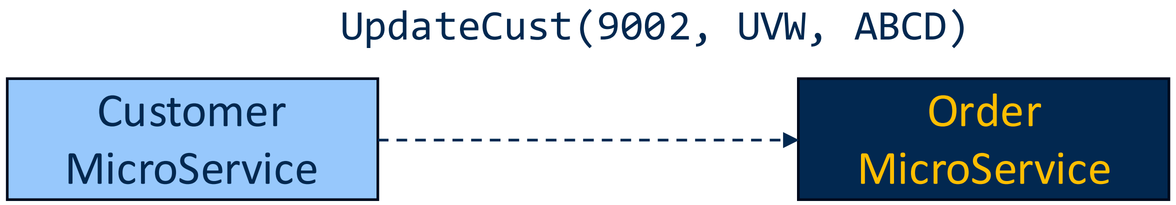
Kafka: a use case for high-throughput data systems

Tapti Palit

UCDAVIS

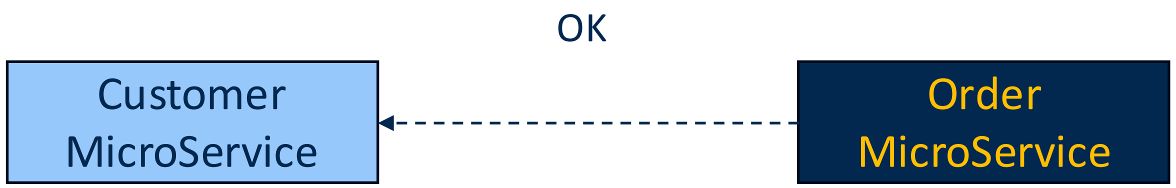
The problem with request/response

- Caller blocks until the response arrives
- If the callee is down, the caller fails or must retry



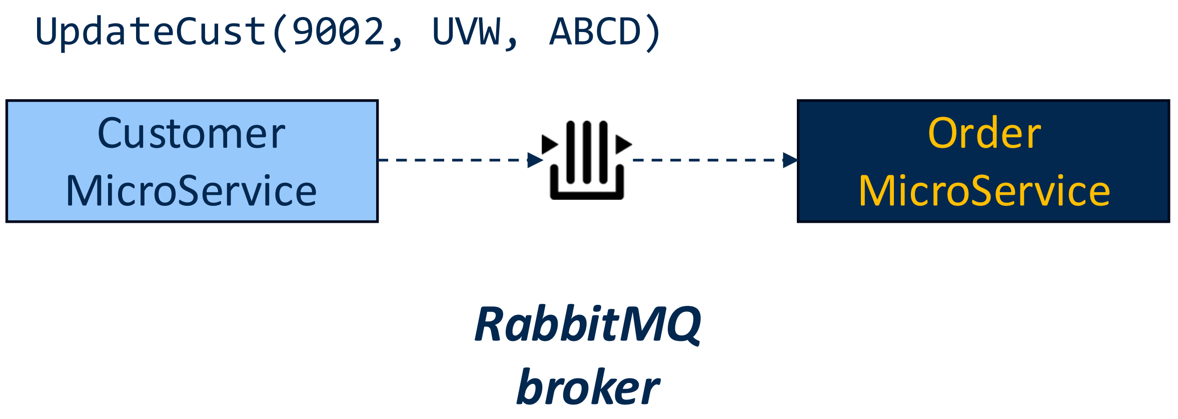
The problem with request/response

- Caller blocks until the response arrives
- If the callee is down, the caller fails or must retry



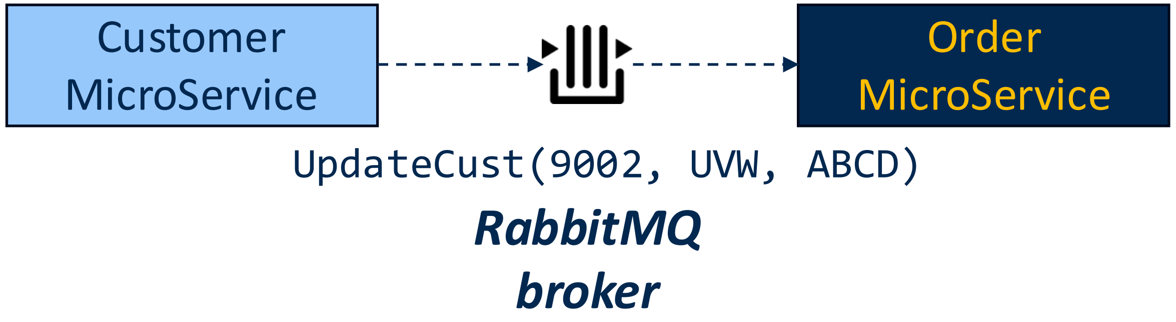
The problem with request/response

- Message queues mitigate some of these problems
- But still, the caller must know the callee (tight coupling)



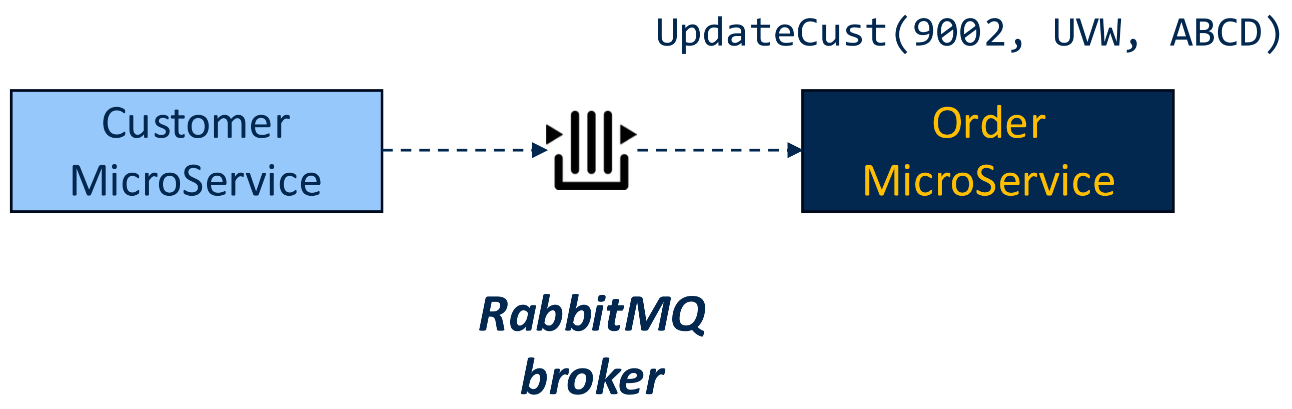
The problem with request/response

- Message queues mitigate some of these problems
- But still, the caller must know the callee (tight coupling)



The problem with request/response

- Message queues mitigate some of these problems
- But still, the caller must know the callee (tight coupling)



** Note that the broker here deletes the message once it's consumed*

Messages vs events

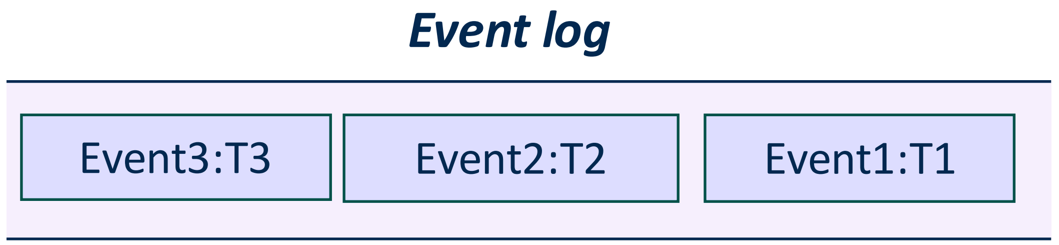
- Kafka uses events instead of messages or commands
- Message or command: `UpdateCust(9002, UVW, ABCD)`
  - Directed at a specific service (Order microservice)
  - Implies a known recipient and expected action
- Event: `CustomerUpdated(9002, UVW, ABCD)`
  - A fact that happened
  - Implies no specific recipient – anyone can subscribe

What is Apache Kafka?

- A distributed event streaming platform
- Originally built at LinkedIn for website activity data
- Open-sourced in 2011, graduated from Apache Incubator in 2012
- Used at Netflix, LinkedIn, Uber, and thousands of companies
- Forms the substrate on which many streaming frameworks operate
  - Apache Flink, Apache Spark (out of scope for this class)
- Processes trillions of events per day at scale

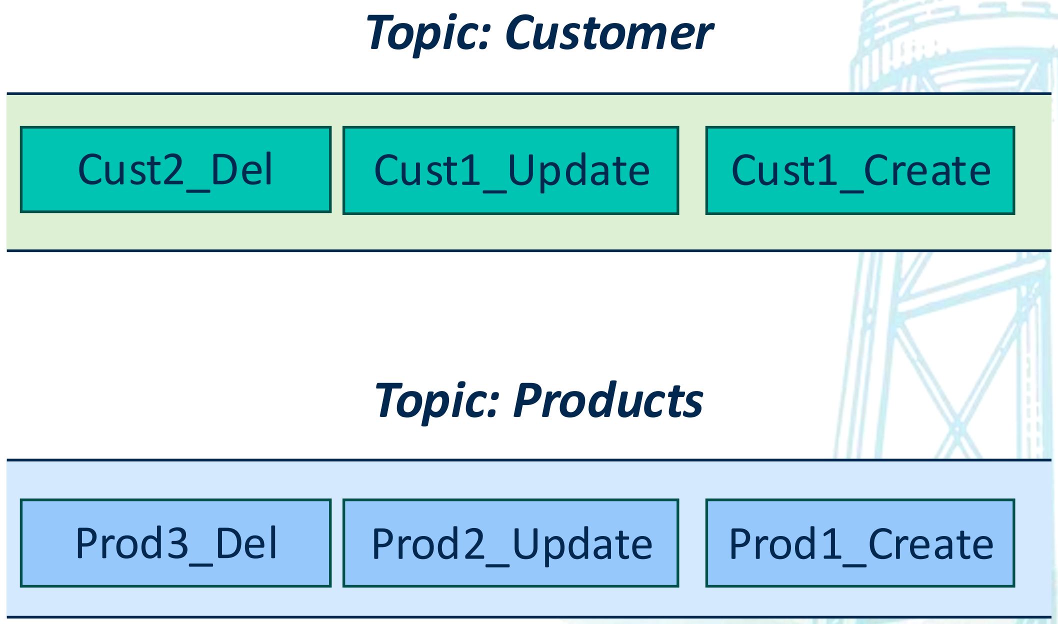
Kafka uses the log abstraction

- Producers append the events to a log
- Consumers read from the log



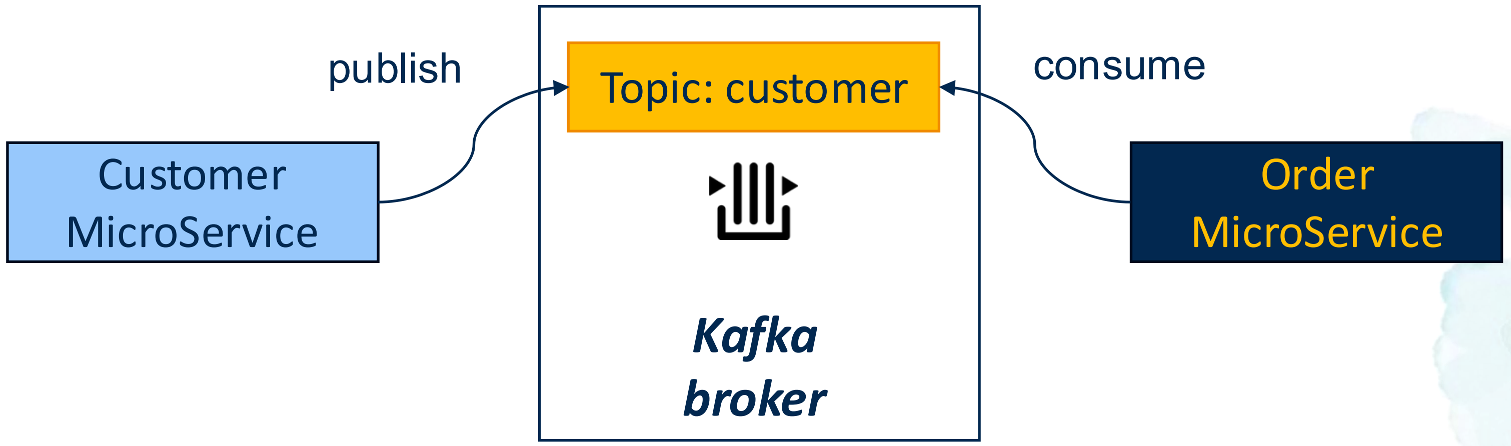
Kafka topics

- Kafka events are organized into "topics"
- A topic is a named logical abstraction
  - A feed of related events
  - E.g: 'customers', 'orders', 'products'



Kafka topics

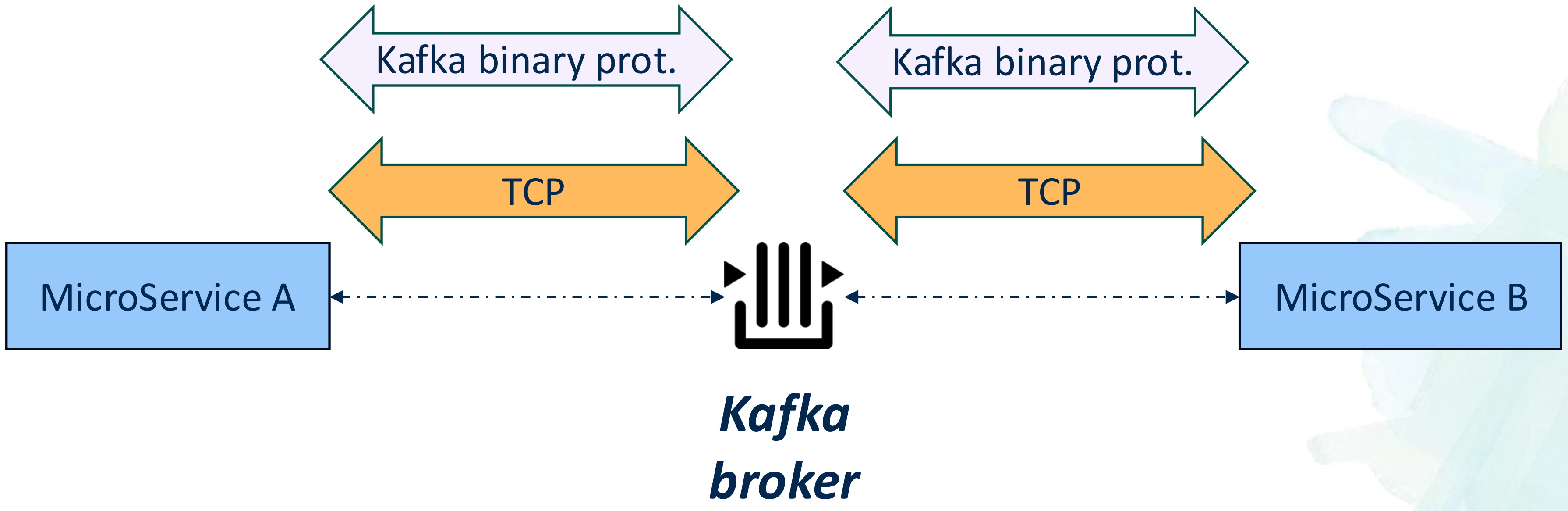
- Topics are units of subscription:
  - Producers write events to a topic
  - Consumers subscribe to one or more topics



- Topics also help improve concurrency (more later)

Kafka uses a binary protocol

Kafka uses a binary protocol over TCP



The Kafka Record

- All Kafka events have the same record format

Key (optional)	**Value**	**Timestamp**	**Headers**

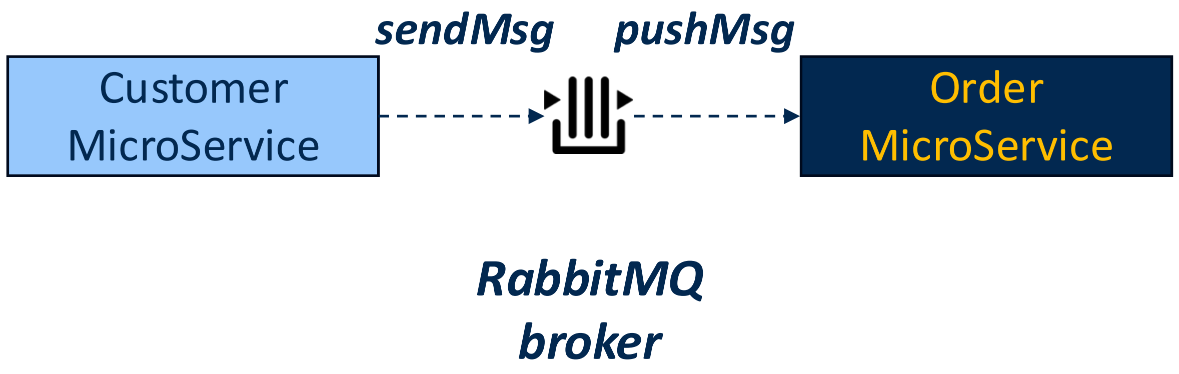
- Keys and values are byte arrays
- Serialization and deserialization is the client’s responsibility
  - For example, using protobuf

Events as immutable facts

- Once an event is written to Kafka, it cannot be modified or deleted
- An event is a fact: "`CustomerUpdated at time T with these details`"
- If something changes, produce a new event: "`CustomerUpdated at time T+1`"
- The log captures the complete history of what happened
- Almost as a database: ***"Data on the outside"***

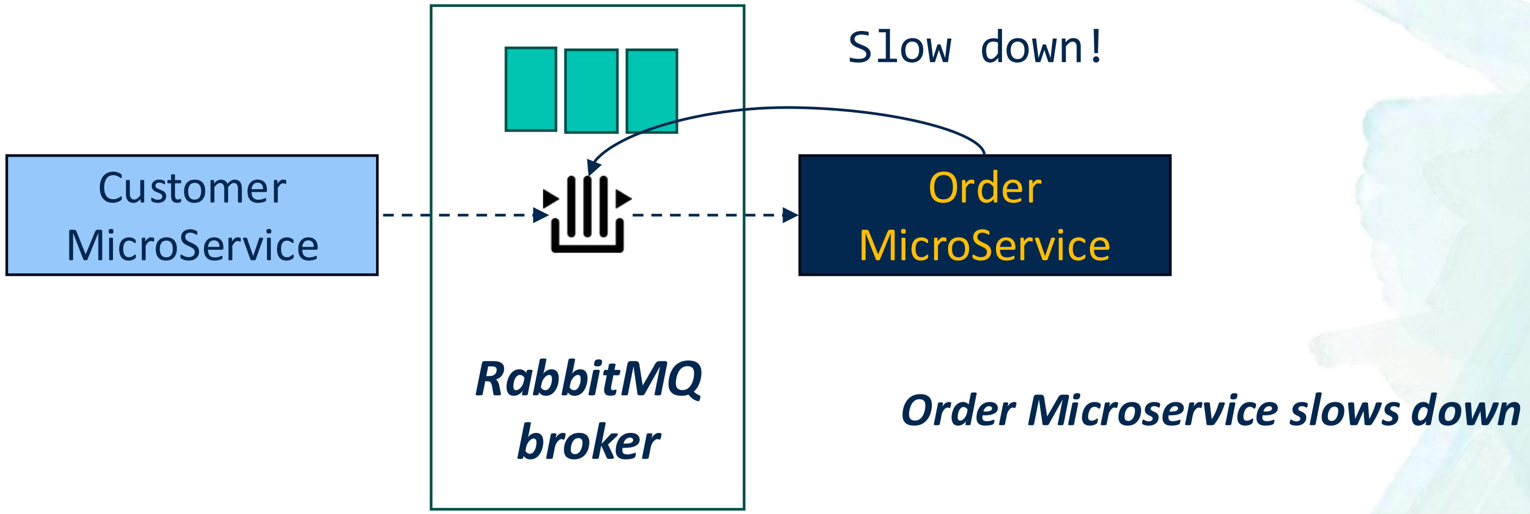
Consumer basics – pull vs. push

- Traditional message brokers (e.g., RabbitMQ): push model
  - Broker actively sends messages to each consumer



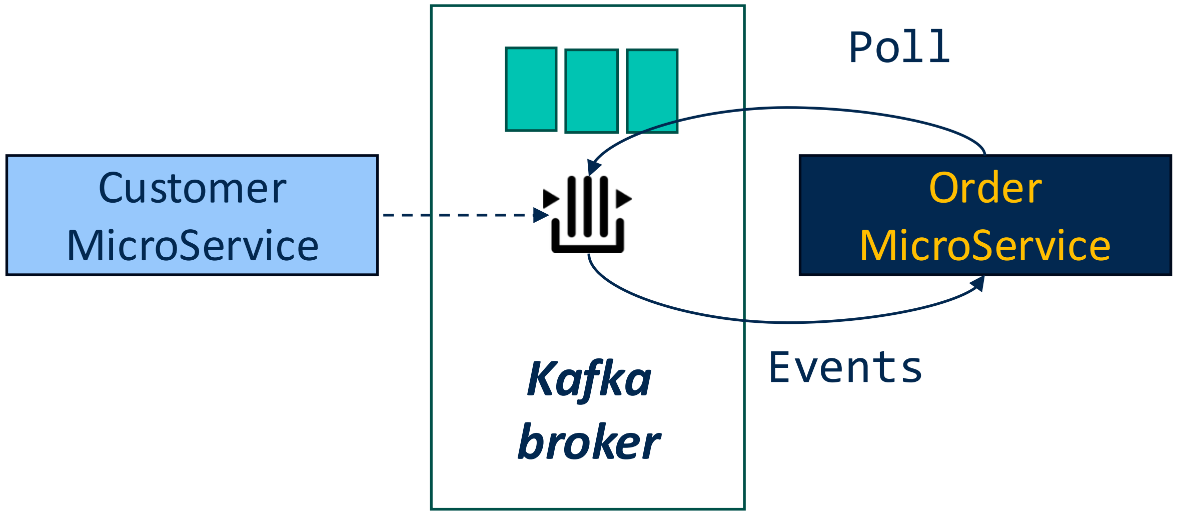
Consumer basics – pull vs. push

- Broker must know consumer speed / capacity
- Slow consumer → broker queues messages or drops them
- Need separate (often complex) backpressure mechanisms
  - Usually done by withholding message acknowledgements



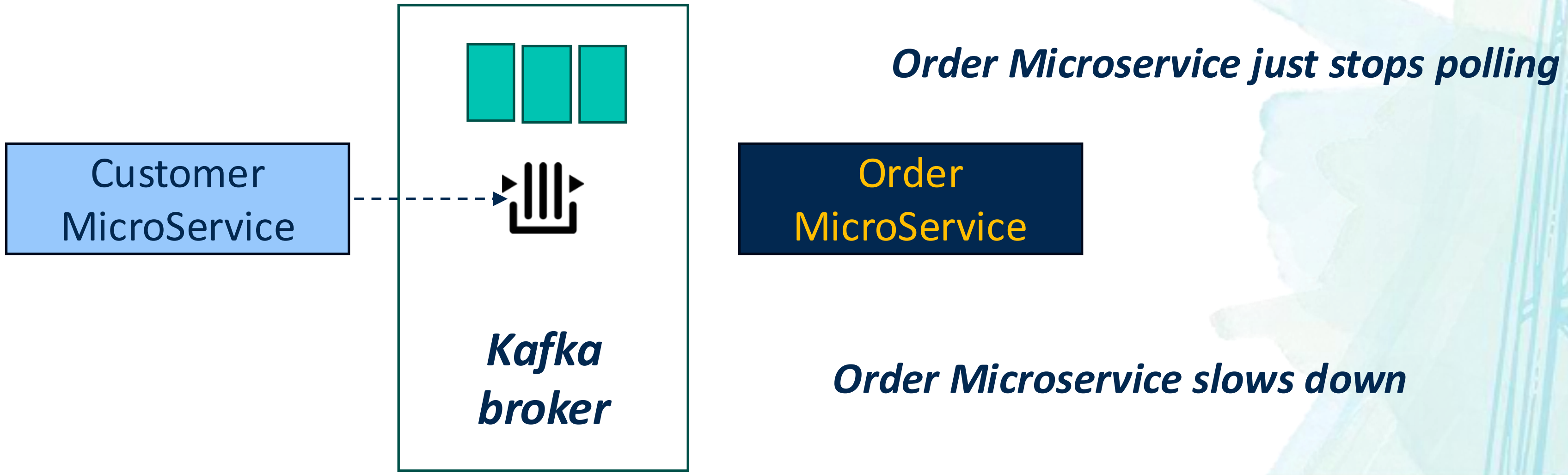
Consumer basics – pull vs. push

- Kafka: pull model — consumer requests messages from broker
- Consumer controls its own read rate and throughput
  - Scales easily
- Consumer-driven: each app controls its own consumption rate



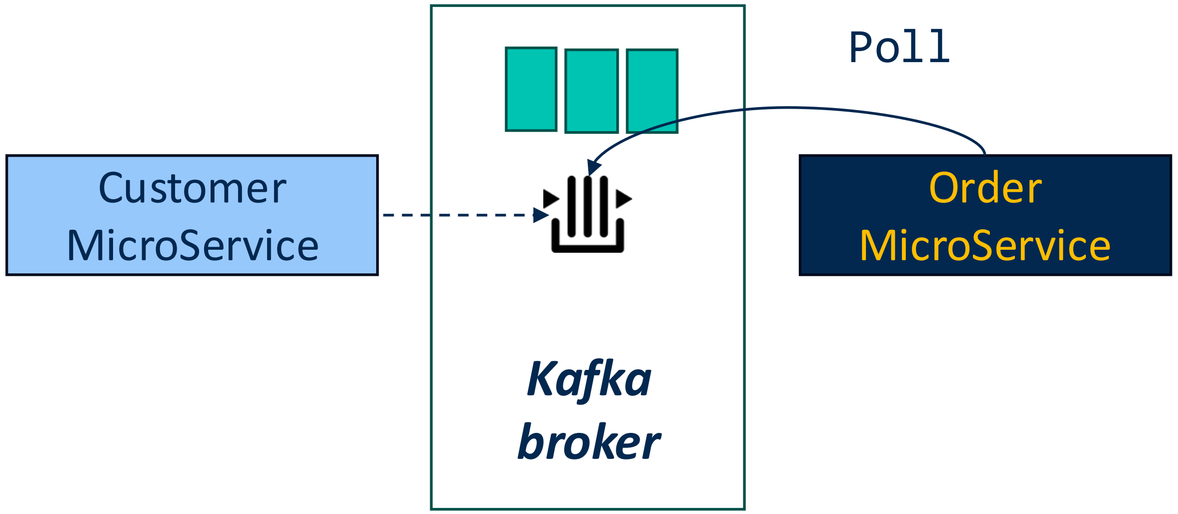
Consumer basics – pull vs. push

- Kafka: pull model — consumer requests messages from broker
- Consumer controls its own read rate and throughput
  - Scales easily
- Consumer-driven: each app controls its own consumption rate


Customer MicroService
Kafka broker
Order MicroService
Order Microservice just stops polling
Order Microservice slows down

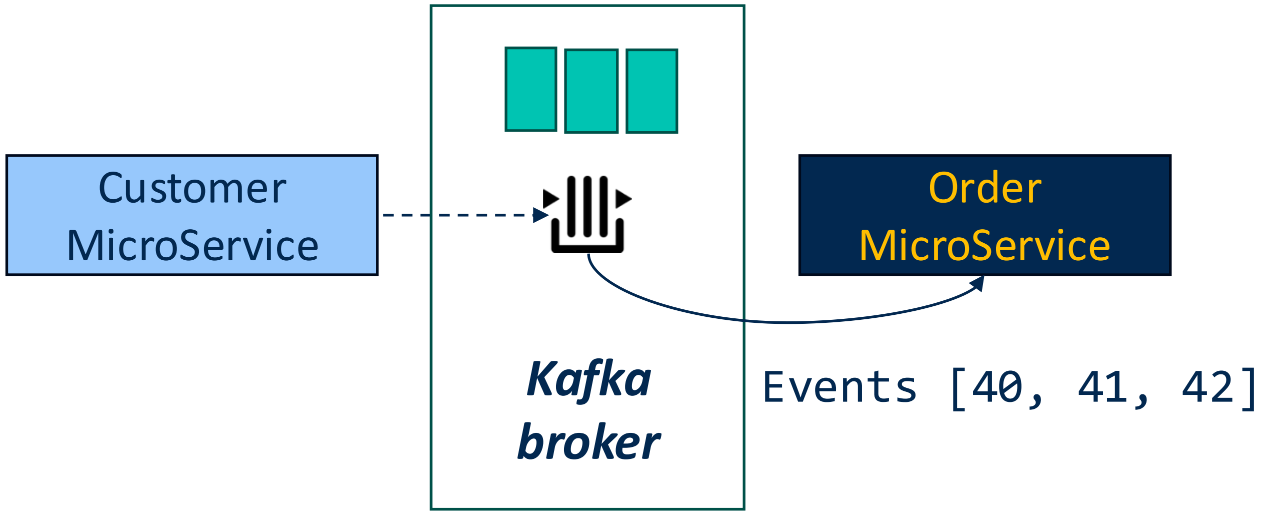
Consumer *committed* state

- Consumer can crash; needs to remember offset read
- Unlike traditional MQs, the consumer must commit the offset up to which it has processed
- Kafka broker will remember the last committed offset



Consumer *committed* state

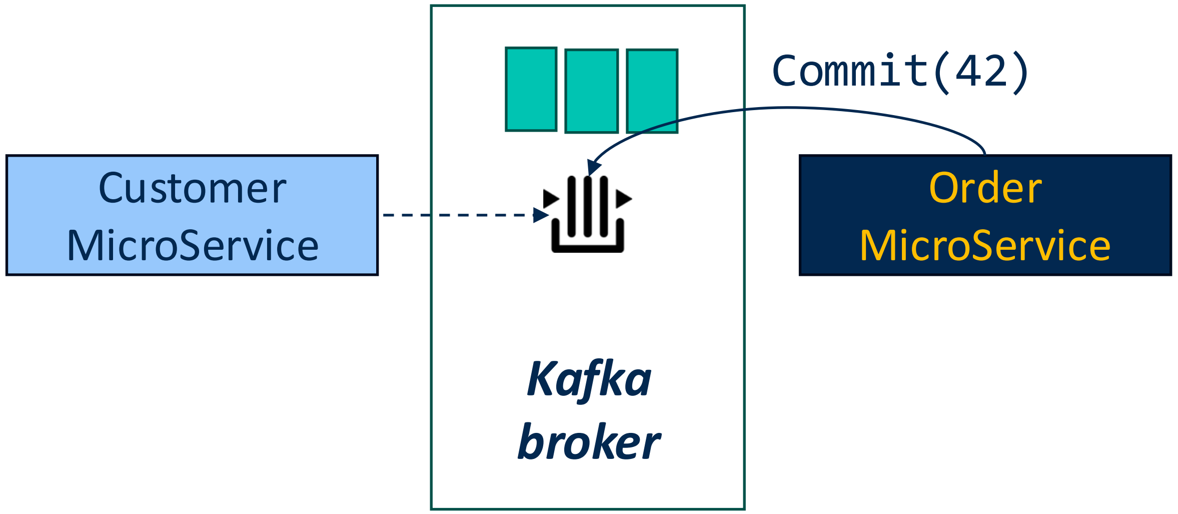
- Consumer can crash; needs to remember offset read
- Unlike traditional MQs, the consumer must commit the offset up to which it has processed
- Kafka broker will save the last committed offset on disk



UCDAVIS

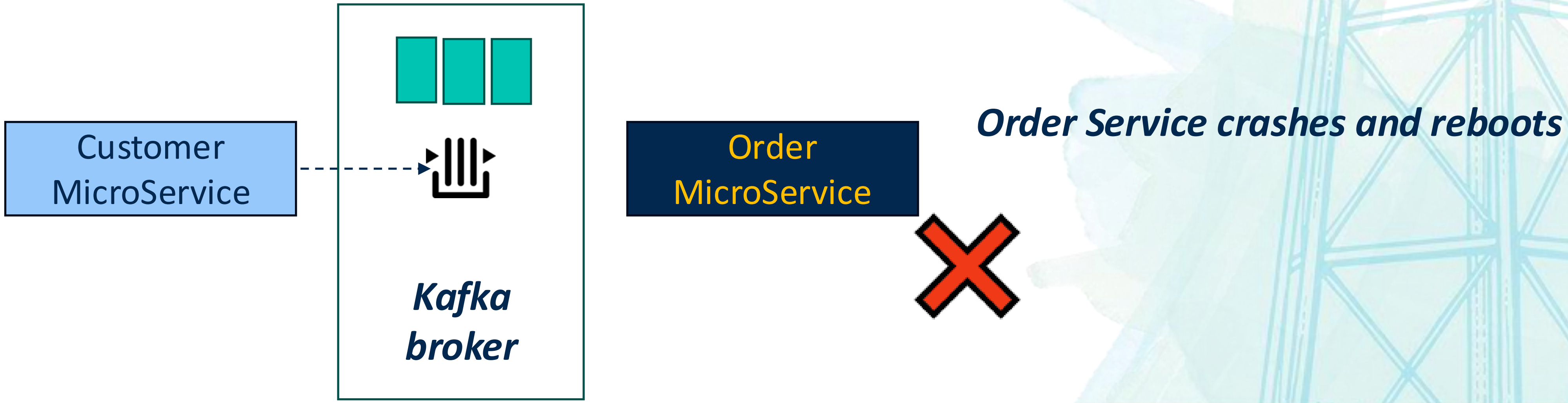
Consumer *committed* state

- Consumer can crash; needs to remember offset read
- Unlike traditional MQs, the consumer must commit the offset up to which it has processed
- Kafka broker will save the last committed offset on disk



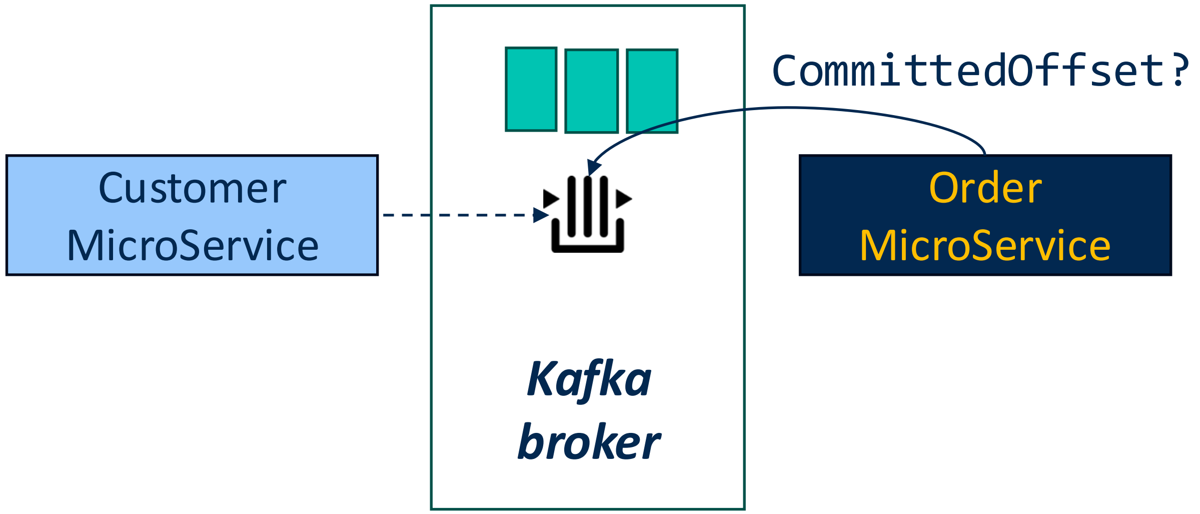
Consumer *committed* state

- Consumer can crash; needs to remember offset read
- Unlike traditional MQs, the consumer must commit the offset up to which it has processed
- Kafka broker will save the last committed offset on disk



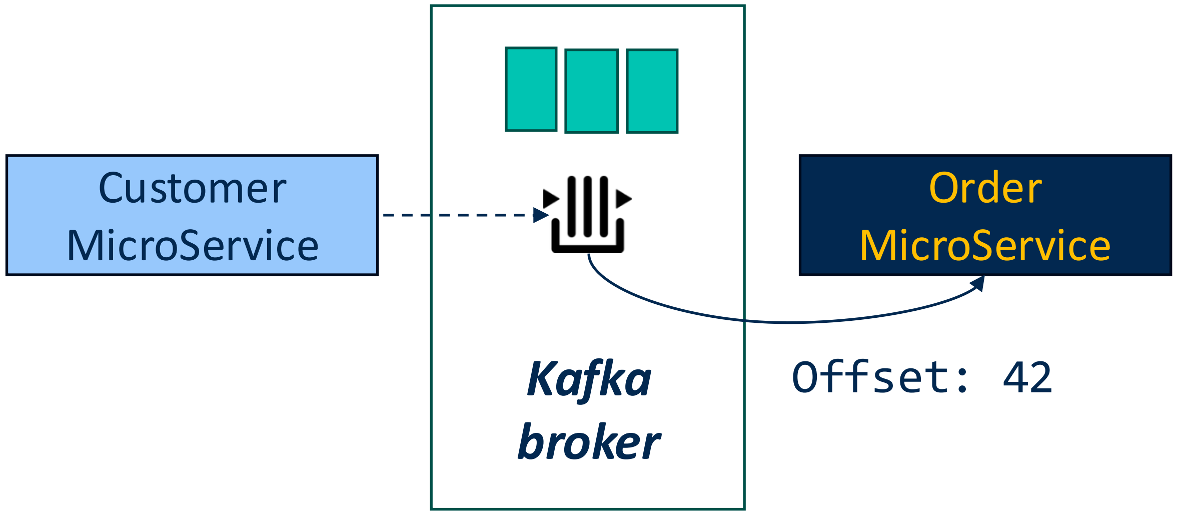
Consumer *committed* state

- Consumer can crash; needs to remember offset read
- Unlike traditional MQs, the consumer must commit the offset up to which it has processed
- Kafka broker will save the last committed offset on disk



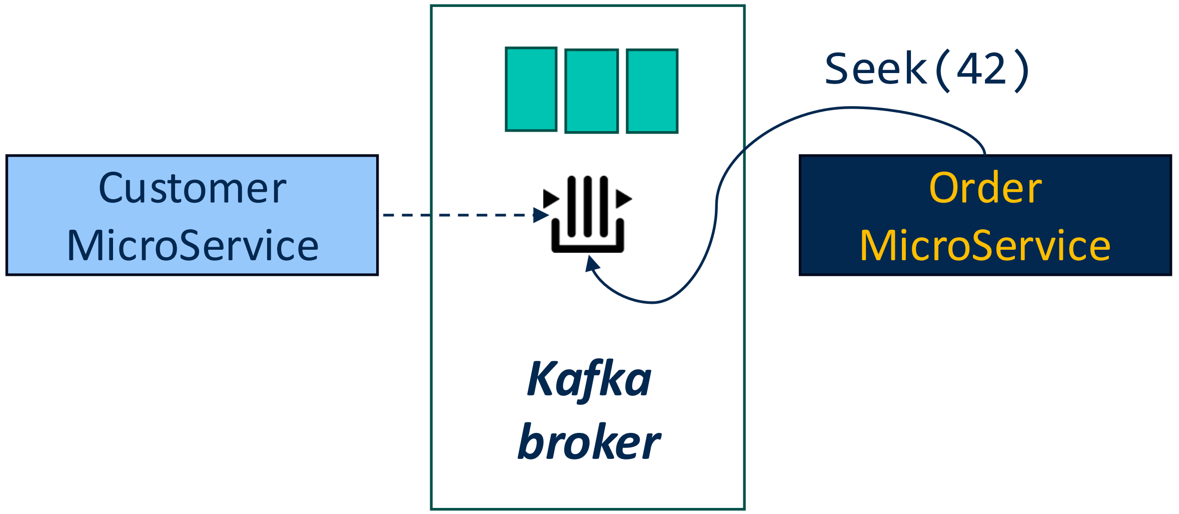
Consumer *committed* state

- Consumer can crash; needs to remember offset read
- Unlike traditional MQs, the consumer must commit the offset up to which it has processed
- Kafka broker will save the last committed offset on disk



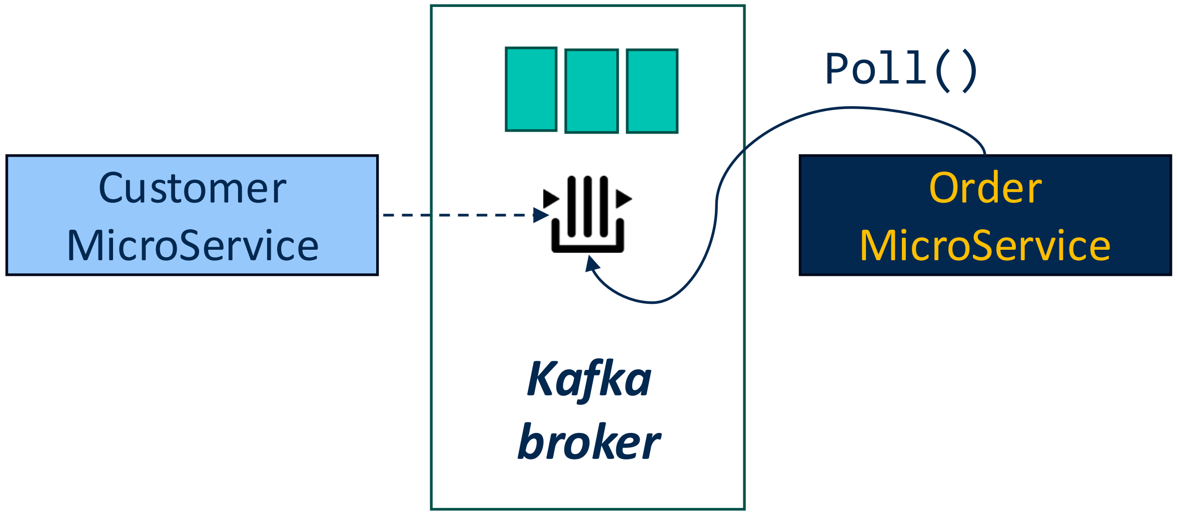
Consumer *committed* state

- Consumer can crash; needs to remember offset read
- Unlike traditional MQs, the consumer must commit the offset up to which it has processed
- Kafka broker will save the last committed offset on disk



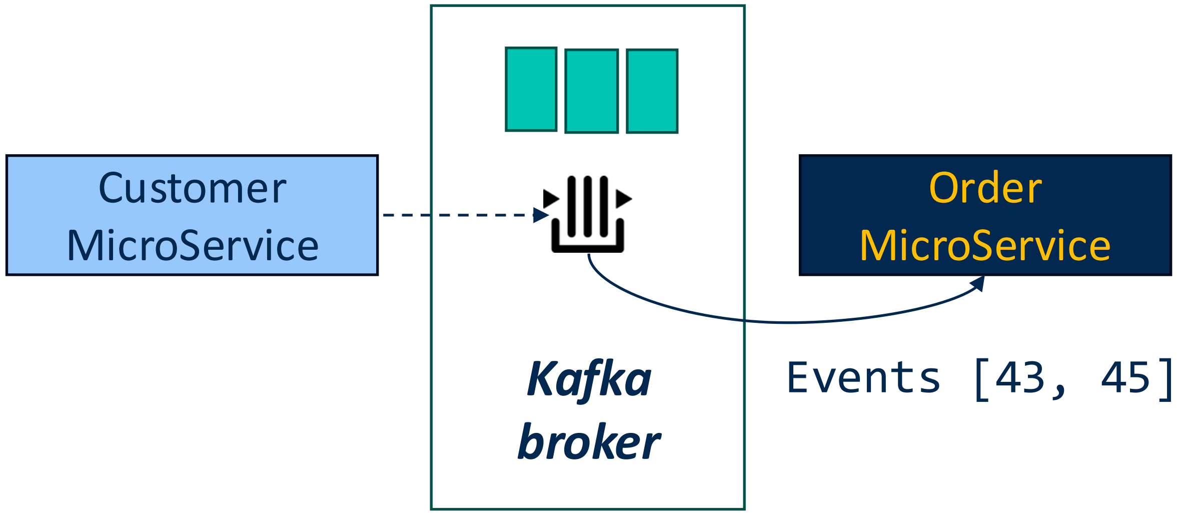
Consumer *committed* state

- Consumer can crash; needs to remember offset read
- Unlike traditional MQs, the consumer must commit the offset up to which it has processed
- Kafka broker will save the last committed offset on disk



Consumer *committed* state

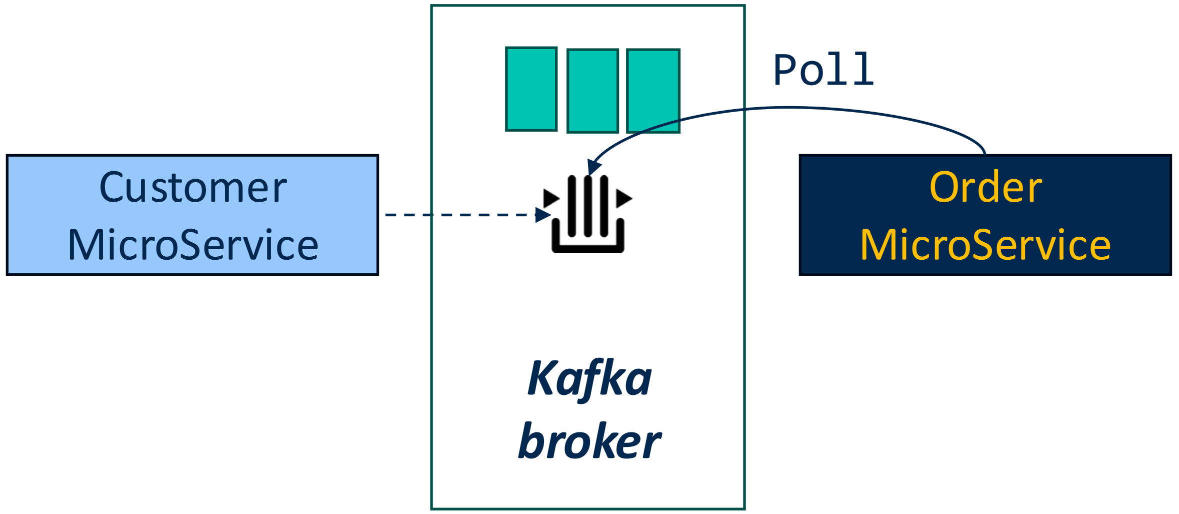
- Consumer can crash; needs to remember offset read
- Unlike traditional MQs, the consumer must commit the offset up to which it has processed
- Kafka broker will save the last committed offset on disk



UCDAVIS

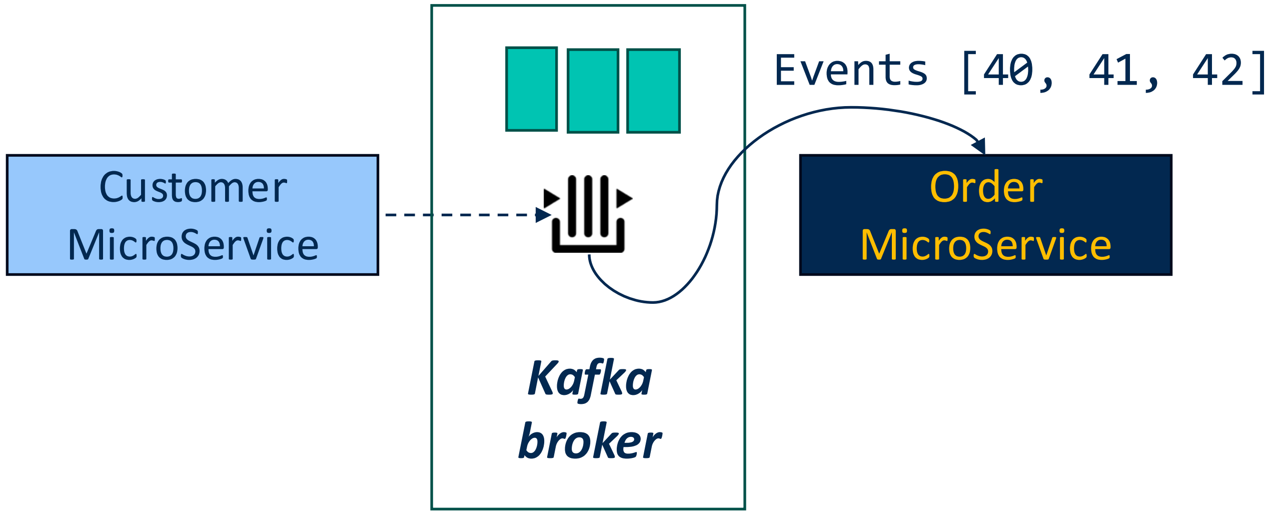
At-most once vs. at-least once delivery guarantees

- ***When*** the consumer commits determines delivery semantics
- Before processing -> **at-most-once** delivery guarantees



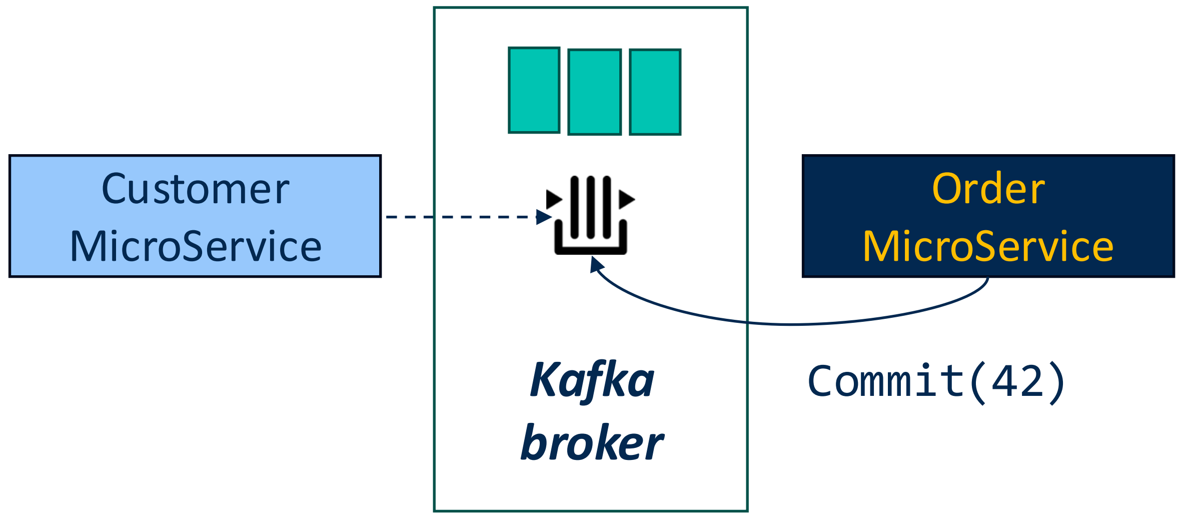
At-most once vs. at-least once delivery guarantees

- ***When*** the consumer commits determines delivery semantics
- Before processing -> **at-most-once** delivery guarantees



At-most once vs. at-least once delivery guarantees

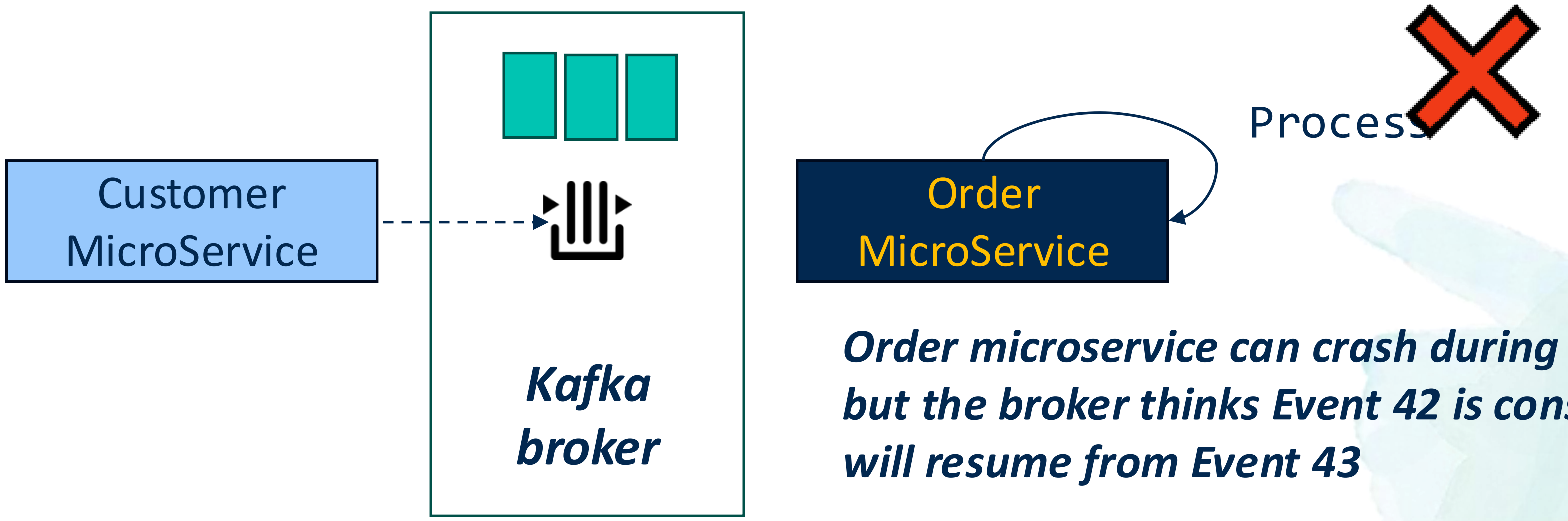
- ***When*** the consumer commits determines delivery semantics
- Before processing -> **at-most-once** delivery guarantees



UCDAVIS

At-most once vs. at-least once delivery guarantees

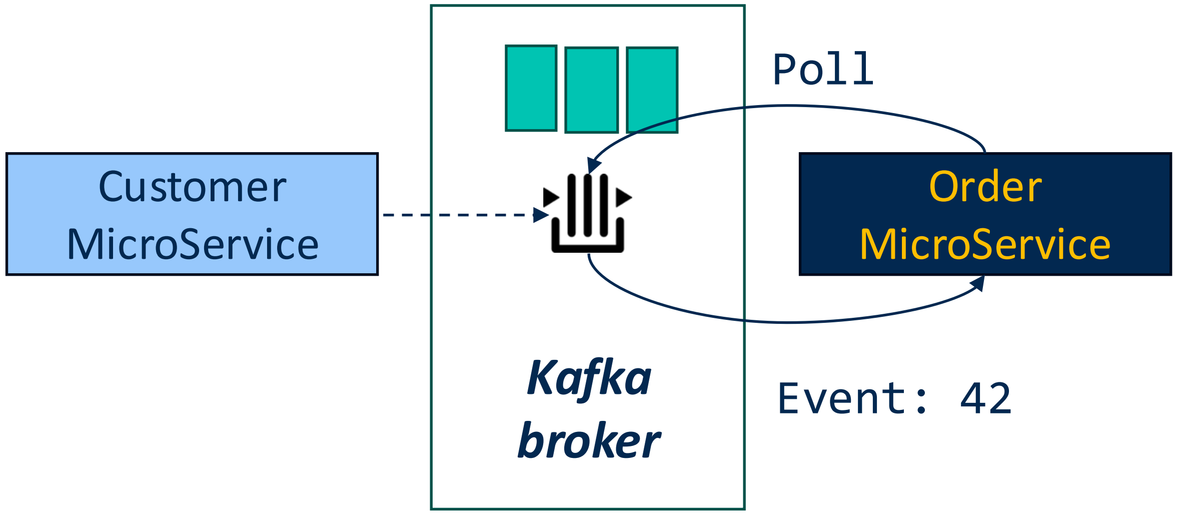
- ***When*** the consumer commits determines delivery semantics
- Before processing -> **at-most-once** delivery guarantees



Order microservice can crash during processing; but the broker thinks Event 42 is consumed and will resume from Event 43

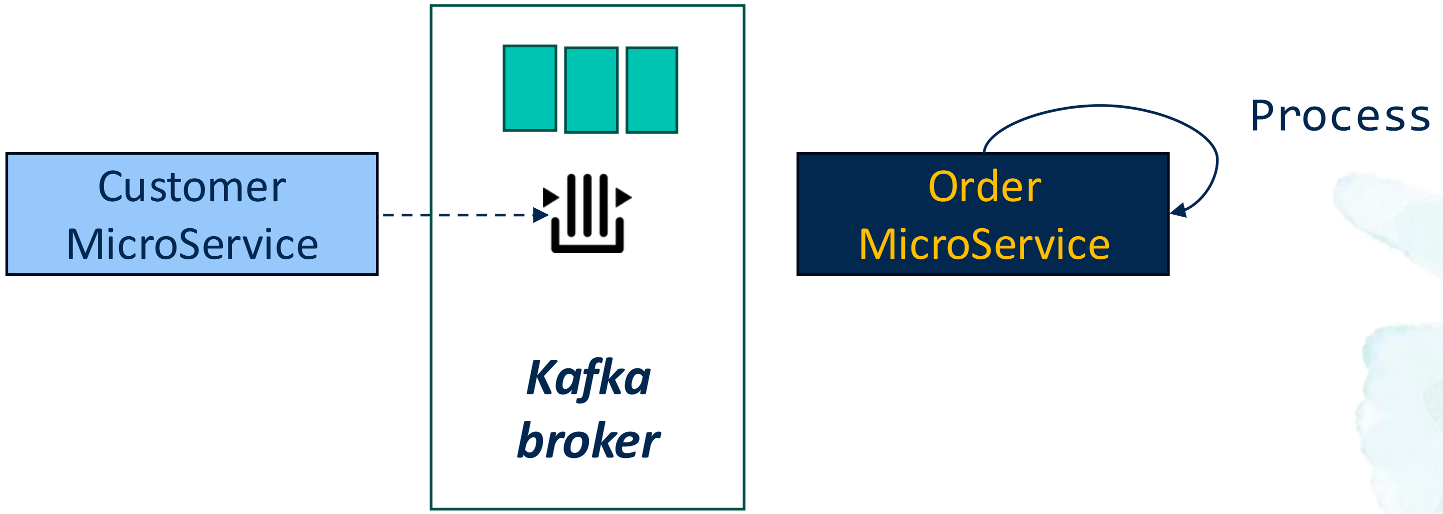
At-most once vs. at-least once delivery guarantees

- ***When*** the consumer commits determines delivery semantics
- After processing -> **at-least-once** delivery guarantees



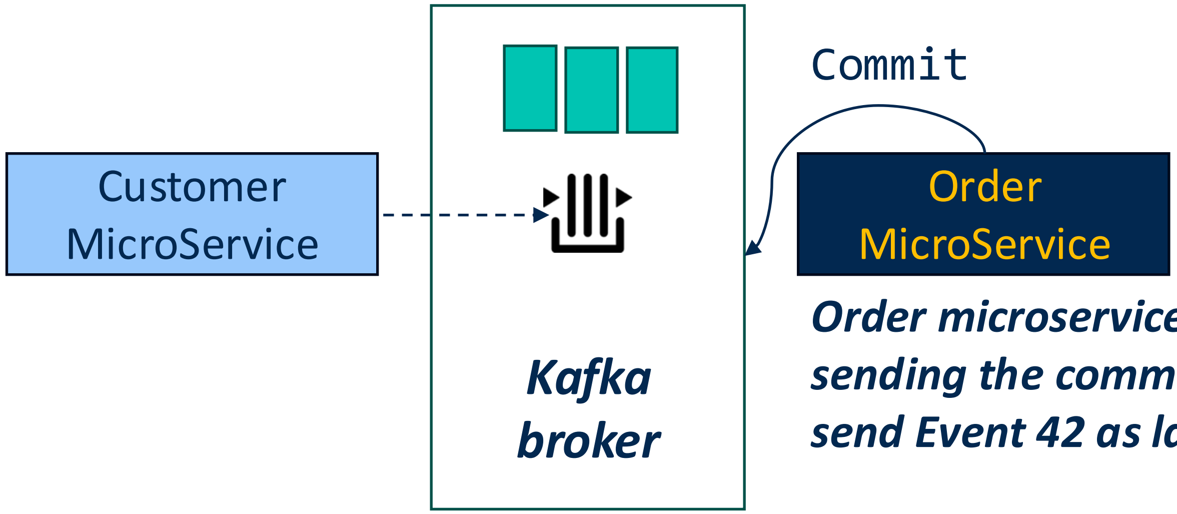
At-most once vs. at-least once delivery guarantees

- ***When*** the consumer commits determines delivery semantics
- After processing -> **at-least-once** delivery guarantees



At-most once vs. at-least once delivery guarantees

- ***When*** the consumer commits determines delivery semantics
- After processing -> **at-least-once** delivery guarantees



Order microservice can crash AFTER processing; but BEFORE sending the commit message. This will lead the broker to send Event 42 as last committed event

UCDAVIS

At-most once vs. at-least once delivery guarantees

- Selecting the correct delivery guarantees is use-case specific
- At-most vs at-least delivery guarantees assumes client is relying solely on the broker to maintain its state
  - Consumer can maintain state locally to augment broker state maintenance
- Ideally processing should be idempotent
  - E.g.: `setBankBalance(1000)` instead of `incrementBankBalanceBy(100)`

UCDAVIS

Kafka Architecture

A systems perspective

UCDAVIS

Kafka is a distributed log

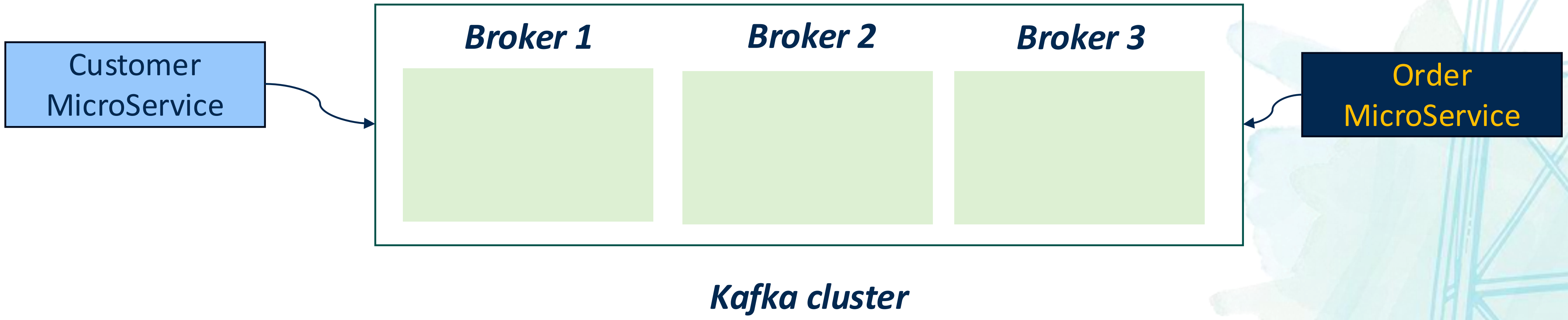
- Kafka is an append-only, ordered, immutable log
- Every event is appended to the end of a log
- Events are never modified or deleted (within the retention period)
- Note: unlike SSTables and LSM trees, consumers can only read sequentially

The scalability problem

- A single log on a single machine has limited throughput
- What if a topic receives millions of events per second?
- A single machine's disk I/O and network bandwidth become bottlenecks
- Solution: split the topic's log across machines

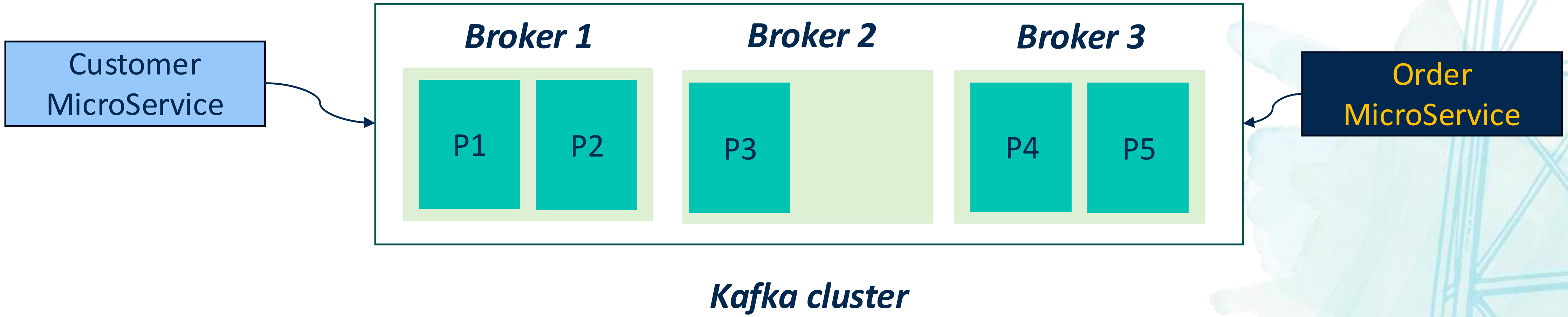
Scaling Kafka

- Kafka usually consists of a cluster of brokers
- Each broker is a single node or machine



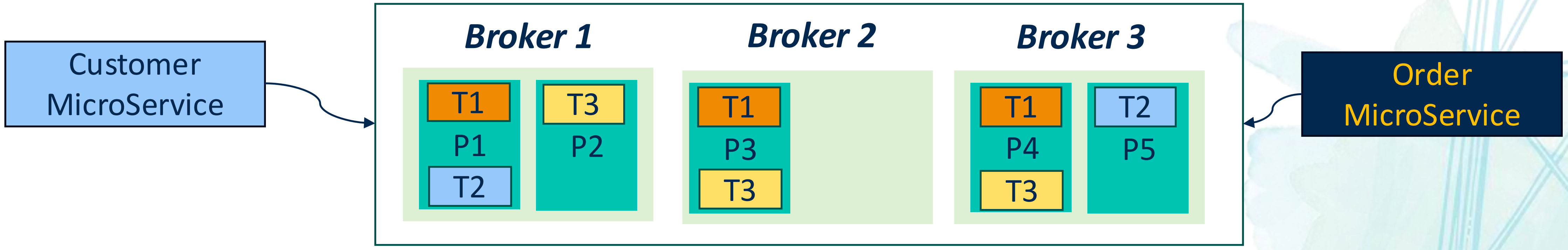
Scaling Kafka

- The logical "log" is divided into physical partitions
- A partition is a single, ordered, immutable log
- Each partition lives on a single broker



Scaling Kafka

- Each topic is divided into one or more partitions
- A topic *can* live in many partitions on the same broker, but that limits concurrency – ideally a topic is distributed among partitions on different brokers



Kafka cluster

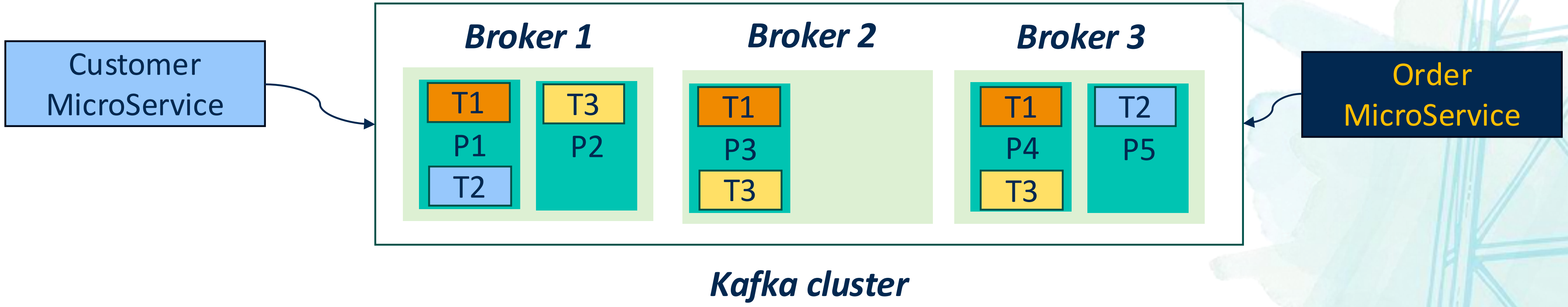
Ordering within partitions

- Ordering is guaranteed within a partition, NOT across partitions
  - Events in partition 0 are ordered among themselves
  - Events in partition 1 are ordered among themselves
  - No ordering guarantee between partition 0 and partition 1
- Key trade-off: more partitions = more throughput but weaker global ordering

Message to partition mapping

Each topic has event records under it

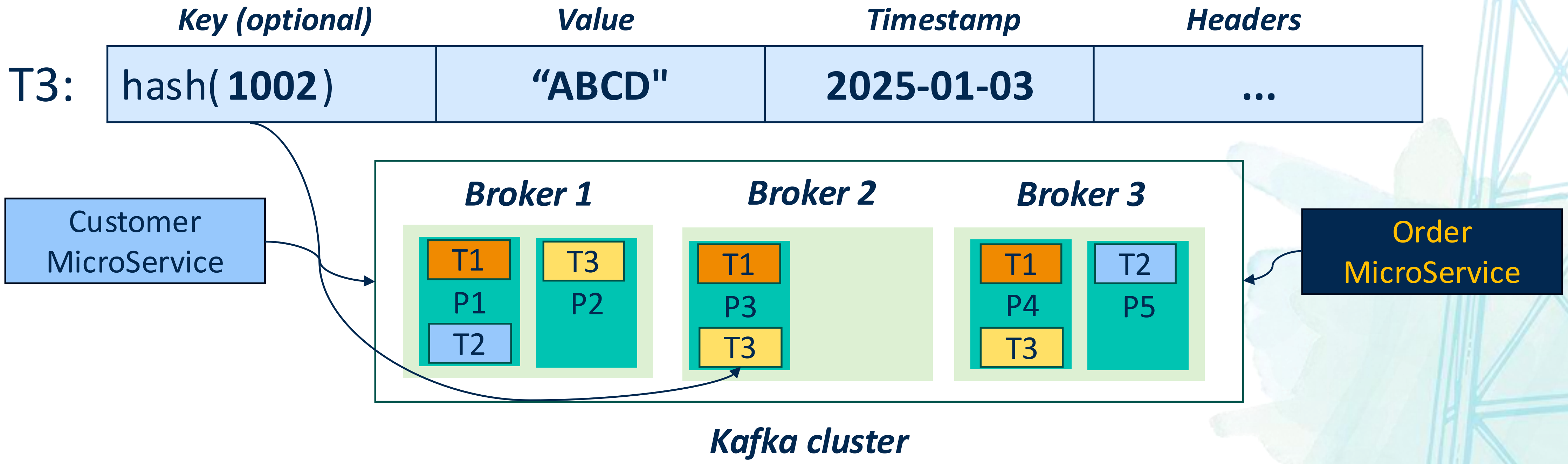
	Key (optional)	*Value*	*Timestamp*	*Headers*
T3:	**1002**	**“ABCD"**	**2025-01-03**	**...**



Question: which partition should the event record be stored?

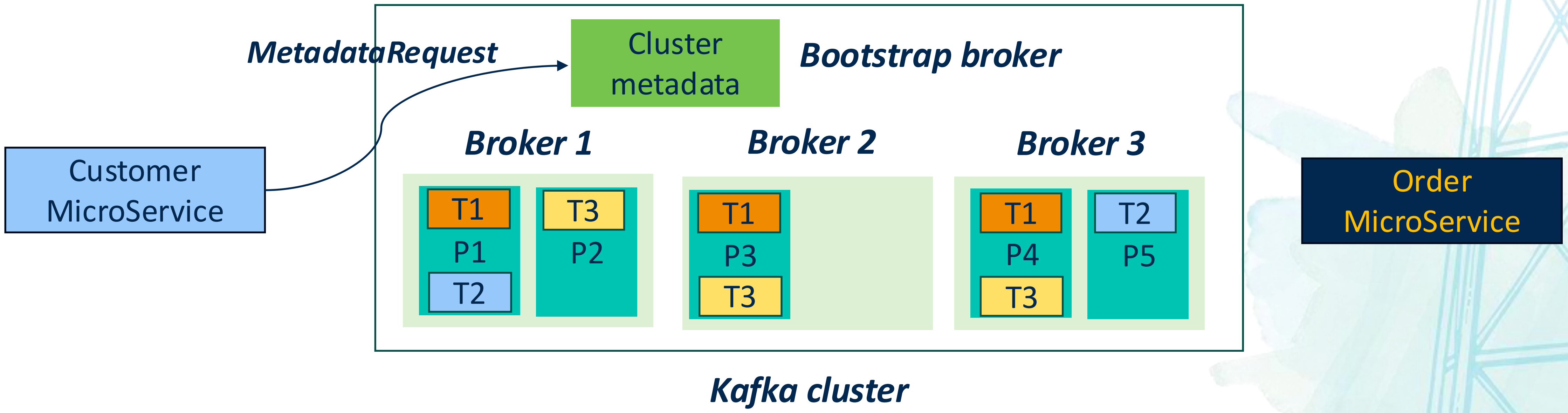
Message to partition mapping

- partition = hash(key) % num_partitions
- no key → round-robin partitions



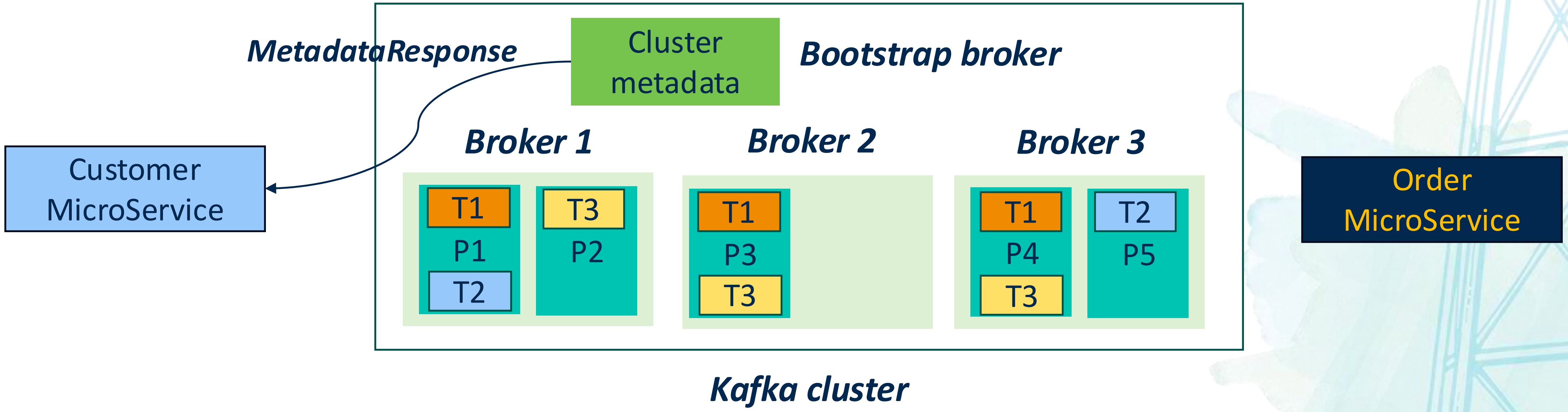
Bootstrap broker

- Kafka clients connect to ”bootstrap broker” to know the partitions for a topic



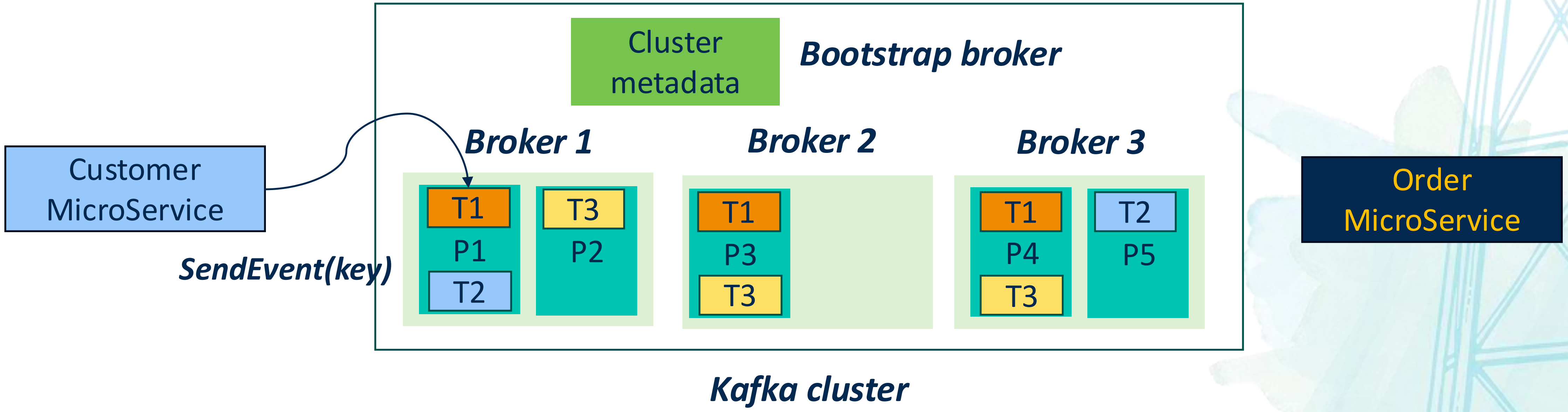
Bootstrap broker

- Kafka clients connect to ”bootstrap broker” to know the partitions for a topic



Bootstrap broker

- Kafka clients connect to ”bootstrap broker” to know the partitions for a topic
- Can compute the partition for a particular key using `hash(key) % num_partitions`



UCDAVIS

Implications of key-based partitioning

- All events with the same key land in the same partition
- Guarantees ordering for events with the same key
- For example, the “key” can be the customer ID, ensuring all events for a particular customer goes to the same partition and are ordered
- Incorrect partitioning schemes can also result in imbalanced clusters
    - Reduces throughput
- Conclusion: need to design partitioning correctly

Kafka architecture summary

- Kafka cluster consists of multiple brokers (servers)
  - Each broker hosts some partitions of various topics
- Producers send events to specific topic-partitions
- Consumers read events from specific topic-partitions
- A metadata system coordinates the cluster
- ***Remaining challenge:*** what happens if a broker fails?

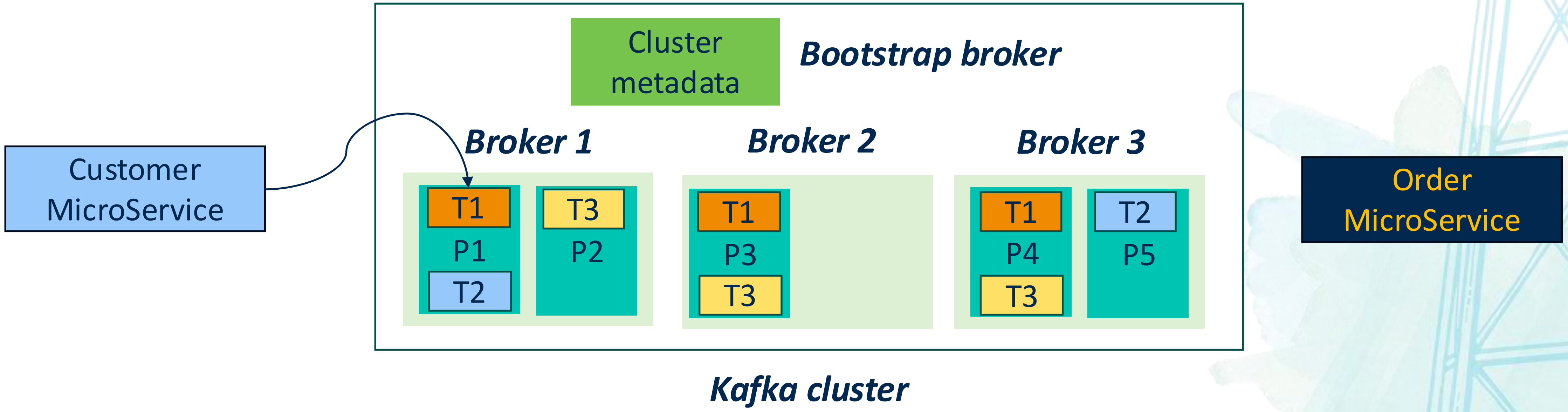
Replication

- A single copy of data on one broker is a single point of failure
- If that broker's disk fails, the data is lost
- Replication: keep multiple copies on different brokers
- Configured per topic with the replication factor (e.g., 3)
  - Replication-factor = 3 means 3 copies for each partition
  - Cluster can tolerate (replication-factor - 1) broker failures

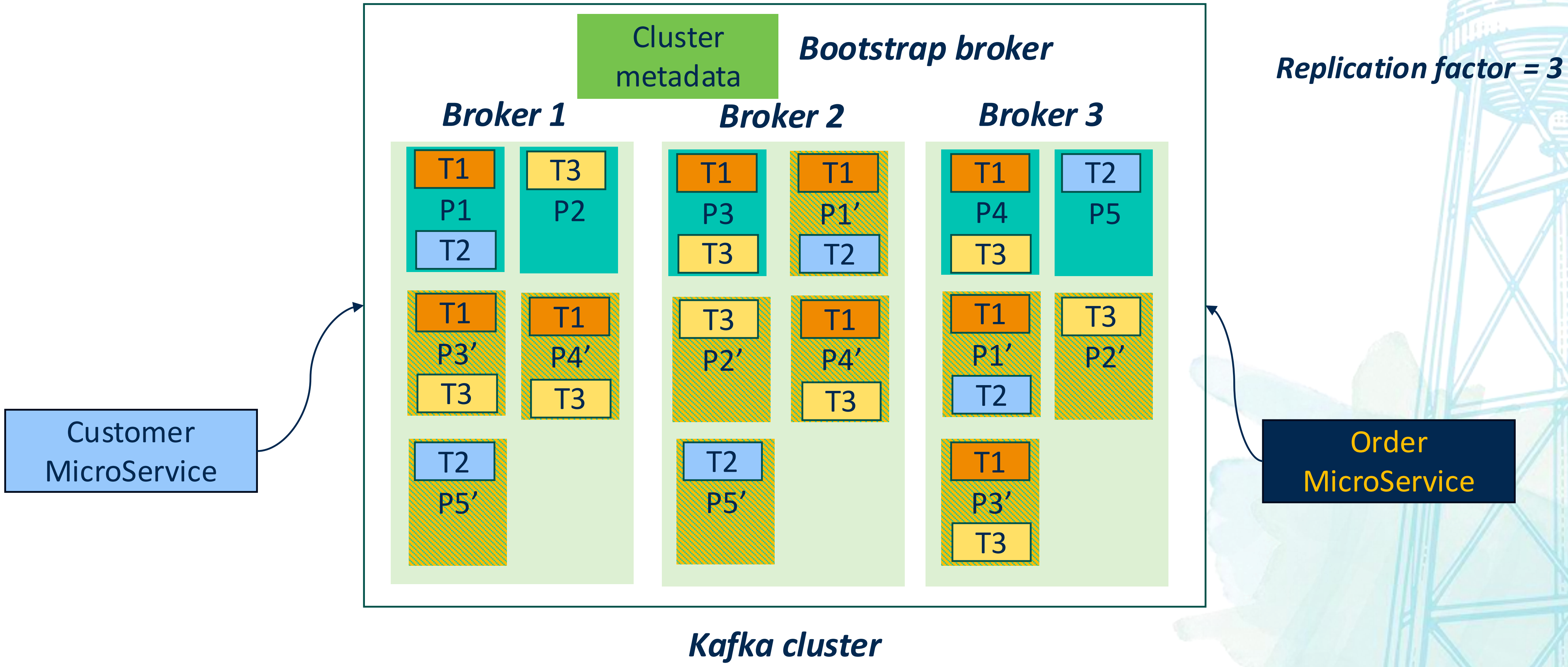
Leader and in-sync replicas

- One replica is the leader, the others are followers
- Followers don’t serve any requests; only aim to stay in-sync with leader
- Replicas which are in sync are called in-sync replicas (ISR)
- **Important:** replicas are passive; do not serve any requests (unless they become leaders due to leader failure)

Kafka architecture (only leader partitions)



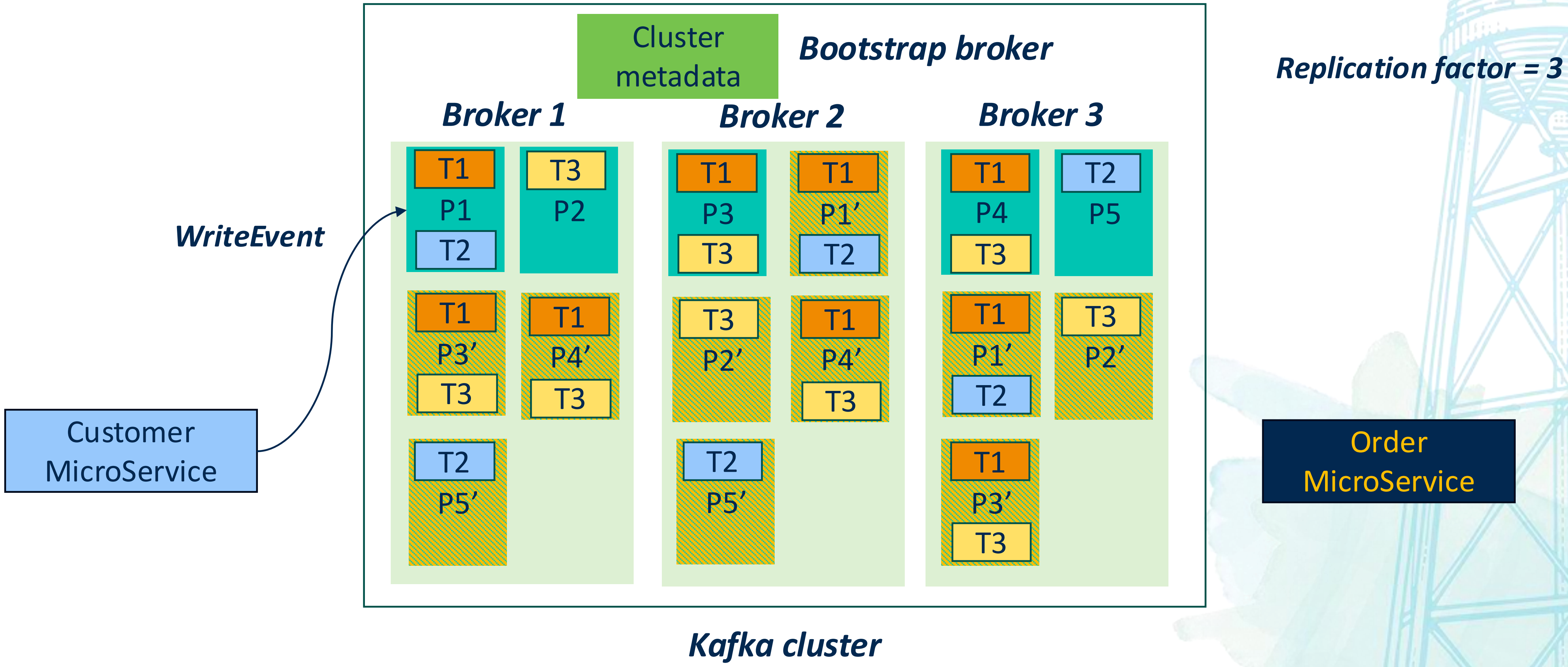
Kafka full architecture



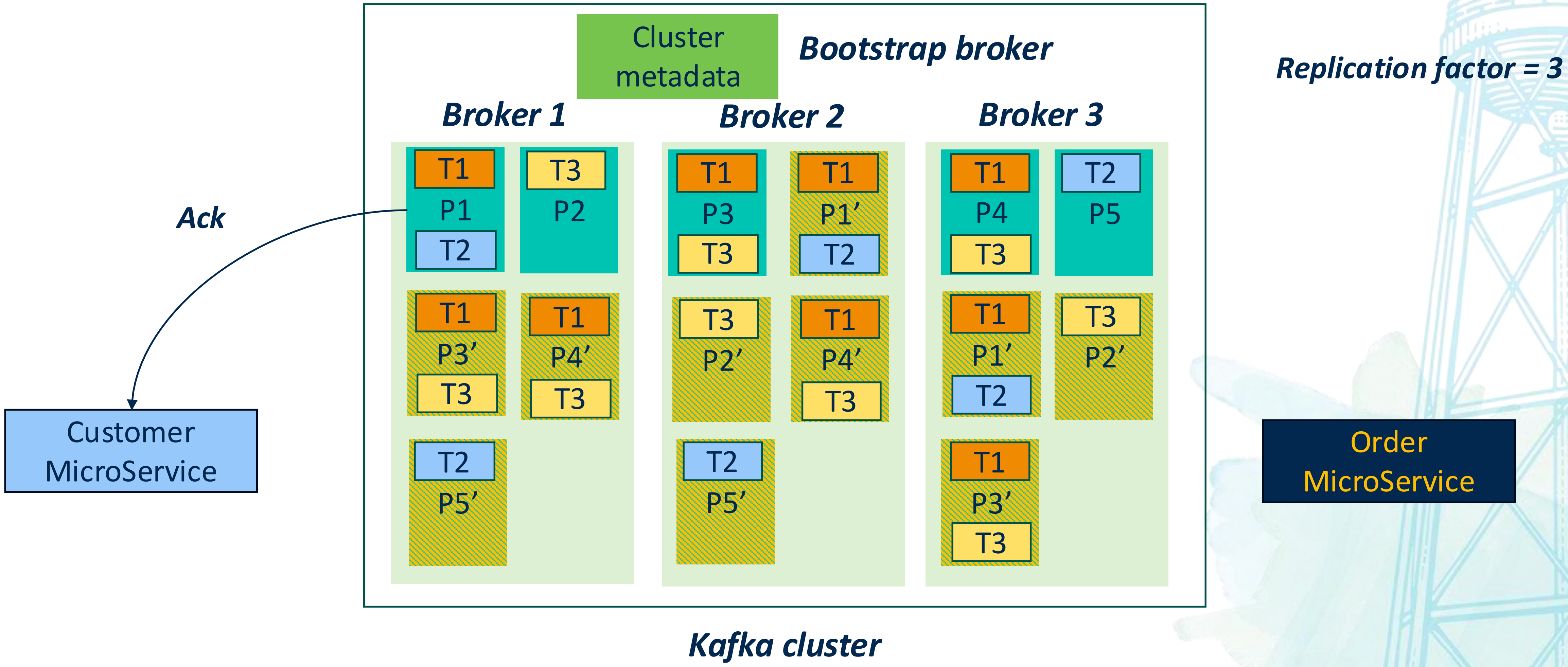
Write path with replication

- Producer creates events and writes to partition leader
- Kafka broker (partition leader) acks the event
- Acknowledgement modes
  - acks = 0: Producer does not wait for an ack
  - acks = 1: Leader writes the record and sends ack; producer waits for ack
  - acks = all: Leader writes the record, waits for replicas to replicate the record, then sends the ack; producer waits for the ack
- Tradeoff: durability vs. latency

Write path with replication for acks = 1

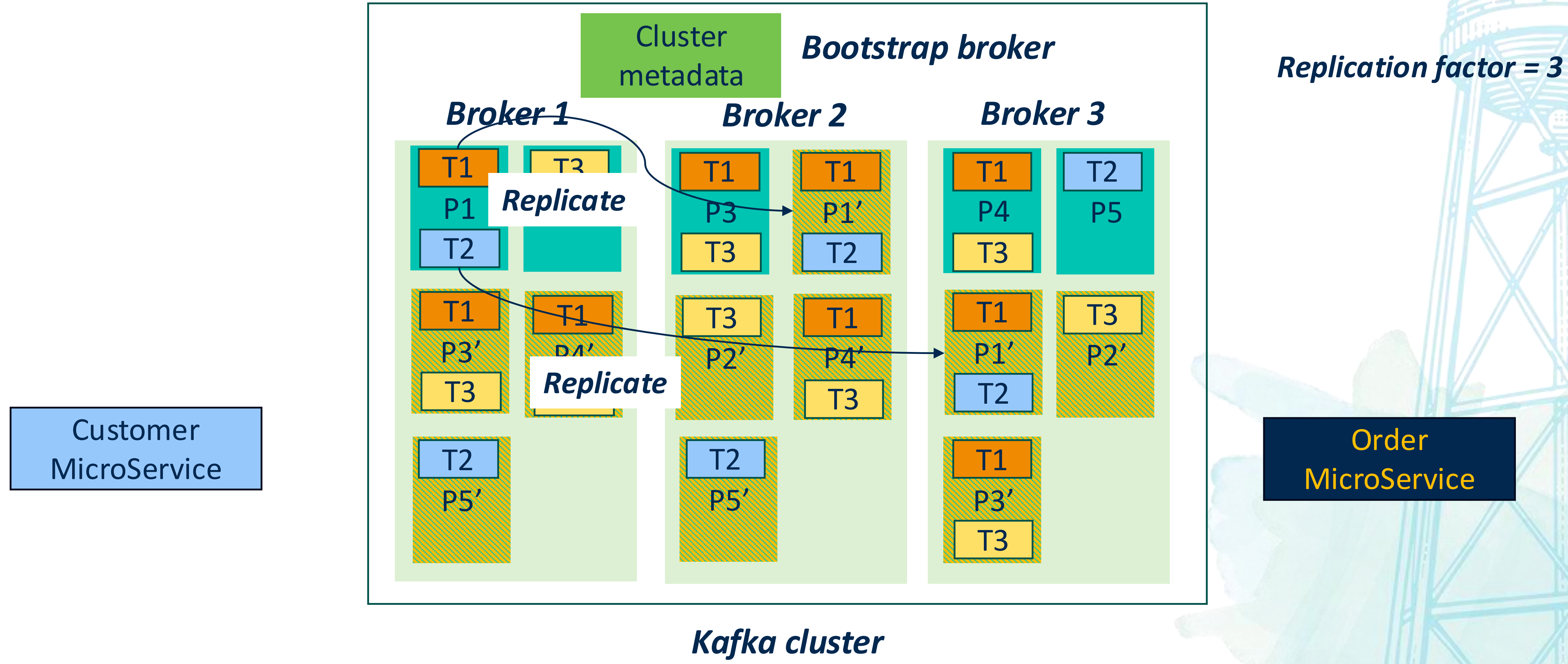


Write path with replication for acks = 1



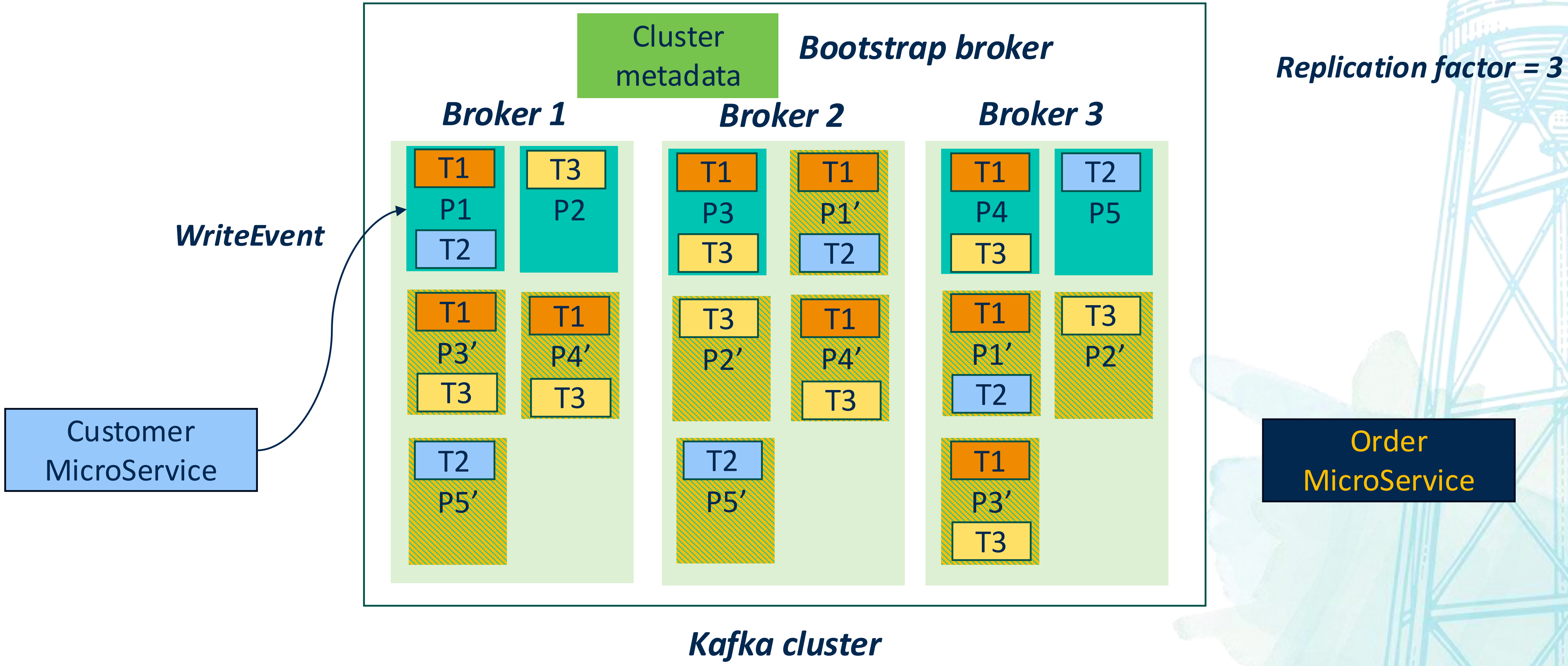
UCDAVIS

Write path with replication for acks = 1

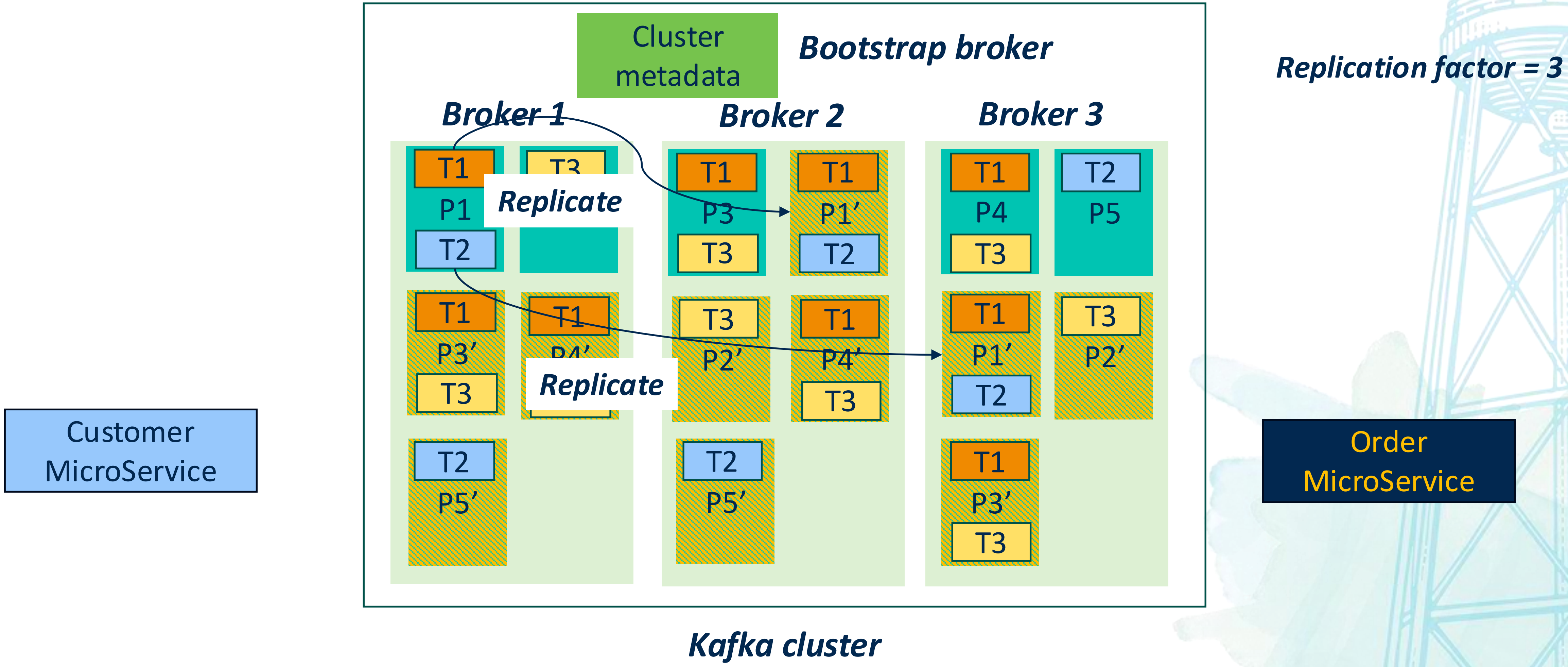


UCDAVIS

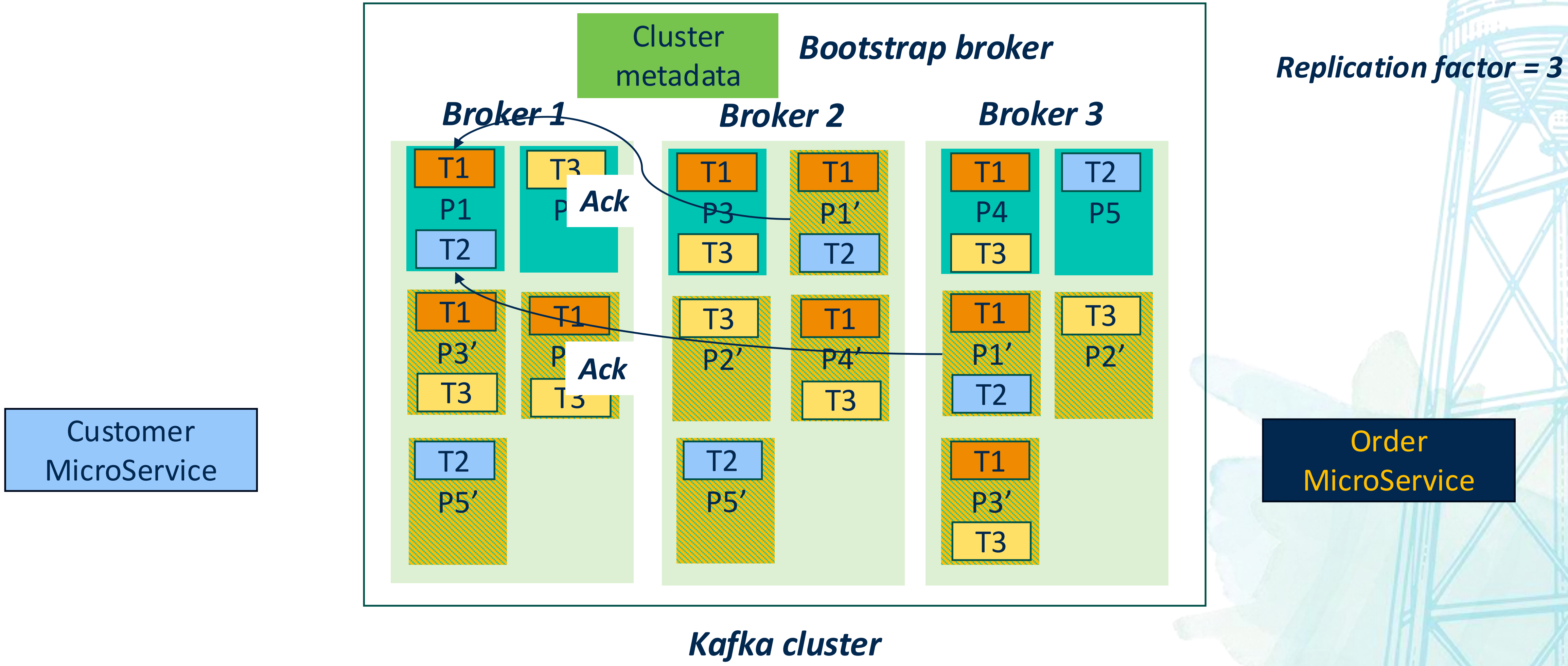
Write path with replication for acks = all



Write path with replication for acks = all

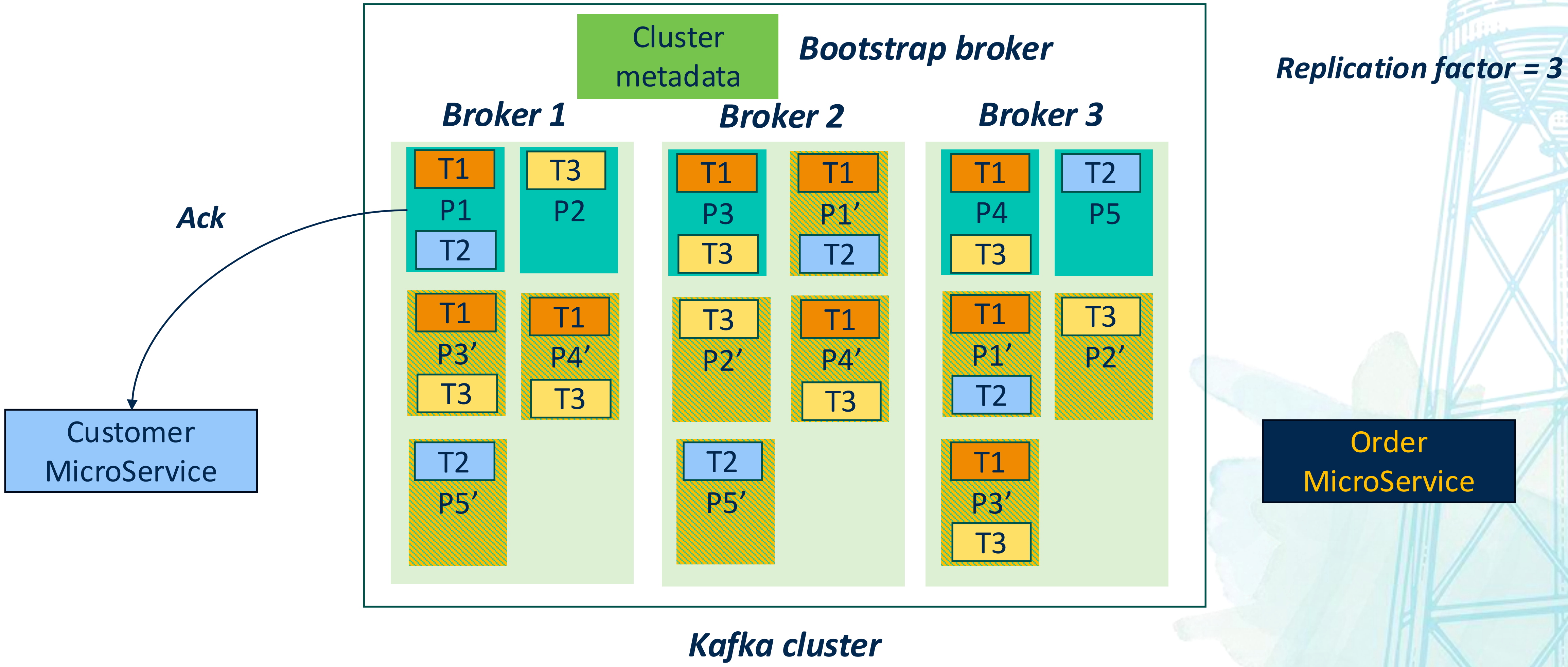


Write path with replication for acks = all

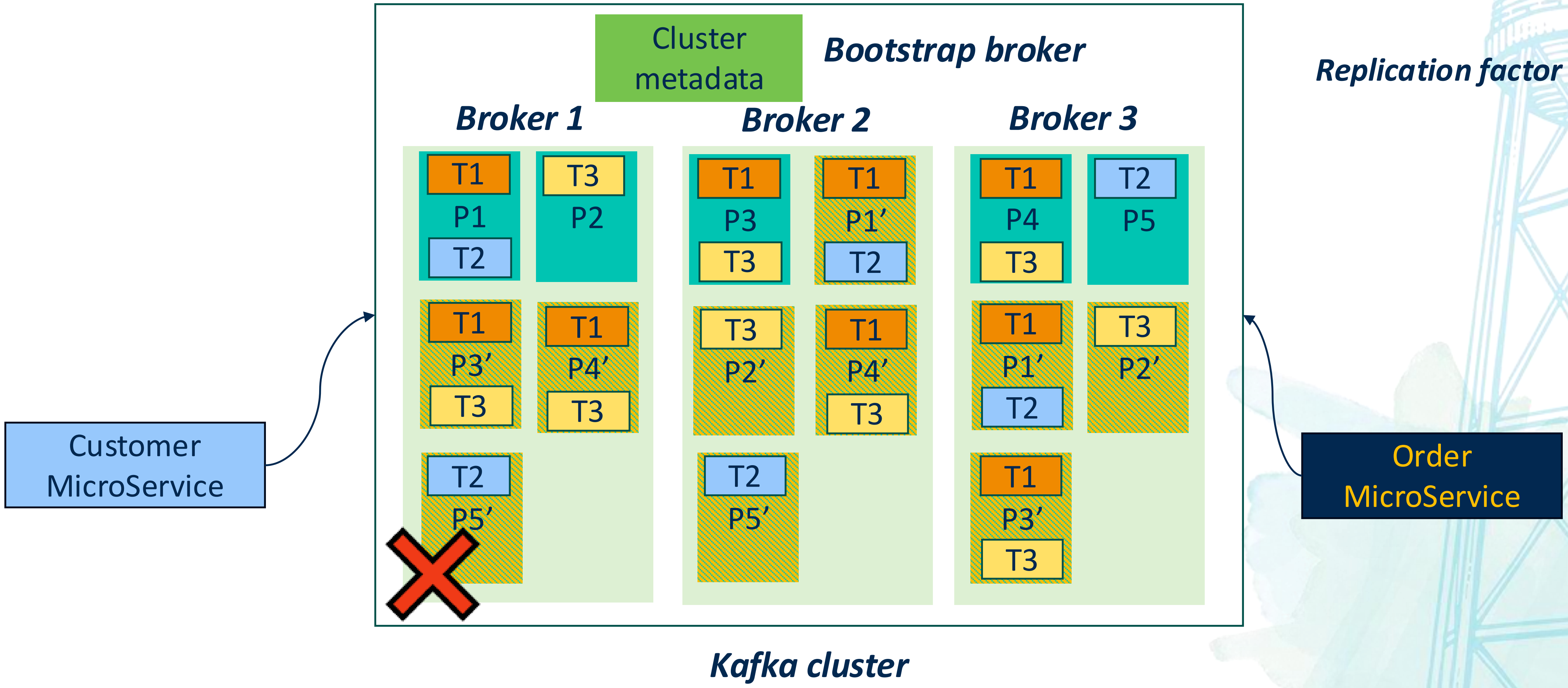


UCDAVIS

Write path with replication for acks = all

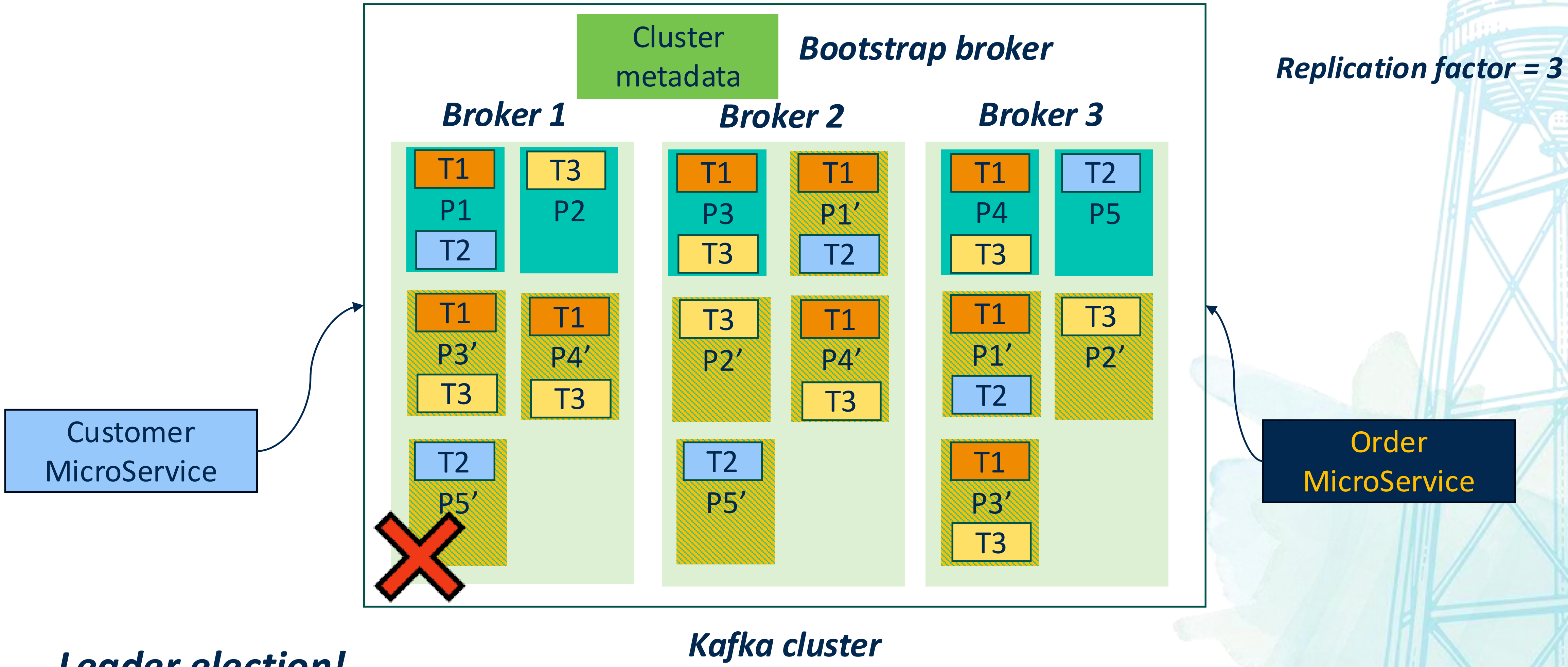


Leader failure and election



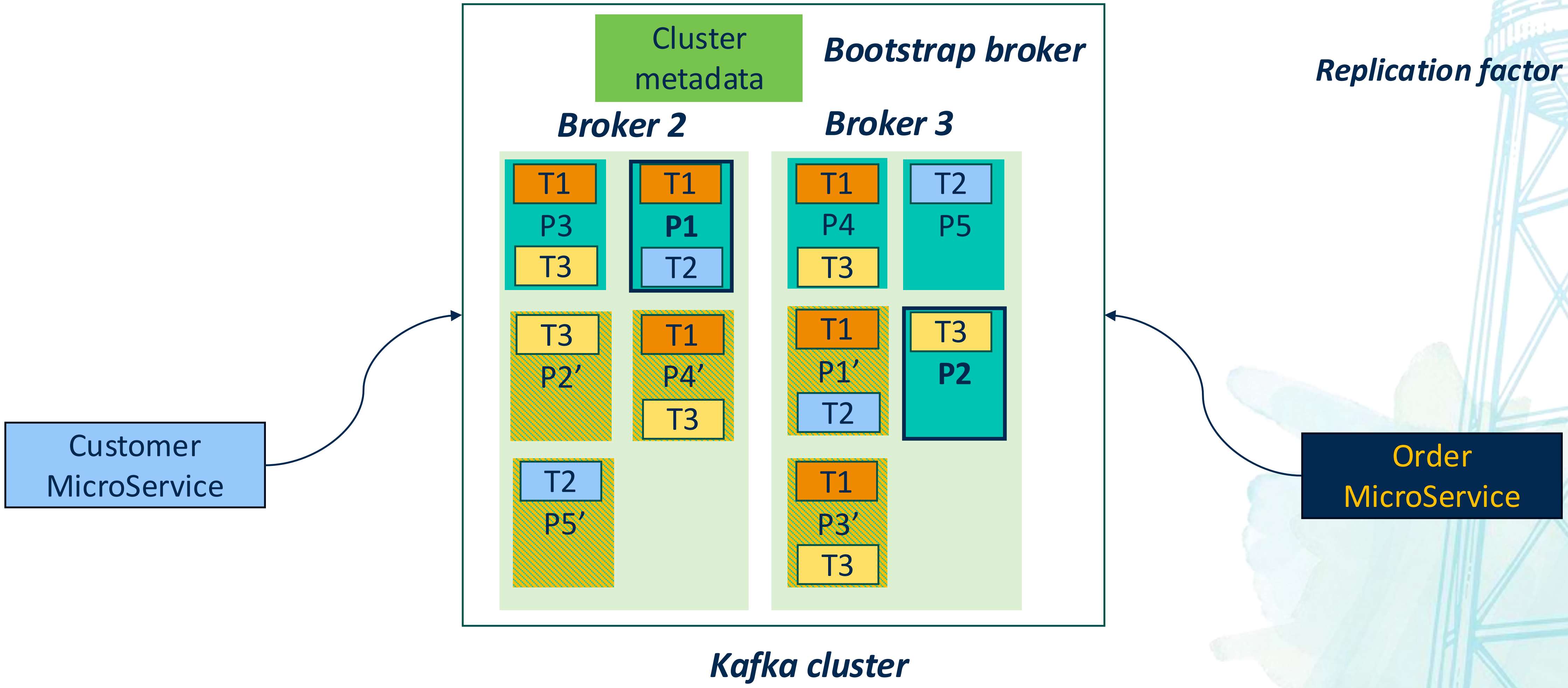
UCDAVIS

Leader failure and election



Leader election!

Leader failure and election



Replication factor = 3

Metadata coordination

- Cluster must maintain metadata
  - Which broker is the leader of which partition
  - Which replicas are in-sync
  - Which brokers are alive
- Metadata changes continuously
  - Leader elections, broker failures, topic creation/deletion

Metadata coordination

- All nodes must agree on the same view
- Cluster metadata requires strong consistency — Kafka handles this internally with KRaft
- Raft and Paxos-family algorithms are consensus protocols used to ensure consistency in a distributed system (beyond the scope of this class)

Kafka summary

- Events are immutable facts; Kafka is an append-only distributed log
- Topics organize events into named feeds; partitions enable parallelism and throughput
- Replication ensures failure tolerance

Kafka summary

- Kafka illustrates many strategies and patterns used in many other distributed systems
- Append-only logs is used in many distributed databases
- Partitioning is used widely to ensure high throughput
- Replication is used widely to ensure failure tolerance
- Metadata management using Paxos/Raft is common for many distributed system (including Kubernetes: next module)