COMP5338 – Advanced Data Models

Week 9: Key Value Storage Systems

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Outline

- **Overview**
  - **K-V store**
  - **Memcached brief intro**
- **Dynamo**
  - **Overveiw**
  - **Partitioning Algorithm**
  - **Replication and Consistency**

Key-Value Data Model

- Simplest form of data model
  - Each data “record” contains a key and a value
    - All queries are key based
  - Similar concept in programming language/data structure
    - Associative array, hash map, hashtable, dictionary
  - Basic API similar to those in hashtable
    - **`put`** `key value`
    - value = **get** key
- There are many such systems
  - Some just provides pure K-V form
    - The system treats **`value`** as uninterpretable string/byte array
  - Others may add further dimensions in the value part
    - The value can be a json document, e.g HyperDex
    - The value can contain columns and corresponding values, e.g. Bigtable/HBase

From Keys to Hashes

- In a key-value store, or key-value data structure, the key can be of any type
  - String, Number, Date and Time, Complex object,
- They are usually hashed to get a value of fixed size
  - Hash function is any function that can be used to map data of arbitrary size to data of a fixed size
    - E.g. any Wikipedia page's content can be hashed by SHA-1 algorithm to produce a message-digest of 160-bit value
  - The result is called a hash value, hash code, hash sum or hash
- Hash allows for efficient storage and lookup

key	Hash
Alice	1
Tom	3
Bob	4

Hash Entry	Data
1	(Alice, 90)
3	(Tom, 85)
4	(Bob, 87)

Memcached: motivation

- Memcached is a very early in-memory key-value store
- The main use case is to provide caching for web application, in particular, caching between the database and application layer
- Motivations:
  - Database queries are expensive, cache is necessary
  - Cache on DB nodes would make it easy to share query results among various requests
    - But the raw memory size is limited
  - Caching more on Web nodes would be a natural extension but requests by default have their own memory spaces and do not share with each other
- Simple solution
  - "Have a **global hash table** that all Web processes on all machines could access simultaneously, instantly seeing one another's changes"

https://www.linuxjournal.com/article/7451

Memcached: features

- As a cache system for query results
  - Durability is not part of the consideration
    - Data is persisted in the database
    - No replication is implemented
  - Mechanisms for guarantee freshness should be included
    - Expiration mechanism
  - Cache miss is a norm
    - But want to minimize that
- Distributed cache store
  - Utilizing free memories on all machines
  - Each machine may run one or many Memcached server instances
  - It is beneficial to run multiple Memcached instances on single machine if the physical memory is larger than the address space supported by the OS

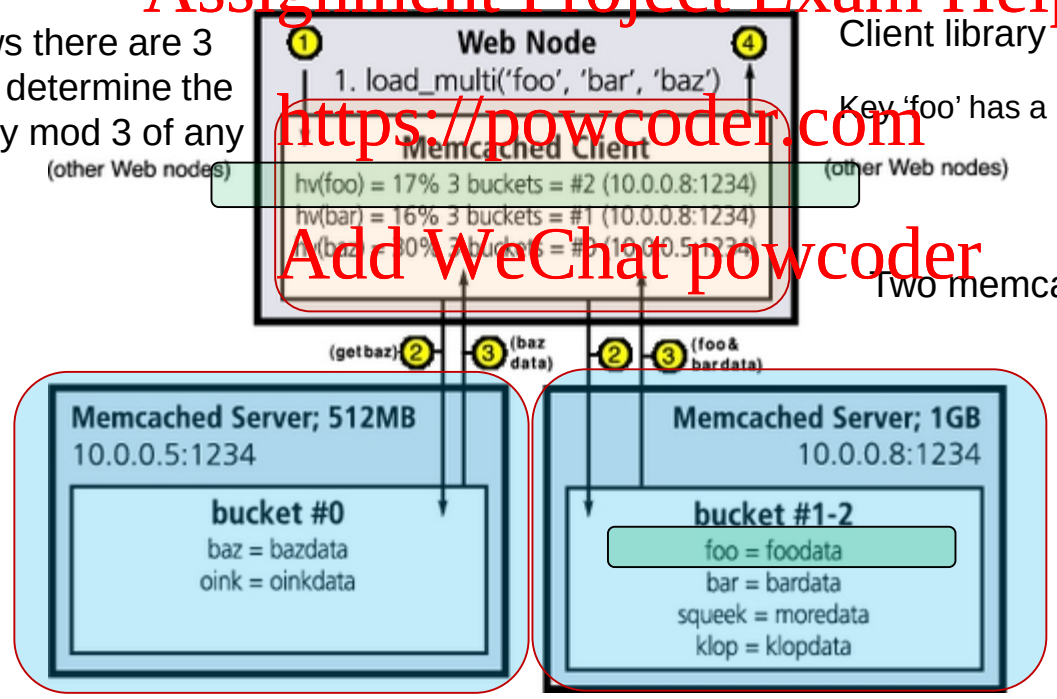
Memcached: the distributed caching

- The keys of the global hash table are distributed among a number of Memcached server instances
  - How do we know the location of a particular key
- Simple solution
  - Each memcached instance is totally independent
  - A given key is kept in the same server
  - Client library knows the list of servers and can use a predetermined partition algorithm to work out the designated server of a key
- Client library runs on web node
- There are many implementations
- May have different ways to partition keys
  - Simple hash partition or consistent hashing

Memcached: basic hash partition

- Treat Memcached instanced as buckets
  - Instance with larger memory may represent more buckets
- Use modulo function to determine the location of each key
  - Hash(key) **mod** #buckets

Client library knows there are 3 buckets, so would determine the location of a key by mod 3 of any key's hash value



Client library runs on web node

Key 'foo' has a hash value of 17, mod 3 is 2

Two memcached servers

One server has 512M memory for Memcached, and is considered as one bucket with id 0

Another server has 1G memory for Memcached, and is considered as two bucket with id 1 and 2

This key should be stored on the server managed bucket id 2

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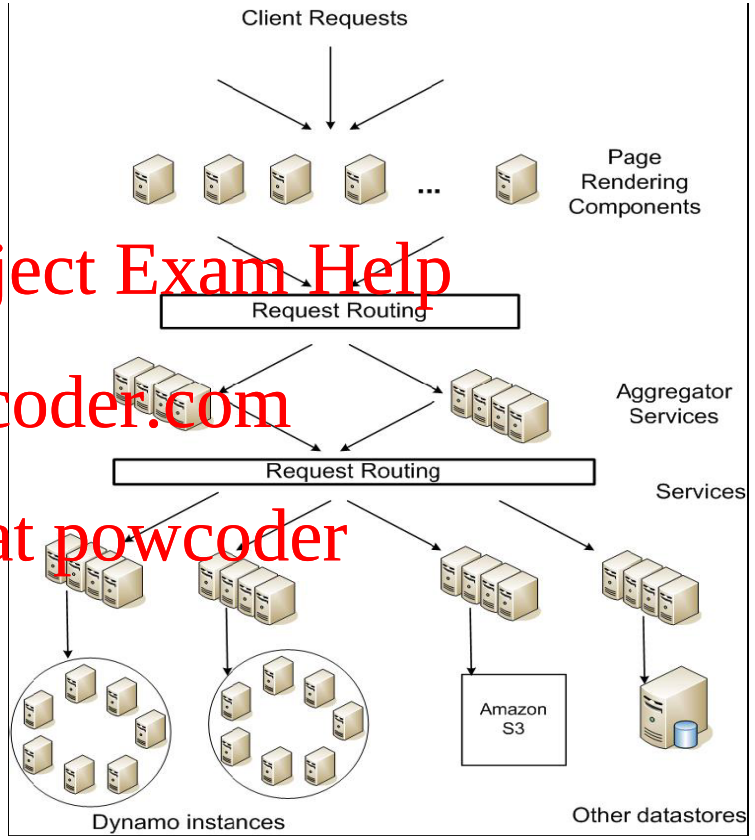
Dynamo

- Motivation
  - Many services in Amazon *only need primary key access* to data store
    - E.g. shopping cart
  - Both scalability and availability are essential terms in the service level agreement
    - Always writable (write never fails)
    - Guaranteed latency
    - Highly available
- Design consideration
  - Simple key value model
  - Sacrifice strong consistency for availability
  - Conflict resolution is executed during **read** instead of write
  - Incremental scalability

Service Level Agreements (SLA)

- Application can deliver its functionality in a bounded time: Every dependency in the platform needs to deliver its functionality with even tighter bounds.
- Example: service guaranteeing that it will provide a response within 300ms for 99.9% of its requests for a peak client load of 500 requests per second.



Dynamo Techniques Summary

- Dynamo is a decentralized **peer-to-peer** system
  - All nodes taking the same role
  - There is no master node

Problem	Technique	Advantage
Partitioning	**Consistent Hashing**	**Incremental Scalability**
High Availability for writes	**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.
Recovering from permanent failures	Anti-entropy using Merkle trees	Synchronizes divergent replicas in the background.
Membership and failure detection	**Gossip-based membership** protocol and failure detection.	Preserves symmetry and avoids having a centralized registry for storing membership and node liveness information.

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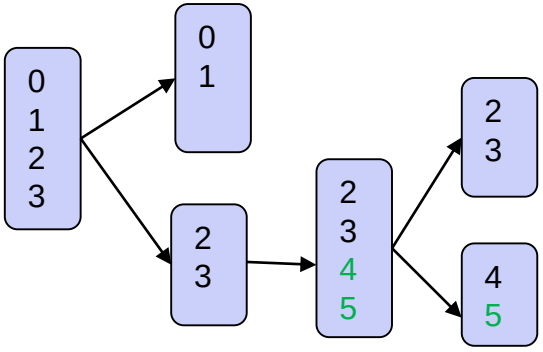
Partitioning Algorithm

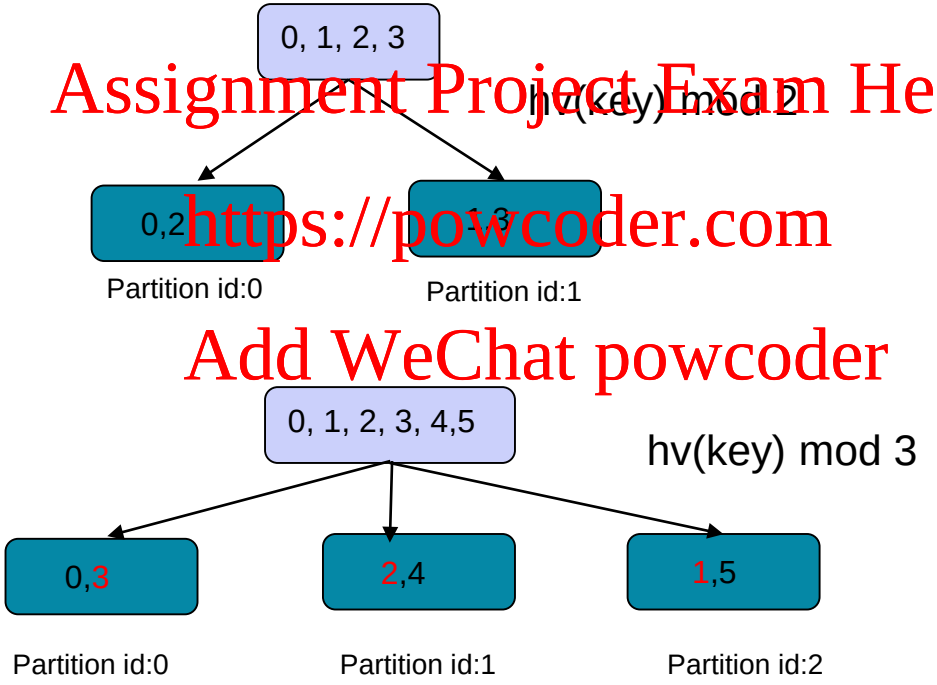
- Partition or shard a data set
  - There is a partition or shard key
    - System default vs. user specified key
  - There is an algorithm to decide which data goes to which partition
    - Range partition vs. Random(Hash) partition
- What happens when data grows
  - Bigtable/HBase way: split a partition that grows beyond threshold



- Split happens locally, does not have global impact
- Data may not be evenly distributed in each partition

Hash Partition- Repartition

- Repartition may involves a lot of data movement
  - The modulo function of key's hash value will redistribute large number of keys to different partitions



Consistent Hashing

- Consistent hashing
  - " a special kind of hashing such that when a hash table is resized, only **K/n** keys need to be remapped on average, where **K** is the number of keys, and **n** is the number of slots."

[Wikipedia: Consistent Hashing]

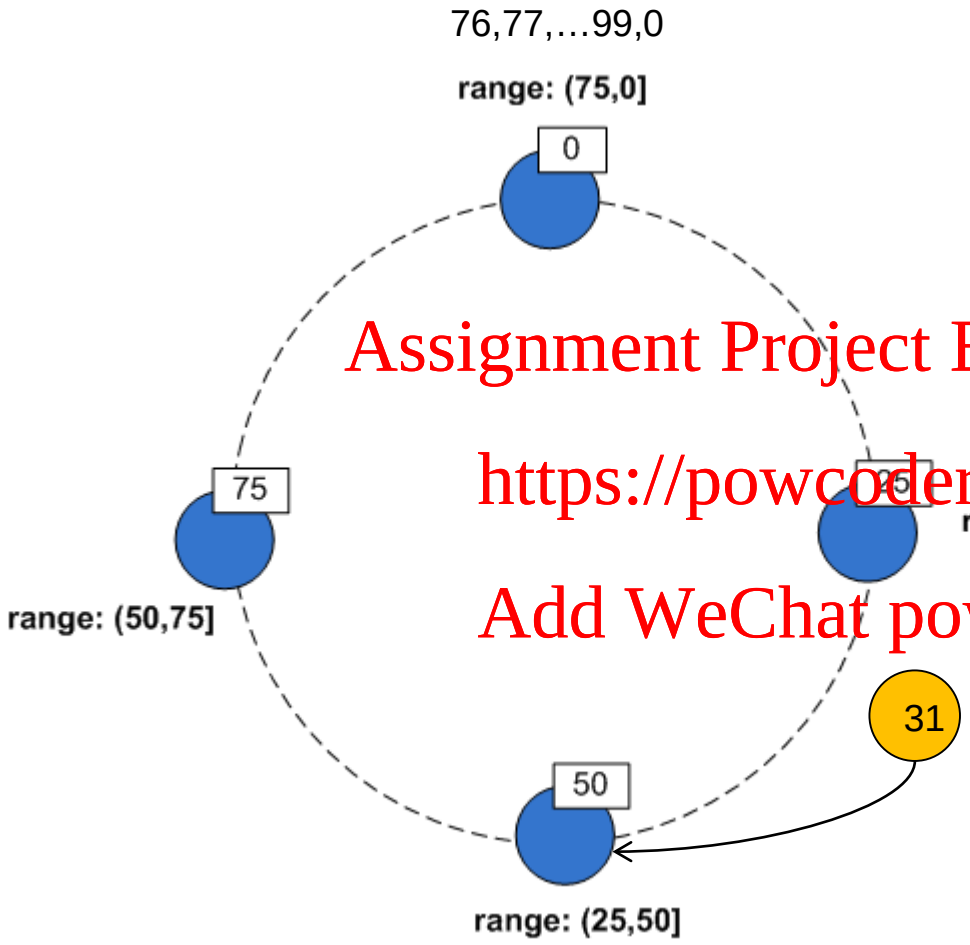
  - It does not identify each partition as a number in [**0,n-1**]
  - The output range of a hash function is treated as a fixed circular space or "ring" (i.e. the largest hash value wraps around to the smallest hash value).

  - Each partition represents a range in the ring space, identified by its position value (token)
  - The hash of a data record's key will uniquely locate in a range
  - In a distributed system, each node represents one partition or a number of partitions if "virtual node" is used.

Consistent Hashing

- Each node in the Dynamo cluster is assigned a “token” representing its position in the “ring”
- Each node is responsible for the region in the ring between it and its predecessor node
- The ring space is the MD5 Hash value space (128 bit)
  - 0 to 2^{127} -1
- The MD5 Hash of the key of any data record is used to determine which node is the coordinator of this key. The coordinator is responsible for
  - Storing the row data locally
  - Replicating the row data in N-1 other nodes, where N is the replication factor

Consistent hashing example



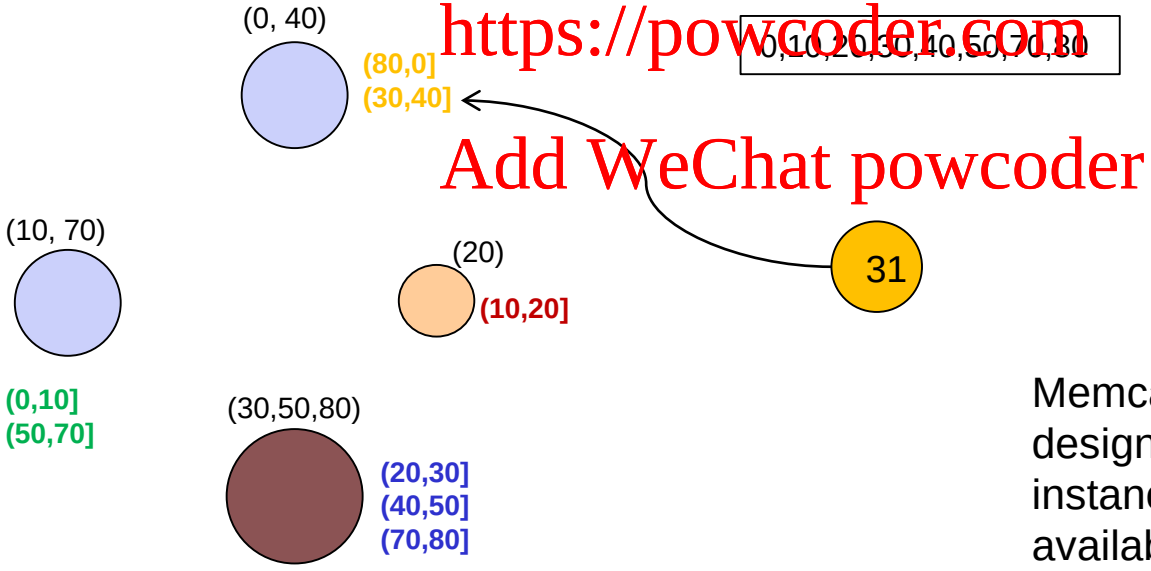
Ring space: 0~99

row key: “bsanderson”
is hashed to a number **31**

The node with token 50 is responsible for this key
This is called the ***coordinator*** of this key

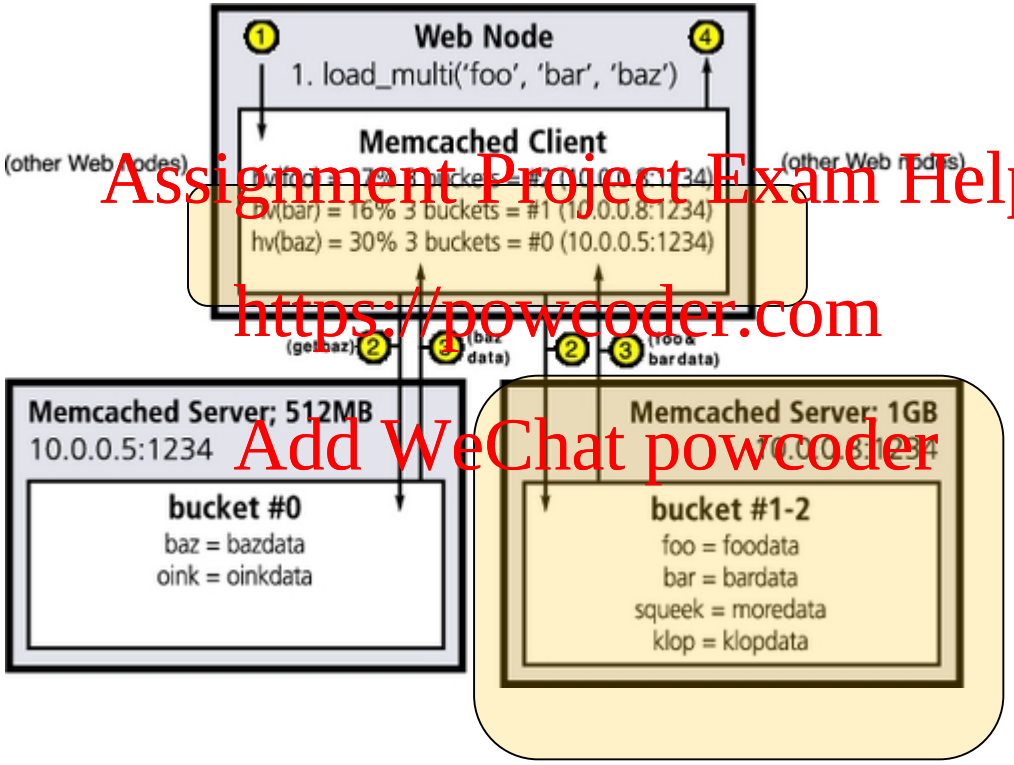
Virtual Nodes

- Possible issue of the basic consistent hashing algorithm
  - Position is randomly assigned, cannot guarantee balanced distribution of data on node
  - Assume node have similar capacity, each is handling one partition
- It does not guarantee that similar row keys will be stored/managed by the same node
- Virtual nodes and multiple partitions per node



Memcached has similar design consideration: an instance with a lot of available memories can be allocated more than one buckets

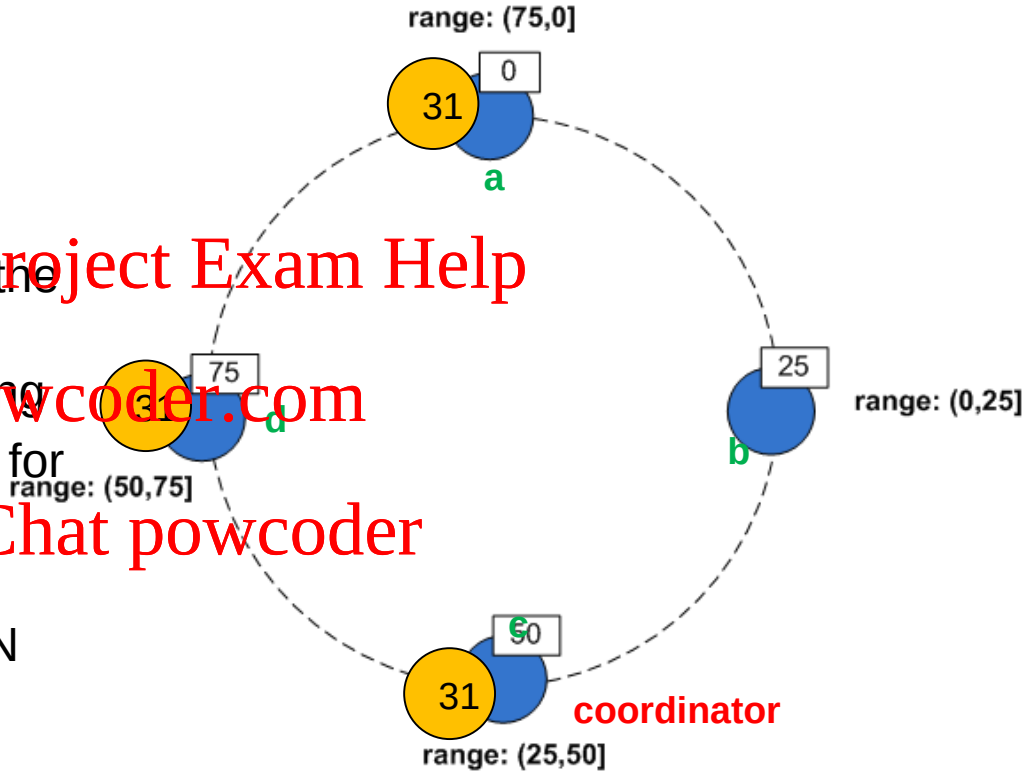
Revisit: Memcached distributed hashing



The server with 1G memory is allocated two buckets

Replication

- Replication is essential for high availability and durability
  - Replication factor (N)
  - Coordinator
  - Preference list
- Each key (and its data) is stored in the coordinator node as well as N-1 clockwise successor nodes in the ring
- The list of nodes that is responsible for storing a particular key is called the *preference list*
- Preference list contains more than N nodes to allow for node failures
  - Some node are used as temporary storage.
  - Can be computed on the fly by any node in the system



Preference list for this key: {c,d,a,b}

Membership and Failure Detection

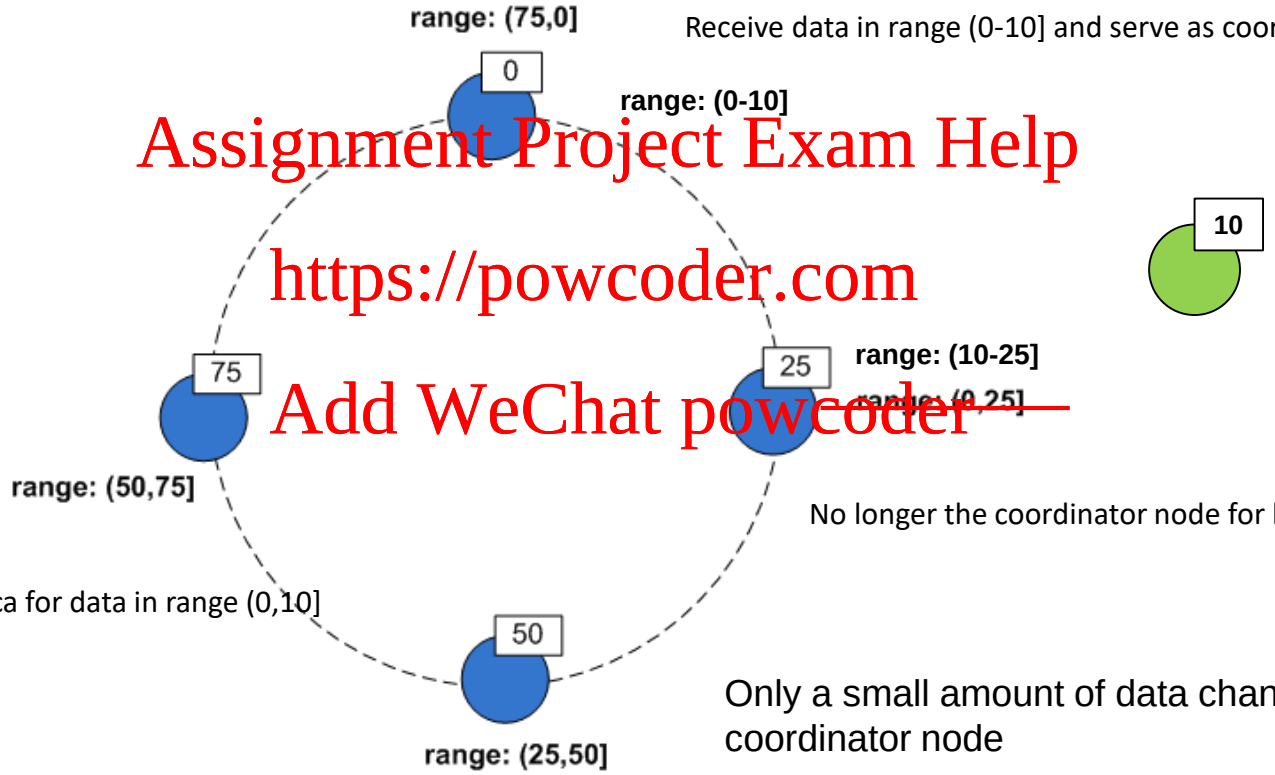
- Each node in the cluster is aware of the token range handled by its peers
  - This is done using a gossip protocol
  - New node joining the cluster will randomly pick a token
  - The information is gossiped around the cluster
- Failure detection is also achieved through gossip protocol
  - Local knowledge
  - Nodes do not have to agree on whether or not a node is “really dead”.
  - Used to handle temporary node failure to avoid communication cost during read/write
  - Permanent node departure is handled externally

Adding Storage Node

Receive data in range (50,75] and serve as replica

Receive data in range (75,0] and serve as replica

Receive data in range (0-10] and serve as coordinator



No longer the coordinator node for keys in (1-10]

No longer a replica for data in range (0,10]

Only a small amount of data change their coordinator node

No longer a replica for data in range (50,75]

http://www.datastax.com/dev/blog/virtual-nodes-in-cassandra-1-2

Outline

- Overview
- Partitioning algorithm

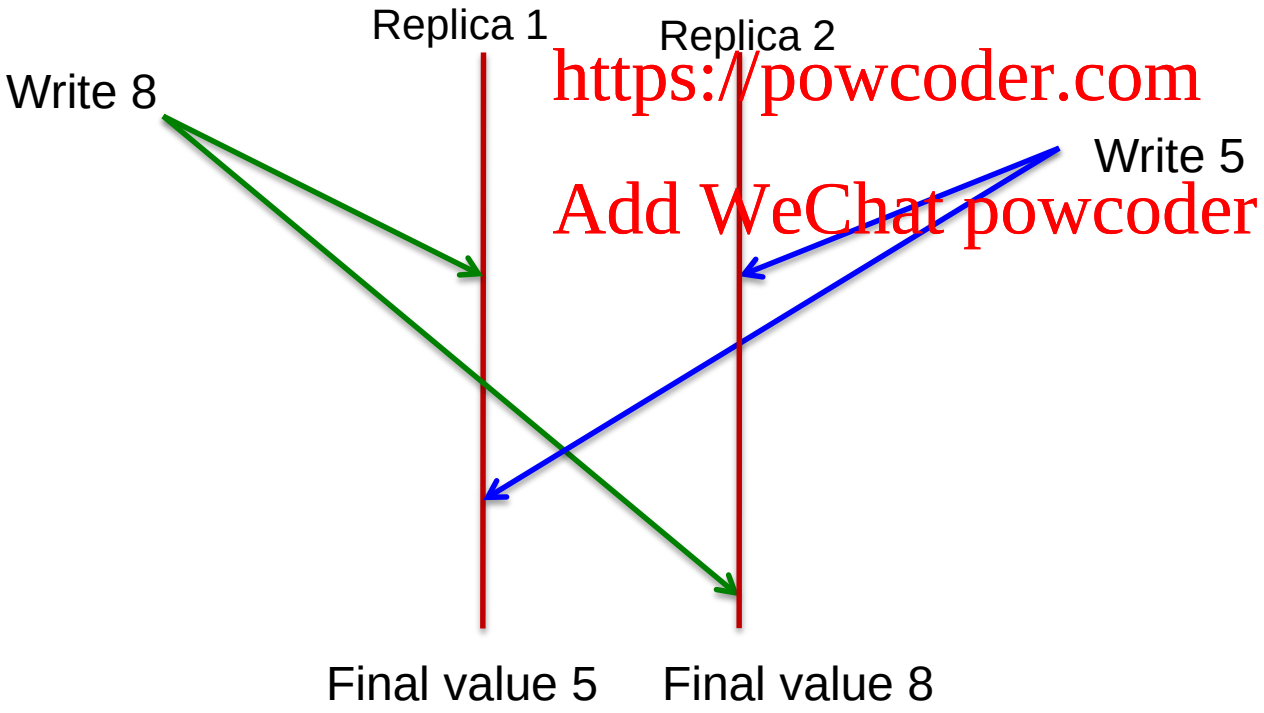
- **Replication and Consistency**

Read and Write with Replication

- When there are replicas, there are many options for read/write
- In a typical Master/Slave replication environment
  - Write happens on the master and may propagate to the replica immediately and wait for all to ack before declaring success, or lazily and declare success after the master finishes write
  - Read may happen on the master (strong consistency) or at one replica (may get stale data)
- In an environment where there is no designated master/coordinator, other mechanisms need to be used to ensure certain level of consistency
  - Order of concurrent writes
  - How many replica to contact before answering/acknowledging

Concurrent Write

- Different clients may try to update an item simultaneously
- If nothing special is done, system could end with "split-brain"

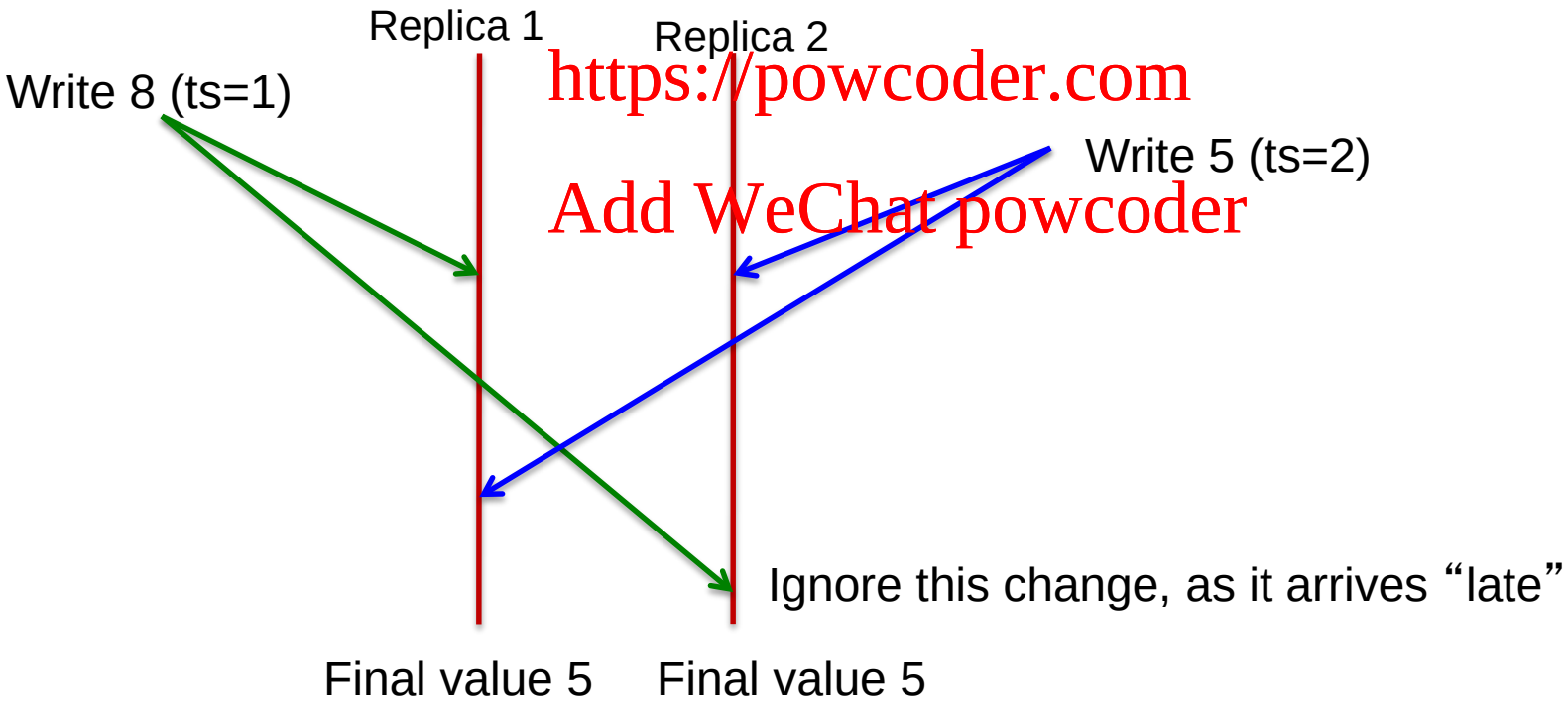


Timestamp is a typical way to order concurrent writes

Slide based on material by Alan Fekete

Ordering concurrent writes

- Associate timestamps on the writes, and let higher timestamp win
  - Node ignores a write whose timestamp is lower than the value already there (Thomas Write Rule)



Slide based on material by Alan Fekete

Quorums

- Suppose each write is *initially* done to W replicas (out of N)
  - Other replicas will be updated later, after write has been acked to client
- How can we find the current value of the item when reading?
- Traditional "quorum" approach is to look at R replicas
  - Consider the timestamp of value in each of these
  - Choose value with highest timestamp as result of the read
- If W>N/2 and R+W>N, this works properly
  - any write and read will have at least one site in common (quorums intersect)
- Any read will see the most recent completed write,
  - There will be at least one replica that is BOTH among the W written and among the R read

Slide based on material by Alan Fekete

Dynamo Mechanisms

- Vector Clock
  - Aid for resolving version conflict
- Sloppy Quorum + hinted hand off
  - Achieve the "always writable" feature
  - Eventual consistency

Dynamo Read/Write Route

- Any node is eligible to receive client read/write request
  - get (key) or put (key, value)
- The node receives the request can direct the request to the node that has the data and is available
  - Any node knows the token of other nodes
  - Any node can compute the hash value of the key in the request and the preference list
  - A node has local knowledge of node failure
- In Dynamo, “A node handling a read or write operation is known as the coordinator. Typically, this is the first among the top N nodes in the preference list.”, which is usually the coordinator of that key unless that node is not available.
  - Every node can be the coordinator of some operation
  - For a given key, the read/write is usually handled by its coordinator or one of the other top N nodes in the preference list

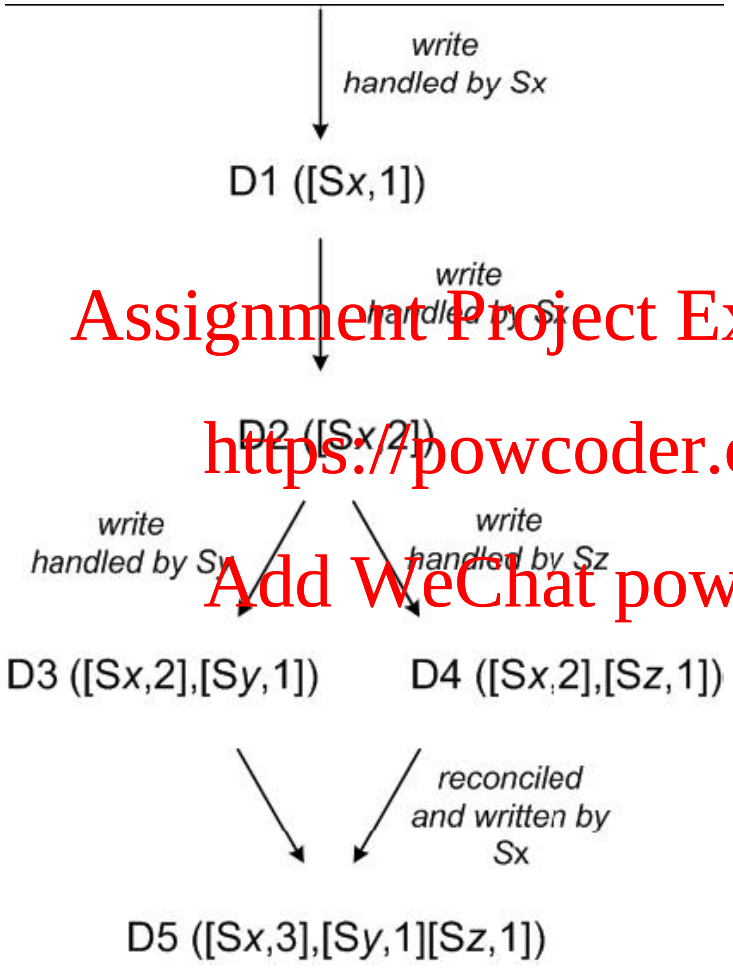
Data Versioning

- A **put()** call may return to its caller before the update has been applied at all the replicas
  - W < N
- A **get()** call may return many versions of the same object/value.
  - R > 1 and R < N
- Typically when N = 3, we may have W = 2 and R = 2
- Challenge: an object may have distinct version sub-histories, which the system will need to reconcile in the future.
- Solution: uses vector clocks in order to capture causality between different versions of the same object.

Vector Clock

- "A vector clock is effectively a list of (node, counter) pairs. One vector clock is associated with every version of every object."
  - E.g. [(n0,1),(n1,1)], [(n1,2),(n2,0),(n3,2)]
- "One can determine whether two versions of an object are on parallel branches or have a causal ordering, by examine their vector clocks. If the counters on the first object's clock are less-than-or-equal to all of the nodes in the second clock, then the first is an ancestor of the second and can be forgotten. Otherwise, the two changes are considered to be in conflict and require reconciliation. "
  - [(n0,**1**),(n1,**1**)] < [(n0,**2**),(n1,**1**),(n3,**1**)]
  - [(n0,**1**),(n1,**1**)] ?? [(n0,**2**),(n2,**1**)]

Vector Clock Example



A node with D1 when receiving D2 in a write request can determine that D2 is the latest and D1 should be garbage collected.

A node with D1 or D2 when receiving D3 in a write request can determine that D3 is the latest and D1 or D2 should be garbage collected.

A node with D3 when receiving D4 in a write request cannot determine which one should be kept and will save both. The conflict needs to be resolved by client with a new version and vector clock written.

Vector Clock More Examples

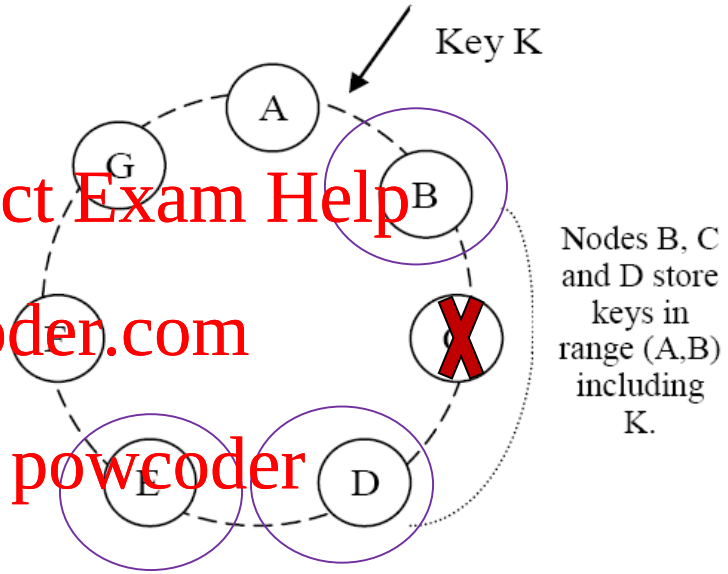
- In a system with 6 nodes: n0~n5, for a key with preference list {n1~n4} which of the following vector clock pair(s) has(have) causal order:
  - [(n1, **1**), (n2,**2**)] and [(n2,**1**)]
  - [(n1, **3**), (n3,**1**)] and [(n1,**2**),(n2,**1**)]
  - [(n1,**2**),(n3,**1**)] and [(n1,**4**),(n2,**1**),(n3,**1**)]

Sloppy Quorum

- Quorum members may include nodes that do not store a replica
  - Preference list is larger than N
  - Read/Write may have quorum members that do not overlap
- Both read and write will contact the first N *healthy* nodes from the preference list and wait for **R** or **W** responses
- Write operation will use hinted handoff mechanism if the node contacted does not store a replica of the data

Hinted Handoff

- Assume N = 3. When C is temporarily down or unreachable during a write, send replica to E.
- E is hinted that the replica belongs to C and it should deliver to C when C is recovered.
- Sloppy quorum does not guarantee that read can always return the latest value
  - Write set: (**B**,D,**E**)
  - Read set: (B,**C**,**D**)



References

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- Giuseppe DeCandia, Deniz Hastorun, Madan Jampani, Gunavardhan Kakulapati, Avinash Lakshman, Alex Pilchin, Swaminathan Sivasubramanian, Peter Vosshall, and Werner Vogels. 2007. **Dynamo: amazon's highly available key-value store**. In *Proceedings of twenty-first ACM SIGOPS symposium on Operating systems principles* (SOSP '07). 205-220.