# 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

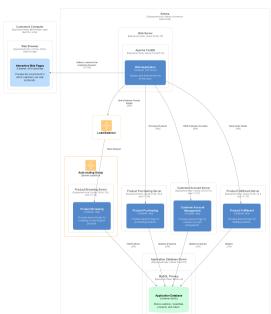
Distributed II Complexities of stateful systems

Distributed III Hard problems in distributed systems

# Previously in Distributed I: Benefits...

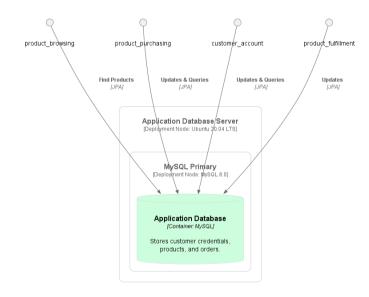
- Improved *reliability*
- Improved *scalability*
- Improved *latency*

# Previously in Distributed I...



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

INFS2200 Assessment methods



#### Advanced Database Systems (INFS3200)

#### Course level Undergraduate Faculty Engineering, Architecture & Information Technology School Info Tech & Elec Engineering Units Duration One Semester Class contact 2 Lecture hours, 1 Tutorial hour, 1 Practical or Laboratory hour Incompatible INFS7907 Prerequisite

#### 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

How do we fix database scaling issues?

How do we fix database scaling issues?

#### Answer

Replication

How do we fix database scaling issues?

- Replication
- Partitioning

How do we fix database scaling issues?

- Replication
- Partitioning
- Independent databases

How do we fix database scaling issues?

- Replication
- Partitioning
- Independent databases

What is *replication*?

# 

#### 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 0. Replica

Database node which stores a copy of the data.

What are the advantages of *replication*?

What are the advantages of *replication*?

#### Answer

• Scale our database to cope with higher loads.

What are the advantages of *replication*?

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

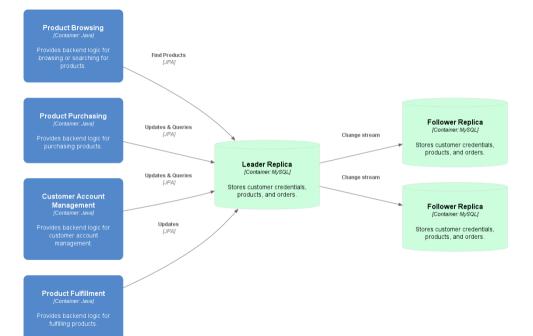
What are the advantages of *replication*?

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

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.

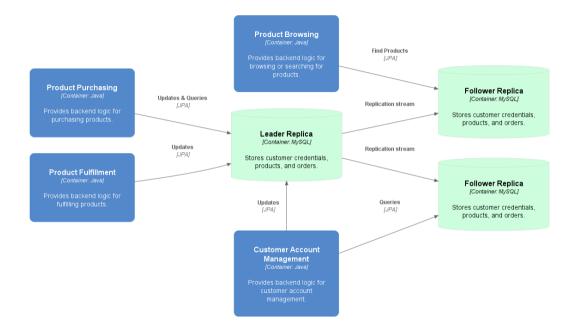
# Leader-based Replication

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

## Leader-based Replication

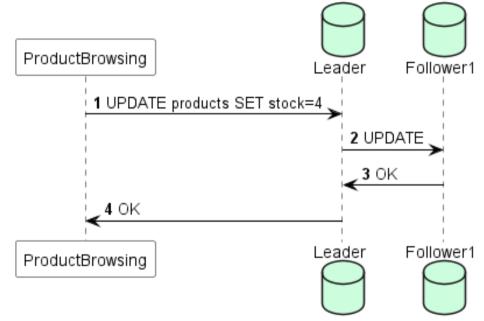
On write Writes sent to *leader*, change is propagated via change stream.

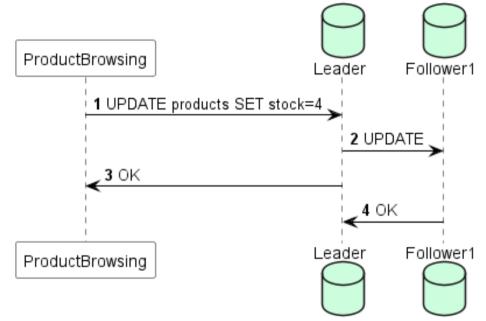
On read Any *replica* can be queried.

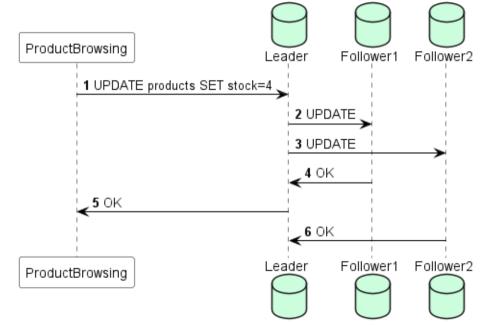


# Propagating Changes

Synchronous vs. Asynchronous







# $Synchronous\ Propagation$

• 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

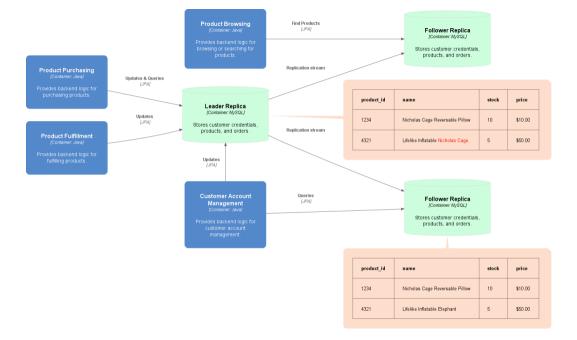
- Writes *don't* have to *wait* for propagation.
- If the leader goes down before propagating, the *write is lost*.

### 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.

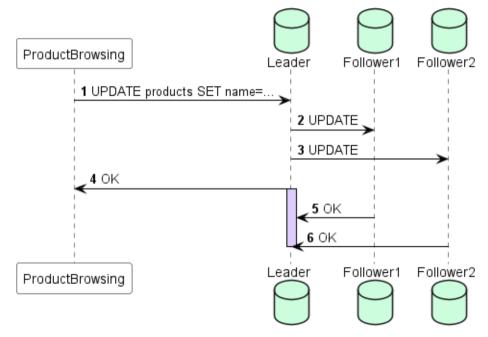
### Definition 0. Stale data

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.



Eventually, all replicas must become consistent

The system is eventually consistent.

### Eventual Consistency

Sufficient? Problems?



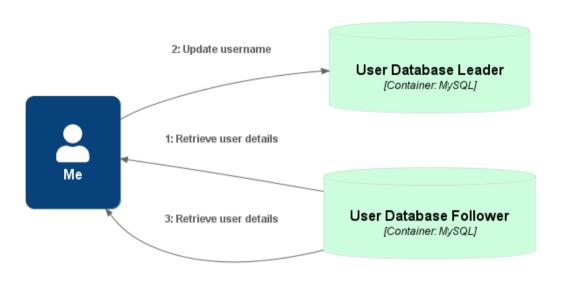


Name: Brae
Cancel Save









## $Definition\ 0.$ Read-your-writes Consistency

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



My fist post



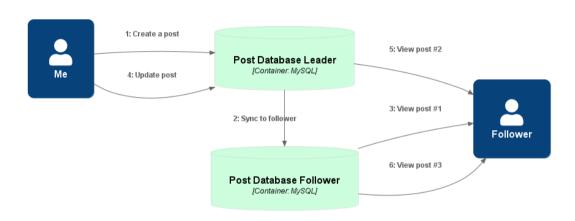


My first post









### Definition 0. Monotonic Reads

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

### Definition 0. Causal Consistency

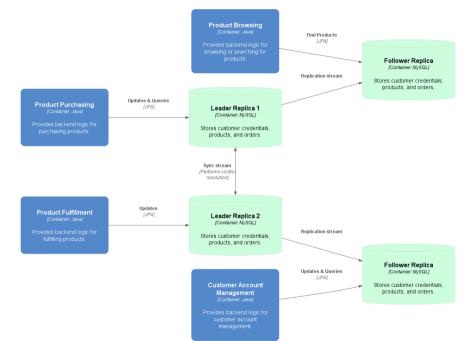
Causally related updates appear in order (e.g., comments appear under the right post).

### 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

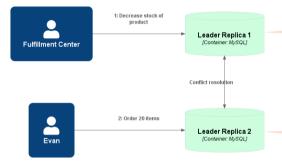
What might go wrong?

### Question

What might go wrong?

Answer

Write conflicts

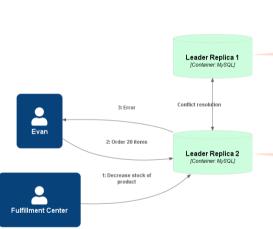


product_id	name	stock	price
1234	Nicholas Cage Reversable Pillow	19	\$10.00
4321	Lifelike Inflatable Elephant	5	\$50.00

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



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

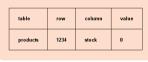
• Assign each *write* a unique ID

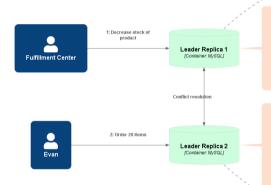
### Convergence Strategies

- 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





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.

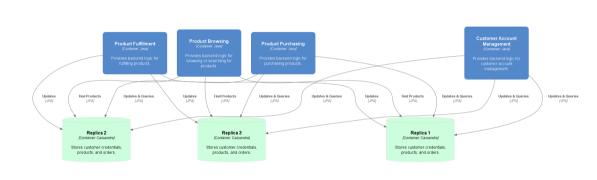
Example: Last Write Wins (LWW) in DynamoDB.

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?

110 w wo they worm.

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

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

Replica 3 [Container: Cassandra]

Replica 2 [Container: Cassandra]

Client 1: Rename Inflatable

2: Rename Inflatable

Replica 1 [Container: Cassandra]

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

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

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

2: Query Products

Replica 3 [Container: Cassandra]

1: Query Products

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

## How are changes propagated?

• Read Repair

## How are changes propagated?

- Read Repair
- Anti-Entropy Process

How do we know it's consistent?

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

Replica 2
[Container: Cassandra]

Client

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	

How do we know it's consistent?

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

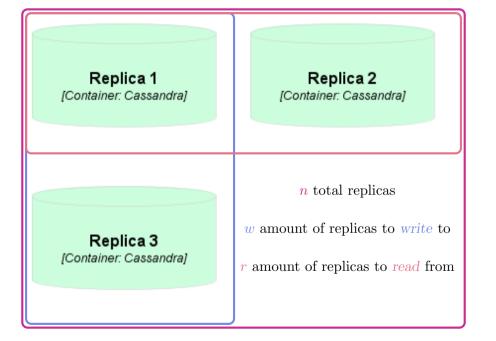
$$2+2>3$$

 $\begin{array}{c} n \end{array}$  total replicas  $\begin{array}{c} w \end{array}$  amount of replicas to  $\begin{array}{c} w \end{array}$  amount of replicas to  $\begin{array}{c} r \end{array}$  amount of replicas to  $\begin{array}{c} r \end{array}$ 

### Quorum Consistency

$$1 + 3 > 3$$

n total replicas w amount of replicas to w to v amount of replicas to v amount of replicas to v are v and v are v a



What about write conflicts?

What about write conflicts?

Answer

Same problem as with Multi-leader replication.



#### Replica 3 (Container: Cassandra)

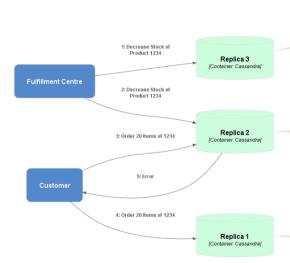


	1: Query Product 1234	Replica 2 [Container: Cassandra]
Customer	2: Query Product 1234	

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

Rep	lica 1
[Container:	Cassandra

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

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	20	\$10.00
4321	Lifelike Inflatable Elephant	5	\$50.00

• Replication copies data to multiple replicas.

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

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

- 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.

- 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.

How do we fix database scaling issues?

How do we fix database scaling issues?

#### Answer

- Replication
- Partitioning
- Independent databases

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*.

## 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

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	

What is the problem with this?

What is the problem with this?

#### Answer

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

How should we decide where data is stored?

How should we decide where data is stored?

Answer

Maximize spread of requests, avoiding *skewing*.

Have we seen this before?

Have we seen this before?

Answer

Hashing?

What is the problem with this?

What is the problem with this?

#### Answer

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

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.



Forward request

# Student Database

[Partition 0]

Student ID ranges [s00000000-s10000000]

#### Student Database

[Partition 1]

Student ID ranges [s1000001-s2000000]

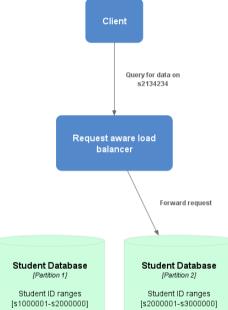
## Student Database

[Partition 2]

Student ID ranges [s2000001-s3000000]

# Query-Sensitive Load Balancer

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



#### Student Database [Partition 0]

Student ID ranges [s0000000-s1000000]

# Client-aware Queries

Place the responsibility on clients to choose the correct node.



Query for data on s2134234

# Student Database

Student ID ranges [s0000000-s1000000]

## Student Database

[Partition 1]

Student ID ranges [s1000001-s2000000]

## Student Database

[Partition 2]

Student ID ranges [s2000001-s3000000]

• Partitioning splits data across multiple nodes.

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

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

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

# Summary Partitioning splits data across

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

How do we fix database scaling issues?

How do we fix database scaling issues?

#### Answer

- Replication
- Partitioning
- Independent databases

How do we fix database scaling issues?

#### Answer

- Replication
- Partitioning
- Independent databases

Replications

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

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

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

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

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

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