Distributed Systems

14. Distributed File Systems

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Accessing files

FTP, telnet:

- Explicit access
- User-directed connection to access remote resources

We want more transparency

- Allow user to access remote resources just as local ones

NAS: Network Attached Storage

File service types

Upload/Download model

- *Read file:* copy file from server to client
- *Write file:* copy file from client to server

Advantage

- **Simple**

Problems

- **Wasteful**: what if client needs small piece?
- **Problematic**: what if client doesn’t have enough space?
- **Consistency**: what if others need to modify the same file?

File service types

Remote access model

File service provides functional interface:

- *create, delete, read bytes, write bytes, etc…*

Advantages:

- Client gets only what's needed
- Server can manage coherent view of file system

Problem:

- Possible server and network congestion
  - Servers are accessed for duration of file access
  - Same data may be requested repeatedly

Remote File Service

File Directory Service

– Maps textual names for file to internal locations that can be used by file service

File service

– Provides file access interface to clients

Client module (driver)

– Client side interface for file and directory service

– if done right, helps provide access transparency

e.g. implement the file system under the VFS layer

Semantics of file sharing

Sequential semantics

Read returns result of last write

Easily achieved *if*

- Only one server
- Clients do not cache data

BUT

- Performance problems if no cache
  - Obsolete data
- We can ***write-through***
  - Must notify clients holding copies
  - Requires extra state, generates extra traffic

Session semantics

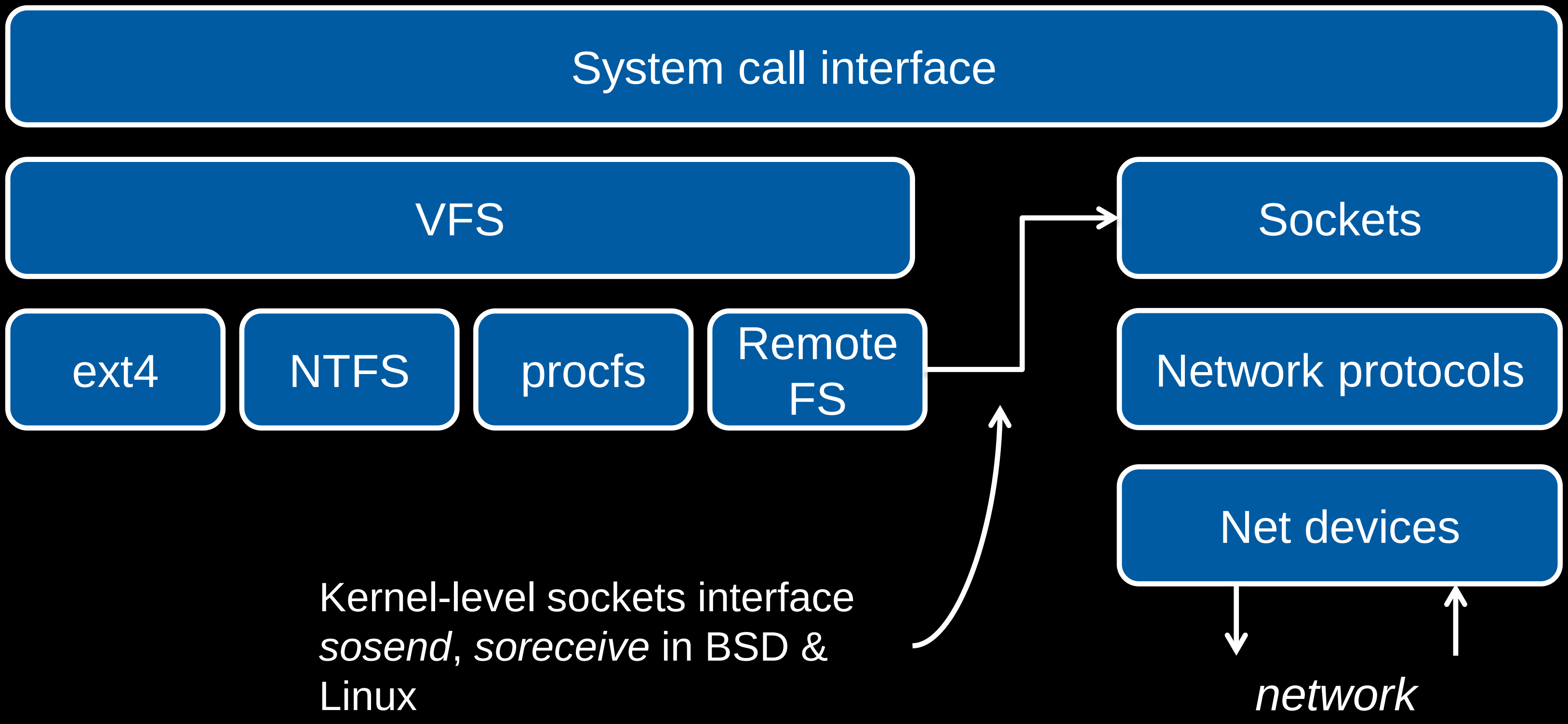
Relax the rules

- Changes to an open file are initially visible only to the process (or machine) that modified it.
- Last process to modify the file wins.

System design issues

Accessing Remote Files

Implement the client module as a file system type under VFS



Stateful or stateless design?

Stateful

- Server maintains client-specific state

- Shorter requests
- Better performance in processing requests
- Cache coherence is possible
  - Server can know who's accessing what
- File locking is possible

Stateful or stateless design?

Stateless

- Server maintains *no* information on client accesses

- Each request must identify file and offsets
- Server can crash and recover
  - No state to lose
- Client can crash and recover
- No open/close needed
  - They only establish state
- No server space used for state
  - Don’t worry about supporting many clients
- Problems if file is deleted on server
- File locking not possible

Caching

Hide latency to improve performance for repeated accesses

Four places

- Server's disk
- Server's buffer cache
- Client's buffer cache
- Client's disk

WARNING:
cache consistency problems

Approaches to caching

- Write-through
  - What if another client reads its own (out-of-date) cached copy?
  - All accesses will require checking with server
  - Or … server maintains state and sends invalidations
- Delayed writes (write-behind)
  - Data can be buffered locally
    (watch out for consistency – others won't see updates!)
  - Remote files updated periodically
  - One bulk wire is more efficient than lots of little writes
  - Problem: semantics become ambiguous

Approaches to caching

- Read-ahead (prefetch)
  - Request chunks of data before it is needed.
  - Minimize wait when it actually is needed.

- Write on close
  - Admit that we have session semantics.

- Centralized control
  - Keep track of who has what open and cached on each node.
  - Stateful file system with signaling traffic.

NFS

Network File System

Sun Microsystems

NFS Design Goals

- Any machine can be a client or server
- Must support diskless workstations
- Heterogeneous systems must be supported
  - Different HW, OS, underlying file system
- Access transparency
  - Remote files accessed as local files through normal file system calls (via VFS in UNIX)
- Recovery from failure
  - Stateless, UDP, client retries
- High Performance
  - use caching and read-ahead

NFS Design Goals

No support for UNIX file access semantics

- Stateless design: file locking is a problem.
- All UNIX file system controls may not be available.

NFS Design Goals

Devices

Must support diskless workstations where *every* file is remote.

Remote devices refer back to local devices.

NFS Design Goals

Transport Protocol

Initially NFS ran over UDP using Sun RPC

Why was UDP chosen?

- Slightly faster than TCP
- No connection to maintain (or lose)
- NFS is designed for Ethernet LAN environment – relatively reliable
- Error detection but no correction.
    - NFS retries requests

NFS Protocols

Mounting protocol

Request access to exported directory tree

Directory & File access protocol

Access files and directories
(read, write, mkdir, readdir, …)

Mounting Protocol

- Send pathname to server
- Request permission to access contents

client: parses pathname
contacts server for file handle

- Server returns file handle
  - File device #, inode #, instance #

client: create in-memory VFS inode at mount point.
internally points to **rnode** for remote files
- *Client keeps state, not the server*

Mounting Protocol

static mounting

– mount request contacts server

Server: edit `/etc/exports`

Client: `mount fluffy:/users/paul /home/paul`

Directory and file access protocol

- First, perform a *lookup* RPC
  - returns file handle and attributes

- lookup is ***not*** like *open*
  - No information is stored on server

- handle passed as a parameter for other file access functions
  - e.g. `read(handle, offset, count)`

Directory and file access protocol

NFS has 16 functions

- (version 2; six more added in version 3)

null
lookup

create
remove
rename

read
write

link
symlink
readlink

mkdir
rmdir
readdir

getattr
setattr

statfs

NFS Performance

- Usually slower than local
- Improve by caching at client
  - Goal: reduce number of remote operations
  - Cache results of
    read, readlink, getattr, lookup, readdir
  - Cache file data at client (buffer cache)
  - Cache file attribute information at client
  - Cache pathname bindings for faster lookups
- Server side
  - Caching is “automatic” via buffer cache
  - All NFS writes are *write-through* to disk to avoid unexpected data loss if server dies

Inconsistencies may arise

Try to resolve by validation

- Save timestamp of file
- When file opened or server contacted for new block
  - Compare last modification time
  - If remote is more recent, invalidate cached data

Validation

- Always invalidate data after some time
  - After 3 seconds for open files (data blocks)
  - After 30 seconds for directories
- If data block is modified, it is:
  - Marked *dirty*
  - Scheduled to be written
  - Flushed on file close

Improving read performance

- Transfer data in large chunks
  - 8K bytes default
- Read-ahead
  - Optimize for sequential file access
  - Send requests to read disk blocks before they are requested by the application

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Problems with NFS

- File consistency
- Assumes clocks are synchronized
- Open with append cannot be guaranteed to work
- Locking cannot work
  - Separate lock manager added (stateful)
- No reference counting of open files
  - You can delete a file you (or others) have open!
- Global UID space assumed

Problems with NFS

- File permissions may change
  - Invalidating access to file
- No encryption
  - Requests via unencrypted RPC
  - Authentication methods available
    - Diffie-Hellman, Kerberos, Unix-style
  - Rely on user-level software to encrypt

Improving NFS: version 2

- User-level lock manager
  - Monitored locks
    - status monitor: monitors clients with locks
    - Informs lock manager if host inaccessible
    - If server crashes: status monitor reinstates locks on recovery
    - If client crashes: all locks from client are freed
- NV RAM support
  - Improves write performance
  - Normally NFS must write to disk on server before responding to client *write* requests
  - Relax this rule through the use of non-volatile RAM

Improving NFS: version 2

- Adjust RPC retries dynamically
  - Reduce network congestion from excess RPC retransmissions under load
  - Based on performance
- Client-side disk caching
  - cacheFS
  - Extend buffer cache to disk for NFS
    - Cache in memory first
    - Cache on disk in 64KB chunks

More improvements… NFS v3

- Updated version of NFS protocol
- Support 64-bit file sizes
- TCP support and large-block transfers
  - UDP caused more problems on WANs (errors)
  - All traffic can be multiplexed on one connection
    - Minimizes connection setup
  - No fixed limit on amount of data that can be transferred between client and server
- Negotiate for optimal transfer size
- Server checks access for entire path from client

More improvements… NFS v3

- New *commit* operation
  - Check with server after a *write* operation to see if data is committed
  - If *commit* fails, client must **resend** data
  - Reduce number of *write* requests to server
  - Speeds up *write* requests
    - Don't require server to write to disk immediately
- Return file attributes with each request
  - Saves extra RPCs

AFS

Andrew File System

Carnegie Mellon University

c. 1986(v2), 1989(v3)

AFS

- Developed at CMU
- Became a commercial spin-off
  - Transarc
- IBM acquired Transarc

Currently open source under IBM Public License

Also:

OpenAFS, Arla, and Linux version

AFS Design Goal

Support information sharing
on a ***large*** scale

e.g., 10,000+ systems

AFS Assumptions

- Most files are small
- Reads are more common than writes
- Most files are accessed by one user at a time
- Files are referenced in bursts (locality)
  - Once referenced, a file is likely to be referenced again

AFS Design Decisions

Whole file serving

- Send the entire file on *open*

Whole file caching

- Client caches entire file on local disk
- Client writes the file back to server on *close*
  - if modified
  - Keeps cached copy for future accesses

AFS Design

- Each client has an AFS disk cache
  - Part of disk devoted to AFS (e.g. 100 MB)
  - Client manages cache in LRU manner

- Clients communicate with set of trusted servers

- Each server presents one identical name space to clients
  - All clients access it in the same way
  - Location transparent

AFS Server: cells

- Servers are grouped into administrative entities called cells

- Cell: collection of
  - Servers
  - Administrators
  - Users
  - Clients
- Each cell is autonomous but cells may cooperate and present users with one **uniform name space**

AFS Server: volumes

Disk partition contains

file and directories

Grouped into volumes

Volume

- Administrative unit of organization
  - e.g. user's home directory, local source, etc.
- Each volume is a directory tree (one root)
- Assigned a name and ID number
- A server will often have 100s of volumes

Namespace management

Clients get information via cell directory server (Volume Location Server) that hosts the Volume Location Database (VLDB)

Goal:

everyone sees the same namespace

/afs/cellname/path

/afs/mit.edu/home/paul/src/try.c

Internally on the server

- Communication is via RPC over UDP
- Access control lists used for protection
  - Directory granularity
  - UNIX permissions ignored (except execute)

AFS cache coherence

On open:

- Server sends entire file to client

  and provides a callback promise:

- *It will notify the client when any other process modifies the file*

AFS cache coherence

If a client modified a file:

- Contents are written to server on *close*

When a server gets an update:

- it notifies *all* clients that have been issued the callback promise
- Clients invalidate cached files

AFS cache coherence

If a client was down, on startup:

- Contact server with timestamps of all cached files to decide whether to invalidate

If a process has a file open, it continues accessing it even if it has been invalidated

- Upon close, contents will be propagated to server

AFS: Session Semantics

(vs. sequential semantics)

AFS: replication and caching

- Read-only volumes may be replicated on multiple servers
- Whole file caching not feasible for huge files
  - AFS caches in 64KB chunks (by default)
  - Entire directories are cached
- Advisory locking supported
  - Query server to see if there is a lock

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AFS summary

Whole file caching

- offers dramatically reduced load on servers

Callback promise

- keeps clients from having to check with server to invalidate cache

AFS summary

AFS benefits

- AFS scales well
- Uniform name space
- Read-only replication
- Security model supports mutual authentication, data encryption

AFS drawbacks

- Session semantics
- Directory based permissions
- Uniform name space

SMB

Server Message Blocks

Microsoft

c. 1987

SMB Goals

- File sharing protocol for Windows 95/98/NT/200x/ME/XP/Vista/Windows 7
- Protocol for sharing:

    Files, devices, communication abstractions (named pipes), mailboxes

- Servers: make file system and other resources available to clients
- Clients: access shared file systems, printers, etc. from servers

Design Priority:

locking and consistency over client caching

SMB Design

- Request-response protocol
  - Send and receive ***message blocks***
    - name from old DOS system call structure
  - Send *request* to server (machine with resource)
  - Server sends response
- Connection-oriented protocol
  - Persistent connection – “session”
- Each message contains:
  - Fixed-size header
  - Command string (based on message) or reply string

Message Block

- Header: [fixed size]
  - Protocol ID
  - Command code (0..FF)
  - Error class, error code
  - Tree ID – unique ID for resource in use by client (handle)
  - Caller process ID
  - User ID
  - Multiplex ID (to route requests in a process)
- Command: [variable size]
  - Param count, params, #bytes data, data

SMB Commands

- Files
  - Get disk attr
  - create/delete directories
  - search for file(s)
  - create/delete/rename file
  - lock/unlock file area
  - open/commit/close file
  - get/set file attributes

SMB Commands

- Print-related
  - Open/close spool file
  - write to spool
  - Query print queue

- User-related
  - Discover home system for user
  - Send message to user
  - Broadcast to all users
  - Receive messages

Protocol Steps

- Establish connection

Protocol Steps

- Establish connection
- Negotiate protocol
  - ***negprot*** SMB
  - Responds with version number of protocol

Protocol Steps

- Establish connection
- Negotiate protocol
- Authenticate/set session parameters
  - Send ***sesssetupX*** SMB with username, password
  - Receive NACK or UID of logged-on user
  - UID must be submitted in future requests

Protocol Steps

- Establish connection
- Negotiate protocol - *negprot*
- Authenticate - *sesssetupX*
- Make a connection to a resource (similar to *mount*)
  - Send *tcon* (tree connect) SMB with name of shared resource
  - Server responds with a **tree ID** (TID) that the client will use in future requests for the resource

Protocol Steps

- Establish connection
- Negotiate protocol - *negprot*
- Authenticate - *sesssetupX*
- Make a connection to a resource – *tcon*
- Send open/read/write/close/… SMBs

CODA

COnstant Data Availability

Carnegie-Mellon University

c. 1990-1992

CODA Goals

Descendant of AFS

CMU, 1990-1992

Goals

Provide better support for replication than AFS
- support shared read/write files

Support mobility of PCs

Mobility

- Provide **constant** data availability in disconnected environments
- Via **hoarding** (user-directed caching)
  - Log updates on client
  - Reintegrate on connection to network (server)

- Goal: Improve fault tolerance

Modifications to AFS

- Support replicated file volumes
- Extend mechanism to support disconnected operation
- A volume can be replicated on a group of servers
  - **Volume Storage Group (VSG)**

Volume Storage Group

- Volume ID used in the File ID is
  - **Replicated volume ID**
- One-time lookup
  - Replicated volume ID $\rightarrow$ list of servers and *local* volume IDs
  - Cache results for efficiency
- Read files from *any* server
- Write to **all available servers**

Disconnection of volume servers

AVSG: Available Volume Storage Group

- Subset of VSG

What if some volume servers are down?

On first download, contact everyone you can and get a version timestamp of the file

Disconnected servers

If the client detects that some servers have old versions

- Some server resumed operation

- Client initiates a **resolution process**
  - Updates servers: notifies server of stale data
  - Resolution handled entirely by servers
  - Administrative intervention may be required (if conflicts)

AVSG = Ø

- If no servers are available
  - Client goes to **disconnected operation mode**
- If file is not in cache
  - Nothing can be done… fail
- Do not report failure of update to server
  - Log update locally in **Client Modification Log** (CML)
  - User does not notice

Reintegration

Upon reconnection

- Commence **reintegration**

Bring server up to date with CML **log playback**

- Optimized to send latest changes

Try to resolve conflicts automatically

- Not always possible

Support for disconnection

Keep important files up to date

- Ask server to send updates if necessary

Hoard database

- Automatically constructed by monitoring the user's activity
- And user-directed prefetch

CODA summary

- Session semantics as with AFS
- Replication of read/write volumes
  - Client-driven reintegration
- Disconnected operation
  - Client modification log
  - Hoard database for needed files
    - User-directed prefetch
  - Log replay on reintegration

DFS

Distributed File System

Open Group

DFS

- Part of Open Group's Distributed Computing Environment
- Descendant of AFS - AFS version 3.x
- Development stopped c. 2005

- Assume (like AFS):
  - Most file accesses are sequential
  - Most file lifetimes are short
  - Majority of accesses are whole file transfers
  - Most accesses are to small files

DFS Goals

Use **whole file caching** (like original AFS)

But…

session semantics are hard to live with

Create a **strong consistency** model

DFS Tokens

Cache consistency maintained by **tokens**

Token:

- Guarantee from server that a client can perform certain operations on a cached file

DFS Tokens

- *Open* tokens
  - Allow token holder to open a file.
  - Token specifies access (read, write, execute, exclusive-write)
- *Data* tokens
  - Applies to a byte range
  - *read* token - can use cached data
  - *write* token - write access, cached writes
- *Status* tokens
  - *read*: can cache file attributes
  - *write*: can cache modified attributes
- *Lock* token
  - Holder can lock a byte range of a file

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Living with tokens

- Server grants and revokes tokens
  - Multiple *read* tokens OK
  - Multiple *read* and a *write* token or multiple *write* tokens not OK if byte ranges overlap
    - Revoke all other *read* and *write* tokens
    - Block new request and send revocation to other token holders

DFS design

- Token granting mechanism
  - Allows for long term caching <u>and</u> strong consistency
- Caching sizes: 8K – 256K bytes
- Read-ahead (like NFS)
  - Don't have to wait for entire file
- File protection via ACLs
- Communication via authenticated RPCs

DFS Summary

Essentially AFS v2 with server-based token granting

- Server keeps track of who is reading and who is writing files
- Server must be contacted on each *open* and *close* operation to request token

CIFS

Common Internet File System

Microsoft, Compaq, …

c. 1995?

SMB evolves

SMB was reverse-engineered

- **samba** under Linux

Microsoft released protocol to X/Open in 1992

Microsoft, Compaq, SCO, others joined to develop an enhanced public version of the SMB protocol:

Common Internet File System

(CIFS)

Original Goals

- Heterogeneous HW/OS to request file services over network
- Based on SMB protocol
- Support
  - Shared files
  - Byte-range locking
  - Coherent caching
  - Change notification
  - Replicated storage
  - Unicode file names

Original Goals

- Applications can register to be notified when file or directory contents are modified
- Replicated virtual volumes
  - For load sharing
  - Appear as one volume server to client
  - Components can be moved to different servers without name change
  - Use *referrals*
  - Similar to AFS

Original Goals

- Batch multiple requests to minimize round-trip latencies
  - Support wide-area networks
- Transport independent
  - But need reliable connection-oriented message stream transport
- DFS support (compatibility)

Caching and Server Communication

- Increase effective performance with
  - Caching
    - Safe if multiple clients reading, nobody writing
  - read-ahead
    - Safe if multiple clients reading, nobody writing
  - write-behind
    - Safe if only one client is accessing file

- Minimize times client informs server of changes

Oplocks

Server grants **opportunistic locks** (**oplocks**) to client

- Oplock tells client how/if it may cache data
- Similar to DFS tokens (but more limited)

Client must request an oplock

- oplock may be
  - Granted
  - Revoked
  - Changed by server

Level 1 oplock (exclusive access)

- Client can open file for exclusive access
- Arbitrary caching
- Cache lock information
- Read-ahead
- Write-behind

If another client opens the file, the server has former client *break its oplock*:

- Client must send server any lock and write data and acknowledge that it does not have the lock
- Purge any read-aheads

Level 2 oplock (one writer)

- Level 1 oplock is replaced with a Level 2 lock if another process tries to read the file
- Request this if expect others to read
- Multiple clients may have the same file open as long as none are writing
- Cache reads, file attributes
  - Send other requests to server
- Level 2 oplock revoked if another client opens the file for writing

Batch oplock (remote open even if local closed)

- Client can keep file open on server even if a local process that was using it has closed the file
  - Exclusive R/W open lock + data lock + metadata lock

- Client requests batch oplock if it expects programs may behave in a way that generates a lot of traffic (e.g. accessing the same files over and over)
  - Designed for Windows batch files

- Batch oplock revoked if another client opens the file

Filter oplock (allow preemption)

- Open file for read or write
- Allow clients with *filter oplock* to be suspended while another process preempted file access.
  - E.g., indexing service can run and open files without causing programs to get an error when they need to open the file
    - Indexing service is notified that another process wants to access the file.
    - It can abort its work on the file and close it or finish its indexing and then close the file.

No oplock

- All requests must be sent to the server
- Can work from cache only if byte range was locked by client

Naming

- Multiple naming formats supported:
  - `N:\junk.doc`
  - `\\myserver\users\paul\junk.doc`
  - `file://grumpy.pk.org/users/paul/junk.doc`

Microsoft Dfs

- "Distributed File System"
  - Provides a logical view of files & directories
- Each computer hosts volumes

      \\servername\dfsname

  Each Dfs tree has one root volume and one level of leaf volumes.

- A volume can consist of multiple shares
  - Alternate path: load balancing (read-only)
  - Similar to Sun's automounter
- Dfs = SMB + naming/ability to mount server shares on other server shares

Redirection

- A share can be replicated (read-only) or moved through Microsoft's Dfs

- Client opens old location:
  - Receives STATUS_DFS_PATH_NOT_COVERED
  - Client requests referral:
    TRANS2_DFS_GET_REFERRAL
  - Server replies with new server

CIFS Summary

- A “standard” SMB
- Oplocks mechanism supported in base OS: Windows NT/XP/Vista/7/8, 20xx
- Oplocks offer flexible control for distributed consistency
- Dfs offers namespace management

NFS version 4

Network File System

Sun Microsystems

NFS version 4 enhancements

- Stateful server
- Compound RPC
  - Group operations together
  - Receive set of responses
  - Reduce round-trip latency
- Stateful open/close operations
  - Ensures atomicity of share reservations for windows file sharing (CIFS)
  - Supports exclusive creates
  - Client can cache aggressively

NFS version 4 enhancements

- create, link, open, remove, rename
  - Inform client if the directory changed during the operation
- Strong security
  - Extensible authentication architecture
- File system replication and migration
  - To be defined
- No concurrent write sharing or distributed cache coherence

NFS version 4 enhancements

- Server can delegate specific actions on a file to enable more aggressive client caching
  - Similar to CIFS oplocks
- Callbacks
  - Notify client when file/directory contents change

Other
(less conventional)
Distributed File Systems

WebDAV

- *Not a file system – but a network protocol*
- Web-based Distributed Authoring [and Versioning] RFC 2518
- Extension to HTTP to make the Web writable
- New HTTP Methods
  - PROPFIND: retrieve properties from a resource, including a collection (directory) structure
  - PROPPATCH: change/delete multiple properties on a resource
  - MKCOL: create a collection (directory)
  - COPY: copy a resource from one URI to another
  - MOVE: move a resource from one URI to another
  - LOCK: lock a resource (shared or exclusive)
  - UNLOCK: remove a lock

Who uses WebDAV?

- File systems:
  - davfs2: Linux file system driver to mount a DAV server as a file system
    - Coda kernel driver and neon for WebDAV communication
  - Native filesystem support in OS X (since 10.0)
  - Microsoft web folders (since Windows 98)
- Apache HTTP server
- Apple iCal & iDisk
- Jakarta Slide & Tomcat
- KDE Desktop
- Microsoft Exchange & IIS
- SAP NetWeaver
- Many others…
- Check out webdav.org

An *ad hoc* file system using Gmail

- Gmail file system (Richard Jones, 2004; Dave Hansen, 2009)
- User-level
  - Python application
  - FUSE userland file system interface
- Supports
  - Read, write, open, close, stat, symlink, link, unlink, truncate, rename, directories
- Each message represents a file
  - Subject headers contain:
    - File system name, filename, pathname, symbolic link info, owner ID, group ID, size, etc.
  - File data stored in attachments
    - Files can span multiple attachments

See http://sr71.net/projects/gmailfs/

Client-server file systems

- Central servers
  - Point of congestion, single point of failure
- Alleviate somewhat with replication and client caching
  - E.g., Coda
  - Limited replication can lead to congestion
  - Separate set of machines to administer
- But … user systems have LOTS of disk space
  - (500 GB disks commodity items @ $45)

Serverless file systems?

- Use workstations cooperating as peers to provide file system service
- Any machine can share/cache/control any block of data

Prototype serverless file system

  - **xFS** from Berkeley demonstrated to be scalable
- Others:
  - See Fraunhofer FS (www.fhgfs.com)

The End