CSE 486/586 Distributed Systems

Case Study: Amazon Dynamo

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Amazon Dynamo

- Distributed key-value storage
  - Objects are accessible only by their (unique) key
  - Provides put(key, value) and get(key) operations
- Used for many Amazon services
  - Shopping cart, best seller lists, customer preferences, product catalog, *etc.*
  - Now in AWS as well (DynamoDB) [1]
- With some Google systems (GFS & Bigtable), Dynamo marks one of the first non-relational storage systems (a.k.a. NoSQL)

Amazon Dynamo

- A synthesis of many techniques we've discussed in class
  - Very good example of developing a principled distributed system
  - Comprehensive picture of the design of 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
  - High Availability

Necessary Pieces?

- We want to design a storage service on a cluster of servers
- What might we need?
  - Membership maintenance
  - Object insert/lookup/delete
  - (Some) Consistency with replication
  - Partition tolerance
- Dynamo is a good example of 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
  - Called "sloppy" quorum
- Merkel tree for resynchronization after failures/partitions
  - (This has not yet been covered in class)

Membership

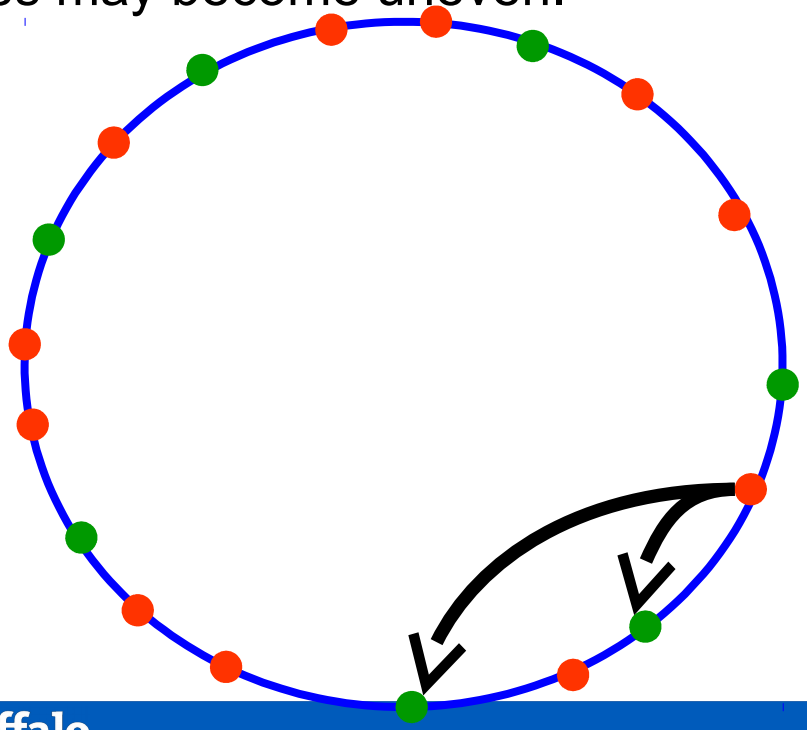
- Nodes are organized in a ring using consistent hashing
- Everyone knows everyone else, unlike Chord.
- Node join/leave
  - Manual operation; an operator uses a console to add/delete a node
  - Reason: it's a well-maintained system; nodes come back pretty quickly and usually don't depart permanently
- Membership change propagation
  - Each node maintains its own view of membership and a history of 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 for failure detection
  - Dynamo has enough requests for this at any given moment
- If a node doesn't respond to a request, it is considered to be failed.

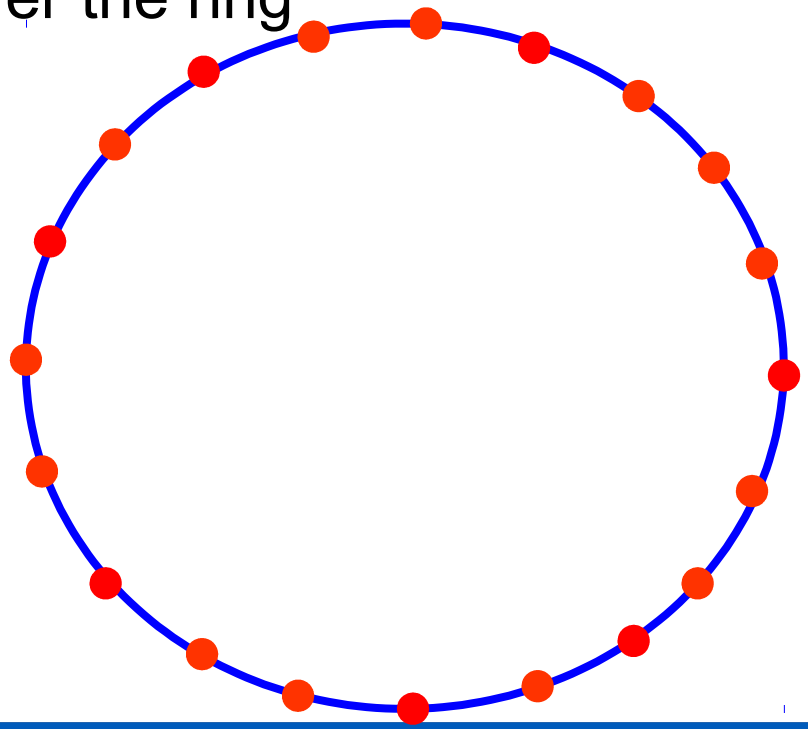
Node & Key Distribution

- Distribution by consistent hashing
- Load may become uneven
  - With a small number of nodes and/or as nodes come and go, partition sizes may become uneven.



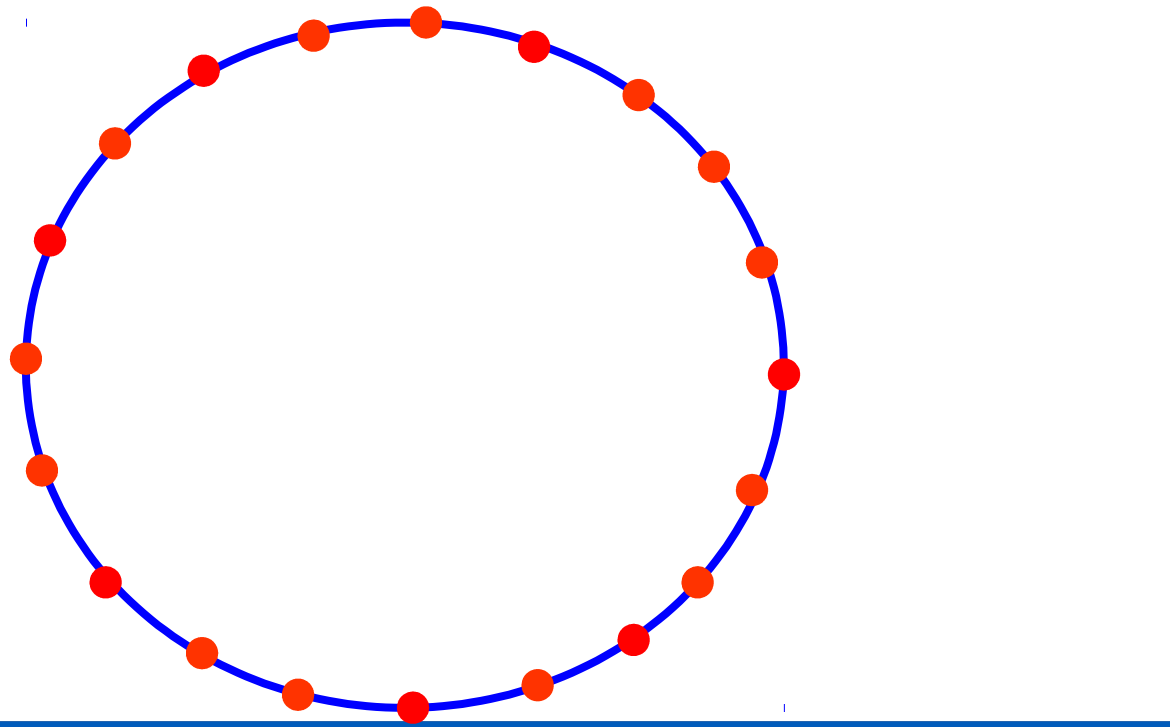
Node & Key Distribution

- Uses consistent hashing with “virtual nodes” for better load balancing
- Starts with a static number of virtual nodes uniformly distributed over the ring



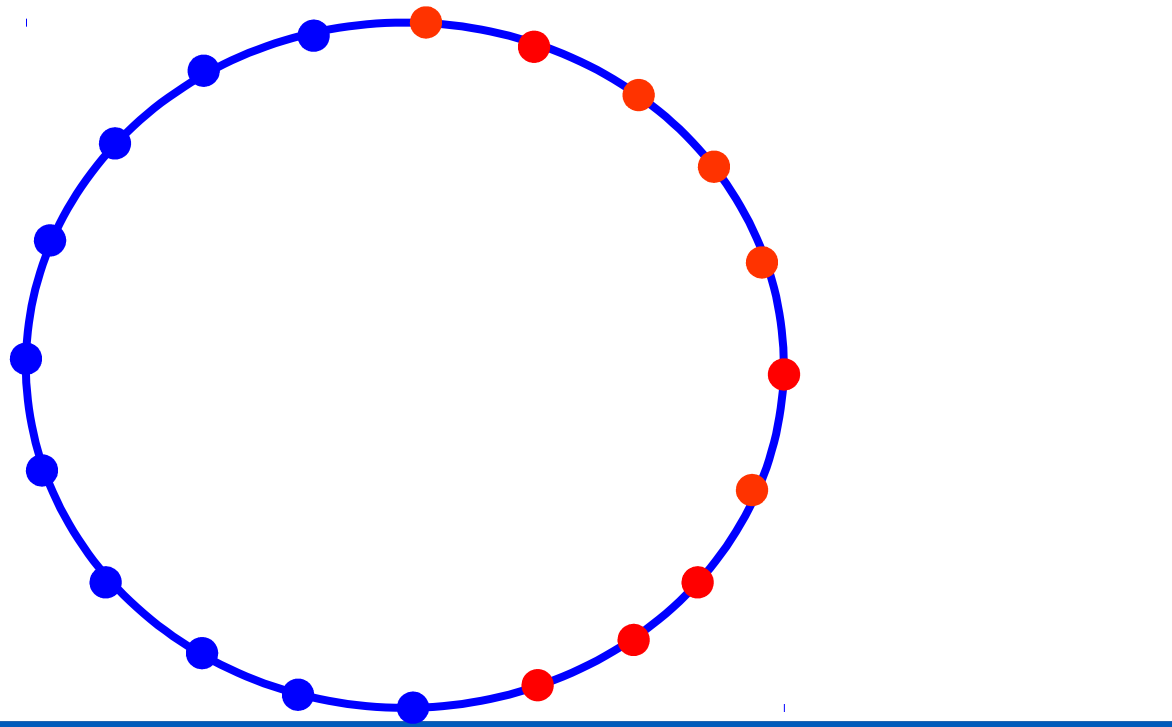
Node & Key Distribution

- One node joins and gets all virtual nodes



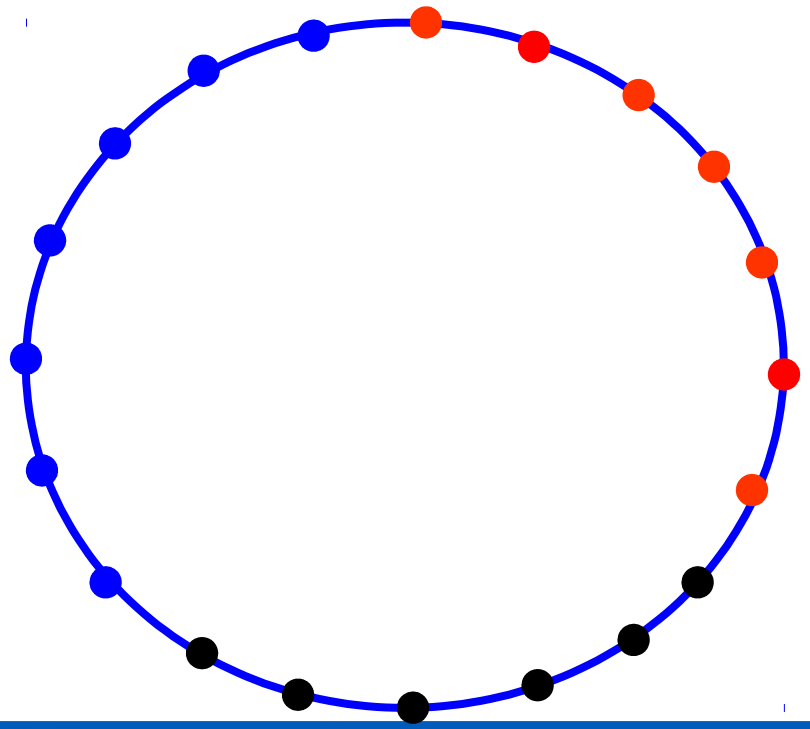
Node & Key Distribution

- A second node joins and takes ½ of the virtual nodes



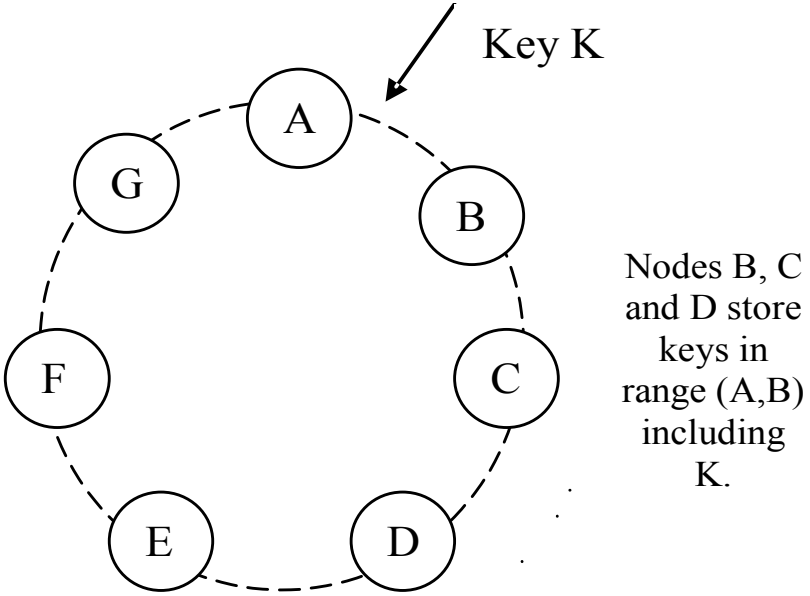
Node & Key Distribution

- One more node joins and gets 1/3 (roughly) of the virtual nodes from the first two



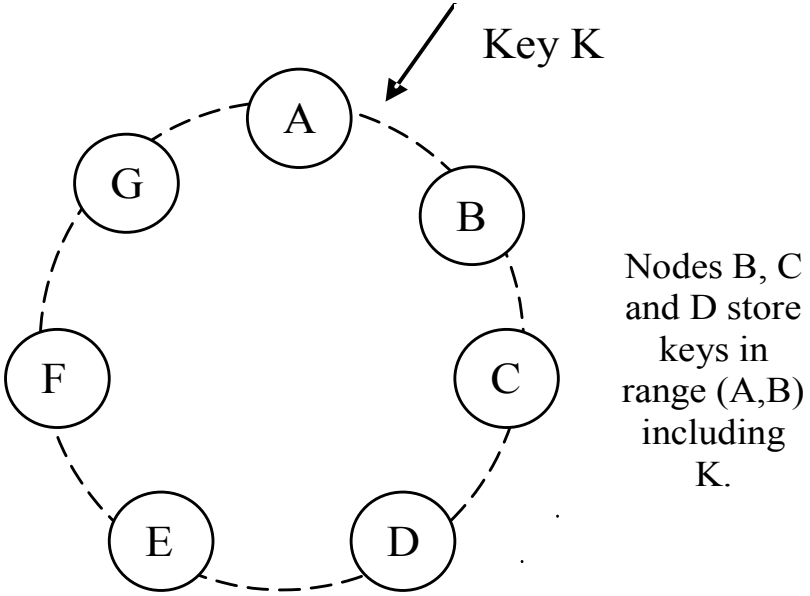
Replication

- Each object is stored on N replicas
- The first is stored normally with consistent hashing
- N-1 replicas are stored in the N-1 (physical) successor nodes (called preference list)



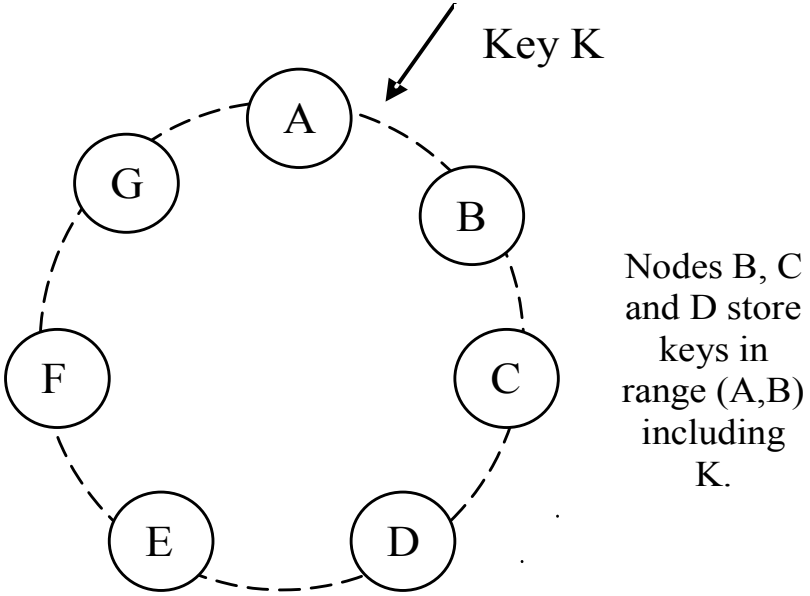
Replication

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



Replication

- Dynamo 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.
  - As long as there’s one reachable server, a write completes.
  - This could lead to inconsistency

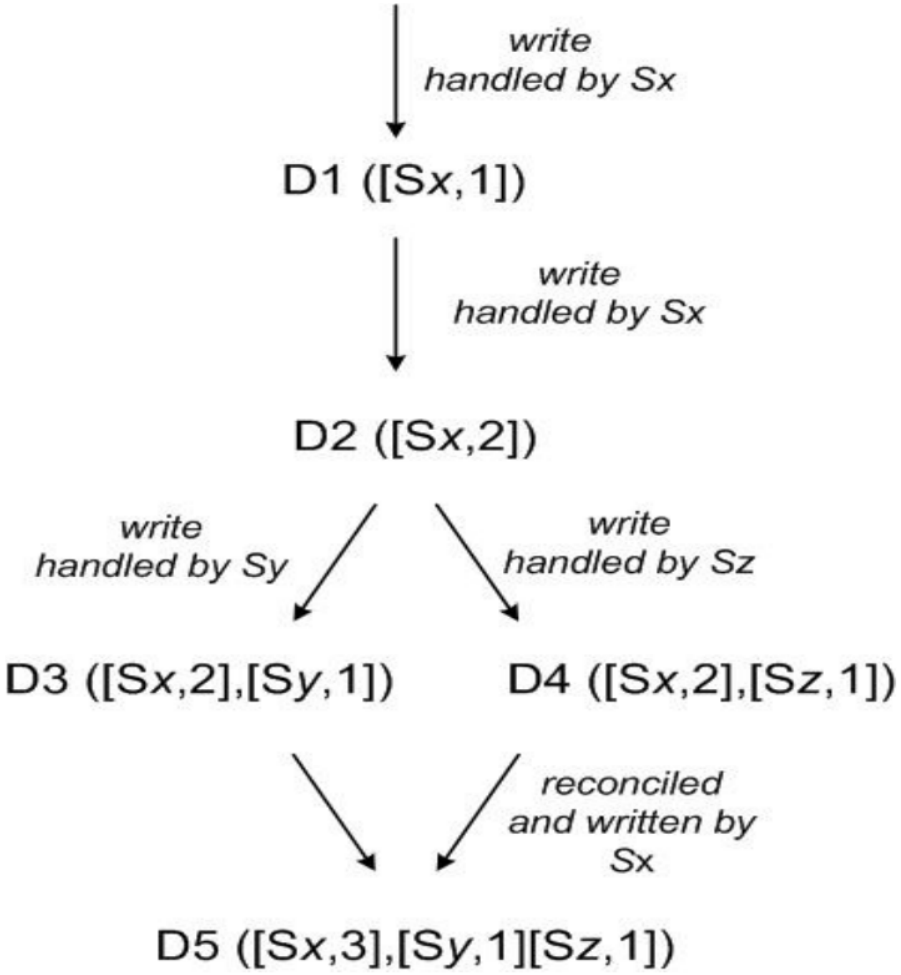


Object Versioning

- Writes should always succeed
  - *E.g.*, “Add to Cart” as long as there’s at least one reachable server
- Object versioning is used to reconcile inconsistency.
- Each object has a vector clock
  - *E.g.*, D1 ([Sx, 1], [Sy, 1]): Object D (version 1) was 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 lead to inconsistency
  - *I.e.*, there are writes that are not causally related.
- If an object is inconsistent, reconcile it later.
  - *E.g.*, deleted items might reappear in the shopping cart.

Object Versioning

- Example



Conflict Detection & Resolution

- Object versioning gives clients the ability to detect write conflicts.
- Reconciliation
  - Simple resolution done by the system (last-write-wins policy)
  - Complex resolution done by individual applications: The system presents all conflicting versions of data to an application.

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

Multiple versions were usually triggered by many concurrent requests issued by robots, not human clients.

Quorums

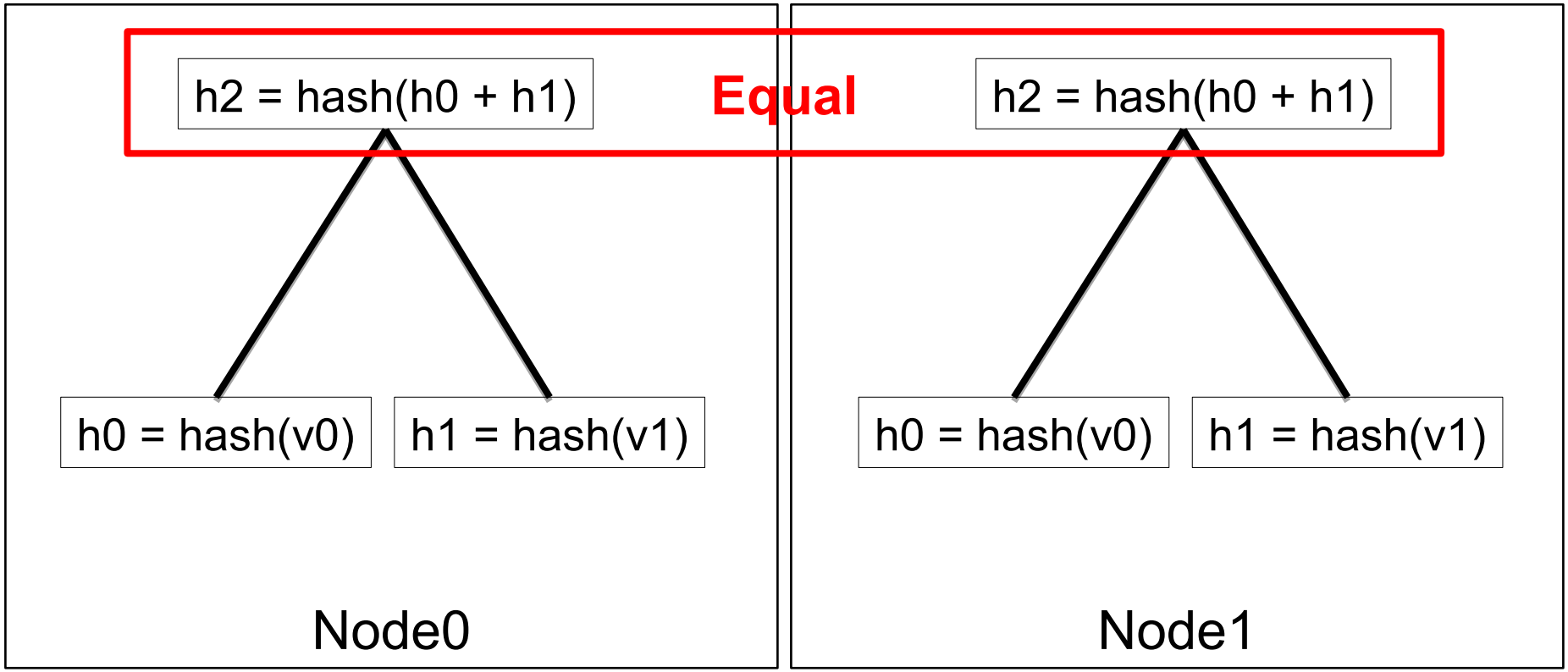
- Parameters
  - N replicas, R readers, W writers
- Static quorum approach: R + W > N, W > N / 2
- Typical Dynamo configuration: (N, R, W) == (3, 2, 2)
- But it depends
  - High performance read (*e.g.*, write-once, read-many data):
    - R==1, W==N
  - Low R & W might lead to more inconsistency
- Dealing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

Replica Synchronization

- Key ranges are replicated.
- Suppose a node fails and recovers; it needs to quickly determine whether it needs to resynchronize or not.
  - Transferring all (key, value) pairs for comparison is not an option
- Merkel trees
  - Leaf values are hashes of the values of individual keys
  - Parent values are hashes of their (immediate) children
  - Comparing parents at the same level identifies differences in children
  - Does not require transferring entire (key, value) pairs

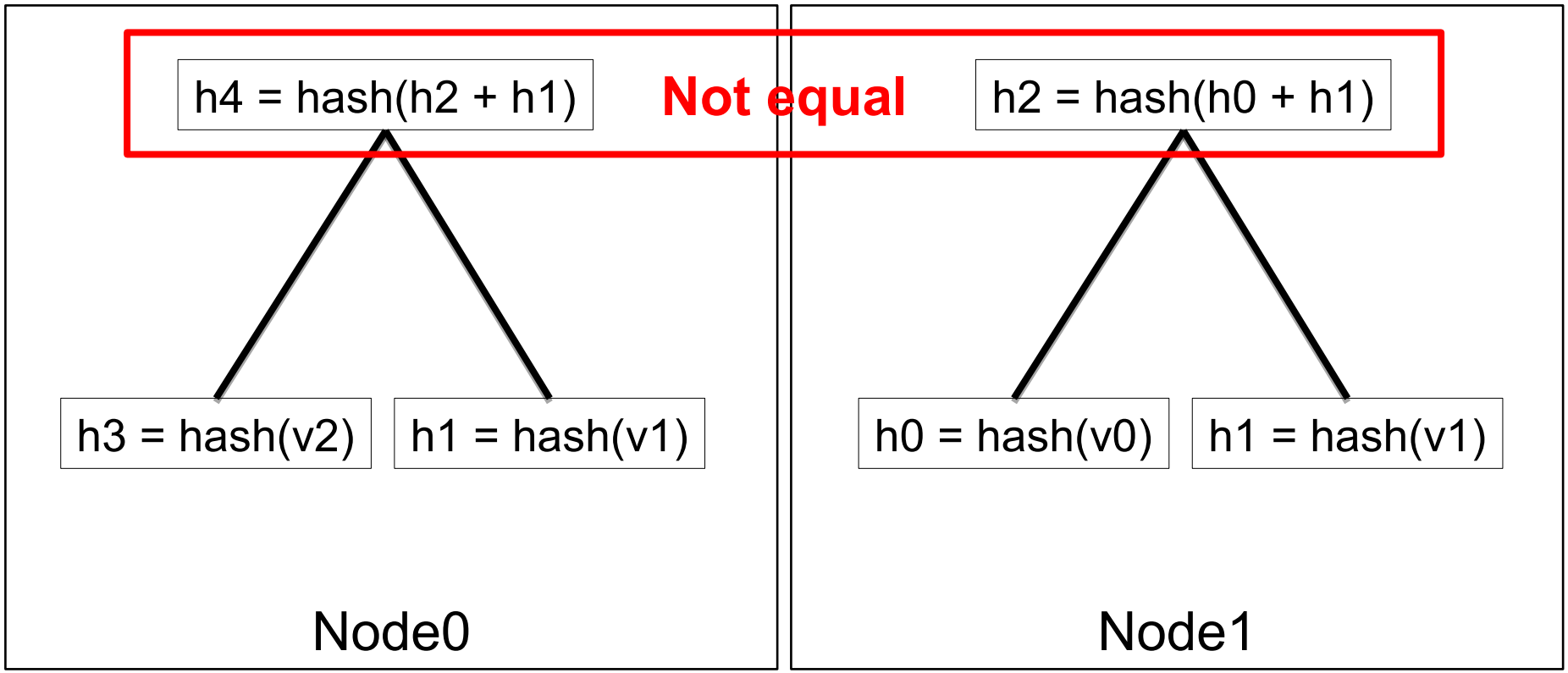
Replica Synchronization

- Comparing two nodes that are synchronized
  - Two <key, value> pairs: <k0, v0> & <k1, v1>



Replica Synchronization

- Comparing two nodes that are not synchronized
  - One has <k0, v2> and <k1, v1>
  - The other has <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

References

[1] Werner Vogels. *Amazon DynamoDB – a Fast and Scalable NoSQL Database Service Designed for Internet Scale Applications*. From the All Things Distributed weblog. **Required Reading.** https://www.allthingsdistributed.com/2012/01/amazon-dynamodb.html

Acknowledgements

- These slides are by Steve Ko, lightly modified and used with permission by Ethan Blanton.
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