CSE 486/586 Distributed Systems
Case Study: Amazon Dynamo

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Recap

- CAP Theorem?
  - Consistency, Availability, Partition Tolerance
  - P then C? A?
- Eventual consistency?
  - Availability and partition tolerance over consistency
- Lazy replication?
  - Replicate lazily in the background
- Gossiping?
  - Contact random targets, infect, and repeat in the next round

Amazon Dynamo

- Distributed key-value storage
  - Only accessible with the primary key
  - put(key, value) & get(key)
- Used for many Amazon services ("applications")
  - Shopping cart, best seller lists, customer preferences, product catalog, etc.
  - Now in AWS as well (DynamoDB) (if interested, read http://www.allthingsdistributed.com/2012/01/amazon-dynamodb.html)
- With other Google systems (GFS & Bigtable), Dynamo marks one of the first non-relational storage systems (a.k.a. NoSQL)

Amazon Dynamo

- A synthesis of techniques we discuss in class
  - Very good example of developing a principled distributed system
  - Comprehensive picture of what it means to design a distributed storage system
- Main motivation: shopping cart service
  - 3 million checkouts in a single day
  - Hundreds of thousands of concurrent active sessions
- Properties (in the CAP theorem sense)
  - Eventual consistency
  - Partition tolerance
  - Availability ("always-on" experience)

Necessary Pieces?

- We want to design a storage service on a cluster of servers
- What do we need?
  - Membership maintenance
  - Object insert/lookup/delete
  - (Some) Consistency with replication
  - Partition tolerance
- Dynamo is a good example as a working system.

Overview of Key Design Techniques

- Gossiping for membership and failure detection
  - Eventually-consistent membership
- Consistent hashing for node & key distribution
  - Similar to Chord
  - But there's no ring-based routing; everyone knows everyone else
- Object versioning for eventually-consistent data objects
  - A vector clock associated with each object
- Quorums for partition/failure tolerance
  - "Sloppy" quorum similar to the available copies replication strategy
- Merkel tree for resynchronization after failures/partitions
  - (This was not covered in class yet)

Membership

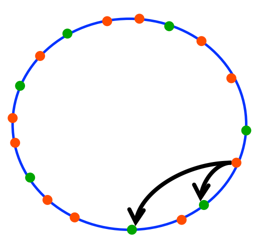
- Nodes are organized as a ring just like Chord using consistent hashing
- But everyone knows everyone else.
- Node join/leave
  - Manually done
  - An operator uses a console to add/delete a node
  - Reason: it's a well-maintained system; nodes come back pretty quickly and don't depart permanently most of the time
- Membership change propagation
  - Each node maintains its own view of the membership & the history of the membership changes
  - Propagated using gossiping (every second, pick random targets)
- Eventually-consistent membership protocol

Failure Detection

- Does not use a separate protocol; each request serves as a ping
  - Dynamo has enough requests at any moment anyway
- If a node doesn't respond to a request, it is considered to be failed.

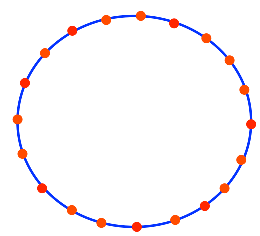
Node & Key Distribution

- Original consistent hashing
- Load becomes uneven



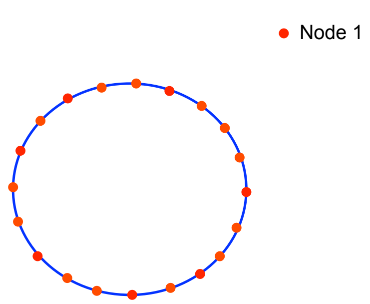
Node & Key Distribution

- Consistent hashing with "virtual nodes" for better load balancing
- Start with a static number of virtual nodes uniformly distributed over the ring



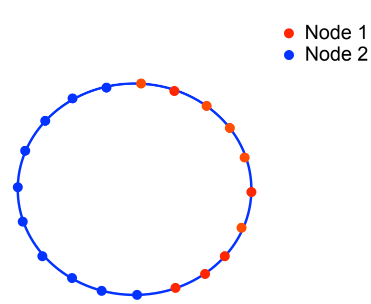
Node & Key Distribution

- One node joins and gets all virtual nodes



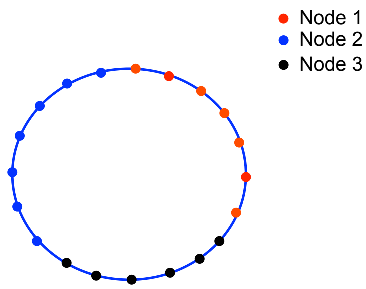
Node & Key Distribution

- One more node joins and gets 1/2



Node & Key Distribution

- One more node joins and gets 1/3 (roughly) from the other two

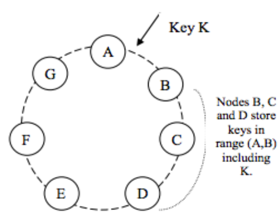


CSE 486/586 Administrivia

- Survey!
  - http://goo.gl/forms/2nZMfdULwG

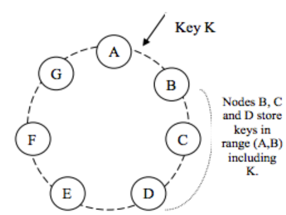
Replication

- N: # of replicas; configurable
- The first is stored regularly with consistent hashing
- N-1 replicas are stored in the N-1 (physical) successor nodes (called preference list)



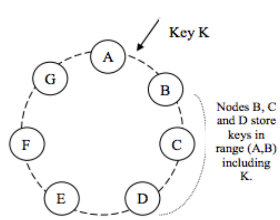
Replication

- Any server can handle read/write in the preference list, but it walks over the ring
  - E.g., try B first, then C, then D, etc.
- Update propagation: by the server that handled the request



Replication

- Dynamo's replication is lazy.
  - A put() request is returned "right away" (more on this later); it does not wait until the update is propagated to the replicas.
- This leads to inconsistency, solved by object versioning

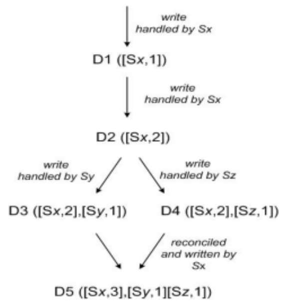


Object Versioning

- Writes should succeed all the time
  - E.g., "Add to Cart"
  - As long as there's at least one reachable server
- Used to reconcile inconsistent data
- Each object has a vector clock
  - E.g., D1 ([Sx, 1], [Sy, 1]): Object D (version 1) has written once by server Sx and Sy.
  - Each node keeps all versions until the data becomes consistent
  - I.e., no overwrite, almost like each write creates a new object
- Causally concurrent versions: inconsistency
- If inconsistent, reconcile later.
  - E.g., deleted items might reappear in the shopping cart.

Object Versioning

- Example



Object Versioning

- Consistency revisited
  - Linearizability: any read operation reads the latest write.
  - Sequential consistency: per client, any read operation reads the latest write.
  - Eventual consistency: a read operations might not read the latest write & sometimes inconsistent versions need to be reconciled.
- Conflict detection & resolution required
- Dynamo uses vector clocks to detect conflicts
- Simple resolution done by the system (last-write-wins policy)
- Complex resolution done by each application
  - System presents all conflicting versions of data

Object Versioning Experience

- Over a 24-hour period
- 99.94% of requests saw exactly one version
- 0.00057% saw 2 versions
- 0.00047% saw 3 versions
- 0.00009% saw 4 versions
- Usually triggered by many concurrent requests issued by robots, not human clients

Quorums

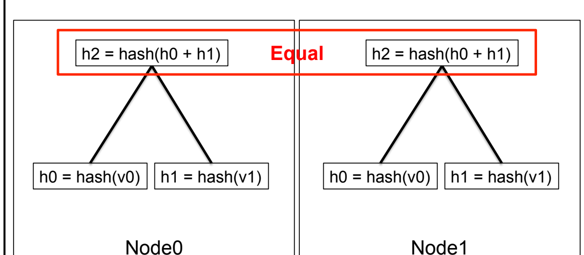
- Parameters
  - N replicas
  - R readers
  - W writers
- Static quorum approach: R + W > N
- Typical Dynamo configuration: (N, R, W) == (3, 2, 2)
- But it depends
  - High performance read (e.g., write-once, read-many): R==1, W==N
  - Low R & W might lead to more inconsistency
- Dealing with failures
  - Another node in the preference list handles the requests temporarily
  - Delivers the replicas to the original node upon recovery

Replica Synchronization

- Key ranges are replicated.
- Say, a node fails and recovers, a node needs to quickly determine whether it needs to resynchronize or not.
  - Transferring entire (key, value) pairs for comparison is not an option
- Merkel trees
  - Leaves are hashes of values of individual keys
  - Parents are hashes of (immediate) children
  - Comparison of parents at the same level tells the difference in children
  - Does not require transferring entire (key, value) pairs

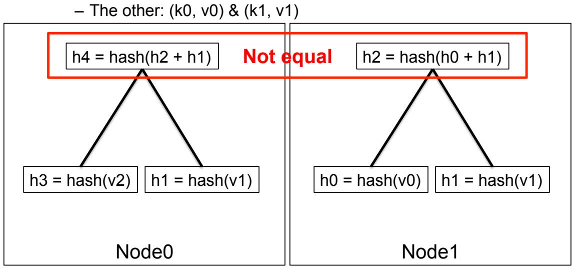
Replica Synchronization

- Comparing two nodes that are *synchronized*
  - Two (key, value) pairs: (k0, v0) & (k1, v1)



Replica Synchronization

- Comparing two nodes that are *not synchronized*
  - One: (k0, v2) & (k1, v1)
  - The other: (k0, v0) & (k1, v1)



Summary

- Amazon Dynamo
  - Distributed key-value storage with eventual consistency
- Techniques
  - Gossiping for membership and failure detection
  - Consistent hashing for node & key distribution
  - Object versioning for eventually-consistent data objects
  - Quorums for partition/failure tolerance
  - Merkel tree for resynchronization after failures/partitions
- Very good example of developing a principled distributed system

Acknowledgements

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