# Distributed systems

## Lecture 8: PubSub; Security; NASD/AFS/Coda

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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.

# Publish-subscribe (PubSub)

- Get more flexibility with publish-subscribe:
  - **Publishers** advertise and publish **events**
  - **Subscribers** register interest in **topics** (i.e. properties of events)
  - **Event-service** notifies subscribers of relevant published events
- Similar to reliable multicast, without ordering focus:
  - Asynchronous structure
  - Allows one-to-many communication
  - Dynamic membership: publishers/subscribers joining/leaving
- Sometimes described as **content-centric networking**
  - Engages not just hosts, but also **network routers**
  - Focus is on data, not network messaging
  - **Reliability** and **persistency** part of the programming model
- In effect the model being implemented by many **Content Distribution Networks (CDNs)** such as Akami, Netflix

# Publish-subscribe: pros and cons

- PubSub useful for ‘ad hoc’ systems such as embedded systems or sensor networks:
  - Client(s) can ‘listen’ for occasional events
  - Don’t need to define semantics of entire system in advance (e.g. what to do if get event <X>)
  - Promoted in recent research for higher-level applications
- Leads to natural “reactive” programming:
  - When <X>, <Y> occur then do <Z>
  - Event-driven systems like Apama can help understand business processes in real-time
- But:
  - Can be awkward to use if application doesn’t fit
  - And difficult to make perform well…

# Distributed-system security

- Distributed systems span **administrative domains**; content from many users and organizations
- 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 such as *personal data privacy*?
  - Allow systems operated by different 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 when under attack?
  - Accept and tolerate nation-state actors as adversaries?
- For a system to offer secure services, it must (itself) be secure
  - **Trusted Computing Base** (**TCB**) – the minimum software (or hardware) required for a system to be secure

# 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

# Recall: access-control matrix

| | **$\text{Object}_1$** | **$\text{Object}_2$** | **$\text{Object}_3$** | **…** |
|---|---|---|---|---|
| $\text{User}_1$ | | +read | | |
| $\text{User}_2$ | +read +write | +read | | |
| $\text{Group}_1$ | -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

# 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?

# 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)
  - Bit like a key or access card that you carry around
- 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

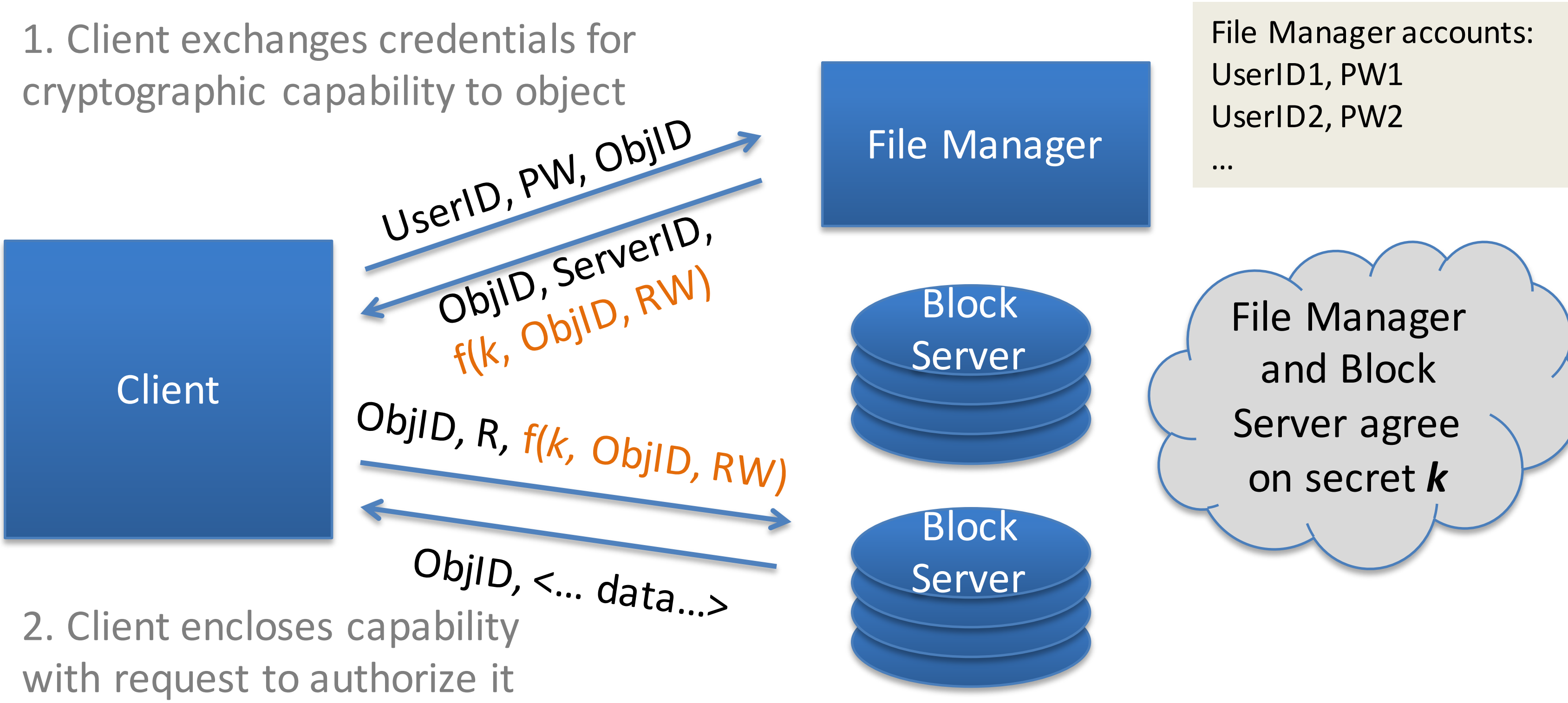
# Access control in distributed systems

- Single systems often have small number of users (**subjects**) and large number of **objects**:
  - E.g. a hundred of users in a Unix system
  - Track subjects (e.g. user IDs) 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 per-user process
- 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/access-control policies
- Not mutually exclusive: ACLs as a policy for granting capabilities
- Can't trust nodes or links: rely on **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 directly disks rather than via through servers
- "File Manager" grants client systems capabilities delegating direct access to objects on network-attached disks

# 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, and storing 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 alumnus)
- 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 eases user burden while maintaining security
  - E.g. Kerberos, Microsoft Active Directory let you authenticate to a single **domain controller**
  - Bootstrap using a password or private key / certificate 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

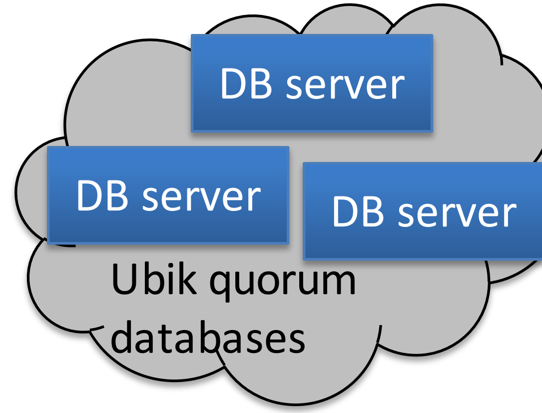
- Two CMU distributed file systems that helped create our understanding of distributed-system scalability
  - **AFS**: Andrew File System "campus-wide" scalability
  - **Coda**: Add write replication, weakly connected or fully disconnected operation for mobile clients
- Scale distributed file systems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

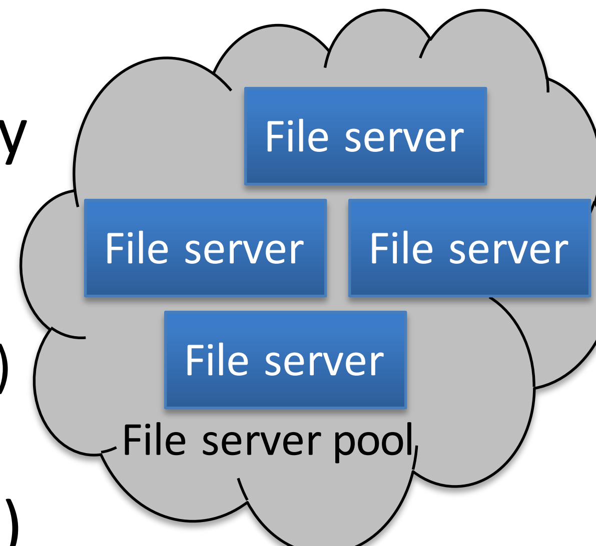
# The Andrew File System (AFS)

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

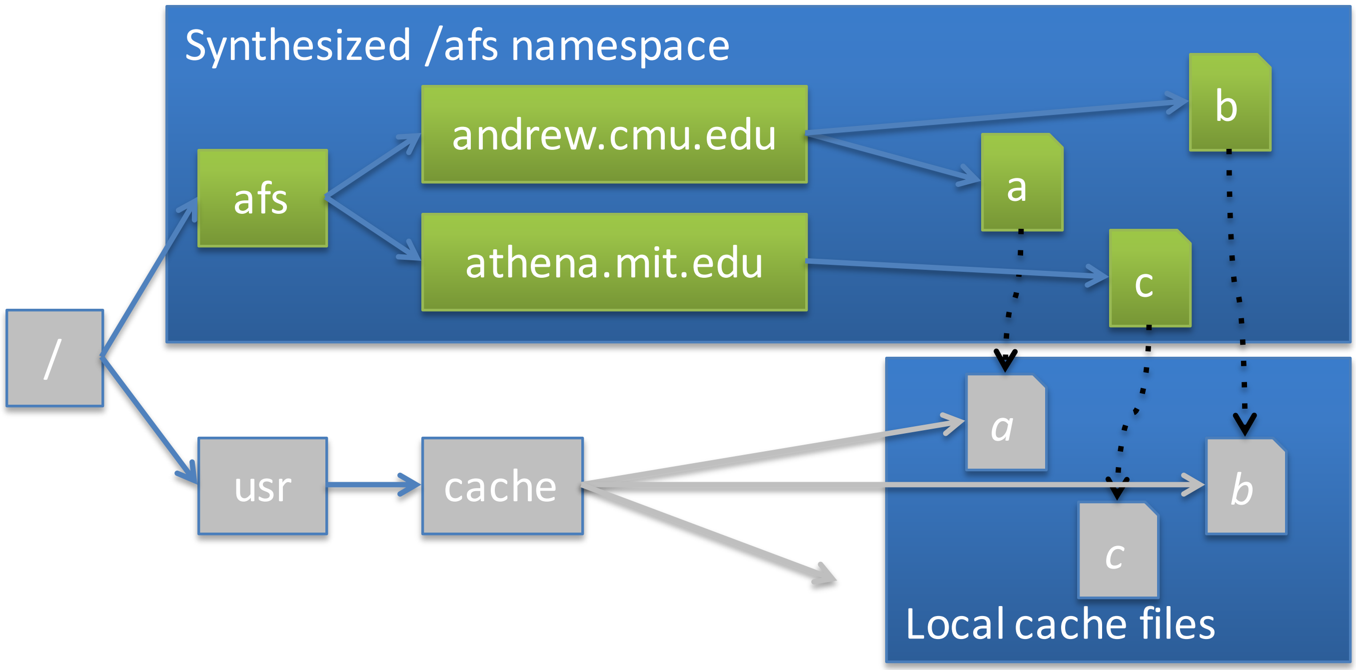
# AFS3 per-cell architecture

- **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 **ViceID**s: {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 in-use volumes to be migrated (with client help)



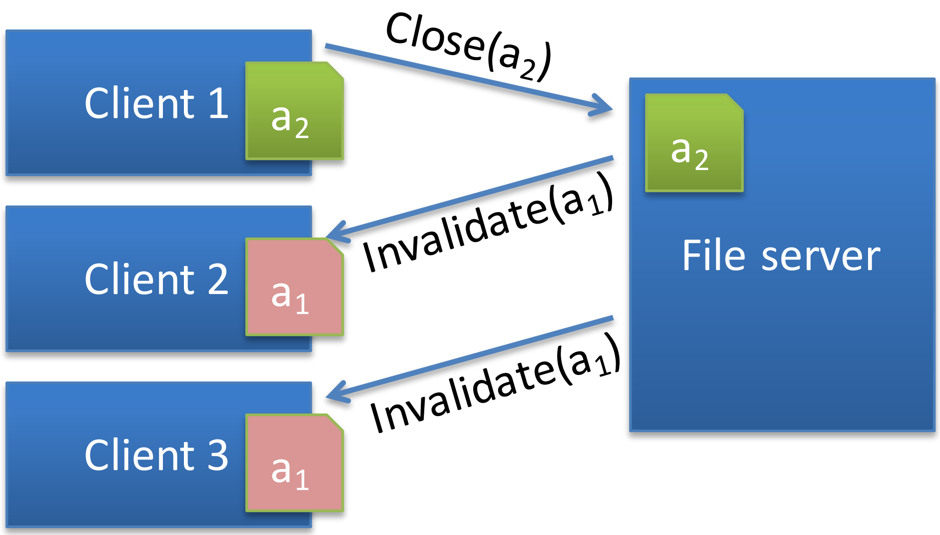



# Persistent client-side caching in AFS




- 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 is 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** through optimistic replication and client-side caching/journaling:
  - Improve availability through **read-write replication**
  - Improve performance for **weakly connected clients**
  - Support mobile (sometimes) **fully disconnected clients**
- Exploit new network features to improve performance:
  - Multicast RPC to efficiently send RPCs to groups of servers
- Key design challenge: trade off exposing weak consistency to user in return for availability

# Coda read-write server replication

- **Volume Storage Groups (VSGs)** rather than per-volume servers
- Each file has a **version vector**
  - Like a vector clock only per-object rather than per process
  - Each vector entry corresponds to one VSG server's version of the file
- Reachable VSG subset is the **Accessible Volume Storage Group (AVSG)**
- Clients **read** from any server, multicast **writes** to all
  - When fully online (AVSG = VSG) , **close**() is synchronous; writes ordered
  - On partition/server outage (AVSG $\subset$ VSG), writes are still permitted
  - As servers recover, client access triggers **server-server resolution**
  - If version vectors allow causal order to be established, automatic resolution
  - Most non-causal directory conflicts can be automatically resolved (why?)
  - For files, **user-directed** or **application-specific conflict resolution** is required
- What if a user is asked to resolve a conflict on a file they didn't modify?

# Coda disconnected operation

- Mobile computing – but devices had weak or intermittent connectivity
- Coda allowed client operations to continue against the persistent cache even when operating disconnected (AVSG = ∅)
- **Hoarding**: prior to going offline, users can provide Coda with policy as to which files should be preemptively loaded into the cache (e.g., user ~)
- Offline writes are logged in the **Client Modification Log (CML)**
  - When going back online, CML is replayed against AVSG (**reintegration**)
  - **CML optimization** deletes NOP sequences: e.g., create+delete a temp file
  - Client-server conflicts, as with server-server, are detected via version vectors
  - User/application must handle conflicts that can't be resolved automatically
  - Is this better than the server-server conflict resolution case?
- If Ethernet unplugged, software builds go faster – why?
  - Clever trick for weakly connected clients: if network is bottleneck, take volume offline and log changes, trickling them back asynchronously until caught up
- These ideas have influenced systems like Microsoft's "offline folders"

# 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