Dynamo: Amazon’s Highly Available Key-value Store

ID2210-VT13

Slides by Tallat M. Shafaat

Dynamo

- An infrastructure to host services
- Reliability and fault-tolerance at massive scale
- Availability providing an ”always-on” experience
- Cost-effectiveness
- Performance

Context

- Amazon's e-commerce platform
  - Shopping cart served tens of millions requests, over 3 million checkouts in a single day
- Unavailability == $$$

- No complex queries
- Managed system
  - Add/remove nodes
  - Security
  - Byzantine nodes

CAP Theorem

- Only two possible at the same time
  - Consistency
  - Availability
  - Partition-tolerance

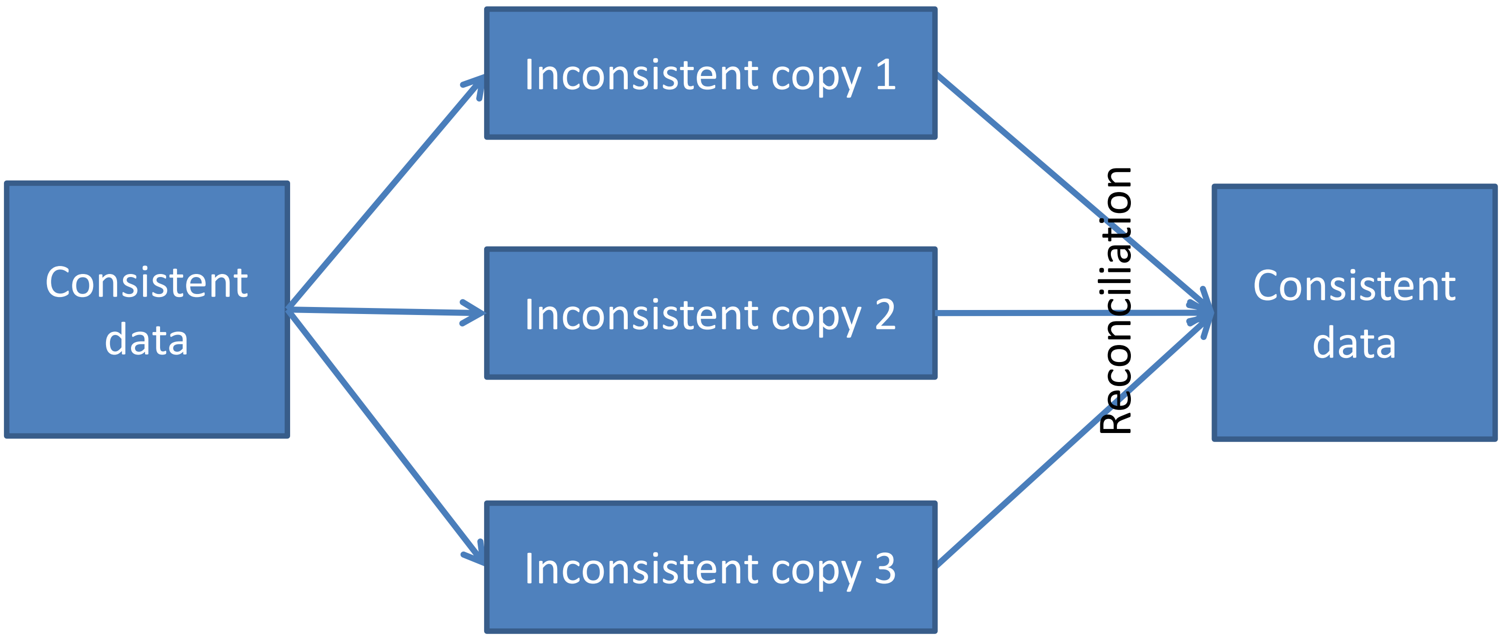
- Dynamo, target applications:
  - Availability and Parition-tolerance
  - Eventual consistency

Clients view on Consistency

- Strong consistency.
  - Single storage image. After the update completes, any subsequent access will return the updated value.
- Weak consistency.
  - The system does not guarantee that subsequent accesses will return the updated value.
  - Inconsistency window.
- Eventual consistency.
  - Form of weak consistency
  - If no new updates are made to the object, eventually all accesses will return the last updated value.

Eventual consistency

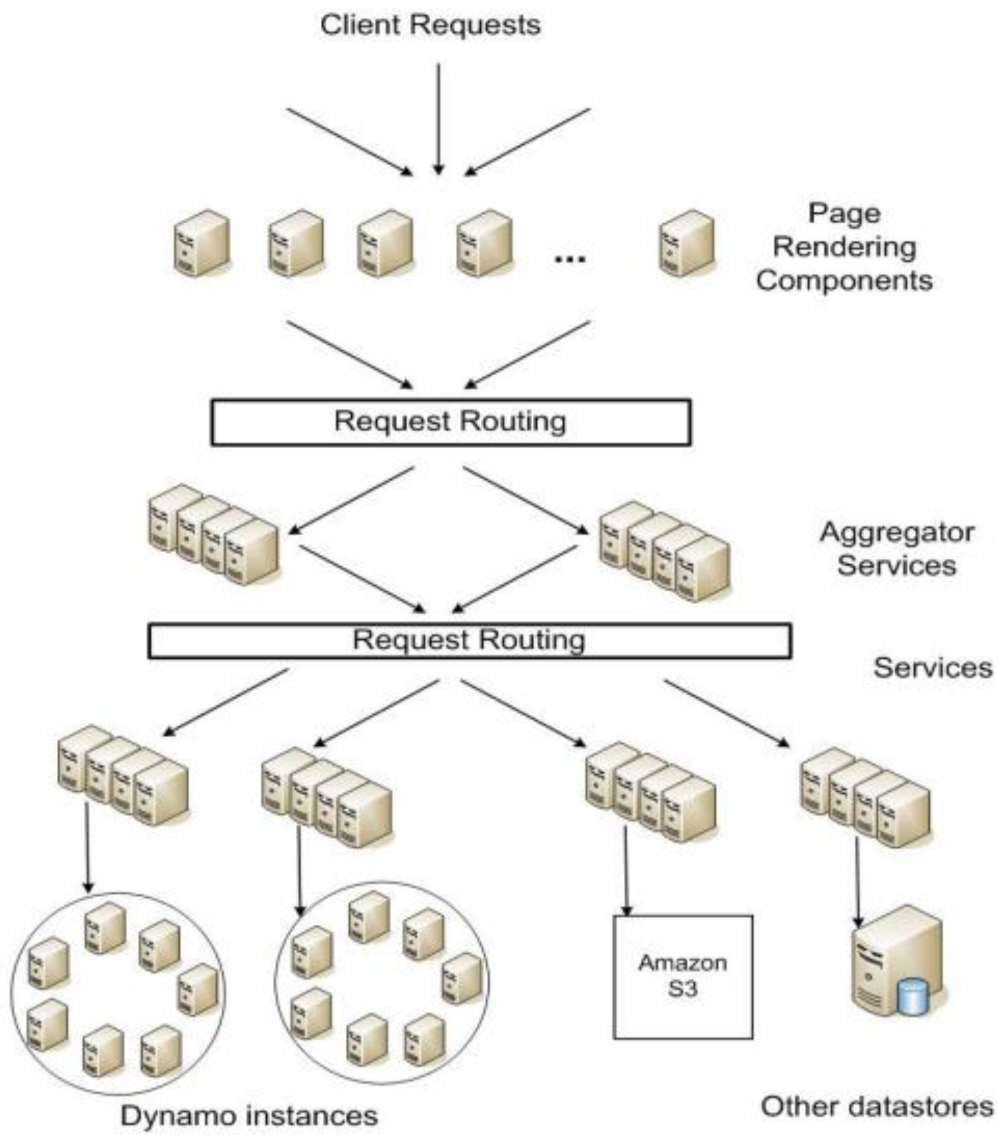
- Causal consistency
- Read-your-writes consistency
- …



Requirements

- Query model
  - Simple read/write operations on small data items
- ACID properties
  - Weaker consistency model
  - No isolation, only single key updates
- Efficiency
  - Tradeoff between performance, cost efficiency, availability and durability guarantees

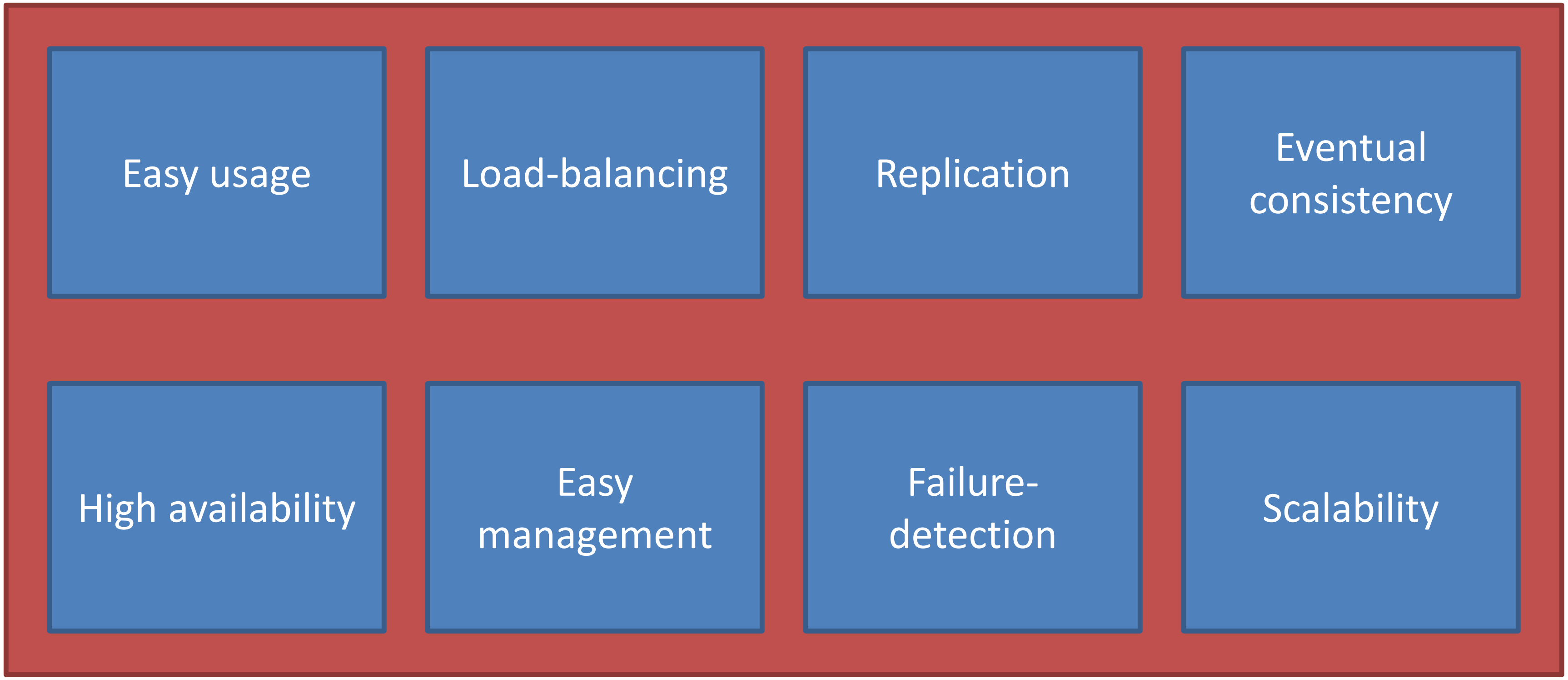
Amazon Store Architecture



Design considerations

- Conflict resolution
  - When
  - Who
- Scalability
- Symmetry
- Decentralization
- Heterogeneity

The big picture

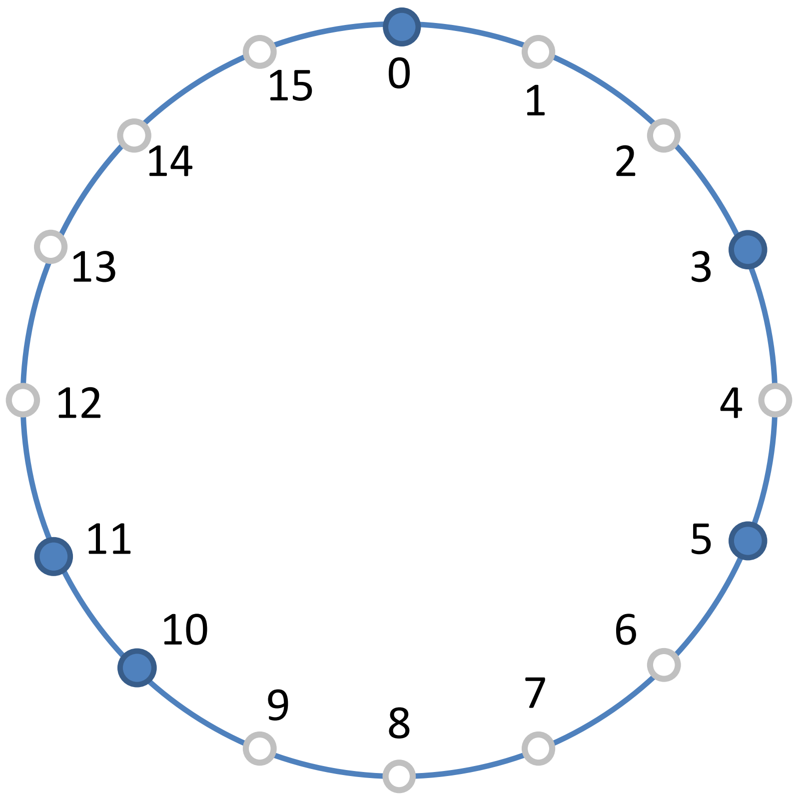


Easy usage: Interface

- get(key)
  - return single object or list of objects with conflicting version and context
- put(key, context, object)
  - store object and context under key
- Context encodes system meta-data, e.g. version number

Data partitioning

- Based on consistent hashing
- Hash key and put on responsible node



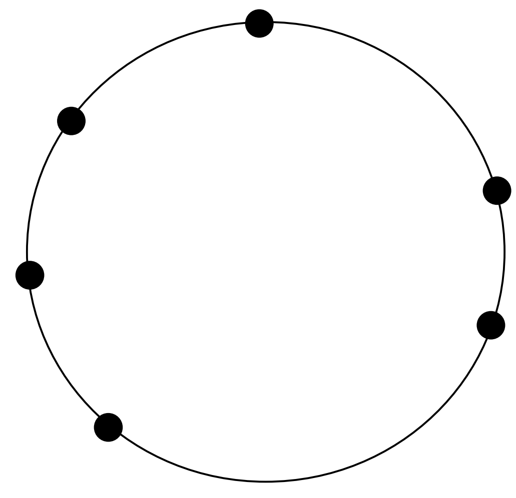
Load balancing

- Load
  - Storage bits
  - Popularity of the item
  - Processing required to serve the item
  - …

- Consistent hashing may lead to imbalance

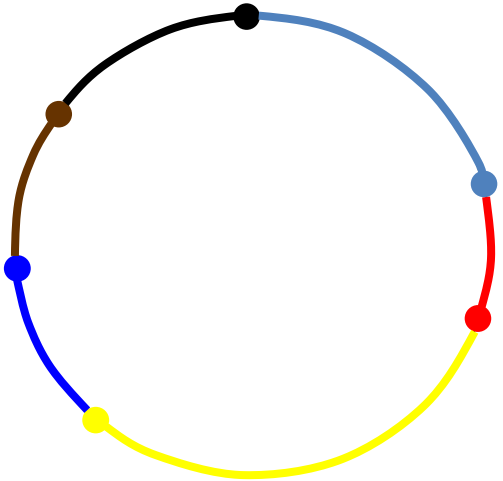
Load imbalance (1/5)

- Node identifiers may not be balanced



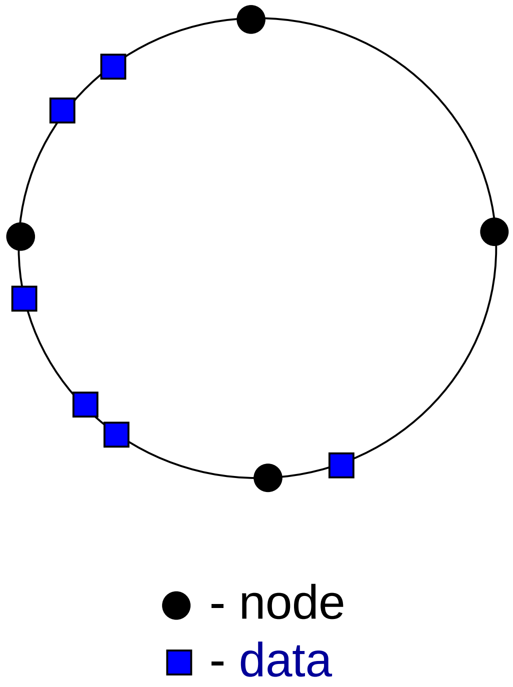
Load imbalance (2/5)

- Node identifiers may not be balanced



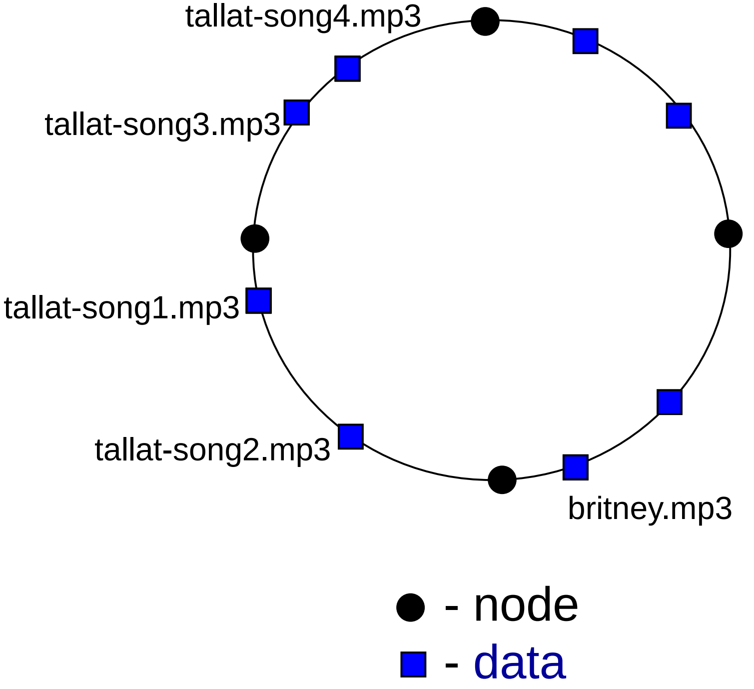
Load imbalance (3/5)

- Node identifiers may not be balanced
- Data identifiers may not be balanced



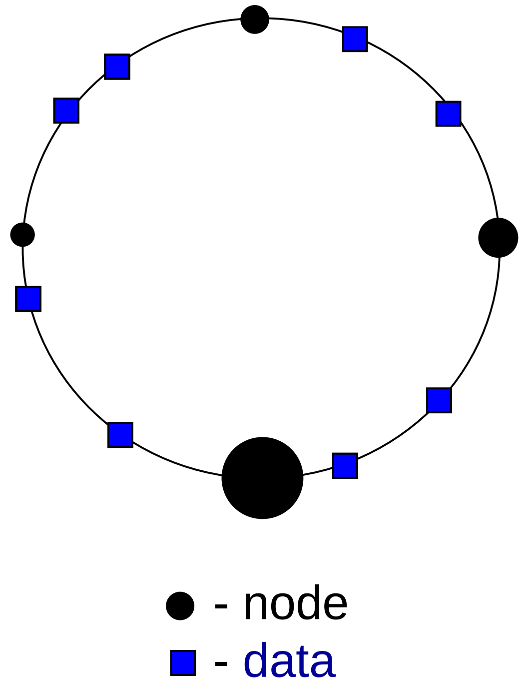
Load imbalance (4/5)

- Node identifiers may not be balanced
- Data identifiers may not be balanced
- Hot spots



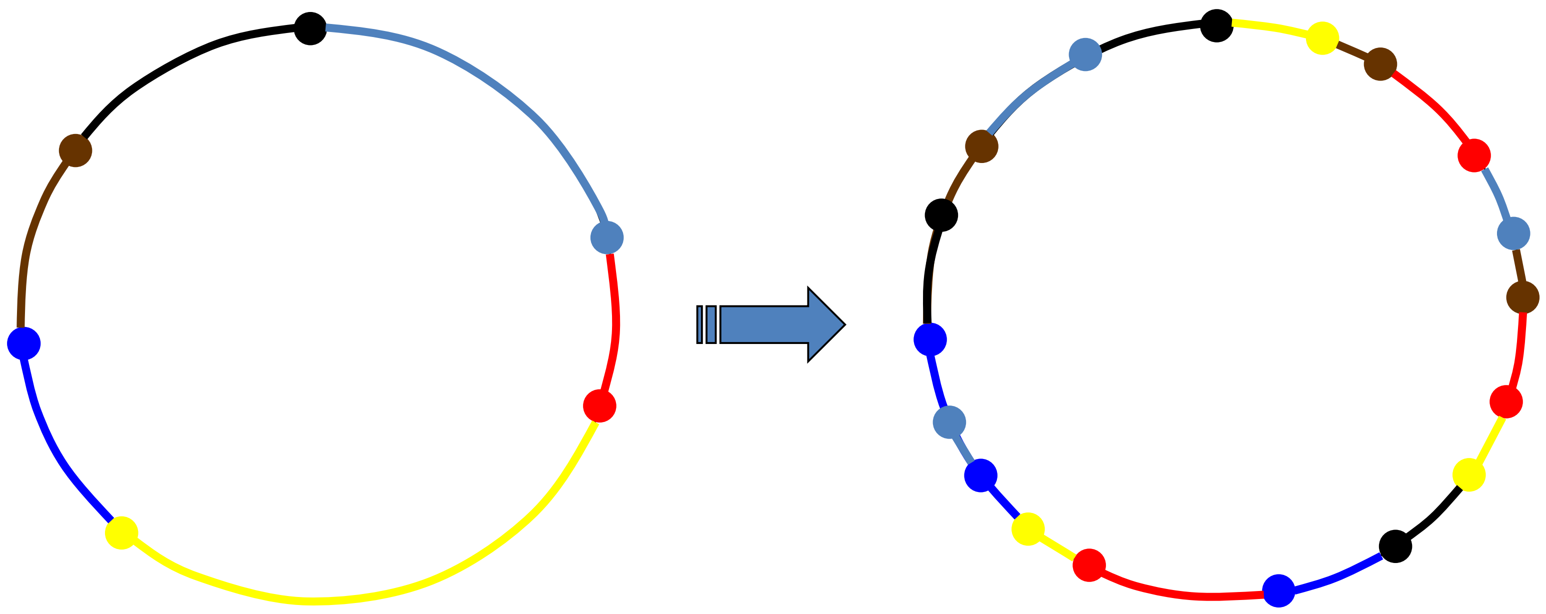
Load imbalance (5/5)

- Node identifiers may not be balanced
- Data identifiers may not be balanced
- Hot spots
- Heterogeneous nodes



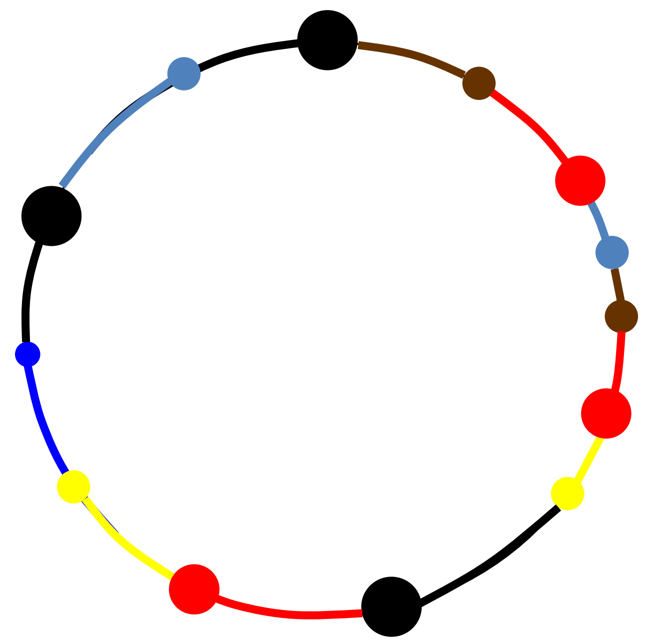
Load balancing via Virtual Servers

- Each physical node picks multiple random identifiers
  - Each identifier represents a virtual server
  - Each node runs multiple virtual servers
- Each node responsible for noncontiguous regions



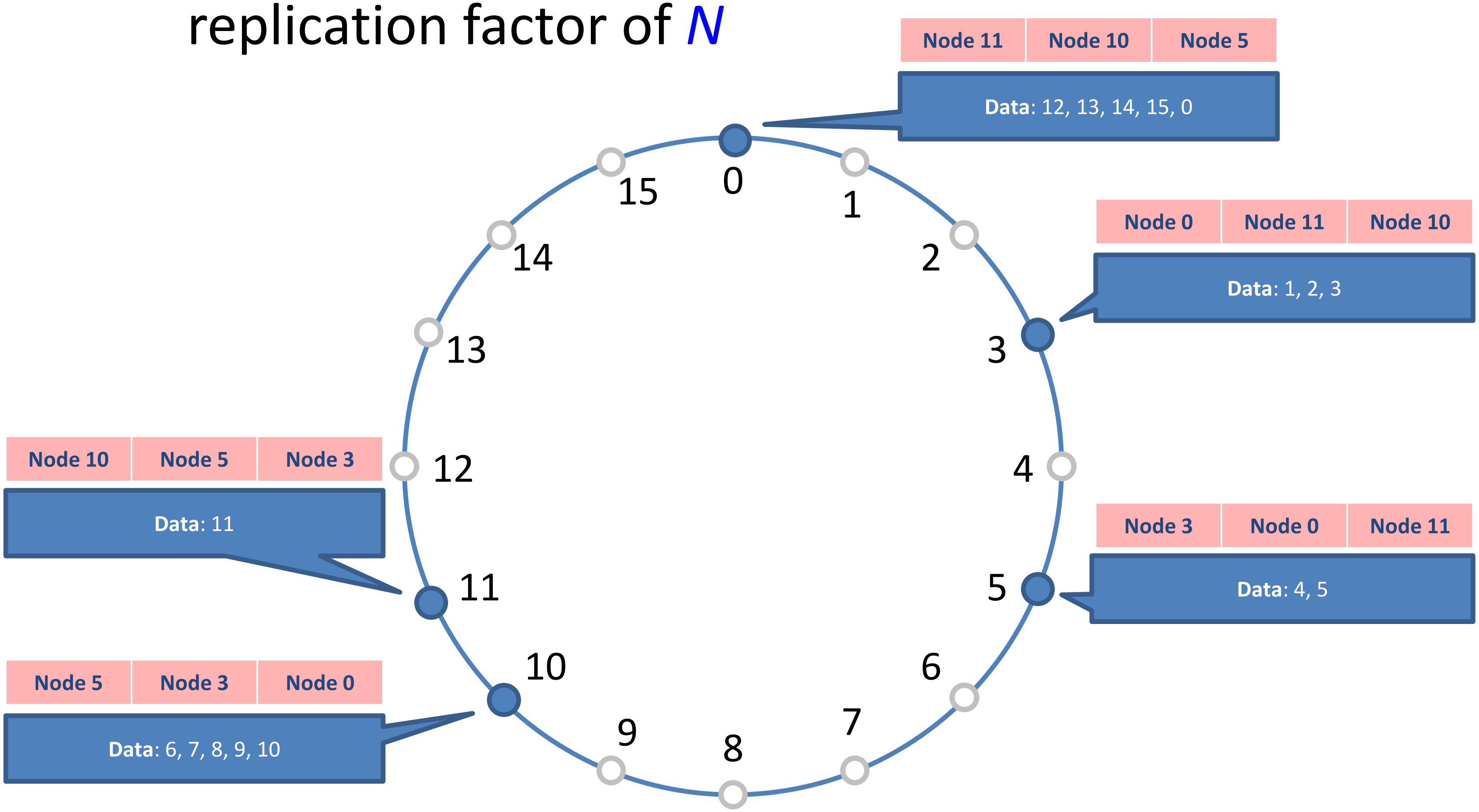
Virtual Servers

- How many virtual servers?
  - For homogeneous, all nodes run **log N** virtual servers
  - For heterogeneous, nodes run **clogN** virtual servers, where ‘c’ is
    - small for weak nodes
    - large for powerful nodes
- Move virtual servers from heavily loaded physical nodes to lightly loaded physical nodes

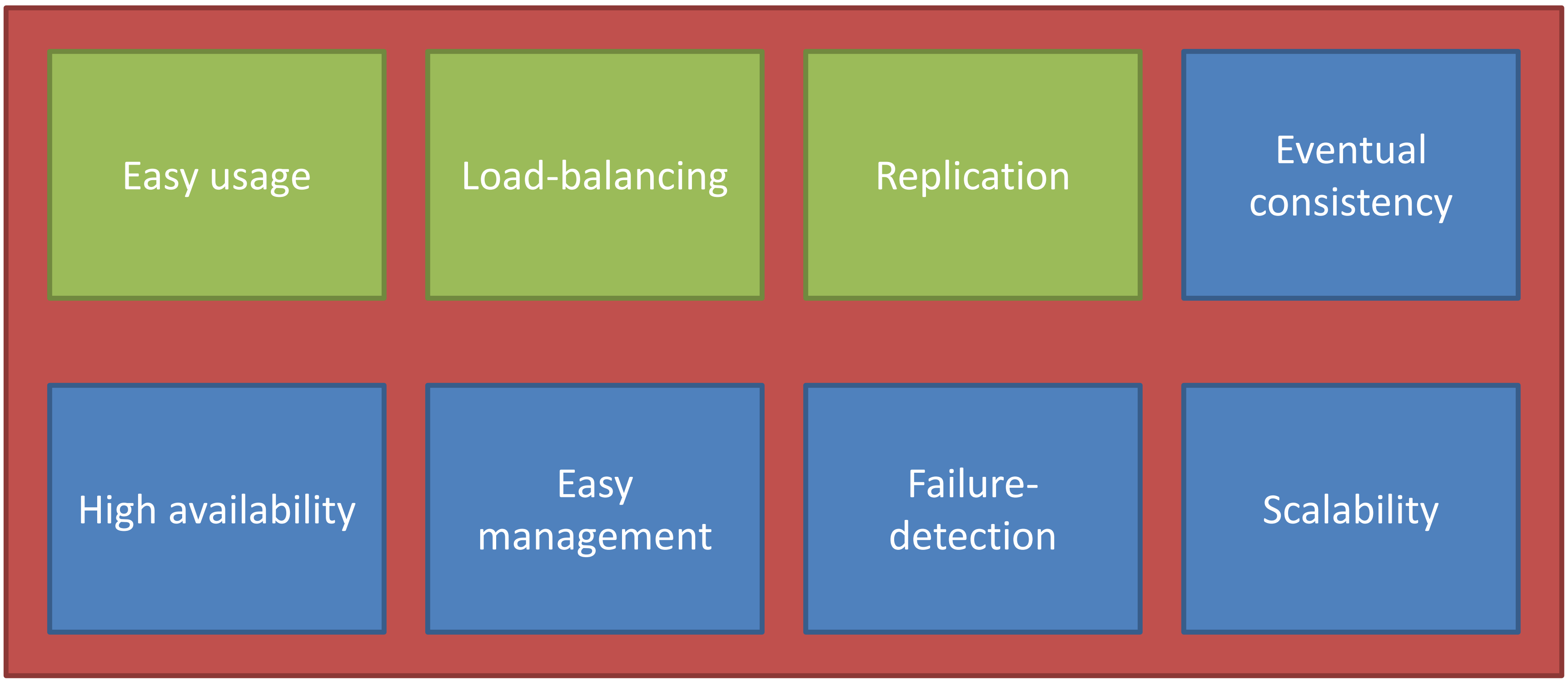


Replication

- Successor list replication
  - Replicate the data of your *N* closest neighbors for a replication factor of *N*



The big picture



Data versioning (1/3)

- Eventual consistency, updates propagated asynchronously
- Each modification is a new and immutable version of the data
  - Multiple versions of an object
- New versions can subsume older versions
  - Syntactic reconciliation
  - Semantic reconciliation

Data versioning (2/3)

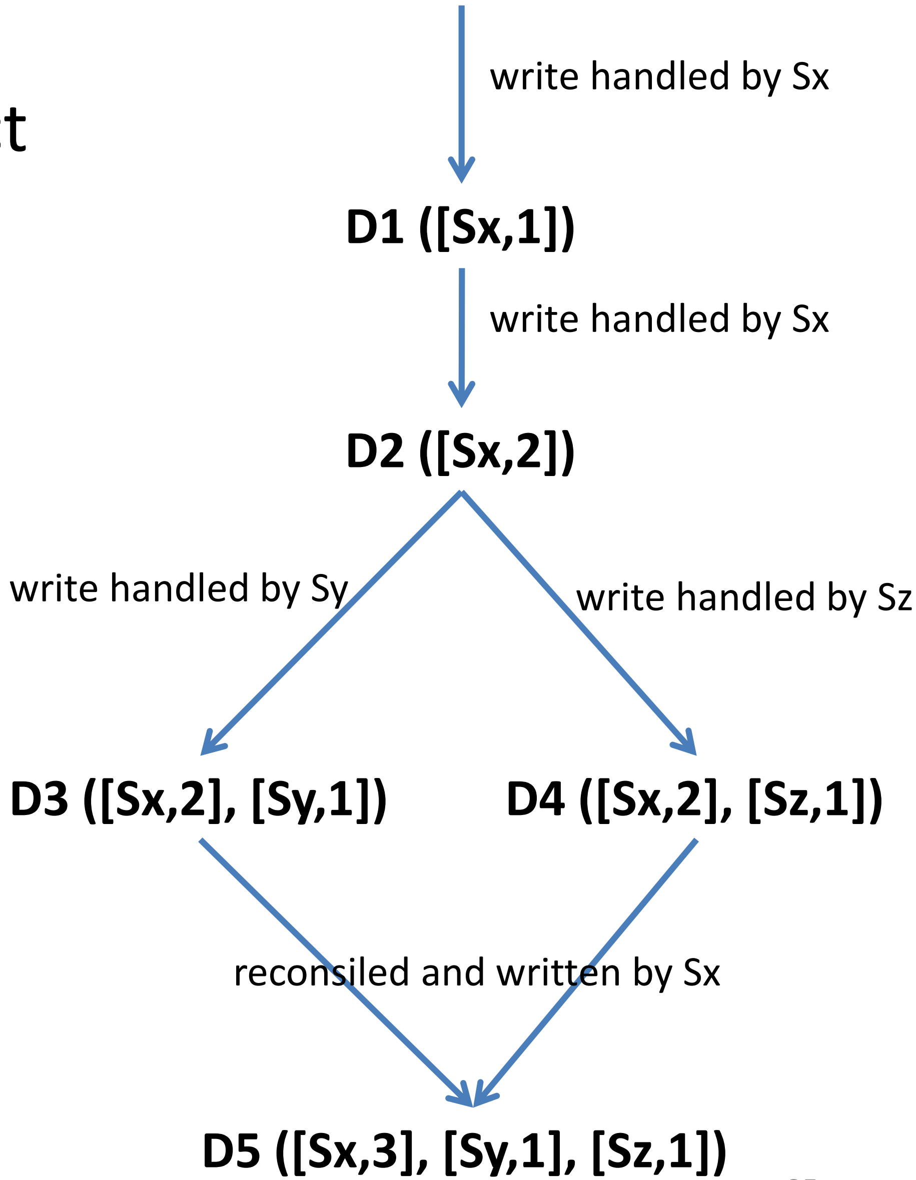
- Version branching due to failures, network partitions, etc.
- Target applications aware of multiple versions

- Use vector clocks for capturing causality
  - If causal, older version can be forgotten
  - If concurrent, conflict exists requiring reconciliation

- A put requires a context, i.e. which version to update

Data versioning (3/3)

- Client C1 writes new object
  - say via Sx
- C1 updates the object
  - say via Sx
- C1 updates the object
  - say via Sy
- C2 reads D2 and updates the object
  - Say via Sz
- Reconciliation



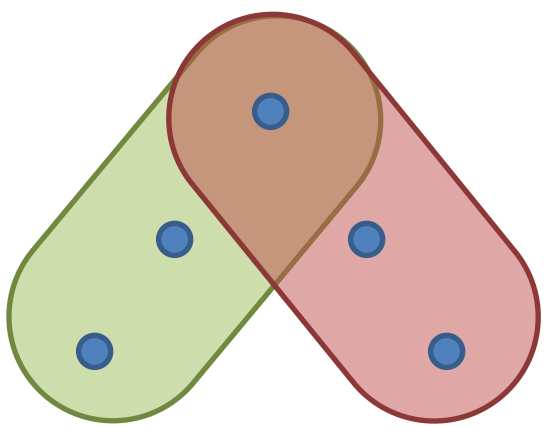
Execution of operations

- put and get operations

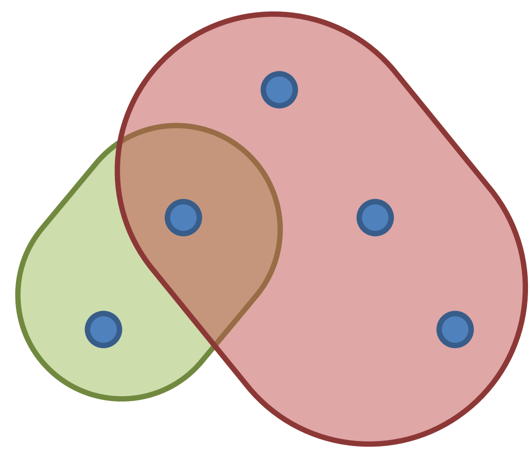
- Client can send the request
  - to the node responsible for the data
    - Save on latency, code on client
  - to a generic load balancer
    - Extra hop

Quorum systems

- R / W : minimum number of nodes that must participate in a successul read / write
- R + W > N (overlap)



R=3, W=3, N=5



R=4, W=2, N=5

put (key, value, context)

- Coordinator generates new vector clock and writes the new version locally
- Send to N nodes
- Wait for response from W-1 nodes

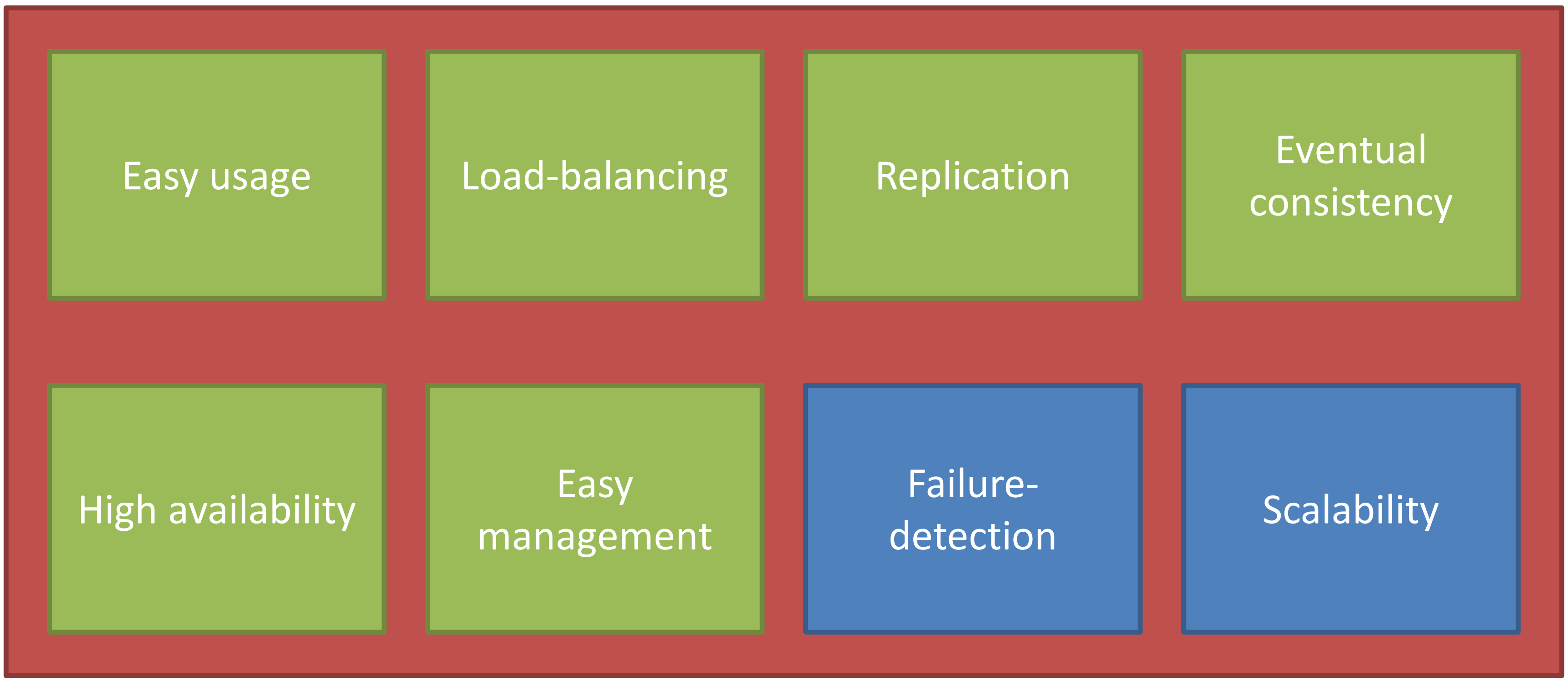
- Using W=1
  - High availability for writes
  - Low durability

(value, context) $\leftarrow$ get (key)

- Coordinator requests existing versions from N
- Wait for response from R nodes
- If multiple versions, return all versions that are causally unrelated
- Divergent versions are then reconciled
- Reconciled version written back

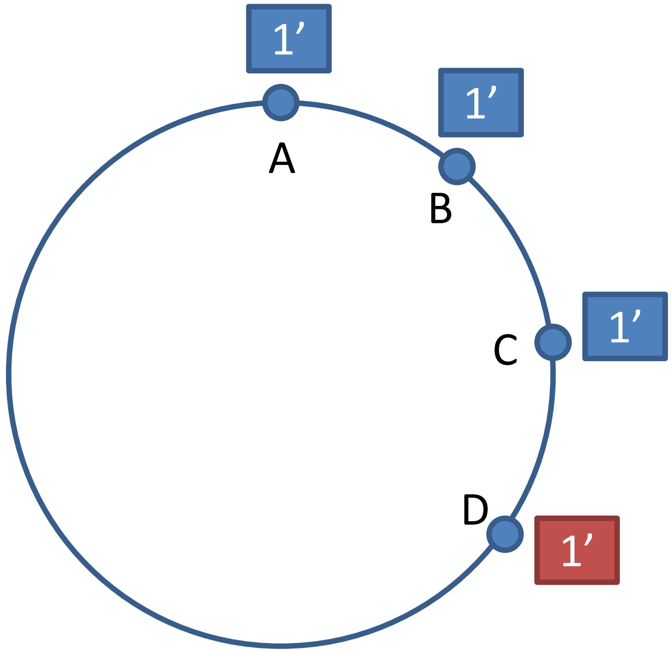
- Using R=1
  - High performance read engine

The big picture

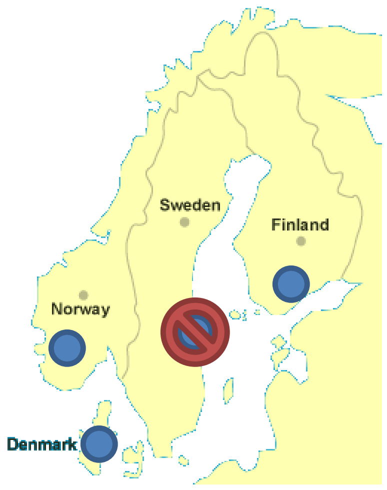


Handling transient failures

- A managed system
- Which N nodes to update?
- Say A is unreachable
- ’put’ will use D
- Later, D detects A is alive
  - send the replica to A
  - remove the replica

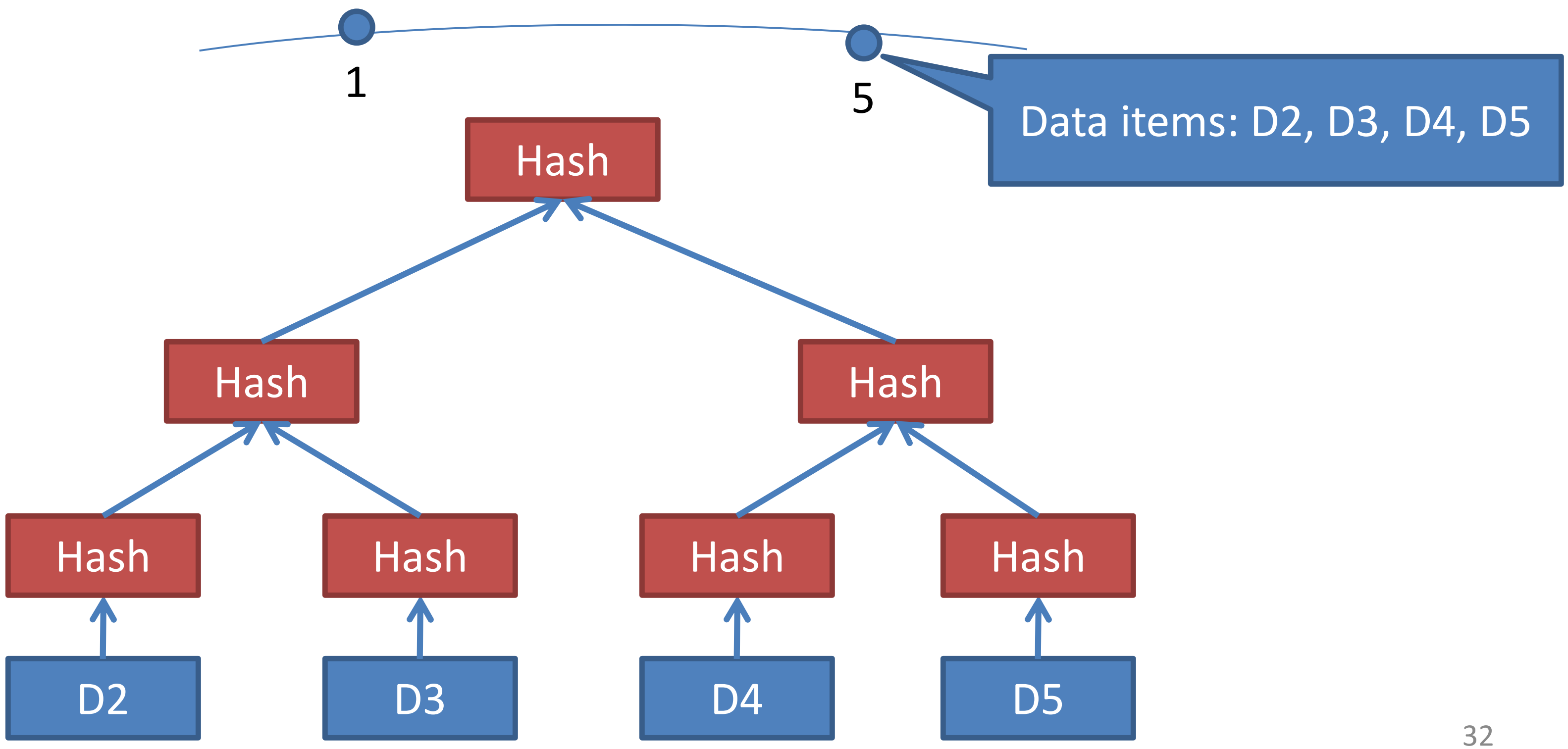


- Tolerate failure of a data center
  - Each object replicated across multiple data centers



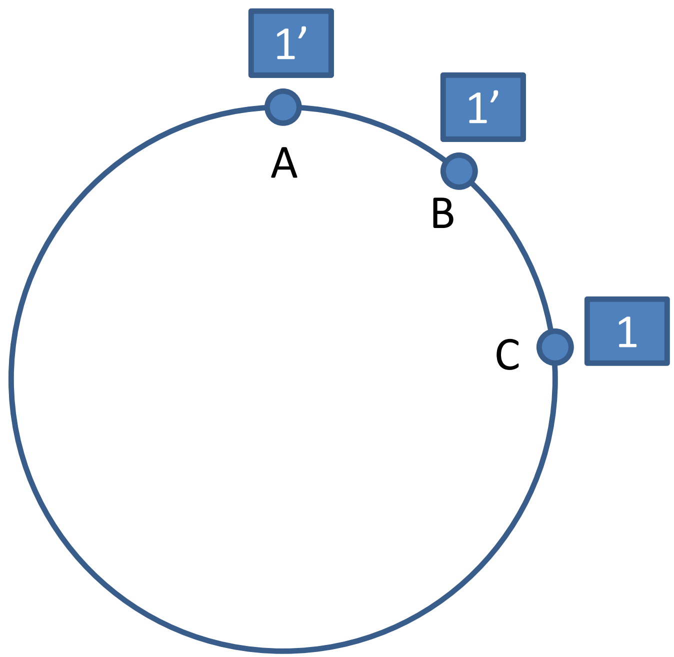
Handling permanent failures (1/2)

- Anti-entropy for replica synchronization
- Use Merkle trees for fast inconsistency detection and minimum transfer of data



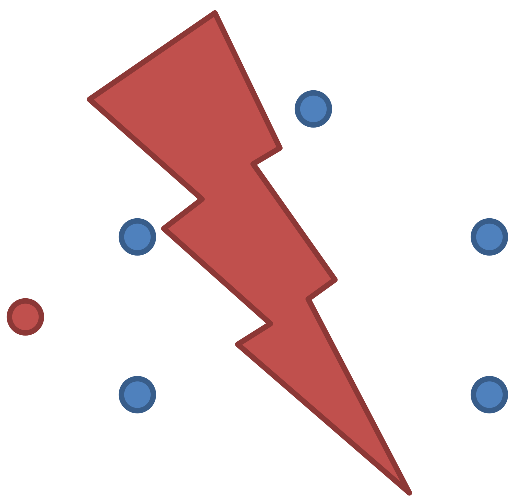
Handling permanent failures (2/2)

- Nodes maintain Merkle tree of each key range
- Exchange root of Merkle tree to check if the key ranges are up-to-date



Quorums under failures systems

- Due to partitions, quorums might not exist
- Create transient replicas
- Reconcile after partition heals



R=3, W=3, N=5

Membership

- A managed system
  - Administrator explicitly adds and removes nodes
- Receiving node stores changes with time stamp
- Gossiping to propagate membership changes
  - Eventually consistent view
  - O(1) hop overlay
    - log(n) hops, e.g. n=1024, 10 hops, 50ms/hop, 500ms

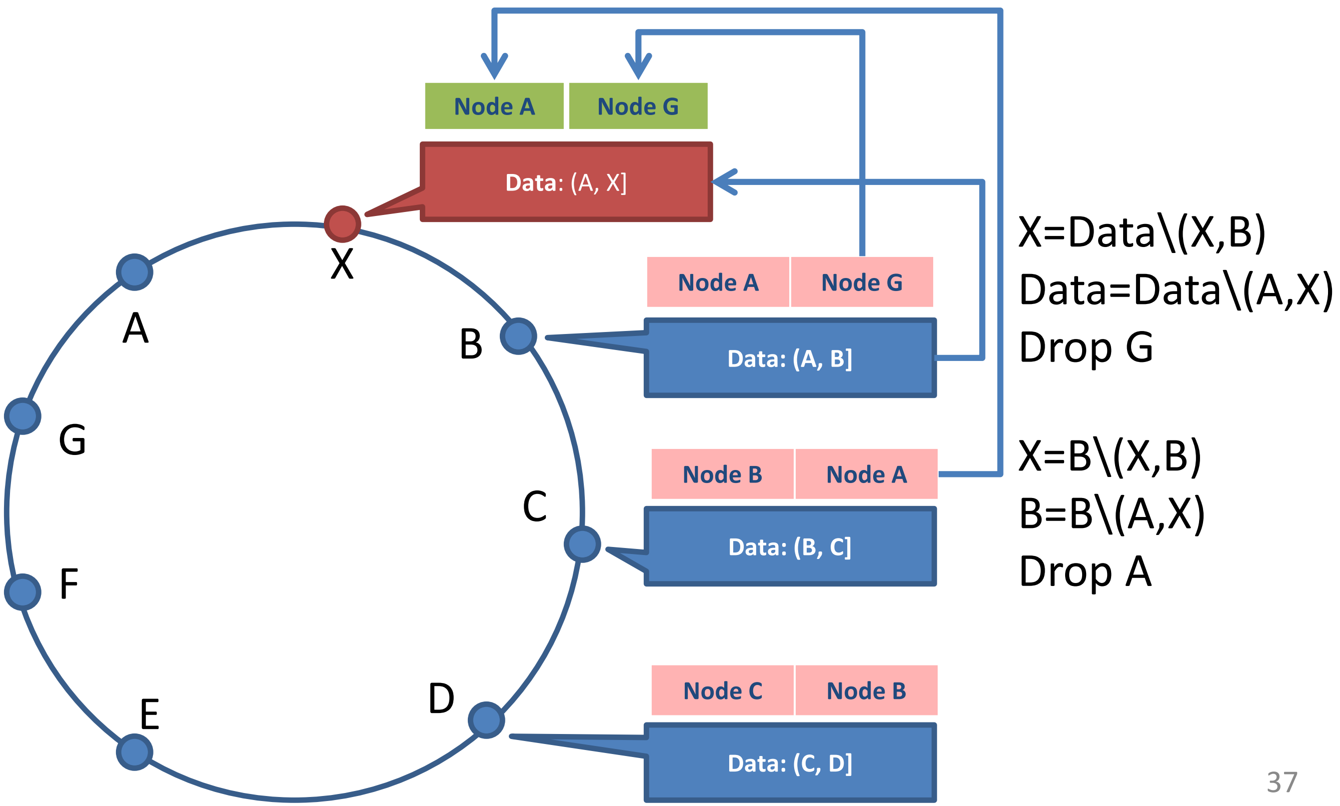
Failure detection

- Passive failure detection
  - Use pings only for detection from failed to alive
  - A detects B as failed if it doesnt respond to a message
  - A periodically checks if B is alive again

- In the absense of client requests, A doesn't need to know if B is alive
  - Permanent node additions and removals are explicit

Adding nodes

- A new node X added to system
- X is assigned key ranges w.r.t. its virtual servers
- For each key range, it transfers the data items



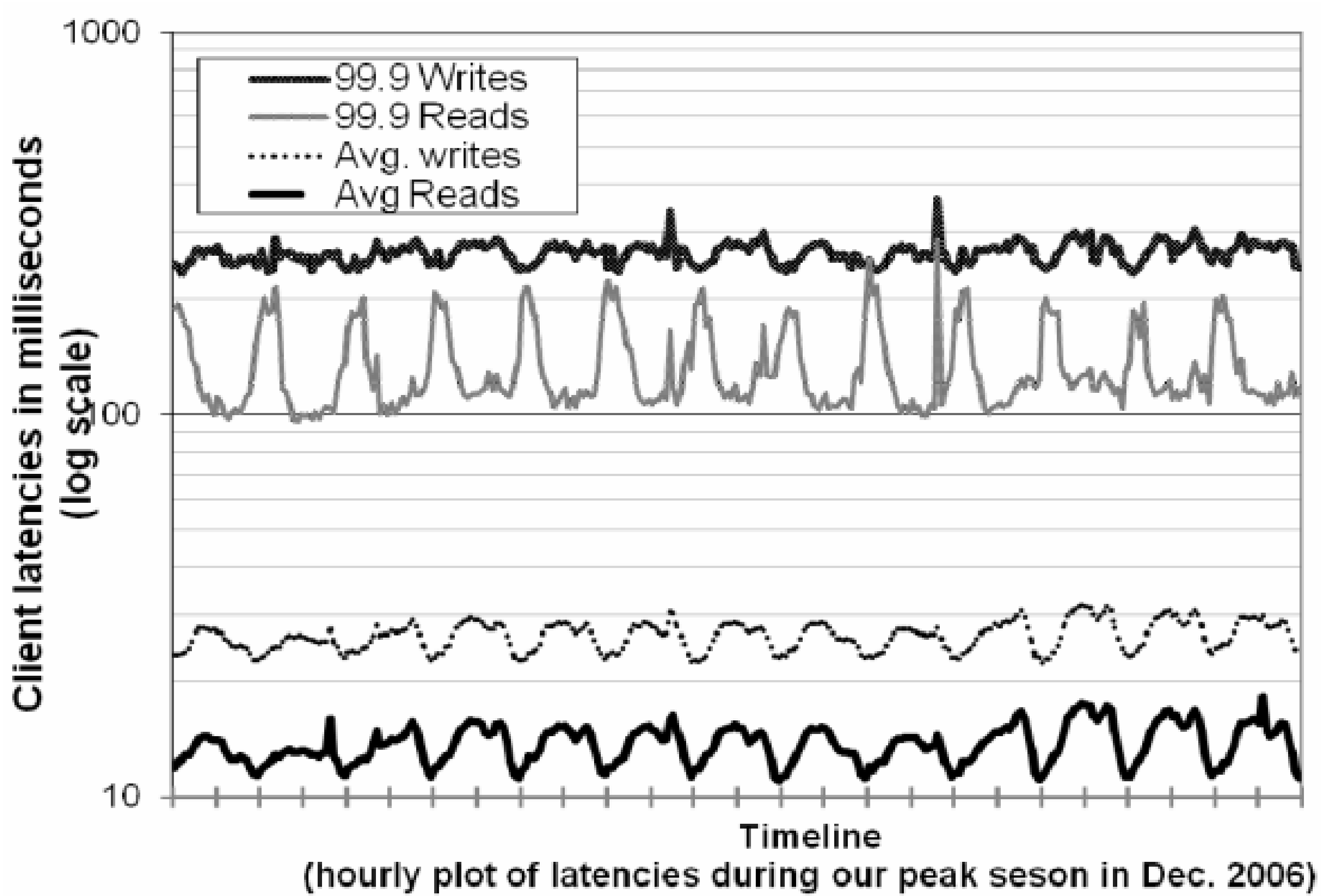
Removing nodes

- Reallocation of keys is a reverse process of adding nodes

Implementation details

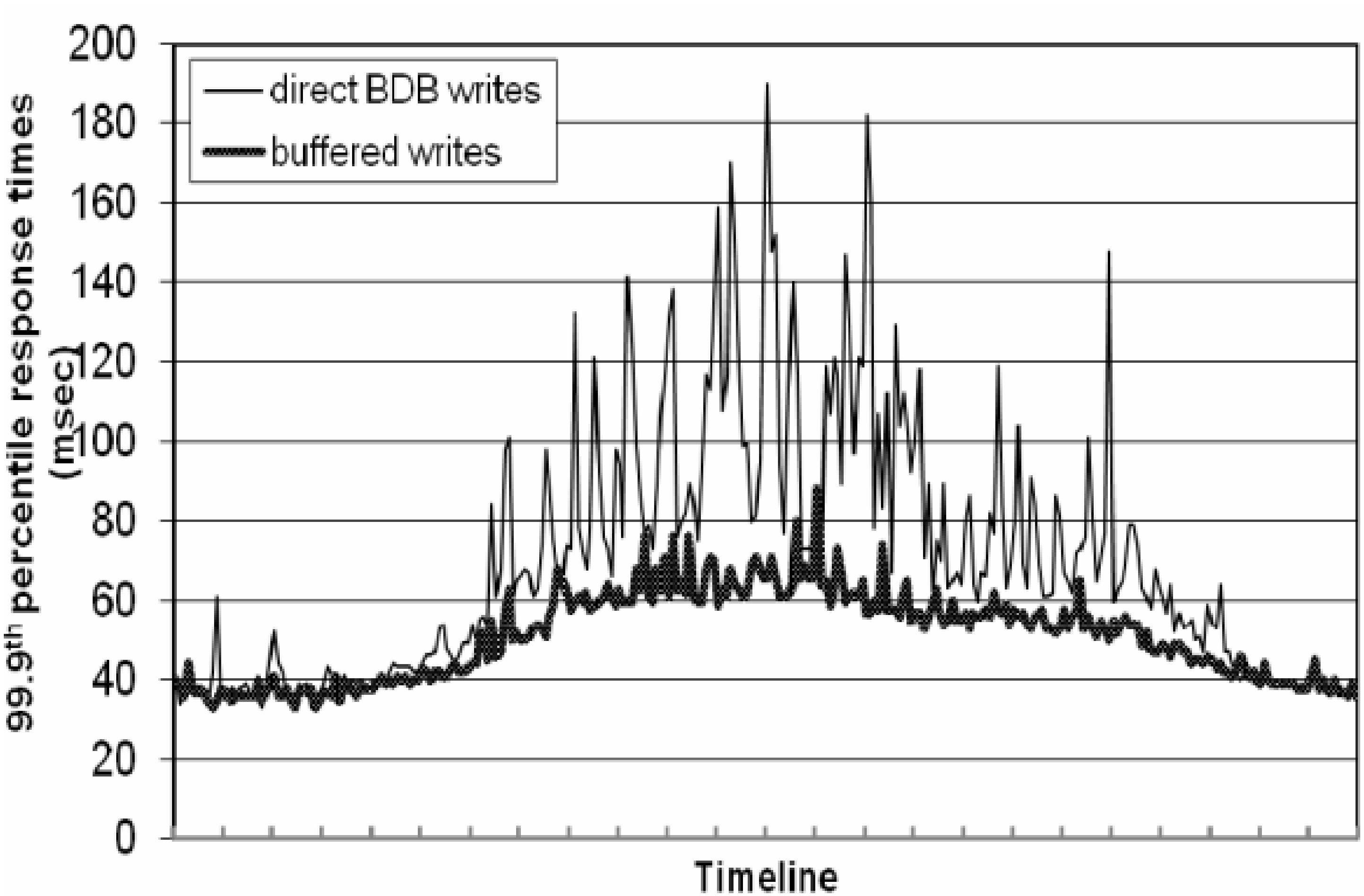
- Local persistence
  - BDS, MySQL, etc.
- Request coordination
  - Read operation
    - Create context
    - Syntactic reconciliation
    - Read repair
  - Write operation
    - Read-your-writes

Evaluation



1000
100
10
99.9 Writes
99.9 Reads
Avg. writes
Avg Reads
Client latencies in milliseconds (log scale)
Timeline
(hourly plot of latencies during our peak seson in Dec. 2006)

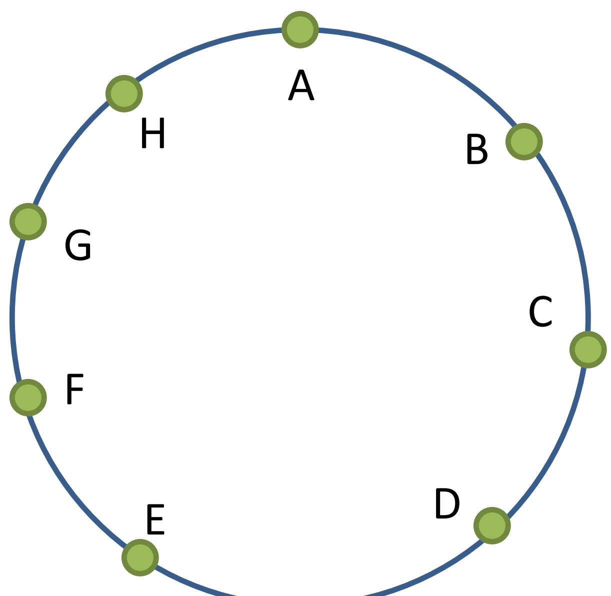
Evaluation



direct BDB writes
buffered writes
99.9th percentile response times (msec)
200
180
160
140
120
100
80
60
40
20
0
Timeline

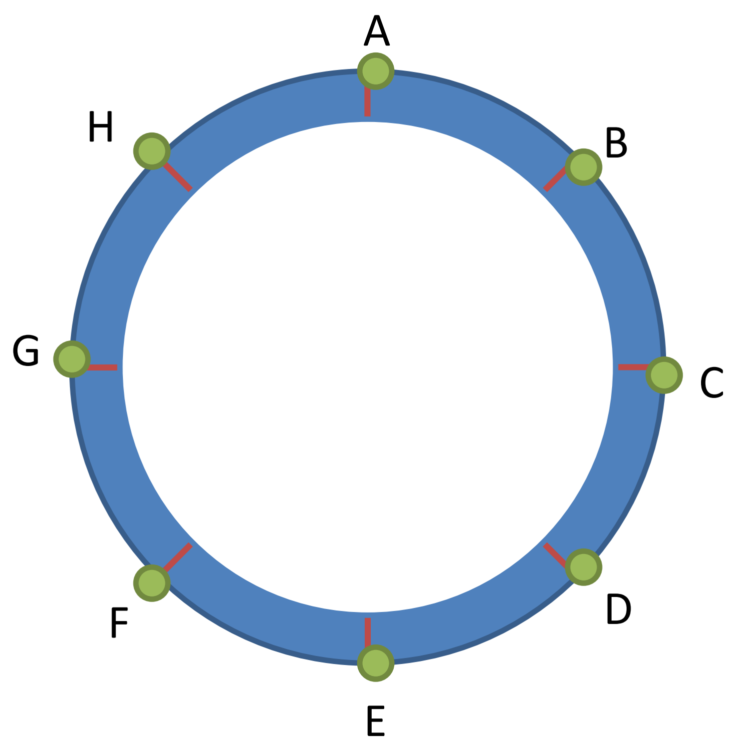
Partitioning and placement (1/2)

- Data ranges are not fixed
  - More time spend to locate items
  - More data storage needed for indexing
- Inefficient bootstrapping
- Difficult to archive the whole data



Partitioning and placement (2/2)

- Divide data space into equally sized ranges
- Assign ranges to nodes



Versions of an item

- Reason
  - Node failures, data center failures, network partitions
  - Large number of concurrent writes to an item
- Occurence
  - 99.94 % one version
  - 0.00057 % two versions
  - 0.00047 % three versions
  - 0.00009 % four versions
- Evaluation: versioning due to concurrent writes

Client vs Server coordination

- Read requests coordinated by any Dynamo node
- Write requests coordinated by a node replicating the data item

- Request coordination can be moved to client
  - Use libraries
  - Reduces latency by saving one hop
  - Client library updates view of membership periodically

End notes

Peer-to-peer techniques have been the key enablers for building Dynamo:

- ”... decentralized techniques can be combined to provide a single highly-available system.”

References

- **Dynamo: amazon's highly available key-value store,** Giuseppe DeCandia et. al., SOSP 2007.
- **Bigtable: A Distributed Storage System for Structured Data,** Fay Chang et. al., OSDI 2006.
- **Casandra** - http://cassandra.apache.org/
- **Eventual consistency -** http://www.allthingsdistributed.com/ 2008/12/eventually_consistent.html
- Key values stores, No SQL