Operating Systems Design
18. Networking: Remote File Systems

Paul Krzyzanowski
pxk@cs.rutgers.edu

1

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

2

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?

3

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

4

Remote File Service

File service
- Runs on the server
- Provides file access interface to clients
- File directory service
  - Maps textual names for file to internal locations that can be used by file service

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

5

Semantics of file sharing

6

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 do ***write-through***
  - Any data written goes to the cache & also to the server
  - Must notify clients holding copies
  - Requires extra state, generates extra traffic

7

Session semantics

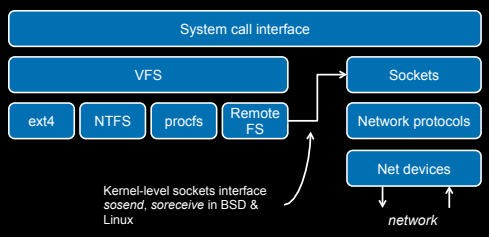
Relax the rules

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

8

Accessing Remote Files

Implement the client module as a file system type under VFS



9

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

10

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

11

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

12

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

13

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
  - Session semantics = changes invisible to others; last one to close a file wins *versus* sequential semantics
- Centralized control
  - Keep track of who has what open and cached on each node
  - Stateful file system with signaling traffic

14

NFS

Network File System

Sun Microsystems

15

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

16

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.

17

NFS Design Goals

Devices

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

Remote devices refer back to local devices.

18

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

19

NFS Protocols

Mounting protocol

Request access to exported directory tree

Directory & File access protocol

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

20

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

21

Mounting Protocol

static mounting

- mount request contacts server

Server: edit `/etc/exports`

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

22

Directory and file access protocol

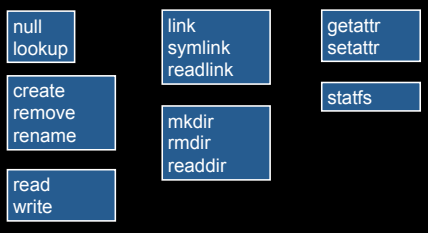
- First, perform a *lookup* RPC
  - returns file handle and attributes
- lookup is ***not*** like *open*
  - No information is stored on server
- handle passed as a parameter for other file access functions
  - e.g. `read(handle, offset, count)`

23

Directory and file access protocol

NFS has 16 functions

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



24

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

25

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

26

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

27

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

28

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

29

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

30

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

31

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

32

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

33

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

34

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

35

Automounter maps

Example:

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

`srcmap` contains:

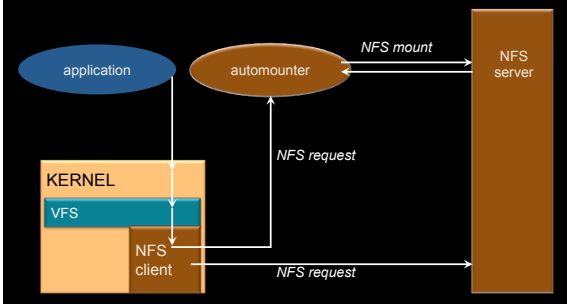
```
cmd    -ro doc:/usr/src/cmd
kernel -ro frodo:/release/src \
          bilbo:/library/source/kernel
lib    -rw sneezy:/usr/local/lib
```

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

Access `/usr/src/kernel`:
ping frodo and bilbo, mount first response

36

The automounter



37

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

38

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

39

Still more … NFS v4

- NFS becomes stateful!
  - Server can return info on how other clients are using the file
  - Callback from server that another client wants to access the file
    - Local caching until that happens
- Byte-range locking
- Compound RPCs: combine multiple requests into one
- Kerberos security
- Named file attributes; text-based users & groups

40

AFS

Andrew File System

Carnegie Mellon University

c. 1986(v2), 1989(v3)

41

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

42

AFS Design Goal

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

e.g., 10,000+ systems

43

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

44

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

45

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

46

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**

47

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

48

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

49

Internally on the server

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

50

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*

51

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

52

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)

53

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

54

AFS summary

Whole file caching
- offers dramatically reduced load on servers

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

55

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

56

SMB

Server Message Blocks

Microsoft

c. 1987

57

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

58

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

59

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

60

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

61

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

62

Protocol Steps

- Establish connection

63

Protocol Steps

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

64

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

65

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

66

Protocol Steps

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

67

The End

68