DYNAMO DB

March 14, 2023

George Porter

UC San Diego

ATTRIBUTION

- These slides are based on material from:
  - **Brad Karp**
  - **Kyle Jamieson and Mike Freedman, Princeton**

Dynamo: The P2P context

- **Chord** intended for **wide-area P2P systems**
  - Individual nodes **at Internet's edge**, file sharing

- Central challenges: low-latency key lookup with **small forwarding state** per node

- **Techniques:**
  - **Consistent hashing** to map keys to nodes

  - **Replication** at successors for availability under failure

Amazon's workload (in 2007)

- **Tens of thousands** of servers in globally-distributed **data centers**
- **Peak load:** Tens of millions of customers
- **Tiered** service-oriented architecture
  - **Stateless** web page rendering servers, atop
  - **Stateless** aggregator servers, atop
  - **Stateful** data stores (**e.g. Dynamo**)
    - **put( ), get( ):** values "usually less than 1 MB"

How does Amazon use Dynamo?

- **Shopping cart**
- **Session info**
  - Maybe “recently visited products” *etc.*?
- **Product list**
  - Mostly read-only, replication for high read throughput

Dynamo requirements

- **Highly available writes** despite failures
  - Despite disks failing, network routes flapping, "data centers destroyed by tornadoes"
  - **Non-requirement:** Security, *viz.* authentication, authorization (used in a non-hostile environment)
- **Low request-response latency:** focus on **99.9%** SLA
- **Incrementally scalable** as servers grow to workload
  - Adding "nodes" should be seamless
- Comprehensible **conflict resolution**
  - High availability in above sense implies conflicts

Design questions

- How is data **placed and replicated?**
- How are **requests routed and handled** in a replicated system?
- How to cope with temporary and permanent **node failures?**

Dynamo's system interface

- Basic interface is a key-value store
  - **get(k)** and **put(k, v)**
  - Keys and values opaque to Dynamo

- get(key) → value, **context**
  - Returns one value or multiple conflicting values
  - Context describes version(s) of value(s)

- put(key, **context**, value) → "OK"
  - **Context** indicates **which versions** this version supersedes or merges

Dynamo's techniques

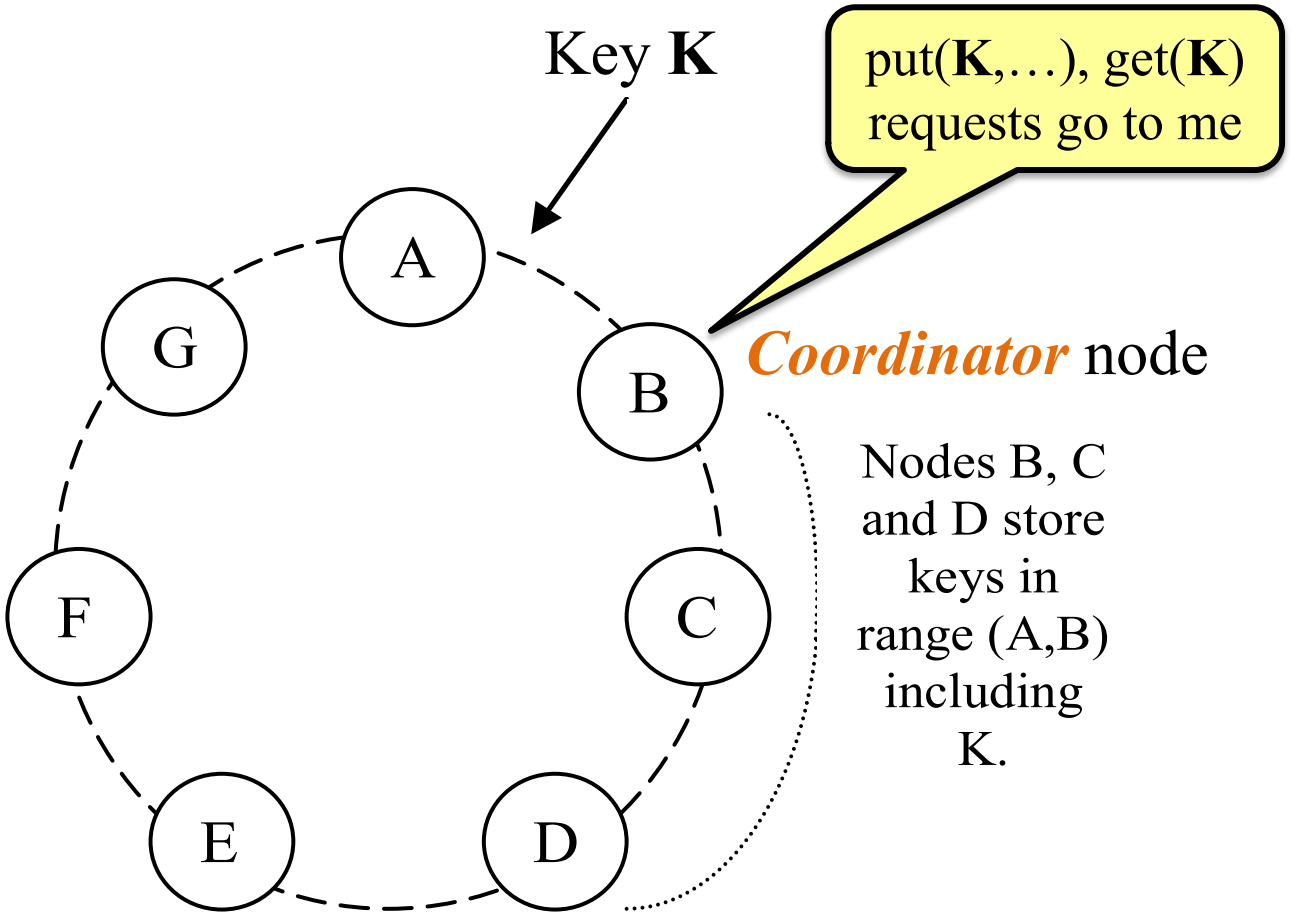
- **Place** replicated data on nodes with **consistent hashing**

- Maintain consistency of replicated data with **vector clocks**
  - **Eventual consistency** for replicated data: prioritize success and low latency of writes over reads
    - And availability over consistency (unlike DBs)
  - Lamport's vector clocks covered in CSE 223B

- Efficiently **synchronize replicas** using **Merkle trees**

Key trade-offs: Response time vs. consistency vs. durability

Data placement



Each data item is **replicated** at ***N*** virtual nodes (e.g., $N = 3$)

Data replication

- Much like in Chord: a key-value pair → key's *N* successors (***preference list***)
  - **Coordinator receives a put** for some key
  - Coordinator then **replicates data onto nodes** in the key's **preference list**

- Preference list **size > N** to account for node failures

- For robustness, the preference list **skips virtual tokens** to **ensure distinct physical nodes**

Gossip and "lookup"

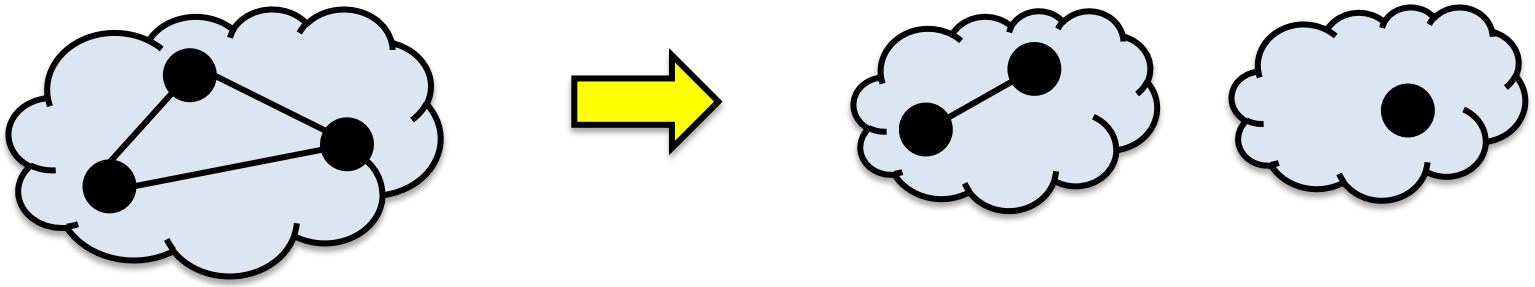
- **Gossip:** Once per second, each node contacts a **randomly chosen other node**
  - They **exchange their lists of known nodes** (including virtual node IDs)

- Each node **learns** which others handle all **key ranges**

  - **Result: All** nodes can send **directly to any key's coordinator ("zero-hop DHT")**
    - **Reduces variability** in response times

Partitions force a choice between availability and consistency

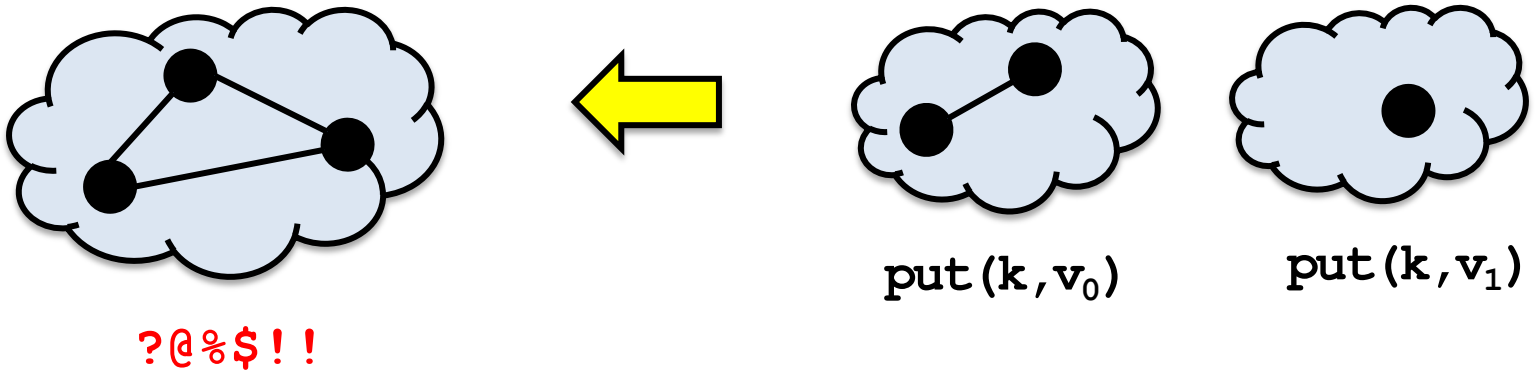
- Suppose **three** replicas are partitioned into **two and one**



- If one replica fixed as master, no client in other partition can write
- With RAFT, no client in the partition of one can write
- Traditional distributed databases emphasize consistency over availability when there are partitions

Alternative: Eventual consistency

- Dynamo emphasizes **availability over consistency** when there are partitions
- Tell client write complete when only some replicas have stored it
- Propagate to other replicas in background
- **Allows writes in both partitions**…but risks:
  - Returning **stale data**
  - **Write conflicts** when partition heals:



Mechanism: Sloppy quorums

- If **no failure**, reap **consistency benefits** of single master
  - Else **sacrifice consistency** to **allow progress**

- Dynamo tries to store all values put() under a key on **first *N* live nodes** of coordinator's **preference list**

- **BUT to speed up** get() and put():
  - Coordinator returns "success" for **put** when **W** < N replicas have completed **write**
  - Coordinator returns "success" for **get** when **R** < N replicas have completed **read**

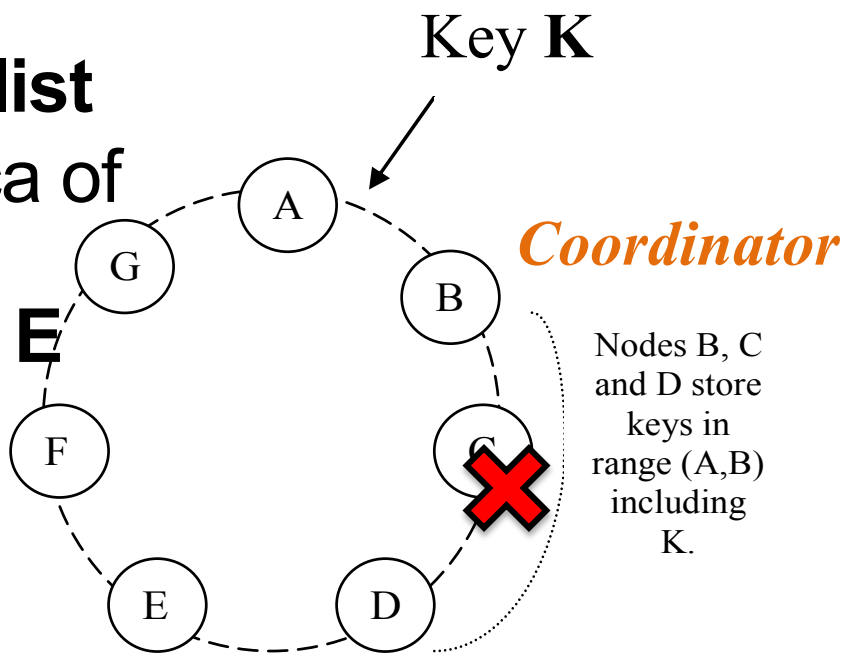
Sloppy quorums: Hinted handoff

- Suppose coordinator **doesn't receive *W* replies** when replicating a put()
  - Could return failure, but remember goal of **high availability for writes…**

- **Hinted handoff:** Coordinator **tries next successors** in preference list (**beyond first *N***) if necessary
  - Indicates the **intended replica node** to recipient
  - **Recipient** will periodically try to forward to the **intended replica node**

Hinted handoff: Example

- Suppose **C fails**
  - **Node E** is in **preference list**
    - Needs to receive replica of the data
  - Hinted Handoff: replica at **E** points to node **C**



- When **C comes back**
  - **E** forwards the replicated data back to **C**

Wide-area replication

- Last ¶, § 4.6: **Preference lists always** contain nodes from **more than one data center**
  - **Consequence:** Data likely to **survive failure** of **entire data center**

- Blocking on **writes to a remote data center** would incur unacceptably high latency
  - **Compromise: W < N**, eventual consistency

Sloppy quorums and get()s

- Suppose coordinator **doesn't receive *R* replies** when processing a get()
  - Penultimate ¶, § 4.5: "*R* is the min. number of nodes that must participate in a successful read operation."
    - Sounds like these get()s fail

- **Why not return whatever data was found, though?**
  - As we will see, consistency not guaranteed anyway…

Sloppy quorums and freshness

- Common case given in paper: **N = 3; R = W = 2**
  - With these values, **do sloppy quorums guarantee a get() sees all prior put()s?**

- If **no failures**, **yes:**
  - **Two writers** saw each put()
  - **Two readers** responded to each get()
  - Write and read **quorums must overlap!**

Sloppy quorums and freshness

- Common case given in paper: **N = 3, R = W = 2**
  - With these values, **do sloppy quorums guarantee a get() sees all prior put()s?**

- With **node failures, no:**
  - **Two nodes** in preference list **go down**
    - put() replicated **outside preference list**
  - **Two nodes** in preference list **come back up**
    - get() occurs before they receive prior put()

Conflicts

- Suppose **N = 3, W = R = 2,** nodes are named **A, B, C**
  - 1st put(k, …) completes on **A** and **B**
  - 2nd put(k, …) completes on **B** and **C**
  - Now get(k) arrives, completes first at **A** and **C**

- **Conflicting results** from **A** and **C**
  - Each has seen a **different put(k, …)**

- **Dynamo returns both results;** what does client do now?

Conflicts vs. applications

- Shopping cart:
  - **Could take union** of two shopping carts
  - What if second put() was result of user deleting item from cart stored in first put()?
    - **Result: "resurrection" of deleted item**

- Can we do better? Can Dynamo resolve cases when multiple values are found?
  - **Sometimes.** If it can't, **application** must do so.

Removing threats to durability

- Hinted handoff node **crashes before it can replicate data** to node in **preference list**
  - Need another way to **ensure** that each key-value pair is **replicated N times**

- **Mechanism: replica synchronization**
  - Nodes nearby on ring periodically **gossip**
    - **Compare** the (k, v) pairs they hold
    - **Copy** any missing keys the other has

How to **compare and copy** replica state **quickly and efficiently?**

Efficient synchronization with Merkle trees

- **Merkle trees** **hierarchically summarize** the key-value pairs a node holds

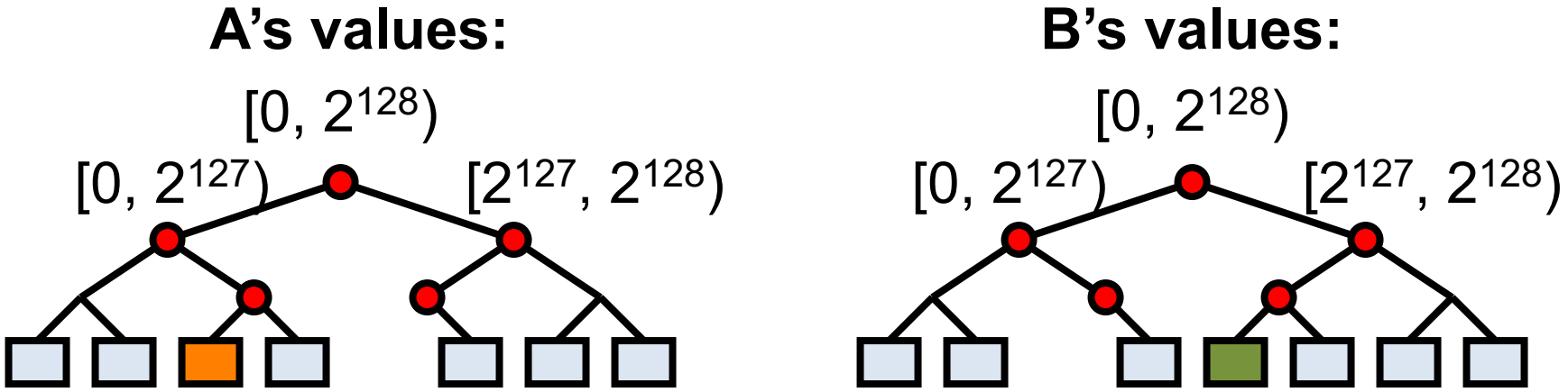
- One Merkle tree for each **virtual node key range**
  - **Leaf node** = hash of **one key's value**
  - **Internal node** = hash of **concatenation of children**

- **Compare roots; if match, values match**
  - If they **don't match**, compare **children**
    - **Iterate** this process down the tree

Merkle tree reconciliation

- **B** is missing orange key; **A** is missing green one

- Exchange and compare hash nodes from root downwards, **pruning when hashes match**



Finds differing keys **quickly** and with minimum information exchange

How useful is it to vary N, R, W?

N	R	W	Behavior
3	**2**	**2**	**Parameters from paper: Good durability, good R/W latency**
3	3	1	Slow reads, **weak durability, fast writes**
3	1	3	**Slow writes,** strong durability, fast reads
3	3	3	More likely that **reads see all prior writes**?
3	1	1	Read quorum **doesn't overlap** write quorum

Dynamo: Take-away ideas

- Consistent hashing broadly useful for replication—not only in P2P systems
- Extreme emphasis on **availability and low latency,** unusually, at the **cost of some inconsistency**
- Eventual consistency lets writes and reads return quickly, **even when partitions and failures**
- **Version vectors** allow some **conflicts to be resolved** automatically; others left to application