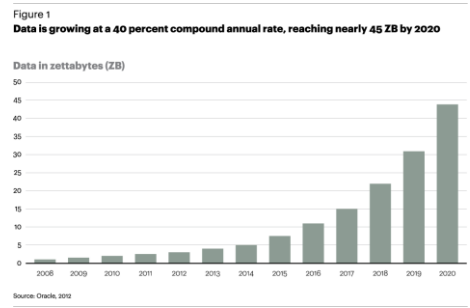


The GFS Paper

- Sanjay Ghemawat, Howard Gobioff, and Shun-Tak Leung. The Google File System, *SOSP'03,* October 19–22, 2003, Bolton Landing, New York, USA.

Big Data Storage Challenges

- Data is exploding!
- Replication systems have security weaknesses
- RAID at petabyte scale leads to data loss
- Multiple copies equals multiple everything



Problems with Traditional Storage

- Traditional storage architectures just weren't designed to handle big data scale.
- **They can't scale.**
- **They're not secure.**
- **They're not reliable.**
- **They're expensive.**

Storage Then and Now

Early days…

…today (Google datacenter at Pryor Oklahoma)

File System Overview

- Permanently stores data
- Usually layered on top of a lower-level (physical storage)
- Divided into logical units called “files”
  - Addressable by a filename (“foo.txt”)
  - Usually supports hierarchical nesting (directories)
- A file path = relative (or absolute) directory + filename
  - /dir1/dir2/foo.txt

Distributed File Systems

- Support access to files on remote servers
- Must support concurrency
  - Make varying guarantees about locking, who "wins" with concurrent writes, etc...
  - Must gracefully handle dropped connections
- Can offer support for replication and local caching

Motivation

- Google needed a good distributed file system
  - Redundant storage of massive amounts of data on cheap and unreliable computers
- Why not use an existing file system?
  - Google's problems are different from anyone else's
    - Different workload and design priorities
  - GFS is designed for Google apps and workloads
  - Google apps are designed for GFS

Design Assumptions 1

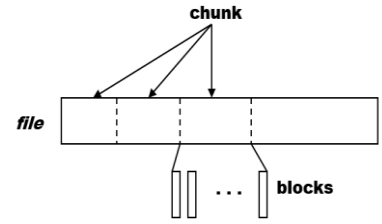
- Component failures are the norm
  - Built from 1000s of inexpensive commodity components
  - Constant monitoring, error detection, fault tolerance, automatic recovery must be integral to the system
- Stores a modest number of "LARGE" files
  - A few millions files, multi-GB files are common
  - Need not optimize for small files

Design Assumptions 2

- Files are write-once, mostly appended to
  - Perhaps concurrently
- Workload
  - Large streaming reads (1MB+)
  - Small random reads (a few KBs)
  - Many large sequential writes
- High sustained bandwidth is more important than low latency

File Structure

- File
  - Divided into 64 MB chunks
- Chunk
  - Divided into 64 KB blocks
  - Replicated (default 3 replicas)
  - Identified by 64-bit handle
- Block
  - Has a 32-bit checksum

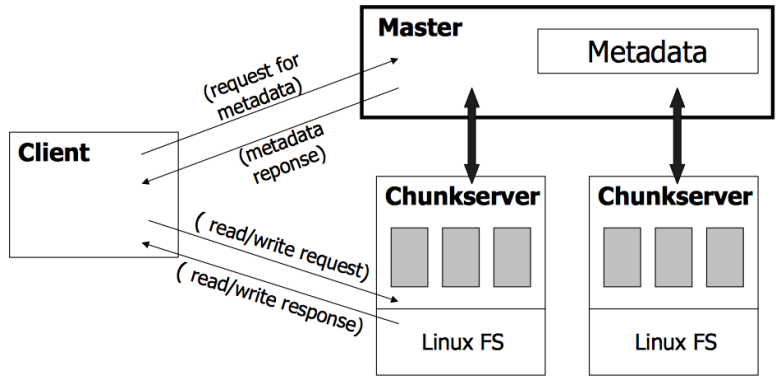


Chunk Size

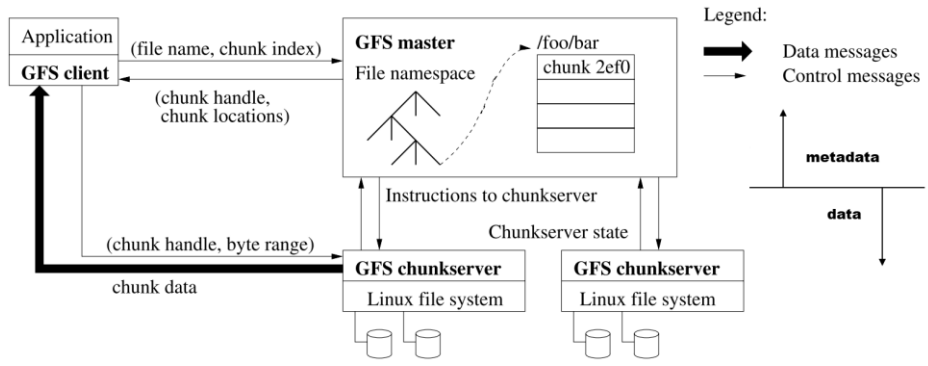
- 64MB
  - Much larger than typical file system block sizes
- Advantages from large chunk size
  - Reduce interaction between client and master
  - Client can perform many operations on a given chunk
    - Reduces network overhead by keeping persistent TCP connection
  - Reduce size of metadata stored on the master
    - The metadata can reside in memory

GFS Architecture 1

- Single Master (maintain metadata)
- Multiple chunkservers (store chunks)



GFS Architecture 2



…Can anyone see a potential weakness in this design?

Master

- A single process running on a separate machine
  - Stores all metadata
  - File and chunk namespace(directory hierarchy)
  - File to chunk mappings
  - Chunk location information
  - Access control information
  - Chunk version numbers
  - Lease Management
  - Manage Garbage Collection
  - Stale Replica Detection
  - Periodically communicate with chunkservers(heartbeat)

Lease Management

- A crucial part of concurrent write/append operation
  - Design to minimize master's management overhead
- One lease per chunk
  - Granted to chunkserver, which becomes the primary
  - Granting a lease increases the version number of the chunk
- The primary can renew the lease before it expire(default 60s)
- The master can grant the lease to another replica if the current lease expires(primary crashed)

Garbage Collection

- Storage reclaimed lazily by GC
- File first renamed to a hidden name
- Hidden files removed 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.

Stale Replica Detection

- Whenever new lease granted, chunk version number is incremented
- A chunkserver that is down will not get the chunk version incremented
- The master removes stale replicas in its regular garbage collection

Heartbeat

- Master issues HeartBeat messages to chunkservers regularly
  - if too much strike, then you're out
  - give instructions:delete chunk, etc
  - collect chunk status:corrupt, possessed, etc.
- A chunkserver sends chunk IDs that it has, and get orphaned chunks in reply
- A chunkserver sends corrupt chunk ID

Single Master

- Single master
  - Global knowledge
  - Better placement / replication
  - Simplifies design
- Problems:
  - Single point of failure
  - Scalability bottleneck
- How to deal with the problems ?

Single Master

- GFS solutions:
  - Master log & checkpoints replicated
  - Outside monitor watches master livelihood
    - Starts new master process as needed
  - Shadow master
    - provide read-only access when primary is down
  - Minimize master involvement
    - never move data through it, use only for metadata
    - large chunk size
    - master delegates authority to primary replicas in data mutations (chunk leases)

Metadata 1

- Global metadata is stored on the master
  - File and chunk namespaces
  - Mapping from files to chunks
  - Locations of each chunk's replicas
- All in memory (64 bytes / chunk)
  - Fast
  - Easily accessible

Metadata 2

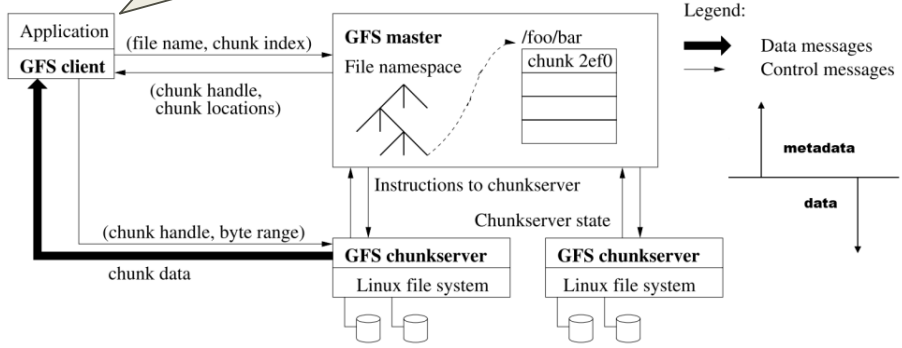
- Master has an operation log for persistent logging of critical metadata updates
  - Persistent on local disk
  - Replicated
  - Checkpoints for faster recovery

Chunkservers

- Stores 64 MB file chunks on local disk using standard Linux file system, each with version number and checksum
- Read/write requests specify chunk handle and byte range
- Chunks replicated on configurable number of chunkservers (default: 3)

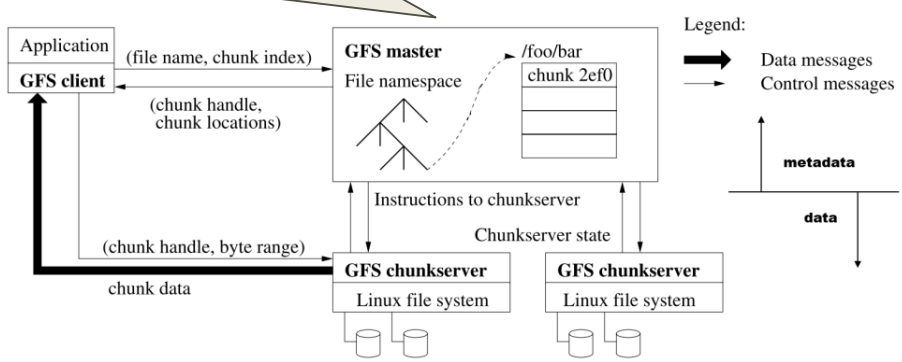
A Simple Read Example

Using fixed chunk size, translate filename & byte offset to chunk index.

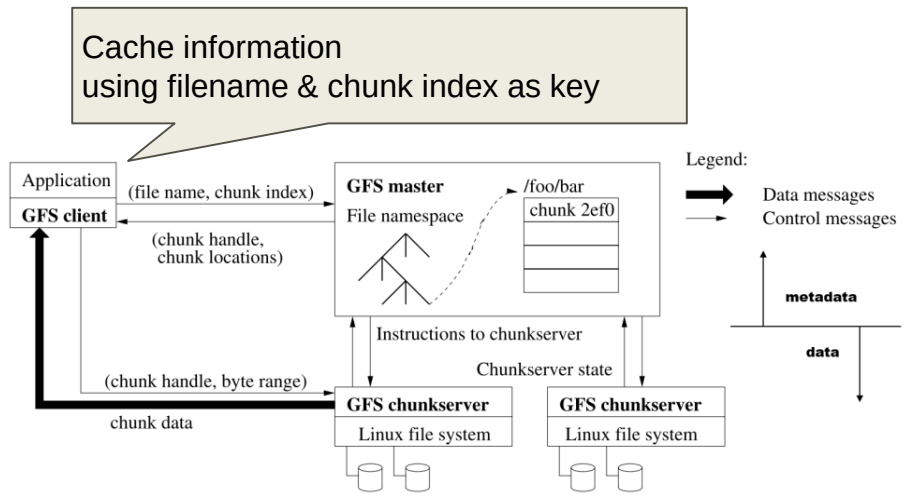


A Simple Read Example (2)

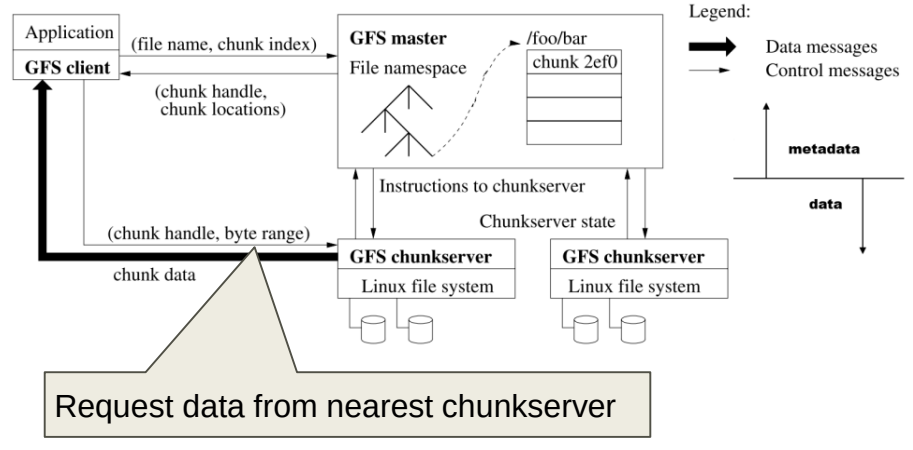
Replies with corresponding chunk handle & locations of replicas (including which is 'primary')



A Simple Read Example (3)

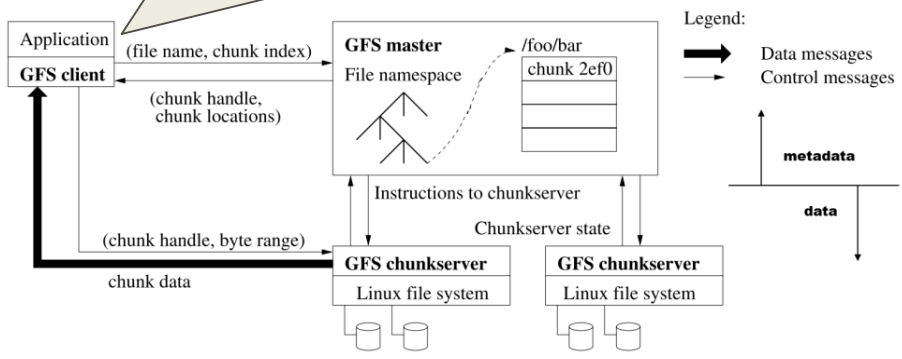


A Simple Read Example (4)



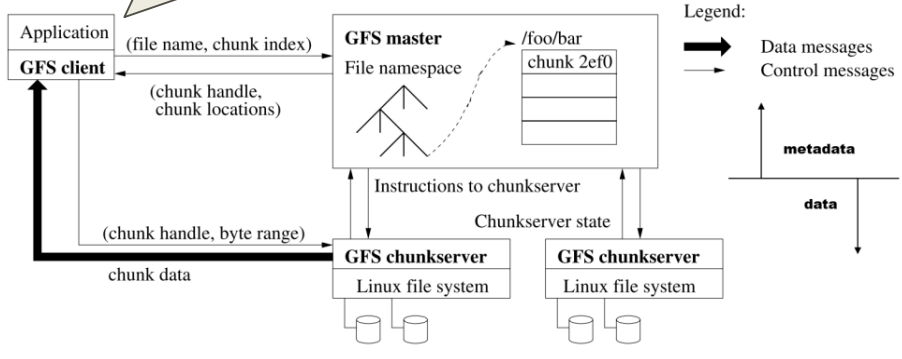
A Simple Read Example (5)

Further reads of the same chunk require no more client-master interaction until the cached information expires or the file is reopened.



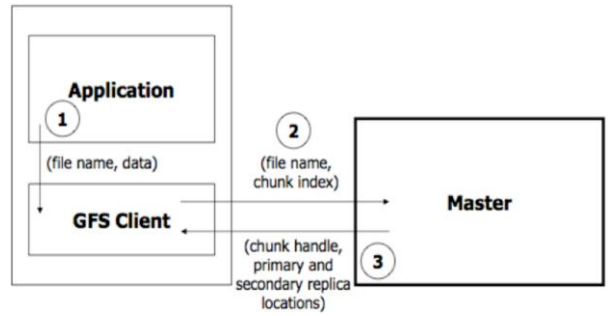
A Simple Read Example (6)

Typically asks for multiple chunks in the same request



Write Operation

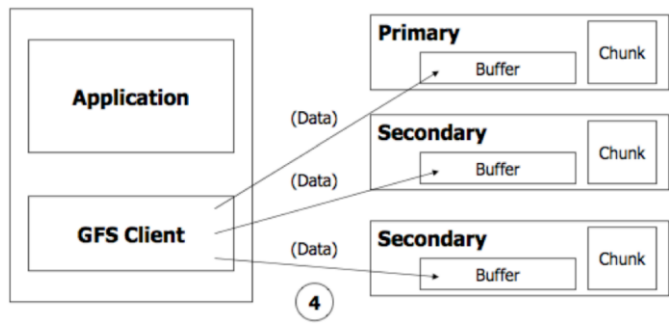
1. Application originates the request
2. GFS client translates request and sends it to master
3. Master responds with chunk handle and replica locations



Write Operation (2)

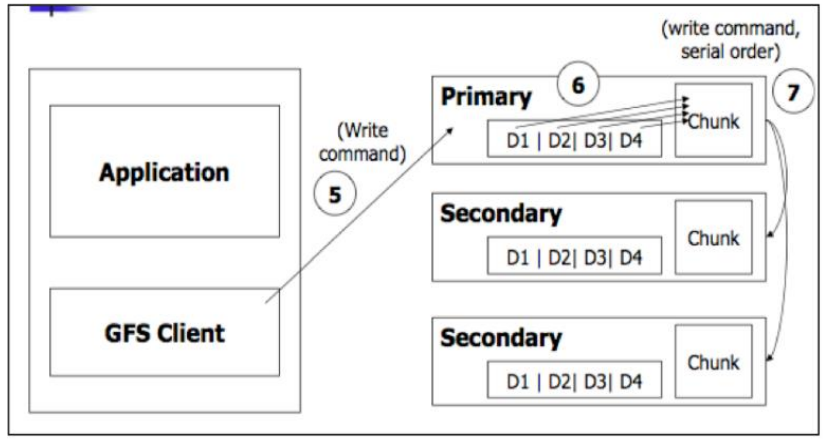
4. Client pushes write data to all locations.

   Data is stored in chunkserver's internal buffers



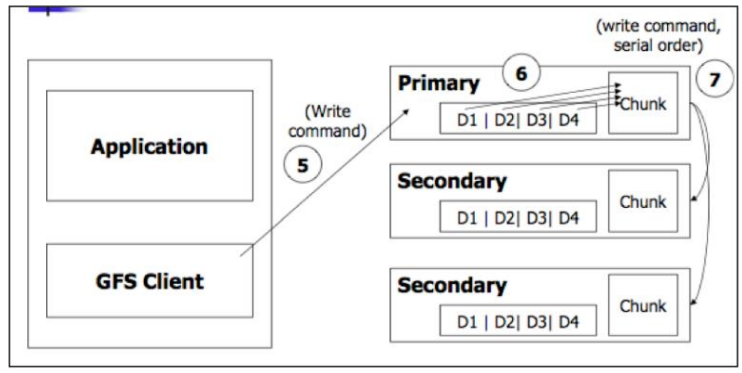
Write Operation (3)

5. Client sends write command to primary



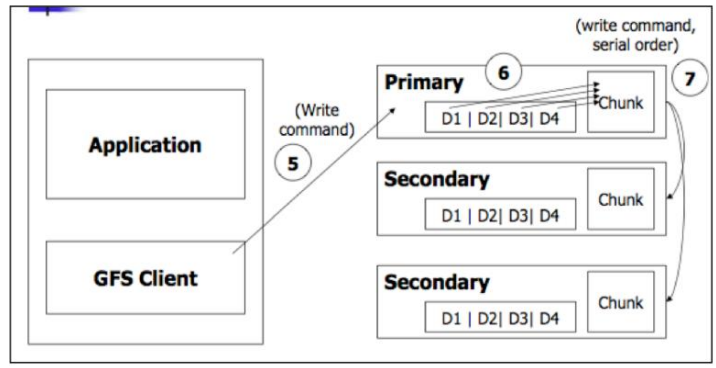
Write Operation (4)

6. Primary determines serial order for data instances in its buffer and writes the instances in that order to the chunk



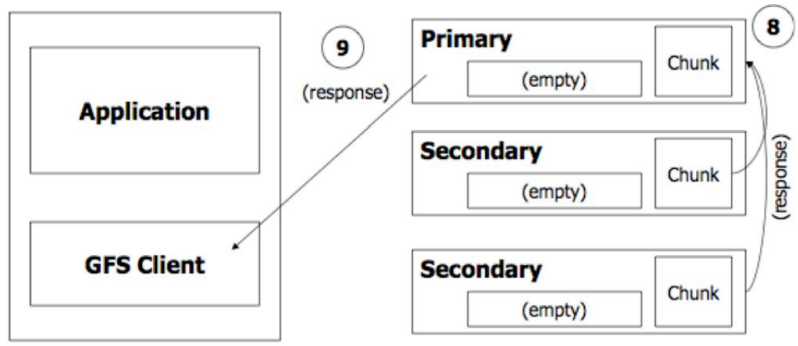
Write Operation (5)

7. Primary sends the serial order to the secondaries and tells them to perform the write



Write Operation (6)

8. Secondaries respond back to primary
9. Primary responds back to the client



Atomic Record Append Operation

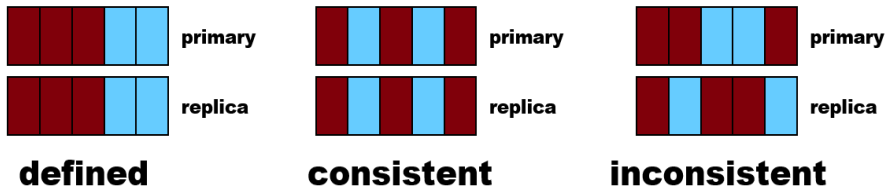
- Performed atomically (one byte sequence)
- At-least-once semantics
- Append offset is chosen by GFS and returned to client
- Same as write, extension to step 7:
  - If record fits in current chunk: write record and tell replicas the offset
  - If record exceeds chunk: pad the chunk, reply to client to use next chunk

File Deletion

- When client deletes file:
  - Master records deletion in its log
  - File renamed to hidden name including deletion timestamp
- Master scans file namespace in background:
  - Removes files with such names if deleted for longer than 3 days (configurable)
  - In-memory metadata erased
- Master scans chunk namespace in background:
  - Removes unreferenced chunks from chunkservers

Relaxed Consistency Model

- Consistent = all replicas have the same value
- Defined = consistent, all clients will always see what the mutation writes in its entirety (all replicas process chunk-mutation requests in same order)



Relaxed Consistency Model

- **Write**
  - Concurrent writes may be consistent but undefined
  - Write operations that are large or cross chunk boundaries are subdivided by client into individual writes
  - Concurrent writes may become interleaved

	Write	Record Append
Serial success	*defined*	*defined* interspersed with *inconsistent*
Concurrent successes	*consistent* but *undefined*	
Failure	*inconsistent*	

Relaxed Consistency Model

- **Record Append**
  - Atomically, at-least-once semantics
  - Client retries failed operation
  - After successful retry, replicas are defined in region of append but may have intervening undefined regions

	Write	Record Append
Serial success	*defined*	*defined* interspersed with *inconsistent*
Concurrent successes	*consistent* but *undefined*	
Failure	*inconsistent*	

Relaxed Consistency Model

- **Application safeguards**
  - Application safeguards (e.g., self-validating, self-identifying records)
  - Insert checksums in record headers to detect fragments
  - Insert sequence numbers to detect duplicates

	Write	Record Append
Serial success	*defined*	*defined* interspersed with *inconsistent*
Concurrent successes	*consistent* but *undefined*	
Failure	*inconsistent*	

Fault Tolerance

- **High availability**
  - Fast recovery
    - Master and chunkservers are designed to restore their states and start in seconds
    - Do not distinguish between normal & abnormal termination
  - Chunk replication
    - 3 replicas (default)
  - Master replication
    - Master log & checkpoints replicated
    - Shadow masters provide read-only access when the primary master is down

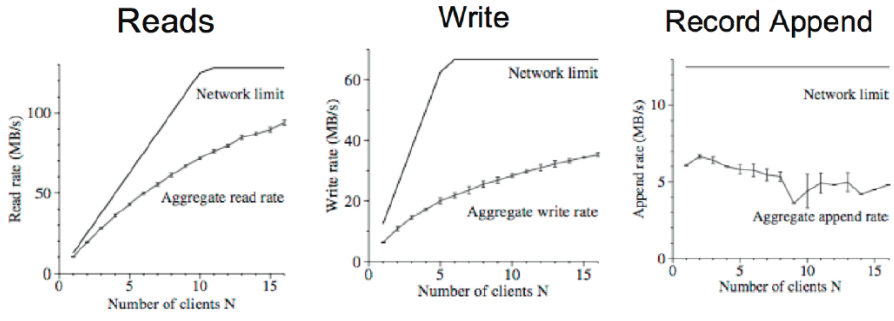
Fault Tolerance (2)

- **Data integrity**
  - Checksum every 64KB block in each chunk
  - Verified at read & write times
  - Background scans for rarely used data

Performance Test

- **Cluster setup:**
  - 1 master
  - 16 chunkservers
  - 16 clients
- Server machines connected to central switch by 100 Mbps Ethernet
- Switches connected with 1 Gbps link

Performance Test



- 1 client:
  - 10 MB/s, 80% limit
- 16 clients:
  - 6 MB/s, 75% limit

- 1 client:
  - 6.3 MB/s, 50% limit
- 16 clients:
  - 35 MB/s, 50% limit
  - 2.2 MB/s per client

- 1 client:
  - 6 MB/s
- 16 clients:
  - 4.8 MB/s per client

GFS Summary

- Success: used actively by Google to support search service and other applications
  - Availability and recoverability on cheap hardware
  - High throughput by decoupling control and data
  - Supports massive data sets and concurrent appends
- Semantics not transparent to apps
  - Must verify file contents to avoid inconsistent regions, repeated appends (at-least-once semantics)
- Performance not good for all apps
  - Assumes read-once, write-once workload (no client caching!)

GFS Conclusions

- GFS demonstrates how to support large-scale processing workloads on commodity hardware
  - design to tolerate frequent component failures
  - optimize for huge files that are mostly appended and read
  - feel free to relax and extend FS interface as required
  - go for simple solutions (e.g., single master)
- GFS has met Google's storage needs, therefore good enough for them.

Transition From GFS to Colossus

- Typical cluster now:
  - 10s of thousands of machines
  - PB of distributed HDD
  - Optional multi-TB local SSD
  - 10 GB/s bisection bandwidth
- Can a 2003 design meet the current demand?

GFS Architectural Problems

- GFS master
  - One machine not large enough for large FS
  - Single bottleneck for metadata operations
  - Fault tolerant, not HA
- Predictable performance
  - No guarantees of latency

Some Obvious GFSv2 Goals

- Bigger!

  Faster!

  More predictable tail latency

- GFS master replaced by **Colossus**
- GFS chunkserver replaced by **D**

Colossus (GFS2)

- Next-generation cluster-level file system
- Automatically sharded metadata layer
- Data typically written using Reed-Solomon (block-based error-correcting codes)
- Client-driven replication, encoding and replication
- Metadata space has enabled availability analyses
- Why Reed-Solomon?
  - Cost. Especially w/ cross cluster replication.
  - Field data and simulations show improved MTTF
  - More flexible cost vs. availability choices

Colossus (GFS2)

- A “multi-cell” approach, which put multiple GFS masters on top of a pool of chunkservers
- Also have Name Spaces, which are a static way of partitioning a namespace that people can use to hide all of this from the actual application a namespace file describes
- The distributed master allows you to grow file counts, in line with the number of machines you’re willing to throw at it

Colossus (GFS2)

- The distributed master system is essentially a whole new design.
- Can aim for something on the order of 100 million files per master.
- You can also have hundreds of masters
- BigTable “as one of the major adaptations made along the way to help keep GFS viable in the face of rapid and widespread change.”

Colossus Impact

- **Colossus** has been extremely useful for optimizing our storage efficiency
- Metadata scaling enables declustering of resources
- Ability to combine disks of various sizes and workloads of varying types is very powerful
- Looking forward, I/O cost trends will require both applications and storage systems to evolve