Distributed Systems (COMP9243)

Lecture 9c: Distributed File Systems

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

Introduction

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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

Challenges

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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

Challenges

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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

The Client's Perspective: File Services

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

File Service Interface:

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- ➜ 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*

File Access Semantics

UNIX semantics:

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- ➜ A READ after a WRITE returns the value just written
- ➜ When two WRITEs follow in quick succession, the second persists
- ➜ Trivial with a single file server and without caching, but...
- ➜ A single file server contradicts scalability
- ➜ Caches are needed for performance & write-through is expensive
- ➜ UNIX semantics is too strong for a distributed file system

Session semantics:

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- ➜ 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.

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:

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

The Server's Perspective: Implementation

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Design Depends On the 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

This was found by Satyanarayanan for the use of UNIX in a university.

There are also varying reasons for using a DFS:

- ➜ Big file system, many users
- ➜ 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.

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Update protocols:

- ➜ *Primary copy replication*: Primary logs changes; then, applies them locally; and finally, instructs secondaries.
- ➜ *Voting*: Multiple servers have to give permissions before a client can read or write.

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Case Studies

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

Network File System (NFS)

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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

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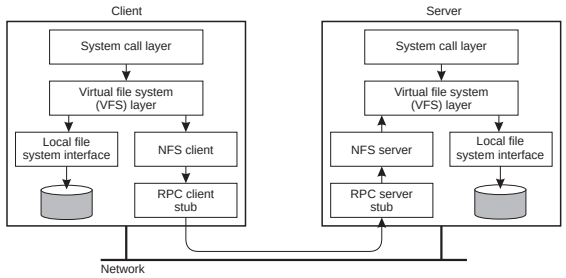

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Server side:

- NFS protocol independent of underlying FS
- NFS server runs as a daemon
- `/etc/export`: specifies what directories are exported to whom under which policy
- Transparent caching

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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

Client side:

- Explicit mounting versus automounting
- Hard mounts versus soft mounts
- Supports diskless workstations
- Caching of file attributes and file data

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Caching:

- Implementation specific
- Caches result of `read`, `write`, `getattr`, `lookup`, `readdir`
- Consistency through polling and timestamps
- Cache entries are discarded after a fixed period of time
- Modified files are sent to server asynchronously (when closed, or client performs sync)
- *Read-ahead* and *delayed write* possible

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Security:

Traditionally (NFS v3), clients were trusted. Three ways of authentication:

- System authentication
  Client passes user ID and group ID to server.
  (i.e., almost no security)
- Secure NFS using Diffie-Hellman (public key crypto)
  ✗More complex (implementation and key management)
  ✗Very short key length
- Kerberos
  ☑Secure
  ✗Entry costs

Enhanced security with NFS v4:

- RPCSEC_GSS as general security framework
- Provides hooks for different authentication systems
- Message integrity and confidentiality

ANDREW FILE SYSTEM (AFS) & CODA

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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)
- Trusted servers collectively called *Vice*
- Cache on local disk

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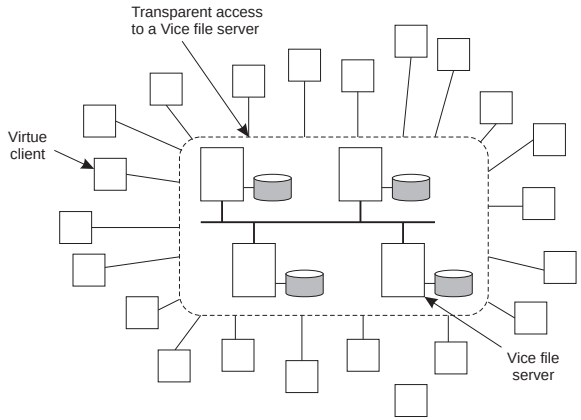

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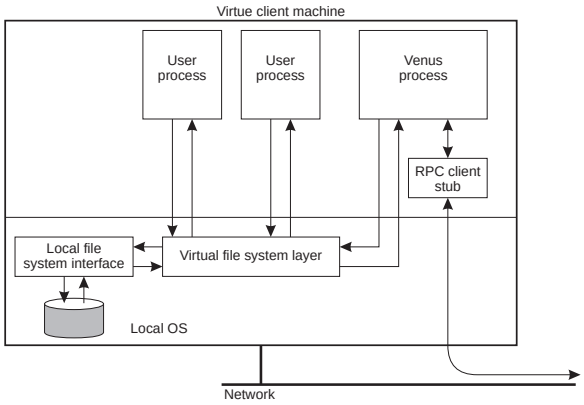

Scalability:

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- ➜ 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)
- ➜ Modified files are written back to server on `close()`
- ➜ Result: Very little cache validation traffic
- ➜ Flexible *volume* per user (resize, move to other server)
- ➜ Read-only volumes for software

Security – Authentication:

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- ➜ AFS does not trust UNIX user IDs
- ➜ AFS IDs managed at cell level
- ➜ Users authenticate to cells with Kerberos (`klog` command)
- ➜ Users get *token* (required for AFS commands and file accesses, stored in local cache manager)
- ➜ Tokens have time stamp and expire

Security – Authorisation:

- ➜ Access Control Lists (ACLs)
- ➜ Directory based
- ➜ Finer grained access modes than UNIX

CODA

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- ➜ Developed at CMU by M. Satyanarayanan's group
- ➜ Successor of the Andrew File System (AFS)
- ➜ Supports disconnected, mobile operation of clients
- ➜ System architecture quite similar to AFS

DESIGN & ARCHITECTURE

Disconnected operation:

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- ➜ All client updates are logged in a *Client Modification Log (CML)*
- ➜ On re-connection, the operations registered in the CML are replayed on the server
- ➜ CML is optimised (e.g. file creation and removal cancels out)
- ➜ On weak connection, CML is reintegrated on server by *trickle reintegration*
- ➜ 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
- ➜ Conflict resolution for temporarily disconnected servers

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Servers:

- ➜ Read/write replication servers are supported
- ➜ 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)

GOOGLE FILE SYSTEM

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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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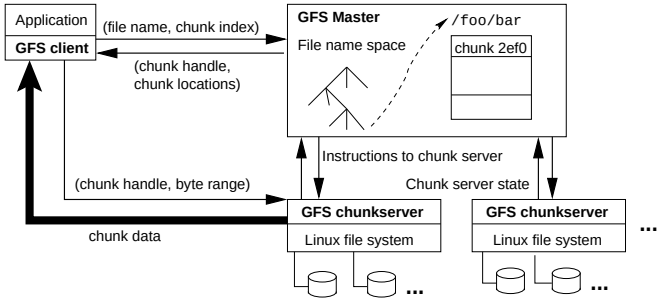
Architecture:



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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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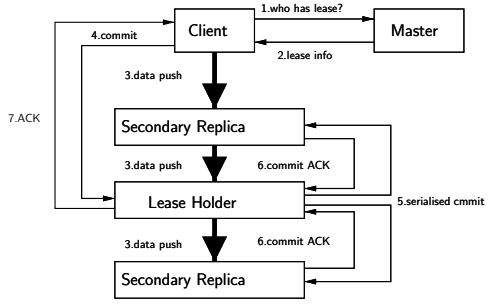
Example: Write:

`Write(filename, offset, data)`



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Example: Append:

`RecordAppend(filename, data)`

- ➜ Primary has extra logic
- ➜ Check if fits in current chunk
  - If not pad and tell client to try again
  - Otherwise continue as with write
- ➜ Guarantees that data is written *at least once* atomically

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Consistency:

- ➜ Relaxed

	Write	Record Append
Serial success	defined	defined/inconsistent
Concurrent success	consistent & undefined	defined/inconsistent
Failure	inconsistent	inconsistent

RE-EVALUATING GFS AFTER 10 YEARS

Workload has changed → changed assumptions

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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

READING LIST

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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 LDAP

The Google File System GFS