[544] Kafka Reliability

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Learning Objectives

- describe how leader and follower replicas work in Kafka (to record messages, handle failover, etc.)
- apply the definition of "committed" messages to reason about when messages (a) are acknowledged to producers and (b) can be read by consumers
- configure Kafka and write producer/consumer code to achieve "exactly once semantics"

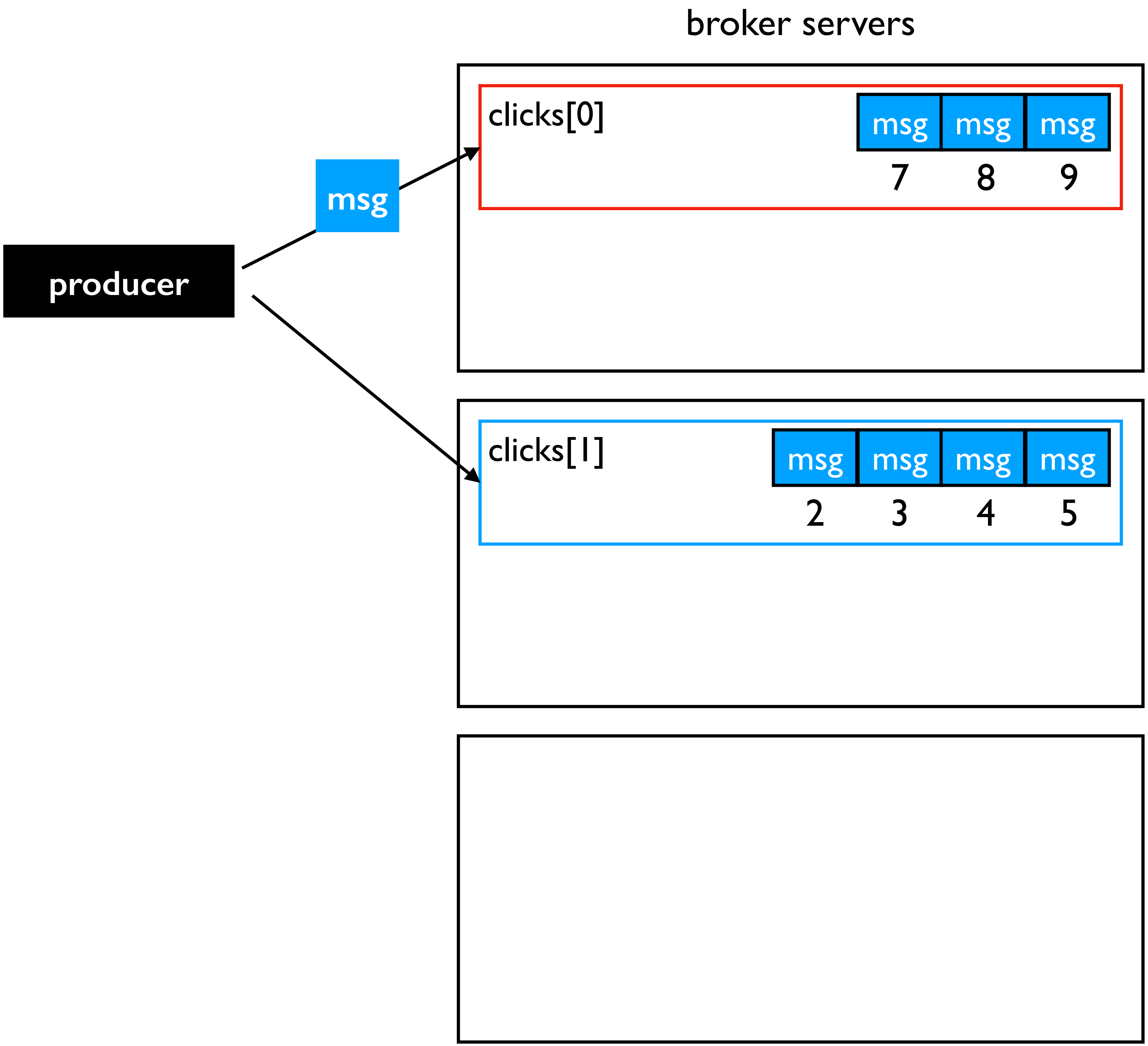
Outline: Kafka Reliability

Kafka Replication

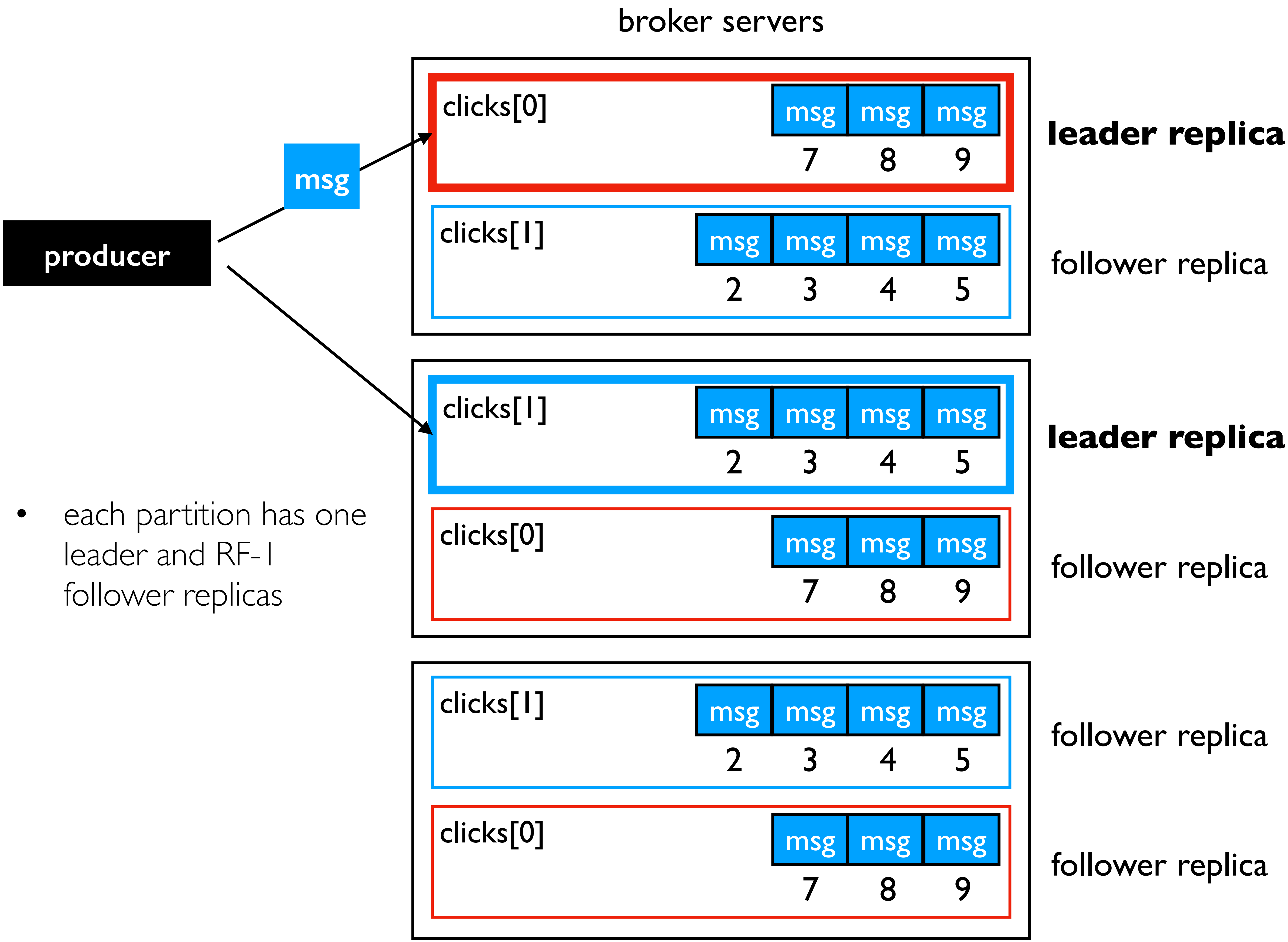
Fault Tolerance

Exactly-Once Semantics

Three brokers, 2 partitions, replication factor=1

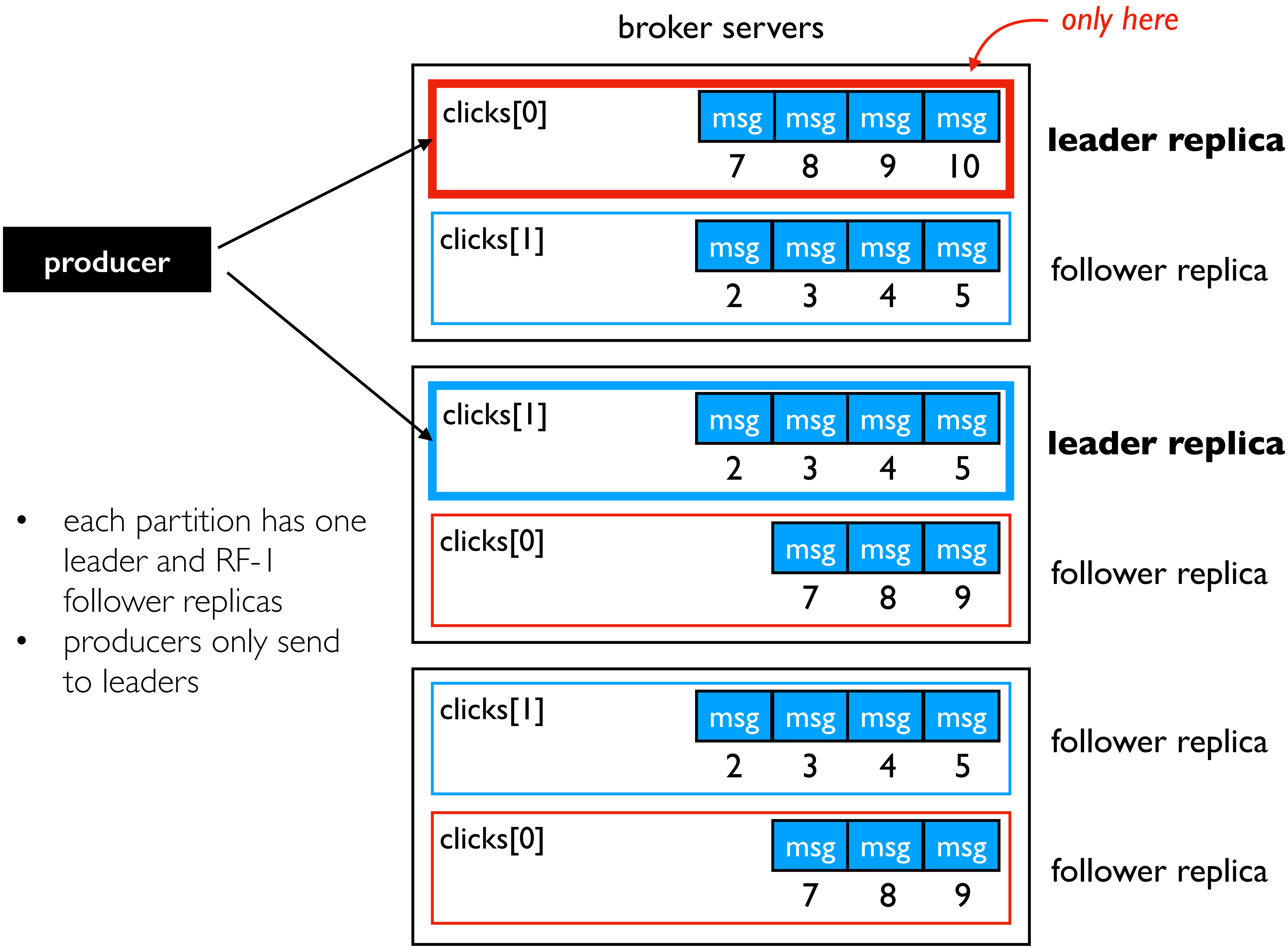


Three brokers, 2 partitions, replication factor=3



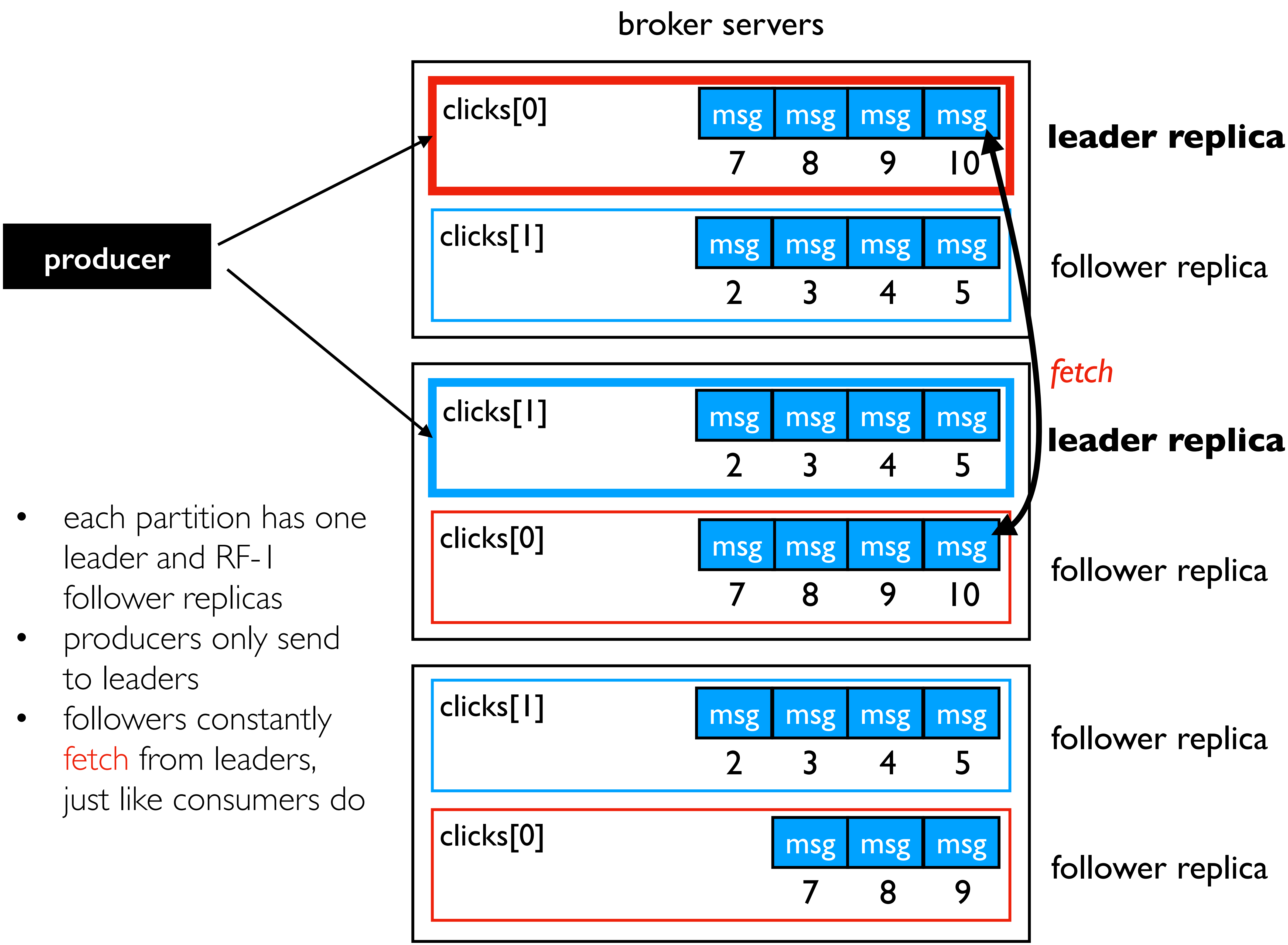
- each partition has one leader and RF-1 follower replicas

Three brokers, 2 partitions, replication factor=3



- each partition has one leader and RF-1 follower replicas
- producers only send to leaders

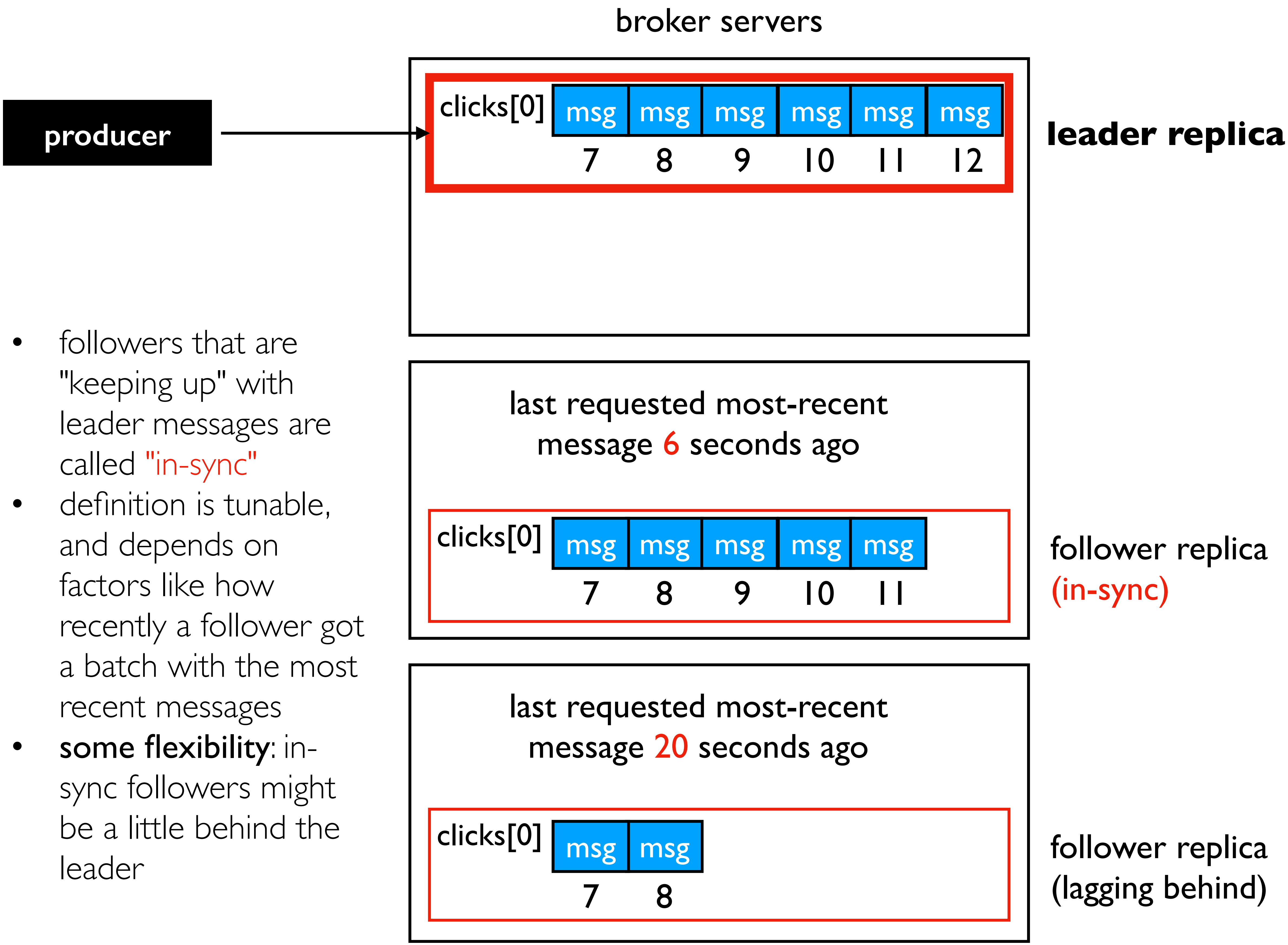
Fetch Requests



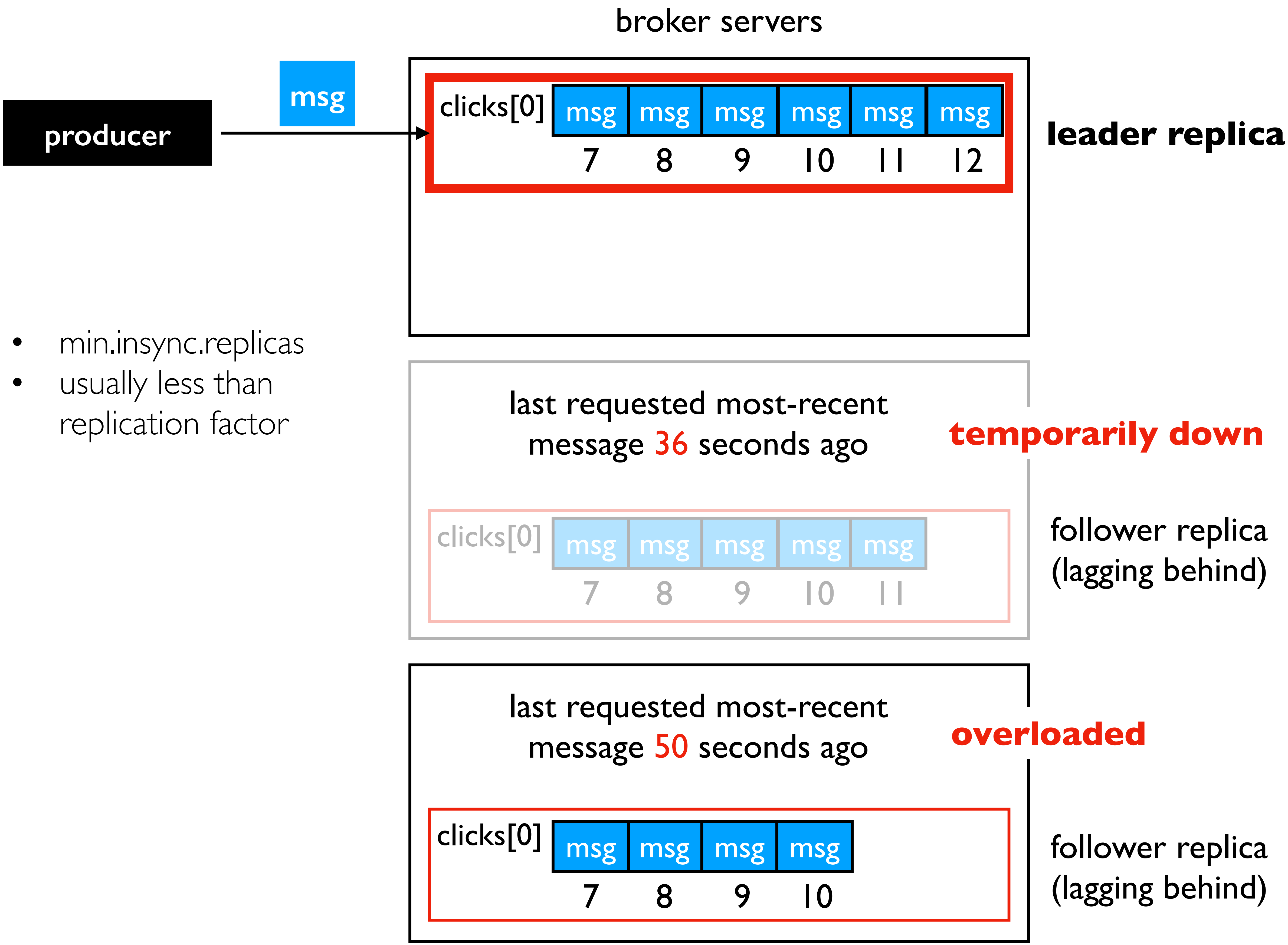
- each partition has one leader and RF-1 follower replicas
- producers only send to leaders
- followers constantly fetch from leaders, just like consumers do

Followers: In-Sync and/or Lagging Behind

- followers that are "keeping up" with leader messages are called "in-sync"
- definition is tunable, and depends on factors like how recently a follower got a batch with the most recent messages
- **some flexibility**: in-sync followers might be a little behind the leader

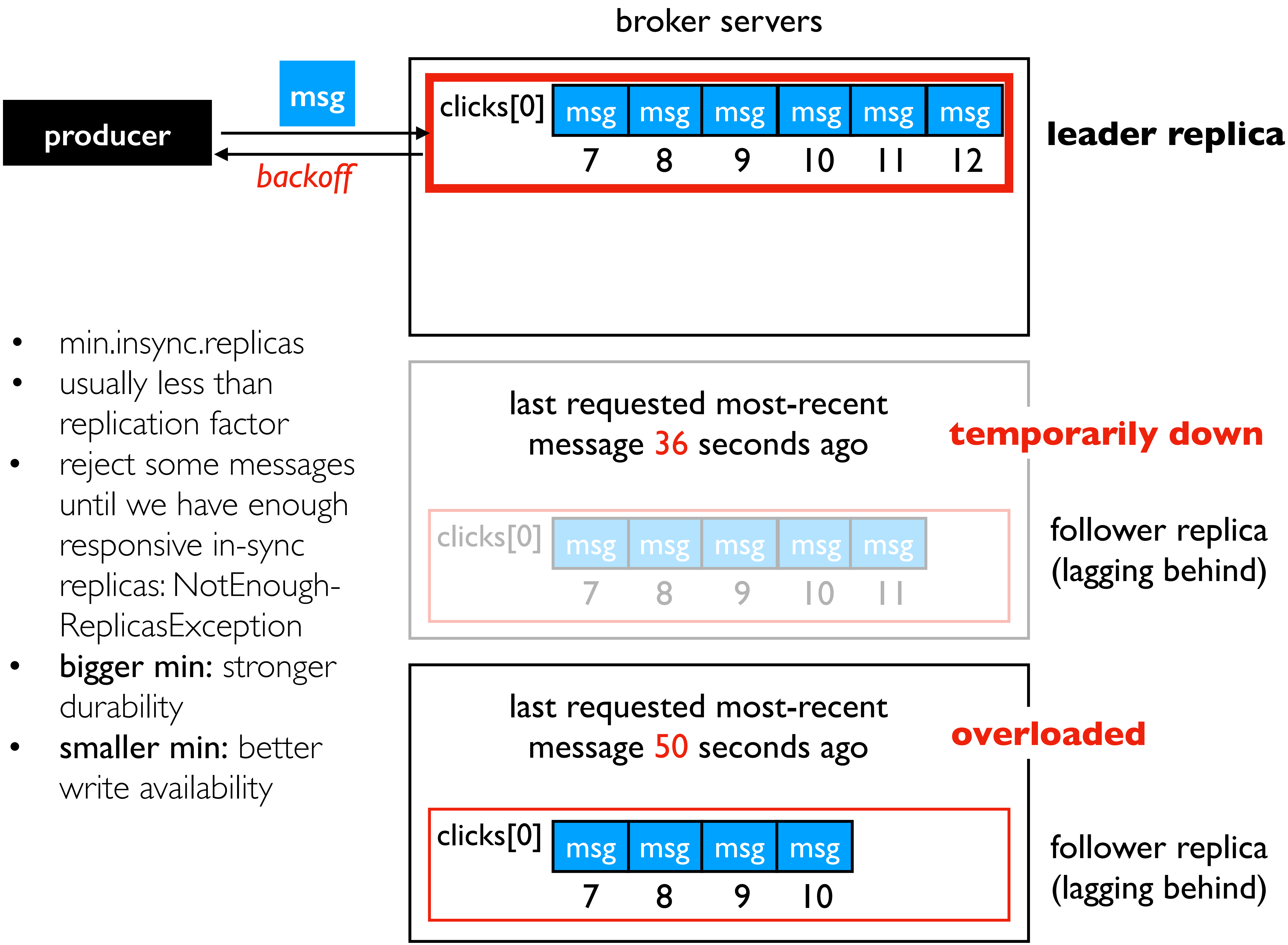


Minimum In-Sync Replicas (Assume 2 Here)



- min.insync.replicas
- usually less than replication factor

Backoff: Not Enough Replicas Exception



- min.insync.replicas
- usually less than replication factor
- reject some messages until we have enough responsive in-sync replicas: NotEnough-ReplicasException
- **bigger min:** stronger durability
- **smaller min:** better write availability

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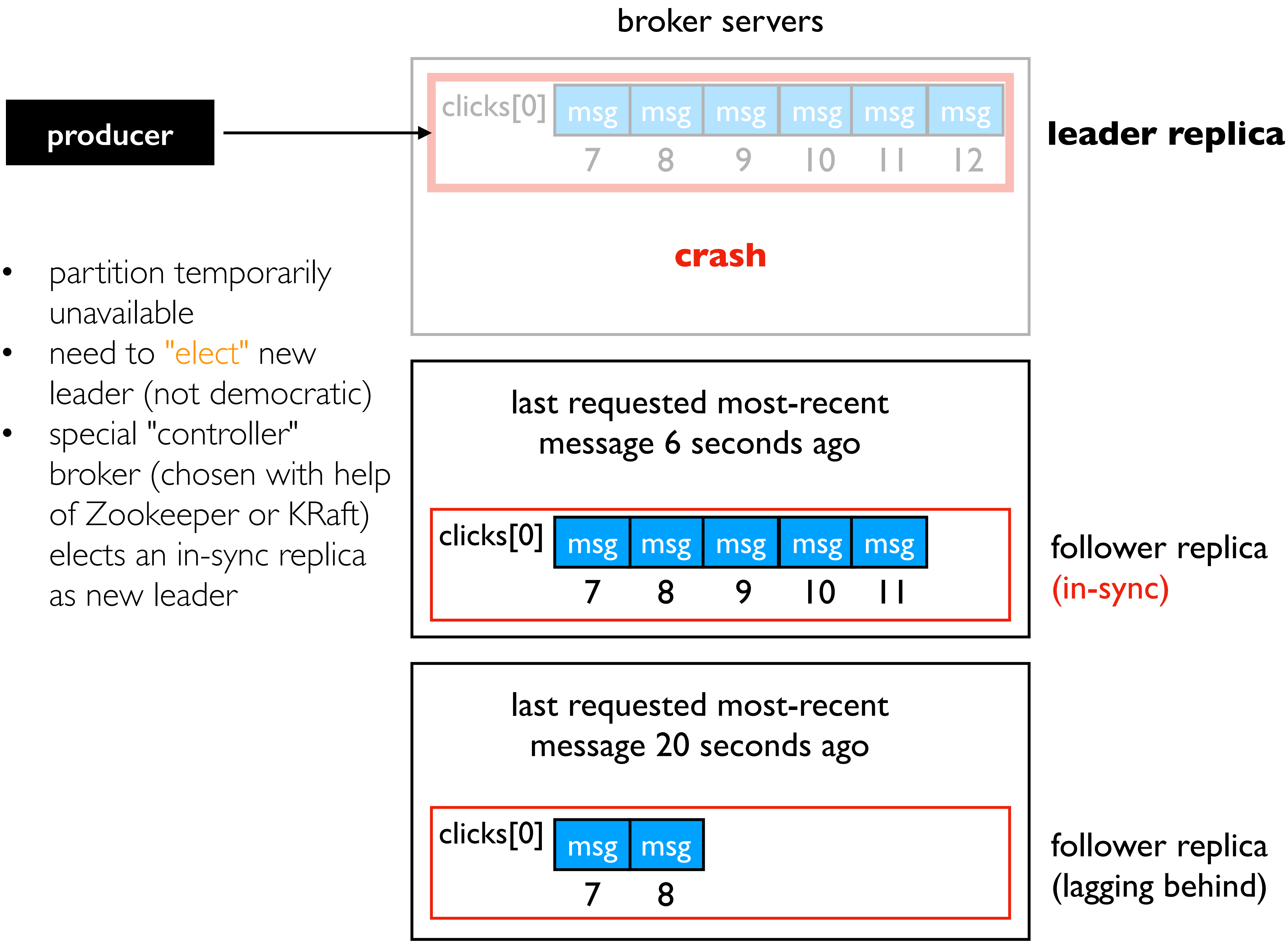
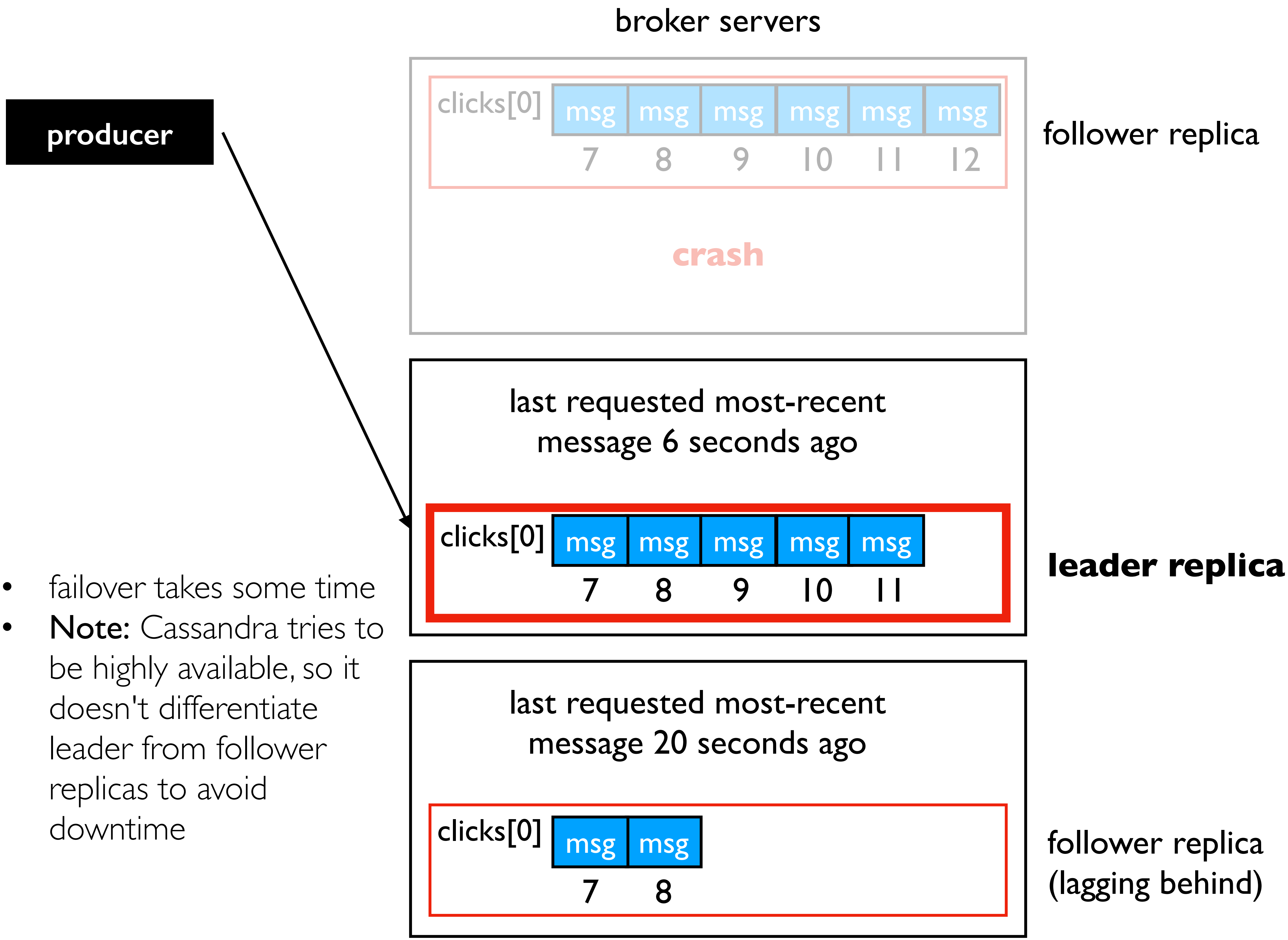
Exactly-Once Semantics

What if the leader fails? Elect a new one!



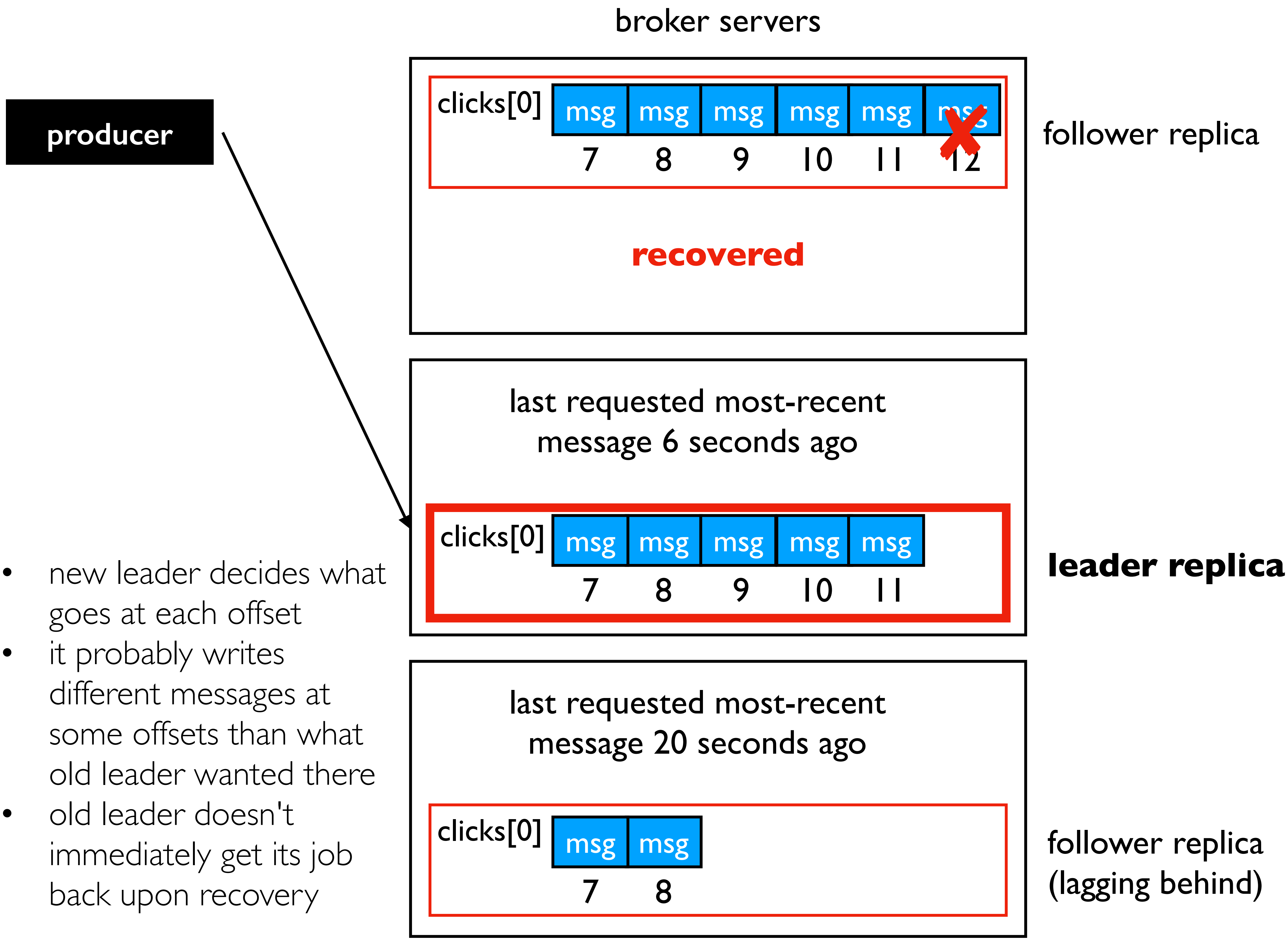
- partition temporarily unavailable
- need to "elect" new leader (not democratic)
- special "controller" broker (chosen with help of Zookeeper or KRaft) elects an in-sync replica as new leader

Kafka Replica Failover



- failover takes some time
- **Note:** Cassandra tries to be highly available, so it doesn't differentiate leader from follower replicas to avoid downtime

Some Messages Seen by Old Leader Lost



- new leader decides what goes at each offset
- it probably writes different messages at some offsets than what old leader wanted there
- old leader doesn't immediately get its job back upon recovery

Review "Committed": WhatsApp Acks Example

How to check read receipts

Copy link

Android iPhone KaiOS

Check marks will appear next to each message you send. Here's what each one indicates:

- ✓ The message was successfully sent.
- ✓✓ The message was successfully delivered to the recipient's phone or any of their linked devices.
- ✓✓ The recipient has read your message.

https://faq.whatsapp.com/665923838265756

these are examples of "acks" (acknowledgements)

In distributed storage systems/databases, an ack means our data is *committed*.

"Committed" means our data is "safe", even if bad things happen. The definition varies system to system, based on what bad things are considered. For example:

- a node could hang until rebooted; a node's disk could permanently fail
- a rack could lose power; a data center could be destroyed

In Kafka's leader/follower replica design, what are some "bad things" we might worry about?

Kafka: Committed Messages

Messages are "committed" when written to ALL in-sync replicas.

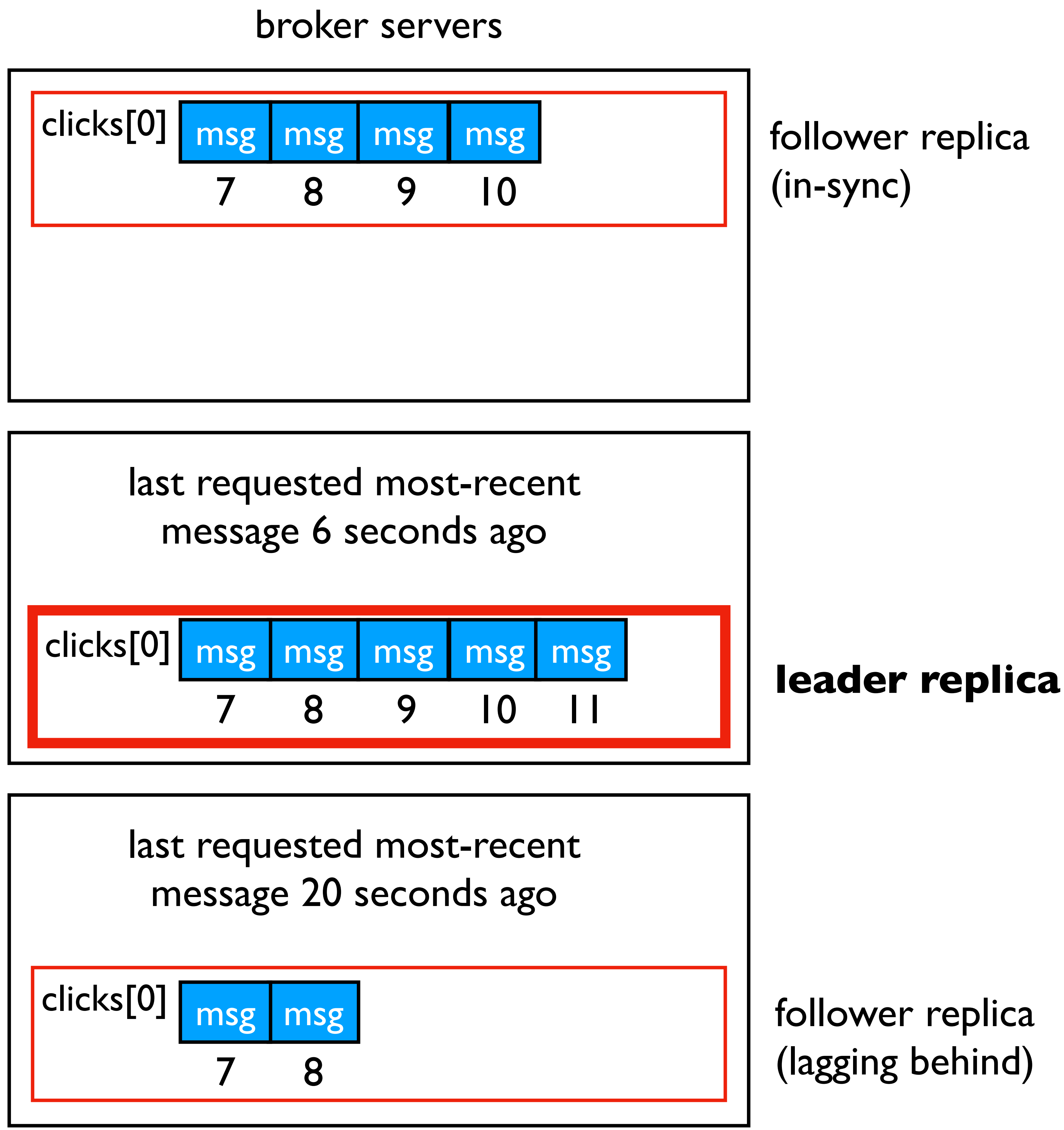
Depending on how many are in-sync, the strength of the guarantee can vary, but min.insync.replicas lets us specify a worst case.

If number of concurrent broker failures < min.insync.replicas, then our committed data is safe, even if the leader fails (because we can elect another in-sync replica, and all in-sync replicas have all committed data).

Committed Messages

What is committed?

- assume RF=3 and minimum in-sync=2
- is message 8 committed?
- message 10?
- message 11?



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Working with Committed Data

How can we avoid "anomalies" (unexpected system behavior) by taking advantage of committed data?

Example 1: Write Anomaly

Scenario:
- producer writes a message
- produce receives an ACK (acknowledgement) from the broker
- consumers never see the message

Cause: maybe the leader sent an ACK back, then crashed, before replicating the message to the followers.

How to avoid it? *Use strong acks.*

Consumer initialization:
- `KafkaProducer(..., acks=0)`
  don't wait for leader to send back ACK
- `KafkaProducer(..., acks=1)`
  ACK after leader writes to its own log
- `KafkaProducer(..., acks="all")`
  ACK after data is committed (slowest but strongest)

If you don't get an ACK that data is committed, usually best to retry in a loop (Kafka can be configured to do this for you).

Example 2: Read Anomaly

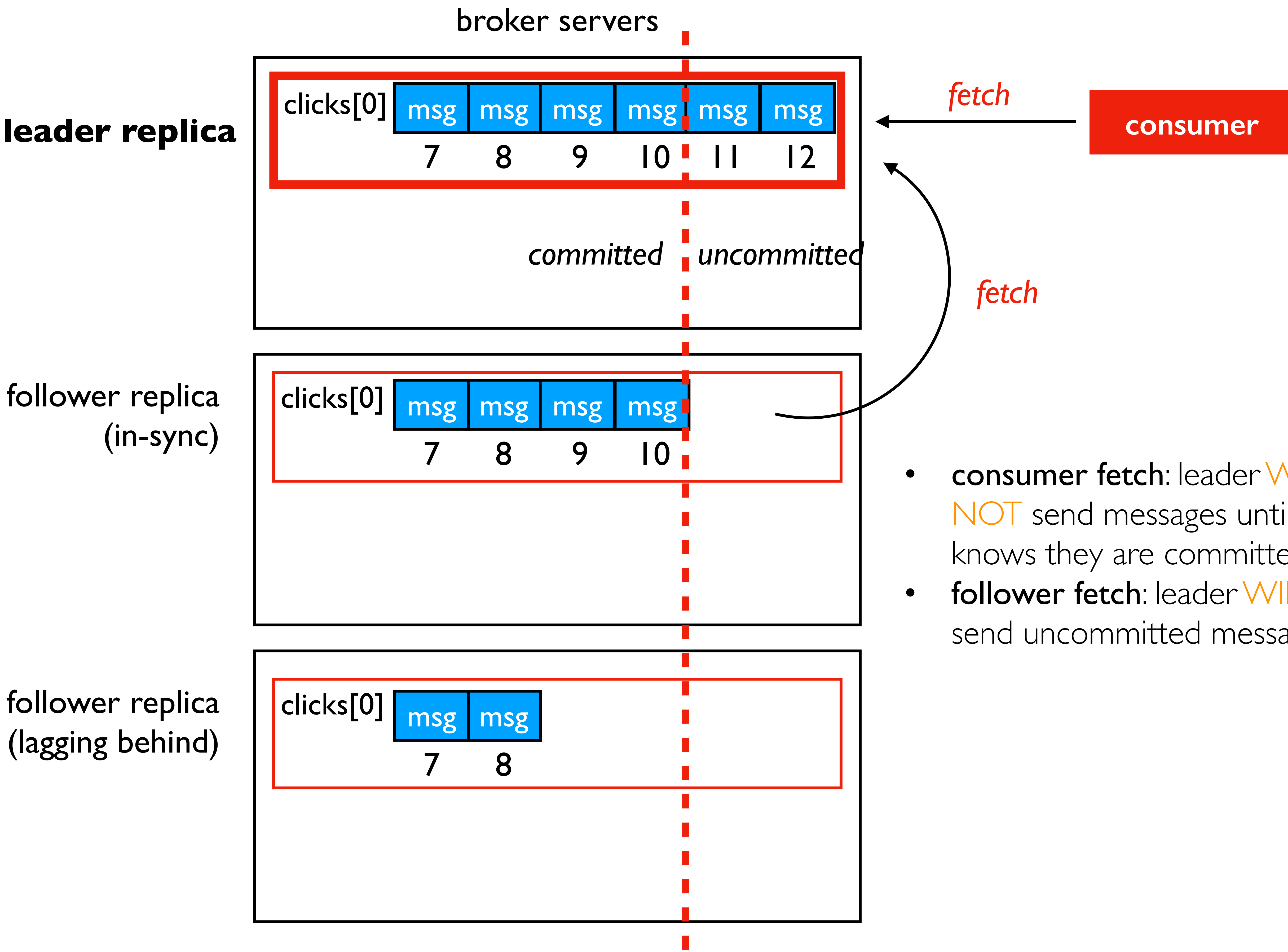
Scenario:
- a consumer reads a message
- there is an attempt to read the message again later (same consumer, or other)
- message is gone, or changed

Cause: maybe the message was consumed from the leader before it was replicated to the followers; then the leader crashed and the new leader doesn't have that message for future consumption.

How to avoid it? *Never read un-committed data.*

The leader does this automatically.

Fetch Behavior: Consumer vs. Follower



- **consumer fetch**: leader WILL NOT send messages until it knows they are committed
- **follower fetch**: leader WILL send uncommitted messages

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Exactly-Once Semantics

Semantics (Meaning)

Dictionary

Definitions from Oxford Languages · Learn more

se·man·tics

noun

noun: **semantics**; noun: **logical semantics**; noun: **lexical semantics**

the branch of linguistics and logic concerned with meaning. There are a number of branches and

Programming Example:

- **Runtime bug:** the program crashed, there was clearly a problem
- **Semantic bug:** you need to understand the meaning of the results to say whether or not the program behaved correctly

In Systems:

- what does it mean when we get we get an **ACK**, or a **write returns**?
- the meaning depends on how we configured things...

At-most-once semantics

```
producer = KafkaProducer(..., acks=1)
producer.send("my-topic", b"some-value")
```

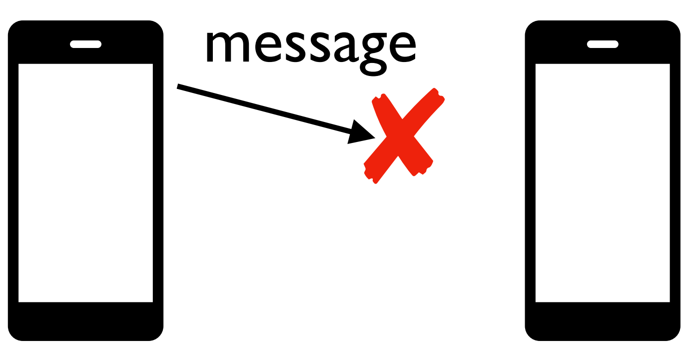
With acks as 0 or 1 and no retry, a successful write means the data was recorded at most once (ideally once, but if the leader crashes at a bad time, maybe zero times).

Using strong ACKs and retry

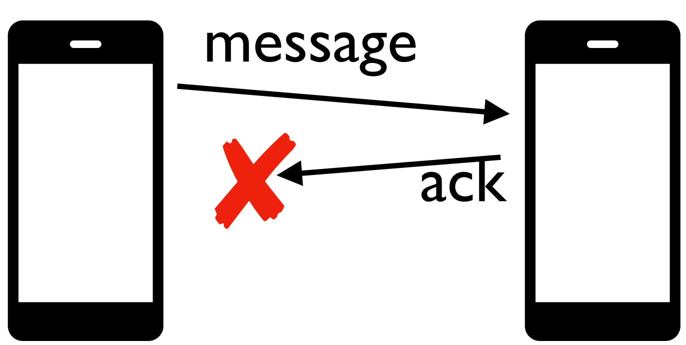
```
producer = KafkaProducer(..., acks="all", retries=10)
producer.send("my-topic", b"some-value")
```

Keep retrying until success (within reason -- for example, 10 times)

Problem: there are two reasons we might not get an ACK:



scenario 1



scenario 2

Using strong ACKs and retry

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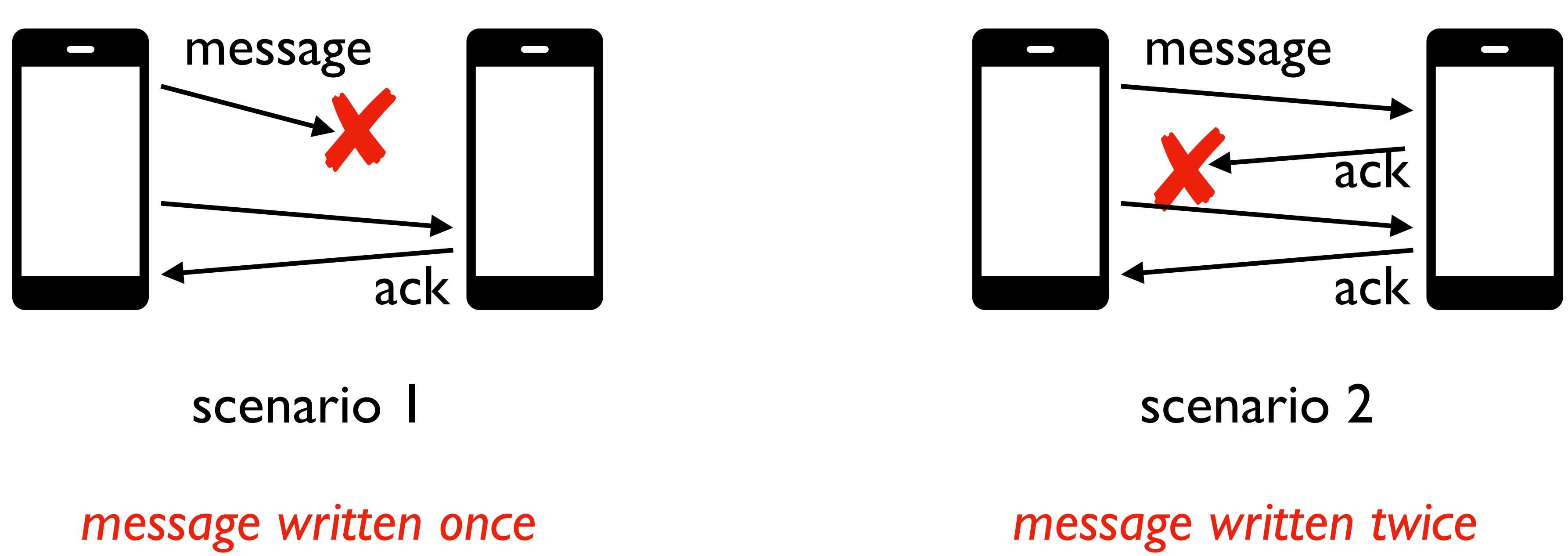


A strong ACK with retry provides *at-least-once semantics* because we're guaranteed 1+ messages upon success

Are duplicate messages OK?

Yes, if they're idempotent.

"An operation is called idempotent when the effect of performing the operation multiple times is equivalent to the effect of performing the operation a single time"
~ *Operating Systems: Three Easy Pieces, by Arpaci-Dusseau*

```
x = 0
y = 0

def set_x(value):
    global x
    x = value

def inc_y(value):
    global y
    y += value
```

```
# if we just do once, is it the same?
set_x(123)
set_x(123)
set_x(123)

# if we just do once, is it the same?
inc_y(3)
inc_y(3)
inc_y(3)
```

TopHat

Suppressing Duplicates

With some cleverness, we can make ANYTHING idempotent.

```
y = 0
completed_ops = set()

def inc_y(value, operation_id):
    global y
    if not operation_id in completed_ops:
        y += value
        completed_ops.add(operation_id)

inc_y(3, 1251253)
inc_y(3, 1251253)    # no effect
inc_y(3, 1251253)    # no effect

inc_y(3, 9876)
inc_y(3, 9876)       # no effect

inc_y(1, 5454)
```

Exactly-Once Semantics: Producer Side

Upon a successful write, the message will be considered exactly once (duplicates will be suppressed by brokers or consumers).

Producer settings:

- acks="all"
- retry=N
- enable.idempotence=True

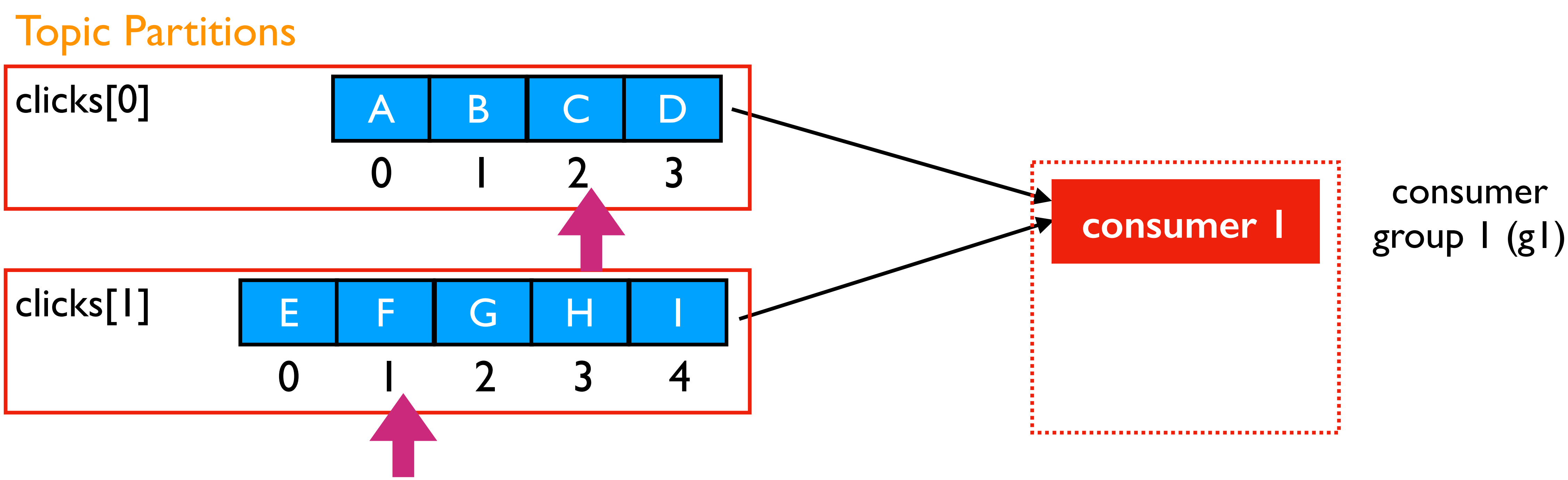
With idempontence enabled, producers automatically generate unique operation IDs and brokers suppress duplicates (this has an extra cost).

You can use enable.idempotence in Java, but the kafka-python package doesn't support it.:

- need to handle it yourself
- often, messages have a unique ID anyway, so consumers can ignore dups
- Example: weather stations that emit one record per day -- if a consumer sees a date for a station it has seen before, ignore it

Exactly-Once Semantics: Consumer Side

```
c = KafkaConsumer("clicks",
                  group_id="g1",
                  ...)
while True:
   batch = c.poll(1000)
   ...
```



Suppose consumer dies and is replaced by another in the same group

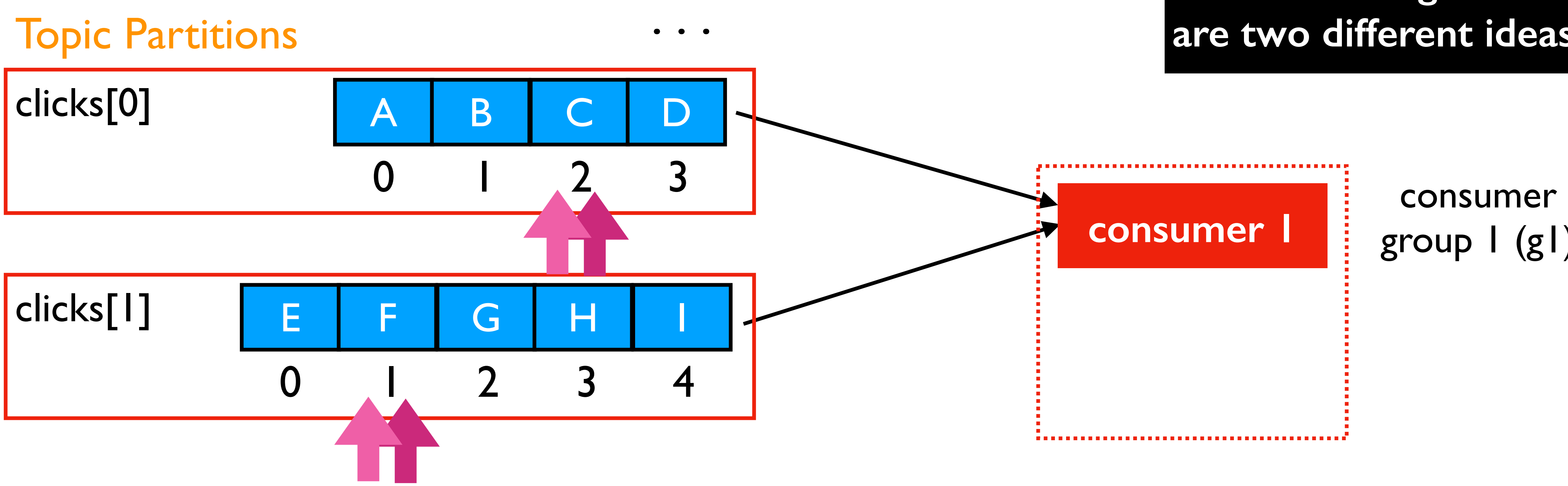
- don't want replacement to miss any messages
- don't want replacement to repeat any processing

	g1 offsets
clicks[0]	2
clicks[1]	1

Exactly-Once Semantics: Consumer Side

```
c = KafkaConsumer("clicks",
                  group_id="g1",
                  enable_auto_commit=True,
                  auto_commit_interval_ms=5000,
                  ...)
while True:
   batch = c.poll(1000)
   ...
```

Note! Committing messages and commiting read offsets are two different ideas.



	g1 offsets
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Kafka

	g1 offsets
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consumer

Exactly-Once Semantics: Consumer Side

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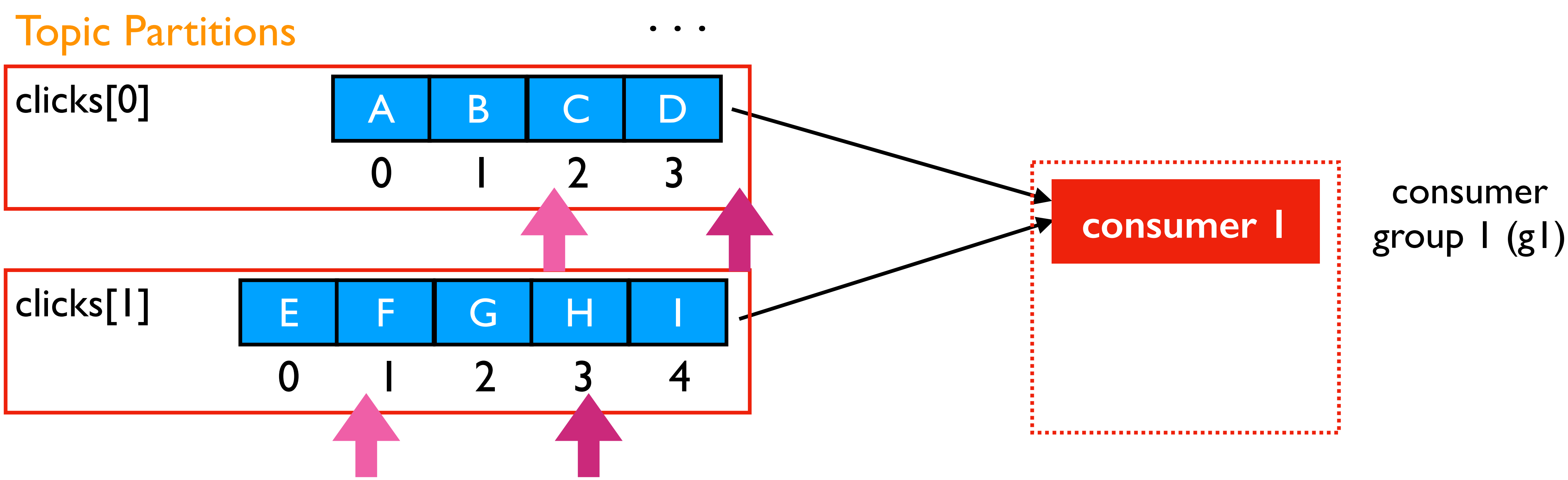


	g1 offsets
clicks[0]	2
clicks[1]	1

Kafka

If we crash at a bad time, the offsets the next consumer gets from Kafka will only be approximately correct.

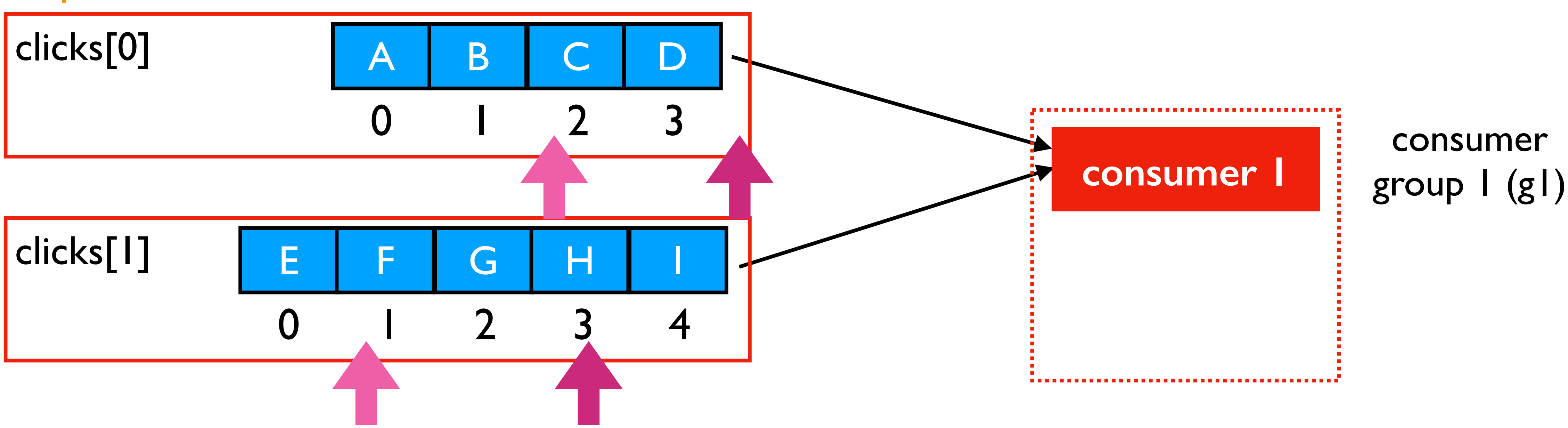
	g1 offsets
clicks[0]	4
clicks[1]	3

consumer

Approach 1: Manually Commit Offsets

```
c = KafkaConsumer("clicks",
                  group_id="g1",
                  enable_auto_commit=False,
                  ...)
while True:
   batch = c.poll(1000)
   ...
   c.commit() # manually commit read offsets
```

Topic Partitions



	g1 offsets
clicks[0]	2
clicks[1]	1

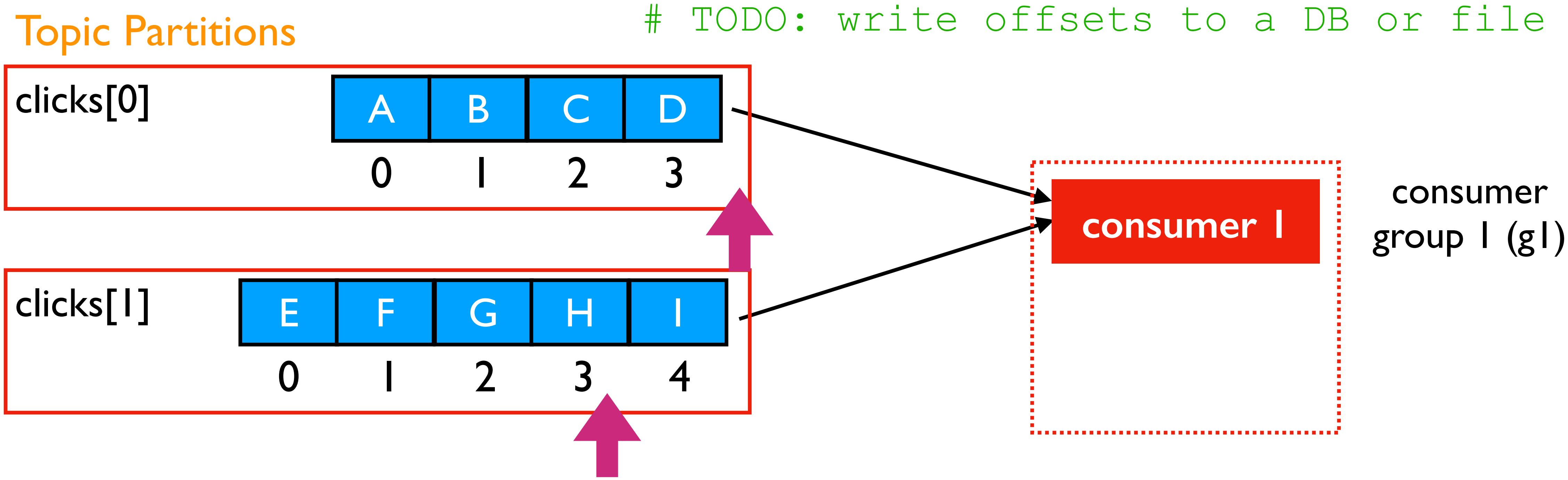
Kafka

	g1 offsets
clicks[0]	4
clicks[1]	3

consumer

Approach 2: Externally Save Commits

```
c = KafkaConsumer("clicks",
                  group_id="g1",
                 ...)
# TODO: seek to previous position
while True:
   batch = c.poll(1000)
   ...
   # TODO: write offsets to a DB or file
```



	g1 offsets
clicks[0]	4
clicks[1]	3

consumer

Conclusion

Every part of the system has a part to play in reliability and exactly-once semantics.

Producer:

- requesting strong acks
- retry
- idempotence

Broker:

- replicating data to followers
- failing over to new leader
- sending acks
- helping producer suppress duplicates
- keeping uncommitted data hidden from consumers

Consumer:

- carefully handling read offsets
- sometimes suppressing duplicates (if not handled by producers+brokers)