7. Distributed File Systems

Sistemes Distribuïts en Xarxa (SDX)
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  - **Client-server architectures**
  - Cluster-based architectures
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- Consistency & replication
- Fault tolerance

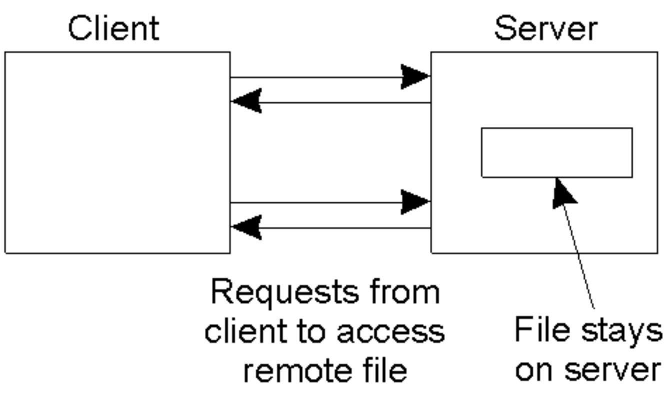
Client-server architectures

a) **Remote access model** (a.k.a. remote file service)

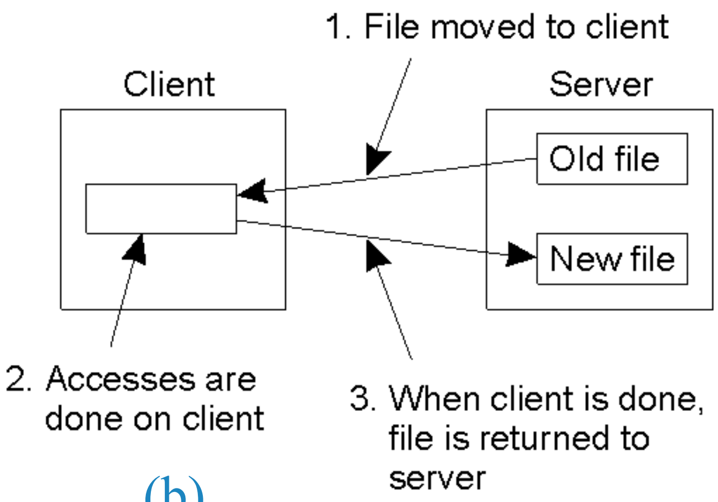
- Client is offered transparent access to a file system that is managed by a remote server (e.g. NFS)

b) **Upload/download model**

- Client accesses locally to a file after downloading it from the server (e.g. Coda)



(a)



(b)

Client-server architectures

Remote access model

- Most of the work done at the server
- ↑ Consistency is easy
- ↑ Client does not need storage
- ↓ Server is a bottleneck
- ↓ Low tolerance to server crash and partitions
- Low communication cost to open files but high to operate on them

Upload/download model

- Most of the work done at the client
- ↓ Consistency is hard
- ↓ Client downloads file: needs storage
- ↑ Load is distributed
- ↑ Tolerance to server crash and partitions
- High communication cost to open files but low to operate on them

Client-server architectures

Stateful server

- Server provides open and close operations
- Server keeps client state between requests on the same file

↑ Better performance

↓ Server state must be recovered after a crash

Stateless server

- Server does not keep any client state between requests
  - A request must provide all the needed data to execute the operation

↓ Worse performance

↑ No need to restore any state after a crash

↓ Cannot be always followed to full extent
  - e.g. file locking

Sun Network File System (NFS)

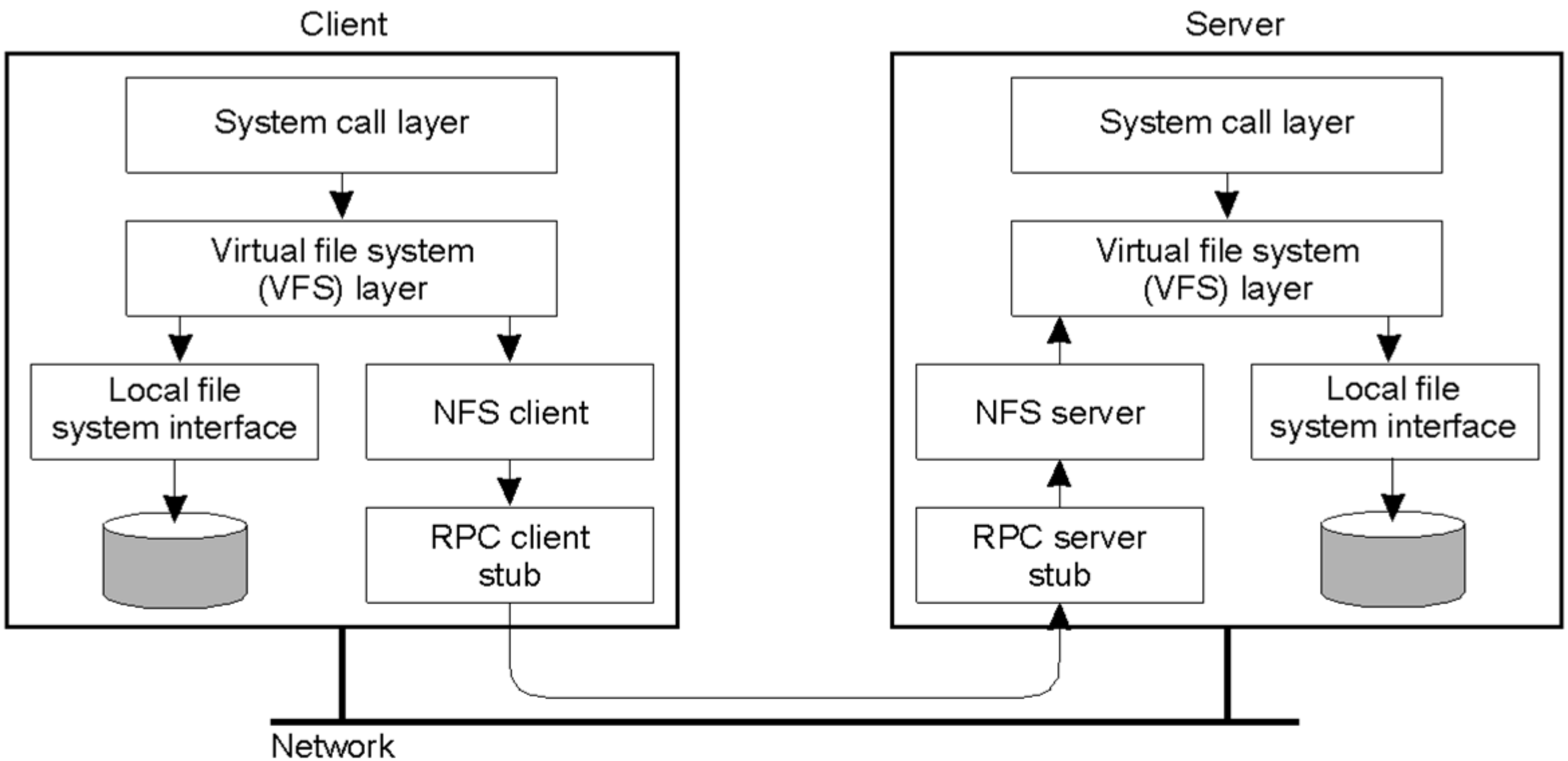
- Designed for use on UNIX-based systems, but has been implemented for many OS
- Client-server (remote) file system
  - Each server provides a standardized view of its local file system, no matter how it is implemented
  - Clients access files via a communication protocol
- File system model similar to UNIX
  - Files treated as uninterpreted sequences of bytes
  - Files have name, but are referred by a file handle
- NFS was initially stateless, v4 is stateful

NFS operations

Operation	V3	v4	Description
create	Yes	No	Create a regular file
create	No	Yes	Create a nonregular file (symbolic link, directory, special 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 (also create a regular 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	Read 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

NFS architecture

- **Virtual File System** (VFS) provides uniform & transparent access to local and remote files



Coda File System

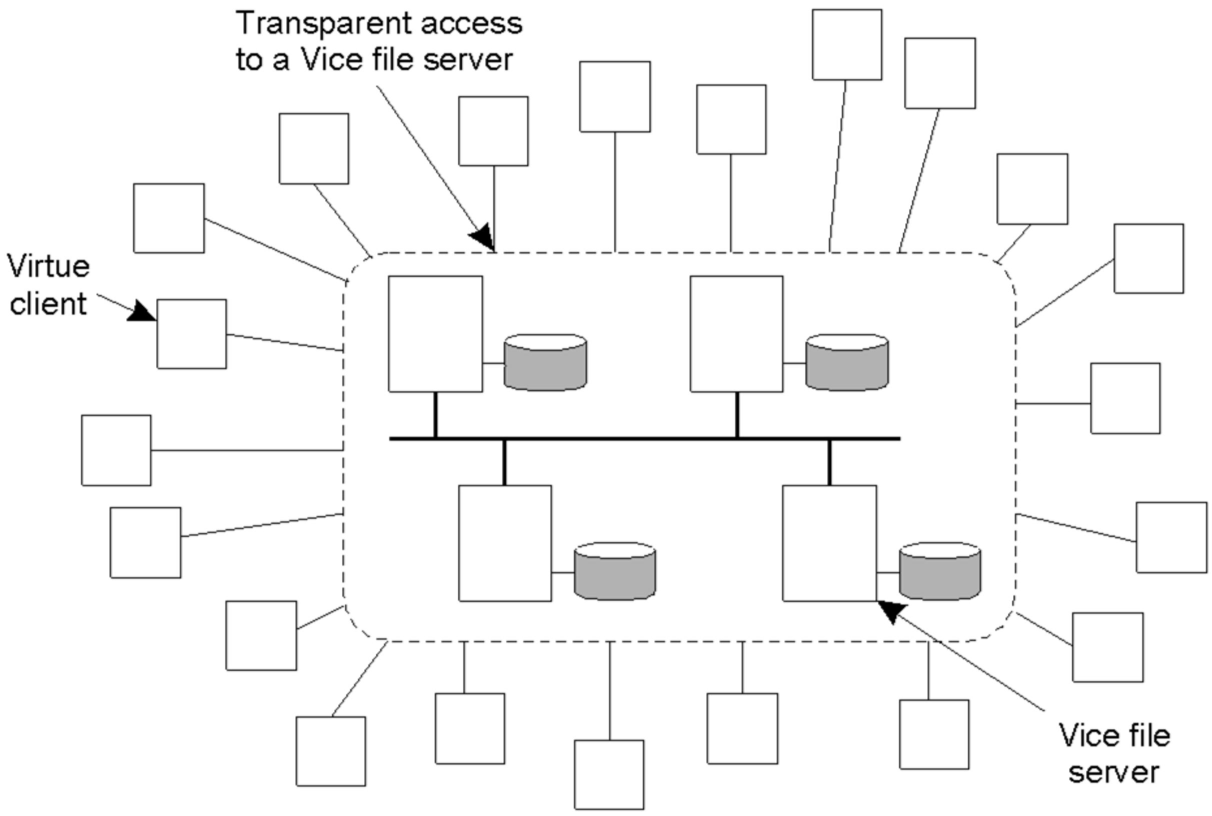
- Based on Andrew File System (AFS v2)
- Design philosophy: "Scalability and availability are more important than consistency"
  - Scalability: support a large number of users
  - Availability: tolerate server/communication failures and voluntary client disconnections (mobile users)

⇒ Use upload/download model

  - Whole-file serving and caching
    - AFS v3 allows file data to be transferred and cached in 64-kbyte blocks

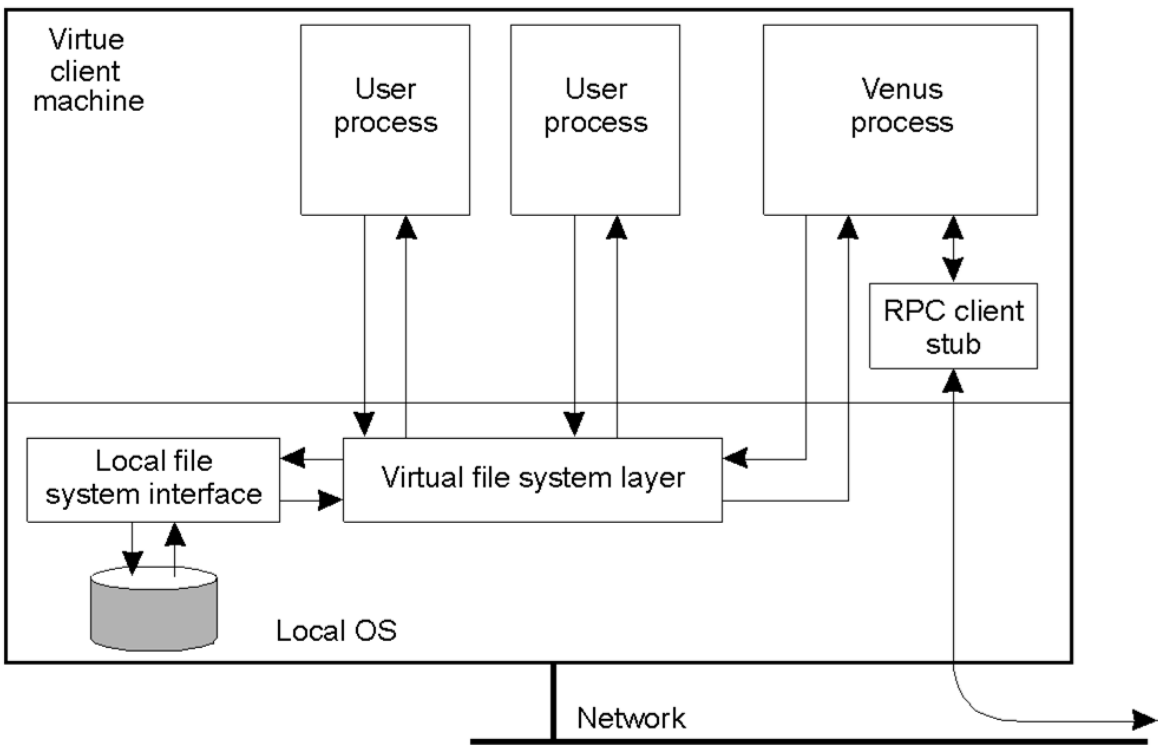
Coda architecture

- Few centrally administered **Vice** file servers
- A large number of **Virtue** clients



Coda architecture

- Clients host a user-level process **Venus** (~NFS client)
- Clients use VFS (as NFS does)
  - Coda looks like a traditional UNIX file system



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  - **Cluster-based architectures**
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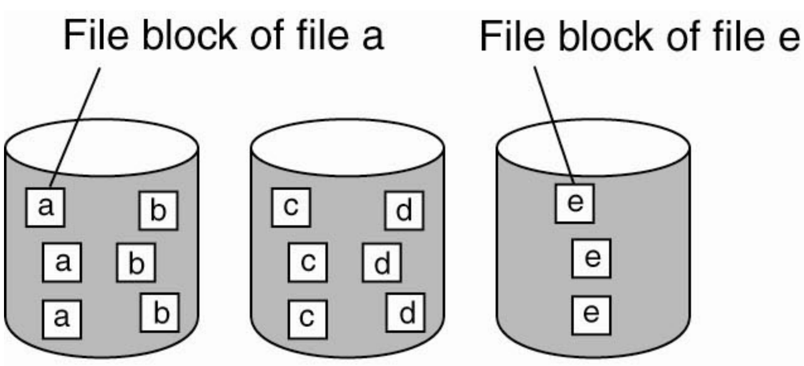
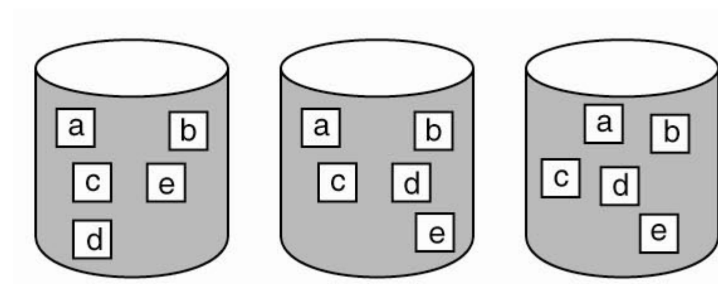
Cluster-based architectures

- How to improve performance in server clusters with very large data collections?
- **File-striping** techniques by which files can be fetched in parallel
  - A single file is distributed across multiple servers



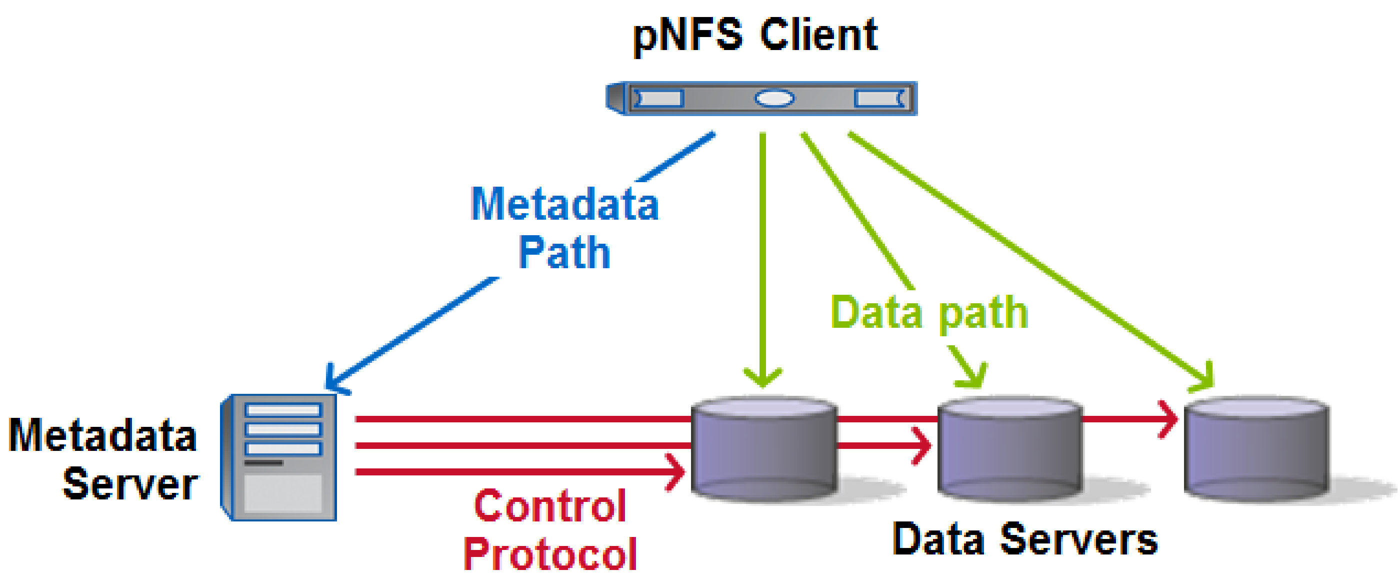
whole-file distribution



file-stripped system

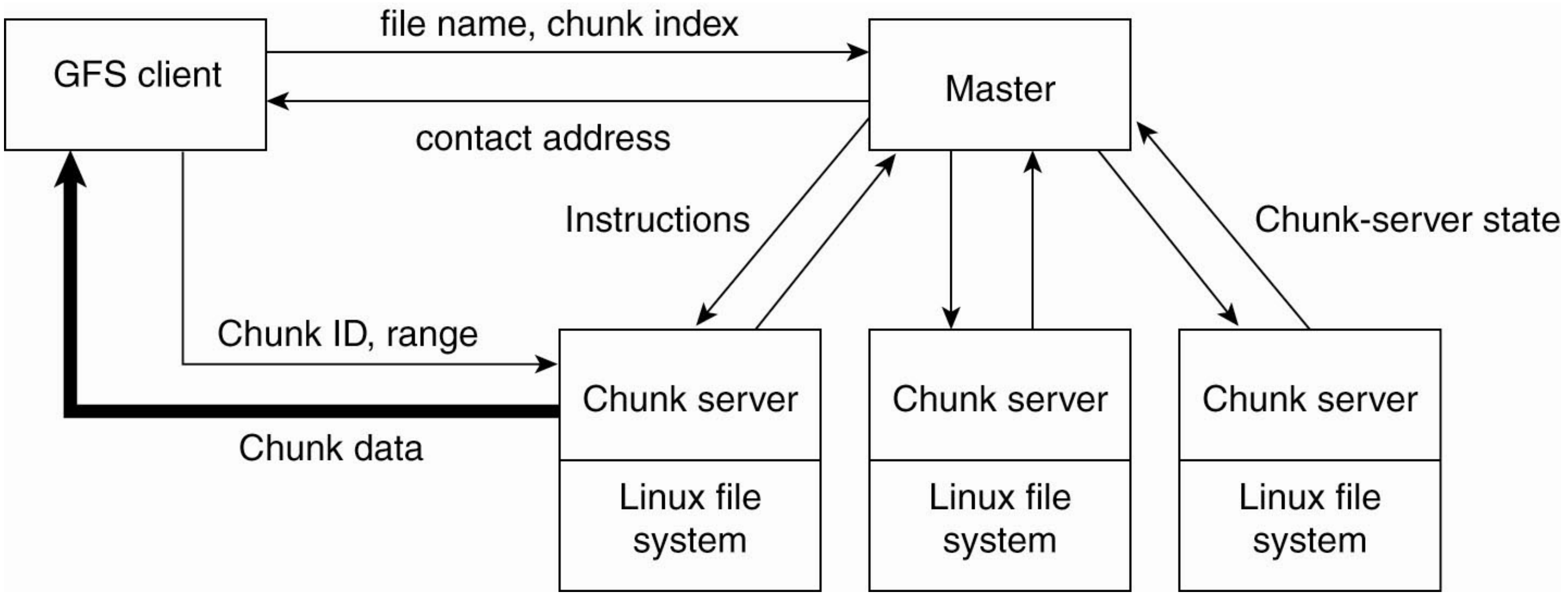
Cluster-based architectures

- Ex: pNFS (part of NFS v4.1)
  - Metadata and data separation
    - Metadata server is out of the data path
  - Files are striped across a number of data servers



Cluster-based architectures

- Ex: Google File System (GFS)
  - Each GFS cluster: 1 master, N chunk servers
  - Files divided into 64 MB chunks, which are <u>replicated</u> and <u>distributed</u> across chunk servers



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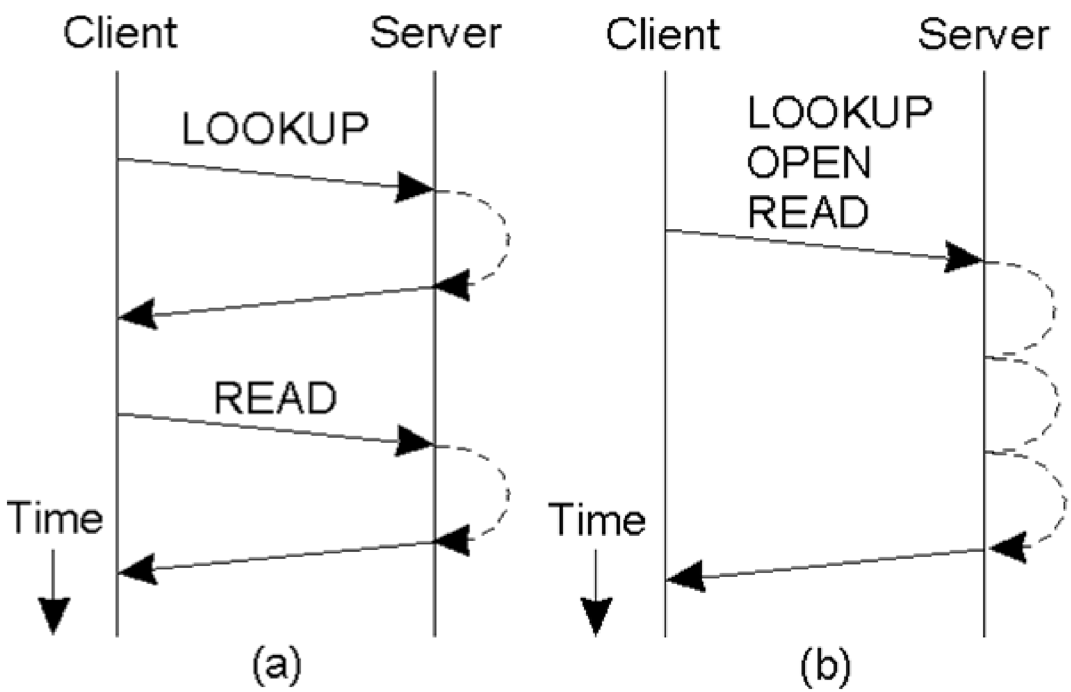
NFS communication

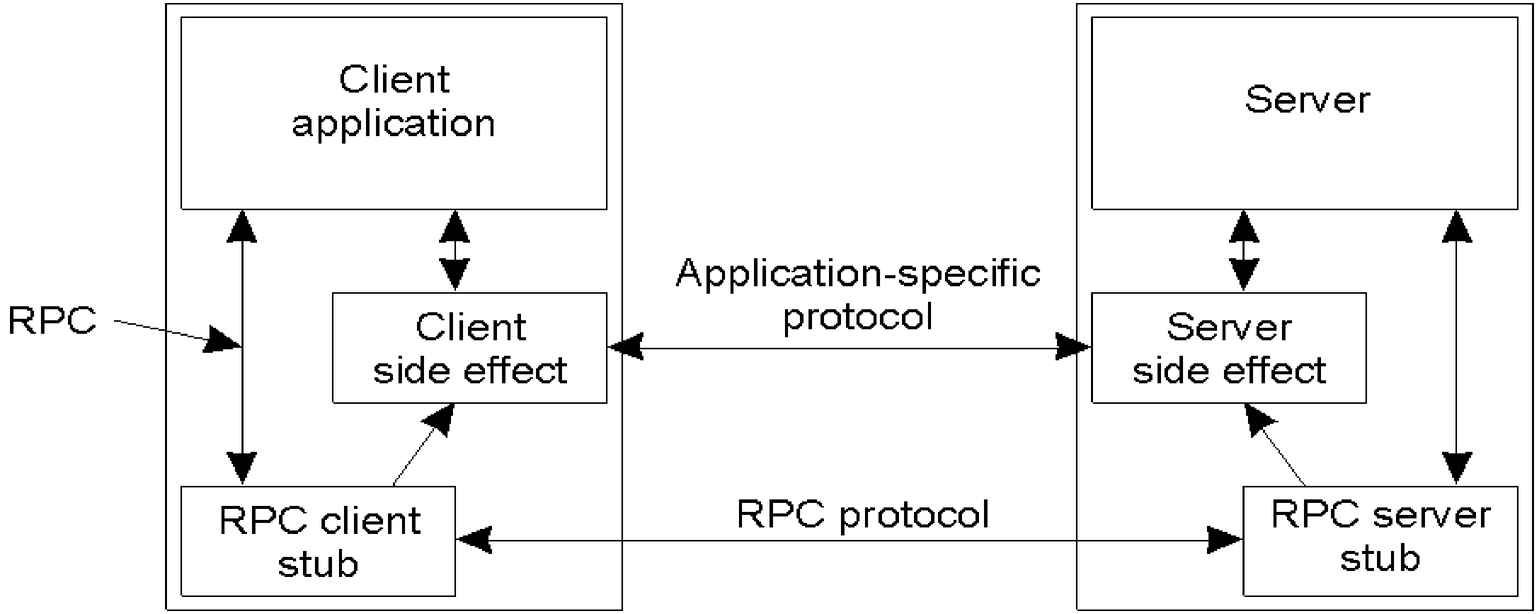
- RPC-based communication (ONC RPC)
  - ↑ RPC hides the differences between distinct OS
- NFS v4 supports **compound procedures**



- Group multiple operations into a single RPC request
- Handled in order as if sent separately
- If one fails, the rest terminate
  - ↑ Save latency of doing multiple RPCs

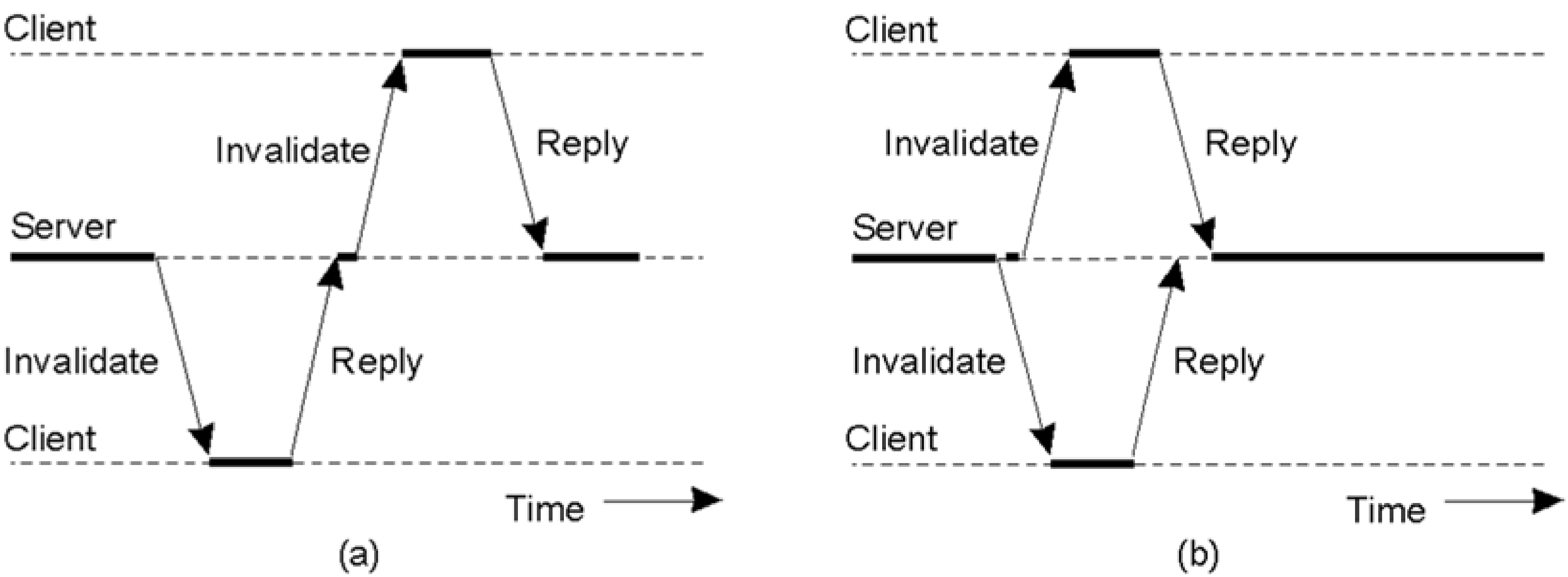
Coda communication

- Based on **RPC2**
  - Reliable transmission on top of UDP (unreliable)
  - Supports **side-effects**, i.e. user-defined protocols
    - e.g. isochronous mode for a video stream



Coda communication

- Support for multicast transparent to the client through **MultiRPC** (part of RPC2)
  - Send multiple RPCs in parallel (e.g. invalidations)

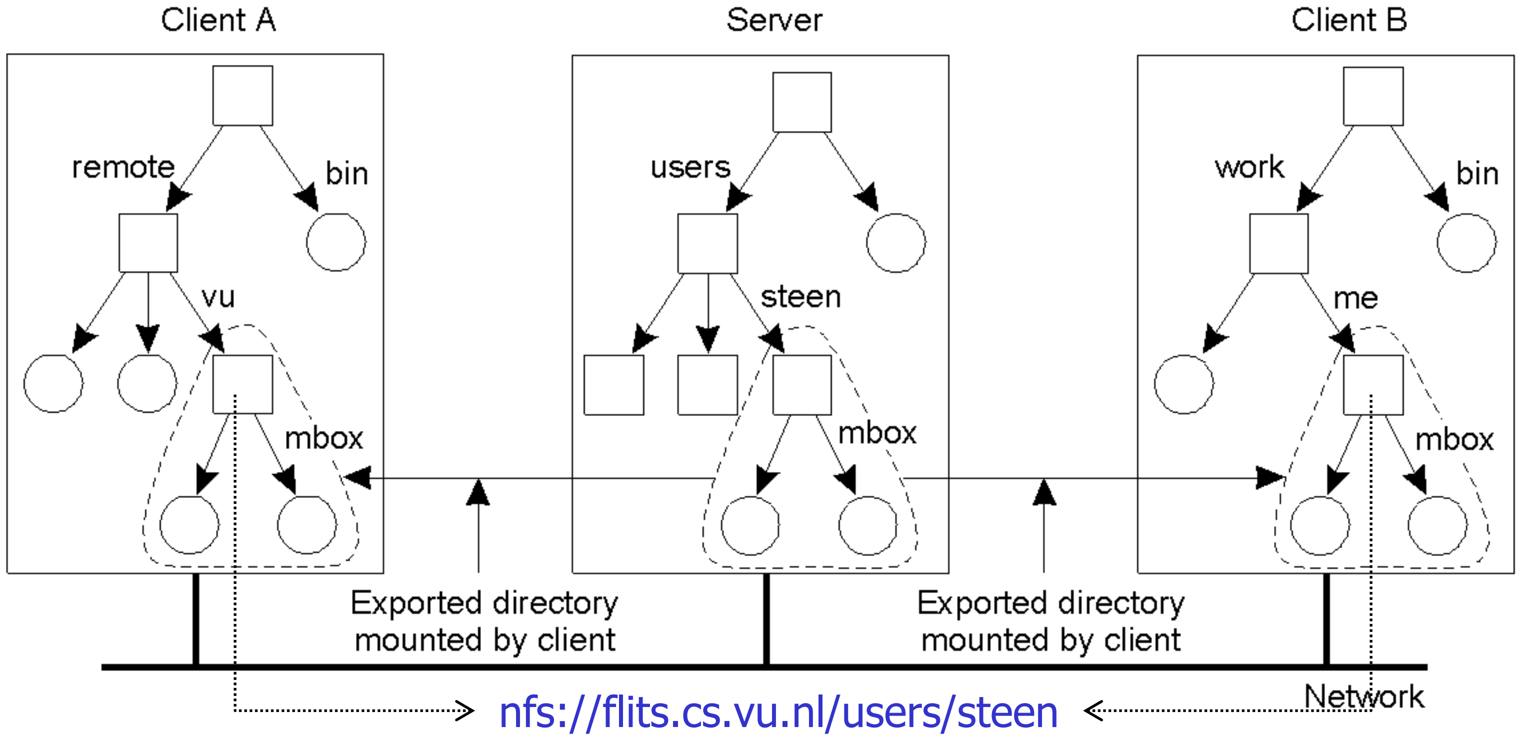


Sending invalidation messages one at a time (a) vs. in parallel (b)

Contents

NFS naming

- Transparent access to remote file system
  - By allowing a client to **mount** (part of) a remote file system into its own local file system

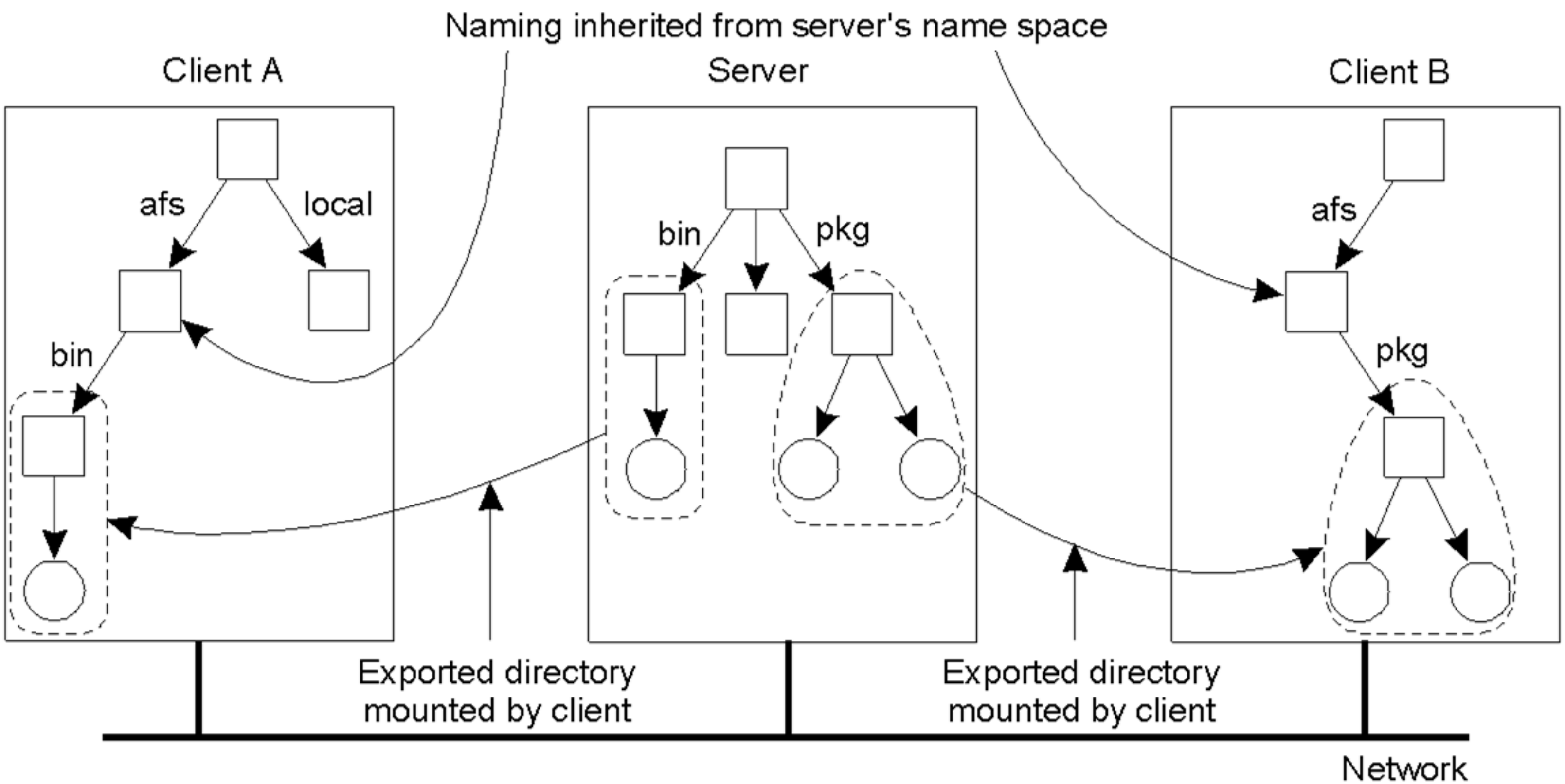


NFS naming

- Pathnames are not globally unique, as they depend on the clients' local name spaces
  - ↓ Referring to shared files is harder
  - ⇒ Partly standardized name space (e.g. /usr/bin)
- Name resolution in NFS v3 is <u>iterative</u>
  - NFS v4 supports recursive lookups within a server
- File handle created by server hosting the file
  - Unique with respect to all its exported file systems
  - File handles must be <u>identifiers</u>
    - File has the same unique file handle during its lifetime, which should not be reused (even after file deletion)

Coda naming

- Single global shared name space at **/afs**
  - All clients see the same names (unlike NFS)



Coda naming

- File handles are globally unique
  - vs. server unique in NFS
- Files are grouped into **volumes**
  - Each file contained in exactly one volume
  - Volumes may be <u>mounted</u>
    - A volume is the mounting unit
  - Volumes may be <u>replicated</u> among several servers
    - A volume is the unit of server-side replication
  - Distinction between physical and logical volumes
    - A replicated volume consists of several physical volumes that are managed as one logical volume

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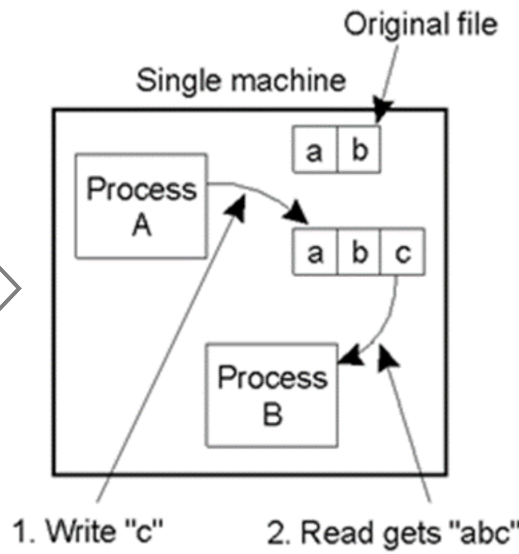
- Fault tolerance

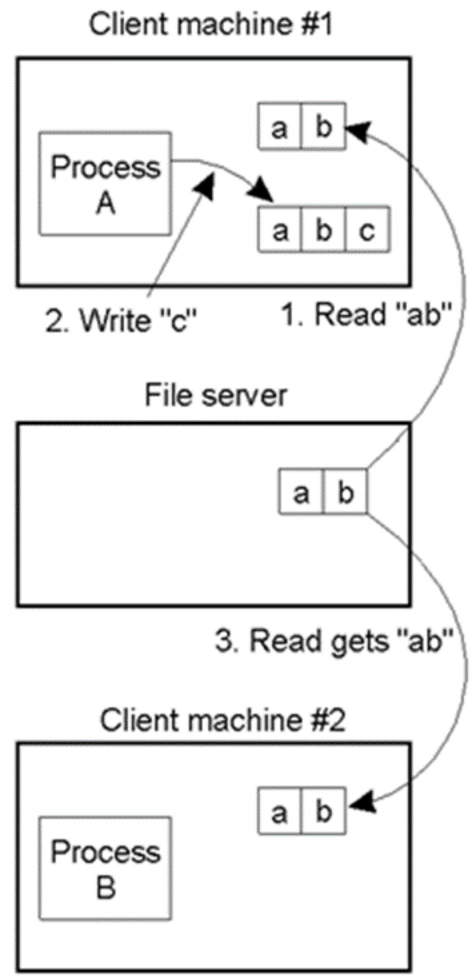
Semantics of file sharing

a) In a single machine, a read following a write returns the value just written



(a)

b) In distributed system with caching, stale values may be returned



(b)

Semantics of file sharing

- 4 approaches for dealing with shared files

Method	Comment
UNIX semantics	Every operation on a file is instantly visible to all processes
Session semantics	No changes are visible to other processes until the file is closed
Immutable files	No updates are possible, but files can be replaced
Transactions	All changes occur atomically, isolated from other transactions

  - NFS can use remote access model for providing UNIX semantics $\Rightarrow$ performance problem
  - Most NFS implementations use <u>local caches</u> for performance implementing **session semantics**
  - Coda treats sessions (open…close) as <u>transactions</u>

File locking

- NFS v1-v3: use a separate (stateful) lock manager
- NFS v4: integrated into NFS file access protocol
  - Multiple readers/single writer: read locks vs. write locks
  - Locks granted for a specific time (i.e. **lease**)

Operation	Description
Lock	Request a lock for a range of bytes (non-blocking)
Lockt	Test whether a conflicting lock has been granted
Locku	Remove a lock from a range of bytes
Renew	Renew the lease on a specified lock

- In addition, **share reservations** can be used
  - Implicit way to lock a file, independent from locks

File locking

- Result of open operation with share reservations
  a) Client requests file access given current denial state
  b) Client requests denial state given current file access state

(a) Requested file access — Current file denial state

	NONE	READ	WRITE	BOTH
READ	Succeed	Fail	Succeed	Fail
WRITE	Succeed	Succeed	Fail	Fail
BOTH	Succeed	Fail	Fail	Fail

(b) Current file access state — Requested file denial state

	NONE	READ	WRITE	BOTH
READ	Succeed	Fail	Succeed	Fail
WRITE	Succeed	Succeed	Fail	Fail
BOTH	Succeed	Fail	Fail	Fail

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NFS client-side caching

- Preferred technique to attain <u>performance</u>

a) <u>Data and metadata caching</u>

  - Cache the results of read, write, getattr, lookup, and readdir operations
    - i.e. file data, file handles, attributes, directories
  - Carry out write operations locally
    - Modified blocks are marked as ‘dirty’
    - **Closing** the file (or explicit sync) implies flushing dirty blocks to the server
  - Validate cached blocks when they are used using a timestamp-based procedure

NFS client-side caching

- Each cache block has two timestamps
  - Tc: time when cache block was last validated
  - Tm: time when block was last modified at the server
- A block is valid at time T if either:
  i. T – Tc < F (a.k.a. freshness interval)
     - Can be evaluated without accessing the server
     - F is typically 3-30s for files, 30-60s for directories

  ii. Tm (at server) = Tm (at client)
     - Tm (at server) checked only if (i) is false
       - If (ii) is true, Tc is set to T
       - If (ii) is false, get fresh data from the server and set Tm (at client) and Tc to T

NFS client-side caching

- Close-to-open cache consistency
  - Extends the previous procedure to support the typical file sharing scenario
    - i.e. sequential file sharing: client A opens a file, writes something and closes it; then client B opens the same file and reads the changes
  - Client forces a cache validity check with the server when the file is opened
    - Ignoring any cache time remaining
  - On closing the file, pending changes are flushed to the server so that the next opener can view them

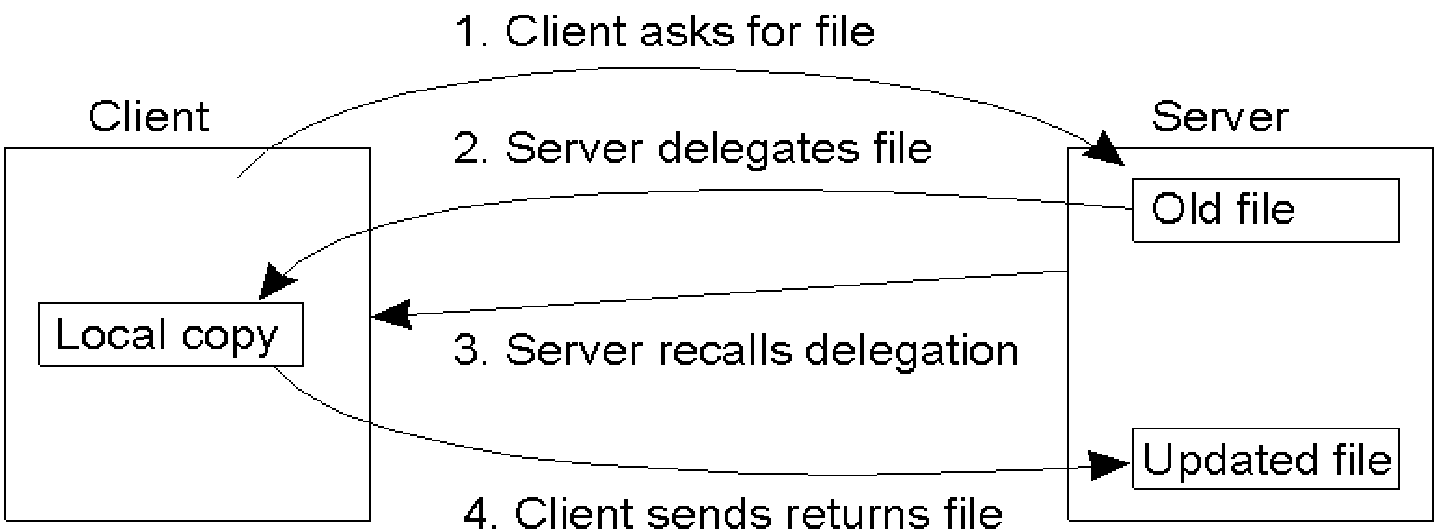
NFS client-side caching

b) NFS v4 supports **open delegation**

- Server voluntarily and temporarily transfers the control of operations on a file to the client
  - Decision is made by the server based on a set of conditions such as the recent history of the file
- During the duration of the delegation, client can treat the file as if no other conflicting accesses are performed by other clients
  - Client can locally service operations such as open, close, or lock without interaction with the server
  - Client can access the file in the cache without sending validation requests to the server

NFS client-side caching

- Delegations can be recalled by the server using callbacks (i.e. RPC to the client)
  - When another client requests access to the file that conflicts with the granted delegation
  - They have also a <u>lease</u> that is subject to renewal



NFS client-side caching

- Read delegation
  - Awarded on a file opened for reading (not denying read access to others)
    - Multiple read delegations to different clients can be outstanding simultaneously
  - Allows the client to handle locally requests to:
    - Open for reading (not denying read access to others)
    - Read from the cache without checking validity
  - Requests to open the file for writing or to lock the file must still be sent to the server
  - Recalled when another client requests to open the file for writing (or denying read access)

NFS client-side caching

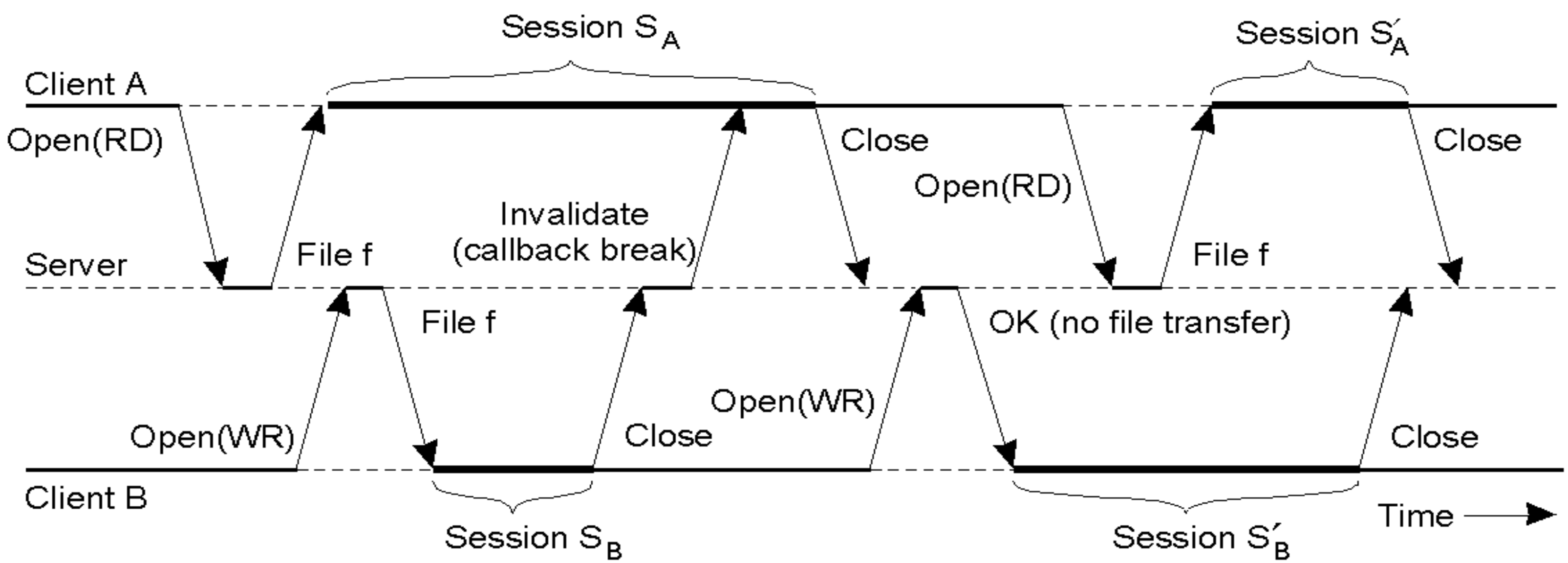
- Write delegation
  - Awarded on a file opened for writing (or r/w)
    - Only one write delegation may exist for a given file at a time, and it is inconsistent with any read delegations
  - While the delegation is outstanding, all the operations in the file can be handled locally
  - Recalled when another client requests to open the file (independently on the requested access)
    - On returning the delegation, the client will commit all dirty data to the server

Coda client-side caching

- Coda creates a local copy of the file when it is opened (entire file is cached)
  - All read/write operations done on the local copy
  - Updates are sent to server when the file is closed
- Consistency maintained using **callbacks**
  - On opening a file, client gets a callback promise for the file from the server
  - When another client updates the file, the server breaks the promise (it can also expire by timeout)
    - Server tracks all the clients that have a copy of the file

Coda client-side caching

- If the promise is valid, a cached file can be re-opened without fetching it from the server
- If the promise has been canceled, re-opening implies fetching a fresh copy of the file

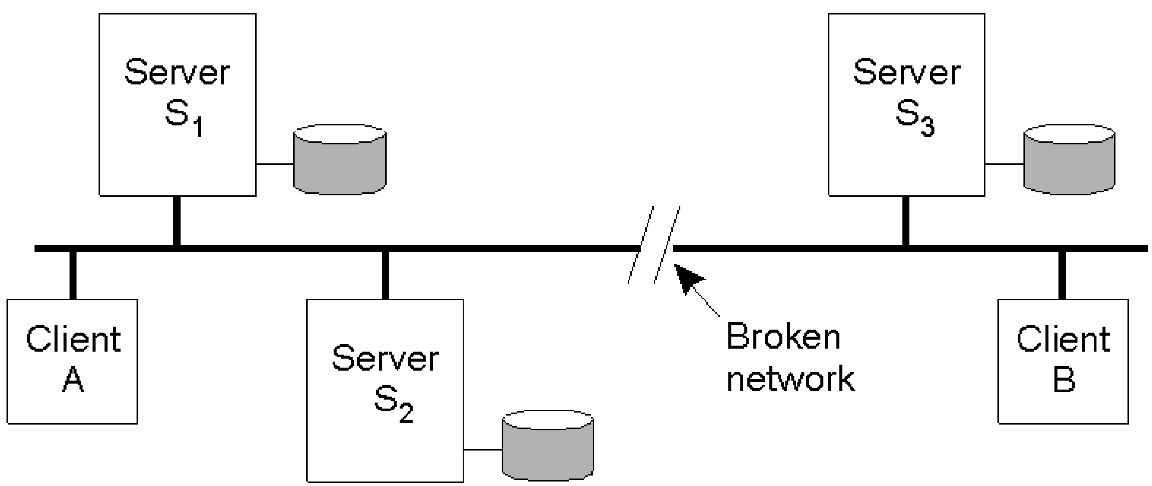


Coda server-side replication

- This is generally used for fault tolerance
- VSG: Volume Storage Group
  - Collection of servers that have a copy of a volume
- AVSG: Accessible VSG
  - Servers in the VSG that the client can contact
  - If AVSG is empty, the client is disconnected
- Replicated-write protocol to keep consistency
  - Variant of ROWA: Read-One Write-All
  - Client opens a file: contact one server in the AVSG
  - Client closes an updated file: multicast file to all the servers in the AVSG using MultiRPC

Coda server-side replication

- What happens in the presence of partitions?
  - Possible inconsistency: use versioning to detect
    - Version vector when partition happens: [1,1,1]
    - A updates file; version vector in its partition: [2,2,1]
    - B updates file; version vector in its partition: [1,1,2]
    - Partition repaired, compare version vectors: **conflict**!



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NFS fault tolerance

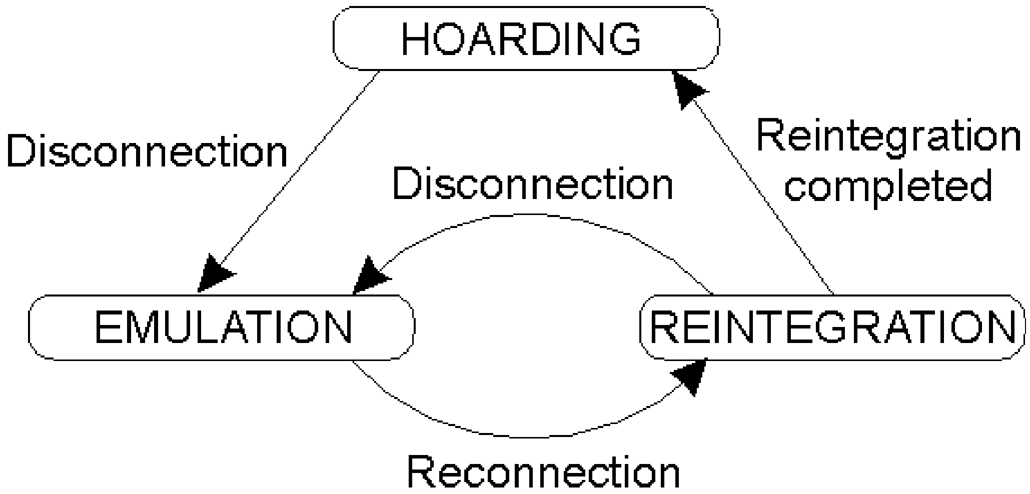
- Communication failures
  - Most operations are idempotent: can be retried until receiving a reply (at-least-once semantics)
  - Number requests to deal with duplicated non-idempotent operations (as discussed in Lesson 2)
- Client failures (addressed with leases)
  - Server can recover client's locks and delegations when the associated leases have expired
  - Delegations may need to be reclaimed after client restarts to reestablish the file state on the server
    - Client may have unsaved file data stored locally

NFS fault tolerance

- Server failure (addressed with grace periods)
  - When the server restarts, it initiates a grace period of length equal to the lease period
  - During the grace period, clients and server work to reestablish the server state that existed prior to the failure
  - Clients send reclaim-type open and lock requests
    - Corresponding to the locks and open files they had prior to the failure
  - Server rejects new open and lock requests
    - Unless it can reliably determine that granting any such request cannot conflict with a subsequent reclaim

Coda fault tolerance

- Disconnected operation $\Rightarrow$ high availability
  - HOARDING: Normal operation + cache in advance files that should be available during the disconnection (advised by client)
  - EMULATION: When disconnected, all file requests are serviced using the locally cached copy of the files
  - REINTEGRATION: transfer updates to servers; detect conflicts



Summary

Issue	NFS	Coda
Design goals	Access transparency	High availability
Access model	Remote	Upload/Download
Communication	RPC (ONC RPC)	RPC (RPC2)
Client process	Thin/Fat	Fat
Server groups	No	Yes
Mount granularity	Directory	File system (volume)
Name space	Per client	Global
File ID scope	File server	Global
Sharing semantics	Session	Transactional
Cache consistency	Write-back	Write-back
Replication	Minimal	ROWA
Fault tolerance	Reliable communication	Replication & caching
Recovery	Client-based	Reintegration

Summary

- Further details:
  - [Tanenbaum]: chapters 2.3.3, 6.3.5, and 7.5.3 (and chapter 11 in 2^{nd} Ed.)
  - [Coulouris]: chapters 12, 18.4.3, and 21.5.1