GEORGE MASON UNIVERSITY

KVS

NoSQL

Amazon Dynamo

CS 475: Concurrent & Distributed Systems (Fall 2021)

Lecture 13

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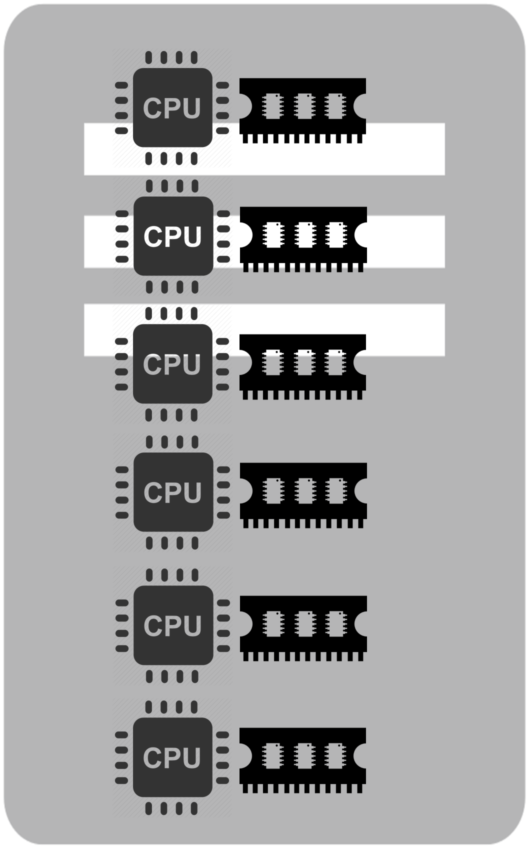
Some material taken/derived from:

- Princeton COS-418 materials created by Michael Freedman.
- MIT 6.824 by Robert Morris, Frans Kaashoek, and Nickolai Zeldovich.

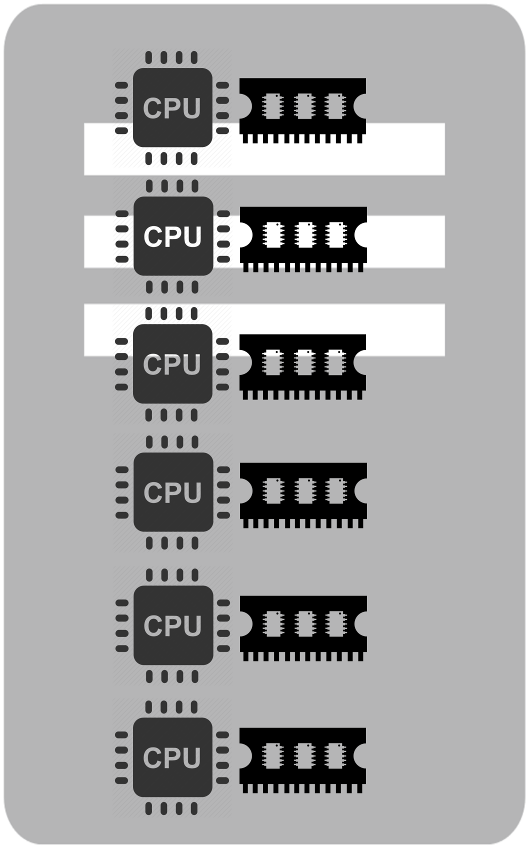
Horizontal or vertical scalability

shared mem .



Vertical scaling
(Scaling-up)

Horizontal or vertical scalability



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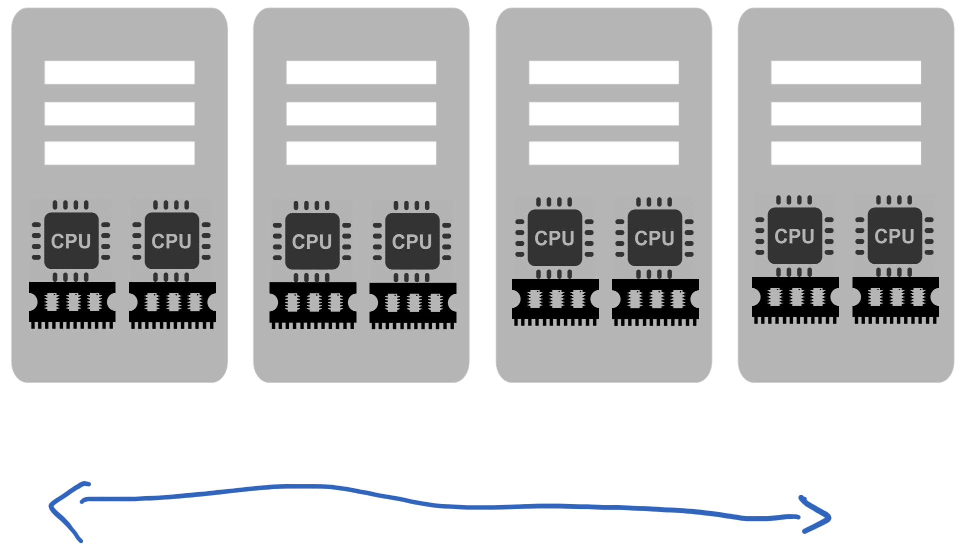

Horizontal scaling
(Scaling-out)

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!

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

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Main challenge: Coping with constant failures

Outline

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
  - 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

Scaling out: Partition management

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

Modulo hashing

- First consider problem of data partition:
  - Given object id X, choose one of *k* servers to use

- Suppose we use modulo hashing:
  - Place *X* on server *i* = hash(*X*) mod *k*

key

size of cluster.

Modulo hashing

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- Suppose we use modulo hashing:
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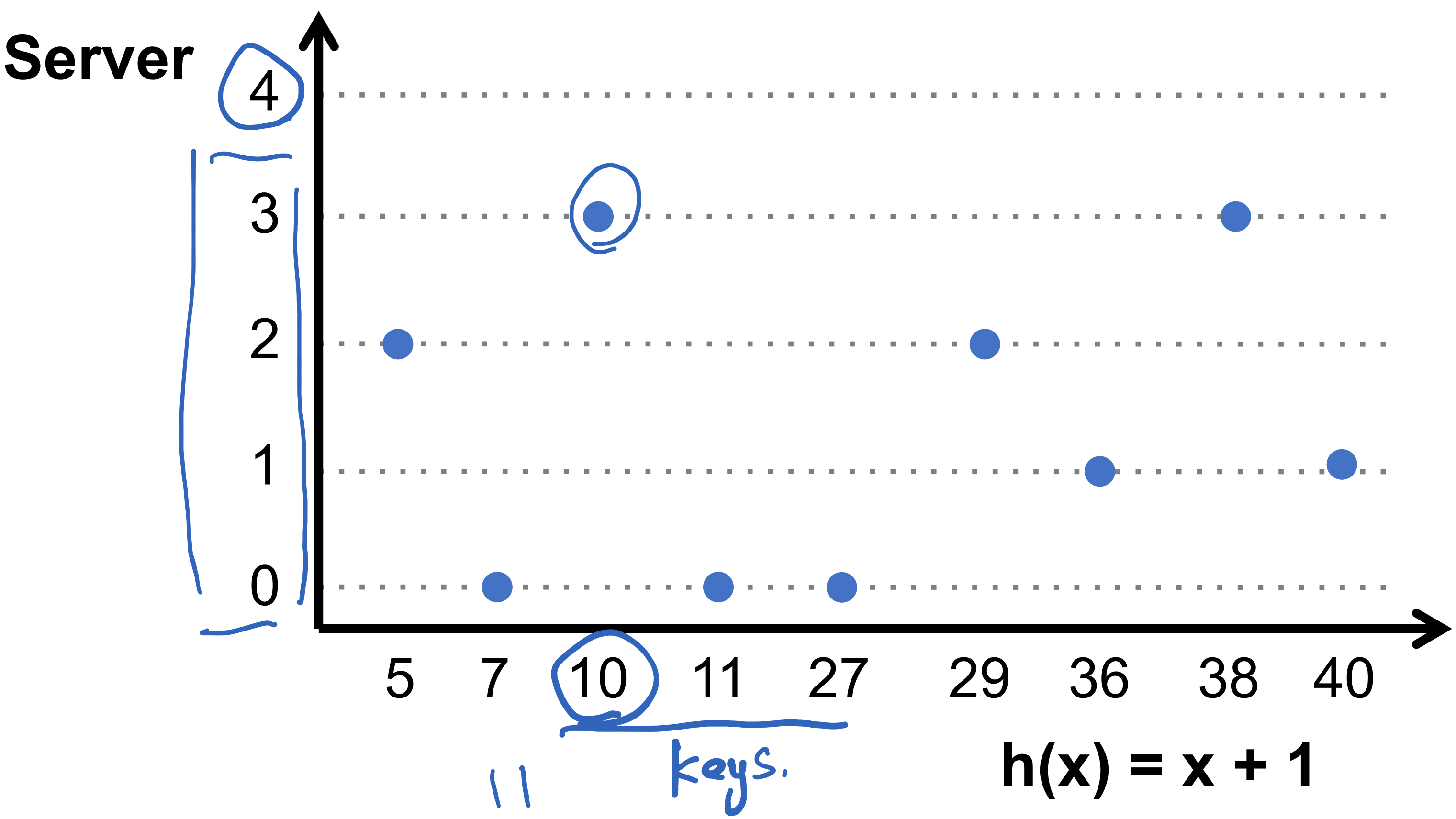
- What happens if a server fails or joins (k ← k±1)?
  - or different clients have different estimate of k?

Problem for modulo hashing: Changing number of servers

i = h(*x*) mod 4

11 % 4 = 3.



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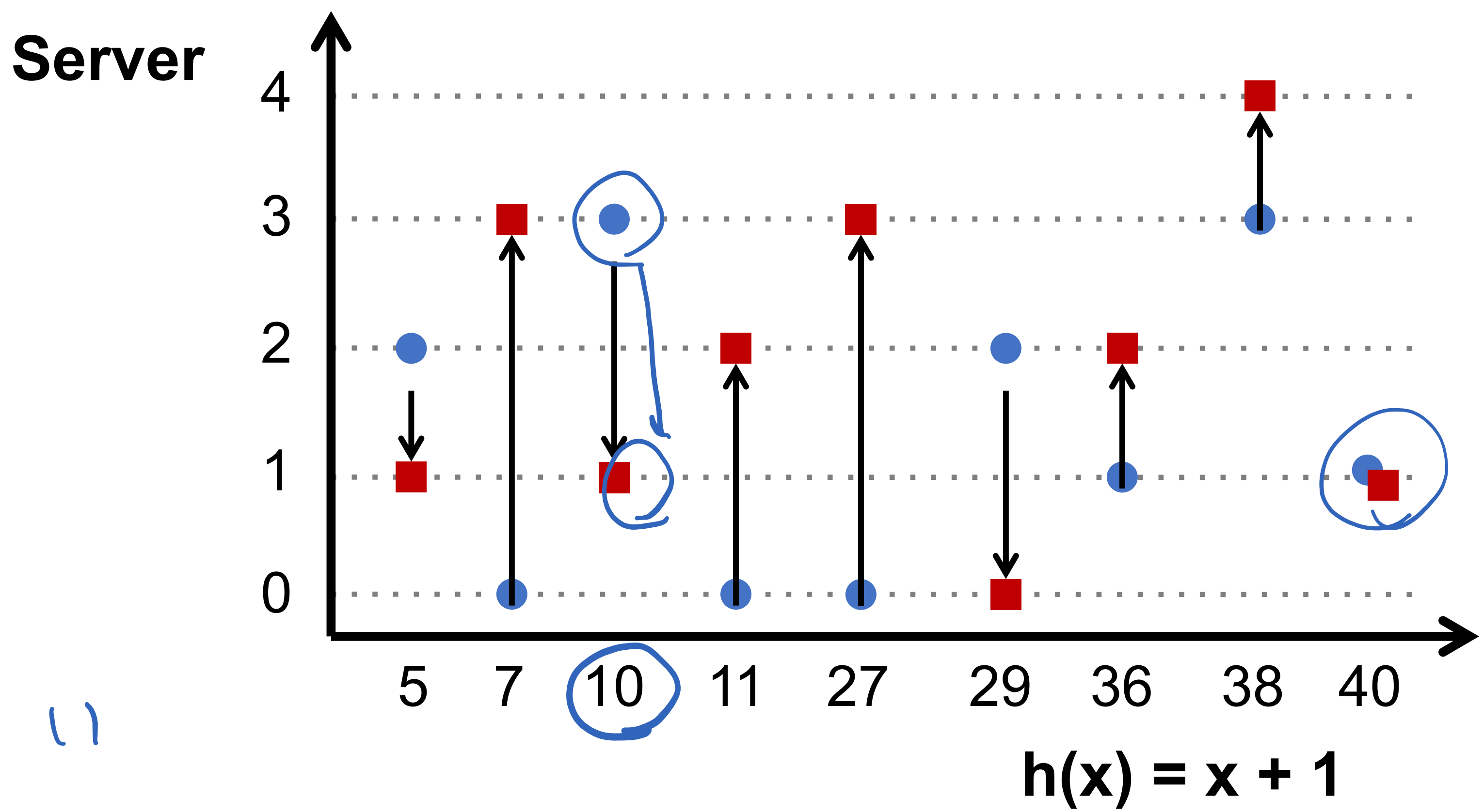

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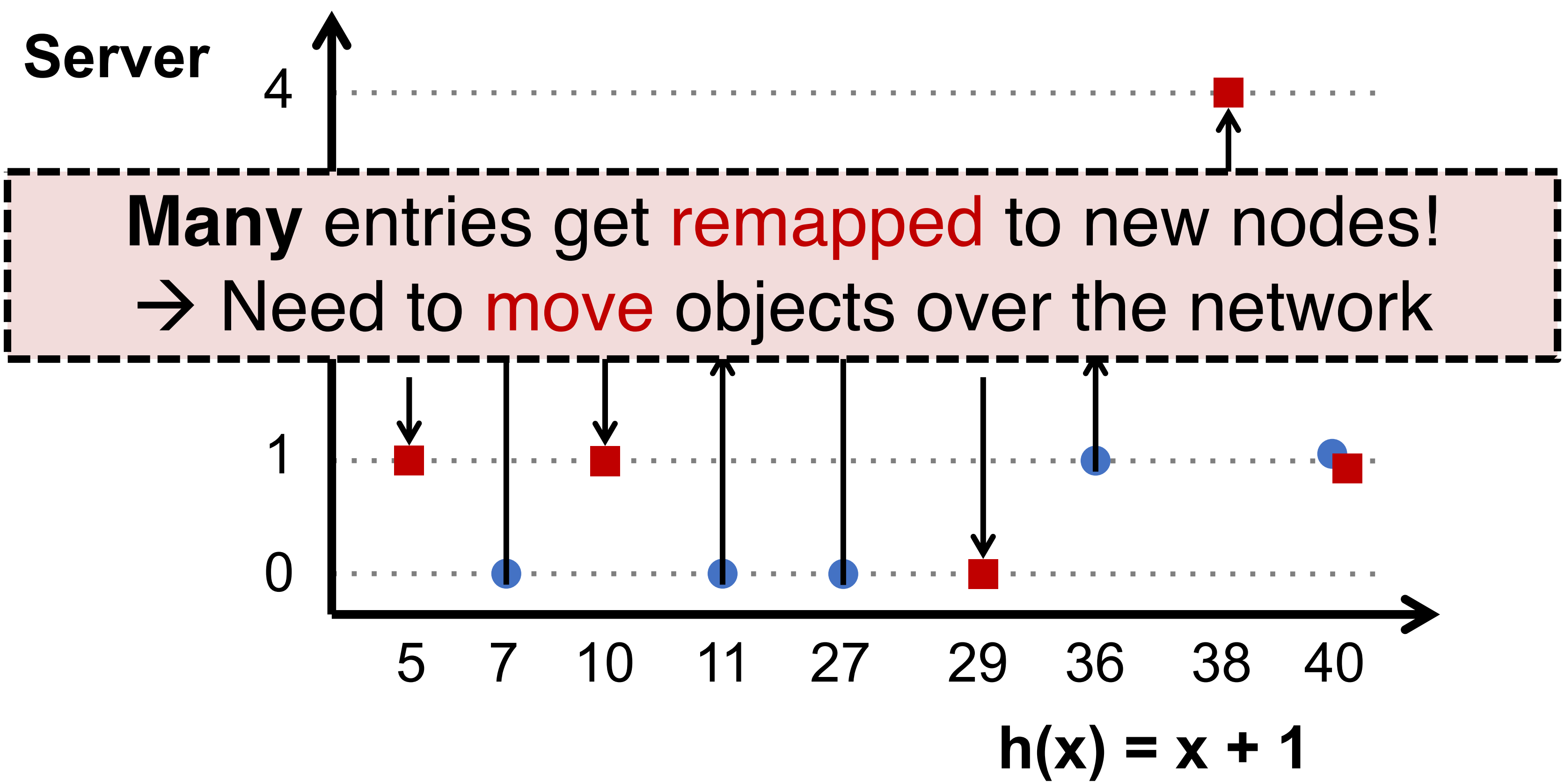
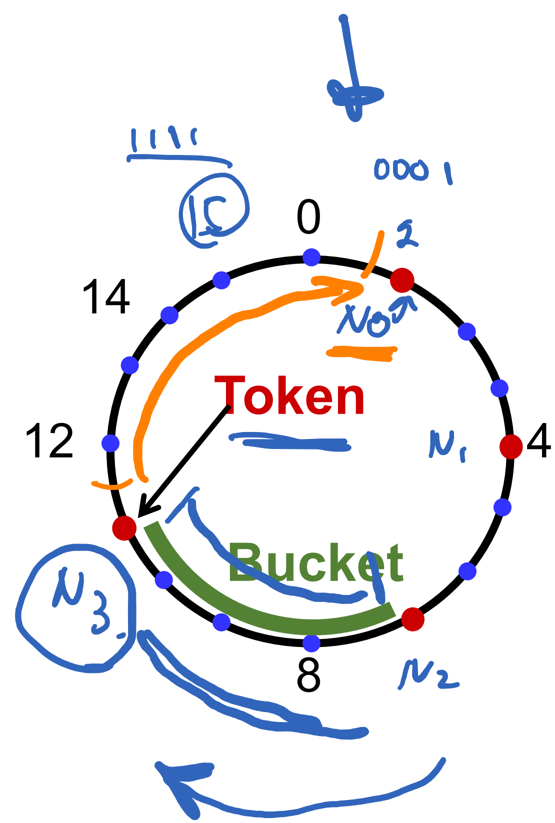


Consistent hashing

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



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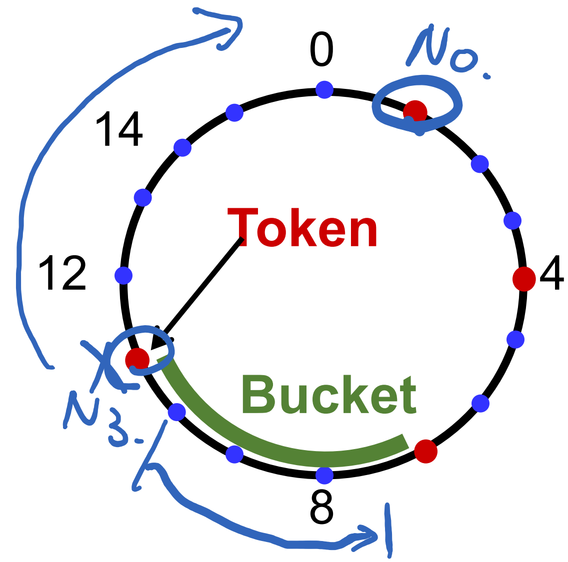
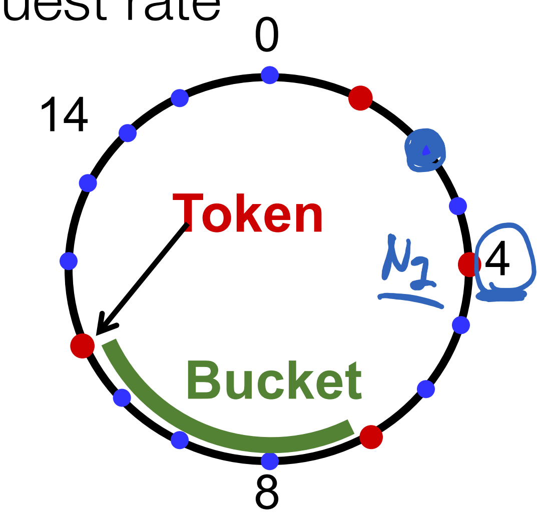


- **Desirable features:**
  - Balance: No bucket has "too many" objects; E(bucket size)=1/ n^{th}
  - Smoothness: Addition/removal of token minimizes object movements for other buckets

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



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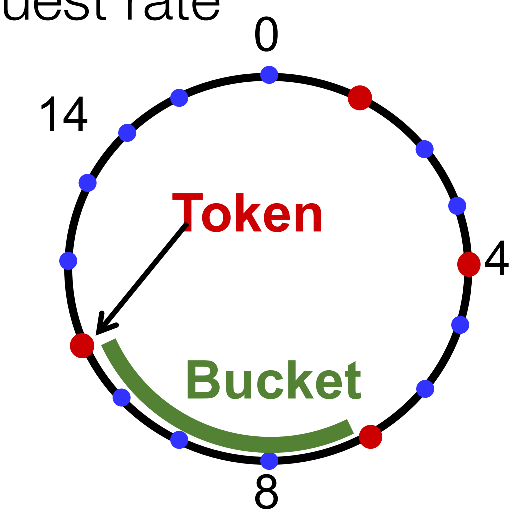

- If a node fails, its successor takes over bucket
  - Smoothness goal ✓: Only localized shift, not O(n)
  - But now successor owns **two** buckets: 2/nth of key space
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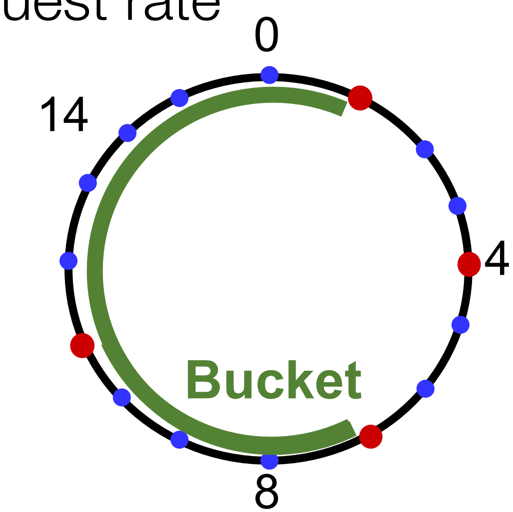

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Virtual nodes

- **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

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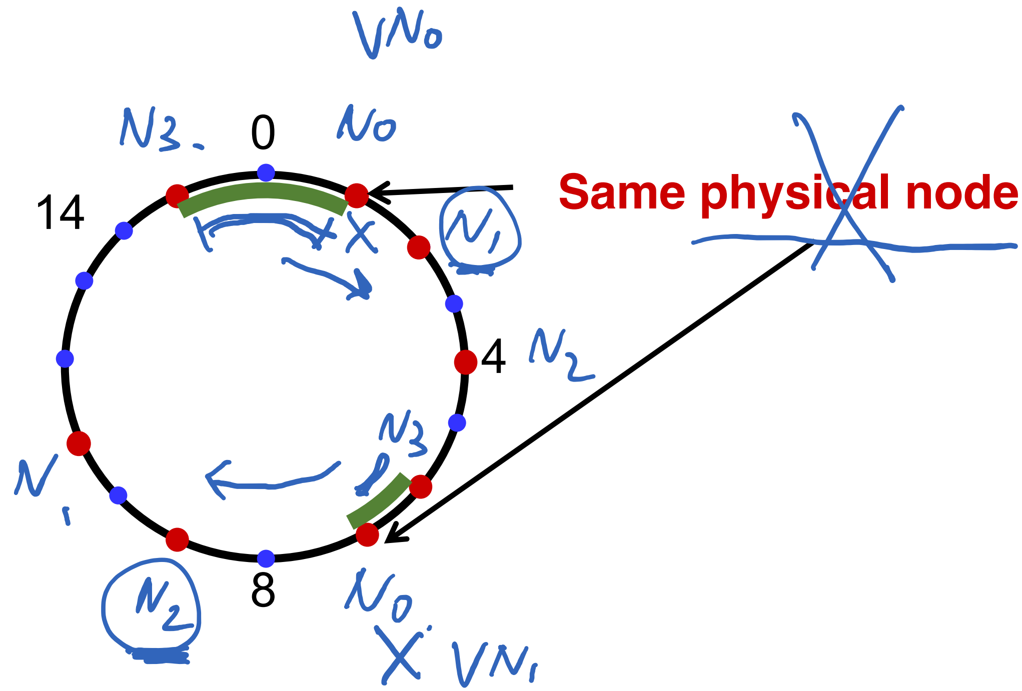
- Upon a physical node's failure, v virtual nodes fail
  - Each of their successors takes over $1/(vn)^{th}$ more
    - Expected to be distributed across physical nodes

Virtual nodes: Example

4 Physical Nodes

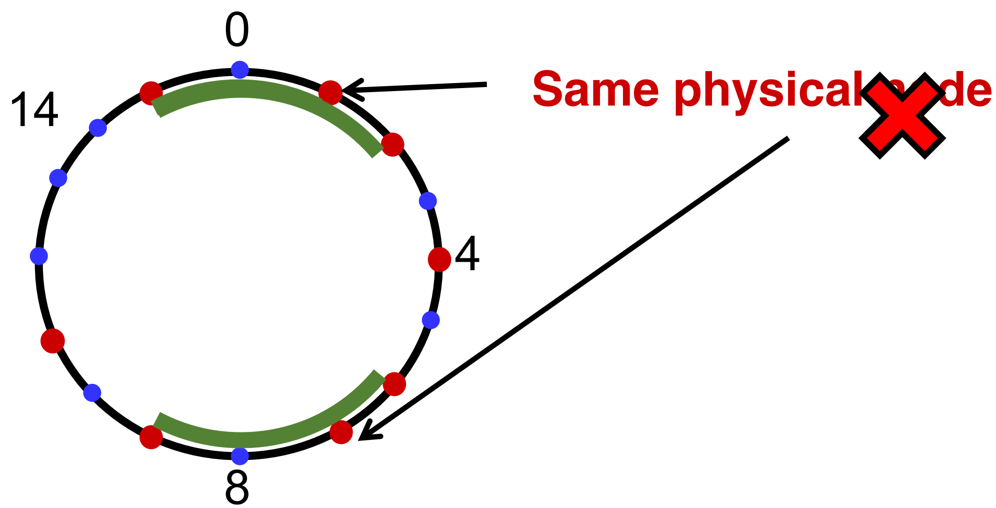
V=2



Virtual nodes: Example

4 Physical Nodes

V=2



Result: Better load balance with larger v

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Dynamo: The P2P context

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Dynamo: The P2P context

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  - Individual nodes at Internet's edge, file sharing

- Central challenge: low-latency key lookup with high availability
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- 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

SOA

- 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
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Each instance contains **a few hundred** servers

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

Service-level Agreement

- 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

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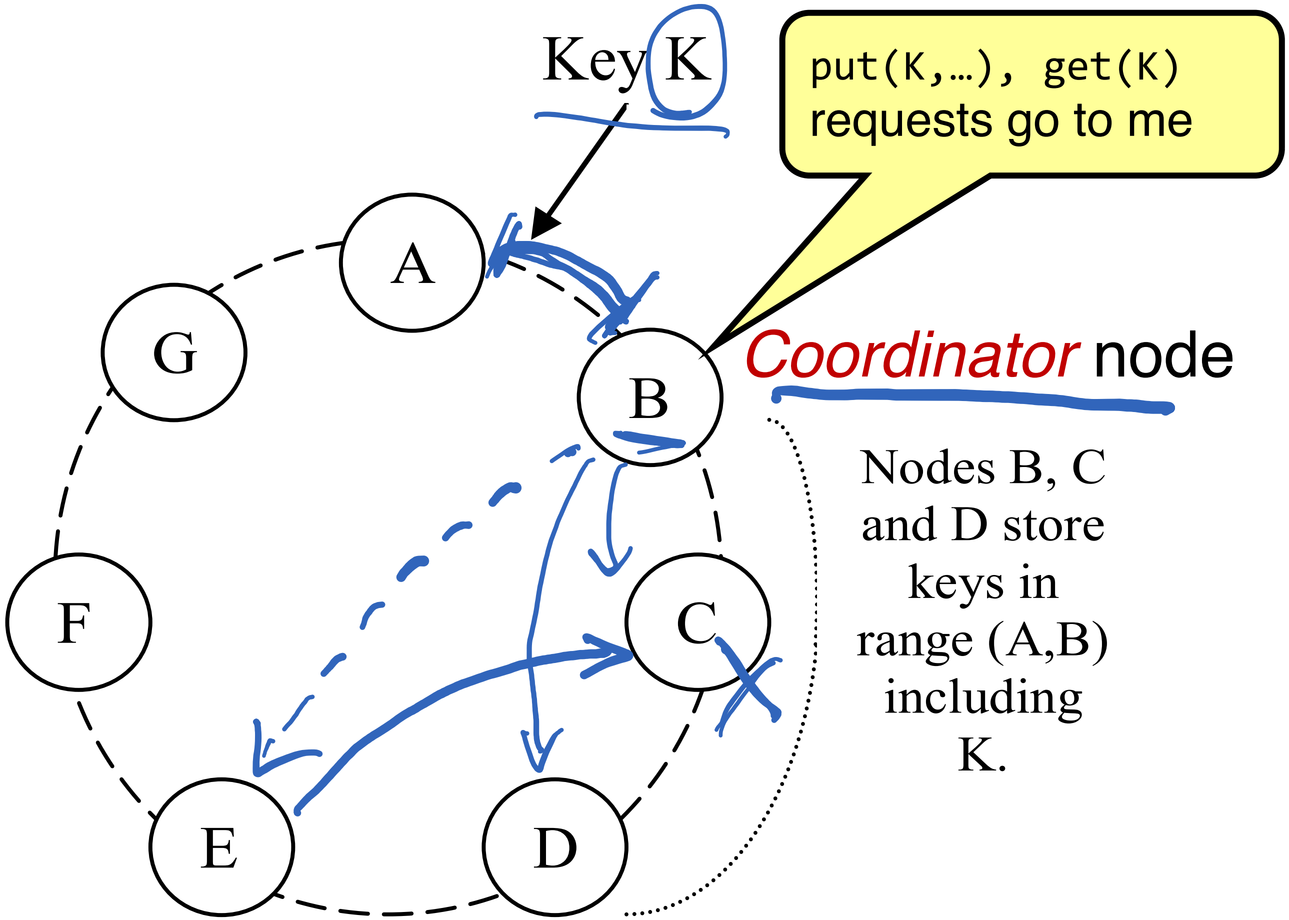
Key tradeoffs: Response time vs. consistency vs. durability

Data placement



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

Data replication

- A key-value pair → key's *N* successors (*preference list*)
  - **Coordinator receives a put** for some key
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- 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

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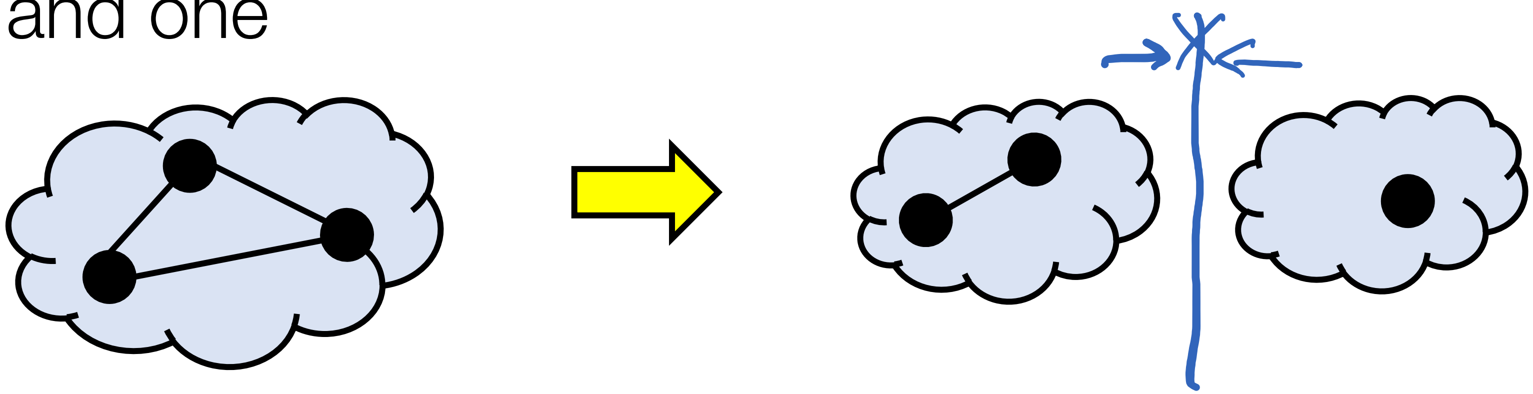
  - Result: All nodes can send directly to any key's coordinator ("zero-hop DHT")
    - Reduces variability in response times

Partitions force a choice between availability and consistency

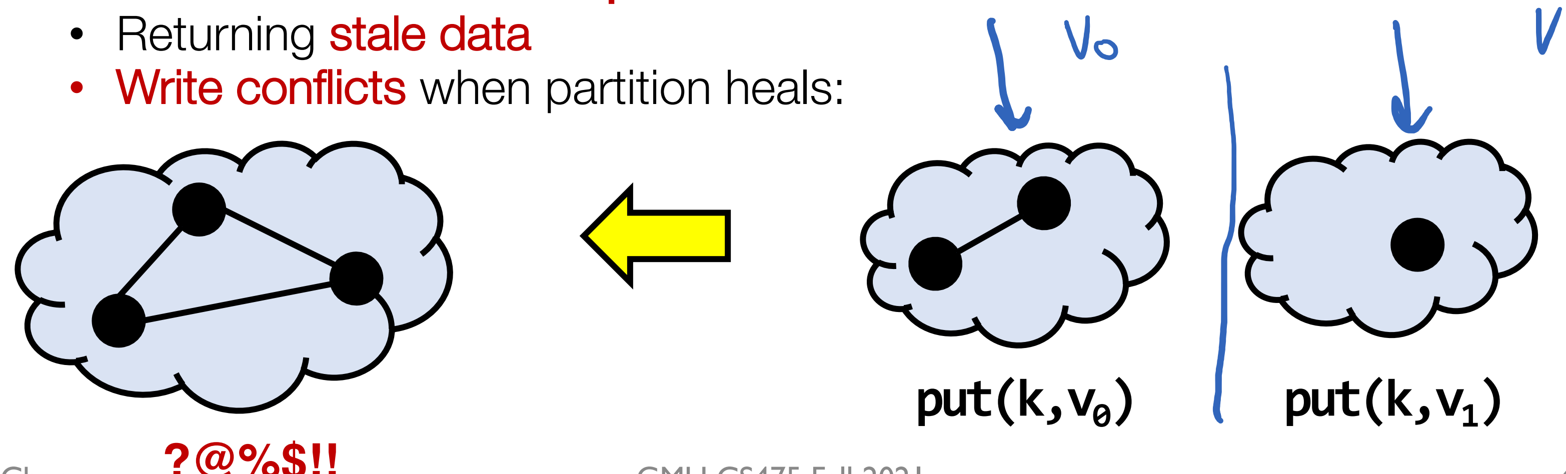
- Suppose three replicas are partitioned into two and one



- 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

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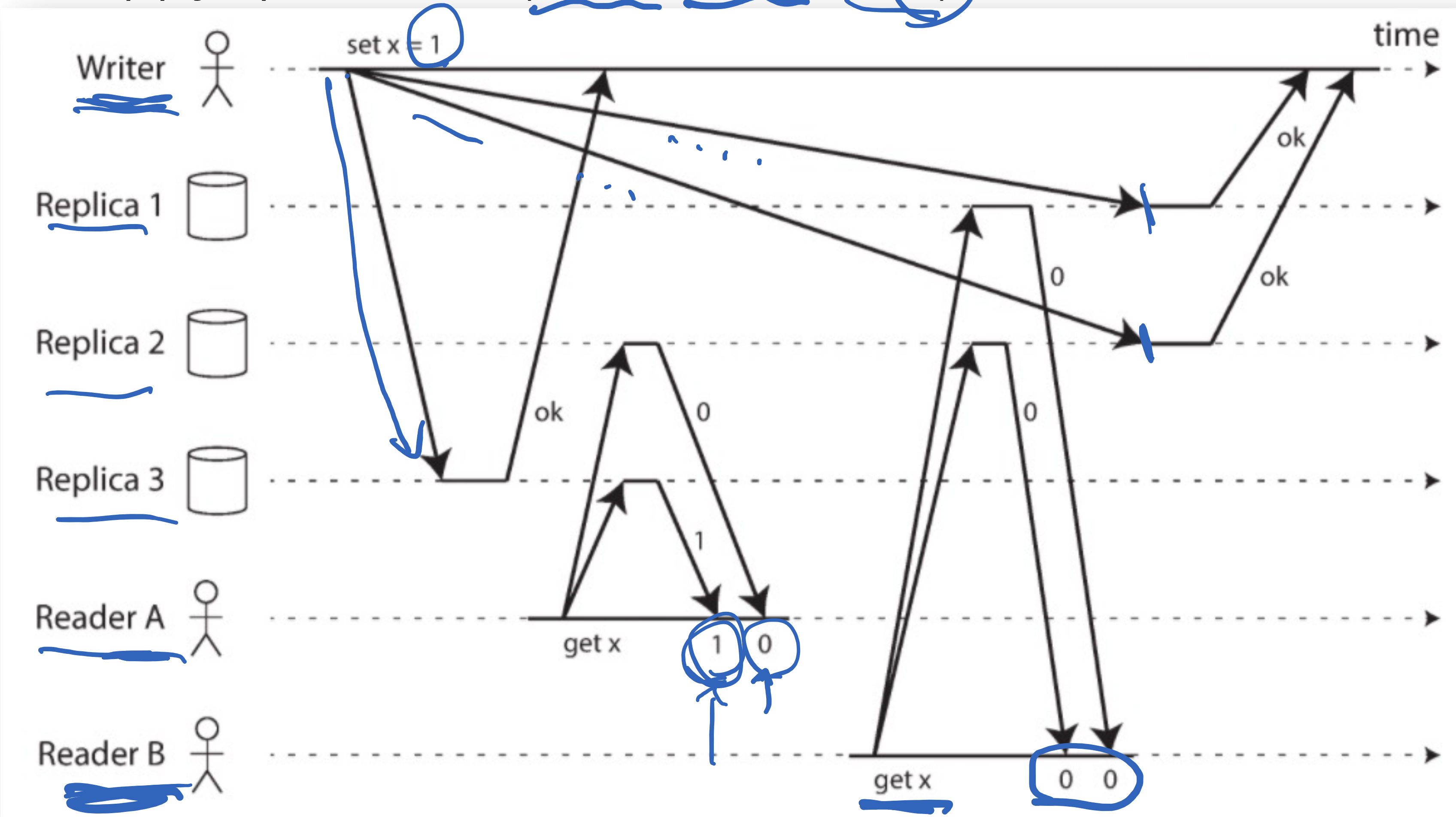
- BUT to speed up `get()` and `put()`:
  - Coordinator returns "`success`" for `put` when W < N replicas have completed **write**
  - Coordinator returns "`success`" for `get` when R < N replicas have completed **read**

N = 3
W = 2
R = 2.

Consistency under sloppy quorums != linearizability

Sloppy quorum of (N=3, W=3, R=2)



*: https://www.oreilly.com/library/view/designing-data-intensive-applications/9781491903063/ (Page 334)

Sloppy quorums: Hinted handoff

- Suppose coordinator doesn't receive *W* replies when replicating a `put()`
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- Suppose coordinator **doesn't receive *W* replies** when replicating a `put()`
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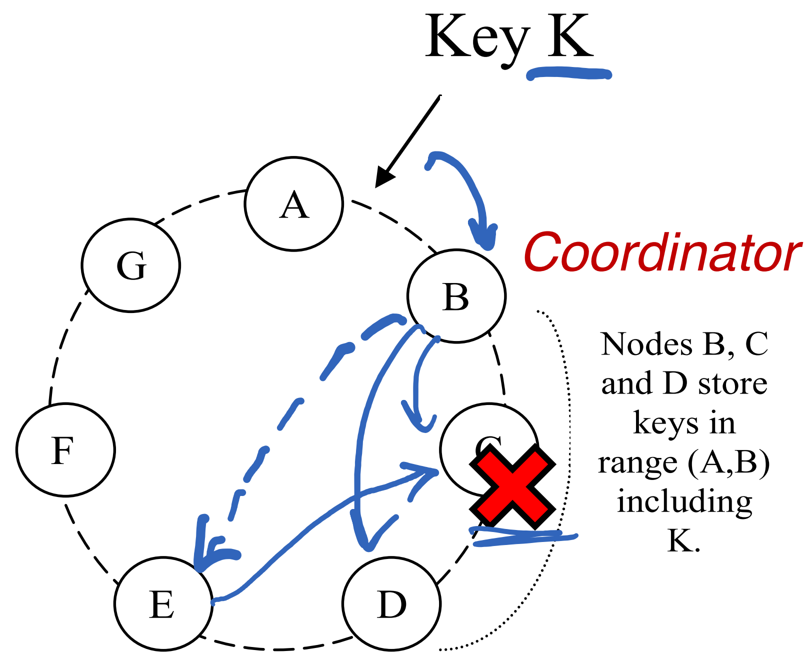
- Hinted handoff: Coordinator **tries further nodes** in preference list (**beyond first *N***) if necessary
  - Indicates the **intended replica node** to recipient
  - **Recipient** will periodically try to forward to the **intended replica node**

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**



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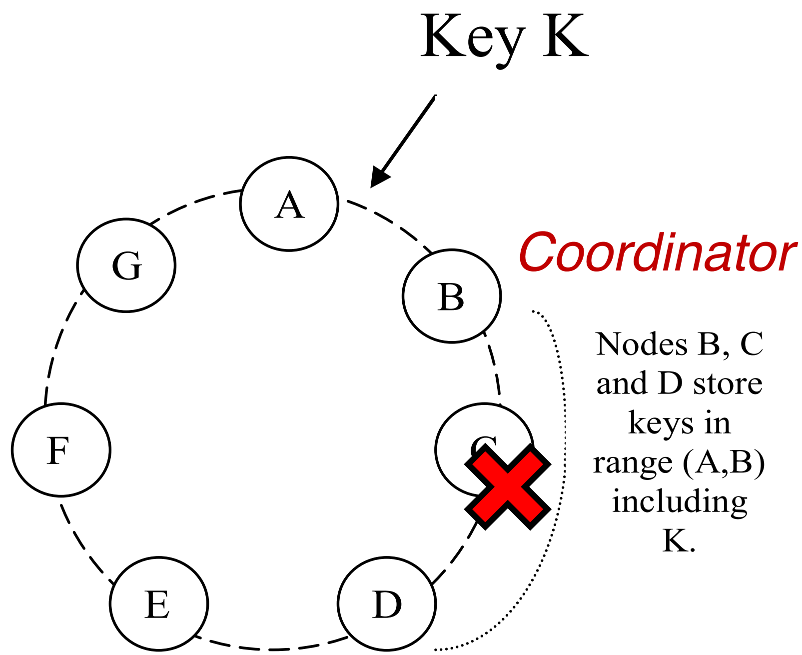

- When C comes back
  - E forwards the replicated data back to C

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

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**?

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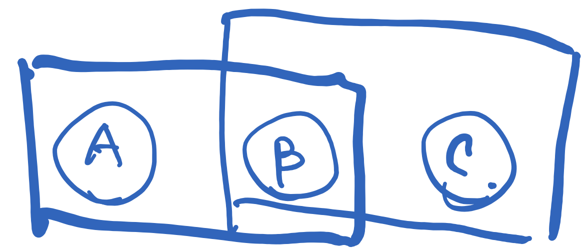

- If **no failures**, yes:
  - **Two writers** saw each `put()`
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- If no failures, yes:
  - Two writers saw each `put()`
  - Two readers responded to each `get()`
  - Write and read quorums must overlap!

Sloppy quorums and freshness

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

Version vectors (vector clocks)

- *Version vectors:* List of (**coordinator node, counter**) pairs
  - *e.g.*, [(A, 1), (B, 3), …]
- Dynamo stores a version vector with **each stored** key-value **pair**
- Tracks causal relationship between different versions of data stored under the same key **k**

Version vectors (VV) in Dynamo

causal

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

$v1 \neq v2. \rightarrow v1 \parallel v2.$

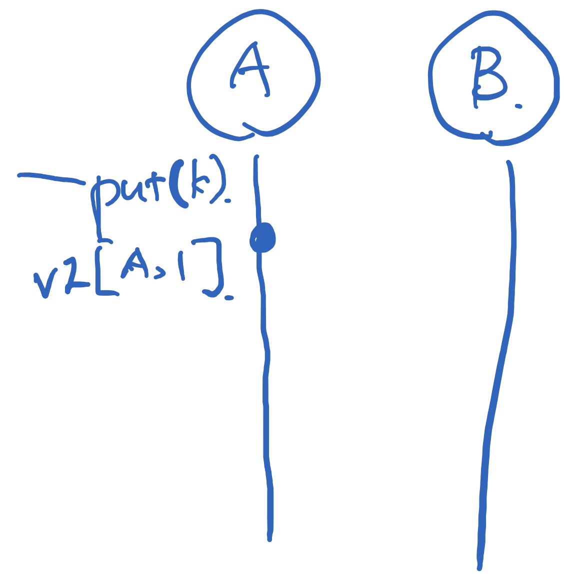
- Each time a `put()` occurs, Dynamo increments the counter in the V.V. for the coordinator node

- 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)

put handled
by node A

v1 [(A,1)]



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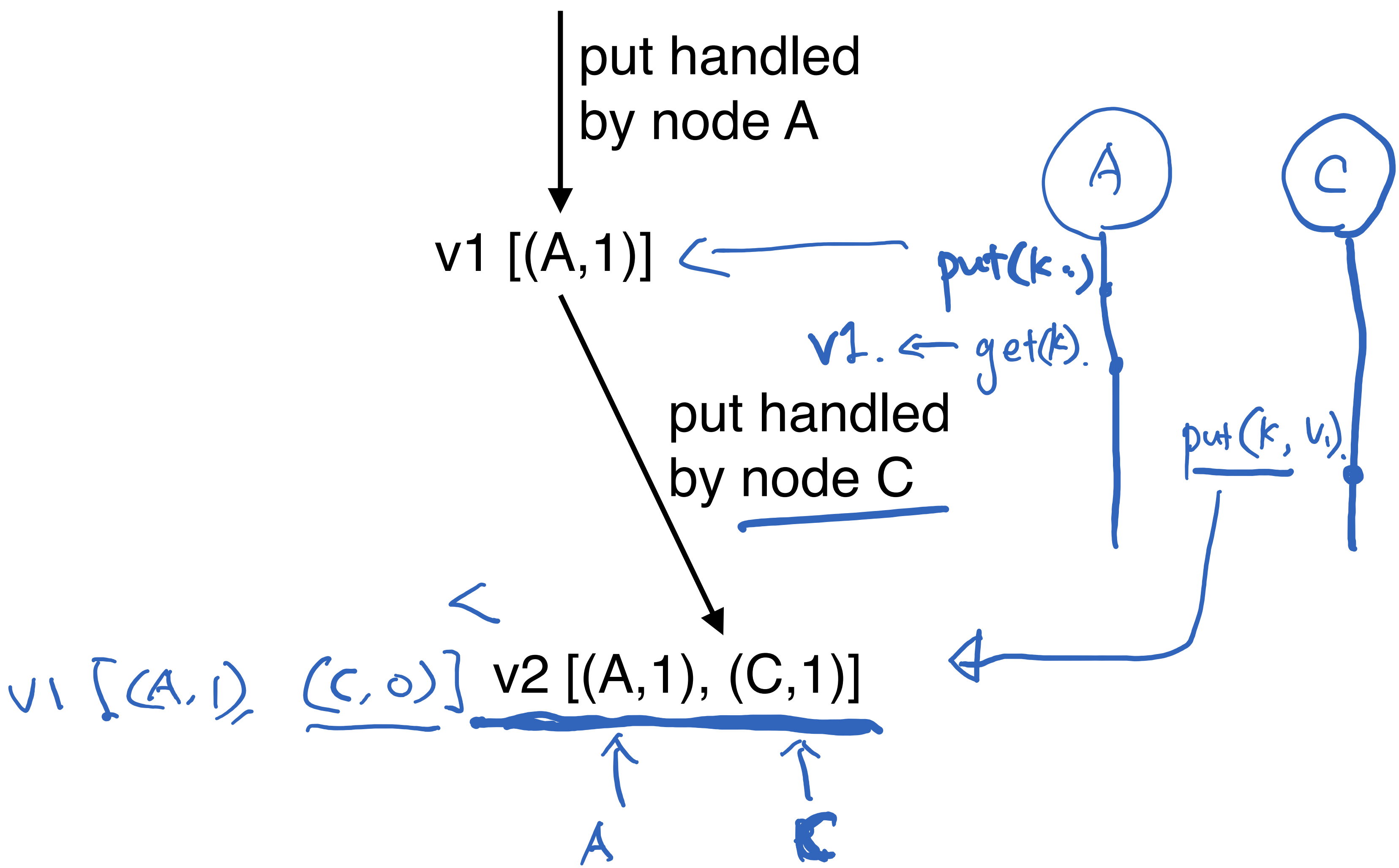

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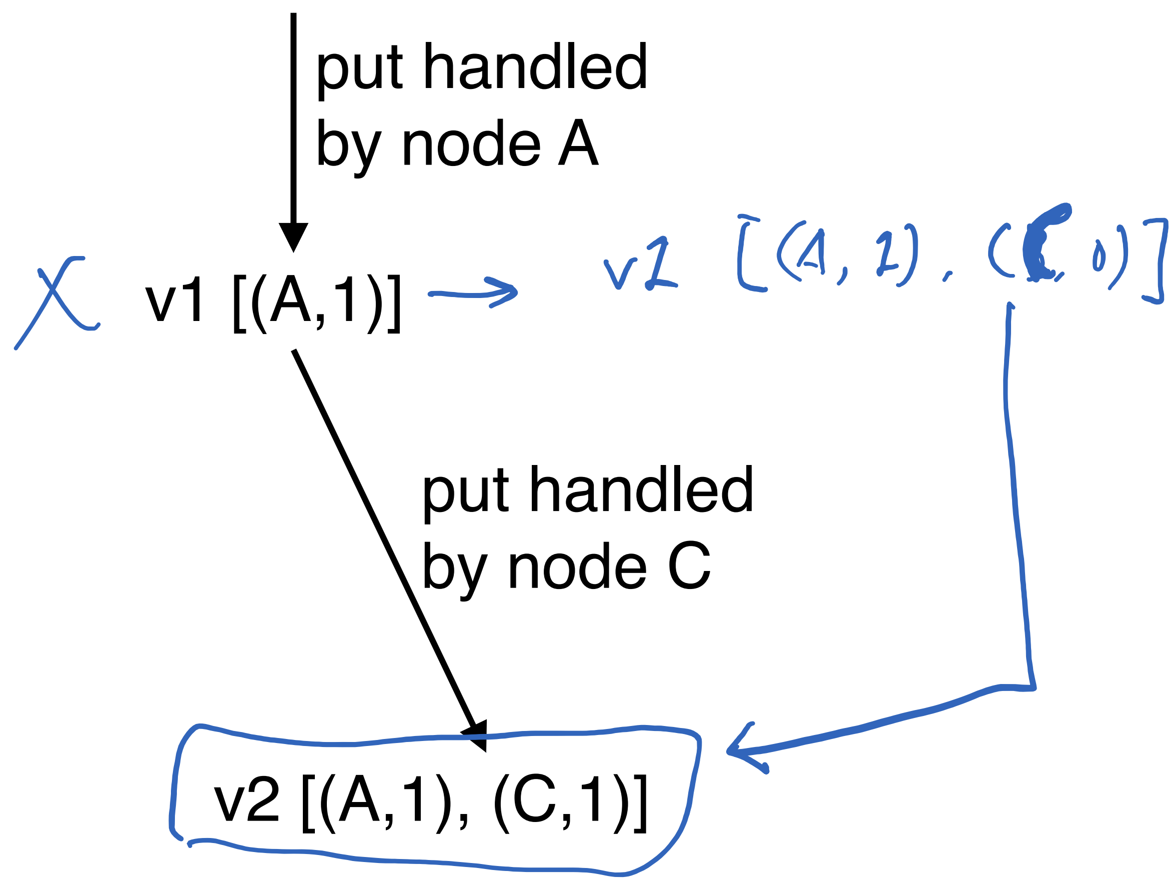
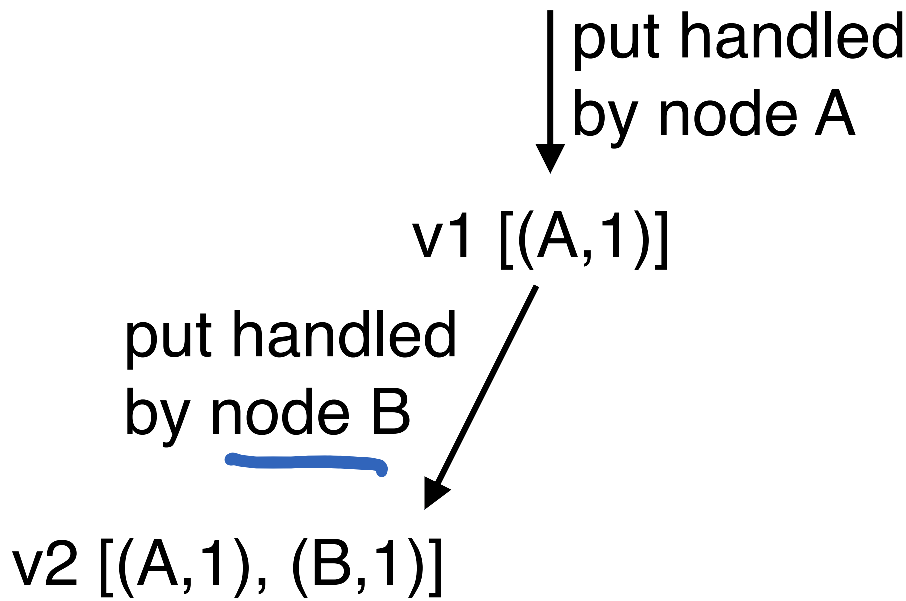


v2 > v1, so Dynamo nodes automatically drop v1, for v2

Version vectors (app-resolving case)



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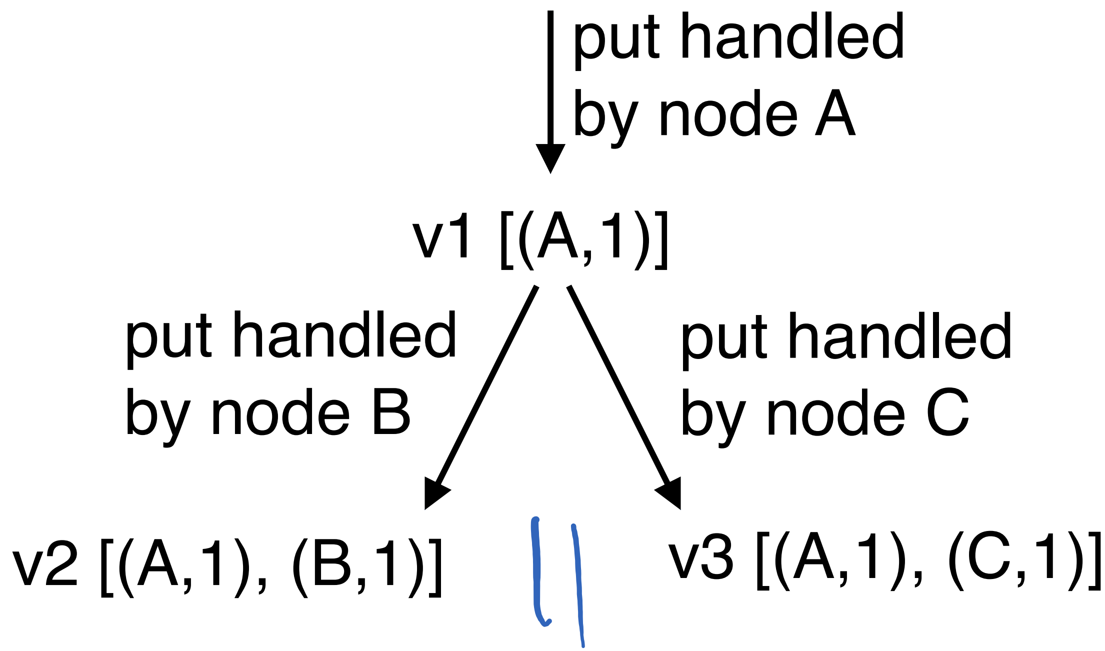

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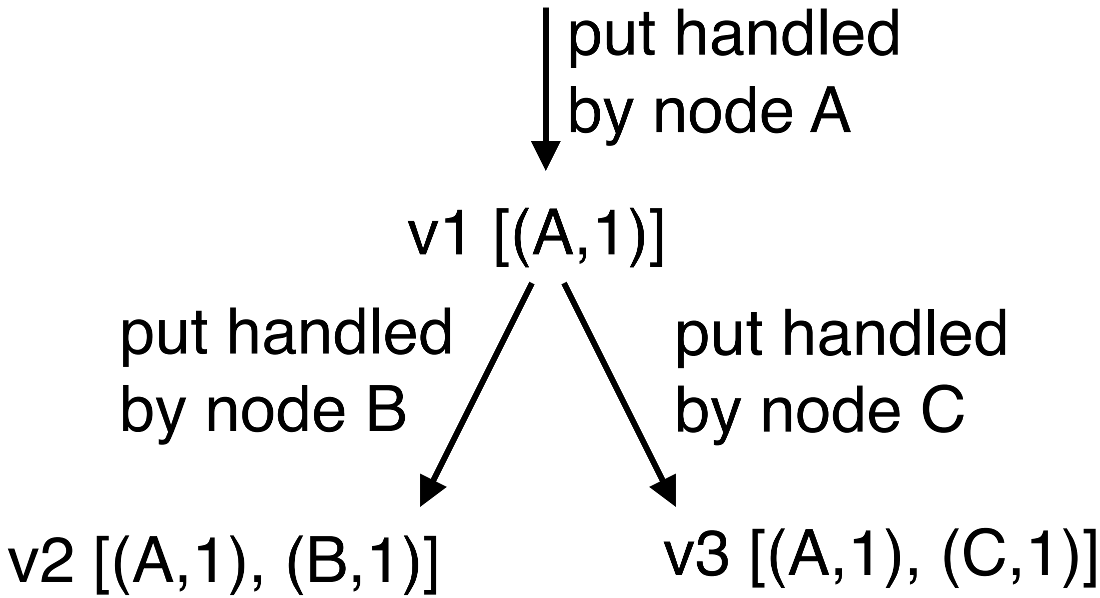
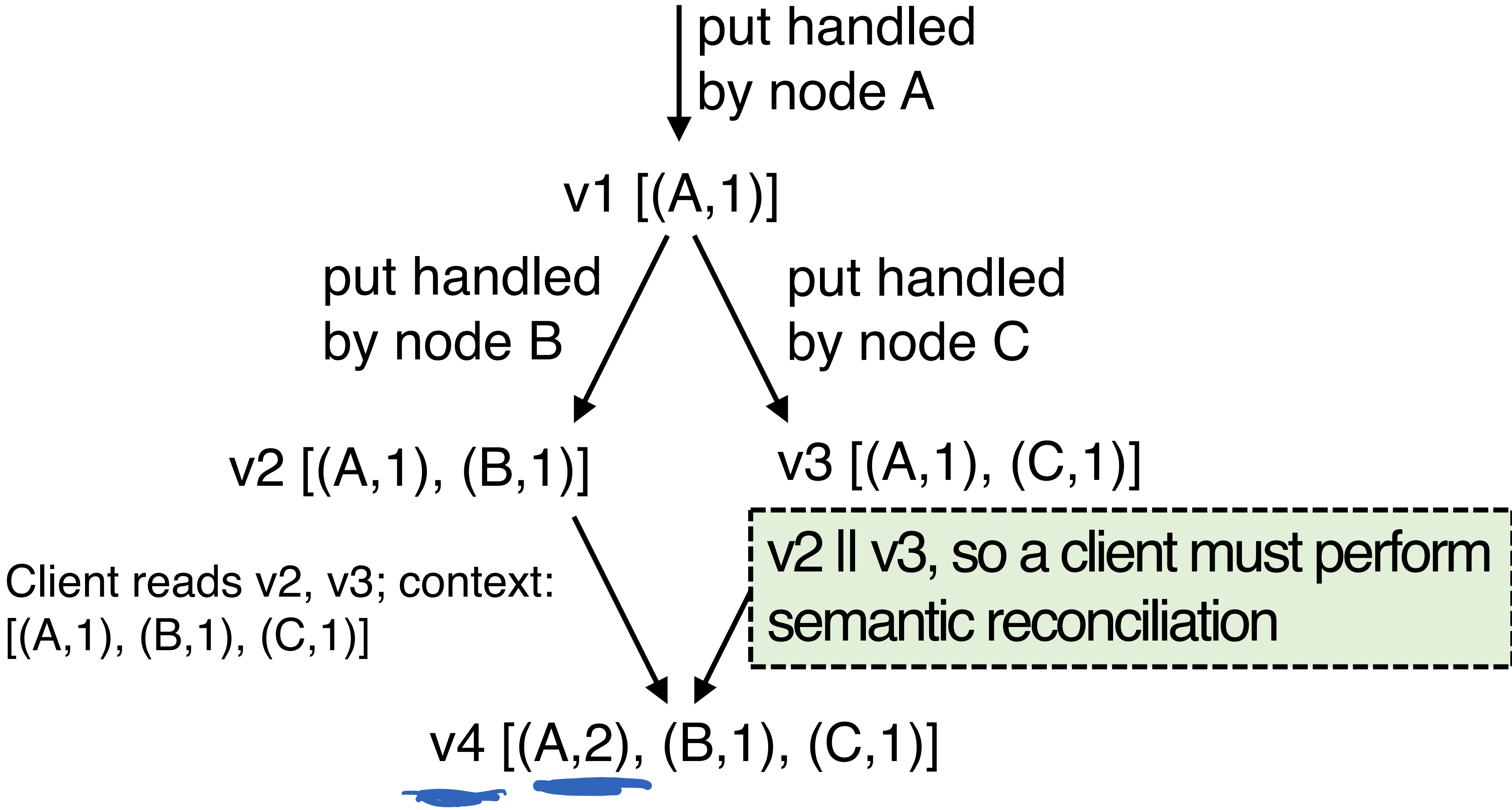


v2 || v3, so a client must perform semantic reconciliation

Version vectors (app-resolving case)



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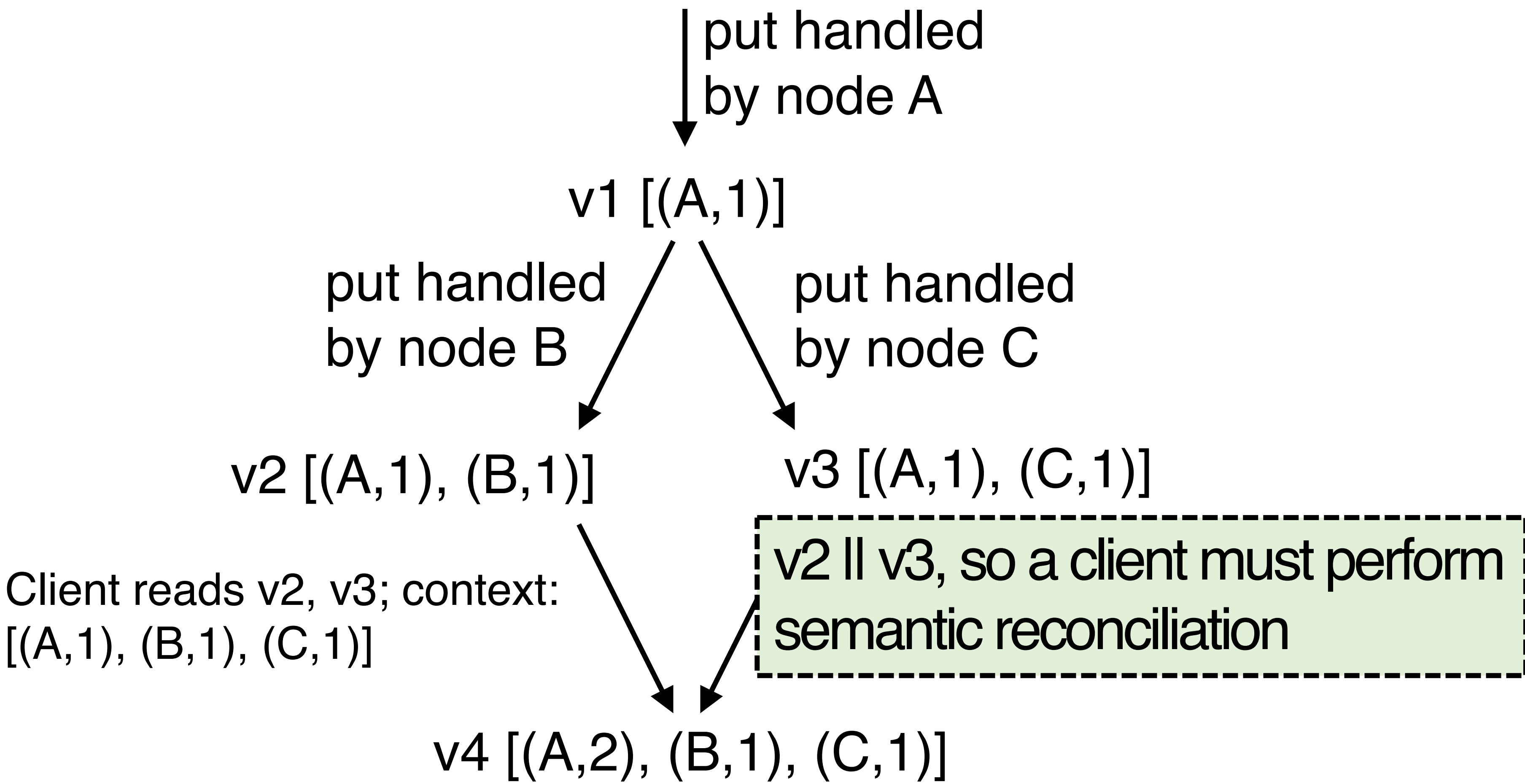

Client reconciles v2 and v3; node A handles the put

Trimming version vectors

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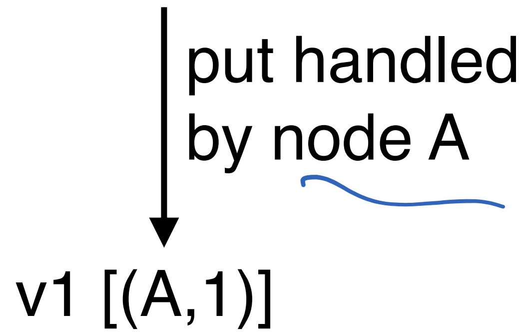
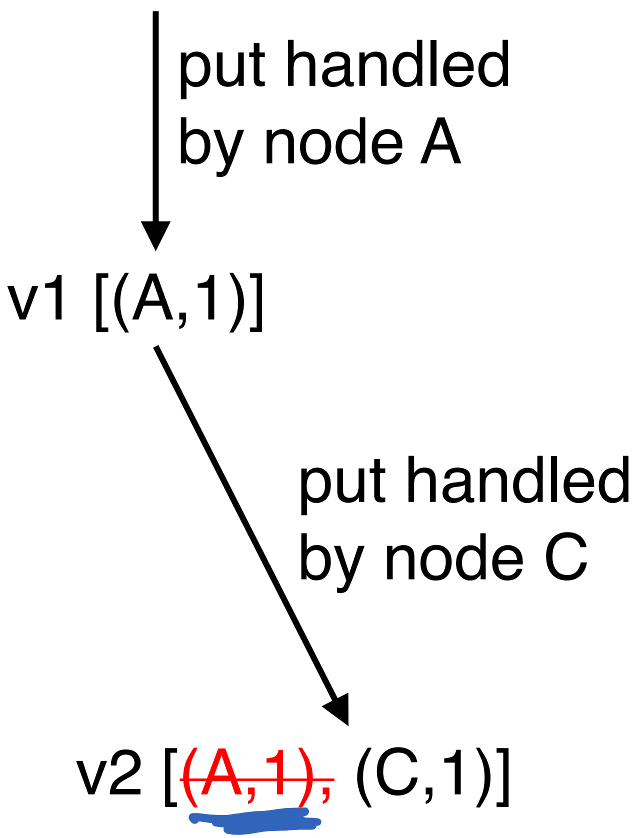
  - In practice, unlikely: unless failures, upper limit of **N**

- Dynamo also uses a clock truncation scheme
  - 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

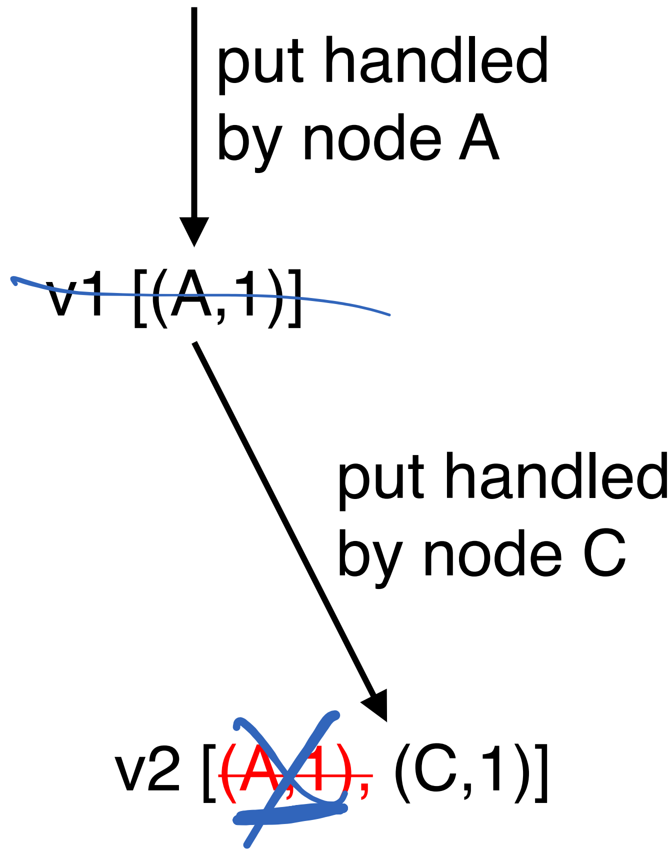
Impact of deleting a VV entry



Impact of deleting a VV entry



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?

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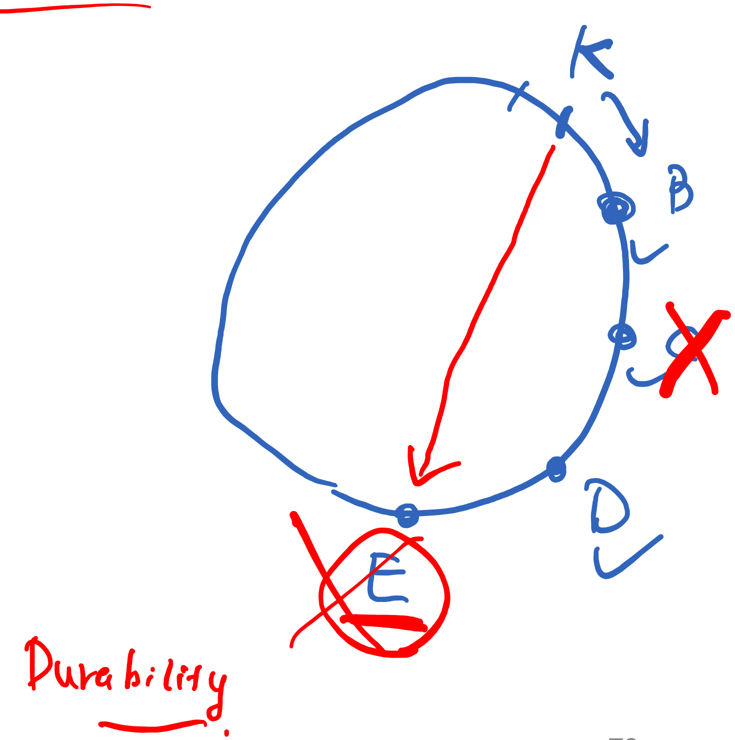
- Will coordinator create two versions with conflicting VVs?
  - We want that outcome, otherwise one was thrown away
  - Paper doesn't say, but coordinator could detect problem via `put()` context

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



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

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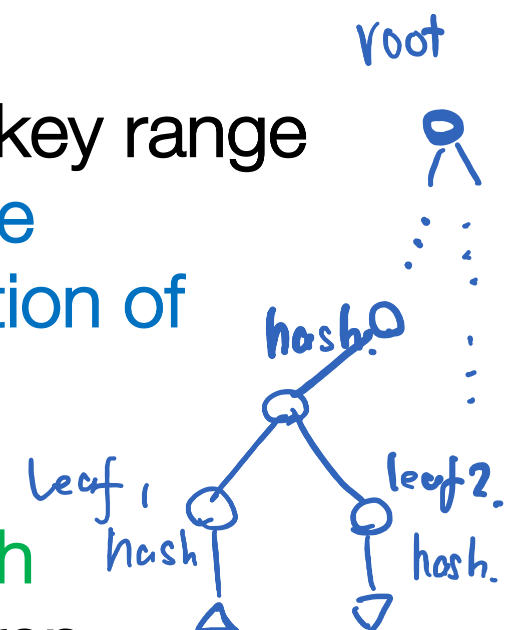
How to compare and copy replica state quickly and efficiently?

Efficient synchronization with Merkle trees

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

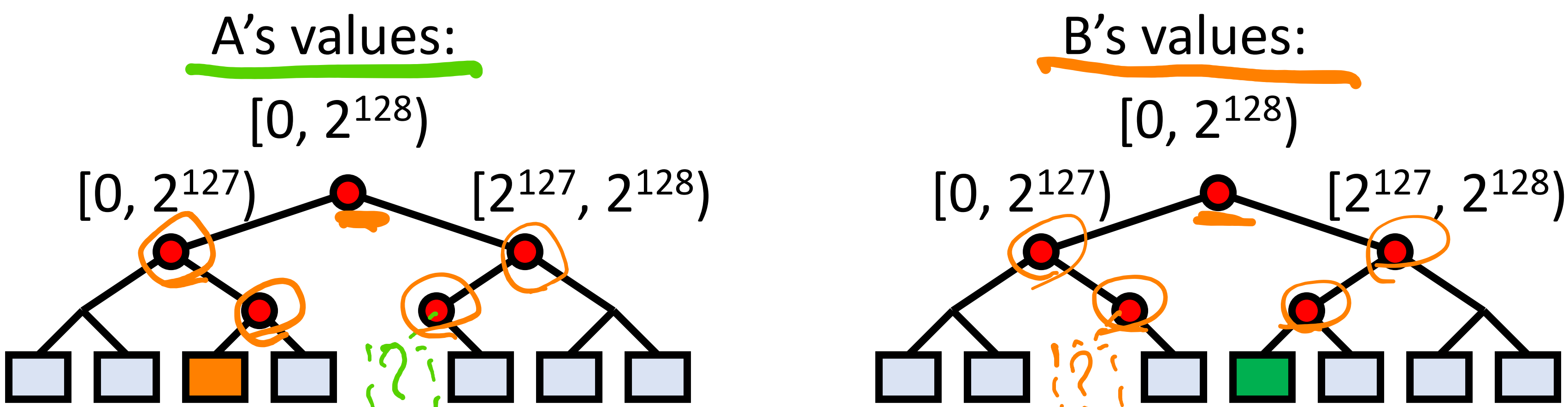
- One Merkle tree for each **virtual node key range**
  - **Leaf node** = hash of one key's value
  - **Internal node** = hash of concatenation of children



- **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?

Sloppy Quorum

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-aways

- 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