Distributed Systems

CS425/ECE428

April 30 2021

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Acknowledgements for the materials: Indy Gupta

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.

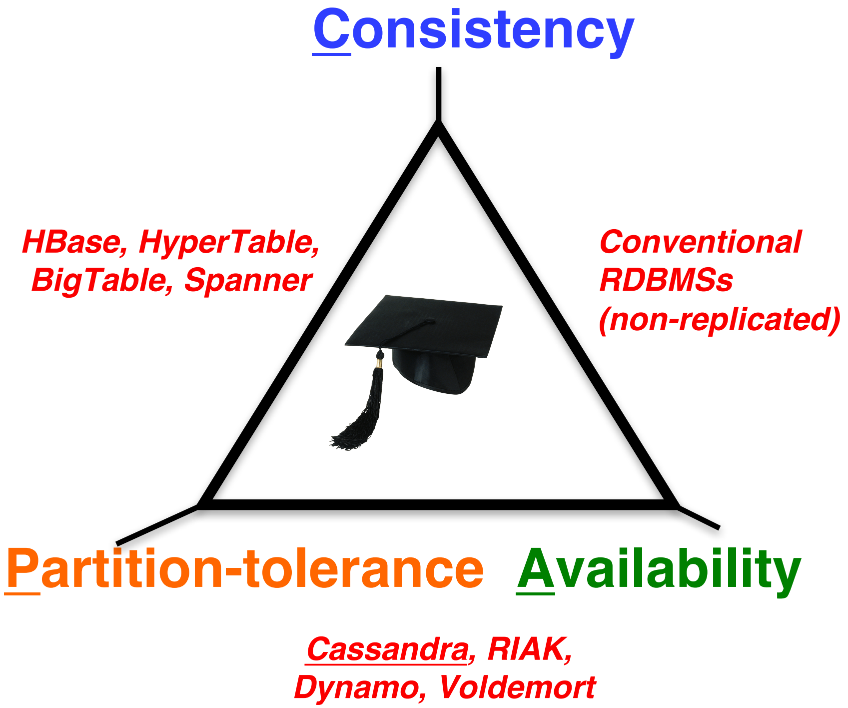
- Key-value stores in the cloud
    - How to run large-scale distributed computations over key-value stores?
        - Map-Reduce Programming Abstraction
    - How to design a large-scale distributed key-value store?
        - Case-study: Facebook's Cassandra

Distributed datastores

- Distributed datastores
  - Service for managing distributed storage.
- Distributed NoSQL key-value stores
  - BigTable by Google
  - HBase open-sourced by Yahoo and used by Hadoop.
  - DynamoDB by Amazon
  - Cassandra by Facebook
  - Voldemort by LinkedIn
  - MongoDB,
  - …
- *Spanner is not a NoSQL datastore. It's more like a distributed relational database.*

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

Data Partitioning and Replication

- Partitioner: identifies primary replica for a key
    - hash-based or range based.

- Replication in multi-DC environments
    - replicate across datacenters.
    - replicate across different racks within a datacenter.

- Writes:
    - Client send writes to the *coordinator*.
    - Coordinator sends query to all replicas.
    - Waits for X replicas to respond before returning acknowledgement to client.
        - X determines consistency level. To be discussed.
    - Hinted handoffs to ensure writes are eventually written to all replicas.

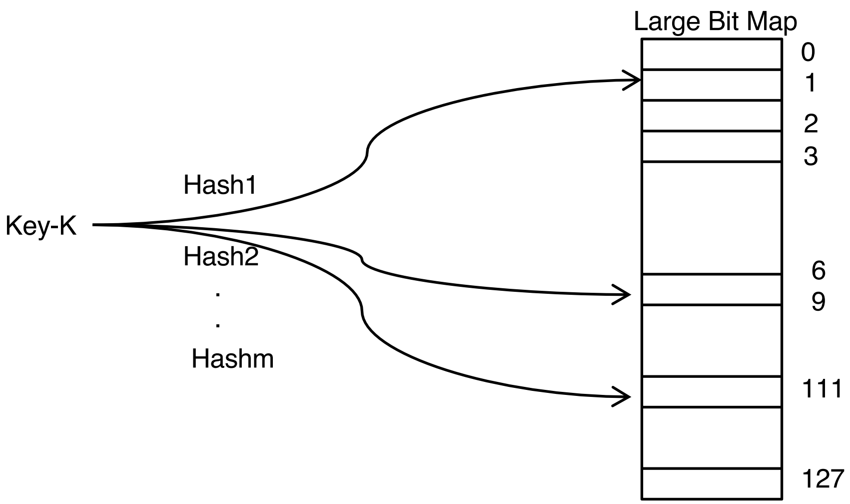
Writes at a replica node

On receiving a write

1. Log it in disk commit log (for failure recovery)
2. Make changes to appropriate memtables
    - **Memtable** = In-memory representation of multiple key-value pairs
    - Cache that can be searched by key
    - Write-back cache as opposed to write-through
3. Later, when memtable is full or old, flush to disk
    - Data File: An **SSTable** (Sorted String Table) – list of key-value pairs, sorted by key
    - Index file: An SSTable of (key, position in data sstable) pairs
    - And a Bloom filter (for efficient search) – next slide.

Bloom Filter

- Compact way of representing a set of items.
- Checking for existence in set is cheap.
- Some probability of false positives: an item not in set may check true as being in set.
- No false negatives.



On insert, set all hashed bits.

On check-if-present,
return true if all hashed bits set.

- False positives

False positive rate low

- m=4 hash functions
- 100 items
- 3200 bits
- FP rate = 0.02%

Compaction

- Data updates accumulate over time and over multiple SSTables.
- Need to be compacted.
- The process of compaction merges SSTables, i.e., by merging updates for a key.
- Run periodically and locally at each server.

Deletes

Delete: don’t delete item right away

- Write a **tombstone** for the key.
- Eventually, when compaction encounters tombstone it will delete item

Reads

- Coordinator contacts X replicas (e.g., in same rack)
  - Coordinator sends read to replicas that have responded quickest in past.
  - When X replicas respond, coordinator returns the latest-timestamped value from among those X.
  - X = based on consistency spectrum (more later).
- Coordinator also fetches value from other replicas
  - Checks consistency in the background, initiating a **read repair** if any two values are different.
  - This mechanism seeks to eventually bring all replicas up to date.
- At a replica
  - Read looks at Memtables first, and then SSTables.
  - A row may be split across multiple SSTables => reads need to touch multiple SSTables => reads slower than writes (but still fast).

Cross-DC coordination

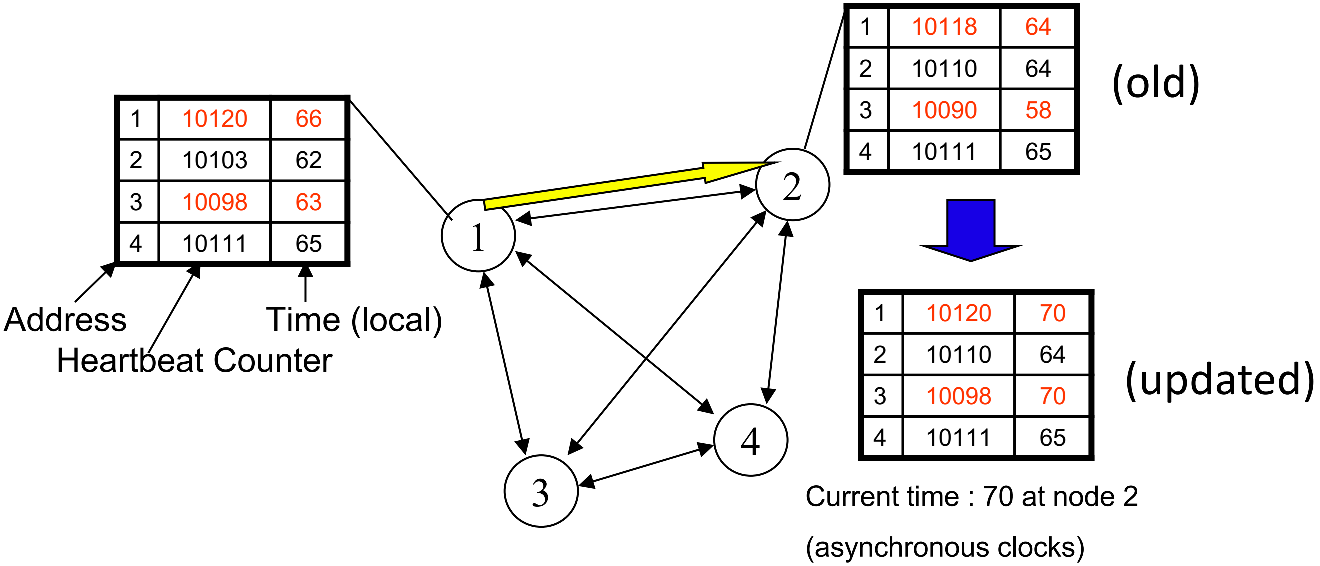
- Replicas may span multiple datacenters.
- Per-DC coordinator elected to coordinate with other DCs.
- Election done via Zookeeper which runs a Bully algorithm variant.

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



1	10120	66
2	10103	62
3	10098	63
4	10111	65

Address

Heartbeat Counter

Time (local)

1	10118	64
2	10110	64
3	10090	58
4	10111	65

(old)

1	10120	70
2	10110	64
3	10098	70
4	10111	65

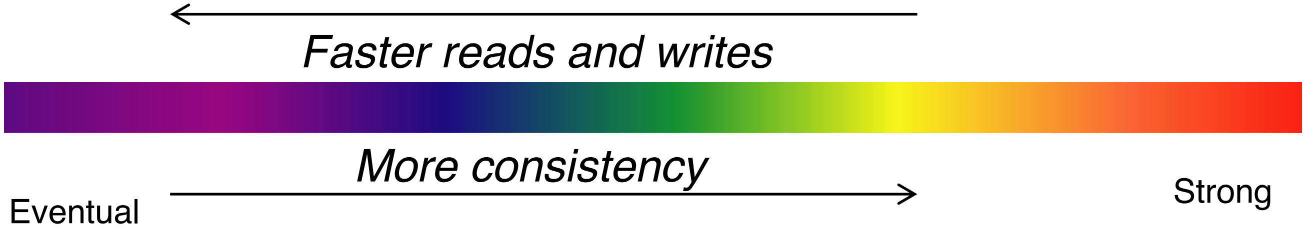
(updated)

Current time : 70 at node 2

(asynchronous clocks)

- 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



Faster reads and writes

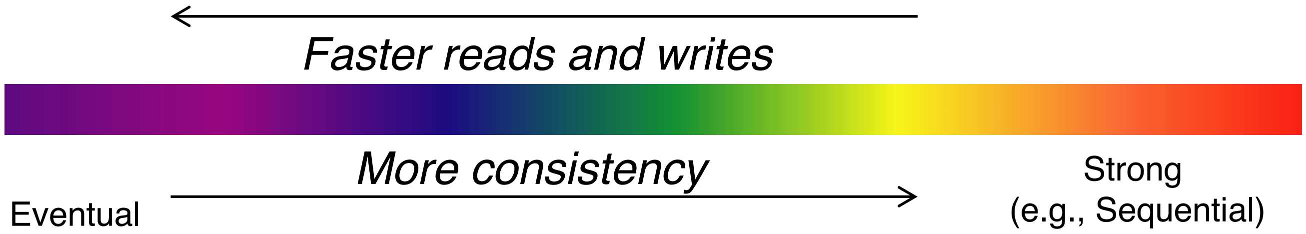
More consistency

Eventual

Strong

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.

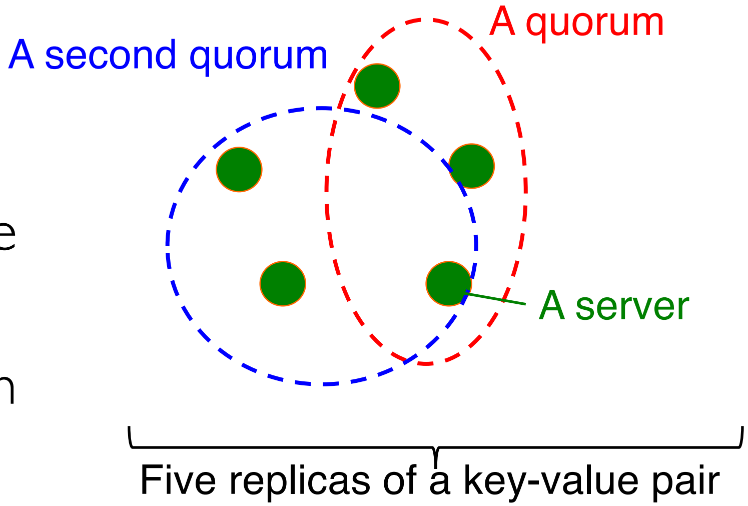
Consistency levels: value of X

- 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

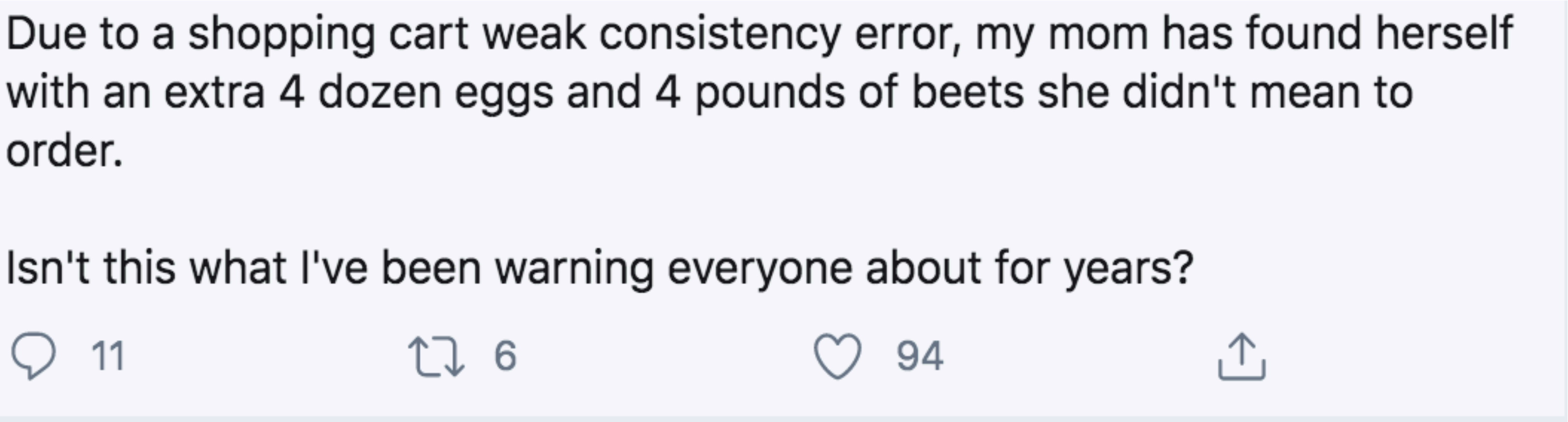
- MySQL is one of the most popular RDBMS (and has been for a while)
- On > 50 GB data
- MySQL
  - Writes 300 ms avg
  - Reads 350 ms avg
- Cassandra
  - Writes 0.12 ms avg
  - Reads 15 ms avg
- Orders of magnitude faster.

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.
- …..

Is it a good idea to trade-off consistency for availability?

A recent tweet by a distributed systems researcher:



Due to a shopping cart weak consistency error, my mom has found herself with an extra 4 dozen eggs and 4 pounds of beets she didn't mean to order.

Isn't this what I've been warning everyone about for years?

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.