Dynamo

Big Data Systems

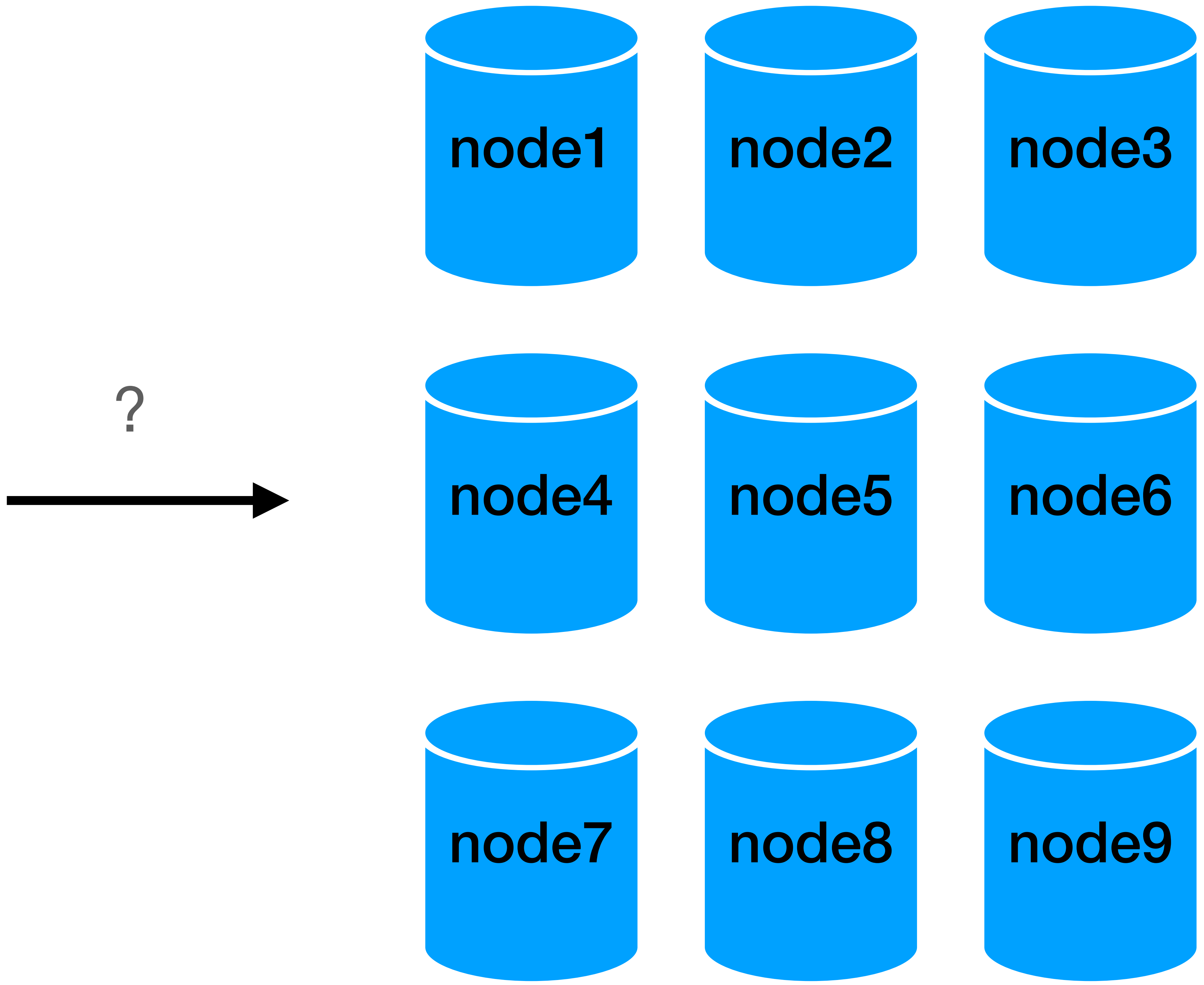
Dr. Rubi Boim

A quick reminder / motivation

Previously - Going distributed

- **Not trivial**… :)

- Starting with:
  - Data fragmentation
  - Data distribution
  - Data replication



Data fragmentation (horizontal)

<u>user_id</u>	fname	lname	city	country	account	brithdate
101	Rubi	Boim	Tel Aviv	Israel	Normal	<null>
102	Tova	Milo	Tel Aviv	Israel	Premium	<null>
103	Lebron	James	Los Angeles	USA	Premium	30/12/1984
104	Michael	Jordan	Chicago	USA	Normal	17/02/1963

- Choose an attribute
- Assign a “range” to each “node”

node1

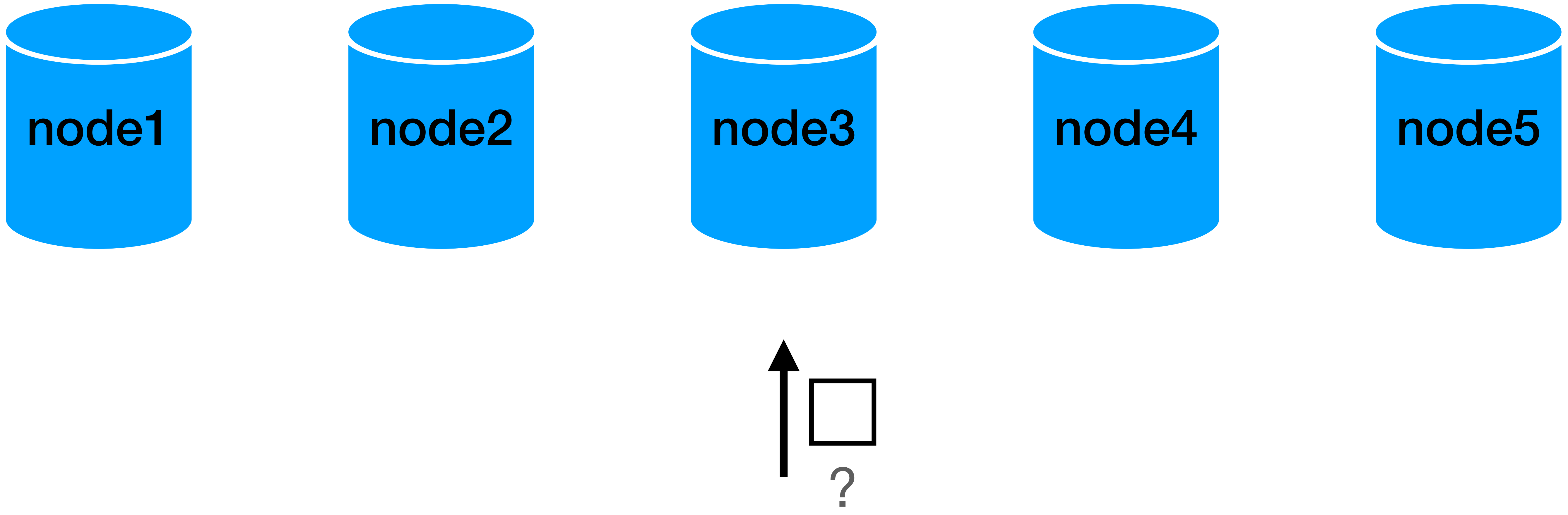
<u>user_id</u>	fname	lname	city	country	account	brithdate
101	Rubi	Boim	Tel Aviv	Israel	Normal	<null>
104	Michael	Jordan	Chicago	USA	Normal	17/02/1963

node2

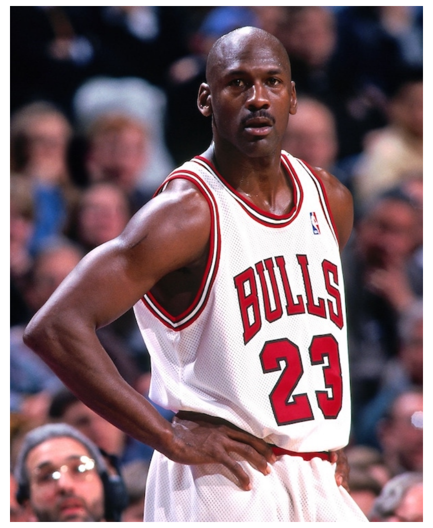
<u>user_id</u>	fname	lname	city	country	account	brithdate
102	Tova	Milo	Tel Aviv	Israel	Premium	<null>
103	Lebron	James	Los Angeles	USA	Premium	30/12/1984

Data distribution

- How can the DB decide where the data is located?

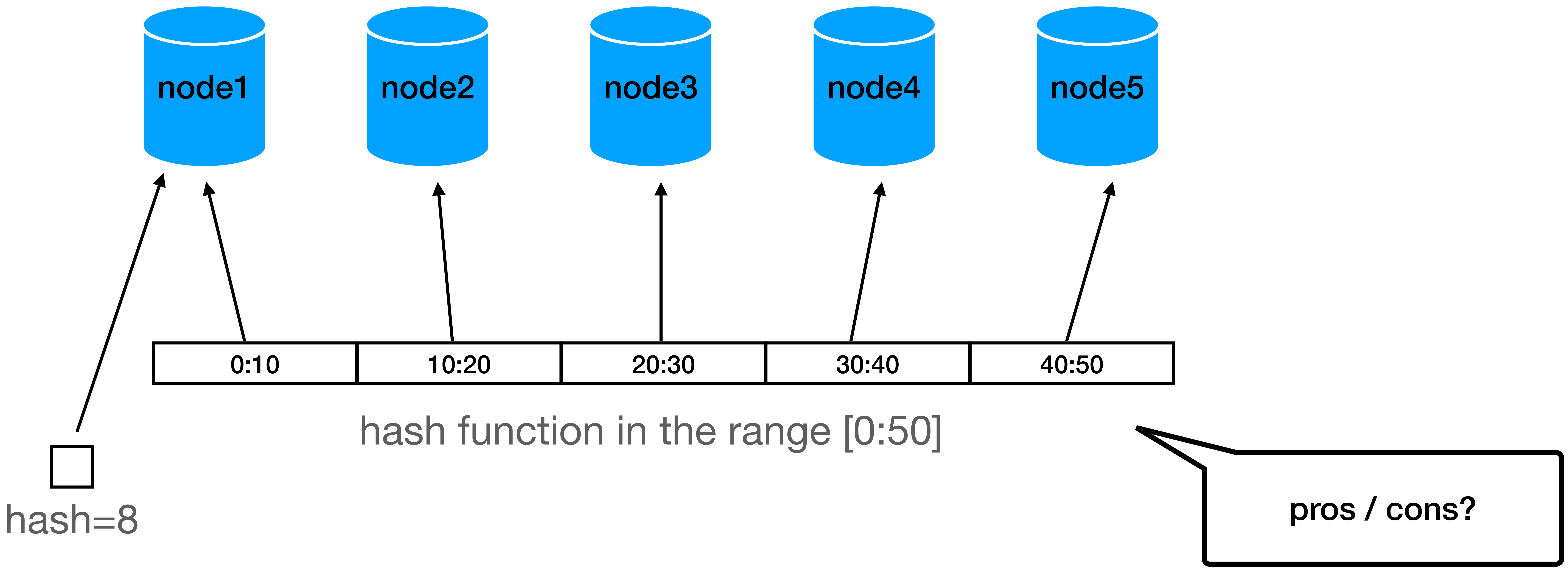


INSERT INTO users VALUES(x,y,z)



add new data /
query existing data

Data distribution- Range on hashes



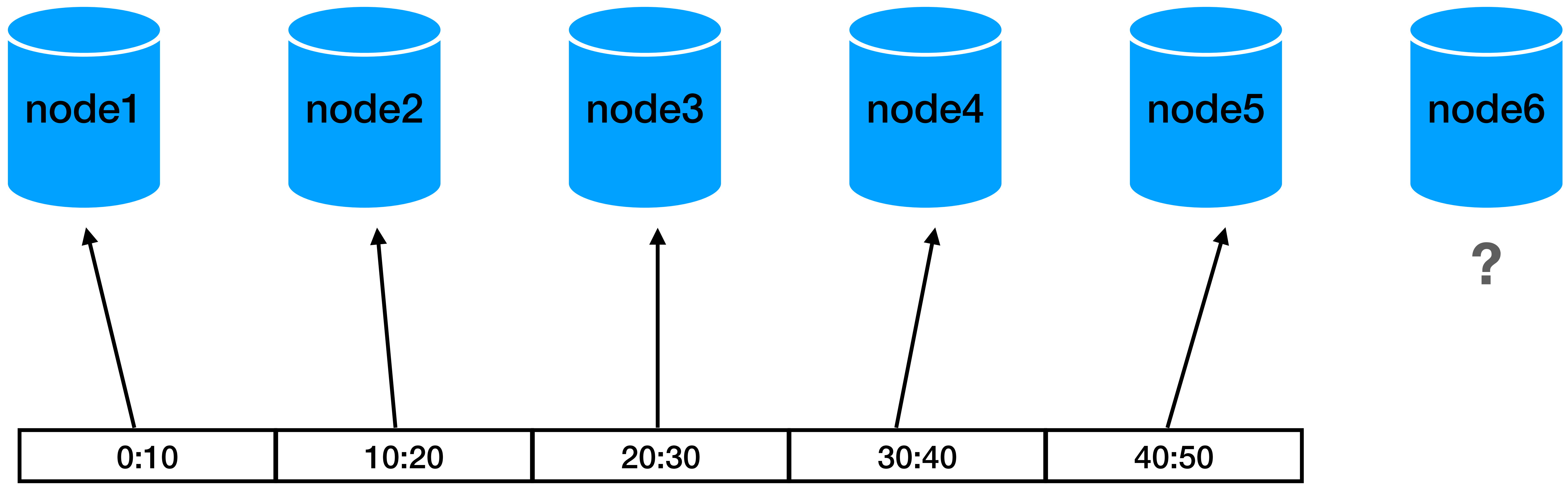
hash function in the range [0:50]

hash=8

pros / cons?

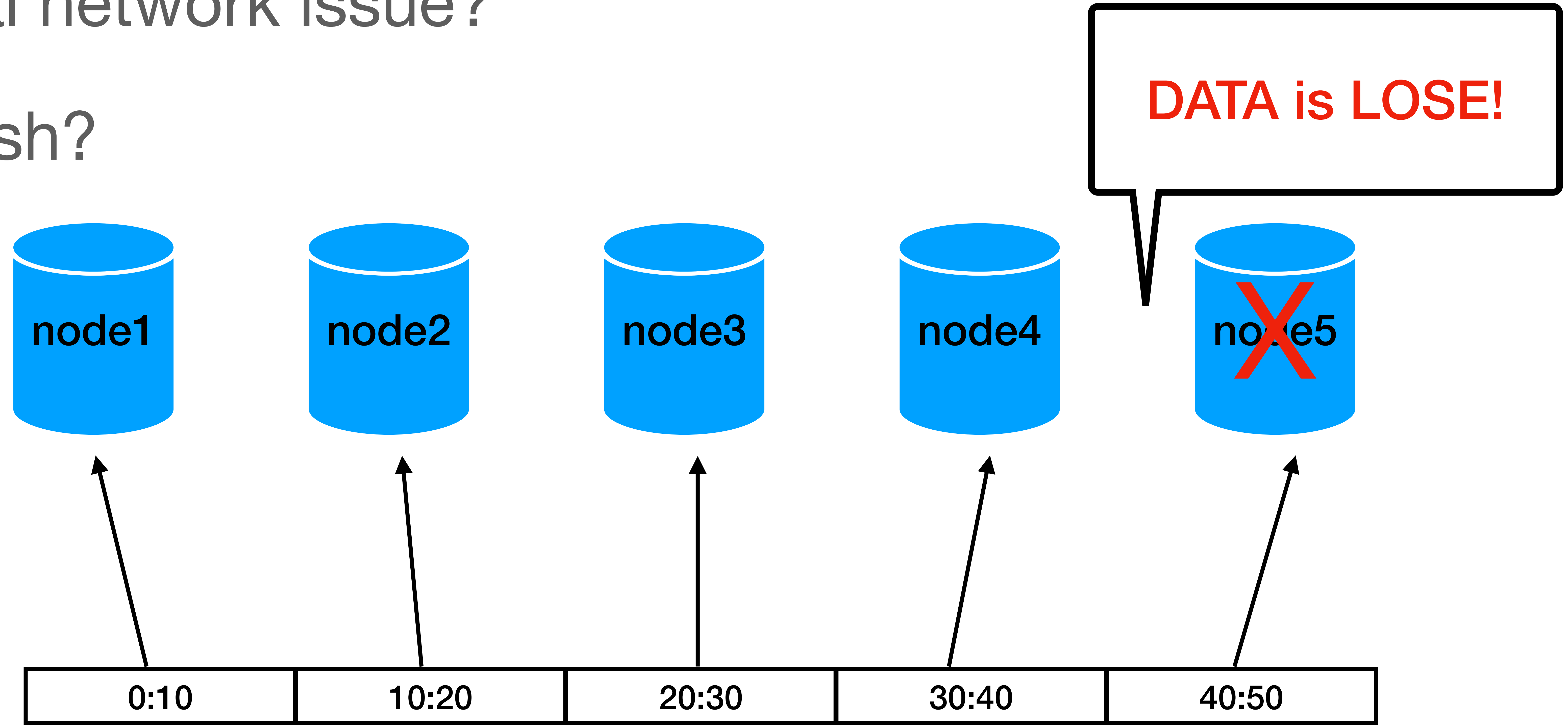
Data distribution - scaling

- What happens if we want to add a node?
  - new data?
  - existing data?



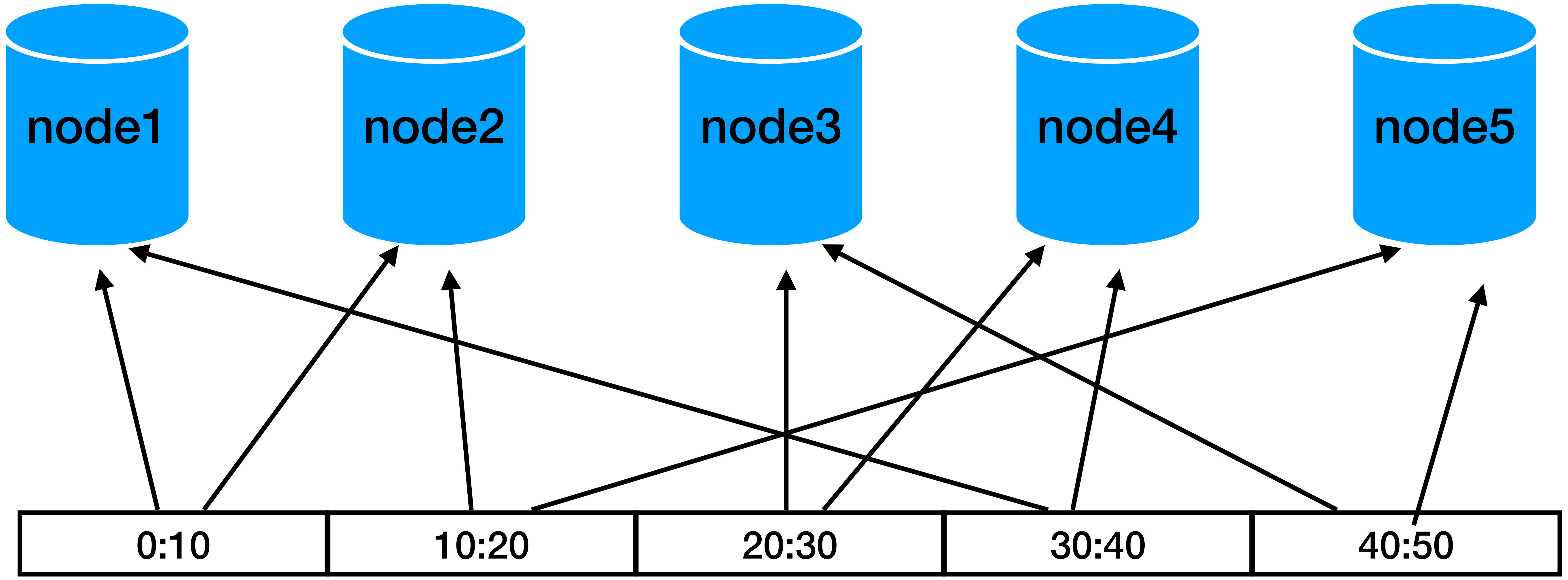
Stuff happens

- What happens if a node fails?
  - temporal network issue?
  - disk crash?



Data replication

- (re)distribute among all nodes



replication factor = 2

How do we manage all this?

and much more

Dynamo

- Create by Amazon in 2007
  paper: Dynamo: Amazon’s Highly Available Key-value Store
- The techniques developed here are used in many other systems
  not just NoSQL and not just by Amazon

Requirement: Key-Value store

- `put(key, object)`
- `get(key)`

- Sounds simple.
- How would you implement it? Single server?

Dynamo topics for today

- Requirements
- Partition algorithm
- Replication
- Data versioning
- `get()` and `put()` execution
- Failures
- Ring membership

Requirements (1)

Incremental scalability

- scale out one node at a time
- support thousands of servers, multi data centers

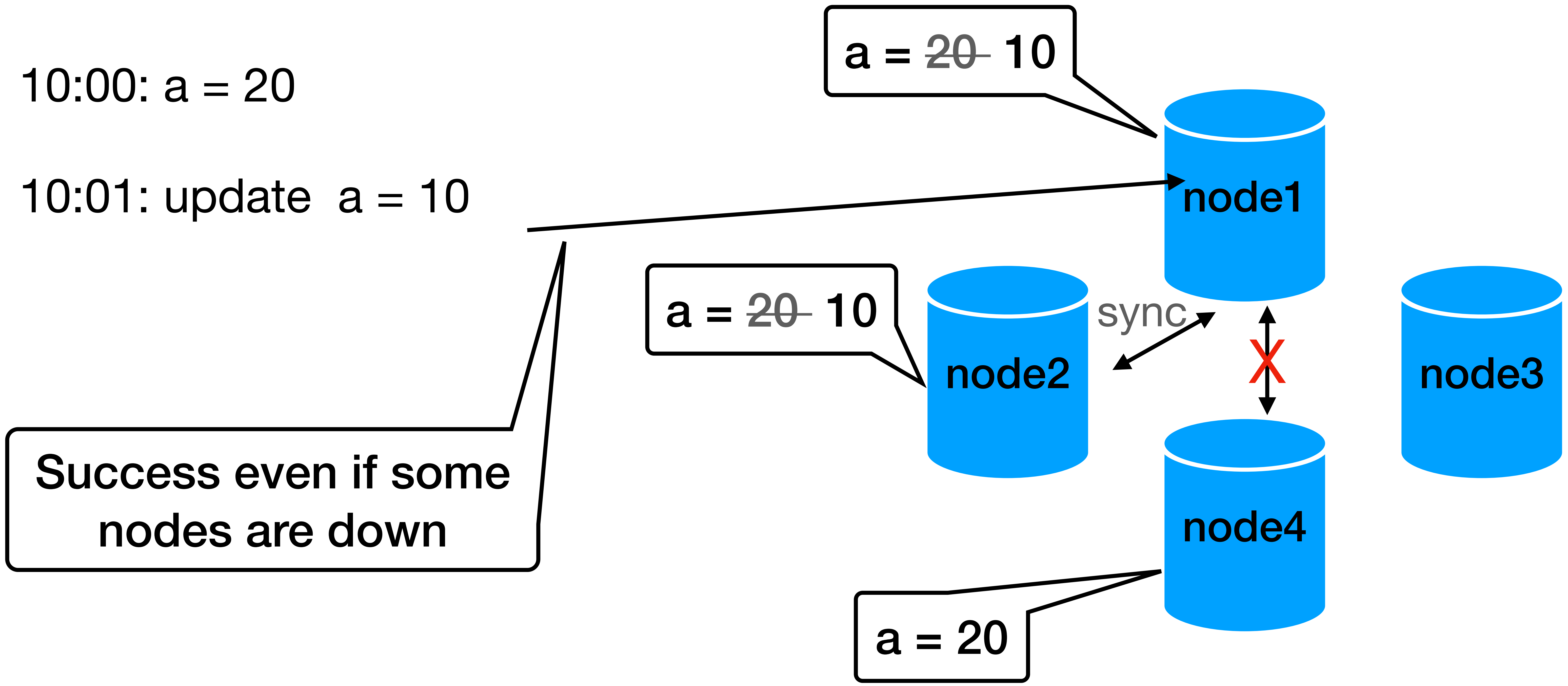
Requirements (2)

Highly available

- “always writable” data store

10:00: a = 20

10:01: update a = 10

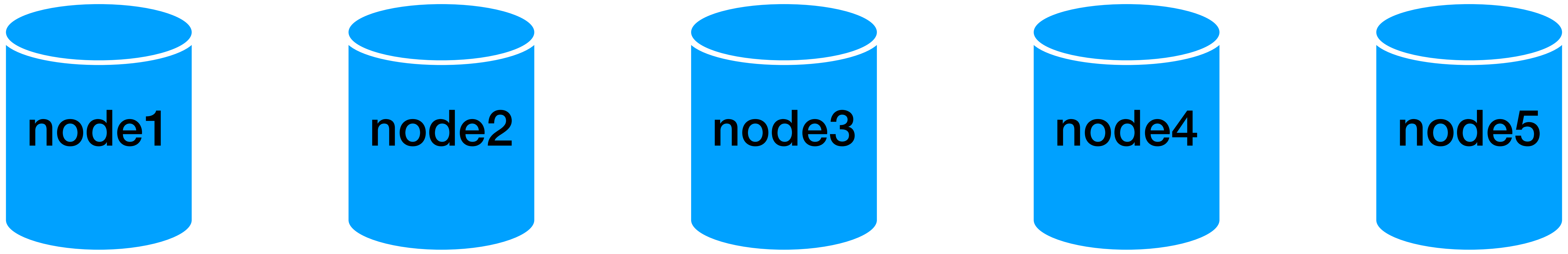


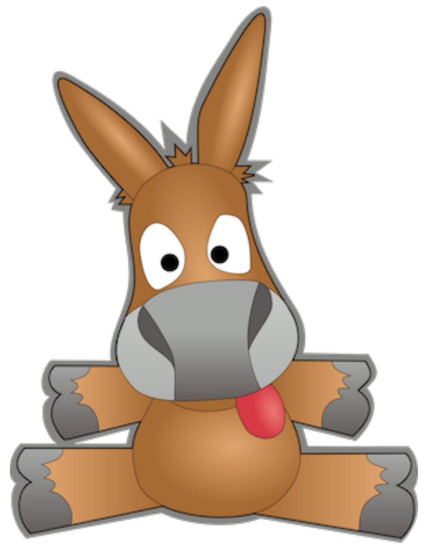
Success even if some nodes are down

Requirements (3)

Decentralized / Symmetry

- all nodes are equal, **no master** / SPOF

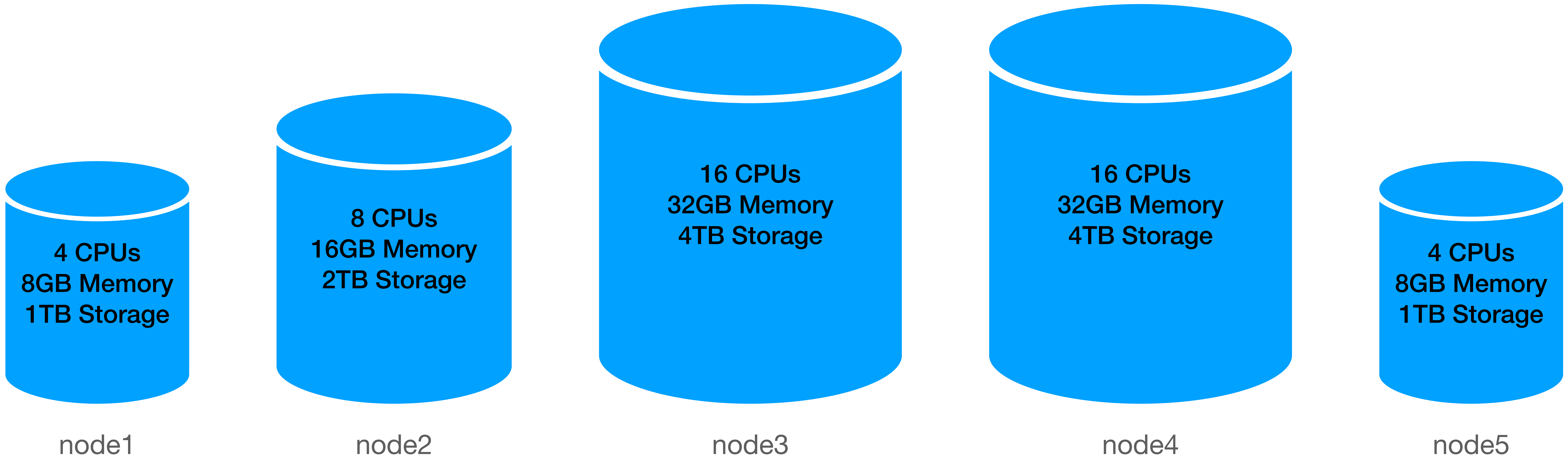




Requirements (4)

Node heterogeneity

- work distribution must be proportional to the capabilities of each node



4 CPUs
8GB Memory
1TB Storage

node1

8 CPUs
16GB Memory
2TB Storage

node2

16 CPUs
32GB Memory
4TB Storage

node3

16 CPUs
32GB Memory
4TB Storage

node4

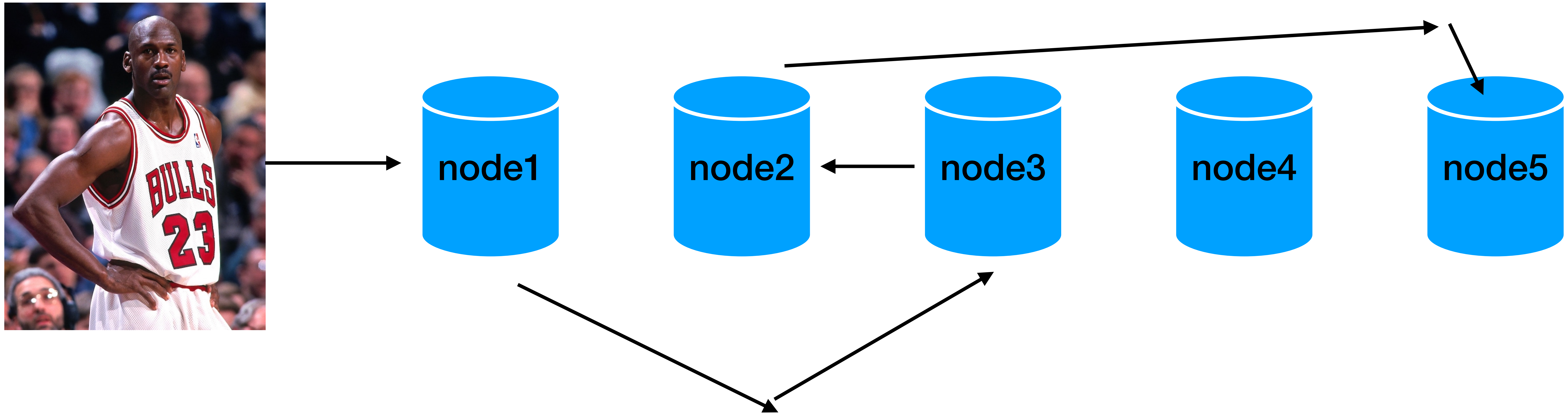
4 CPUs
8GB Memory
1TB Storage

node5

Requirements (5)

Performance

- 99.9% with 300 milliseconds response
  —> **avoid** routing request through multiple nodes as used in P2P DHT (distributed hash table) such as Chord or Pastry



Requirements (all together)

- Incremental scalability
  scale out one node at a time
  support thousands of servers, multi data centers
- Highly available
  “always writable” data store
- Decentralized / Symmetry
  all nodes are equal, **no master** / SPOF
- Node heterogeneity
  work distribution must be proportional to the capabilities of each node
- Performance
  99.9% with 300 milliseconds response
  —> avoid routing request through multiple nodes as
  used in P2P DHT (distributed hash table) such as Chord or Pastry

Requirements: Interface

- `put(key, context, object)`
- `get(key)`
  - `context` = system metadata / versioning (opaque to the user)
  - `get` returns <u>all versions</u> of the associated object
    * we will later see when can we have multi versions

Dynamo topics

- Requirements
- Partition algorithm
- Replication
- Data versioning
- `get()` and `put()` execution
- Failures
- Ring membership

Partitioning algorithm (1)

- Scale incrementally —>
  a mechanism is required to dynamically partition the data over a set of nodes
- How do we match nodes and keys (hashes)?

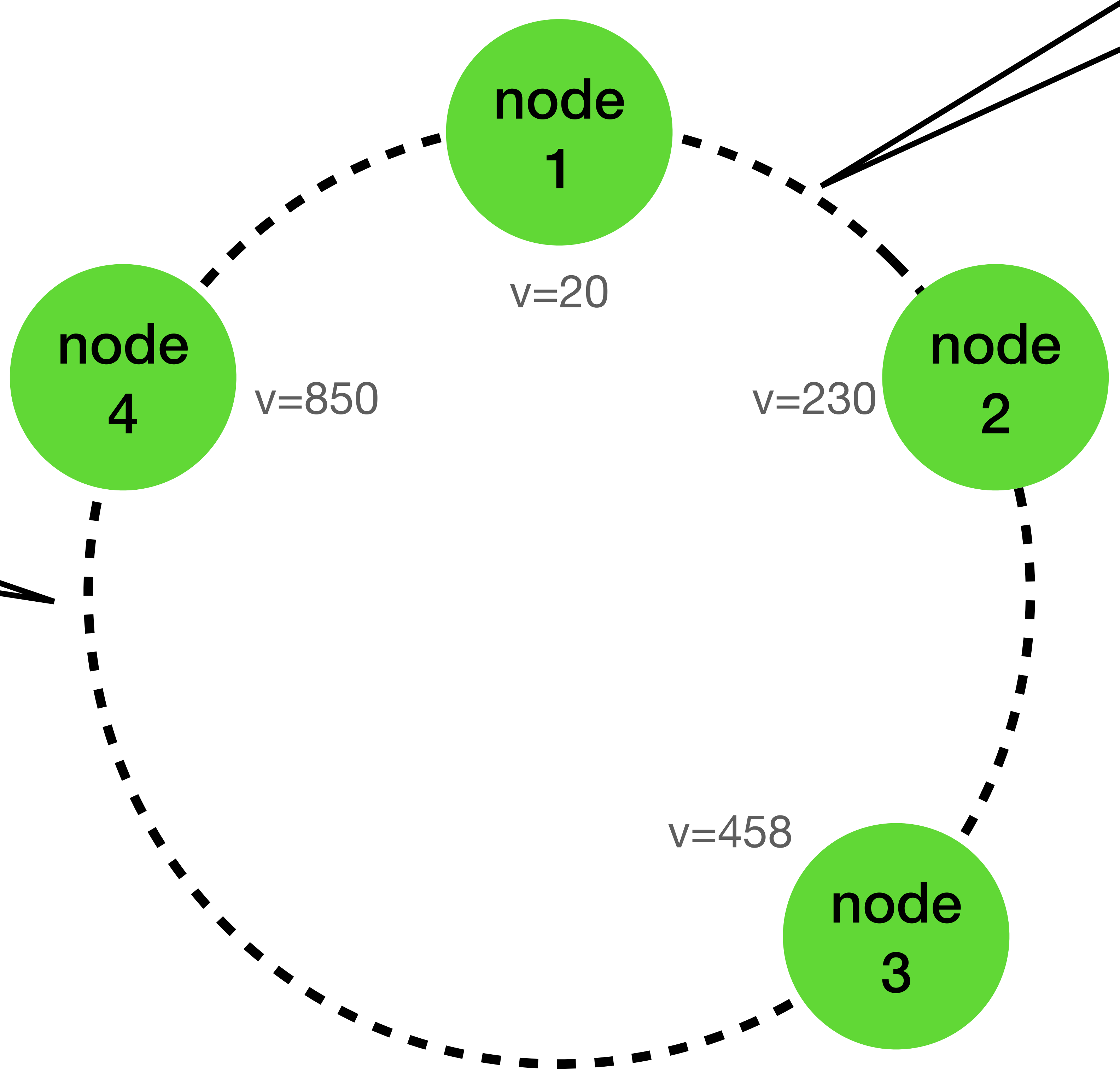
Partitioning algorithm (2)

Consistent hashing

- Hash function output is treated as a “ring”
- Each node is assigned a random value within the space (“location on the ring”)
- Assignment to a node is done by taking the hash of the key and “walking (clockwise) on the ring till a node”

Partitioning algorithm (3)

Consistent hashing

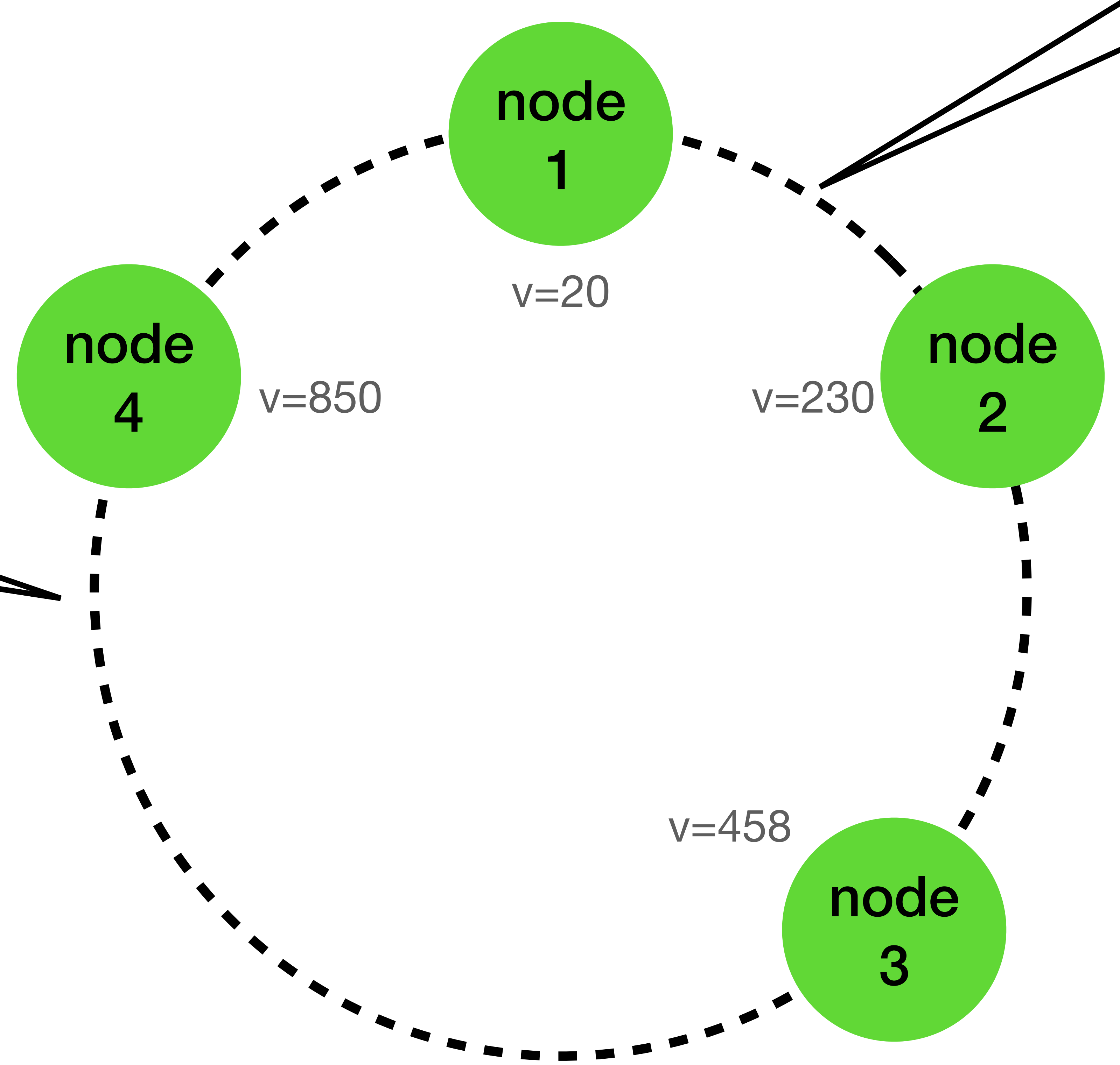


Range is [0:1000] for the example

Each node is responsible to the range between it and its predecessor

Partitioning algorithm (3)

Consistent hashing



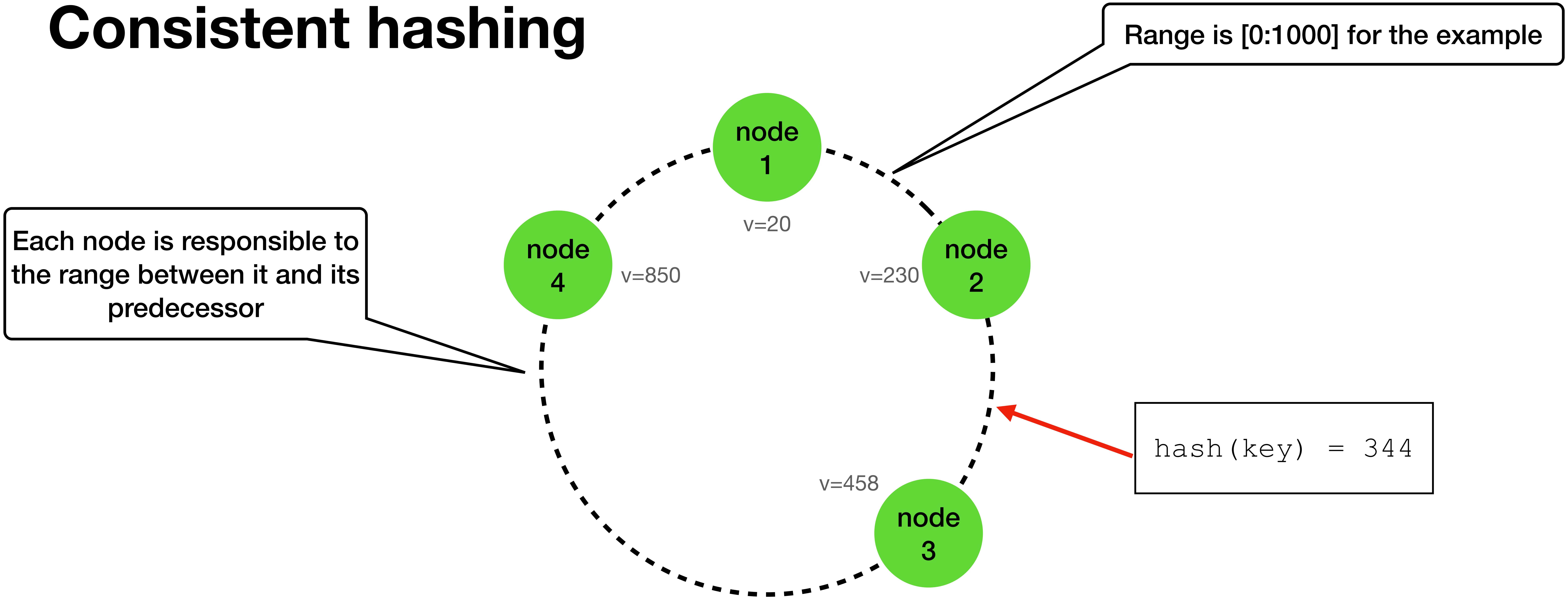
Range is [0:1000] for the example

Each node is responsible to the range between it and its predecessor

```
hash(key) = 344
```

Partitioning algorithm (3)

Consistent hashing



Partitioning algorithm (3)

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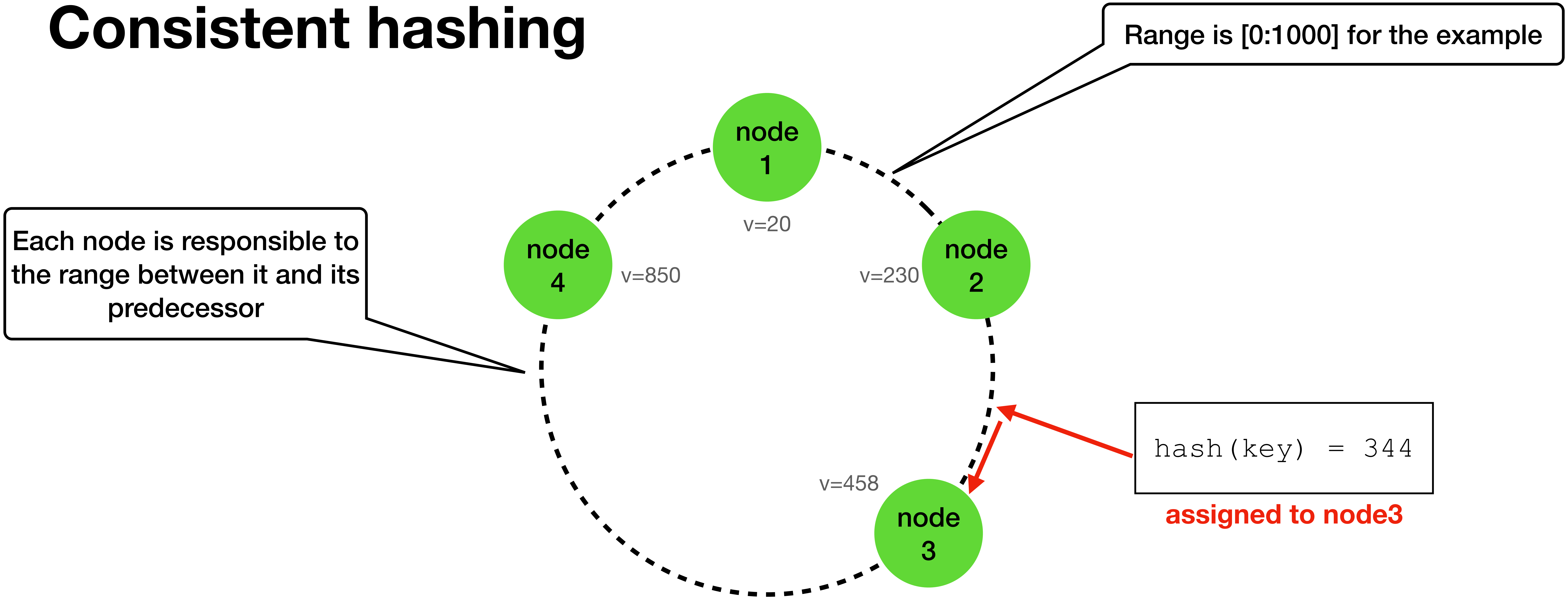

Partitioning algorithm (3)

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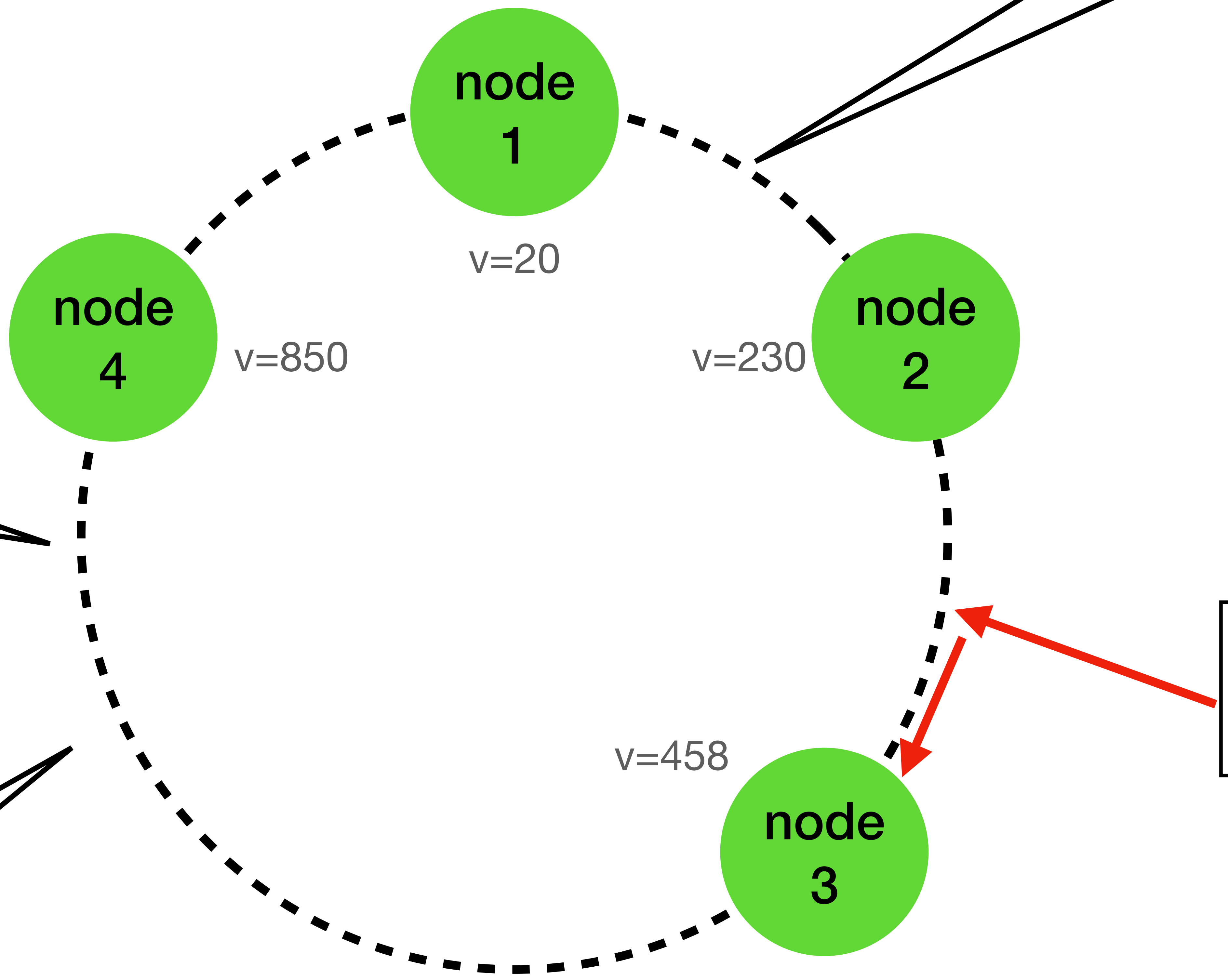

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Each node is responsible to the range between it and its predecessor

adding / removing a node only affect its neighbors

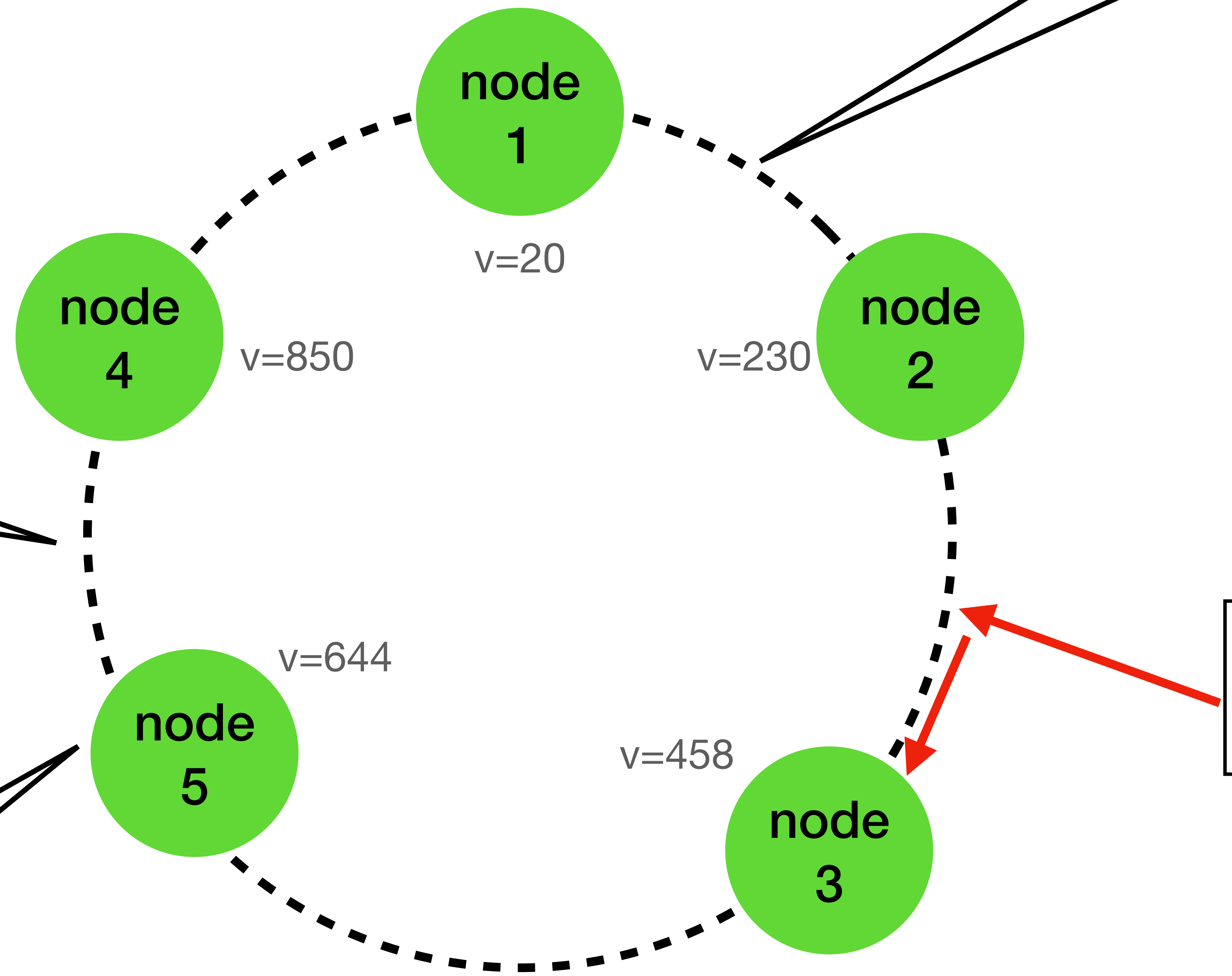
`hash(key) = 344`

assigned to node3

Partitioning algorithm (3)

Consistent hashing

Range is [0:1000] for the example



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Partitioning algorithm (4)

Consistent hashing - challenges

- Random positioning —> non uniform data distribution
- Node heterogeneity is not supported
  node hardware is not considered

Partitioning algorithm (5)

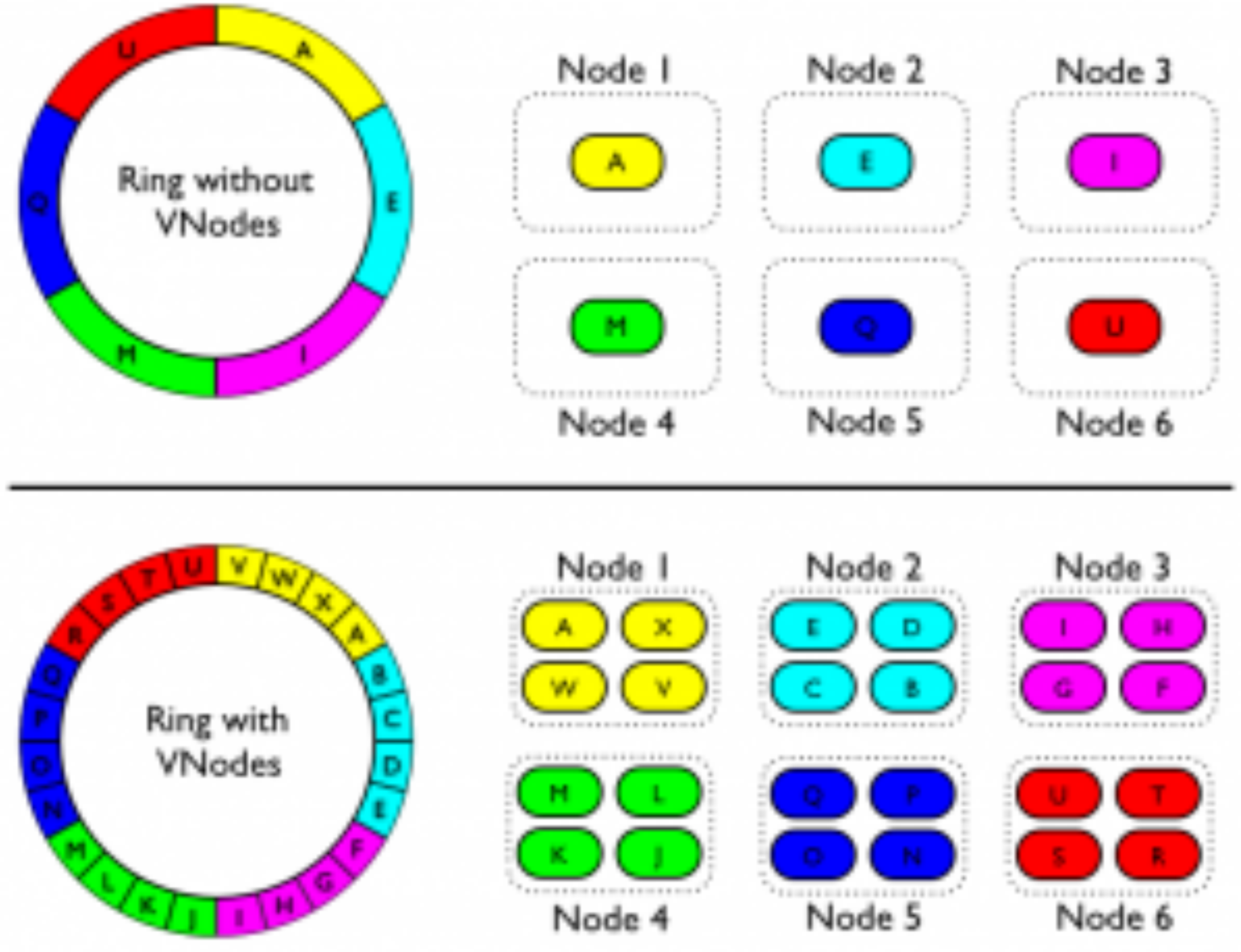
Dynamo consistent hashing

- Instead of a single “token” for a node, ,map vnodes

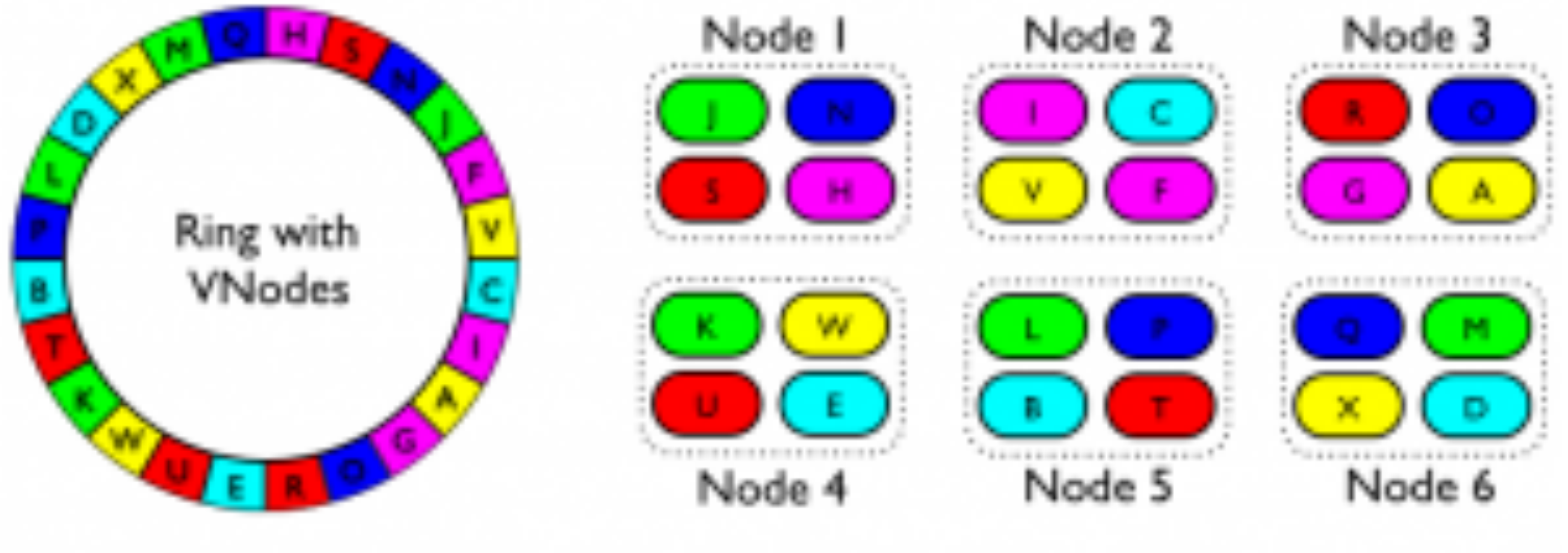
  vnode looks like a “normal” node
  each node manage several vnodes

Partitioning algorithm (6)

Dynamo consistent hashing



VNodes before shuffling



VNodes after shuffling

* Images from DataStax website

Partitioning algorithm (7)

Dynamo consistent hashing

- With vnodes:

—> data is distributed more evenly

—> #vnodes for each node is proportional to its hardware

—> If we add/remove a node, the load is now distributed among much mode nodes

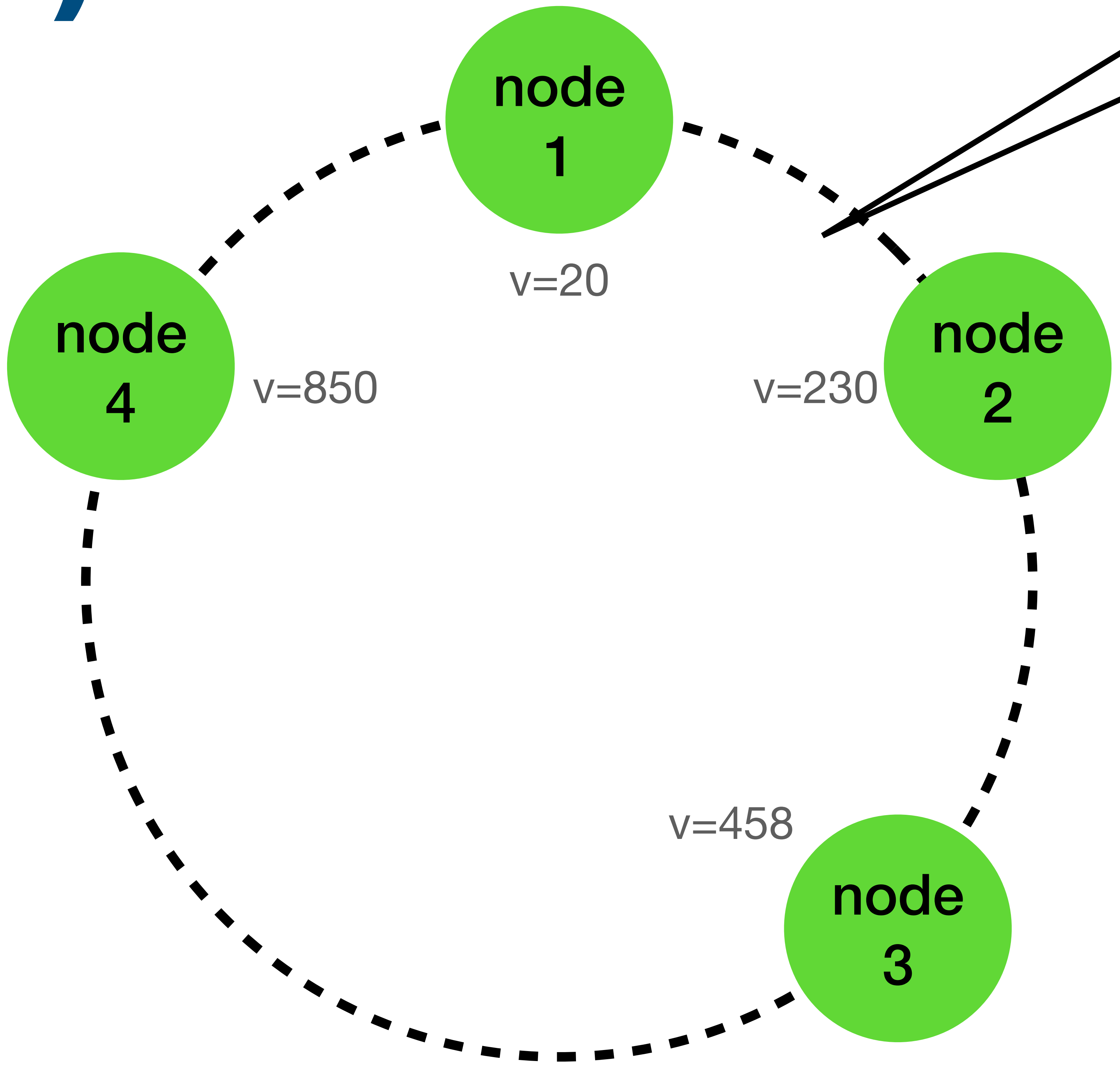
Dynamo topics

- Requirements
- Partition algorithm
- Replication
- Data versioning
- `get()` and `put()` execution
- Failures
- Ring membership

Replication (1)

- To achieve High availability and Durability, Dynamo replicates its data on N nodes (configurable)
- A key is assigned to a coordinator
  coordinator = the mapped node from the consistent hashing
- The coordinator stores locally + on the next N-1 nodes
  automatically skips vnodes of “existing” nodes as we want to store the data on N physically different nodes

Replication (2)



Range is [0:1000] for the example, N=3

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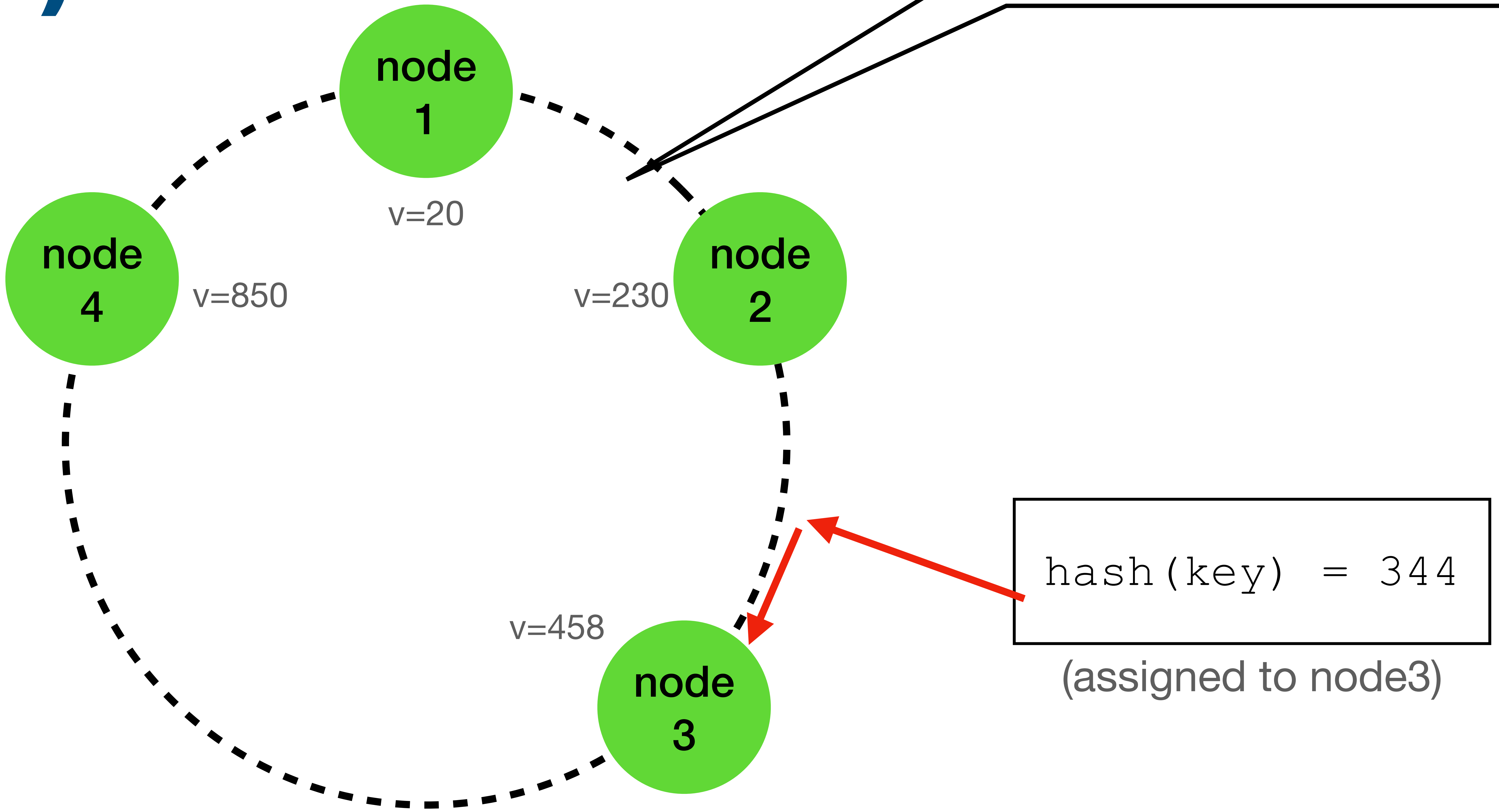

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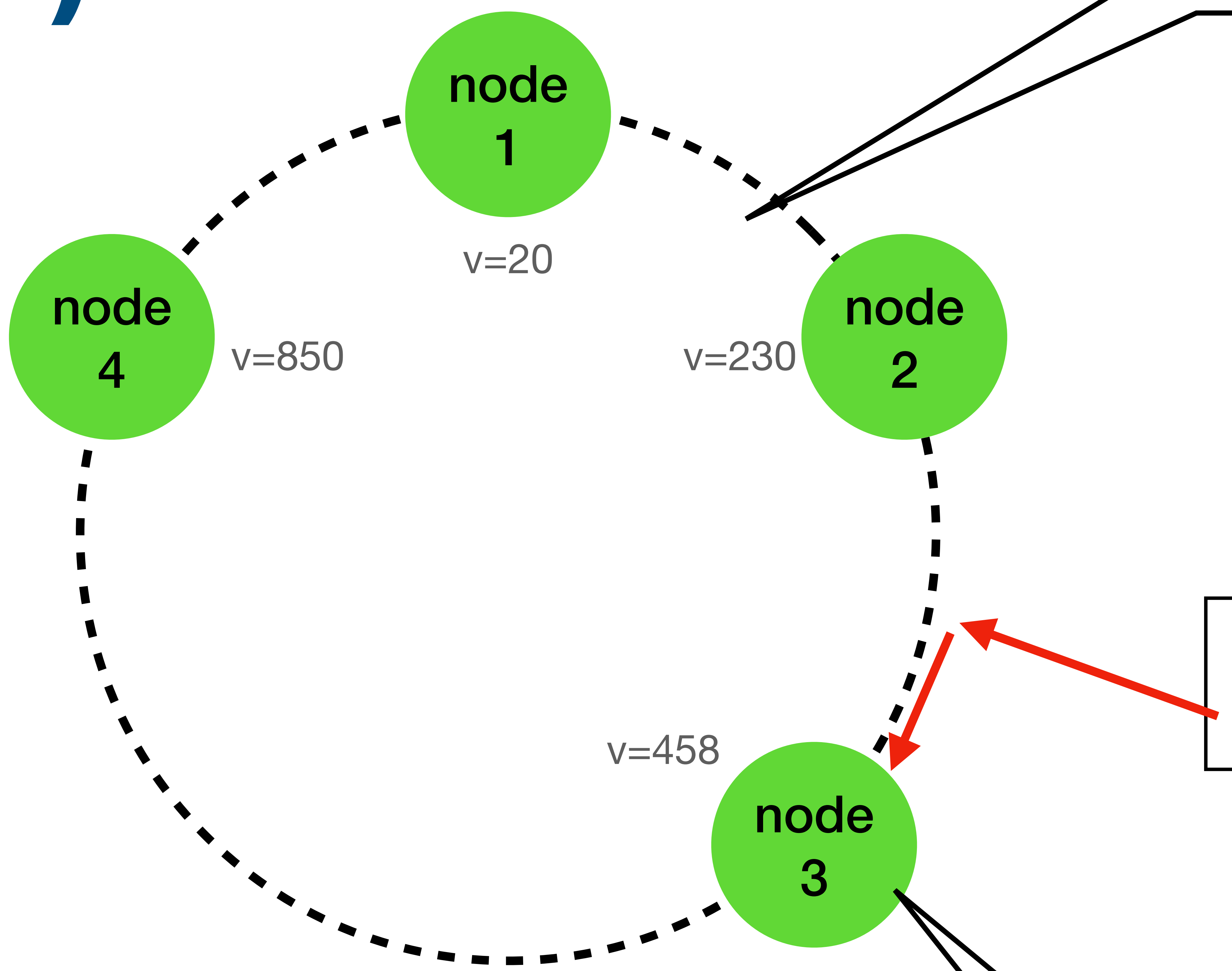

Range is [0:1000] for the example,
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node3 is the coordinator. It will store the value locally and on node4 and node1

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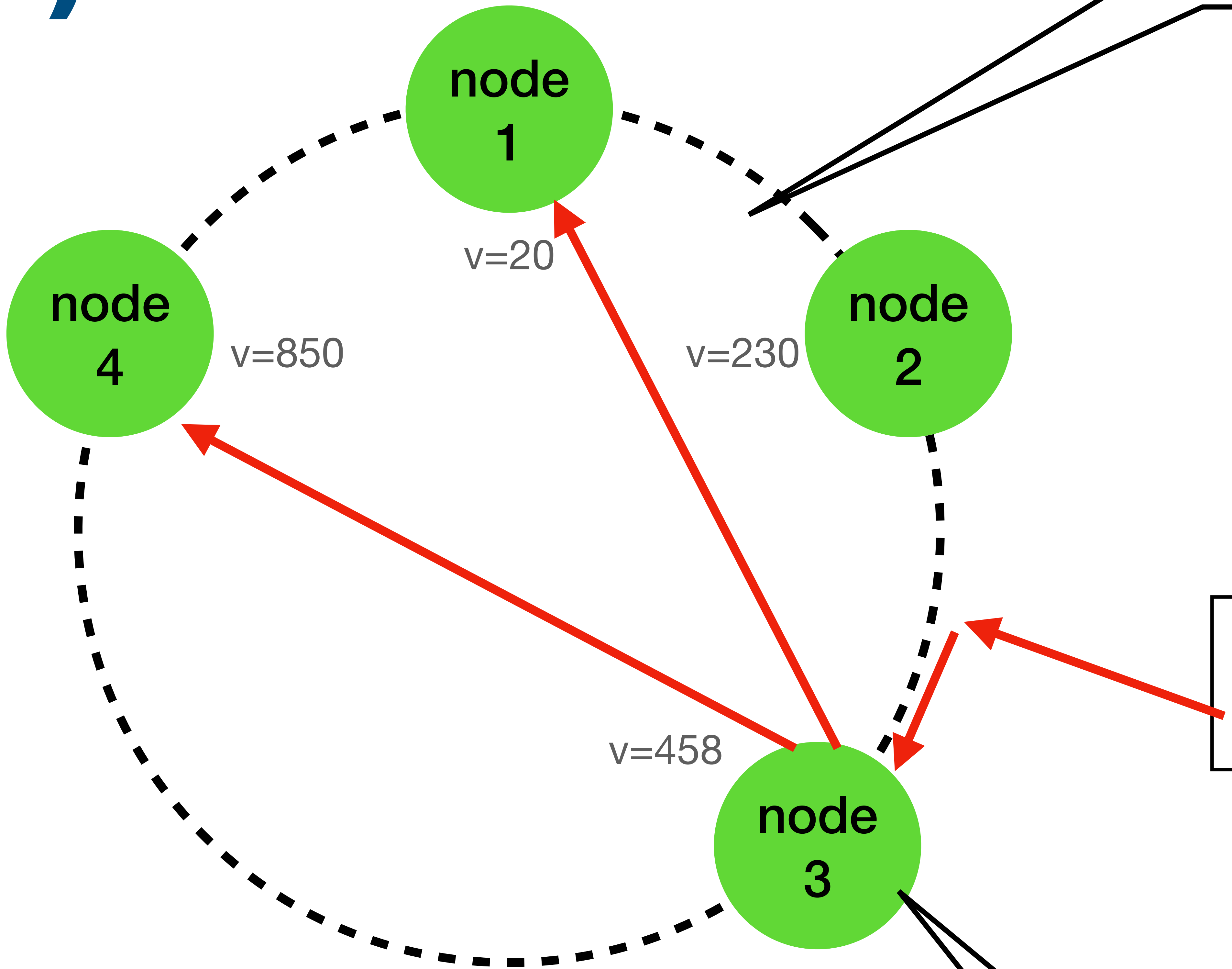

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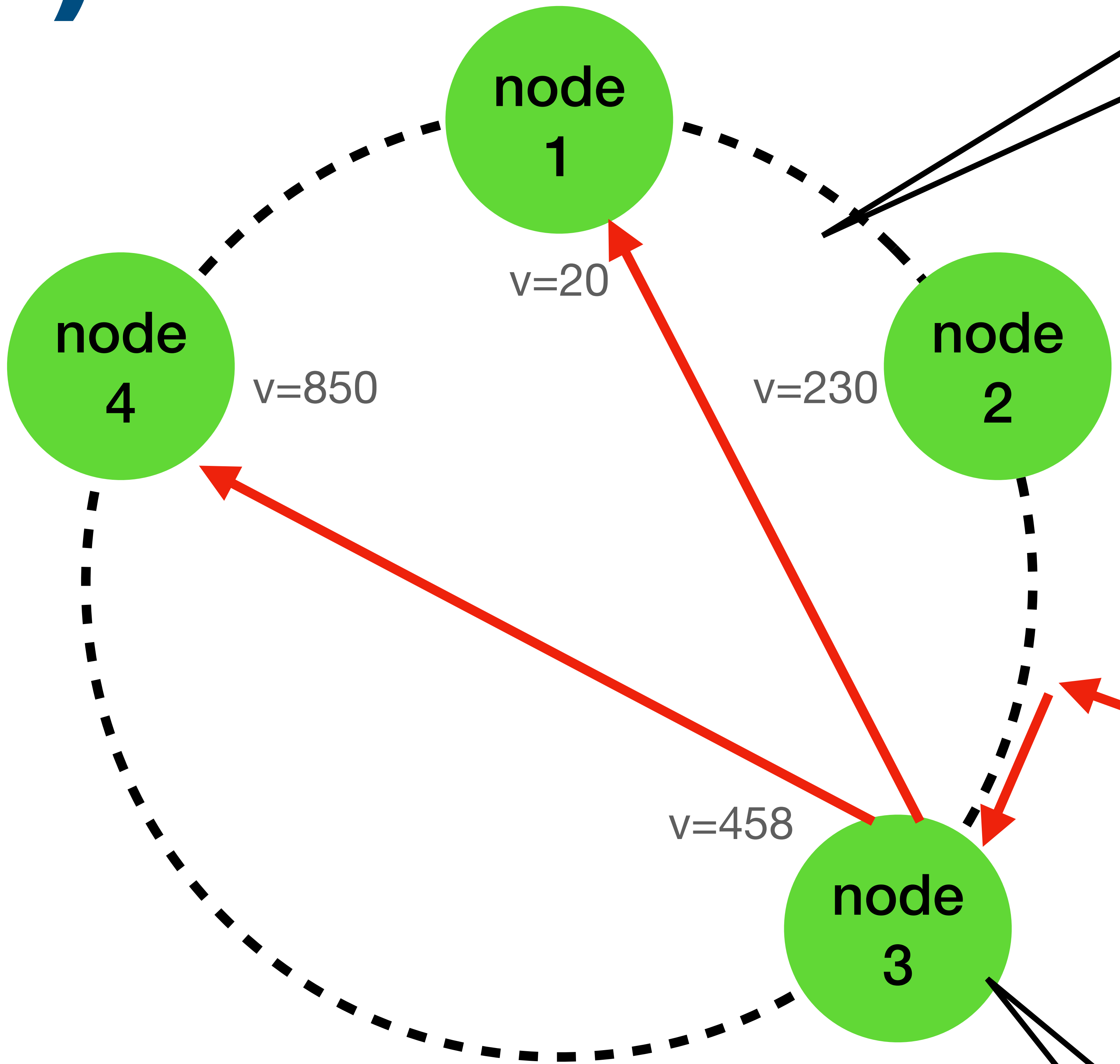

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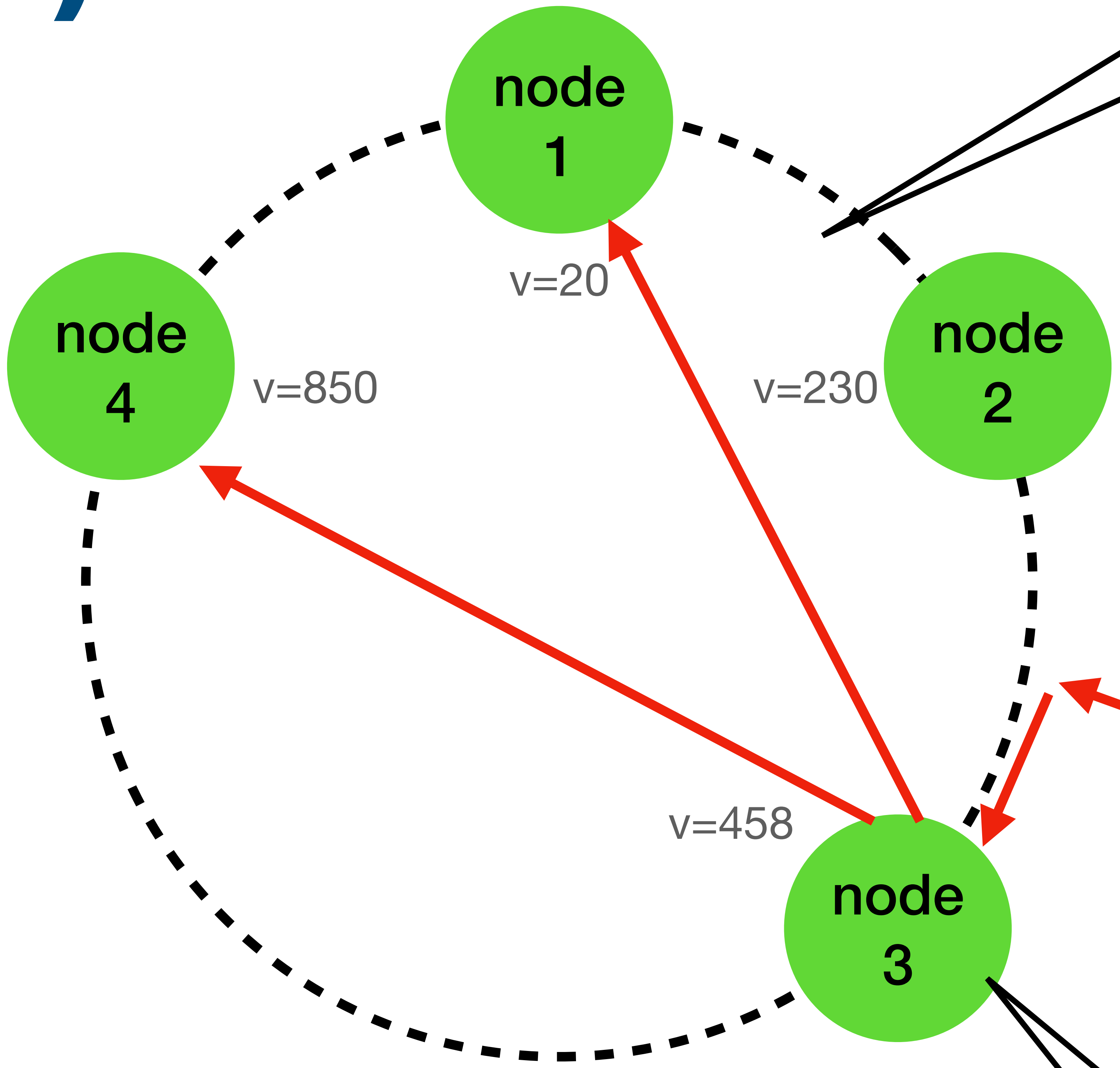

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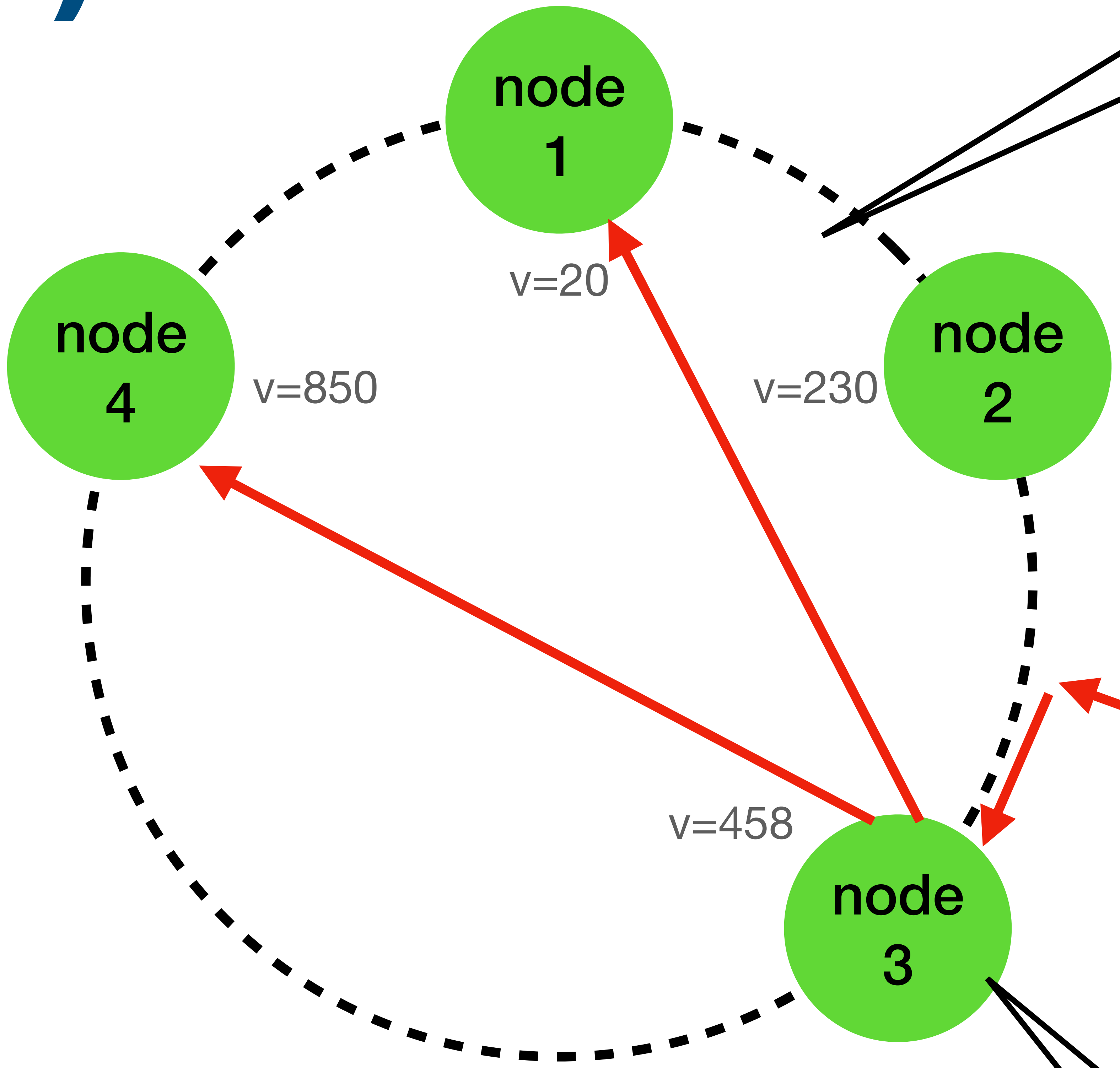

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A “preference list” can contain more than N nodes in order to handle “fail nodes”. For example, if node4 fails, that value will be stored on node3, node1 and node2

Replication (2)

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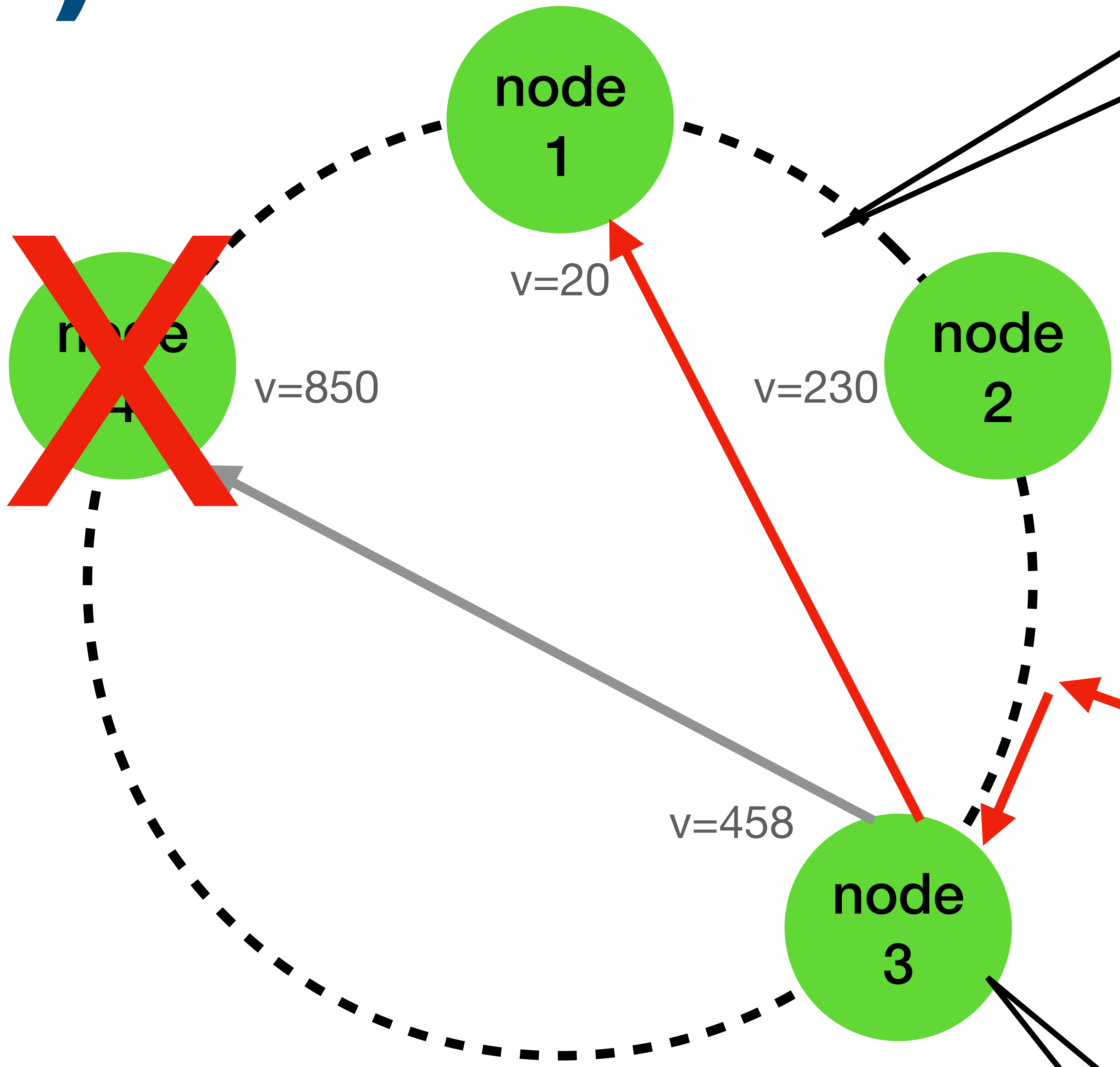

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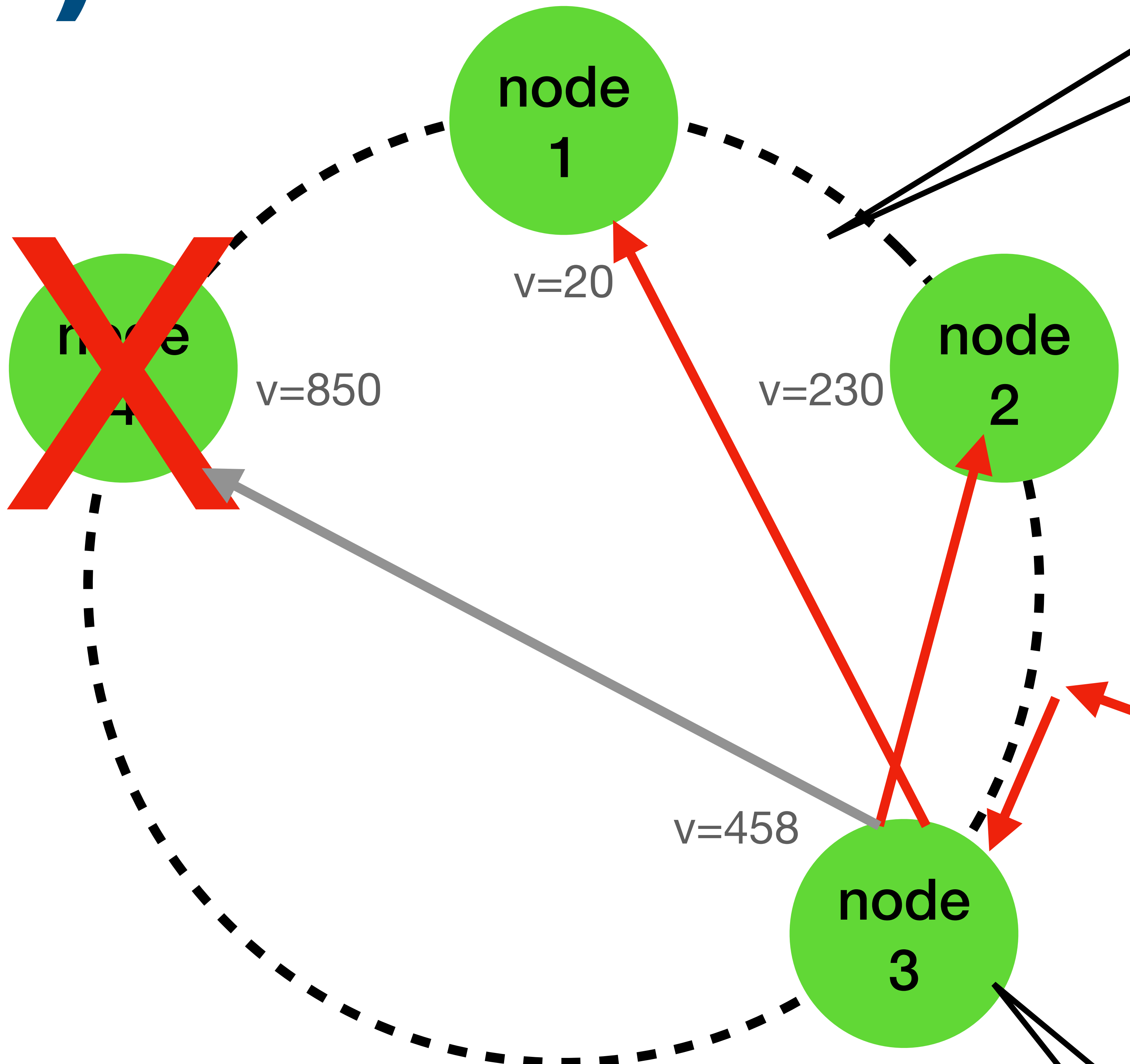

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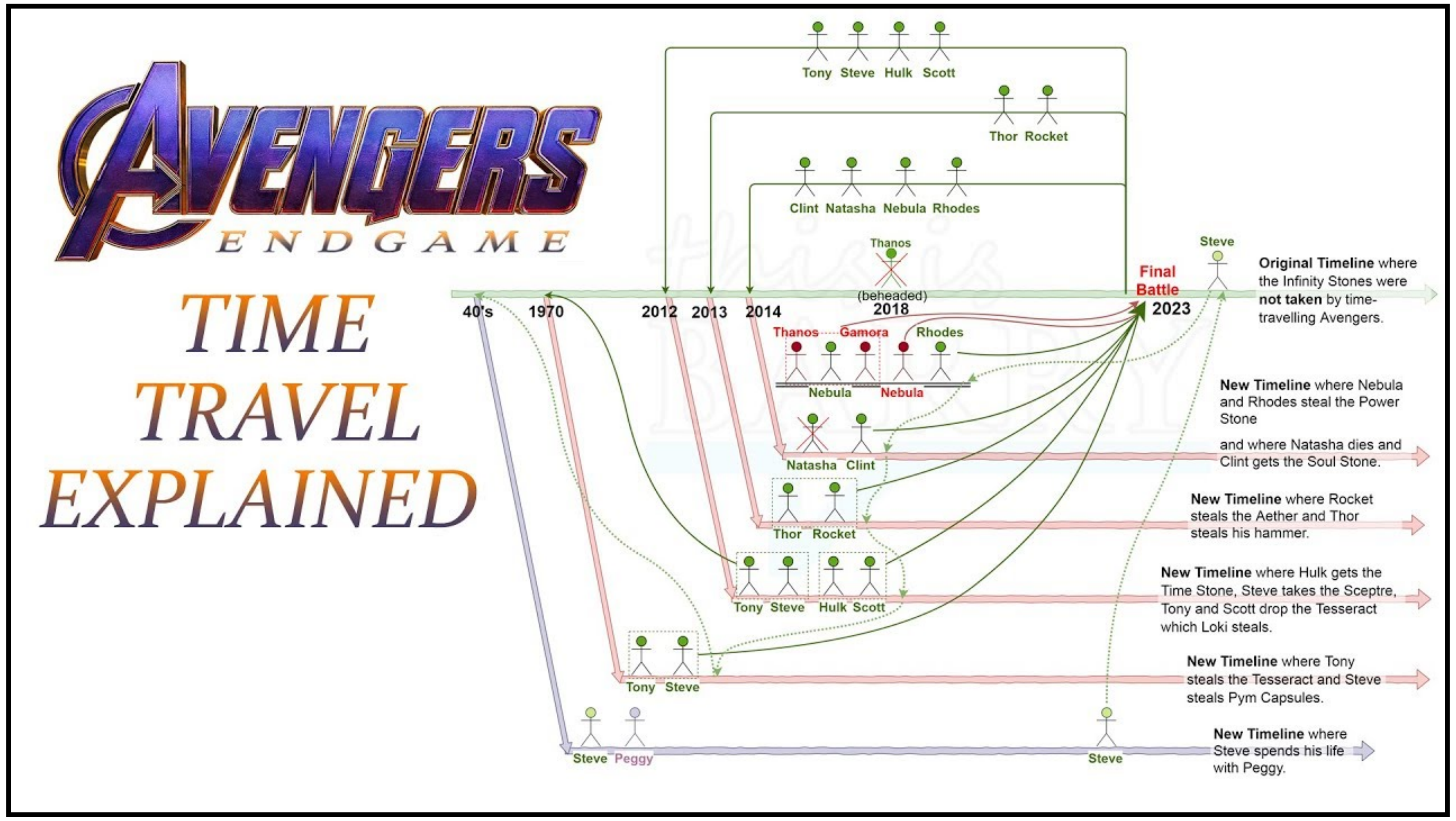
Data versioning



Original Timeline where the Infinity Stones were **not taken** by time-travelling Avengers.

New Timeline where Nebula and Rhodes steal the Power Stone

and where Natasha dies and Clint gets the Soul Stone.

New Timeline where Rocket steals the Aether and Thor steals his hammer.

New Timeline where Hulk gets the Time Stone, Steve takes the Sceptre, Tony and Scott drop the Tesseract which Loki steals.

New Timeline where Tony steals the Tesseract and Steve steals Pym Capsules.

New Timeline where Steve spends his life with Peggy.

https://www.youtube.com/watch?v=kn2IoDzI8L0

Reminder: Requirements: Interface

- `put(key, context, object)`
- `get(key)`
  - `context` = system metadata / versioning (opaque to the user)
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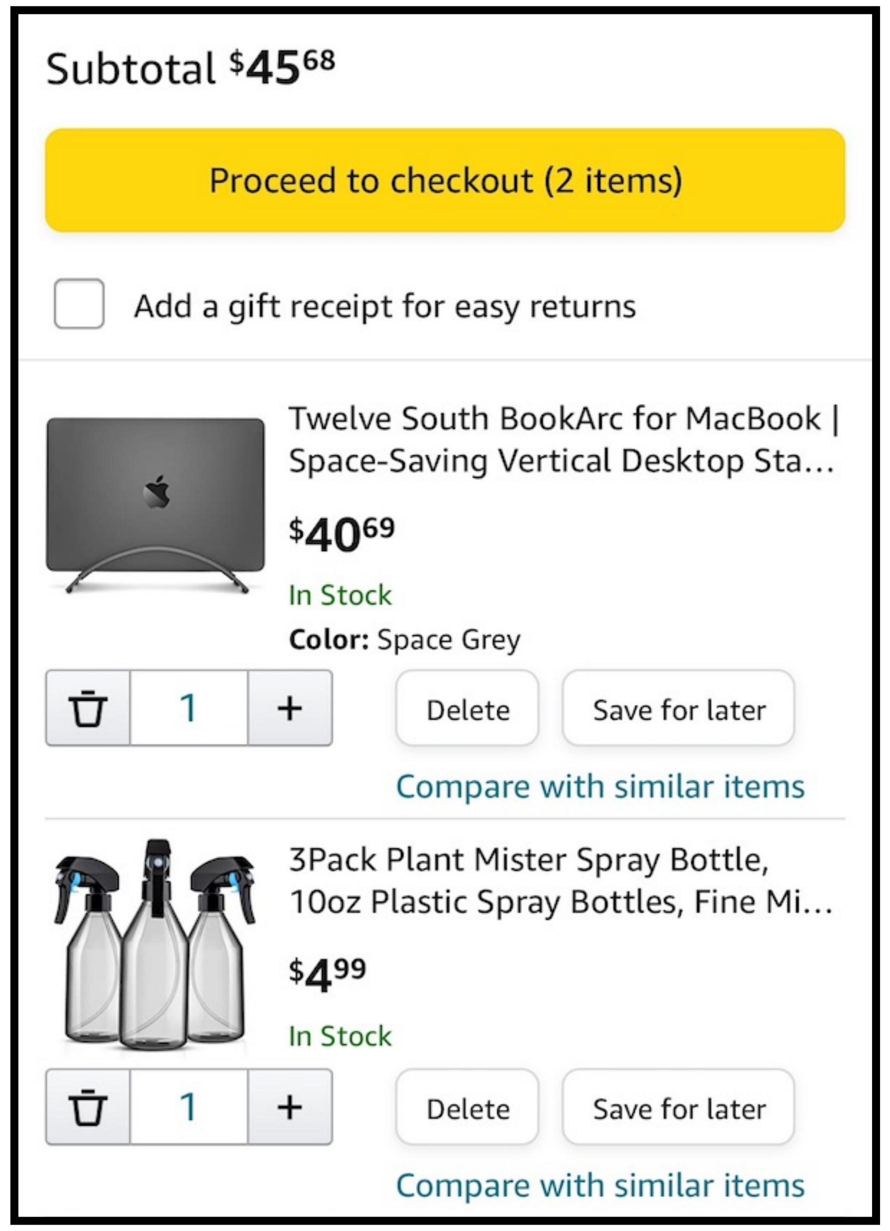
    * we will later see when can we have multi versions

Data versioning (1)

- Dynamo provides “Eventual consistency”
- A `put()` may returned before updating all replicas
- A subsequent `get()` may return not latest value
- If no node fails, there is a bound on the propagation time
- **On node failures,** it may take a while, and the problems begins

Data versioning (2) - motivation

- Apps that can tolerate some “inconsistencies”
  for example, shopping cart
- **“Add to cart” should never fails**
- If previous value is unavailable, we should still be able to add a new item
  and **“merge”** the “old” cart once available
- Both add/delete from cart are translated to `put()`
  each update is a new immutable version of the data
- On conflicts, the client app “reconcile” by a merge
  this guarantees that an added item is never lost
  but deleted items can resurface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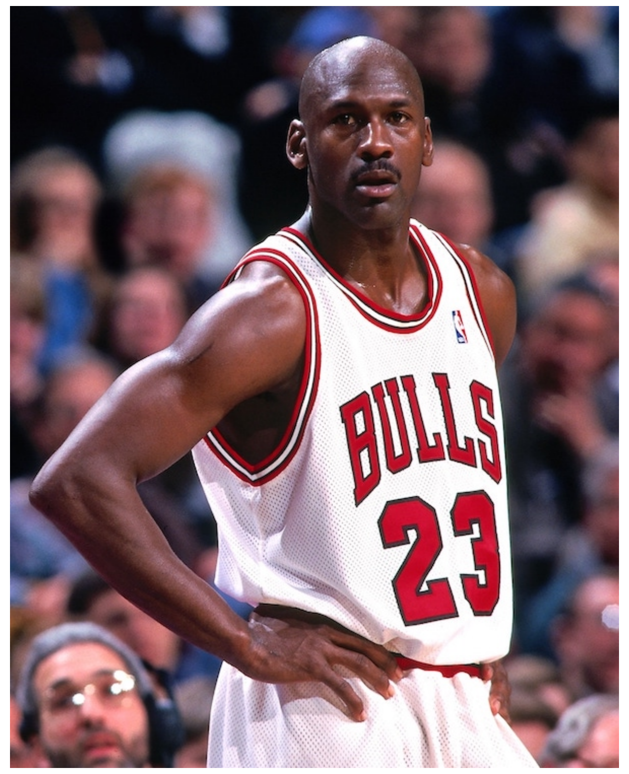
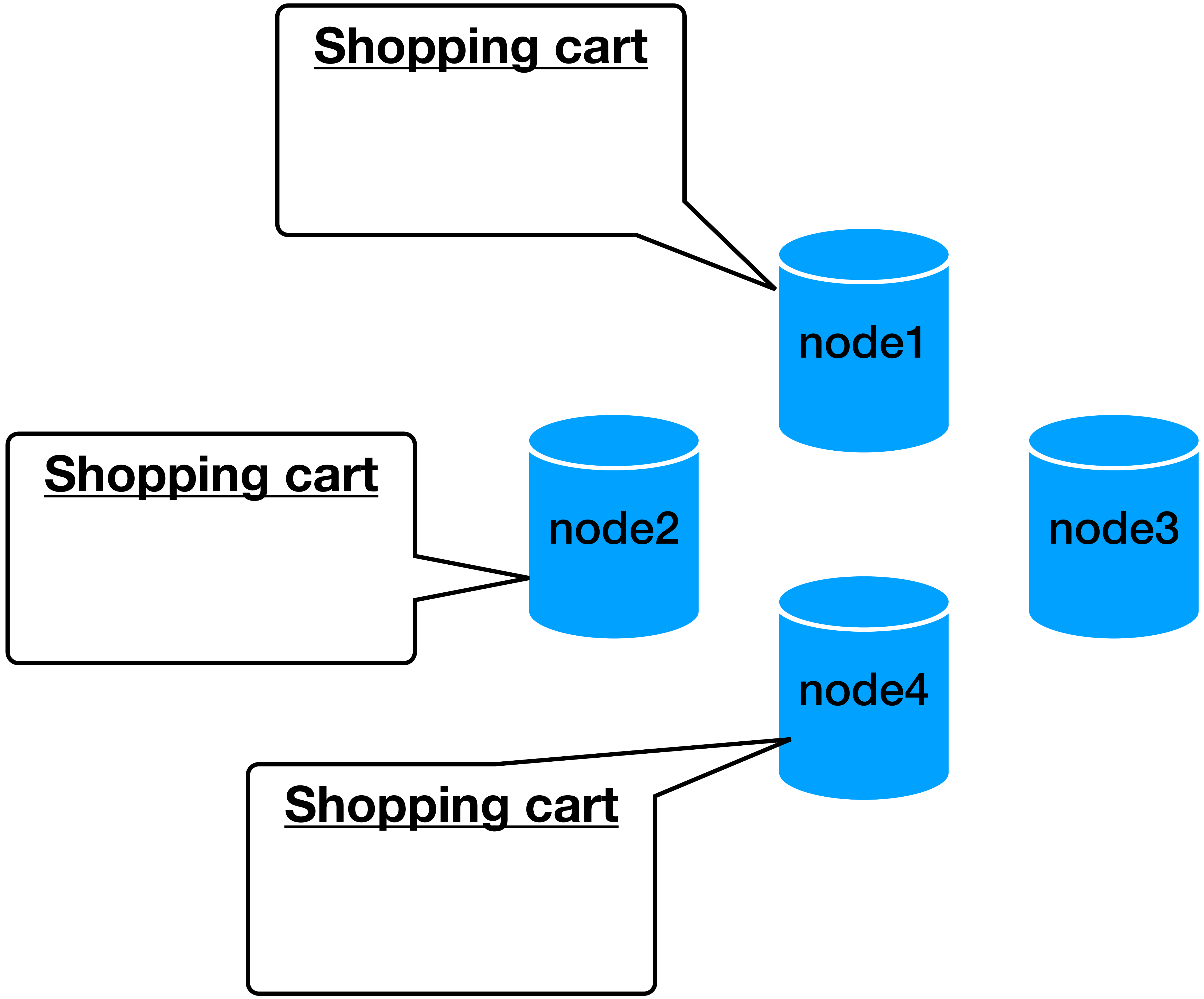
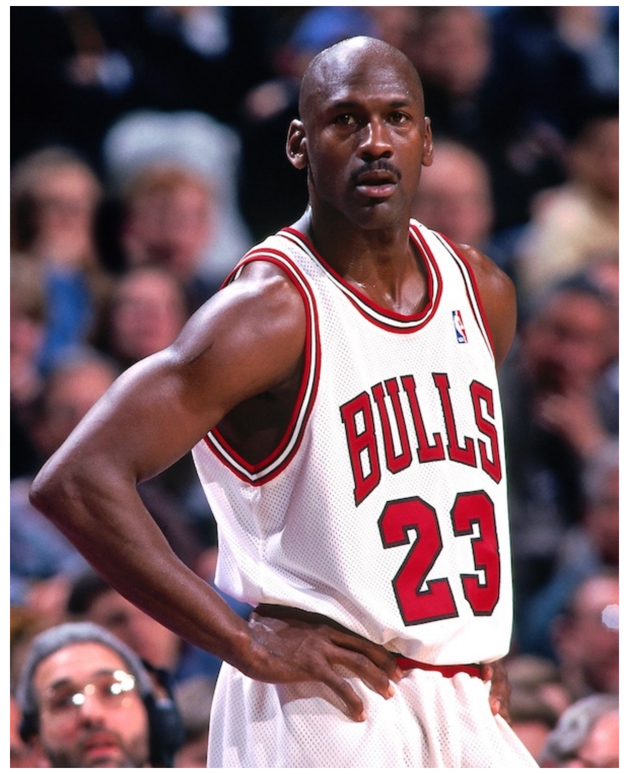
Data versioning (2) - motivation example



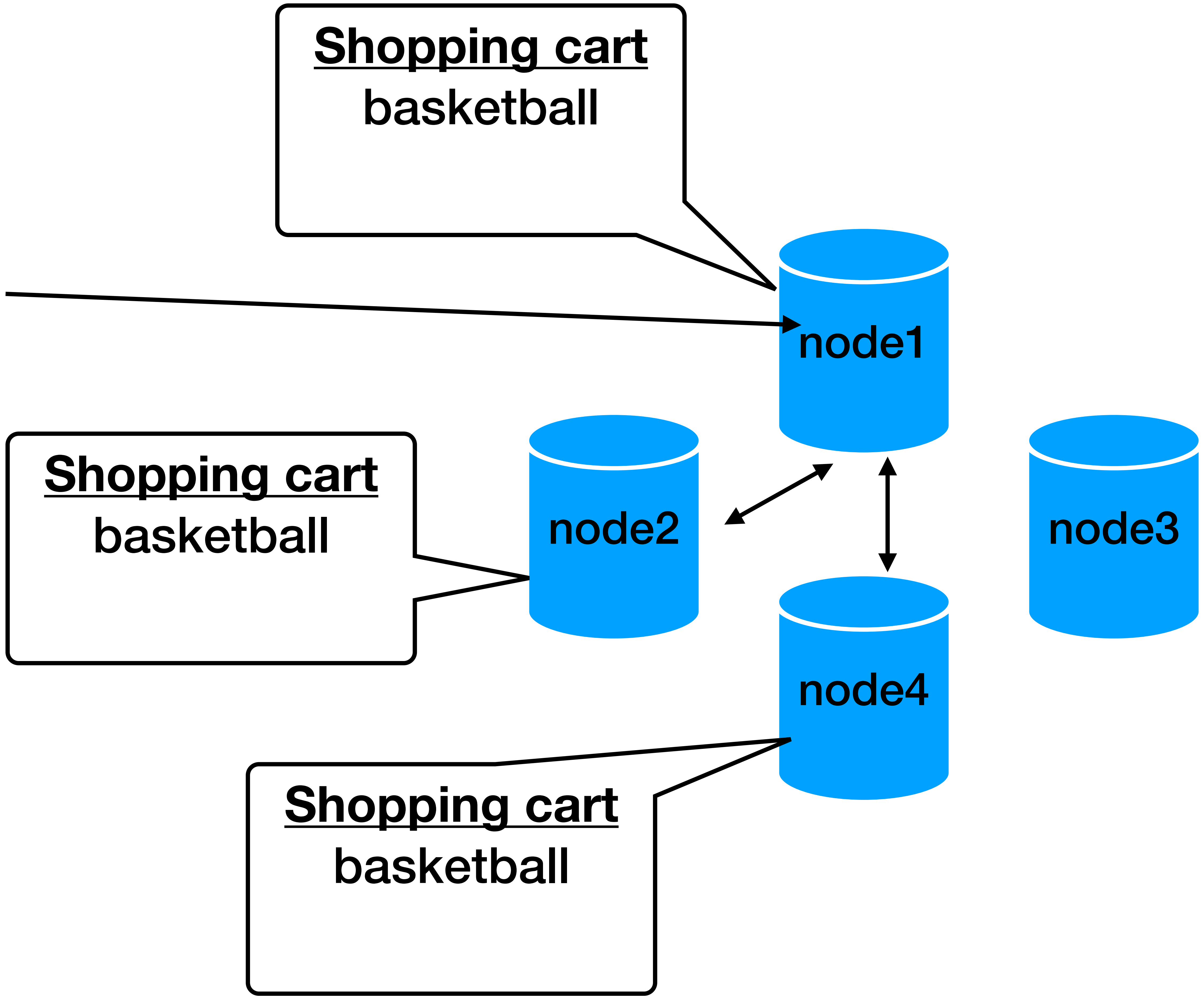
10:00: empty cart



Data versioning (2) - motivation example



10:00: empty cart
10:01: added basketball

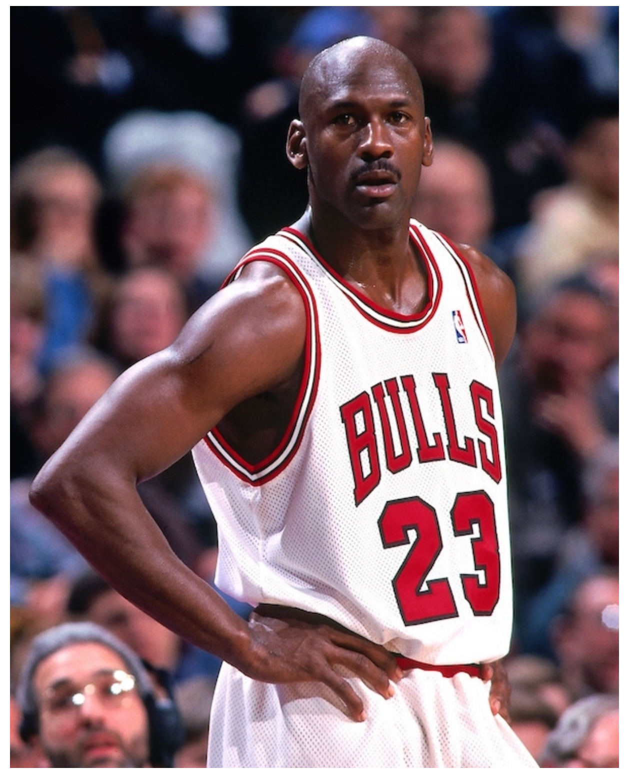


Shopping cart
basketball

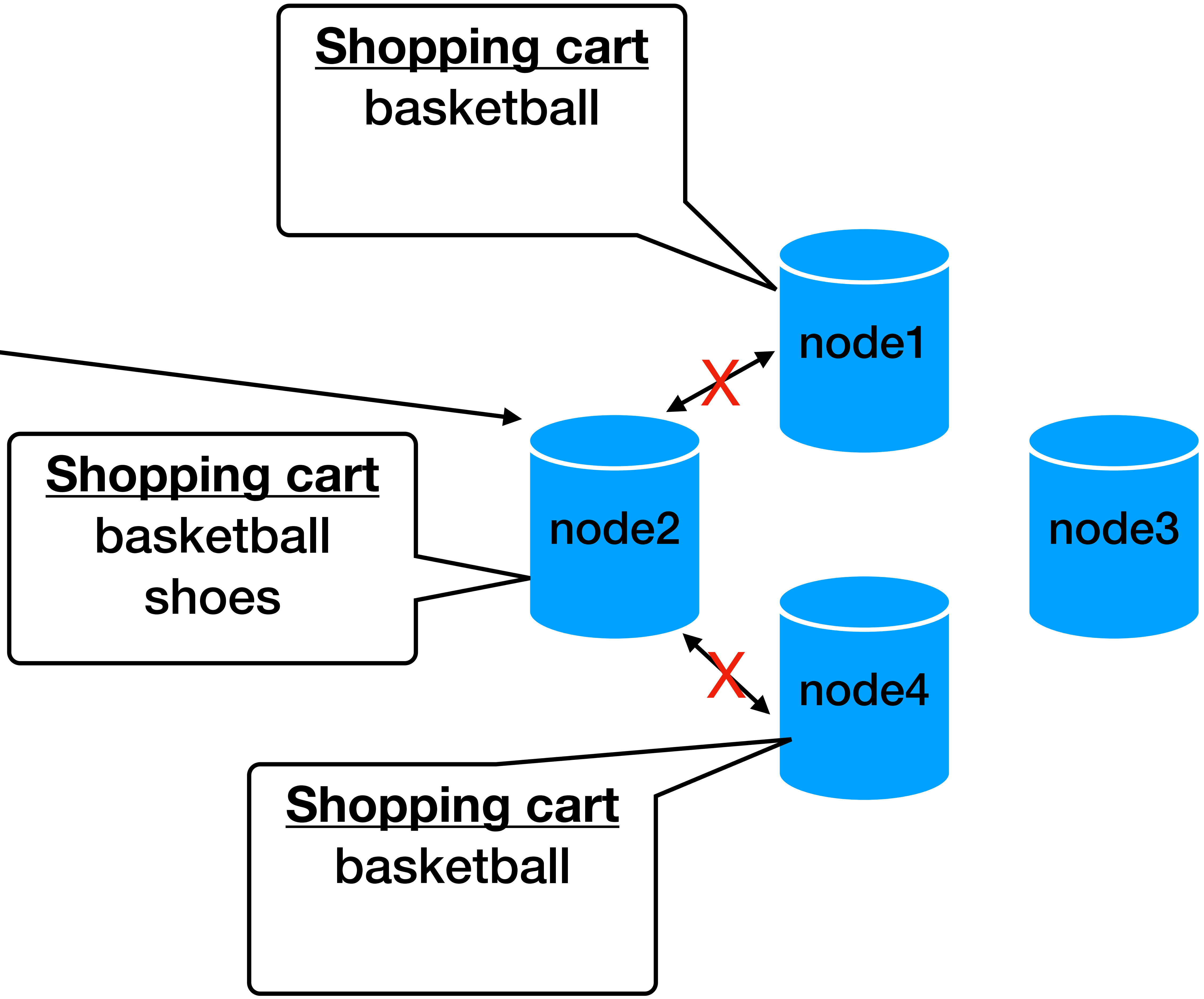
Shopping cart
basketball

Shopping cart
basketball

Data versioning (2) - motivation example



10:00: empty cart
10:01: added basketball
10:02: added shoes



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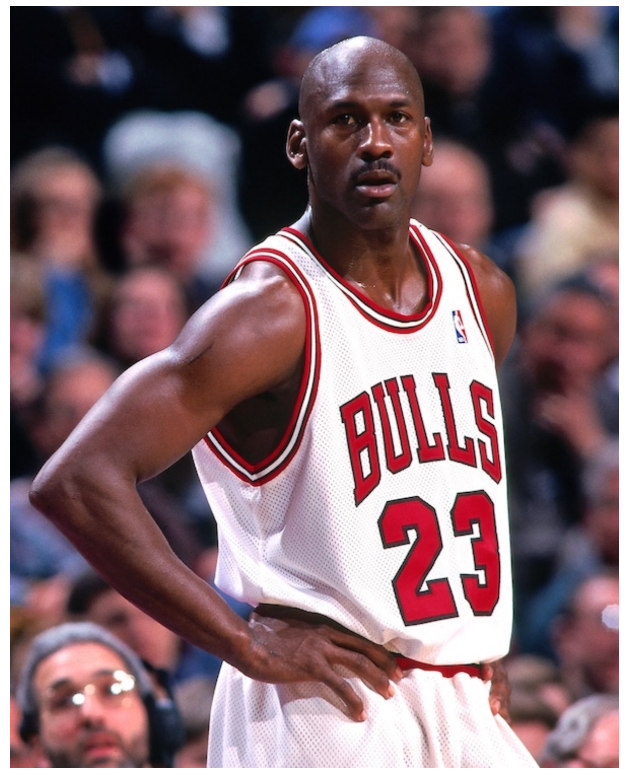
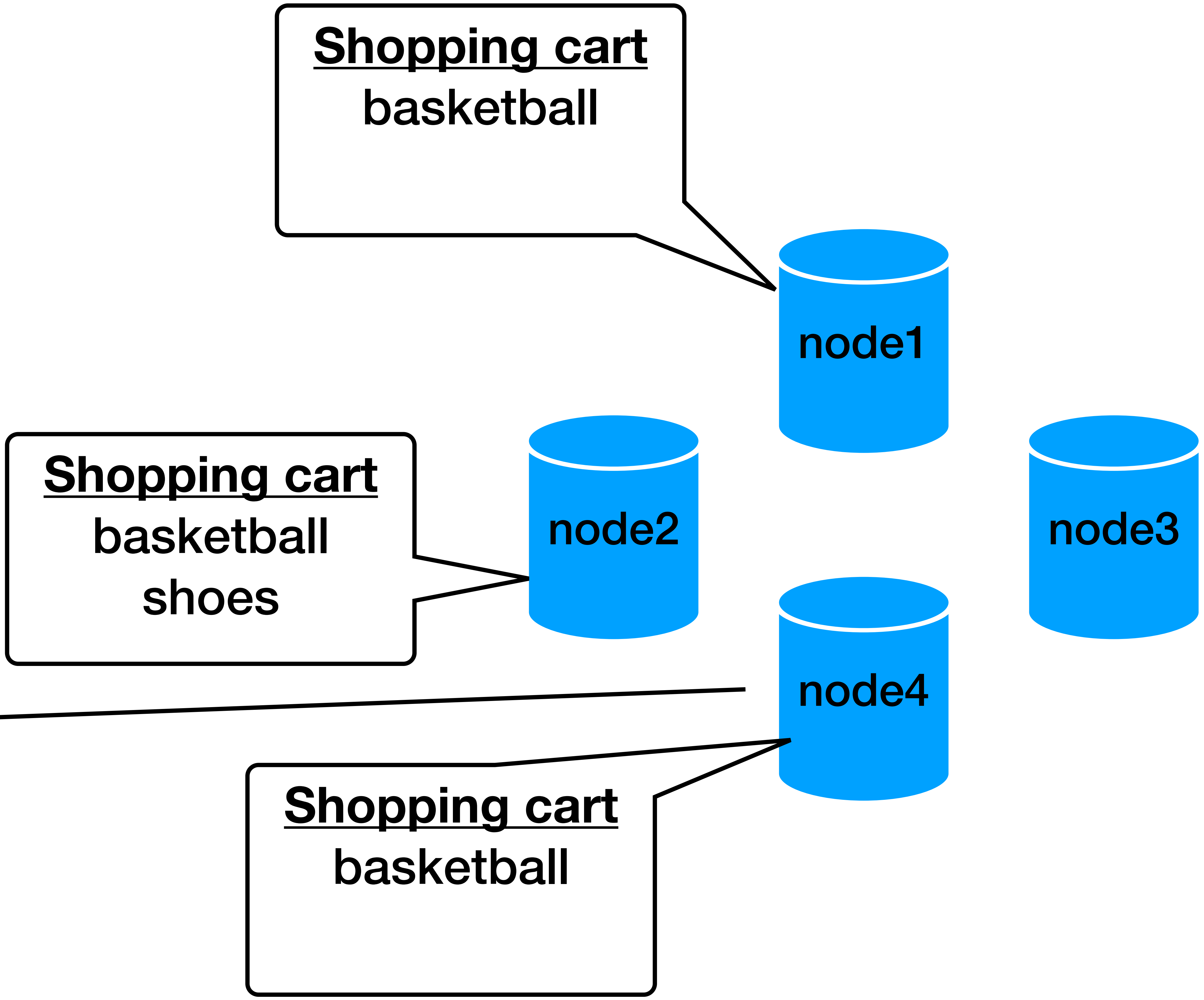


10:00: empty cart
10:01: added basketball
10:02: added shoes
10:03: reopen the app



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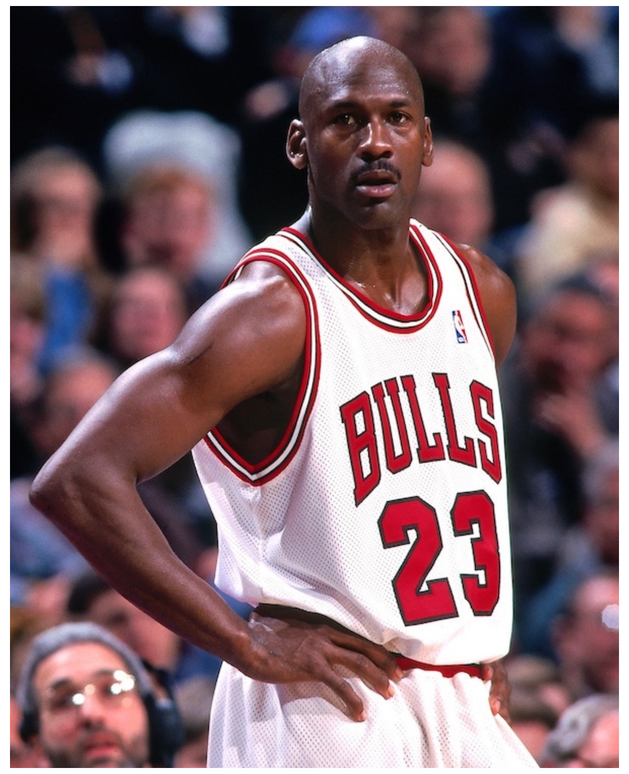
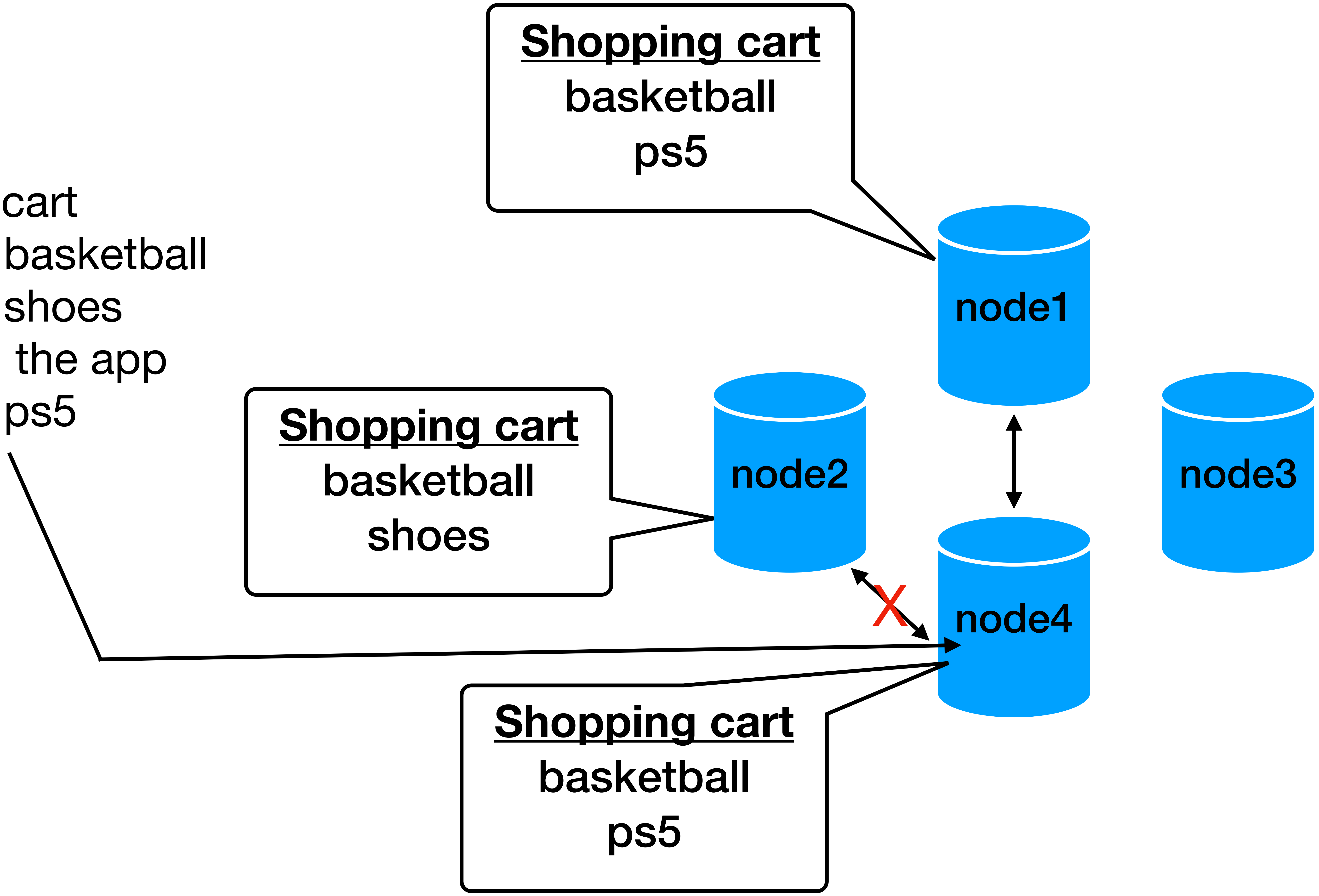


10:00: empty cart
10:01: added basketball
10:02: added shoes
10:03: reopen the app
10:04: added ps5

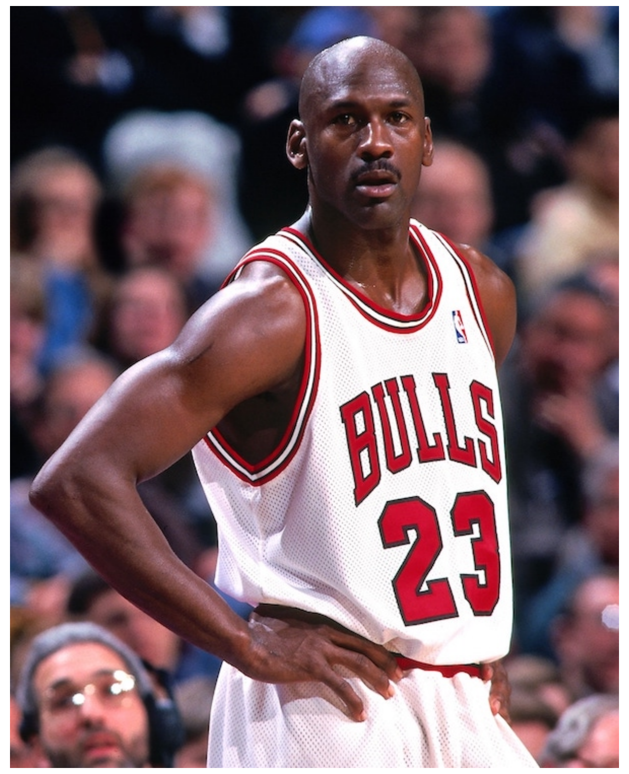


Shopping cart
basketball
ps5

Shopping cart
basketball
shoes

Shopping cart
basketball
ps5

Data versioning (2) - motivation example



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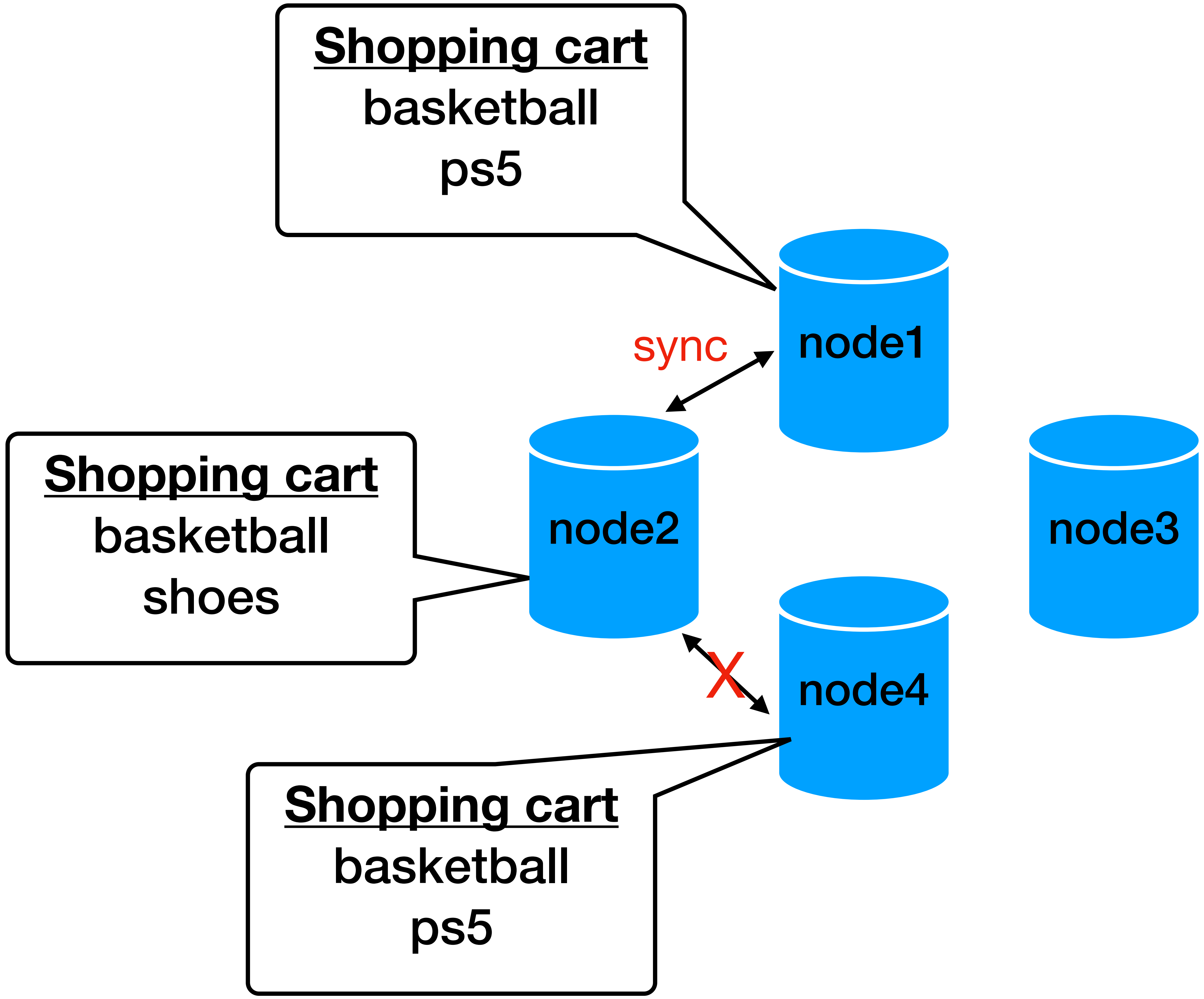
10:04: added ps5



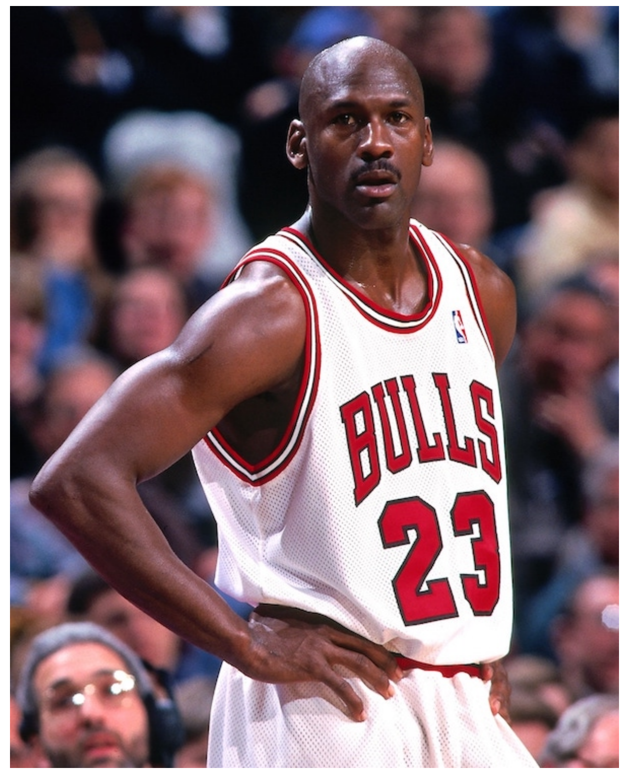
Shopping cart
basketball
ps5

sync

Shopping cart
basketball
shoes

Shopping cart
basketball
ps5

Data versioning (2) - motivation example



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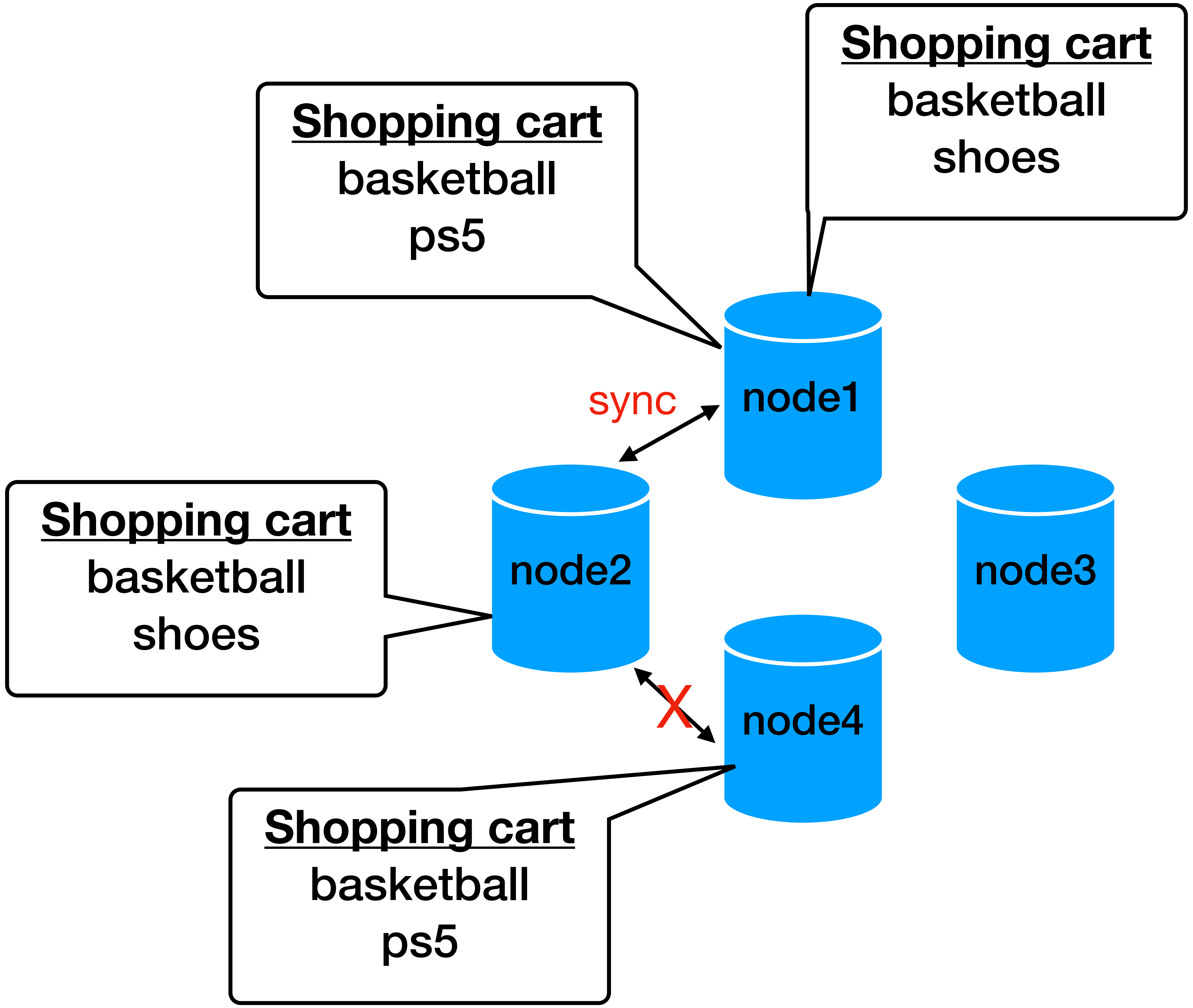

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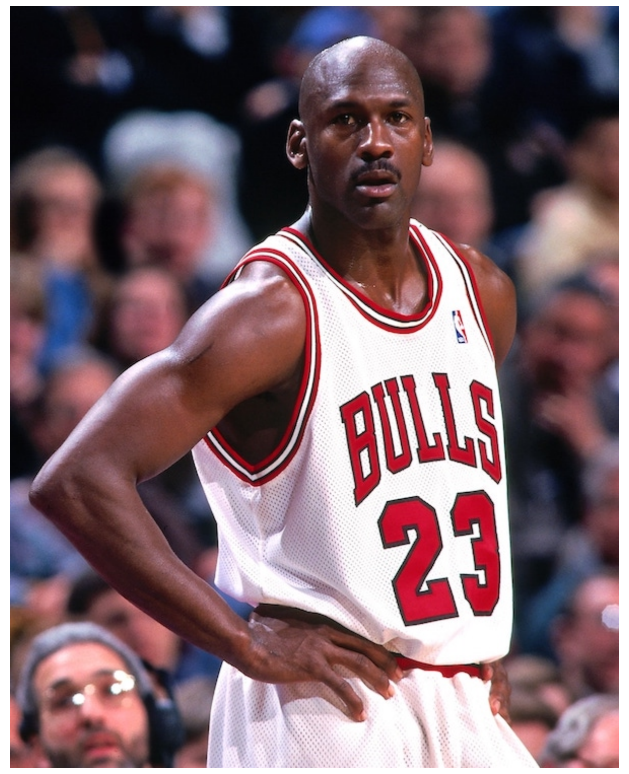

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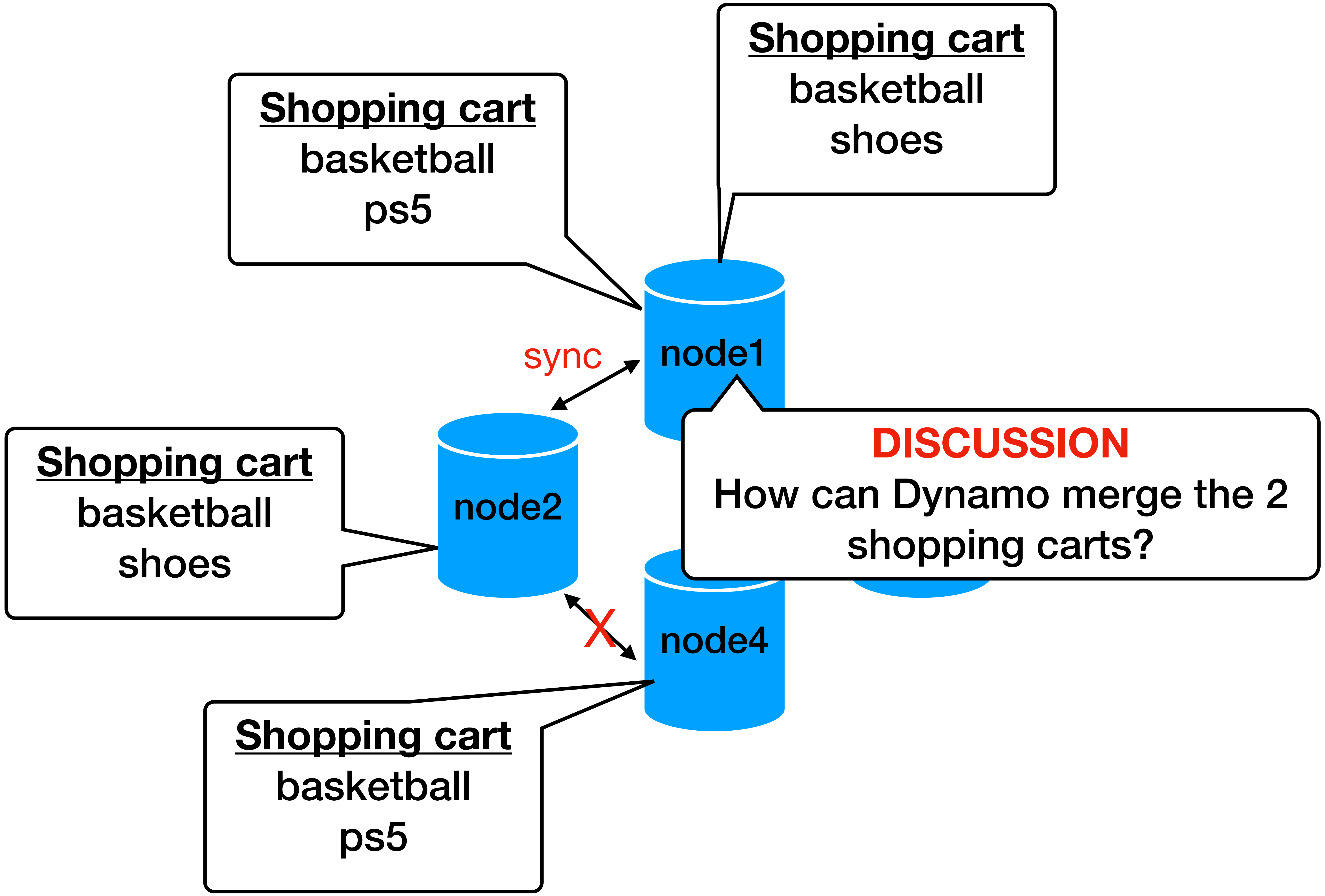


Shopping cart
basketball
ps5

Shopping cart
basketball
shoes

sync

node1

node2

Shopping cart
basketball
shoes

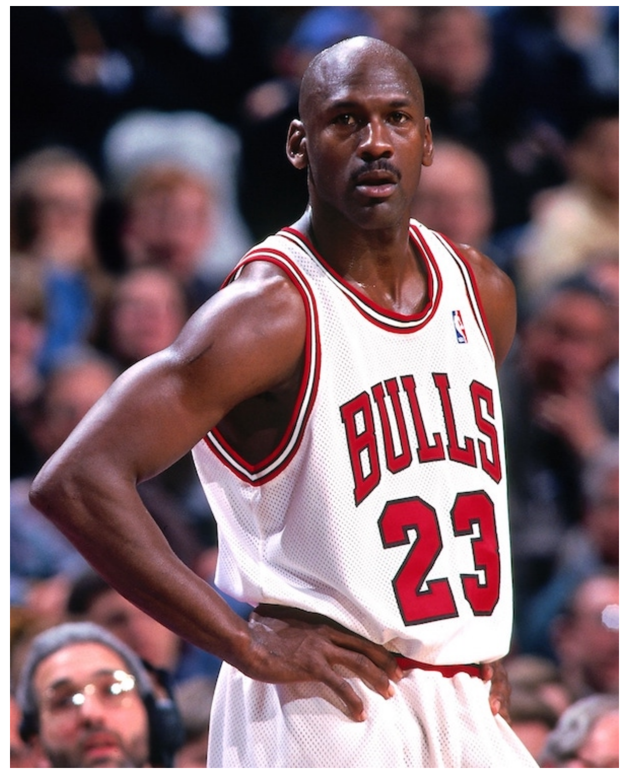
X

node4

Shopping cart
basketball
ps5

DISCUSSION
How can Dynamo merge the 2 shopping carts?

Data versioning (2) - motivation example



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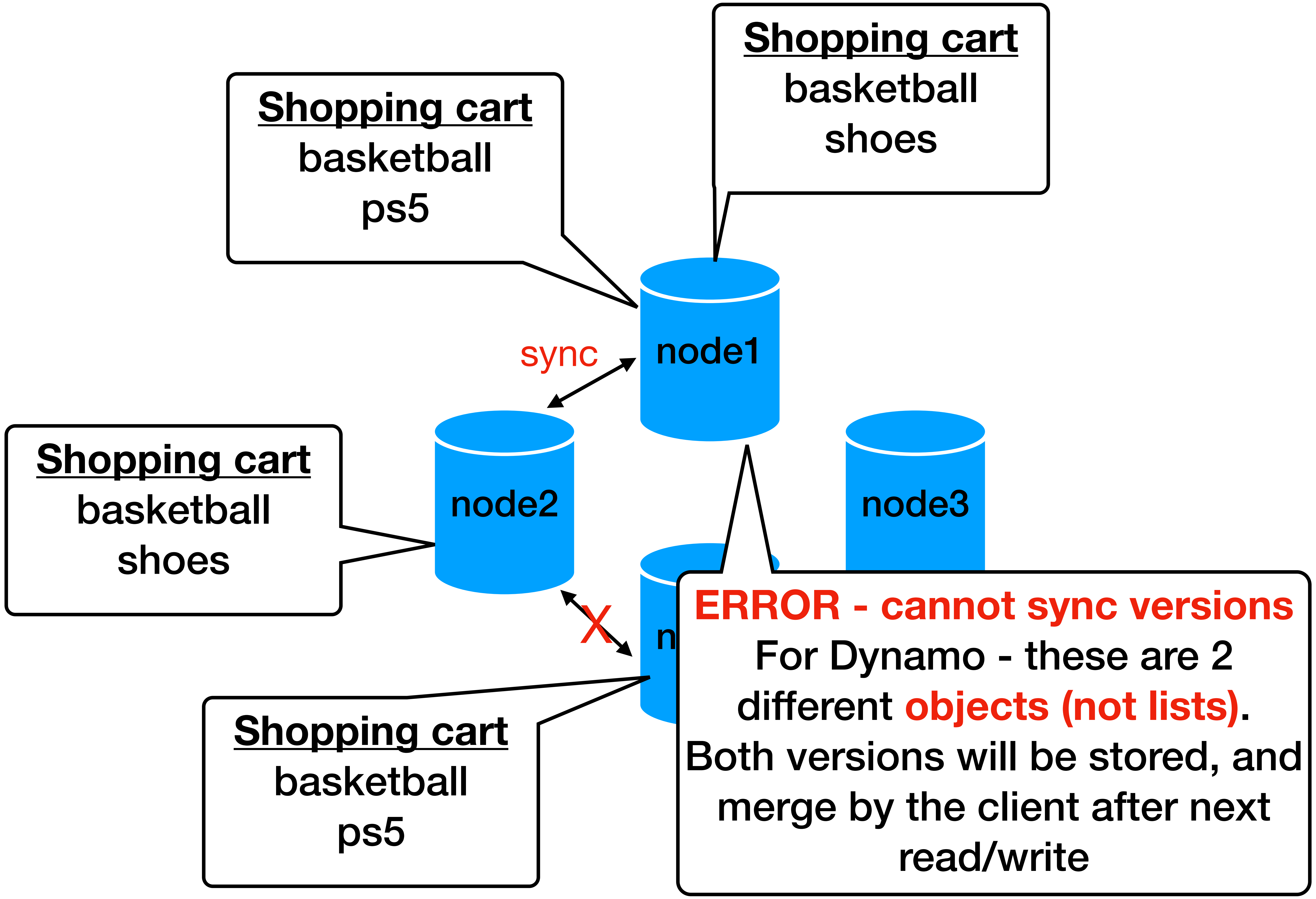


Shopping cart
basketball
ps5

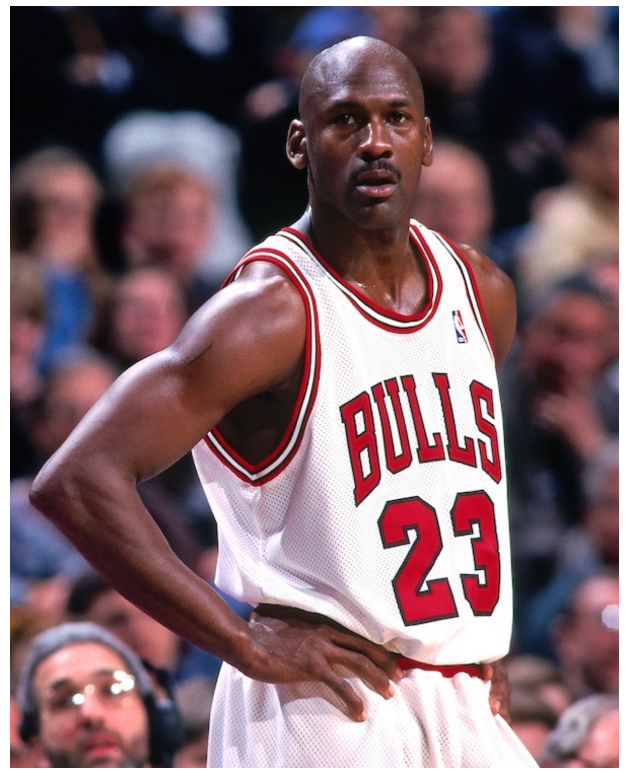
Shopping cart
basketball
shoes

Shopping cart
basketball
shoes

Shopping cart
basketball
ps5

ERROR - cannot sync versions
For Dynamo - these are 2 different **objects (not lists)**.
Both versions will be stored, and merge by the client after next read/write

Data versioning (2) - motivation example



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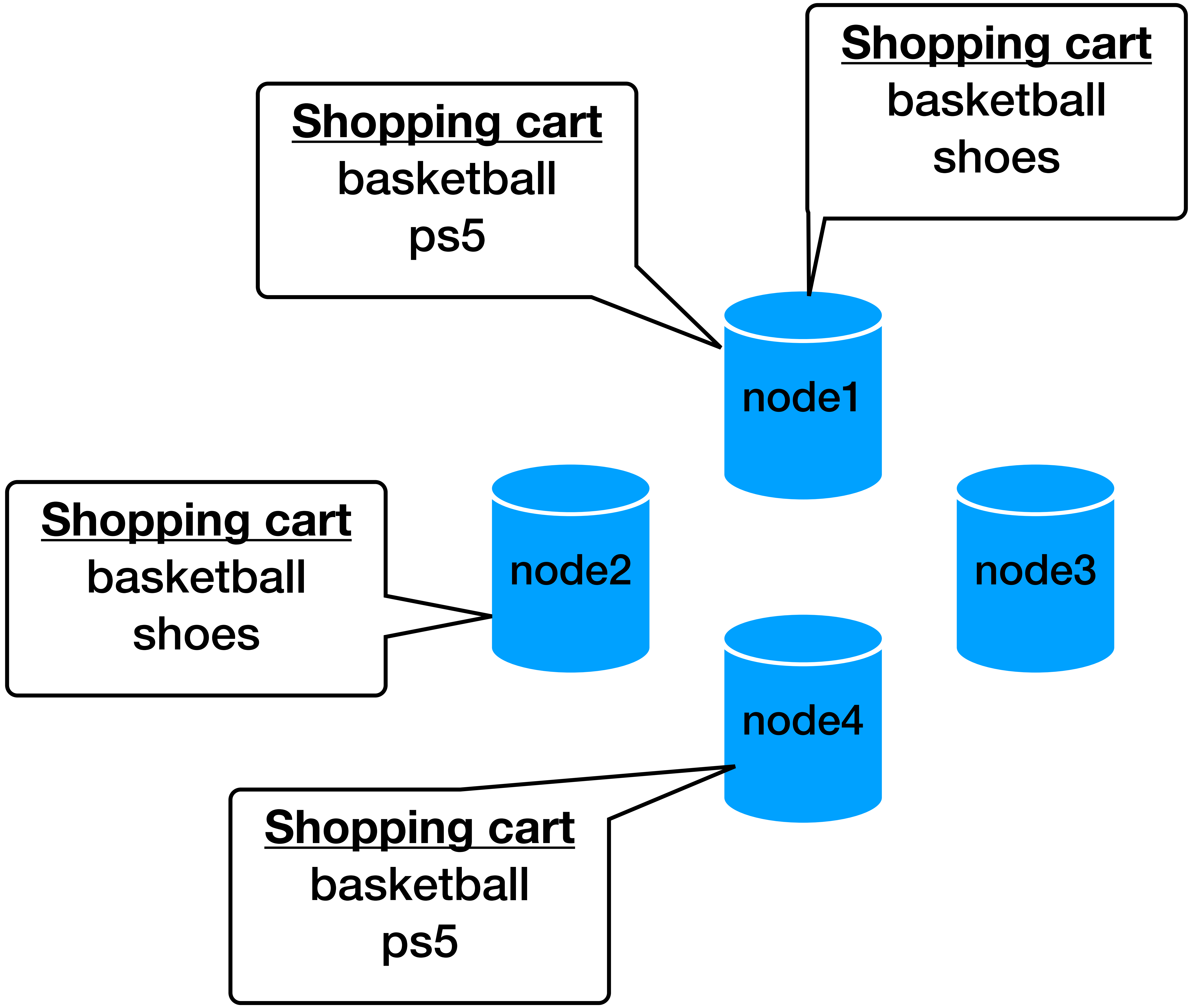


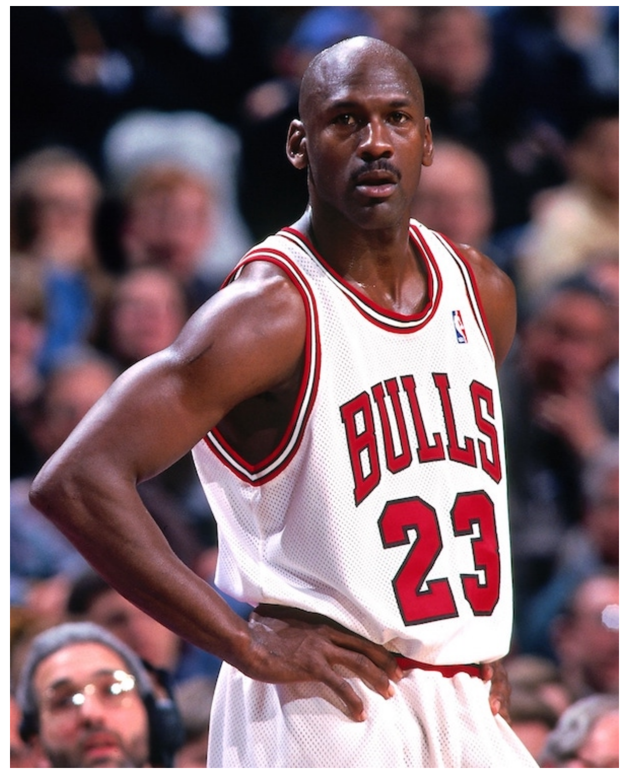
Shopping cart
basketball
shoes

Shopping cart
basketball
ps5

Shopping cart
basketball
shoes

Shopping cart
basketball
ps5

Data versioning (2) - motivation example



10:00: empty cart
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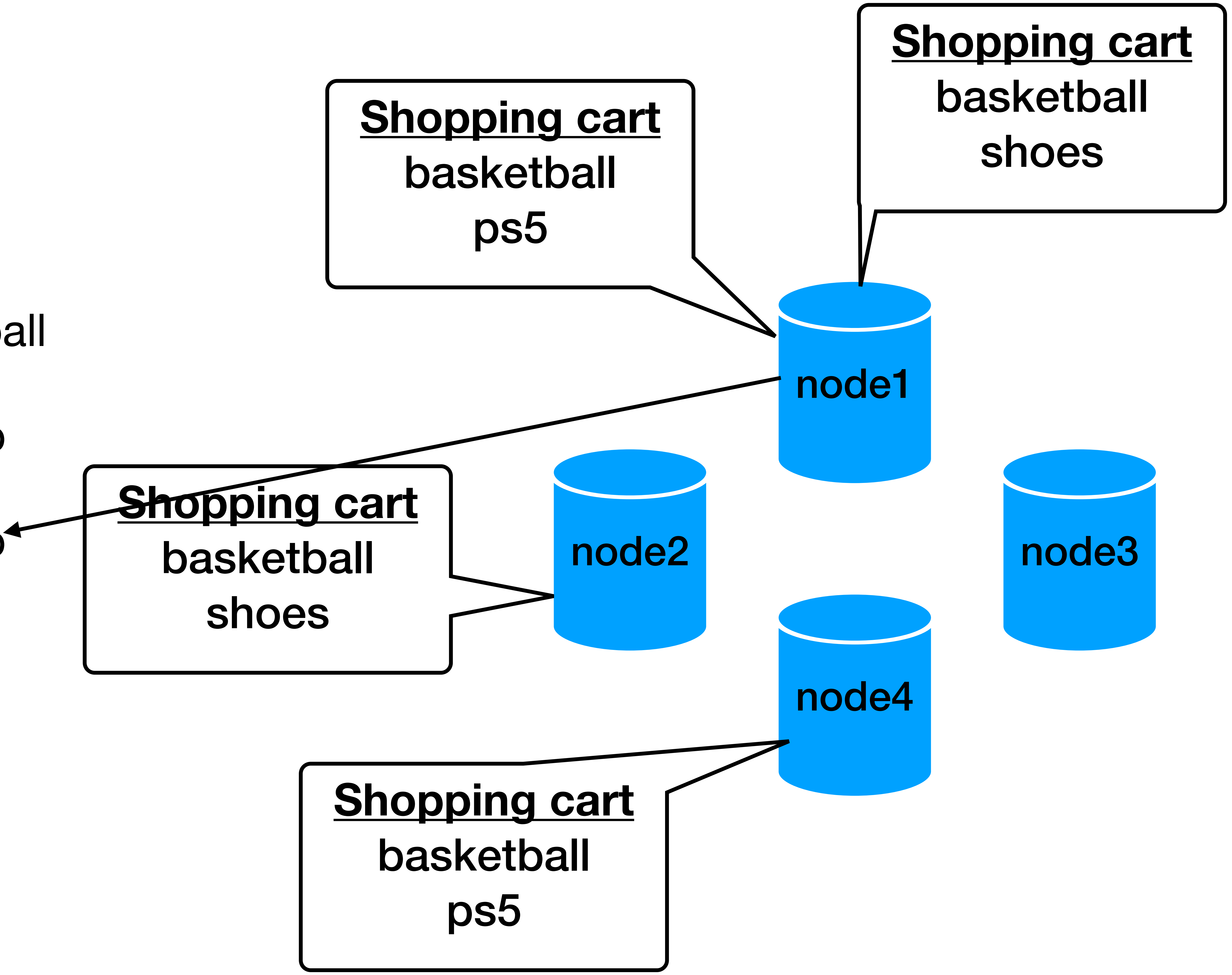
10:04: added ps5
10:06: reopen the app



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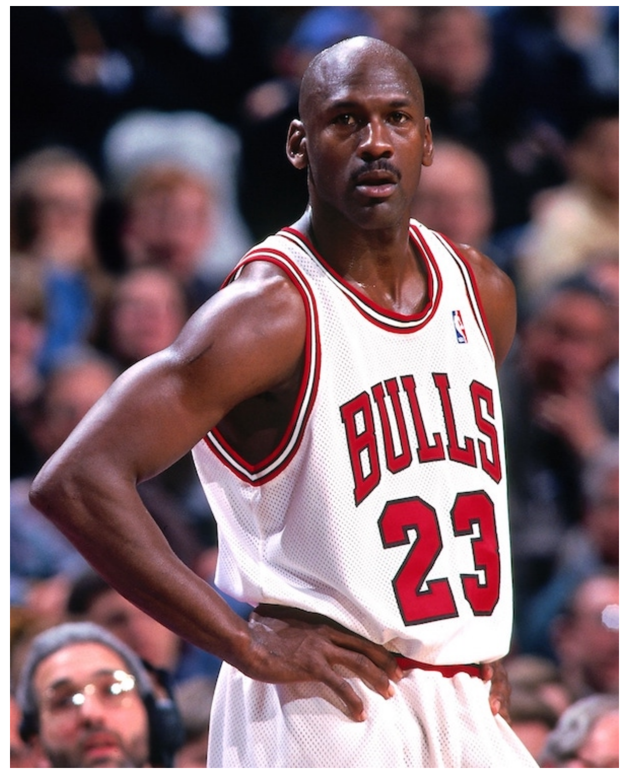

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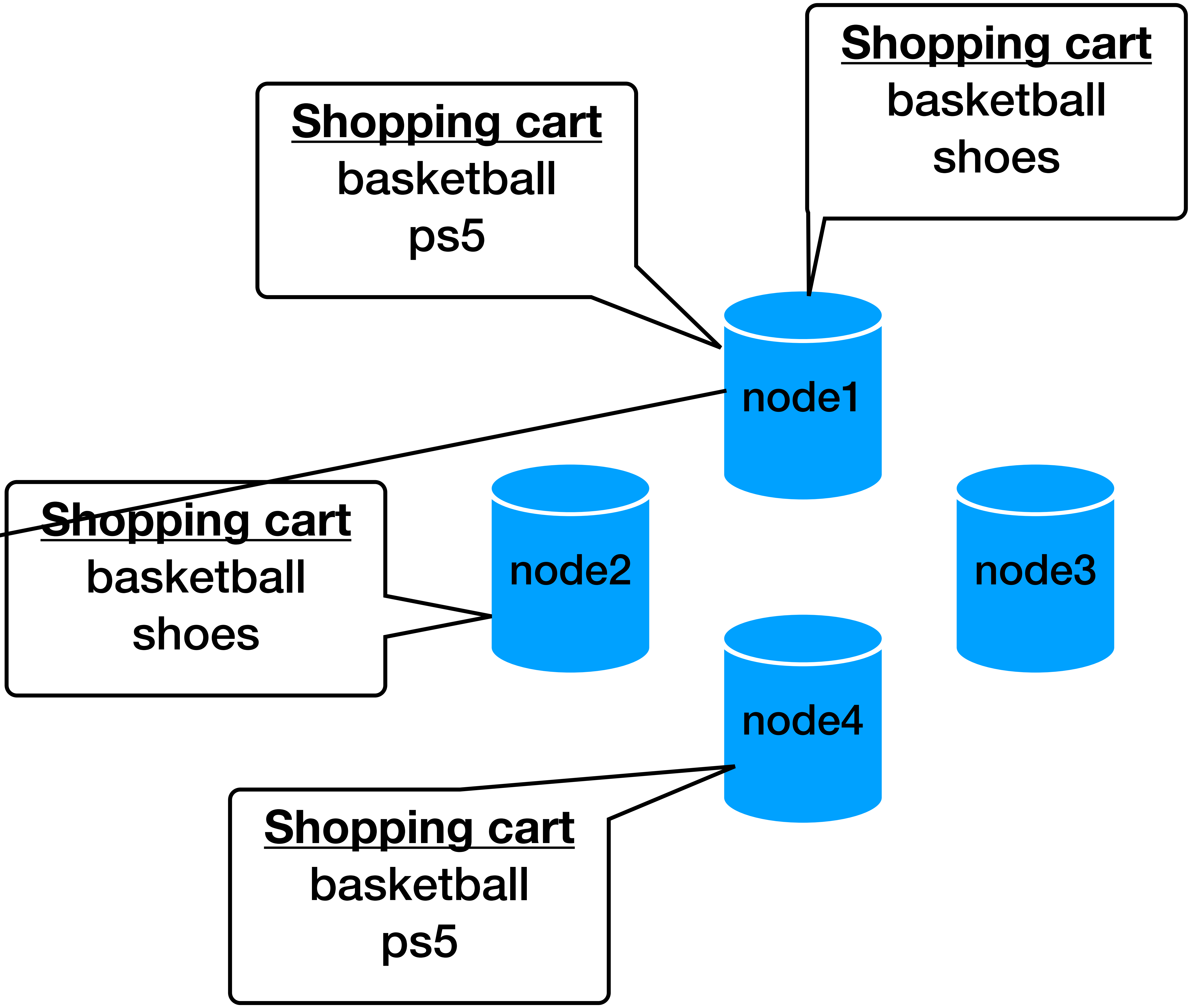
Shopping cart
basketball
ps5

Shopping cart
basketball
shoes

Shopping cart
basketball
shoes
ps5



Shopping cart
basketball
ps5

Shopping cart
basketball
shoes

node1

Shopping cart
basketball
shoes

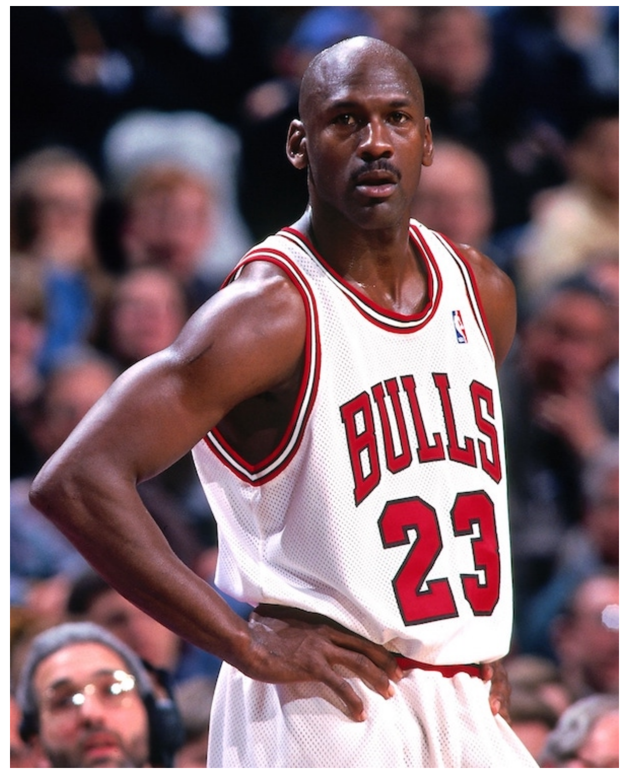
node2

node3

node4

Shopping cart
basketball
ps5

Data versioning (2) - motivation example



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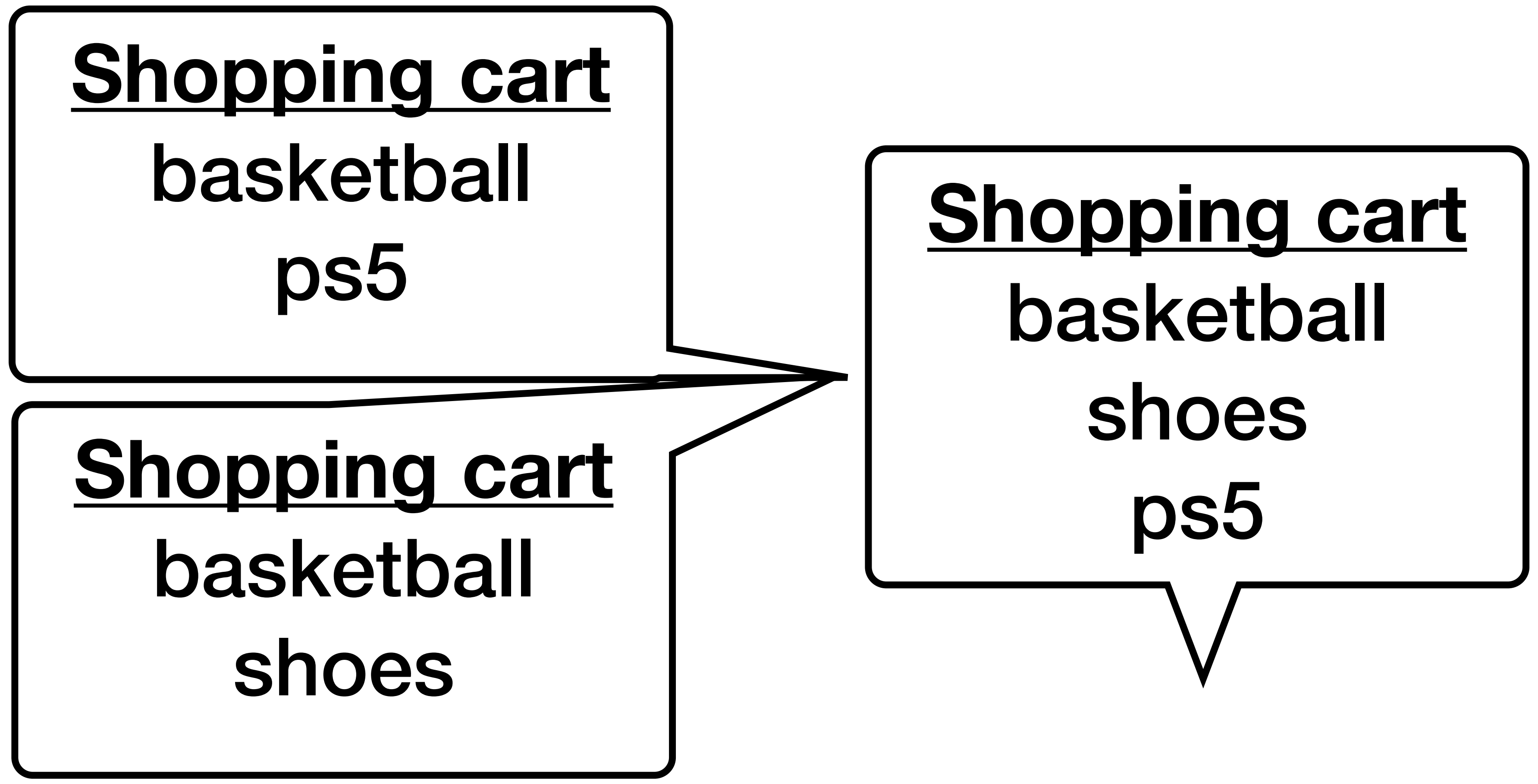
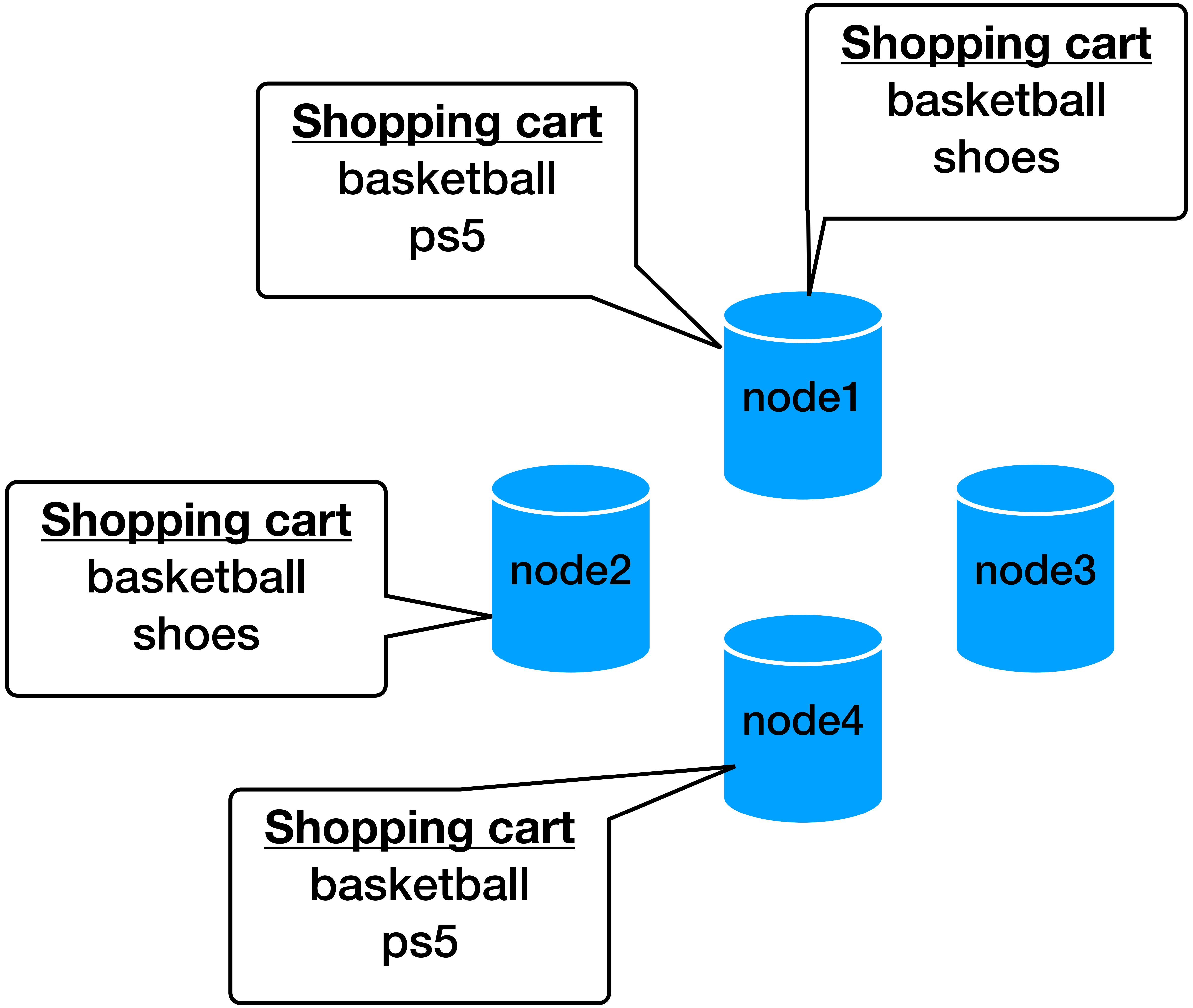
10:04: added ps5
10:06: reopen the app
10:07: delete basketball



Shopping cart
basketball
ps5

Shopping cart
basketball
shoes

Shopping cart
basketball
shoes
ps5



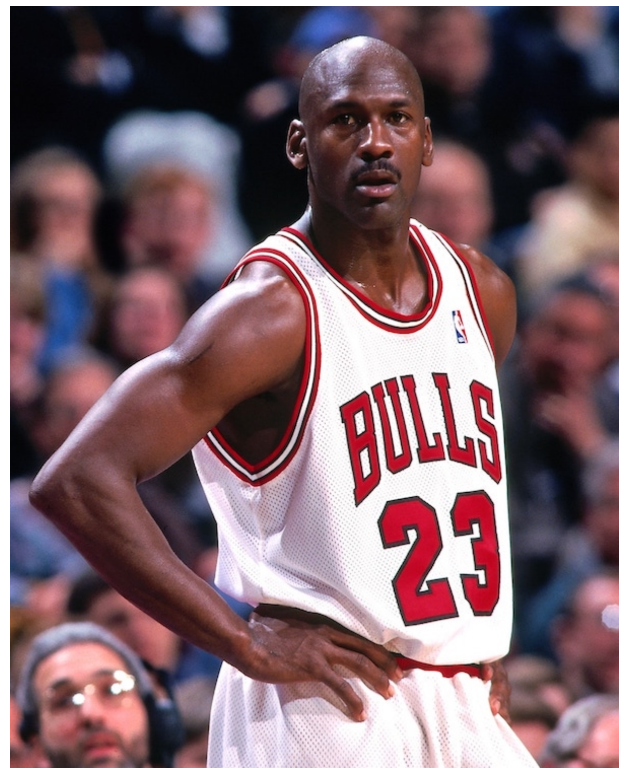
Shopping cart
basketball
ps5

Shopping cart
basketball
shoes

Shopping cart
basketball
shoes

Shopping cart
basketball
ps5

Data versioning (2) - motivation example



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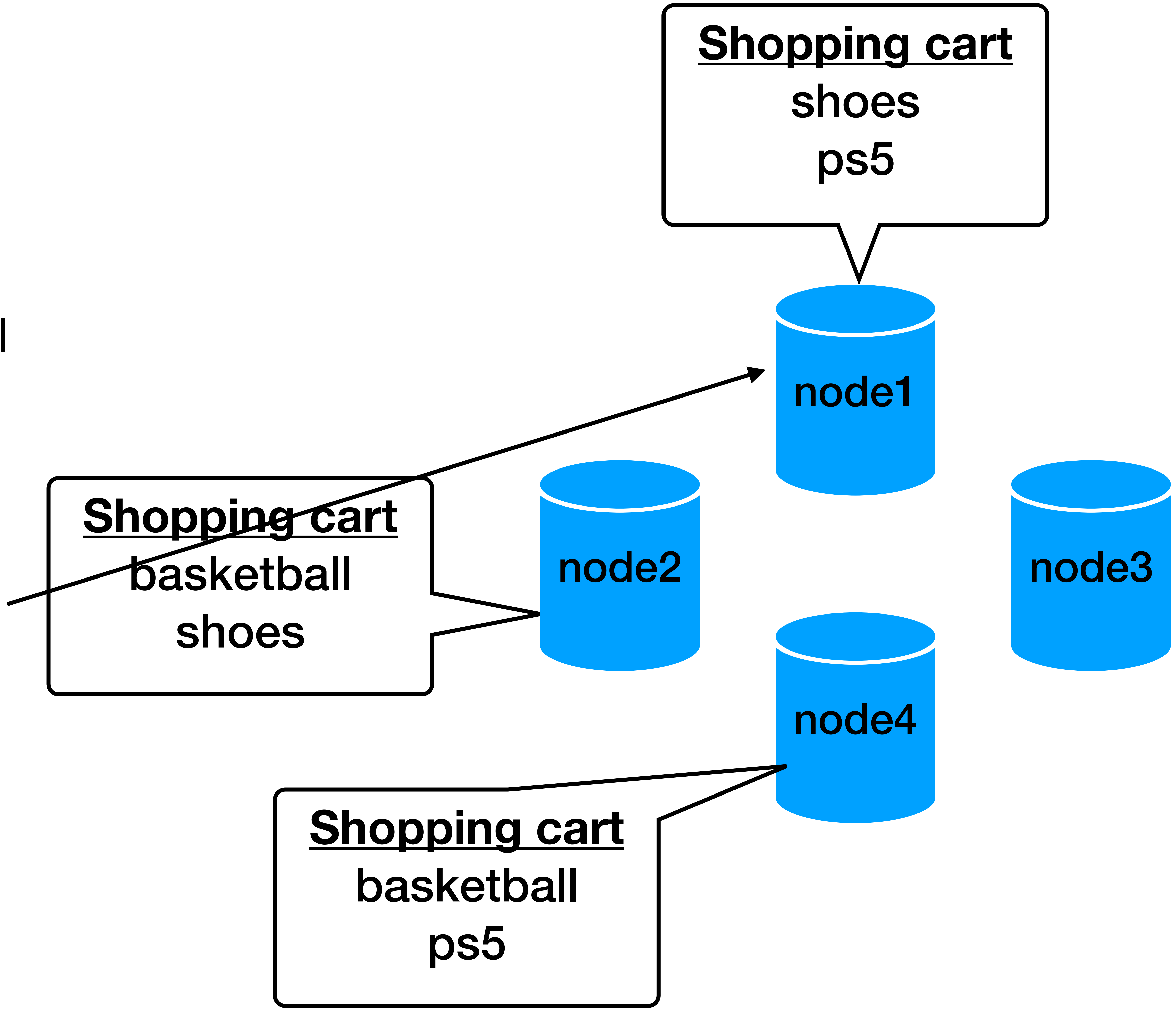
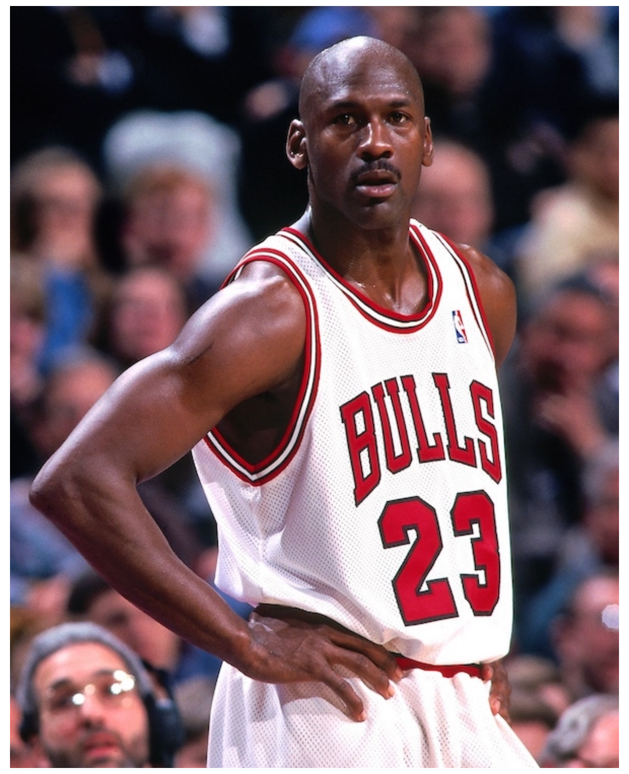


Data versioning (2) - motivation example



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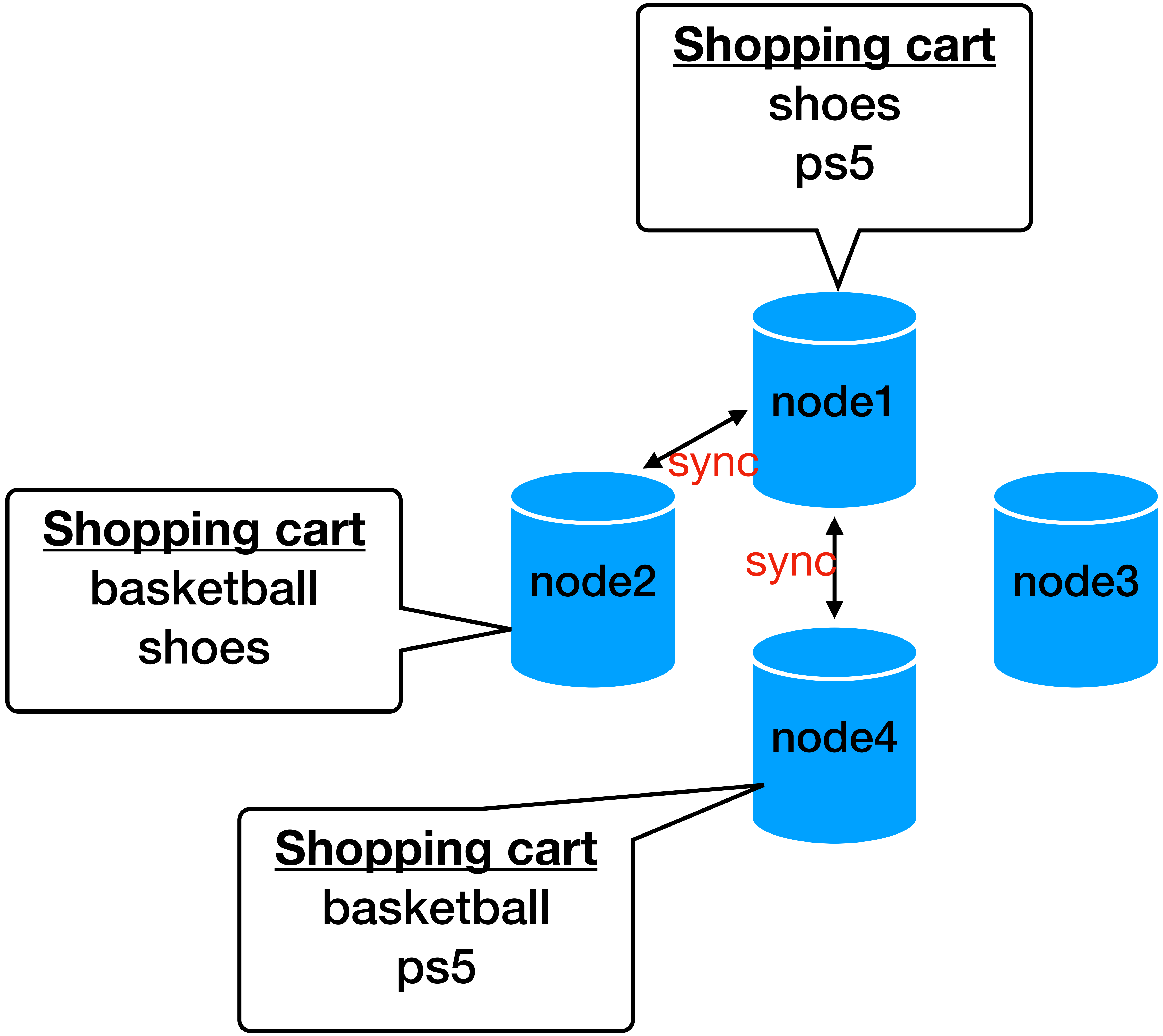
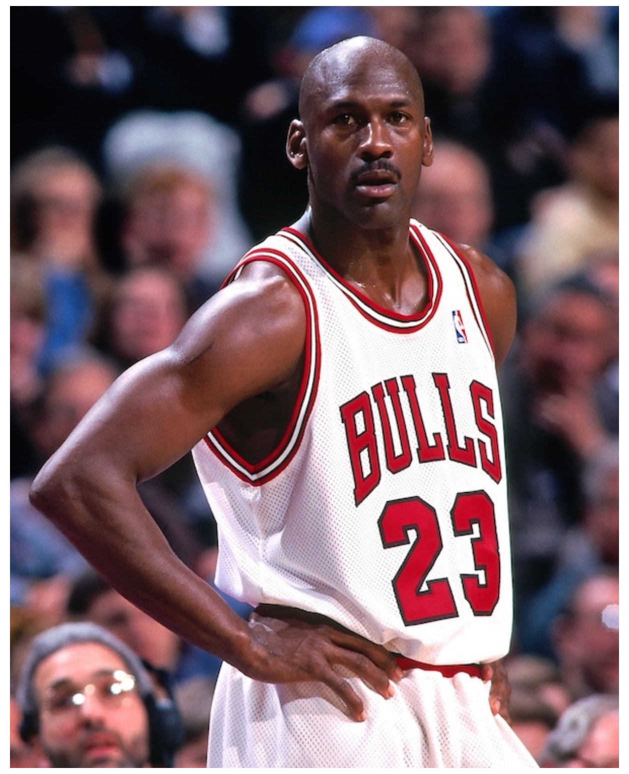


Data versioning (2) - motivation example



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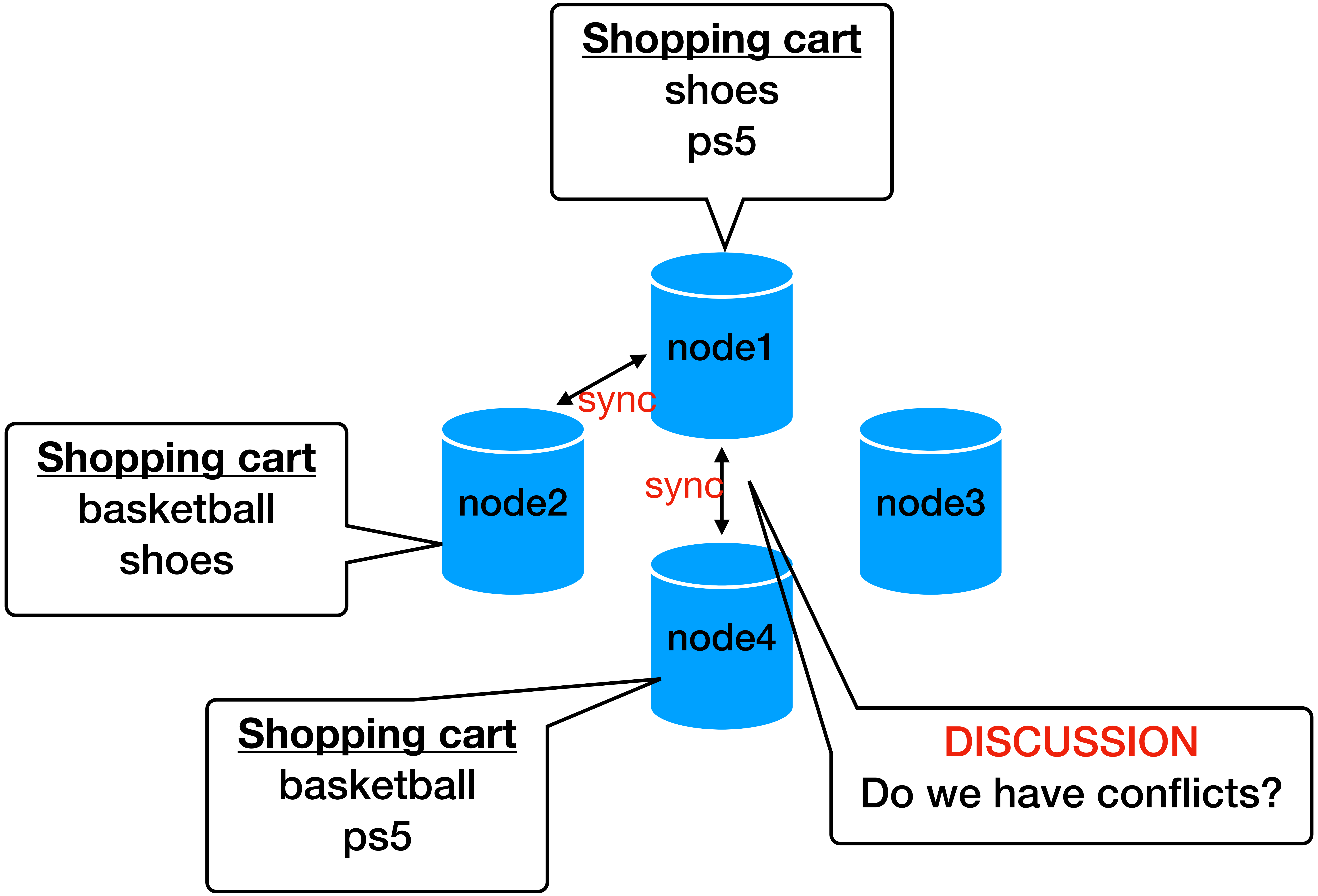


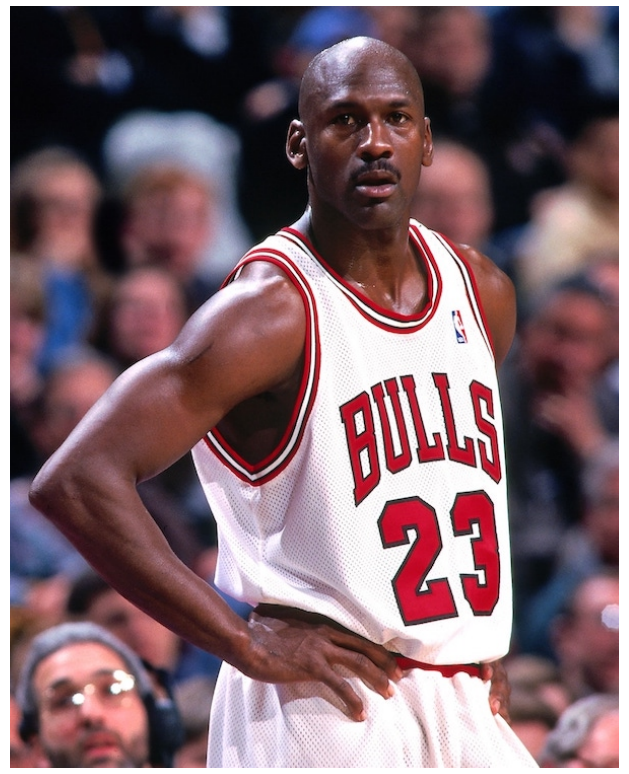
Shopping cart
shoes
ps5

Shopping cart
basketball
shoes

Shopping cart
basketball
ps5

DISCUSSION
Do we have conflicts?

Data versioning (2) - motivation example



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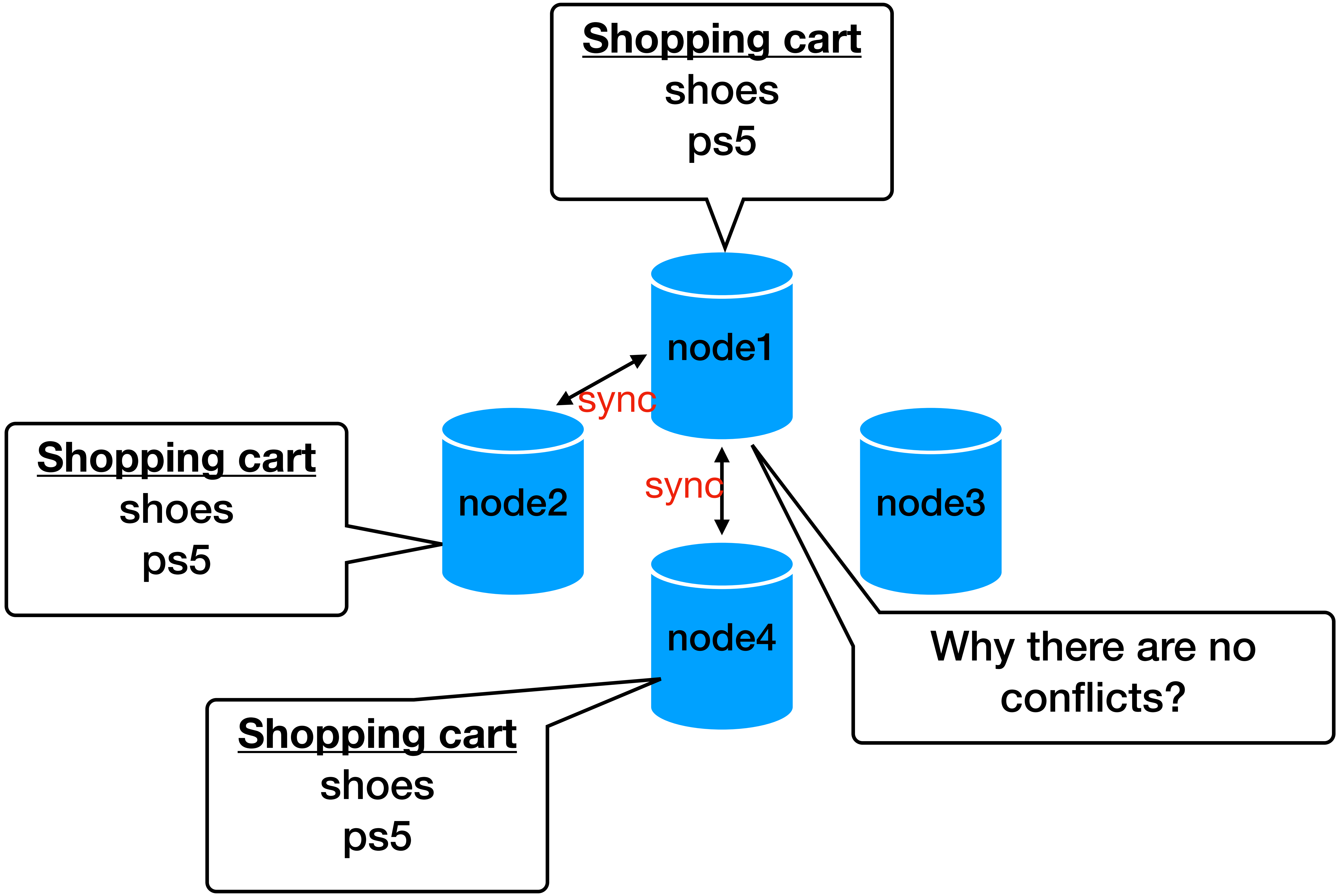


Shopping cart
shoes
ps5

Shopping cart
shoes
ps5

Shopping cart
shoes
ps5

Why there are no conflicts?

Data versioning (3) - Vector clocks

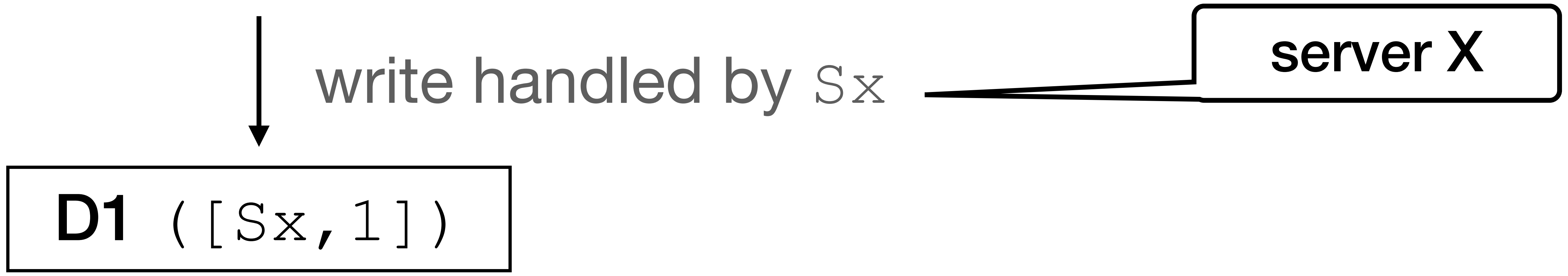
- Used to capture causality between versions
  (of the same object)
- Vector clock = a list of `[node, counter]` pairs
  one list is a attached to every version of every object

```
IF      all the counters on the first object's clocks <=
        all the counters on the second object
THEN
        first is ancestor of the second and can be forgotten
ELSE
        there is a conflict, the client should reconcile
```

Data versioning (4) - Interface

- `put(key, context, object)`
- `get(key)`
  - `get` returns all versions of the associated object AND a `context`
  - `context` = system metadata / versioning (opaque to the user)
    holds the vector clocks
- If the response of a `get()` contained multiple versions, the next update (with the retrieved `context`) will reconcile the versions

Data versioning (5) - example

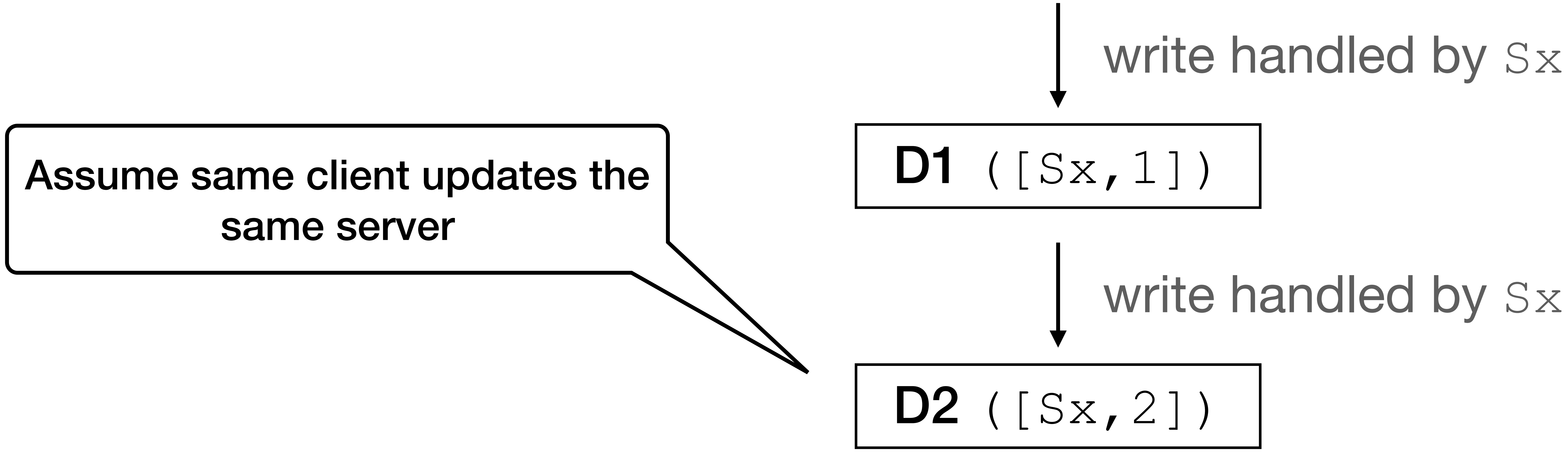


write handled by `Sx`

server X

D1 `([Sx,1])`

Data versioning (5) - example



write handled by `Sx`

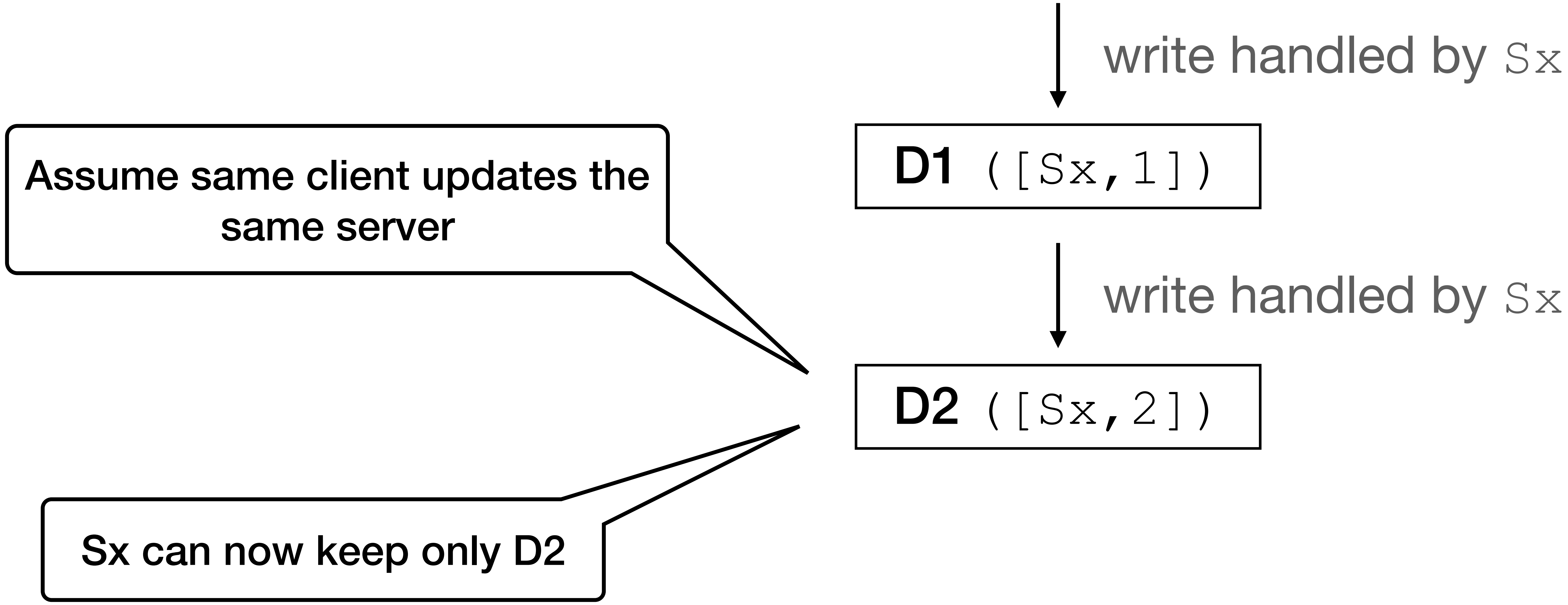
D1 `([Sx,1])`

write handled by `Sx`

D2 `([Sx,2])`

Assume same client updates the same server

Data versioning (5) - example



write handled by `Sx`

D1 `([Sx,1])`

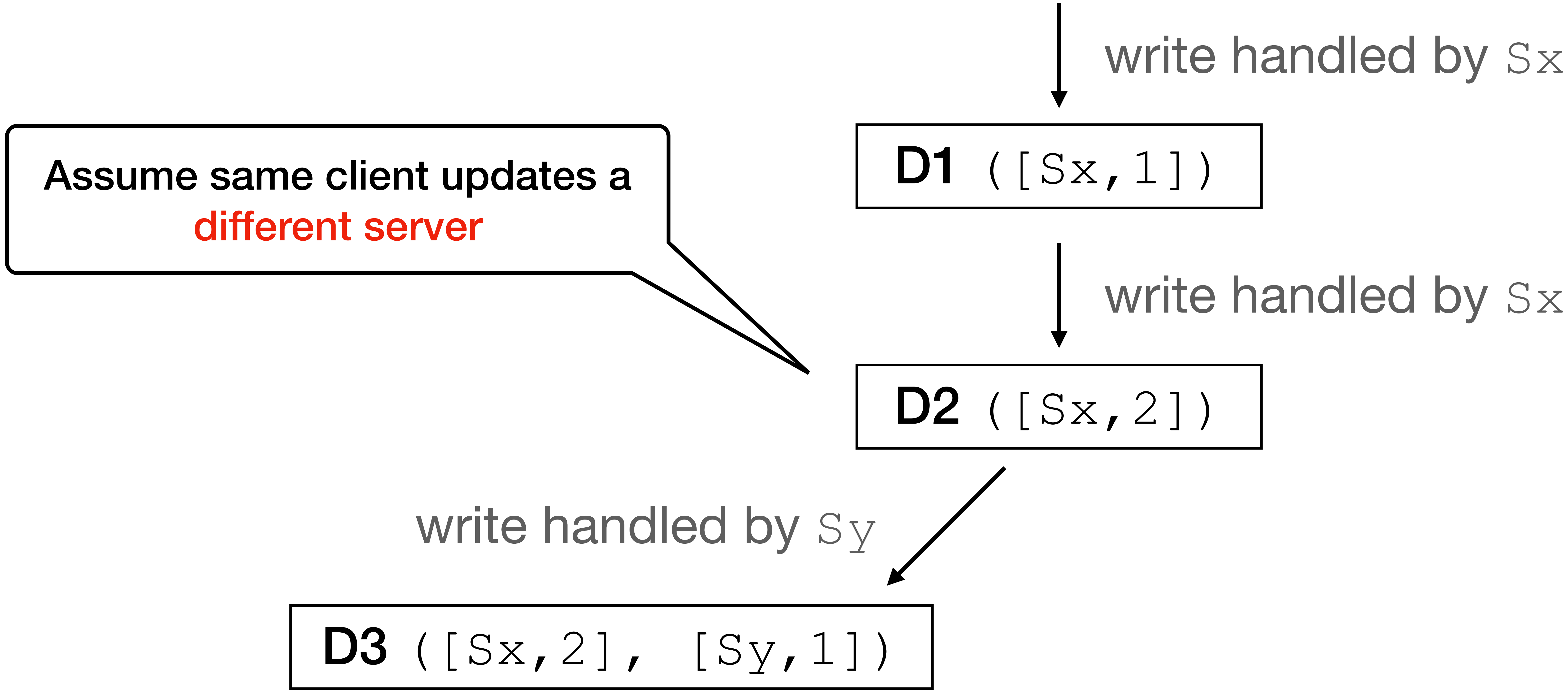
write handled by `Sx`

D2 `([Sx,2])`

Assume same client updates the same server

Sx can now keep only D2

Data versioning (5) - example



write handled by `Sx`

D1 `([Sx,1])`

Assume same client updates a different server

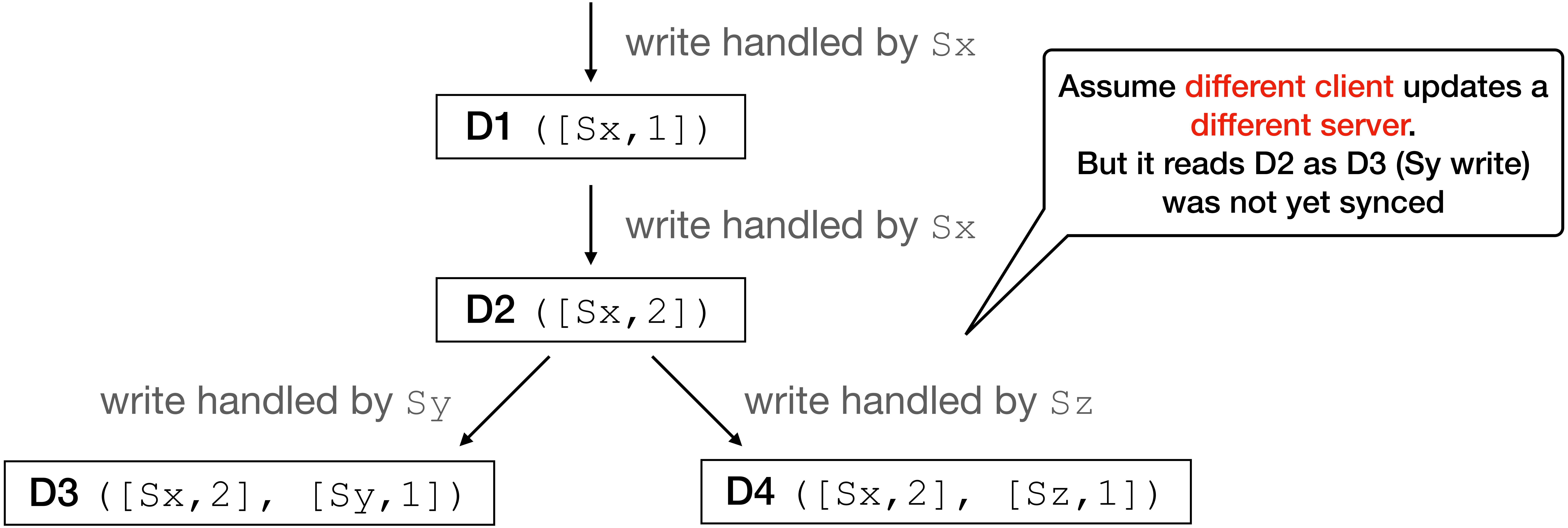
write handled by `Sx`

D2 `([Sx,2])`

write handled by `Sy`

D3 `([Sx,2], [Sy,1])`

Data versioning (5) - example



write handled by `Sx`

D1 `([Sx,1])`

write handled by `Sx`

D2 `([Sx,2])`

write handled by `Sy`

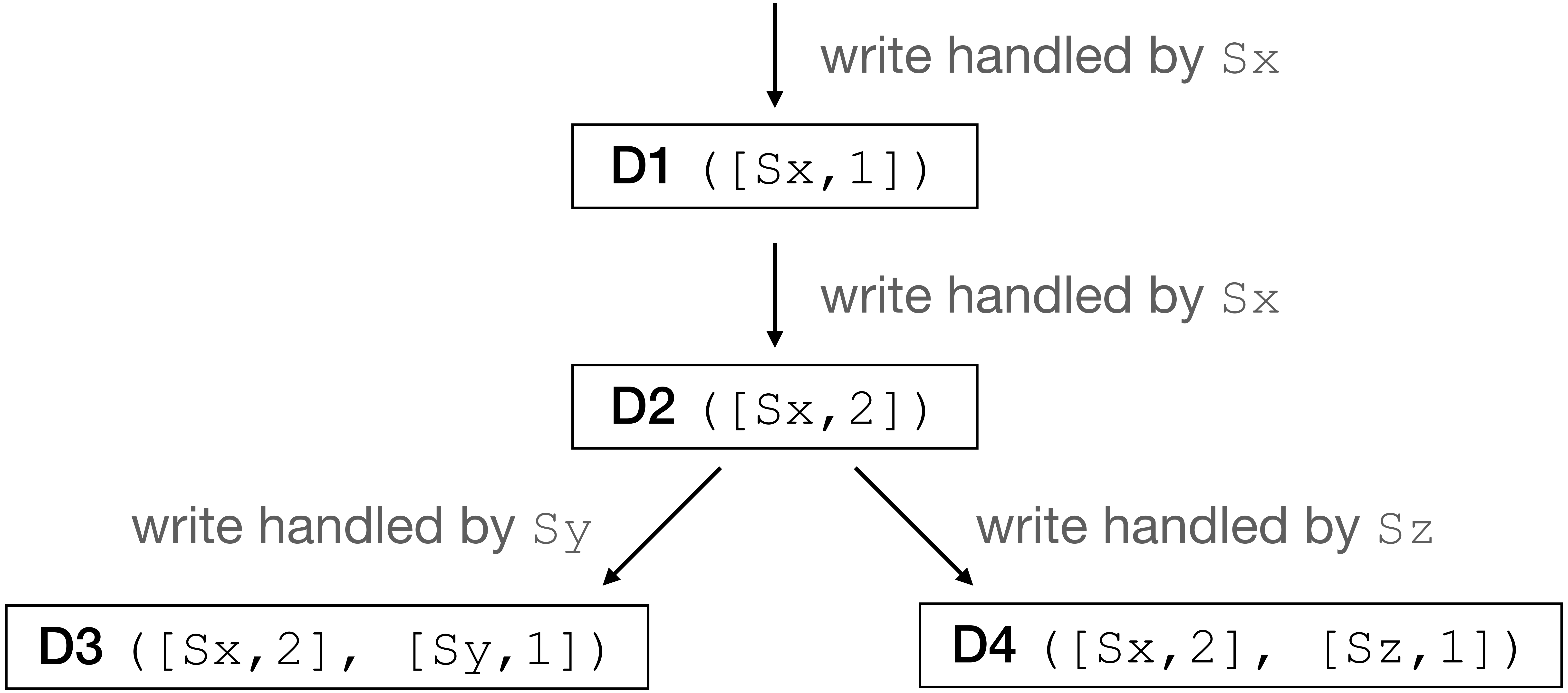
D3 `([Sx,2], [Sy,1])`

write handled by `Sz`

D4 `([Sx,2], [Sz,1])`

Assume different client updates a different server.
But it reads D2 as D3 (Sy write) was not yet synced

Data versioning (5) - example



write handled by `Sx`

D1 `([Sx,1])`

write handled by `Sx`

D2 `([Sx,2])`

write handled by `Sy`

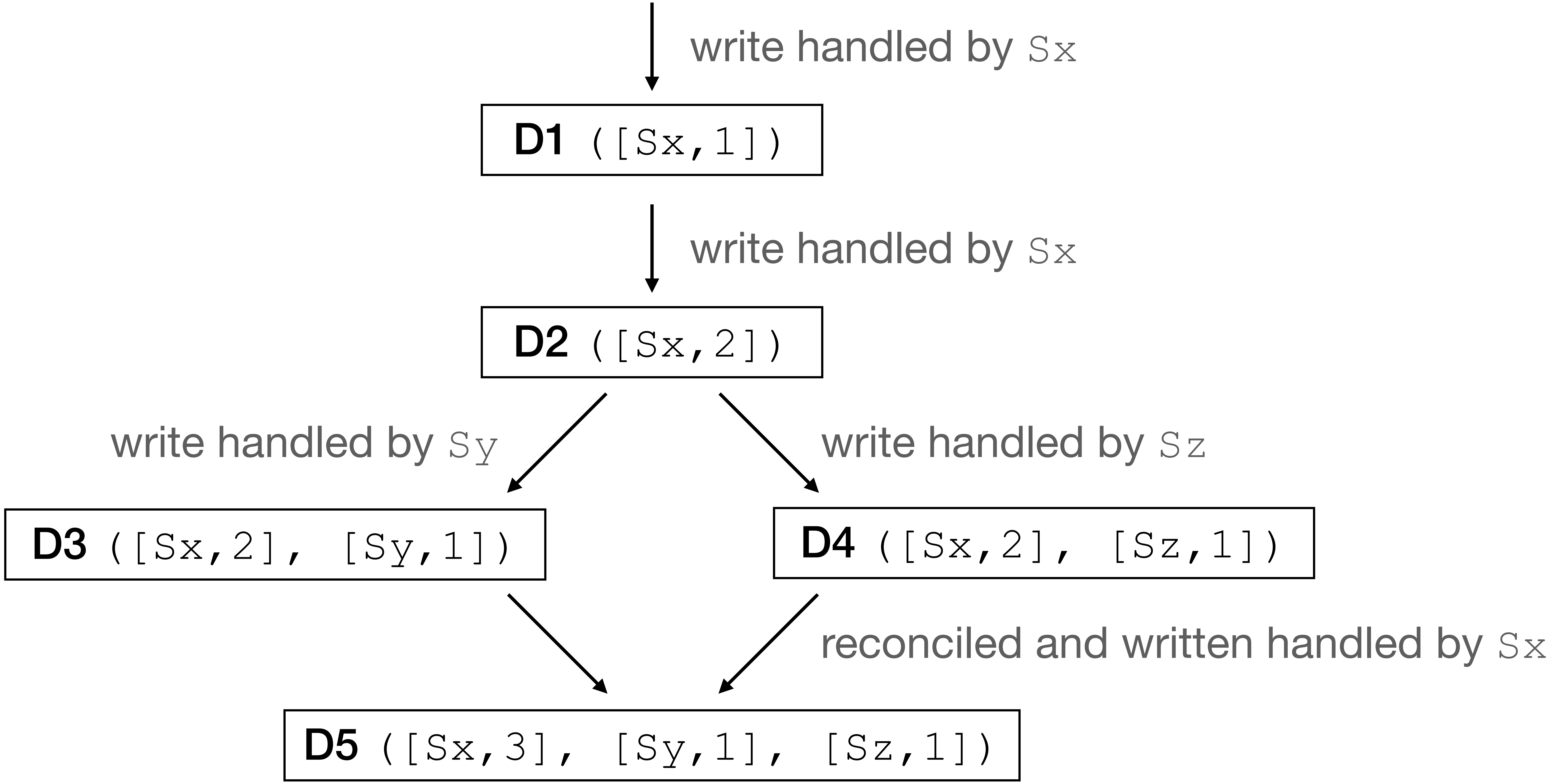
write handled by `Sz`

D3 `([Sx,2], [Sy,1])`

D4 `([Sx,2], [Sz,1])`

Assume Sy and Sz are getting synced. They can NOT merge D3 and D4 automatically. It will be done on the next update by the client

Data versioning (5) - example



write handled by `Sx`

D1 `([Sx,1])`

write handled by `Sx`

D2 `([Sx,2])`

write handled by `Sy`

write handled by `Sz`

D3 `([Sx,2], [Sy,1])`

D4 `([Sx,2], [Sz,1])`

reconciled and written handled by `Sx`

D5 `([Sx,3], [Sy,1], [Sz,1])`

Data versioning (6) - Vector clocks size

- In theory, the size of the vector clocks can grow if many servers coordinate the write
  “preference list”

- In practice, it is always handled by one of the top N

- Amazon added a threshold (10) that above that,
  the oldest pair gets removed
  - can lead for reconciliation problems
  - this problem has not surfaced in production (according to Amazon)

Bonus clip

https://www.youtube.com/watch?v=cMalJkGJzYU

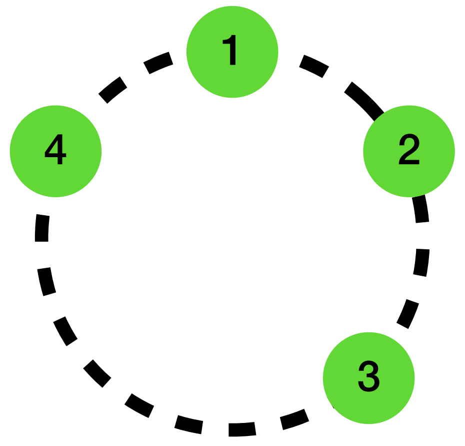
Dynamo topics

- Requirements
- Partition algorithm
- Replication
- Data versioning
- `get()` and `put()` execution
- Failures
- Ring membership

`get()` and `put()` execution (1)

The client can initiate an HTTP call by

- (1) via a load balancer
  - \+ the client is unaware of any dynamo logic
  - \- more latency as another forwarding step may be required (if the reached node is NOT part of the top N nodes in the preference list)



- (2) via a partition aware client driver
  - \+ lower latency
  - \- client need to maintain the logic / sync with the ring nodes

`get()` and `put()` execution (2)

Consistency

- Dynamo uses a quorum protocol
  just like the one we saw in the CAP theorem

N	#nodes that store replicas of the data
W	#replicas that need to acknowledge the receipt of the update
R	#replicas that are contacted for a read

$W + R > N$

(2,2,3 is a common setting)

`get()` and `put()` execution (3)

For `put()` the coordinator

- Writes the data + the new vector clock locally
- Send it to N-1 nodes from the preference list
- Waits for W-1 to return success

In a failure free environment

For `get()` the coordinator

- Request all versions from the N-1 nodes in the preference list
- Wait for R response to return success
  if more than 1 version returned, return all versions for the client to reconcile

Dynamo topics

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- `get()` and `put()` execution
- Failures
- Ring membership

Failures

- Temporary (from milliseconds to 3 hours)
- Permanet

Failures - Temporary (1)

- In a cloud environment there are (possibly) frequent temporal errors
  network partitions, vm fails, power…
- Temporal = from seconds to minutes (3 hours max)
- Can easily cause an availability issue (“strict quorum”)
  can you think of an example?

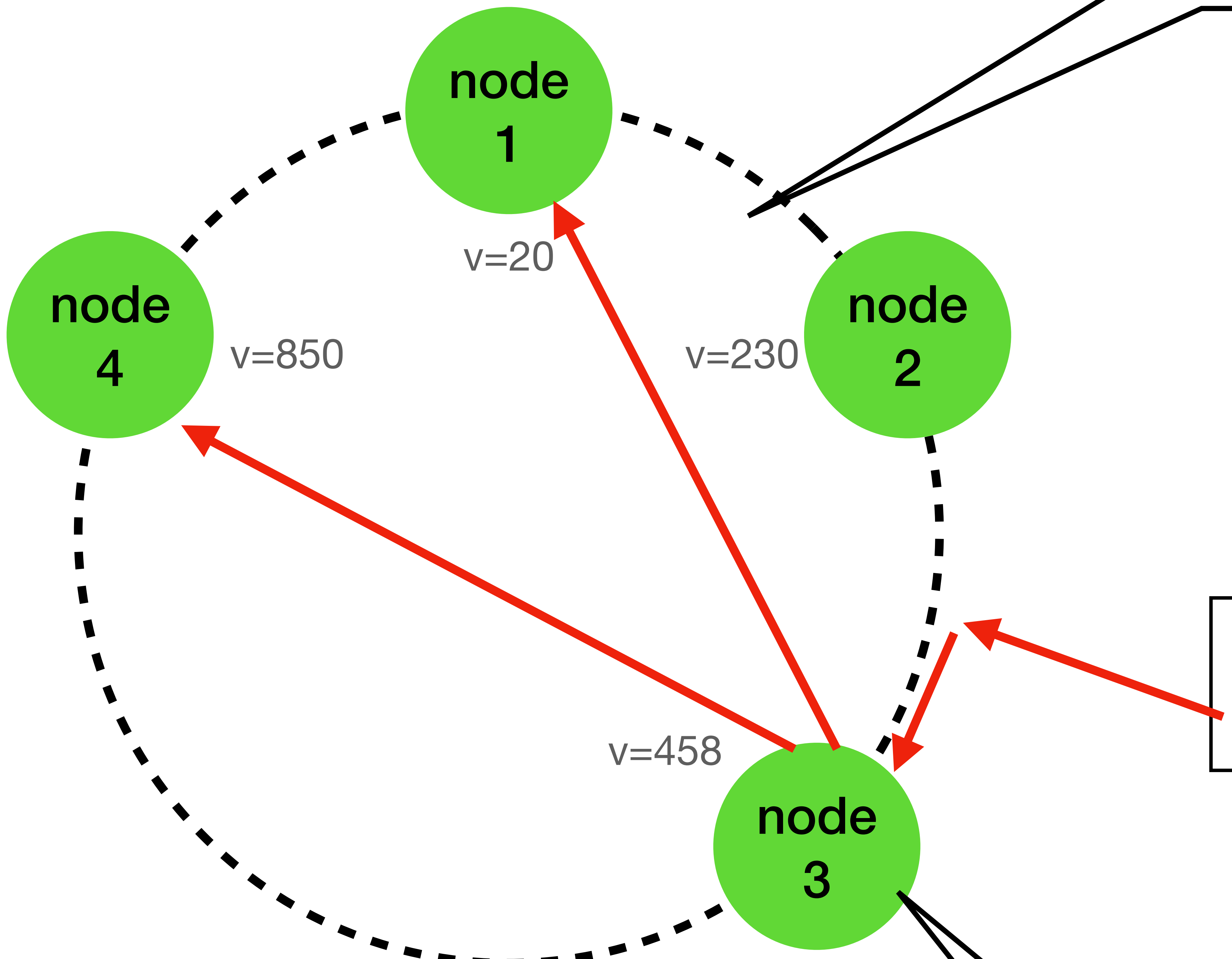
Strict = the nodes which are ″mapped″ to store the data

Failures - Temporary (2)

Hinted handoff

- Sloppy quorum - all reads/writes are performed on the first N healthy nodes from the preference list
  may not be the first N nodes if some fail
- On nodes failures, we use the next nodes (on the ring) as replicas and store an additional “hint” on the metadata
  suggesting which node was originally intended to be written
- These hinted handoffs will be stored on a separate local list, and will be used to update the failed nodes once are back online

Failures - Temporary (3) - example



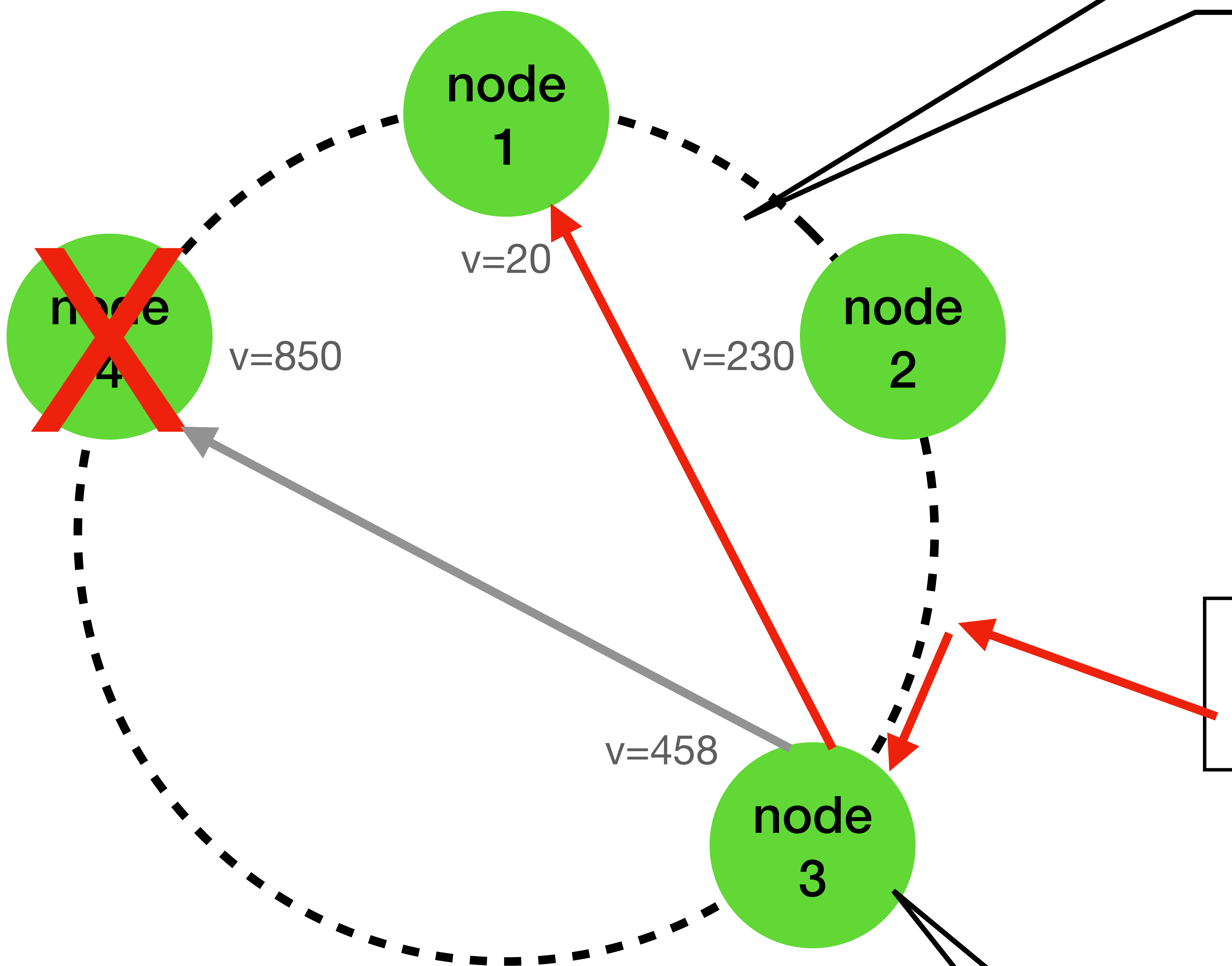
Range is [0:1000] for the example, N=3

`hash(key) = 344`

(assigned to node3)

node3 is the coordinator. It will store the value locally and on node4 and node1

Failures - Temporary (3) - example



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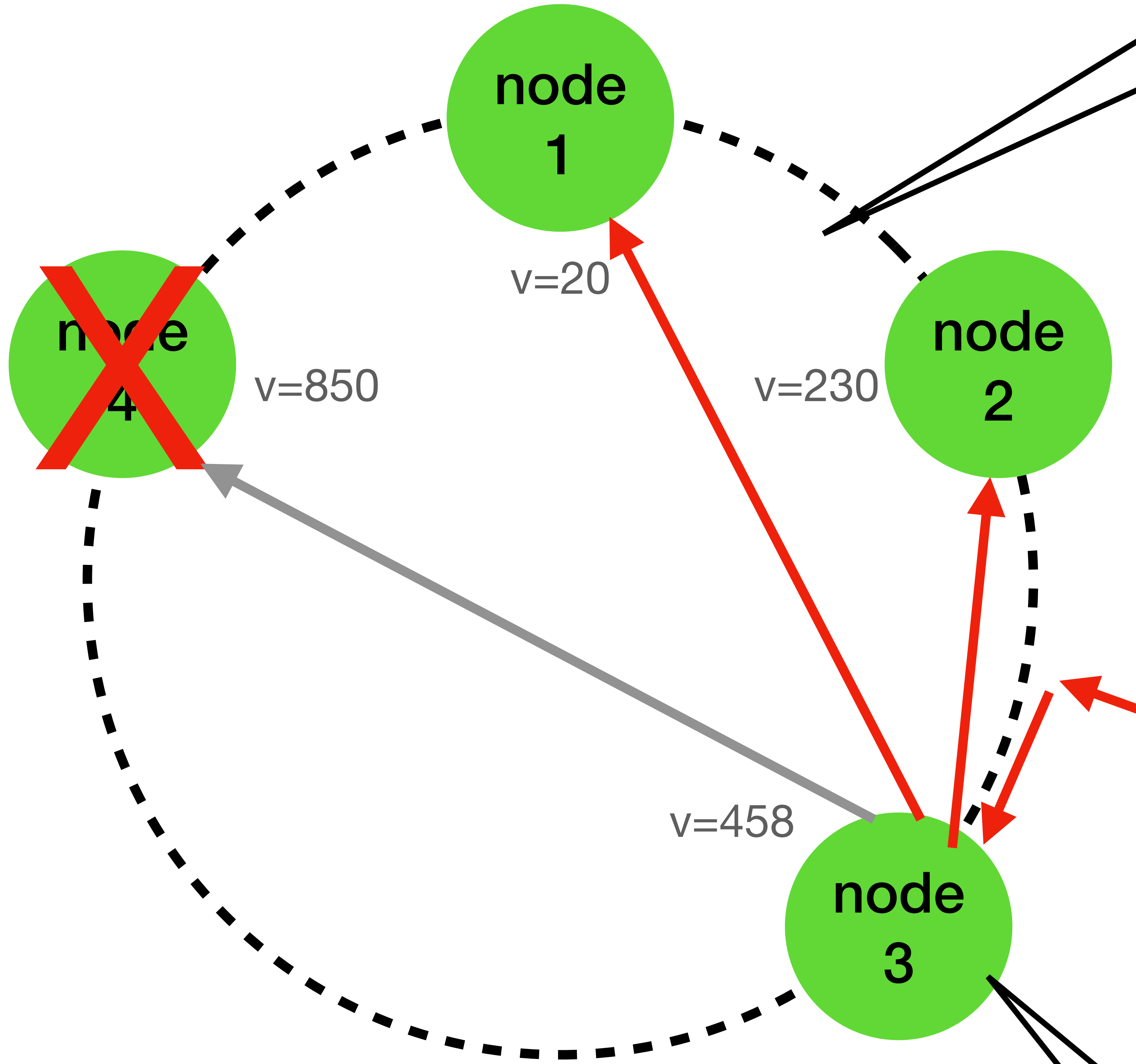


Range is [0:1000] for the example, N=3

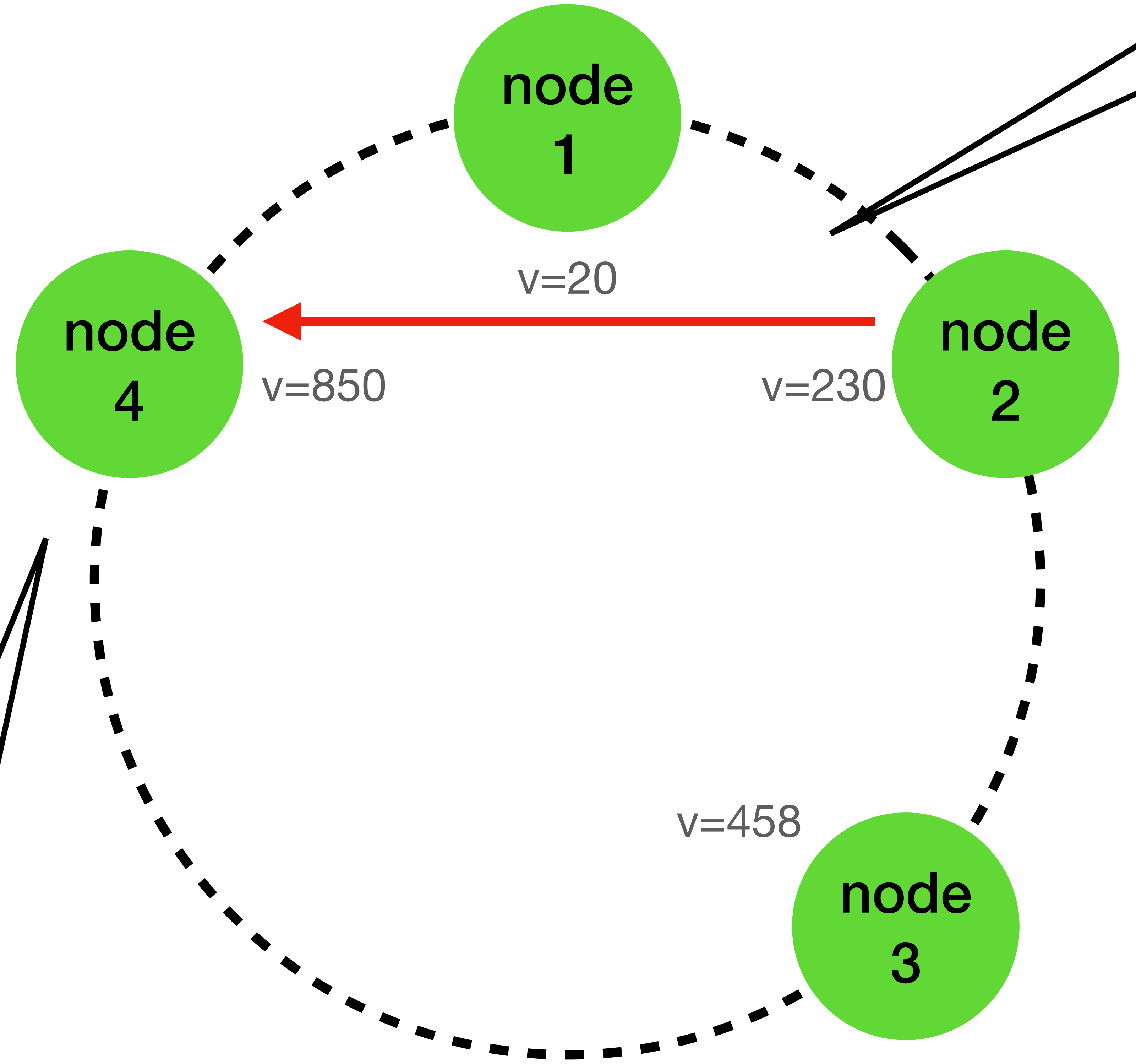
Assume node4 fails. To maintain durability (N=3), we write on node2

`hash(key) = 344`

(assigned to node3)

node3 is the coordinator. It will store the value locally and on node4 and node1

Failures - Temporary (3) - example



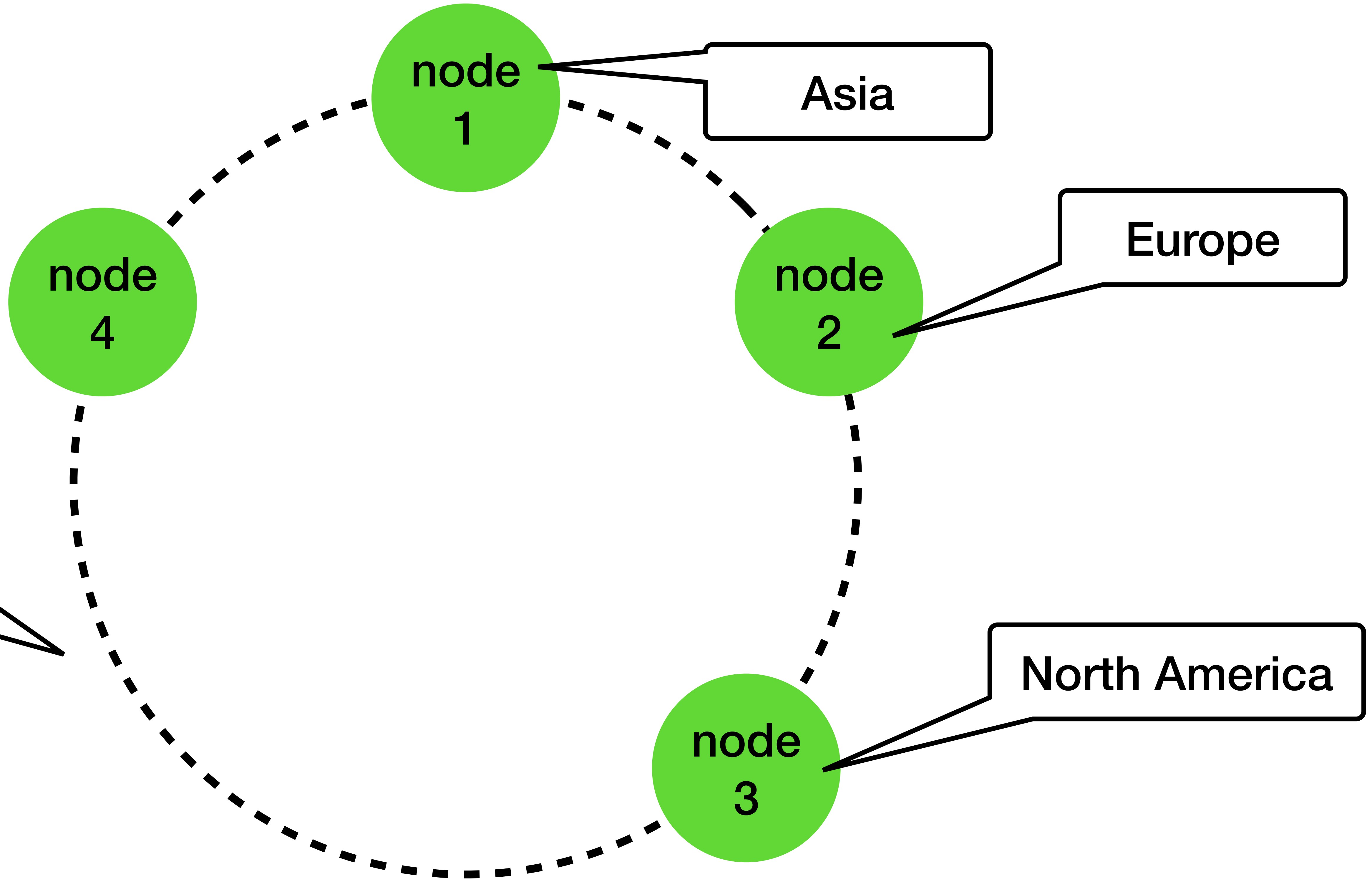
Range is [0:1000] for the example, N=3

Assume node4 fails. To maintain durability (N=3), we write on node2

Once node4 resumes, node2 will update node4 and delete the data

Failures - Temporary (4)

- It is crucial for an highly available system to be able of handing the failure of an entire data center
  power outages, cooling/network failures, natural disasters…



Dynamo can be configured such that the preference list is spread among different data centers

Failures - Permanent (1)

Hinted handoff works best when

- Node failures are transient
- System membership churn is low

<u>What to do when</u>

- The node with the hinted replicas fails
- Other durability threats

Failures - Permanent (2)

Anti entropy (replica synchronization)

- A protocol to keep replicas synchronized

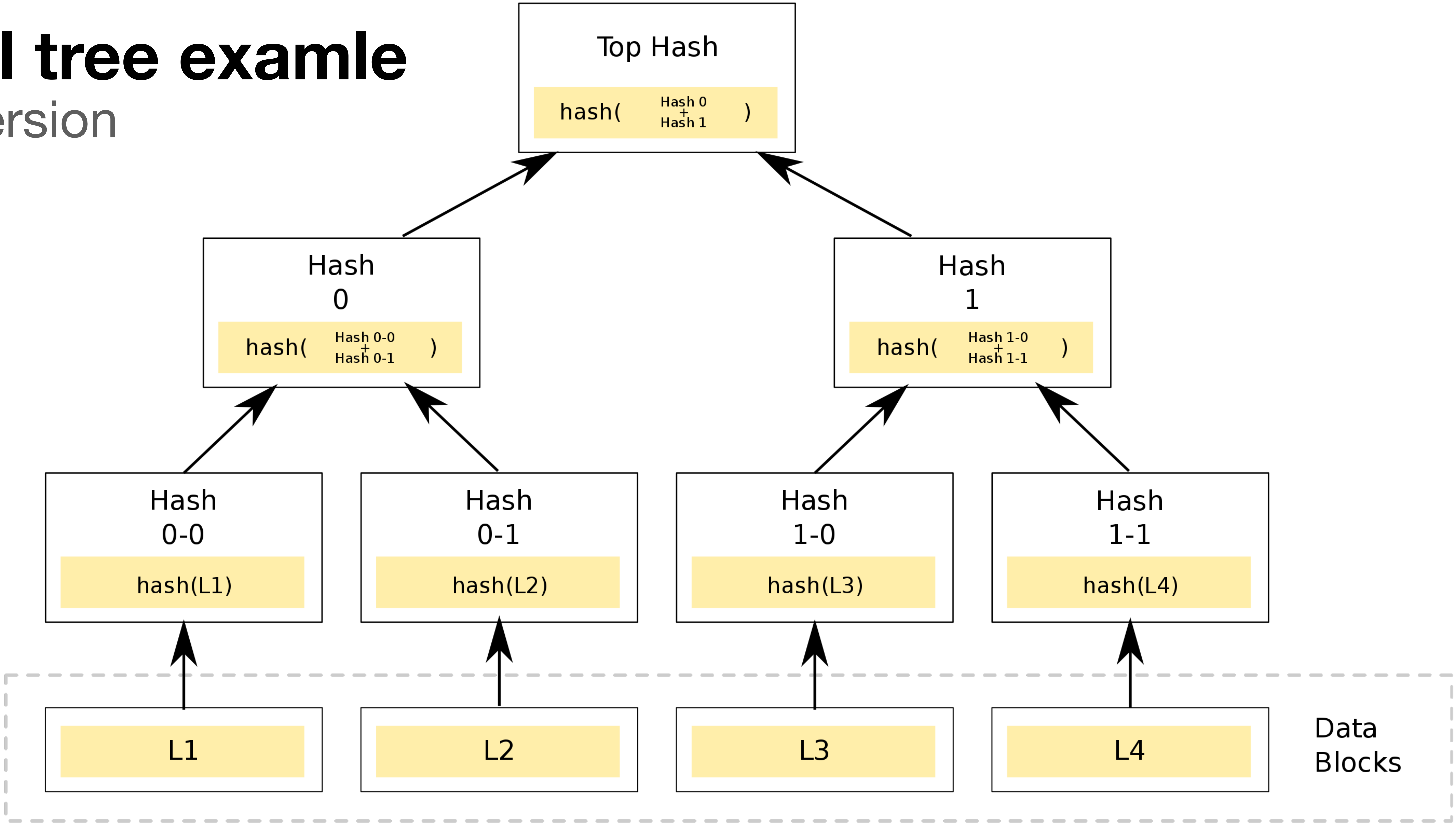
To detect inconsistencies between replicas and to minimize the amount of transferred data, Dynamo uses Merkle trees:

A Merkle tree is a hash tree where leaves are hashes of the values of individual keys. Parent nodes higher in the tree are hashes of their respective children

Failures - Permanent (3)

Merkel tree examle

binary version



Failures - Permanent (4)

Dynamo uses Merkel tree as follows

- Each node maintain a separate Merkel tree for each key range

  the set of keys covered by a virtual node

- Nodes can compare each matching range by exchanging the matching tree roots

- On “out of sync” - nodes can exchange only the subset of their children to avoid transmitting all data

Dynamo topics

- Requirements
- Partition algorithm
- Replication
- Data versioning
- `get()` and `put()` execution
- Failures
- Ring membership

Ring membership

Assumption

- Node outages are often transient
- Permanent departures are rare
  - —> do not automatically rebalanced the ring when (temporal) error occurs

- To add / remove nodes (which rebalance the ring) use an explicit mechanism (via API)

Ring membership - Gossip protocol

- Recall we do not have a master node (fully distributed)
- When a node is added/removed (and thus the ring changes), a gossip based protocol is used to update the ring status
  —> eventually consistent view of the ring
- **Gossip protocol**: every second each node contact a random different node and the two nodes “reconcile” their ring membership view
  also used for other Dynamo needs

Ring membership - Failure detection (1)

- Used to avoid communicating with unreachable nodes
  during get() and put()

Local notion of failure (decentralized)

- Node A may consider node B failed
  if B does not response to A's message
- But node C can consider node B alive
  if B is responsive to C's message

Ring membership - Failure detection (2)

- Under normal operation, Node A can quickly discover that node B is unresponsive when B fails to respond to a message
  derived from `put()` / `get()` calls
- A periodically retires to B are made to check for B's recovery
- If 2 nodes are not "near" in the ring, neither needs to know whether the other is reachable and responsive

Dynamo topics

- Requirements
- Partition algorithm
- Replication
- Data versioning
- `get()` and `put()` execution
- Failures
- Ring membership

These topics are used by wide column databases

(and many other Big Data platforms)