15-440 Distributed Systems

Lecture 7 – Distributed File Systems 1

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Outline

- Why Distributed File Systems?
- Basic mechanisms for building DFSs
  - Using NFS and AFS as examples
- Design choices and their implications
  - Caching
  - Consistency
  - Naming
  - Authentication and Access Control

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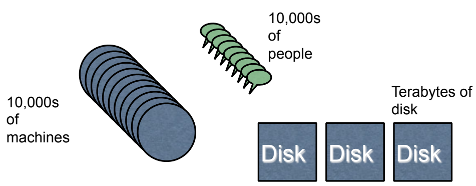
andrew.cmu.edu

- Let’s start with a familiar example: andrew



Goal: Have a consistent namespace for files across computers. Allow any authorized user to access their files from any computer

Why DFSs are Useful

- Data sharing among multiple users
- User mobility
- Location transparency
- Backups and centralized management

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What Distributed File Systems Provide

- Access to data stored at servers using file system interfaces
- What are the file system interfaces?
  - Open a file, check status of a file, close a file
  - Read data from a file
  - Write data to a file
  - Lock a file or part of a file
  - List files in a directory, create/delete a directory
  - Delete a file, rename a file, add a symlink to a file
  - etc

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Challenges

- Remember our initial list of challenges...
- Heterogeneity (lots of different computers & users)
- Scale (10s of thousands of peeps!)
- Security (my files! hands off!)
- Failures
- Concurrency
- oh no... we’ve got ‘em all.

How can we build this??

Just as important: non-challenges

- Geographic distance and high latency
  - Andrew and AFS target the campus network, *not* the wide-area

Prioritized goals? / Assumptions

- Often very useful to have an explicit list of prioritized goals. Distributed filesystems almost always involve trade-offs
- Scale, scale, scale
- User-centric workloads... how do users use files (vs. big programs?)
  - Most files are personally owned
  - Not too much concurrent access; user usually only at one or a few machines at a time
  - Sequential access is common; reads much more common that writes
  - There is locality of reference (if you've edited a file recently, you're likely to edit again)

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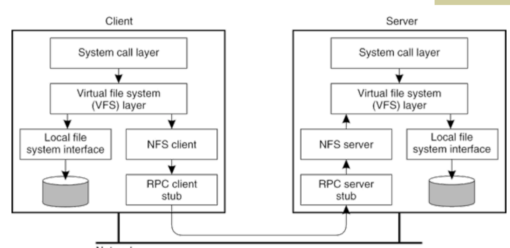
Components in a DFS Implementation

- Client side:
  - What has to happen to enable applications to access a remote file the same way a local file is accessed?
  - Accessing remote files in the same way as accessing local files → kernel support
- Communication layer:
  - Just TCP/IP or a protocol at a higher level of abstraction?
- Server side:
  - How are requests from clients serviced?

VFS interception

- VFS provides "pluggable" file systems
- Standard flow of remote access
  - User process calls read()
  - Kernel dispatches to VOP_READ() in some VFS
  - nfs_read()
    - check local cache
    - send RPC to remote NFS server
    - put process to sleep
  - server interaction handled by kernel process
    - retransmit if necessary
    - convert RPC response to file system buffer
    - store in local cache
    - wake up user process
  - nfs_read()
    - copy bytes to user memory

VFS Interception



A Simple Approach

- Use RPC to forward every filesystem operation to the server
  - Server serializes all accesses, performs them, and sends back result.
- Great: Same behavior as if both programs were running on the same local filesystem!
- Bad: Performance can stink. Latency of access to remote server often much higher than to local memory.
- For andrew context: bad bad bad: server would get hammered!

Lesson 1: Needing to hit the server for every detail impairs performance and scalability.

Question 1: How can we avoid going to the server for everything? *What* can we avoid this for? What do we lose in the process?

NFS V2 Design

- "Dumb", "Stateless" servers w/ smart clients
- Portable across different OSes
- Low implementation cost
- Small number of clients
- Single administrative domain

Some NFS V2 RPC Calls

- NFS RPCs using XDR over, e.g., TCP/IP

Proc.	Input args	Results
LOOKUP	dirfh, name	status, fhandle, fattr
READ	fhandle, offset, count	status, fattr, data
CREATE	dirfh, name, fattr	status, fhandle, fattr
WRITE	fhandle, offset, count, data	status, fattr

- fhandle: 32-byte opaque data (64-byte in v3)

Server Side Example: mountd and nfsd

- mountd: provides the initial file handle for the exported directory
  - Client issues nfs_mount request to mountd
  - mountd checks if the pathname is a directory and if the directory should be exported to the client
- nfsd: answers the RPC calls, gets reply from local file system, and sends reply via RPC
  - Usually listening at port 2049
- Both mountd and nfsd use underlying RPC implementation

NFS V2 Operations

- V2:
  - NULL, GETATTR, SETATTR
  - LOOKUP, READLINK, READ
  - CREATE, WRITE, REMOVE, RENAME
  - LINK, SYMLINK
  - READIR, MKDIR, RMDIR
  - STATFS (get file system attributes)

NFS V3 and V4 Operations

- V3 added:
  - READDIRPLUS, COMMIT (server cache!)
  - FSSTAT, FSINFO, PATHCONF
- V4 added:
  - COMPOUND (bundle operations)
  - LOCK (server becomes more stateful!)
  - PUTROOTFH, PUTPUBFH (no separate MOUNT)
  - Better security and authentication
  - Very different than V2/V3 → stateful

Operator Batching

- Should each client/server interaction accomplish one file system operation or multiple operations?
  - Advantage of batched operations?
  - How to define batched operations
- Examples of Batched Operators
  - NFS v3:
    - READDIRPLUS
  - NFS v4:
    - COMPOUND RPC calls

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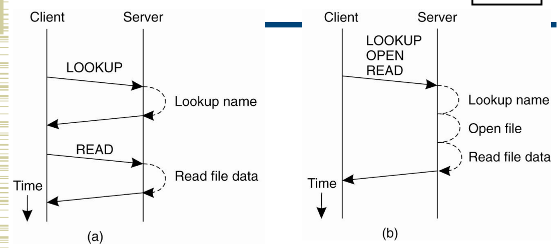
Remote Procedure Calls in NFS



- (a) Reading data from a file in NFS version 3
- (b) Reading data using a compound procedure in version 4.

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AFS Goals

- Global distributed file system
  - "One AFS", like "one Internet"
    - Why would you want more than one?
- **LARGE** numbers of clients, servers
  - 1000 machines could cache a single file,
  - Most local, some (very) remote
- Goal: O(0) work per client operation
  - O(1) may just be too expensive!

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AFS Assumptions

- Client machines are un-trusted
  - Must **prove** they act for a specific user
    - Secure RPC layer
  - Anonymous "system:anyuser"
- Client machines have disks(!!)
  - Can cache whole files over long periods
- Write/write and write/read sharing are rare
  - Most files updated by one user, on one machine

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AFS Cell/Volume Architecture

- Cells correspond to administrative groups
  - /afs/andrew.cmu.edu is a ***cell***
- Cells are broken into ***volumes*** (miniature file systems)
  - One user's files, project source tree, ...
  - Typically stored on one server
  - Unit of disk quota administration, backup
- Client machine has cell-server database
  - ***protection server*** handles authentication
  - ***volume location server*** maps volumes to servers

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Topic 1: Client-Side Caching

- Huge parts of systems rely on two solutions to every problem:
  1. "All problems in computer science can be solved by adding another level of indirection. But that will usually create another problem." -- David Wheeler
  2. Cache it!

Client-Side Caching

- So, uh, what do we cache?
  - Read-only file data and directory data → easy
  - Data written by the client machine → when is data written to the server? What happens if the client machine goes down?
  - Data that is written by other machines → how to know that the data has changed? How to ensure data consistency?
  - Is there any pre-fetching?
- And if we cache... doesn't that risk making things inconsistent?

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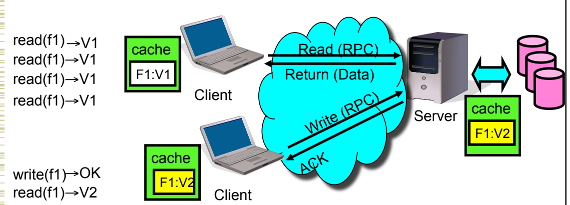
Failures

- Server crashes
  - Data in memory but not disk lost
  - So... what if client does
    - seek() ; /* SERVER CRASH */; read()
    - If server maintains file position, this will fail. Ditto for open(), read()
- Lost messages: what if we lose acknowledgement for delete("foo")
  - And in the meantime, another client created foo anew?
- Client crashes
  - Might lose data in client cache

Use of caching to reduce network load



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Client Caching in NFS v2

- Cache both clean and dirty file data and file attributes
- File attributes in the client cache expire after 60 seconds (file data doesn't expire)
- File data is checked against the modified-time in file attributes (which could be a cached copy)
  - Changes made on one machine can take up to 60 seconds to be reflected on another machine
- Dirty data are buffered on the client machine until file close or up to 30 seconds
  - If the machine crashes before then, the changes are lost

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Implication of NFS v2 Client Caching

- Advantage: No network traffic if open/read/write/close can be done locally.
- But…. Data consistency guarantee is very poor
  - Simply unacceptable for some distributed applications
  - Productivity apps tend to tolerate such loose consistency
- Generally clients do not cache data on local disks

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NFS' s Failure Handling – Stateless Server

- Files are state, but...
- Server exports files without creating extra state
  - No list of "who has this file open" (permission check on each operation on open file!)
  - No "pending transactions" across crash
- Crash recovery is "fast"
  - Reboot, let clients figure out what happened
- State stashed elsewhere
  - Separate MOUNT protocol
  - Separate NLM locking protocolStateless design
- Stateless protocol: requests specify exact state. read() → read([position]). no seek on server.

NFS' s Failure Handling

- Operations are idempotent
  - How can we ensure this? Unique IDs on files/directories. It' s not delete("foo"), it' s delete(1337f00f), where that ID won' t be reused.
- Write-through caching: When file is closed, all modified blocks sent to server. close() does not return until bytes safely stored.
  - Close failures?
    - retry until things get through to the server
    - return failure to client
  - Most client apps can' t handle failure of close() call.
  - Usual option: hang for a long time trying to contact server

NSF Results

- NFS provides transparent, remote file access
- Simple, portable, *really popular*
  - (it' s gotten a little more complex over time, but...)
- Weak consistency semantics
- Requires hefty server resources to scale (write-through, server queried for lots of operations)

Let' s look back at Andrew

- NFS gets us partway there, but
  - Probably doesn' t handle scale (* - you can buy huge NFS appliances today that will, but they' re $$$-y).
  - Is very sensitive to network latency
- How can we improve this?
  - More aggressive caching (AFS caches on disk in addition to just in memory)
  - Prefetching (on open, AFS gets entire file from server, making later ops local & fast).
    - Remember: with traditional hard drives, large sequential reads are much faster than small random writes. So easier to support (client a: read whole file; client B: read whole file) than having them alternate. Improves scalability, particularly if client is going to read whole file anyway eventually.

Client Caching in AFS

- Callbacks! Clients register with server that they have a copy of file;
  - Server tells them: "Invalidate!" if the file changes
  - This trades state for improved consistency
- What if server crashes? Lose all callback state!
  - Reconstruct callback information from client: go ask everyone "who has which files cached?"

AFS v2 RPC Procedures

- Procedures that are not in NFS
  - Fetch: return status and optionally data of a file or directory, and place a callback on it
  - RemoveCallBack: specify a file that the client has flushed from the local machine
  - BreakCallBack: from server to client, revoke the callback on a file or directory
    - What should the client do if a callback is revoked?
  - Store: store the status and optionally data of a file
- Rest are similar to NFS calls

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Topic 2: File Access Consistency

- In UNIX local file system, concurrent file reads and writes have “sequential” consistency semantics
  - Each file read/write from user-level app is an atomic operation
    - The kernel locks the file vnode
  - Each file write is immediately visible to all file readers
- Neither NFS nor AFS provides such concurrency control
  - NFS: “sometime within 30 seconds”
  - AFS: session semantics for consistency

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Session Semantics in AFS v2

- What it means:
  - A file write is visible to processes on the same box immediately, but not visible to processes on other machines until the file is closed
  - When a file is closed, changes are visible to new opens, but are not visible to “old” opens
  - All other file operations are visible everywhere immediately
- Implementation
  - Dirty data are buffered at the client machine until file close, then flushed back to server, which leads the server to send “break callback” to other clients

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AFS Write Policy

- Writeback cache
  - Opposite of NFS “every write is sacred”
  - Store chunk back to server
    - When cache overflows
    - On last user close()
  - ...or don't (if client machine crashes)
- Is writeback crazy?
  - Write conflicts “assumed rare”
  - Who wants to see a half-written file?

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Results for AFS

- Lower server load than NFS
  - More files cached on clients
  - Callbacks: server not busy if files are read-only (common case)
- But maybe slower: Access from local disk is much slower than from another machine’s memory over LAN
- For both:
  - Central server is bottleneck: all reads and writes hit it at least once;
  - is a single point of failure.
  - is costly to make them fast, beefy, and reliable servers.

Topic 3: Name-Space Construction and Organization

- NFS: per-client linkage
  - Server: export /root/fs1/
  - Client: mount server:/root/fs1 /fs1
- AFS: global name space
  - Name space is organized into Volumes
    - Global directory /afs;
    - /afs/cs.wisc.edu/vol1/…; /afs/cs.stanford.edu/vol1/…
  - Each file is identified as fid = <vol_id, vnode #, unique identifier>
  - All AFS servers keep a copy of “volume location database”, which is a table of vol_id→ server_ip mappings

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Implications on Location Transparency

- NFS: no transparency
  - If a directory is moved from one server to another, client must remount
- AFS: transparency
  - If a volume is moved from one server to another, only the volume location database on the servers needs to be updated

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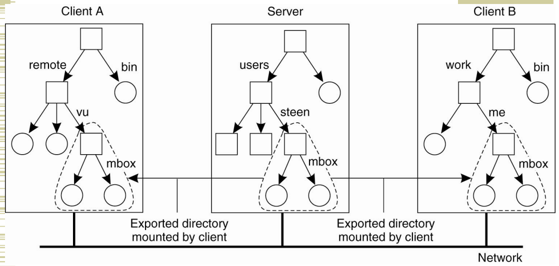
Naming in NFS (1)



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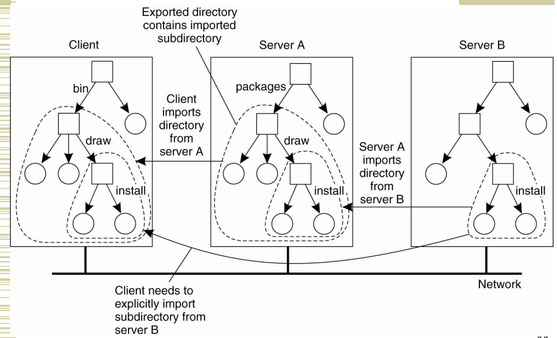
Naming in NFS (2)



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Topic 4: User Authentication and Access Control

- User X logs onto workstation A, wants to access files on server B
  - How does A tell B who X is?
  - Should B believe A?
- Choices made in NFS V2
  - All servers and all client workstations share the same <uid, gid> name space → B send X's <uid,gid> to A
    - Problem: root access on any client workstation can lead to creation of users of arbitrary <uid, gid>
  - Server believes client workstation unconditionally
    - Problem: if any client workstation is broken into, the protection of data on the server is lost;
    - <uid, gid> sent in clear-text over wire → request packets can be faked easily

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User Authentication (cont'd)

- How do we fix the problems in NFS v2
  - Hack 1: root remapping → strange behavior
  - Hack 2: UID remapping → no user mobility
  - Real Solution: use a centralized Authentication/ Authorization/Access-control (AAA) system

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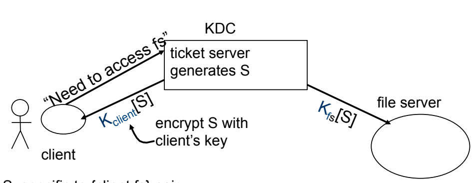
A Better AAA System: Kerberos

- Basic idea: shared secrets
  - User proves to KDC who he is; KDC generates shared secret between client and file server



S: specific to {client,fs} pair;
"short-term session-key"; expiration time (e.g. 8 hours)

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Today's bits

- Distributed filesystems almost always involve a tradeoff: consistency, performance, scalability.
- We've learned a lot since NFS and AFS (and can implement faster, etc.), but the general lesson holds. Especially in the wide-area.
- We'll see a related tradeoff, also involving consistency, in a while: the CAP tradeoff. Consistency, Availability, Partition-resilience.

More bits

- Client-side caching is a fundamental technique to improve scalability and performance
  - But raises important questions of cache consistency
- Timeouts and callbacks are common methods for providing (some forms of) consistency.
- AFS picked close-to-open consistency as a good balance of usability (the model seems intuitive to users), performance, etc.
  - AFS authors argued that apps with highly concurrent, shared access, like databases, needed a different model

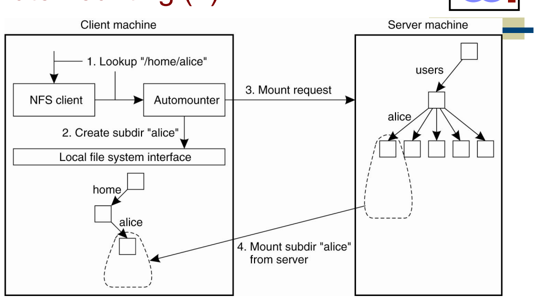
AFS Retrospective

- Small AFS installations are hard
  - Step 1: Install Kerberos
    - 2-3 servers
    - Inside locked boxes!
  - Step 2: Install ~4 AFS servers (2 data, 2 pt/vldb)
  - Step 3: Explain Kerberos to your users
    - Ticket expiration!
  - Step 4: Explain ACLs to your users

AFS Retrospective

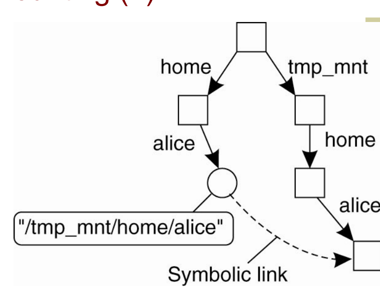
- Worldwide file system
- Good security, scaling
- Global namespace
- “Professional” server infrastructure per cell
  - Don't try this at home
  - Only ~190 AFS cells (2002-03)
    - 8 are cmu.edu, 14 are in Pittsburgh
- “No write conflict” model only partial success

Automounting (1)



- A simple automounter for NFS.

Automounting (2)



- Using symbolic links with automounting.

Access Consistency in the "Sprite" File System

- Sprite: a research file system developed in UC Berkeley in late 80's
- Implements "sequential" consistency
  - Caches only file data, not file metadata
  - When server detects a file is open on multiple machines but is written by some client, client caching of the file is disabled; all reads and writes go through the server
  - "Write-back" policy otherwise
    - Why?

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Implementing Sequential Consistency

- How to identify out-of-date data blocks
  - Use file version number
  - No invalidation
  - No issue with network partition
- How to get the latest data when read-write sharing occurs
  - Server keeps track of last writer

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Implication of "Sprite" Caching

- Server must keep states!
  - Recovery from power failure
  - Server failure doesn't impact consistency
  - Network failure doesn't impact consistency
- Price of sequential consistency: no client caching of file metadata; all file opens go through server
  - Performance impact
  - Suited for wide-area network?

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"Tokens" in DCE DFS

- How does one implement sequential consistency in a file system that spans multiple sites over WAN
- Callbacks are evolved into 4 kinds of "Tokens"
  - Open tokens: allow holder to open a file; submodes: read, write, execute, exclusive-write
  - Data tokens: apply to a range of bytes
    - "read" token: cached data are valid
    - "write" token: can write to data and keep dirty data at client
  - Status tokens: provide guarantee of file attributes
    - "read" status token: cached attribute is valid
    - "write" status token: can change the attribute and keep the change at the client
  - Lock tokens: allow holder to lock byte ranges in the file

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Compatibility Rules for Tokens

- Open tokens:
  - Open for exclusive writes are incompatible with any other open, and "open for execute" are incompatible with "open for write"
  - But "open for write" can be compatible with "open for write" --- why?
- Data tokens: R/W and W/W are incompatible if the byte range overlaps
- Status tokens: R/W and W/W are incompatible
- Data token and status token: compatible or incompatible?

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Token Manager

- Resolve conflicts: block the new requester and send notification to other clients' tokens
- Handle operations that request multiple tokens
  - Example: rename
  - How to avoid deadlocks

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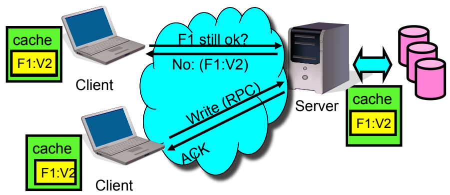
NFS Cache consistency

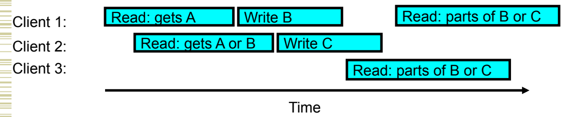
- Client polls server periodically to check for changes
  - Polls server if data hasn't been checked in last 3-30 seconds (exact timeout is tunable parameter).
  - When file is changed on one client, server is notified, but other clients use old version of file until timeout.



- What if multiple clients write to same file?
  - In NFS, can get either version (or parts of both)
  - Completely arbitrary!

Sequential Ordering Constraints

- What sort of cache coherence might we expect?
  - i.e. what if one CPU changes file, and before it's done, another CPU reads file?
- Example: Start with file contents = "A"



- What would we actually want?
  - Assume we want distributed system to behave exactly the same as if all processes are running on single system
    - If read finishes before write starts, get old copy
    - If read starts after write finishes, get new copy
    - Otherwise, get either new or old copy
  - For NFS:
    - If read starts more than 30 seconds after write, get new copy; otherwise, could get partial update

Andrew File System

- Andrew File System (AFS, late 80's) → DCE DFS (commercial product)
- Callbacks: Server records who has copy of file
  - On changes, server immediately tells all with old copy
  - No polling bandwidth (continuous checking) needed
- Write through on close
  - Changes not propagated to server until close()
  - Session semantics: updates visible to other clients only after the file is closed
    - As a result, do not get partial writes: all or nothing!
    - Although, for processes on local machine, updates visible immediately to other programs who have file open
- In AFS, everyone who has file open sees old version
  - Don't get newer versions until reopen file

Andrew File System (con't)

- Data cached on local disk of client as well as memory
  - On open with a cache miss (file not on local disk):
    - Get file from server, set up callback with server
  - On write followed by close:
    - Send copy to server; tells all clients with copies to fetch new version from server on next open (using callbacks)
- What if server crashes? Lose all callback state!
  - Reconstruct callback information from client: go ask everyone "who has which files cached?"
- AFS Pro: Relative to NFS, less server load:
  - Disk as cache ⇒ more files can be cached locally
  - Callbacks ⇒ server not involved if file is read-only
- For both AFS and NFS: central server is bottleneck!
  - Performance: all writes→server, cache misses→server
  - Availability: Server is single point of failure
  - Cost: server machine's high cost relative to workstation

Communication Layer Example: Remote Procedure Calls (RPC)

RPC call

xid
"call"
service
version
procedure
auth-info
arguments ….

RPC reply

xid
"reply"
reply_stat
auth-info
results …

- Failure handling: timeout and re-issue

Extended Data Representation (XDR)

- Argument data and response data in RPC are packaged in XDR format
  - Integers are encoded in big-endian format
  - Strings: len followed by ascii bytes with NULL padded to four-byte boundaries
  - Arrays: 4-byte size followed by array entries
  - Opaque: 4-byte len followed by binary data
- Marshalling and un-marshalling data
- Extra overhead in data conversion to/from XDR

Client Caching in AFS v2

- Client caches both clean and dirty file data and attributes
  - The client machine uses local disks to cache data
  - When a file is opened for read, the whole file is fetched and cached on disk
    - Why? What's the disadvantage of doing so?
- However, when a client caches file data, it obtains a "callback" on the file
- In case another client writes to the file, the server "breaks" the callback
  - Similar to invalidations in distributed shared memory implementations
- Implication: file server must keep state!

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Semantics of File Sharing

Method	Comment
UNIX semantics	Every operation on a file is instantly visible to all processes
Session semantics	No changes are visible to other processes until the file is closed
Immutable files	No updates are possible; simplifies sharing and replication
Transactions	All changes occur atomically

- Four ways of dealing with the shared files in a distributed system.

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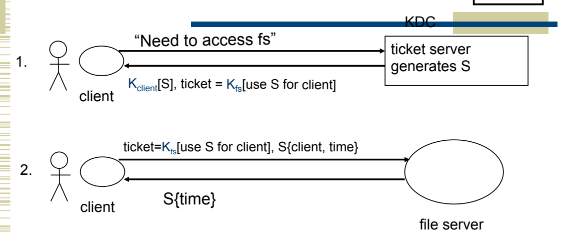
Kerberos Interactions



- Why "time"?: guard against replay attack
- mutual authentication
- File server doesn't store S, which is specific to {client, fs}
- Client doesn't contact "ticket server" every time it contacts fs

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AFS Security (Kerberos)

- Kerberos has multiple administrative domains (realms)
  - principal@realm
  - srini@cs.cmu.edu sseshan@andrew.cmu.edu
- Client machine presents Kerberos ticket
  - Arbitrary binding of (user,machine) to Kerberos (principal,realm)
    - dongsuh on grad.pc.cs.cmu.edu machine can be srini@cs.cmu.edu
- Server checks against access control list (ACL)

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AFS ACLs

- Apply to directory, not to file
- Format:
  - sseshan rlidwka
  - srini@cs.cmu.edu rl
  - sseshan:friends rl
- Default realm is typically the cell name (here andrew.cmu.edu)
- Negative rights
  - Disallow "joe rl" even though joe is in sseshan:friends

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Failure Recovery in AFS & NFS

- What if the file server fails?
- What if the client fails?
- What if both the server and the client fail?
- Network partition
  - How to detect it? How to recover from it?
  - Is there anyway to ensure absolute consistency in the presence of network partition?
    - Reads
    - Writes
- What if all three fail: network partition, server, client?

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Key to Simple Failure Recovery

- Try not to keep any state on the server
- If you must keep some state on the server
  - Understand why and what state the server is keeping
  - Understand the worst case scenario of no state on the server and see if there are still ways to meet the correctness goals
  - Revert to this worst case in each combination of failure cases

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