Large Scale File Systems

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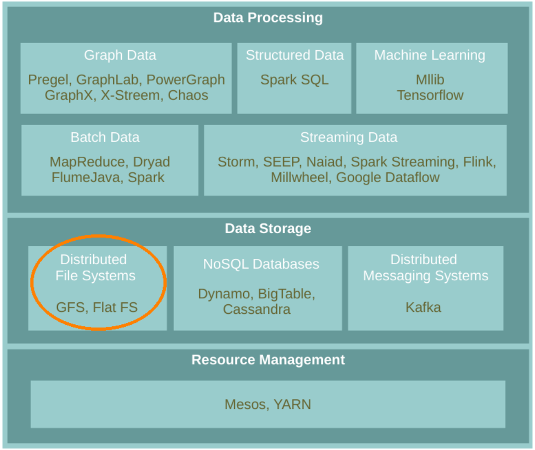
The Course Web Page

https://id2221kth.github.io

https://tinyurl.com/y4qph82u

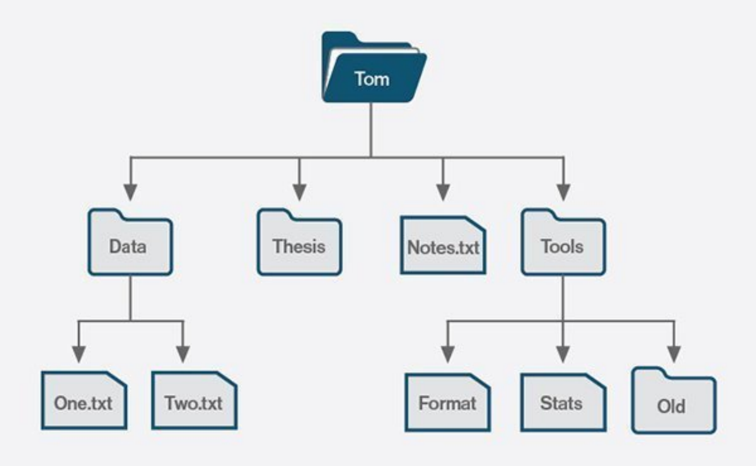
Where Are We?



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

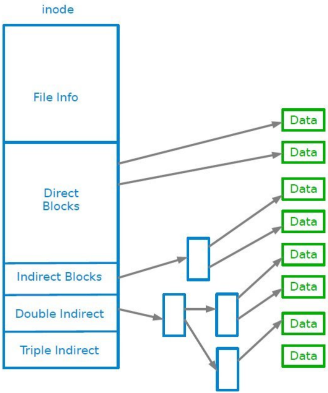
File System

What is a File System?



What is a File System?

- Controls how data is stored in and retrieved from disk.



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.

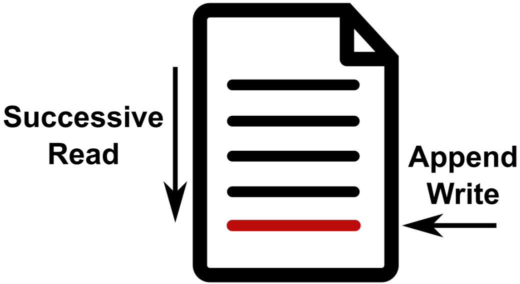
Google File System (GFS)

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

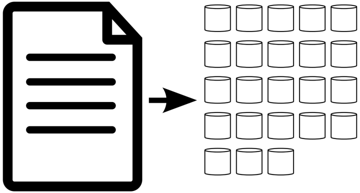
Optimised for Streaming

- Write once, read many.

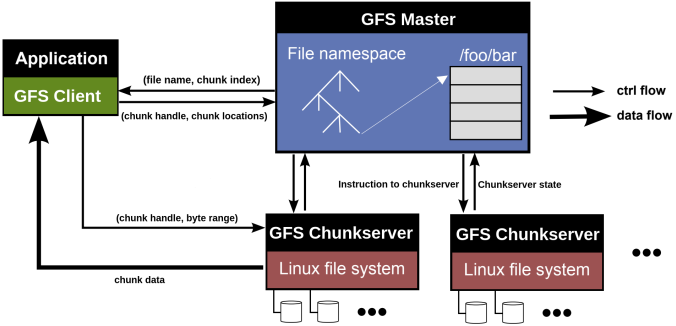


Files and Chunks

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

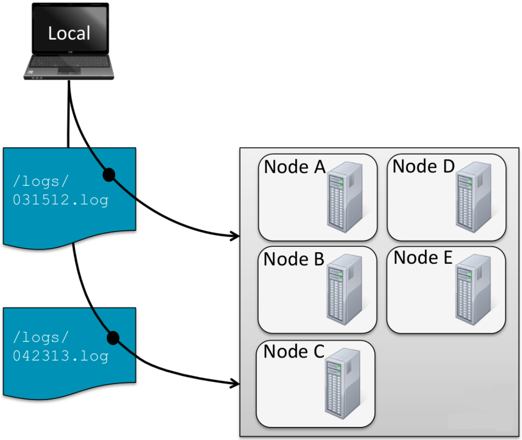


GFS Architecture

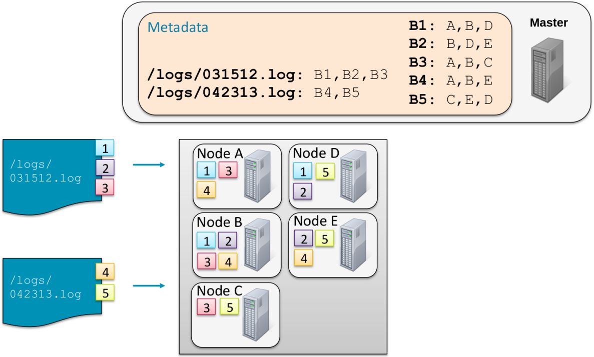


- Main components:
  - GFS master
  - GFS chunkserver
  - GFS client

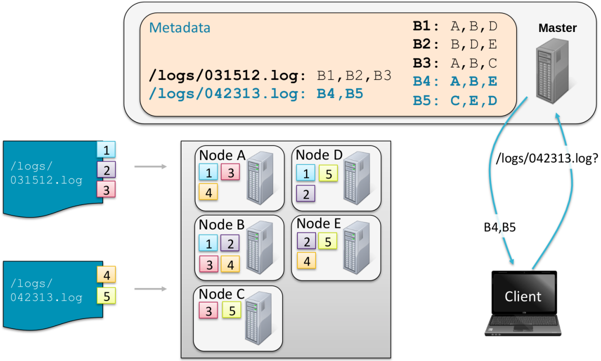
Big Picture - Storing and Retrieving Files (1/4)



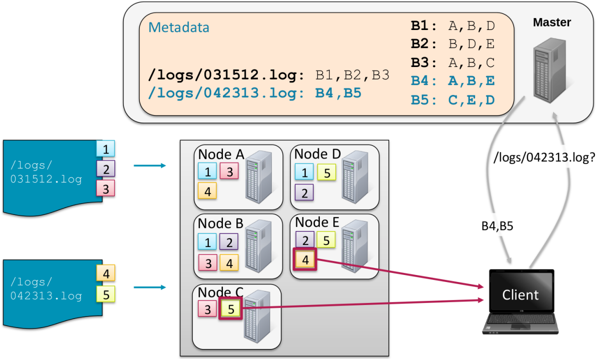
Big Picture - Storing and Retrieving Files (2/4)



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

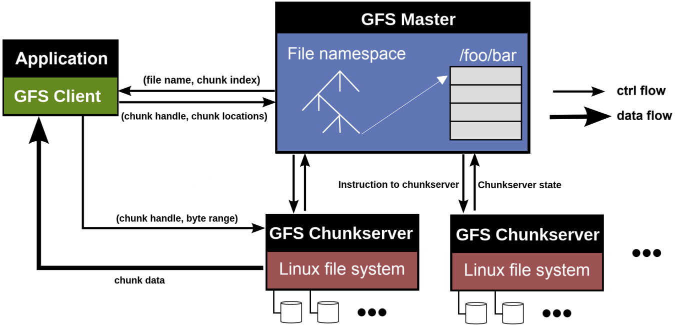


Big Picture - Storing and Retrieving Files (4/4)



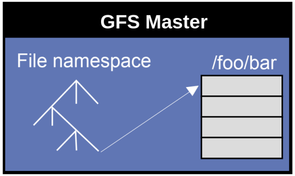
System Architecture Details

GFS Architecture



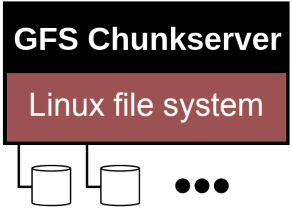
GFS Master

- Responsible for all system-wide activities
- 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



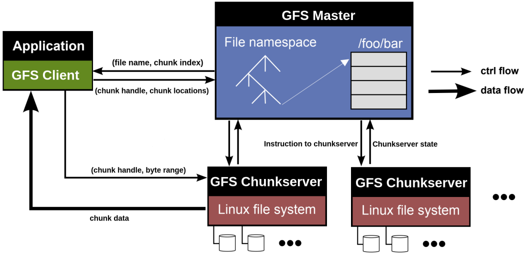
GFS Chunkserver

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



GFS Client

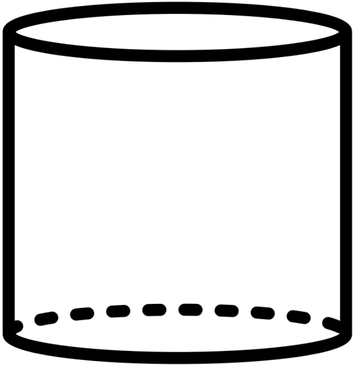
- Issues control requests to master server.
- Issues data requests directly to chunkservers.
- Caches metadata.
- Does not cache data.



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?



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

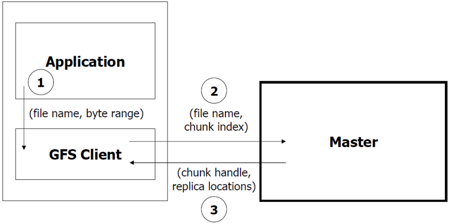
System Interactions

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

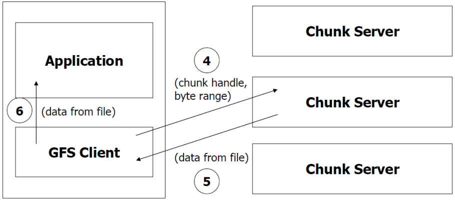
Read Operation (1/2)

- 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.
- 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)

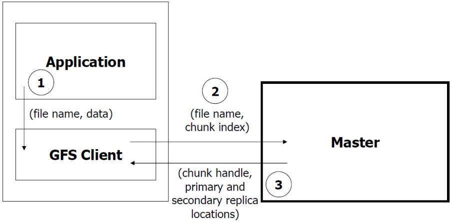
- For correctness there needs to be one single primary for each chunk.
- At any time, at most one server is primary for each chunk.
- Master selects a chunkserver and grants it lease for a chunk.

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.

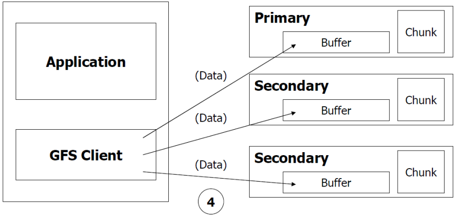
Write Operation (1/3)

- 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.



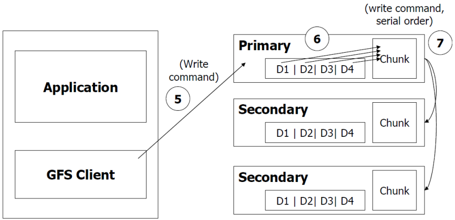
Write Operation (2/3)

- 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.
- 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.

Append Operation (1/2)

- 1. Application originates record append request.
- 2. The client translates request and sends it to the master.
- 3. The master responds with chunk handle and replica locations.
- 4. The client pushes write data to all locations.

Append Operation (2/2)

- 5. The primary checks if record fits in specified chunk.

- 6. If record does not fit, then the primary:
  - Pads the chunk,
  - Tells secondaries to do the same,
  - And informs the client.
  - The client then retries the append with the next chunk.

- 7. If record fits, then the primary:
  - Appends the record,
  - Tells secondaries to do the same,
  - Receives responses from secondaries,
  - And sends final response to the client

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
  - 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)

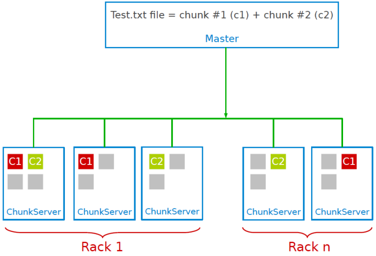
- Represents its namespace as a lookup table mapping pathnames to metadata.
- Each master operation acquires a set of locks before it runs.
- Read lock on internal nodes, and read/write lock on the leaf.
- Example: creating multiple files (`f1` and `f2`) in the same directory (`/home/user/`).
    - Each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

- 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.
- 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.

- 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

HDFS Example (1/2)

```
# Create a new directory /kth on HDFS
hdfs dfs -mkdir /kth
```

```
# Create a file, call it big, on your local filesystem and
# upload it to HDFS under /kth
hdfs dfs -put big /kth
```

```
# View the content of /kth directory
hdfs dfs -ls big /kth
```

```
# Determine the size of big on HDFS
hdfs dfs -du -h /kth/big
```

```
# Print the first 5 lines to screen from big on HDFS
hdfs dfs -cat /kth/big | head -n 5
```

HDFS Example (2/2)

```
# Copy big to /big hdfscopy on HDFS
hdfs dfs -cp /kth/big /kth/big_hdfscopy
```

```
# Copy big back to local filesystem and name it big_localcopy
hdfs dfs -get /kth/big big_localcopy
```

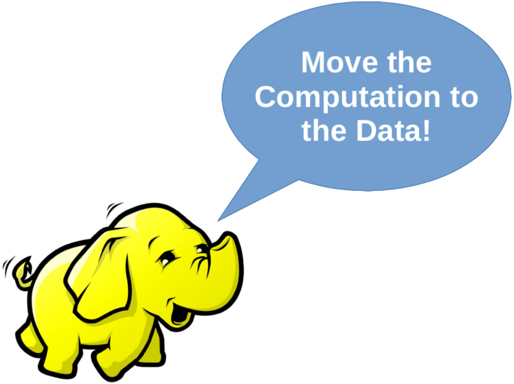
```
# Check the entire HDFS filesystem for problems
hdfs fsck /
```

```
# Delete big from HDFS
hdfs dfs -rm /kth/big
```

```
# Delete /kth directory from HDFS
hdfs dfs -rm -r /kth
```

Flat Datacenter Storage (FDS)

Motivation and Assumptions (1/5)



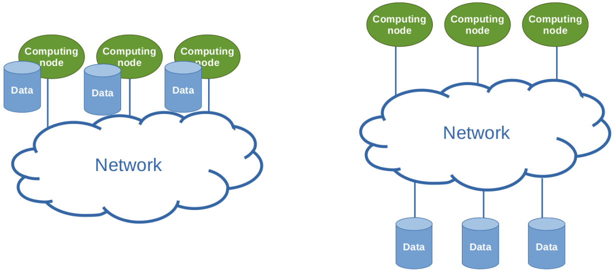
- Why move computation close to data?
  - Because remote access is slow due to oversubscription.

Motivation and Assumptions (2/5)

- Locality adds complexity.
- Need to be aware of where the data is.
  - Non-trivial scheduling algorithm.
  - Moving computations around is not easy.

Motivation and Assumptions (3/5)

- Datacenter networks are getting faster.
- Consequences
  - The networks are not oversubscribed.
  - Support full bisection bandwidth: no local vs. remote disk distinction.
  - Simpler work schedulers and programming models.



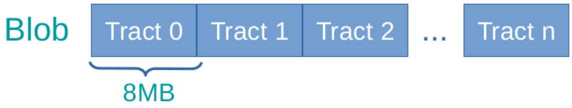
Motivation and Assumptions (4/5)

- File systems like GFS manage metadata centrally.
- On every read or write, clients contact the master to get information about the location of blocks in the system.
  - Good visibility and control.
  - Bottleneck: use large block size
  - This makes it harder to do fine-grained load balancing like our ideal little-data computer does.

Motivation and Assumptions (5/5)

- Let's make a digital socialism
- Flat Datacenter Storage

Blobs and Tracts

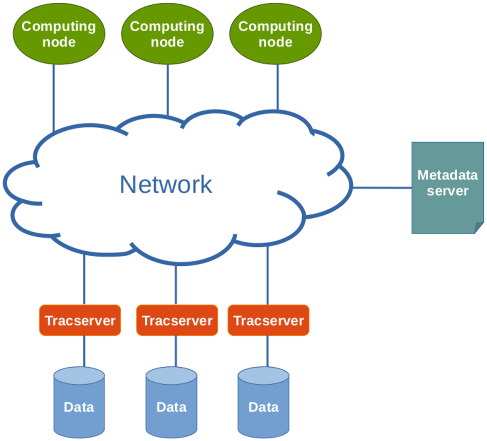


- Data is stored in logical blobs.
  - Byte sequences with a 128-bit Global Unique Identifiers (GUID).
- Blobs are divided into constant sized units called tracts.
  - Tracts are sized, so random and sequential accesses have same throughput.
- Both tracts and blobs are mutable.

FDS API

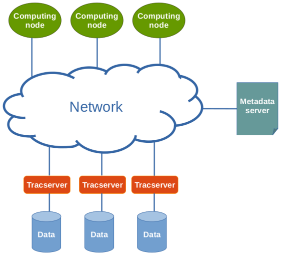
- Reads and writes are atomic.
- Reads and writes not guaranteed to appear in the order they are issued.
- API is non-blocking.
  - Helps the performance: many requests can be issued in parallel, and FDS can pipeline disk reads with network transfers.

FDS Architecture



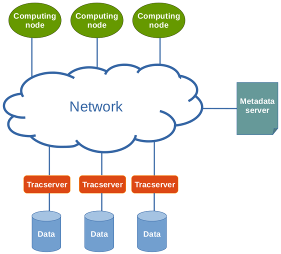
Tractserver

- Every disk is managed by a process called a tractserver.
- Tractservers accept commands from the network, e.g., `ReadTrack` and `WriteTrack`.
- They do not use file systems.
  - They lay out tracts directly to disk by using the raw disk interface.



Metadata Server

- Metadata server coordinates the cluster.
- It collects a list of active tractservers and distribute it to clients.
- This list is called the tract locator table (TLT).
- Clients can retrieve the TLT from the metadata server once, then never contact the metadata server again.



Track Locator Table (1/2)

- TLT contains the address of the tractserver(s) responsible for tracts.
- Clients use the blob's GUID (g) and the tract number (i) to select an entry in the TLT: tract locator

```
TractLocator = (Hash(g) + i) mod TLT Length
```

Locator	Disk 1	Disk 2	Disk 3
0	A	B	C
1	A	D	F
2	A	C	G
3	D	E	G
4	B	C	F
...	...	...	...
1,526	LM	TH	JE

Track Locator Table (2/2)

- The only time the TLT changes is when a disk fails or is added.
- Reads and writes do not change the TLT.
- In a system with more than one replica, reads go to one replica at random, and writes go to all of them.

Per-Blob Metadata

- Per-blob metadata: blob's length and permission bits.
- Stored in tract -1 of each blob.
- The tractserver is responsible for the blob metadata tract.
- Newly created blobs have a length of zero, and applications must extend a blob before writing. The extend operation is atomic.

Fault Tolerance

Replication

- Replicate data to improve durability and availability.
- When a disk fails, redundant copies of the lost data are used to restore the data to full replication.
- Writes a tract: the client sends the write to every tractserver it contains.
  - Applications are notified that their writes have completed only after the client library receives write ack from all replicas.
- Reads a tract: the client selects a single tractserver at random.

Failure Recovery (1/2)

- Step 1: Tractservers send heartbeat messages to the metadata server. When the metadata server detects a tractserver timeout, it declares the tractserver dead.
- Step 2: invalidates the current TLT by incrementing the version number of each row in which the failed tractserver appears.
- Step 3: picks random tractservers to fill in the empty spaces in the TLT where the dead tractserver appeared.

Row	Version	Replica 1	Replica 2	Replica 3
1	8	A	F	B
2	17	B	C	L
3	324	E	D	G
4	3	T	A	H
5	456	F	B	G
6	723	G	E	B
7	235	D	V	C
8	312	H	E	F

Row	Version	Replica 1	Replica 2	Replica 3
1	9	A	F	H
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3	324	E	D	G
4	3	T	A	H
5	457	F	C	G
6	724	G	E	A
7	235	D	V	C
8	312	H	E	F

Failure Recovery (2/2)

- Step 4: sends updated TLT assignments to every server affected by the changes.
- Step 5: waits for each tractserver to ack the new TLT assignments, and then begins to give out the new TLT to clients when queried for it.

Row	Version	Replica 1	Replica 2	Replica 3
1	8	A	F	B
2	17	B	C	L
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6	724	G	E	A
7	235	D	V	C
8	312	H	E	F

Summary

Summary

- Google File System (GFS)
- Files and chunks
- GFS architecture: master, chunk servers, client
- GFS interactions: read and update (write and update record)
- Master operations: metadata management, replica placement and garbage collection

Summary

- Flat Datacenter Storage (FDS)
- Blobs and tracts
- FDS architecture: Metadata server, tractservers, TLT
- FDS interactions: using GUID and track number
- Replication and failure recovery

References

- S. Ghemawat et al., The Google file system, Vol. 37. No. 5. ACM, 2003.
- E. Nightingale et al., Flat Datacenter Storage, OSDI, 2012.

Questions?