Distributed systems

Lecture 16: Security and NASD/AFS/Coda case studies

Michaelmas 2018

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(With thanks to Dr Robert N. M. Watson
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Last time

- Looked at replication in distributed systems
- **Strong consistency**:
  - Approximately as if only one copy of object
  - Requires considerable coordination on updates
  - Transactional consistency & **quorum systems**
- **Weak consistency**:
  - Allow clients to potentially read stale values
  - Some guarantees can be provided (FIFO, eventual, session), but at additional cost to availability
- Amazon/Google case studies
  - Dynamo, MapReduce, BigTable, Spanner

Distributed-system security

- Distributed systems span **administrative domains**
- Natural to extend **authentication**, **access control**, **audit**, to distributed system, but can we:
  - Distribute local notions of a **user** over many machines?
  - Enforce system-wide properties – e.g., **personal data privacy**?
  - Allow systems operated by multiple parties to **interact safely**?
  - Not require that networks be safe from **monitoring/tampering**?
  - **Tolerate compromise** a subset of nodes in the system?
  - Provide **reliable service** to most users even under attack?
  - Accept and tolerate **nation-state actors** as adversaries?
- For a system to offer secure services, it must be secure
  - **Trusted Computing Base** (**TCB**) – minimum software (or hardware) required for a system to be secure
  - Deploy compartmentalization-style sandboxing structures

Access control

- Distributed systems may want to allow access to resources based on a security policy
- As with local systems, three key concepts:
  - **Identification**: who you are (e.g. user name)
  - **Authentication**: proving who you are (e.g. password)
  - **Authorization**: determining what you can do
- Can consider authority to cover actions an authenticated subject may perform on objects
  - **Access Matrix** = set of rows, one per **subject**, where each column holds allowed operations on some **object**

The access-control matrix

	Object_1	Object_2	Object_3	…
User_1		+read		
User_2	+read +write	+read		
Group_1	-read		+read +write	
…				

- **A(i, j)**
  - Rows represent principals (sometimes groups)
  - Columns represent objects
  - **Cell(i, j)** contain access rights of row **i** on object **j**
- Access matrix is typically large & sparse:
  - Just keep non-NULL entries by column or by row
- Tricky questions
  - How do you name/authenticate users, and who can administer groups?
  - How do you compose conflicting access-control rules (e.g., **user1 +read** but **group1 –read**)?
  - What consistency properties do access control, groups, and users require?

Access Control Lists (ACLs)

- Keep columns: for each object, keep **list of subjects** and **allowable access**
  - ACLs stored with **objects** (e.g. local filesystem)
  - Key primitives: **get**/**set**
  - Like a guest list on the door of a night club
- ACL change should (arguably) immediately grant/deny further access
  - What does this mean for distributed systems?
  - Or even local systems (e.g., UNIX)

Capabilities

- Capabilities are **unforgeable tokens of authority**
  - Keep rows: for each subject **S**, keep list of objects / allowable accesses
  - Capabilities stored with **subjects** (e.g. processes)
  - A bit like a key or access card that you carry around
  - Think of as **secure references** – if you hold a reference to an object, you can use the object
- Key primitive: **delegation**
  - Client can delegate capabilities it holds to other clients (or servers) in the system to act on its behalf
  - Downside: **revocation** may now be more complex

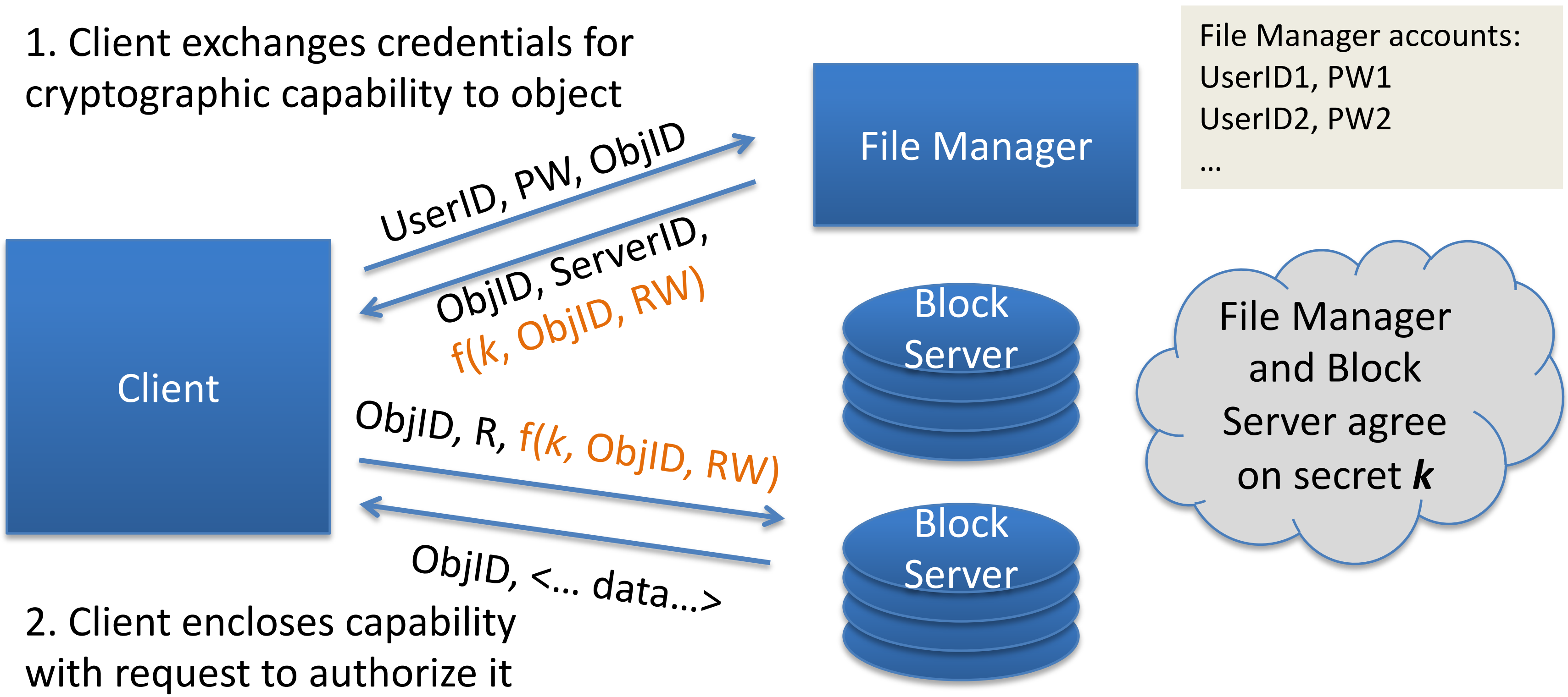
Access control in distributed systems

- Single systems often have small number of users (**subjects**) and large number of **objects**:
  - E.g. users and their files in a Unix system
  - Track subjects (e.g. users) and store ACLs with objects (e.g. files)
- Distributed systems are large & dynamic:
  - Can have huge (and unknown?) number of users
  - Interactions via network; no explicit ‘log in’ or user processes
- Capability model is a more natural fit:
  - Client presents capability with request for operation
  - System only performs operation if capability checks out
  - Avoid synchronous RPCs to check identities/policies
- Not mutually exclusive: ACLs can grant capabilities
- Can’t trust nodes/links: use **cryptography with secret keys**

Cryptographic capabilities

- How can we make capabilities **unforgeable**?
- Capability server could issue capabilities
  - User presents credentials (e.g., username, password) and requests capabilities representing specific rights
  - E.g. capability server has secret key **k** and a one-way function **f**()
  - Issues a capability <*ObjID*, *access*, **f**(**k**, *ObjID*, *access*) >
  - Simple example is **f**(k,o,a) = **SHA256**(k|o|a)
- Client transmits capability with request
  - If object server knows **k**, can check operation
- Can use same capability to access many servers
  - And one server can use it on your behalf (e.g., web tier can request objects from storage tier on user's behalf)
- More mature scheme might use public key crypto (why?)

Distributed capability example: NASD



- **Network-Attached Secure Disks (NASD)** – Gibson, et al 1997 (CMU)
- Clients access remote disks directly rather than via through servers
- “File Manager” grants client systems **capabilities** delegating direct access to objects on network-attached disks – as directed by ACLs

Capabilities: pros and cons

- Relatively simple and pretty scalable
- Allow anonymous access (i.e. server does not need to know identity of client)
  - And hence easily **allows delegation**
- However this also means:
  - Capabilities can be stolen (unauthorized users)…
  - … and are **difficult to revoke** (like someone cutting a copy of your house key)
- Can address these problems by:
  - Having time-limited validity (e.g. 30 seconds)
  - Incorporating version into capability, store version with the object: increasing version => revoke all access

Combining ACLs and capabilities

- Recall one problem with ACLs was inability to scale to large number of users (subjects)
- However in practice we may have a small-ish number of authority levels
  - E.g. moderator versus contributor on chat site
- **Role-Based Access Control (RBAC)**:
  - Have (small-ish) well-defined number of **roles**
  - Store ACLs at objects based on roles
  - Allow subjects to **enter** roles according to some rules
  - Issue capabilities which attest to current role

Role-based access control (RBAC)

- General idea is very powerful
  - Separates { **principal** → **role** }, { **role** → **privilege** }
  - Developers of individual services only need to focus on the rights associated with a role
  - Easily handles evolution (e.g. an individual moves from being an undergraduate to an alumna)
- Possible to have sophisticated rules for role entry:
  - E.g. enter different role according to time of day
  - Or entire role hierarchy (1B student <= CST student)
  - Or parametric/complex roles ("the doctor who is currently treating you")

Single-system sign on

- Distributed systems involve many machines
  - Frustrating to have to authenticate to each one!
- Single-system sign-on: security with lower user burden
  - E.g. Kerberos, Microsoft Active Directory let you authenticate to a single **domain controller**
  - Bootstrap via password/private key + cert. on smart card
  - Get a **session key** and a **ticket** (~= a capability)
  - Ticket is for access to the **ticket-granting server** (**TGS**)
  - When wish to e.g. log on to another machine, or access a remote volume, s/w asks **TGS** for a ticket for that resource
  - Notice: **principals** might could be users … or **services**
- Other wide-area "federated" schemes
  - Multi-realm Kerberos, OpenID, Shibboleth

AFS and Coda

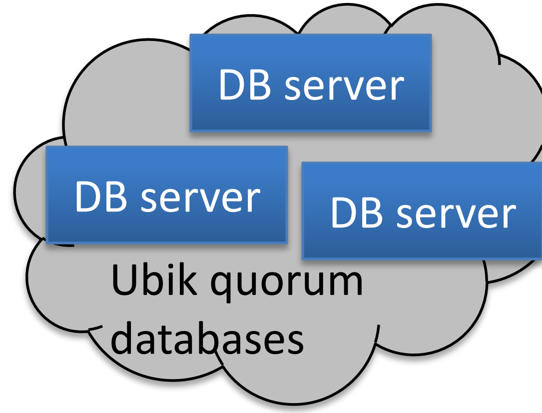
- Two 1990s CMU distributed file systems that helped create our understanding of distributed-system scalability, security, …
  - **AFS**: Andrew File System "campus-wide" scalability
  - **Coda**: Add write replication, weakly connected or fully disconnected operation for mobile clients
- Scale distributed file systems to **global scale** using a concurrent and distributed-system ideas
  - Developed due to NFS scalability failures
  - RPC, close-to-open semantics, pure and impure names, explicit cache management, security, version vectors, optimistic concurrency, quorums, multicast, …

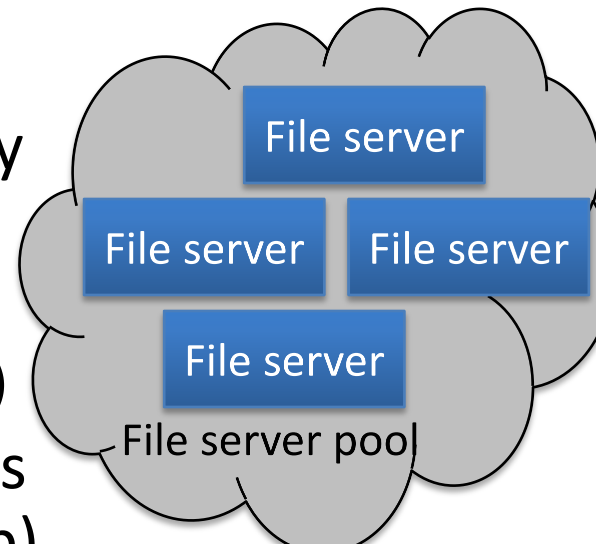
The Andrew File System (AFS)

- Carnegie Mellon University (1980s) address performance, scalability, security weaknesses of NFS
- Global-scale distributed filesystem
  - **/afs/cs.cmu.edu/user/rnw/public_html/index.html**, **/afs/ibm.com/public**
  - **Cells** incorporate dozens or hundreds of servers
  - Clients transparently merge namespaces and hide file replication/migration effects
  - Authentication/access control w/Kerberos, group servers
  - Cryptographic protection of all communications
  - Mature non-POSIX semantics (**close-to-open**, **ACLs**)
- Still in use today; open sourced as OpenAFS
- Inspired **Distributed Computing Environment (DCE)**, **Microsoft's Distributed File System (DFS)**, and **NFSv4**

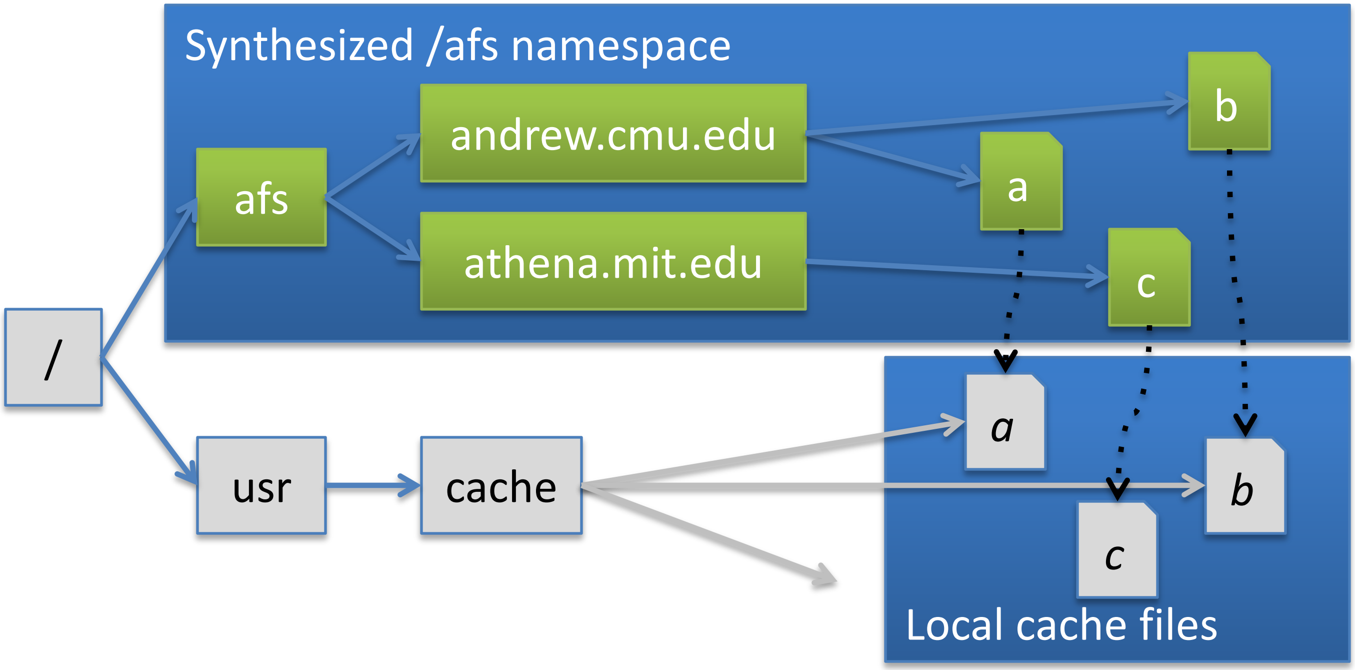
AFS3 per-cell architecture

- **Client-server** and **server-server RPC**
- **Ubik** quorum database for authentication, volume location, and group membership
- Namespace partitioned into volumes; e.g., /**afs**/**cmu.edu**/**user**/**rnw**/public_html traverses four volumes
- Unique **ViceIDs**: **{CellID, VolumeID, FID}**
- Volume servers allow limited redundancy or higher-performance bulk file I/O:
  - **read-write on a single server** (~rnw)
  - **read-only replicas on multiple servers** (/bin)
- Inter-server **snapshotting** allows volumes to migrate transparently (with client help)



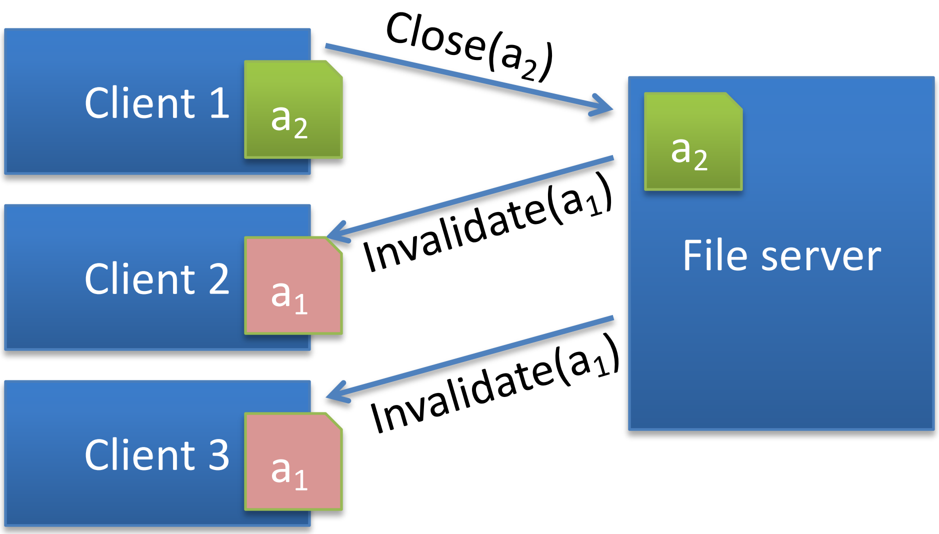


Persistent client-side caching in AFS



- AFS implements **persistent caches** on client-side disks
- Vnode operations on remote files are redirected to local **container files** for local I/O performance
- Non-POSIX **close-to-open semantics** allow writes to be sent to the server only on **close**()

AFS callback promises



- Servers issue **callback promises** on files held in client caches
- When a file server receives a write-**close**() from one client, it issues **callbacks** to invalidate copies in other client caches
- Unlike NFS, no synchronous RPC is required when opening a cached file: if callback has not been broken, cache is fresh
- However, client write-**close**() is **synchronous**: can't return until callbacks acknowledged by other clients – why?

The Coda File System

- Developed at Carnegie Mellon University in the 1990s
  - Starting point: open-sourced AFS2 from IBM
- Improve **availability**: optimistic replication, offline mode:
  - Improve availability through **read-write replication**
  - Improve performance for **weakly connected clients**
  - Support mobile (sometimes) **fully disconnected clients**
- Exploit network features to improve performance:
  - **Multicast RPC** to efficiently send RPCs to groups of servers
- Exchange **weaker consistency** for **stronger availability**
  - **Version vectors** for directories, files identify write conflicts
  - **Users resolve some conflicts** … with (very) mixed results?
- Surprising result: unplug network to make builds go faster
  - It is faster to journal changes to local disk (offline) and reconcile later than synchronously write to distributed filesystem (online)

Summary (1)

- Distributed systems are everywhere
- Core problems include:
  - Inherently concurrent systems
  - Any machine can fail…
  - … as can the network (or parts of it)
  - And we have no notion of global time
- Despite this, we can build systems that work
  - Basic interactions are request-response
  - Can build synchronous RPC/RMI on top of this …
  - Or asynchronous message queues or pub/sub

Summary (2)

- Coordinating actions of larger sets of computers requires higher-level abstractions
  - Process groups and ordered multicast
  - Consensus protocols, and
  - Replication and Consistency
- Various middleware packages (e.g. CORBA, EJB) provide implementations of many of these:
  - But worth knowing what’s going on “under the hood”
- Recent trends towards even higher-level:
  - **MapReduce** and friends