Motivating Application: Google

- Crawl the whole web
- Store it all on “one big disk”
- Process users’ searches on “one big CPU”
- More storage, CPU required than one PC can offer
- Custom parallel supercomputer: expensive (so much so, not really available today)
Cluster of PCs as Supercomputer

- Lots of cheap PCs, each with disk and CPU
  - High aggregate storage capacity
  - Spread search processing across many CPUs
- How to share data among PCs?
- Ivy: shared virtual memory
  - Fine-grained, relatively strong consistency at load/store level
  - Fault tolerance?
- NFS: share fs from one server, many clients
  - Goal: mimic original UNIX local fs semantics
  - Compromise: close-to-open consistency (performance)
  - Fault tolerance?
Cluster of PCs as Supercomputer

GFS: File system for sharing data on clusters, designed with Google’s application workload specifically in mind

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Google Platform Characteristics

• 100s to 1000s of PCs in cluster
• Cheap, commodity parts in PCs
• Many modes of failure for each PC:
  – App bugs, OS bugs
  – Human error
  – Disk failure, memory failure, net failure, power supply failure
  – Connector failure
• Monitoring, fault tolerance, auto-recovery essential
Google File System: Design Criteria

- Detect, tolerate, recover from failures automatically
- Large files, \( \geq 100 \) MB in size
- Large, streaming reads (\( \geq 1 \) MB in size)
  - Read once
- Large, sequential writes that append
  - Write once
- Concurrent appends by multiple clients (e.g., producer-consumer queues)
  - Want atomicity for appends without synchronization overhead among clients
GFS: Architecture

- One master server (state replicated on backups)
- Many chunk servers (100s – 1000s)
  - Spread across racks; intra-rack b/w greater than inter-rack
  - Chunk: 64 MB portion of file, identified by 64-bit, globally unique ID
- Many clients accessing same and different files stored on same cluster
GFS: Architecture (2)
Master Server

• Holds all metadata:
  – Namespace (directory hierarchy)
  – Access control information (per-file)
  – Mapping from files to chunks
  – Current locations of chunks (chunkservers)
• Manages chunk leases to chunkservers
• Garbage collects orphaned chunks
• Migrates chunks between chunkservers
Master Server

- Holds all metadata:
  - Namespace (directory hierarchy)
  - Current locations of chunks (chunkservers)
- Holds all metadata in RAM; very fast operations on file system metadata
- Manages chunk leases to chunkservers
- Garbage collects orphaned chunks
- Migrates chunks between chunkservers
Chunkserver

- Stores 64 MB file chunks on local disk using standard Linux filesystem, each with version number and checksum
- Read/write requests specify chunk handle and byte range
- Chunks replicated on configurable number of chunkservers (default: 3)
- No caching of file data (beyond standard Linux buffer cache)
Client

- Issues control (metadata) requests to master server
- Issues data requests directly to chunkservers
- Caches metadata
- Does no caching of data
  - No consistency difficulties among clients
  - Streaming reads (read once) and append writes (write once) don’t benefit much from caching at client
Client API

• Is GFS a filesystem in traditional sense?
  – Implemented in kernel, under vnode layer?
  – Mimics UNIX semantics?
• No; a library apps can link in for storage access
• API:
  – open, delete, read, write (as expected)
  – snapshot: quickly create copy of file
  – append: at least once, possibly with gaps and/or inconsistencies among clients
Client Read

- Client sends master:
  - `read(file name, chunk index)`

- Master’s reply:
  - `chunk ID, chunk version number, locations of replicas`

- Client sends “closest” chunkserver w/replica:
  - `read(chunk ID, byte range)`
  - “Closest” determined by IP address on simple rack-based network topology

- Chunkserver replies with data
Client Write

• Some chunkserver is **primary** for each chunk
  – Master grants **lease** to primary (typically for 60 sec.)
  – Leases renewed using periodic **heartbeat messages**
    between master and chunkservers

• Client asks master for primary and secondary replicas for each chunk

• Client sends data to replicas in **daisy chain**
  – Pipelined: each replica forwards as it receives
  – Takes advantage of full-duplex Ethernet links
Client Write (2)

- All replicas acknowledge data write to client
- Client sends write request to primary
- Primary assigns serial number to write request, providing ordering
- Primary forwards write request with same serial number to secondaries
- Secondaries all reply to primary after completing write
- Primary replies to client
Client Write (3)
Client Record Append

- Google uses large files as queues between multiple producers and consumers
- Same control flow as for writes, except...
- Client pushes data to replicas of last chunk of file
- Client sends request to primary
- Common case: request fits in current last chunk:
  - Primary appends data to own replica
  - Primary tells secondaries to do same at same byte offset in theirs
  - Primary replies with success to client
Client Record Append (2)

• When data won’t fit in last chunk:
  – Primary fills current chunk with padding
  – Primary instructs other replicas to do same
  – Primary replies to client, “retry on next chunk”

• If record append fails at any replica, client retries operation
  – So replicas of same chunk may contain different data—even duplicates of all or part of record data

• What guarantee does GFS provide on success?
  – Data written at least once in atomic unit
GFS: Consistency Model

- Changes to namespace (i.e., metadata) are atomic
  - Done by single master server!
  - Master uses log to define global total order of namespace-changing operations

- Data changes more complicated

- Consistent: file region all clients see as same, regardless of replicas they read from

- Defined: after data mutation, file region that is consistent, and all clients see that entire mutation
GFS: Data Mutation Consistency

<table>
<thead>
<tr>
<th></th>
<th>Write</th>
<th>Record Append</th>
</tr>
</thead>
<tbody>
<tr>
<td>serial success</td>
<td>defined</td>
<td>defined</td>
</tr>
<tr>
<td>concurrent successes</td>
<td>consistent but undefined</td>
<td>interspersed with inconsistent</td>
</tr>
<tr>
<td>failure</td>
<td></td>
<td>inconsistent</td>
</tr>
</tbody>
</table>

- Record append **completes at least once, at offset of GFS’ choosing**
- **Apps must cope with Record Append semantics**
Applications and Record Append Semantics

• Applications should include **checksums** in records they write using Record Append
  – Reader can identify padding / record fragments using checksums

• If application cannot tolerate duplicated records, should include **unique ID** in record
  – Reader can use unique IDs to filter duplicates
Logging at Master

• Master has all metadata information
  – Lose it, and you’ve lost the filesystem!
• Master logs all client requests that modify metadata to disk sequentially
• Replicates log entries to remote backup servers
• Only replies to client after log entries safe on disk on self and backups!
Chunk Leases and Version Numbers

- If no outstanding lease when client requests write, master grants new one
- Chunks have version numbers
  - Stored on disk at master and chunkservers
  - Each time master grants new lease, increments version, informs all replicas
- Master can revoke leases
  - e.g., when client requests rename or snapshot of file
What If the Master Reboots?

• Replays log from disk
  – Recovers namespace (directory) information
  – Recovers file-to-chunk-ID mapping

• Asks chunkservers which chunks they hold
  – Recovers chunk-ID-to-chunkserver mapping

• If chunk server has older chunk, it’s stale
  – Chunk server down at lease renewal

• If chunk server has newer chunk, adopt its version number
  – Master may have failed while granting lease
What if Chunkserver Fails?

• Master notices missing heartbeats
• Master decrements count of replicas for all chunks on dead chunkserver
• Master re-replicates chunks missing replicas in background
  – Highest priority for chunks missing greatest number of replicas
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
What About Small Files?

• Most files stored in GFS are multi-GB; a few are shorter

• Instructive case: storing a short executable in GFS, executing on many clients simultaneously
  – 3 chunkservers storing executable overwhelmed by many clients’ concurrent requests
  – App-specific fix: replicate such files on more chunkservers; stagger app start times
Write Performance (Distinct Files)

![Graph showing write performance over number of clients]

- **Y-axis**: Write rate (MB/s)
- **X-axis**: Number of clients N
- **Key points**:
  - Network limit
  - Aggregate write rate
Record Append Performance (Same File)
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!)