Distributed Systems

Distributed File Systems

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Data Storage

How can we store data on a computer?

Data Storage Systems

	File systems	**Database systems**	**Object management systems**
Content	universal	mass data of a few structural types	focus on relationships
Stored information	passive	passive	active
Semantics defining code	external	external	internal (via types)
access	by name, simple navigation	complex associative search functions	complex search and navigation functions

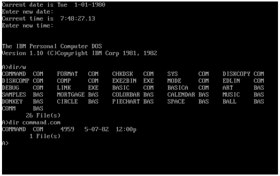
Challenges

Which challenges does any file system need to tackle?
Which functionalities need to be provided?

Models of File Systems

Files as a classical abstraction in operating systems

Historical development considered in the following



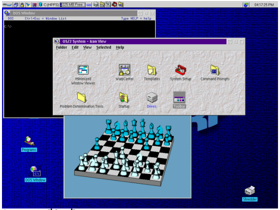
1 computer, 1 user, 1 process

- Problems to solve:
  - Structure of the file system
  - Naming
  - Programming interface
  - Mapping to physical memory
  - Integrity
- Examples
  - PC-DOS
  - classic MacOS

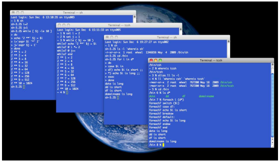
More Challenges

Which additional challenges arise due to multiple processes and multiple users?

Models of File Systems (2)



Source: Wikipedia



1 computer, 1 user, multiple processes

- Additional problems
  - *Concurrency control*
- Examples
  - OS/2

1 computer, multiple users, multiple processes

- Additional problems
  - *Security and access control*
- Examples
  - UNIX

Distributed Challenges

Which additional challenges arise when files are stored in a distributed manner?

Distributed File Systems

multiple computers, multiple users, multiple processes

- Additional problems
  - Distributedness
    - Visible overall structure
    - Access model
    - Location
    - Replication
    - Availability
    - ...
  - No access to shared block memory of nodes → shared nothing
- Client/Server model
  - Dedicated file server
- Peer-to-Peer model
  - Everyone can provide files

Sharing common hard disks between nodes will be considered at the end of this lecture (→ Storage Area Networks (SAN))

Historical Predecessors

Complete separation

- Only local access
- File transfer between isolated file systems (download/upload model)
- Example: UNIX uucp, ftp, rcp, scp

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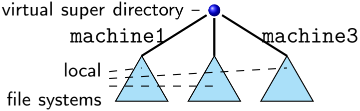
Early distributed file systems (adjunct file systems)

- Access to remote files
- Explicitly addressing the file's location as part of its name
- Example: Newcastle Connection



`/machine1/<localpath>`

`machine2!<localpath>`

`/../machine3/<localpath>`

Distributed file system

Definition

A distributed file system provides a unified file system to the users on all hosts of a network.

Which types of transparency are possible?

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- Access transparency
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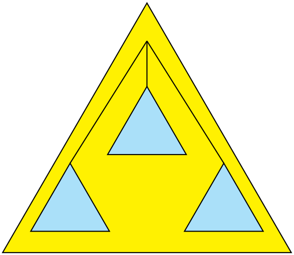

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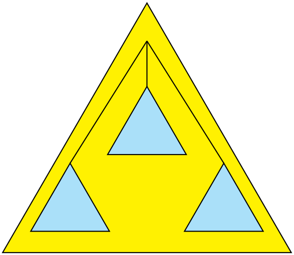

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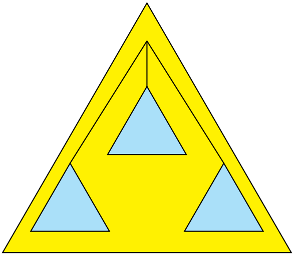
Possibly types of transparency:

- Location transparency
  - The file name does not contain any location information
- Access transparency
  - Common API for local and remote files
- Replication transparency
- ...



Typical Design Goals

- High degree of transparency
  - → previous slide
- Performance
  - Comparable to local access
- High availability and failure tolerance
- Security
- Scalability
- Support for mobile nodes with temporary disconnectivity
- Support for shared disk and shared nothing nodes
- Cloud connection

Backup and Disaster Recovery

Backup

Describes the process of duplicating data to a remote location in order to provide an alternative source for the data in case the primary source becomes unavailable.

Disaster Recovery

Describes the entire process to safeguard against various types of problems and restore it in the case of an failure. Backups are an essential part of disaster recovery.

Various ways to manage remote data for disaster recovery

- Backup via file transfer (e.g., `rsync`)
- Synchronization via a cloud backend (e.g., Nextcloud or Dropbox)
- Use of a version control system (e.g., Subversion or git)

Distributed file systems themselves do not provide a backup per se.

Exemplary Solutions

- Network File System (NFS) — since 1985
- Andrew File System (AFS) + Coda — since 1985
- Common Internet File System (CIFS) + Server Message Block (SMB)
- GlusterFS (Gluster Inc. → Red Hat 2011)
- IBM General Parallel File System (GPFS) (ursprünglich Cluster File System, weiterentwickelt)
- Google File System (GFS)
- Apache Hadoop
- ...

Implementation

How could we implement a distributed file system?

Typical API

Typical file system API calls comprise...

- `open`
- `close`
- `read`
- `write`
- `mkdir`
- `rmdir`
- `lookup`
- `getattribute`
- `setattribute`
- `link`
- `unlink`
- ...

Agenda

- Basics
- NFS
- AFS and Coda
- Storage Networks

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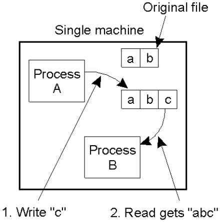
Access Consistency Problem

(a): Modifications are immediately visible for everyone

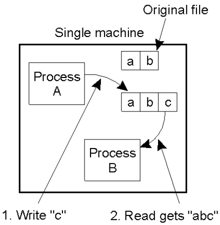


(a)

Fig. from Tanenbaum/Steen

Access Consistency Problem

- (a): Modifications are immediately visible for everyone
- (b): Visible values may be outdated



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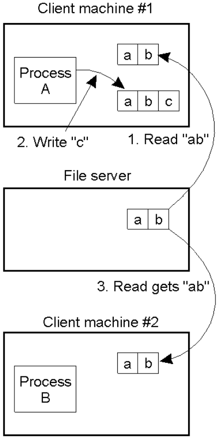

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- **Read-Only Files**
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  - Common use and replicate are significantly simplified
- **Transaction Semantics**
  - Modifications on a set of files take place in an atomic operation

Stateless and Stateful Servers

Advantage of stateless servers

- Recovery can be easily implemented
- No problems with client crashes
- Opening and closing of files is unnecessary
- Number of *opened* files unlimited

Stateless

→ Server has no memory

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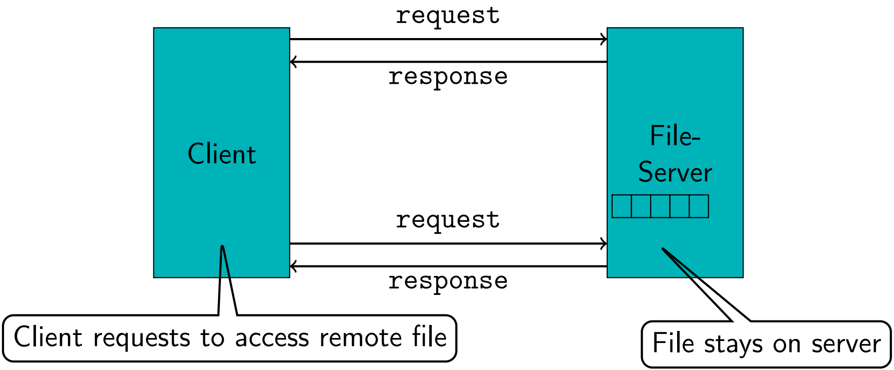
Advantages of stateful servers

- Shorter messages
- Higher performance
- Read-ahead possible
- Idempotence of operations easier to implement
- File locks are possible

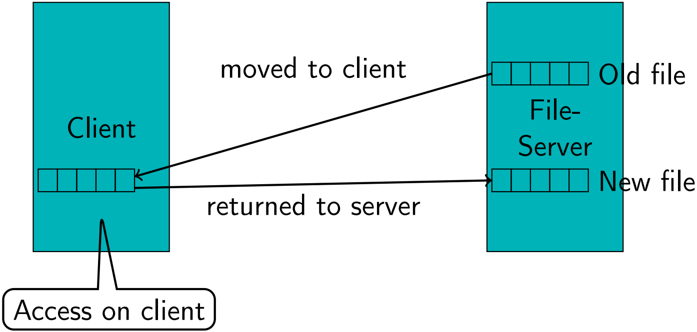
Stateless

$\rightarrow$ Server has no memory

Remote Access Model



Remote Copy Model



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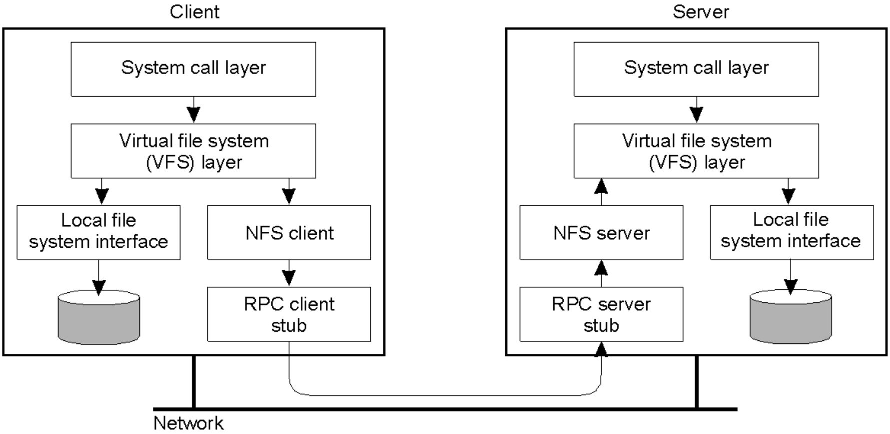
Network File System (NFS)

Design Goals (1985)

- Sharing in a network of heterogeneous systems
  - Starting point: Diskless workstations
- Access transparency
  - No particular path names, libraries, or recompilation
- Portability
  - Definition of NFS as interface
  - Implementation of client and server side may be differ
- Simple handling of site failures
  - Statelessness of server
- Performance
  - Equivalent to local disk access
- Industry standard
  - By interface disclosure and reference implementation

Overall Architecture



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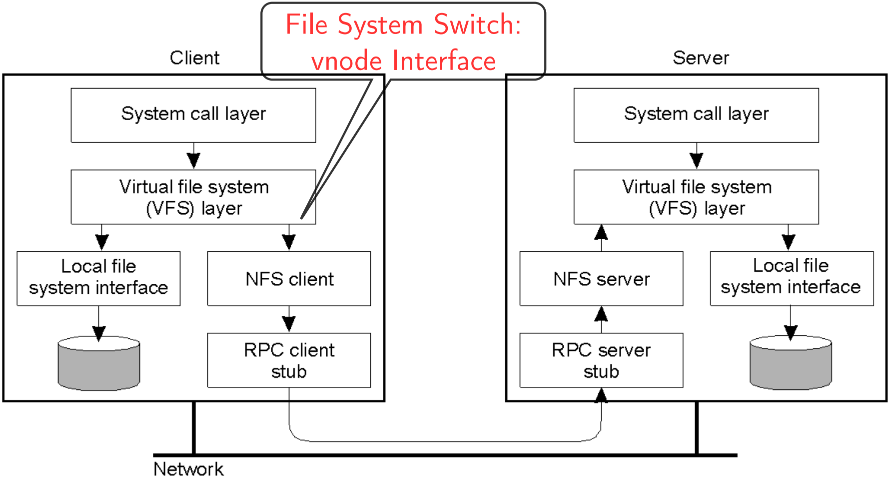

Fig. from Tanenbaum/Steen

Operating Principle

- **Roles**
  - Each node can be client and server simultaneously
  - Each NFS server exports one or multiple directories (including the entire subtree)
  - Common access by multiple clients is possible
  - Client access requires mounting

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- **Locating**
  - Local mount table in the OS

  ⇒ No protocol for locating required

Directory Structure

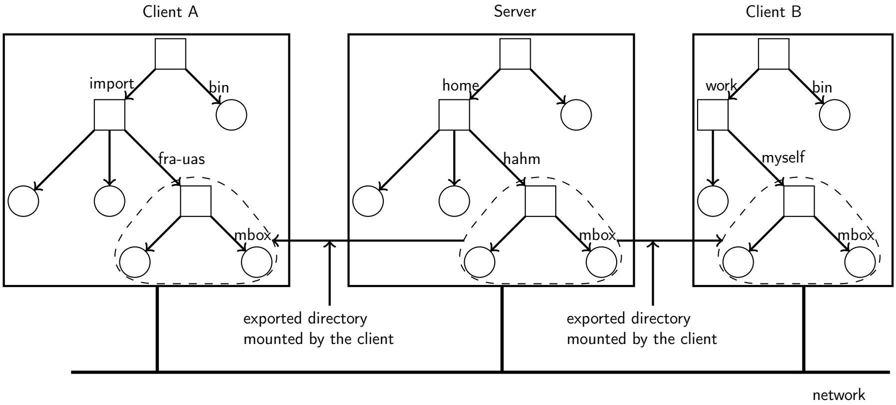

Fig. after Tanenbaum/Steen

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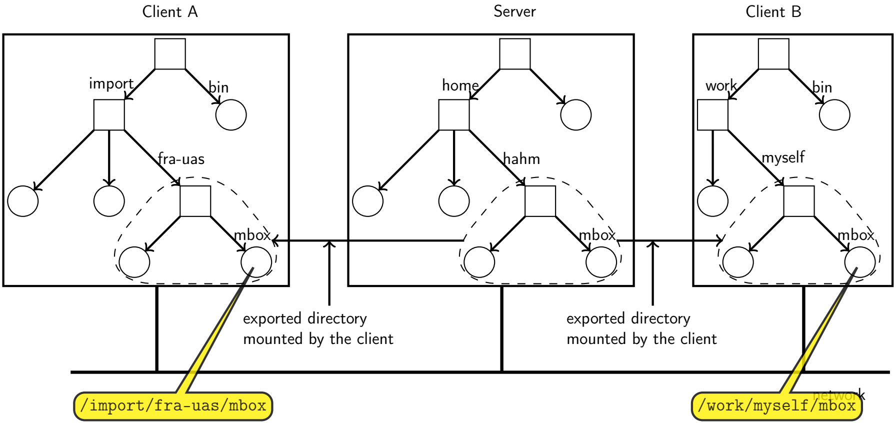

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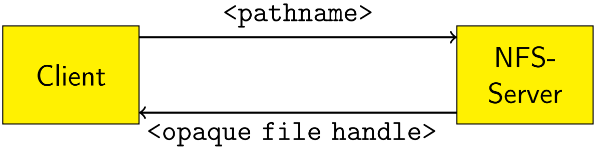
Mount Protocol

- Exists as subprotocol until version 3
- Integrated into the general access protocol since version 4



- **Static mounting**
  - Happens at boot time
- Problem:
  - Under certain circumstances server is not available at the time of mounting
  - → Client cannot boot without problems

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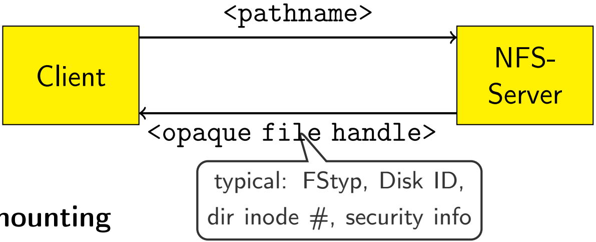

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Automounter

Introduced to solve problems of static mounting

Operating Principle

- Mapping:
  local mountpoint $\leftrightarrow$ set of exported directories
- No action at boot time
- First access below the mountpoint causes a message to each server in the set
- Who replies first, gets mounted
  - Failing server do not respond and can be tolerated
  - Load balancing is possible
- No support for general replication
  $\Rightarrow$ Often only used for read-only file systems (e.g., `/usr`)

Access Protocol: Differences between Version 3 and 4

For access to directories and files, analog to UNIX system calls

Differences between version 3 and newer version 4

- Version 3 is stateless
  - No support for `open` and `close`
  - `read`/`write` have to provide required environment (`file handle, offset, nbytes`)
  - No file locks, only via separate lock server
- Version 4 is not stateless!
  - Goal: Allow for efficient use of NFS for WANs
  - Requires efficient client-side caching
  - Impossible to solve stateless
  - File locks are possible

Access Protocol: RPC

Underlying Protocol

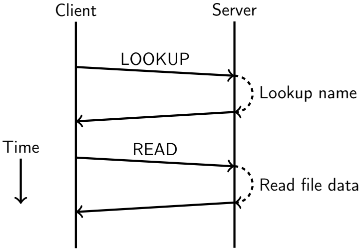
- SunRPC (ONC RPC) with XDR data encoding
- *at-least-once-semantics*
- Uses UDP/IP

Service Interface

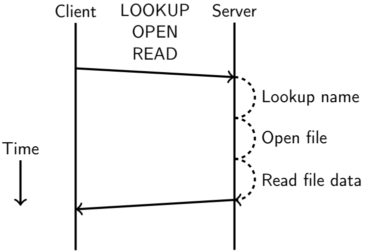
Operation	v3	v4	Description
`create`	Yes	No	Create a regular file
`create`	No	Yes	Create a nonregular file
`link`	Yes	Yes	Create a hard link to a file
`symlink`	Yes	No	Create a symbolic link to a file
`mkdir`	Yes	No	Create a subdirectory in a given directory
`mknod`	Yes	No	Create a special file
`rename`	Yes	Yes	Change the name of a file
`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	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

Access Protocol: Compound Operations

- *Performance improvement* in version 4
- Particularly relevant for WANs
- No concurrency control or atomicity



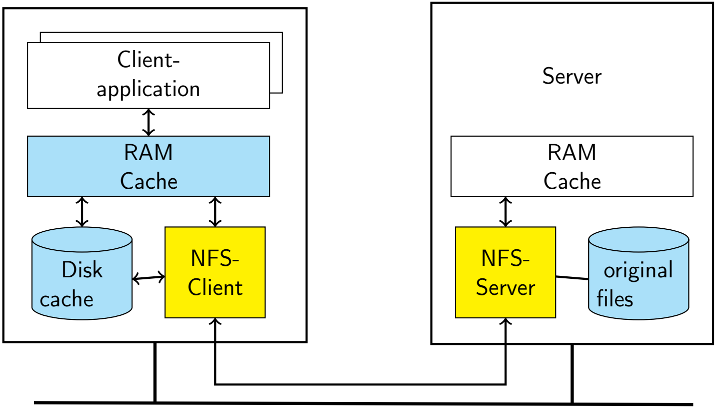
until Version 3



Version 4

Caching

Client side caching



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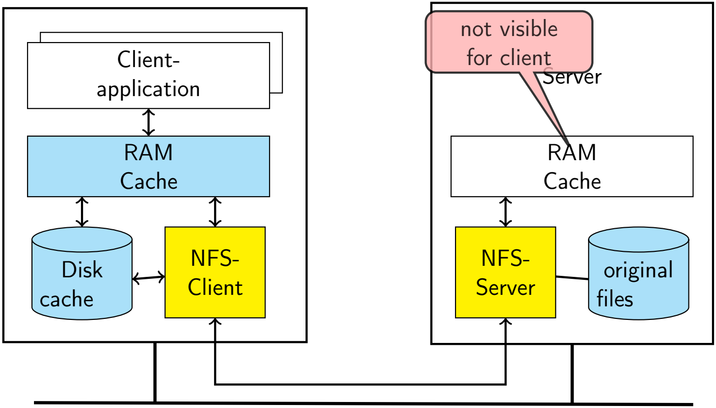

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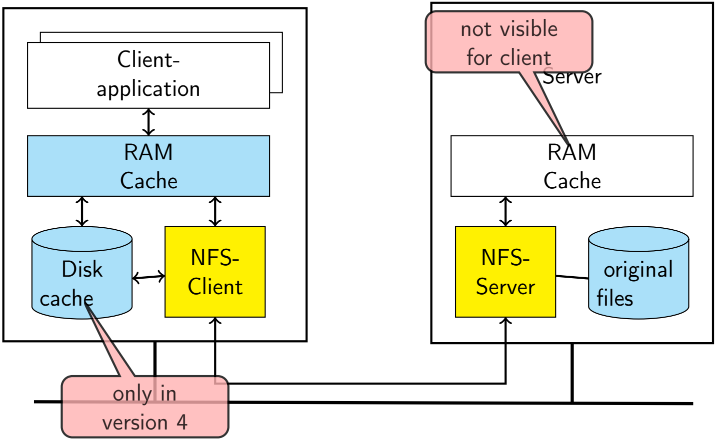

RAM Cache

- Caching individual blocks of remote files
- Big block size for efficient transfer, typical 8 KB
- Read-ahead for the next block
- Access to executable files with *size* < *thresshold* results in complete transfer

How can we ensure cache co-
herency?

Cache Coherency

- **Not** given for version 3
  - **Problem:** Multiple clients may cache or even modify blocks of the same file/directory
  - Timestamp based weak validation scheme
    - Validation on `open()`, cache miss and timeout
      (typical: files 3 s, directories 30 s)
    - After checking its validity this assumed for a certain duration
    - Write-through for blocks of directories
    - All modified blocks are transferred to the server at latest on `close()`
  - Cache may contain outdated files and directories

  ⇒ Cooperation of processes via file system not always correct for NFSv3
- Given for version 4
  - Cache invalidation of outdated files, checked on `open()`
  - Session semantics

Caching and File Delegation

- Only for version 4
- Delegation of server tasks to the client. This checks `open()` and `close()` operations of other clients
- Possibility to revoke delegation is required

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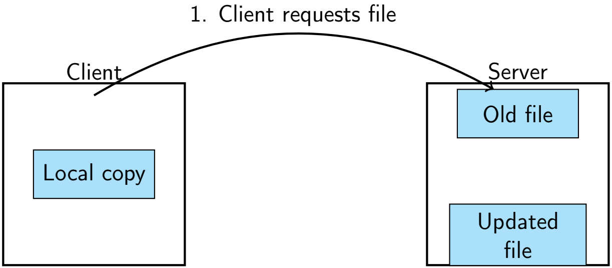

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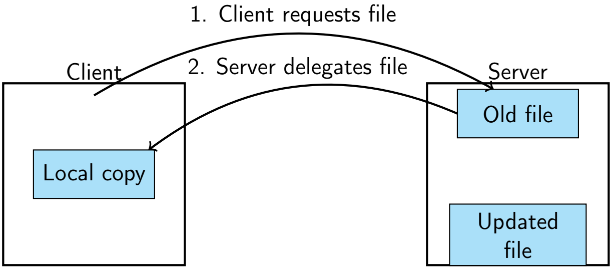

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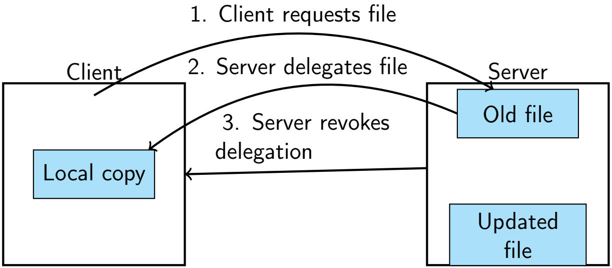

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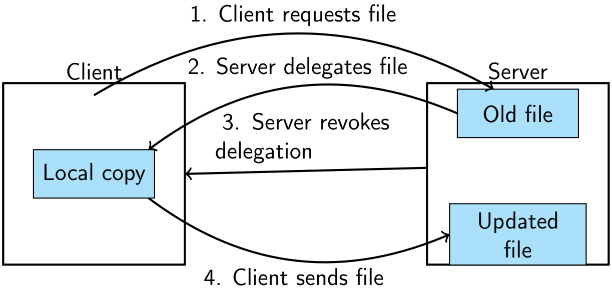

What about Security?

Which security considerations do we need to take into account?
Where in the system do we need to put security measures into place?

Security

Principal Architecture

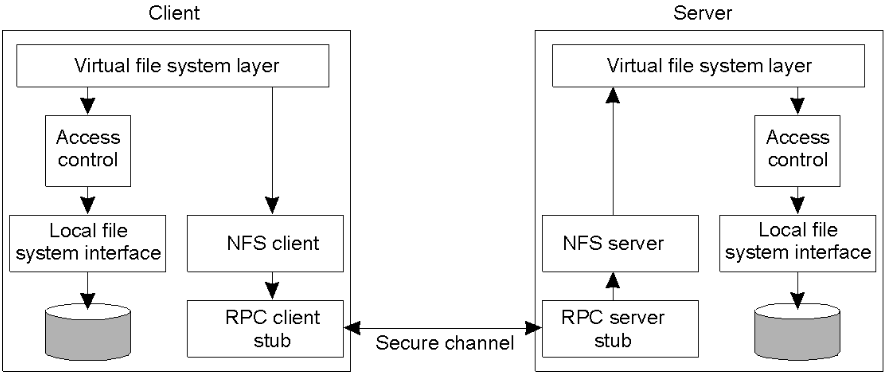

Fig. from Tanenbaum/Steen

Security

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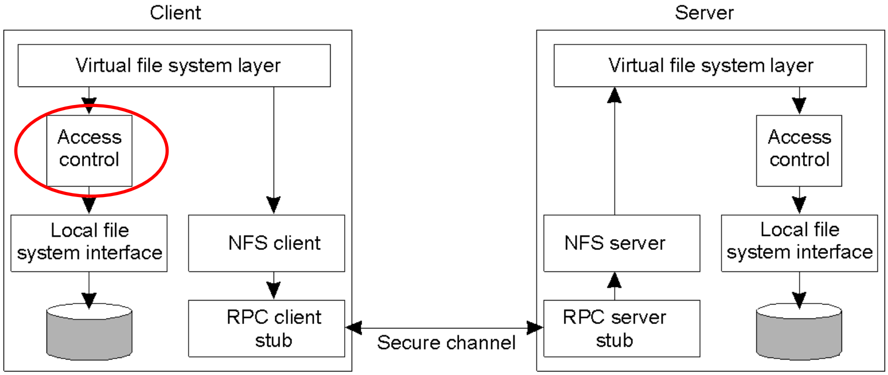

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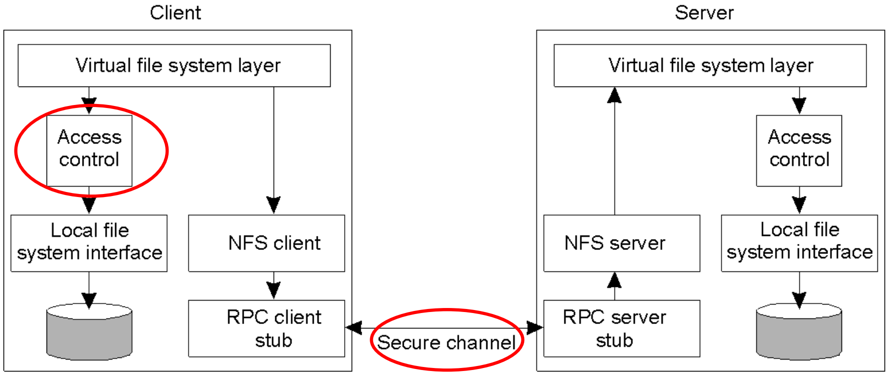

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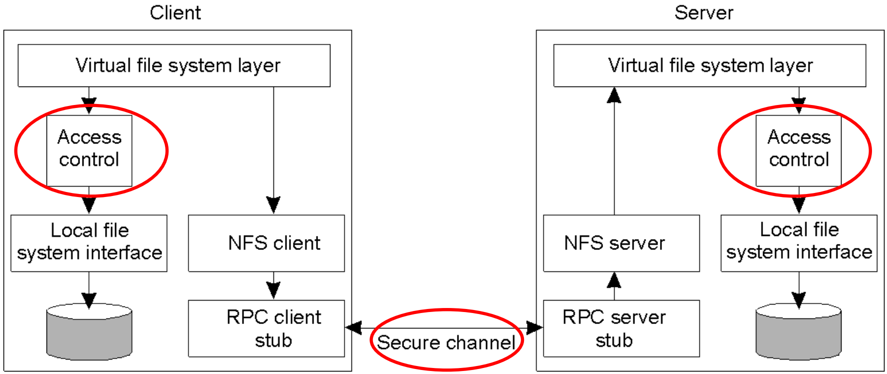

Fig. from Tanenbaum/Steen

Secure RPCs

in version 3:

- Only authentication
  - System
    - Based on UNIX IDs (`uid, gid`)
    - Transferred unencrypted without signature (server trusts client)
  - Diffie-Hellman
    - rarely used
    - Nowadays considered insecure because of too short key length
  - Kerberos

in version 4:

- No built-in mechanisms
- Supports `RPCSEC_GSS`
  - Security environment for various mechanisms that can be hooked in
  - Besides authentication it supports integrity and confidentiality

Secure RPCs for Version 4

Architectures of secure RPCs in version 4:

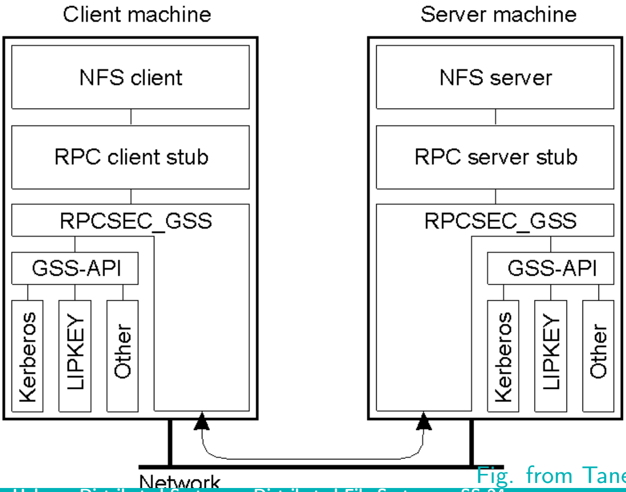

Fig. from Tanenbaum/Steen

Access Control

in version 3:

- UNIX permission checking (uid, gid) at server side

in version 4:

- ACL based
- Subjects strongly differentiated

UNIX permissions

- Which scopes (or classes) are defined?
- Which permissions can be specified?

Access Control Operations

Operation	Description
read_data	Permission to read the data contained in a file
write_data	Permission to modify a file's data
append_data	Permission to append data to a file
execute	Permission to execute a file
list_directory	Permission to list the contents of a directory
add_file	Permission to add a new file to a directory
add_subdirectory	Permission to create a subdirectory to a directory
delete	Permission to delete a file
delete_child	Permission to delete a file or directory within a directory
read_acl	Permission to read the ACL
write_acl	Permission to write the ACL
read_attributes	The ability to read the other basic attributes of a file
write_attributes	Permission to change the other basic attributes of a file
read_named_attrs	Permission to read the named attributes of a file
write_named_attrs	Permission to write the named attributes of a file
write_owner	Permission to change the owner
synchronize	Permission to access a file locally at the server with synchronous reads and writes

Access Control Subjects

User type	Description
Owner	The owner of a file
Group	The group of users associated with a file
Everyone	Any user of a process
Interactive	Any process accessing the file from an interactive terminal
Network	Any process accessing the file via the network
Dialup	Any process accessing the file through a dialup connection to the server
Batch	Any process accessing the file as part of a batch job
Anonymous	Anyone accessing the file without authentication
Authenticated	Any authenticated user of a process
Service	Any system-defined service process

According to Tanenbaum/Steen

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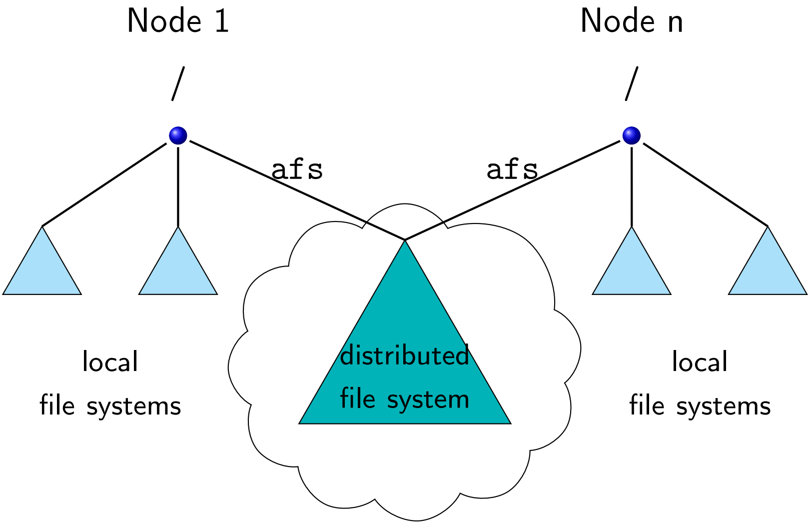
Andrew File System (AFS)

- Carnegie Mellon University (CMU) with IBM, 1983 – 1989, later Transarc and OpenAFS
- File system for the campus with more than 5,000 active students
- **Goals**
  - Location transparency, common global file namespace, accessible via the local name `/afs`
  - High performance
  - High availability
    - Replication
  - High security
    - Secure authentication
    - Encrypted transfer
    - ACLs for access control
  - Automatic migration of home directories of users

Coda

Newer versions of AFS-2

File Namespace



Overall Architecture

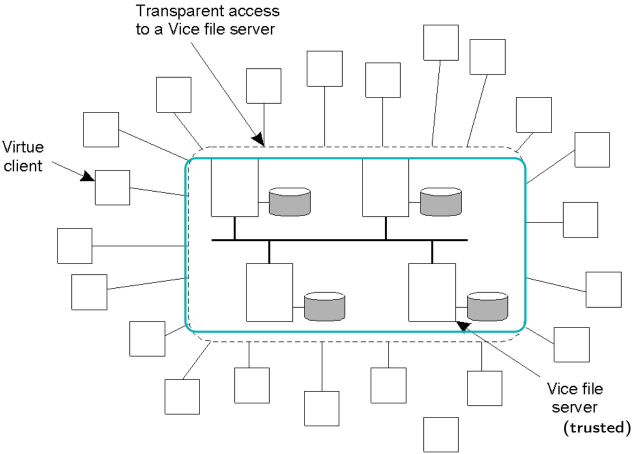
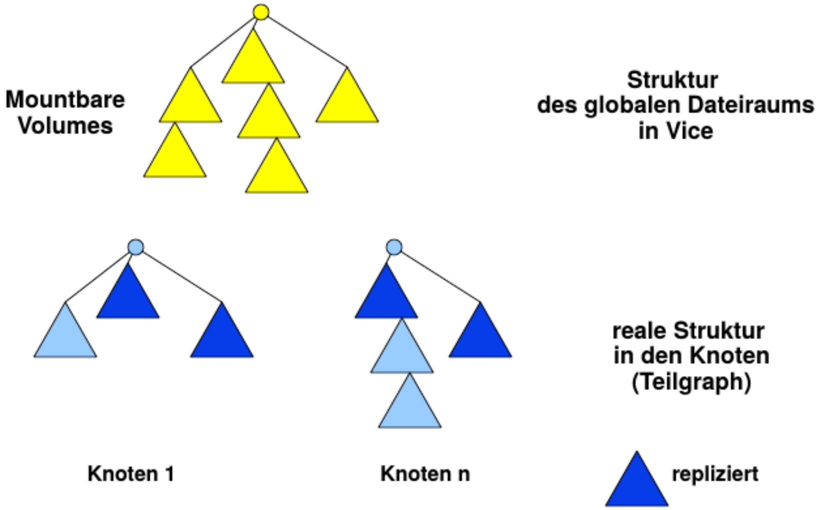


Fig. from Tanenbaum/Steen

Volumes


Mountbare Volumes
Struktur des globalen Dateiraums in Vice
reale Struktur in den Knoten (Teilgraph)
Knoten 1
Knoten n
repliziert

Virtue Client Architecture

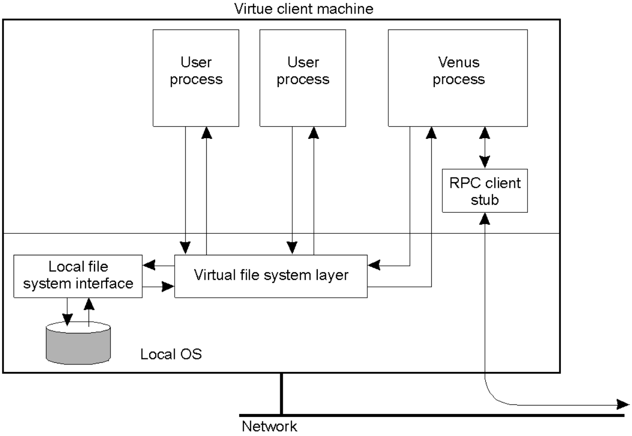
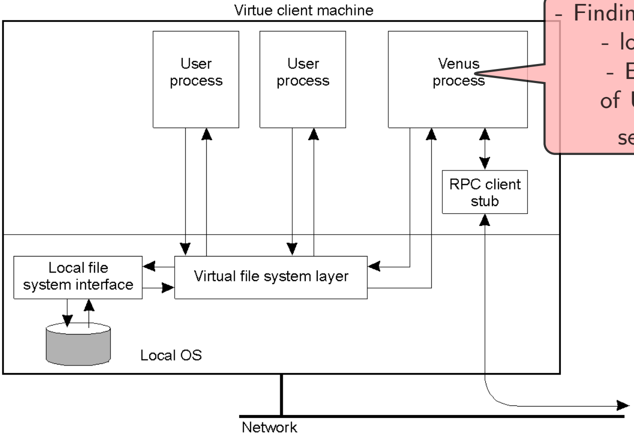


Fig. from Tanenbaum/Steen

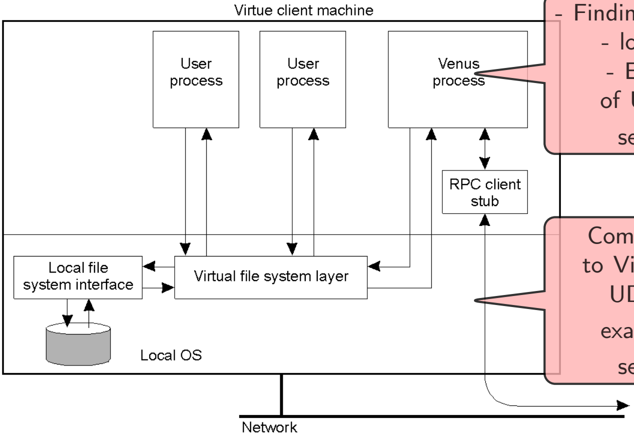
Virtue Client Architecture



- Finding files in Vice
- local cache
- Emulation of UNIX file-semantics

Fig. from Tanenbaum/Steen

Virtue Client Architecture



- Finding files in Vice
- local cache
- Emulation of UNIX file-semantics

Communication to Vice via RPC
UDP based
exactly-once-semantics

Fig. from Tanenbaum/Steen

Properties

- Commonly used files with *session semantics*
- Local caching: of entire files until AFS-2/of big file blocks (64 kB) since AFS-3
- *Cache coherency*
  - Check the cache validity not required for each `open()`
  - Callback procedure, i.e., explicit *invalidation* by the server before another client gets write permissions

Security

- **Organisation**
  - Vice-Server are trusted
  - No client applications on servers
  - Introduction of administrative cells to increase scalability
- **Subjects**
  - User
  - Groups
- **Authentication**
  - Particular authentication server, Kerberos (since AFS-3)
  - Secure RPC
- **Access Control**
  - ACLs defined for directories, apply for all files of the directory

Coda

- Further development of AFS-2 since 1987
- *Goals:*
  - High availability of the files
  - Client can continue to work, even when the server is temporarily not reachable (*network partioning*)
  - Inclusion of *mobile computers* (intentional network partioning)

File IDs

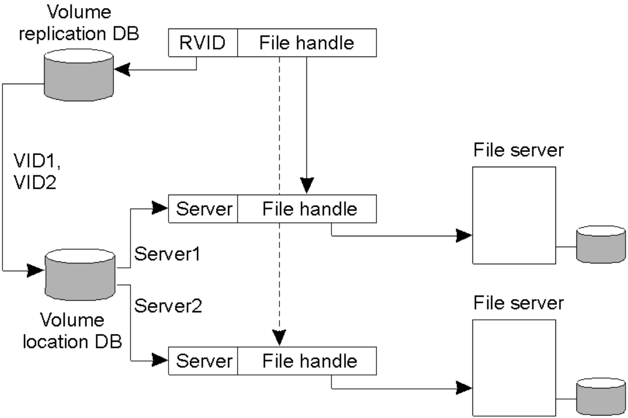


Fig. from Tanenbaum/Steen

File IDs

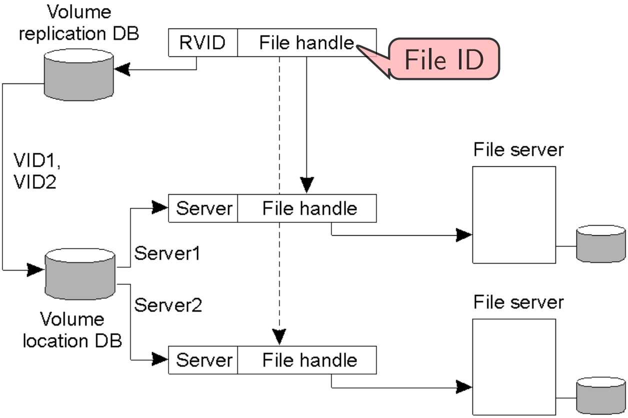


Fig. from Tanenbaum/Steen

File IDs

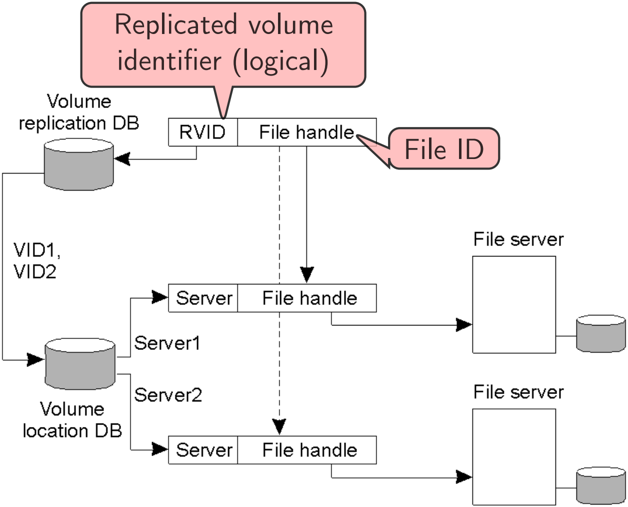


Fig. from Tanenbaum/Steen

File IDs

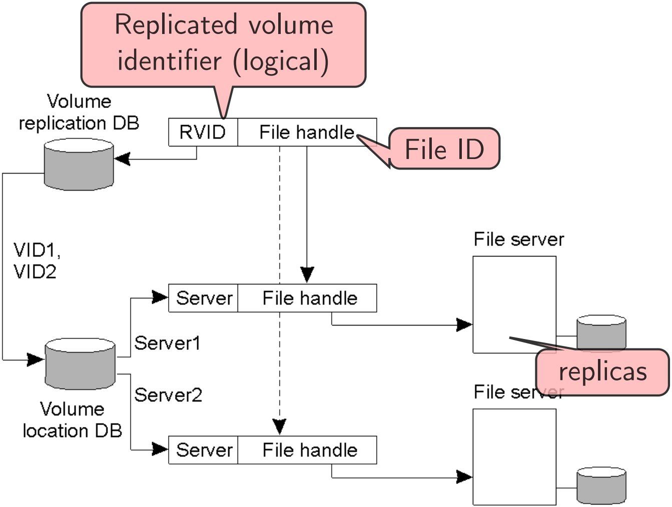


Fig. from Tanenbaum/Steen

Properties for Normal Operation

- Session semantics
- One *writer*
- Multiple *readers*

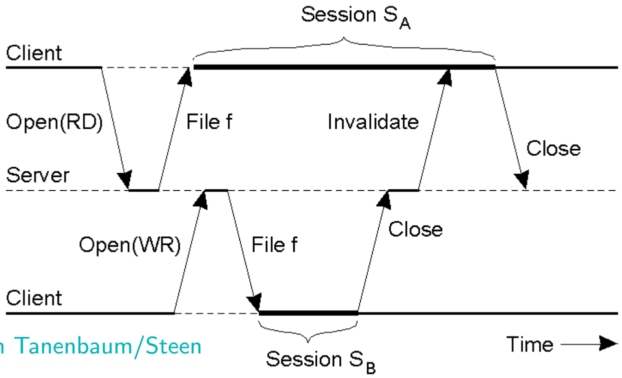


Fig. from Tanenbaum/Steen

Properties for Normal Operation

- Session semantics
- One *writer*
- Multiple *readers*

noncritical: A reads from older file version, processes this

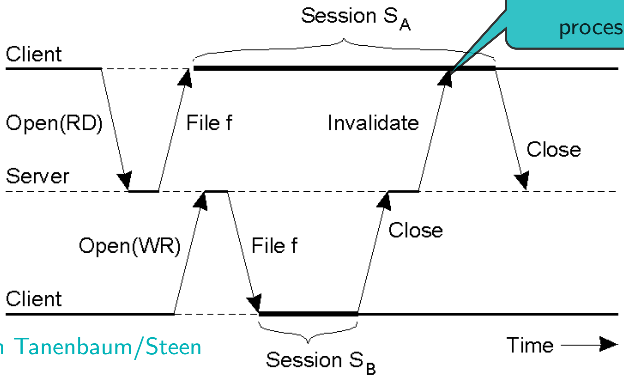
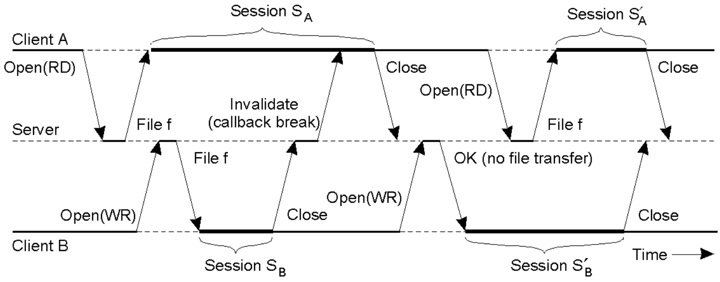


Fig. from Tanenbaum/Steen

Caching

- On `open()` the file is loaded into the client's cache
- Server makes callback promise
- For invalidation the server sends a callback break



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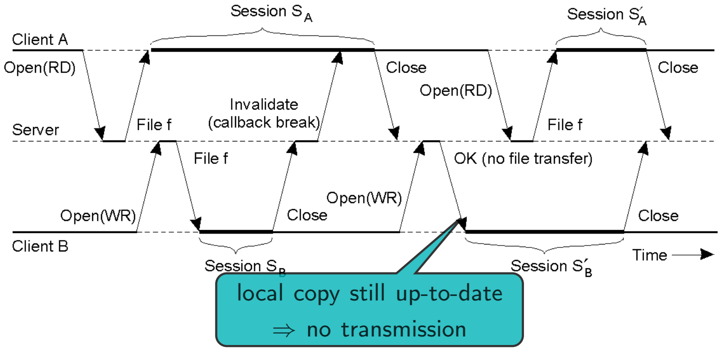

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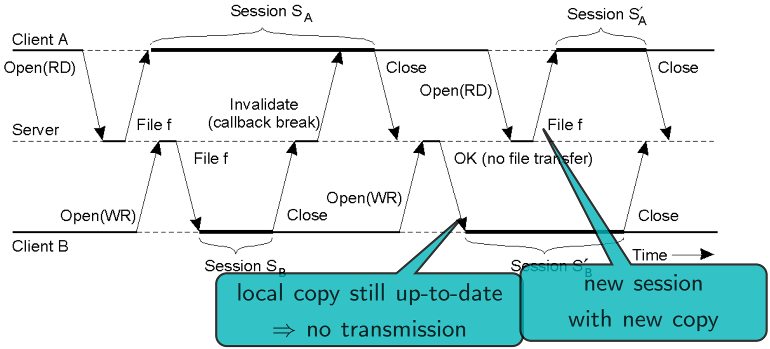

Fig. from Tanenbaum/Steen

Server Replication and Network Partitioning

- Volume is the unit for replication
- Volume Storage Group (VSG)
  - Set of servers with a copy of a volume
- Accessible Volume Storage Group (AVSG)
  - Subset of VSG which can be accessed from the client
- Reading from a replica, write to all via MultiRPC
- Optimistic strategy for file replication
  - On partitioning multiple writers may exist and write back to their respective AVSGs
- Maintaining of version vectors ($\rightarrow$ vector timestamps), check on update
- Merge of multiple versions later on, may require manual assistance

Connectionless Operation

- Connectionless: AVSG$= \emptyset \Rightarrow$ use of local copy
- Conflict detection on transmission to server

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Connectionless Operation

- Connectionless: AVSG$= \emptyset \Rightarrow$ use of local copy
- Conflict detection on transmission to server
- Observation
  - Conflicts are rare since modifications to one file by multiple processes are infrequent
- Problem
  - Keep relevant files in local cache when disconnect happens

Hoarding

How can we select the files to be stored in the local cache?

Hoarding

How can we select the files to be stored in the local cache?

- **Approach:** Hoarding (of files)
  - Heuristic method
  - Explicit declaration of files and directories by the user
  - Prioritisation by matching with current access information
  - Cache alignment (hoard walk) every 10 minutes
  - Good experiences, but of course it happens that occasionally relevant files are missing

Summary

Issue	NFS	Coda
Design goals	Access transparency	High availability
Access model	Remote	Up/Download
Communication	RPC	RPC
Client process	Thin/Fat	Fat
Server groups	No	Yes
Mount granularity	Directory	File system
Name space	Per client	Global
File ID scope	File server	Global
Sharing sem.	Session	Transactional
Cache consist.	write-back	write-back
Replication	Minimal	ROWA
Fault tolerance	Reliable comm.	Replication and caching
Recovery	Client-based	Reintegration
Secure channels	Existing mechanisms	Needham-Schroeder
Access control	Many operations	Directory operations

According to Tanenbaum/Steen

Agenda

- Basics
- NFS
- AFS and Coda
- Storage Networks

Storage Networks

Use of network technology and distributed systems in a storage system

Motivation

- Cost reduction
  - Reduced provided storage capacities
  - Central administration
- More flexible provisioning
  - Faster adaption to changing requirements
- Scalability
  - From small to very large storage capacities
- Options for disaster recovery
  - Data mirroring at remote locations

Architecture Approaches

Today's essential architectural approaches

- Direct Attached Storage (DAS) (traditional local storage)
- Storage Area Networks (SAN)
- Network-Attached Storage (NAS)
- Content Addressed Storage (CAS)

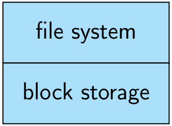
Storage Systems as Layered Systems

Basic breakdown of the data storage functionality

block storage	Mapping to phys. storage device

Storage Systems as Layered Systems

Basic breakdown of the data storage functionality



Mapping to logical set of blocks,
e.g., NFS, AFS, Microsoft SMB/CIFS

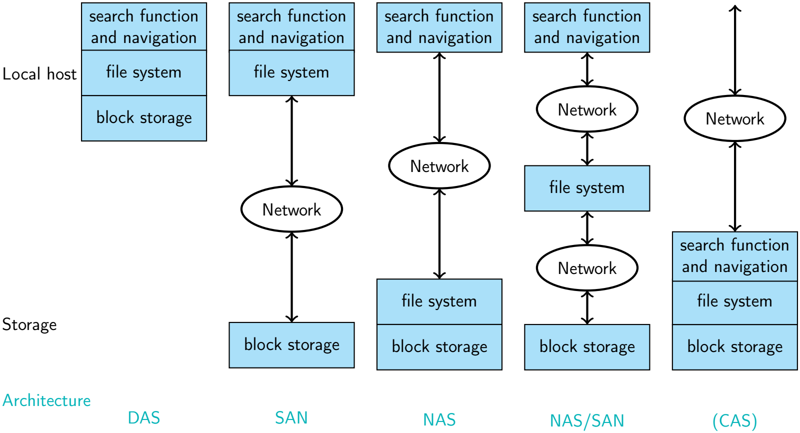
Mapping to phys. storage device

Storage Systems as Layered Systems

Basic breakdown of the data storage functionality

search function and navigation	path names, query, index, metadata, ...
file system	Mapping to logical set of blocks, e.g., NFS, AFS, Microsoft SMB/CIFS
block storage	Mapping to phys. storage device

Overview for Integration of Networks



Direct Attached Storage (DAS)

- Traditional, locally attached storage devices
- Local OS contains file system and device driver
- Typical device interfaces
  - IDE/ATA, SCSI, Serial ATA (SATA), ...
- Limitations
  - Number of available channels
  - Number of attachable devices per channel
  - maximum distance ($\approx 1 - 25$ m)
  - $\Rightarrow$ No disaster recovery possible
  - Performance
  - $\Rightarrow$ Not very scalable

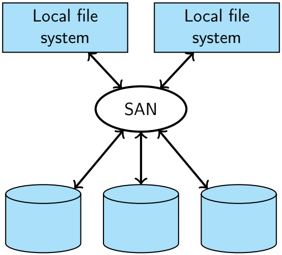
Storage Area Network (SAN)

Operating principle

- SAN provides block storage (e.g., hard disks as logical devices)
- Server operating systems provide one or multiple file system
- Block storage is accessed by the servers via SAN

Advantages

- Very simple extensibility
- Very high degree of flexibility in assignability
- Very scalable
- Basis for replication, also for disaster recovery
- Bootable network partitions
- Especially suited for applications who works with volumes (without file system), e.g., DBMS



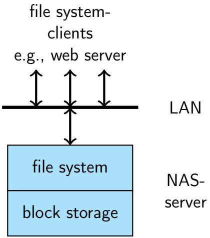
Network Attached Storage (NAS)

Operating principle

- NAS provides network file systems (e.g., NFS, SMB/CIFS)
- Clients may use these file systems

Advantages

- Storage consolidation
- Expandability
- Scalability
- Manageability
- Especially suited for applications which are based on file access, e.g., web applications or home directories



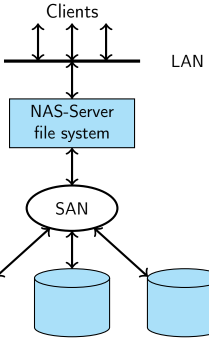
NAS Examples

- Home server
  - Synology
  - ZyXEL
  - My Cloud
  - OpenMediaVault (Software)
- IBM SONAS and Storwize
- Buffalo TeraSTation
- CTERA Networks

Combination of NAS and SAN

Operating principle

- NAS and SAN can be used combined
- Advantages can be combined



Content Addressable Storage (CAS)

Main idea: Immutable information

- ⇒ also called Fixed Content Storage (FCS)
- Goal: archive storage

Subproblem of the Information Lifecycle Management (ILM)

- Mass data (hundreds of terabytes or even petabytes)
- Longevity
- Integrity
- Immutability of documents, partly required by law

Usage for content management

- Digital media (audio or image documents)
- Email archiving
- Health care (X-ray images etc.)
- ...

CAS: Operating Principle

- Content identifier as reference
- Determination of a content identifier
  - Only by its content ($\rightarrow$ hash value) $\Rightarrow$ location independent
  - Or by its storage location (inverted)
- System determines location for access via its content identifier

Examples

- First System: EMC Centera 2002
- iTernity iCAS (Software solution)
- Various open source solutions, e.g., Keep Content Addressable Storage

Important takeaway messages of this chapter

- Distributed file systems enable concurrent access access to files by different users, independent of their storage location.
- Access to files can lead to different results depending on the consistency semantics.
- By dividing the functionality for information storage on different systems in the network, scalability, fault tolerance, etc. can be improved.