

Distributed Systems II

Software Architecture

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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

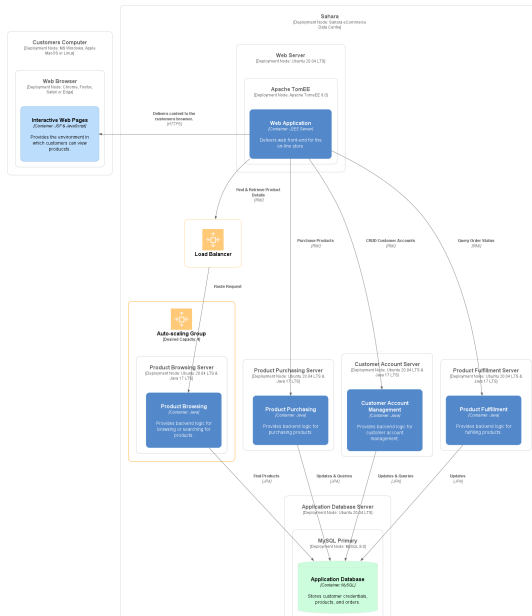
Distributed II *Complexities* of *stateful*
systems

Distributed III Hard problems in distributed
systems

Previously in Distributed I: Benefits...

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

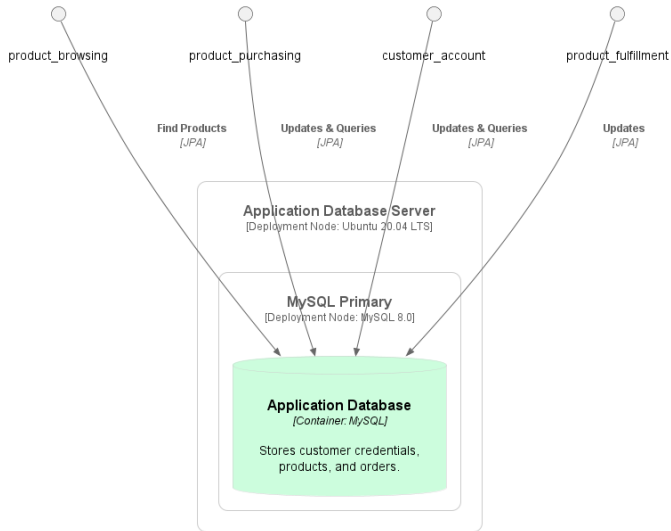
Previously in Distributed I...



Question

What is the *problem*?

Database



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

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

Examinations and coursework

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?

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Answer

- Replication

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- Replication
- Partitioning

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- Replication
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- Independent databases

Question

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- *Replication*
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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
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Definition 0. Replica

Database node which stores a copy of the data.

Question

What are the advantages of *replication*?

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Answer

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

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

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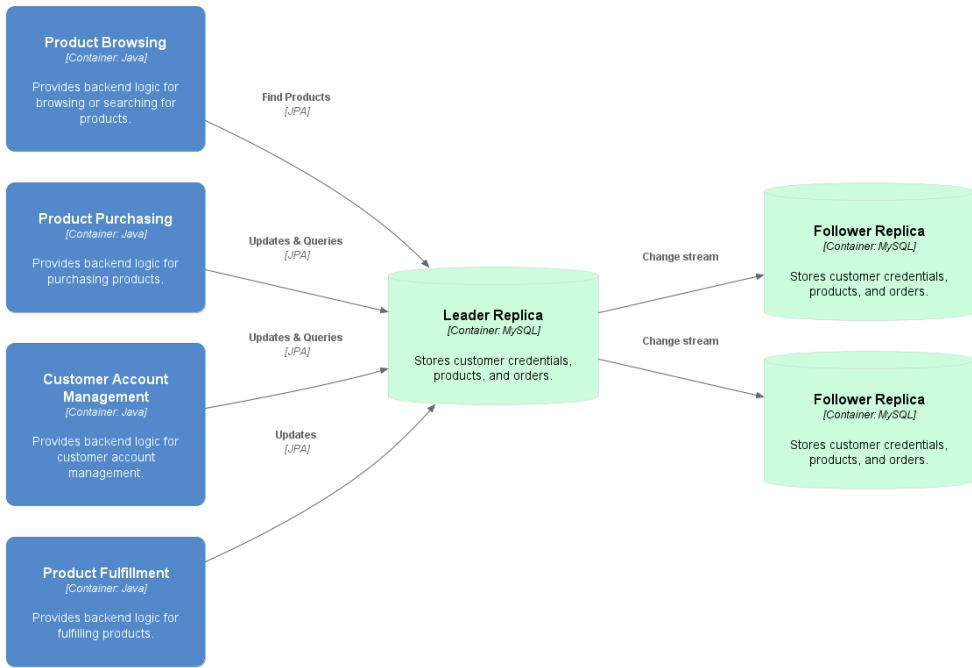
- *Scale* our database to cope with higher loads.
- Provide *fault tolerance* from a single instance failure.
- Locate instances *closer to end-users*.

Question

How do we replicate our data?

First Approach

Leader-Follower Replication



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.

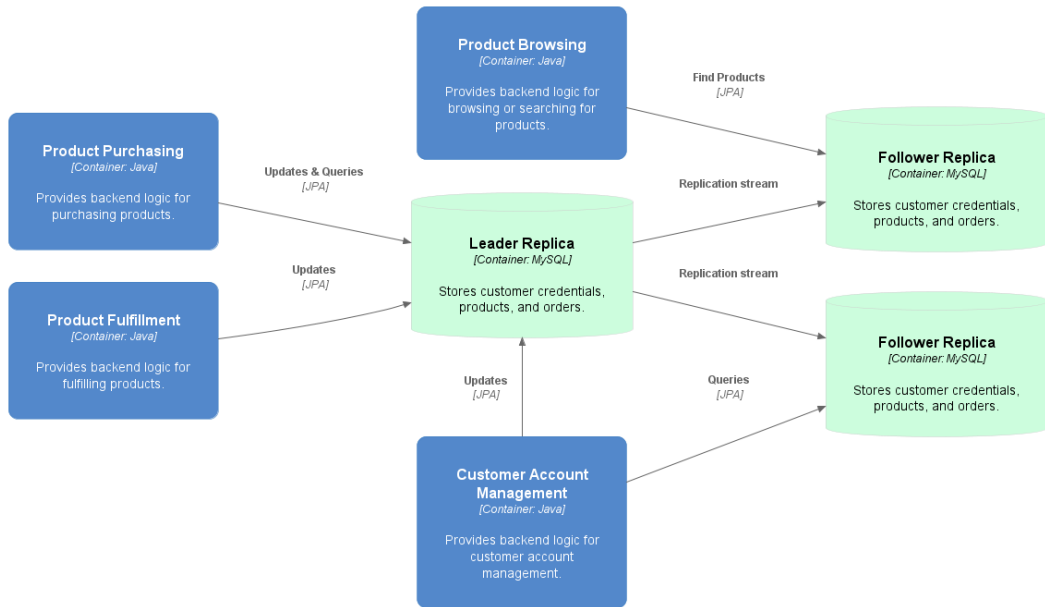
Leader-based Replication

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

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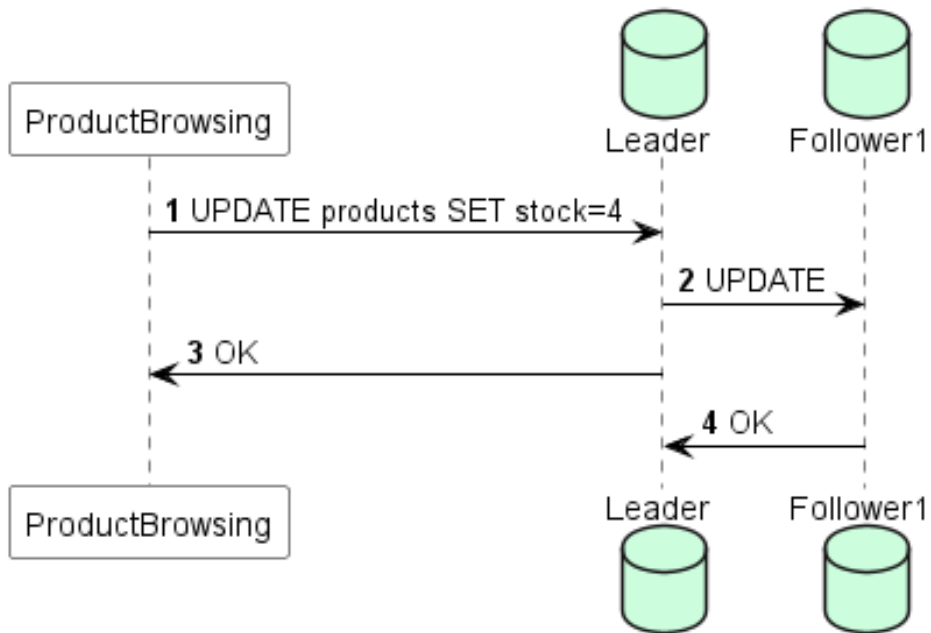
On read Any *replica* can be queried.



Propagating Changes

Synchronous vs. *Asynchronous*







Synchronous Propagation

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

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Synchronous Propagation

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- *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.

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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.

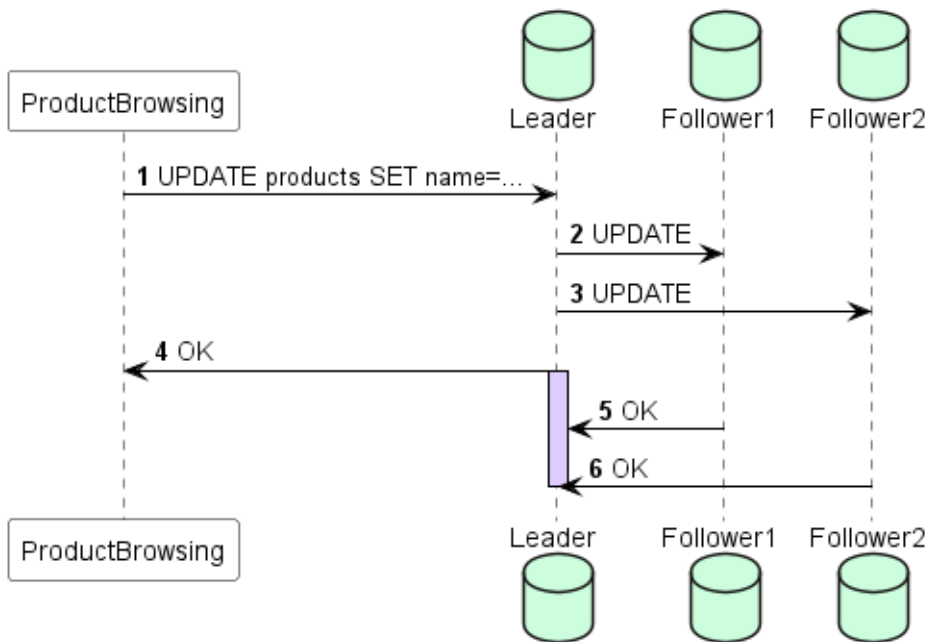
Definition 0. Stale data

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.



Eventually, all replicas must become consistent

The system is *eventually consistent*.

Eventual Consistency

Sufficient? Problems?



Brae Webb
@braewebb



Brae Webb

@braewebb

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



Brae Webb

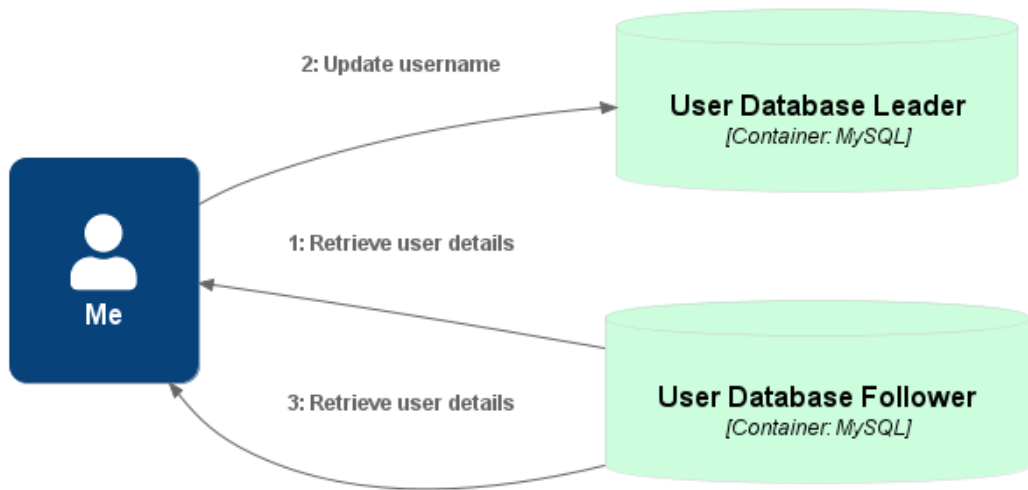
@braewebb

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



Brae Webb

@braewebb



Definition 0. Read-your-writes Consistency

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



Brae Webb

@braewebb

My fist post



Brae Webb

@braewebb

My fist post



Brae Webb

@braewebb

My first post



Brae Webb

@braewebb

My fist post



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@braewebb

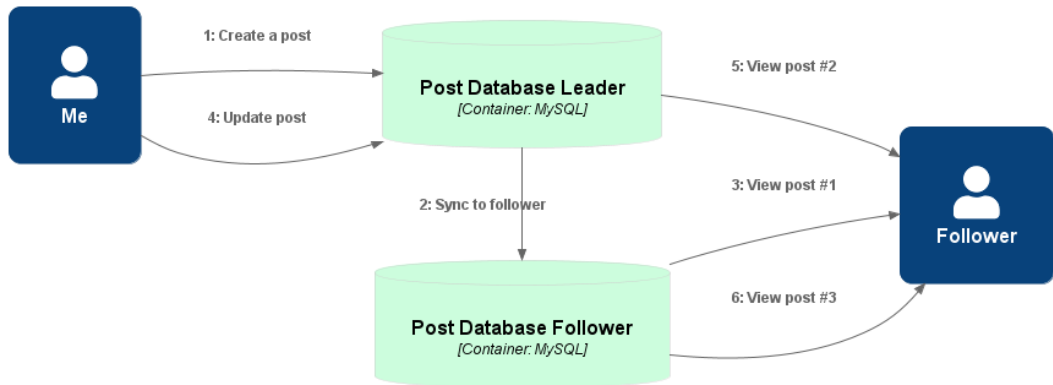
My first post



Brae Webb

@braewebb

My fist post



Definition 0. Monotonic Reads

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

Definition 0. Causal Consistency

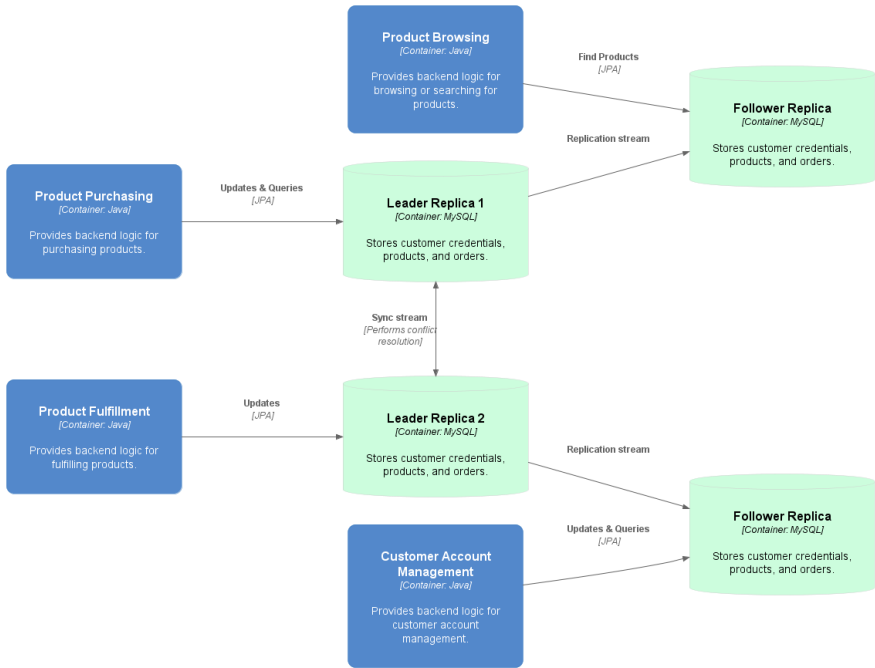
Causally related updates appear in order (e.g., comments appear under the right post).

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



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

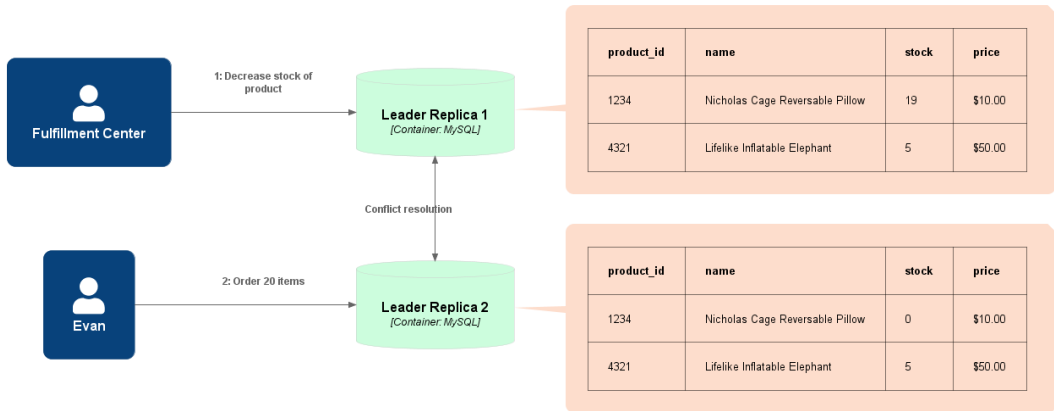
What might go wrong?

Question

What might go wrong?

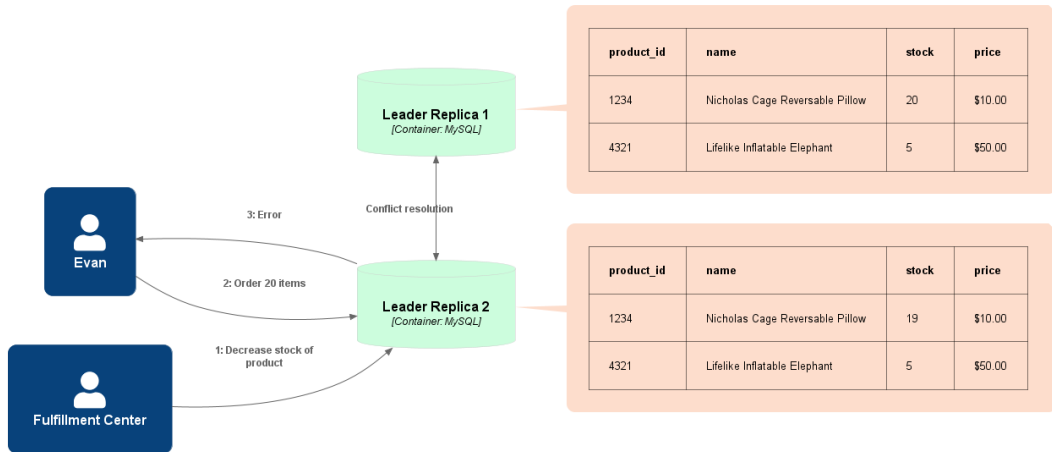
Answer

Write conflicts



Where possible

Avoid write conflicts



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



1: Decrease stock of product



Conflict resolution



2: Order 20 items



table	row	column	value
products	1234	stock	0

product_id	name	stock	price
1234	Nicholas Cage Reversible Pillow	19	\$10.00
4321	Lifelike Inflatable Elephant	5	\$50.00

product_id	name	stock	price
1234	Nicholas Cage Reversible 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.

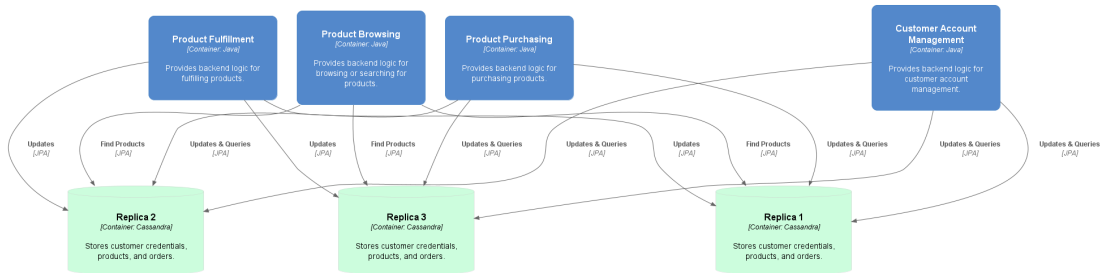
Example: Last Write Wins (LWW) in DynamoDB.

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

Example: *git pull*

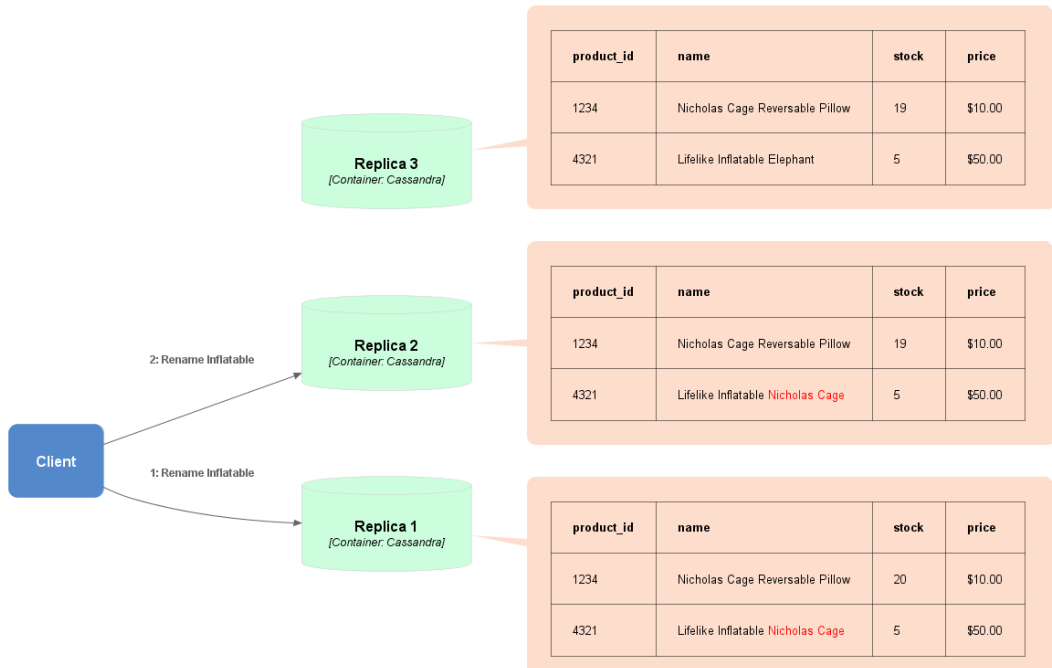
Third Approach

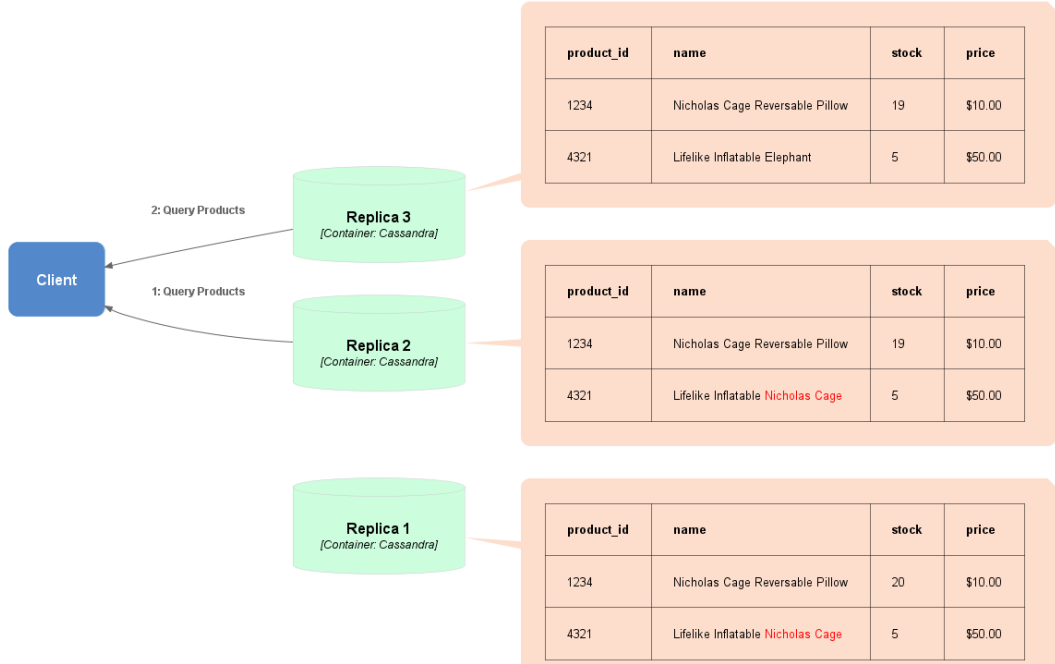
Leaderless Replication



How do they work?

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





How are changes propagated?

- Read Repair

How are changes propagated?

- Read Repair
- Anti-Entropy Process

Question

How do we know it's consistent?



1: Query Products



Replica 3

[Container: Cassandra]

product_id	name	stock	price
1234	Nicholas Cage Reversible Pillow	19	\$10.00
4321	Lifelike Inflatable Elephant	5	\$50.00



Replica 2

[Container: Cassandra]

product_id	name	stock	price
1234	Nicholas Cage Reversible Pillow	19	\$10.00
4321	Lifelike Inflatable Nicholas Cage	5	\$50.00



Replica 1

[Container: Cassandra]

product_id	name	stock	price
1234	Nicholas Cage Reversible Pillow	20	\$10.00
4321	Lifelike Inflatable Nicholas Cage	5	\$50.00

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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

Question

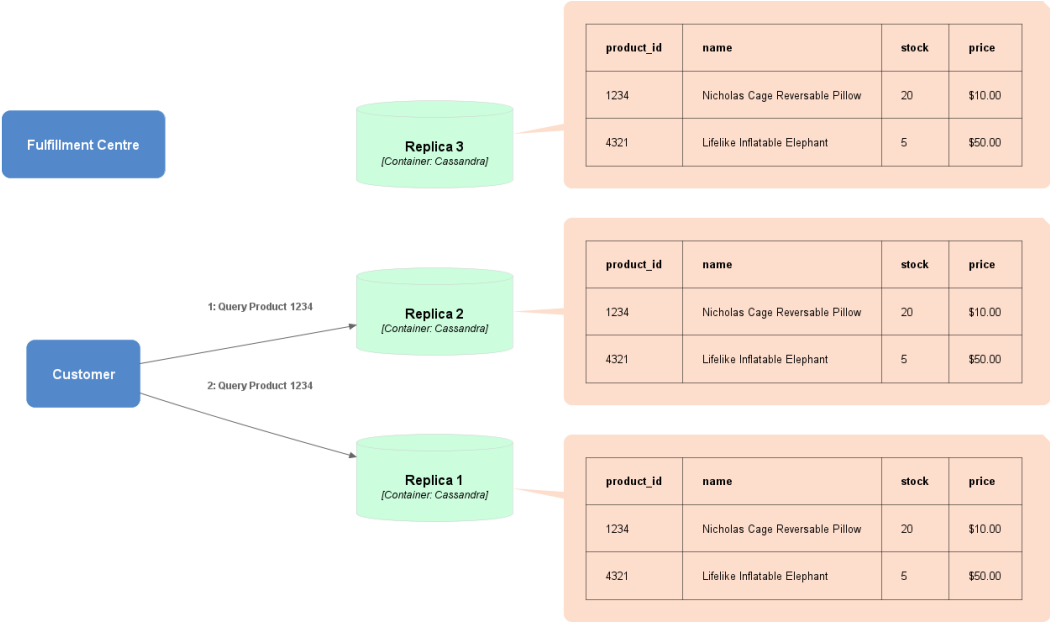
What about write conflicts?

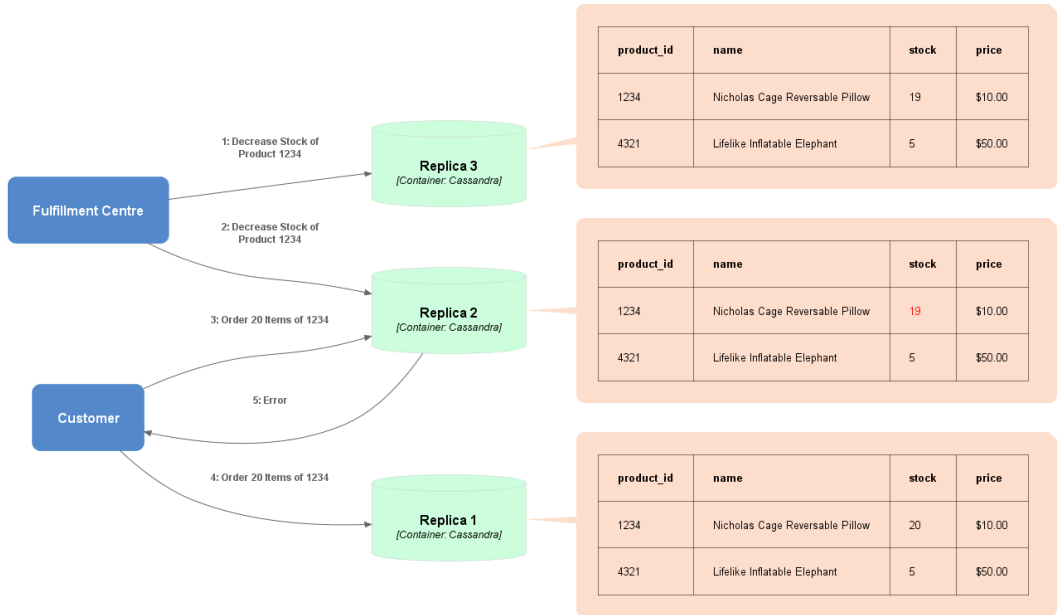
Question

What about write conflicts?

Answer

Same problem as with Multi-leader replication.





Summary

- *Replication* copies data to multiple replicas.

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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?

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Answer

- *Replication*
- Partitioning
- Independent databases

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Definition 0. 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

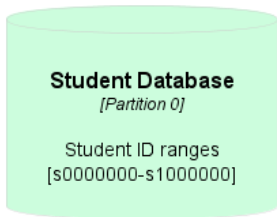
[Container: MySQL]

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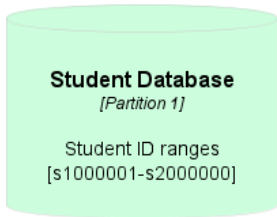
product_id	name	stock	price
1234	Nicholas Cage Reversible Pillow	10	\$10.00

Question

How should we decide which data is stored where?



student_id	name	...
s0746283	Bobby Tables	...
...



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 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?

Question

What is the problem with this?

Question

What is the problem with this?

Answer

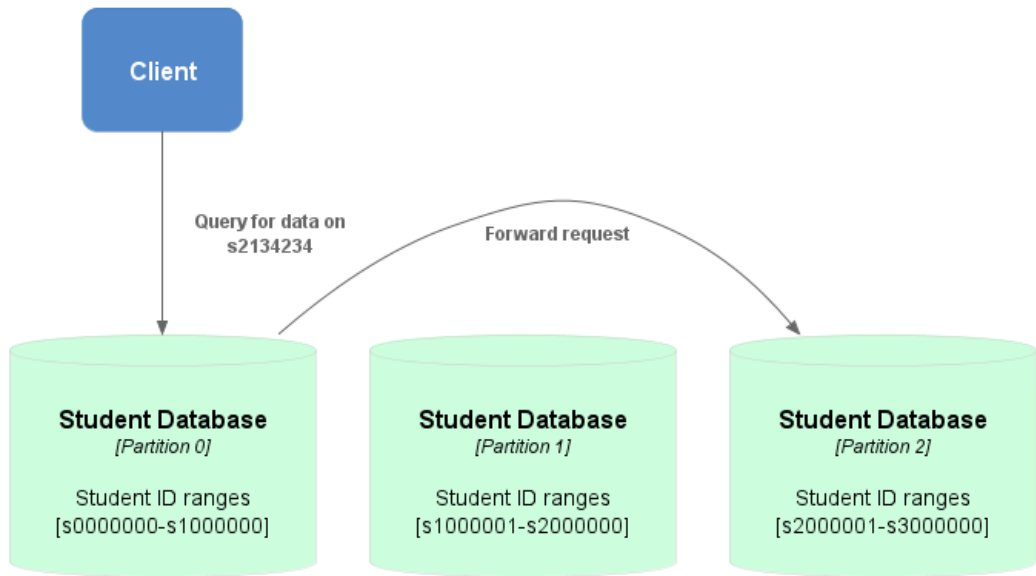
Range queries are inefficient, i.e. get all students between s4444444 and s4565656.

Question

How do we route queries?

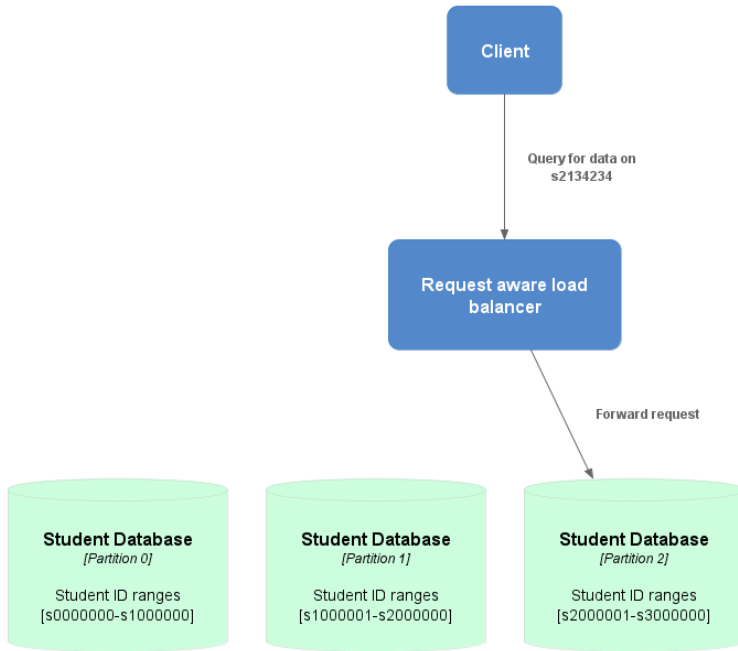
Query-Insensitive Load Balancer

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



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.

Client

Query for data on
s2134234

Student Database

[Partition 0]

Student ID ranges
[s0000000-s1000000]

Student Database

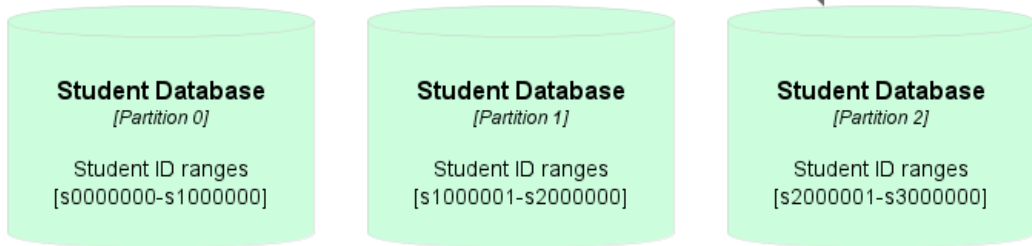
[Partition 1]

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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- Requires a *consistent method* to choose appropriate node.

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- *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.

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