Distributed Systems

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

Focus on file system for now

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…*

<u>Advantages</u>:

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

<u>Problem</u>:

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

File server

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. under vnode 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.

Other solutions

Make files **immutable**

- Aids in replication
- Does not help with detecting modification

Or…

Use **atomic transactions**

- Each file access is an atomic transaction
- If multiple transactions start concurrently
    - Resulting modification is serial

File usage patterns

- We can't have the best of all worlds
- Where to compromise?
  - Semantics vs. efficiency
  - Efficiency = client performance, network traffic, server load
- Understand how files are used
- 1981 study by Satyanarayanan

File usage

Most files are <10 Kbytes

- 2005: average size of 385,341 files on my Mac =197 KB
- 2007: average size of 440,519 files on my Mac =451 KB
- (files accessed within 30 days:
  147,398 files. average size=56.95 KB)
- Feasible to transfer entire files (simpler)
- Still have to support long files

Most files have short lifetimes

- Perhaps keep them local

Few files are shared

- Overstated problem
- Session semantics will cause no problem most of the time

System design issues

Where do you find the remote files?

Should all machines have the exact same view of the directory hierarchy?

- e.g., global root directory?

  `//server/path`

- or forced "remote directories":

  `/remote/server/path`

or....

Should each machine have its own hierarchy with remote resources located as needed?

`/usr/local/games`

How do you access them?

- Access remote files as local files
- Remote FS name space should be syntactically consistent with local name space

1. redefine the way all files are named and provide a syntax for specifying remote files
   - e.g. //server/dir/file
   - Can cause legacy applications to fail
2. use a file system *mounting* mechanism
   - Overlay portions of another FS name space over local name space
   - This makes the remote name space look like it's part of the local name space

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.

Distributed File Systems Case Studies

NFS • AFS • CODA • DFS • SMB • CIFS
Dfs • WebDAV • Gmail-FS? • xFS

NFS
Network File System

Sun Microsystems

c. 1985

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 migration transparency
  - If resource moves to another server, client must remount resource.

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 UDP?

- 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-code vnode at
         mount point.
         (points to inode for local files)
         points to rnode for remote files
                 - stores state on client
```

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
- *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

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

- No reference counting of open files
  - You can delete a file you (or others) have open!

- Common practice
  - Create temp file, delete it, continue access
  - Sun's hack:
    - If same process with open file tries to delete it
    - Move to temp name
    - Delete on close

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

The automounter

Problem with mounts

- If a client has many remote resources mounted, boot-time can be excessive
- Each machine has to maintain its own name space
  - Painful to administer on a large scale

Automounter

- Allows administrators to create a global name space
- Support *on-demand* mounting

Automounter

- Alternative to static mounting
- Mount and unmount in response to client demand
  - Set of directories are associated with a local directory
  - None are mounted initially
  - When local directory is **referenced**
    - OS sends a message to **each** server
    - First reply wins
  - Attempt to unmount every 5 minutes

Automounter maps

Example:

```
automount /usr/src srcmap
```

`srcmap` contains:

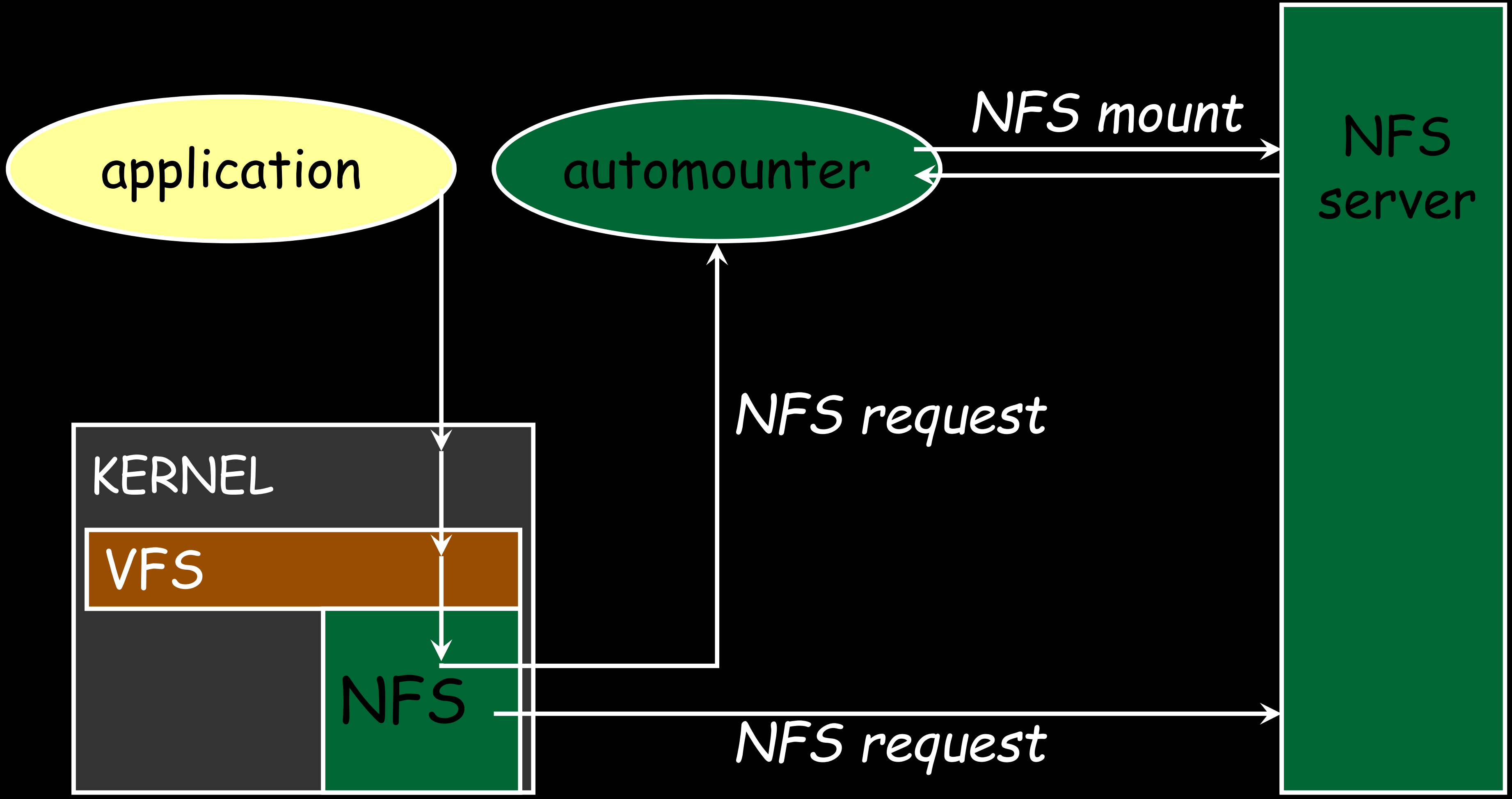
```
cmd         -ro  doc:/usr/src/cmd
kernel      -ro  frodo:/release/src \
                 bilbo:/library/source/kernel
lib         -rw  sneezy:/usr/local/lib
```

Access `/usr/src/cmd`: request goes to doc

Access `/usr/src/kernel`:

ping frodo and bilbo, mount first response

The automounter



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
- 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

Accessing an AFS file

1. Traverse AFS mount point
   E.g., /afs/cs.rutgers.edu
2. AFS client contacts Volume Location DB on Volume Location server to look up the volume
3. VLDB returns volume ID and list of machines (>1 for replicas on read-only file systems)
4. Request root directory from any machine in the list
5. Root directory contains files, subdirectories, and mount points
6. Continue parsing the file name until another mount point (from step 5) is encountered. Go to step 2 to resolve it.

Internally on the server

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

Authentication and access

Kerberos authentication:

- Trusted third party issues tickets
- Mutual authentication

Before a user can access files

- Authenticate to AFS with *klog* command
  - "Kerberos login" – centralized authentication
- Get a token (ticket) from Kerberos
- Present it with each file access

Unauthorized users have id of **`system:anyuser`**

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

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

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

Sample Deployment (2008)

- Intel engineering (2007)
  - 95% NFS, 5% AFS
  - Approx 20 AFS cells managed by 10 regional organization
  - AFS used for:
    - CAD, applications, global data sharing, secure data
  - NFS used for:
    - Everything else
- Morgan Stanley (2004)
  - 25000+ hosts in 50+ sites on 6 continents
  - AFS is primary distributed filesystem for all UNIX hosts
  - 24x7 system usage; near zero downtime
  - Bandwidth from LANs to 64 Kbps inter-continental WANs

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 (AFS v3.x)

Distributed File System

Open Group

DFS

- Part of Open Group’s Distributed Computing Environment
- Descendant of AFS - AFS version 3.x

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

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 (AFS v3) 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

SMB
Server Message Blocks

Microsoft

c. 1987

SMB Goals

- File sharing protocol for Windows 95/98/NT/2000/ME/XP/Vista
- 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
  - 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

Locating Services

- Clients can be configured to know about servers
- Each server broadcasts info about its presence
  - Clients listen for broadcast
  - Build list of servers
- Fine on a LAN environment
  - Does not scale to WANs
  - Microsoft introduced *browse servers* and the *Windows Internet Name Service* (WINS)
  - or … explicit pathname to server

Security

- Share level
  - Protection per “share” (resource)
  - Each share can have password
  - Client needs password to access all files in share
  - Only security model in early versions
  - Default in Windows 95/98
- User level
  - protection applied to individual files in each share based on access rights
  - Client must login to server and be authenticated
  - Client gets a UID which must be presented for future accesses

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
- SMB + 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

- Proposed standard has not yet fully materialized
  - Future direction uncertain
- Oplocks mechanism supported in base OS: Windows NT, 2000, XP
- Oplocks offer flexible control for distributed consistency

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

Others…

Google File System: Application-Specific

- Component failures are the norm
  - *Thousands* of storage machines
  - Some are not functional at any given time
- Built from inexpensive commodity components
- Datasets of many terabytes with billions of objects

Google File System usage needs

- Stores modest number of large files
  - Files are huge by traditional standards
    - Multi-gigabyte common
  - Don't optimize for small files
- Workload:
  - Large streaming reads
  - Small random reads
  - Most files are modified by appending
  - Access is mostly read-only, sequential
- Support concurrent appends
- High sustained BW more important than latency
- Optimize FS API for application
  - E.g., atomic *append* operation

Google file system

- GFS cluster
  - Multiple chunkservers
    - Data storage: fixed-size chunks
    - Chunks replicated on several systems (3 replicas)
  - One master
    - File system metadata
    - Mapping of files to chunks
- Clients ask master to look up file
  - Get (and cache) chunkserver/chunk ID for file offset
- Master replication
  - Periodic logs and replicas

WebDAV

- *Not a file system - just a 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?

- Davfs2: Linux file system driver to mount a DAV server as a file system
  - Coda kernel driver and neon for WebDAV communication
- 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)
- User-level
  - Python application
  - FUSE userland file system interface
- Supports
  - Read, write, open, close, stat, symlink, link, unlink, truncate, rename, directories
- Metadata stored in the body of emails sent by the Gmail user
- File data stored in attachments
  - Files can span multiple attachments
- Subject lines have a file system name.

File servers

- 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
  - (120 GB disks commodity items @ $120)

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.