Cassandra Architecture Review

Apache Cassandra:
Operations and Performance Tuning

Learning Objectives

- **Review Cassandra, tables and Keyspaces**
- **Review insert, upsert and select**
- Review nodes, clusters, data centers
- Review how requests are coordinated
- Review replication
- Review how to tune consistency
- Review how nodes communicate
- Review read and write paths

What is Cassandra?

DATASTAX

- Massively linearly scalable NoSQL database
  - Fully distributed, with no single point of failure
  - Free and open source, with deep developer support
  - Highly performant, with near-linear *horizontal* scaling in proper use cases
  - Fully peer-to-peer—no master/slave architecture
  - Data center aware

What are Keyspaces?

DATASTAX

- A namespace for tables in a cluster
  - All data will reside in some keyspace
  - Main function: Control replication
  - Data with different replication requirements will be in different keyspaces
  - Somewhat analogous to a schema in the relational model
- Replication Factor (RF) and replication strategy specified when creating a keyspace
  - They may be changed later
- Below is the CQL (Cassandra Query Language) to create a keyspace
  - It uses SimpleStrategy and has an RF of 1
  - You can change the RF using the ALTER KEYSPACE command

```
CREATE KEYSPACE stockwatcher WITH REPLICATION =
{'class' : 'SimpleStrategy', 'replication_factor': 1};
```

What are tables?

DATASTAX

- Tables store data in a Cassandra database
  - Define columns and their metadata (e.g. data type)
  - Analogous to a relational table
  - Were called Column Families in the Thrift API
- **CREATE TABLE** is used in CQL to define a table
  - A table must reside in a keyspace
  - Either selected with USE, or as part of the name of the table, e.g. stockwatcher.user
  - A table must specify a primary key

```
USE stockwatcher;  // Execute any time before the CREATE
CREATE TABLE user ( username TEXT PRIMARY KEY,
                    userid TIMEUUID,
                    phonenumber BIGINT);
```

Inserting Data

DATASTAX

- For this simple table, we can insert into a row using the INSERT examples below
  - This results in the rows being written to Cassandra
  - This should also seem familiar to SQL users
- All writes for a row (including inserts/updates/deletes) are done atomically and in isolation
  - Inserting or updating (multiple) columns in a row is one write operation
  - We'll cover this in more detail shortly

```
INSERT INTO User (first_name, last_name, display_name)
   VALUES ('Lebron', 'James','King James');
INSERT INTO User (first_name, last_name, display_name)
   VALUES ('Eldrick', 'Woods', 'Tiger Woods');
INSERT INTO User (first_name, last_name, display_name)
   VALUES ('Eli','Manning', 'Two-Time Super Bowl Winner');
```

INSERT is Always UPSERT

- An insert with an existing primary key becomes an update
  - Cassandra will just write the new column value(s) provided
  - Each column inserted will supersede any older values
- For two concurrent writes with the same primary key, the last write wins
  - i.e. the last write to finish will be returned in subsequent queries
- Review the following inserts, and the results of the CQL query
  - Note that an insert doesn't necessarily have to insert all columns

```
INSERT INTO User (first_name, last_name, display_name)
    VALUES ('Lebron', 'James','Lebron James');
INSERT INTO User (first_name, display_name)
    VALUES ('L','Lebron James');
```

```
cqlsh:stockwatcher> select * from user;

 display_name | first_name | last_name
--------------+------------+-----------
 Lebron James |          L |     James
```

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- Review Cassandra, tables and Keyspaces
- Review insert, upsert and select
- **Review clusters, data centers, nodes**
- Review replication
- Review how requests are coordinated
- Review how to tune consistency
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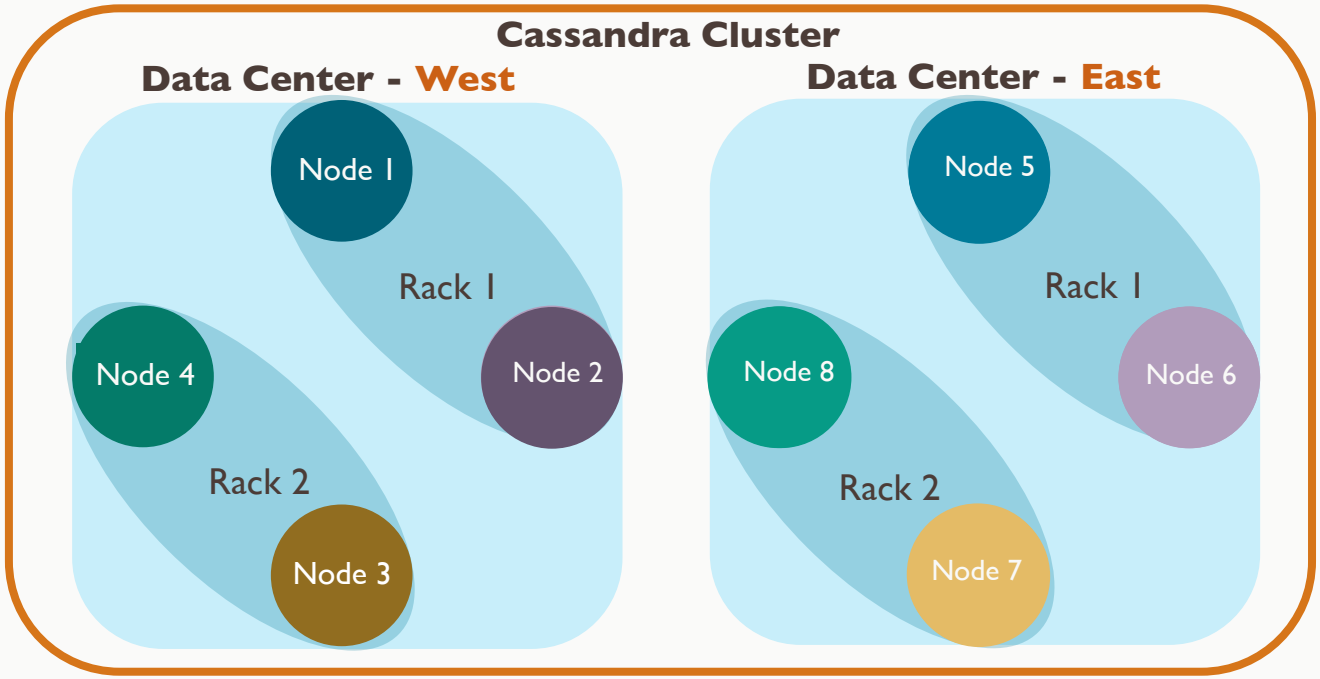
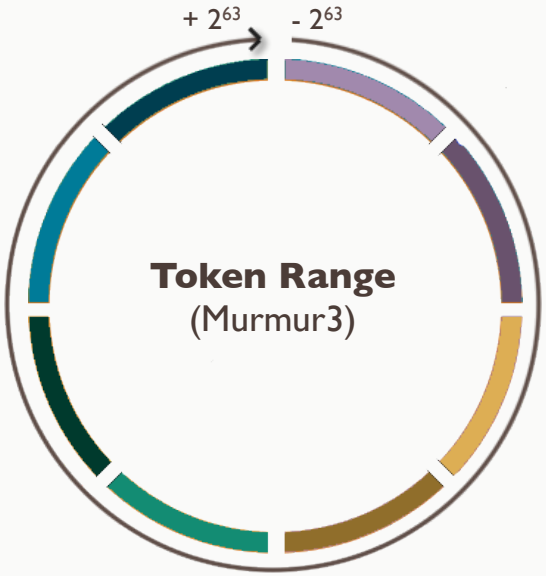
- Review read and write paths

What is a cluster?

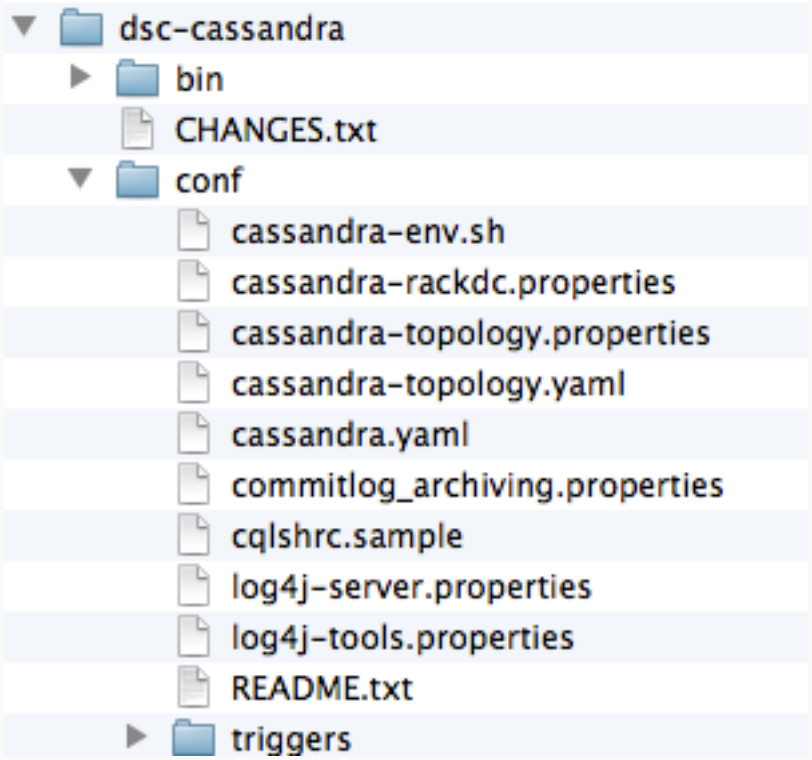
- A peer to peer set of nodes
  - Node – one Cassandra instance
  - Rack – a logical set of nodes
  - Data Center – a logical set of racks
  - Cluster – a ring of nodes





Configuration files

- cassandra.yaml
  - One file per node, must agree with other node's files
  - Parameters defined throughout
- cassandra-env.sh
  - Memory settings
  - JMX settings
- log4j-server.properties
  - Error log settings



What key properties are set in *cassandra.yaml*?

DATASTAX

- cluster_name *(default: 'Test Cluster')*
  - All nodes in a cluster must have the same value.
- listen_address *(default: localhost)*
  - Defines the network interface for gossip connections
- rpc_address
  - Network interface for client connections (0.0.0.0 means all interfaces)
- rpc_port *(default: 9160)*
  - port for Thrift client connections
- native_transport_port *(default: 9042)*
  - port on which CQL native transport listens for clients

Key properties in *cassandra.yaml*

DATASTAX

- commitlog_directory *(default: /var/lib/cassandra/commitlog)*
  - Best practice to mount on a separate disk in production (unless SSD)
- data_file_directories *(default: /var/lib/cassandra/data)*
  - List of storage directories for data tables (SSTables)
- saved_caches_directory *(default: /var/lib/cassandra/saved_caches)*
  - Storage directory for key and row caches

What key properties are set in *cassandra-env.sh*?

DATASTAX

- JVM Heap Size settings
  - MAX_HEAP_SIZE="*value*"
    - Maximum recommended in production is currently 8G due to current limitations in Java garbage collection

System Memory	Heap Size
Less than 2GB	1/2 of system memory
2GB to 4GB	1GB
Greater than 4GB	1/4 system memory, but not more than 8GB

  - HEAP_NEWSIZE="*value*"
    - Generally set to ¼ of MAX_HEAP_SIZE
- This file computes the default values, but you can override them as necessary.

What key properties are set in *log4j-server.properties*?

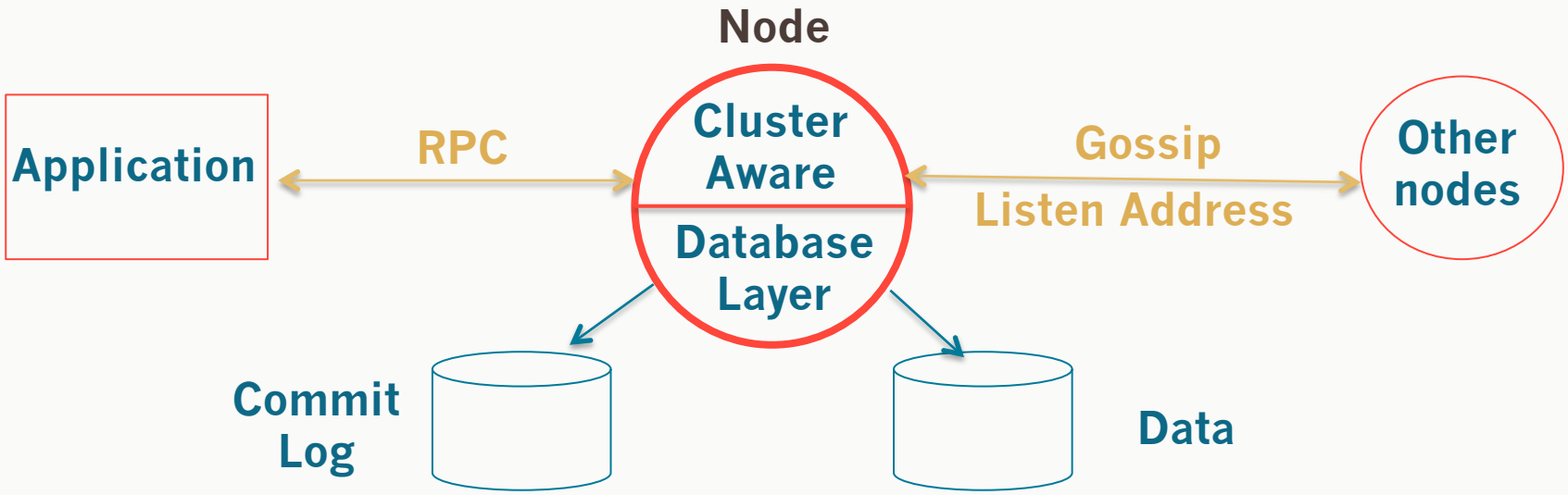
DATASTAX

- Cassandra system.log location
  - Default location is */var/log/cassandra/system.log*
  - `system.log` is numerically renamed as it grows over time
- Cassandra logging level
  - Default logging level is *INFO*

```
# output messages into a rolling log file as well as stdout
log4j.rootLogger=INFO,stdout,R
```

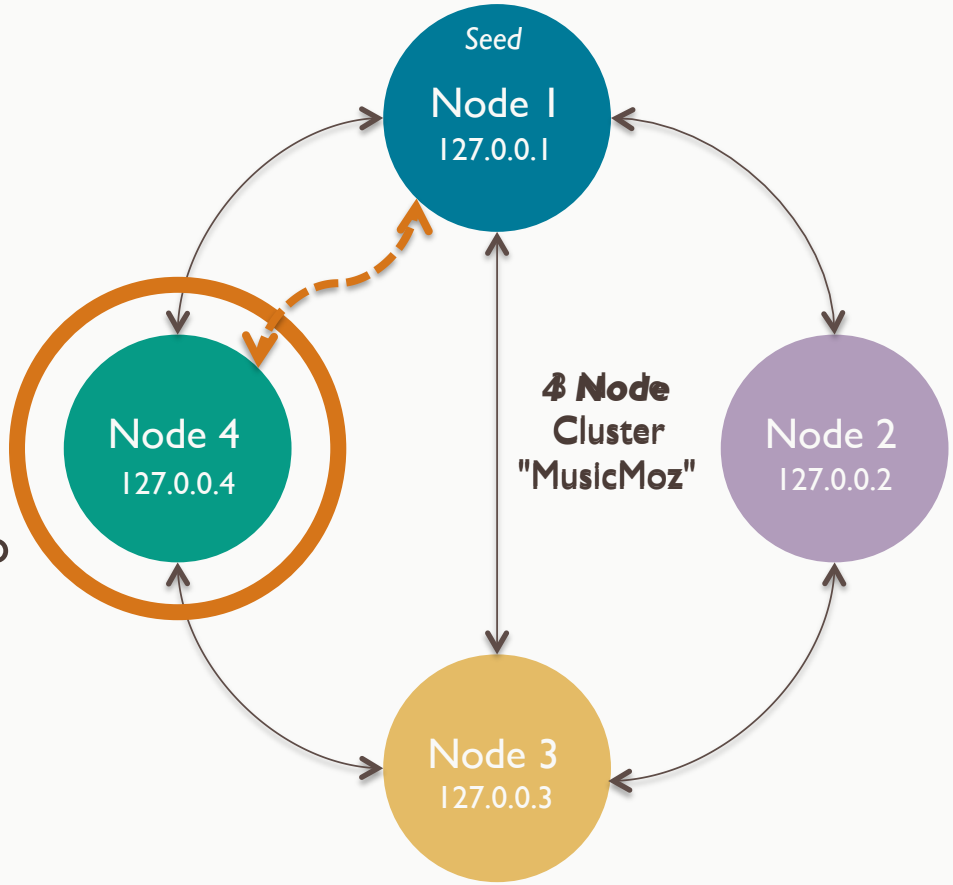
What is a node?

- Single node database
- rpc_address—used to setup how clients come into a cluster
- rpc_port (9160)—thrift, how node talks to the application
- native_transport_port (9042)—native connections
- default—localhost which means you are stuck with only local clients
- 0.0.0.0 means clients can come in from anywhere



What is a cluster?

- Nodes join a cluster based on the configuration of their own *conf/cassandra.yaml* file
- Key settings include
  - cluster_name – shared name to logically distinguish a set of nodes
  - seeds – IP addresses of initial nodes for a new node to contact and discover the cluster topology (best practice to use the same two per data center)
  - listen_address – IP address to determine adaptor through which this particular node communicates to other nodes

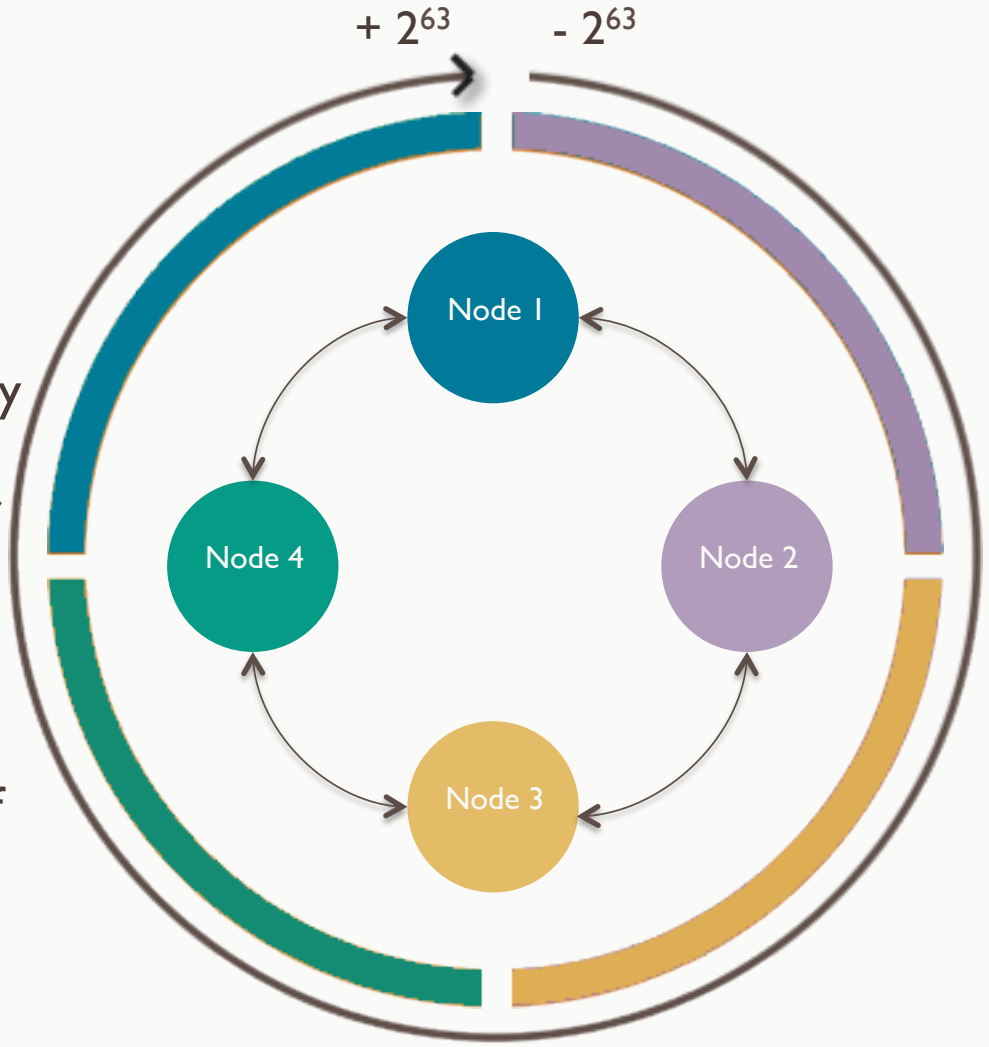


Where does my data go?

- Cassandra automatically shards your data.
- It will put one or more copies of your data on your nodes.

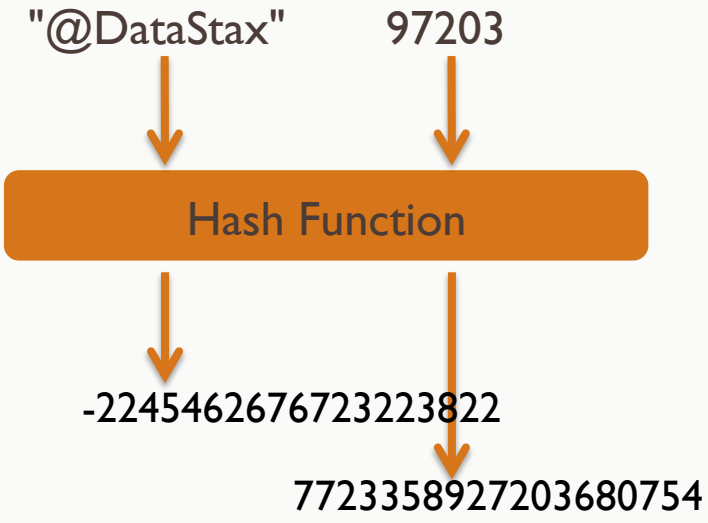
What is consistent hashing?

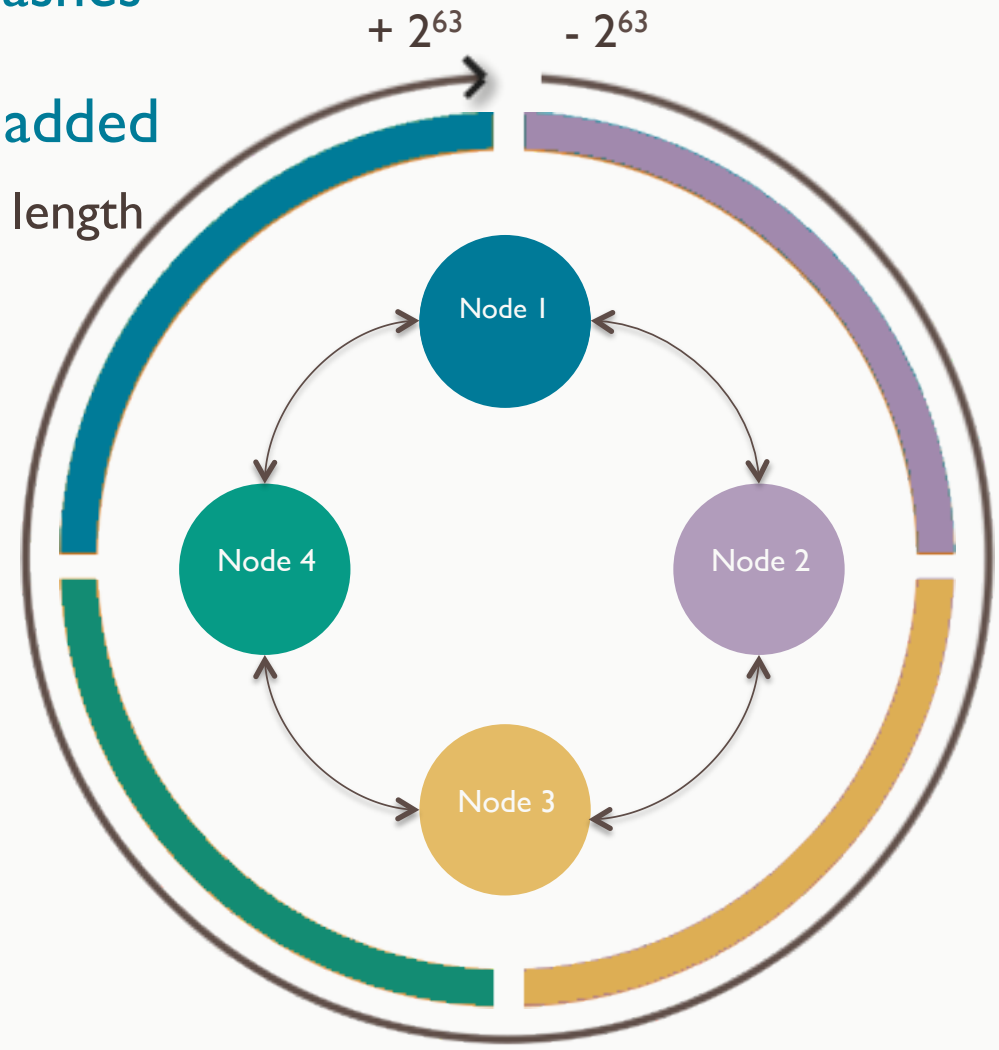
- Data is stored on *nodes* in *partitions*, each identified by a *partition key*.
  - Partition – a storage location on a node (analogous to a "table row")
  - Token – 64 bit integer, generated by a hashing algorithm, identifying a partition's location within a cluster
- The 2^{64} value *token range* for a cluster is used as a single ring
  - So, any partition in a cluster is locatable from one *consistent* set of hash values, regardless of its node
  - Specific token range varies by choice of *partitioner*
  - Partitioner options discussed ahead



What is the partitioner?

- A system on each node which hashes keys to create a token from designated values in rows being added
  - Hash function – converts a variable length value to a corresponding fixed length value

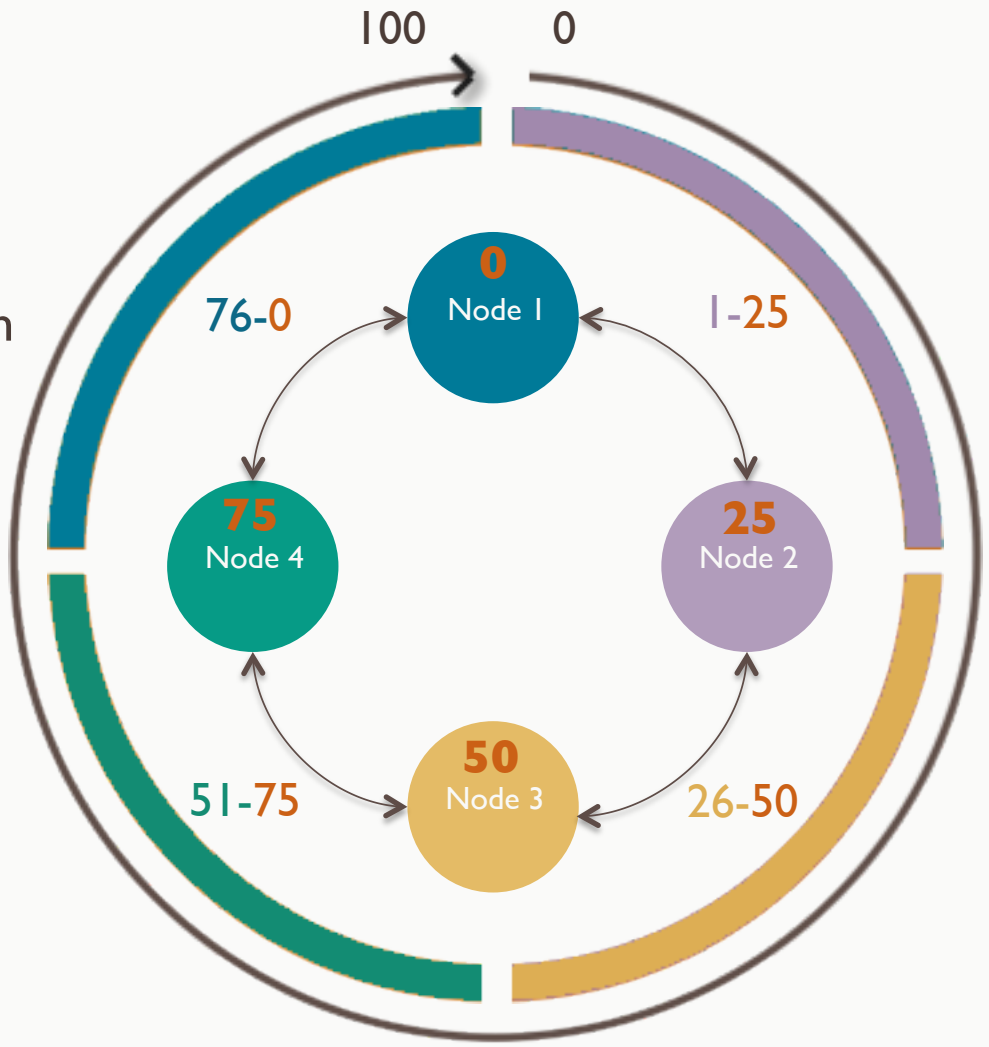




- Various partitioners available

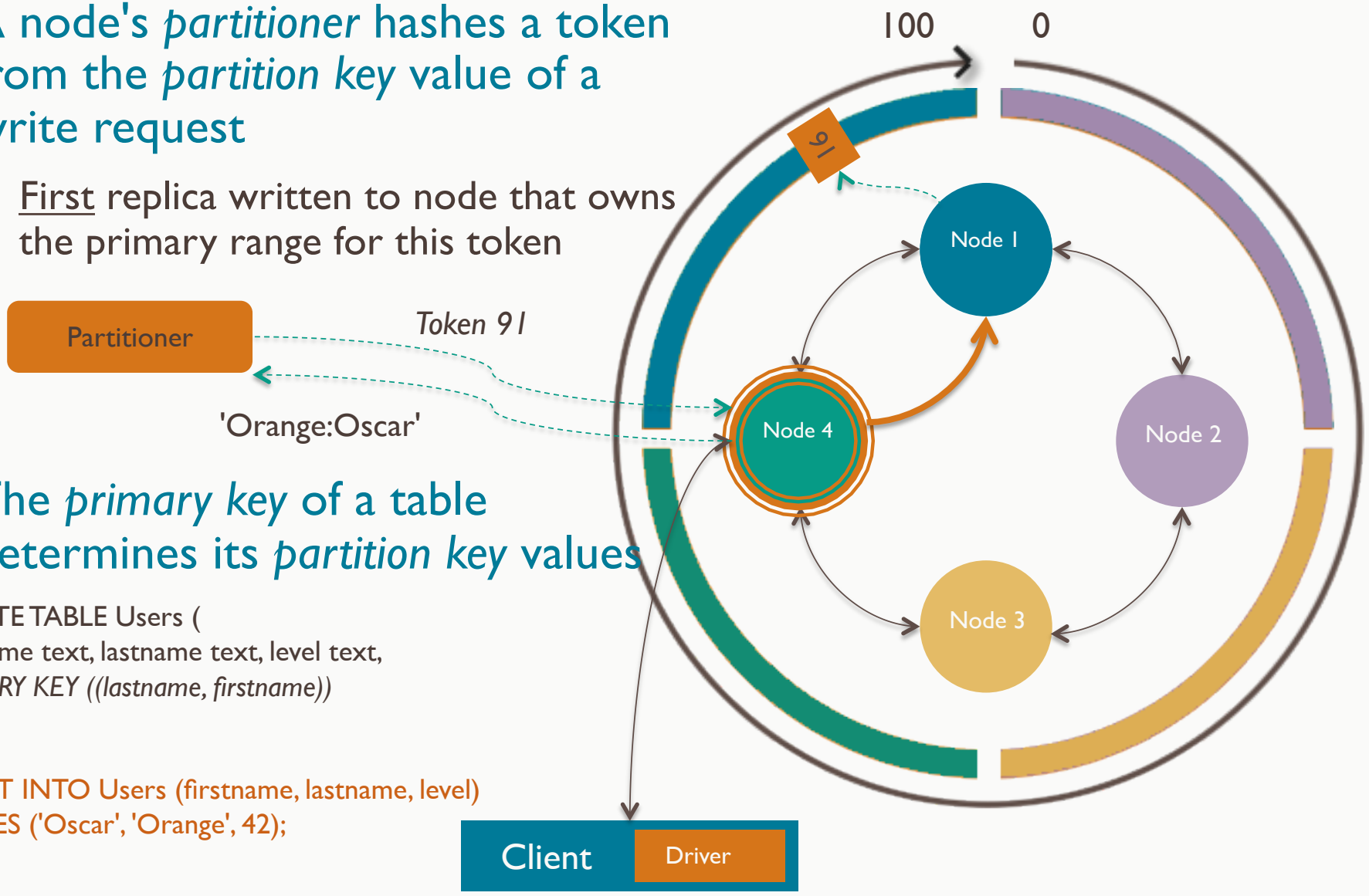
What is the partitioner?

- Imagine a 0 to 100 token range (instead of -2^{63} to $+2^{63}$)
  - Each node is assigned a token, just like each of its partitions
  - *Node tokens* are the highest value in the segment owned by that node
- This segment is the *primary token range* of replicas owned by this node
  - Nodes also store *replicas* keyed to tokens outside this range ("secondary range")



How does a partitioner work?

- A node's *partitioner* hashes a token from the *partition key* value of a write request
  - First replica written to node that owns the primary range for this token



- The *primary key* of a table determines its *partition key* values

```
CREATE TABLE Users (
firstname text, lastname text, level text,
PRIMARY KEY ((lastname, firstname))
);

INSERT INTO Users (firstname, lastname, level)
VALUES ('Oscar', 'Orange', 42);
```

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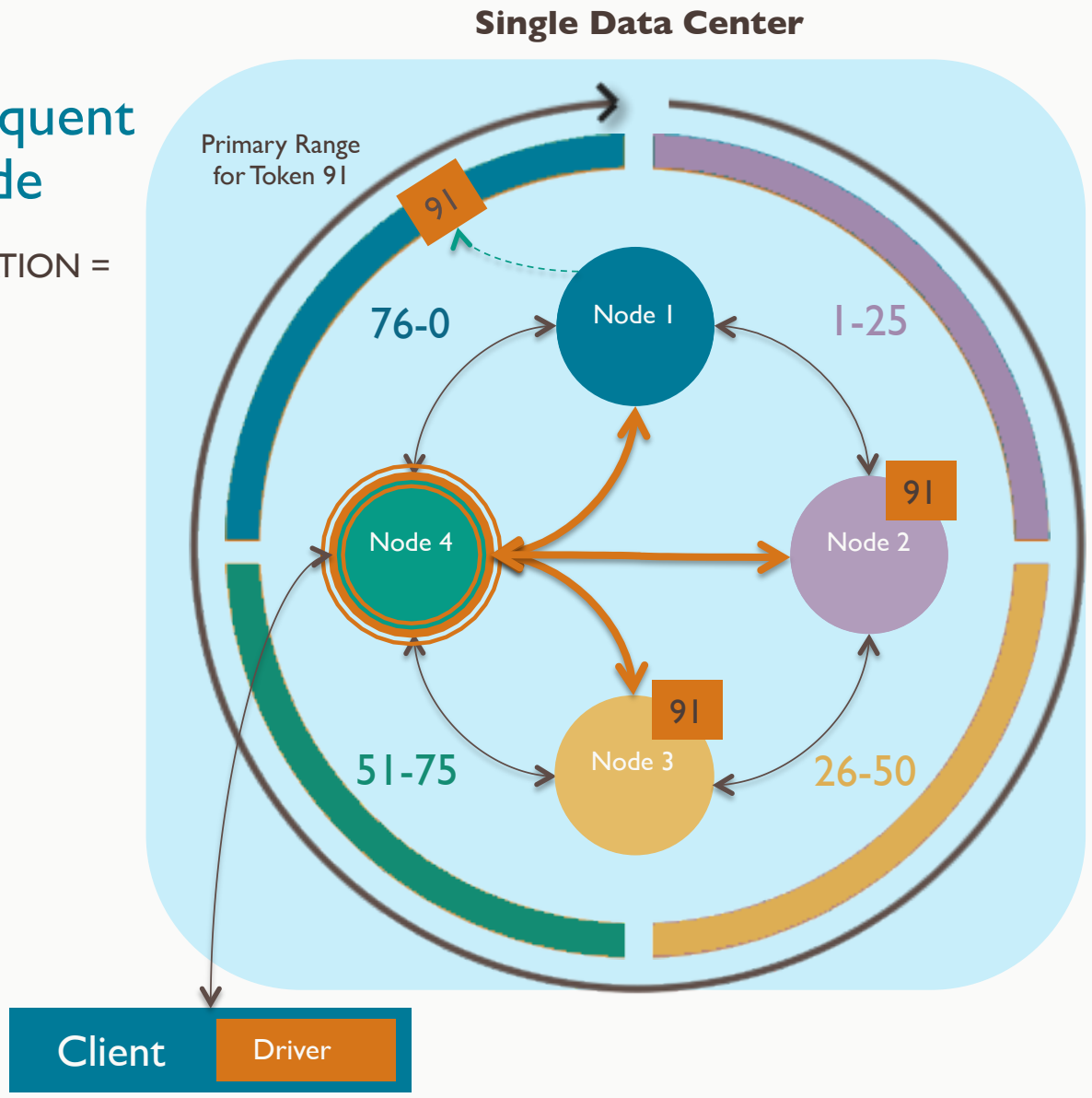
How is data replicated among nodes?

- SimpleStrategy – create replicas on nodes subsequent to the *primary range* node

```
CREATE KEYSPACE demo WITH REPLICATION =
{'class':'SimpleStrategy',
 'replication_factor':3}
```

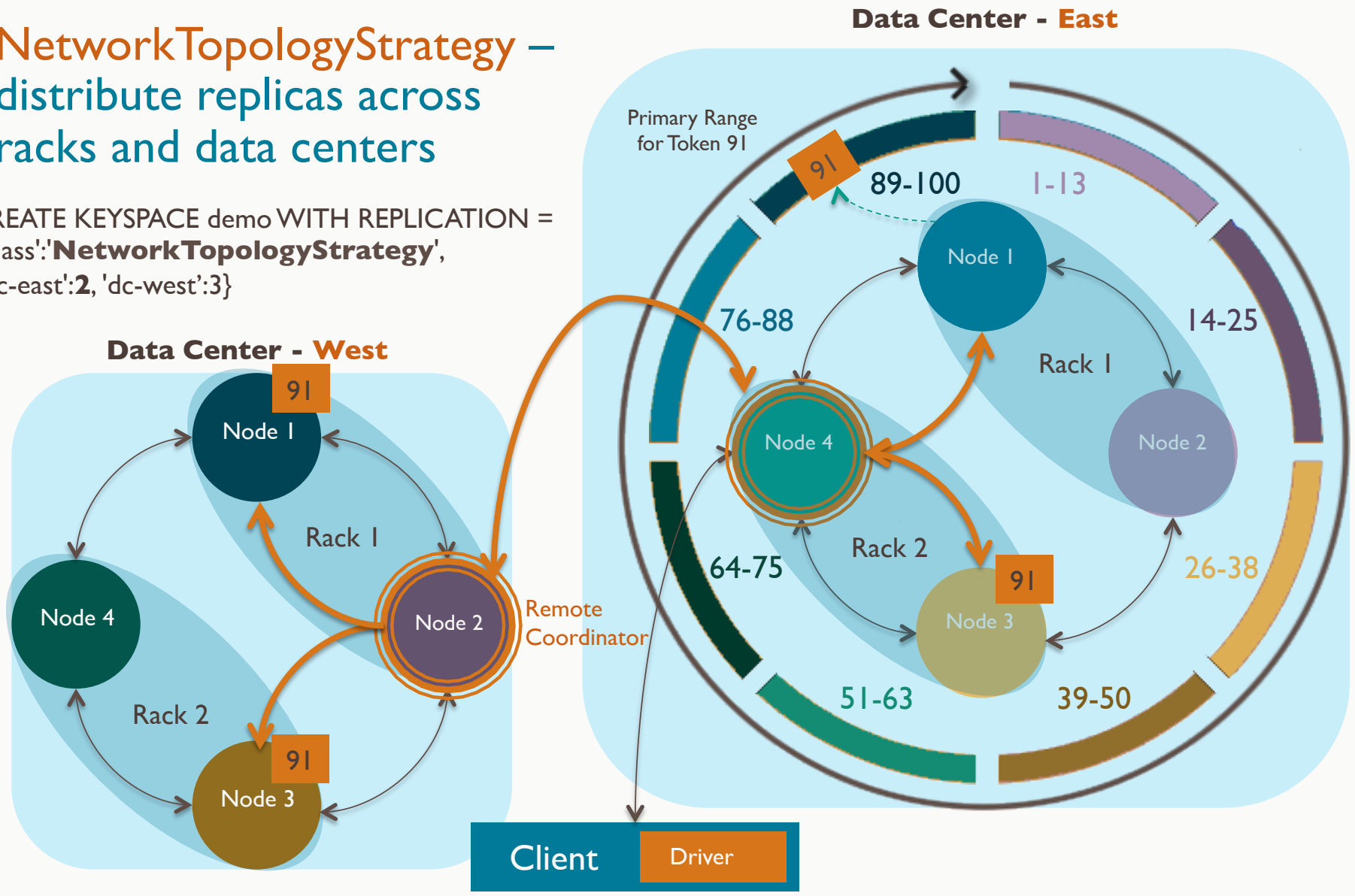
  - *replication factor* of 3 is a recommended minimum



How is data replicated between data centers?

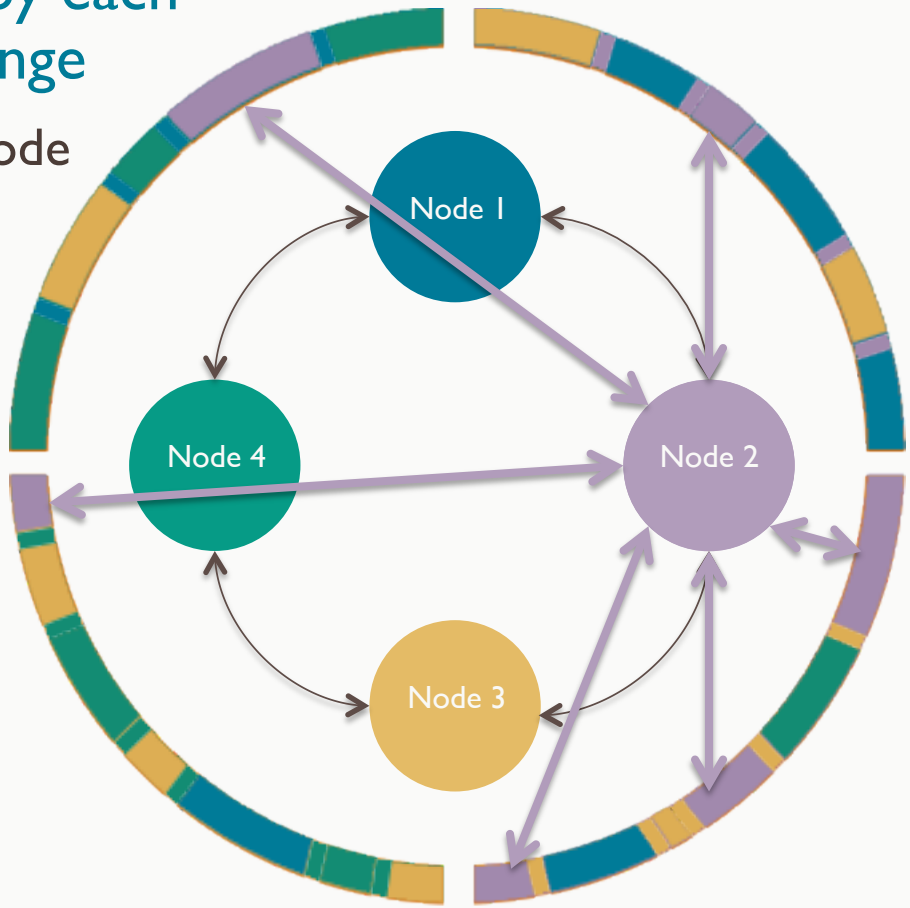
- NetworkTopologyStrategy – distribute replicas across racks and data centers

CREATE KEYSPACE demo WITH REPLICATION = {'class':'**NetworkTopologyStrategy**', 'dc-east':**2**, 'dc-west':3}



What are virtual nodes?

- Multiple smaller primary range segments – virtual nodes – can be owned by each machine, instead of one larger range
  - virtual nodes behave like a regular node
  - available in Cassandra 1.2+
  - default is 256 per machine
  - not available on nodes combining Cassandra with Solr or Hadoop
- How are virtual nodes helpful?
  - token ranges are distributed, so machines bootstrap faster
  - impact of virtual node failure is spread across entire cluster
  - token range assignment automated



What are virtual nodes?

- Virtual nodes are enabled in *cassandra.yaml*
  - *partitions*, *regular nodes*, and *virtual nodes* are each identified by a *token*
  - regular or virtual node tokens are the highest value in one segment of the total token range for a cluster, which is the *primary range* of that node

*cassandra.yaml

```
# Cassandra storage config YAML

# This defines the number of tokens randomly assigned to this node on the ring
# The more tokens, relative to other nodes, the larger the proportion of data
# that this node will store. You probably want all nodes to have the same number
# of tokens assuming they have equal hardware capability.
#
# If you leave this unspecified, Cassandra will use the default of 1 token
# for legacy compatibility, and will use the initial_token as described below.
#
# Specifying initial_token will override this setting.
#
# If you already have a cluster with 1 token per node, and wish to migrate to
# multiple tokens per node, see http://wiki.apache.org/cassandra/Operations
num_tokens: 256
```

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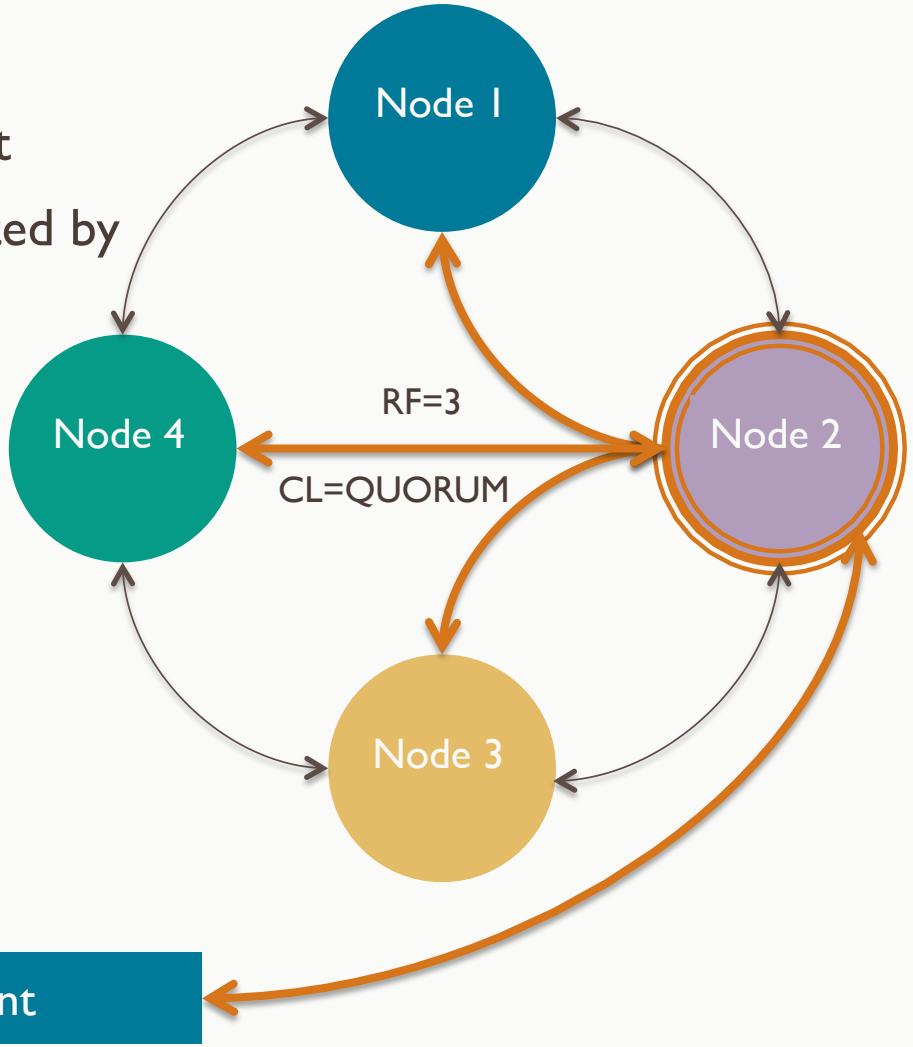
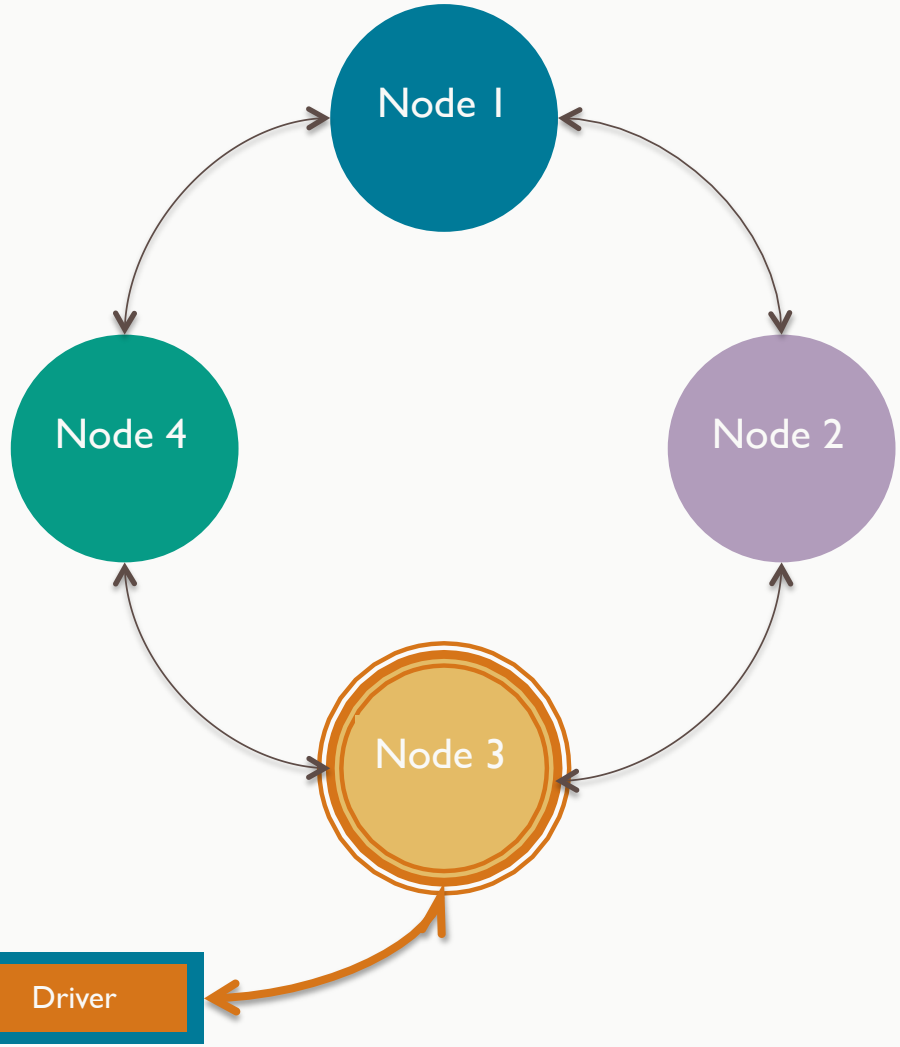
What is a coordinator?

- The *node* chosen by the client to receive a particular read or write request to its *cluster*
  - Any node can coordinate any request
  - Each client request may be coordinated by a different node
- No single point of failure
  - This principle is fundamental to Cassandra's architecture



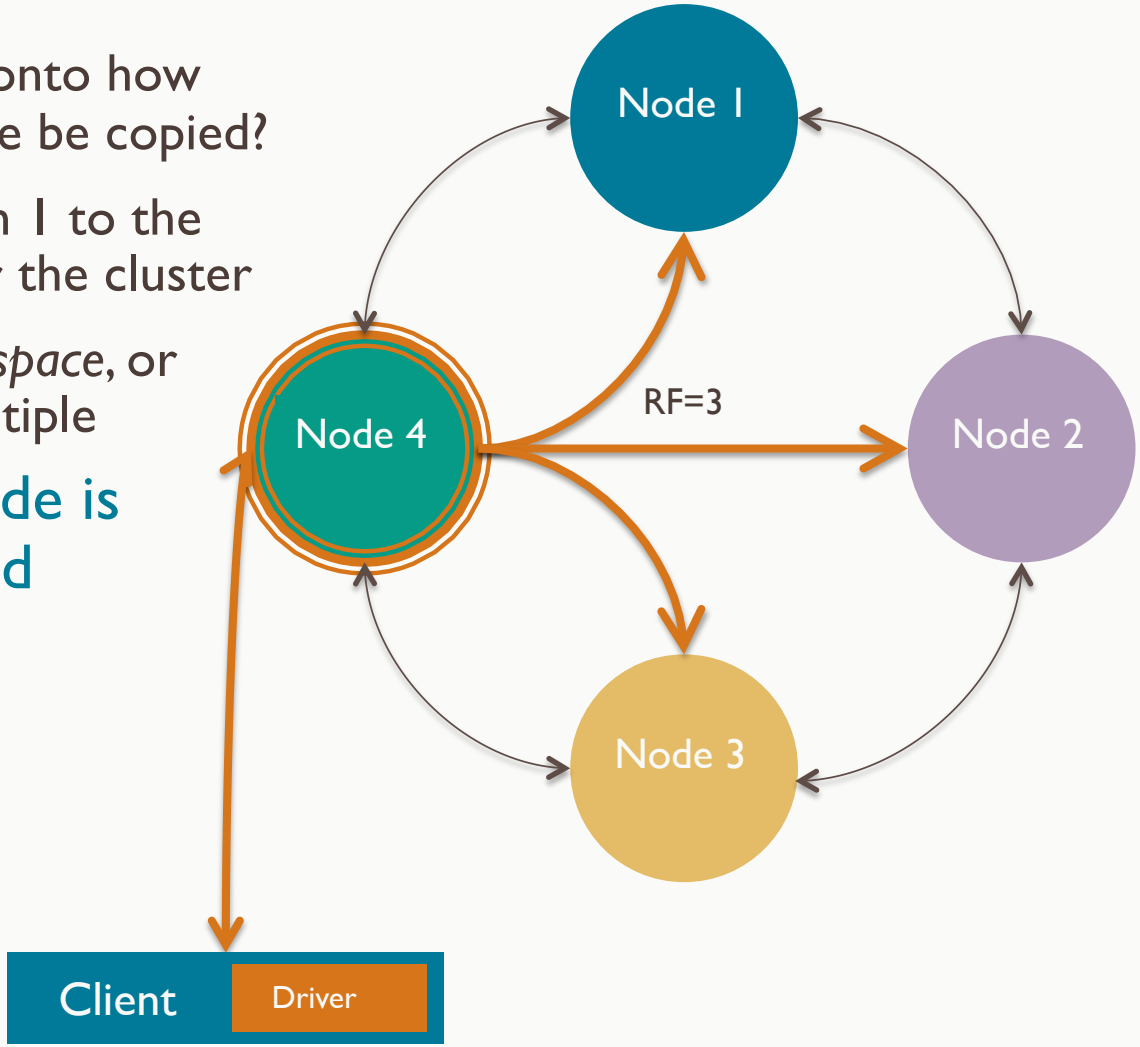
How are client requests coordinated?

- The *Cassandra driver* chooses the node to which each read or write request is sent
  - Client library providing APIs to manage client read/write requests
  - Round-robin pattern by default
  - DataStax maintains open source drivers for Java, Python, C++, C#
  - Cassandra Community maintains drivers for Node.js, PHP, Perl, Go, Clojure, Haskell, R, Ruby, Scala
- Client development is taught in the *Apache Cassandra: Building Scalable Applications* course



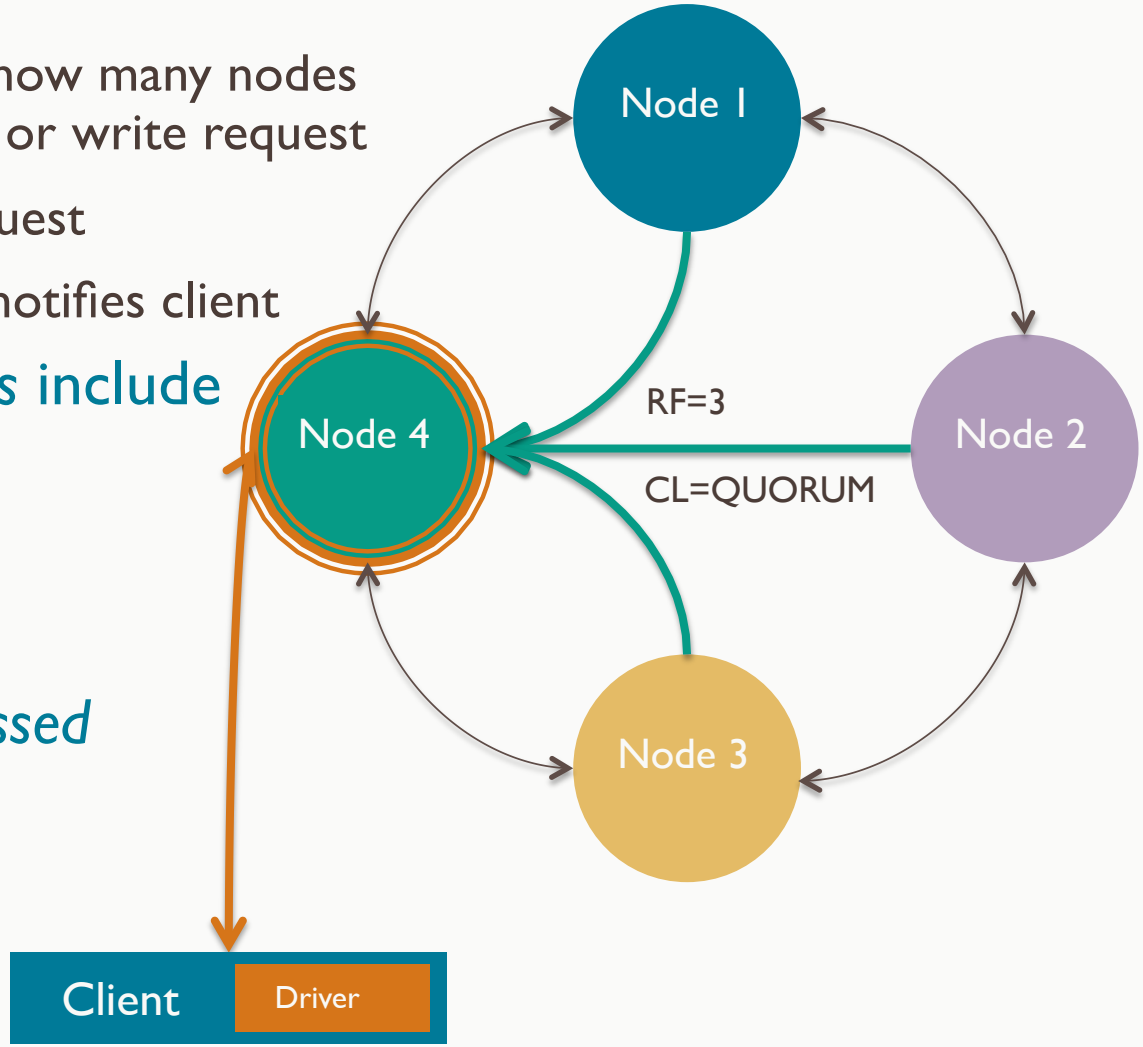
How are client requests coordinated?

- The coordinator manages the Replication Factor (RF)
  - Replication factor (RF) – onto how many nodes should a write be copied?
  - Possible values range from 1 to the total of planned nodes for the cluster
  - RF is set for an entire *keyspace*, or for each *data center*, if multiple
- Every write to every node is individually time-stamped



How are clients requests coordinated?

- The coordinator also applies the Consistency Level (CL)
  - Consistency level (CL) – how many nodes must acknowledge a read or write request
  - CL may vary for each request
  - On success, coordinator notifies client
- Possible *consistency levels* include
  - ONE
  - QUORUM (RF / 2) + 1
  - ALL
- *Consistency Level is discussed further ahead*



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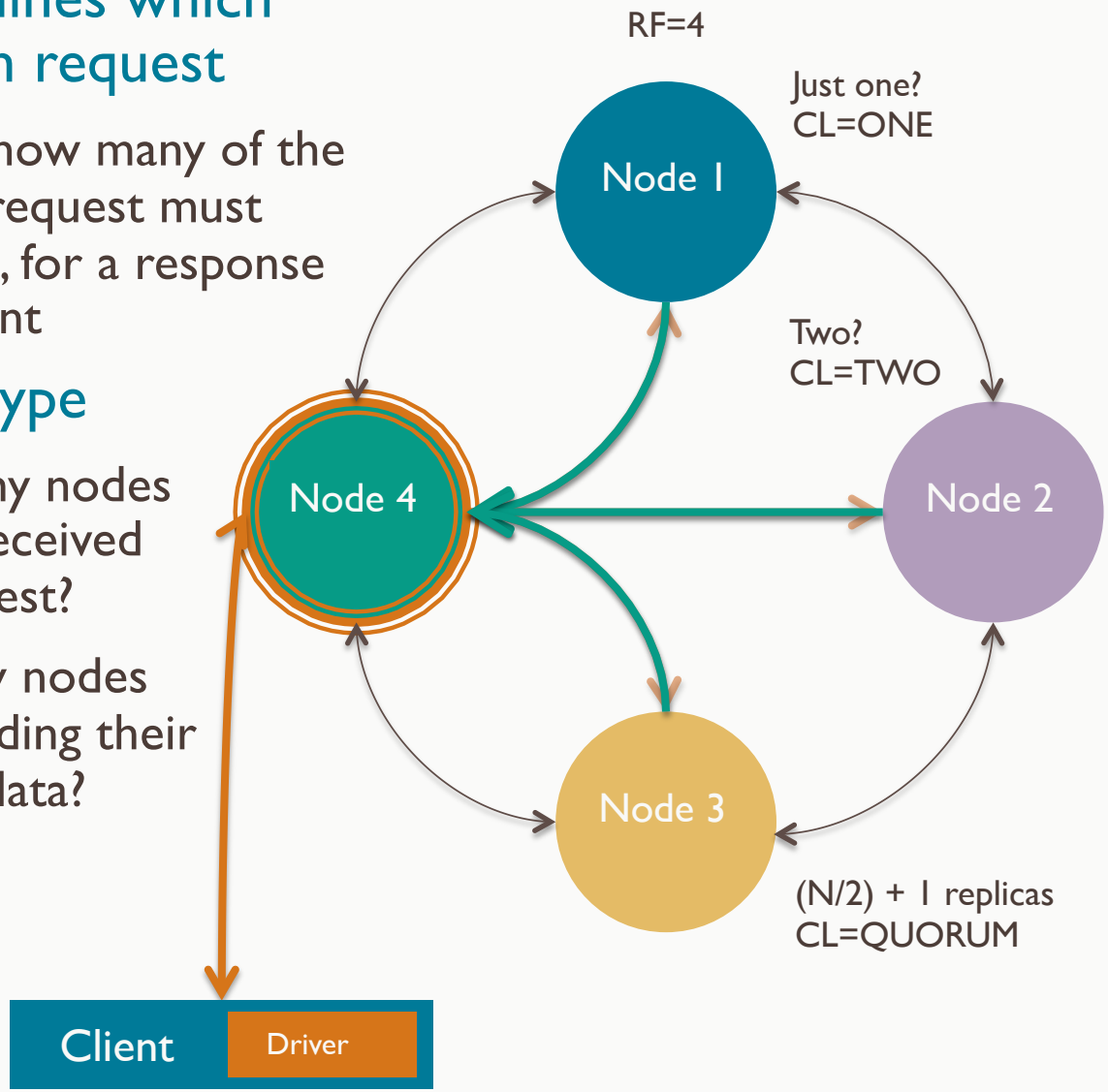
What is consistency?

- The *partition key* determines which nodes are sent any given request
  - Consistency Level – sets how many of the nodes to be sent a given request must acknowledge that request, for a response to be returned to the client
- The meaning varies by type
  - Write request – how many nodes must acknowledge they received and wrote the write request?
  - Read request – how many nodes must acknowledge by sending their most recent copy of the data?



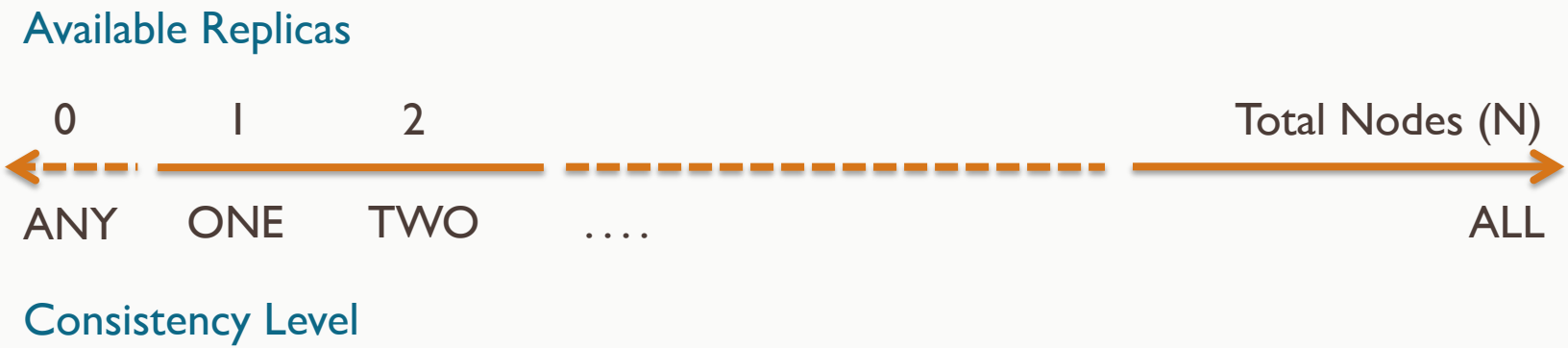
What consistency levels are available?

DATASTAX

Name	Description	Usage
ANY (writes only)	Write to any node, and store *hinted handoff* if all nodes are down.	Highest availability and lowest consistency (writes)
ALL	Check all nodes. Fail if any is down.	Highest consistency and lowest availability
ONE (TWO, THREE)	Check closest node to coordinator.	Highest availability and lowest consistency (reads)
QUORUM	Check quorum of available nodes.	Balanced consistency and availability
LOCAL_ONE	Check closest node to coordinator, in the local data center only.	Highest availability, lowest consistency, and no cross-data-center traffic
LOCAL_QUORUM	Check quorum of available nodes, in the local data center only.	Balanced consistency and availability, with no cross-data-center traffic
EACH_QUORUM	Only valid for writes. Check quorum of available nodes, in each data center of the cluster.	Balanced consistency and availability, with cross-data-center consistency
SERIAL	Conditional write to quorum of nodes. Read current state with no change.	Used to support linearizable consistency for lightweight transactions
LOCAL_SERIAL	Conditional write to quorum of nodes in local data center.	Used to support linearizable consistency for lightweight transactions

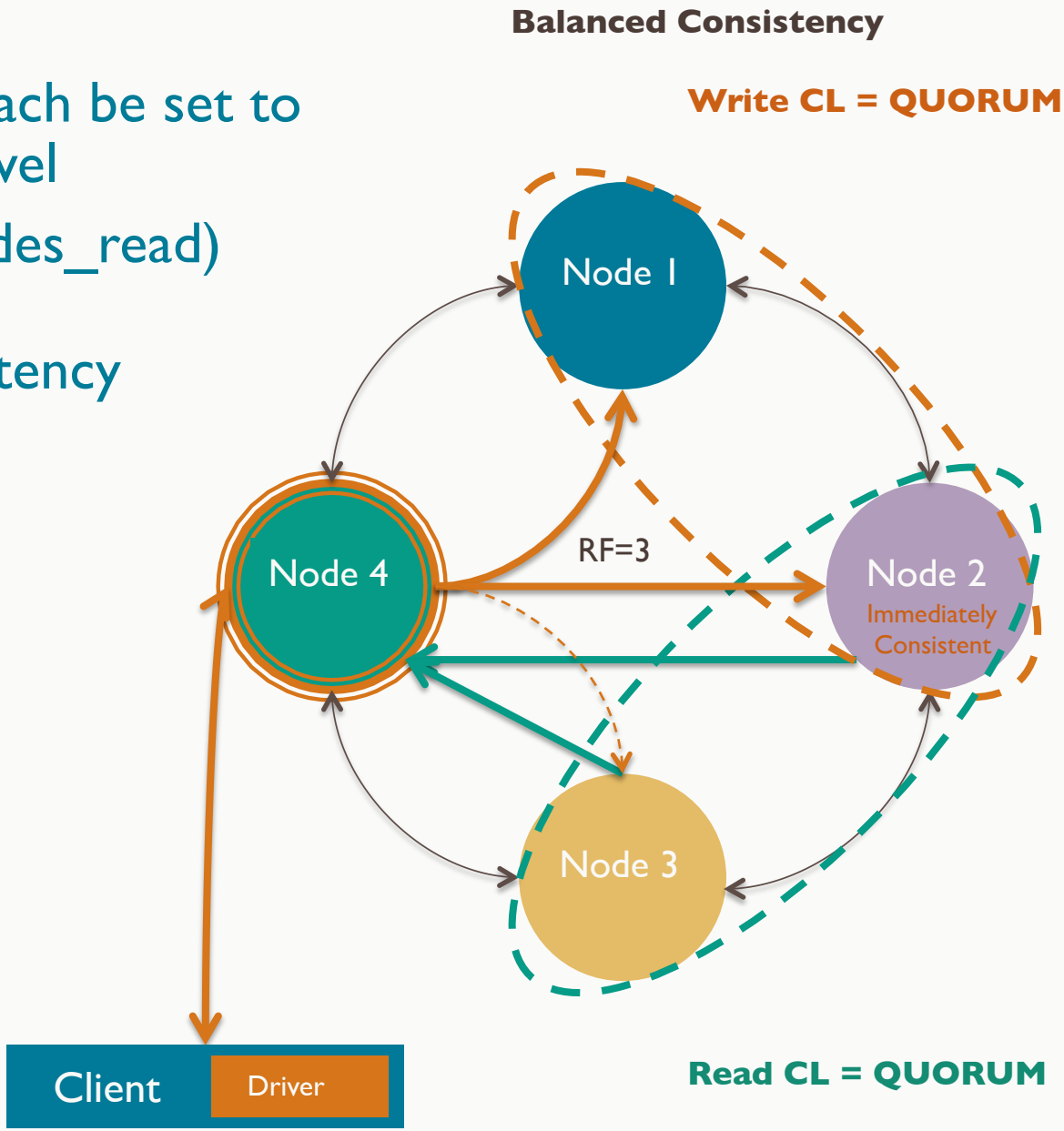
What is immediate vs. eventual consistency?

- For any given read, how likely is it the data may be stale?
- Immediate Consistency – reads always return the most recent data
  - Consistency Level ALL guarantees immediate consistency, because all replica nodes are checked and compared before a result is returned
  - *Highest latency* because all replicas are checked and compared
- Eventual Consistency – reads may return stale data
  - Consistency Level ONE carries the highest risk of stale data, because the replica from the first node to respond is immediately returned
  - *Lowest latency* because the first replica is immediately returned



What does it mean to tune consistency?

- Reads and writes may each be set to a specific consistency level
- **if** (nodes_written + nodes_read) > replication_factor
  then immediate consistency



How do you choose a consistency level?

DATASTAX

- In any given scenario, is the value of immediate consistency worth the latency cost?
  - Netflix uses CL ONE and measures its "eventual" consistency in milliseconds
  - Consistency Level ONE is your friend …

Consistency Level ONE	Consistency Level QUORUM	Consistency Level ALL
Lowest latency	Higher latency (than ONE)	Highest latency
Highest throughput	Lower throughput	Lowest throughput
Highest availability	Higher availability (than ALL)	Lowest availability
Stale read possible (if read CL + write CL < RF)	No stale reads (if read and write at quorum)	No stale reads (if either read or write at ALL)

- If "stale" is measured in milliseconds, how much are those milliseconds worth?

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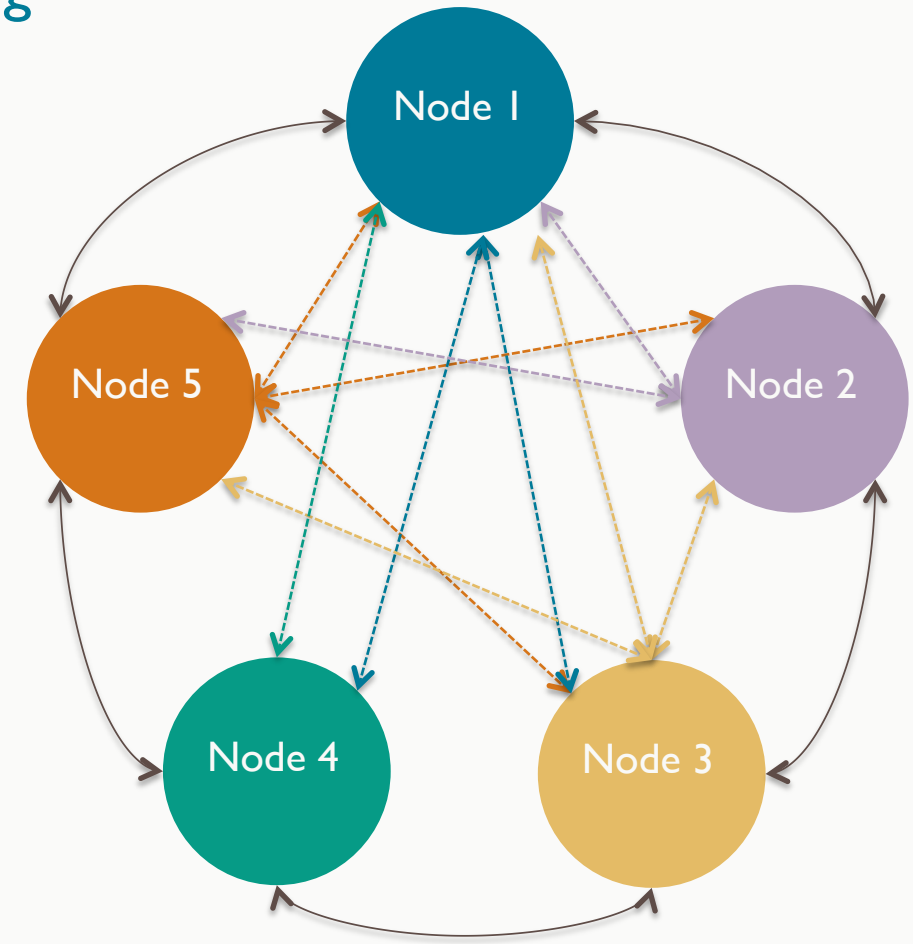
What is the Gossip protocol?

- Once per second, each node contacts 1 to 3 others, requesting and sharing updates about
  - Known node states ("heartbeats")
  - Known node locations
  - Requests and acknowledgments are timestamped, so information is continually updated and discarded



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The write path

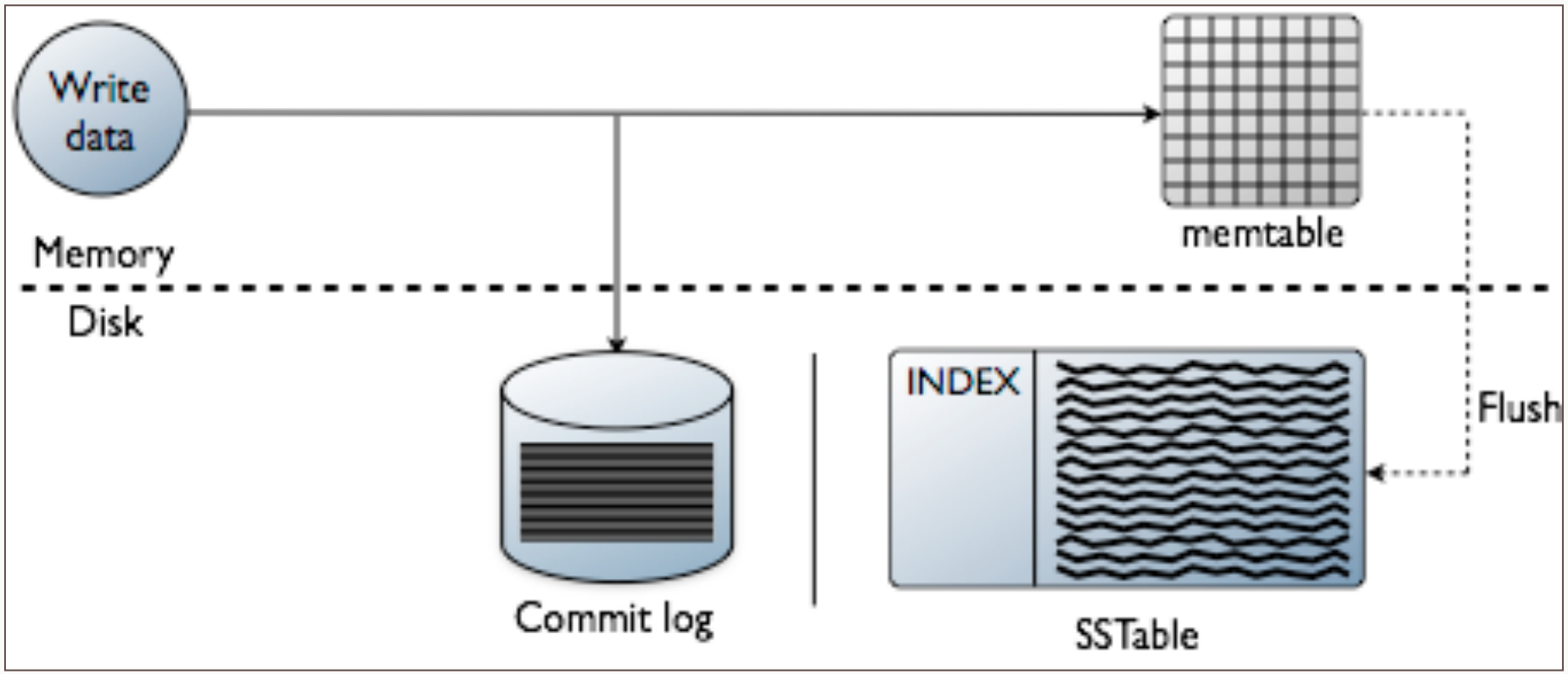
- On a write, Cassandra first appends writes to the commit log on disk
  - The write is durable once the data is in the commit log
    - Actually - once fsync is called and the OS flushes its own cache to disk
  - The commit log is append only, so there is no seek necessary for the append
    - Assuming a dedicated disk for the commit log (a recommended practice)
- A write also stores the data in memory
  - In a structure called the memtable
- A write is successful once written to the commit log and memory
- Very fast - Very little disk I/O at time of write

Memtables and SSTables

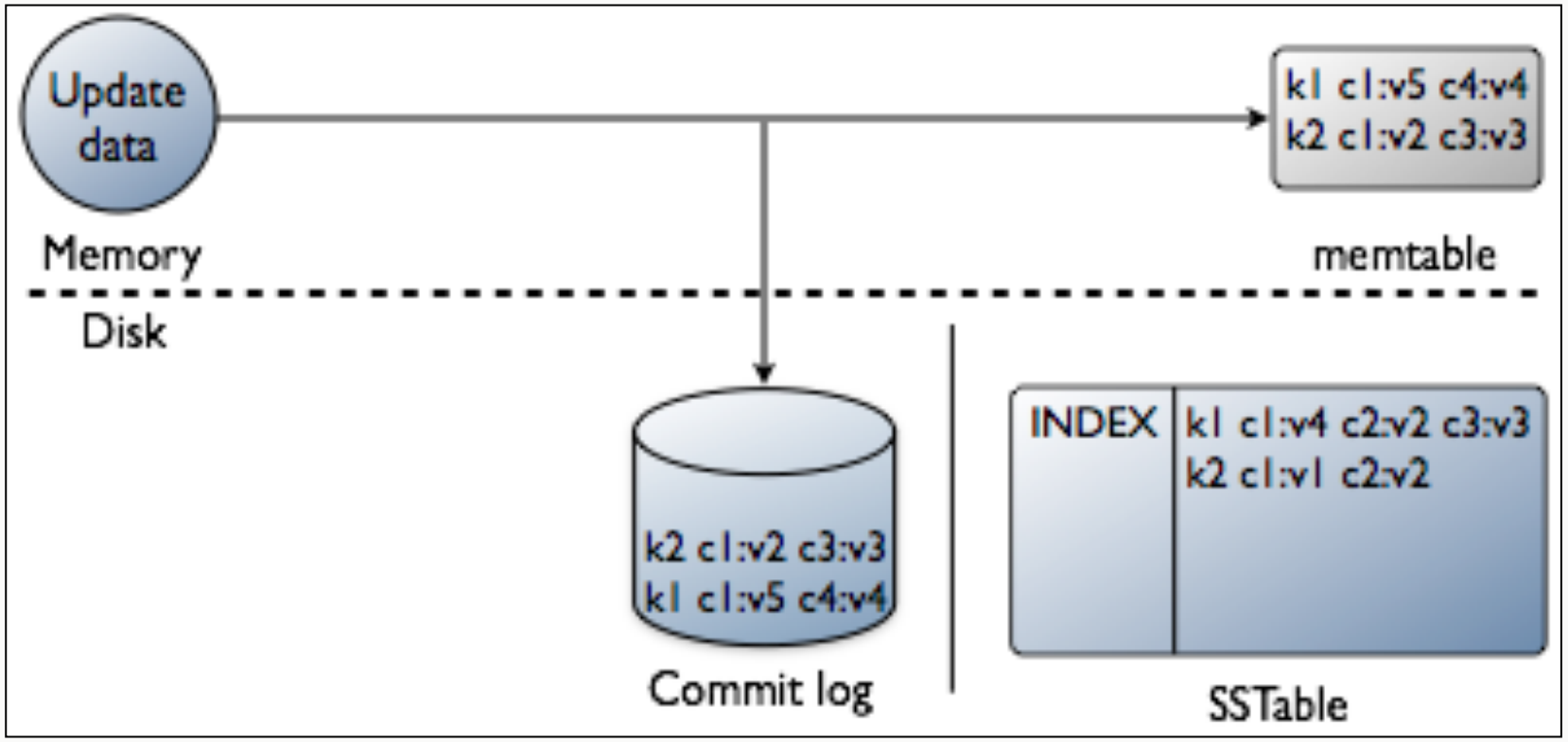
DATASTAX

- Memtables are organized in sorted order by partition key
  - There is one memtable per table per node
  - Updates to a column values in the memtable overwrites the existing column values
  - Accessing them is very fast since they are in-memory
  - Updates are also merged in-memory for a given partition key
- Memtables are eventually flushed to SSTables (Sorted String Tables) on disk
- So they don't grow too large in memory
  - Flushed using sequential I/O - no random seeking so it's fast
  - SSTables are immutable once they are written to disk
- Updates to data already in an SSTable go into a memtable, then eventually into a different SSTable
  - So data for a given partition key may be in several places

The write path illustrated



Memtable flushing illustrated



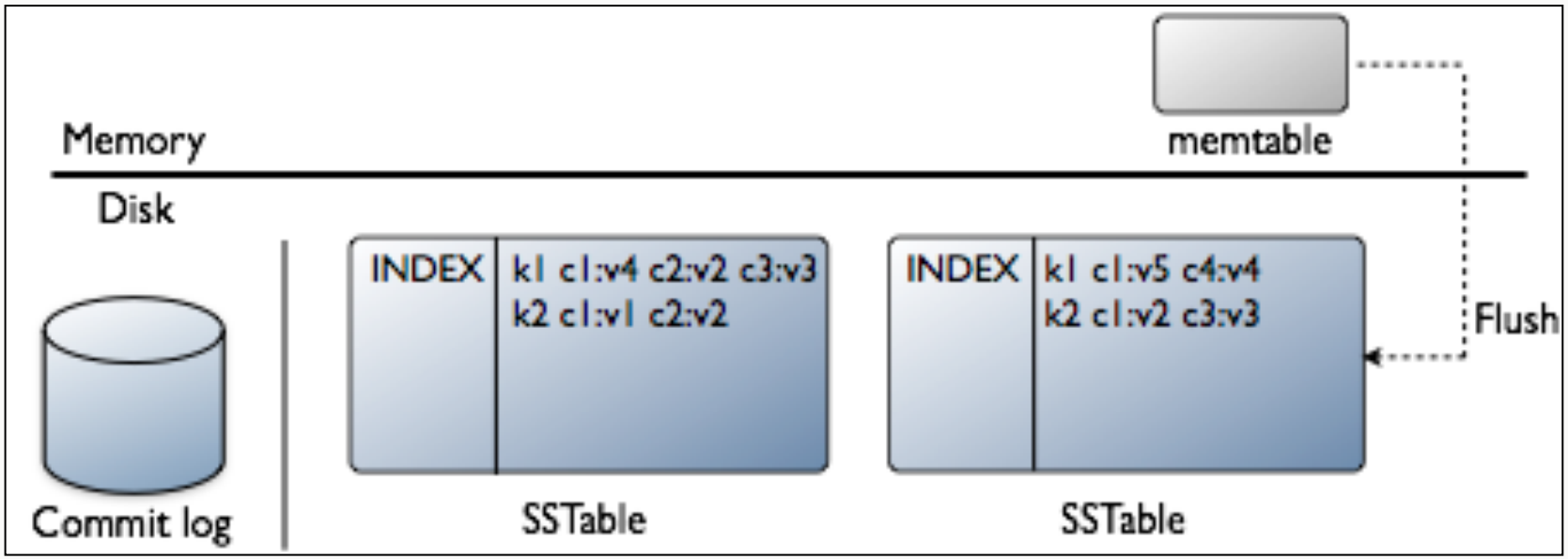
- After flushing, the memtable is emptied.

About SSTables

DATASTAX

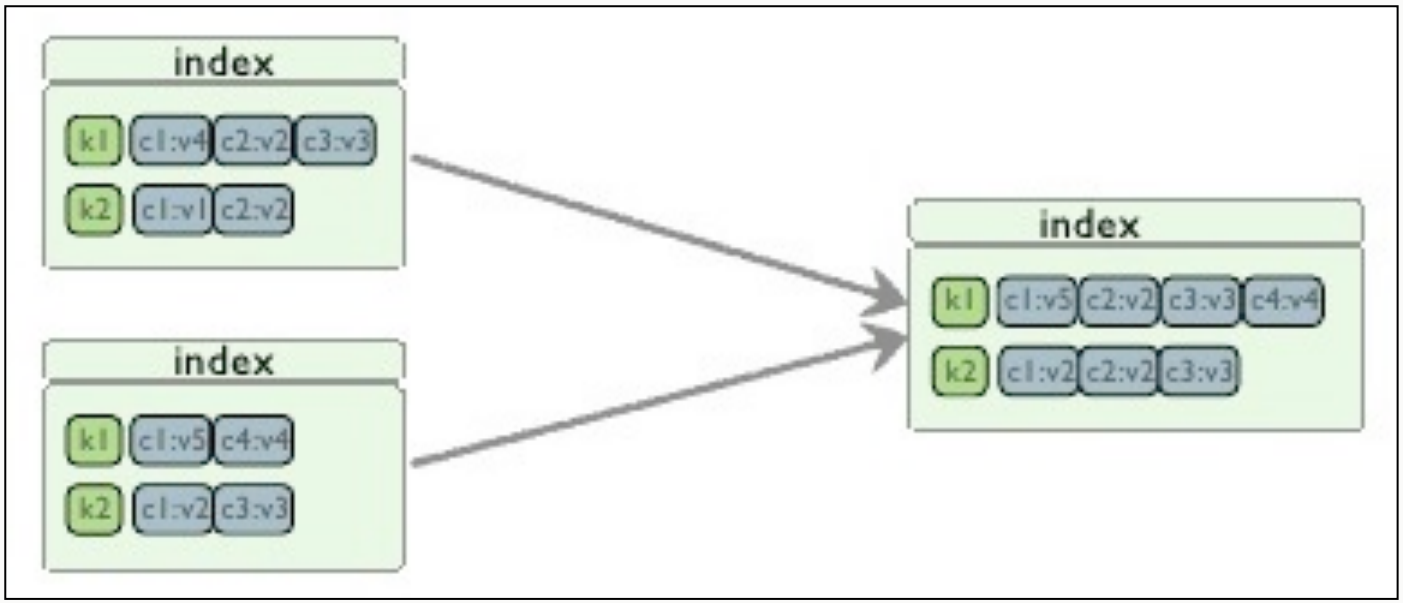
- SSTable is immutable once it is written
  - Mutations to keys already in an SSTable eventually end up in another SSTable
  - Never any updates to existing data in SSTable
  - Meaning no disk seeks on write - speeds up writes
- Reads may need to go to multiple SSTables for a given key
  - Because multiple writes may have created fragments in multiple SSTables for a given key
- SSTables contain structures to speed up reads
  - Bloom filters and indexes
  - More on this later

SSTables illustrated



Compaction

- **Compaction:** Merges SSTables for a data table into one SSTable - eliminating fragments
  - Reduces number of SSTables to be accessed for a read request
  - Runs asynchronously in the background
  - Uses sequential I/O - fast
  - When merging multiple column values, latest timestamped value is used
  - See notes for more details



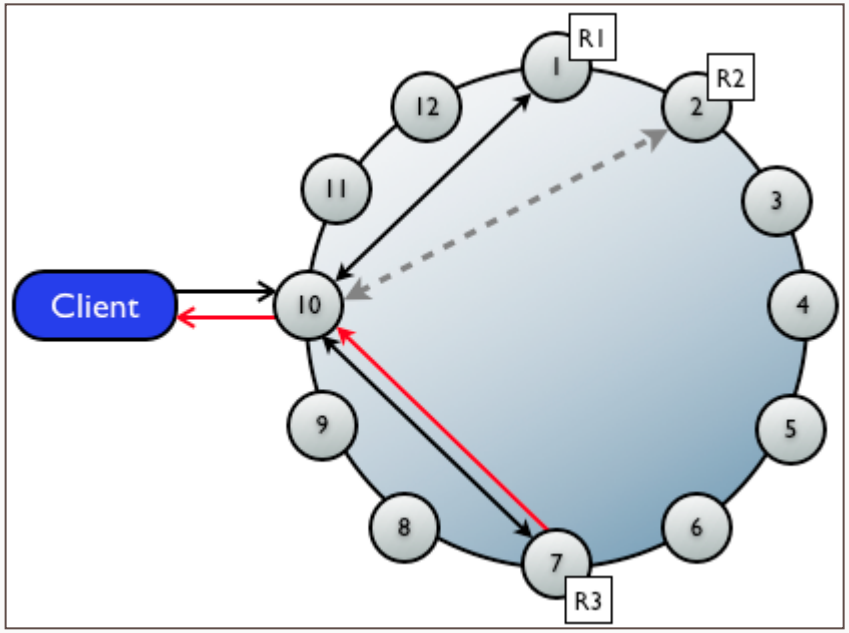
Read overview

DATASTAX

- Cassandra must access multiple locations to read data
- Across replicas
  - Data can be replicated across multiple replicas
  - Replicas may not be consistent at any given time (eventual consistency)
- Within a replica, data may be
  - In an unflushed memtable
  - In multiple SSTables
  - In a cache
- We will cover some of the details and ramifications of this

Client read requests

- Client requests are made to a coordinator
  - The coordinator contacts replicas based on the request CL (1)
- In the request below, we have RF=3 (data on nodes R1, R2, and R3)
  - Assume CL=QUORUM - so the coordinator contacts two replicas - in this case R1 and R3
  - Let's look at the details of how this read request is processed



Merging replica data

DATASTAX

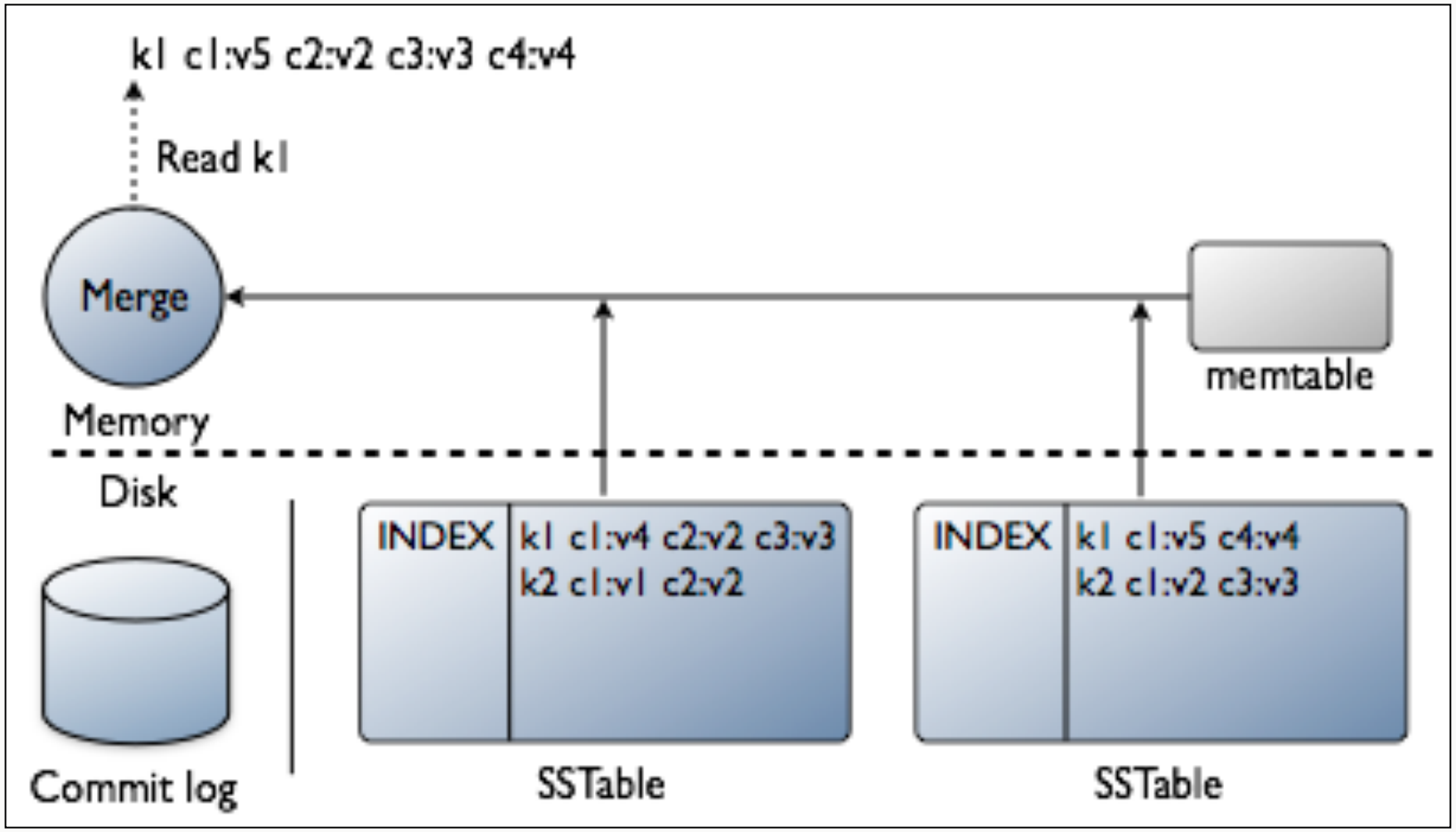
- The coordinator may read data from multiple replicas
  - The data may not be consistent (a write may not have propagated)
- If multiple replicas are contacted, the rows from each replica are compared for consistency
  - If consistent, then the data is just returned
  - If not consistent, then the most recent data is used
    - Based on the timestamp value that is contained in the internal storage cell
- Cassandra uses a mechanism, **read repair**, to ensure that all replicas are updated to the latest version of data
  - We cover this next

Read processing in a node

DATASTAX

- To satisfy a read request for a given partition key, a node combines data from
  - Any unflushed memtables
  - All SSTables on the node that contain data for that partition key
- For a write, C* only stores the column values that are updated
  - On the next slide, we can see that for k1, one SSTable has values for c1, c2, and c3
  - The other SSTable has values for c1 and c4

Read processing in a node illustrated



Optimizing reads—bloom filters

DATASTAX

- Cassandra uses Bloom filters to minimize SSTable reads
  - Each SSTable read is a disk I/O, so we want to minimize them
- Bloom filters are used to check if an SSTable has data for a particular partition key
  - One per SSTable
  - Saved on disk, but kept in memory (off heap)
  - On a read, the node checks the Bloom filter for each SSTable
  - The SSTable is only read from disk if the Bloom filter indicates there is data for the key
  - This helps make Cassandra very performant on reads

Full read path

DATASTAX

- Row Cache (off heap): If found here, just return the data, otherwise continue with steps below
- Memtable (on heap): Read current memtable, and memtables awaiting flush. Get row fragments for the given row.
- Bloom Filter (off heap): Check for each SSTable to build list of candidate SSTables
- Key Cache (on heap): (If enabled) For each SSTable from above, probe the key cache to get position in data file. This may miss.
- SSTable Index summary (on heap): Probe here to find start of range in index file, seek to this position in the index file, then scan until you find the key
- SSTable (on disk): Seek to the row position in the SSTable and get the data
- Merge all row fragments, and reconcile duplicates via timestamp
- Update row cache
- Return results to client

Guided Demo 1: Analyze the environment

Summary

- A Cassandra *cluster* is comprised of peer-to-peer *nodes* logically organized into *racks* within *data centers*
- Any node may *coordinate* any *request* issued by a Cassandra *client*
- Data is organized into *partitions* ("rows") identified by *tokens* in a 2^{127}-1 integer range
- The total *token range* is treated internally as a ring whose segments are owned by nodes
- Nodes are identified by the highest token in their segment of the total range
- A node's *partitioner* hashes a token from the *partition key* of a value being written
- The *first replica* ("copy") of a *partition* is written to the *node* owning *the primary range* containing its *token*
- *Replication factor* (RF) determines how many replicas ("copies") are made of each partition
- *Replication strategy* determines how replicas are distributed across the cluster
- A per-request *consistency level* (CL) determines how many nodes must acknowledge
- Nodes continually exchange state and location information via the *Gossip* protocol
- Each node includes a *Snitch* which tracks and reports on the current cluster topology

Review Questions

- Describe the relationship of nodes, racks, clusters, and data centers
- What is the function of the partitioner?
- Can a node hold a partition with a token outside its primary range?
- In a 3 node cluster with RF=2, how much total data volume does each node own?
- What is a remote coordinator?
- How could RF and CL be tuned to ensure immediate consistency?