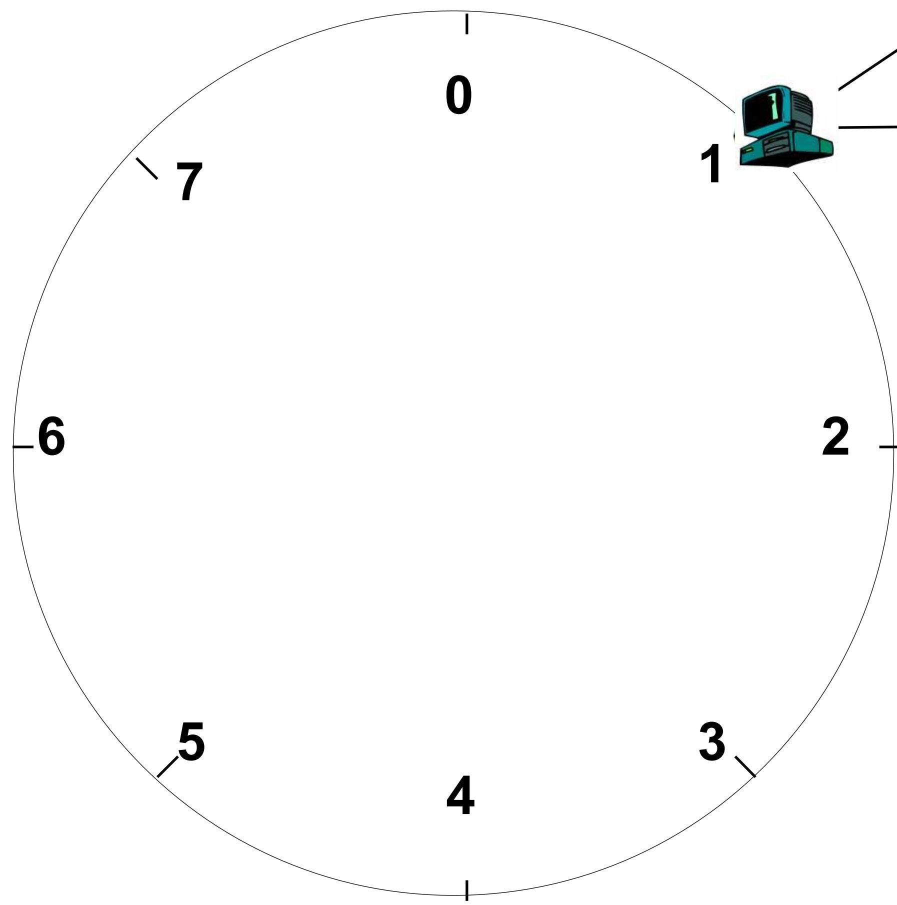
DHT: Chord Join

- Assume an identifier space [0..8]
- Node n1 joins

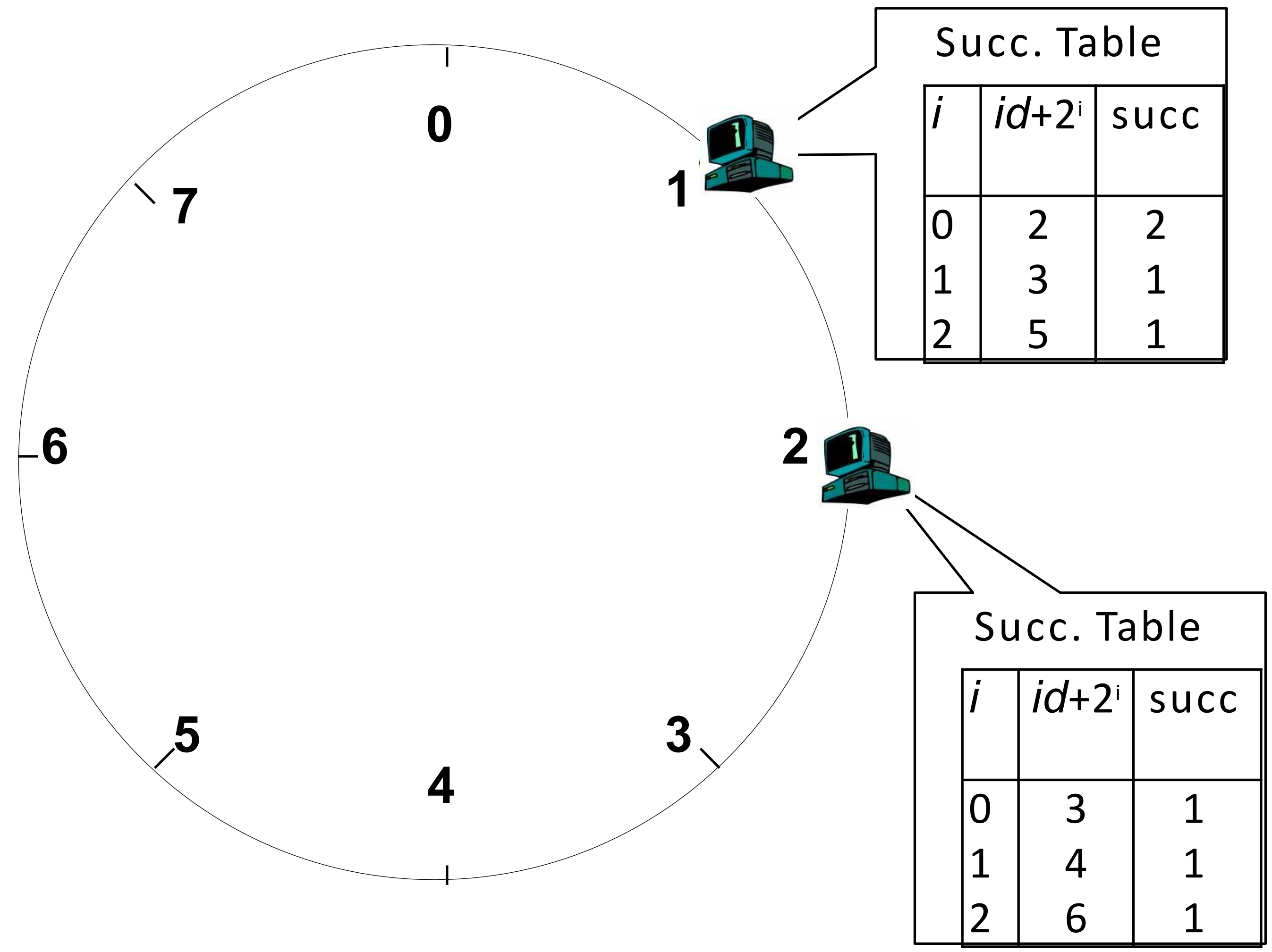


Succ. Table

i	*id*+2^i	succ
0	2	1
1	3	1
2	5	1

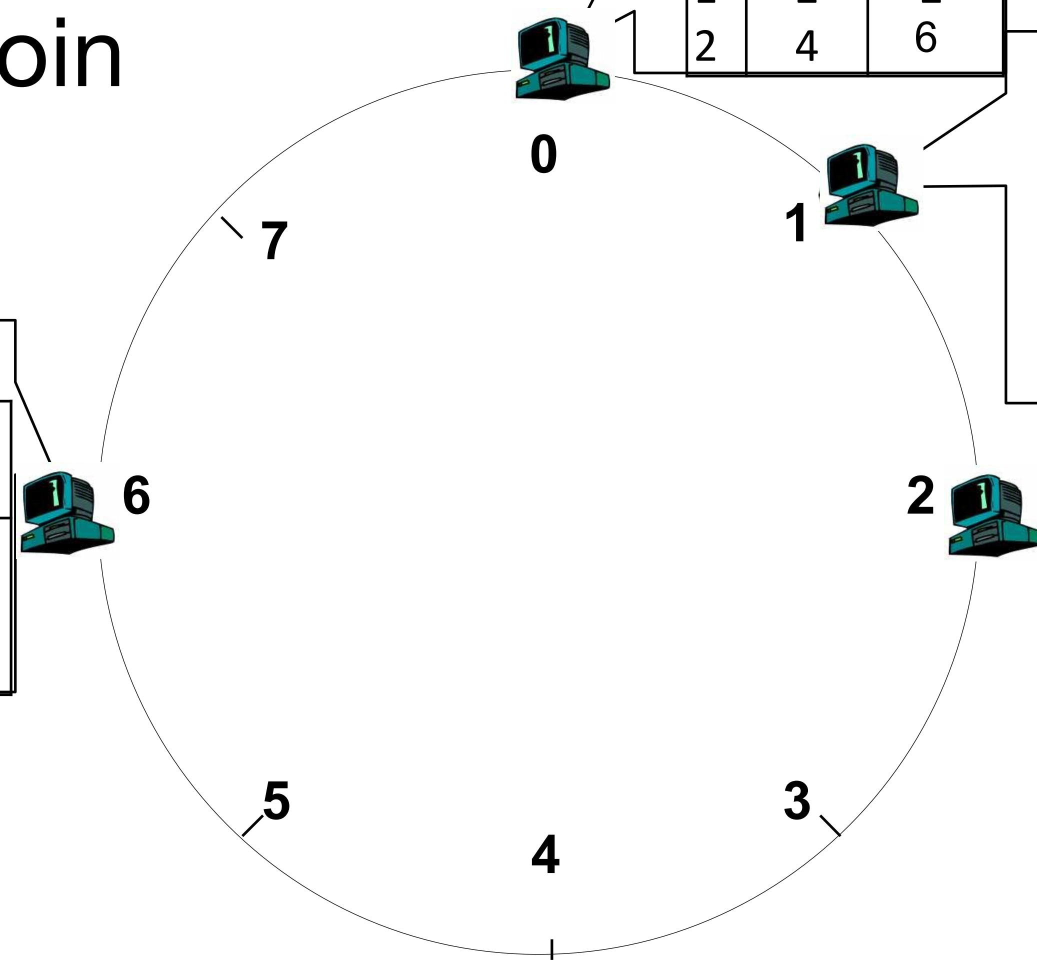
DHT: Chord Join

- Node n2 joins



DHT: Chord Join

- Nodes n0, n6 join



Succ. Table

i	$id+2^i$	succ
0	1	1
1	2	2
2	4	6

Succ. Table

i	$id+2^i$	succ
0	2	2
1	3	6
2	5	6

Succ. Table

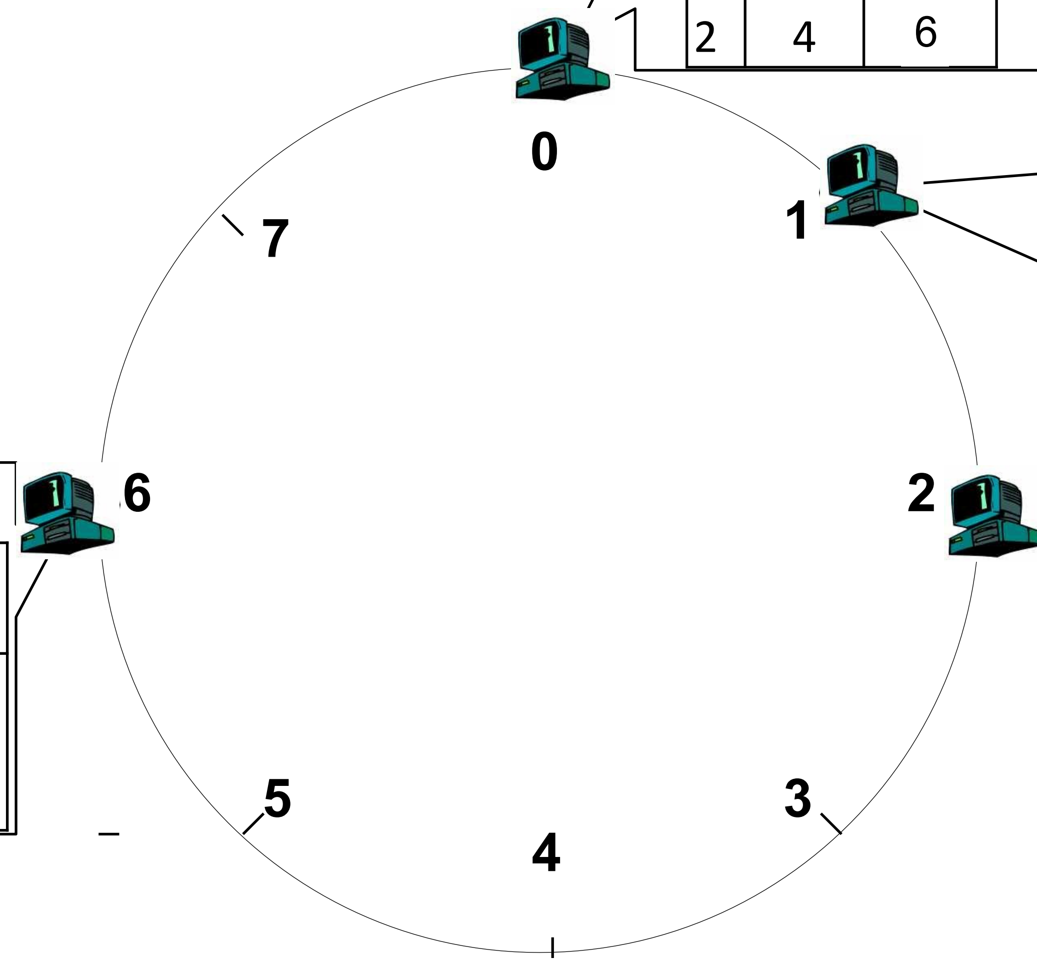
i	$id+2^i$	succ
0	3	6
1	4	6
2	6	6

Succ. Table

i	$id+2^i$	succ
0	7	0
1	0	0
2	2	2

DHT: Chord Join

- Nodes:
  n1, n2, n0, n6
- Items: f7, f1



Node 0 — Succ. Table

i	$id+2^i$	succ
0	1	1
1	2	2
2	4	6

Items: 7

Node 1 — Succ. Table

i	$id+2^i$	succ
0	2	2
1	3	6
2	5	6

Items: 1

Node 2 — Succ. Table

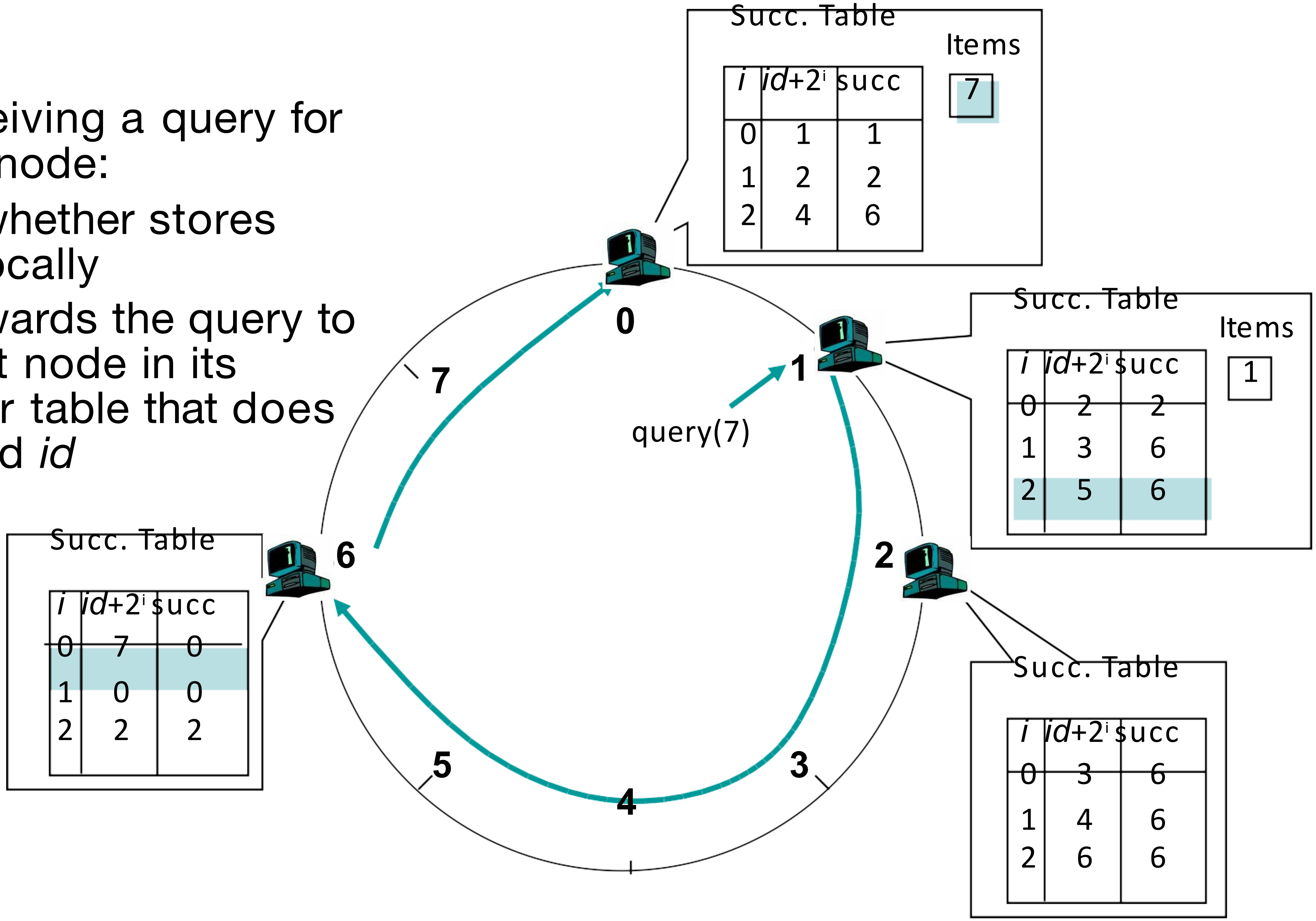
i	$id+2^i$	succ
0	3	6
1	4	6
2	6	6

Node 6 — Succ. Table

i	$id+2^i$	succ
0	7	0
1	0	0
2	2	2

DHT: Chord Routing

- Upon receiving a query for item *id*, a node:
- Checks whether stores the item locally
- If not, forwards the query to the largest node in its successor table that does not exceed *id*



DHT: Chord Summary

- Routing table size?
  - Log *N* fingers
- Routing time?
  - Each hop expects to 1/2 the distance to the desired id => expect O(log *N*) hops.

Case Study: Amazon Dynamo Key-Value Store

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
  - **Stateless** aggregator servers
  - **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**

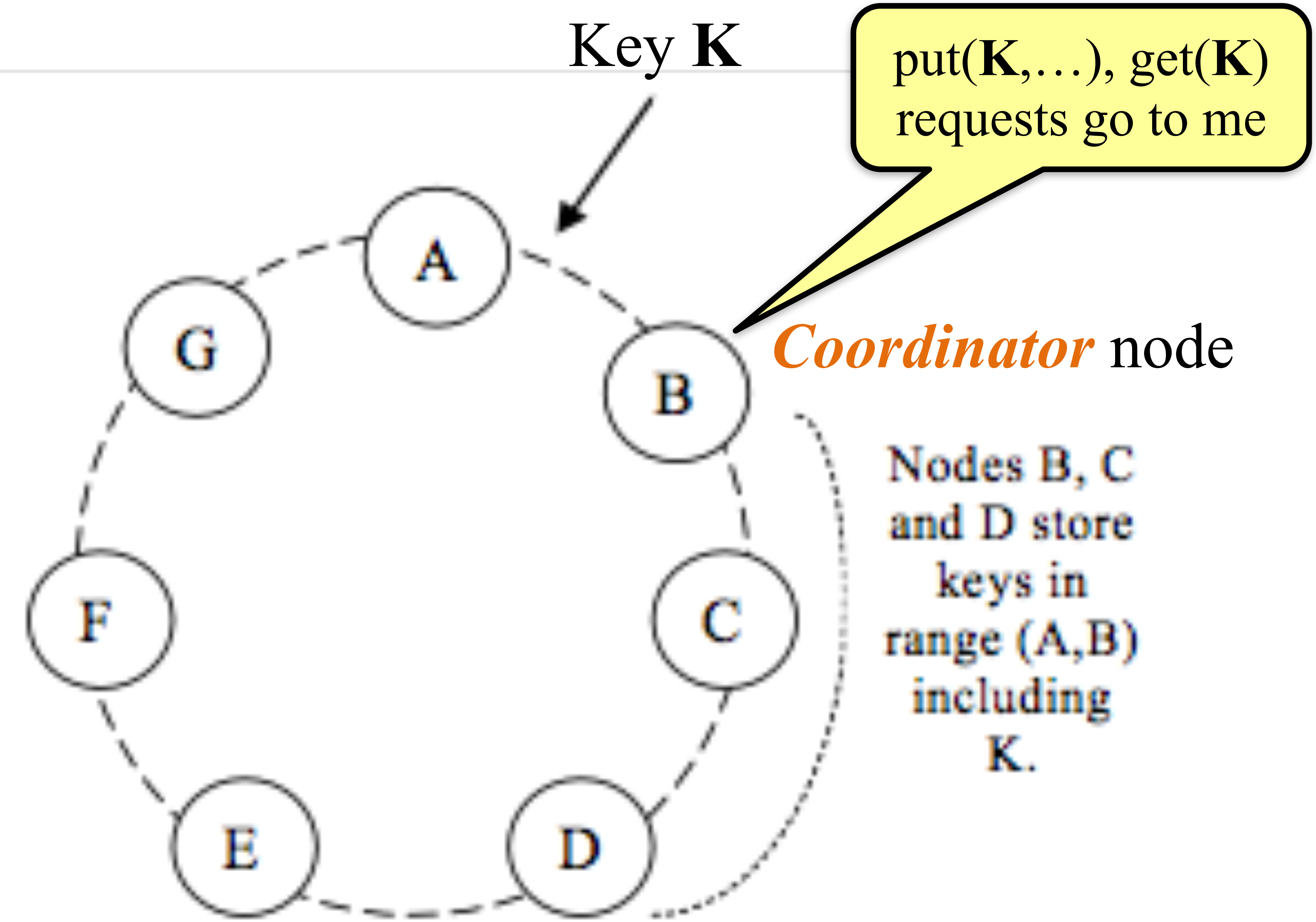
Maintain consistency of replicated data with **vector clocks**

- **Eventual consistency** for replicated data: prioritize success and low latency of writes over reads
  - And availability over consistency (unlike DBs)

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 tokens** to **ensure distinct physical nodes**

Gossip and “lookup”

Gossip: Once per second, each node contacts a **randomly chosen other node**

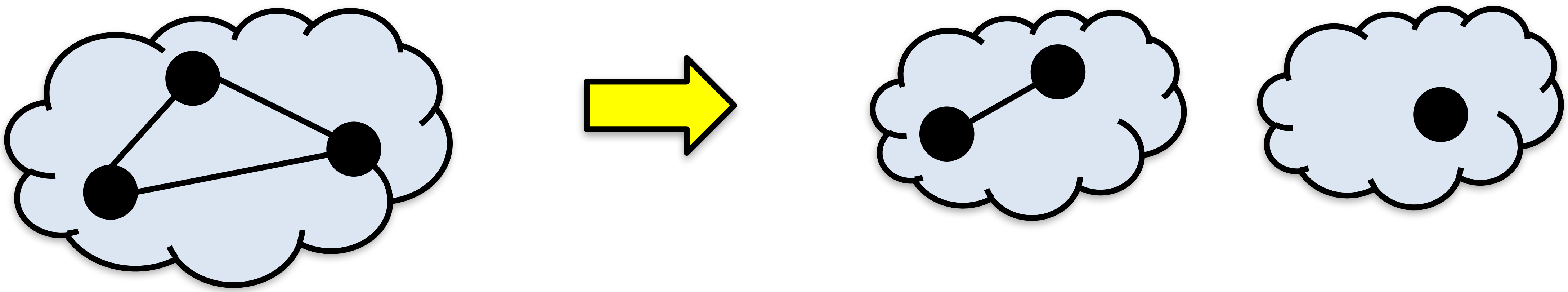
- They **exchange their lists of known nodes** (including virtual node IDs)

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

In Paxos-based primary-backup, no client in the partition of one can write

Traditional distributed databases emphasize consistency over availability when there are partitions

Alternative: Eventual consistency

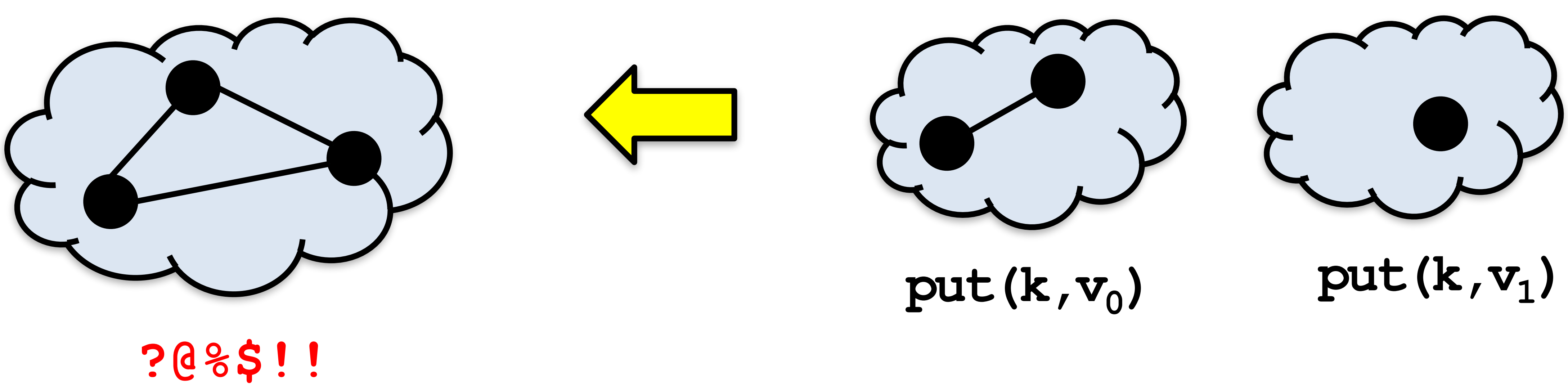
Dynamo emphasizes **availability over consistency** when there are partitions

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 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**

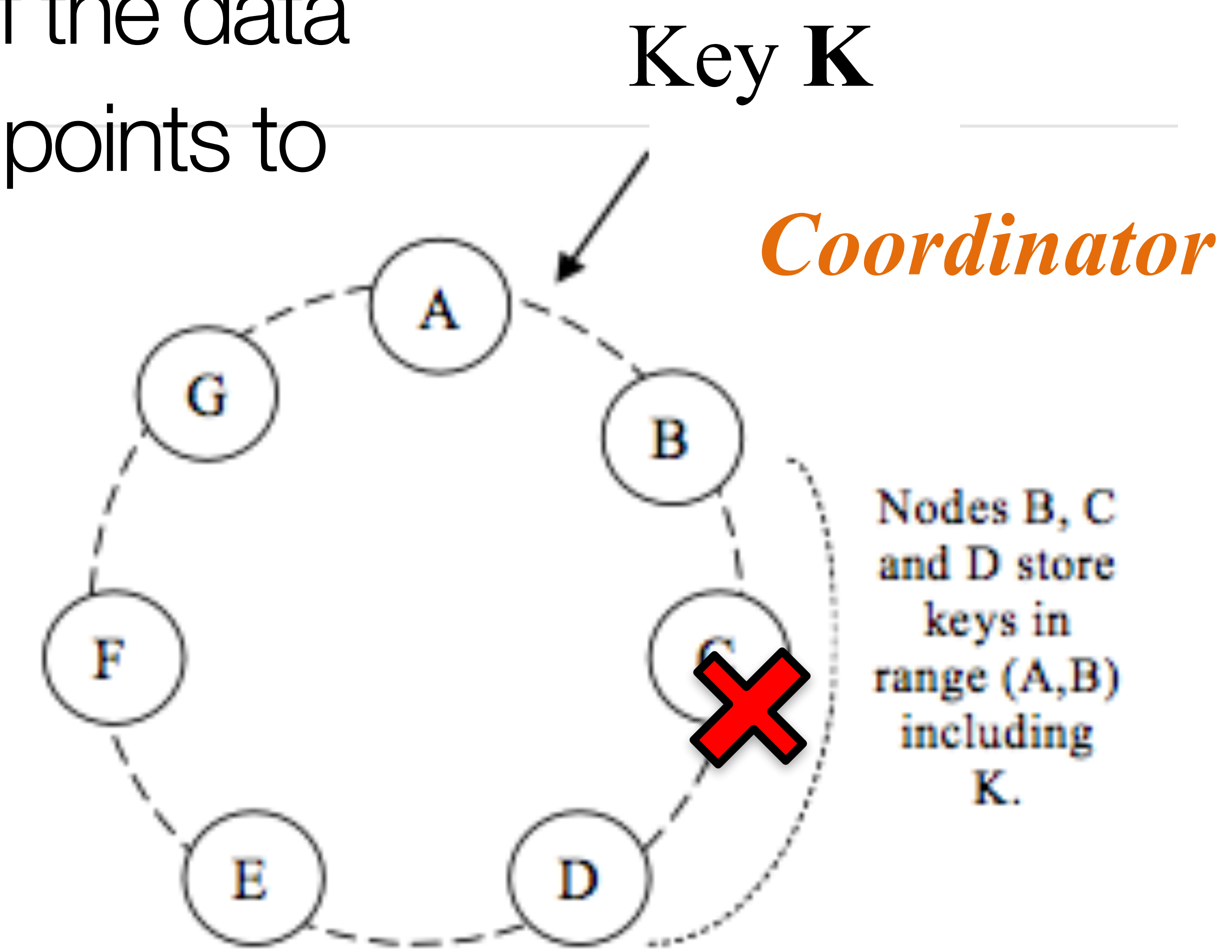
Hinted handoff: Example

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**



When **C comes back**

– **E** forwards the replicated data back to **C**

Sloppy quorums and get()s

Suppose coordinator **doesn't receive *R* replies** when processing a get()

- "*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

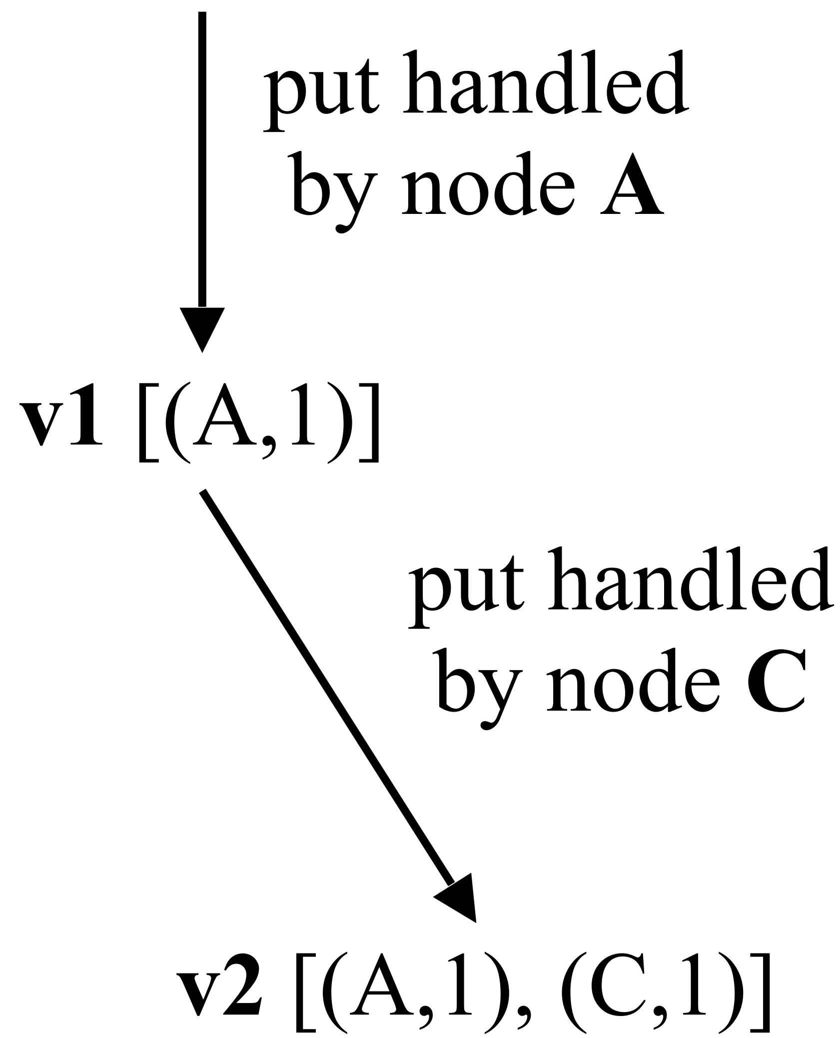
Rule: If vector clock comparison of v1 < v2, then the first is an ancestor of the second – **Dynamo can forget v1**

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")

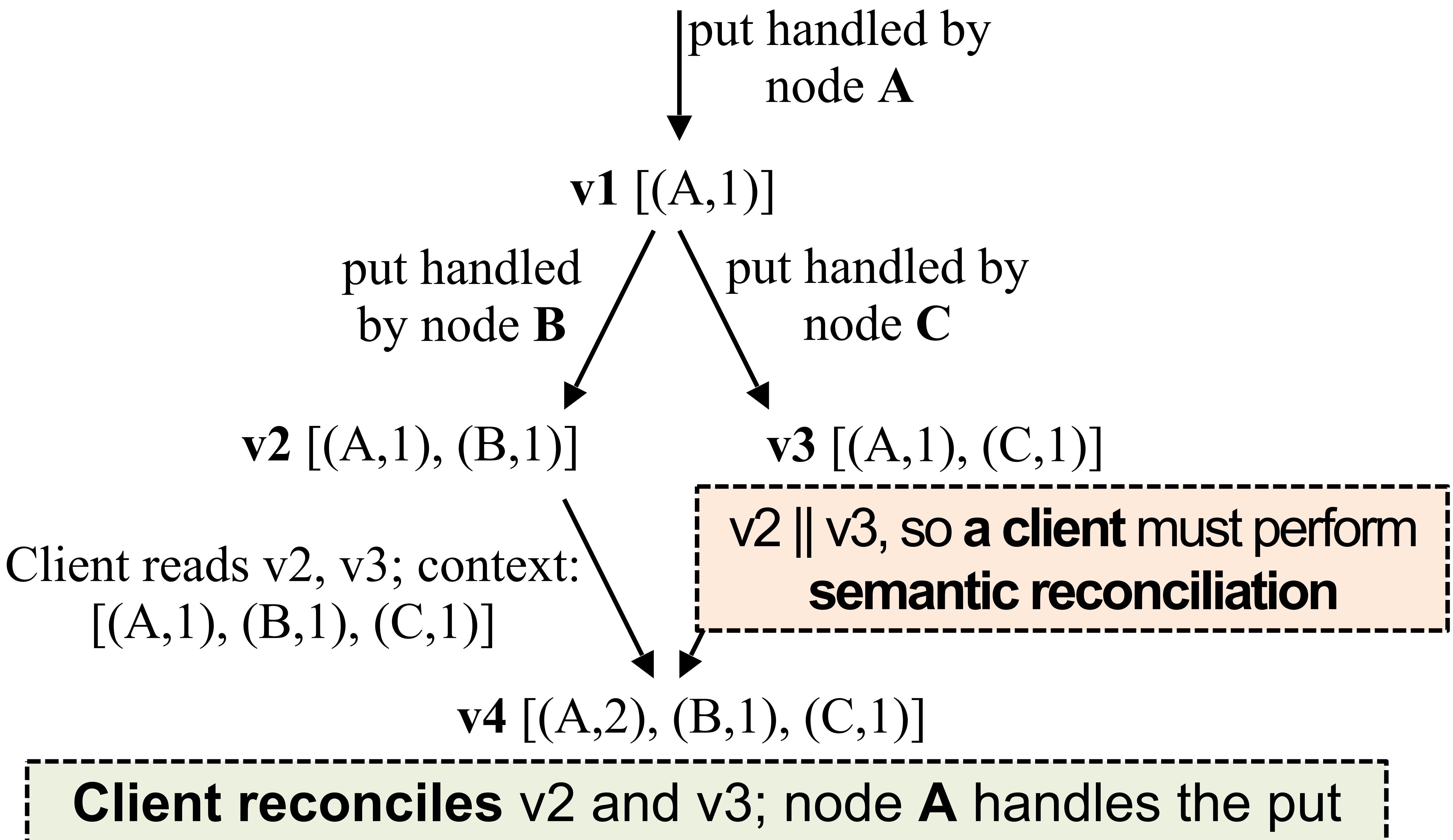
- Then users **must supply that context** to put()s that modify the same key

Version vectors (auto-resolving case)



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

Version vectors (app-resolving case)



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**

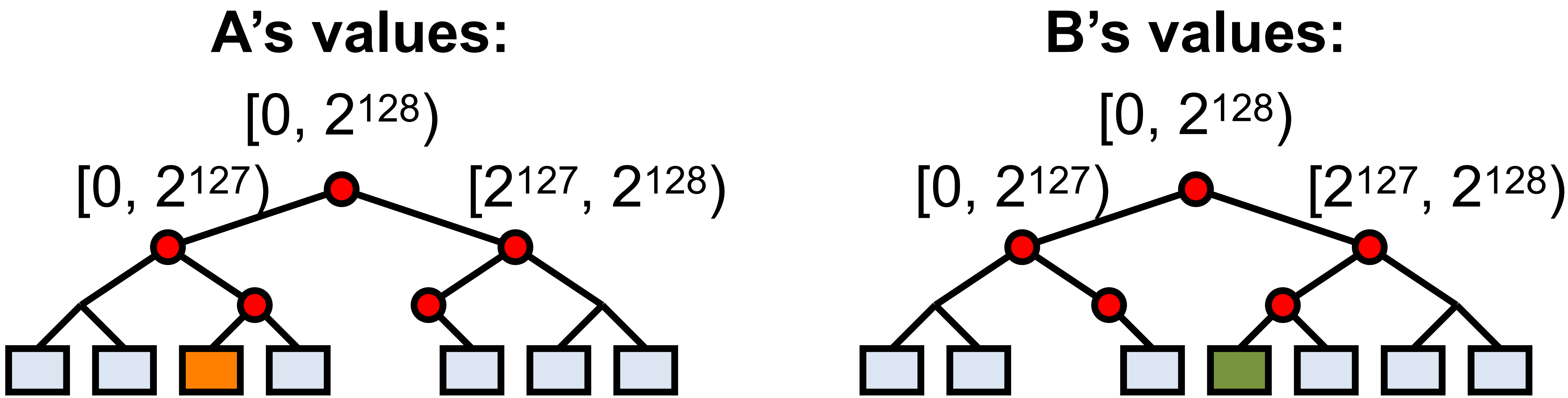
Compare roots; if match, values match

- 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

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