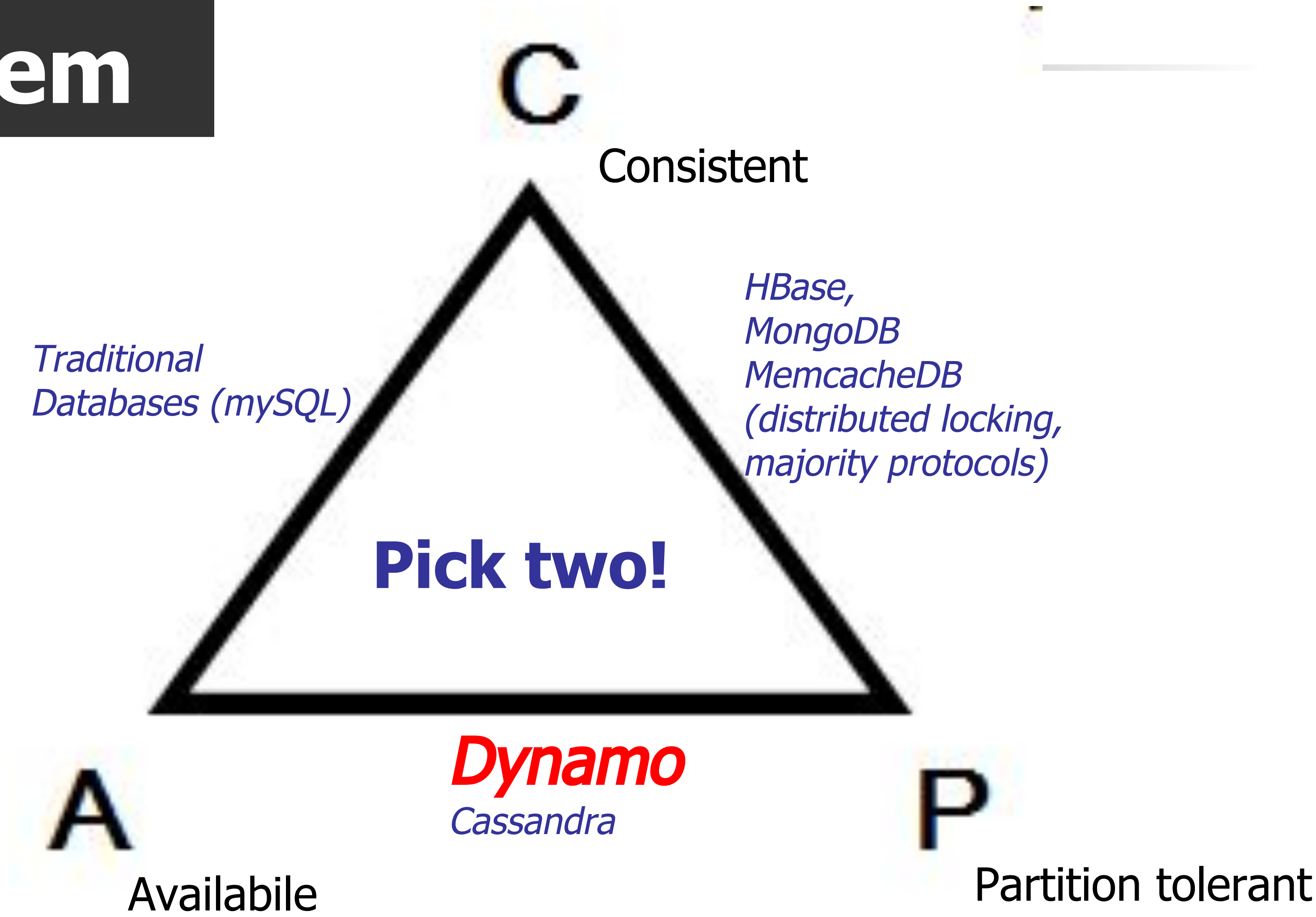
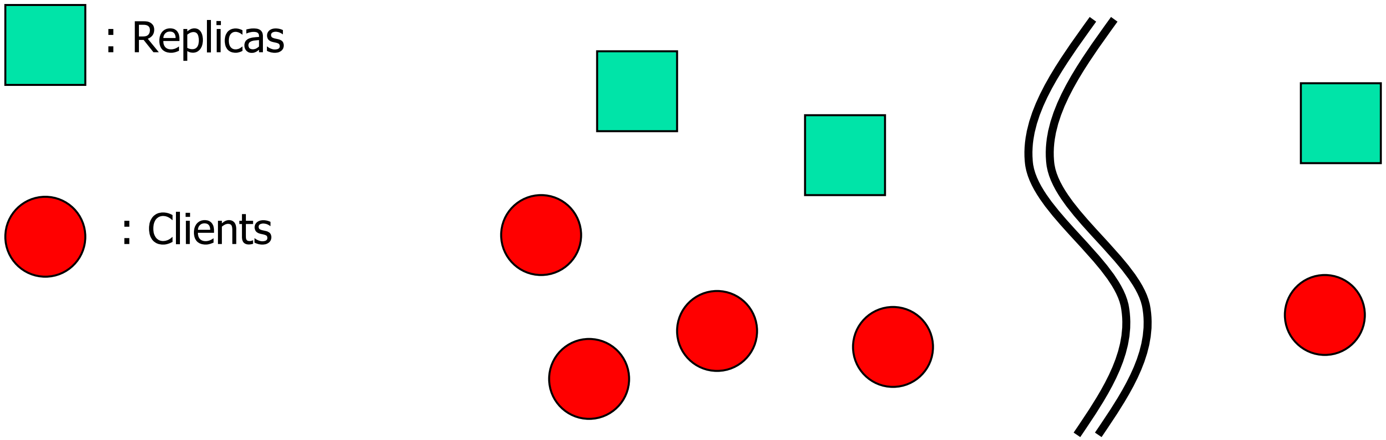
CAP Theorem



CAP Twelve Years After – How the "Rules" Have Changed, IEEE Spectrum 2012 [link]
Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services, SIGACT News 33(2): 51-59 (2002)



C+PT (-A) (-L)

Option 1: reads

accept reads

accept

reject writes

reject

Option 2:

writes

accept reads

reject

reads

accept writes

reject

writes

A+PT (-C) (+L)

writes

accept reads + writes

accept reads +

'inconsistent' results

'inconsistent'

results

Amazon's Dynamo:

if partitioning □ favor Availability (over Consistency)

normal operation □ favor low latency (over Consistency)

PAC / ELC

- If there is a partition (**P**):
  - How does system tradeoff A and C?
- **E**lse (no partition)
  - How does system tradeoff L and C?

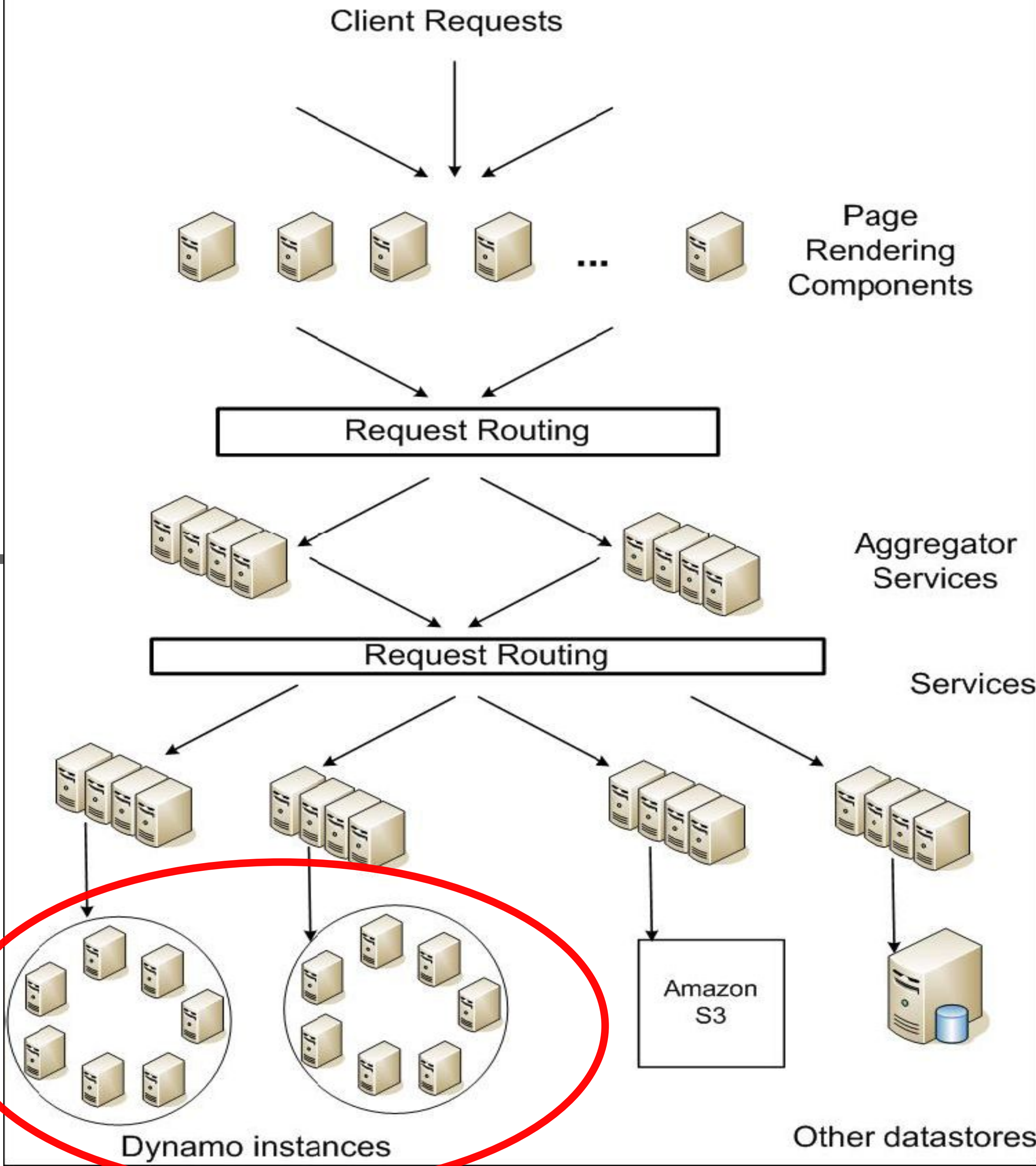
Amazon's Dynamo: PA/EL

http://dbmsmusings.blogspot.com/2010/04/problems-with-cap-and-yahoos-little.html

Dynamo: Amazon's Highly Available Key-value Store

(SOSP'07)

Giuseppe DeCandia, Deniz Hastorun, Madan Jampani, Gunavardhan Kakulapati, Avinash Lakshman, Alex Pilchin, Swaminathan Sivasubramanian, Peter Vosshall and Werner Vogels



Amazon eCommerce platform

Throughput

- 80M checkout operations per day (peak season) [2017]

Massive scale

- At this scale component-level outages are continuous!
- Slightest outage has significant financial consequences
  - $1M/minute (2021)
  - ….and impacts customer trust

Application Requirements

- (1) High data *availability*; (2) always writeable data store

Favor availability
(vs. consistency)

Favor low latency
(vs. consistency)

Favor writes
(vs. reads)

Why favor availability over consistency?

"even the slightest outage has significant financial consequences and impacts customer trust"

- … consistency violations may as well have financial consequences and impact customer trust
  - But not in (a majority of) Amazon's services
  - NB: Billing is a separate story

Why favour writes vs. reads?

Architectural requirements

- Incremental scalability
- Symmetry (no ‘special’ node)
- Ability to run on a heterogeneous platform

Data Access Model

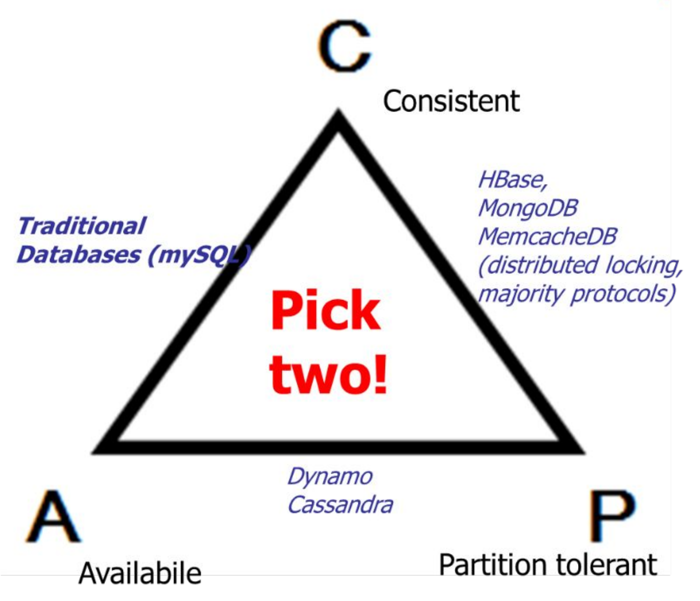
- Data stored as (key, object) pairs:
  - Interface *put(key, object), get(key)*
    - ‘identifier’ (key) generated as a hash for object
  - Objects: Opaque

Application scenarios: shopping carts, customer preferences, session management, sales rank, product catalog, S3

Further assumptions:

- Relatively small objects (<1MB)
- Query by objectID only
- Operations do not span multiple objects
- Friendly (cooperative) environment
- One Dynamo instance per service ☐ 100s to 1,000s hosts/service

Why not a database?



Requirements: High availability / always writeable store / low (write) latency

Key ideas

(1) Multiple replicas …

- … but avoid *synchronous* replica coordination …

  [used by solutions that provide strong/sequential consistency]

- ... 'weak consistency' makes it possible to provide availability

- However need subsequent decisions:
  - **WHEN** to resolve possible consistency conflicts,
    - Dynamo: at read time (allows providing an "always writeable" data store)
  - **WHO** should solve them
    - Dynamo: the data store [if it can], **OR** [if that fails] the application (configurable, app specific)

(2) Vector clocks [to keep track of causality]

(3) Quorum protocols [to reduce latency / manage tradeoffs]

Key issues

- Partitioning the key/data space. Request routing
- High availability for writes
- Handling temporary node failures
- Recovering from permanent failures
- Membership and failure detection

Things to remember from last time …

- Vector clocks
  - Can be used to model causality dependence.

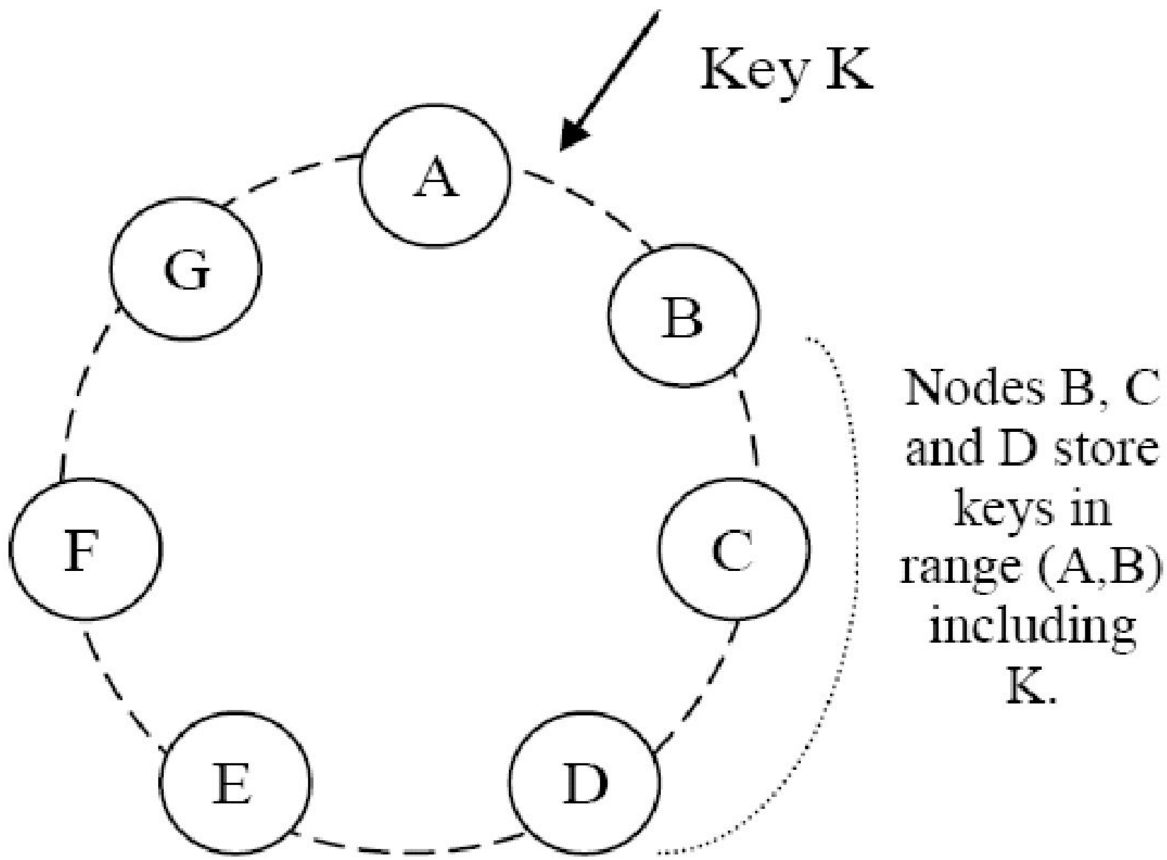
    So far two usage examples
    - [Causally ordered] Group communication
    - [Replica management] Determine replica divergence and the causally related stream of updates

- Voting-based / Quorum-based protocols
  - More examples later

Problem	Technique	Advantage
Partitioning / Request routing	▪ Consistent hashing	Incremental scalability, load balancing, etc.
High availability for writes	▪ Eventual consistency ▪ Reconciliation during reads (uses vector clocks) ▪ Quorum protocol	Low latency writes
Handling temporary failures	▪'Sloppy' quorum protocol and hinted handoff	Provides availability and durability when some of the replicas are temporarily not available.
Recovering from permanent failures	▪ Anti-entropy using Merkle trees	Synchronizes divergent nodes in the background.
Membership and failure detection	▪ epidemic-based membership protocol	Preserves symmetry and avoids having a centralized registry for storing membership and node liveness information.

Partition Algorithm: Consistent hashing

- Each data item is replicated at N hosts (successors)



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Traditional quorum system:

- R/W: the minimum number of nodes that must participate in a successful read/write operation.
  - Latency of a read/write operation: the slowest of the R (or W) replicas
  - To improve latency R and W are usually configured to be less than N.
- R + W > N and W > N/2 yields a quorum-like system.

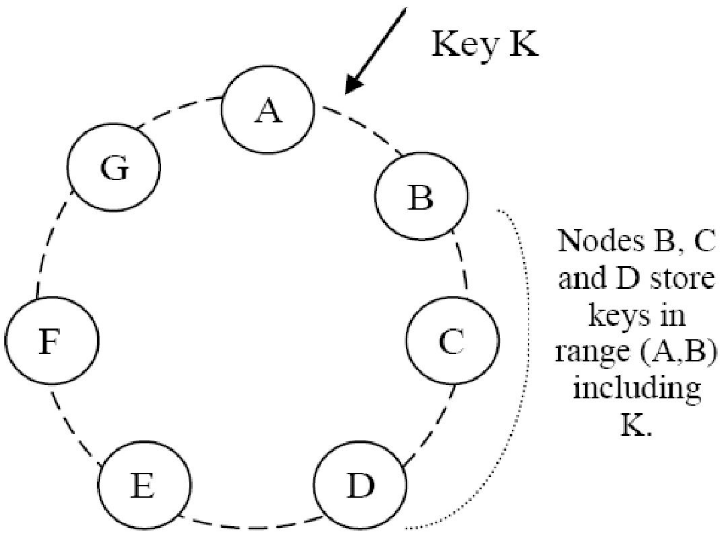
Dynamo's "Sloppy" quorum:

- A put() may return before W replicas updated!

  [A first factor leading to inconsistencies]

A second factor for inconsistencies: Dealing with temporary failures through "Hinted handoff"

- Assume replication factor R = 3.
- Replicas on next R nodes.
- When A is temporarily down
  - (or unreachable) during a write,
  - send the write to D.
- D is 'hinted' that the replica belongs to A and will deliver it A when A recovers.



- Objective: "always writeable"

Data versioning

- Multiple replicas …
  - … but with focus on availability they may diverge
- The issues this introduces:
  - **when** to resolve possible conflicts?
    - Dynamo's solution: at read time (allows providing an "always writeable" data store)
      - A *put()* may return before the update has been applied at all the replicas
      - A *get()* call may return different versions of the same object.
  - **who** should solve them?
    - the data store ☐ use *vector clocks to capture causality* between different versions of the same object. **OR**
    - the application ☐ uses application specific logic.

How does the data-store solve conflicts: Vector Clocks?

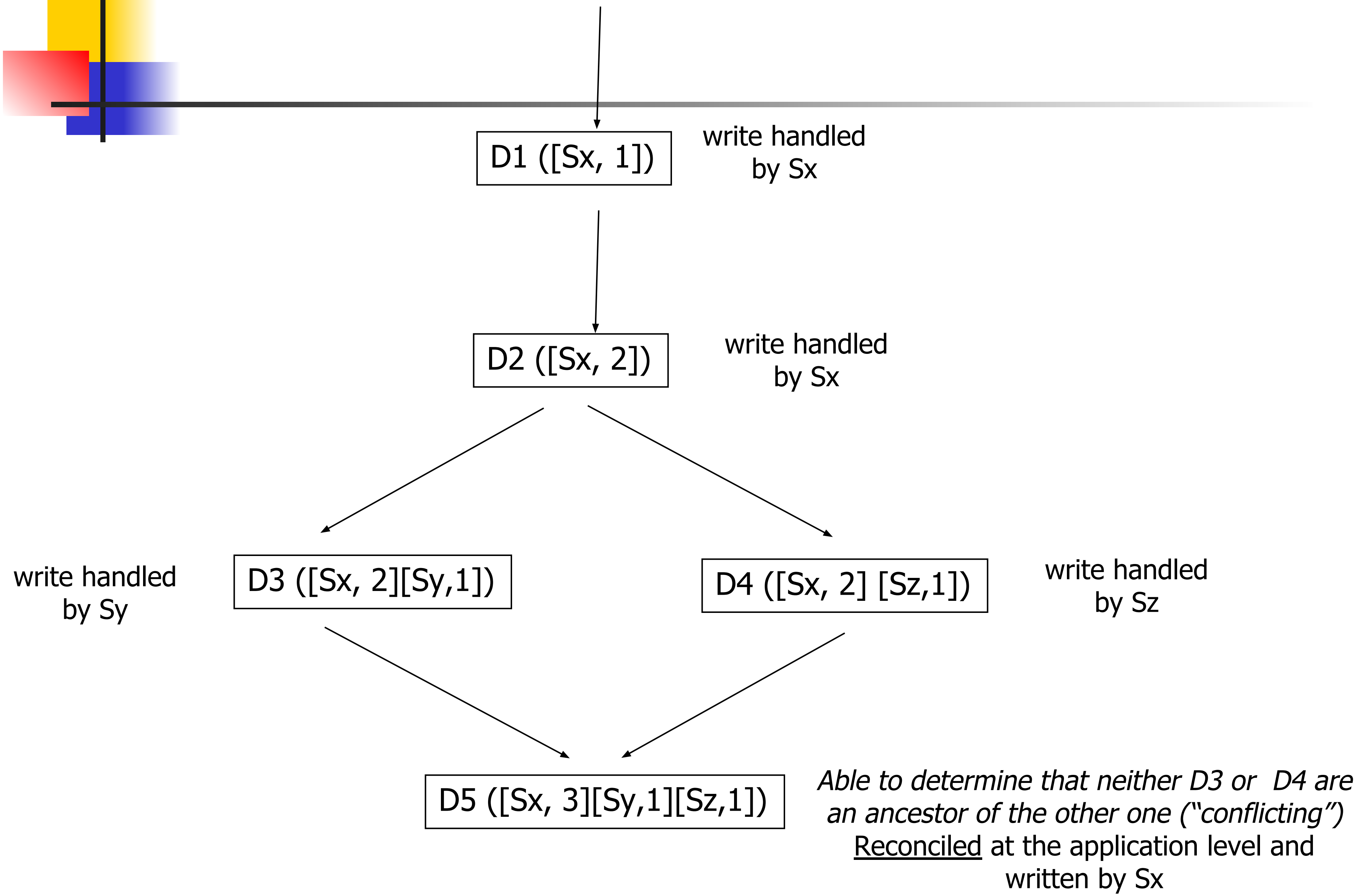
Each version of each object has one associated vector clock.

- list of (node, counter) pairs.

Data store: Which version to keep V′ or V″?

- If V′ is a direct ancestor of V″ then keep V″
  - direct ancestor: each counter on the V′ vector clock is each less-or-equal than corresponding counter in V″

- Otherwise: application-level reconciliation


D1 ([Sx, 1])
write handled by Sx
D2 ([Sx, 2])
write handled by Sx
write handled by Sy
D3 ([Sx, 2][Sy,1])
D4 ([Sx, 2] [Sz,1])
write handled by Sz
D5 ([Sx, 3][Sy,1][Sz,1])
Able to determine that neither D3 or D4 are an ancestor of the other one ("conflicting")
Reconciled at the application level and written by Sx

Divergent versions rarely created in practice

1 version □ 99.94%

2 versions □ 0.0057%

3 versions □ 0.00047%

4 versions □ 0.00007%

Live production environment; % versions reconciled using application logic

Source: Clients with high volume of concurrent writes (not failures)

… these may be robots

Problem	Technique	Advantage
Partitioning	▪ Consistent hashing	Incremental scalability, load balancing, etc.
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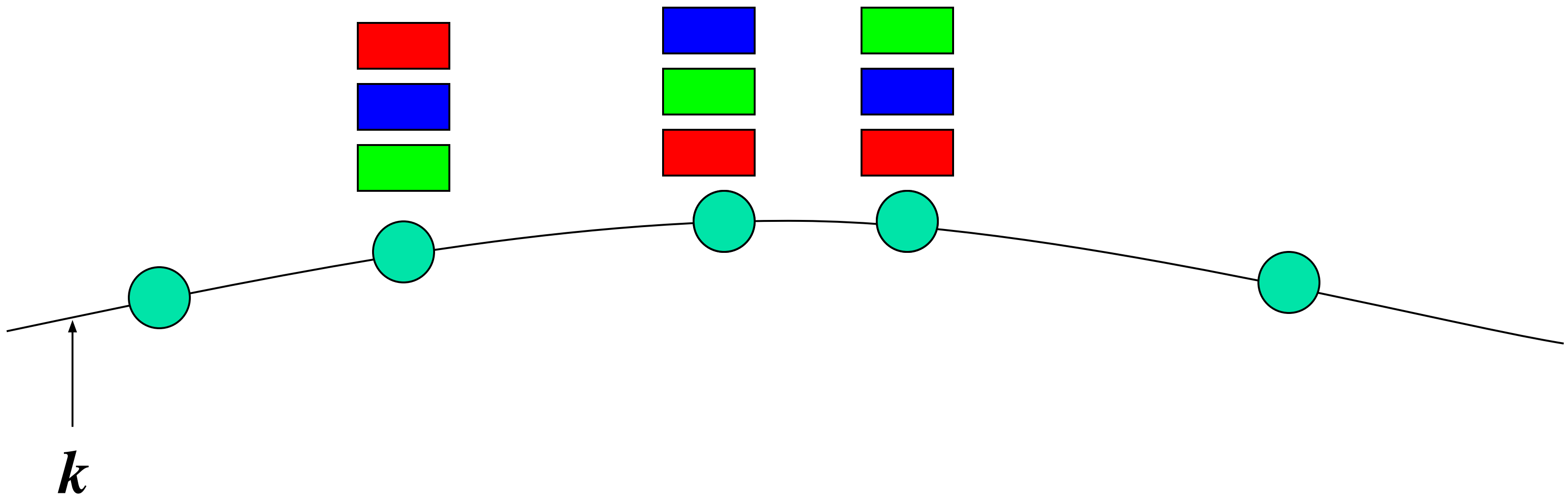
Reconciliation

- Dynamo will replicate each data item on N successors
  - A pair (*k*,*v*) is stored by the node closest to *k* and replicated on N successors of that node
- Why is this may be hard?
  - As nodes may be slow, fail temporarily …sloppy quorum, hinted handoff
  - Need to reconciliate keysets



Replication Meets Epidemics

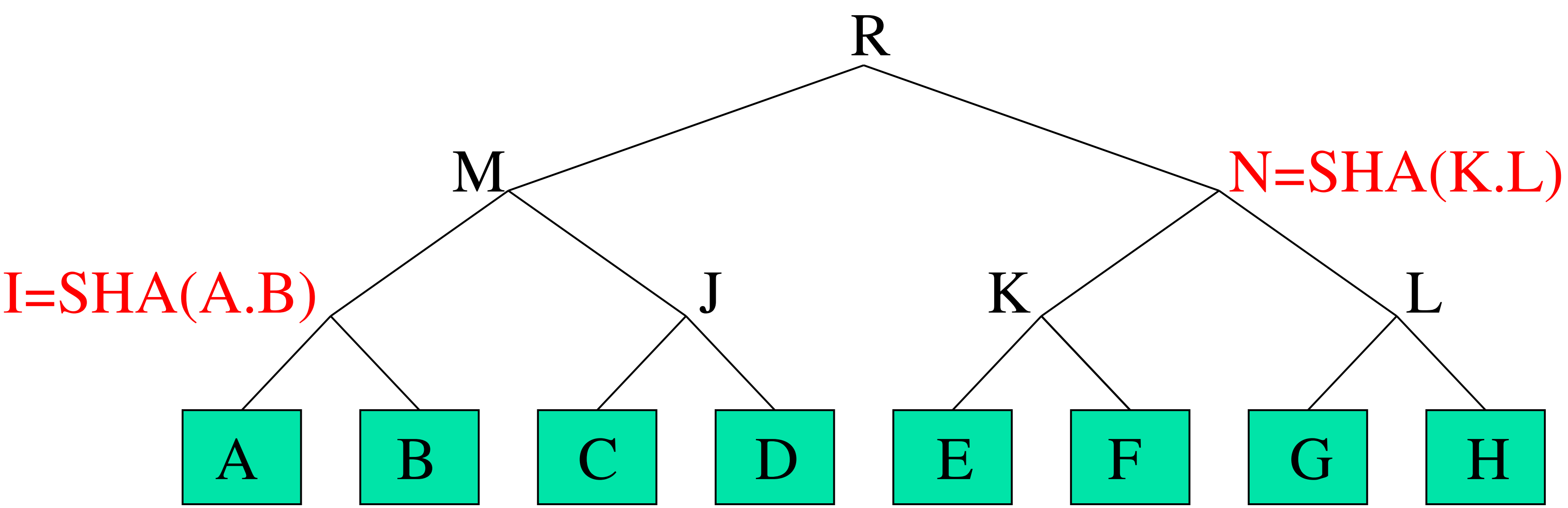
Goal: synchronize sets of key/value pairs on two nodes

- Candidate Algorithm
  - For each (*k*,*v*) stored locally, compute SHA(*k.v*)
  - Every period, pick a <u>random</u> leaf-set neighbor
  - Ask neighbor for all its hashes
  - For each unrecognized hash, ask for key and value
    - (if needed use vector timestamps to reason about version freshness)

- This is an epidemic algorithm All *N* members will have all (*k*,*v*) in *log(N)* periods
  - But (above) the cost is O(*C*), where *C* is the size of the set of items stored at the original node

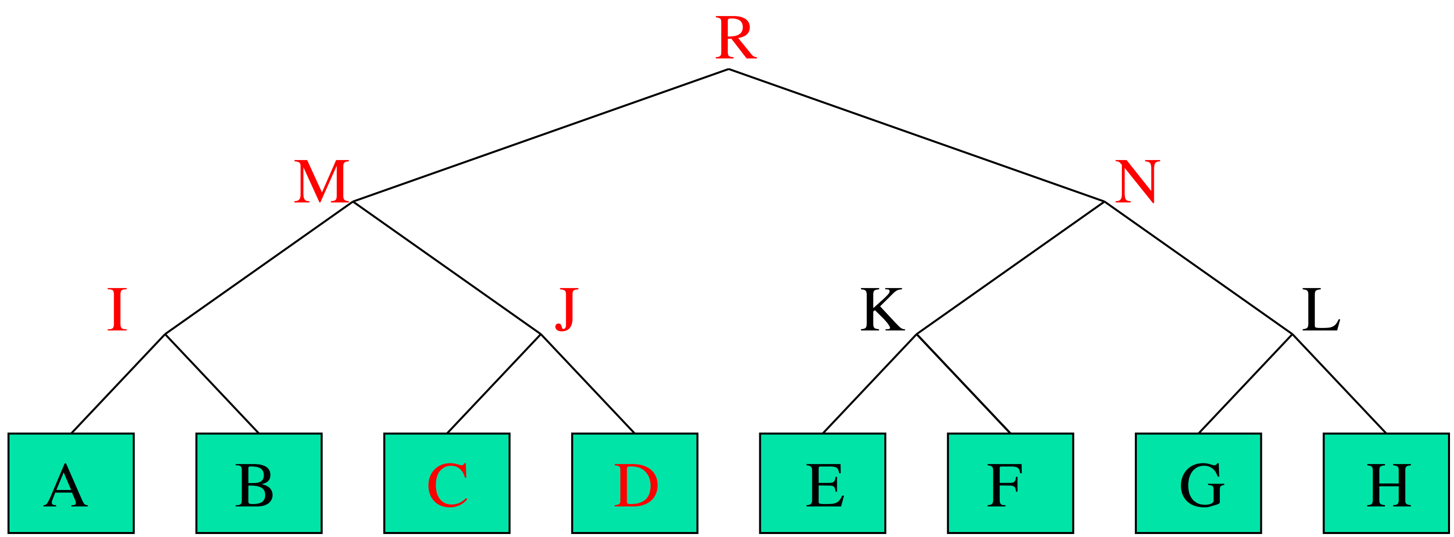
Merkle Trees

- An efficient summarization technique
  - Interior nodes are the secure hashes of their children
  - E.g., I = SHA(A.B), N = SHA(K.L), etc.



Merkle Trees

- Merkle trees are an efficient summary technique
  - If the top node is signed and distributed, this signature can later be used to verify any individual block, using only O(log *n*) nodes, where *n* = # of leaves
  - E.g., to verify block C, need only R, N, I, C, & D

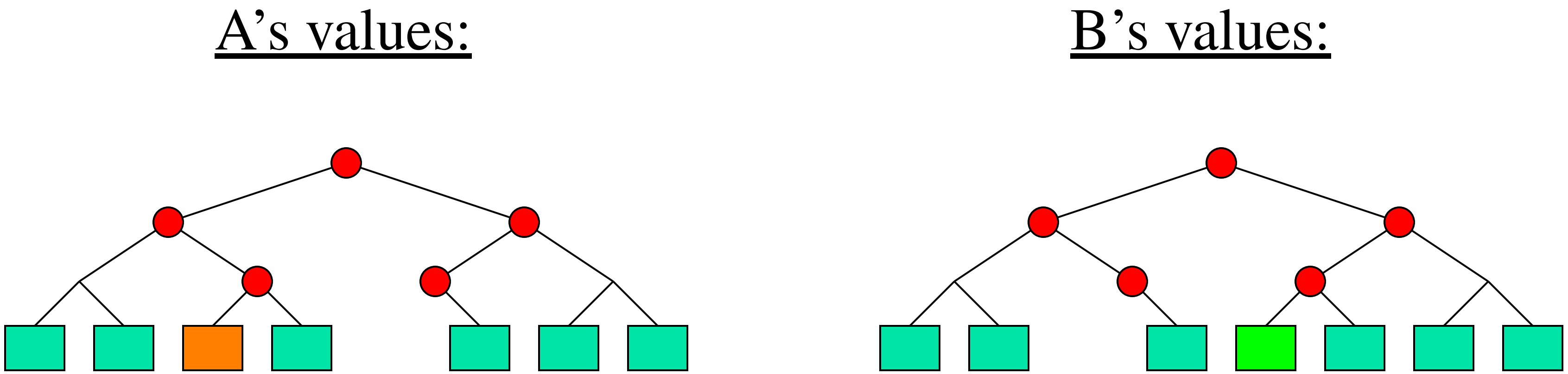


One use: enables client to verify integrity of data stored in a cloud

Using Merkle Trees as Summaries

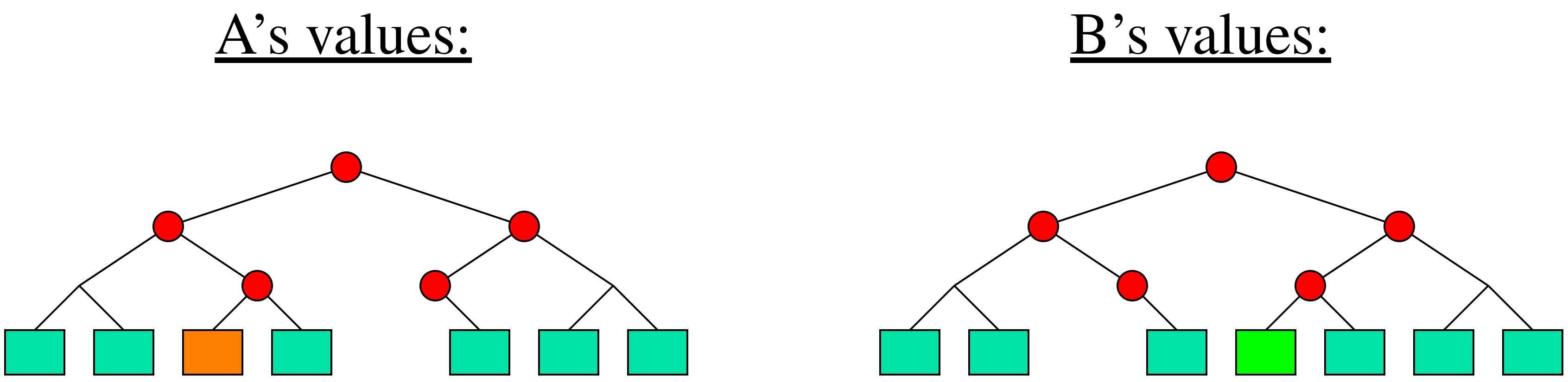
- Use Merkle tree to accelerate set comparison (and identify differences)
  - B gets tree root from A, if same as local root, done
  - Otherwise, recurse down tree to find difference

[assumption: sets diverge little]



Using Merkle Trees as Summaries

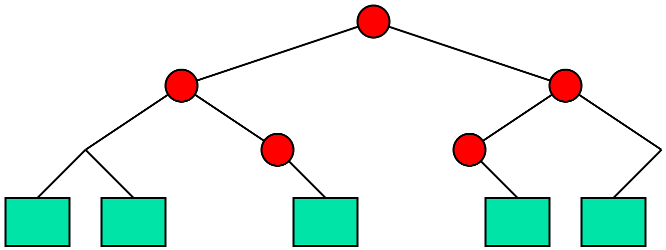
- Use Merkle tree to accelerate set comparison (and identify differences)
  - B gets tree root from A, if same as local root, done
  - Otherwise, recurse down tree to find difference
- New cost is O(d log C)
  - d = number of differences, C = size of disk



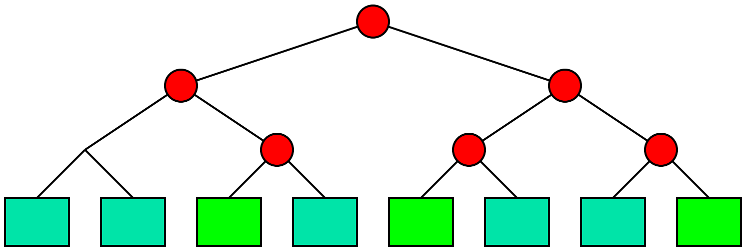
Using Merkle Trees as Summaries

- Still too costly:
  - If A is down for an hour, then comes back, changes will be randomly scattered throughout tree

A's values:



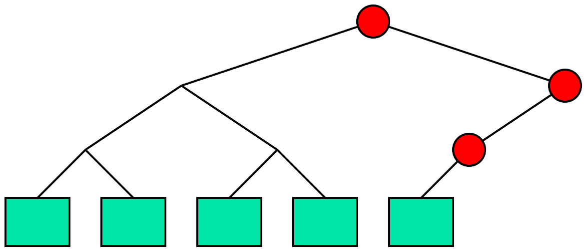
B's values:



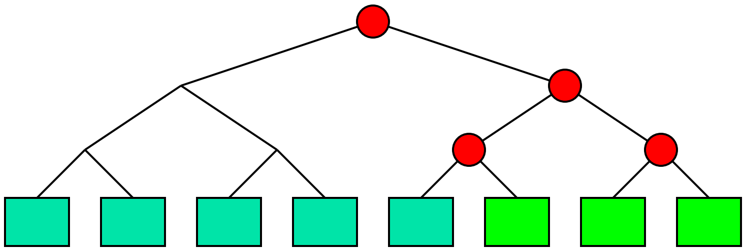
Using Merkle Trees as Summaries

- Still too costly:
  - If A is down for an hour, then comes back, changes will be randomly scattered throughout tree
- Solution: order values by time instead of hash
  - Localizes values to one side of tree

A's values:



B's values:



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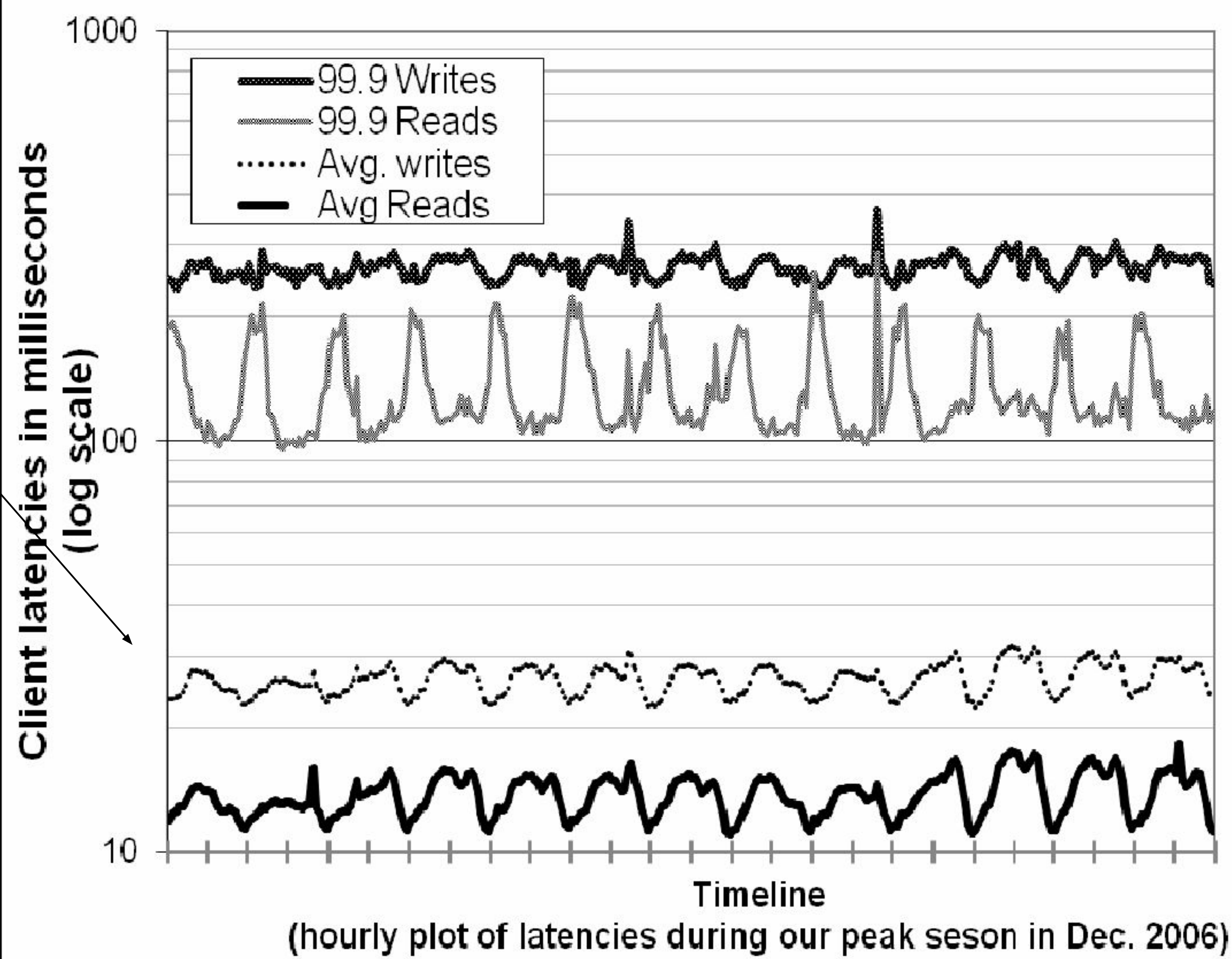
Dynamo Implementation

- Java
  - non-blocking IO
- Local persistence component allows for different storage engines to be plugged in:
  - Berkeley Database (BDB) Transactional Data Store: object of tens of kilobytes
  - MySQL: larger objects

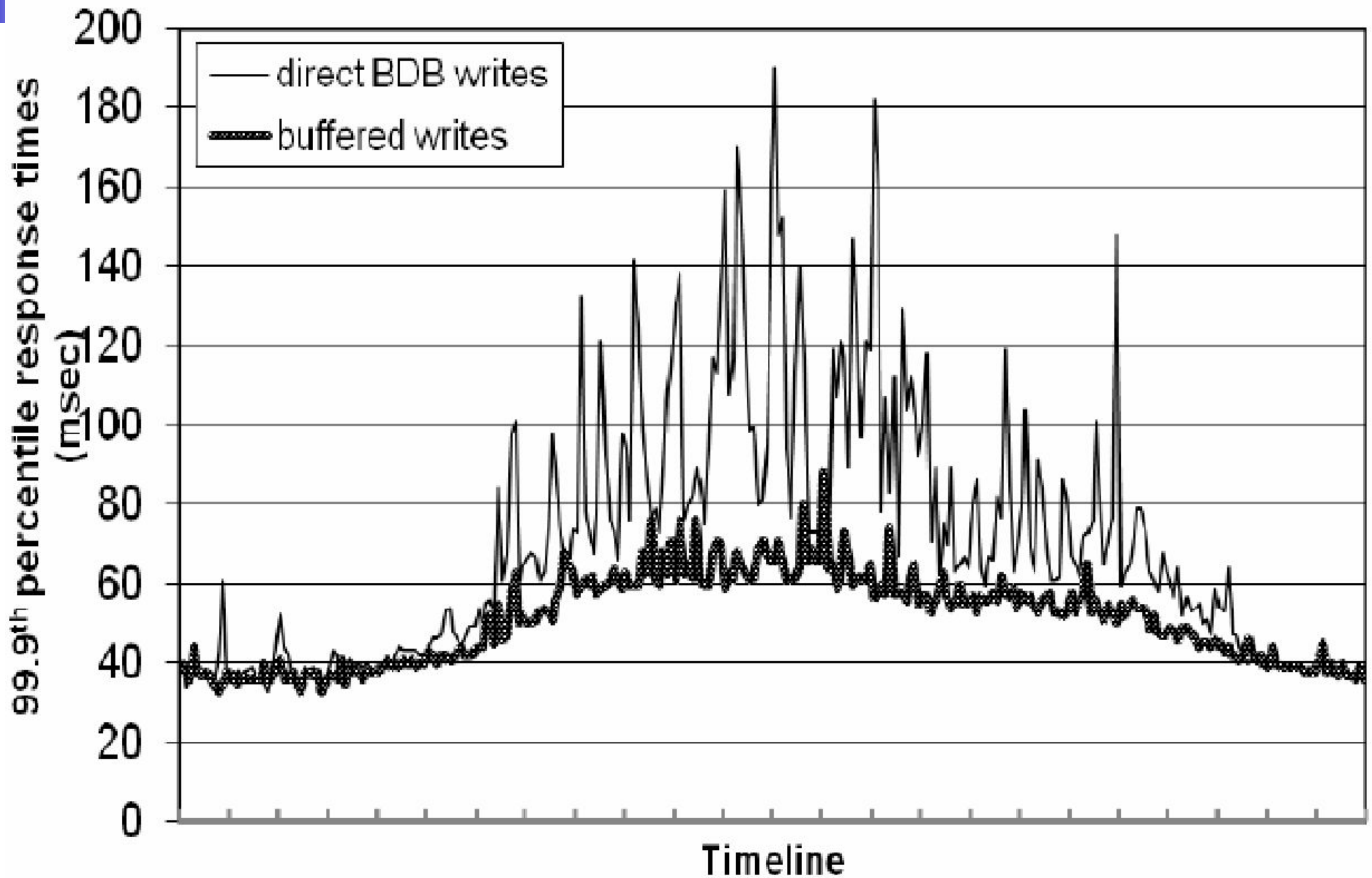
- Quorum choices (N,W,R) □ influence object availability, durability, consistency

Performance evaluation

Writes



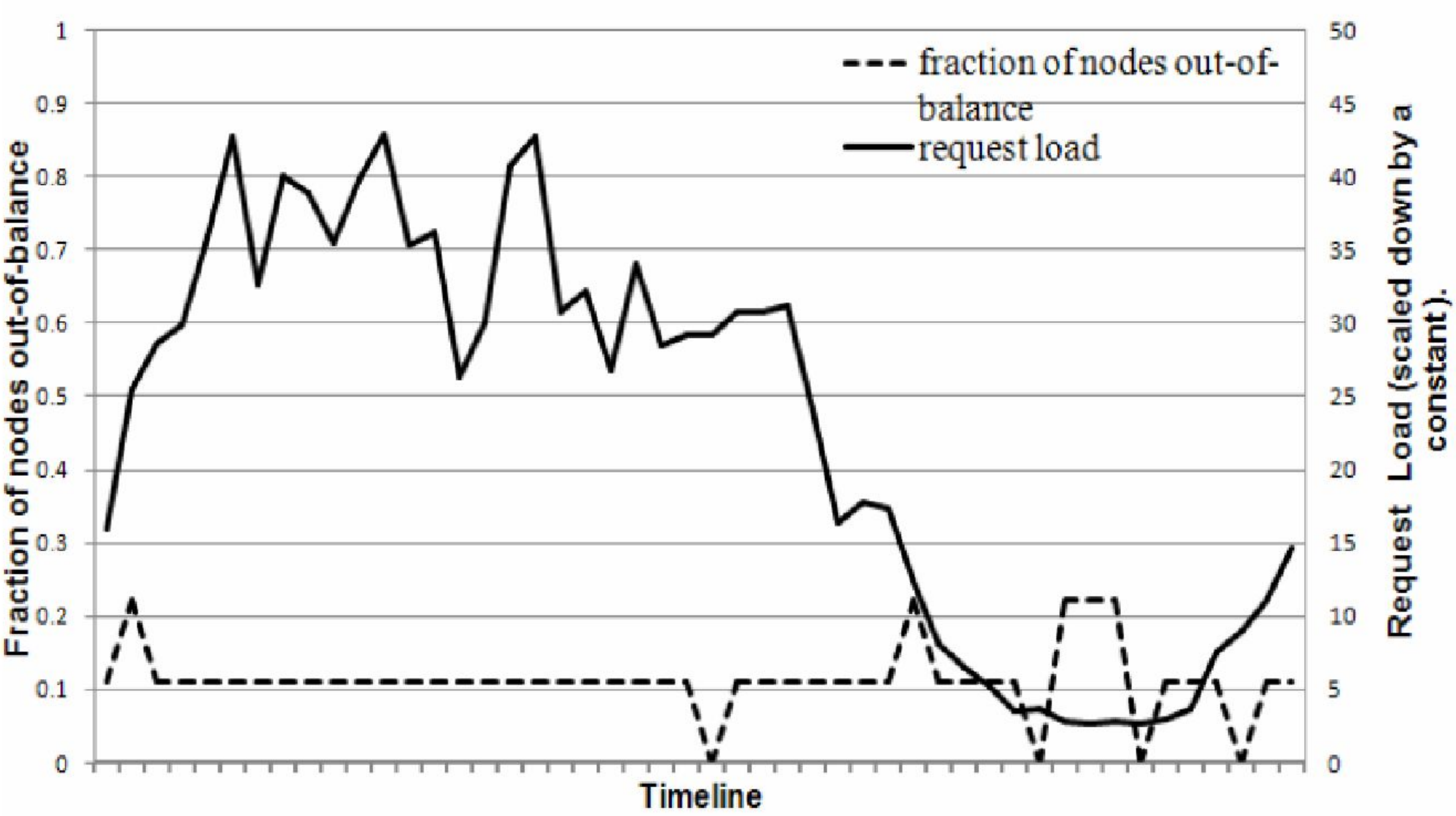
Trading between latency & durability



Comparison of performance of 99.9th %-tile latencies for buffered vs. non-buffered writes over 24 hours. The intervals between consecutive ticks in the x-axis correspond to one hour.

Load balance

~~out-of-balance~~: nodes with request load above 15% from the average system load



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1 version ☐ 99.94%

2 versions ☐ 0.0057%

3 versions ☐ 0.00047%

4 versions ☐ 0.00007

Source: High volume of concurrent writes … robots?

Problem	Technique	Advantage
Partitioning	Consistent Hashing	Incremental Scalability
High Availability for writes	▪ Eventual consistency ▪ Vector clocks with reconciliation during reads	Version size is decoupled from update rates.
Handling temporary failures	▪ ‘Sloppy’ quorum and hinted handoff	Provides high availability and durability guarantee when some of the replicas are not available.
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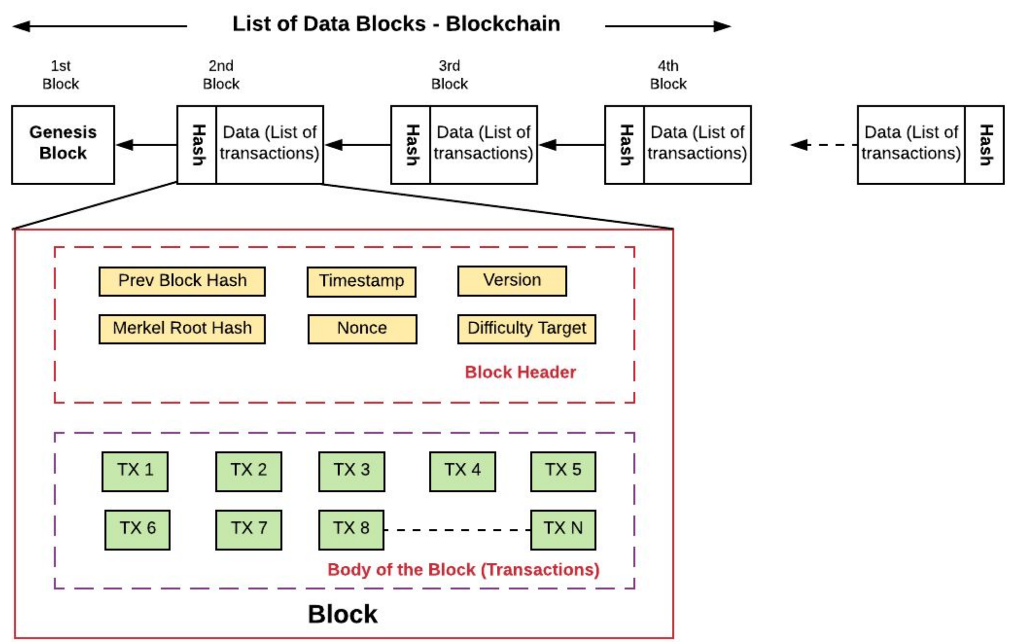
Large set *S*: say 1M elements, each element 1KB-1MB

- P1: Need to test for differences between two sets
  - isDifferent (S1, S2) ☐ list of differences
- P2: You also know that if there is a difference between S1 and S2, it's small
- Bonus: Verifiable proof of membership



Gilbert/Lynch theorems

Theorem 1: It is impossible in the **asynchronous** network model to implement a read/write object store that guarantees

- Availability AND
- Atomic consistency

in all executions (including those in which messages are lost)

asynchronous networks: no clocks, message delays unbounded

Gilbert/Lynch theorems

Theorem 2: It is impossible in the **partially synchronous** network model to implement a read/write object store that guarantees

- Availability AND
- Atomic consistency

in all executions (including those in which messages are lost)

partially synchronous network model. Bounds on:

- a) time it takes to deliver messages that are NOT lost, and
- b) message processing time

exist and are known, **but process clocks are not synchronized**