Distributed Systems

CS425/ECE428

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Acknowledgements for the materials: Indy Gupta

Logistics

- HW5 due today.
- MP3 due on April 29.
- Second chance for MP1 functionality and MP2 with 30% penalty (due May 8^{th})

Today's focus

- Brief overview of key-value stores
- Distributed Hash Tables
  - Peer-to-peer protocol for efficient insertion and retrieval of key-value pairs.
- Key-value stores in the cloud
  - How to run large-scale distributed computations over key-value stores?
    - Map-Reduce Programming Abstraction
    - Cloud Scheduling
  - How to design a large-scale distributed key-value store?
    - Case-study: Facebook's Cassandra

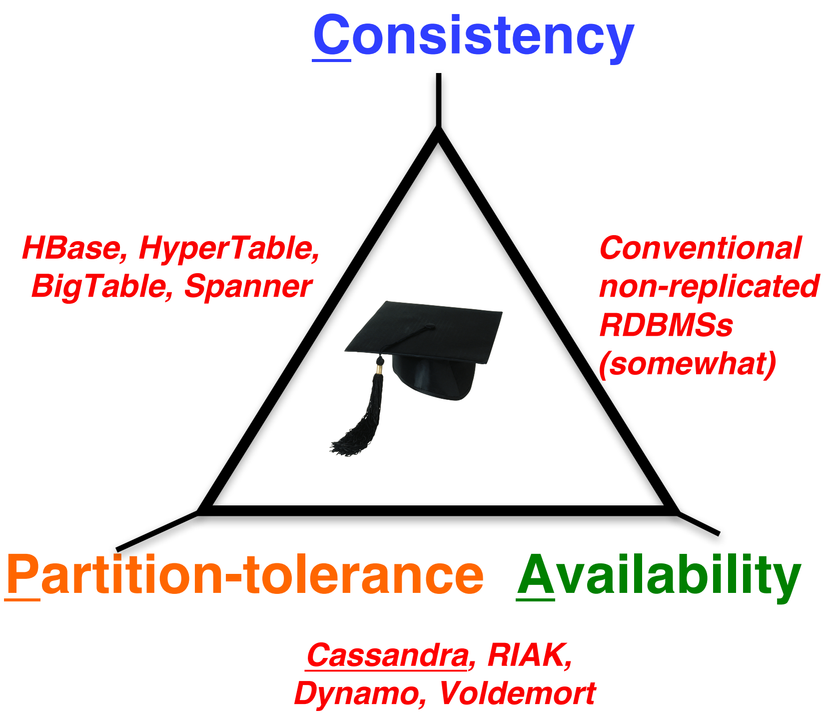
How to design a distributed key-value datastore?

CAP Theorem

- **C**onsistency**:** reads return latest written value by any client (all nodes see same data at any time).
- **A**vailability**:** every request received by a non-failing node in the system must result in a response (quickly).
- **P**artition-tolerance**:** the system continues to work in spite of network partitions.
- **In a distributed system you can only guarantee at most 2 out of the above 3 properties.**
  - Proposed by Eric Brewer (UC Berkeley)
  - Subsequently proved by Gilbert and Lynch (NUS and MIT)

CAP Tradeoff

- Starting point for NoSQL Revolution
- A distributed storage system can achieve at most two of C, A, and P.
- When partition-tolerance is important, you have to choose between consistency and availability



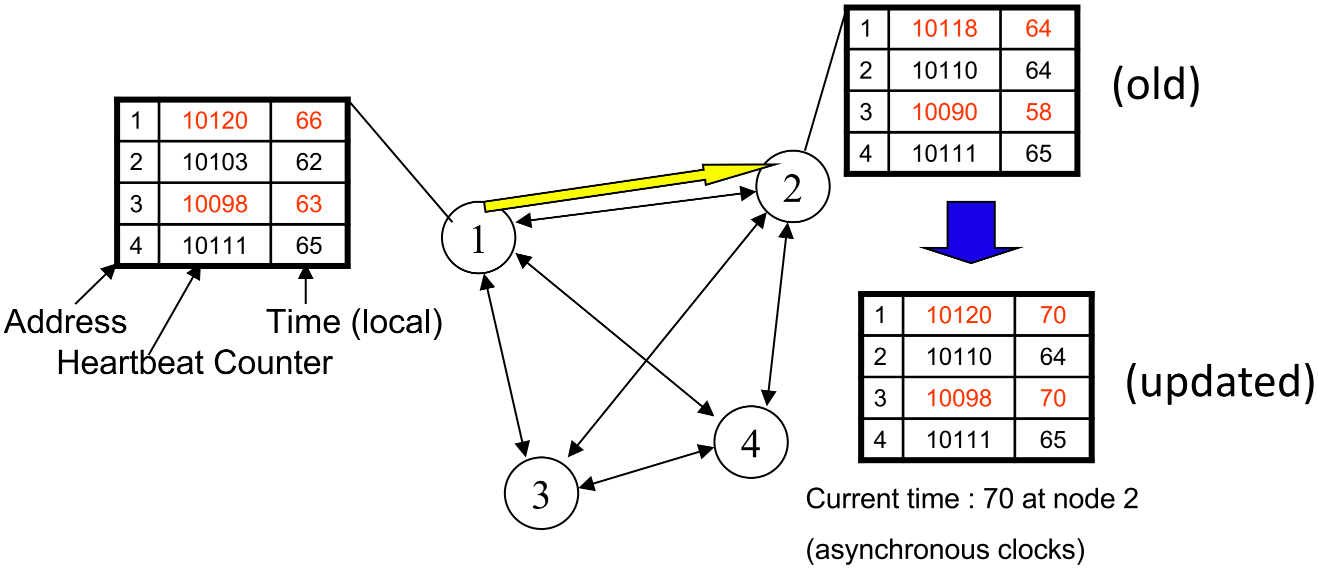
Case Study: Cassandra

Membership

- Any server in cluster could be the leader.
- So every server needs to maintain a list of all the other servers that are currently in the cluster.
- List needs to be updated automatically as servers join, leave, and fail.

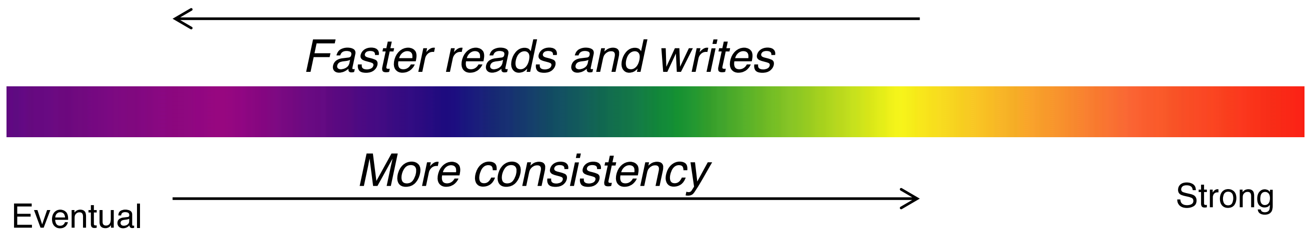
Cluster Membership

Cassandra uses gossip-based cluster membership



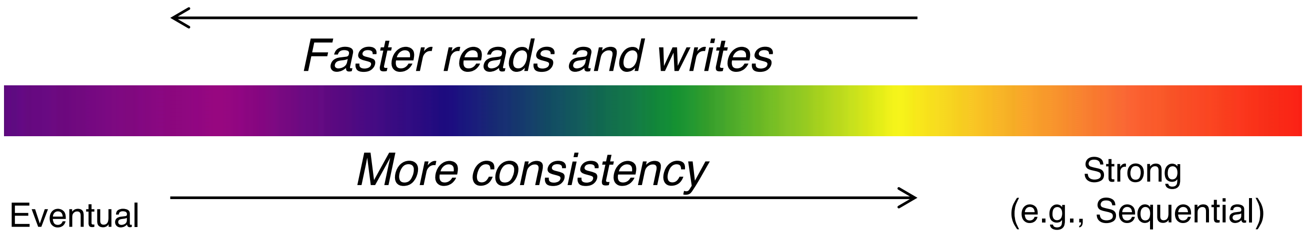
- Nodes periodically gossip their membership list
- On receipt, the local membership list is updated, as shown
- If any heartbeat older than Tfail, node is marked as failed

Consistency Spectrum



Eventual Consistency

- Cassandra offers Eventual Consistency
  - If writes to a key stop, all replicas of key will converge.
  - Originally from Amazon's Dynamo and LinkedIn's Voldemort systems



Cassandra write and read recap

- Writes
  - Client sends write request to a *coordinator*.
  - Coordinator writes to all replicas.
  - Waits for X replicas to respond before returning acknowledgement to the client.
  - Hinted handoff: if a replica is down, it receives the write request once it comes back up.
- Reads
  - Client sends read request to a *coordinator*.
  - Coordinator contacts X replicas, and returns the latest returned value.
  - Read repair: After returning a response, coordinator continues with fetching values from other replicas, and initiates repairs to outdated values.

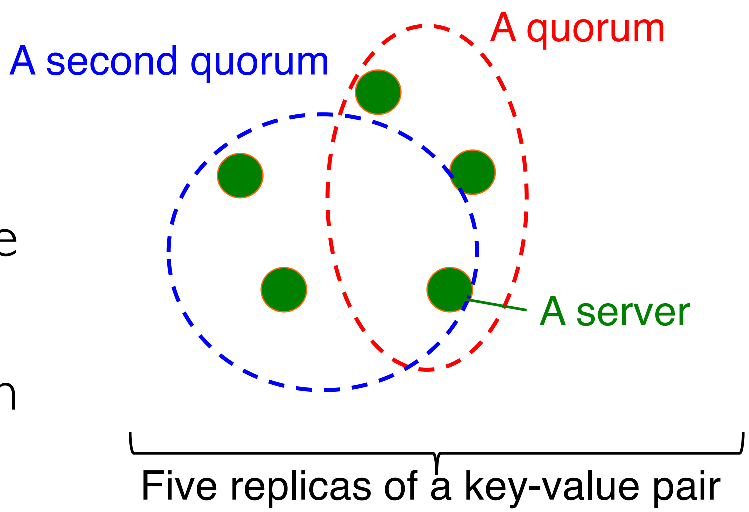
Consistency levels: value of X

- Cassandra has consistency levels.
- Client is allowed to choose a consistency level for each operation (read/write)
  - ANY: any server (may not be replica)
    - Fastest: coordinator caches write and replies quickly to client
  - ALL: all replicas
    - Ensures strong consistency, but slowest
  - ONE: at least one replica
    - Faster than ALL, but cannot tolerate a failure
  - QUORUM: quorum across all replicas in all datacenters (DCs)

Quorums?

In a nutshell:

- Quorum = (typically) majority
- Any two quorums intersect
  - Client 1 does a write in red quorum
  - Then client 2 does read in blue quorum
- At least one server in blue quorum returns latest write
- Quorums faster than ALL, but still ensure strong consistency
- Several key-value/NoSQL stores (e.g., Riak and Cassandra) use quorums.



Read Quorums

- Reads
  - Client specifies value of R ($\leq$ N = total number of replicas of that key).
  - R = read consistency level.
  - Coordinator waits for R replicas to respond before sending result to client.
  - In background, coordinator checks for consistency of remaining (N-R) replicas, and initiates read repair if needed.

Write Quorums

- Client specifies W (≤ N)
- W = write consistency level.
- Client writes new value to W replicas and returns when it hears back from all.
  - Default strategy.

Quorums in Detail (Contd.)

- R = read replica count, W = write replica count
- Necessary conditions for consistency:
  1. W+R > N
     - Write and read intersect at a replica. Read returns latest write.
  2. W > N/2
     - Two conflicting writes on a data item don't occur at the same time.
- Select values based on application
  - (W=N, R=1):
    - great for read-heavy workloads
  - (W=1, R=N):
    - great for write-heavy workloads with no conflicting writes.
  - (W=N/2+1, R=N/2+1):
    - great for write-heavy workloads with potential for write conflicts.
  - (W=1, R=1):
    - very few writes and reads / high availability requirement.

Cassandra Consistency Levels

- Client is allowed to choose a consistency level for each operation (read/write)
  - ANY: any server (may not be replica)
    - Fastest: coordinator may cache write and reply quickly to client
  - ALL: all replicas
    - Slowest, but ensures strong consistency
  - ONE: at least one replica
    - Faster than ALL, and ensures durability without failures
  - QUORUM: quorum across all replicas in all datacenters (DCs)
    - Global consistency, but still fast
  - EACH_QUORUM: quorum in every DC
    - Lets each DC do its own quorum: supports hierarchical replies
  - LOCAL_QUORUM: quorum in coordinator's DC
    - Faster: only waits for quorum in first DC client contacts

Eventual Consistency

- Sources of inconsistency:
  - Quorum condition not satisfied $R + W < N$.
    - R and W are chosen as such.
    - when write returns before W replicas respond.
      - Sloppy quorum: when value stored elsewhere if intended replica is down, and later moved to the replica when it is up again.
  - When local quorum is chosen instead of global quorum.
- Hinted-handoff and read repair help in achieving *eventual consistency*.
  - If all writes (to a key) stop, then all its values (replicas) will converge eventually.
  - May still return stale values to clients (e.g., if many back-to-back writes).
  - But works well when there a few periods of low writes – system converges quickly.

Cassandra vs. RDBMS

- MySQL is one of the most popular RDBMS (and has been for a while)
- On > 50 GB data
- MySQL
  - Writes 300 ms avg
  - Reads 350 ms avg
- Cassandra
  - Writes 0.12 ms avg
  - Reads 15 ms avg
- Orders of magnitude faster.

Other similar NoSQL stores

- Amazon's DynamoDB
    - Cassandra's data partitioning, replication, and eventual consistency strategies inspired from Dynamo.
    - Uses sloppy quorum as the default mechanism for eventual consistency with availability.
    - Uses vector clocks to capture causality between different versions of an object.
    - Dynamo: Amazon's Highly Available Key-value Store, SOSP'2007.
- LinkedIn's Voldemort
    - Inspired from DynamoDB.
- …..

Summary

- CAP theorem: cannot only achieve 2 out of 3 among consistency, availability, and partition-tolerance.
- Partition-tolerance is required in distributed datastores.
  - Choose between consistency and availability.
- Many modern distributed NoSQL key-value stores (e.g. Cassandra) choose availability, providing only eventual consistency.

Next week

- Monday:
  - Guest lecture by my PhD student, Sachin Ashok
  - *Microservice based cloud applications*

- Wednesday:
  - Q/A session in class (optional attendance)