Scaling Out Key-Value Storage

COS 418: *Distributed Systems*

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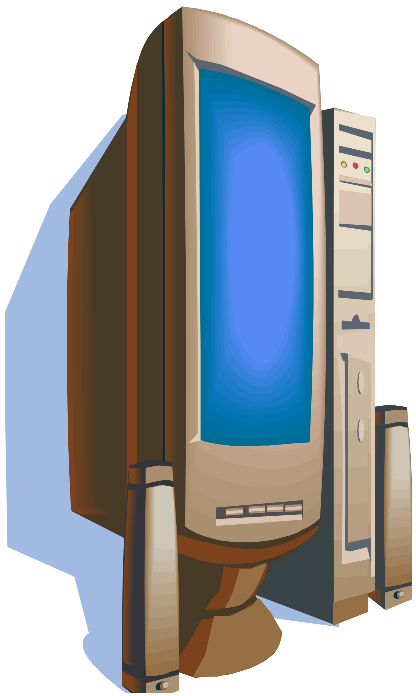
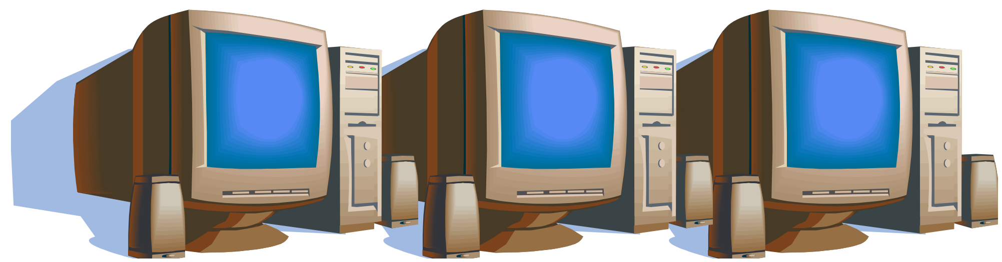
[Adapted from K. Jamieson, M. Freedman, B. Karp]

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: Placement

- 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: Partition Management

- **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

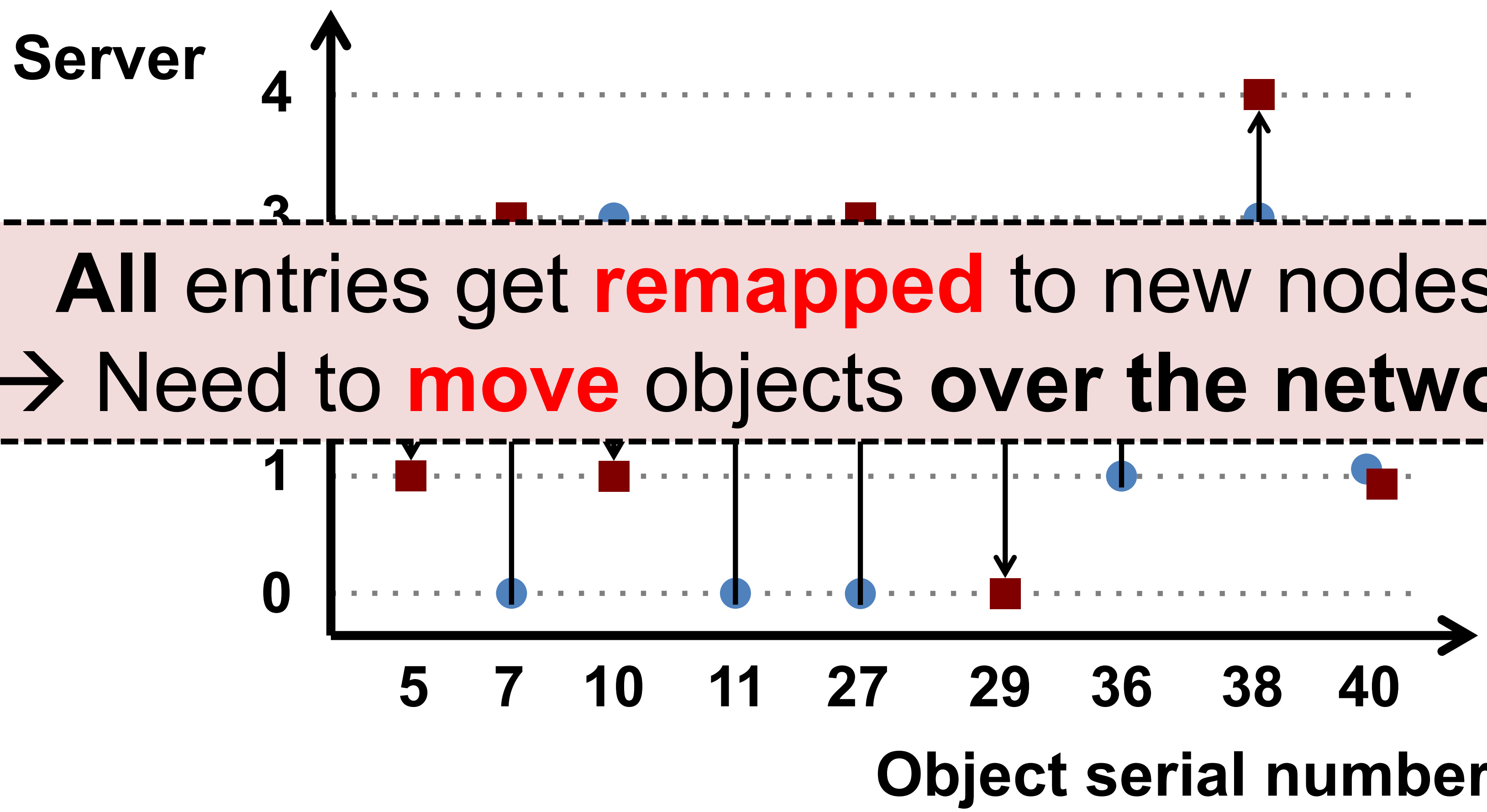
Modulo hashing

- 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 ← k±1)?
  - or different clients have **different estimate** of k?

Problem for modulo hashing: Changing number of servers

h(*x*) = *x* + 1 (mod 4)

Add one machine: h(*x*) = *x* + 1 (mod 5)

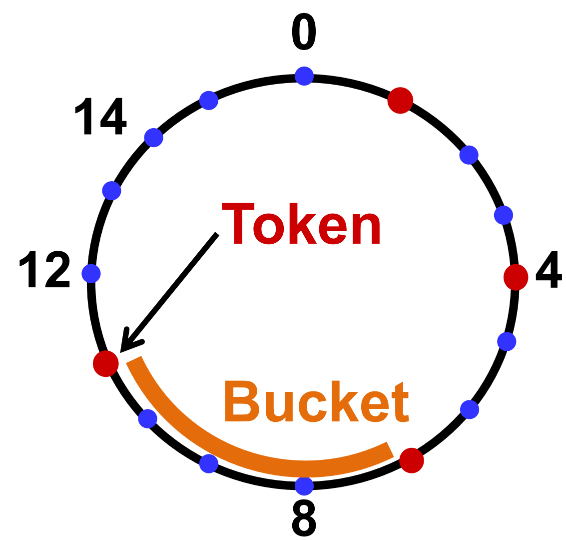


All entries get **remapped** to new nodes!

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

Consistent hashing

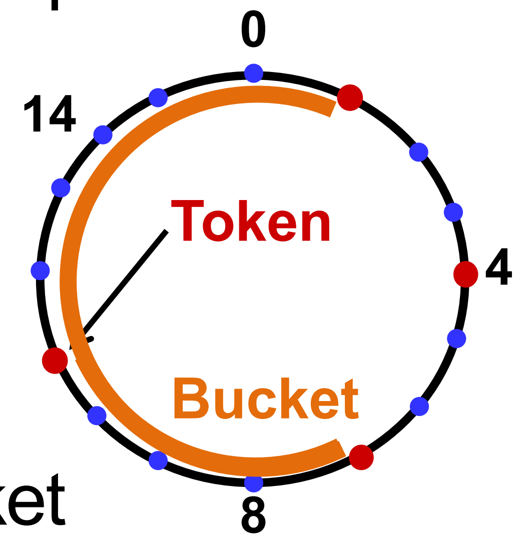
- Assign *n* ***tokens*** to random points on mod 2^k circle; hash key size = *k*
- Hash object to random circle position
- Put object in **closest clockwise** **bucket**
  - ***successor*** (key) → bucket



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

Consistent hashing's load balancing problem

- Each node owns **1/n^th^** 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^th^ 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)

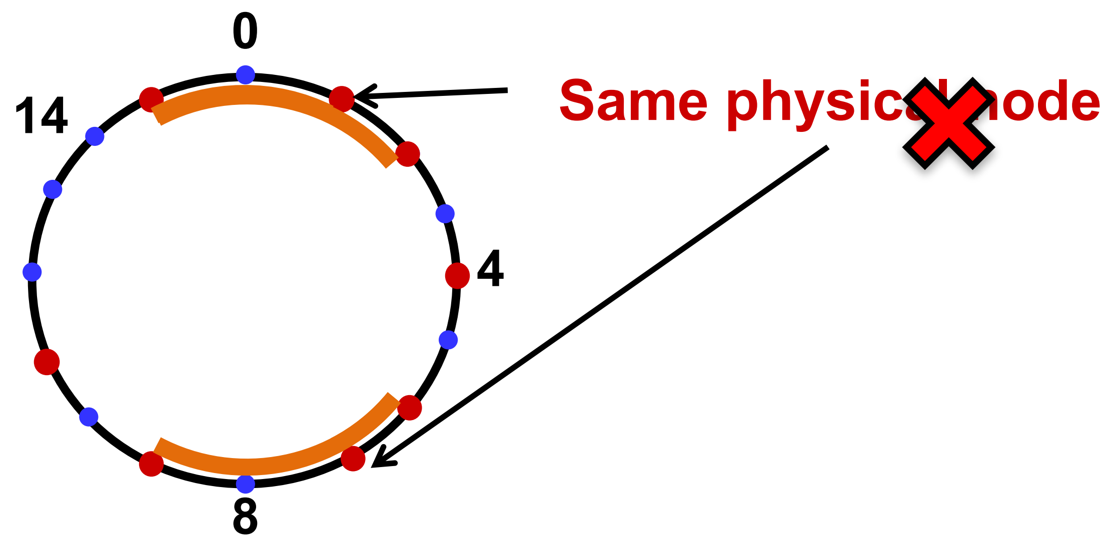
- Each virtual node owns an expected **$1/(vn)^{th}$** of ID space

- **Upon a physical node's failure,** **v** virtual nodes fail
  - Their successors take over $1/(vn)^{th}$ 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 challenge: 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” *et c.*?
- **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

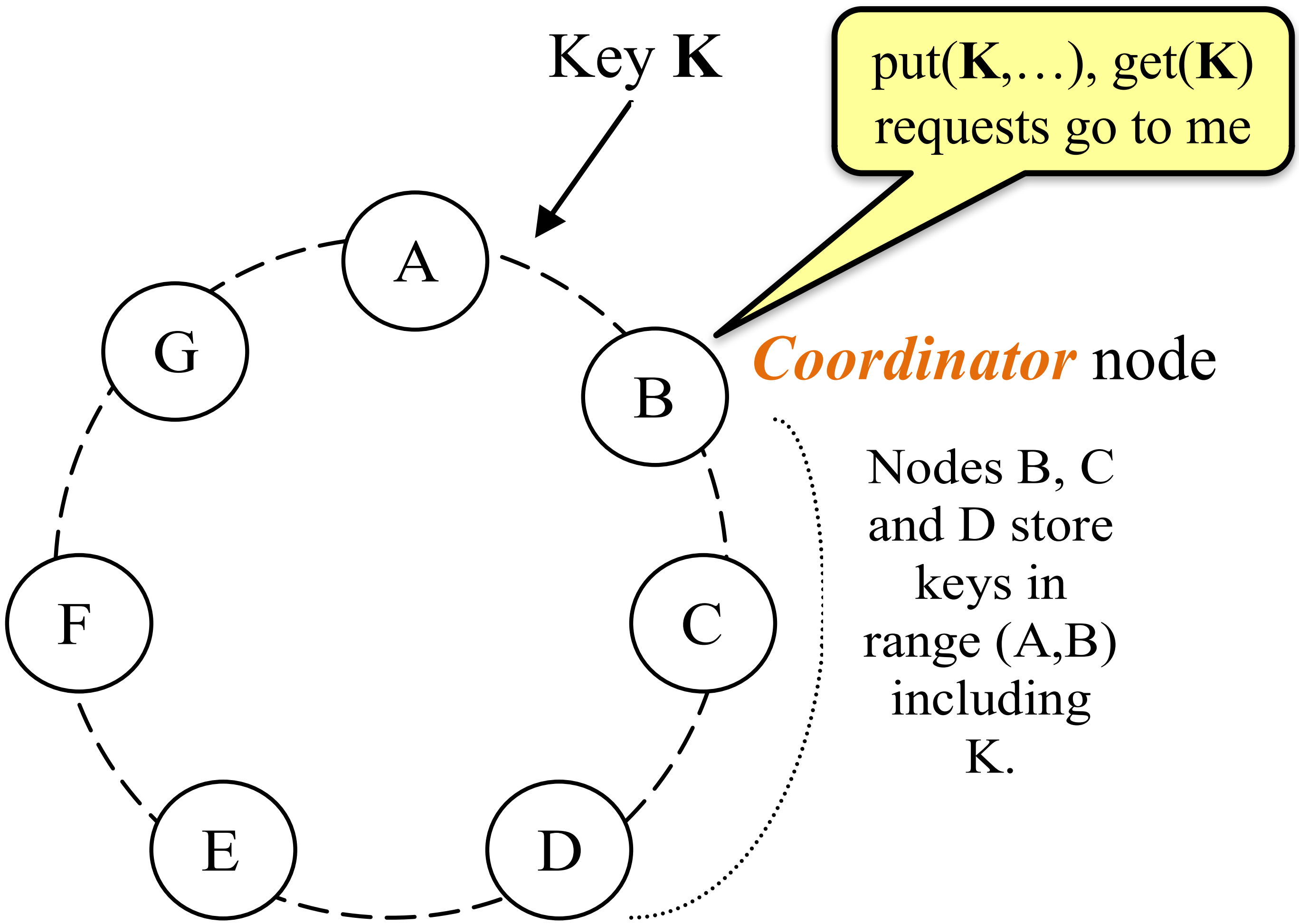
- **Place** replicated data on nodes with **consistent hashing**

- 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

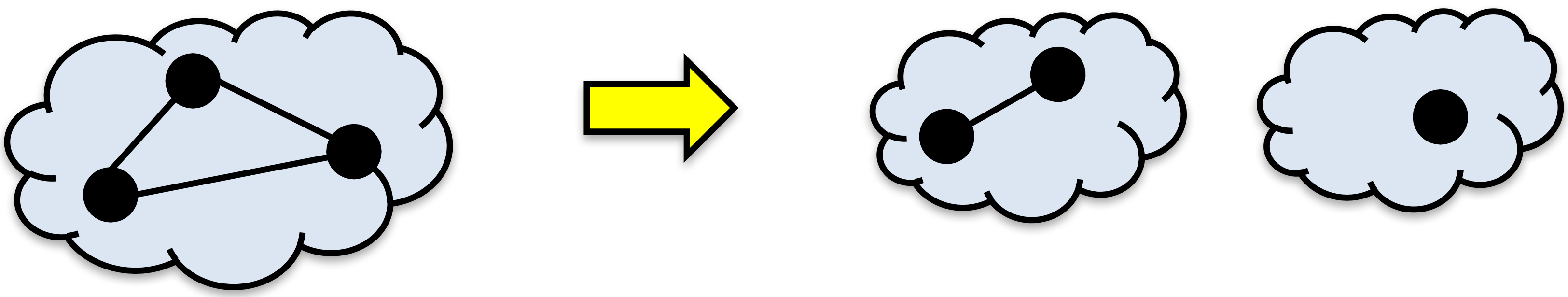
- Much like in Chord: a key-value pair → key's *N* successors (***preference list***)
  - **Coordinator receives a put** for some key
  - Coordinator then **replicates data onto nodes** in the key's **preference list**
- Writes to more than just *N* successors in case of failure
- For robustness, the 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

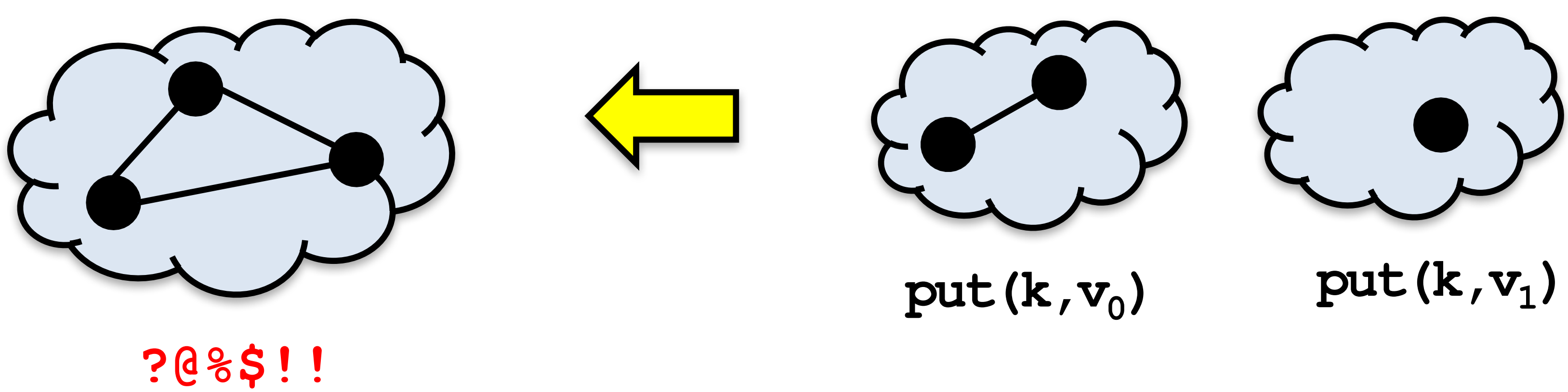
- Suppose **three** replicas are partitioned into **two and one**



- 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**

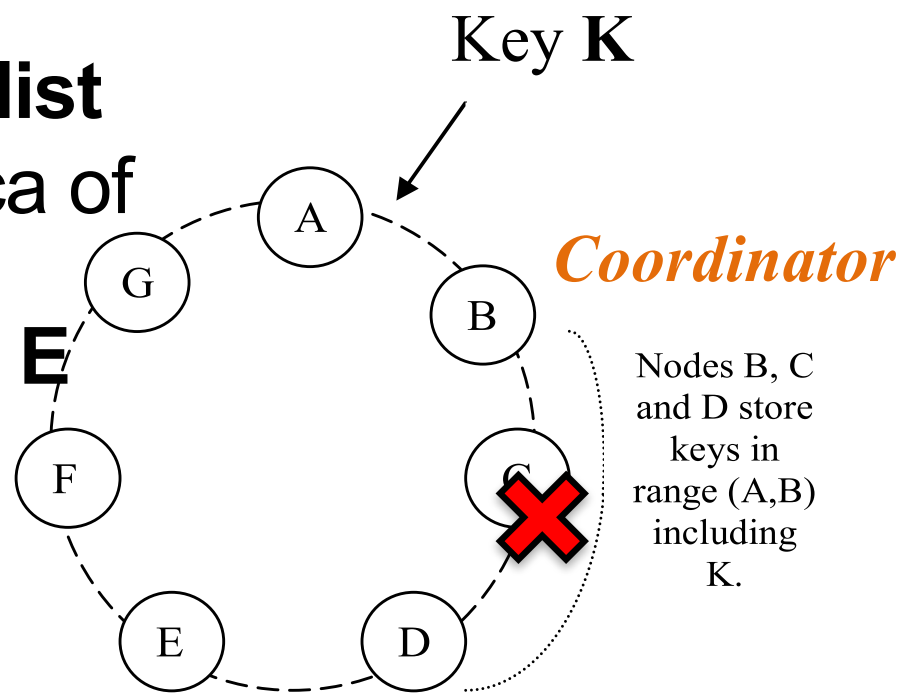
Sloppy quorums: Hinted handoff

- 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 further nodes** 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;** Hinted handoff nodes have data
  - **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

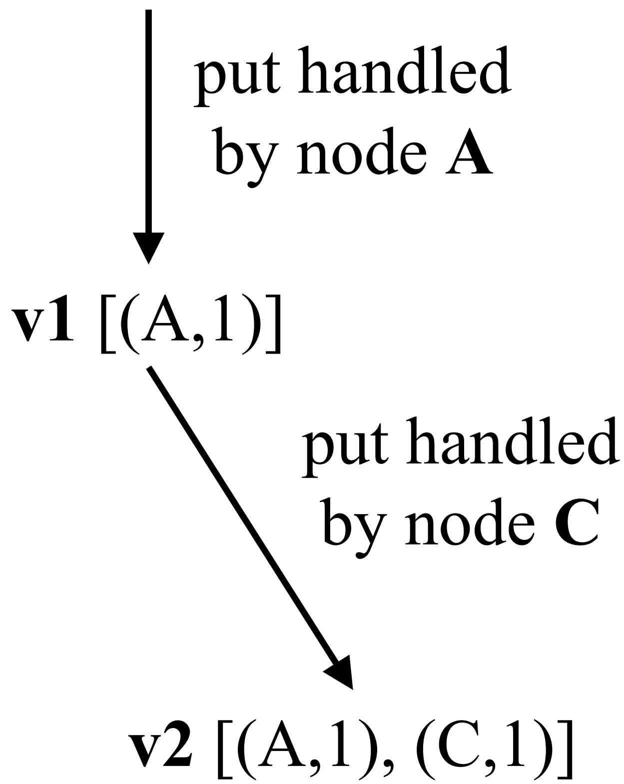
- **Rule:** If vector clock comparison of v1 < v2, then the first is an ancestor of the second – **Dynamo can forget v1**

- 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")

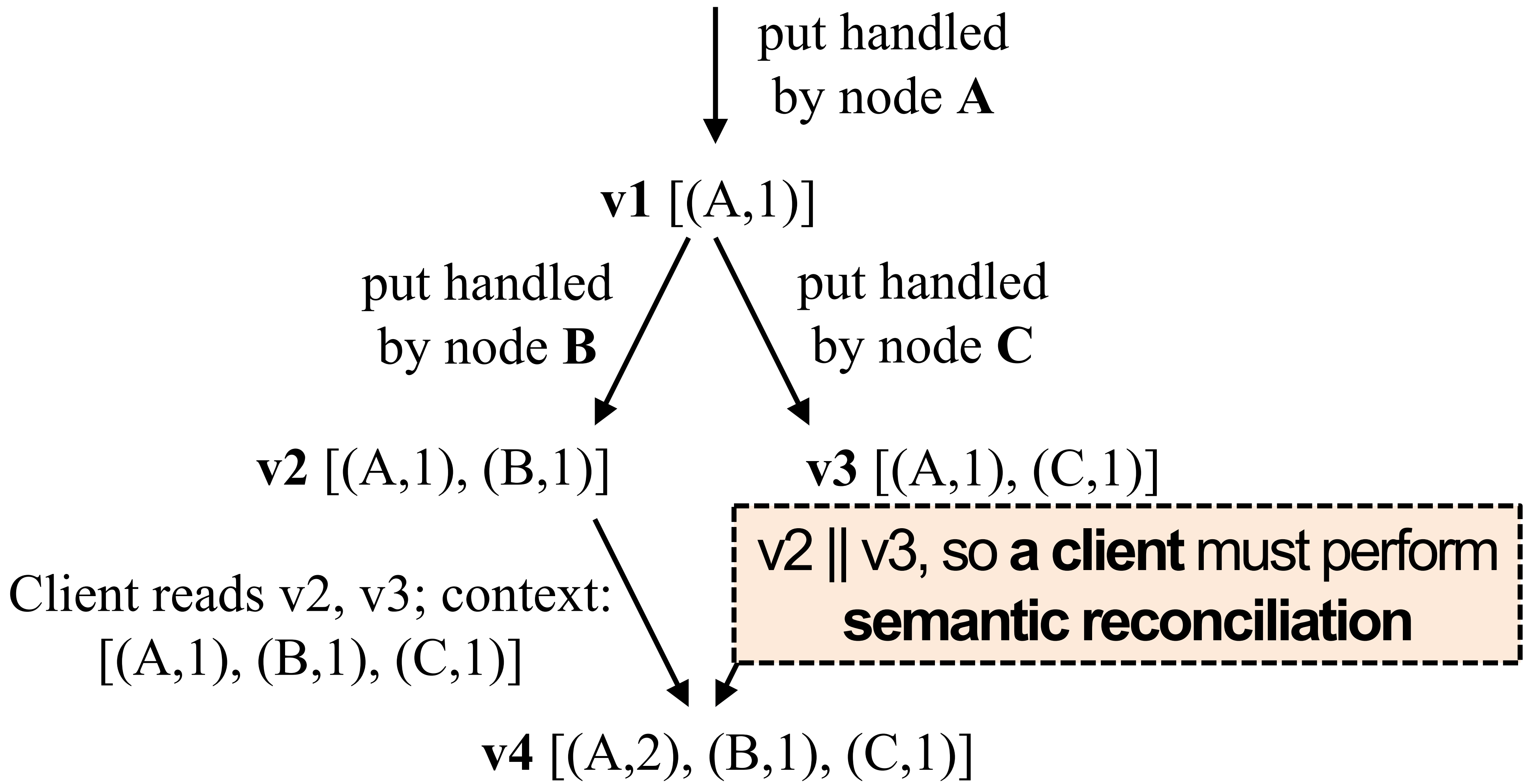
  – Then users **must supply that context** to put()s that modify the same key

Version vectors (auto-resolving case)



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

Version vectors (app-resolving case)



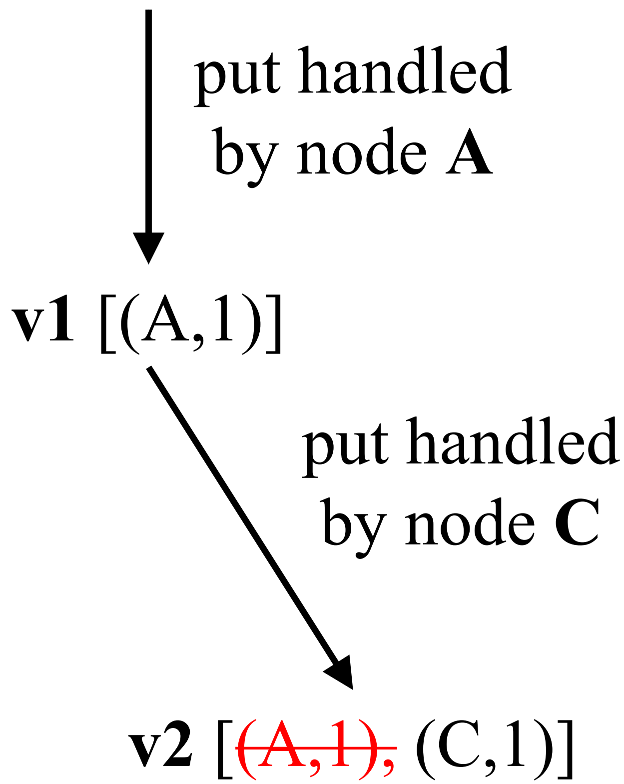
Client reconciles v2 and v3; node **A** handles the put

Trimming version vectors

- **Many nodes** may process a series of put()s to **same key**
  - Version vectors **may get long** – do they grow forever?
  - In practice, unlikely: unless **failures**, upper limit of **N**

- 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

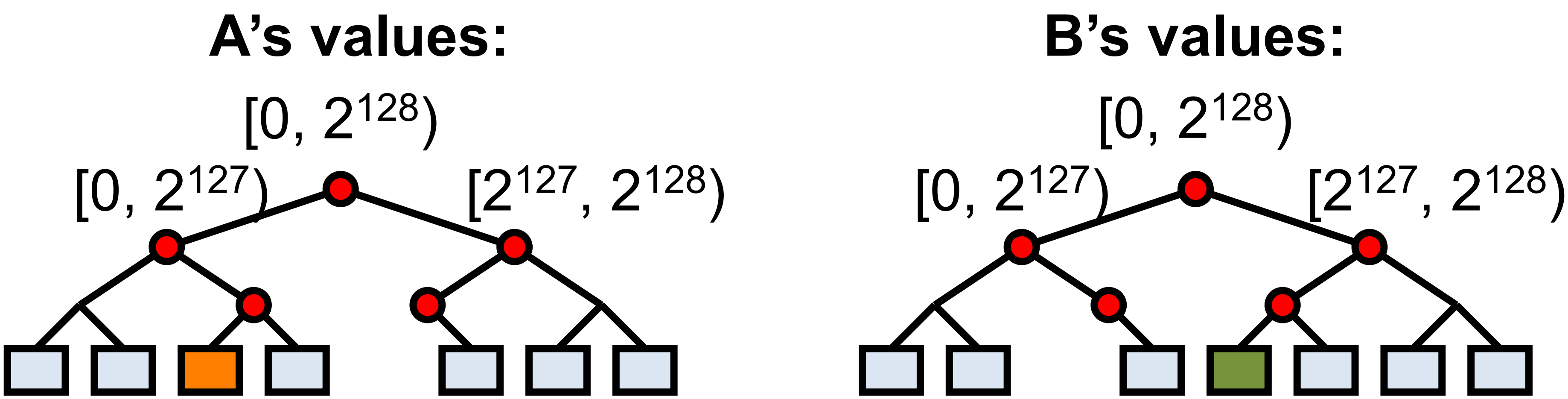
How to **compare and copy** replica state **quickly and efficiently?**

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	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