The Google File System

Hadoop is *heavily* inspired by it.

One way (not *the* way) to design a distributed file system.

there are always alternatives

MapReduce & Hadoop

"MapReduce is a programming model for expressing **distributed** computations on **massive amounts of data** and an execution framework for large-scale data processing on clusters of **commodity servers**."

-Jimmy Lin

GFS

Hadoop is an **open-source implementation** of the MapReduce framework.

HDFS

hadoop

History of MapReduce (and GFS)

- Developed by researchers at **Google** around **2003**
  - Built on principles in parallel and distributed processing
- Seminal papers:
  - *The Google file system* by Sanjay Ghemawat, Howard Gobioff, and Shun-Tak Leung (2003)
  - *MapReduce: Simplified Data Processing on Large Clusters.* by Jeffrey Dean and Sanjay Ghemawat (2004)

- *The Hadoop distributed file system* by Konstantin Shvachko, Hairong Kuang, Sanjay Radia, and Robert Chansler (2010)

What is a file system?

- File systems determine **how** data is stored and retrieved
- **Distributed file systems** manage the storage across a network of machines
  - Added complexity due to the network
- GFS/HDFS are distributed file systems

Question: which file systems do you know?

GFS Assumptions

based on Google's main use cases

- Hardware **failures are common** (commodity hardware)
- **Files are large** (GB/TB) and their number is limited (millions, not billions)
- Two main types of reads: **large streaming reads** and **small random reads**
- Workloads with **sequential writes** that **append** data to files
- Once written, files are **seldom modified** (!=append) again
  - Random modification in files possible, but not efficient in GFS
- High sustained bandwidth trumps low latency

Question: which of the following scenarios fulfil the brief?

- Global company dealing with the data of its 100 million employees (salary, bonuses, age, performance, etc.)
- A search engine’s query log (a record of what kind of search requests people make)
- A hospital’s medical imaging data generated from an MRI scan
- Data sent by the Hubble telescope
- A search engine’s index (used to serve search results to users)

Disclaimer

- GFS/HDFS are not a good fit for:
  - **Low latency data access** (in the milliseconds range)
    - Solution: use HBase instead [later in the course]
  - **Many small files**
    - Solution: *.har *.warc **[later in this lecture]**
  - **Constantly changing data**

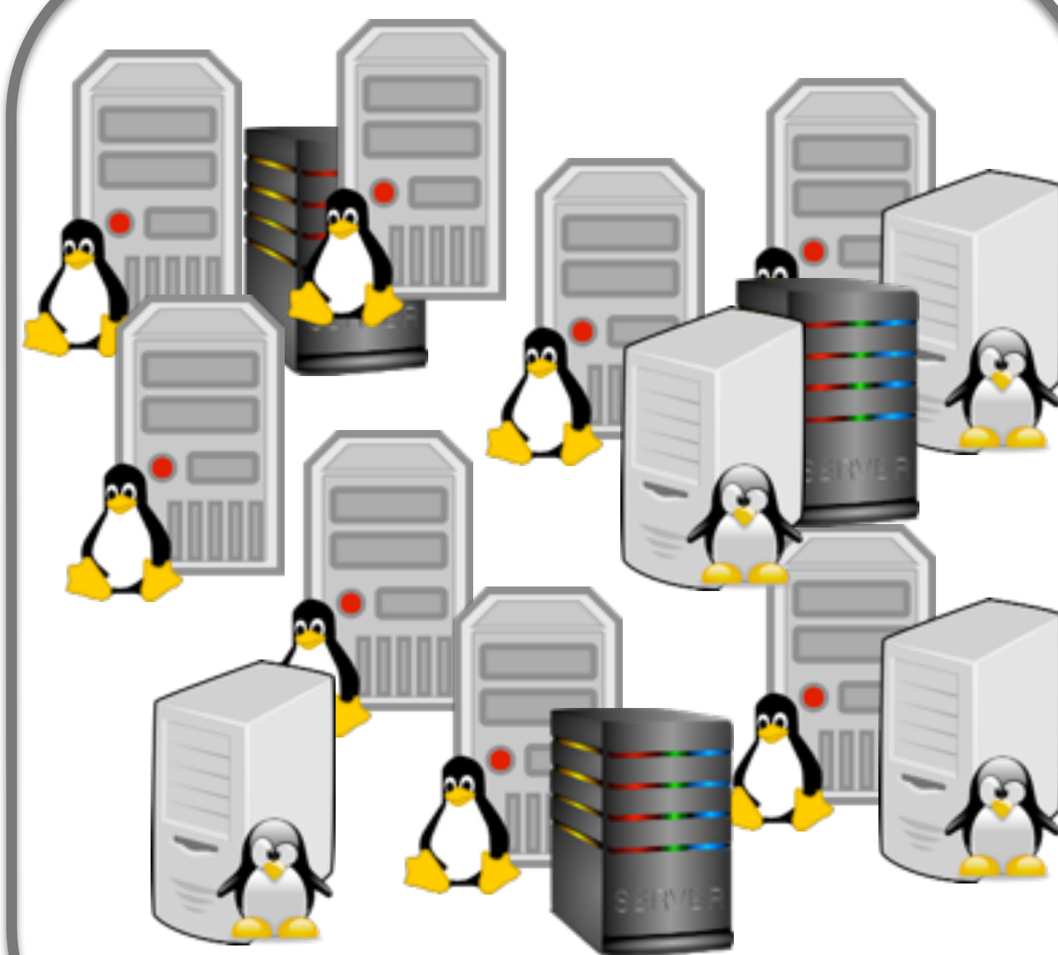
- Not all details of GFS are public knowledge

Question: how would you design a distributed file system?

Application

How to write data to the cluster?

How to read data from the cluster?



our cluster

Source: http://static.googleusercontent.com/media/research.google.com/en//archive/gfs-sosp2003.pdf

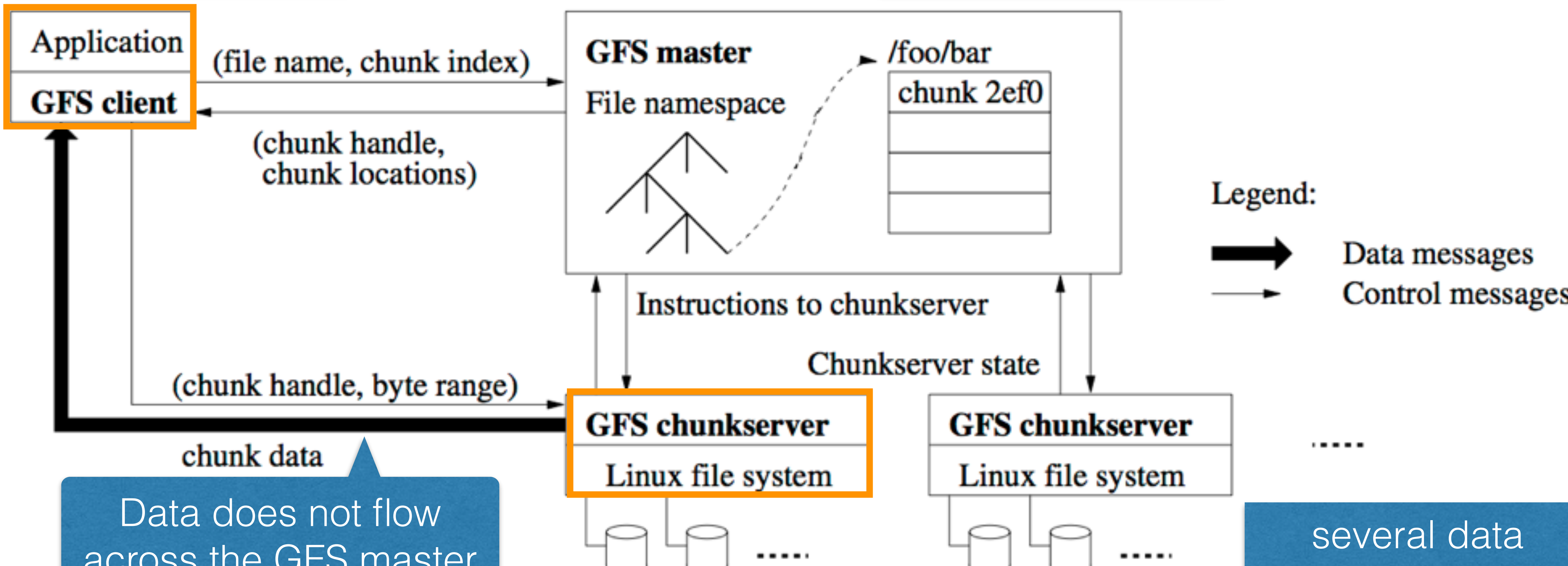
GFS architecture

user level processes: they can run on the same physical machine

Remember: **one way, not the way**.

several clients

a single master (metadata)



Data does not flow across the GFS master

several data servers

Source: http://static.googleusercontent.com/media/research.google.com/en//archive/gfs-sosp2003.pdf

GFS: Files

Files on GFS

- A **single file** can contain **many objects** (e.g. Web documents)

- Files are divided into **fixed size chunks** (64MB) with unique 64 bit identifiers

Question: what does this ↑ mean for the maximum allowed file size in a cluster?

Linux files

  - Reading & writing of data specified by the **tuple** `(chunk_handle, byte_range)`

Question: what is the purpose of `byte_range`?

Files on GFS

- A **single file** can contain **many objects** (e.g. Web documents)

- Files are divided into **fixed size chunks** (64MB) with unique 64 bit identifiers
  - IDs assigned by GFS master at chunk creation time

- **chunkservers** store chunks on local disk as "normal" Linux files
  - Reading & writing of data specified by the **tuple** `(chunk_handle, byte_range)`

Question: what is the purpose of `byte_range`?

Master

- Files are **replicated** (by default 3 times) across all chunk servers
- **master** maintains all **file system metadata**
  - Namespace, access control information, **mapping from file to chunks**, **chunk locations**, garbage collection of orphaned chunks, chunk migration, …

distributed systems are complex!

- **Heartbeat** messages between master and chunk servers
  - Is the chunk server still **alive**? **What chunks are stored at the chunkserver?**
- **To read/write data**: client communicates with master (metadata operations) and chunk servers (data)

Files on GFS

- seek time: 10ms
- transfer rate: 100MB/s
- What is the chunk size to make the seek time 1% of the transfer rate?

- Clients **cache metadata**
- Clients do **not** cache file data

Question: why don't clients store file data?

Question: why not increase the chunk size to more than 128MB? (Hint: Map tasks operate on one chunk at a time**)**

- A single file can be **larger** than a node's disk space
- Fixed size makes **allocation computations easy**

Files on GFS

- seek time: 10ms
- transfer rate: 100MB/s
- What is the chunk size to make the seek time 1% of the transfer rate?

- Clients **cache metadata**
- Clients do **not** cache file data
- Chunkservers do **not** cache file data (responsibility of the **underlying file system**: Linux's buffer cache)
- Advantages of (large) fixed-size chunks:
  - **Disk seek time small compared to transfer time**
  - A single file can be **larger** than a node's disk space
  - Fixed size makes **allocation computations easy**

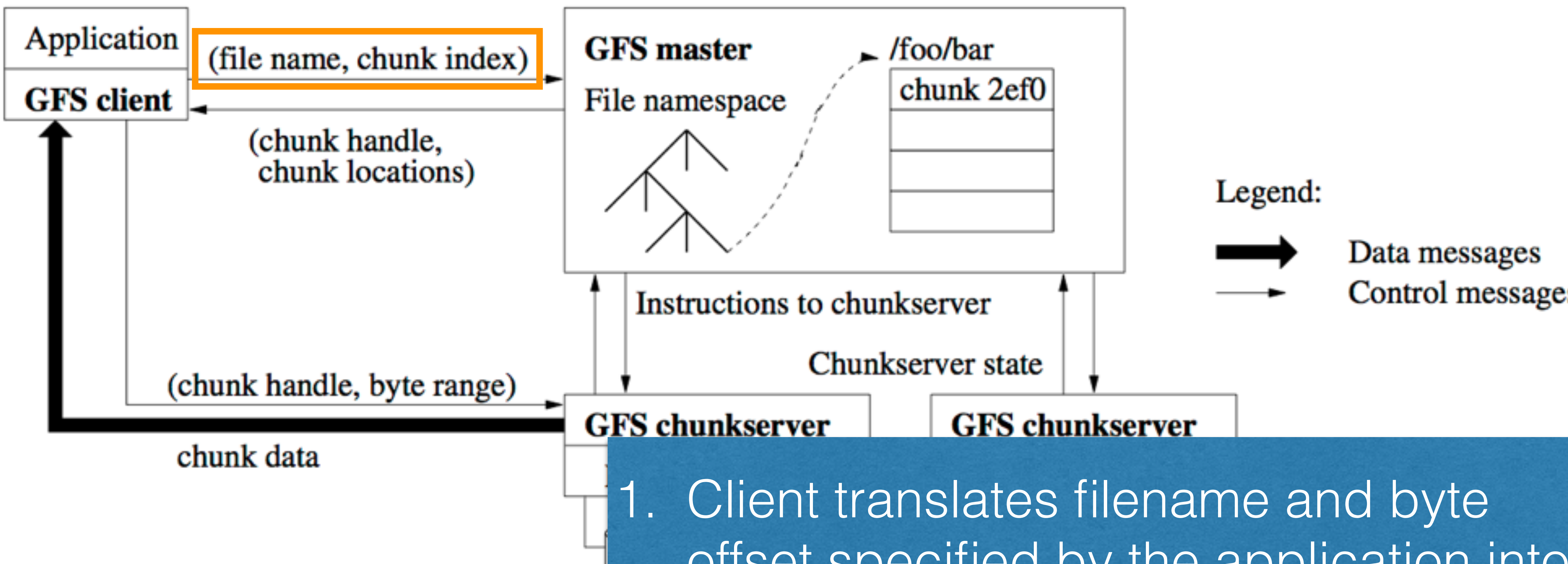
GFS: Master

One master

- Single master **simplifies the design** tremendously
  - Chunk placement and replication with **global knowledge**
- Single master in a large cluster can become a **bottleneck**
  - Goal: **minimize the number of reads and writes** (thus metadata vs. data)

Question: as the cluster grows, can the master become a bottleneck?

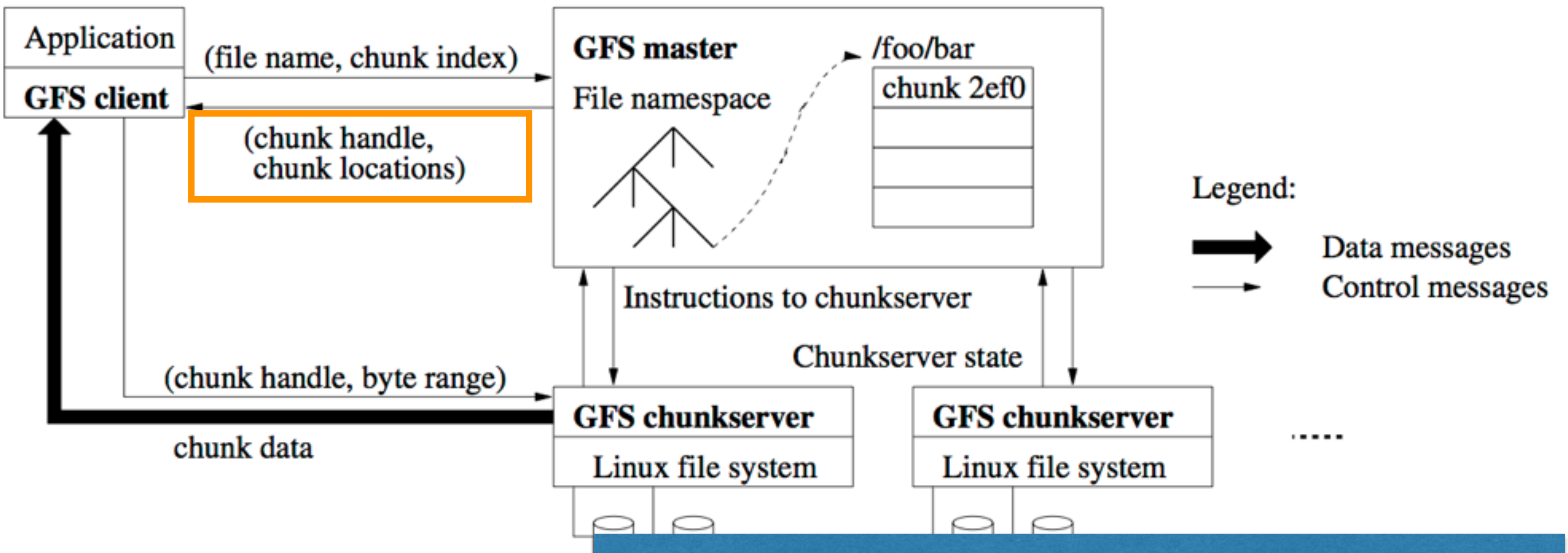
A read operation (in detail)



1. Client translates filename and byte offset specified by the application into a chunk index within the file. Sends request to master.

Source: http://static.googleusercontent.com/media/research.google.com/en//archive/gfs-sosp2003.pdf

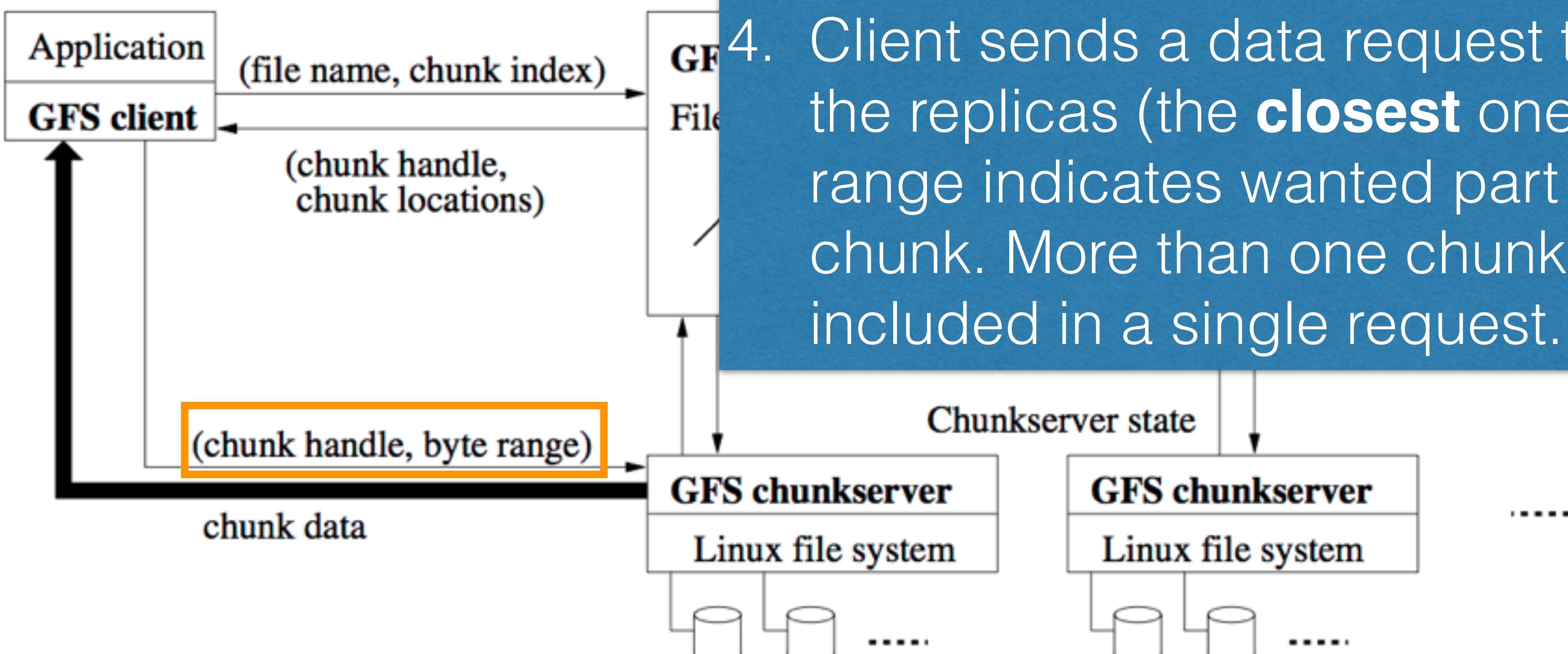
A read operation (in detail)



2. Master replies with chunk handle and locations.

Source: http://static.googleusercontent.com/media/research.google.com/en//archive/gfs-sosp2003.pdf

A read operation (in detail)



3. Client caches the metadata.

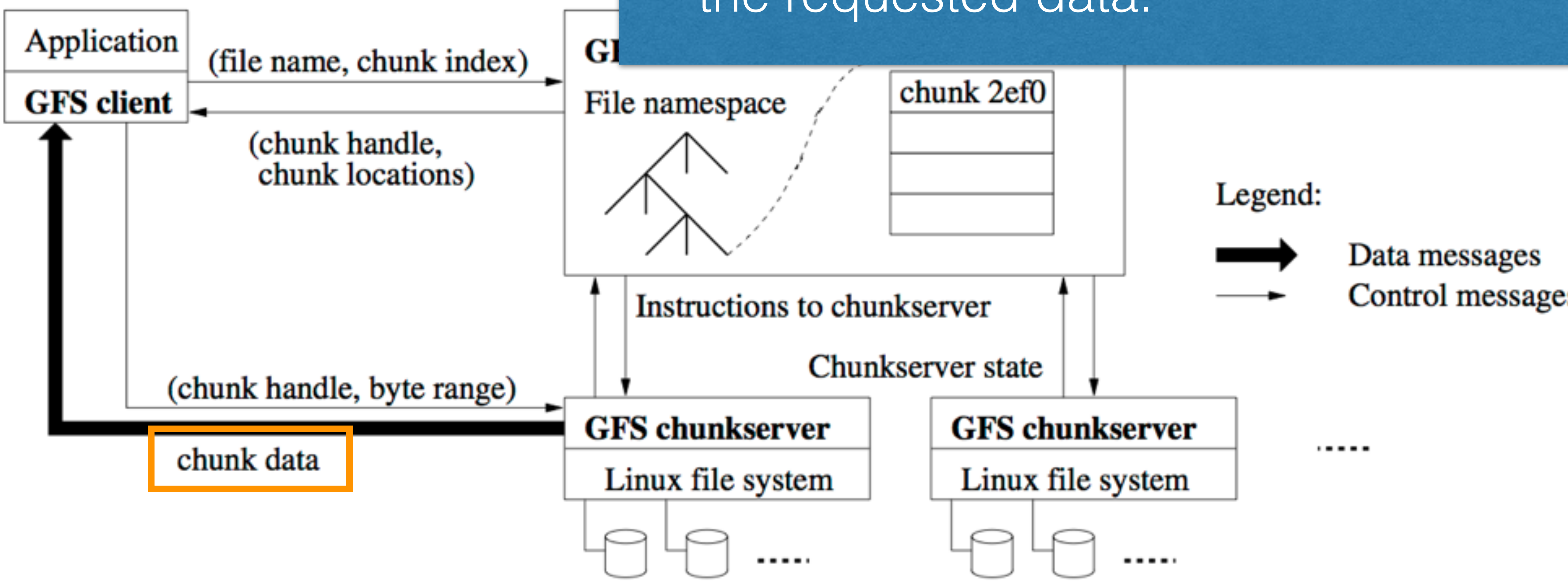
4. Client sends a data request to one of the replicas (the **closest** one). Byte range indicates wanted part of the chunk. More than one chunk can be included in a single request.

Question: how can the cluster topology be discovered automatically?

Source: http://static.googleusercontent.com/media/research.google.com/en//archive/gfs-sosp2003.pdf

A read operation (in detail)

5. Contacted chunk server replies with the requested data.



Source: http://static.googleusercontent.com/media/research.google.com/en//archive/gfs-sosp2003.pdf

Metadata on the master

- **3 types of metadata**
  - Files and chunk namespaces
  - Mapping from files to chunks
  - Locations of each chunk's replicas

Question: what happens to the cluster if the master crashes?

- All metadata is kept in master's **memory** (fast random access)
  - Sets limits on the entire system's capacity

- **Operation log** is kept on master's local disk: in case of the master's crash, master state can be recovered
  - Namespaces and mappings are logged
  - Chunk locations are **not** logged

GFS: Chunks

Chunks

- 1 chunk = 64MB or 128MB (can be changed); chunk stored as a **plain Linux file** on a chunk server

- Advantages of large (but not too large) chunk size
  - **Reduced** need for client/master **interaction**
  - 1 request per chunk suits the target workloads
  - Client can **cache all the chunk locations** for a multi-TB working set
  - **Reduced size of metadata** on the master (kept in memory)

- Disadvantage: chunkserver can become **hotspot** for popular file(s)

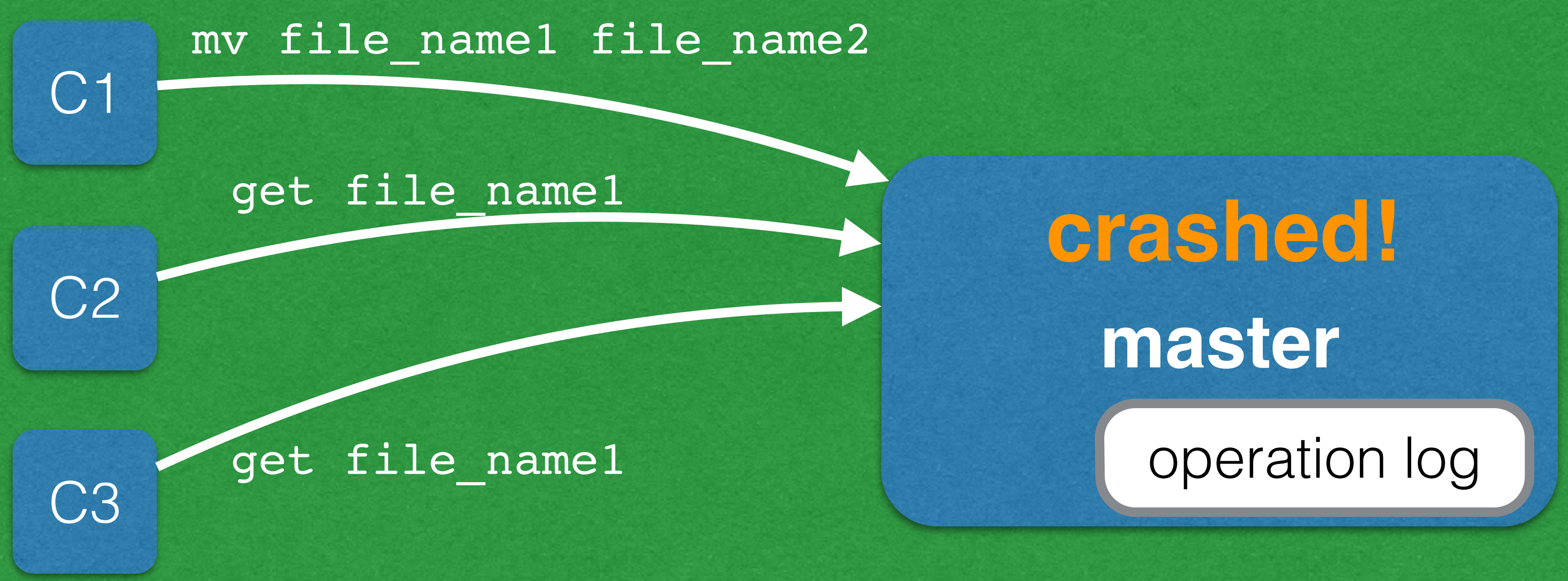
Question: how could the hotspot issue be solved?

Chunk locations

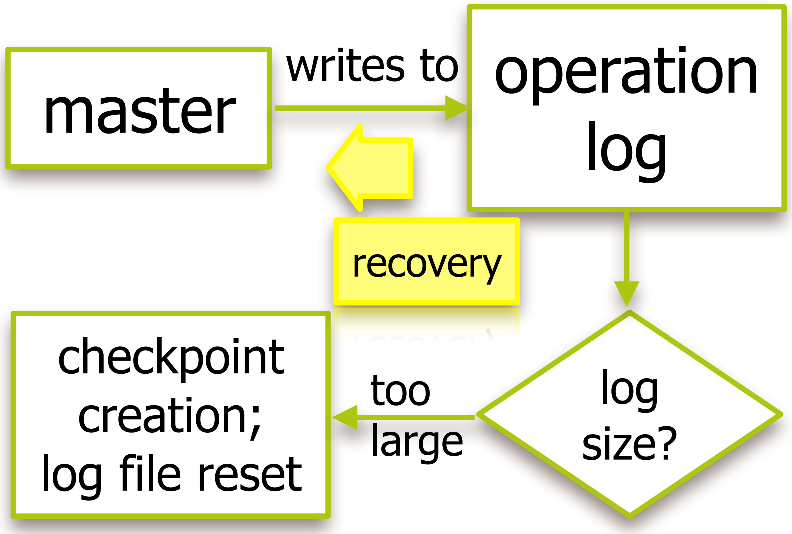
- Master does **not** keep a **persistent record** of chunk replica locations
- Master **polls** chunkservers about their chunks at **startup**
- Master keeps up to date through **periodic HeartBeat messages**
    - Master/chunkservers easily kept in sync when chunk servers leave/join/fail/restart [regular event]
    - Chunkserver has the final word over what chunks it has

Operation log

- Persistent record of critical metadata changes
- Critical to the recovery of the system



Question: when does the master relay the new information to the clients? Before or after having written it to the op. log?



Operation log

- Persistent record of critical metadata changes
- Critical to the recovery of the system
- Changes to metadata are only made visible to clients **after** they have been written to the operation log
- Operation log **replicated** on multiple remote machines
  - **Before** responding to client operation, log record must have been **flashed locally and remotely**
- **M**aster recovers its file system from checkpoint + operation

Chunk replica placement

- **Creation** of (initially empty) chunks
  - **Use under-utilised** chunk servers; spread across racks
  - Limit number of recent creations on each chunk server
- **Re-replication**
  - Started once the available replicas fall below setting
  - Master instructs chunkserver to copy chunk data directly from existing valid replica
  - Number of active clone operations/bandwidth is limited
- **Re-balancing**
  - Changes in replica distribution for better load balancing; gradual filling of new chunk servers

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 writer, multiple reader model	single writer, multiple reader model
chunk: 64KB data and 32bit checksum pieces	per HDFS block, two files created on a DataNode: data file & metadata file (checksums, timestamp)
default block size: 64MB	default block size: 128MB

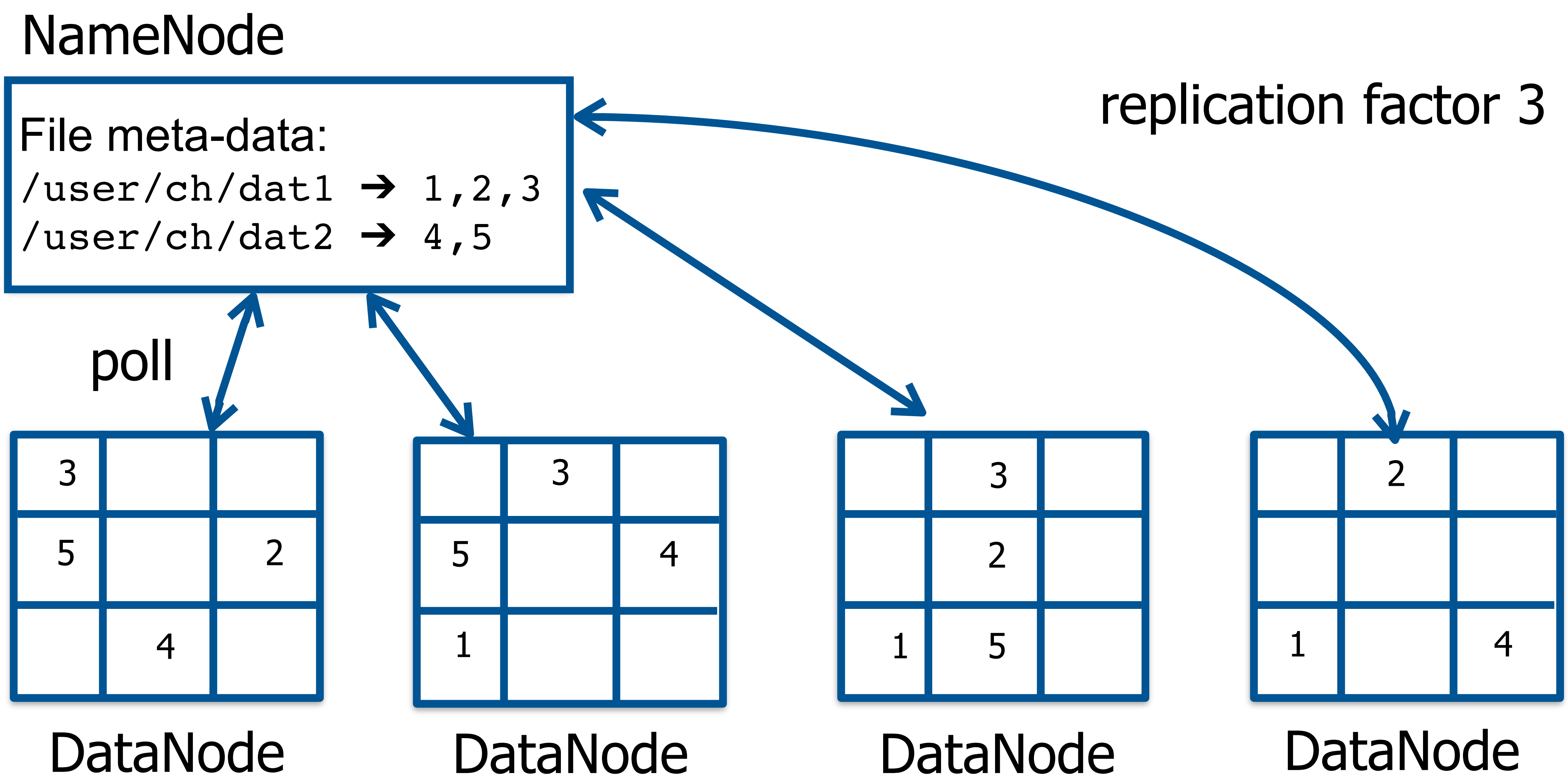
Hadoop's architecture O.X and 1.X

- **NameNode**
  - **Master** of HDFS, directs the slave DataNode daemons to perform low-level I/O tasks
  - Keeps track of file splitting into blocks, replication, block location, etc.

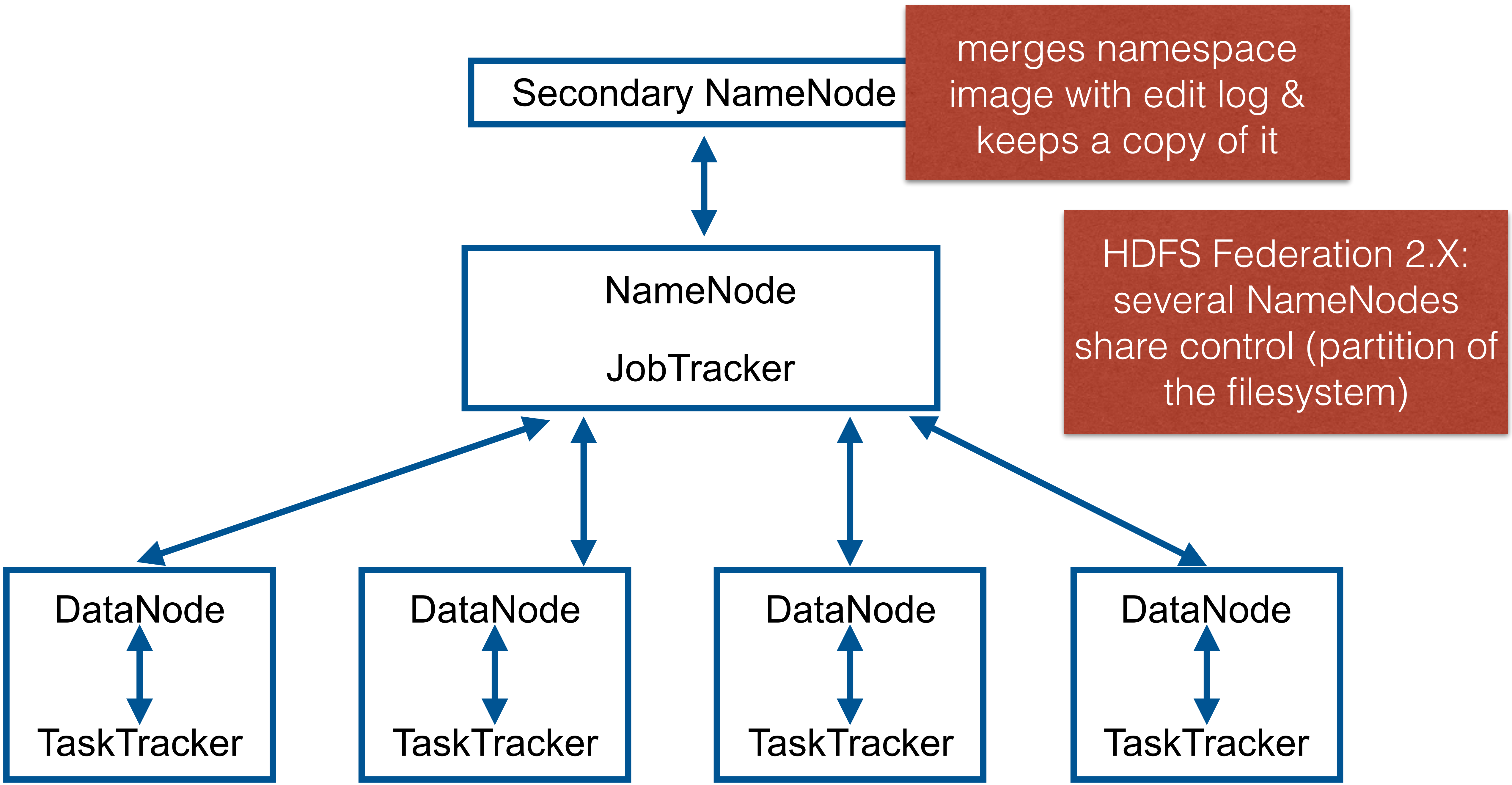
- **Secondary NameNode**: takes snapshots of the NameNode

- **DataNode**: each slave machine hosts a DataNode daemon

NameNodes and DataNodes



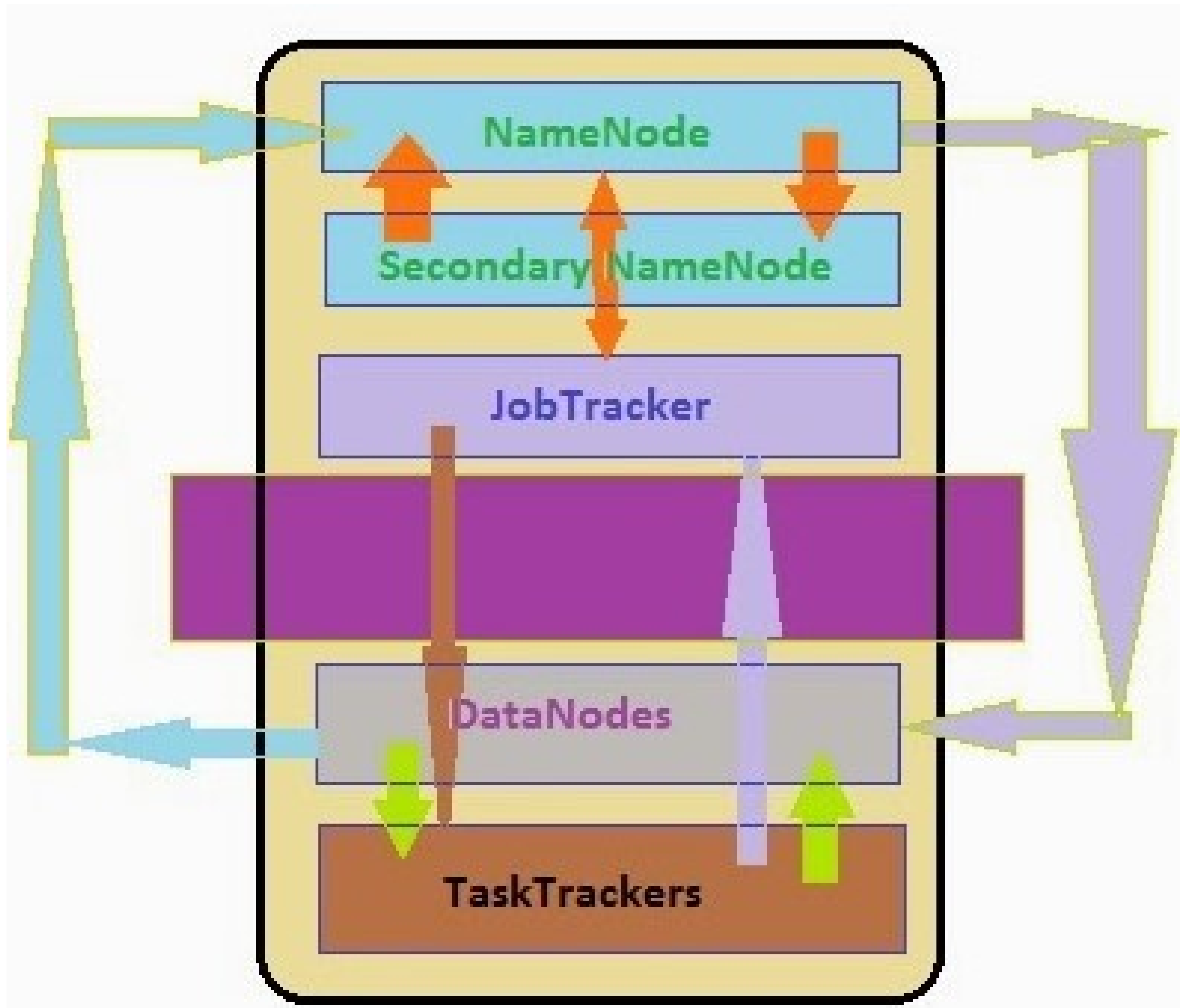
Hadoop cluster topology



JobTracker and TaskTracker are coming into picture when we required processing to data set. In hadoop system there are five services always running in background (called hadoop daemon services).

1. Namenodes
2. Secondary Namenodes
3. Jobtracker
4. Datanodes
5. Tasktracker

Above three services 1, 2, 3 can talk to each other and other two services 4,5 can also talk to each other. Namenode and datanodes are also talking to each other as well as Jobtracker and Tasktracker are also.



-> The file systems comes with the MapReduce engine, which consists of one JobTracker, to which client applications submit MapReduce jobs.

-> The JobTracker pushes work out to available TaskTracker nodes in the cluster, striving to keep the work as close to the data as possible.

-> With a rack-aware file system, the JobTracker knows which node contains the data, and which other machines are nearby.

-> If the work cannot be hosted on the actual node where the data resides, priority is given to nodes in the same rack. This reduces network traffic on the main backbone network.

-> If a TaskTracker fails or times out, that part of the job is rescheduled.

-> The TaskTracker on each node spawns off a separate Java Virtual Machine process to prevent the TaskTracker itself from failing if the running job crashes the JVM.

-> A heartbeat is sent from the TaskTracker to the JobTracker every few minutes to check its status.

-> The Job Tracker and TaskTracker status and information is exposed by Jetty and can be viewed from a web browser.

-> If the JobTracker failed on Hadoop 0.20 or earlier, all ongoing work was lost. Hadoop version 0.21 added some checkpointing to this process; the JobTracker records what it is up to in the file system. When a JobTracker starts up, it looks for any such data, so that it can restart work from where it left off.

Hadoop 1.x MapReduce System is composed of the JobTracker, which is the master, and the per-node slaves- TaskTrackers