# Large Scale File Systems

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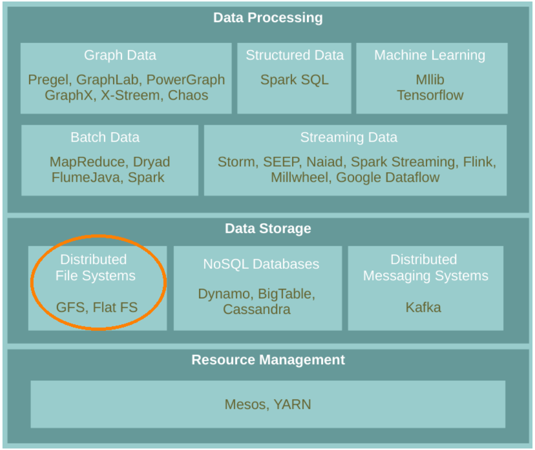
# The Course Web Page

https://id2221kth.github.io

https://tinyurl.com/y4qph82u

# Where Are We?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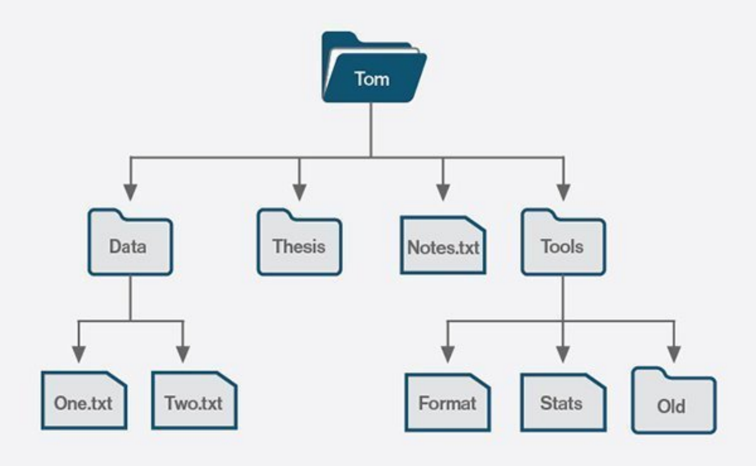
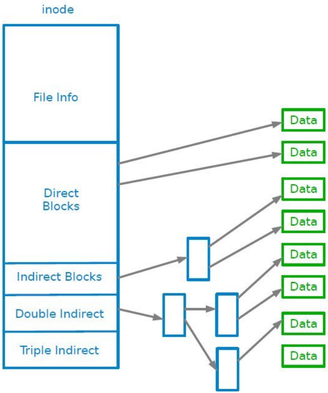
# File System

# 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.

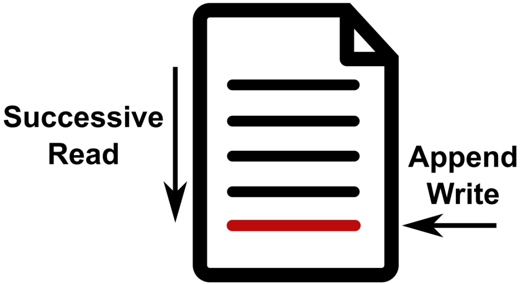
# Google File System (GFS)

# 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

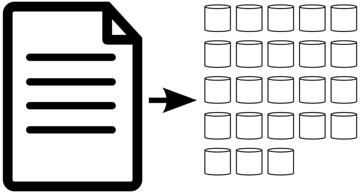
# Optimised for Streaming

- Write once, read many.

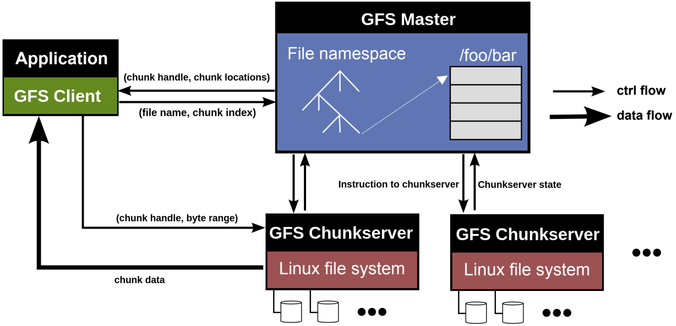


# Files and Chunks

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

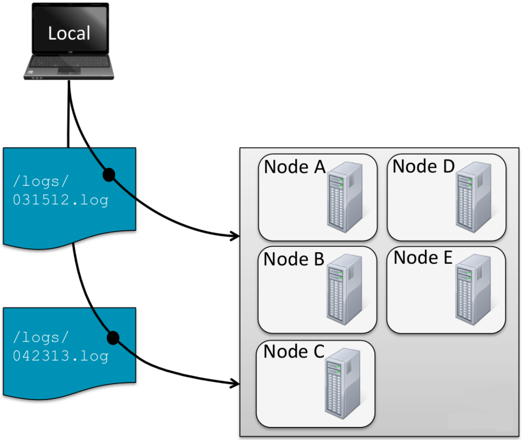


# GFS Architecture

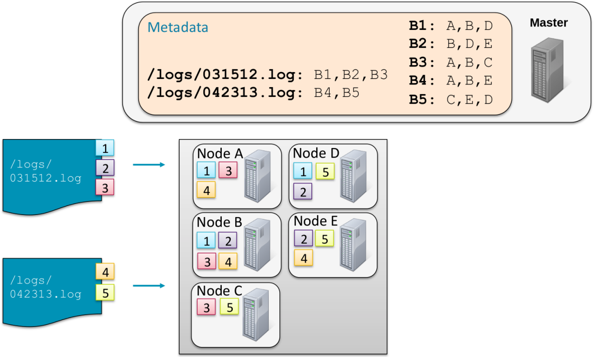



- Main components:
  - GFS master
  - GFS chunkserver
  - GFS client

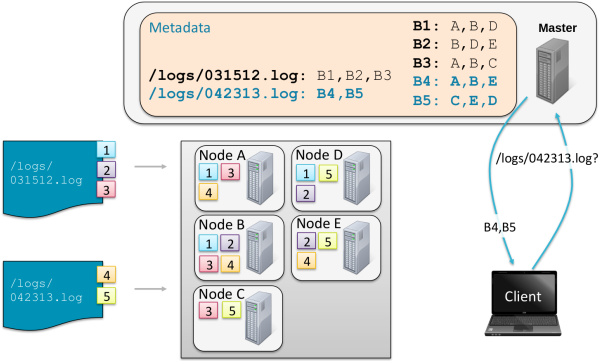
# Big Picture - Storing and Retrieving Files (1/4)



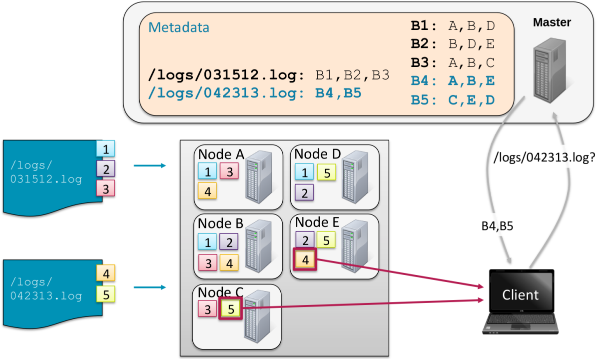
# Big Picture - Storing and Retrieving Files (2/4)



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

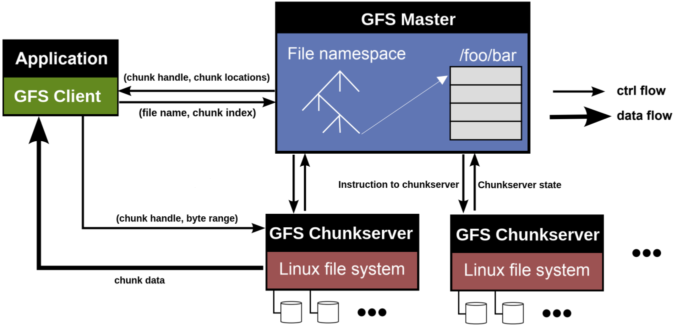


# Big Picture - Storing and Retrieving Files (4/4)



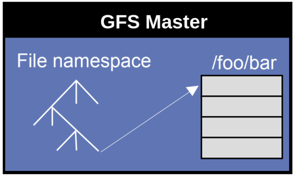
# System Architecture Details

# GFS Architecture



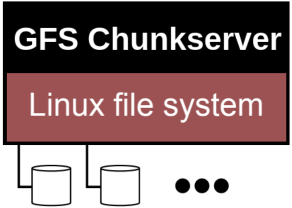
# GFS Master

- 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



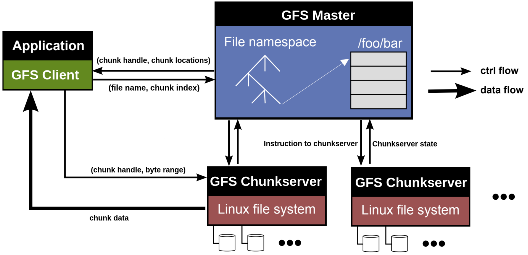
# GFS Chunkserver

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



# GFS Client

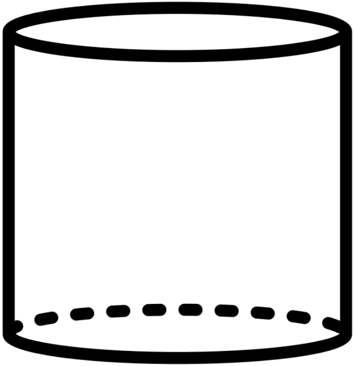
- Issues control requests to master server.
- Issues data requests directly to chunkservers.
- Caches metadata.
- Does not cache data.



# 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

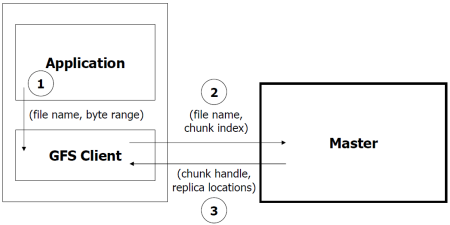
# System Interactions

# 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

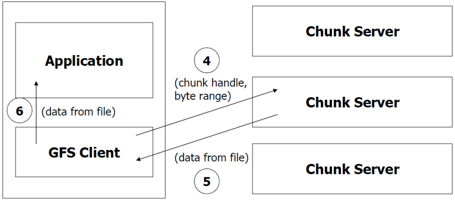
# Read Operation (1/2)

- 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)

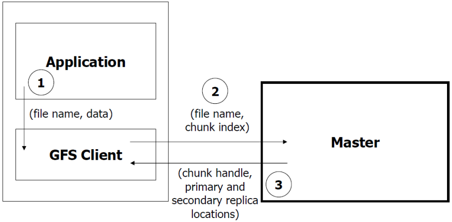
- For correctness there needs to be one single primary for each chunk.
- At any time, at most one server is primary for each chunk.
- Master selects a chunkserver and grants it lease for a chunk.

# 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.

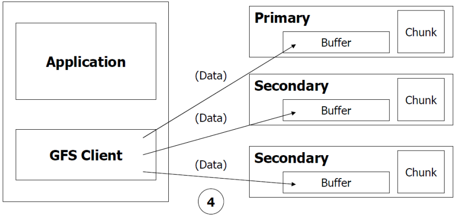
# Write Operation (1/3)

- 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.



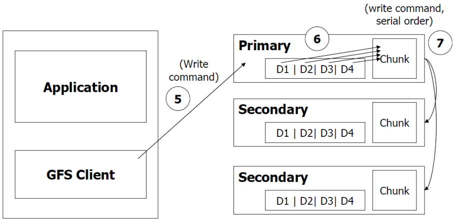
# Write Operation (2/3)

- 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)

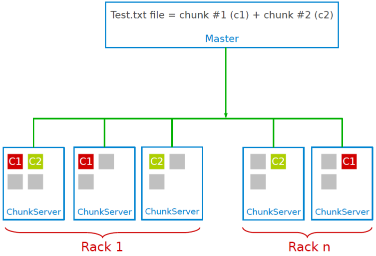
- Represents its namespace as a lookup table mapping pathnames to metadata.
- Each master operation acquires a set of locks before it runs.
- Read lock on internal nodes, and read/write lock on the leaf.
- Example: creating multiple files (`f1` and `f2`) in the same directory (`/home/user/`).
  - Each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

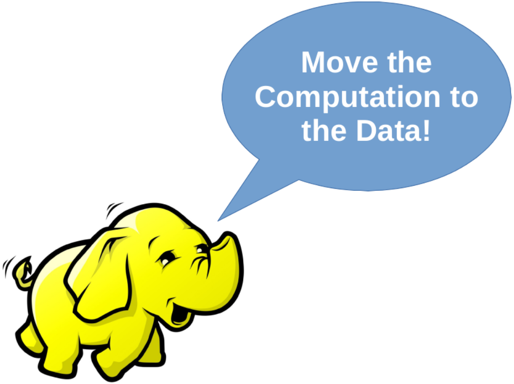
```
# Check the entire HDFS filesystem for problems
hdfs fsck /
```

```
# 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)



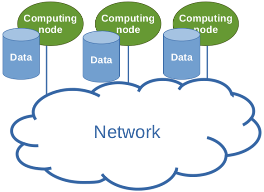

- Why move computation close to data?
  - Because remote access is slow due to oversubscription.

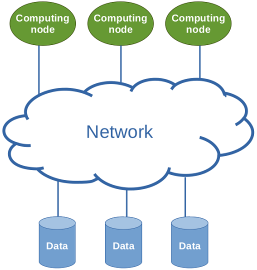
# Motivation and Assumptions (2/5)

- 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.



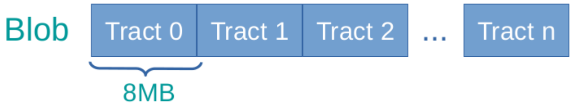
# Motivation and Assumptions (4/5)

- 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

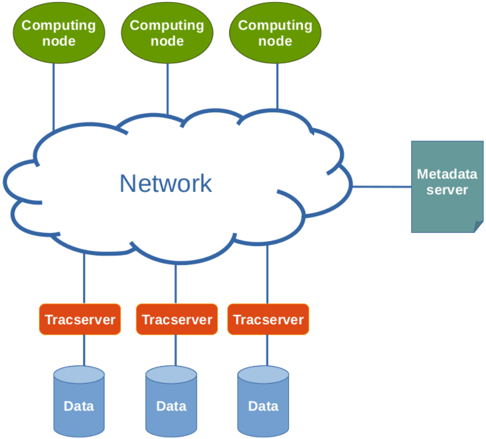



- Data is stored in logical blobs.
  - Byte sequences with a 128-bit Global Unique Identifiers (GUID).
- Blobs are divided into constant sized units called tracts.
  - Tracts are sized, so random and sequential accesses have same throughput.
- Both tracts and blobs are mutable.

# FDS API

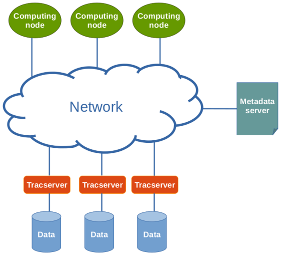
- Reads and writes are atomic.
- Reads and writes not guaranteed to appear in the order they are issued.
- API is non-blocking.
  - Helps the performance: many requests can be issued in parallel, and FDS can pipeline disk reads with network transfers.

# FDS Architecture



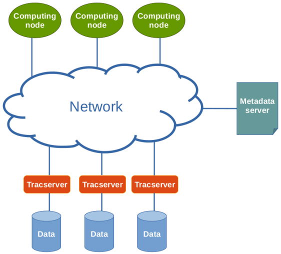
# Tractserver

- 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 |
| 2 | 18 | I | C | L |
| 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 |
| 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 |

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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?