Distributed Systems II

Software Architecture

Brae Webb

March 27, 2023

Distributed Systems Series

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

Distributed II *Complexities* of *stateful* systems.

Distributed III *Hard problems* in distributed systems.

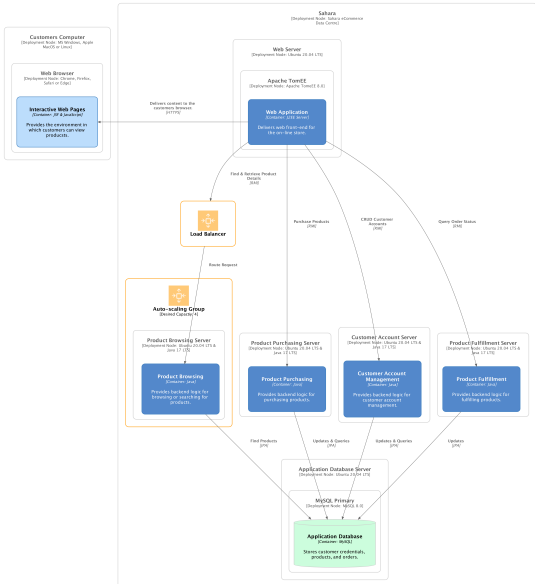
Distributed Systems Series

Distributed I Reliability and scalability of stateless systems.

Distributed II *Complexities* of *stateful* systems.

Distributed III Hard problems in distributed systems.

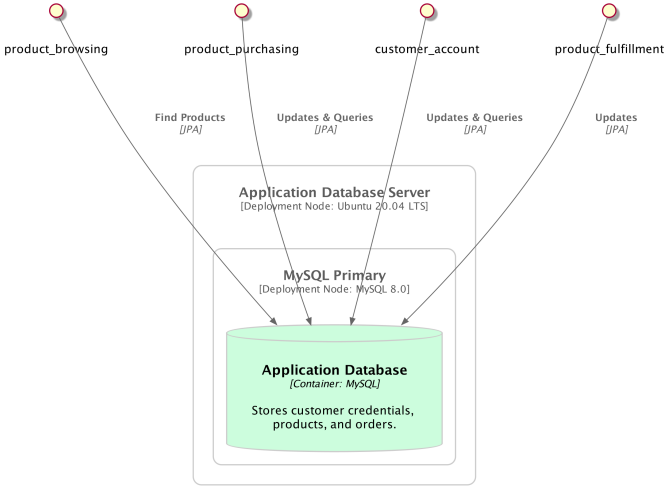
Previously in CSSE6400...



Question

What is the *problem*?

Database


product_browsing
product_purchasing
customer_account
product_fulfillment
Find Products
[JPA]
Updates & Queries
[JPA]
Updates & Queries
[JPA]
Updates
[JPA]
Application Database Server
[Deployment Node: Ubuntu 20.04 LTS]
MySQL Primary
[Deployment Node: MySQL 8.0]
Application Database
[Container: MySQL]
Stores customer credentials, products, and orders.

Disclaimer

This is *not* a database course.

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
Semester 1, 2022	St Lucia	Internal	COURSE PROFILE
Semester 1, 2022	External	External	COURSE PROFILE
Semester 2, 2022	External	External	PROFILE UNAVAILABLE
Semester 2, 2022	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
Semester 1, 2021	St Lucia	Flexible Delivery	COURSE PROFILE
Semester 1, 2021	External	External	COURSE PROFILE
Semester 2, 2021	External	External	COURSE PROFILE
Semester 2, 2021	St Lucia	Internal	COURSE PROFILE
Semester 1, 2020	St Lucia	Internal	COURSE PROFILE

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

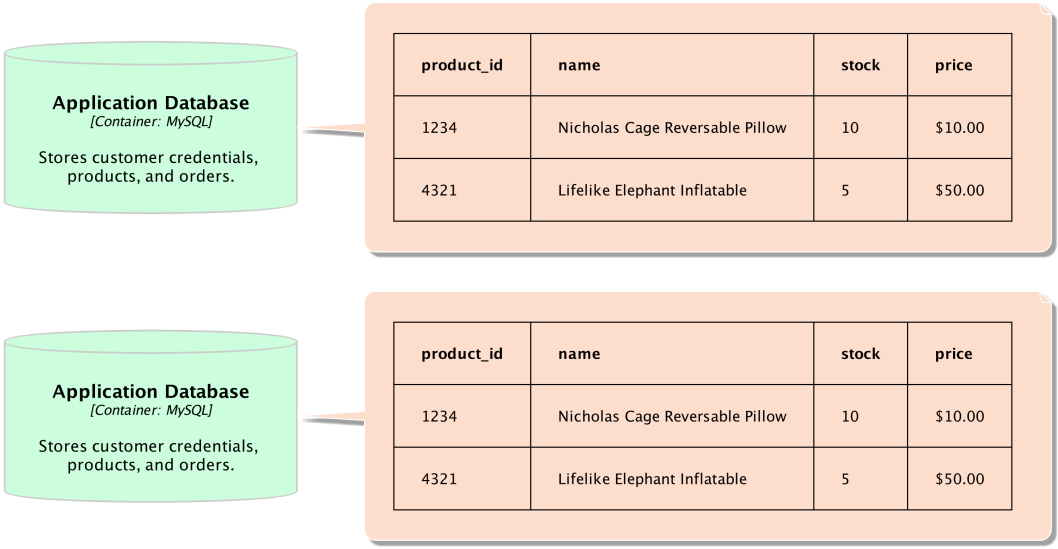
- *Replication*
- Partitioning
- Independent databases

Question

What is *replication*?

Definition 1. Replication

Data copied across multiple different machines.


Application Database
[Container: MySQL]
Stores customer credentials, products, and orders.
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
10
$10.00
4321
Lifelike Elephant Inflatable
5
$50.00
Application Database
[Container: MySQL]
Stores customer credentials, products, and orders.
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
10
$10.00
4321
Lifelike Elephant Inflatable
5
$50.00

Definition 2. 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* out our to cope with higher loads.

Question

What are the advantages of *replication*?

Answer

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

Question

What are the advantages of *replication*?

Answer

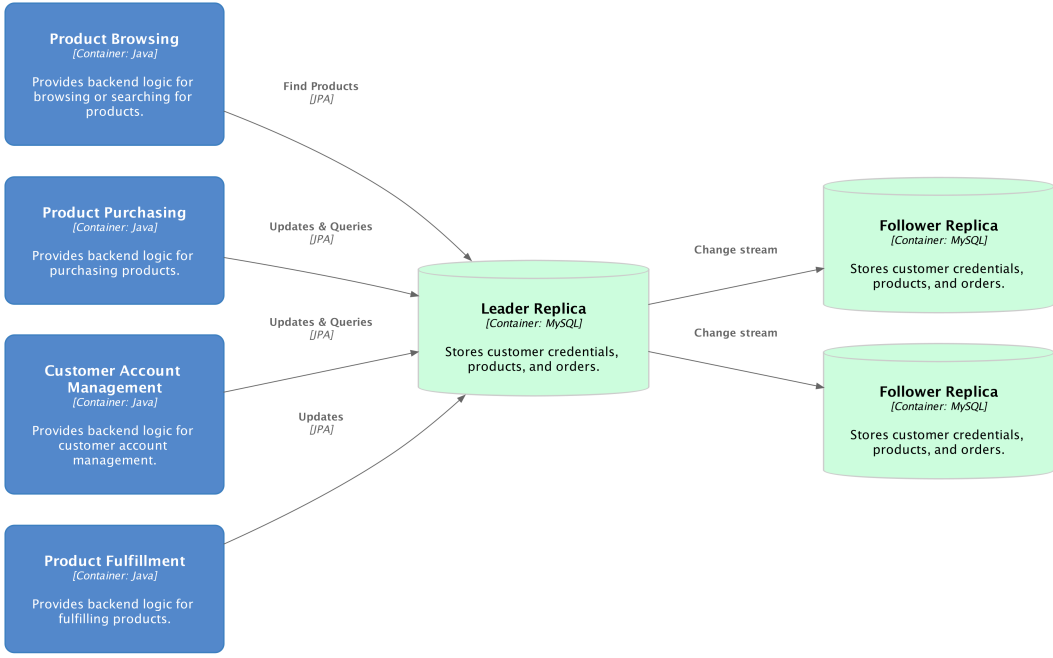
- *Scale* out our to cope with higher loads.
- Provide *fault tolerance* from a single instance failure.
- Locate instances *closer to end-users*.

Question

How do we replicate our data?

First approach

Leader-follower Replication


Product Browsing
[Container: Java]
Provides backend logic for browsing or searching for products.
Find Products
[JPA]
Product Purchasing
[Container: Java]
Provides backend logic for purchasing products.
Updates & Queries
[JPA]
Customer Account Management
[Container: Java]
Provides backend logic for customer account management.
Updates & Queries
[JPA]
Product Fulfillment
[Container: Java]
Provides backend logic for fulfilling products.
Updates
[JPA]
Leader Replica
[Container: MySQL]
Stores customer credentials, products, and orders.
Change stream
Change stream
Follower Replica
[Container: MySQL]
Stores customer credentials, products, and orders.
Follower Replica
[Container: MySQL]
Stores customer credentials, products, and orders.

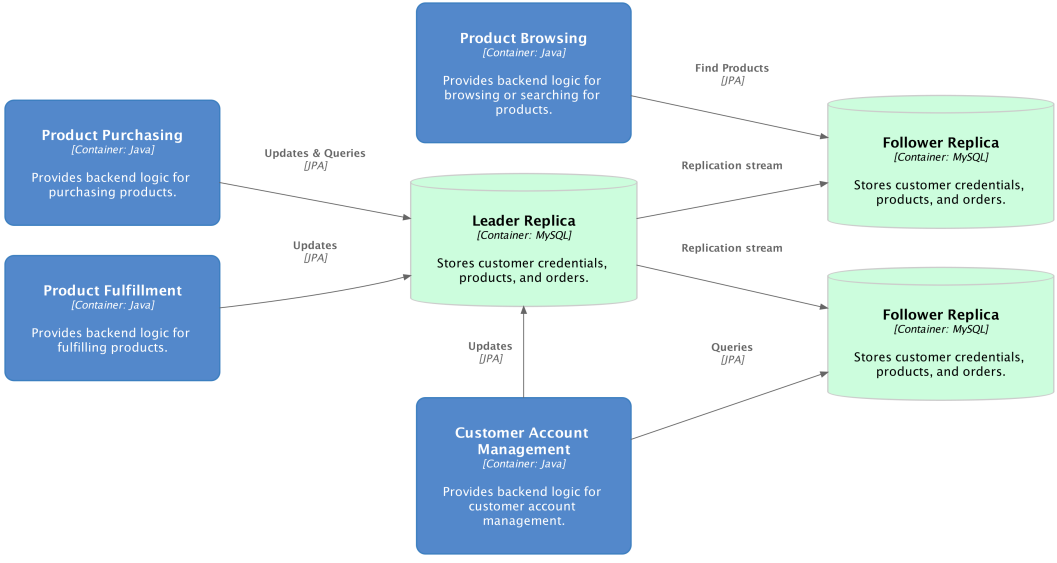
Leader-based Replication

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

Leader-based Replication

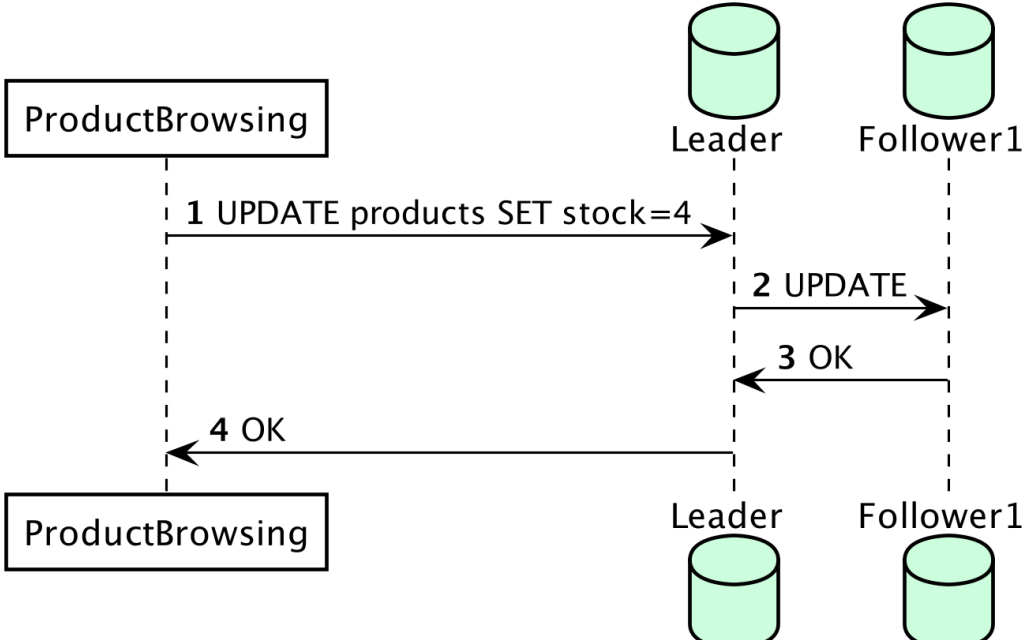
On write Writes sent to leader, change is propagated via change stream.

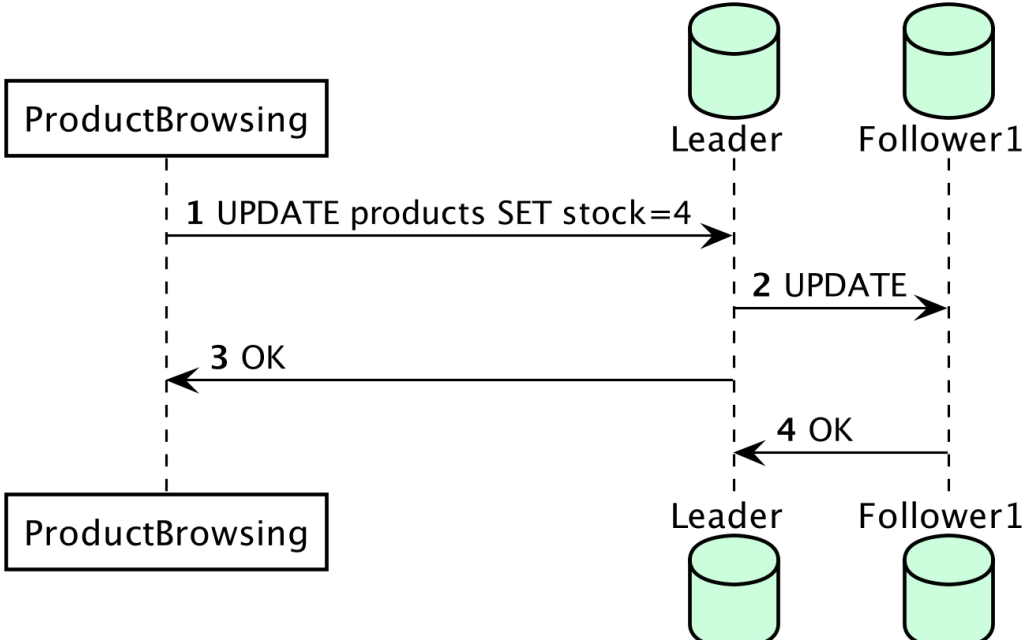
On read Any replica can be queried.


Product Browsing
[Container: Java]
Provides backend logic for browsing or searching for products.
Find Products
[JPA]
Follower Replica
[Container: MySQL]
Stores customer credentials, products, and orders.
Product Purchasing
[Container: Java]
Provides backend logic for purchasing products.
Updates & Queries
[JPA]
Replication stream
Leader Replica
[Container: MySQL]
Stores customer credentials, products, and orders.
Updates
[JPA]
Replication stream
Product Fulfillment
[Container: Java]
Provides backend logic for fulfilling products.
Follower Replica
[Container: MySQL]
Stores customer credentials, products, and orders.
Updates
[JPA]
Queries
[JPA]
Customer Account Management
[Container: Java]
Provides backend logic for customer account management.

Propogating changes

Synchronous vs. *Asynchronous*


ProductBrowsing
Leader
Follower1
1 UPDATE products SET stock=4
2 UPDATE
3 OK
4 OK
ProductBrowsing
Leader
Follower1


ProductBrowsing
Leader
Follower1
1 UPDATE products SET stock=4
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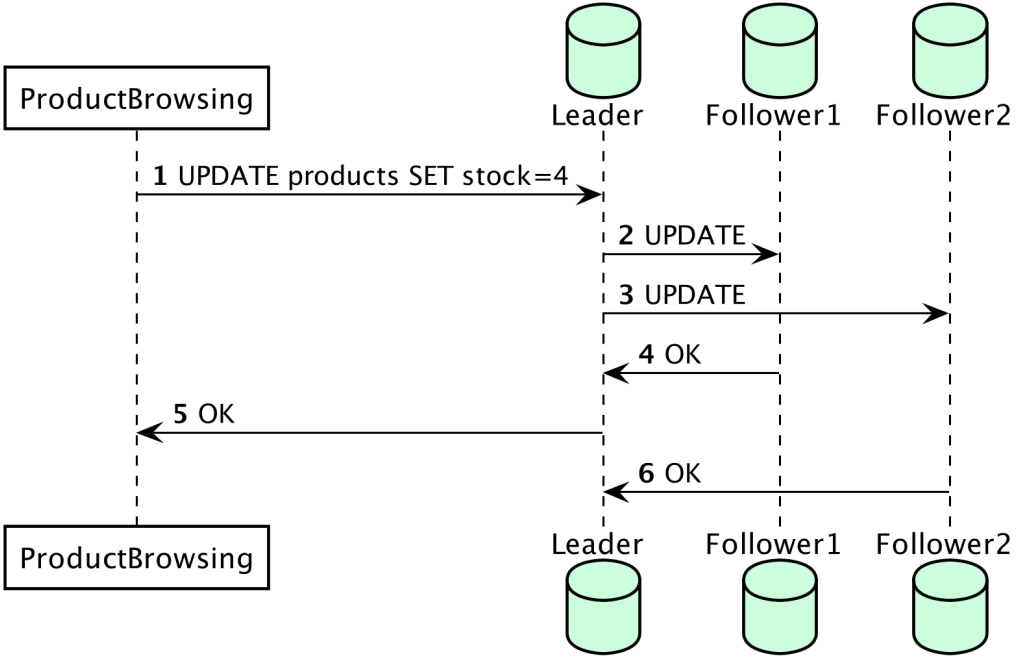
3 OK
4 OK
ProductBrowsing
Leader
Follower1


ProductBrowsing
Leader
Follower1
Follower2
1 UPDATE products SET stock=4
2 UPDATE
3 UPDATE
4 OK
5 OK
6 OK
ProductBrowsing
Leader
Follower1
Follower2

Synchronous propagation

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

Synchronous propagation

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- *Any* replica goes down, *all* replicas are un-writable.

Synchronous propagation

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

Asynchronous propagation

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

Asynchronous propagation

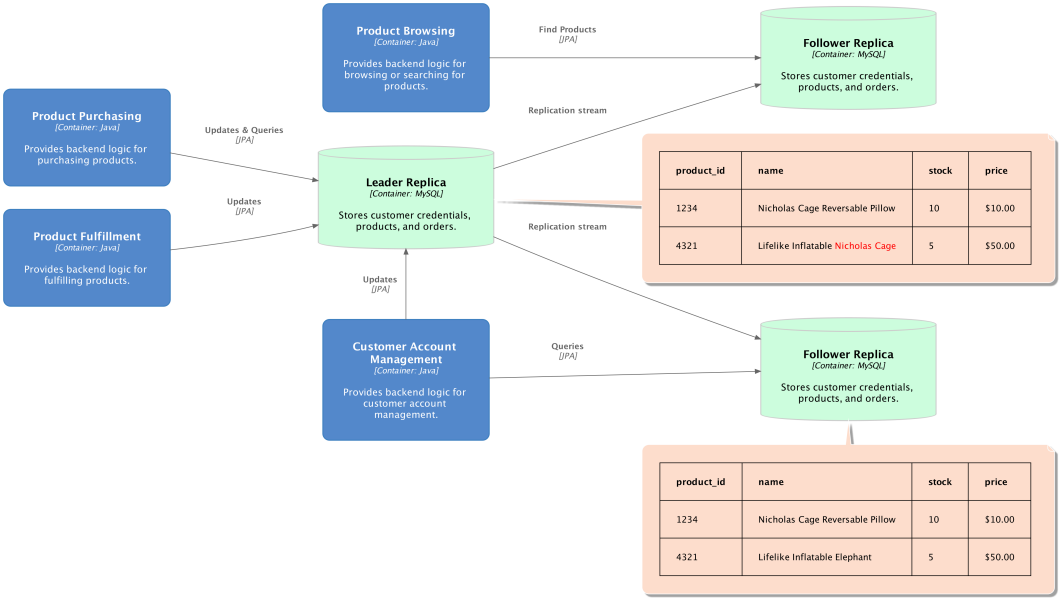
- Writes *don't* have to *wait* for propagation.
- If the leader goes down before propagating, the *write is lost*.

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 3. Replication Lag

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


Product Browsing
[Container: Java]
Provides backend logic for browsing or searching for products.
Find Products
[JPA]
Follower Replica
[Container: MySQL]
Stores customer credentials, products, and orders.
Product Purchasing
[Container: Java]
Provides backend logic for purchasing products.
Updates & Queries
[JPA]
Replication stream
Leader Replica
[Container: MySQL]
Stores customer credentials, products, and orders.
Updates
[JPA]
Product Fulfillment
[Container: Java]
Provides backend logic for fulfilling products.
Replication stream
Updates
[JPA]
Customer Account Management
[Container: Java]
Provides backend logic for customer account management.
Queries
[JPA]
Follower Replica
[Container: MySQL]
Stores customer credentials, products, and orders.
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
10
$10.00
4321
Lifelike Inflatable Nicholas Cage
5
$50.00
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
10
$10.00
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Lifelike Inflatable Elephant
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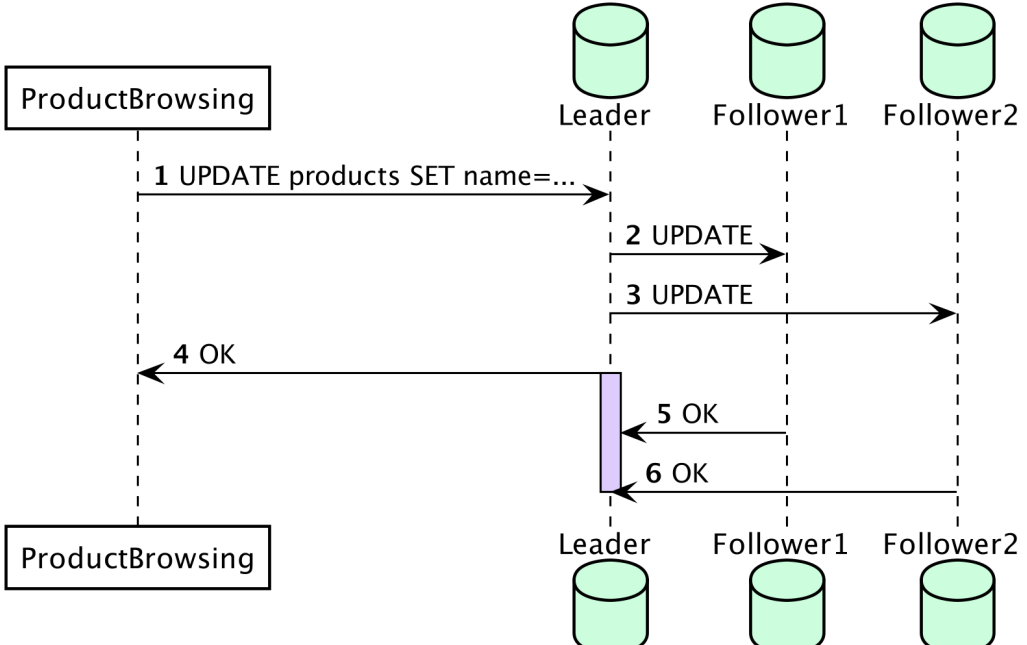

ProductBrowsing
Leader
Follower1
Follower2
1 UPDATE products SET name=...
2 UPDATE
3 UPDATE
4 OK
5 OK
6 OK
ProductBrowsing
Leader
Follower1
Follower2

Eventually, all replicas must become consistent

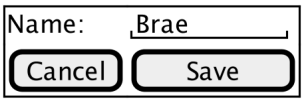
The system is *eventually consistent*

Eventual Consistency

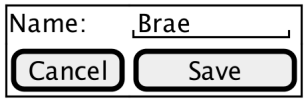
Problems?

Brae Webb
@braewebb

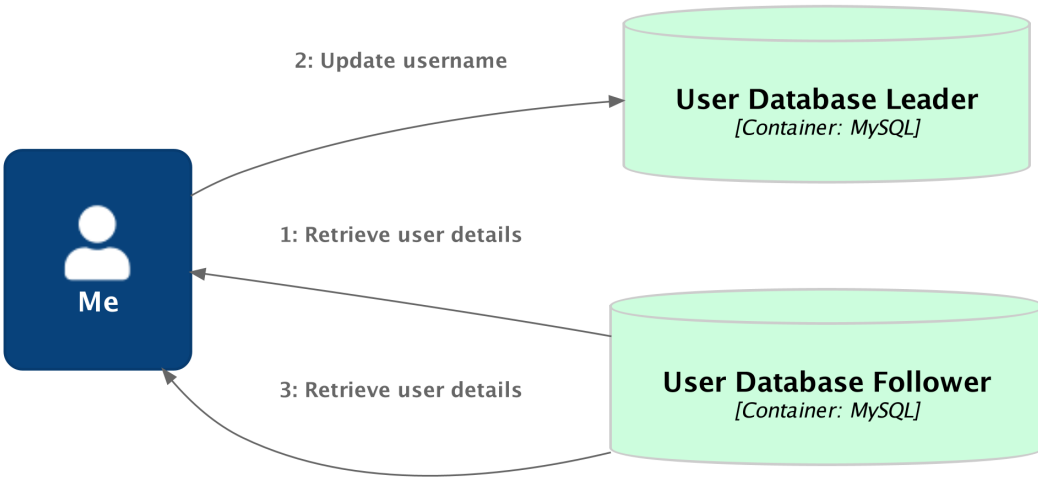
Brae Webb
@braewebb



Brae Webb
@braewebb



Brae Webb
@braewebb


2: Update username
User Database Leader
[Container: MySQL]
Me
1: Retrieve user details
User Database Follower
[Container: MySQL]
3: Retrieve user details

Definition 4. Read-your-writes Consistency

Users always see the updates that *they have made*.

Brae Webb
@braewebb

My fist post

Brae Webb
@braewebb

My fist post

Brae Webb
@braewebb

My first post

Brae Webb
@braewebb

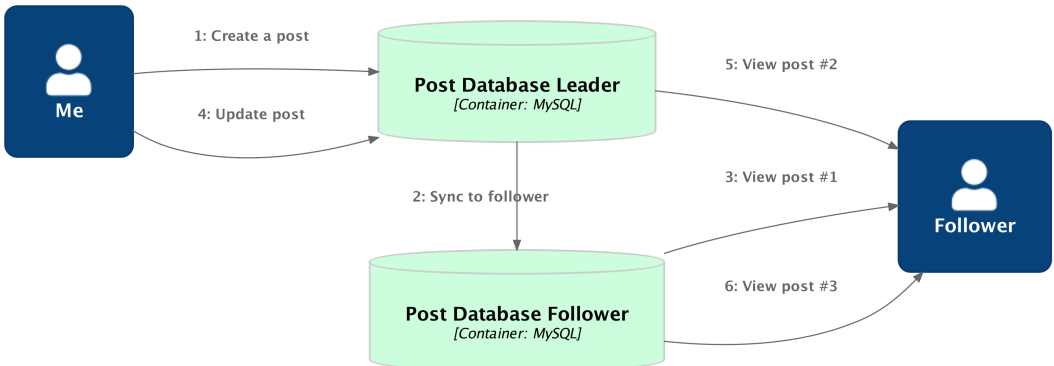
My fist post

Brae Webb
@braewebb

My first post

Brae Webb
@braewebb

My fist post


Me
1: Create a post
4: Update post
Post Database Leader
[Container: MySQL]
2: Sync to follower
Post Database Follower
[Container: MySQL]
5: View post #2
3: View post #1
6: View post #3
Follower

Definition 5. Monotonic Reads

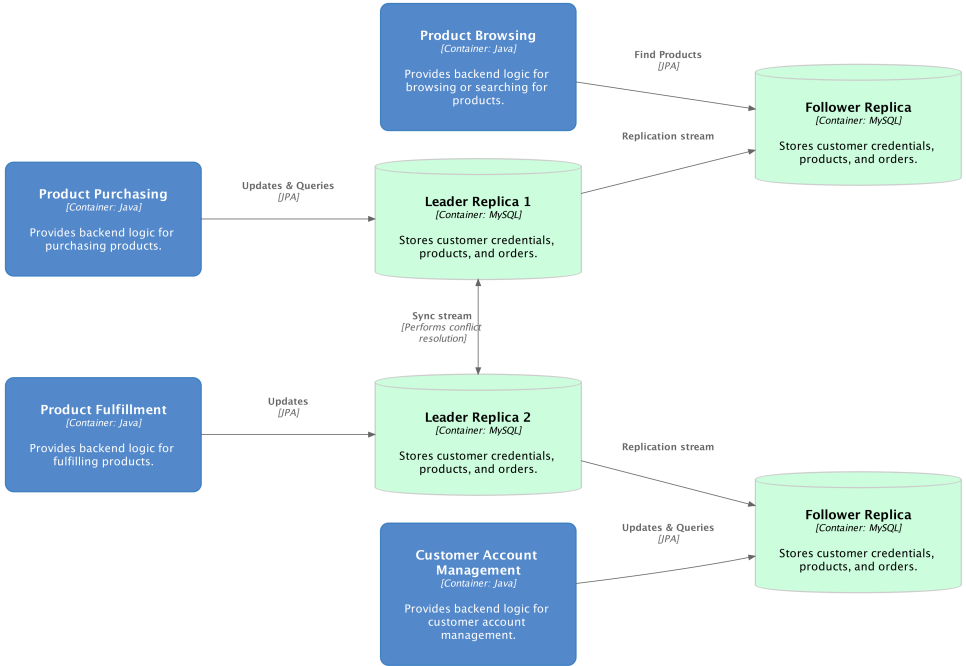
Once a user reads an updated value, they don't later see the old value.

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


Product Browsing
[Container: Java]
Provides backend logic for browsing or searching for products.
Find Products
[JPA]
Follower Replica
[Container: MySQL]
Stores customer credentials, products, and orders.
Replication stream
Product Purchasing
[Container: Java]
Provides backend logic for purchasing products.
Updates & Queries
[JPA]
Leader Replica 1
[Container: MySQL]
Stores customer credentials, products, and orders.
Sync stream
[Performs conflict resolution]
Product Fulfillment
[Container: Java]
Provides backend logic for fulfilling products.
Updates
[JPA]
Leader Replica 2
[Container: MySQL]
Stores customer credentials, products, and orders.
Replication stream
Follower Replica
[Container: MySQL]
Stores customer credentials, products, and orders.
Customer Account Management
[Container: Java]
Provides backend logic for customer account management.
Updates & Queries
[JPA]

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*.

Question

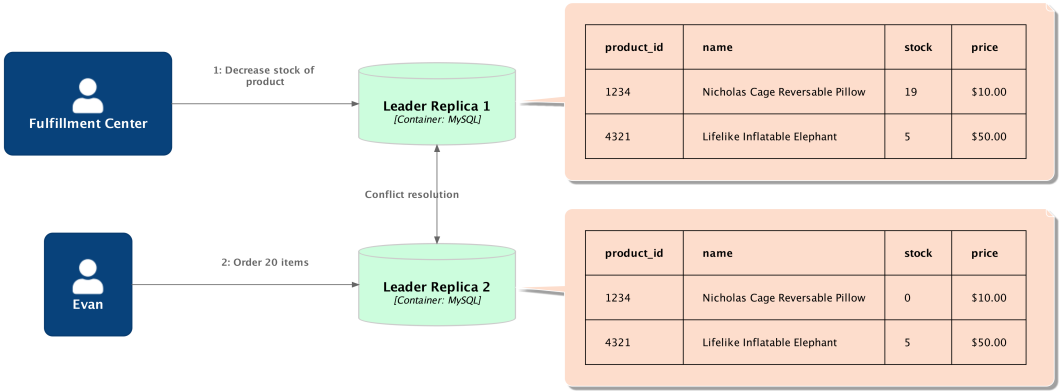
What might go wrong?

Question

What might go wrong?

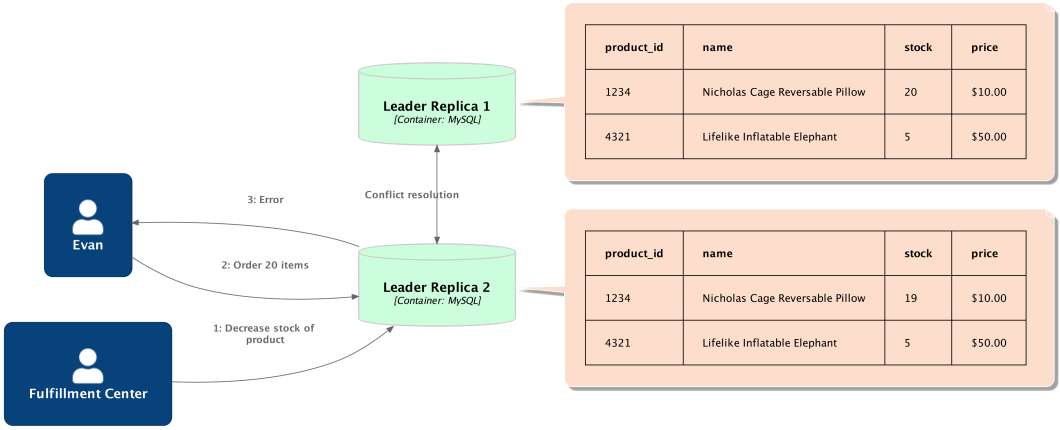
Answer

Write conflicts


Fulfillment Center
1: Decrease stock of product
Leader Replica 1
[Container: MySQL]
Conflict resolution
Evan
2: Order 20 items
Leader Replica 2
[Container: MySQL]
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
19
$10.00
4321
Lifelike Inflatable Elephant
5
$50.00
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
0
$10.00
4321
Lifelike Inflatable Elephant
5
$50.00

Where possible

Avoid write conflicts


Leader Replica 1
[Container: MySQL]
Conflict resolution
Leader Replica 2
[Container: MySQL]
Evan
3: Error
2: Order 20 items
Fulfillment Center
1: Decrease stock of product
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
20
$10.00
4321
Lifelike Inflatable Elephant
5
$50.00
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
19
$10.00
4321
Lifelike Inflatable Elephant
5
$50.00

Where impossible

Convergence

Convergence Strategies

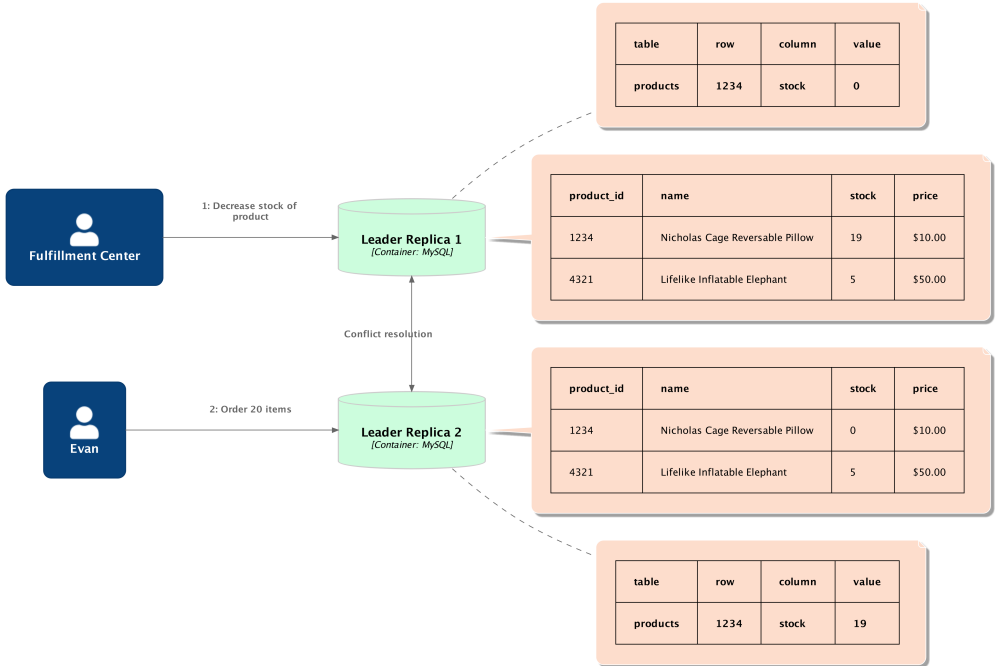
- Assign each *write* a unique ID.

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.


Fulfillment Center
1: Decrease stock of product
Leader Replica 1
[Container: MySQL]
Conflict resolution
Evan
2: Order 20 items
Leader Replica 2
[Container: MySQL]
table
row
column
value
products
1234
stock
0
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
19
$10.00
4321
Lifelike Inflatable Elephant
5
$50.00
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
0
$10.00
4321
Lifelike Inflatable Elephant
5
$50.00
table
row
column
value
products
1234
stock
19

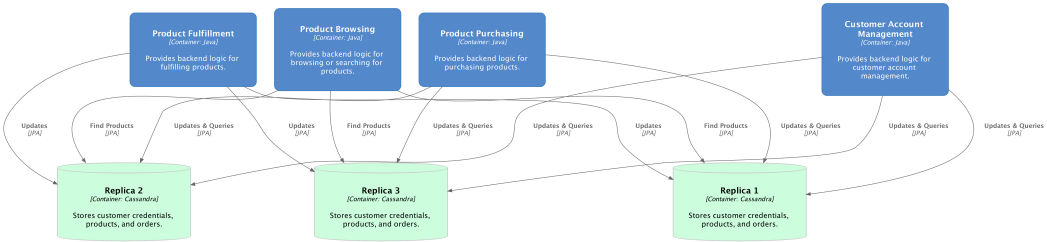
Resolving Conflicts

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

On Read When a conflict is next read, ask for a resolution.

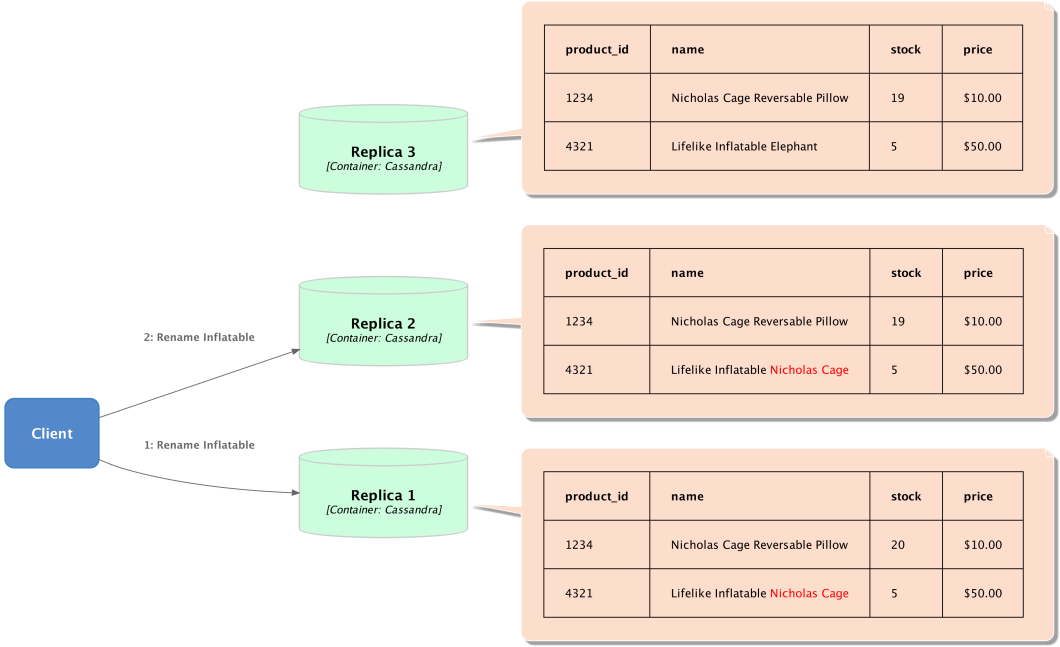
Third Approach

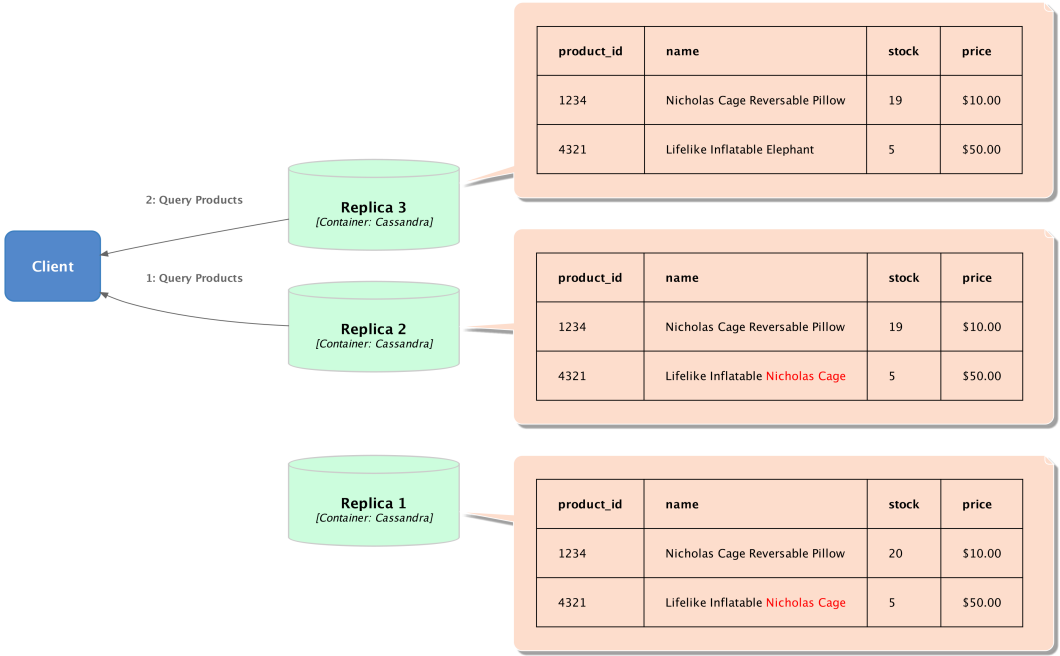
Leaderless Replication


Product Fulfillment
[Container: Java]
Provides backend logic for fulfilling products.
Product Browsing
[Container: Java]
Provides backend logic for browsing or searching for products.
Product Purchasing
[Container: Java]
Provides backend logic for purchasing products.
Customer Account Management
[Container: Java]
Provides backend logic for customer account management.
Updates
[JPA]
Find Products
[JPA]
Updates & Queries
[JPA]
Updates
[JPA]
Find Products
[JPA]
Updates & Queries
[JPA]
Updates & Queries
[JPA]
Updates
[JPA]
Find Products
[JPA]
Updates & Queries
[JPA]
Updates & Queries
[JPA]
Updates & Queries
[JPA]
Replica 2
[Container: Cassandra]
Stores customer credentials, products, and orders.
Replica 3
[Container: Cassandra]
Stores customer credentials, products, and orders.
Replica 1
[Container: Cassandra]
Stores customer credentials, products, and orders.

How do they work?

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


Replica 3
[Container: Cassandra]
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
19
$10.00
4321
Lifelike Inflatable Elephant
5
$50.00
Replica 2
[Container: Cassandra]
2: Rename Inflatable
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
19
$10.00
4321
Lifelike Inflatable Nicholas Cage
5
$50.00
Client
1: Rename Inflatable
Replica 1
[Container: Cassandra]
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
20
$10.00
4321
Lifelike Inflatable Nicholas Cage
5
$50.00


Client
2: Query Products
1: Query Products
Replica 3
[Container: Cassandra]
Replica 2
[Container: Cassandra]
Replica 1
[Container: Cassandra]
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
19
$10.00
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$50.00
product_id
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Lifelike Inflatable Nicholas Cage
5
$50.00
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
20
$10.00
4321
Lifelike Inflatable Nicholas Cage
5
$50.00

How are changes propagated?

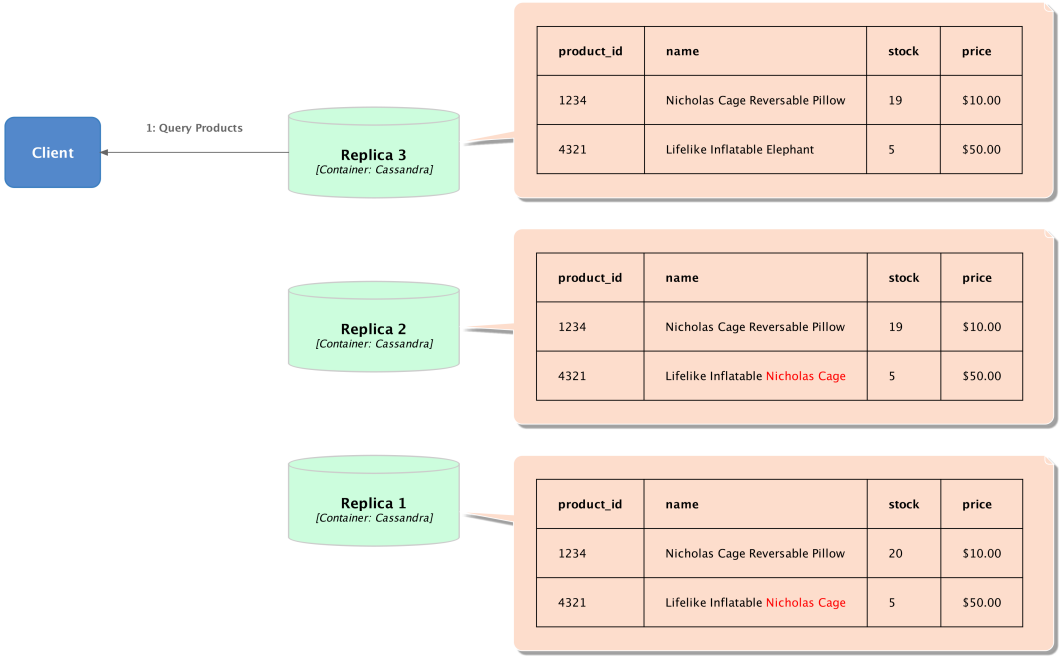
- Read Repair

How are changes propagated?

- Read Repair
- Anti-entropy Process

Question

How do we know it's consistent?


Client
1: Query Products
Replica 3
[Container: Cassandra]
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
19
$10.00
4321
Lifelike Inflatable Elephant
5
$50.00
Replica 2
[Container: Cassandra]
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
19
$10.00
4321
Lifelike Inflatable Nicholas Cage
5
$50.00
Replica 1
[Container: Cassandra]
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
20
$10.00
4321
Lifelike Inflatable Nicholas Cage
5
$50.00

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

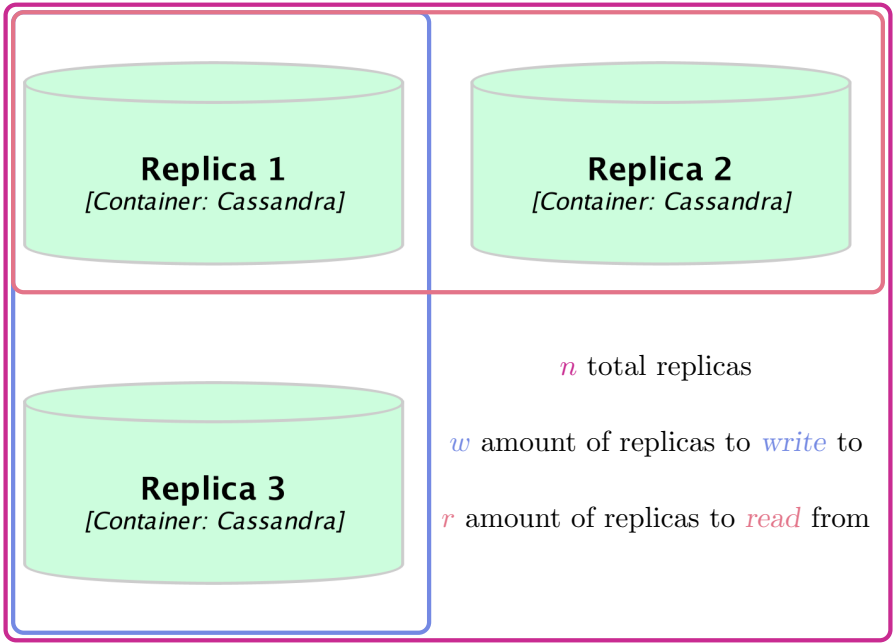
Quorum Consistency

$$1 + 3 > 3$$

n total replicas

w amount of replicas to *write* to

r amount of replicas to *read* from


Replica 1
[Container: Cassandra]
Replica 2
[Container: Cassandra]
Replica 3
[Container: Cassandra]
n total replicas
w amount of replicas to *write* to
r amount of replicas to *read* from

Summary

- *Replication* copies data to multiple replicas.

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- *Multi-leader* replication scales writes as well as reads but introduces *write conflicts*.

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

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Answer

- *Replication*
- Partitioning
- Independent databases

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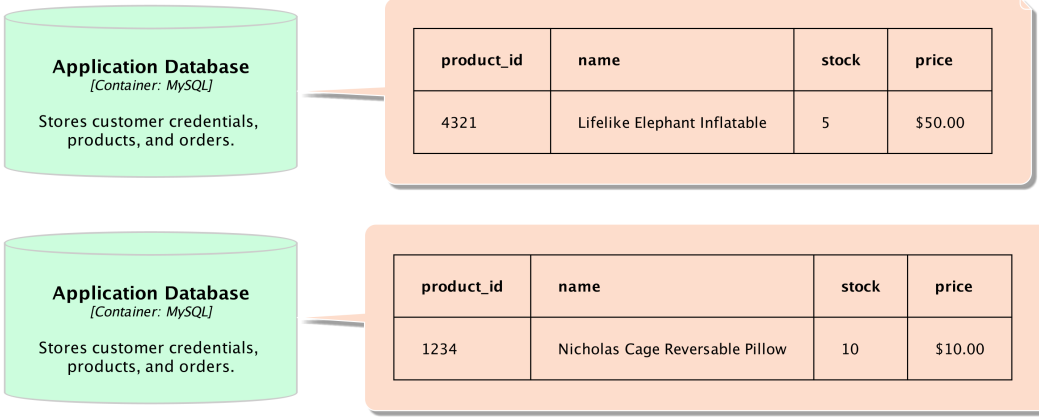
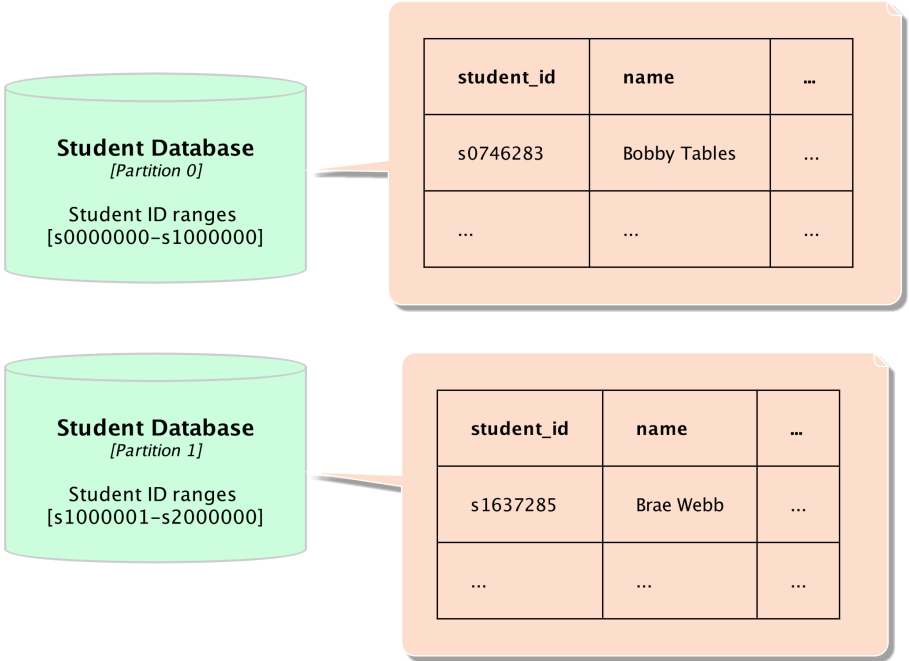
Definition 6. Partitioning

Split the data of a system onto multiple nodes, these nodes are *partitions*.


Application Database
[Container: MySQL]
Stores customer credentials, products, and orders.
product_id
name
stock
price
4321
Lifelike Elephant Inflatable
5
$50.00
Application Database
[Container: MySQL]
Stores customer credentials, products, and orders.
product_id
name
stock
price
1234
Nicholas Cage Reversable Pillow
10
$10.00

Question

How should we decide which data is stored where?


Student Database
[Partition 0]
Student ID ranges
[s0000000–s1000000]
student_id
name
...
s0746283
Bobby Tables
...
...
...
...
Student Database
[Partition 1]
Student ID ranges
[s1000001–s2000000]
student_id
name
...
s1637285
Brae Webb
...
...
...
...

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 which data is stored where?

Question

How should we decide which data is stored where?

Answer

Maximize spread of requests, avoiding *skewing*.

Question

Have we seen this before?

Question

Have we seen this before?

Answer

Hashing?

Question

What is the problem with this?

Question

What is the problem with this?

Answer

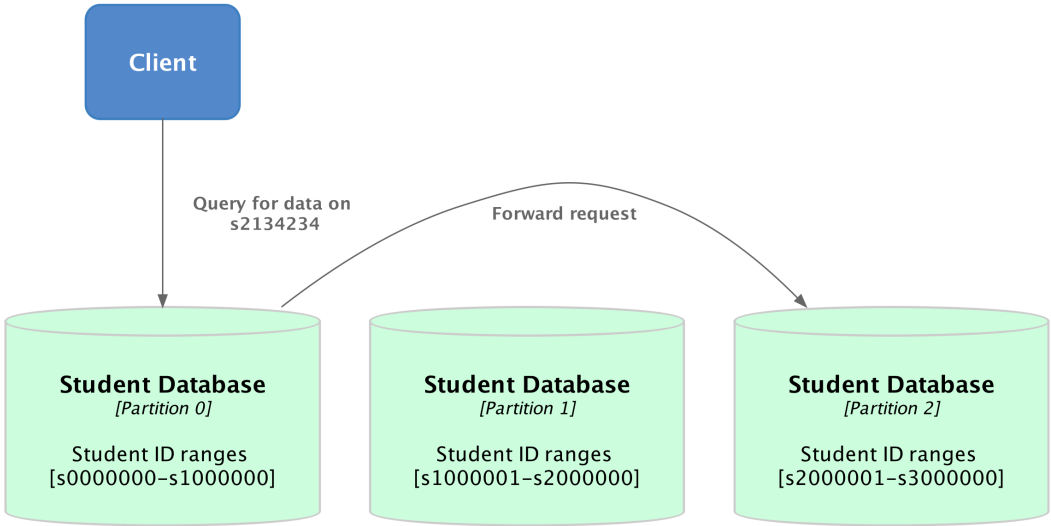
Range queries are inefficient, i.e. get all students between s4444444 and s4565656

Question

How do we route queries?

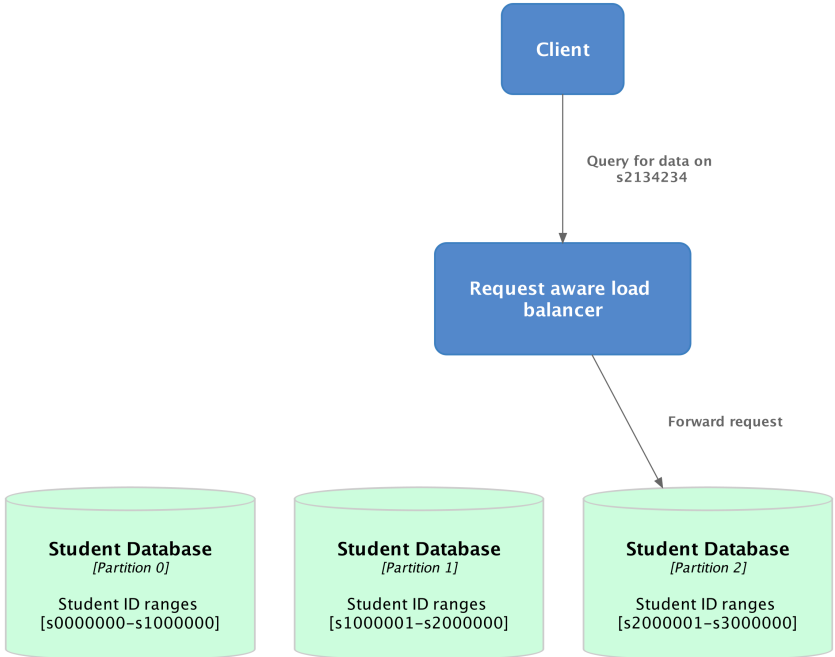
Query-insensitive Load Balancer

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


Client
Query for data on
s2134234
Forward request
Student Database
[Partition 0]
Student ID ranges
[s0000000-s1000000]
Student Database
[Partition 1]
Student ID ranges
[s1000001-s2000000]
Student Database
[Partition 2]
Student ID ranges
[s2000001-s3000000]

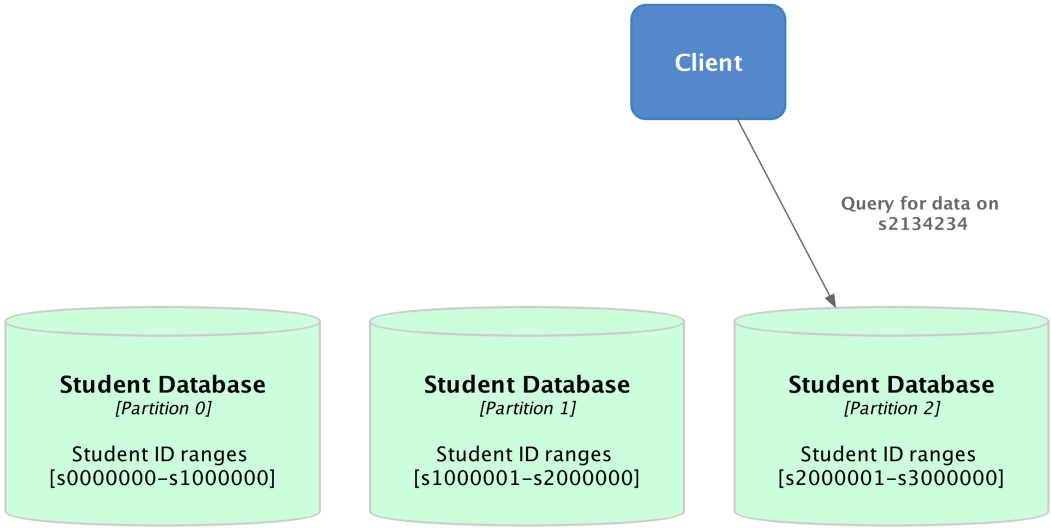
Query-sensitive Load Balancer

A load balancer which understands which queries should be forwarded to which node.


Client
Query for data on s2134234
Request aware load balancer
Forward request
Student Database
[Partition 0]
Student ID ranges [s0000000-s1000000]
Student Database
[Partition 1]
Student ID ranges [s1000001-s2000000]
Student Database
[Partition 2]
Student ID ranges [s2000001-s3000000]

Client-aware Queries

Place the responsibility on clients to choose the correct node.


Client
Query for data on
s2134234
Student Database
[Partition 0]
Student ID ranges
[s0000000-s1000000]
Student Database
[Partition 1]
Student ID ranges
[s1000001-s2000000]
Student Database
[Partition 2]
Student ID ranges
[s2000001-s3000000]

Summary

- *Partitioning* splits data across multiple nodes.

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- *Partitioning* splits data across multiple nodes.
- A *consistent method* to chose which node is required.
- 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.

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Summary

- Replications
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  - Eventual consistency
  - Write conflicts
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  - Consistent method to pick nodes for data
  - Avoiding skewing