

# Distributed Systems II

*Software Architecture*

Brae Webb & Richard Thomas & Guangdong Bai

March 31, 2025

*Distributed Systems Series*

Distributed I    *Reliability* and *scalability* of  
*stateless* systems

Distributed II    *Complexities* of *stateful*  
systems

Distributed III    *Hard problems* in distributed  
systems

## *Distributed Systems Series*

Distributed I Reliability and scalability of  
stateless systems

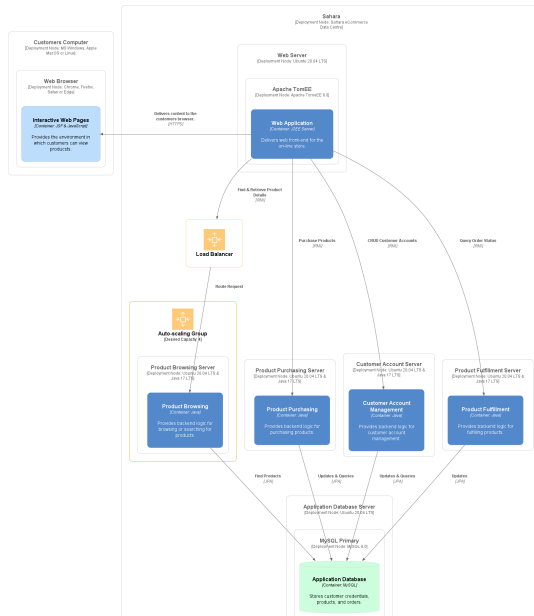
Distributed II *Complexities* of *stateful*  
systems

Distributed III Hard problems in distributed  
systems

*Previously in Distributed I: Benefits...*

- Improved *reliability*
- Improved *scalability*
- Improved *latency*

## Previously in Distributed I...



- We scaled a stateless service.
- Stateless: Services don't require persistent data *between* requests.
- Persistent state is saved in the database.
- This is normally easy to do.

*Question*

What is the *problem*?

The database

## Database



- Database has state, persistent data.
- This is much harder to scale.

## *Stateless vs. Stateful Systems*

Stateless Does *not* utilise *persistent data*. Or:  
each request is independent.

Stateful Does utilise *persistent data*. Or: the  
server or service remembers and uses  
data from previous interactions.



*Disclaimer*

This is *not* a database course



my.UQ

UQ HOME CONTACTS STUDY MAPS NEWS EVENTS LIBRARY MY.UQ

Search... 60

HOME STARTING AT UQ PROGRAMS AND COURSES FACULTIES AND SCHOOLS

Advanced Database Systems

Print Feedback

## Advanced Database Systems (INFS3200)

### Course level

Undergraduate

### Faculty

Engineering, Architecture & Information Technology

### School

Info Tech & Elec Engineering

### Units

2

### Duration

One Semester

### Class contact

2 Lecture hours, 1 Tutorial hour, 1 Practical or Laboratory hour

### Incompatible

INFS7907

### Prerequisite

INFS2200

### Assessment methods

### Current course offerings

Course offerings	Location	Mode	Course Profile
<a href="#">Semester 1, 2022</a>	St Lucia	Internal	<a href="#">COURSE PROFILE</a>
<a href="#">Semester 1, 2022</a>	External	External	<a href="#">COURSE PROFILE</a>
<a href="#">Semester 2, 2022</a>	External	External	PROFILE UNAVAILABLE
<a href="#">Semester 2, 2022</a>	St Lucia	Internal	PROFILE UNAVAILABLE

Please Note: Course profiles marked as not available may still be in development.

### Course description

Distributed database design, query and transaction processing, data integration, data warehousing, data cleansing, management of spatial data, and data from large scale distributed devices.

### Archived offerings

Course offerings	Location	Mode	Course Profile
<a href="#">Semester 1, 2021</a>	St Lucia	Flexible Delivery	<a href="#">COURSE PROFILE</a>
<a href="#">Semester 1, 2021</a>	External	External	<a href="#">COURSE PROFILE</a>
<a href="#">Semester 2, 2021</a>	External	External	<a href="#">COURSE PROFILE</a>
<a href="#">Semester 2, 2021</a>	St Lucia	Internal	<a href="#">COURSE PROFILE</a>
<a href="#">Semester 1, 2020</a>	St Lucia	Internal	<a href="#">COURSE PROFILE</a>

This is a database course.

*Question*

How do we fix database scaling issues?

*Question*

How do we fix database scaling issues?

*Answer*

- Replication

*Question*

How do we fix database scaling issues?

*Answer*

- Replication
- Partitioning

*Question*

How do we fix database scaling issues?

*Answer*

- Replication
- Partitioning
- Independent databases

*Question*

How do we fix database scaling issues?

*Answer*

- *Replication*
- Partitioning
- Independent databases

*Question*

What is *replication*?



*Definition 0.* Replication

Data copied across multiple different machines.



product_id	name	stock	price
1234	Nicholas Cage Reversible Pillow	10	\$10.00
4321	Lifelike Elephant Inflatable	5	\$50.00



product_id	name	stock	price
1234	Nicholas Cage Reversible Pillow	10	\$10.00
4321	Lifelike Elephant Inflatable	5	\$50.00

*Definition 0.* Replica

Database node which stores a copy of the data.

*Question*

What are the advantages of *replication*?

*Question*

What are the advantages of *replication*?

*Answer*

- *Scale* our database to cope with higher loads.

*Question*

What are the advantages of *replication*?

*Answer*

- *Scale* our database to cope with higher loads.
- Provide *fault tolerance* from a single instance failure.

*Question*

What are the advantages of *replication*?

*Answer*

- *Scale* our database to cope with higher loads.
  - Provide *fault tolerance* from a single instance failure.
  - Locate instances *closer to end-users*.
- Scalability
  - Reliability
  - Performance

### *Question*

How do we replicate our data?

- Easy without updates, just copy it.
- Updates, or writes, must *propagate* changes.



*First Approach*

Leader-Follower Replication



- Leader-Follower is the most common implementation.
- Multiple followers, only *one* leader.

*Definition 0.* Leader-based Replication

one node (the leader) handles all write operations, and multiple other nodes (followers) replicate the data and handle read operations.

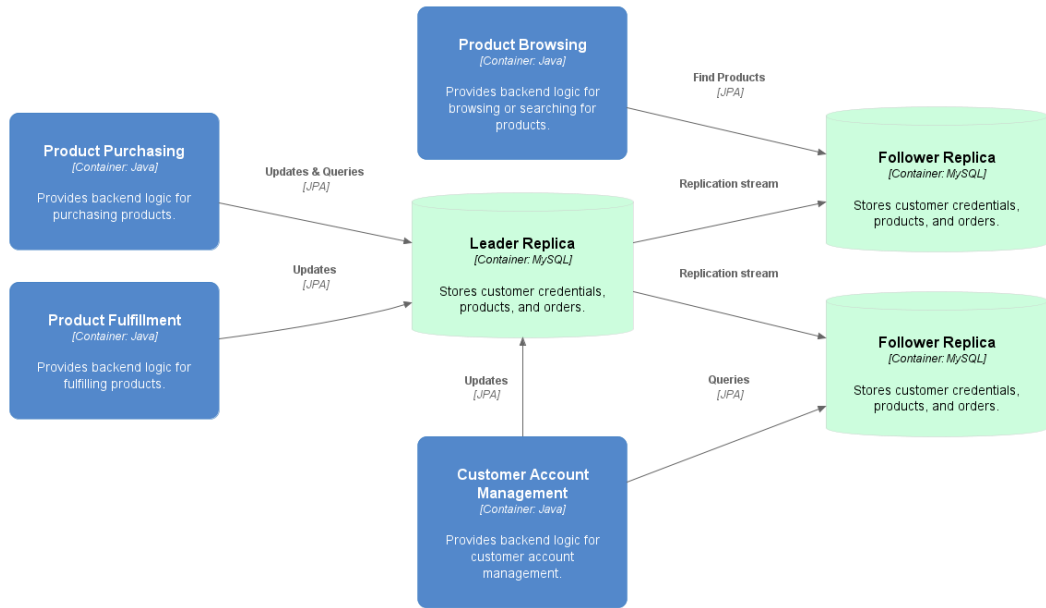
## *Leader-based Replication*

On write Writes sent to *leader*, change is propagated via change stream.

### *Leader-based Replication*

On write Writes sent to *leader*, change is propagated via change stream.

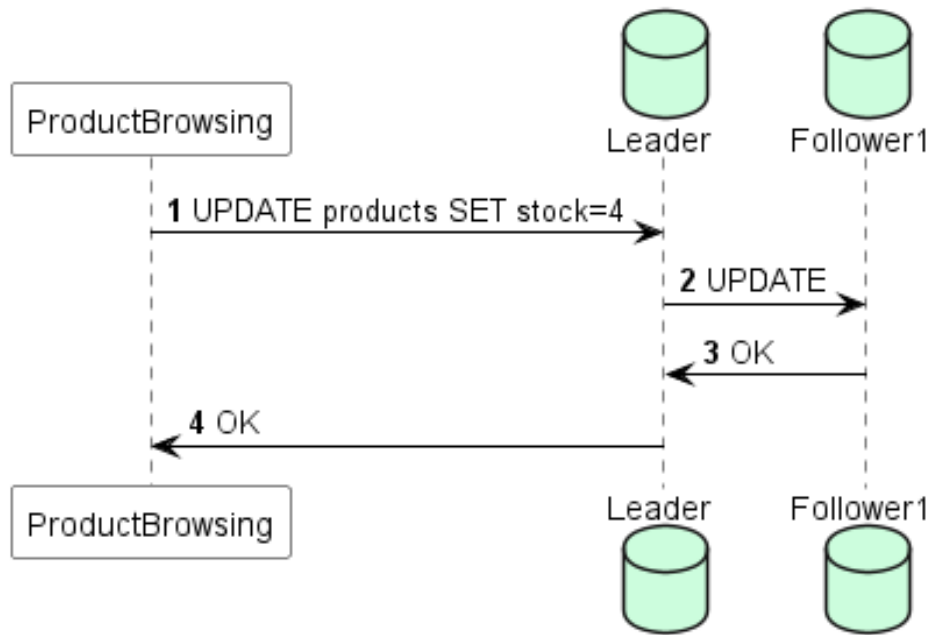
On read Any *replica* can be queried.



- Built-in to PostgreSQL, MySQL, MongoDB, RethinkDB, and Espresso.
- Can be added to Oracle and SQL Server.

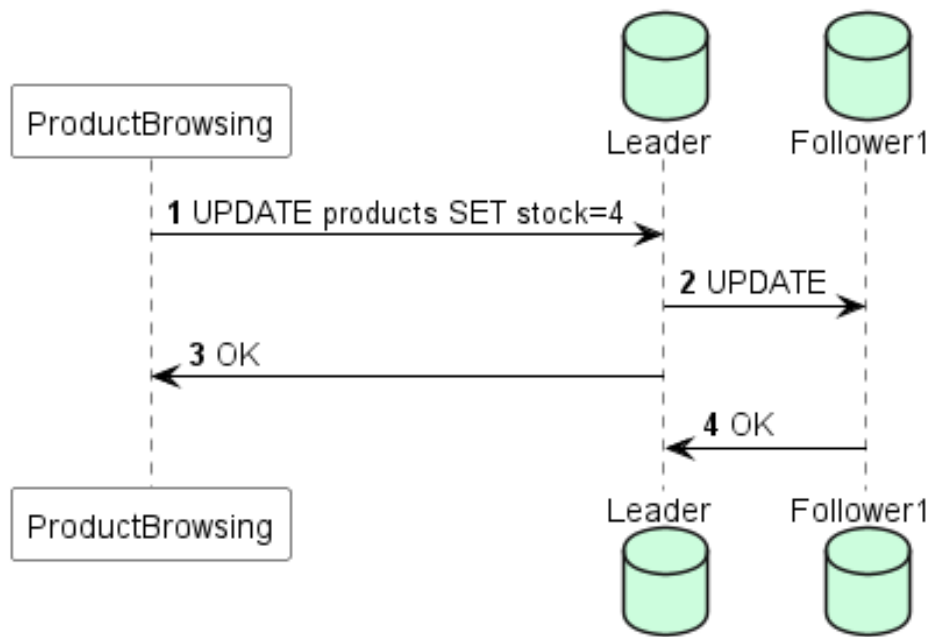
*Propagating Changes*

*Synchronous* vs. *Asynchronous*

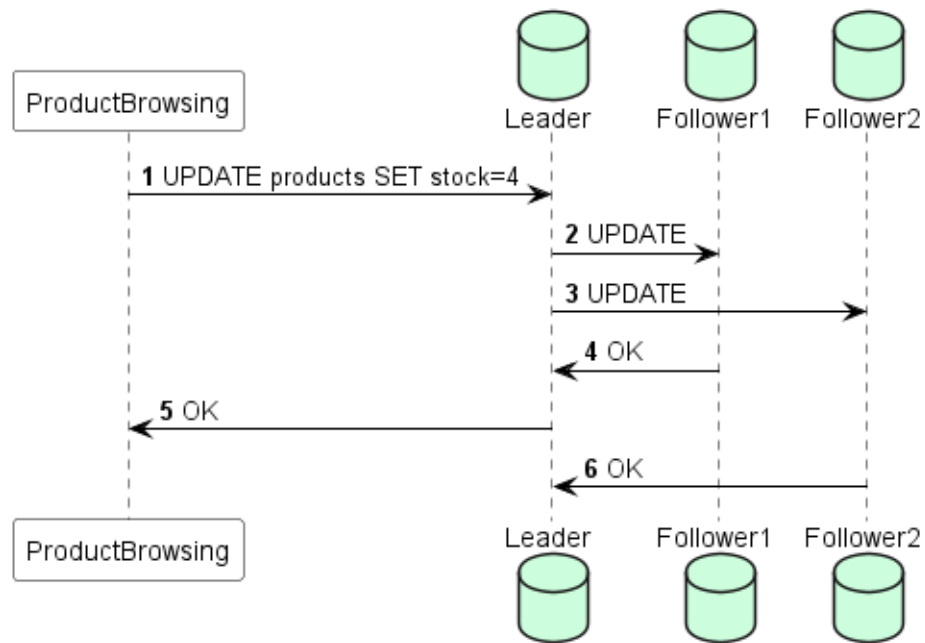


Synchronous update.





Asynchronous update.



- What could go wrong here?
- *Follower1* can get out of sync with *Follower2*.
- Following material deals with *leader* or a *replica* going down.

## *Synchronous Propagation*

- Writes must propagate to *all followers* before being successful.

## *Synchronous Propagation*

- Writes must propagate to *all followers* before being successful.
- *Any* replica goes down, *all* replicas are un-writeable.

## *Synchronous Propagation*

- Writes must propagate to *all followers* before being successful.
- *Any* replica goes down, *all* replicas are un-writeable.
- Writes must *wait* for propagation to *all* replicas.

## *Asynchronous Propagation*

- Writes *don't* have to *wait* for propagation.

### *Asynchronous Propagation*

- Writes *don't* have to *wait* for propagation.
- If the leader goes down before propagating, the *write is lost*.

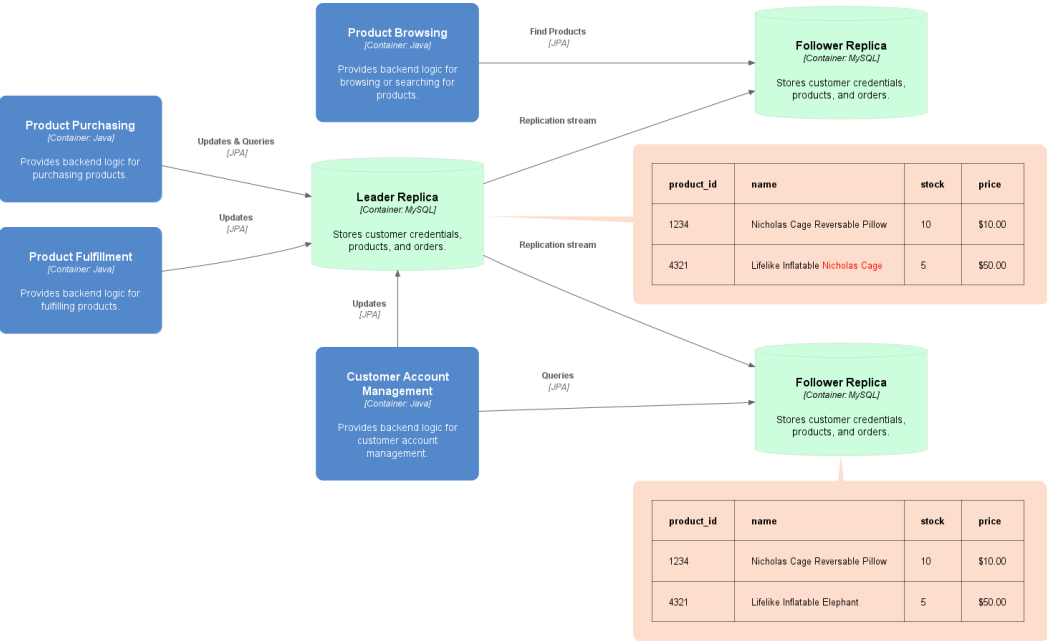
### *Asynchronous Propagation*

- Writes *don't* have to *wait* for propagation.
- If the leader goes down before propagating, the *write is lost*.
- Replicas can have out-dated or *stale* data.



*Definition 0.* Stale data

Outdated or inconsistent data that does not reflect the latest updates, mainly due to replication delays, caching, or network issues in distributed systems.



*Definition 0.* Replication Lag

The time taken for replicas to update *stale* data.

*Replication Lag:* Time it takes for the product name change to update across *all* followers.



The purple lifeline bar is *replication lag*.

*Eventually, all replicas must become consistent*

The system is *eventually consistent*.

- If writes stop for long enough.
- Eventually is intentionally *ambiguous*.

*Eventual Consistency*

Sufficient? Problems?



**Brae Webb**  
@braewebb

1. Read user details.



**Brae Webb**  
@braewebb

Name:	<input type="text" value="Brae"/>
<input type="button" value="Cancel"/>	<input type="button" value="Save"/>

1. Read user details.
2. Decide I don't like my name.
3. Update name.





**Brae Webb**

@braewebb

Name:	<input type="text" value="Brae"/>
<input type="button" value="Cancel"/>	<input type="button" value="Save"/>



**Brae Webb**

@braewebb

1. Read user details.
2. Decide I don't like my name.
3. Update name.
4. Read user details.



- Typical interaction in simple Leader-Follower replication.
- Write is to *leader*.
- Read is from *follower*.
- *Replication lag* means reading a field immediately after updating it *may* lead to reading *stale* data.

*Definition 0.* Read-your-writes Consistency

Users always see the updates that *they have made* (even though others see stale data).

Doesn't care what other users see.



**Brae Webb**

@braewebb

My fist post

1. Misspell a tweet.



**Brae Webb**

@braewebb

My fist post



**Brae Webb**

@braewebb

My first post

1. Misspell a tweet.

2. Correct spelling, and I see my *updated* tweet.



**Brae Webb**

@braewebb

My fist post



**Brae Webb**

@braewebb

My first post

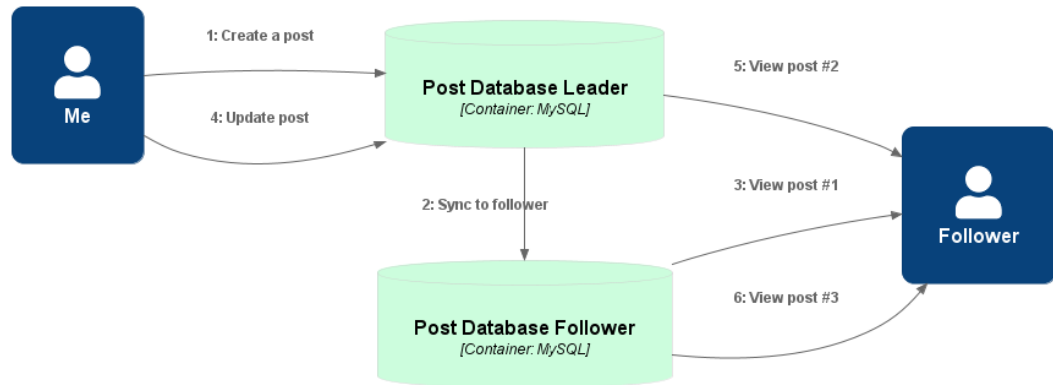


**Brae Webb**

@braewebb

My fist post

1. Misspell a tweet.
2. Correct spelling, and I see my *updated* tweet.
3. Other users may still see *stale*, misspelt post.



- Go through each step in sequence.
- Step 6: 3rd view post, gets *old value*.

*Definition 0.* Monotonic Reads

Once a user reads an updated value, they don't later see the old value.

User doesn't travel back in time.



*Definition 0.* Causal Consistency

Causally related updates appear in order (e.g., comments appear under the right post).

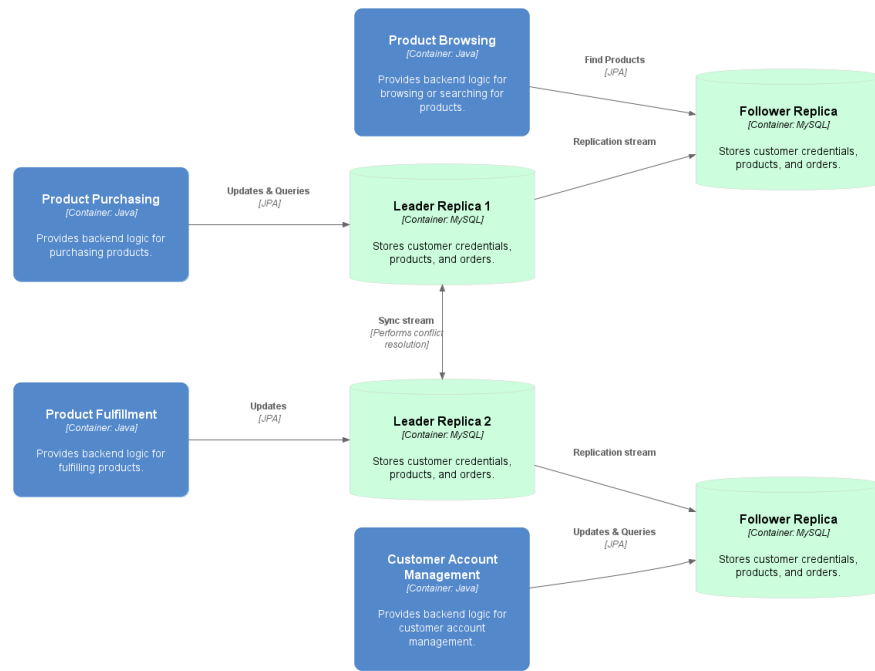
To generalize time to any dependent relations.

## Summary

- Leader-follower databases allow *reads to scale* more effectively.
- Asynchronous propagation weakens consistency to *eventually consistent*.
- Leader-follower databases still have a *leader write bottle-neck*.

*Second approach*

Multi-leader Replication



- Application can be partitioned to perform certain types of writes to a specific leader.
- Reads are from replicas, as with Leader-Follower replication.

*Why multi-leader?*

- If you have multiple leaders, you can write to any, allowing *writes to scale*.

### *Why multi-leader?*

- If you have multiple leaders, you can write to any, allowing *writes to scale*.
- A leader going down doesn't prevent writes, giving *better fault-tolerance*.
- Available via extensions in most databases, often not supported natively.
- Best to avoid where possible.
- Example: Globally distributed data centres.

*Question*

What might go wrong?

*Question*

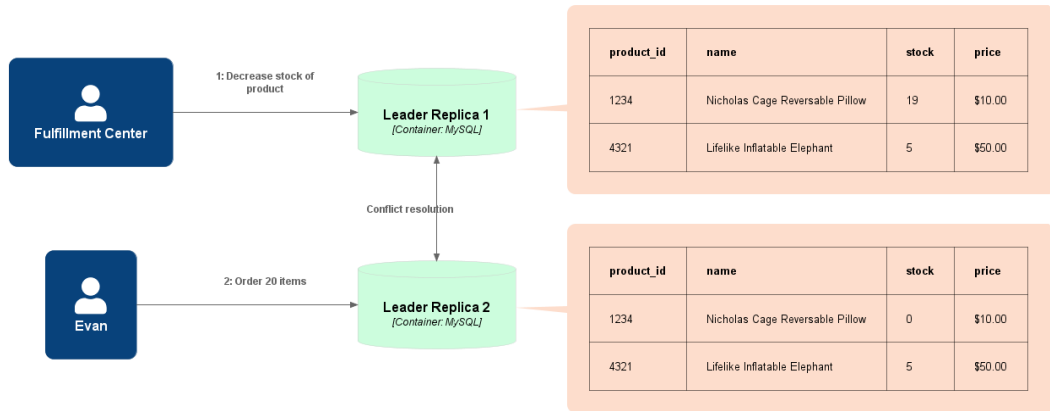
What might go wrong?

*Answer*

Write conflicts

Conflict needs to be *resolved*.

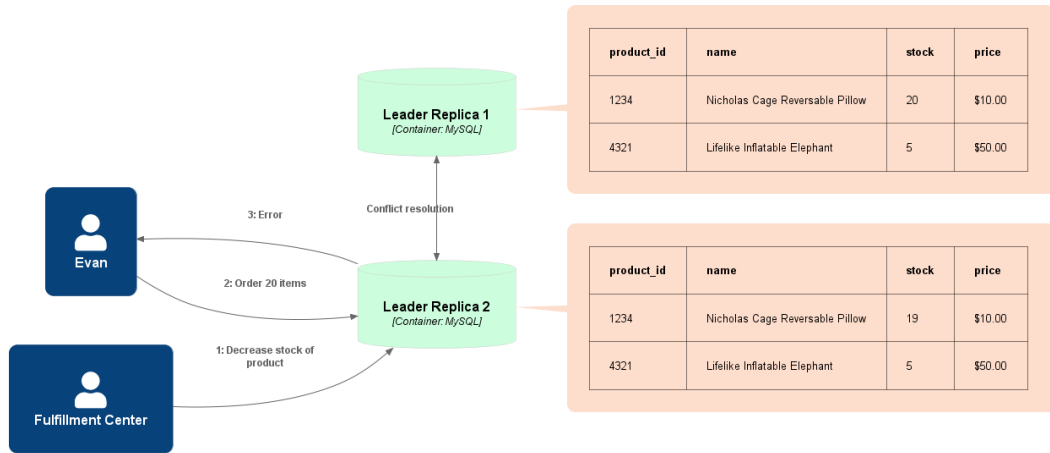




1. Fulfilment centre finds faulty pillow and decreases inventory.
2. Customer orders 20 pillows, what they saw as the number available.
3. -1 Pillows?
4. How do we resolve this?

*Where possible*

Avoid write conflicts



Requires application to ensure all writes to a field/table/shard are via the *same* leader.

*Where impossible*  
Convergence

## *Convergence Strategies*

- Assign each *write* a unique ID

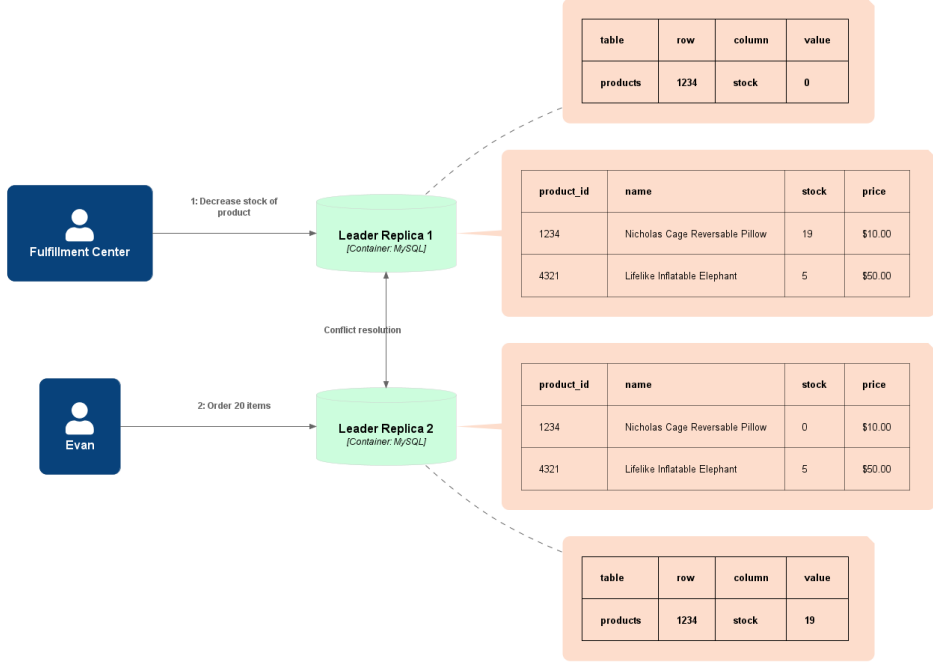
### *Convergence Strategies*

- Assign each *write* a unique ID
- Assign each *leader replica* a unique ID

## *Convergence Strategies*

- Assign each *write* a unique ID
- Assign each *leader replica* a unique ID
- Custom resolution logic

Yes, this can be *challenging*.





## *Resolving Conflicts*

**On Write** When a conflict is first noticed, take proactive resolution action.

Example: Last Write Wins (LWW) in DynamoDB.

**On Read** Stores all conflicting versions on write. When a conflict is next read, ask for a resolution.

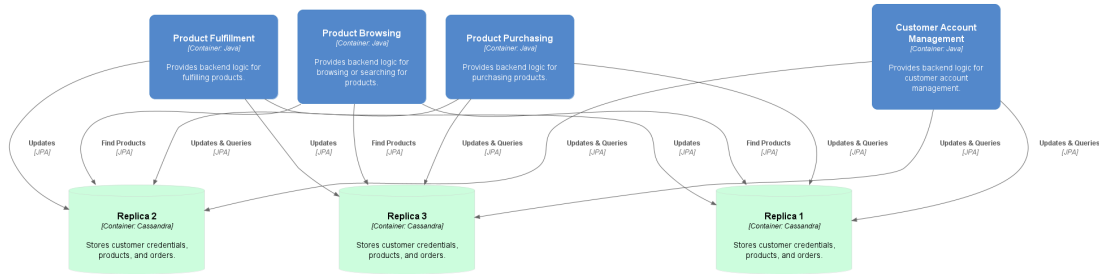
Example: *git pull*

- Bucardo allows a perl script for on write resolution.
- CouchDB prompts reads to resolve the conflict.

### *Third Approach*

## Leaderless Replication

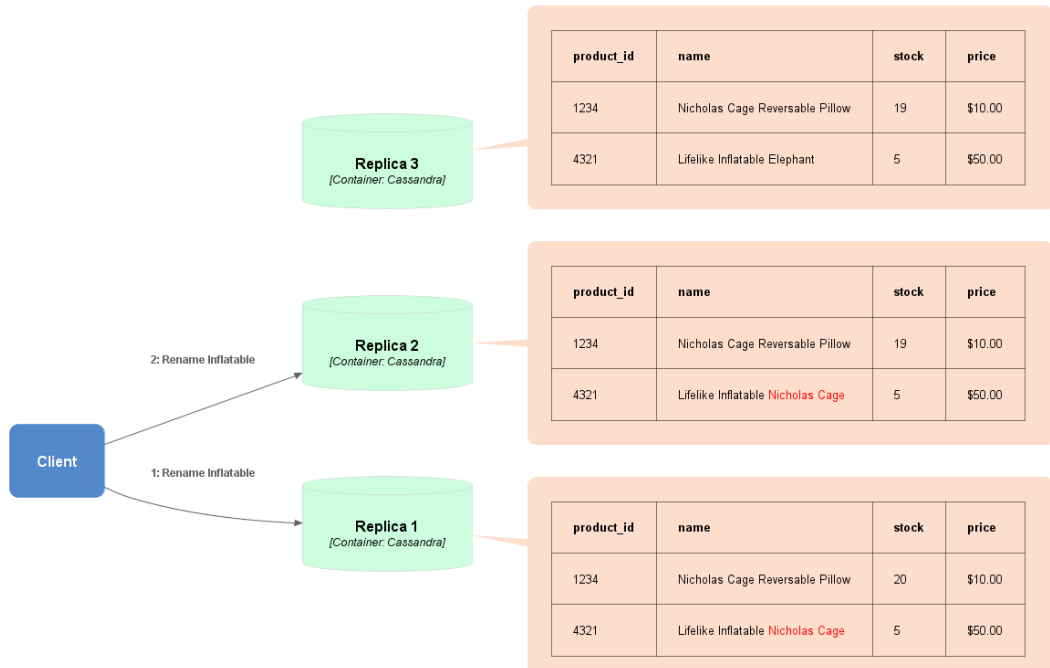
- Early distributed databases were leaderless.
- Resurgence after Amazon created Dynamo.
- Dynamo is an internal service and *not* DynamoDB.
- Riak, Cassandra, and Voldemort are leaderless databases.



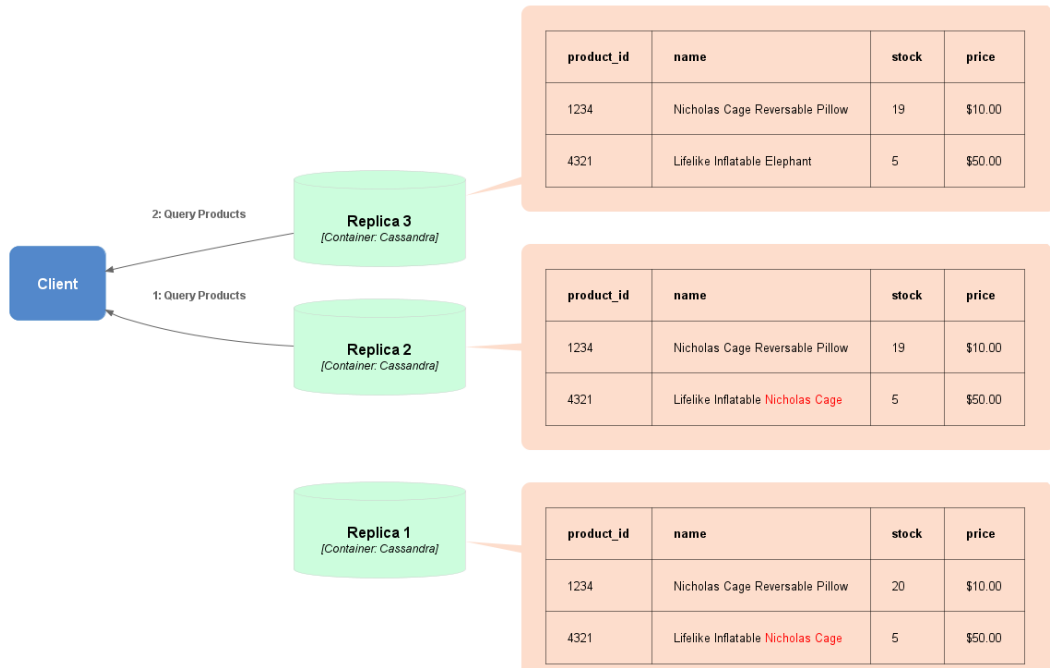
Reads and writes can be written to any node.

*How do they work?*

Each read/write is sent to *multiple* replicas.



Leaderless Write



Leaderless Read: At least one of the reads has the updated value.

*How are changes propagated?*

- Read Repair

1. Read Repair: Client detects stale data on read and writes updated data to that replica.

*How are changes propagated?*

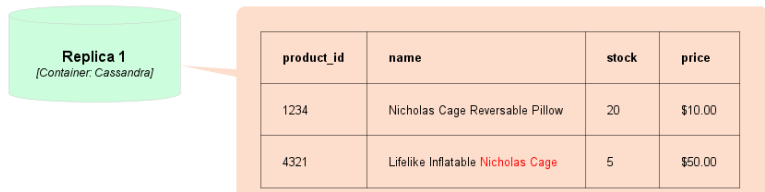
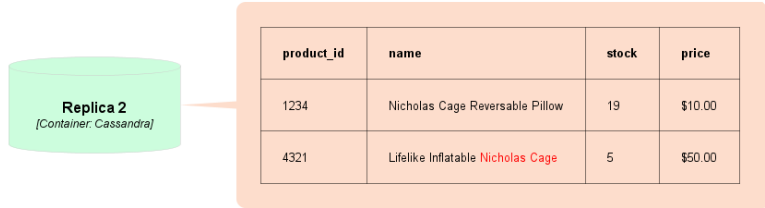
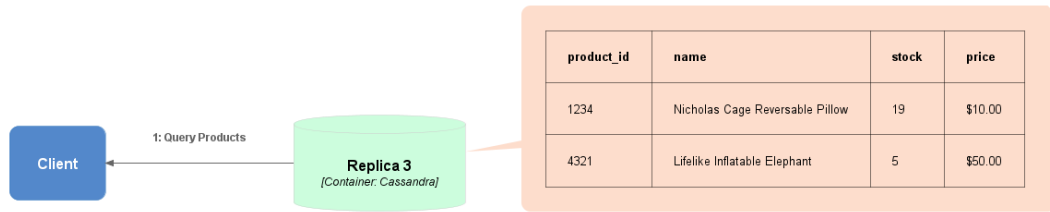
- Read Repair
- Anti-Entropy Process

1. Read Repair: Client detects stale data on read and writes updated data to that replica.
2. Anti-Entropy Process: Background process looks for stale or missing data and updates replicas.



*Question*

How do we know it's consistent?



Reading from a single replica means we can't know if data is stale or inconsistent.

*Question*

How do we know it's consistent?

*Question*

How do we know it's consistent?

*Answer*

Quorum Reads and Writes

## Quorum Consistency

$$w + r > n$$

$n$  total replicas

$w$  amount of replicas to *write* to

$r$  amount of replicas to *read* from

## *Quorum Consistency*

$$2 + 2 > 3$$

$n$  total replicas

$w$  amount of replicas to *write* to

$r$  amount of replicas to *read* from

## *Quorum Consistency*

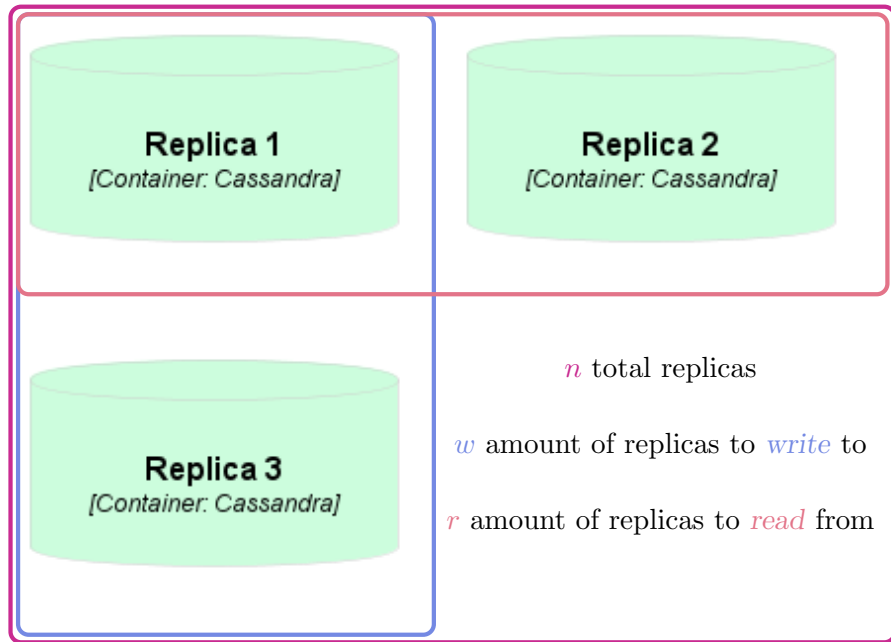
$$1 + 3 > 3$$

$n$  total replicas

$w$  amount of replicas to *write* to

$r$  amount of replicas to *read* from

Nodes read from must overlap with the nodes written to.



- Graphical representation of previous equation.
- **Orange** inner group (*reads*), overlaps with **Blue** inner group (*writes*).
- Showing how reads overlap writes via a quorum.



*Question*

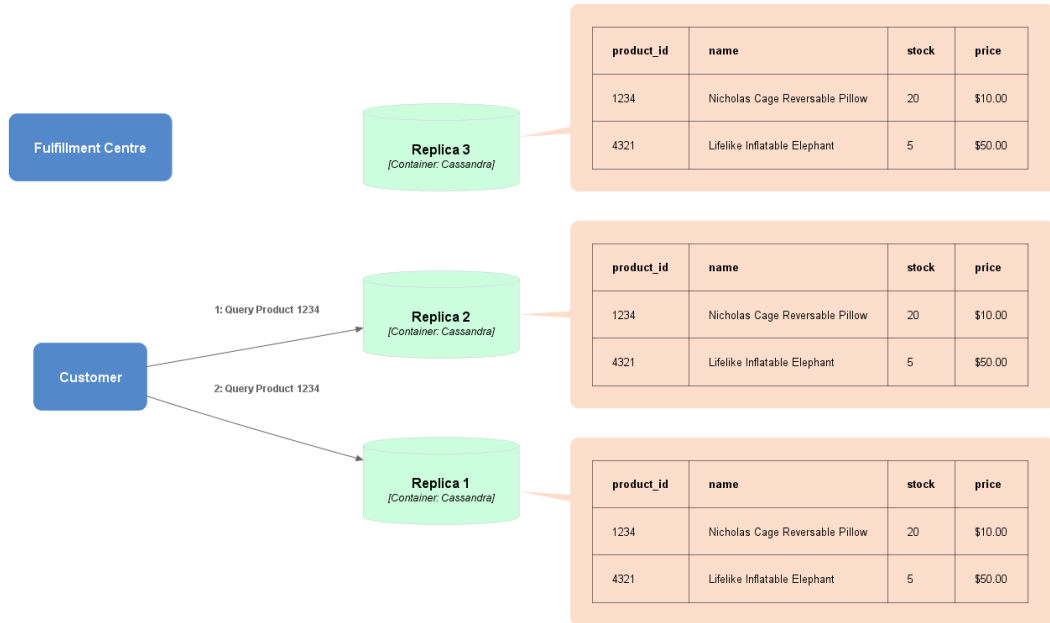
What about write conflicts?

*Question*

What about write conflicts?

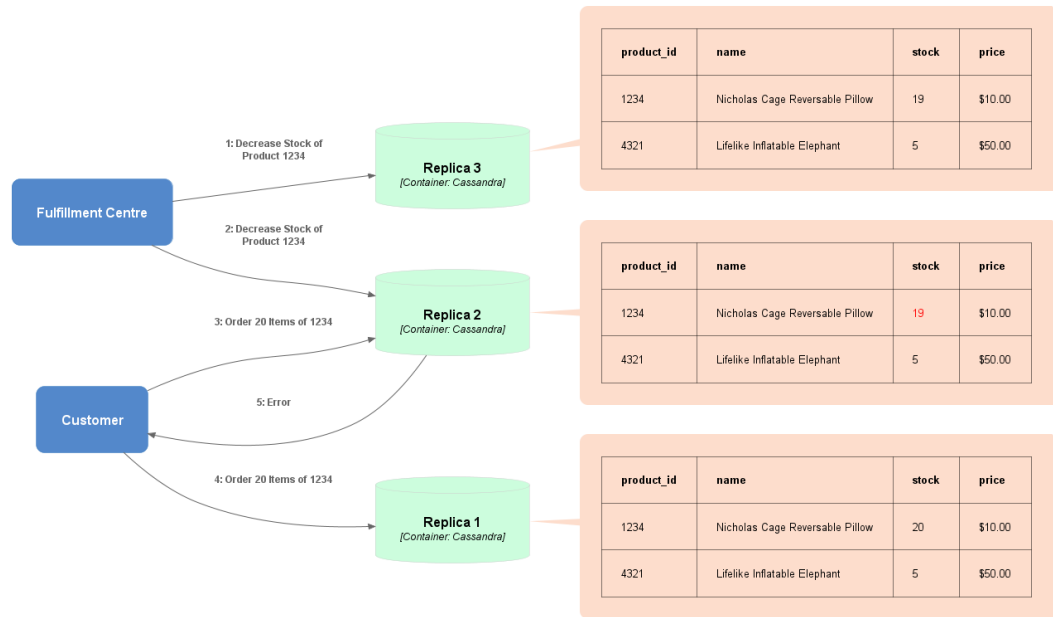
*Answer*

Same problem as with Multi-leader replication.



Same scenario as before:

1. Customer queries how many pillows are available.
2. Retrieves 20.



Same scenario as before:

1. Fulfilment centre finds faulty pillow and decreases inventory.
2. Customer orders 20 pillows, what they saw as the number available.
3. -1 Pillows?
4. How do we resolve this?

## *Summary*

- *Replication* copies data to multiple replicas.

## *Summary*

- *Replication* copies data to multiple replicas.
- *Leader-based* replication is most common and simplest.

## *Summary*

- *Replication* copies data to multiple replicas.
- *Leader-based* replication is most common and simplest.
- Replication introduces *eventual consistency*.

## Summary

- *Replication* copies data to multiple replicas.
- *Leader-based* replication is most common and simplest.
- Replication introduces *eventual consistency*.
- *Multi-leader* replication scales writes as well as reads but introduces *write conflicts*.



## Summary

- *Replication* copies data to multiple replicas.
- *Leader-based* replication is most common and simplest.
- Replication introduces *eventual consistency*.
- *Multi-leader* replication scales writes as well as reads but introduces *write conflicts*.
- *Leaderless* replication is another approach which keeps the problems of multi-leader.

*Question*

How do we fix database scaling issues?

*Question*

How do we fix database scaling issues?

*Answer*

- *Replication*
- Partitioning
- Independent databases

*Question*

How do we fix database scaling issues?

*Answer*

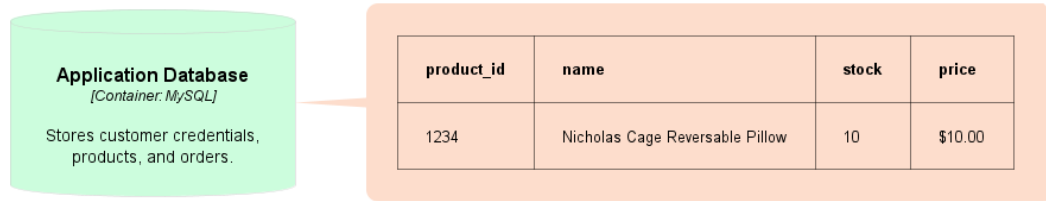
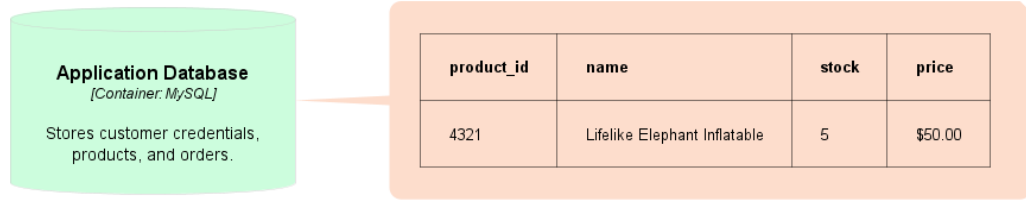
- Replication
- *Partitioning*
- Independent databases

*Definition 0.* Partitioning

Split the data of a system onto multiple nodes.

These nodes are *partitions*.

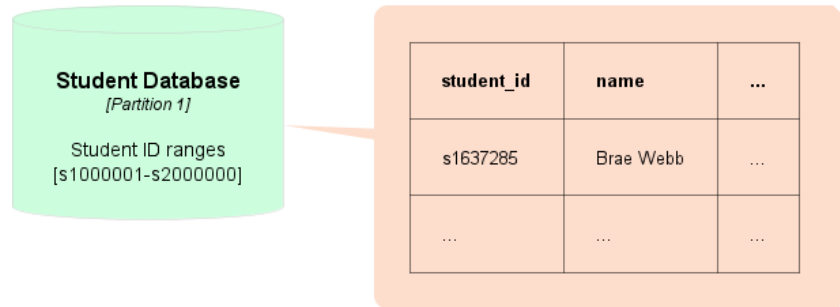
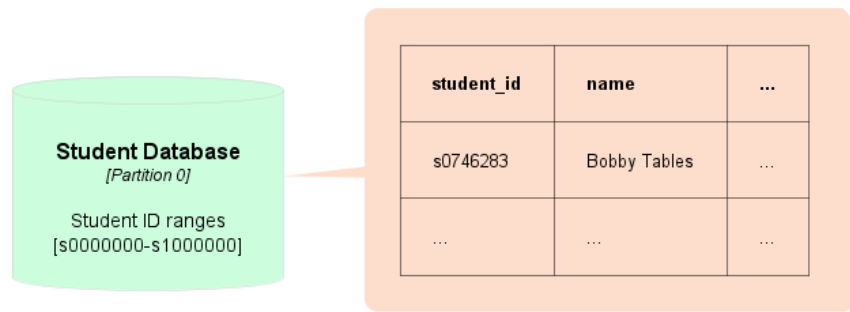
Also called shards, regions, tablets, etc.



- Pioneered in the 1980s.
- Allow scalability of large data, not just large load.
- Partitioning is normally combined with replication.

### *Question*

How should we decide which data is stored where?



An example partitioning based on primary key, student ID.



*Question*

What is the problem with this?

*Question*

What is the problem with this?

*Answer*

Over time some partitions become inactive, while others receive almost all load.

*Question*

How should we decide where data is stored?

*Question*

How should we decide where data is stored?

*Answer*

Maximize spread of requests, avoiding *skewing*.

*Question*

Have we seen this before?

*Question*

Have we seen this before?

*Answer*

Hashing?

Hash tables hash entries to maximize the spread between buckets.

*Question*

What is the problem with this?

*Question*

What is the problem with this?

*Answer*

Range queries are inefficient, i.e. get all students between s4444444 and s4565656.



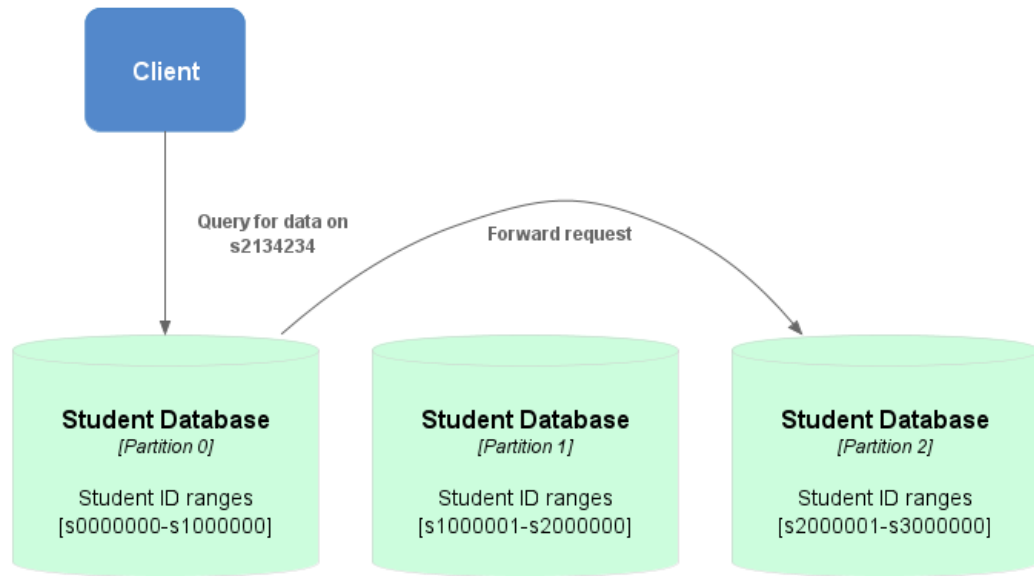
*Question*

How do we route queries?

Unlike stateless, only one node can process queries.

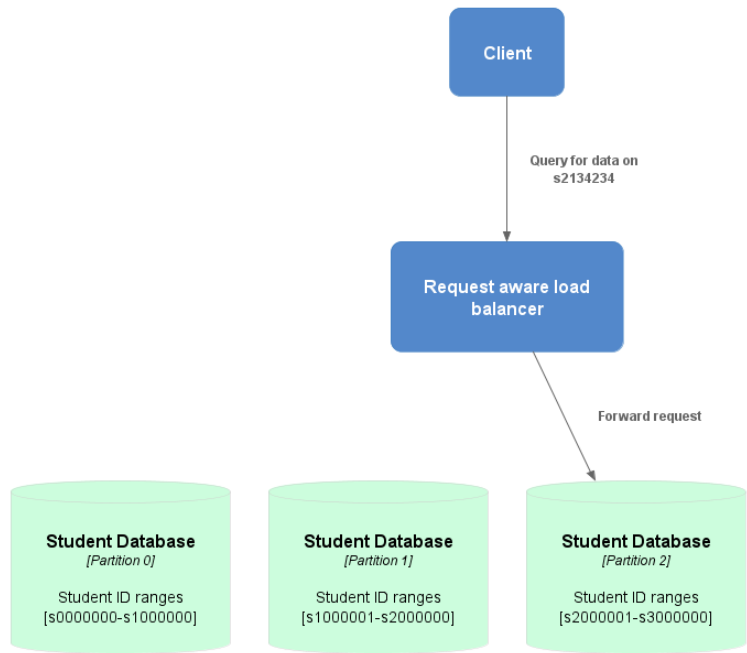
### *Query-Insensitive Load Balancer*

Randomly route to any node, responsibility of the node to re-route to the correct node.



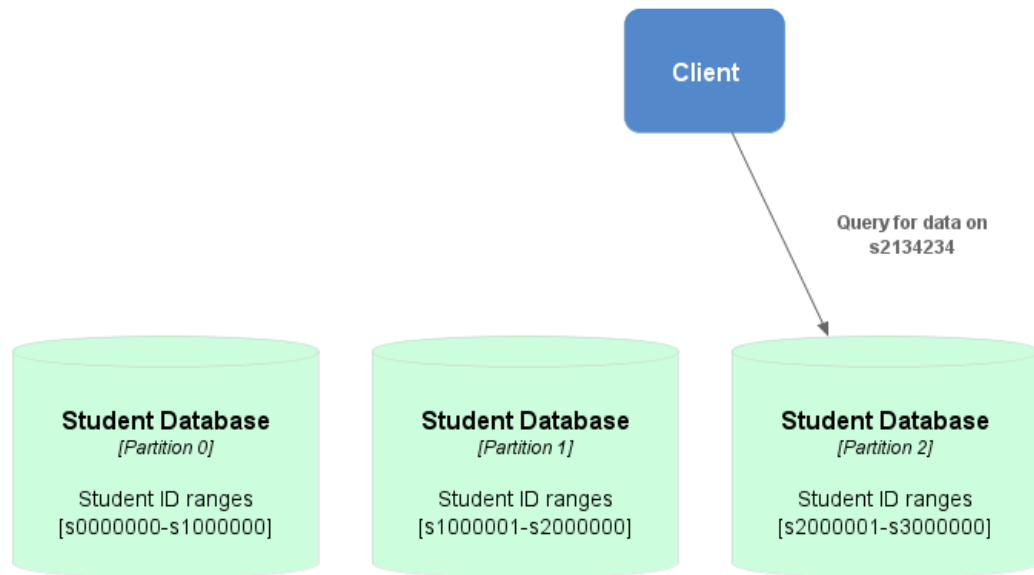
### *Query-Sensitive Load Balancer*

Load balancer understands which queries should be forwarded to which node.



### *Client-aware Queries*

Place the responsibility on clients to choose the correct node.



## Summary

- *Partitioning* splits data across multiple nodes.



### *Summary*

- *Partitioning* splits data across multiple nodes.
- Requires a *consistent method* to chose appropriate node.

### *Summary*

- *Partitioning* splits data across multiple nodes.
- Requires a *consistent method* to choose appropriate node.
- Partitioning by *primary key* can create *skewing*.

### *Summary*

- *Partitioning* splits data across multiple nodes.
- Requires a *consistent method* to choose appropriate node.
- Partitioning by *primary key* can create *skewing*.
- Partitioning by *hash* makes range queries less efficient.

## Summary

- *Partitioning* splits data across multiple nodes.
- Requires a *consistent method* to choose appropriate node.
- Partitioning by *primary key* can create *skewing*.
- Partitioning by *hash* makes range queries less efficient.
- Three approaches to *routing requests*.

### *Disclaimer*

We have ignored the *hard* parts of replication.

*Question*

How do we fix database scaling issues?

*Question*

How do we fix database scaling issues?

*Answer*

- Replication
- *Partitioning*
- Independent databases

*Question*

How do we fix database scaling issues?

*Answer*

- Replication
- Partitioning
- *Independent databases*



## *Summary*

- Replications

## *Summary*

- Replications
  - Leader-based, multi-leader, and leaderless

## *Summary*

- Replications
  - Leader-based, multi-leader, and leaderless
  - Eventual consistency

## *Summary*

- Replications
  - Leader-based, multi-leader, and leaderless
  - Eventual consistency
  - Write conflicts

## *Summary*

- Replications
  - Leader-based, multi-leader, and leaderless
  - Eventual consistency
  - Write conflicts
- Partitioning

## *Summary*

- Replications
  - Leader-based, multi-leader, and leaderless
  - Eventual consistency
  - Write conflicts
- Partitioning
  - Consistent method to pick nodes for data

## *Summary*

- Replications
  - Leader-based, multi-leader, and leaderless
  - Eventual consistency
  - Write conflicts
- Partitioning
  - Consistent method to pick nodes for data
  - Avoiding skewing