Scaling Out Key-Value Storage

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CS 240: Computing Systems and Concurrency
Lecture 8

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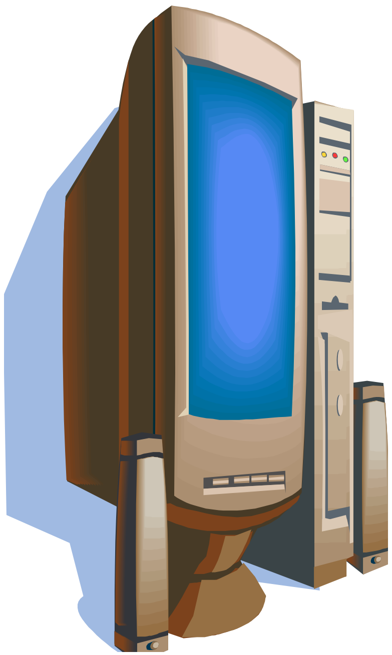
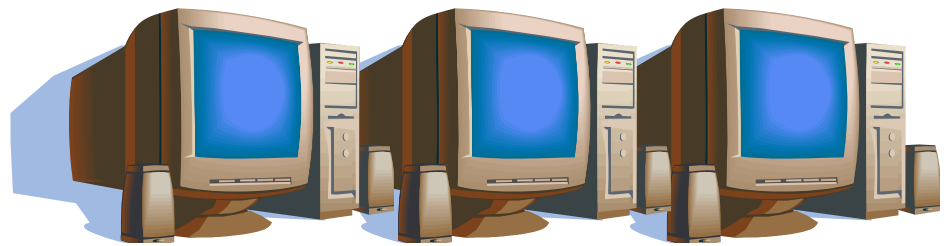
Credits: Michael Freedman and Kyle Jamieson developed much of the original material.
Selected content adapted from B. Karp, R. Morris.

Horizontal or vertical scalability?



Vertical Scaling



Horizontal Scaling

Horizontal scaling is challenging

- Probability of any failure in given period = $1-(1-p)^n$
  - p = probability a machine fails in given period
  - n = number of machines

- For **50K machines**, each with **99.99966% available**
  - **16%** of the time, **data center experiences failures**

- For **100K machines, failures 30%** of the time!

Main challenge: Coping with constant failures

Today

1. **Techniques for partitioning data**
   - **Metrics for success**

2. Case study: Amazon Dynamo key-value store

Scaling out: Placing

- You have key-value pairs to be partitioned across nodes based on an id

- **Problem 1: Data placement**
  - **On which node(s)** to **place** each key-value pair?
    - Maintain mapping from data object to node(s)
    - Evenly distribute data/load

Scaling out: Partitioning

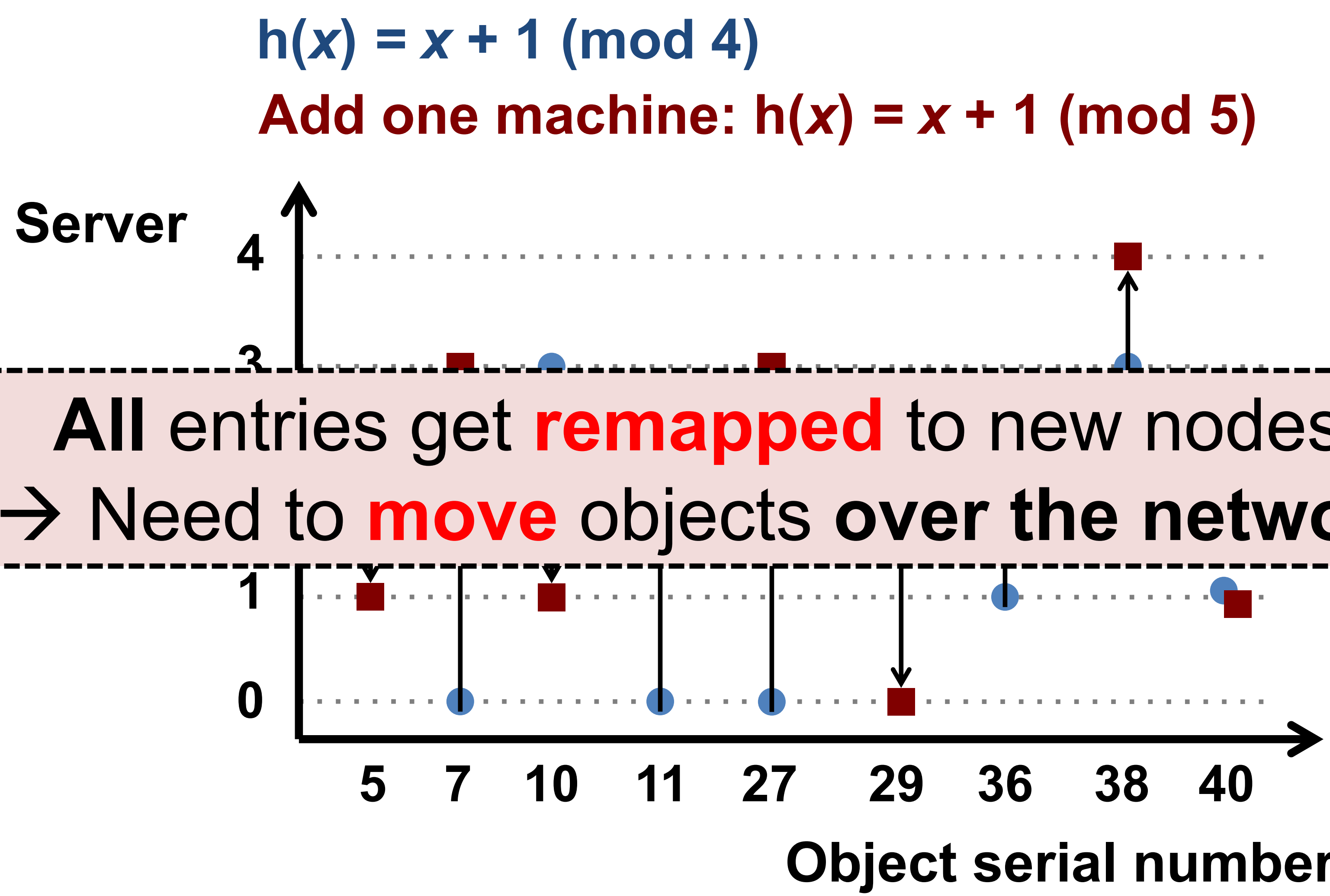
- **Problem 2: Partition management**
  - Including how to recover from node failure
    - *e.g.*, bringing another node into partition group
  - Changes in system size, *i.e.* **nodes joining/leaving**
  - Heterogeneous nodes

- **Centralized:** Cluster manager
- **Decentralized:** Deterministic hashing and algorithms

Modulo hashing

- Consider problem of data partition:
  - Given **object id X**, choose one of ***k*** servers to use
- Suppose instead we use **modulo hashing:**
  - Place ***X*** on server ***i* = hash(*X*) mod *k***
- What happens if a server fails or joins ($k \leftarrow k \pm 1$)?
  - or different clients have **different estimate** of k?

Problem for modulo hashing: Changing number of servers

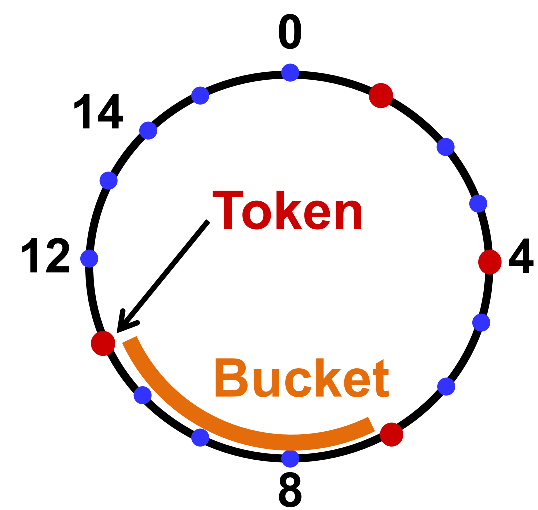


All entries get **remapped** to new nodes!

→ Need to **move** objects **over the network**

Consistent hashing

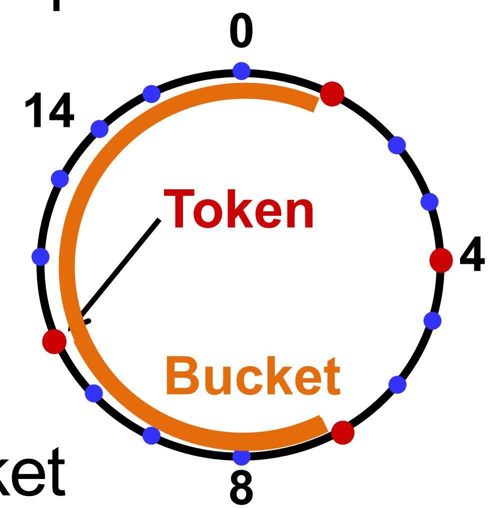
– Assign *n* ***tokens*** to random points on mod 2^k circle; hash key size = *k*
– Hash object to random circle position
– Put object in **closest clockwise bucket**
  – ***successor*** (key) → bucket



- **Desired features –**
  – **Balance:** No bucket has "too many" objects; E(bucket size)=1/n
  – **Smoothness:** Addition/removal of token **minimizes object movements** for other buckets

Consistent hashing's load balancing problem

- Each node owns **1/n** of the ID space in expectation
  - Hot keys => some buckets have higher request rate



- If a node fails, its successor takes over bucket
  - **Smoothness goal ✔:** Only localized shift, not O(n)
  - But now successor owns **two** buckets: **2/n of key space**
    - The failure has **upset the load balance**

Virtual nodes

- **Idea:** Each physical node implements v ***virtual*** nodes
  - Each **physical node** maintains **v > 1 token ids**
    - Each token id corresponds to a virtual node
    - Each **physical node** can have a different v based on strength of node (heterogeneity)

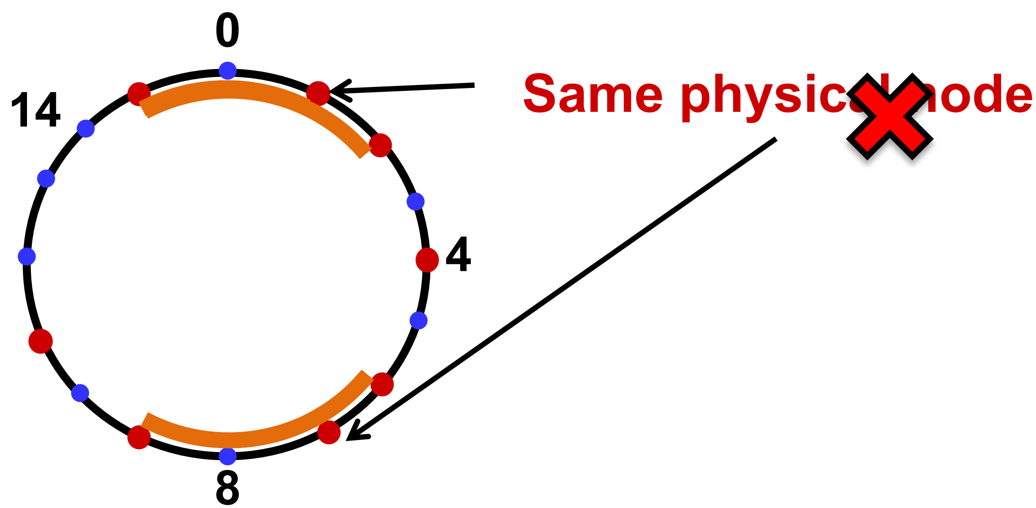
- Each virtual node owns an expected **1/(vn)** of ID space

- **Upon a physical node's failure, v** virtual nodes fail
  - Their successors take over 1/(vn) more
    - Expected to be distributed across physical nodes

Virtual nodes: Example

4 Physical Nodes

V=2



- **Result: Better load balance** with larger v

Today

1. Techniques for partitioning data

2. **Case study: the Amazon Dynamo key-value store**

Dynamo: The P2P context

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

- Central challenges: low-latency key lookup with high availability
  - Trades off **consistency** for **availability** and **latency**

- **Techniques:**
  - **Consistent hashing** to map keys to nodes
  - **Vector clocks** for conflict resolution
  - **Gossip** for node membership
  - **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"
  - Always respond quickly, even during failures → replication

- **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

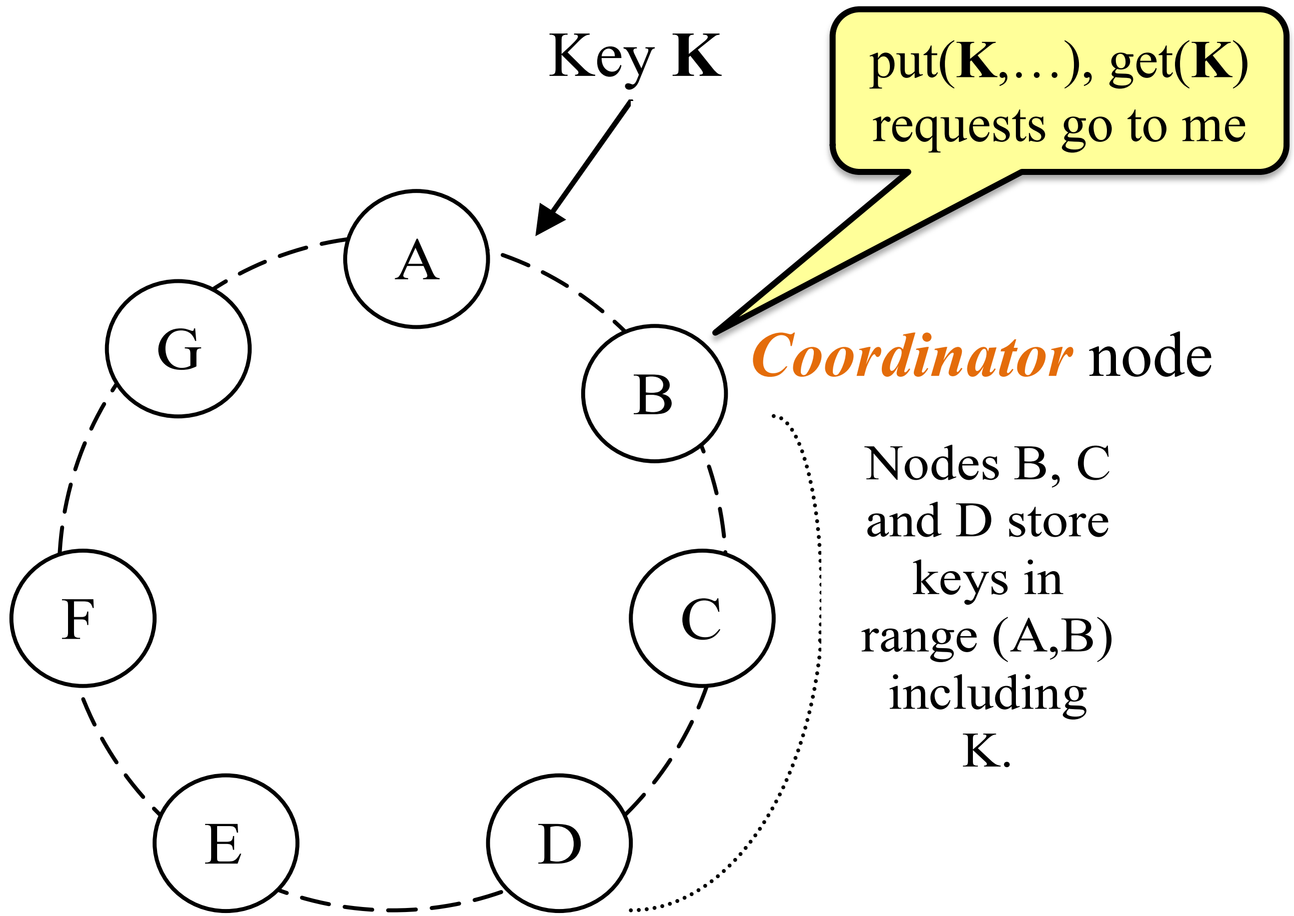
- **Place** replicated data on nodes with **consistent hashing**

- 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)

- 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**

- Writes to **more than just *N*** successors in case of failure

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

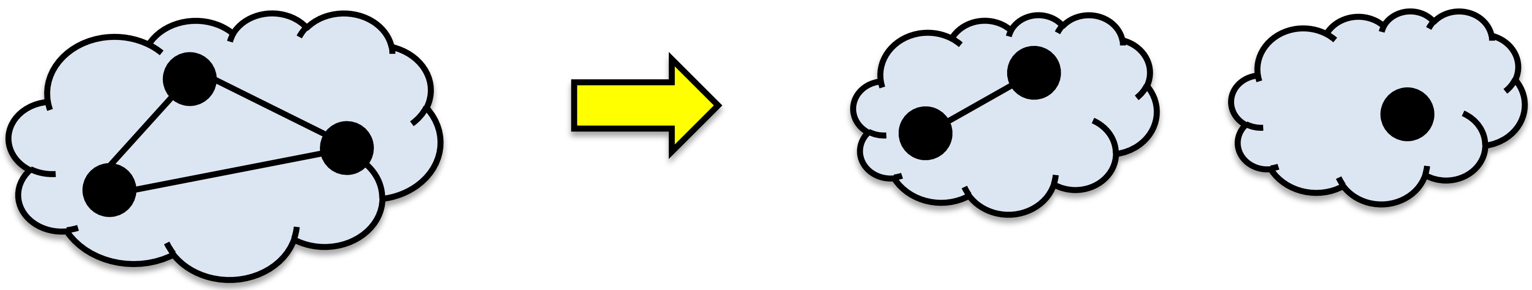
Gossip and "lookup"

- **Gossip:** Once per second, each node contacts a **randomly chosen other node**
  - They **exchange their lists of known nodes** (including virtual node IDs)
- Assumes all nodes will come back eventually, doesn't repartition
- 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

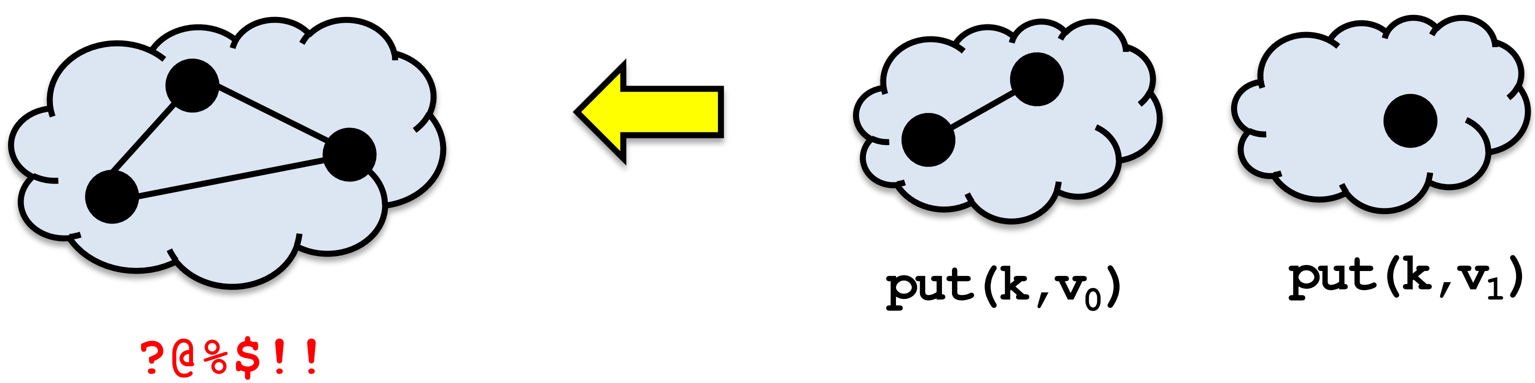
- Suppose **three** replicas are partitioned into **two and one**



- If one replica fixed as master, no client in other partition can write
- 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**

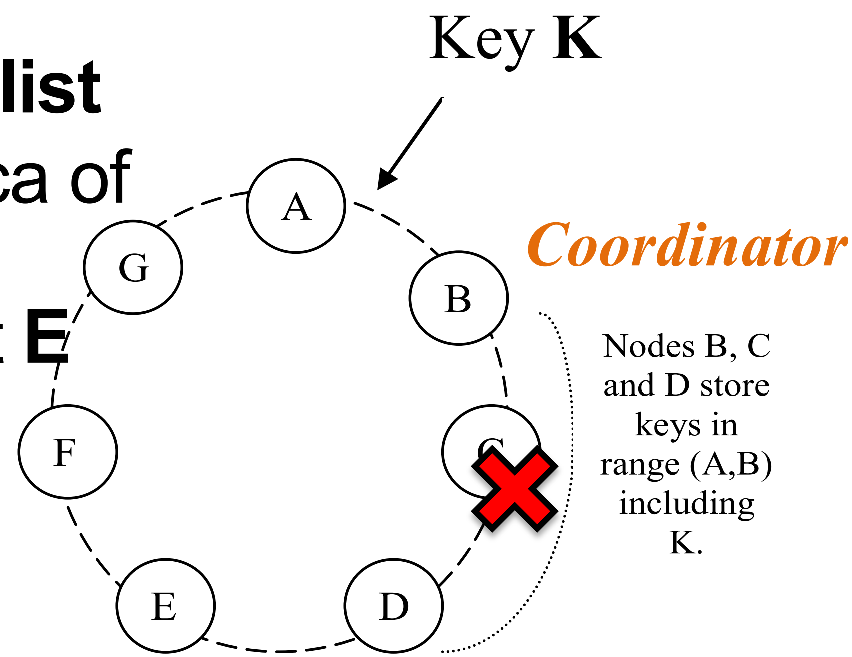
Sloppy quorums: Hinted handoff

- 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; E** periodically forwards to **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
  - Better **durability** & **latency** but worse **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.

Version vectors (vector clocks)

- ***Version vector:*** List of **(coordinator node, counter)** pairs
  - *e.g.*, [(A, 1), (B, 3), …]

- Dynamo stores a version vector with **each stored** key-value **pair**

- **Idea:** track "ancestor-descendant" relationship between different versions of data stored under the same key **k**

Version vectors: Dynamo's mechanism

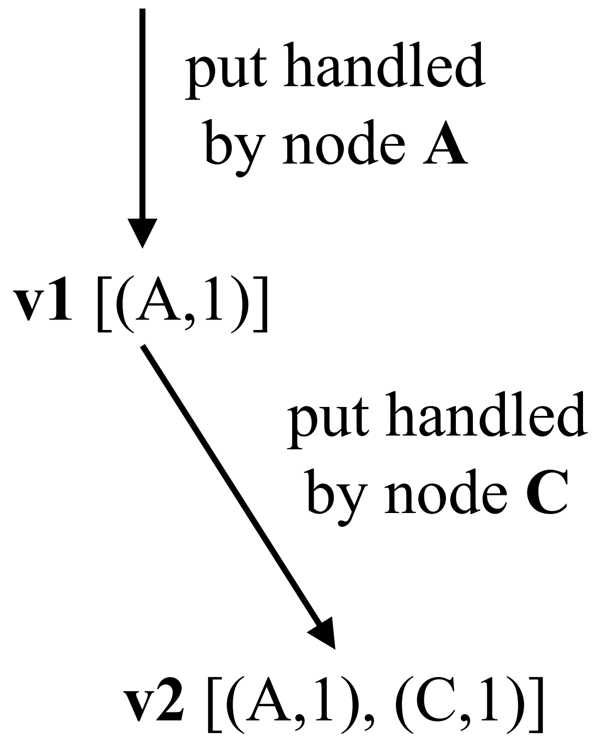
- **Rule:** If vector clock comparison of v1 < v2, then the first is an ancestor of the second – **Dynamo can forget v1**

- Each time a put() occurs, Dynamo increments the counter in the V.V. for the coordinator node

- Each time a get() occurs, Dynamo returns the V.V. for the value(s) returned (in the "context")

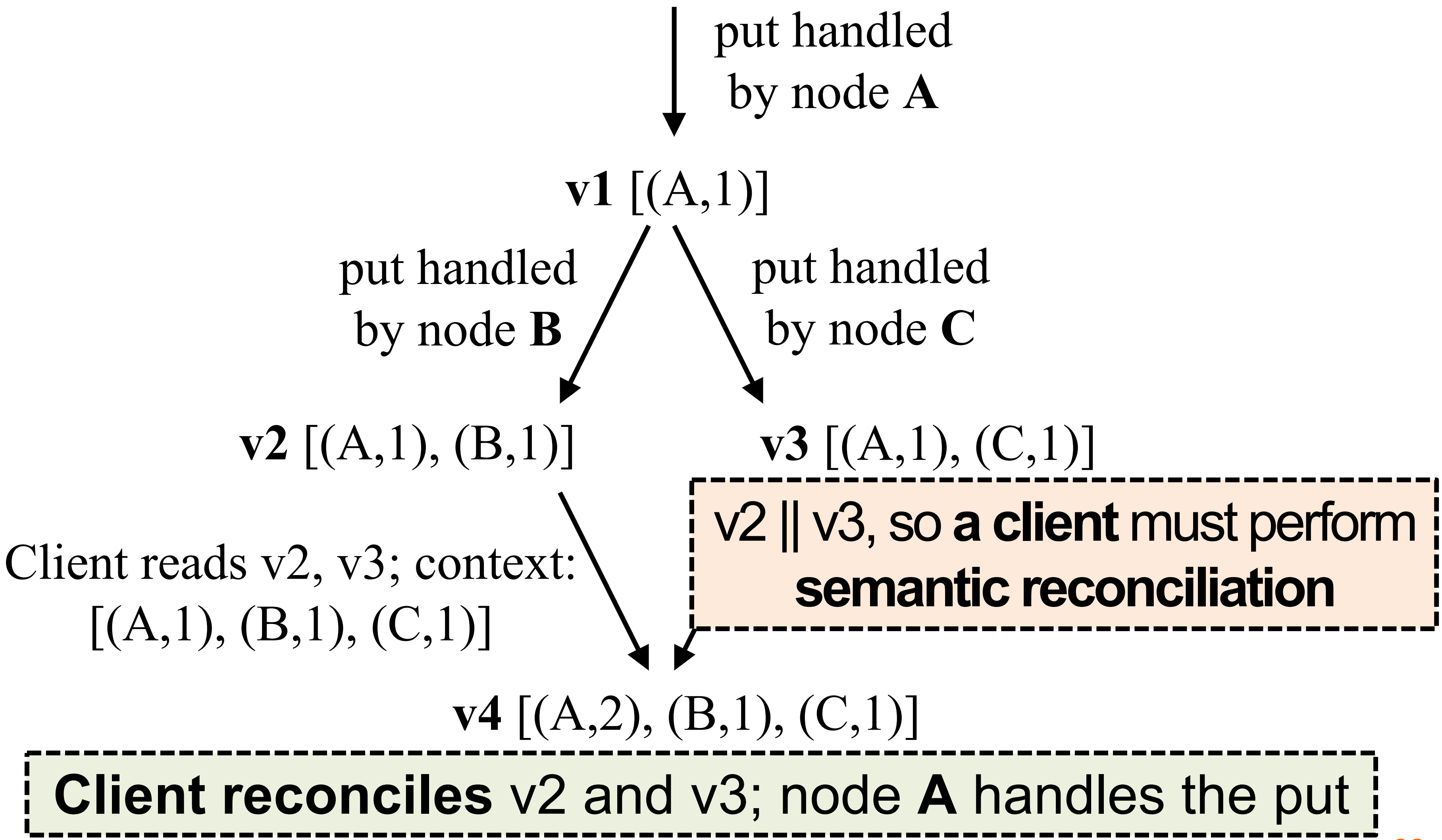
  – Then users **must supply that context** to put()s that modify the same key

Version vectors (auto-resolving case)



v2 > v1, so Dynamo nodes **automatically drop v1**, for **v2**

Version vectors (app-resolving case)

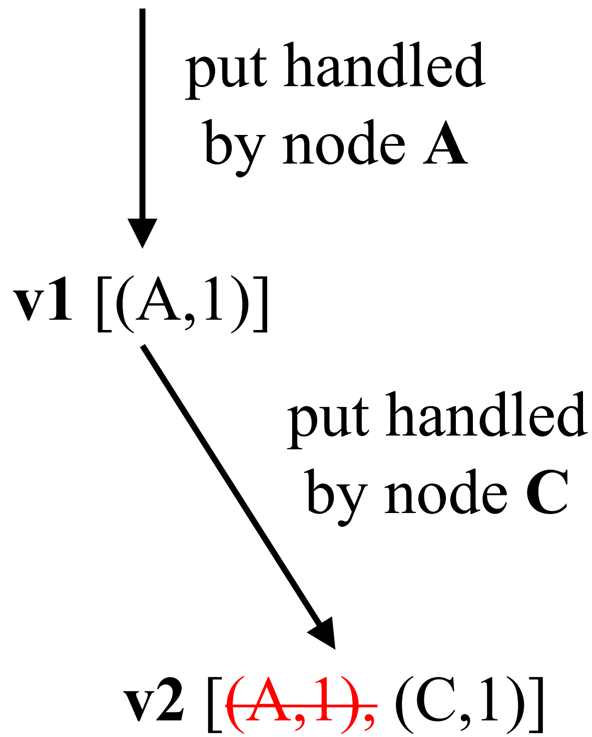


Trimming version vectors

- **Many nodes** may process a series of put()s to **same key**
  - Version vectors **may get long** – do they grow forever?

- No, there is a **clock truncation scheme**
  - Dynamo stores time of modification with each V.V. entry
  - When V.V. > 10 nodes long, V.V. **drops** the timestamp of the **node that least recently processed** that key

Impact of deleting a VV entry?



v2 || v1, so **looks like application resolution** is required

Concurrent writes

- What if two clients concurrently write w/o failure?
  - *e.g.* add **different items** to **same cart** at **same time**
  - Each does get-modify-put
  - They both see the same initial version
    - And they both send put() to **same coordinator**

- Will coordinator create two versions with conflicting VVs?
  - We want that outcome, otherwise one was thrown away
  - Paper doesn't say, but coordinator could detect problem via put() context

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

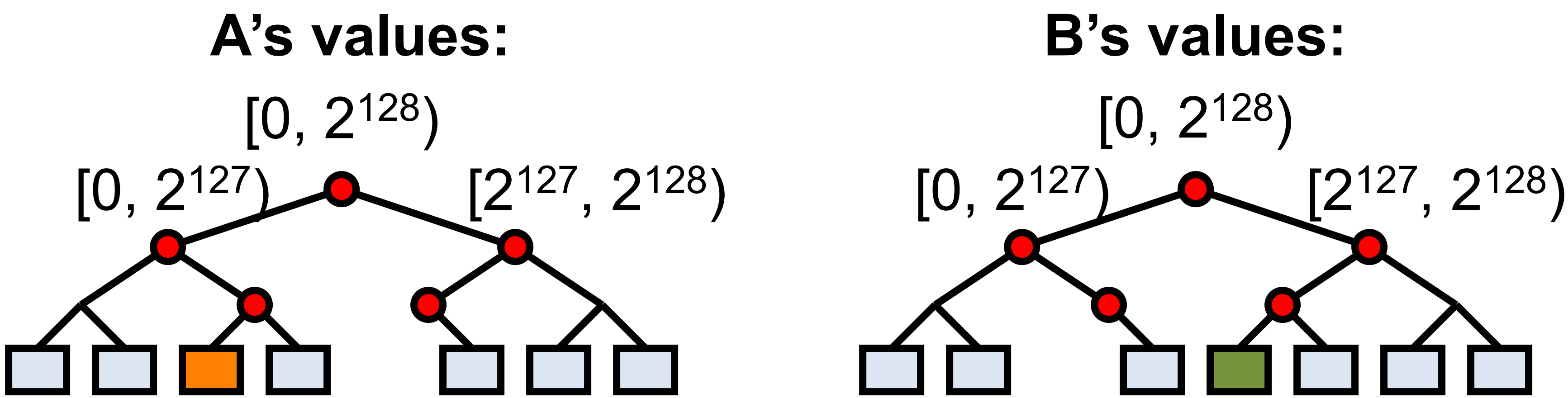
How to **compare and copy** replica state **quickly and efficiently?**

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	
3	1	3	
3	3	3	
3	1	1	

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 **may not 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

Next topic:

Replicated State Machines via Primary Backup