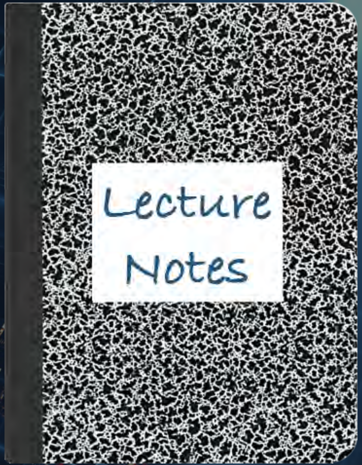
CS 417 – DISTRIBUTED SYSTEMS

Week 6: Distributed File Systems

Part 4: Parallel File Systems



Paul Krzyzanowski

Client-server file systems

- Central servers
  - Point of congestion, single point of failure
- Alleviate somewhat with replication and client caching
  - E.g., Coda, tokens, (aka *leases*, *oplocks*)
  - Limited replication can lead to congestion
- File data is still centralized
  - A file server stores all data from a file – not split across servers
  - Even if replication is in place,
    a client downloads all data for a file from one server
- File sizes are limited to the capacity available on a server
  - What if you need a 1,000 TB file?

What is a parallel file system?

- **Conventional file systems**
  - Store data & metadata on the same storage device
  - Example:
    - Linux directories are just files that contain lists of names & inodes
    - inodes are data structures placed in well-defined areas of the disk that contain information about the file
- **Parallel file systems**
  - File data can span multiple servers
  - Metadata can be on separate servers from the data
  - Metadata = information about the file
    - Includes name, access permissions, timestamps, file size, & locations of data blocks
  - Data = actual file contents

Google File System (GFS)

(≈ Apache Hadoop Distributed File System)

GFS Goals

- Scalable distributed file system
- Designed for large data-intensive applications
- Fault-tolerant; runs on commodity hardware
- Delivers high performance to a large number of clients

Design Assumptions

- Assumptions for conventional file systems don't work
  - E.g., *"most files are small"*, *"lots have short lifetimes"*
- Component failures are the norm, not an exception
  - File system = thousands of storage machines
  - Some % not working at any given time
- Files are huge. Multi-TB files are the norm
  - It doesn't make sense to work with billions of nKB-sized files
  - I/O operations and block size choices are also affected

Design Assumptions

- File access:
  - Most files are appended, not overwritten
    - Random writes within a file are almost never done
    - Once created, files are mostly read; often sequentially
  - Workload is mostly:
    - Reads: large streaming reads, small random reads – *these dominate*
    - Large appends
    - Hundreds of processes may append to a file concurrently
- GFS will store a modest number of files for its scale
  - approx. a few million
- Designing the GFS API together with the design of apps
  - Apps can handle a relaxed consistency model

Basic Design Principles

- Use separate servers to store metadata
  - Metadata includes lists of (*server, block_number*) sets that identify which blocks on which servers hold file data
  - We need more bandwidth for data access than metadata access
    - Metadata is small; file data can be huge
- Use large logical blocks
  - Most "normal" file systems are optimized for small files
    - A block size is typically 4KB
  - Expect huge files, so use *huge blocks* … >1,000x larger
    - The list of blocks that makes up a file becomes easier to manage
- Replicate data
  - Expect some servers to be down
  - Store copies of data blocks on multiple servers

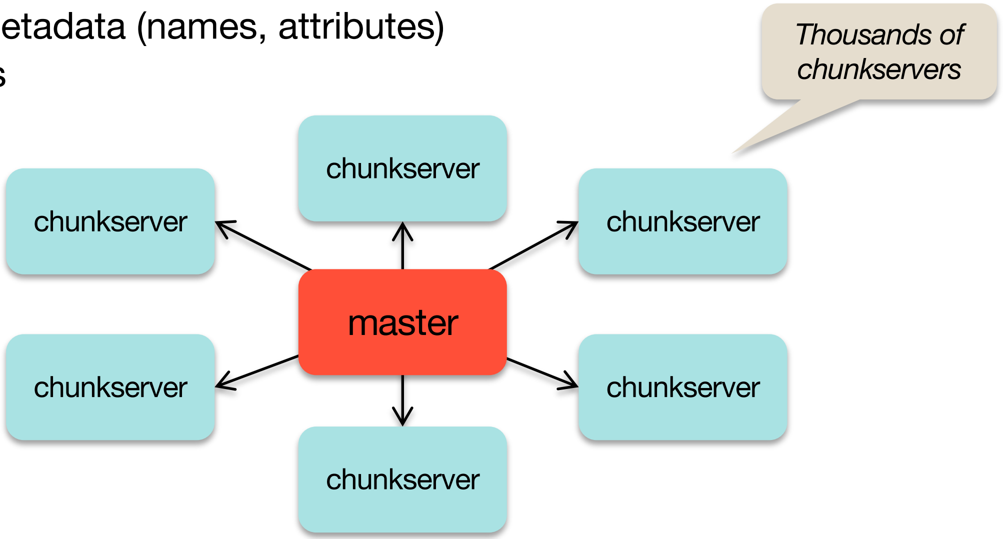
File System Interface

- GFS does *not* have a standard OS-level API
  - No POSIX system call level API – no kernel/VFS implementation
  - User-level API for accessing files
  - GFS servers are implemented in user space using native Linux FS
- Files organized hierarchically in directories
- Operations
  - Basic operations
    - *Create, delete, open, close, read, write*
  - Additional operations
    - *Snapshot:* create a copy of a file or directory tree at low cost
    - *Append:* allow multiple clients to append atomically without locking

GFS Master & Chunkservers

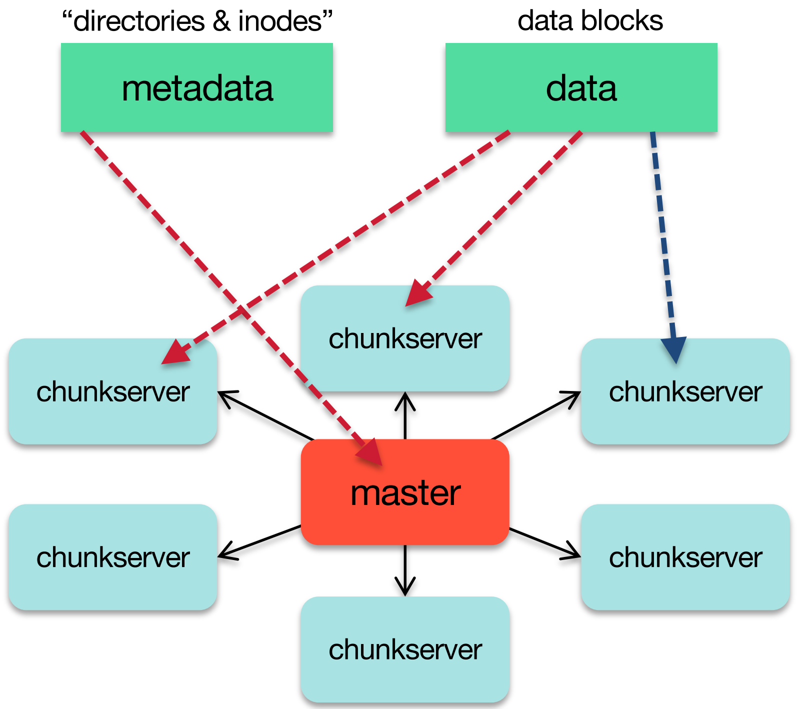
GFS cluster

- Multiple **chunkservers**
  - Data storage: fixed-size chunks
  - Chunks replicated on several systems
- One **master**
  - Stores file system metadata (names, attributes)
  - Maps files to chunks

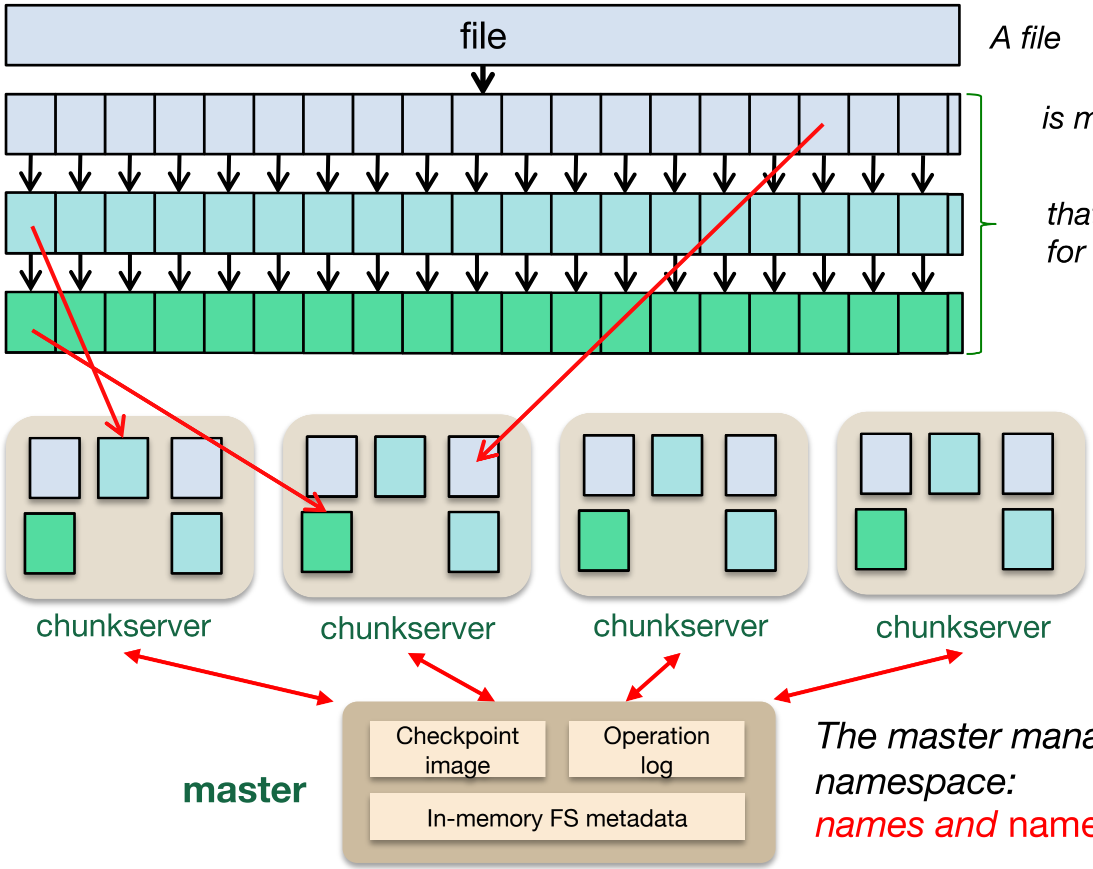


GFS Master & Chunkservers

GFS cluster



GFS Files



A file

is made of 64 MB chunks

that are replicated for fault tolerance

Chunks live on chunkservers

The master manages the file system namespace:
names and name→{chunk list} mappings

Chunks and Chunkservers

- Chunk size = 64 MB (default)
  - Chunkserver stores a 32-bit checksum with each chunk
    - In memory & logged to disk: allows it to detect data corruption
- Chunk Handle: identifies a chunk
  - Globally unique 64-bit number
  - Assigned by the master when the chunk is created
- **Chunkservers** store chunks on local disks as Linux files
- Each chunk is replicated on multiple chunkservers
  - Three replicas (different levels can be specified)
  - Popular files may need more replicas to avoid hotspots

Master

- Maintains all file system metadata
  - Namespace
  - Access control info
  - Filename to chunks mappings
  - Current locations of chunks
- Manages
  - Chunk leases (locks)
  - Garbage collection (freeing unused chunks)
  - Chunk migration (copying/moving chunks)
- Fault tolerance
  - Operation log replicated on multiple machines
  - New master can be started if the master fails
- Periodically communicates with all chunkservers
  - Via heartbeat messages to get state and send commands

Client Interaction Model

- GFS client code linked into each app
  - No OS-level API – you have to use a library
  - Interacts with master for metadata-related operations
  - Interacts directly with chunkservers for file data
    - All reads & writes go directly to chunkservers
    - Master is not a point of congestion
- Neither clients nor chunkservers cache data
  - Except for the caching by the OS system buffer cache
  - Clients cache metadata – e.g., location of a file's chunks

One master = simplified design

- All metadata stored in master's memory
  - Super-fast access
- Namespaces and *name-to-chunk_list* maps
  - Stored in memory
  - Also persist in an *operation log* on the disk
    - Replicated onto remote machines for backup
- **Operation log**
  - Similar to a journal
  - All operations are logged
  - Periodic checkpoints (stored in a B-tree) to avoid playing back entire log
- Master does not store chunk locations persistently
  - This is queried from all the chunkservers: avoids consistency problems

Why Large Chunks?

- Default chunk size = 64MB
  (compare to Linux ext4 block sizes: typically 4 KB and up to 1 MB)
- Reduces need for frequent communication with master to get chunk location info – *one query can give info on location of lots of bytes of data*
- Clients can easily cache info to refer to all data of large files
  - Cached data has timeouts to reduce possibility of reading stale data
- Large chunk makes it feasible to keep a TCP connection open to a chunkserver for an extended time
- Master stores <64 bytes of metadata for each 64MB chunk

Reading Files

1. Contact the master
2. Get file's metadata: list chunk handles
3. Get the location of each of the chunk handles
   – Multiple replicated chunkservers per chunk
4. Contact any available chunkserver for chunk data

Writing to files

- Less frequent than reading

- Master grants a **chunk lease** to one of the replicas
  - This replica will be the **primary replica** chunkserver
  - Primary can request lease extensions, if needed
  - Master increases the chunk version number and informs replicas

Writing to files: two phases

Phase 1: Send data

Deliver data but don't write to the file

– Client asks the master for a list of chunkservers with replicas: primary & secondaries

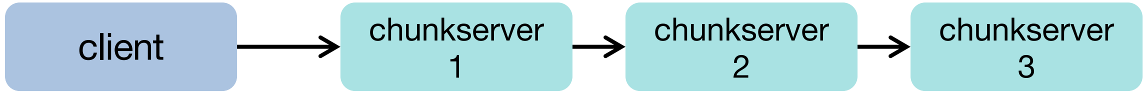
– Client writes to the closest replica chunkserver that has not received the data

- Replica forwards the data to another replica chunkserver
- That chunkserver forwards to another replica chunkserver …

– Chunkservers store this data in a cache – *it's not part of the file yet*

Goal: Maximixe bandwidth via pipelining

Minimize latency by forwarding data while it is being received



Writing to files: two phases

Phase 2: Write data

Add it to the file (commit)

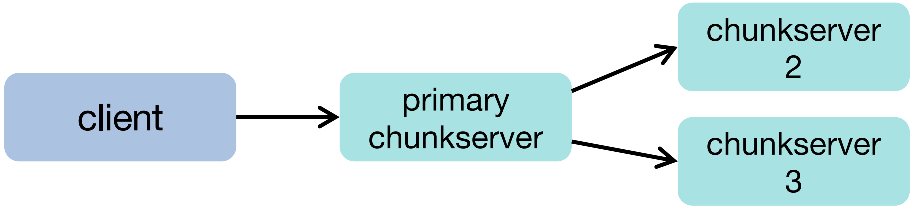
– Client waits for replicas to acknowledge receiving the data

– Sends a *write* request to the primary, identifying the data that was sent

– The primary is responsible for serialization of writes

- Assigns consecutive serial numbers to all writes that it received
- Applies writes in serial-number order and forwards write requests in order to secondaries

– Once all acknowledgements have been received, the primary acknowledges the client



Writing to files: separate data flow & control flow

Data Flow (*phase 1*) is different from **Control Flow** (*phase 2*)

- Data Flow (*upload*):
  - Client to chunkserver to chunkserver to chunkserver…
  - Order does not matter
- Control Flow (*write*):
  - Client to primary; primary to all secondaries
  - Locking used; Order maintained

Chunk version numbers are used to detect if any replica has stale data (was not updated because it was down)

Namespace

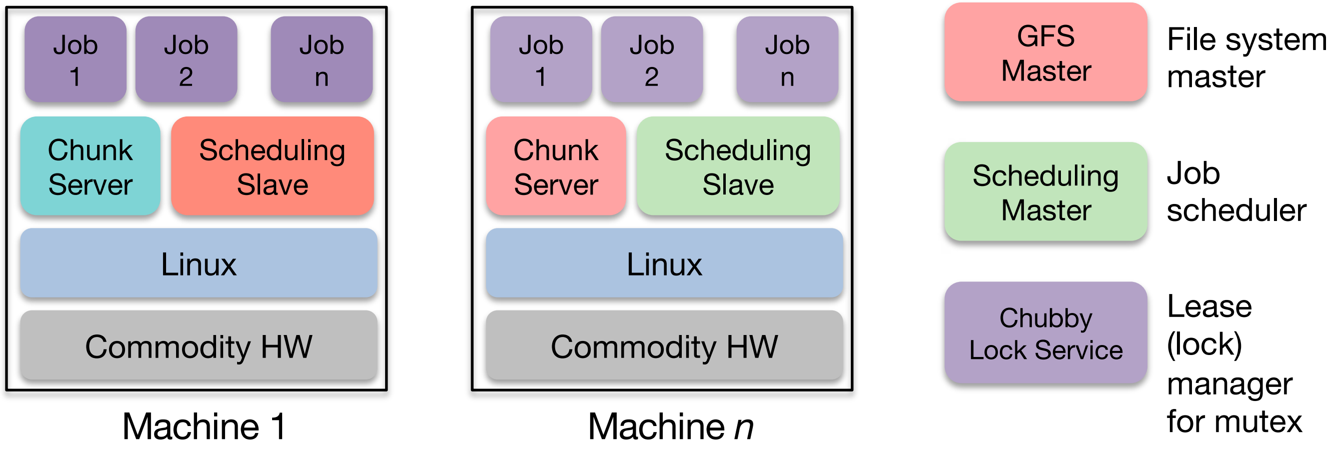
- No per-directory data structure like most file systems
  - E.g., directory file contains names of all files in the directory
- No aliases (hard or symbolic links)
- Namespace is a single lookup table
  - Maps pathnames to metadata

Core Part of Google Cluster Environment

Google Cluster Environment

- Core services: GFS + cluster scheduling system
- Typically 100s to 1000s of active jobs
- 200+ clusters, many with 1000s of machines
- Pools of 1000s of clients
- 4+ PB filesystems, 40 GB/s read/write loads

Bring the computation close to the data



HDFS: Hadoop Distributed File System

- Primary storage system for Hadoop applications
- Apache Hadoop
  - Framework for distributed processing of large data sets across clusters of computers
- Hadoop includes:
  - MapReduce™: software framework for distributed processing of large data sets on compute clusters.
  - Avro™: A data serialization system.
  - Cassandra™: A scalable multi-master database with no single points of failure.
  - Chukwa™: A data collection system for managing large distributed systems.
  - HBase™: A scalable, distributed database that supports structured data storage for large tables.
  - Hive™: A data warehouse infrastructure that provides data summarization and ad hoc querying.
  - Mahout™: A Scalable machine learning and data mining library.
  - Pig™: A high-level data-flow language and execution framework for parallel computation.
  - ZooKeeper™: A high-performance coordination service for distributed applications
  - and more …

HDFS Design Goals & Assumptions

- HDFS is an open source (Apache) implementation inspired by GFS design

- Similar goals and same basic design as GFS
  - Run on commodity hardware
  - Highly fault tolerant
  - High throughput – Designed for large data sets
  - OK to relax some POSIX requirements
  - Large scale deployments
    - Instance of HDFS may comprise 1000s of servers
    - Each server stores part of the file system's data

- But
  - No support for concurrent appends

HDFS Design Goals & Assumptions

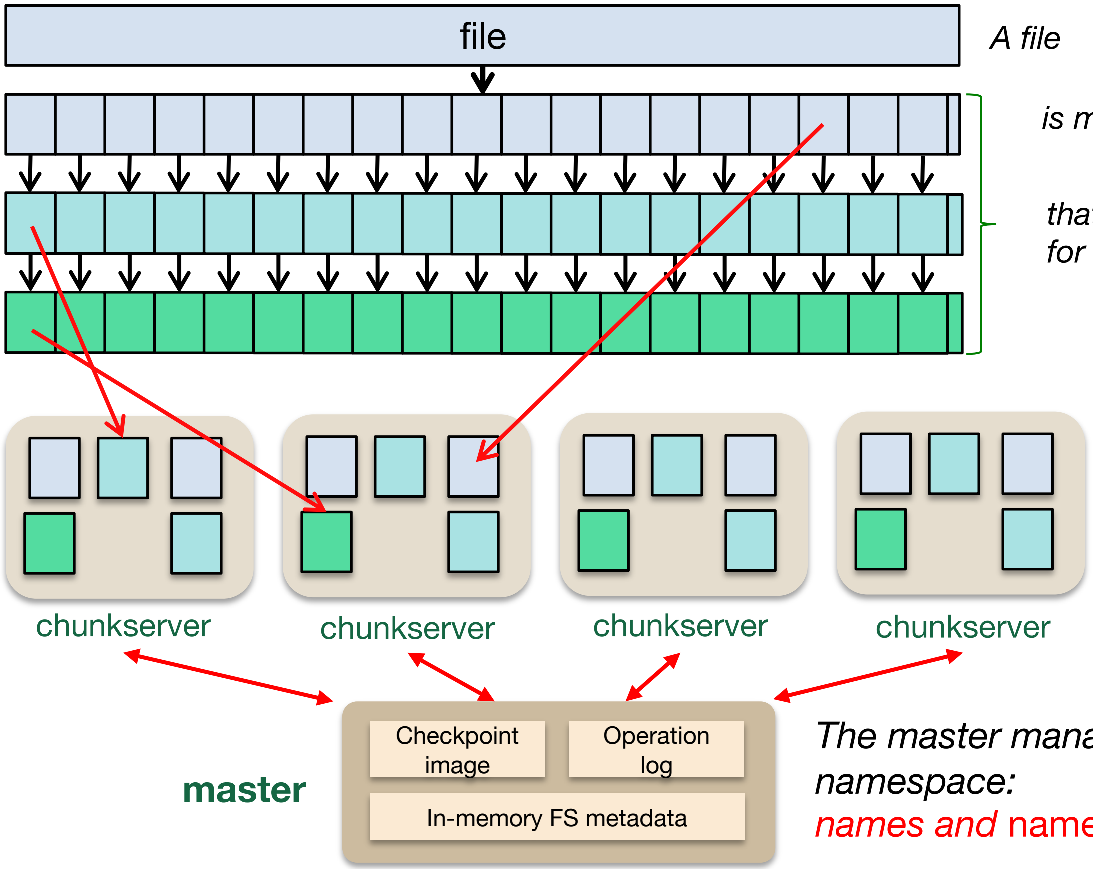
- Write-once, read-many-times file access model

- A file's contents will not change
  - Simplifies data coherency
  - Suitable for web crawlers and MapReduce analytics applications

HDFS Architecture

- Written in Java
- Single NameNode
  - Master server responsible for the namespace & access control
- Multiple DataNodes
  - Responsible for managing storage attached to its node
- A file is split into one or more blocks
  - Typical block size = 128 MB (vs. 64 MB for GFS)
  - Blocks are stored in a set of DataNodes

GFS Files



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Chunks live on chunkservers

The master manages the file system namespace:
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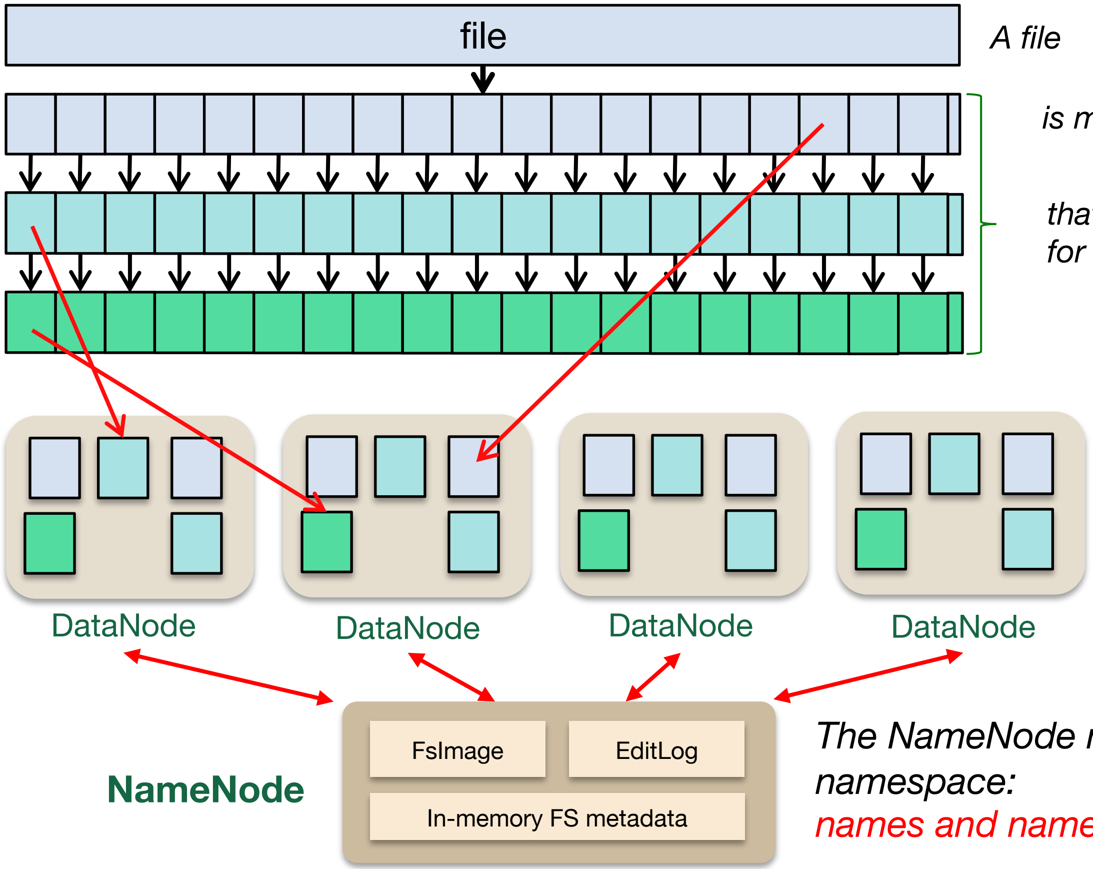
HDFS: same stuff … different names



A file

is made of 128 MB blocks

that are replicated for fault tolerance

Blocks live on DataNodes

The NameNode manages the file system namespace:
names and name→{block list} mappings

NameNode (= GFS master)

- Executes metadata operations
  - *open, close, rename*
  - Maps file blocks to DataNodes
  - Maintains HDFS namespace

- Transaction log (EditLog) records every change that occurs to file system metadata
  - Entire file system namespace + file-block mappings is stored in memory
  - … and stored in a file (FsImage) for persistence

- NameNode receives a periodic *Heartbeat* and *Blockreport* from each DataNode
  - Heartbeat = “I am alive” message
  - Blockreport = list of all blocks managed by a DataNode
    - Keep track of which DataNodes own which blocks & their replication count

DataNode (= GFS chunkserver)

- Responsible for serving read/write requests
- Blocks are replicated for fault tolerance
  - App can specify # replicas at creation time
  - Can be changed later
- Blocks are stored in the local file system at the DataNode

Rack-Aware Reads & Replica Selection

- Client sends request to NameNode
  - Receives list of blocks and replica DataNodes per block

- Client tries to read from the closest replica
  - Prefer same rack
  - Else same data center
  - Location awareness is configured by the admin

Writes

- Client caches file data into a temp file
- When temp file ≥ one HDFS block size
  - Client contacts NameNode
  - NameNode inserts file name into file system hierarchy & allocates a data block
  - Responds to client with the destination data block
  - Client writes to the block at the corresponding DataNode
- When a file is closed, remaining data is transferred to a DataNode
  - NameNode is informed that the file is closed
  - NameNode commits file creation operation into a persistent store (log)
- Data writes are chained: pipelined
  - Client writes to the first (closest) DataNode
  - That DataNode writes the data stream to the second DataNode
  - And so on…

Internet-based file sync & sharing: Dropbox

File synchronization

- Client runs on desktop
- Uploads any changes made within a dropbox folder
- Huge scale
  - 100+ million users syncing 1 billion files per day
- Design
  - Small client that doesn't take a lot of resources
  - Expect possibility of low bandwidth to user
  - Scalable back-end architecture
  - 99%+ of code written in Python

    ⇒infrastructure (storage, monitoring) software migrated to Go in 2013

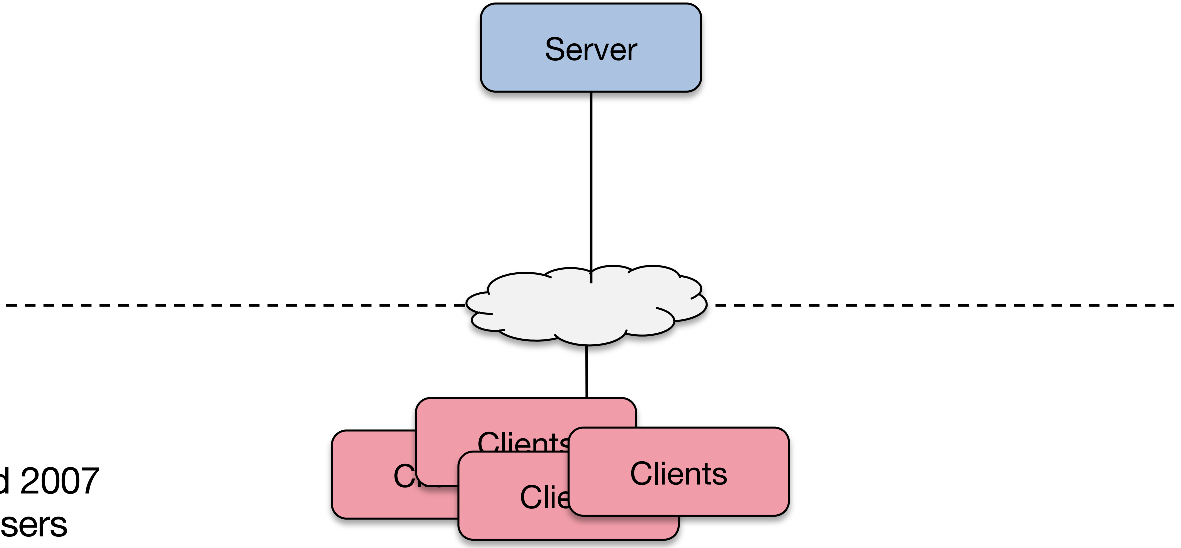
    ⇒a few components running on storage boxes migrated to Rust for memory efficiency

What's different about dropbox?

- Most web-based apps have high read to write ratios
  - E.g., *twitter*, *facebook*, *reddit*, … 100:1, 1000:1, or higher
- But with Dropbox…
  - Everyone's computer has a complete copy of their Dropbox
  - Traffic happens only when changes occur
  - File upload : file download ratio roughly 1:1
    - Huge number of uploads compared to traditional services
- Must abide by most ACID requirements … sort of
  - Atomic: don't share partially-modified files
  - Consistent:
    - Operations have to be in order and reliable
    - Cannot delete a file in a shared folder but have others see
  - Durable: Files cannot disappear
  - (OK to punt on "Isolated")

Dropbox: architecture evolution: version 1

- One server: web server, app server, mySQL database, sync server

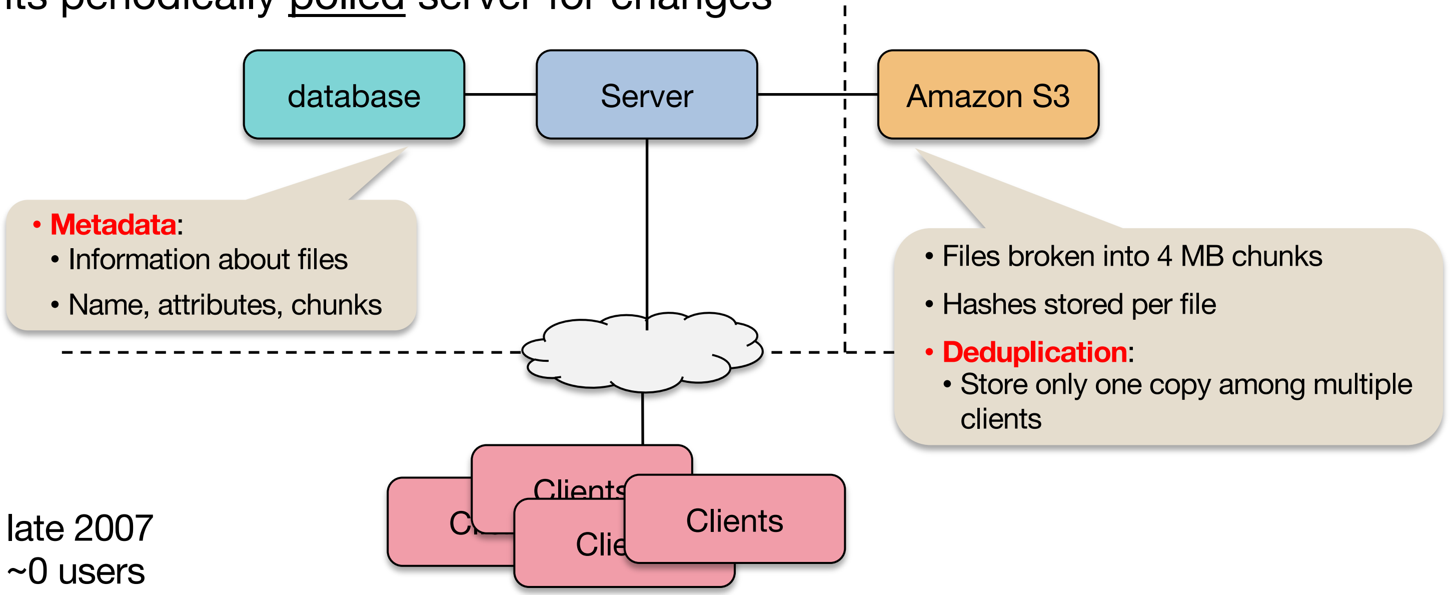


mid 2007
0 users

See http://youtu.be/PE4gwstWhmc

Dropbox: architecture evolution: version 2

- Server ran out of disk space:
  moved data to Amazon S3 service (key-value store)
- Servers became overloaded: moved mySQL DB to another machine
- Clients periodically polled server for changes



- **Metadata**:
  - Information about files
  - Name, attributes, chunks

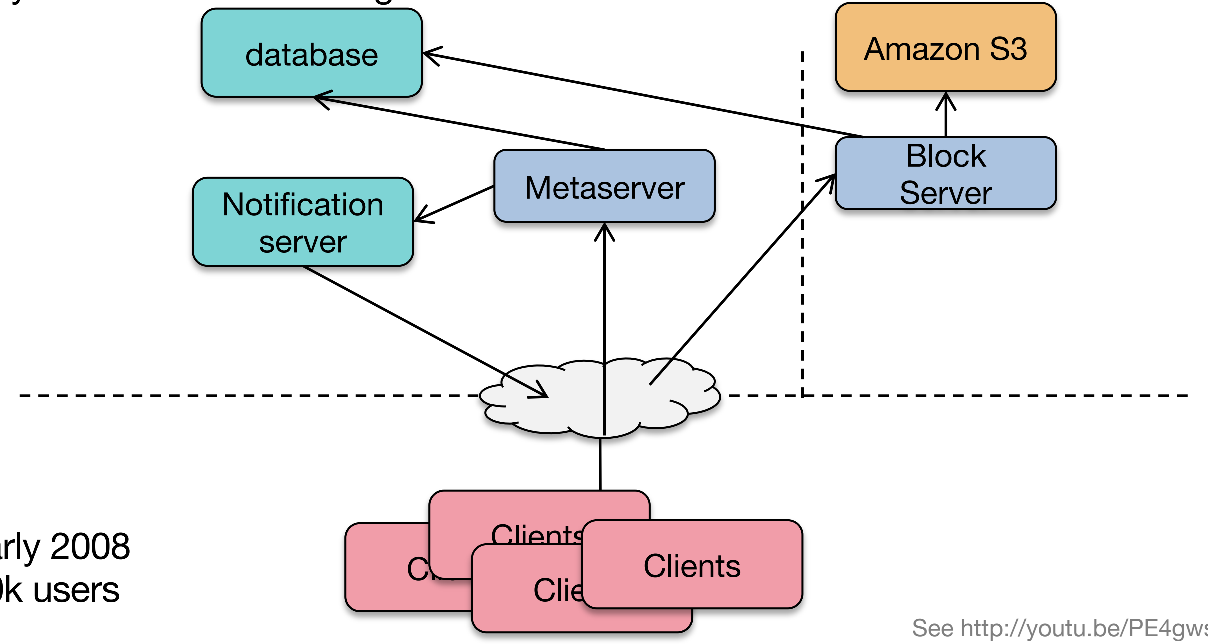
- Files broken into 4 MB chunks
- Hashes stored per file
- **Deduplication**:
  - Store only one copy among multiple clients

late 2007
~0 users

See http://youtu.be/PE4gwstWhmc

Dropbox: architecture evolution: version 3

- Move from polling to notifications: add **notification server**
- Split web server into two:
  - Amazon-hosted server hosts file content and accepts uploads (stored as blocks)
  - Locally-hosted server manages metadata

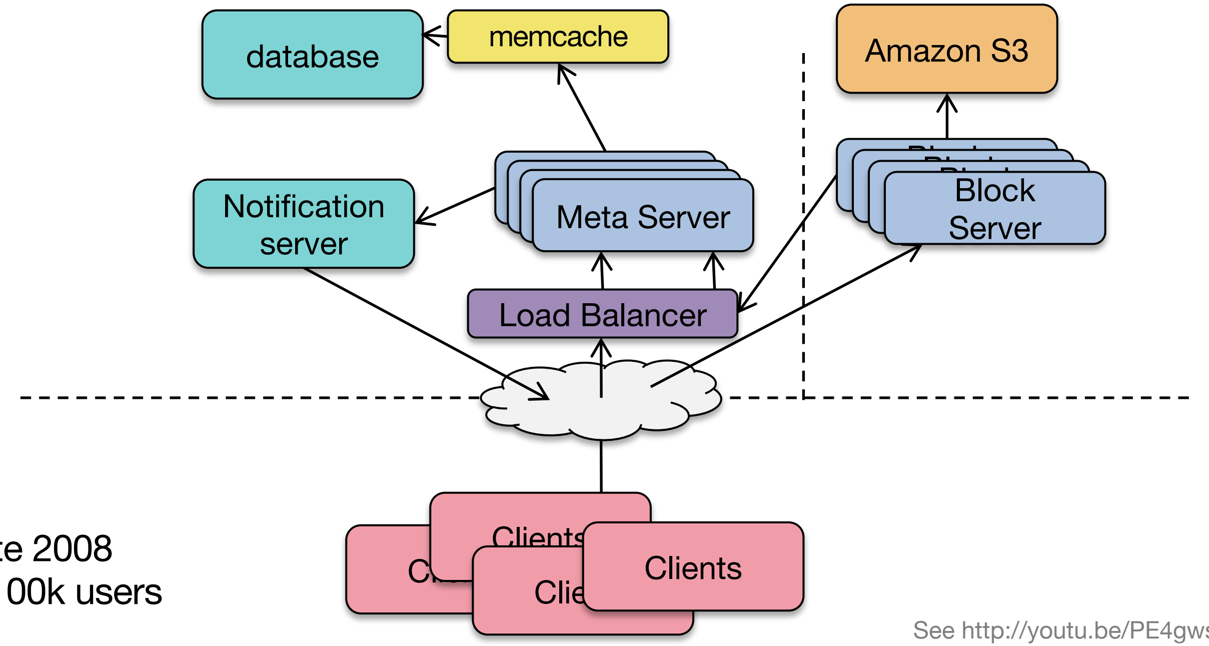


early 2008
50k users

See http://youtu.be/PE4gwstWhmc

Dropbox: architecture evolution: version 4

- Add more metaservers and blockservers
- Blockservers do not access DB directly; they send RPCs to metaservers
- Add a memory cache (memcache) in front of the database to avoid scaling

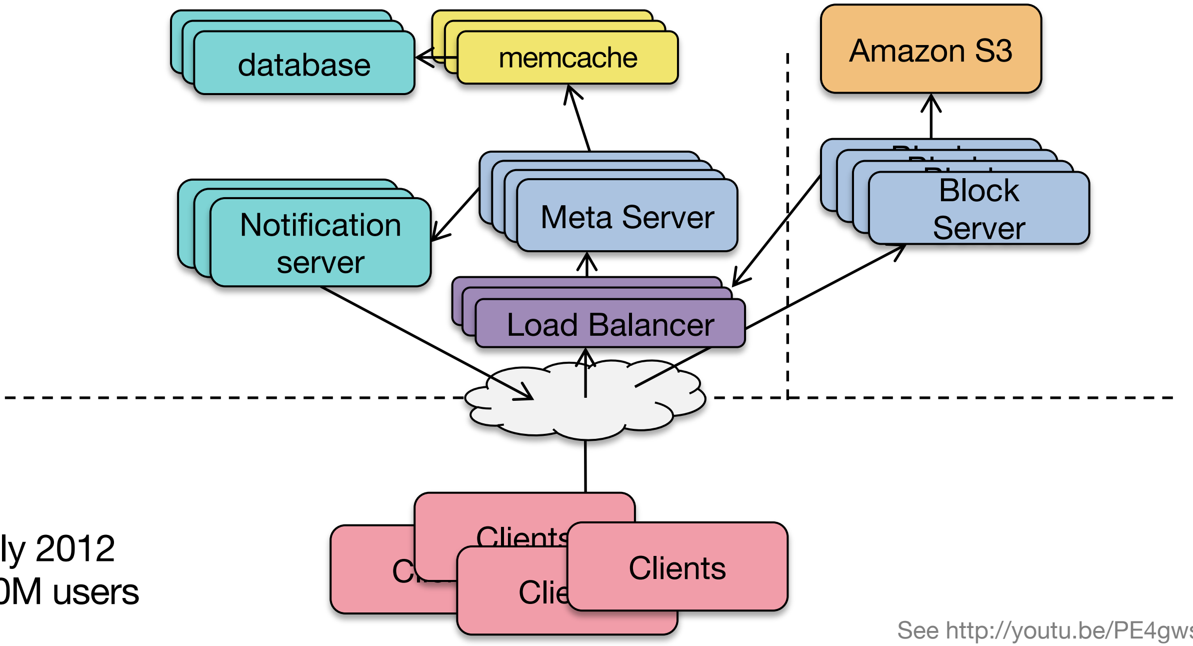


late 2008
~100k users

See http://youtu.be/PE4gwstWhmc

Dropbox: architecture evolution: version 5

- 10s of millions of clients – Clients have to connect before getting notifications
- Add 2-level hierarchy to notification servers: ~1 million connections/server



early 2012
>50M users

See http://youtu.be/PE4gwstWhmc

The End