Dynamo: Amazon’s Highly Available Key-value Store

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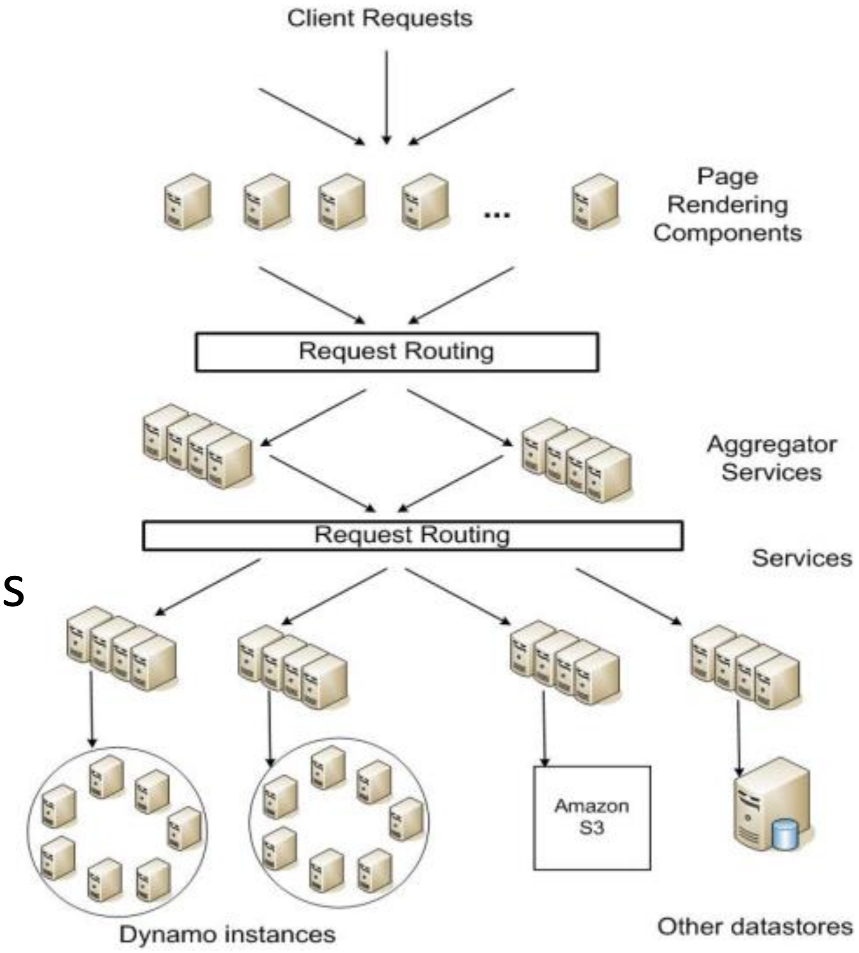
Many slides adapted from a talk by Peter Vosshall

Amazon’s eCommerce Platform Architecture

- Loosely coupled,
  service-oriented architecture
- Stateful services manage their own state
- Stringent latency requirements
  - Services must adhere to formal SLAs
  - Measured at 99.9 percentile
- Availability is paramount
- Large scale, keeps growing
  - 10,000s servers worldwide



How does Amazon use Dynamo?

- Shopping cart
- Session information
  - E.g., recently visited products
- Product list
  - Mostly read-only, replicated for high read throughput

Motivation

- Need a highly available, scalable storage system
- Key-value storage is prevalent, powerful pattern
  - Data is mostly accessed by primary key
  - Data served is often self-describing blobs (not structured)
- RDMS is not a good fit
  - Most features are unused, e.g., query optimizer, stored procedures, triggers, etc.
  - Scales up, out not so easily
  - Strongly consistent, limits availability

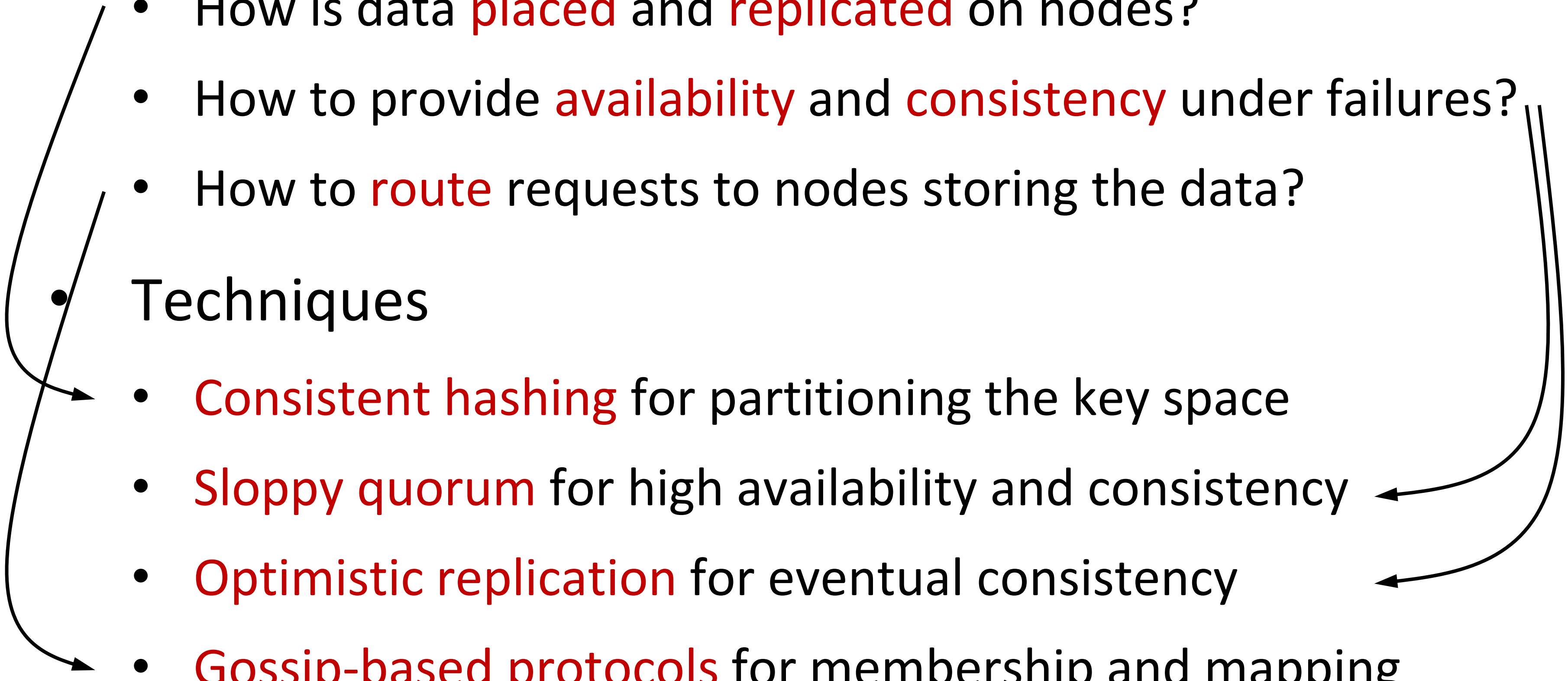
Key Requirements

- High “always writable” availability is critical
  - Accept writes during failure scenarios
    - Total ordering not possible
  - Allow writes without prior context
    - Ordering a client’s writes may not be possible
- User-perceived consistency is also very important
  - Anomalies due to weak consistency should be rare
- Guaranteed latency, measured in 99.9 percentile
- Incremental scalability, reduces TCO
- Tunable latency, consistency, availability, durability

Design Overview

- Dynamo is a decentralized (peer-to-peer) replicated, distributed hash table

- Key design questions



  - How is data placed and replicated on nodes?
  - How to provide availability and consistency under failures?
  - How to route requests to nodes storing the data?

- Techniques
  - Consistent hashing for partitioning the key space
  - Sloppy quorum for high availability and consistency
  - Optimistic replication for eventual consistency
  - Gossip-based protocols for membership and mapping

Dynamo API

- The get(k) and put(k, v) API includes a context that contains version information (discussed later)

```
// get returns one or more object versions, and a context.
//
object[], context = get(key)

// put supplies context returned by previous get.
//
put(key, object, context)
```

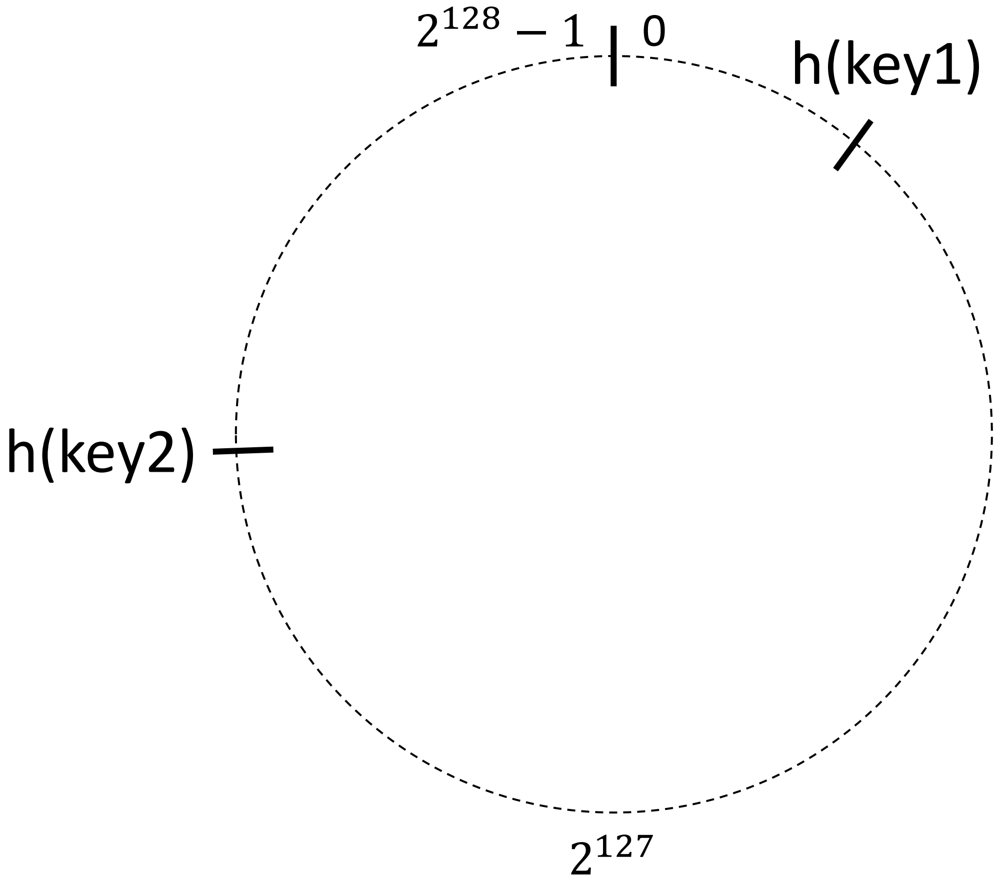
Consistent Hashing

Why Consistent Hashing?

- Enables partitioning the key space across nodes
- Handles adding and deleting nodes
    - If you use standard hashing, why would this be a problem?
    - Enables incremental scalability
- Handles data replication

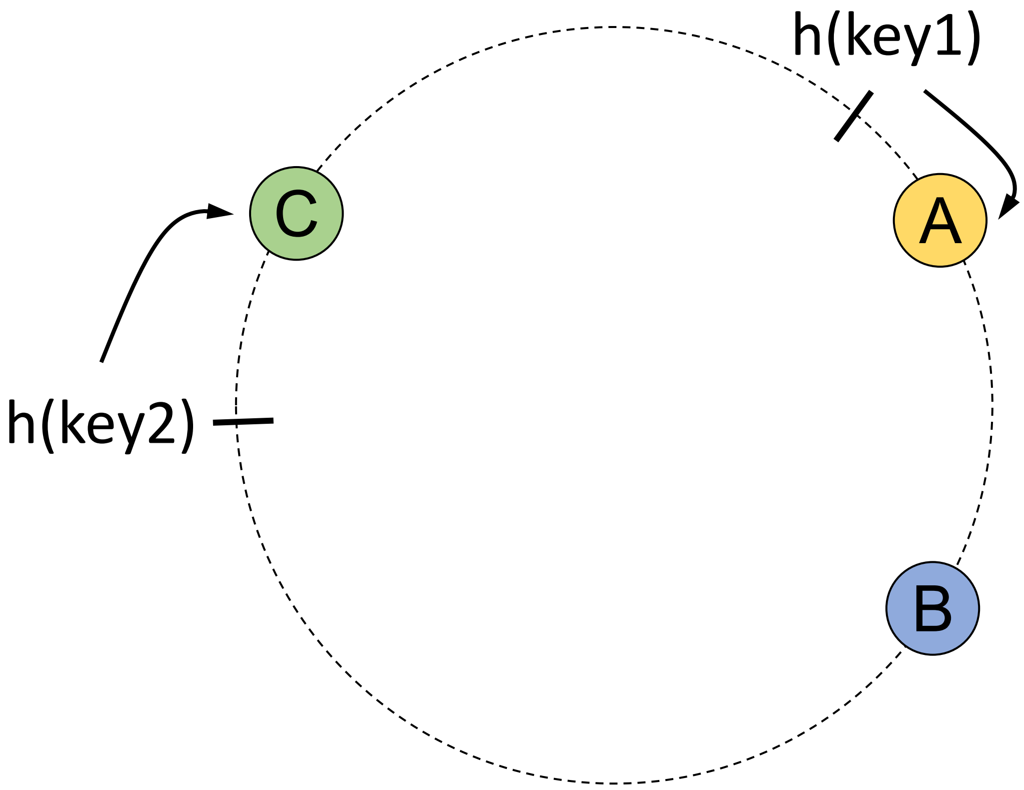
Hash ID

- Hash the key to a 128 bit ID
  - ID = h(key), where h is MD5
- ID lies in a circular key space



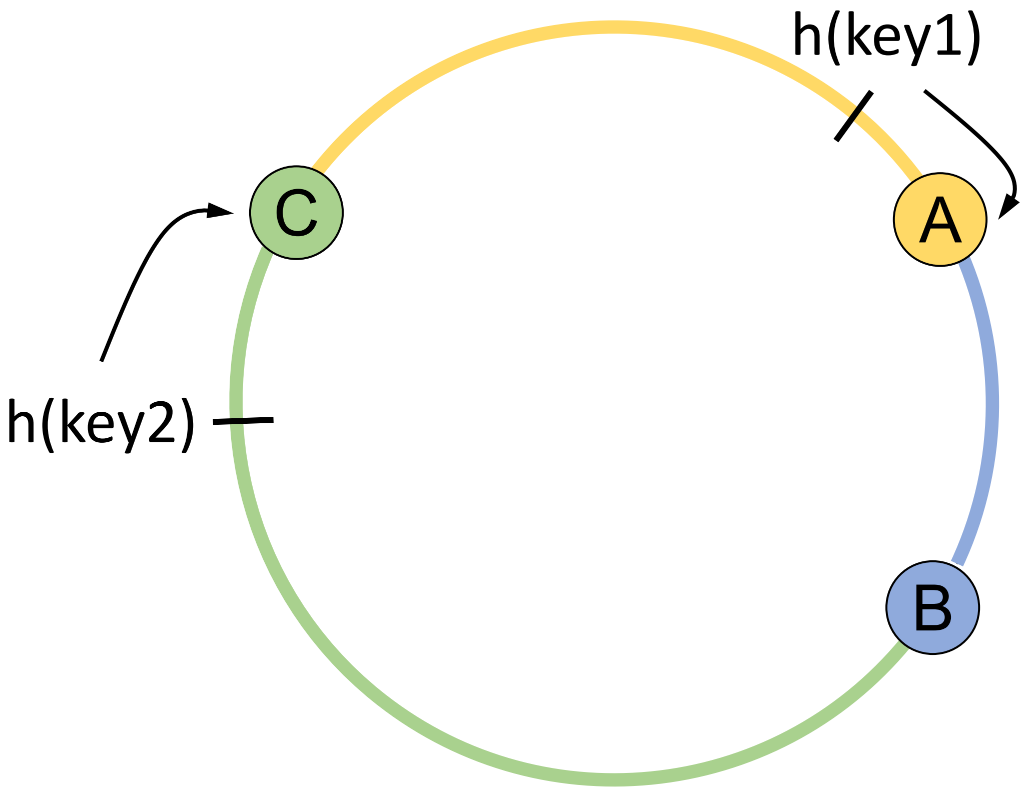
Node and Key Assignment

- Key idea of consistent hashing:
    - Each node is assigned an ID, e.g., h(A), in the key space
    - Each key (based on its ID) is owned by first clockwise node



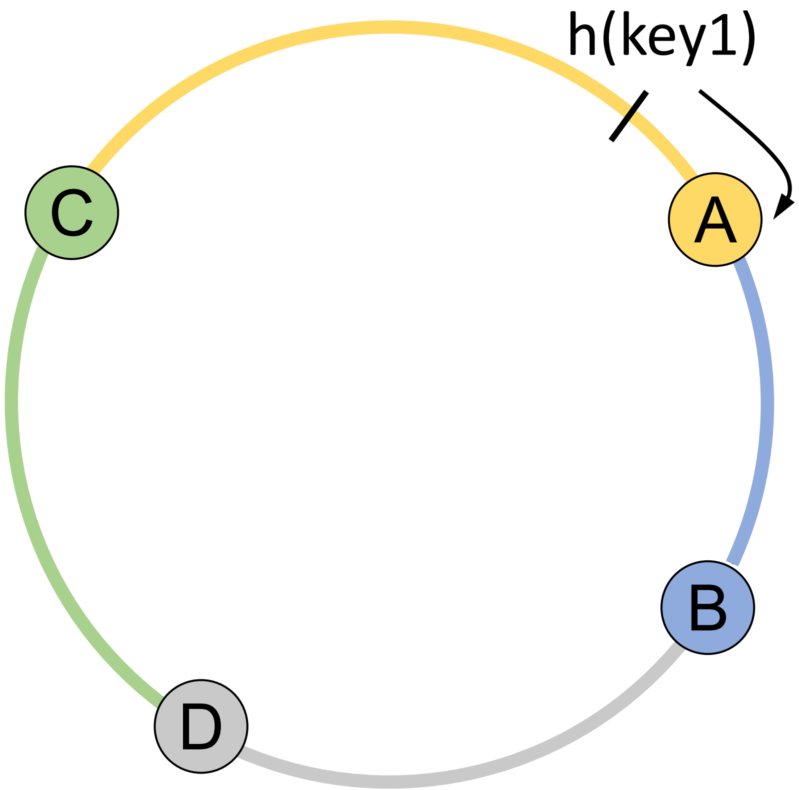
Nodes Store Key Ranges

- Each node owns keys in the range between its predecessor and itself



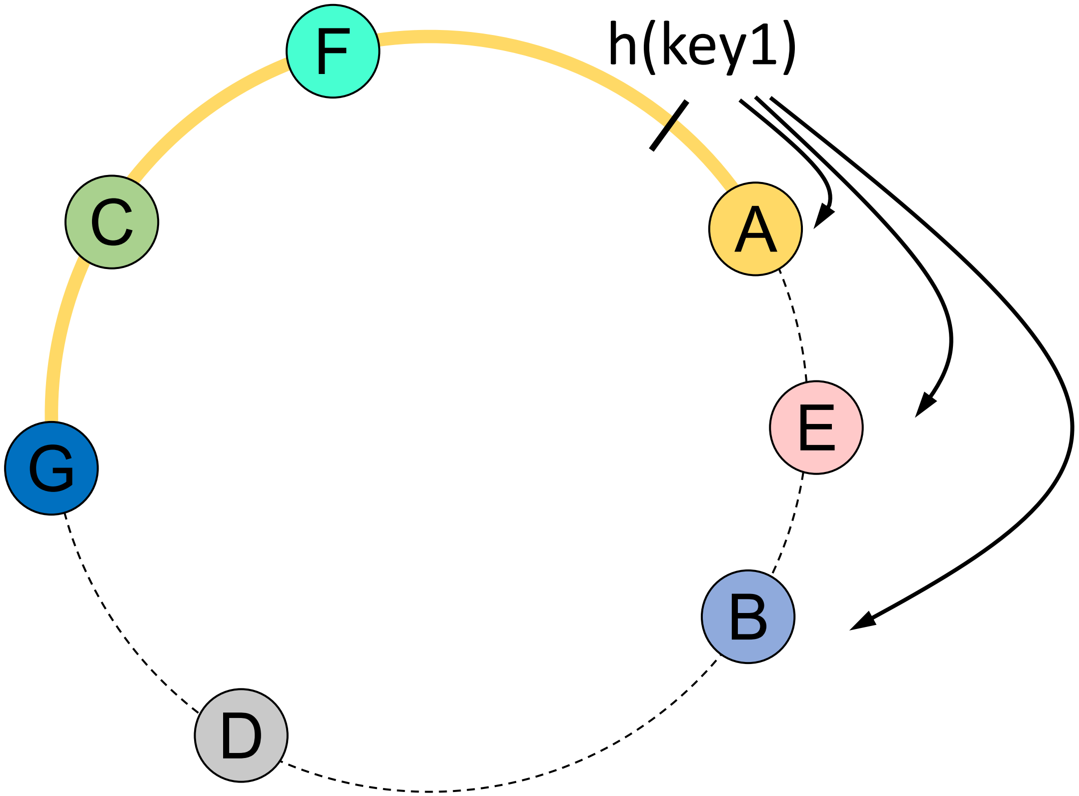
Node Addition/Deletion

- Adding or removing a node affects only a part of the key range



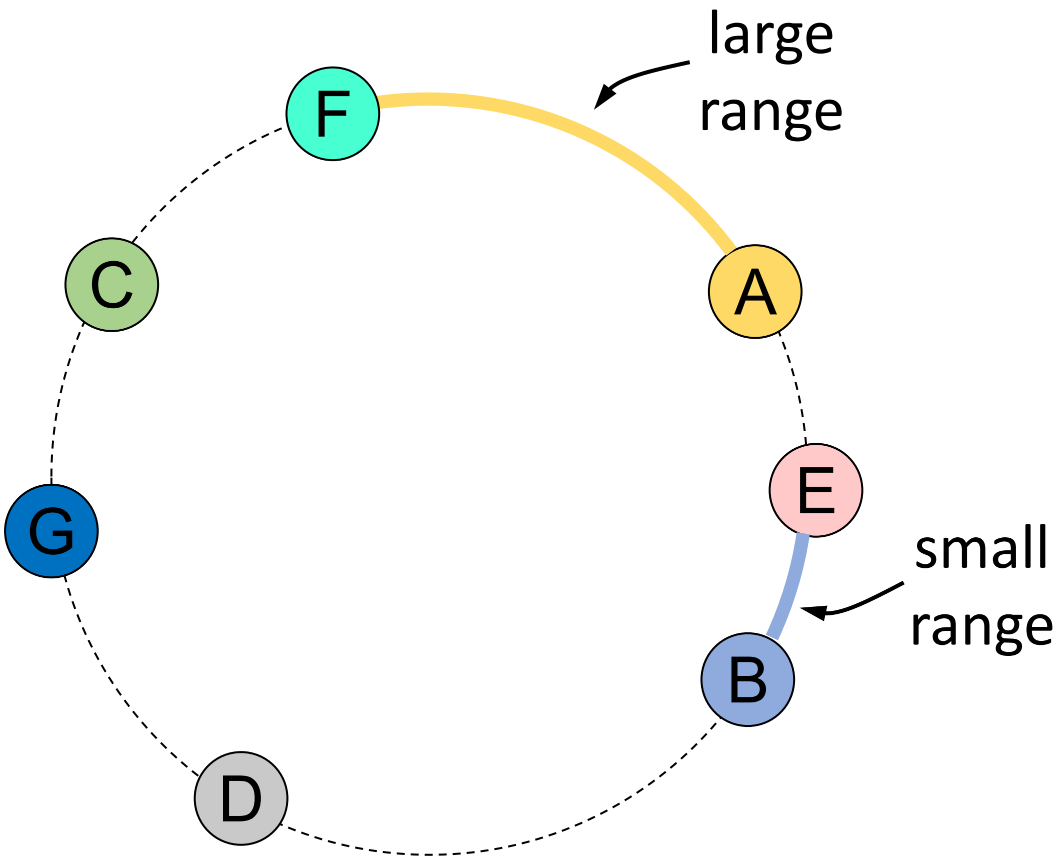
Replication

- A key is replicated at the first 3 clockwise nodes
- So, each node stores key ranges between its 3rd predecessor and itself



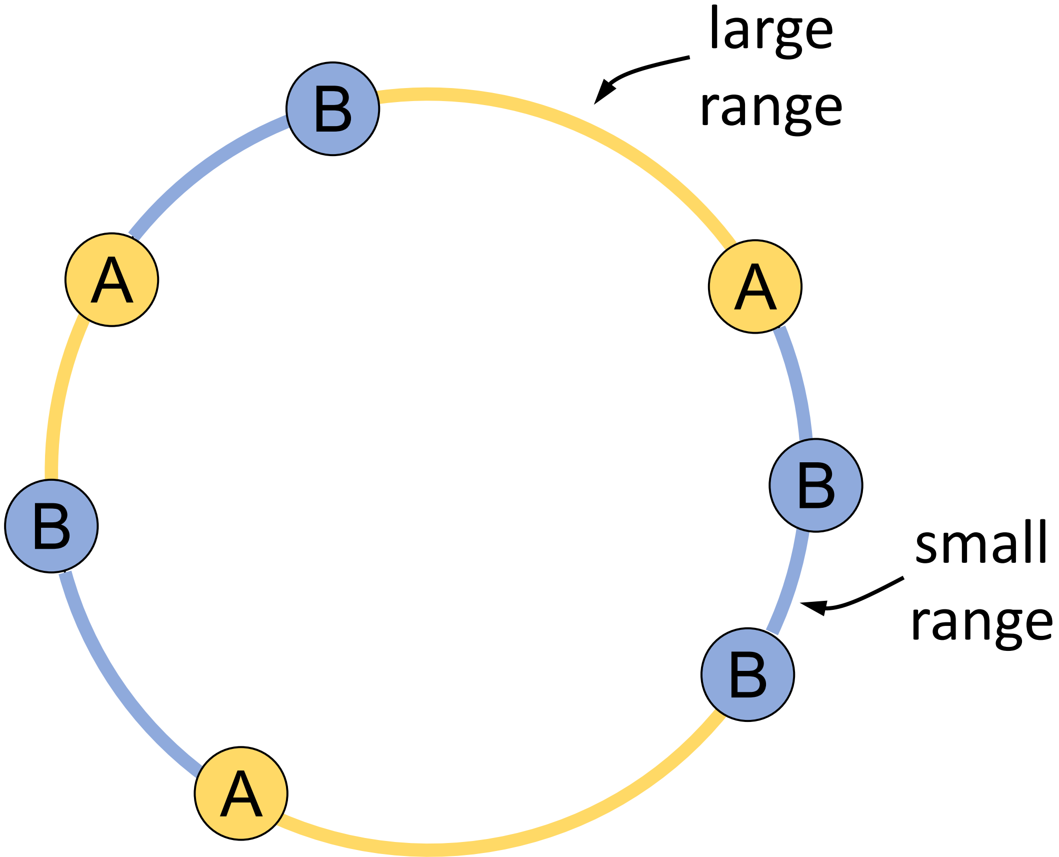
Key Load Imbalance

- Key range can be unbalanced



Load Balancing via Virtual Nodes

- Map each physical node to multiple virtual nodes
  - Pros: reduces key range skew across physical nodes
  - Cons: increases membership size



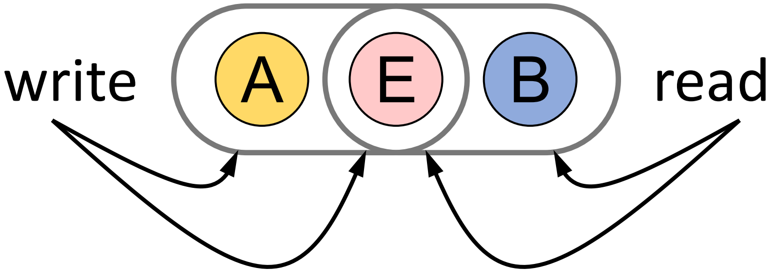
Sloppy Quorum

Why Sloppy Quorum?

- Challenge is to ensure both high availability and user-perceived consistency, with two goals:
  - Data should be always writable
  - Avoid anomalies due to weak consistency with high probability
- Solution: Be available
  - Consistent during normal operation, “sloppy” during failures

Majority Quorum Protocol

- Sloppy quorum builds on majority quorum protocol
- Basic Majority Quorum protocol
  - Assume
    - N: Number of nodes (or replicas) storing a key
    - R: Successful read involves at least R nodes
    - W: Successful write involves at least W nodes
  - Choose: R + W > N
    - Since reads and writes overlap at least one replica, majority quorum ensures reads will read the latest data
  - Example:
    - N = 3, R = 2, W = 2

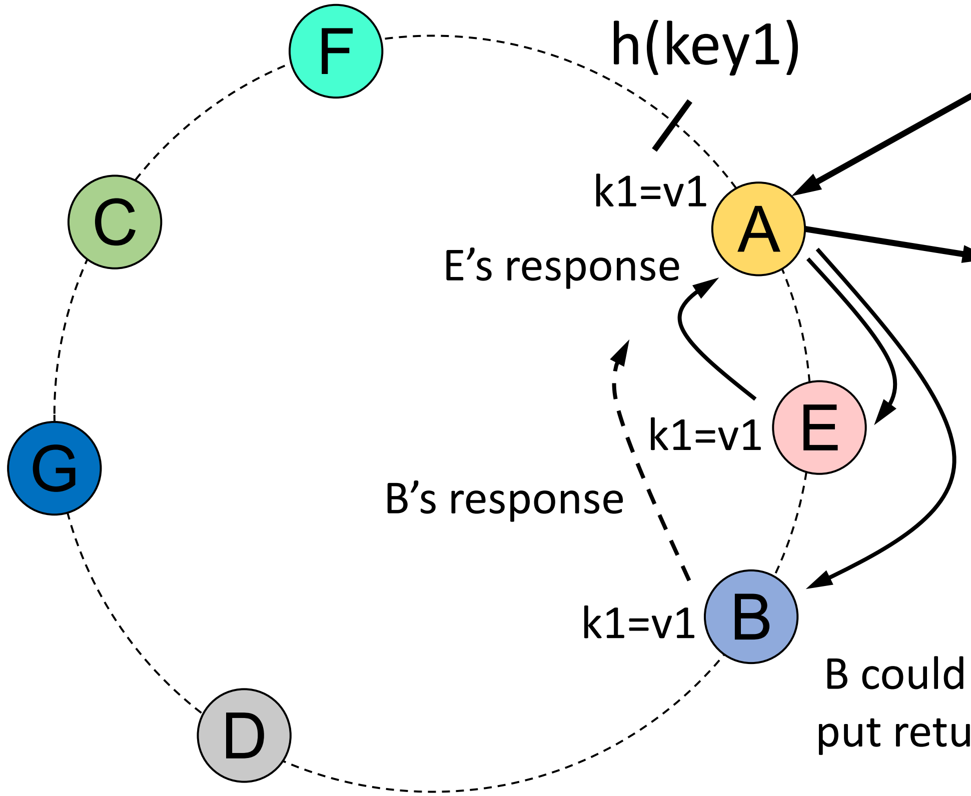


Majority Quorum Example

- Assume N = 3, R = 2, W = 2
- put(k, v)
  - Coordinated by a node that stores key k
    - Typically, first replica is chosen
    - However, other replicas may also be chosen for load balancing
  - Returns when at least W=2 replicas update key and respond to the coordinator
- get(k)
  - Coordinated by any node (whether node stores k or not)
  - Returns when at least R=2 replicas respond with the value of key to the coordinator

Majority Quorum Example

- N = 3, R = 2, W = 2
- Assume client performs put(k1, v1)



put(k1, v1) is performed by coordinator A

put returns when A receives response from E or B

A forwards put to E and B

B could have failed but put returns successfully

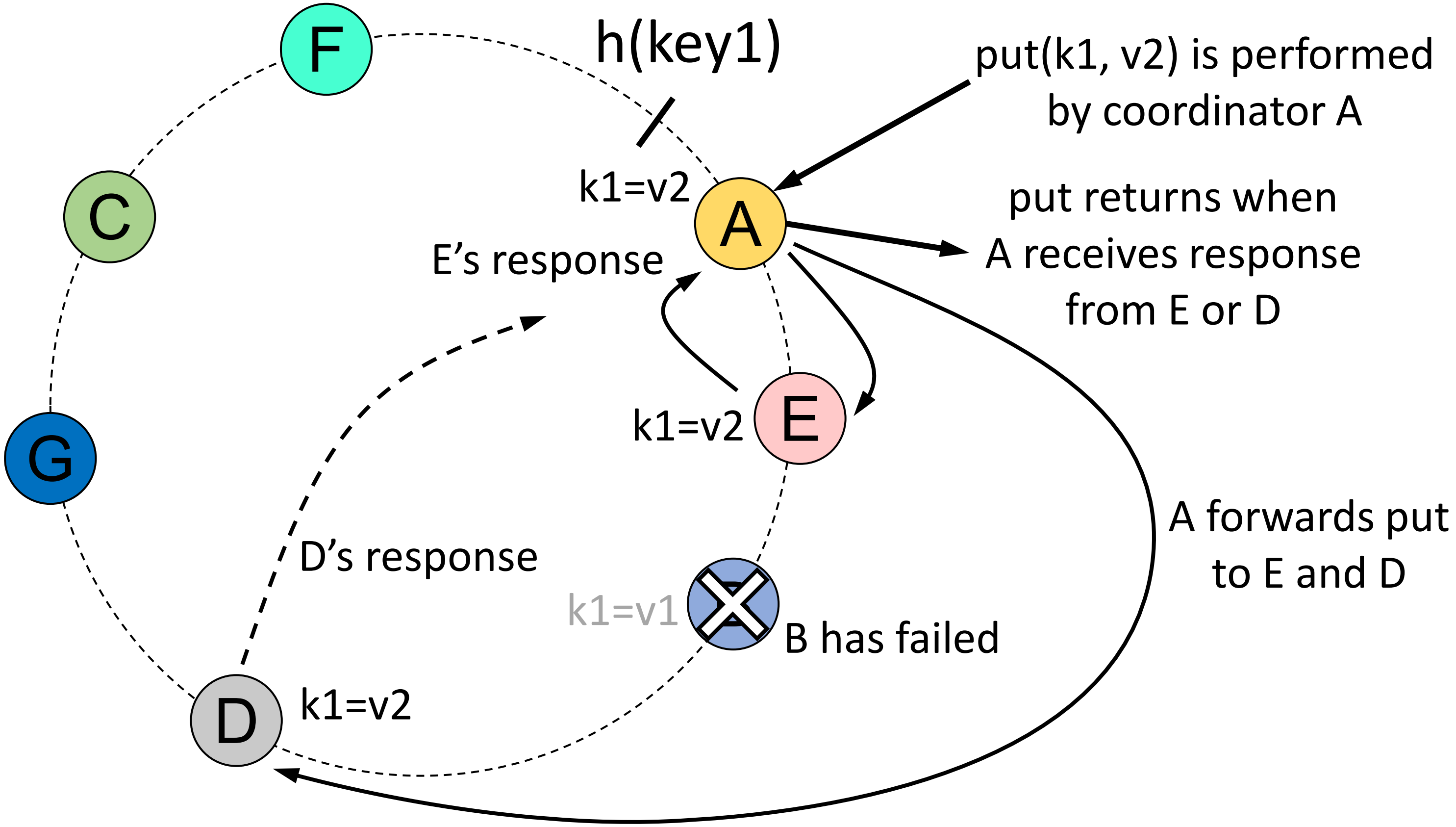
Sloppy Quorum

always writable operation

- When a node is not available, writes sent to a new node
- Reads and writes are performed on N healthy nodes
  - So failed nodes are skipped
  - Sloppy: R+W > N does not guarantee that reads, writes overlap
- However, reads still often read the latest data

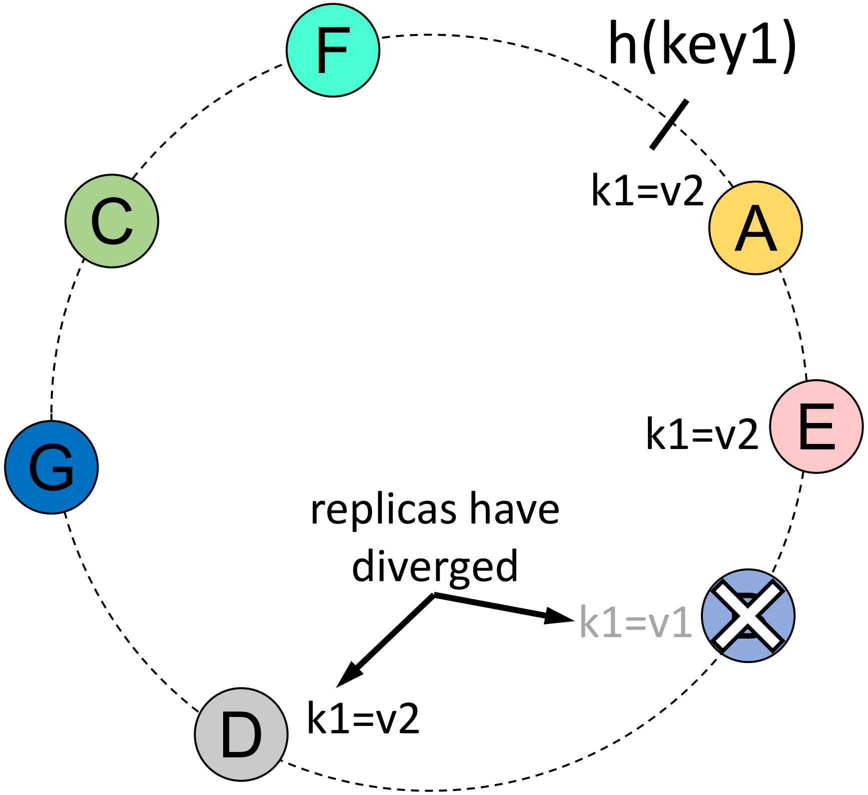
Sloppy Quorum

- Assume client performs put(k1, v2)
- If B fails, A forwards put(k1, v2) to D (temporary replica)
- Even if B restarts, get(k1) often returns latest version


F
h(key1)
put(k1, v2) is performed by coordinator A
C
k1=v2
A
E's response
put returns when A receives response from E or D
k1=v2
E
G
A forwards put to E and D
D's response
k1=v1
B
B has failed
D
k1=v2

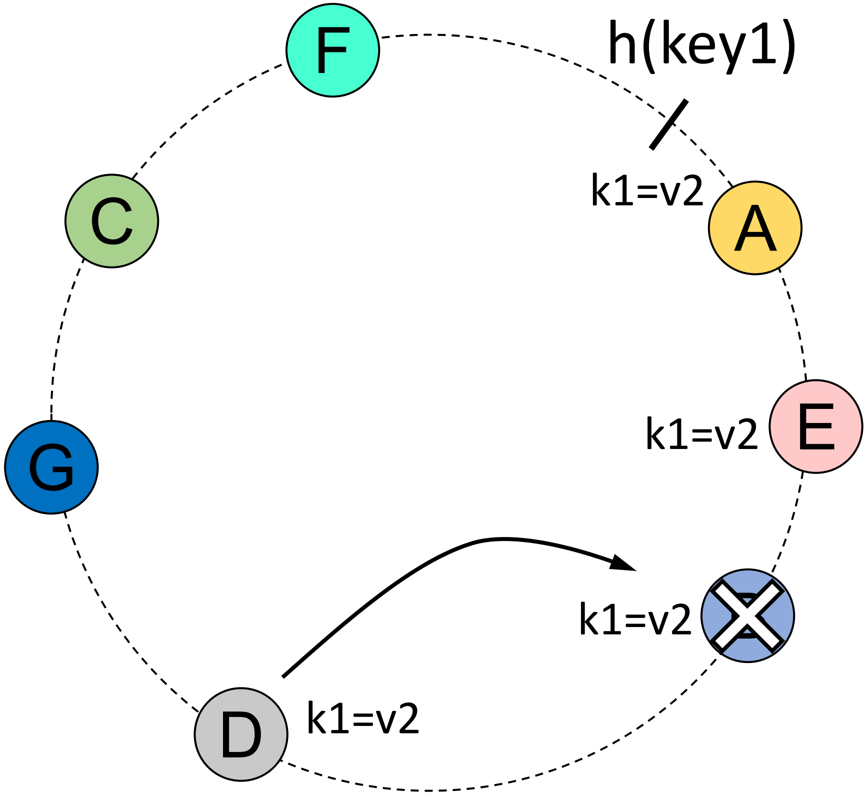
Sloppy Quorum and Replica Divergence

- After node B fails, it will have a stale replica



Sloppy Quorum and Failure Recovery

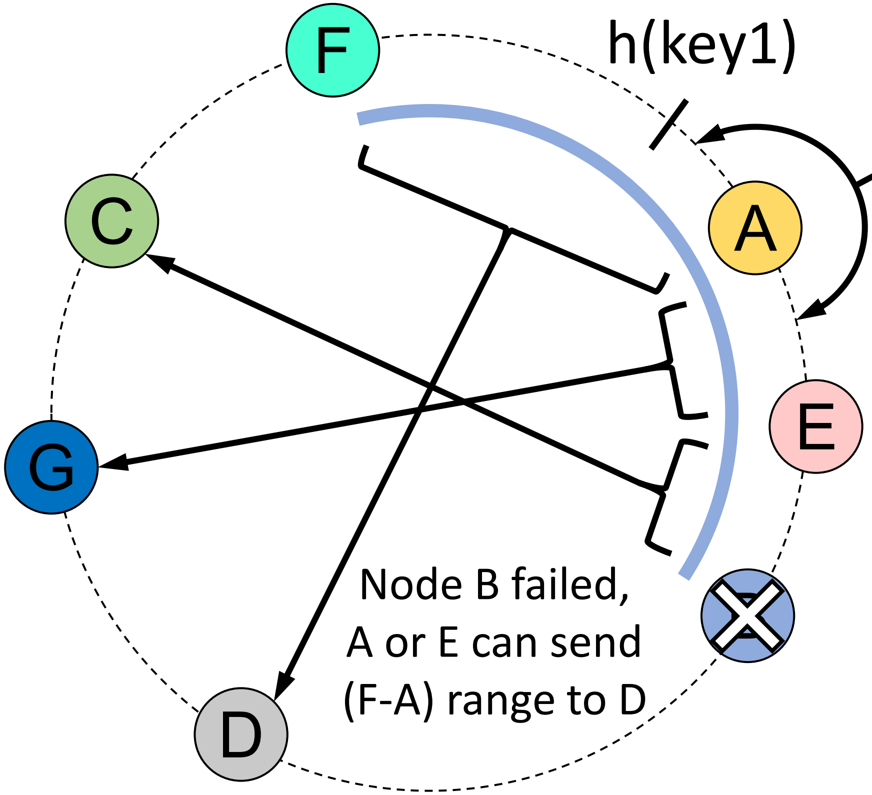
- After node B fails, it will have a stale replica
- When temporary replica D finds that B has recovered:
  - D sends v2 to B, and may delete v2 from its store



Node B recovers from failure

Replica Synchronization

- Nodes may have stale replicas, leave or fail permanently
- Replicas of key ranges are synchronized with an efficient anti-entropy protocol that uses Merkle trees



A and E can compare and update (F-A) range

Node B failed, A or E can send (F-A) range to D

Sloppy Quorum Configuration

N	R	W	Application
3	2	2	Consistent, durable, user state (typical configuration)
N	1	N	High performance read engine
1	1	1	Distributed web cache

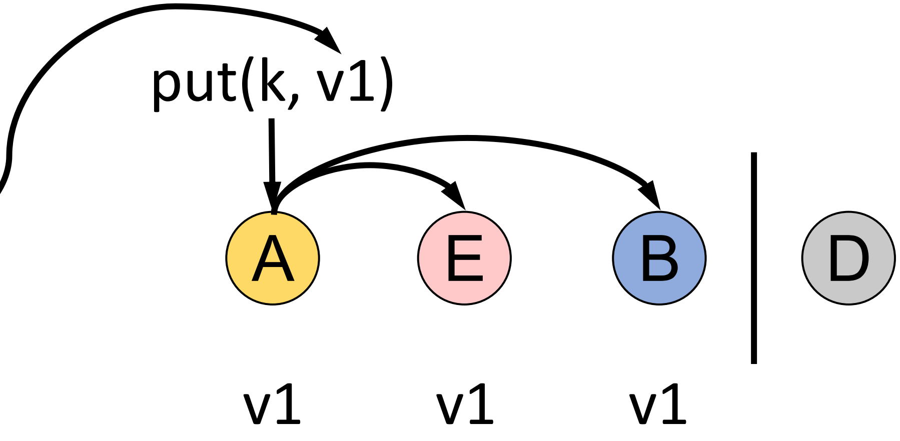
Optimistic Replication

Why Optimistic Replication?

- With sloppy quorum, replicas may be stale or conflicting
  - Stale replica: replica has old version
  - Conflicting replica: process wrote to a stale replica
- Optimistic replication is used to
  - Detect stale and conflicting replicas
  - Synchronize them so replicas become eventually consistent
- Dynamo implements optimistic replication using immutable versions and version histories
  - put() creates new, immutable object version
  - Each node tracks version history, i.e., version information for each object version and how they are related

Optimistic Replication Example

- put(k, v1) writes to A, E, B
  - Assume v1 is both a value, and a new version associated with the value

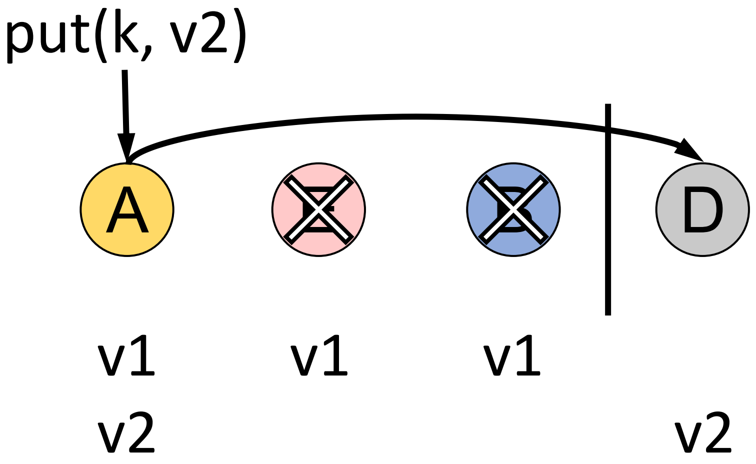


Version history

v1

Example

- B and E fail
- put(k, v2), based on v1, writes to A and D
  - D is a temporary replica
- v1 is an ancestor of v2 in version history



Version history

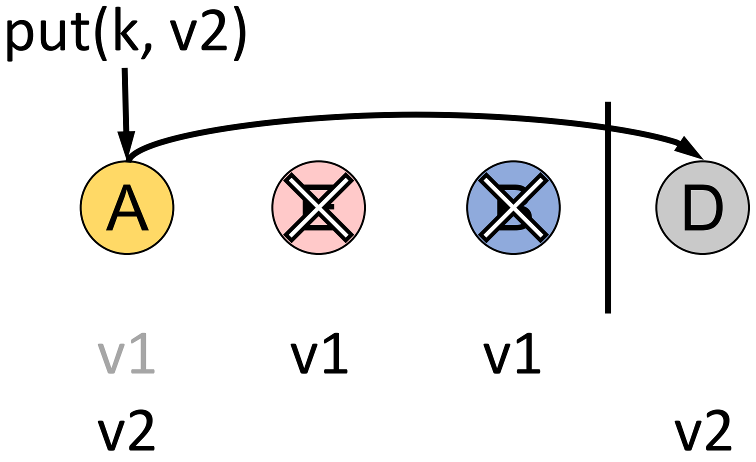
v1

↓

v2

Example

- B and E fail
- put(k, v2), based on v1, writes to A and D
    - D is a temporary replica
- v1 is an ancestor of v2 in version history
- A removes v1 (stale version)



Version history

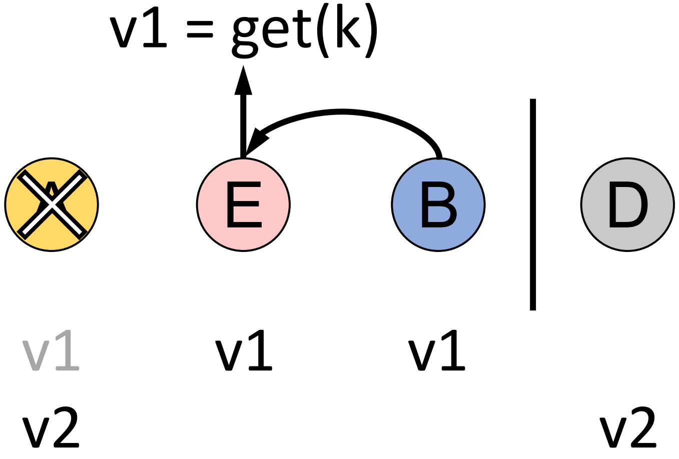
v1

↓

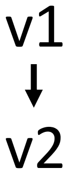
v2

Example

- B and E recover
- A fails
- get(k) reads v1 from E and B
    - v1 is a stale version

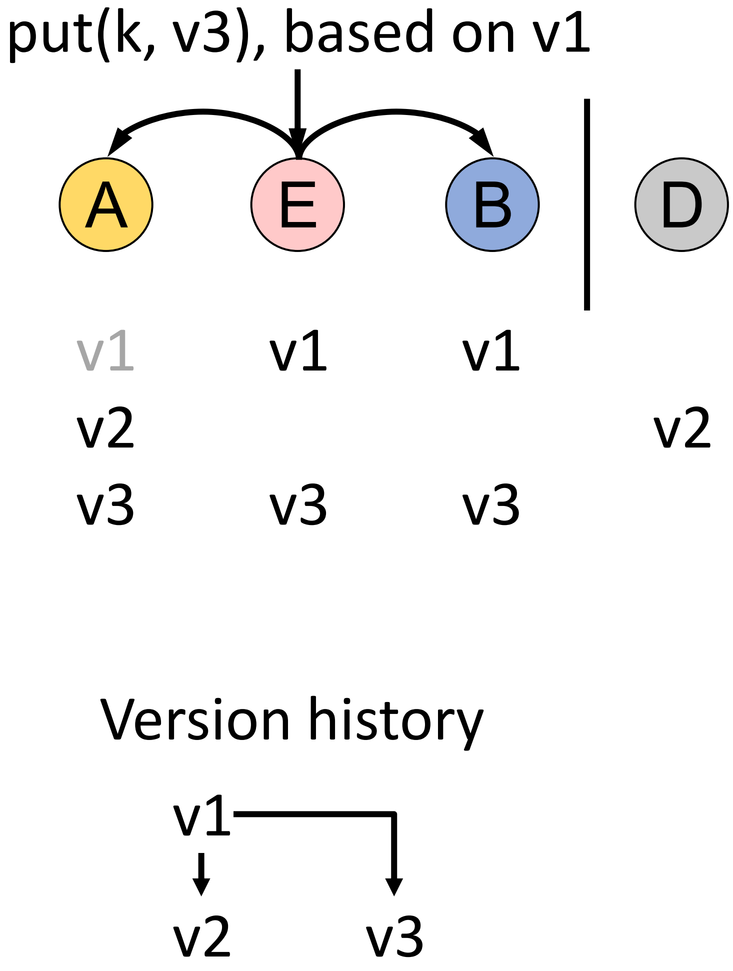


Version history



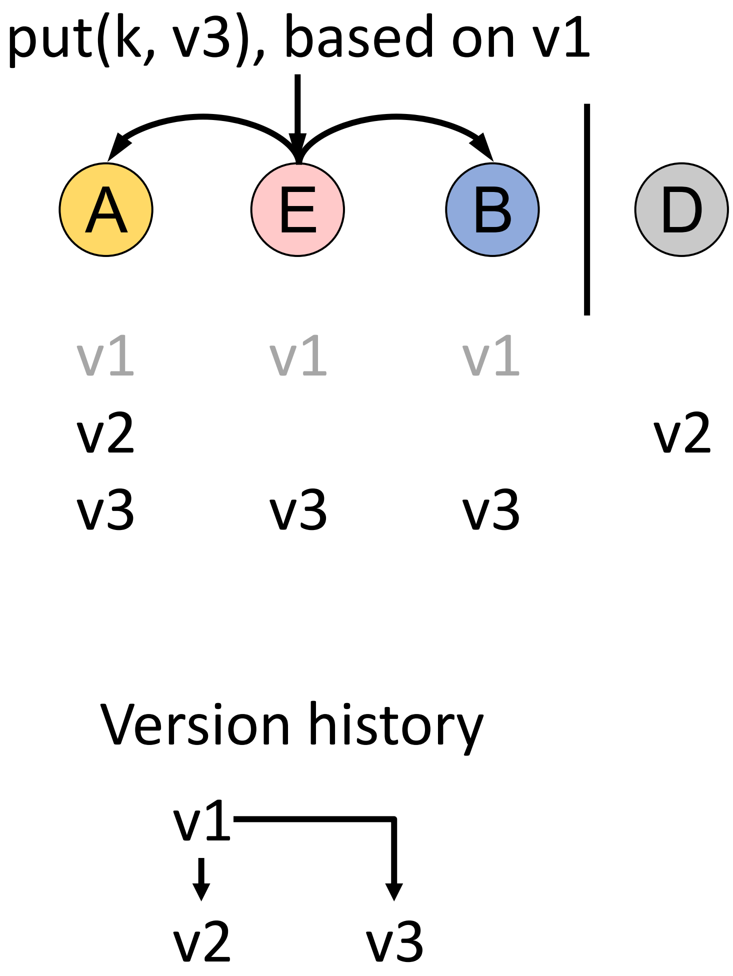
Example

- A recover s
- put(k, v3), based on v1, writes to E, A, B
  - Creates branch in history, since put() performed based on stale version v1



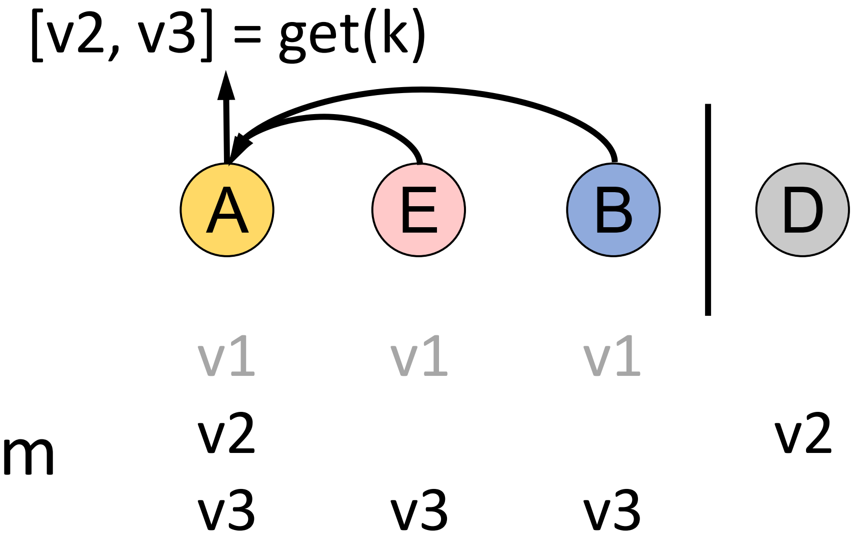
Example

- A recoverss
- put(k, v3), based on v1, writes to E, A, B
  - Creates branch in history, since put() performed based on stale version v1
- Nodes store versions that are leaves in version history
  - E and B remove v1, ancestor of v3
  - A stores v2 and v3, since they conflict

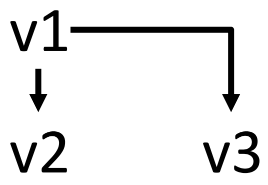


Example

- get(k) reads conflicting [v2, v3] from A, E, B
- Dynamo provides all conflicting versions to client, since client knows best how to reconcile them
  - E.g., app can merge two conflicting shopping carts

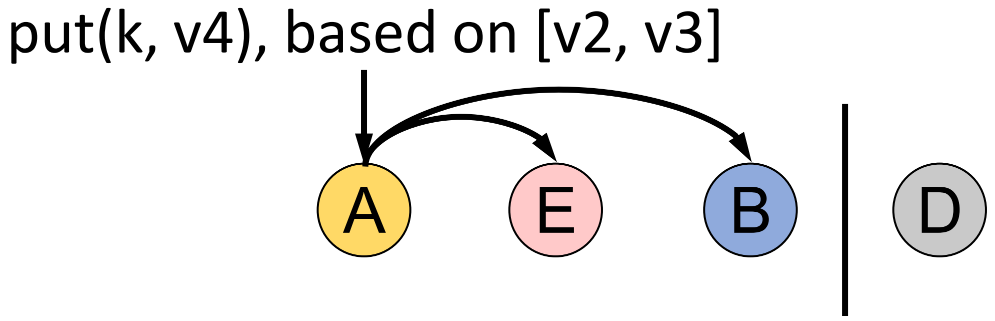


Version history



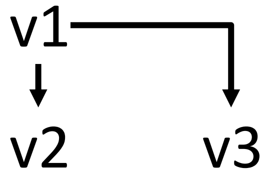
Example

- put(k, v4),
  based on [v2, v3],
  writes to A, E, B
  - Dynamo expects app reconciled [v2, v3] when it created v4



A	E	B	D
v1	v1	v1	
v2			v2
v3	v3	v3	
v4	v4	v4	

Version history



Example

- put(k, v4),
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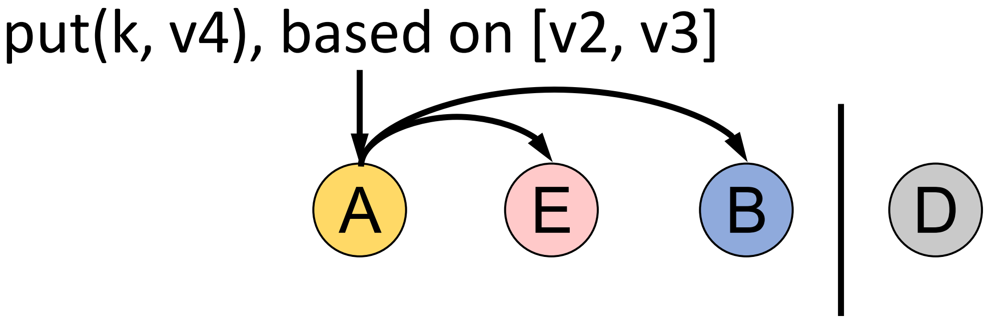
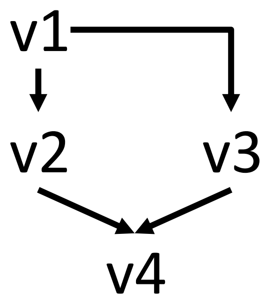
  - Dynamo expects app reconciled [v2, v3] when it created v4
- put() merges conflicting versions into single new version
  - Version history has single head



put(k, v4), based on [v2, v3]

A	E	B	D
v1	v1	v1	
v2			v2
v3	v3	v3	
v4	v4	v4	

Version history



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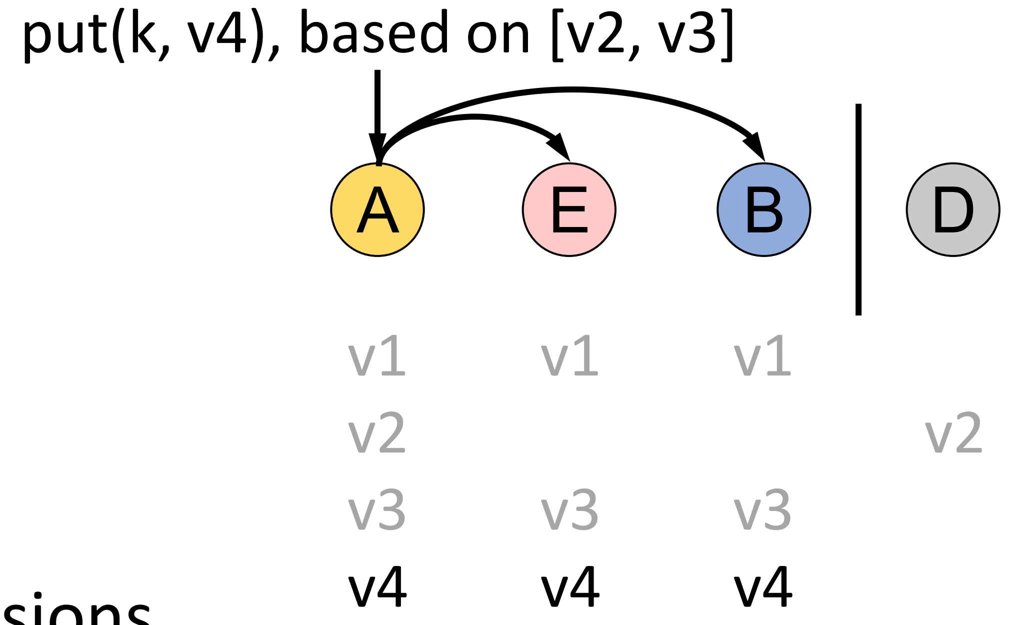
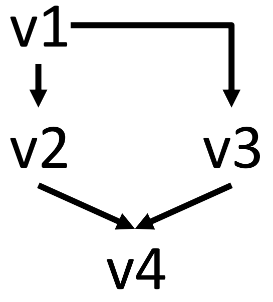
  - Version history has single head
- A, E, B and D can remove stale versions v2 and v3



Version history



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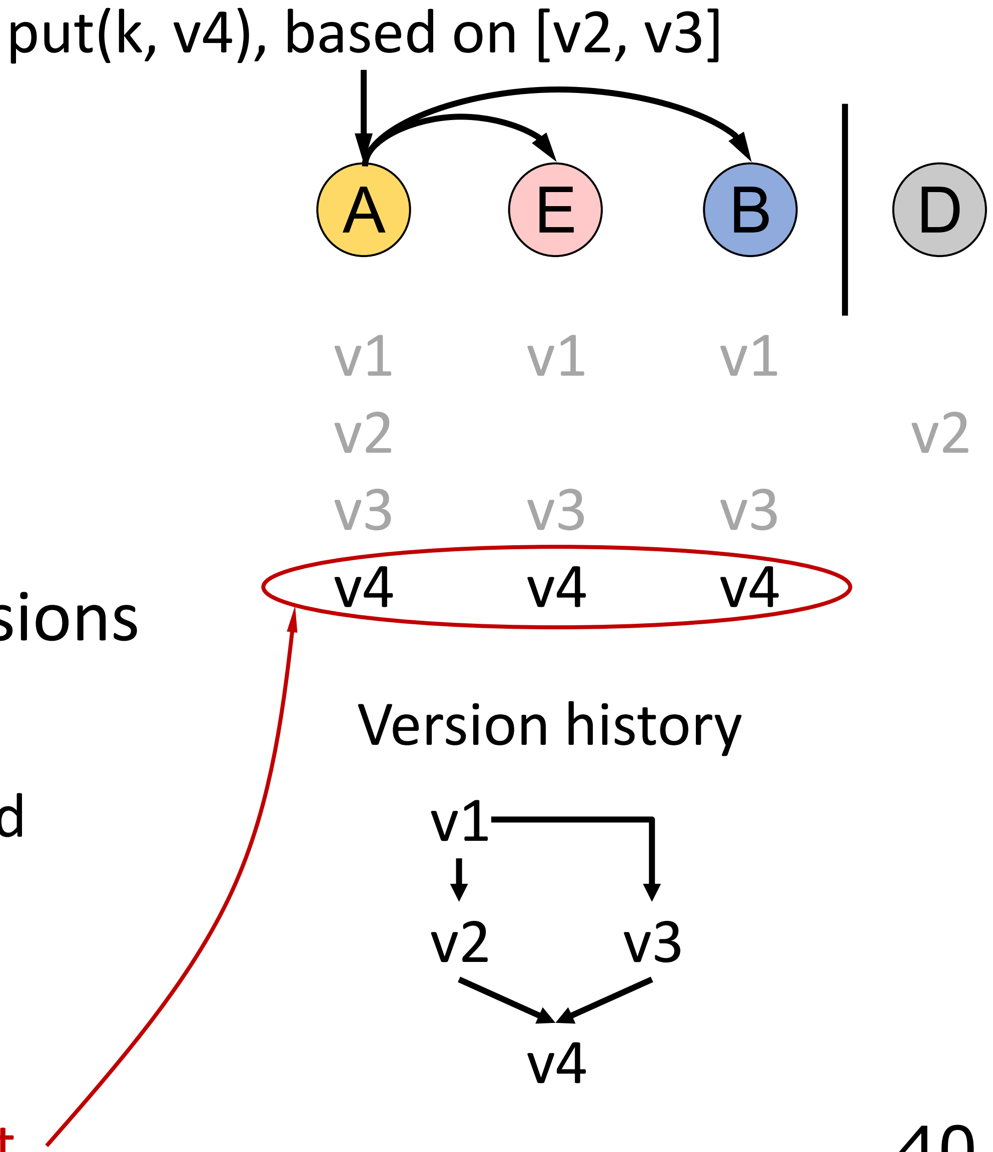
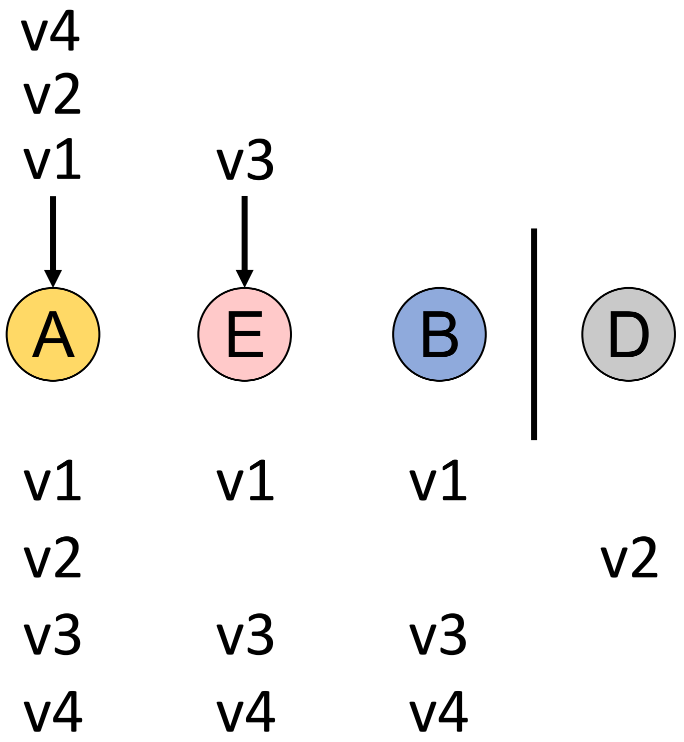
- put() merges conflicting versions into single new version
  - Version history has single head
- A, E, B and D can remove stale versions v2 and v3
  - Object is eventually consistent



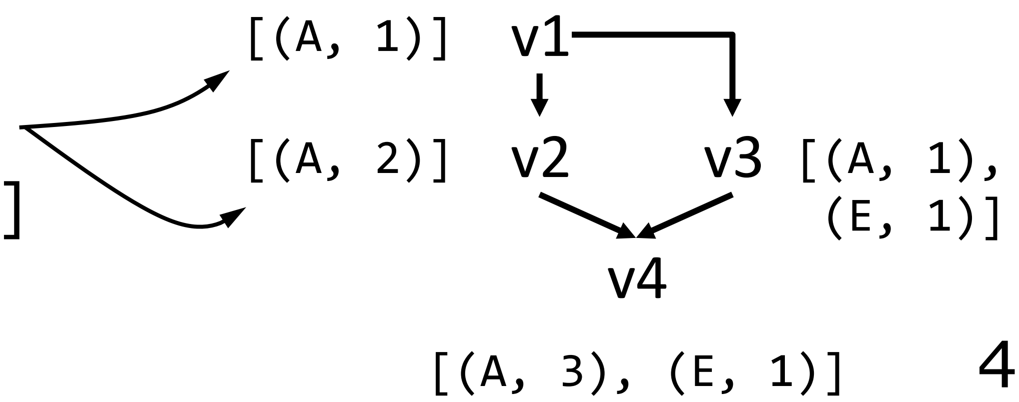
Implementing Version History With Vector Clocks

- Dynamo uses vector clocks to implement version history
- Efficiently capture causality
  - Stale versions can be forgotten
  - Concurrent versions are conflicting, require reconciliation
- Each object version stores a vector clock:

```
[(node1, #updates1),
 (node2, #updates2), …]
```



Version history



Dynamo API With Vector Clocks

- The get(k) and put(k, v) API includes a context that contains version information (vector clock)

```
// get returns one or more object versions, and a context.
// context contains version information for each returned version.
object[], context = get(key)

// put supplies context returned by previous get.
// context helps generate version information for new object version.
put(key, object, context)
```

Gossip-Based Protocols

Why Gossip-Based Protocols?

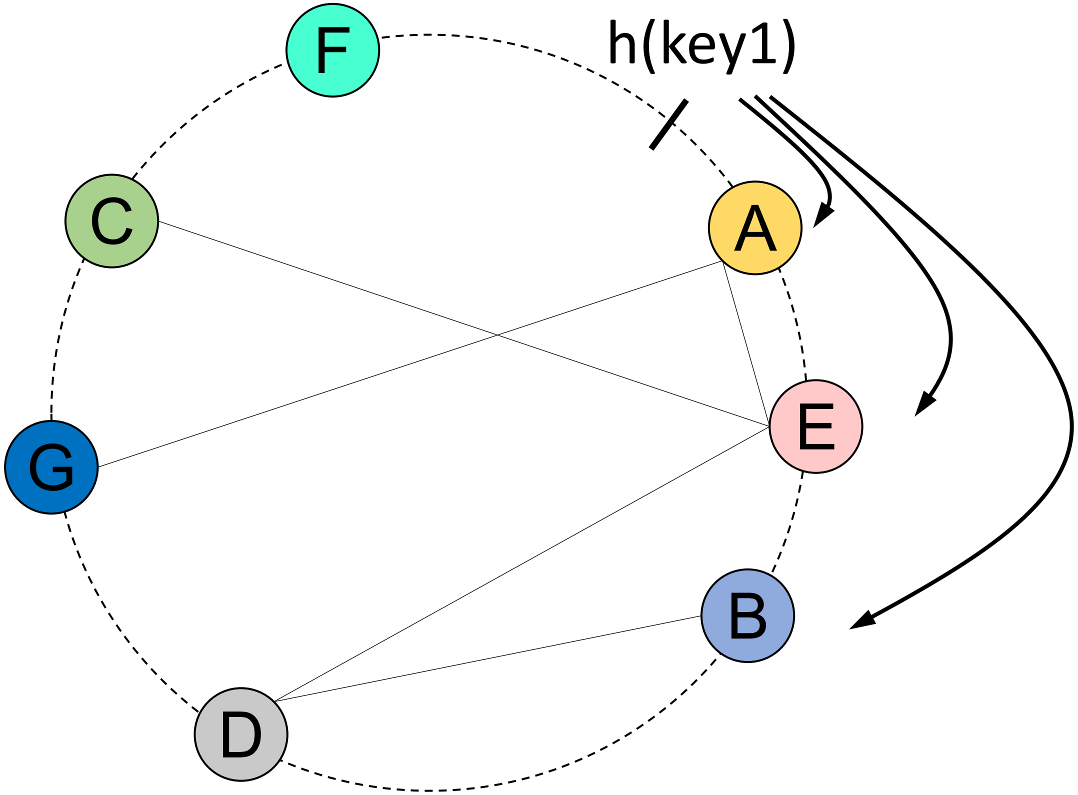
- Gossip protocols exchange information between nodes in a peer-to-peer (symmetric) manner
  - A<->B: A and B learn about each other's state
  - B<->C: B and C learn about each other's state,
    so C learns about A's state as well
- In general, these protocols enable nodes to
  - Learn about the state of other nodes
  - Use version history of state to become eventually consistent
- Tradeoffs:
  - Pros: avoid need for a coordinator, provide higher availability
  - Cons: nodes may have stale information for a while

Membership and Mapping

- Dynamo uses gossiping to propagate membership, mapping information
- Administrator explicitly adds and remove nodes
- Membership: After that, nodes communicate with each other to eventually learn about an added/deleted node
- Mapping information: Nodes also learn about node mappings, i.e., the key ranges stored on a node

Routing Key Lookup

- With gossiping, each node knows about 1) all other nodes, and 2) the key ranges each node stores
- Allows one-hop routing (critical for low latency)

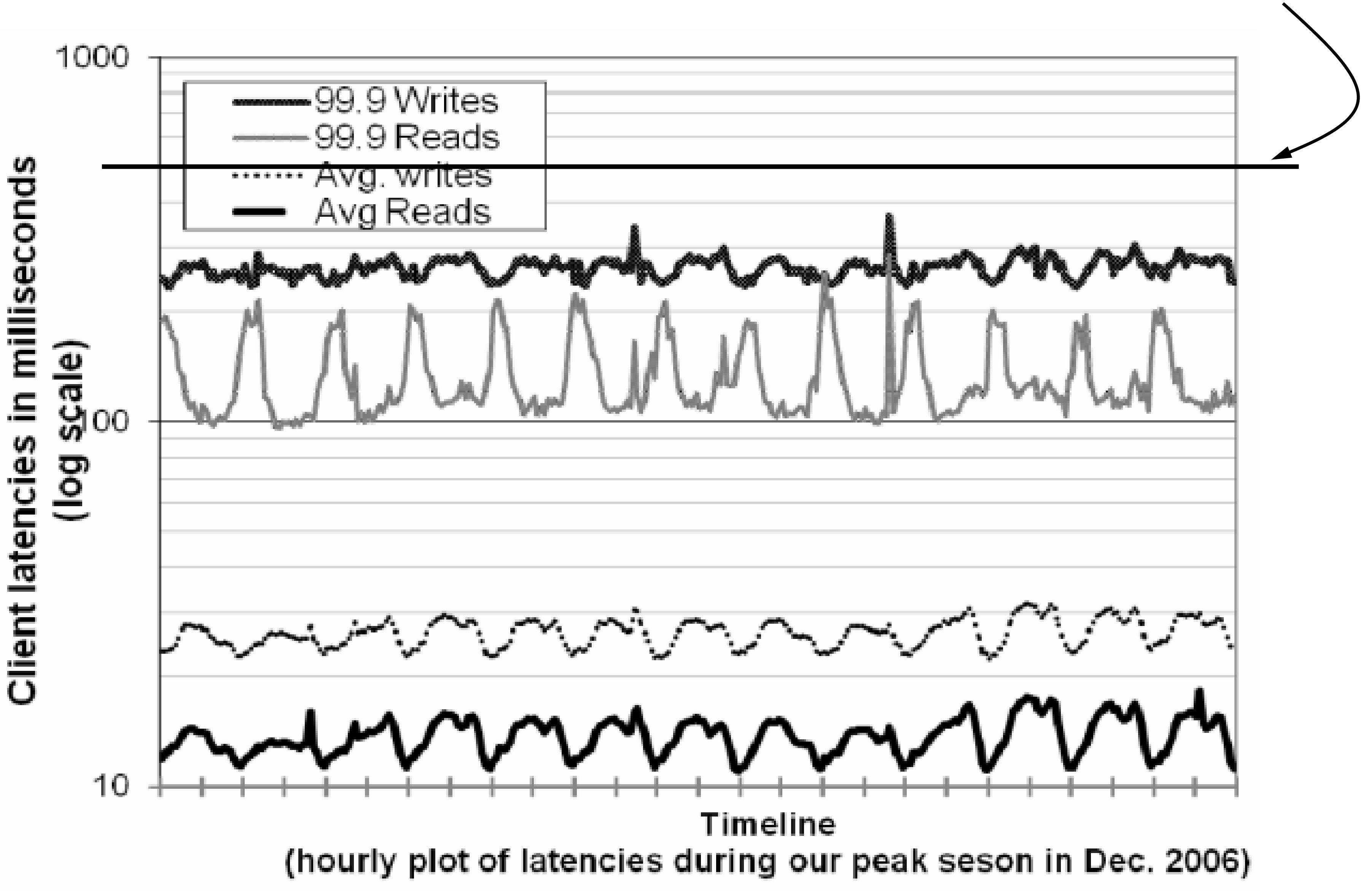


Failure Detection

- Initially implemented node failure detection via gossip
- Not needed due to explicit node add/remove
  - No need to distinguish between temporarily failed/recovering nodes versus removed/added nodes
- Simple failure detection
  - A detects B as failed if it doesnt respond to a ping message
  - A periodically checks if B is alive again
  - In the absense of requests, A doesn’t need to know if B is alive

Evaluation

500 ms SLA for storage system for shopping cart application

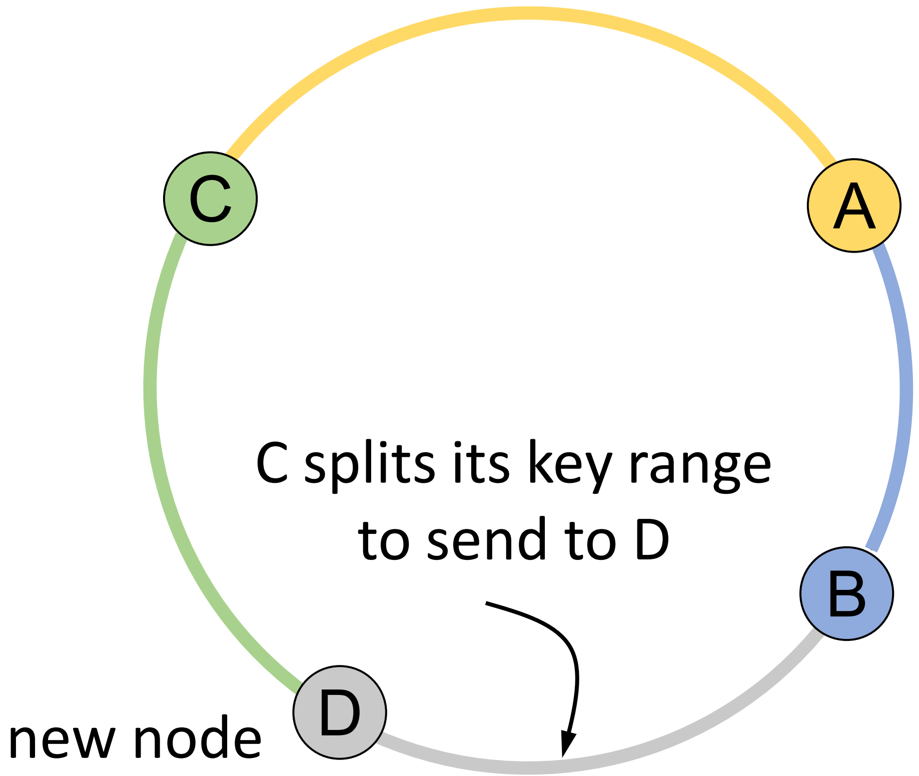


Lessons Learned: Tail Latency

- 99.9 percentile is a high bar
  - Packet losses, waiting on disk, accessing large objects, JVM garbage collection, …
- Techniques used to reduce tail latency
  - Use buffered writes to avoid waiting on disk
    - Need to deal with version consistency, e.g., if version number is increased on disk, but failure loses the object version
  - Lazy removal of stale versions
  - Adaptive throttling of background operations based on observed foreground operation latency

Lessons Learned: Repartitioning

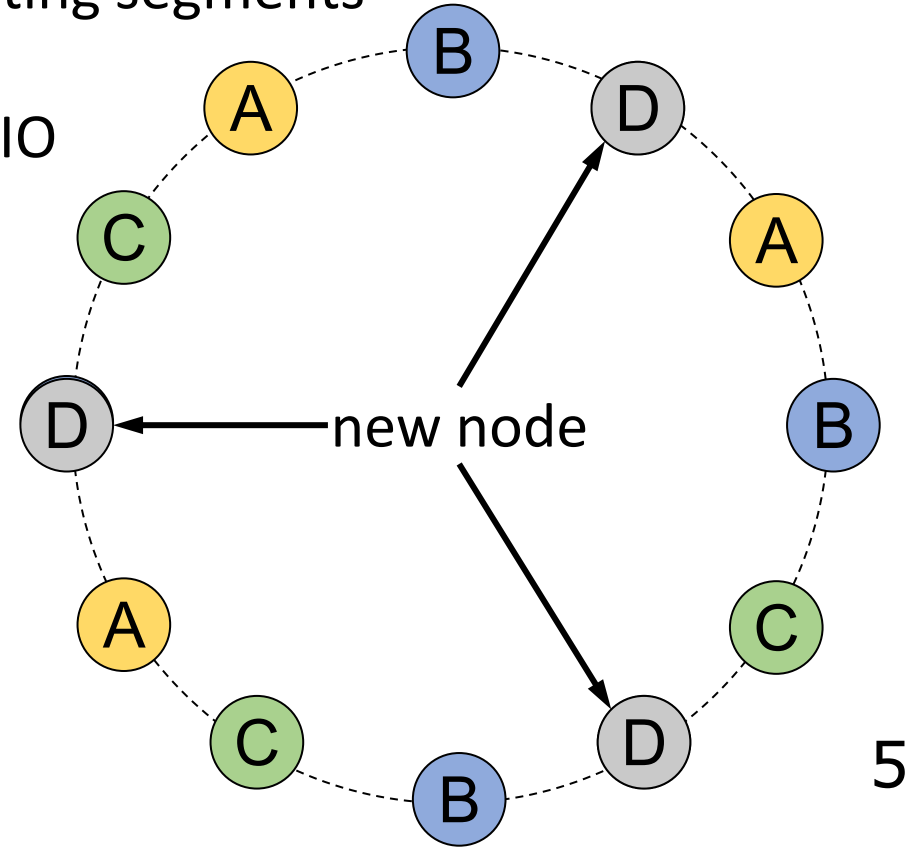
- Slow repartitioning
  - Successor (C) splits key range to bootstrap new node (D)
  - Requires ordered key traversal (scan), causes heavy random disk I/O at C, with throttling, takes hours/days to finish



C splits its key range to send to D

Lessons Learned: Repartitioning

- Use fixed arcs strategy
  - Divide hash ring into many fixed key ranges called segments
  - Coordinate assignment of segments to nodes
  - New node (D) steals entire existing segments from other nodes, allowing simple file transfer, sequential IO
- Scales better
- However, moves away from decentralized principle



Dynamo: Pros and Cons

- Pros
  - Highly available - 99.9995% request success over one year
  - Meets tight latency requirements
  - Incrementally scalable
  - Tunable consistency, durability
- Cons
  - No transactional semantics
  - More challenging programming model, e.g., handling conflicts
  - Doesn’t support ordered key operations, streaming operations
  - Not appropriate for large (> 1MB) objects

Conclusions

- Highly scalable, replicated, eventually consistent key-value store
- Decentralized (peer-to-peer) techniques can be used for building highly available system
  - High availability: provides an ”always-on” experience
  - Mostly consistent: clients rarely see conflicting versions
- Highly influential
  - Apache Cassandra builds on Dynamo’s design
  - Riak KV, Project Voldemort, ...

Discussion

Q1

- What design constraints are imposed by the “always writable” requirement?

Q2

- How would you compare Dynamo against Bigtable in terms of:
    - API
    - Workloads
    - Availability
    - Consistency

Q3

- Say dynamo is heavily loaded, i.e., many of the nodes are loaded, and so the dynamo administrator decides to add a node. Would that help reduce load on all the nodes?

Q4

- Under what scenarios can a client read multiple conflicting versions of an object? Why is this unlikely in Dynamo?

Q5

- What are the scalability limitations of Dynamo?