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Distributed Systems (COMP9243)

Lecture 11: Distributed File Systems

① Introduction
② NFS (Network File System)
③ AFS (Andrew File System) & Coda
④ GFS (Google File System)

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Introduction

Distributed File System Paradigm:

- ➜ File system that is shared by many distributed clients
- ➜ Communication through shared files
- ➜ Shared data remains available for long time
- ➜ Basic layer for many distributed systems and applications

Clients and Servers:

- ➜ Clients access files and directories
- ➜ Servers provide files and directories
- ➜ Servers allow clients to perform operations on the files and directories
- ➜ Operations: add/remove, read/write
- ➜ Servers may provide different views to different clients

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Challenges

Transparency:

- ➜ Location: a client cannot tell where a file is located
- ➜ Migration: a file can transparently move to another server
- ➜ Replication: multiple copies of a file may exist
- ➜ Concurrency: multiple clients access the same file

Flexibility:

- ➜ Servers may be added or replaced
- ➜ Support for multiple file system types

Dependability:

- ➜ Consistency: conflicts with replication & concurrency
- ➜ Security: users may have different access rights on clients sharing files & network transmission
- ➜ Fault tolerance: server crash, availability of files

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Performance:

- ➜ Requests may be distributed across servers
- ➜ Multiple servers allow higher storage capacity

Scalability:

- ➜ Handle increasing number of files and users
- ➜ Growth over geographic and administrative areas
- ➜ Growth of storage space
- ➜ No central naming service
- ➜ No centralised locking
- ➜ No central file store

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THE CLIENT'S PERSPECTIVE: FILE SERVICES

Ideally, the client would perceive remote files like local ones.

File Service Interface:

- File: uninterpreted sequence of bytes
- Attributes: owner, size, creation date, permissions, etc.
- Protection: access control lists or capabilities
- Immutable files: simplifies caching and replication
- *Upload/download model* versus *remote access model*

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FILE ACCESS SEMANTICS

UNIX semantics:

- A READ after a WRITE returns the value just written
- When two WRITES follow in quick succession, the second persists
- Caches are needed for performance & write-through is expensive
- UNIX semantics is too strong for a distributed file system

Session semantics:

- Changes to an open file are only locally visible
- When a file is closed, changes are propagated to the server (and other clients)
- But it also has problems:
  - What happens if two clients modify the same file simultaneously?
  - Parent and child processes cannot share file pointers if running on different machines.

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Immutable files:

- Files allow only CREATE and READ
- Directories can be updated
- Instead of overwriting the contents of a file, a new one is created and replaces the old one
- ✗ Race condition when two clients replace the same file
- ✗ How to handle readers of a file when it is replaced?

Atomic transactions:

- A sequence of file manipulations is executed indivisibly
- Two transaction can never interfere
- Standard for databases
- Expensive to implement

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THE SERVER'S PERSPECTIVE: IMPLEMENTATION

Design Depends On the Use:

- Satyanarayanan, 1980's university UNIX use
- Most files are small—less than 10k
- Reading is much more common than writing
- Usually access is sequential; random access is rare
- Most files have a short lifetime
- File sharing is unusual, Most process use only a few files
- Distinct files classes with different properties exist

Is this still valid?

There are also varying reasons for using a DFS:

- Big file system, many users, inherent distribution
- High performance
- Fault tolerance

STATELESS VERSUS STATEFUL SERVERS

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Advantages of stateless servers:

- ➜ Fault tolerance
- ➜ No OPEN/CLOSE calls needed
- ➜ No server space needed for tables
- ➜ No limits on number of open files
- ➜ No problems if server crashes
- ➜ No problems if client crashes

Advantages of stateful servers:

- ➜ Shorter request messages
- ➜ Better performance
- ➜ Read ahead easier
- ➜ File locking possible

CACHING

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We can cache in three locations:

① Main memory of the server: easy & transparent
② Disk of the client
③ Main memory of the client (process local, kernel, or dedicated cache process)

Cache consistency:

- ➜ Obvious parallels to shared-memory systems, but other trade offs
- ➜ No UNIX semantics without centralised control
- ➜ Plain *write-through* is too expensive; alternatives: delay WRITES and agglomerate multiple WRITES
- ➜ *Write-on-close;* possibly with delay (file may be deleted)
- ➜ Invalid cache entries may be accessed if server is not contacted whenever a file is opened

REPLICATION

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Multiple copies of files on different servers:

- ➜ Prevent data loss
- ➜ Protect system against down time of a single server
- ➜ Distribute workload

Three designs:

- ➜ Explicit replication: The client explicitly writes files to multiple servers (not transparent).
- ➜ Lazy file replication: Server automatically copies files to other servers after file is written.
- ➜ Group file replication: WRITES simultaneously go to a group of servers.

CASE STUDIES

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- ➜ Network File System (NFS)
- ➜ Andrew File System (AFS) & Coda
- ➜ Google File System (GFS)

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NETWORK FILE SYSTEM (NFS)

Properties:

- ➜ Introduced by Sun
- ➜ Fits nicely into UNIX's idea of mount points, but does not implement UNIX semantics
- ➜ Multiple clients & servers (a single machine can be a client and a server)
- ➜ Stateless servers (no OPEN & CLOSE) (changed in v4)
- ➜ File locking through separate server
- ➜ No replication
- ➜ ONC RPC for communication
- ➜ Caching: local files copies
  - consistency through polling and timestamps
  - asynchronous update of file after close

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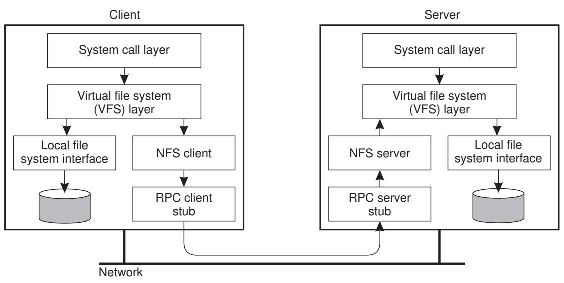

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Operation	v3	v4	Description
Create	Yes	No	Create a regular file
Create	No	Yes	Create a nonregular file
Link	Yes	Yes	Create a hard link to a file
Symlink	Yes	No	Create a symbolic link to a file
Mkdir	Yes	No	Create a subdirectory in a given directory
Mknod	Yes	No	Create a special file
Rename	Yes	Yes	Change the name of a file
Remove	Yes	Yes	Remove a file from a file system
Rmdir	Yes	No	Remove an empty subdirectory from a directory
Open	No	Yes	Open a file
Close	No	Yes	Close a file
Lookup	Yes	Yes	Look up a file by means of a file name
Readdir	Yes	Yes	Read the entries in a directory
Readlink	Yes	Yes	Read the path name stored in a symbolic link
Getattr	Yes	Yes	Get the attribute values for a file
Setattr	Yes	Yes	Set one or more attribute values for a file
Read	Yes	Yes	Read the data contained in a file
Write	Yes	Yes	Write data to a file

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ANDREW FILE SYSTEM (AFS) & CODA

Properties:

- ➜ From Carnegie Mellon University (CMU) in the 1980s.
- ➜ Developed as campus-wide file system: Scalability
- ➜ Global name space for file system (divided in *cells*, e.g. `/afs/cs.cmu.edu`, `/afs/ethz.ch`)
- ➜ API same as for UNIX
- ➜ UNIX semantics for processes on one machine, but globally write-on-close

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System Architecture:

- ➜ Client: User-level process *Venus* (AFS daemon)
- ➜ Cache on local disk
- ➜ Trusted servers collectively called *Vice*

Scalability:

- ➜ Server serves whole files. Clients cache whole files
- ➜ Server invalidates cached files with callback (stateful servers)
- ➜ Clients do not validate cache (except on first use after booting)
- ➜ Result: Very little cache validation traffic

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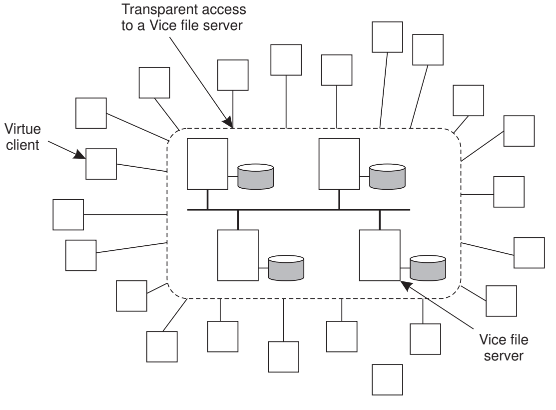

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CODA

- ➜ Successor of the Andrew File System (AFS)
  - System architecture quite similar to AFS
- ➜ Supports disconnected, mobile operation of clients
- ➜ Supports replication

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DESIGN & ARCHITECTURE

Disconnected operation:

- ➜ All client updates are logged in a *Client Modification Log (CML)*
- ➜ On re-connection, CML operations are replayed on the server
- ➜ Trickle reintegration tradeoff: Immediate reintegration of log entries reduces chance for optimisation, late reintegration increases risk of conflicts
- ➜ File hoarding: System (or user) can build a user hoard database, which it uses to update frequently used files in a hoard walk
- ➜ Conflicts: Automatically resolved where possible; otherwise, manual correction necessary

Servers:

- ➜ Read/write replication is organised on a per volume basis
- ➜ Group file replication (multicast RPCs); read from any server
- ➜ Version stamps are used to recognise server with out of date files (due to disconnect or failure)

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Google File System

Motivation:

- ➜ 10+ clusters
- ➜ 1000+ nodes per cluster
- ➜ Pools of 1000+ clients
- ➜ 350TB+ filesystems
- ➜ 500Mb/s read/write load
- ➜ Commercial and R&D applications

Assumptions:

- ➜ Failure occurs often
- ➜ Huge files (millions, 100+MB)
- ➜ Large streaming reads
- ➜ Small random reads
- ➜ Large appends
- ➜ Concurrent appends
- ➜ Bandwidth more important than latency

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Interface:

No common standard like POSIX.
Provides familiar file system interface:

- ➜ `Create`, `Delete`, `Open`, `Close`, `Read`, `Write`

In addition:

- ➜ *Snapshot*: low cost copy of a whole file with copy-on-write operation
- ➜ *Record append*: Atomic append operation

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Design Overview:

- ➜ Files split in fixed size *chunks* of 64 MByte
- ➜ Chunks stored on *chunk servers*
- ➜ Chunks replicated on multiple chunk servers
- ➜ GFS master manages name space
- ➜ Clients interact with master to get *chunk handles*
- ➜ Clients interact with chunk servers for reads and writes
- ➜ No explicit caching

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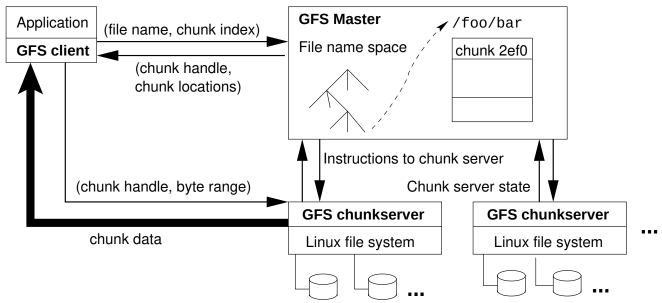
Architecture:



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GFS Master:

- ➜ Single point of failure
- ➜ Keeps data structures in memory (speed, easy background tasks)
- ➜ Mutations logged to *operation log*
- ➜ Operation log replicated
- ➜ Checkpoint state when log is too large
- ➜ Checkpoint has same form as memory (quick recovery)
- ➜ Note: Locations of chunks *not* stored (master periodically asks chunk servers for list of their chunks)

GFS Chunkservers:

- ➜ Checksum blocks of chunks
- ➜ Verify checksums before data is delivered
- ➜ Verify checksums of seldomly used blocks when idle

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Data Mutations:

- ➜ Write, atomic record append, snapshot
- ➜ Master grants *chunk lease* to one of a chunk's replicas
- ➜ Replica with chunk becomes *primary*
- ➜ Primary defines serial order for all mutations
- ➜ Leases typically expire after 60 s, but are usually extended
- ➜ Easy recovery from failed primary: master chooses another replica after the initial lease expires

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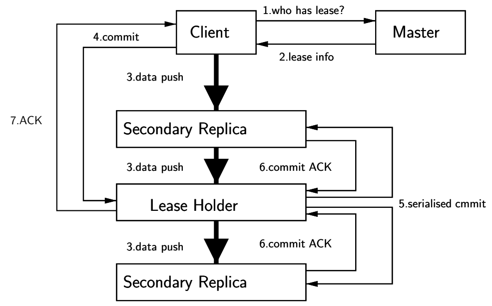
Example: Write:

`Write(filename, offset, data)`



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RE-EVALUATING GFS AFTER 10 YEARS

Workload has changed → changed assumptions

Single Master:

- ✗ Too many requests for a single master
- ✗ Single point of failure
- ☑ Tune master performance
- ☑ Multiple cells
- ☑ Develop distributed masters

File Counts:

- ✗ Too much meta-data for a single master
- ☑ applications rely on Big Table (distributed)

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File Size:

- ✗ Smaller files than expected
- ✓ Reduce block size to 1MB

Throughput vs Latency:

- ✗ Too much latency for interactive applications (e.g. Gmail)
- ✓ Automated master failover
- ✓ Applications hide latency: e.g. multi-homed model

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CHUBBY

Chubby is...:

- ➜ Lock service
- ➜ Simple FS
- ➜ Name service
- ➜ Synchronisation/consensus service

Architecture:

- ➜ Cell: 5 replicas
- ➜ Master:
  - gets all client requests
  - elected with Paxos
  - master lease: no new master until lease expires
- ➜ Write: Paxos agreement of all replicas
- ➜ Read: local by master

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API:

- ➜ Pathname: `/ls/cell/some/file/name`
- ➜ Open (R/W), Close, Read, Write, Delete
- ➜ Lock: Acquire, Release
- ➜ Events: file modified, lock acquired, etc.

Using Chubby: electing a leader:

```
if (open("/ls/cell/TheLeader", W)) {
  write(my_id);
} else {
  wait until "/ls/cell/TheLeader" modified;
  leader_id = read();
}
```

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WHAT ELSE ... ?

Colossus:

- ➜ follow up to GFS

BigTable:

- ➜ Distributed, sparse, storage map
- ➜ Chubby for consistency
- ➜ GFS/Colossus for actual storage

Megastore:

- ➜ Semi-relational data model, ACID transactions
- ➜ BigTable as storage , synchronous replication (using Paxos)
- ➜ Poor write latency (100-400 ms) and throughput

Spanner:

- ➜ Structured storage, SQL-like language
- ➜ Transactions with TrueTime, synchronous replication (Paxos)
- ➜ Better write latency (72-100ms)

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Reading List

Scale and Performance in a Distributed File System File system properties

NFS Version 3: Design and Implementation NFS

Disconnected Operation in the Coda File System Coda

The Google File System GFS

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Homework

➜ Compare Dropbox, Google Drive, or other popular distributed file systems to the ones discussed in class.

Hacker's edition:

➜ See *Naming* slides