Design and Implementation of the Sun Network File System

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Goals

- Designed in early/mid 80s.
  - Before: each computer had its own private file disk + file system.
    - Fine for expensive central time-sharing.
    - Awkward for individual workstation.
- New model: One server, LAN full of client workstations. Not WAN.
  - Allow users to share files easily.
  - Allow a user to sit at any workstation.
  - Diskless workstations could save money

Implementation Goals

- Had to work with existing applications.
- Had to be easy to retro-fit into UNIX O/S.
- Had to implement same semantics as local UNIX FFS.
- Had to be not too UNIX specific
  - work w/ DOS, for example.
- Had to be fast enough to be tolerable
  - (but willing to sacrifice some).

Kernel FS Structure *before* NFS

- Specialized to local file system called Fast File System (FFS).
- Disk inodes.
- O/S keeps in-core copies of inodes that are in use.
  - File descriptors, current directories, executing programs.
- File system system calls used inodes directly.
  - To find e.g. disk addresses for read().
- Disk block cache.
  - Indexed by disk block #.

Why not a Network Disk (ND)?

- What was ND?
  - Server supplied a block store, with JUST read/write block RPCs.
  - This makes read/write sharing awkward.
  - Clients would have to carefully lock disk data structures.
- How is NFS different from ND?
  - Moves complex operations to server.
- Why might NFS be slower than ND?
  - Have to worry about consistency between multiple clients

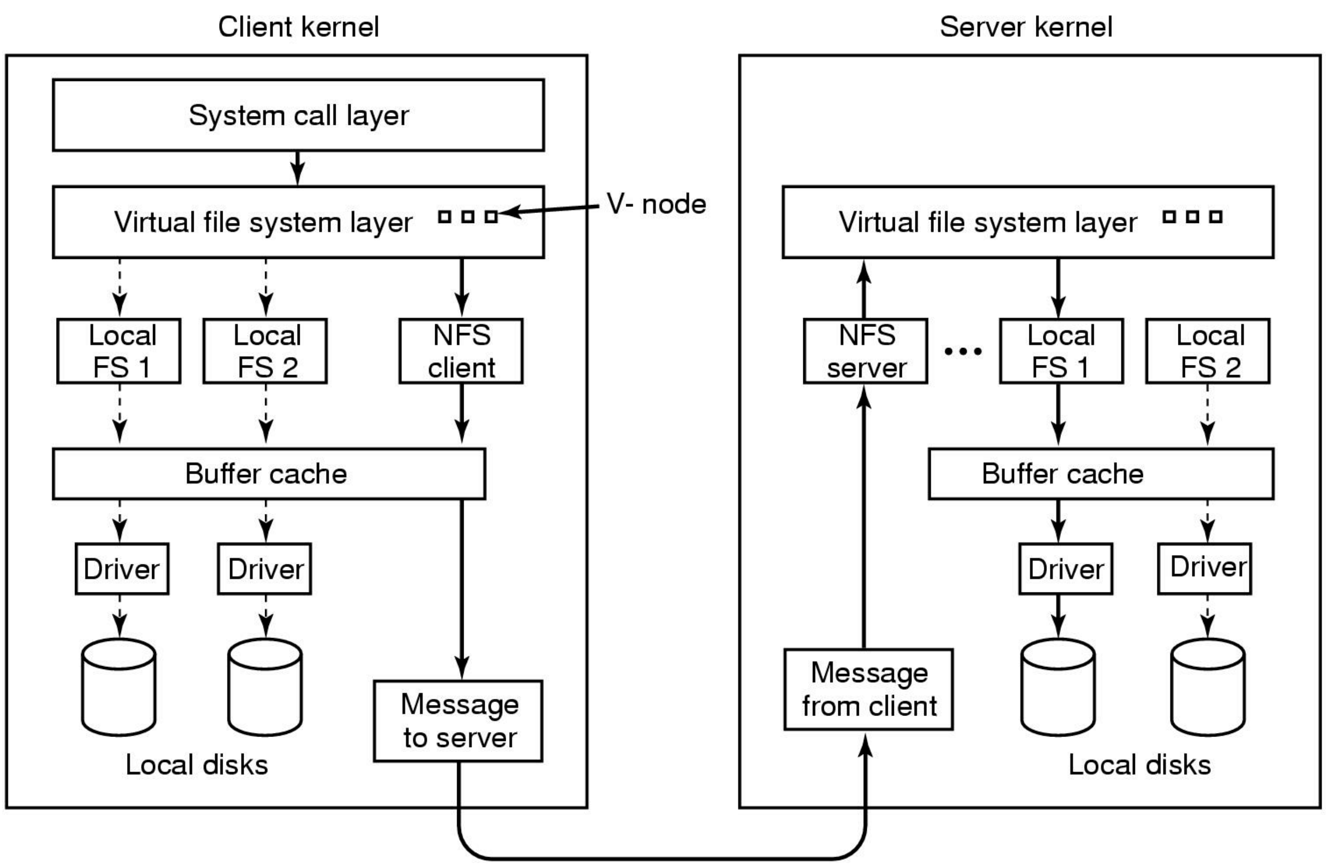
Virtual File System (VFS) Interface

- New "vnode" plan, invented to support NFS.
- Need a layer of indirection, to hide implementation.
  - A file might be FFS, NFS, or something else.
  - Replace inode with vnode object.
  - vnode has lots of methods:
    - open, close, read, remove.
  - Each file system type has its own implementation methods.
- What about disk cache?
  - Replaced with per-vnode list of cached blocks.

NFS Implementation

- Three main layers:
- System call layer:
  - Handles calls like open, read and close
- Virtual File System Layer:
  - Maintains table with one entry (v-node) for each open file
  - v-nodes indicate if file is local or remote
    - If remote it has enough info to access them
    - For local files, FS and i-node are recorded
- NFS Service Layer:
  - This lowest layer implements the NFS protocol

NFS Layer Structure



NFS Client/Server Structure

- Client programs have file descriptors, current directory, &c.
- Inside kernel, these refer to vnodes of type NFS.
- When client programs make system calls:
  - NFS vnode implementation sends RPC to server.
  - Kernel half of that program waits for reply.
  - So we can have one outstanding RPC per program.

NFS Client/Server Structure

- Server kernel has NFS threads, waiting for incoming RPCs.
  - NFS thread acts a lot like user program making system call.
  - Find *vnode* in server corresponding to client's vnode.
  - Call that vnode's relevant method.
  - Server vnodes are typically of type FFS.
  - This saves a lot of code in the server.
  - This means NFS will work with different local file systems.
  - This means files are available on server in the ordinary way.
  - NFS server thread blocks when needed.

How does NFS RPC designate file to read?

- E.g. a read RPC
- Could use file name.
  - Client NFS vnode would contain name, send in rpc.
  - Easy to implement in the server.
- Why doesn't this work?
  - Doesn't preserve UNIX file semantics.
    - Client 1: chdir("dir1");
      fd = open("file");
    - Client 2: rename("dir1", "dir2");
      rename("dir3", "dir1");
    - Client 1: read(fd, buf, n);
  - Does client read current dir1/file, or dir2/file?
  - UNIX says dir2/file.

The NFS File Handle

- What else goes in file handle, besides i-number?
  - File system ID - because server may server multiple file systems
  - Generation number - what is this?
    - Suppose an inode gets deleted & recycled while file/dir still open
    - Don't want old file descriptor referring to new file--very dangerous
    - Solution: Store generation number in inode on disk, change when recycled
    - What happens to read/write of old handle when generation number changes?
    - NFS stale file handle error
    - Sometimes: Inode of export point
  - So server can disallow lookup ("..") past export point
    - (not secure)

The NFS File Handle

- File systems already need a way to name files/inodes
  - E.g., How do directory entries refer to files?
    - Map name -> i-node number ("i-number”)
- Don't want to expose i-node number details to client
  - I.e. client should never have to make up a file reference.
- So file handles are opaque.
  - Client sees them as 32-byte blob.
  - Client gets all file handles from the server.
  - Every client NFS vnode contains the file's handle.
  - Client sends back same handle to server.

NFS RPCs

- lookup
- read
- write
- getattr
- create
- remove, setattr, rename, readlink, link, symlink, mkdir, rmdir, readdir
- ***(no open, close, chdir)*** – why not?
  - Requires state to be maintained at server

Example

- `fd = open("./notes", O_RDONLY);`
- `read(fd, buf, n);`
- Client process has a reference to current directory's vnode.
- Sends `LOOKUP(dir-vnode, "notes")` to server.
- Server extracts i-number from file handle.
- Asks local file system to turn that into a local vnode.
- Every local file system must support file handles...
- Calls the local vnode's lookup method.
- dir->lookup("notes") returns "notes" vnode.
- NFS server code extracts i-number from vnode, creates new file handle.
- Server returns new file handle to client.
- Client creates new vnode, sets its file handle.
- Client creates new file descriptor pointing to new vnode.
- Client app issues read(fd, ...).
- Results in READ(file-handle, ...) being sent to server.

Where does first File Handle come from?

- Every NFS RPC has to be contain a file handle
  - A valid file handle
- Server's mount daemon maps file system name to root file handle.
- Client kernel marks mount point on local file system as special.
- Remembers vnode (and thus file handle) of remote file system.

Crash Recovery

- Suppose server crashes and reboots.
- Clients might not even know.
- File handles held by clients must still work!
- That's why file handle holds i-number, which is basically a disk address.
  - Rather than, say, server NFS code creating an arbitrary map.
  - That is, server is stateless!

What if open file gets deleted by different client?

- UNIX semantics
  - file still exists until I stop using it.
- Would require server to keep reference count per file.
  - Would require open() and close() RPCs to help mantain that count.
- Which would have to persist across server reboots.
- So NFS just does the wrong thing!
- RPCs will fail if some other client deletes a file I have open.
  - this is part of the reason why there is no open() or close() RPC.

What about performance?

- Does *every* program system call go over the wire to the server?
- No: client cache for better performance.
- Per-vnode block cache, name->file handle cache, attribute cache.
- Can satisfy read()s, for example, from block cache.

What about consistency?

- Is it enough to make the data cache write-through?
- No: I read a file, another client writes it, I read it again.
- How do I realize my cache is stale?

Consistency

- What are the semantics of read and write system calls?
- One possibility:
  - read() sees data from most recent write().
  - This is what local UNIX file systems implement.
- How to implement these strong semantics?
  - Turn off client caching altogether.
  - Or have clients check w/ server before every read.
  - Or have server notify clients when other clients write.

NFS chooses poor consistency

- In V2 implementation described, very poor consistency
- In newer implementations, close-to-open consistency
- If I write() and then close(), then you open() and read(), you see my data.
- Otherwise you may see stale data.
- How to implement these strong semantics?
  - Writing client must force dirty blocks during close().
  - Reading client must check w/ server during open().
  - Ask if file has been modified since data were cached.
  - This is much less expensive than strong consistency.
  - Though maybe not very scalable; every open() produces an rpc.

Optimizations

- NFS server and block I/O daemons
- Caching!
  - Client-side buffer cache
    - (write-behind w. flush-on-close)
  - Client-side attribute cache
  - Name cache
- XDR directly to/from mbufs
- Fill-on-demand clustering, swap in small programs

What about Security?

- Server has list of IP addresses.
- Fully trusts any client with that address.
- Client O/S expected to enforce user IDs, send to server.

Other issues

- soft vs hard mounts
- replay cache.
- I can execute files I can't read.
- what if I open(), then chmod u=?
  - owner always allowed to read/write…
- dump+restore may wreck client file handles.

Next Time

- Read *NFS* and write review. *Turn into CMS before class*:
  - *A Toolkit for User-Level File Systems*. David Mazieres. Appears in *Proceedings of the USENIX Annual Technical Conference*, June 2001
  - *Implementing Remote Procedure Calls*. Andrew D. Birrell and Bruce Jay Nelson. Appears in *ACM Transaction on Computer Systems (TOCS)*, 1984
- Do Lab 0---**Due this Thursday, January 29th**
- Be prepared to select paper to present
  - Check schedule on website
  - Sign up to present on Thursday, January 29th
- Check website for updated schedule