CS x55: Distributed Systems [Consistency]

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Frequently asked questions from the previous class survey

- How are vector clocks actually used?
- Causally ordered multicasting
- When would a stream be stateful? Why would we actually need it?

Colorado State University Professor: Shrideep Pallickara Computer Science Department Replication & Consistency L35.2

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Topics covered in this lecture

- Types of replicas
- Replicated write protocols
- Eventually Consistent

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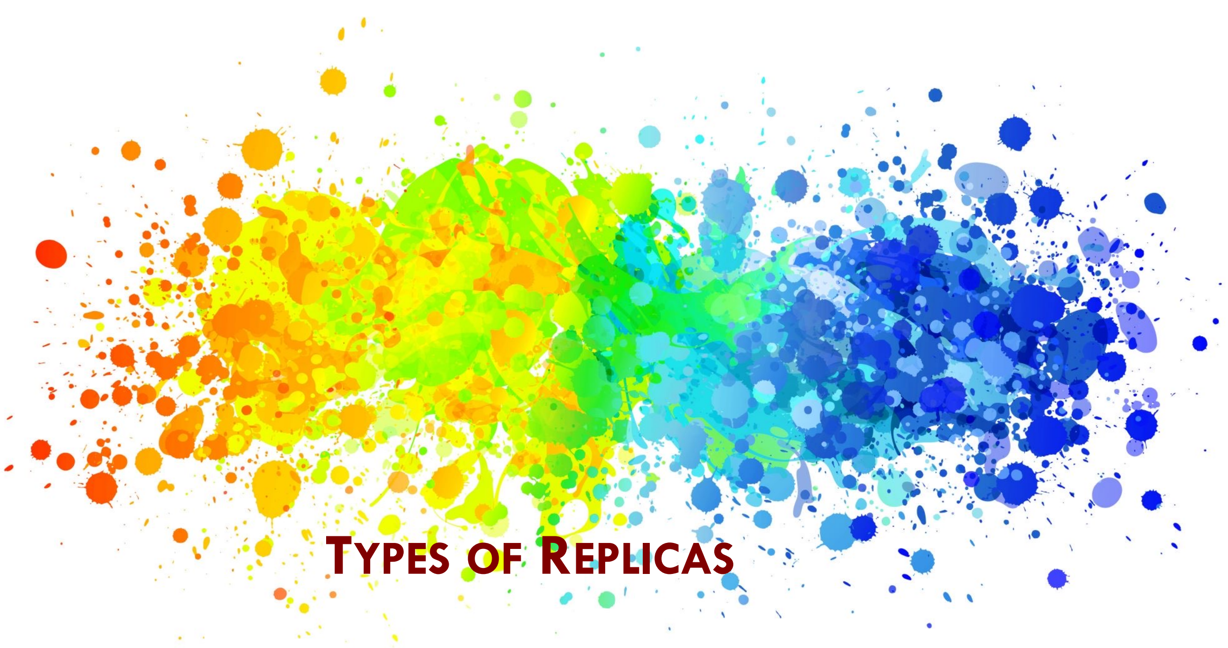

TYPES OF REPLICAS

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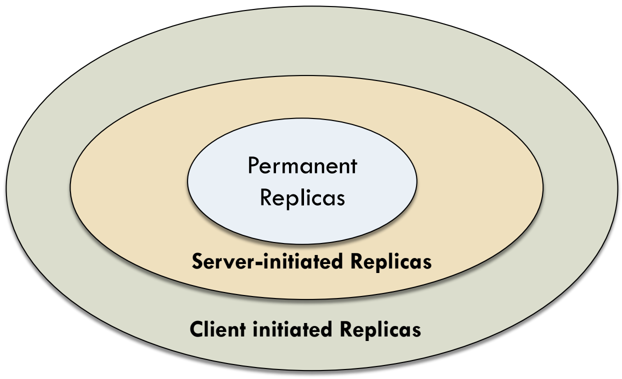
Types of Replicas



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Permanent Replicas

- Initial set of replicas that comprise data store
  - Usually a small set
- Files stored across servers at a *single* location
  - Request forwarded using **round-robin** strategy
- Files copied to **mirror** sites
  - Geographically dispersed

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Server initiated replicas

- Copies that exist to *enhance* performance
- Created at the **initiative** of the owner of data store

Server initiated replicas: Example

- Web server in NYC
  - Can handle dissemination loads effectively
- **Bursts** of traffic over 2-3 days may come in
  - From some specific location (or set of locations)
- Install **temporary replicas** in regions where requests originate

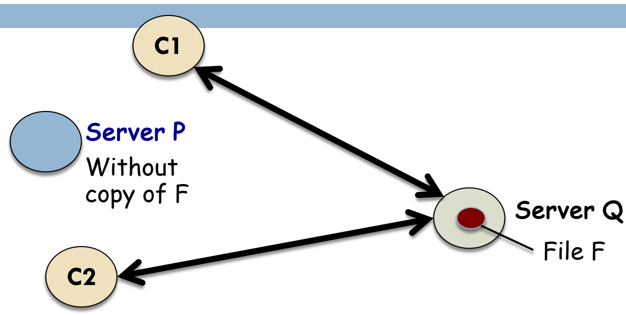
Server initiated replicas: Issues in dynamic replications

- Replication takes place to **reduce load** at server
- *Specific* files on server migrated/replicated to servers in **proximity** of requesting clients

Dynamic replication: Migrating/replicating files

- Each server tracks **access counts** per file
  - And also *who* initiates accesses
- Given a client C
  - Each server can determine which of the servers is closest to C

Counting access requests from clients: C1 and C2 share *closest* server P



- Accesses from C_1, C_2 for file F at server Q are registered as if they are from P
  - $count_Q(P, F)$

Replication threshold: $rep(S, F)$ for file F at server S

- Indicates number of requests for file is **high**
- Might be worth replicating it

Deletion thresholds

- When requests for file F at server S drops below deletion threshold, $del(S,F)$
  - File F removed from S
- Number of replicas reduce
- Higher loads at the other servers
- Ensure *at least one copy* of file continues to exist

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More on replication and deletion thresholds

- $rep(S, F)$ always chosen to be **higher** than the $del(S, F)$
- If a number of requests lie *between* deletion and replication threshold
  - File can only be **migrated**
  - Number of replicas for file should be the same

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Reevaluating the placement of files at a server Q

- Check **access count** for each file
- If number of accesses < $del(Q, F)$?
  - File deleted unless it is the last copy
- For some server P, if $count_Q(P, F)$ is more than ½ of requests for F at Q ?
  - Server P is requested to **take over** copy of F
  - **Migration**

Migration/replication of a file may not always succeed

- Server P might already be heavily overloaded
- Q will then attempt to replicate F *elsewhere*
  - Number of access > $rep(Q, F)$
- If $count_Q(R, F)$ exceeds a certain fraction of all requests for F at Q
  - Try to replicate at R

Client initiated replicas: Client cache

- Temporarily store data that was just requested
  - Could be on client's machine or nearby machine
- Used to improve *access times*
- Data kept in cache for a limited time
  - Avoid *stale data* problem
  - Make room for *other data*
- To improve **cache hits**; cache may be shared between clients

REPLICATED WRITE PROTOCOLS

Replicated write protocols

- Write operations are carried out at multiple replicas
  - Not just 1 (or primary)
- Active Replication
  - Operation forwarded to **all** replicas
- Quorum-based
  - Based on **majority voting**

Active Replication

- Operation is sent to each replica
- Must be carried out in same order everywhere
  - Lamport's clocks
  - Use of a central coordinator: Sequencer
    - Could start to resemble primary-based protocols

Quorum-based protocols:
Clients must request and acquire permissions

- From **multiple** servers
- **Before** reading and writing replicated data items

Quorum-based protocols:
Distributed File System example {Write}

- File is replicated on N servers
- To update a file
  - Client must contact at least $(N/2 + 1)$ servers
    - Majority
  - Get them to agree to do the update
- Upon agreement
  - File is changed and version number incremented

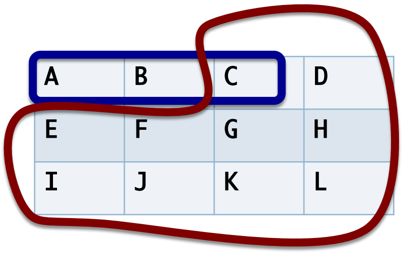
Quorum-based protocols: Reading a replicated file

- Client must contact at least $(N/2 + 1)$ servers
  - Ask them for version numbers of file
- If version numbers agree … most recent version
- With $N=5$, and
  - Clients see 3 responses with version-**8**
  - Then getting 2 responses with verison-**9**?
    - Impossible, because update to version-**9** needs 3 to agree

Quorum-based protocols: When there are N replicas

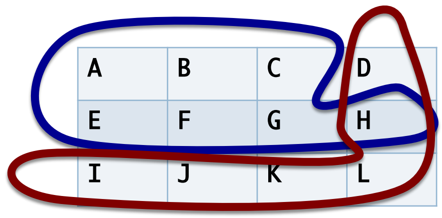
- Read quorum N_R
- To modify a file, write-quorum N_W
- $N_R + N_W > N$
  - Prevent **read-write** conflict
- $N_W > N/2$
  - Prevent **write-write** conflict

Quorum-based protocols: Example 1



$N_R=3$ $N_W=10$

☺



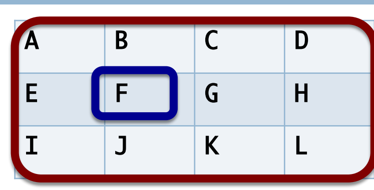
$N_R=7$ $N_W=6$

Write-write conflict ☹

Concurrent writes to
{A, B, C, E, F, G} and {D, H, I, J, K, L}
will be accepted

Read Quorum: —
Write Quorum: —

Quorum-based protocols: Example 2



$N_R=1$ $N_W=12$

☺

Read Quorum: —
Write Quorum: —

EVENTUALLY CONSISTENT

Werner Vogels: Eventually Consistent.
ACM Queue 6(6): 14-19 (2008)

Amazon systems use replication techniques ubiquitously

- Predictable performance
- Availability

Replication helps with these goals, but …

- **Not necessarily transparent**
- Under a number of **conditions**, *consequences* of using replication techniques come to the fore
  - Network partitions
  - Node failures

Ideal world

- One consistency model
- When an update is made all observers see that update

Distribution transparency

- To the user of the system, it *appears* as if there is only one system
  - Instead of a number of collaborating systems
- Approach taken in such systems?
  - Better to fail the complete system rather than break this transparency

In the mid-90s these practices were revisited

- Larger internet systems
- For the first time, **availability** was being considered the most important property

BREWER'S CAP CONJECTURE (AND LATER ON … THEOREM)

Brewer's CAP Theorem

- By Eric Brewer in 2000
- Three properties of shared-data systems
  1. Data **consistency**
  2. System **availability**
  3. Tolerance to network **partitions**
- There are limits to your choices of what can be achieved at a given time

Brewer's CAP: Consequences

- In large-scale distributed systems, network *partitions are common*
- So, consistency and availability cannot be achieved at the same time

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What is the trade-off? [1/2]

- If your application **requires** consistency?
  - And some replicas are disconnected from the other replicas due to a network problem …
  - Then some replicas cannot process requests while they are disconnected:
    - They must either **wait** until the network problem is fixed, **or return an error**
    - Either way, they become **unavailable**

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What is the trade-off? [2/2]

- If your application <u>does not</u> require consistency?
  - Then each replica can process requests independently
    - Even if it is disconnected from other replicas
  - The application can remain available in the face of a network problem, but its <u>behavior is not consistent</u>
- Thus, applications that don't require consistency can be **more tolerant of network problems**

Characterizing CAP correctly [1/3]

- CAP is sometimes presented as Consistency, Availability, Partition tolerance: pick 2 out of 3
  - Unfortunately, putting it this way is **misleading**
- Because network partitions are a kind of fault, they aren't something about which you have a choice:
  - They will happen whether you like it or not

Characterizing CAP correctly [2/3]

- At times when the network (and system) is working correctly, a system can provide both consistency and total availability
- When a network fault occurs, you have to choose between consistency OR total availability

Characterizing CAP correctly [3/3]

- A better way of phrasing CAP would be
  - Either **Consistent or Available when Partitioned**
- A more reliable network needs to make this choice less often, but at *some point* the choice is inevitable!

CAP: Two choices on what to drop

- Relax consistency
  - To allow system to be **available under partitionable conditions**
- Make consistency a priority
  - And the system will be **unavailable under certain conditions**

The choices requires the developer to be aware of what is being offered by system

- If consistency is emphasized?
  - Developer must account for system unavailability
  - If a write fails?
    - Plan on *what will be done* with the data that must be written
- If availability is emphasized?
  - System may always accept writes but …
    - Under certain conditions a read will not reflect the results of a *recently completed* write

The C in ACID is a different kind of consistency
{Atomicity, Consistency, Isolation and Durability}

- When a transaction is finished, the database is in a consistent state
- For e.g., when money is transferred between two accounts?
  - The total money in the two accounts should not change
- This kind of consistency is the **responsibility of the developer** writing the transaction
  - Database assists via managing integrity constraints

The "I" in ACID

- **Isolation**
- Ensures *concurrent execution* of transactions results in a final system state similar to what would be achieved if transactions were executed serially

Consistency: Two ways to look at this

- Client-side
  - How do clients observe updates?
- Server-side
  - How do updates flow through the system?
  - What guarantees can systems give with respect to updates?

CLIENT-SIDE CONSISTENCY

Client-side consistency [1/2]

- Consider a storage system
- Process **A** that writes and reads from the storage system
- Process **B** and **C** are independent of **A**
  - Write and read from the storage system too

Client-side consistency [2/2]

- How and when do observers (**A**, **B**, and **C**) see updates made to a data object?
- **Strong consistency**:
  - After update completes, any subsequent access by (**A**, **B**, or **C**) will return updated value
- **Weak consistency**:
  - No guarantee that subsequent accesses will return updated value
  - Number of conditions to be met before value is returned

The inconsistency window

- **Period** between
  - The *update*
    and
  - When any observer will **always see** the updated value

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Eventual consistency

- A form of **weak consistency**
- Storage system guarantees that if no new updates are made to the object?
  - **Eventually** all accesses will return last updated value
- If no failures occur, size of the inconsistency window is determined by:
  - Communication delays, system load, and number of replicas

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Eventual consistency variations

- Causal consistency
- Read-your-writes consistency
- Session consistency
  - As long as session exists, system guarantees read-your-writes consistency
  - Guarantees *do not overlap* sessions
- Monotonic read consistency
- Monotonic write consistency

RDBMS implement replication in different modes

- **Synchronous**
  - Replica update is part of the transaction
- **Asynchronous**
  - Updates arrive at the backup in a delayed manner
    - **Log shipping**
  - If primary fails before the logs were shipped?
    - Reading from promoted backup will produce old, inconsistent values

Other RDBMS approaches to improve speed

- RDBMSs have also started to provide ability to read from backup
  - Classic case of eventual consistency
- Size of the inconsistency window in such a setting?
  - Periodicity of the log shipping

SERVER SIDE CONSISTENCY

Server-side consistency

- Based on how updates flow through the system
- **N**: Number of nodes that store replicas of data
- **W**: Number of replicas that need to acknowledge receipt of update before it completes
- **R**: Number of replicas that are contacted when data object is accessed through read operation

W+R > N?

- The write-set and read-set overlap
  - Possible to guarantee strong consistency
- Primary-backup RDBMS
  - With synchronous replication
    - N=2, W=2 and R =1
    - Client always reads a consistent answer
  - With asynchronous replication
    - N=2, W=1 and R=1
    - Consistency cannot be guaranteed

In distributed storage systems the number of replicas is higher than two

- Systems that focus on fault tolerance use **N**=3
  - With **W**=2 and **R**=2
- Systems that serve very high read loads
  - Replicate data beyond what is needed for fault tolerance
  - **N** can 10s to 100s of nodes
  - **R** will be set to 1
    - A single read will return the result
  - For consistency **W**=**N** for updates
    - Decreases the probability of write succeeding

For systems concerned about fault tolerance but not consistency

- **W**=1
  - Minimal durability
- Rely on lazy (epidemic) techniques to update other replicas

Configuring values of N, R and W

- Depends on the **common case**
- **Performance path** that needs to be optimized
- If **R**=1 and **N**=**W** ?
  - We optimize for the read case
- If **W**=1 and **R**=**N** ?
  - We optimize for a very fast write
  - Durability is not guaranteed
  - If **W** < (**N**+1)/2 there is a possibility of conflicting writes when the write-sets do not overlap

Weak/eventual consistency

- Also arises when **W**+ **R** <= **N**
  - Possibility that the read and write set will not overlap
- If it's deliberate and not based on failure cases?
  - Hardly makes sense to set **R** to anything but 1

Weak/eventual consistency: Two common cases where R=1

- Massive replication for read scaling
- When data access is more complicated
  - In simple <key, value> systems easy to compare versions to determine latest written value
  - When set of objects are returned, reasoning gets more complicated

When partitions occur

- Some nodes cannot reach a set of other nodes
- With a classic majority quorum approach
  - Partition that has **W** nodes of the replica set continues to take updates
  - The other partition becomes unavailable

For some applications unavailability of partitions is unacceptable

- Important that clients, that reach a partition, can progress
- Merge operation is executed when partition heals
- Amazon shopping-cart?
  - **Write-always** system
  - Customer can continue to put items in the cart even when original cart lives on other partitions

The contents of this slide-set are based on the following references

- *Distributed Systems: Principles and Paradigms. Andrew S. Tanenbaum and Maarten Van Steen. 2nd Edition. Prentice Hall. ISBN: 0132392275/978-0132392273.* [Chapter 7]
- Werner Vogels: Eventually Consistent. ACM Queue 6(6): 14-19 (2008)
- Martin Kleppmann. Designing Data-Intensive Applications: The Big Ideas Behind Reliable, Scalable, and Maintainable Systems. 1st Edition. O'Reilly Media. 2017. [Chapter 9]