Avoiding Coordination with Network Ordering: NOPaxos and Eris

Ellis Michael

Server failures are the common case in data centers

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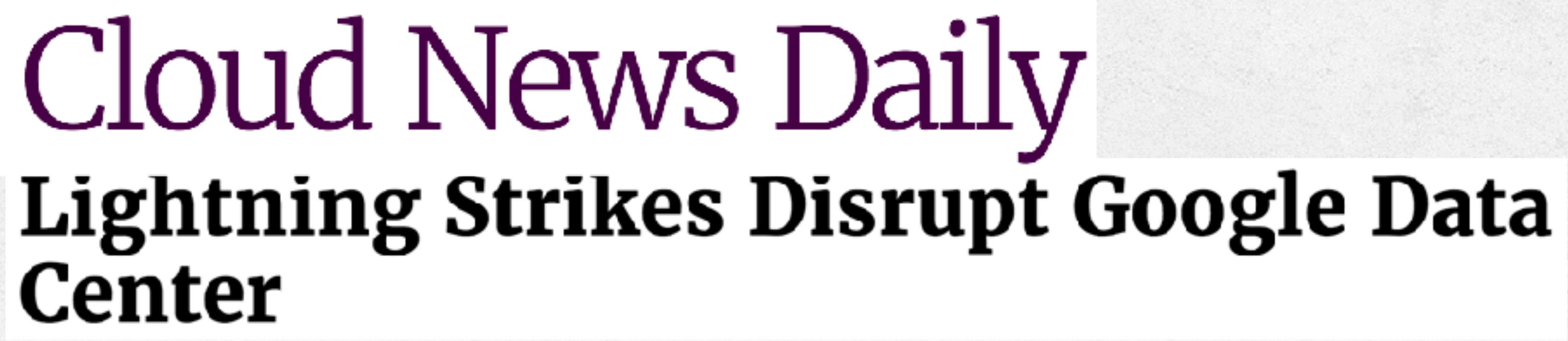

Cloud News Daily

Lightning Strikes Disrupt Google Data Center

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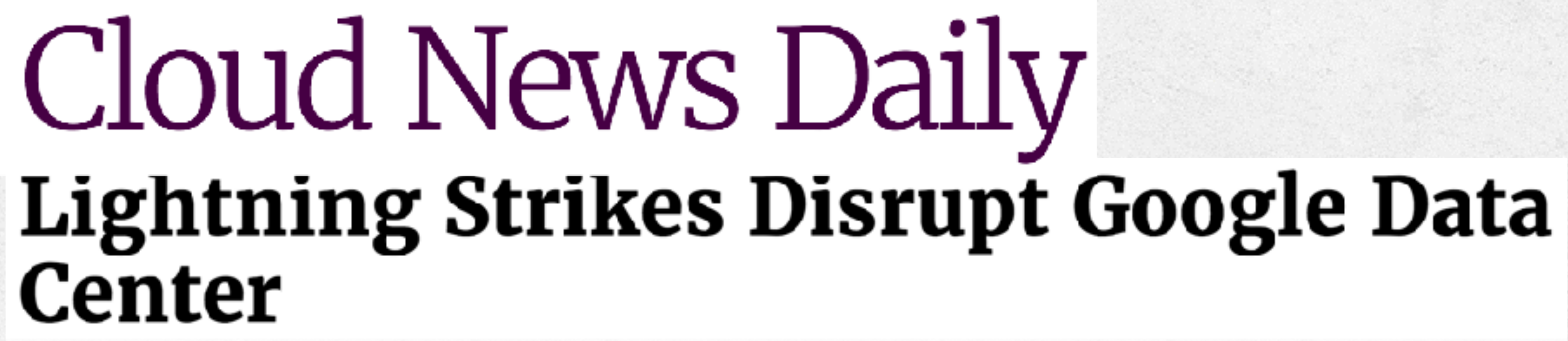

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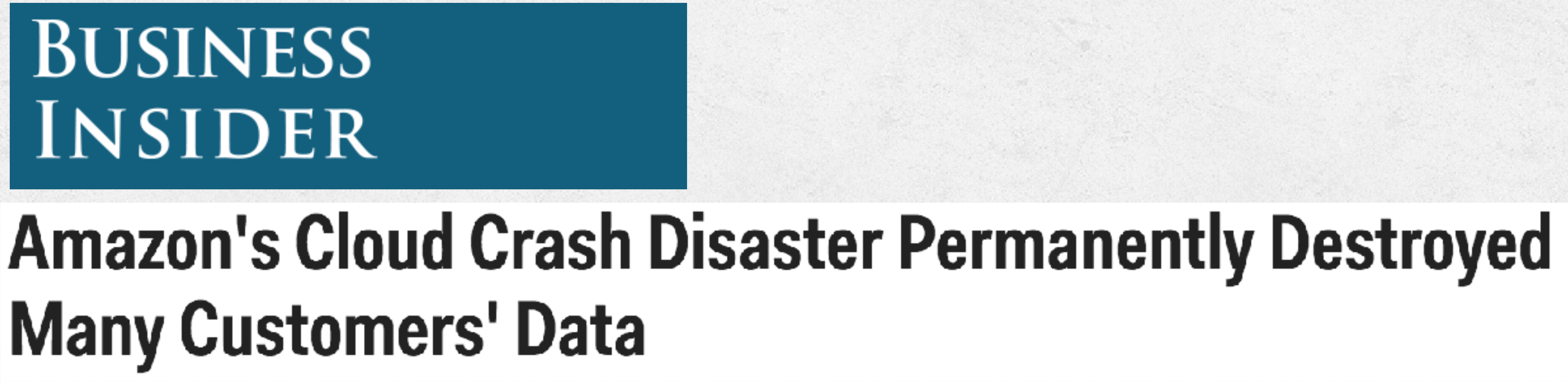
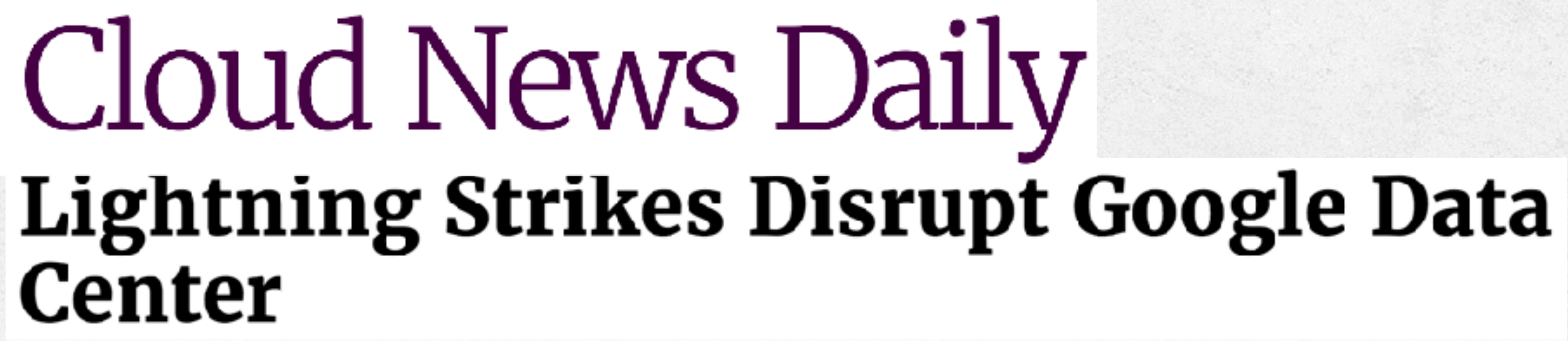


Business Insider

Amazon's Cloud Crash Disaster Permanently Destroyed Many Customers' Data

SERVER FAILURES ARE THE COMMON CASE IN DATA CENTERS



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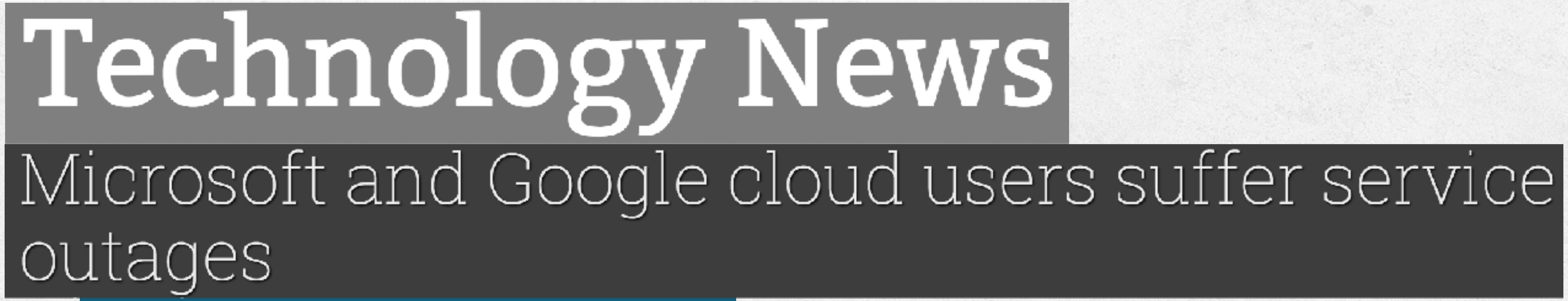
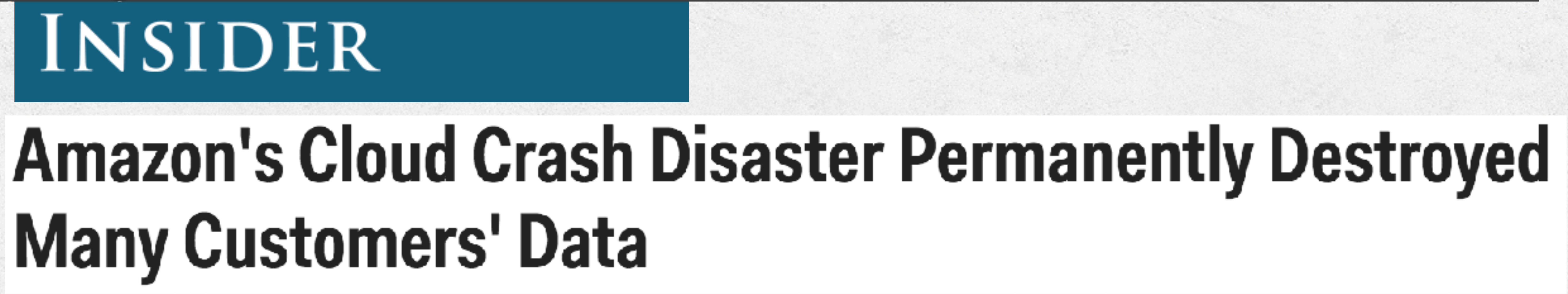


Technology News

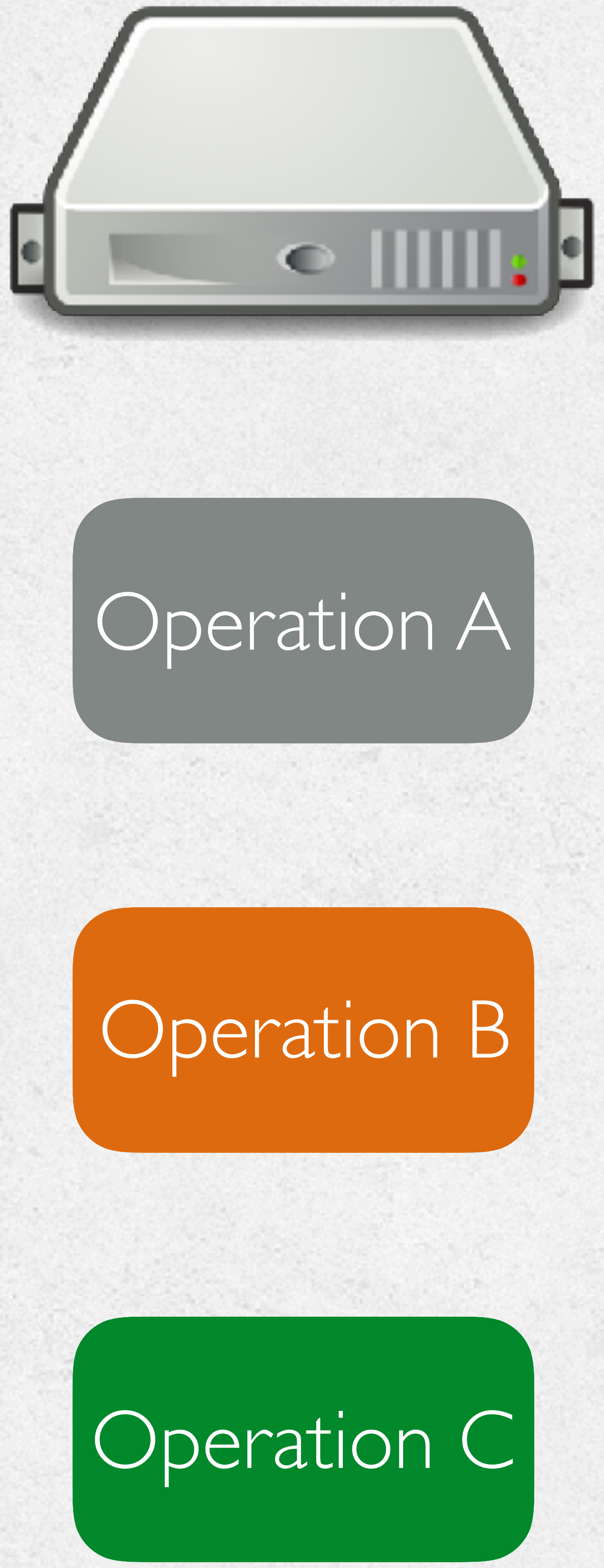
Microsoft and Google cloud users suffer service outages



INSIDER

Amazon's Cloud Crash Disaster Permanently Destroyed Many Customers' Data

State Machine Replication

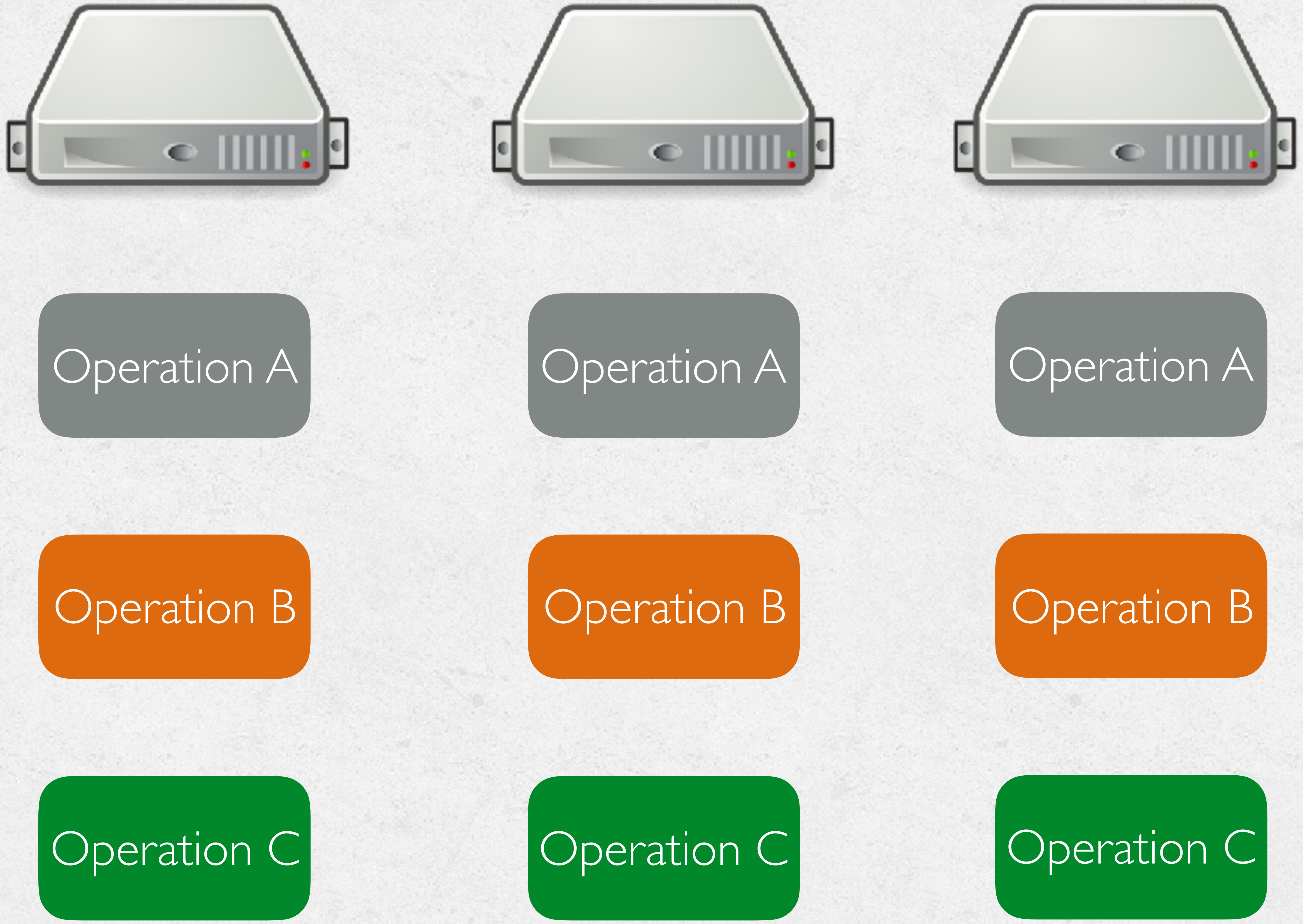


Operation A

Operation B

Operation C

State Machine Replication

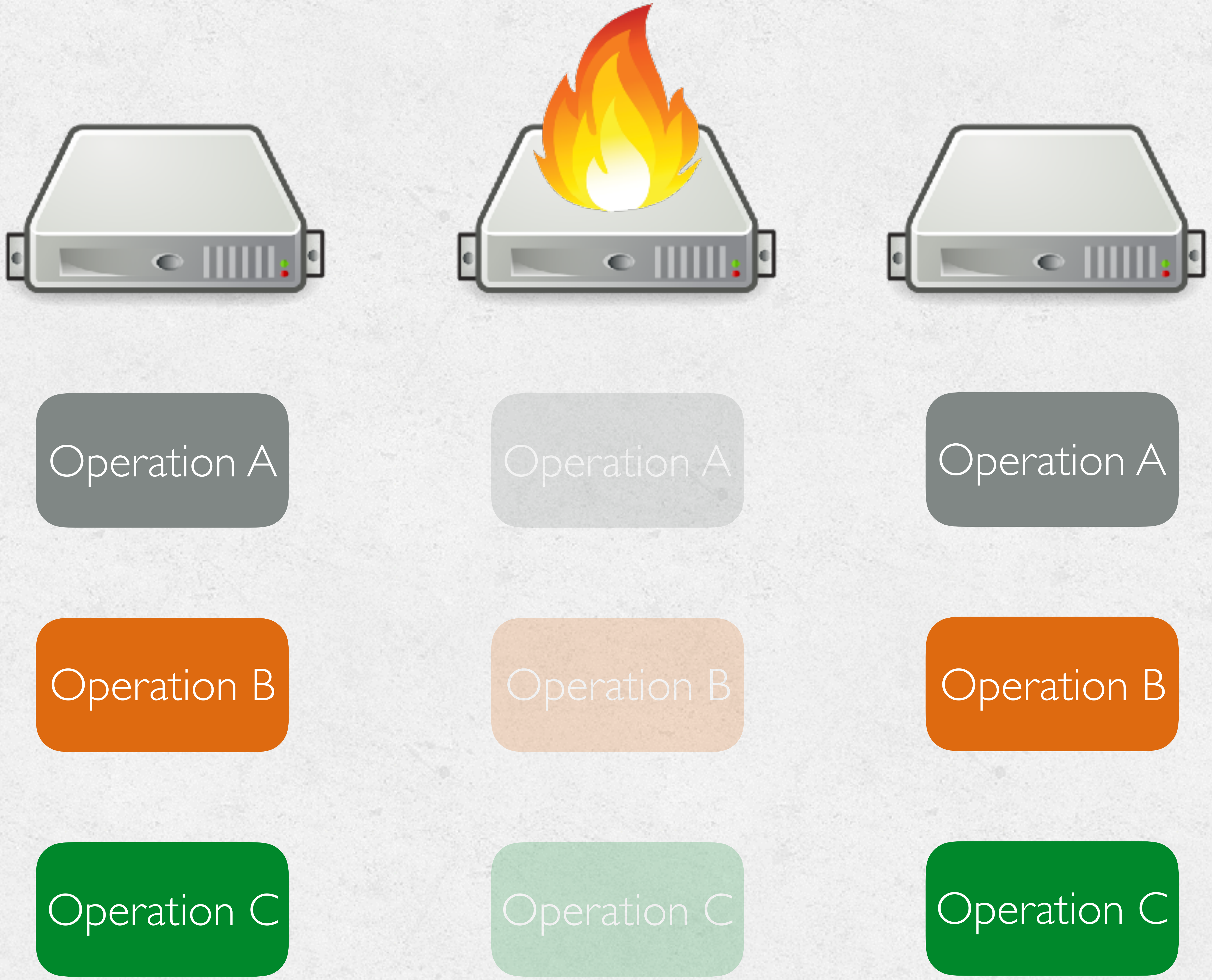


Operation A Operation A Operation A

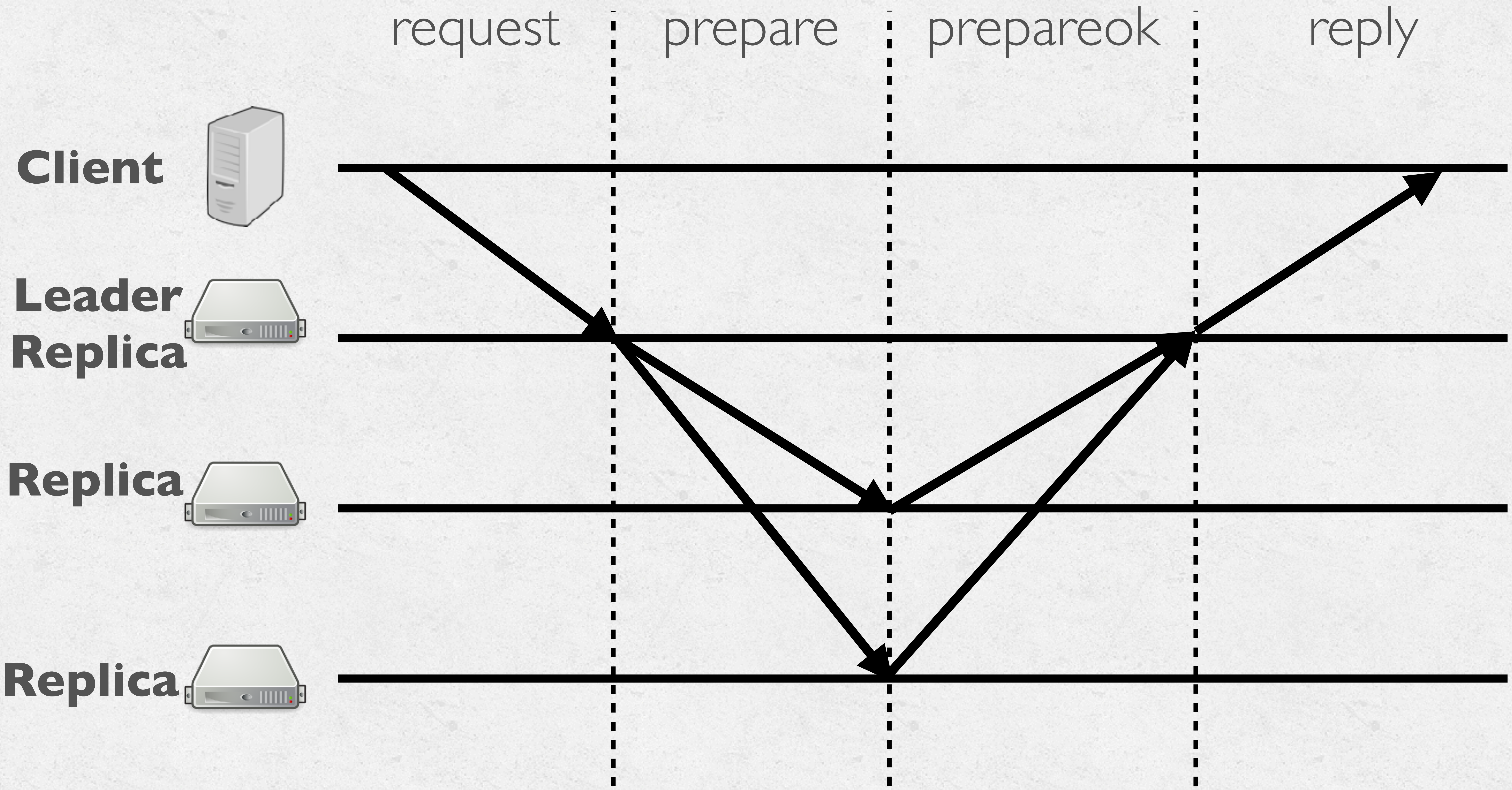
Operation B Operation B Operation B

Operation C Operation C Operation C

State Machine Replication



Paxos for state machine replication



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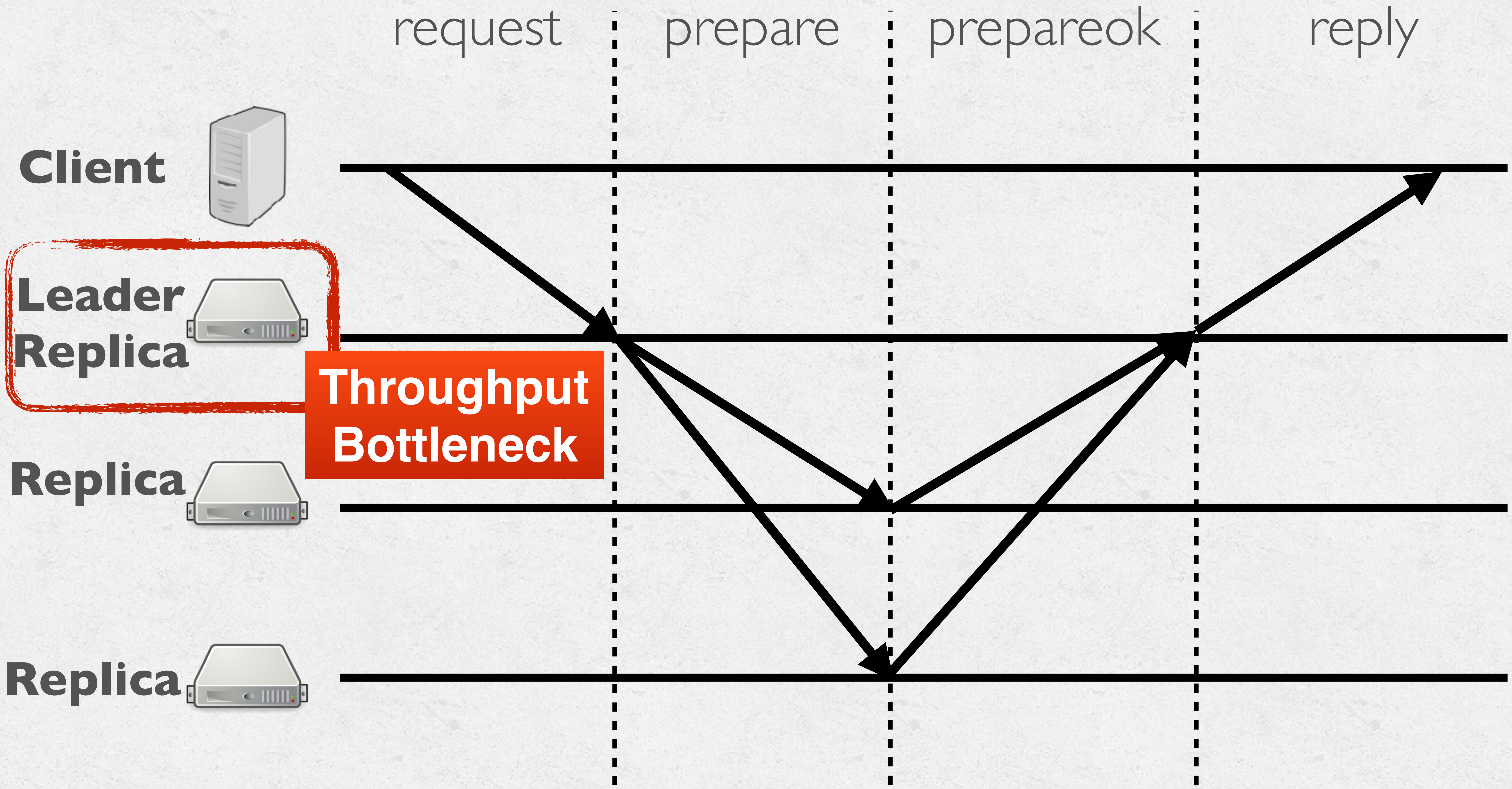
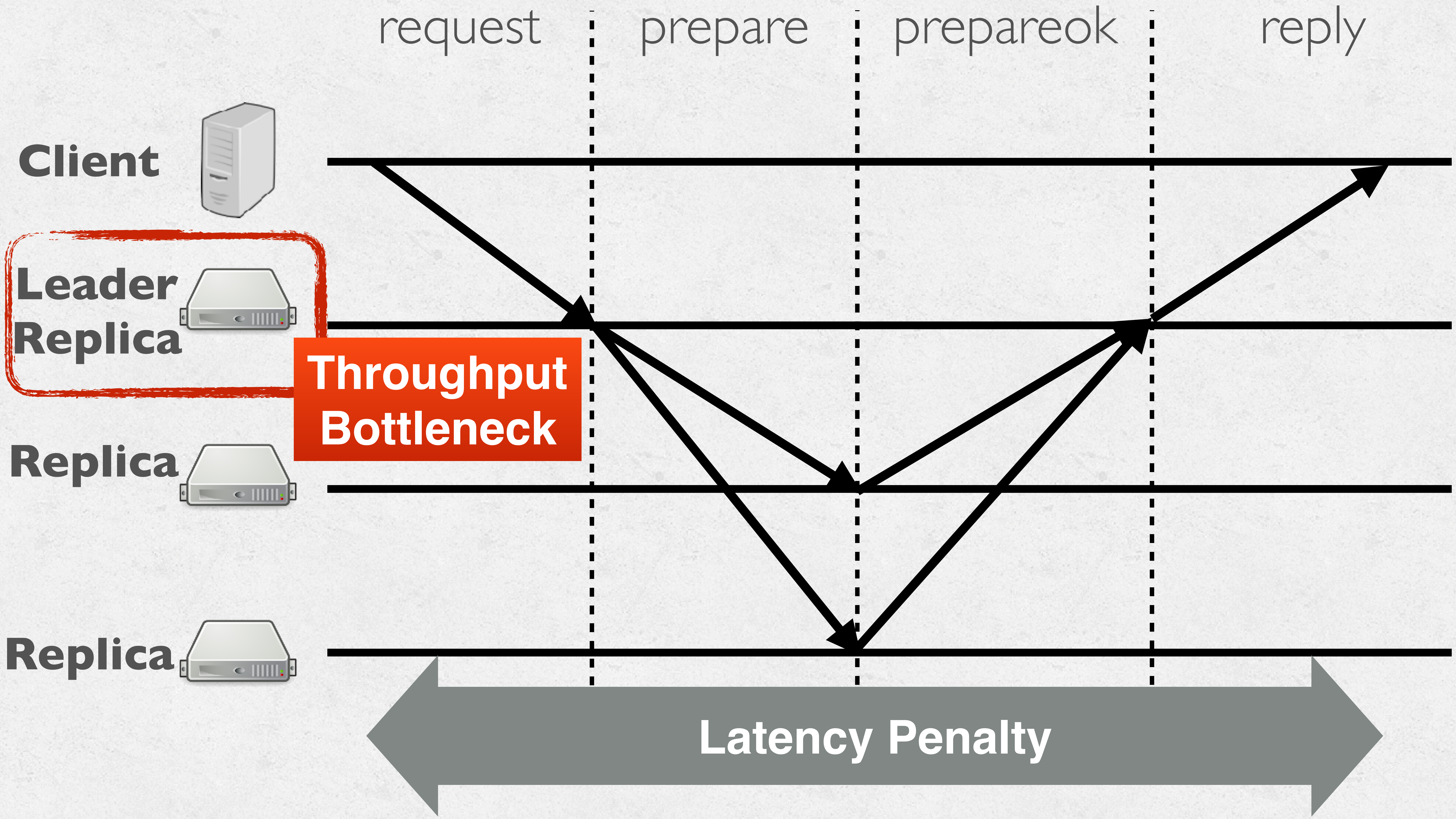
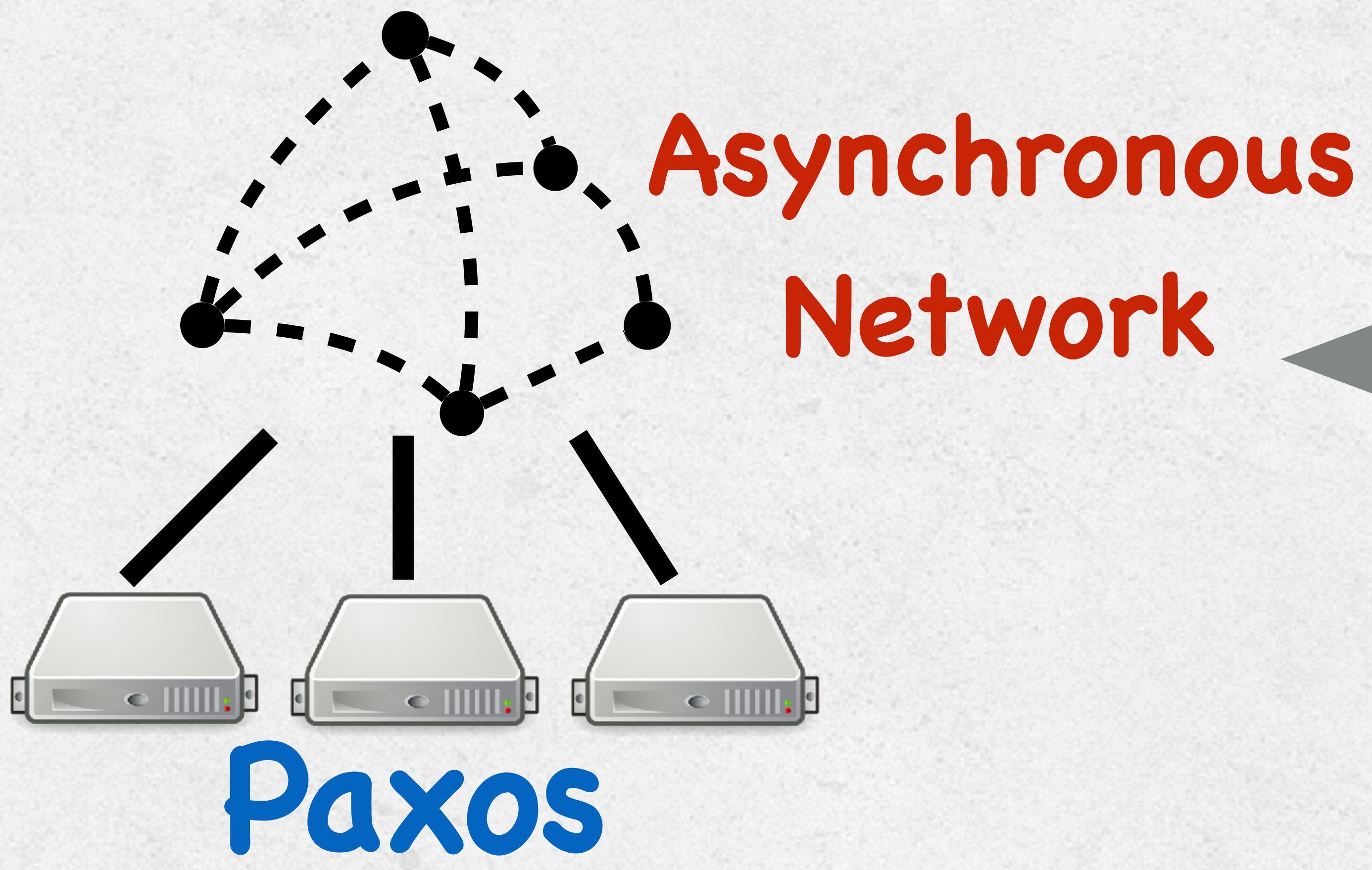


PAXOS FOR STATE MACHINE REPLICATION



Network properties determine replication complexity

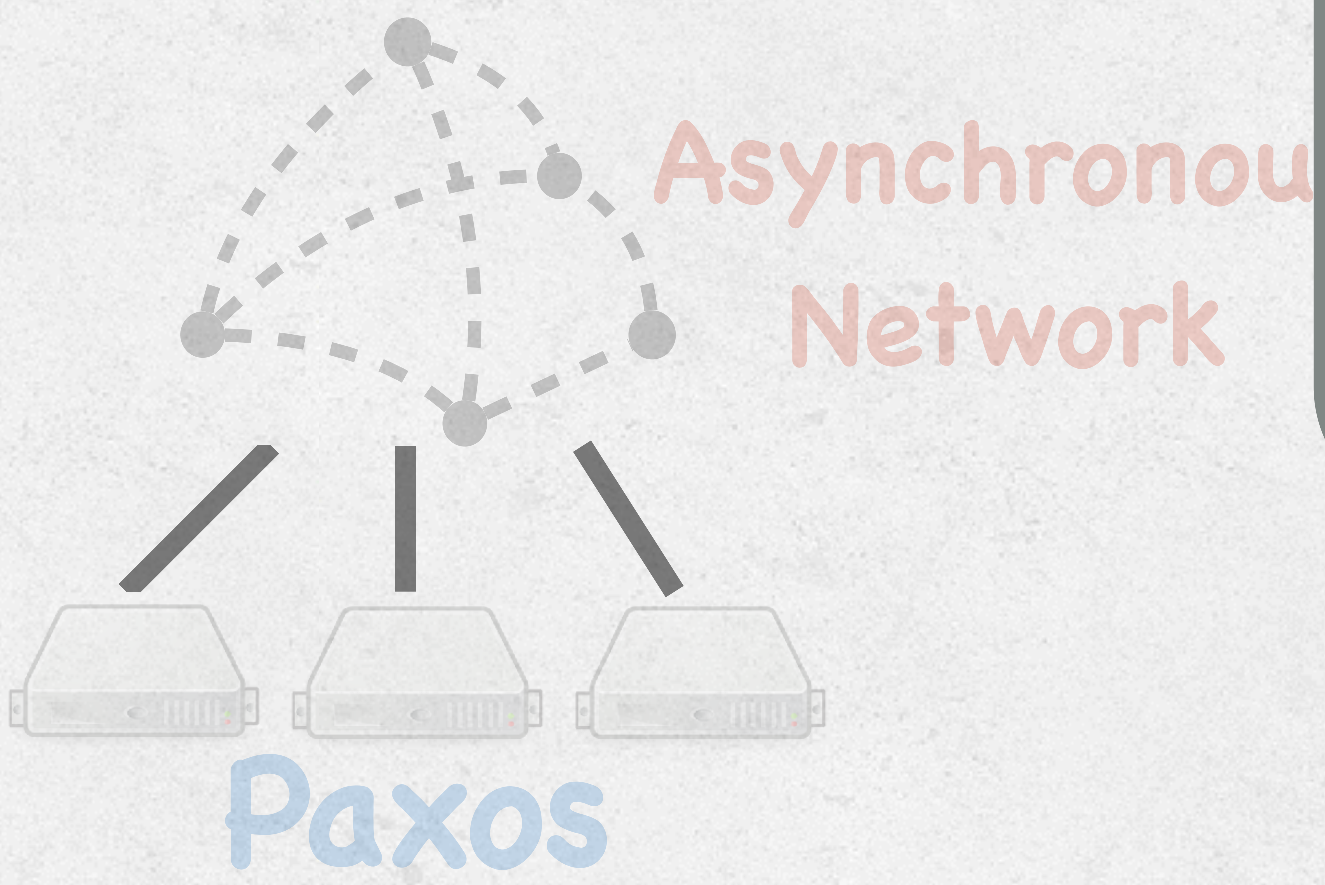


Messages may be:

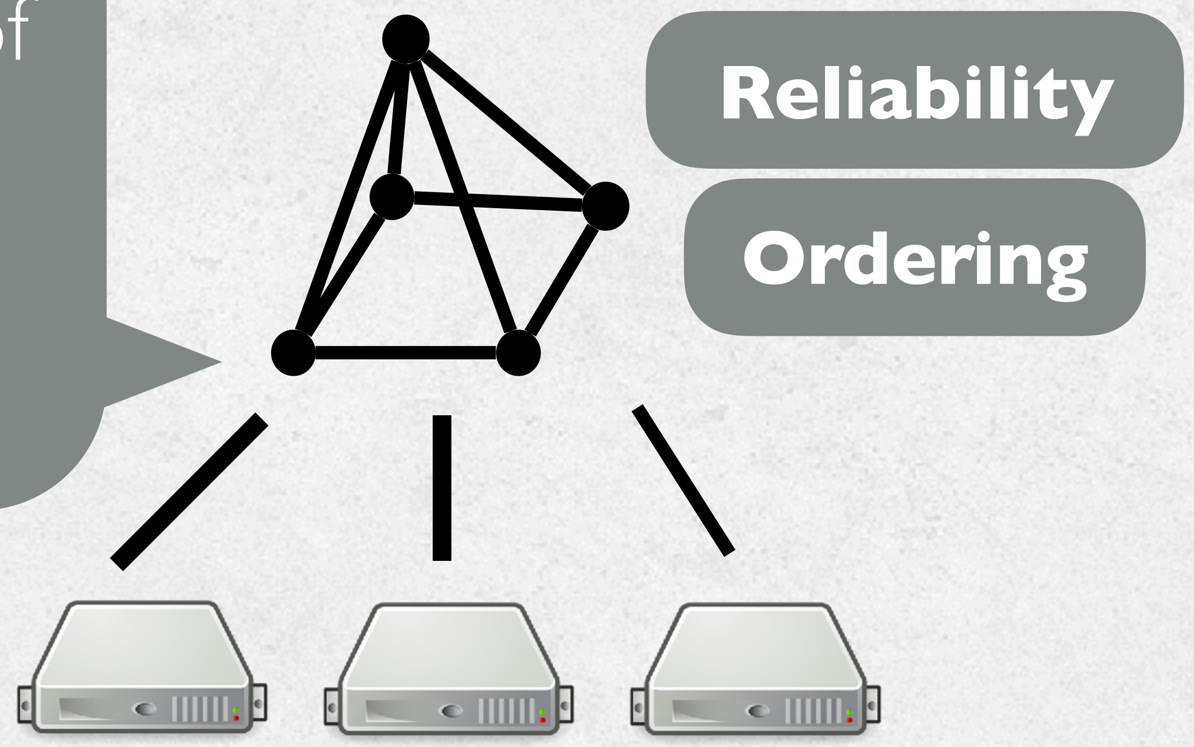
- dropped
- reordered
- delivered with arbitrary latency

- Paxos protocol on every operation
- High performance cost

Network properties determine replication complexity



All replicas:
- receive the same set of messages
- receive them in the same order



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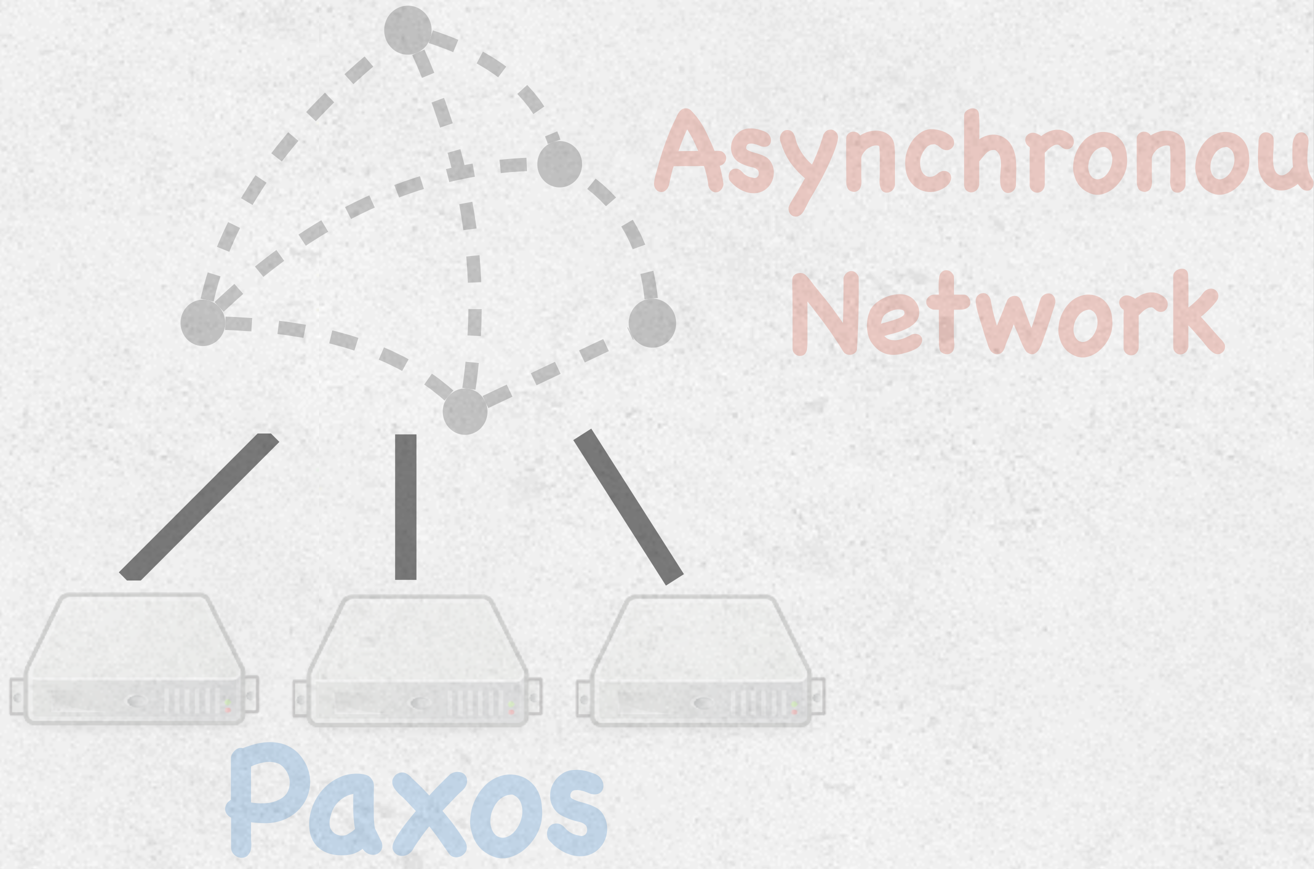

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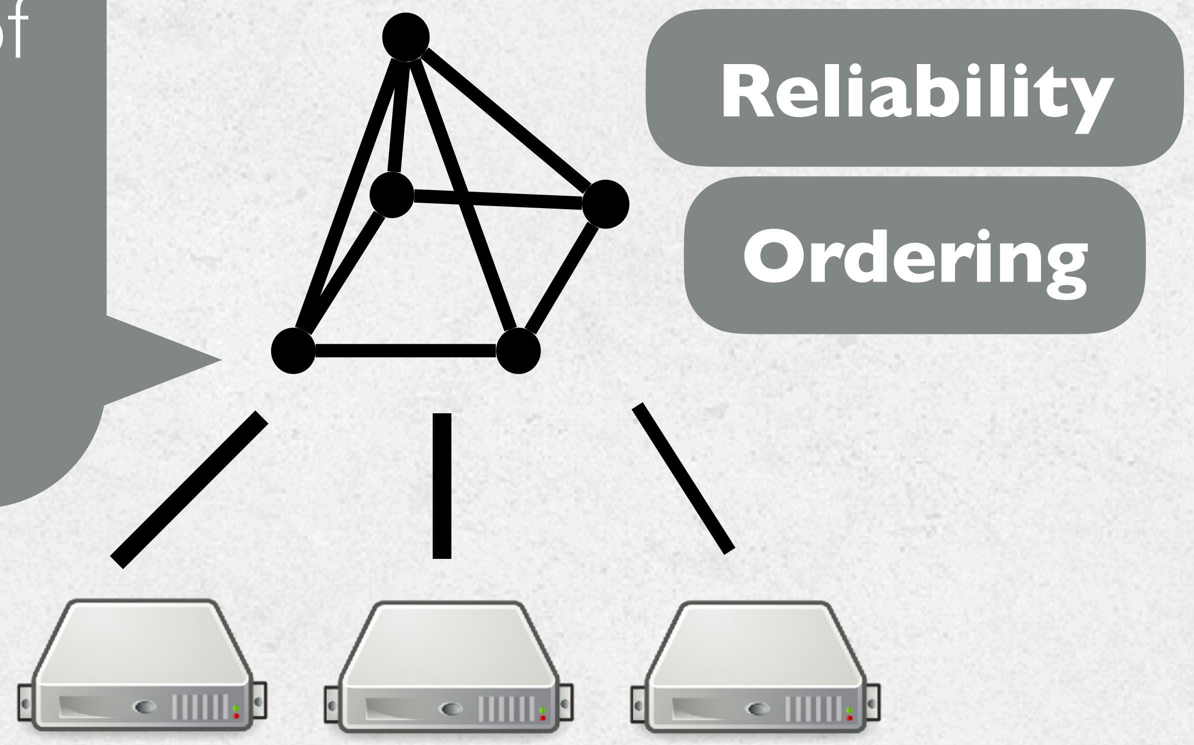
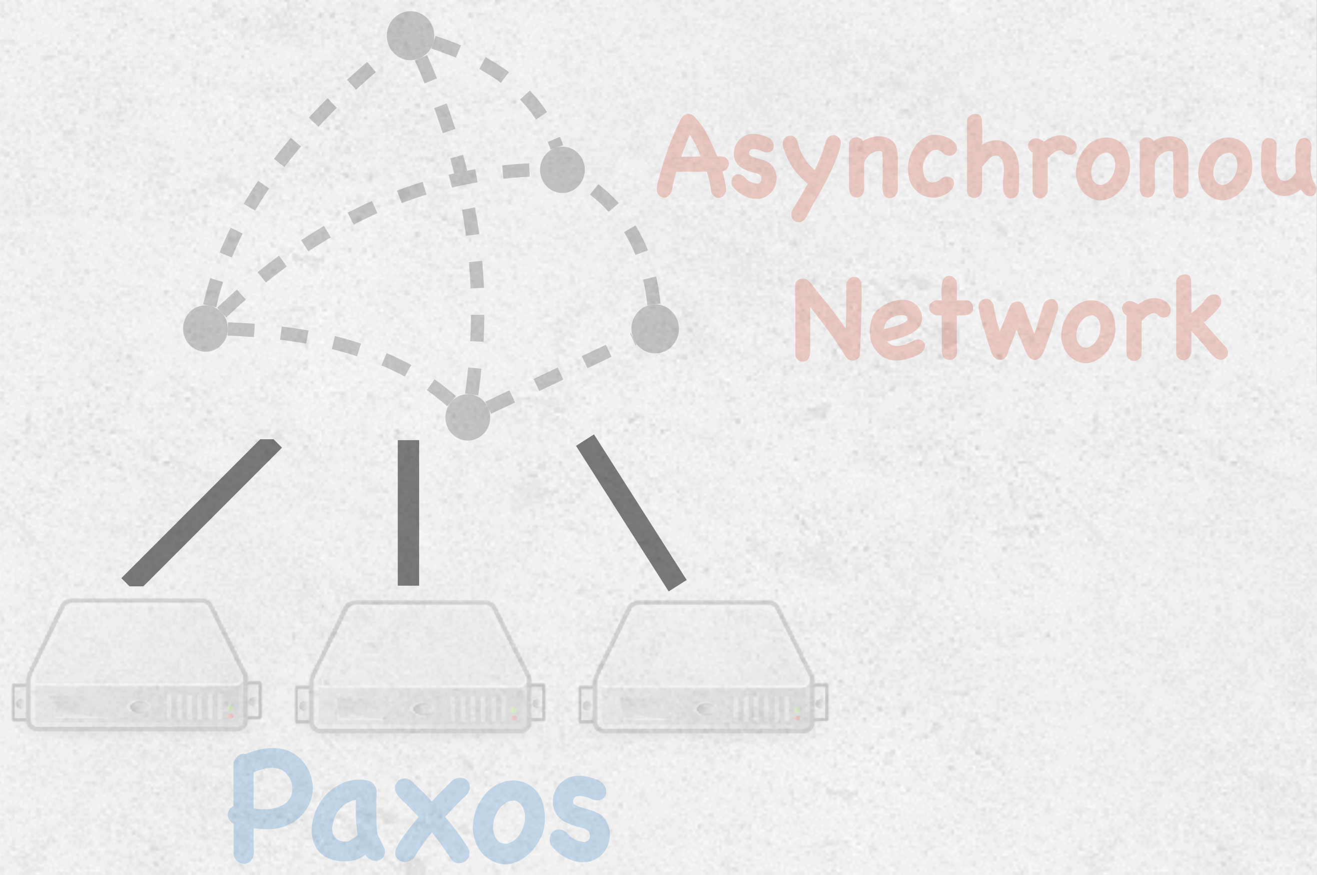


- Replication is trivial

Network properties determine replication complexity



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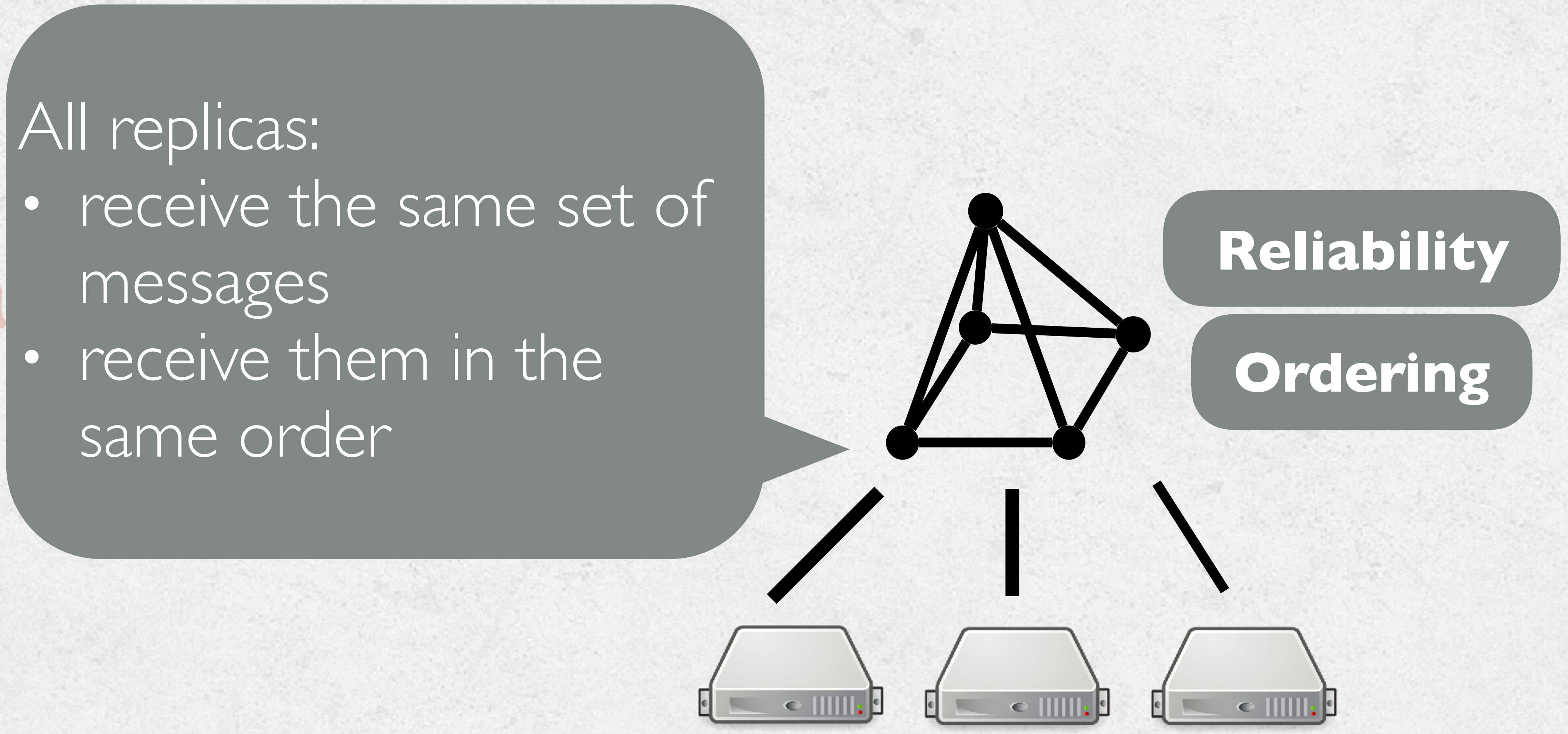
All replicas:

- receive the same set of messages
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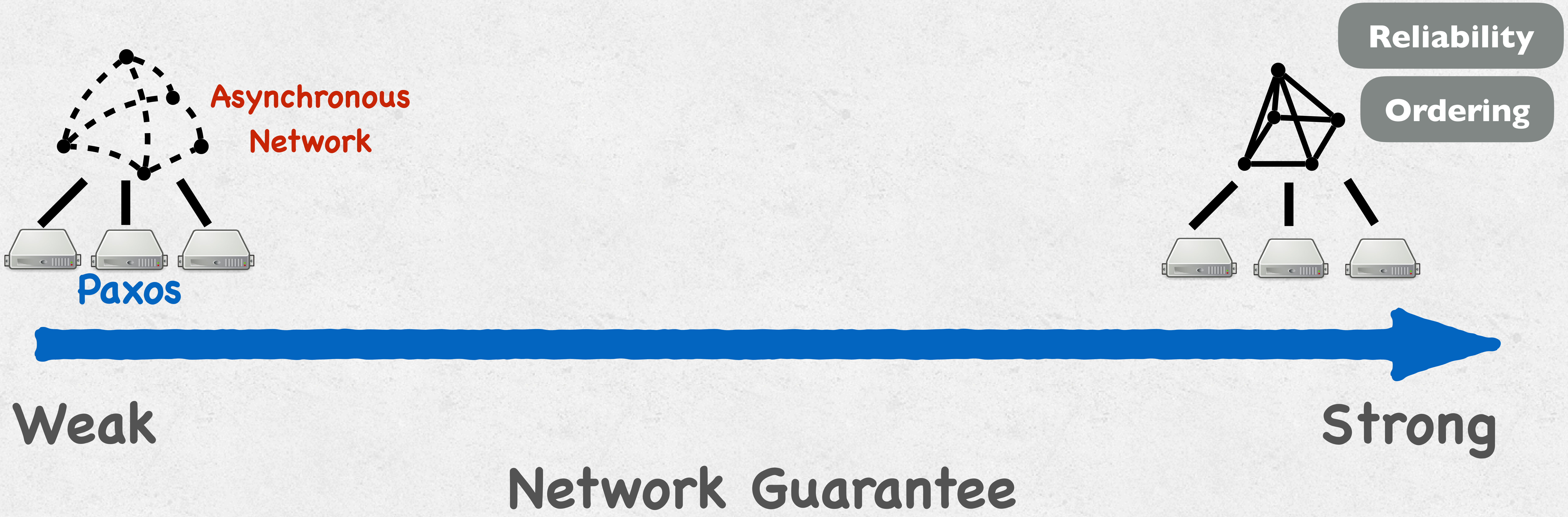
- Replication is trivial
- Network implementation has the same complexity as Paxos



Asynchronous Network

Paxos

Reliability

Ordering

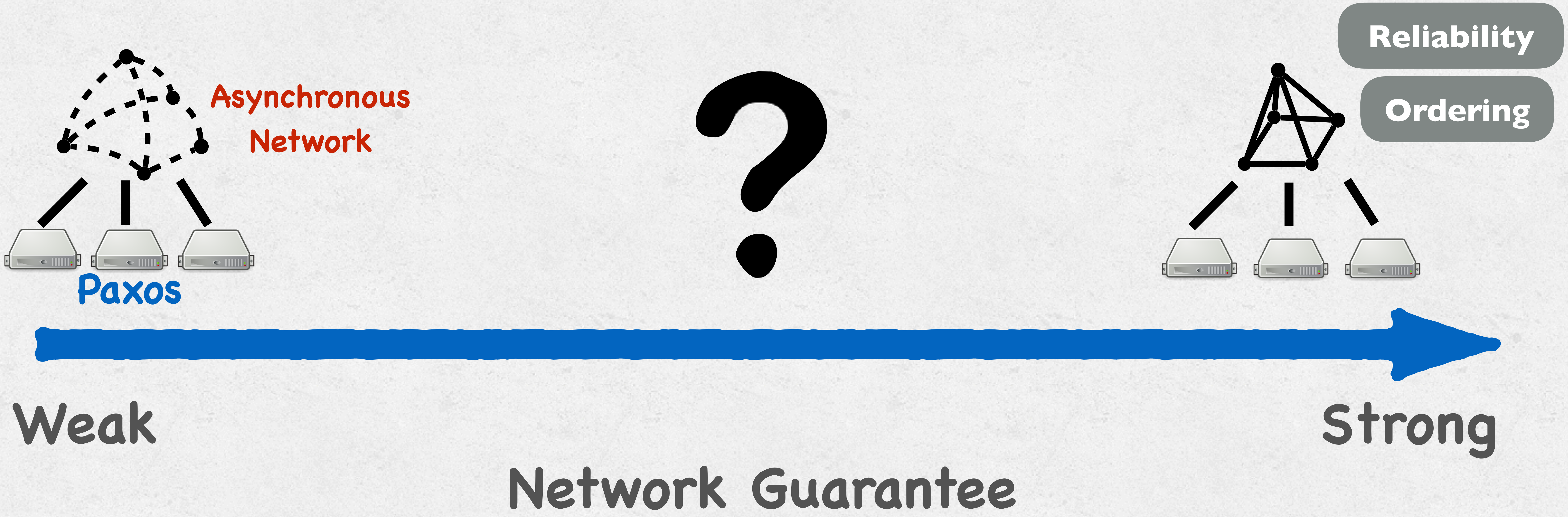
Weak

Strong

Network Guarantee

Can we build a network model that:

- provides **performance benefits**
- can be implemented more **efficiently**



SpecPaxos assumed the network was *mostly ordered*

What if it could provide an *ordering guarantee*?

Towards an ordered but unreliable network

Key Idea: Separate **ordering** from **reliable delivery** in state machine replication

Network provides **ordering**

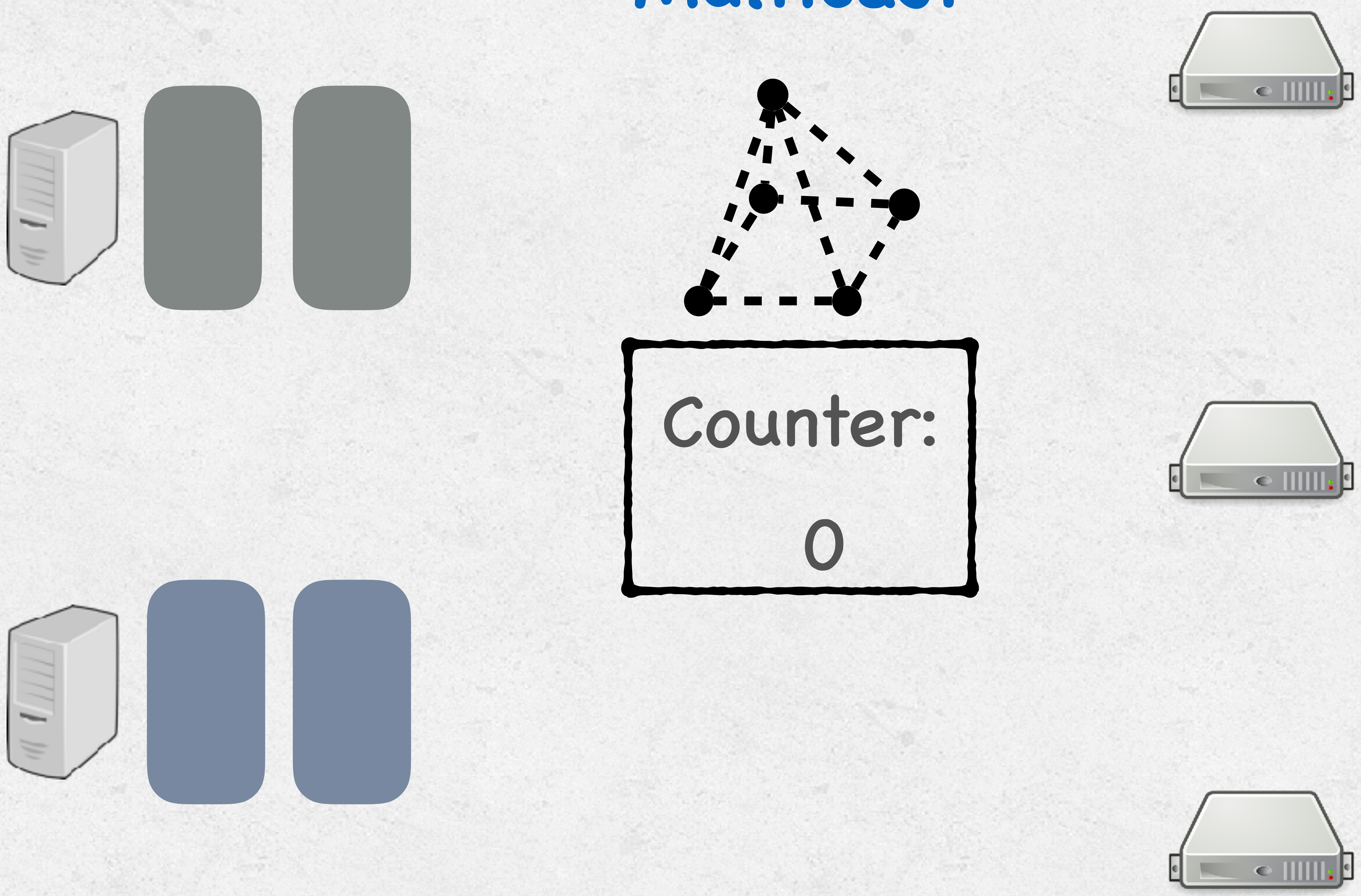
Replication protocol handles **reliability**

OUM Approach

- Designate one **sequencer** in the network
- Sequencer maintains a counter for each OUM group

1. Forward OUM messages to the sequencer
2. Sequencer increments counter and writes counter value into packet headers
3. Receivers use sequence numbers to detect **reordering** and **message drops**

Ordered Unreliable Multicast



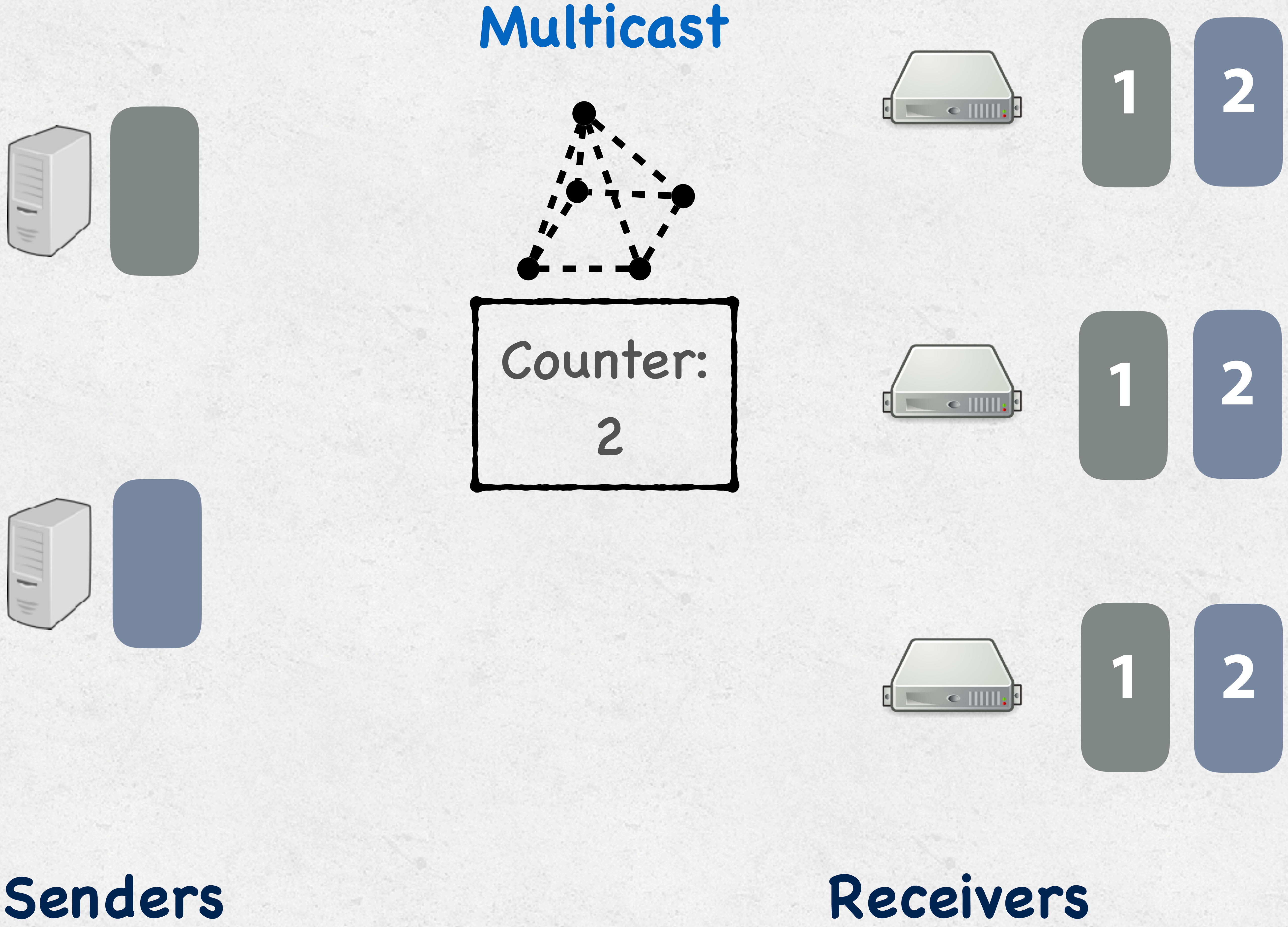
Counter:

0

Senders

Receivers

Ordered Unreliable Multicast



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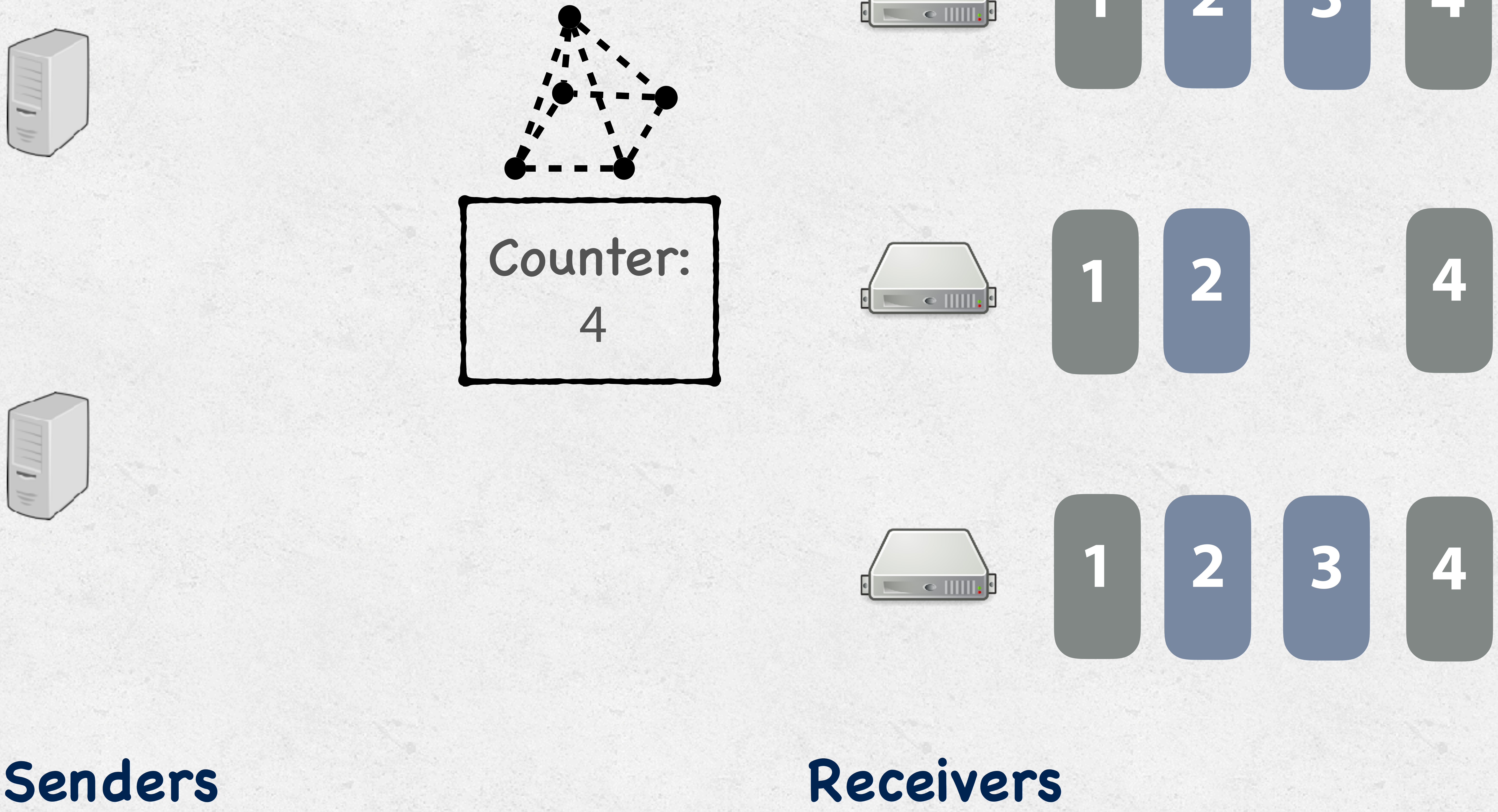

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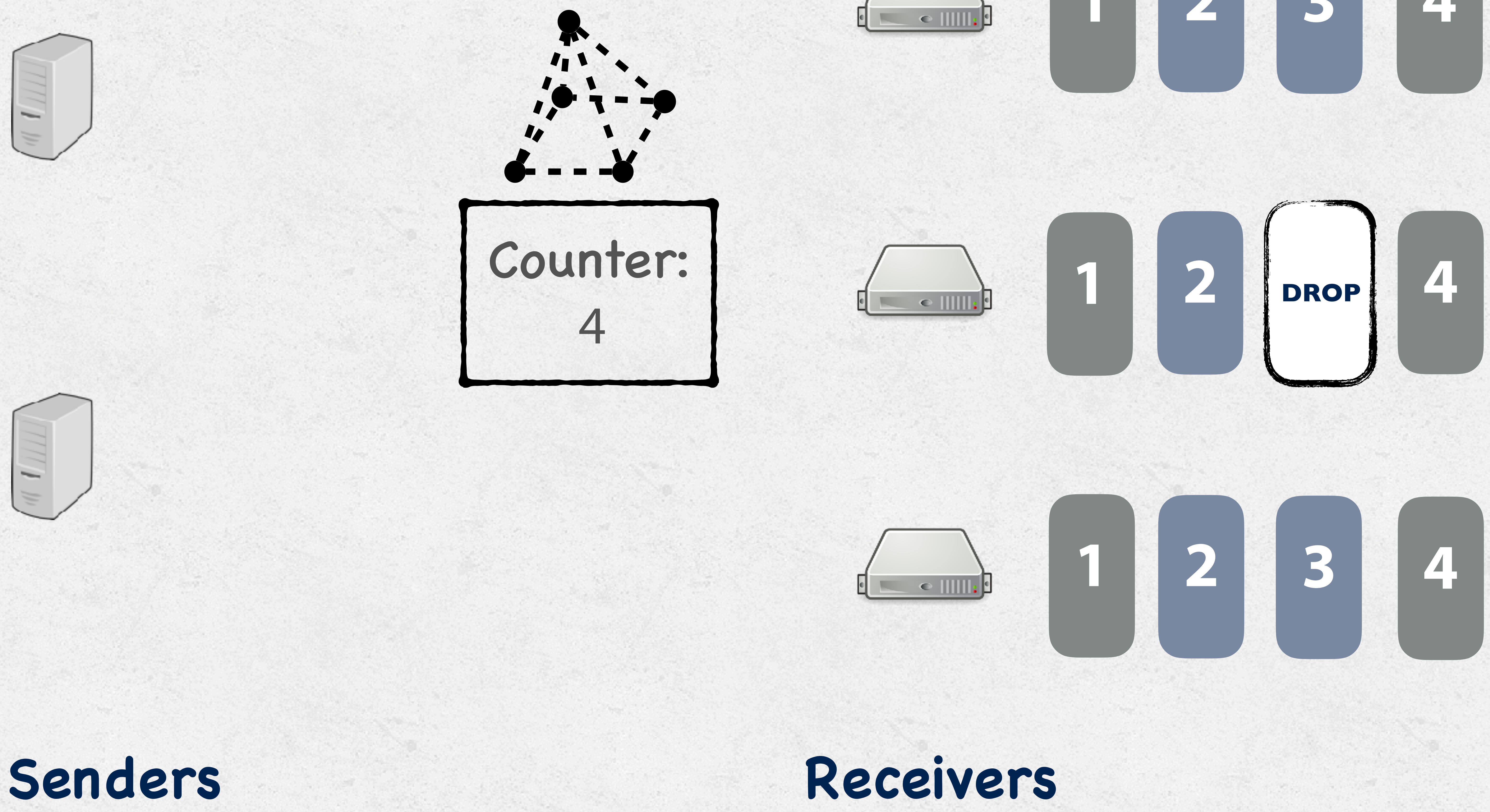
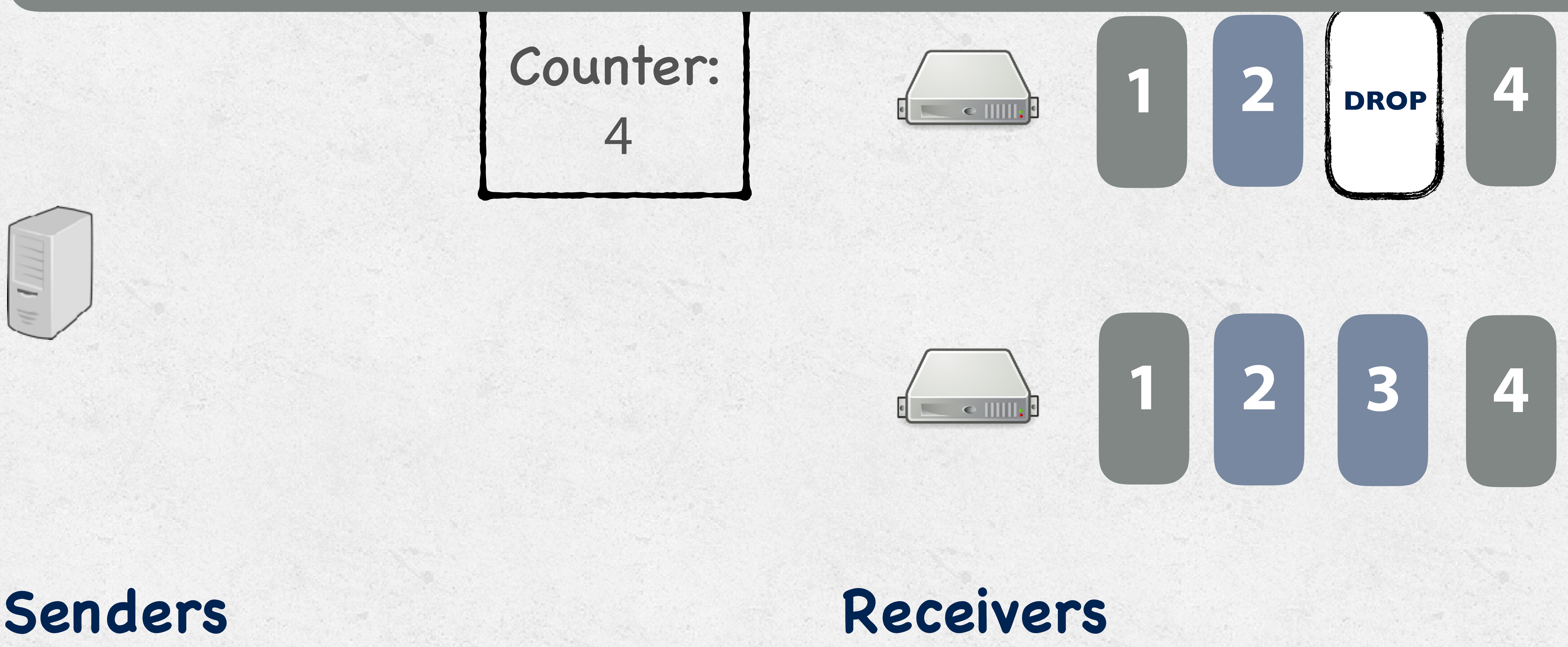
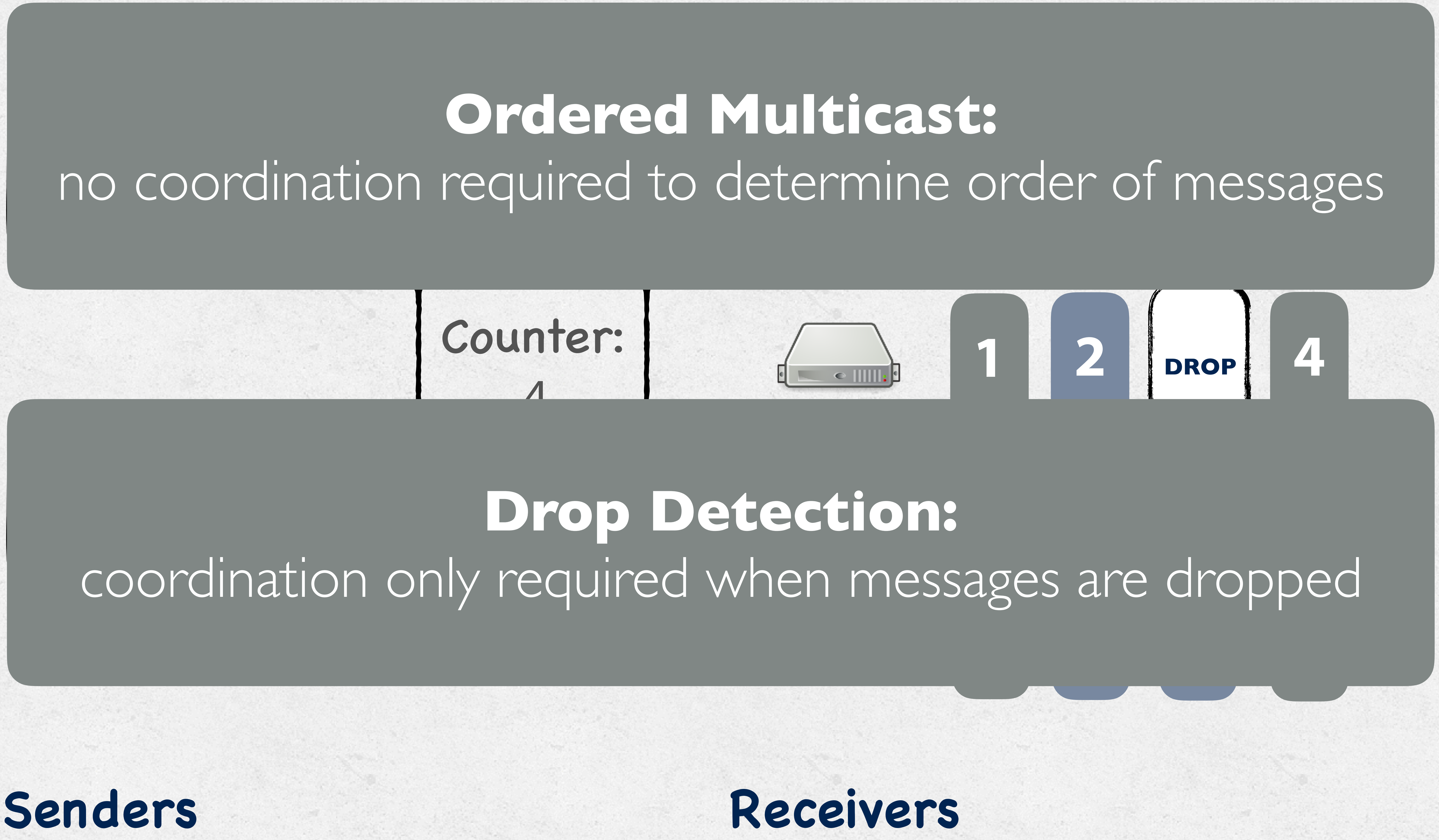


Ordered Unreliable

Ordered Multicast:
no coordination required to determine order of messages



Ordered Unreliable



Ordered Multicast:
no coordination required to determine order of messages

Drop Detection:
coordination only required when messages are dropped

Sequencer Implementations

In-switch sequencing

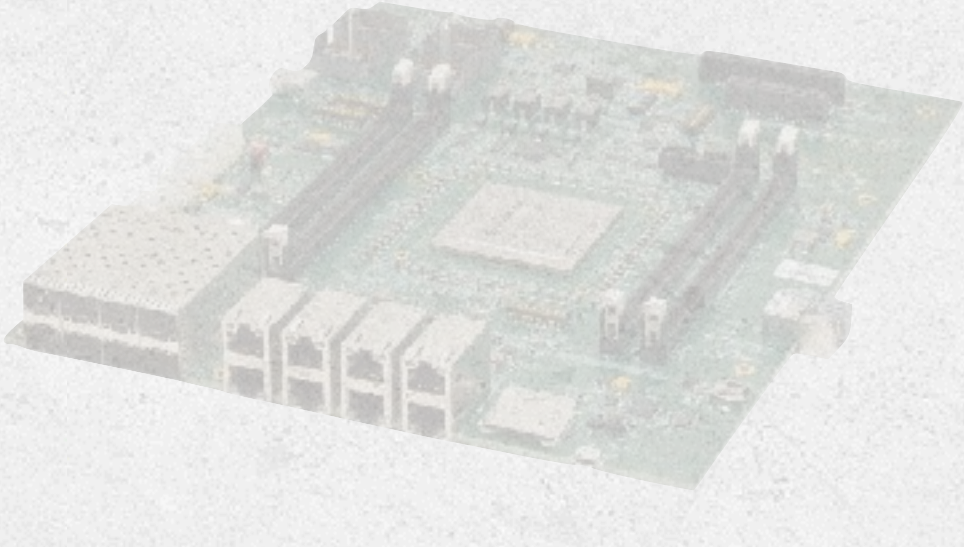
- next generation programmable switches
- implemented in P4
- nearly **zero cost**

Middlebox prototype

- Cavium Octeon network processor
- connects to root switches
- adds 8 us latency

End-host sequencing

- no specialized hardware required
- incurs higher latency penalties
- similar throughput benefits



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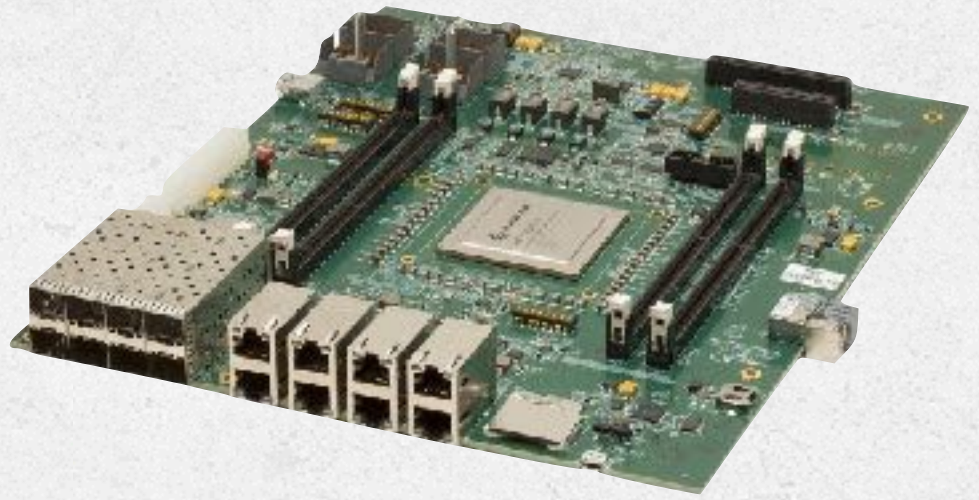

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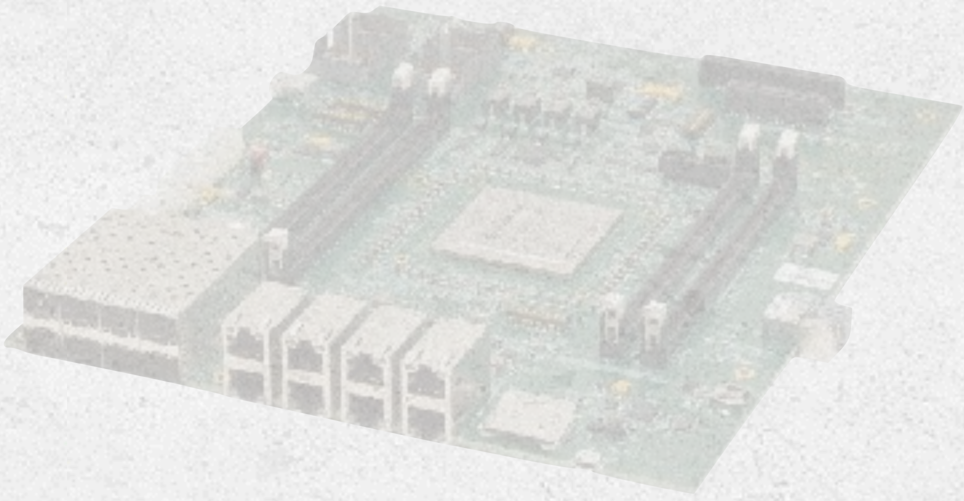


NOPaxos Overview

- Built on top of the guarantees of OUM
- Client requests are **totally ordered** but can be dropped
- **No coordination** in the common case
- Replicas run agreement on drop detection
- View change protocol for leader or sequencer failure

Normal Operation

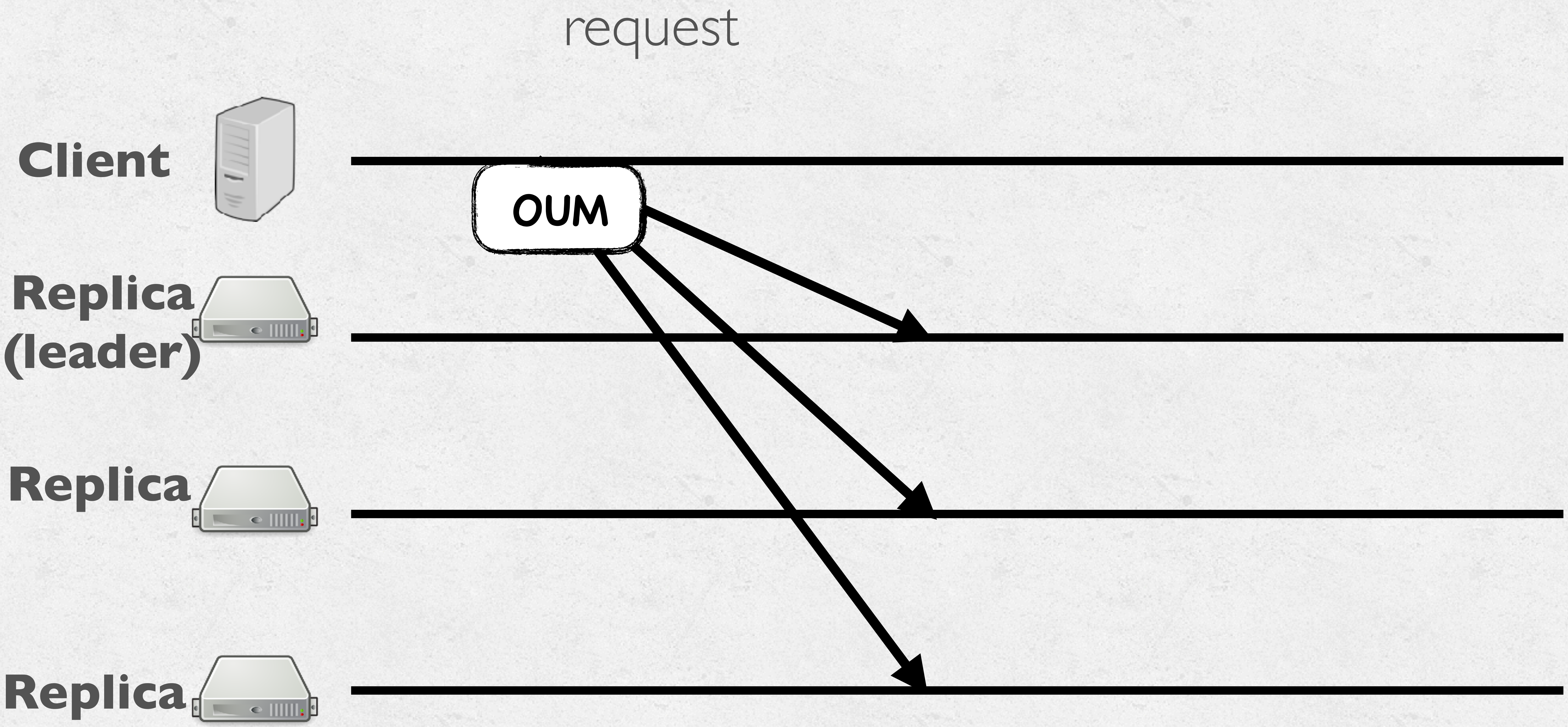
Client

Replica (leader)

Replica

Replica

Normal Operation



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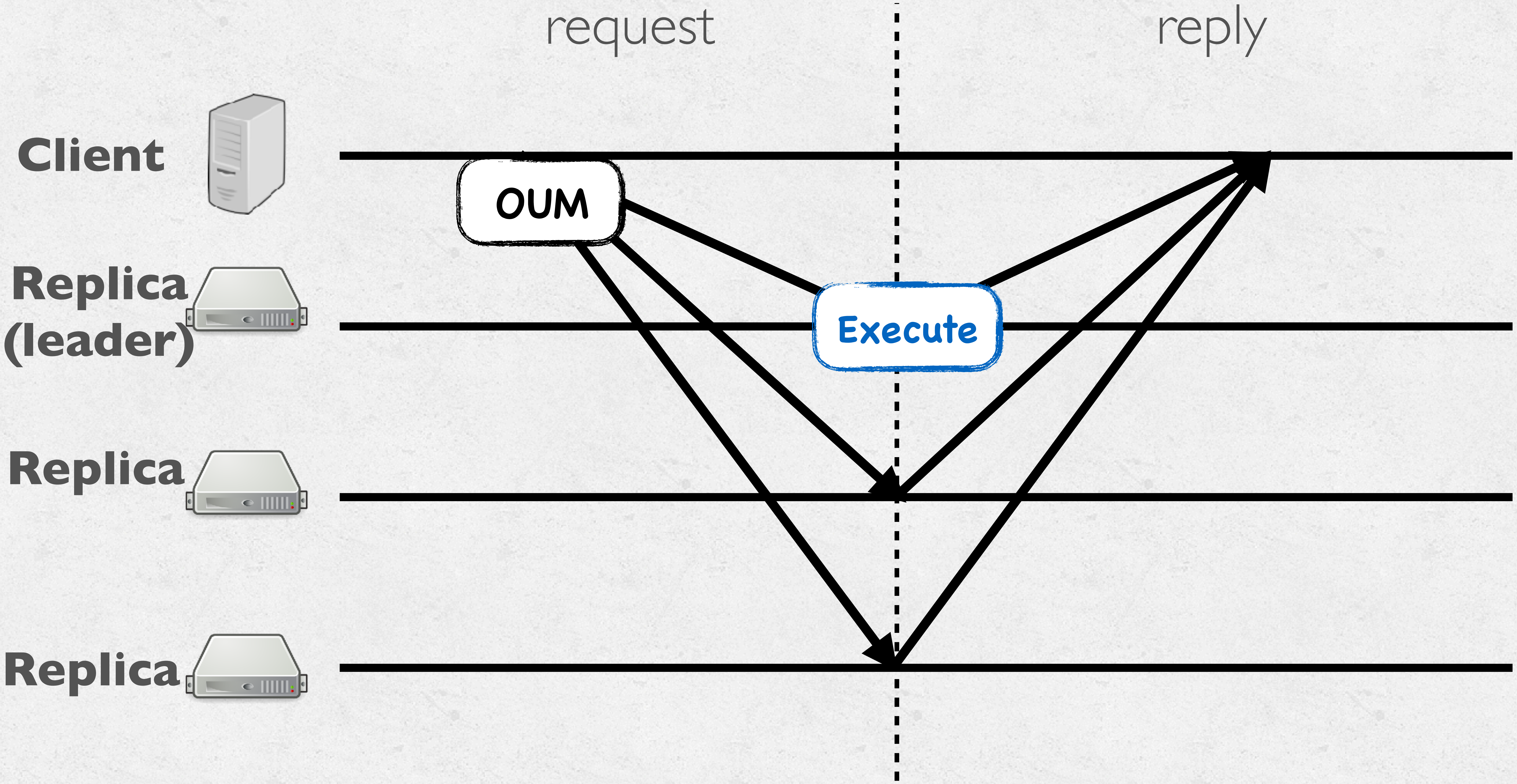

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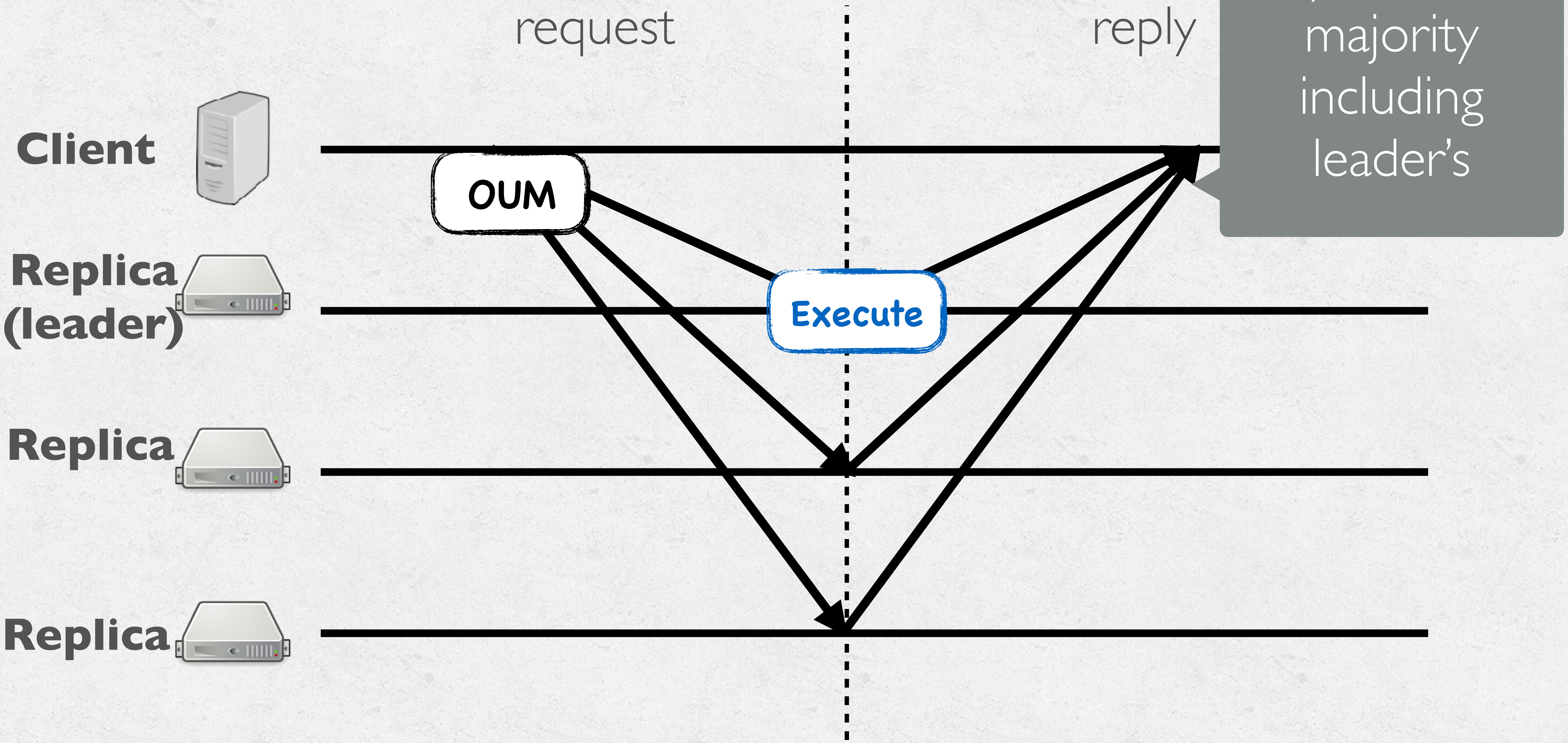
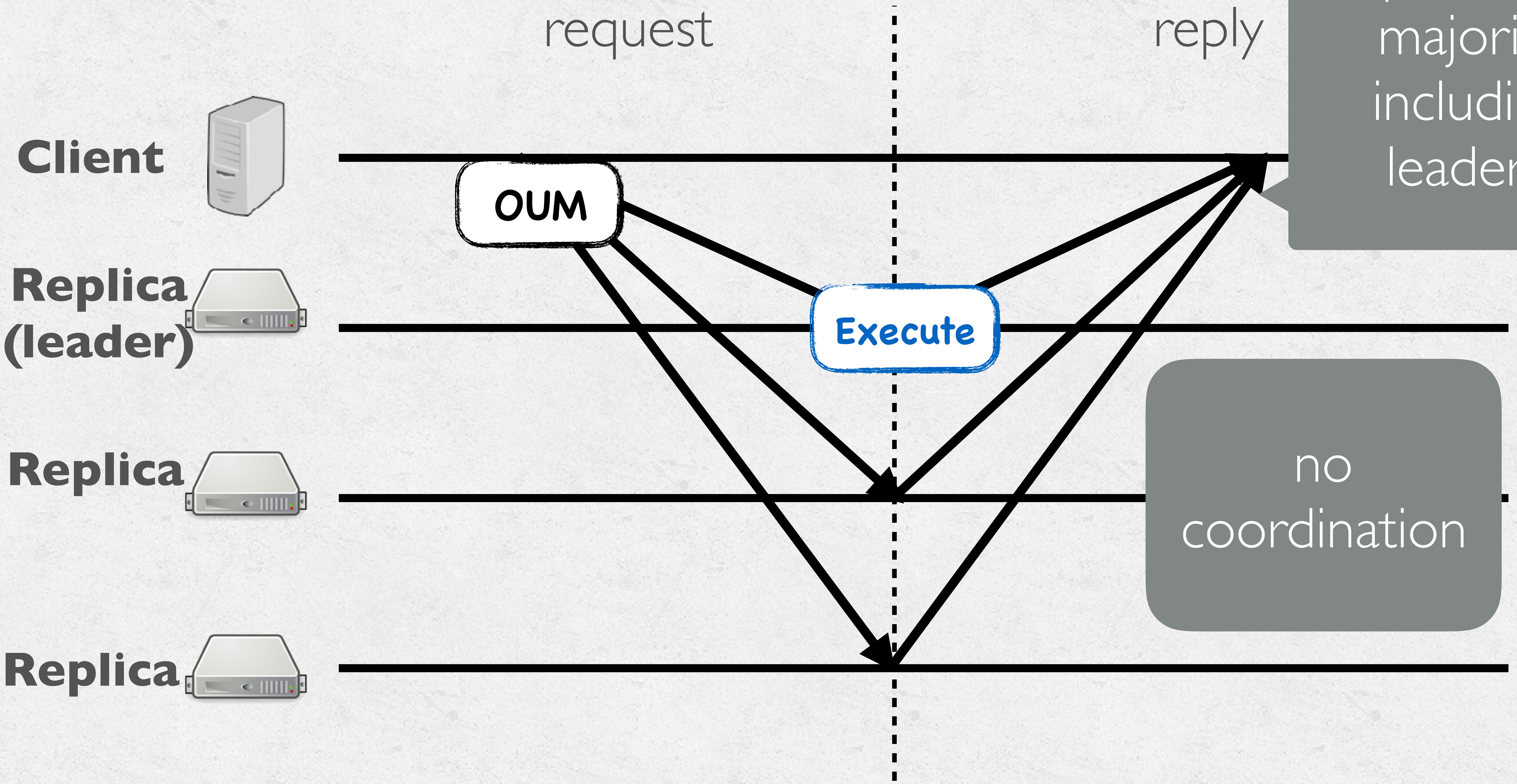


waits for replies from majority including leader’s

Normal Operation



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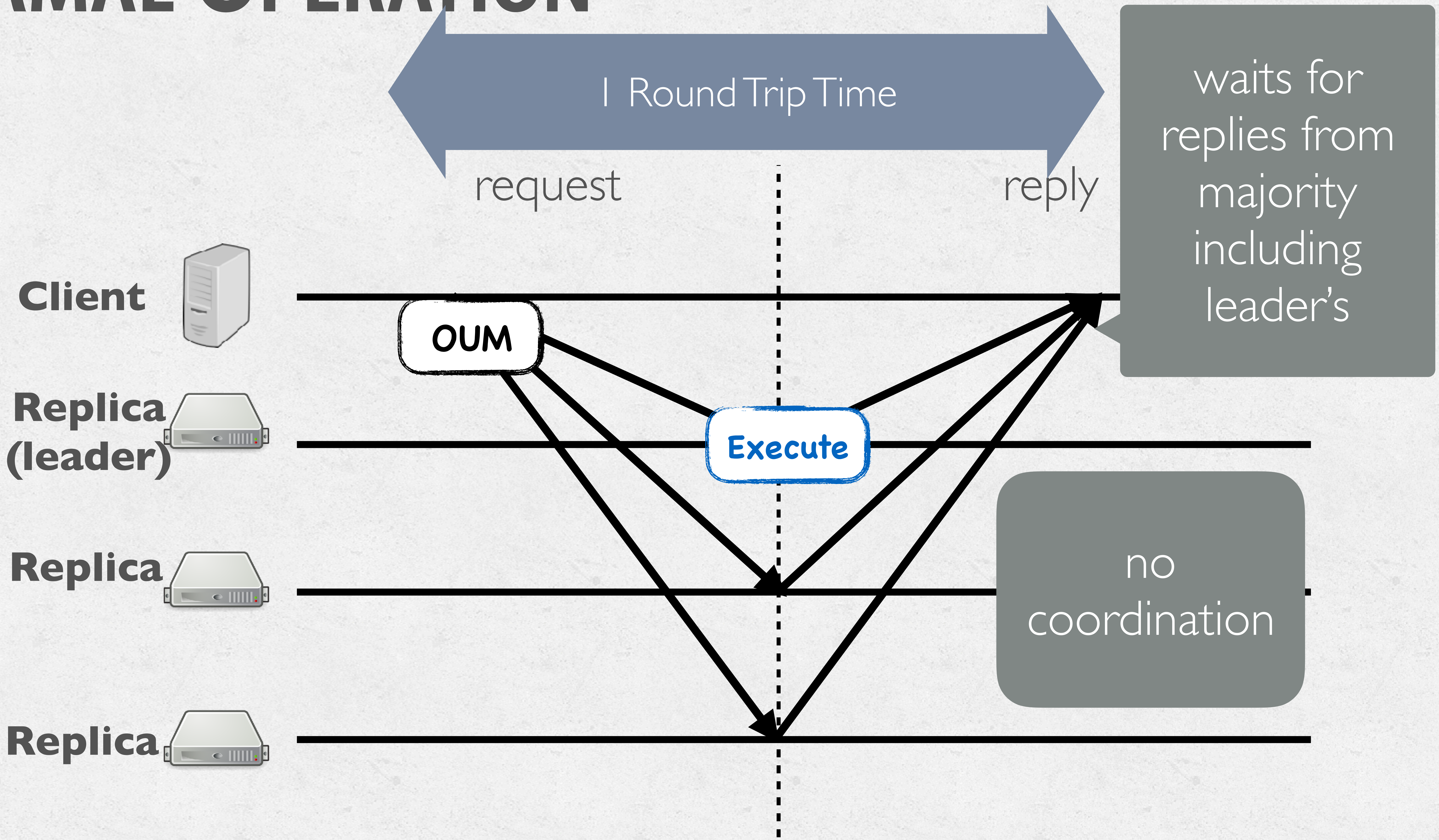


waits for replies from majority including leader’s

no coordination

Gap Agreement

Replicas detect message drops.

- **Non-leader replicas:** recover the missing message from the leader
- **Leader replica:** coordinates to commit a NO-OP (Paxos)

- Efficient recovery from network anomalies

Why Do Followers Not Execute?

- Request logs in NOPaxos are **non-authoritative**. The followers might not be involved in the quorum to commit a no-op. The leader might get replaced.

- Followers simply log operations. Operations are permanently committed with periodic **synchronization**.

- If a leader gets replaced and discovers that some of its commands weren't actually committed, it can roll-back or get a state transfer.

View Change

- Handles leader or sequencer failure
- Ensures that all replicas are in a **consistent state** and agree on all of the commands and no-ops committed in the previous view.
- Runs a view change protocol similar to VR
- *view-number* is a tuple of *<leader-number, session-number>*

NOPAXOS ACHIEVES BETTER THROUGHPUT AND LATENCY

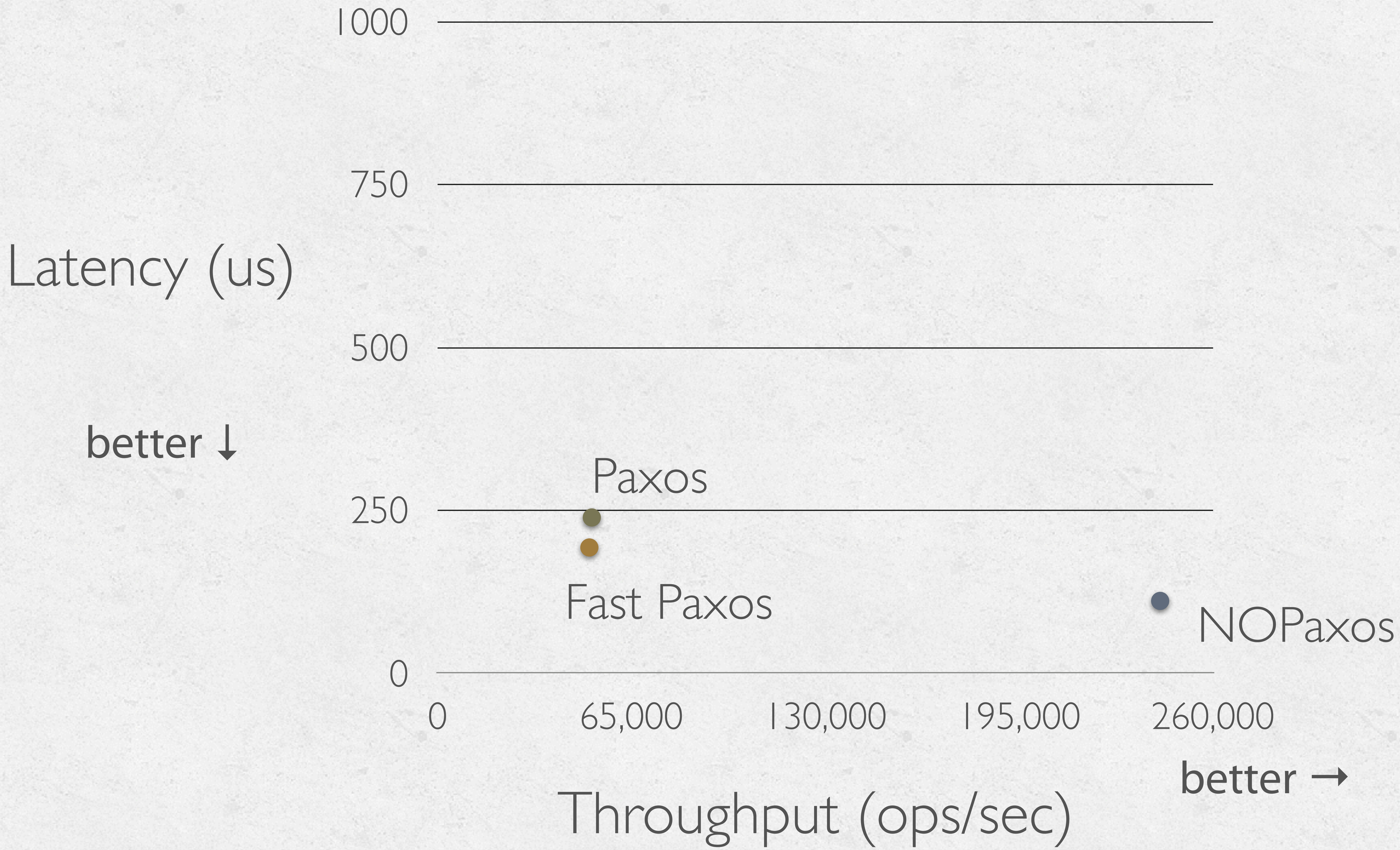
Latency (us)

better ↓

better →

Throughput (ops/sec)

NOPaxos achieves better throughput and latency



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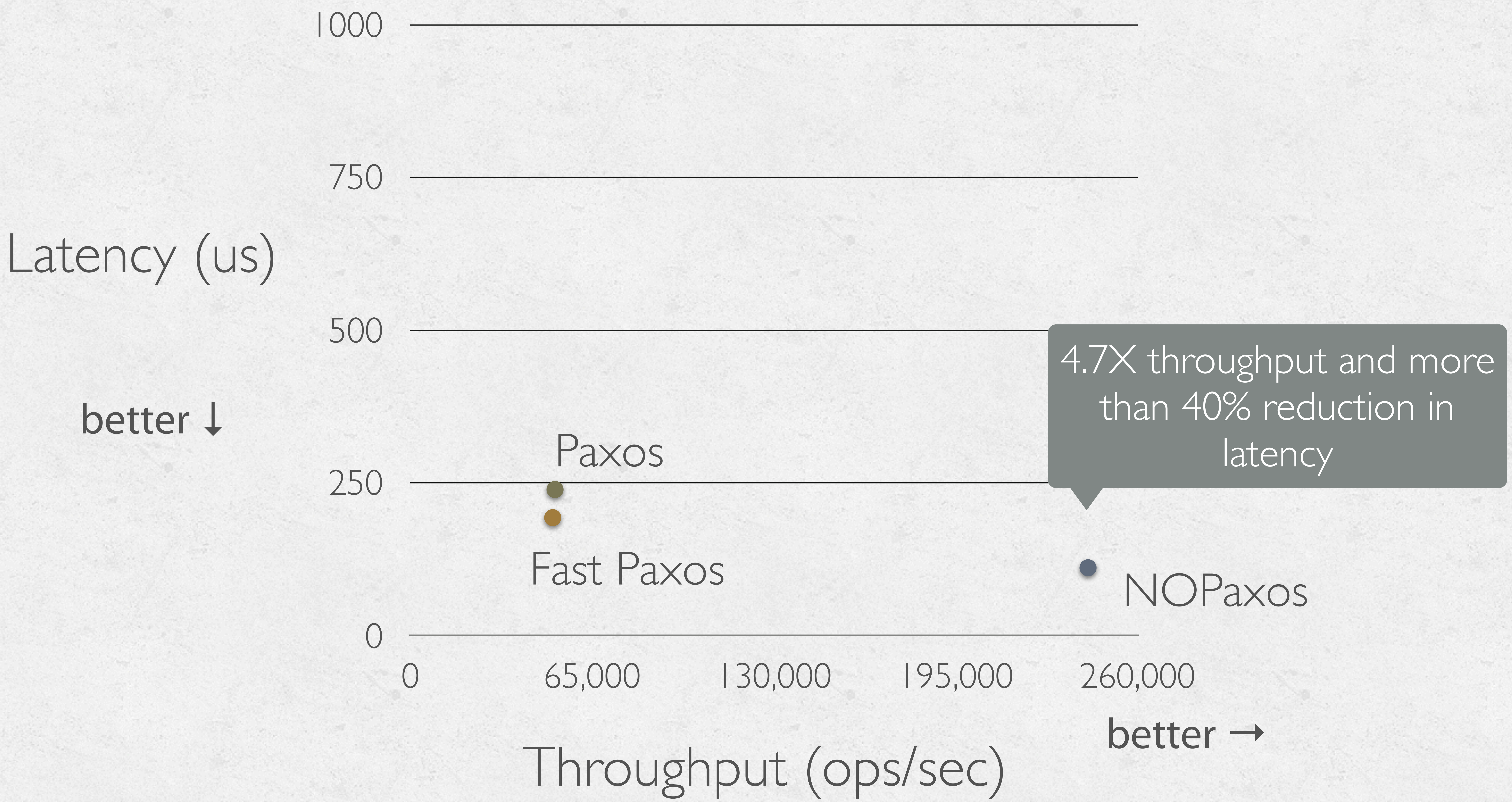
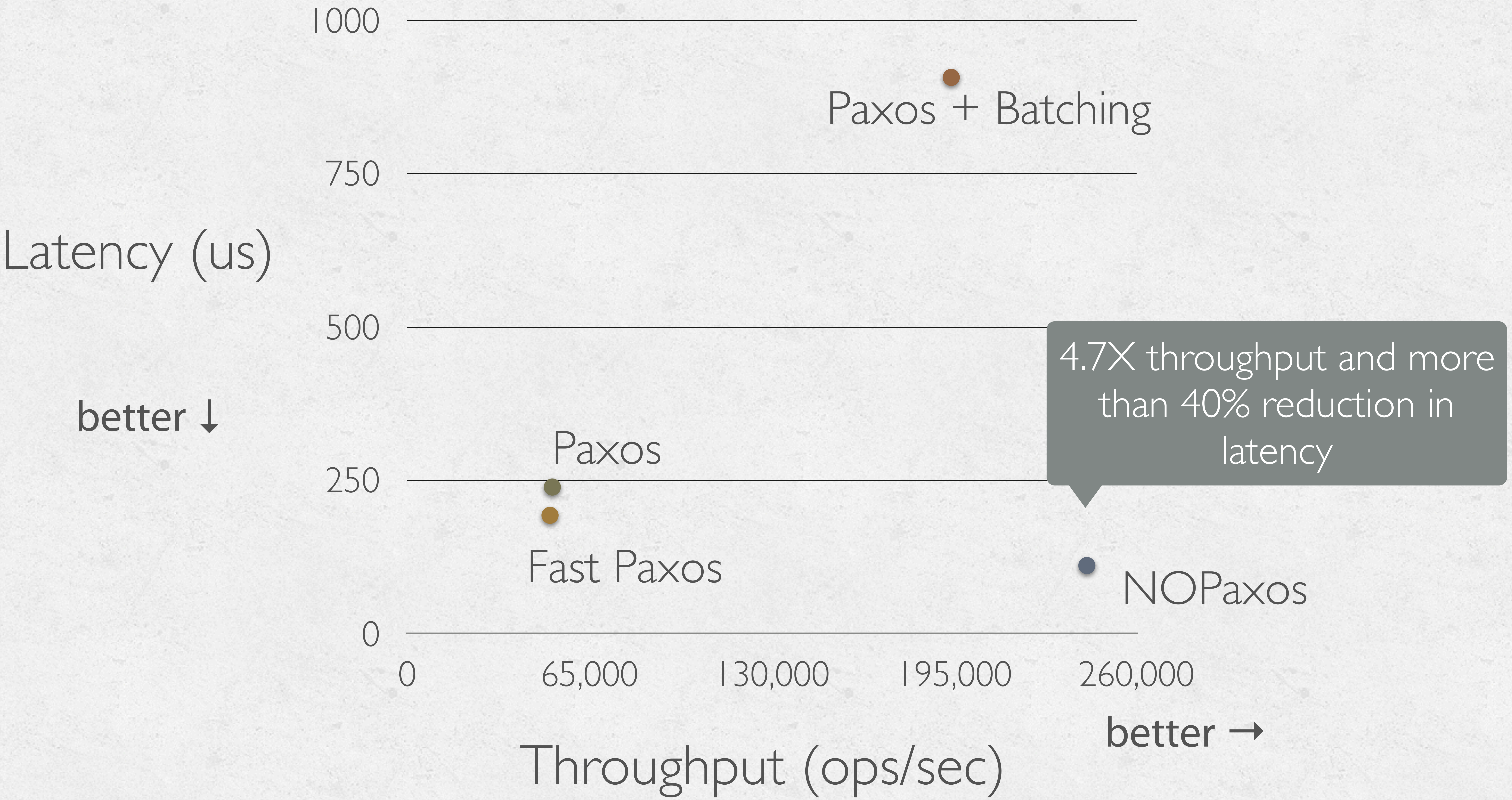


4.7X throughput and more than 40% reduction in latency

NOPaxos achieves better throughput and latency



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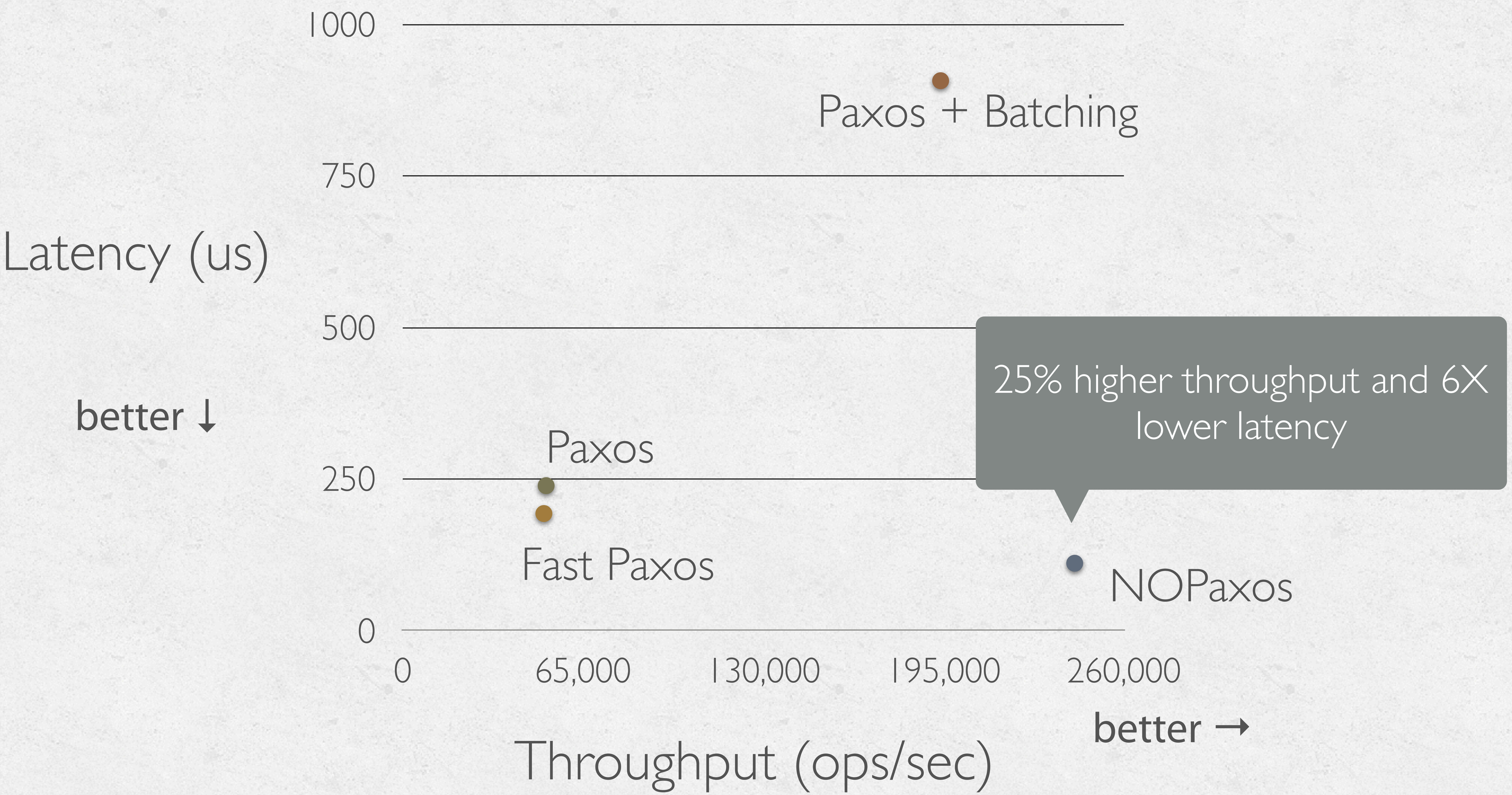
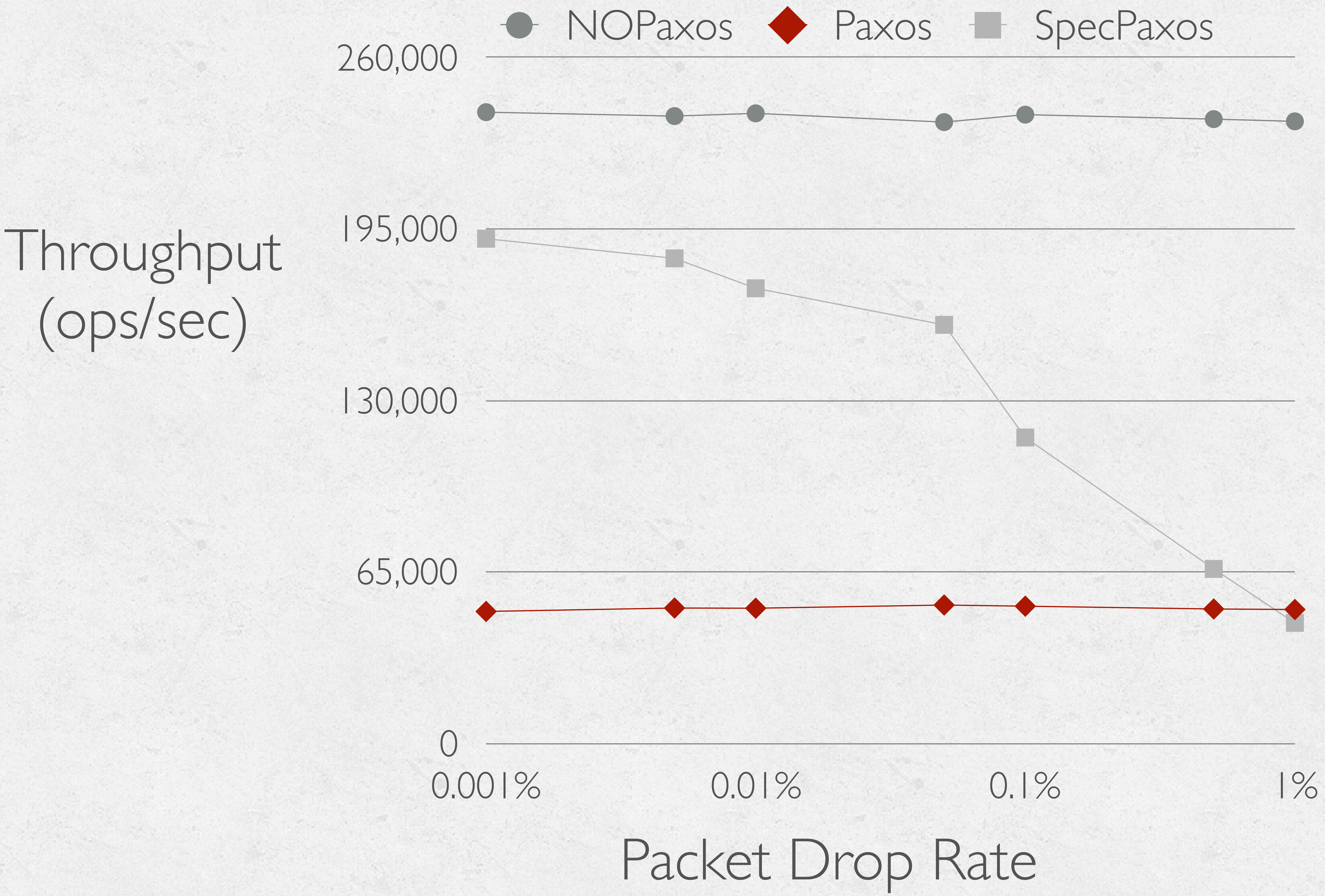
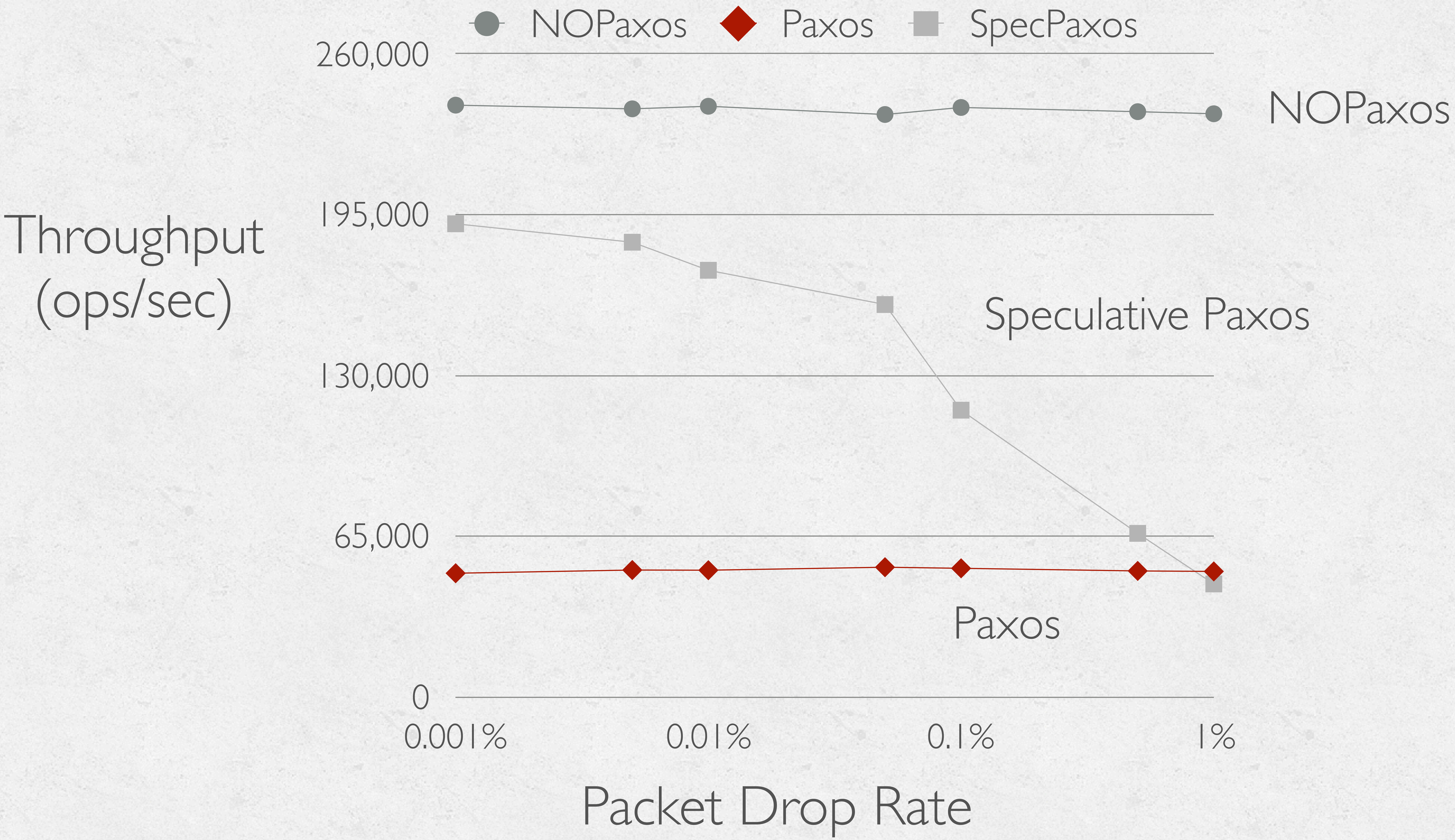


25% higher throughput and 6X lower latency

NOPaxos is resilient to network anomalies



NOPAXOS IS RESILIENT TO NETWORK ANOMALIES



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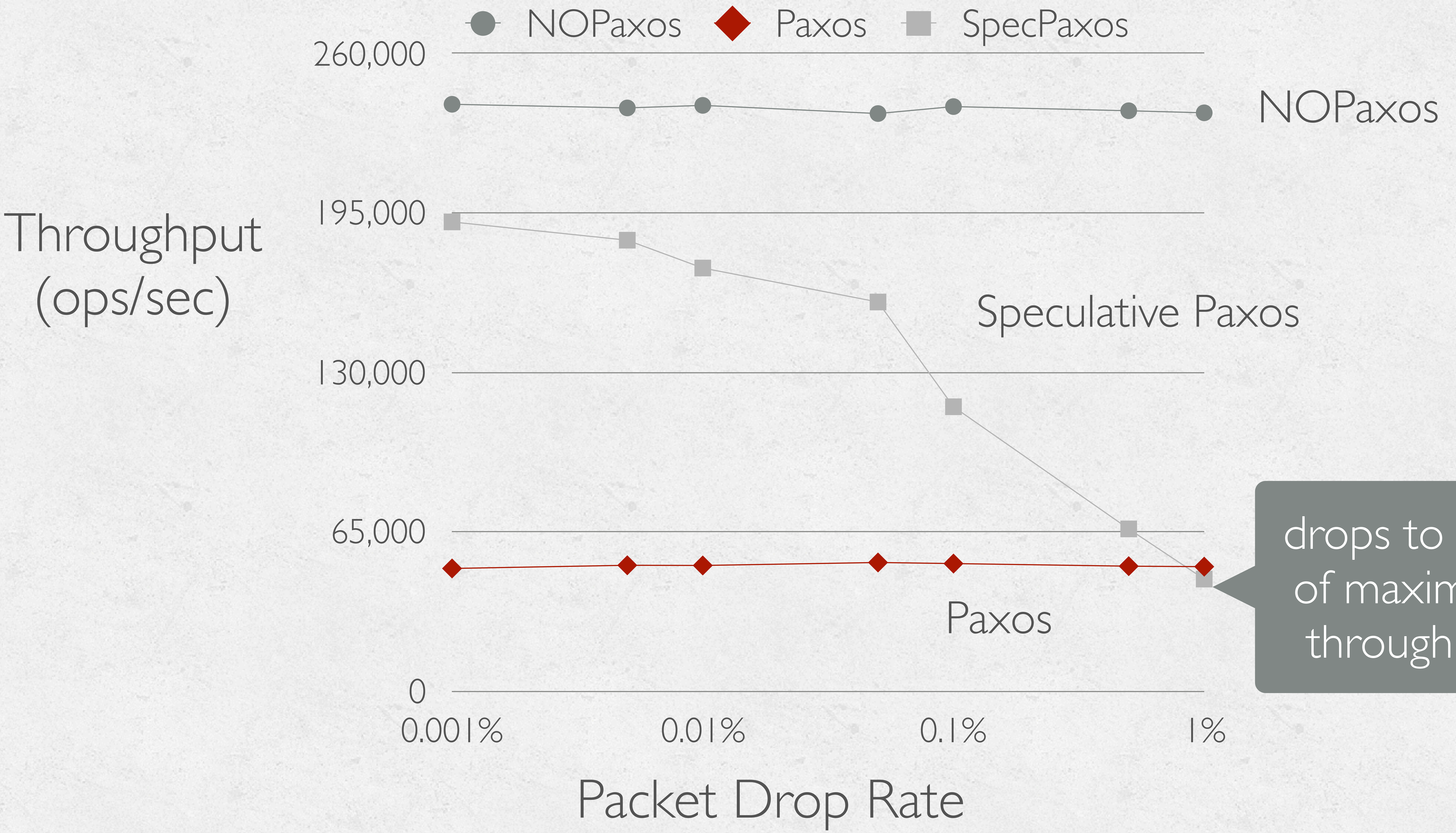
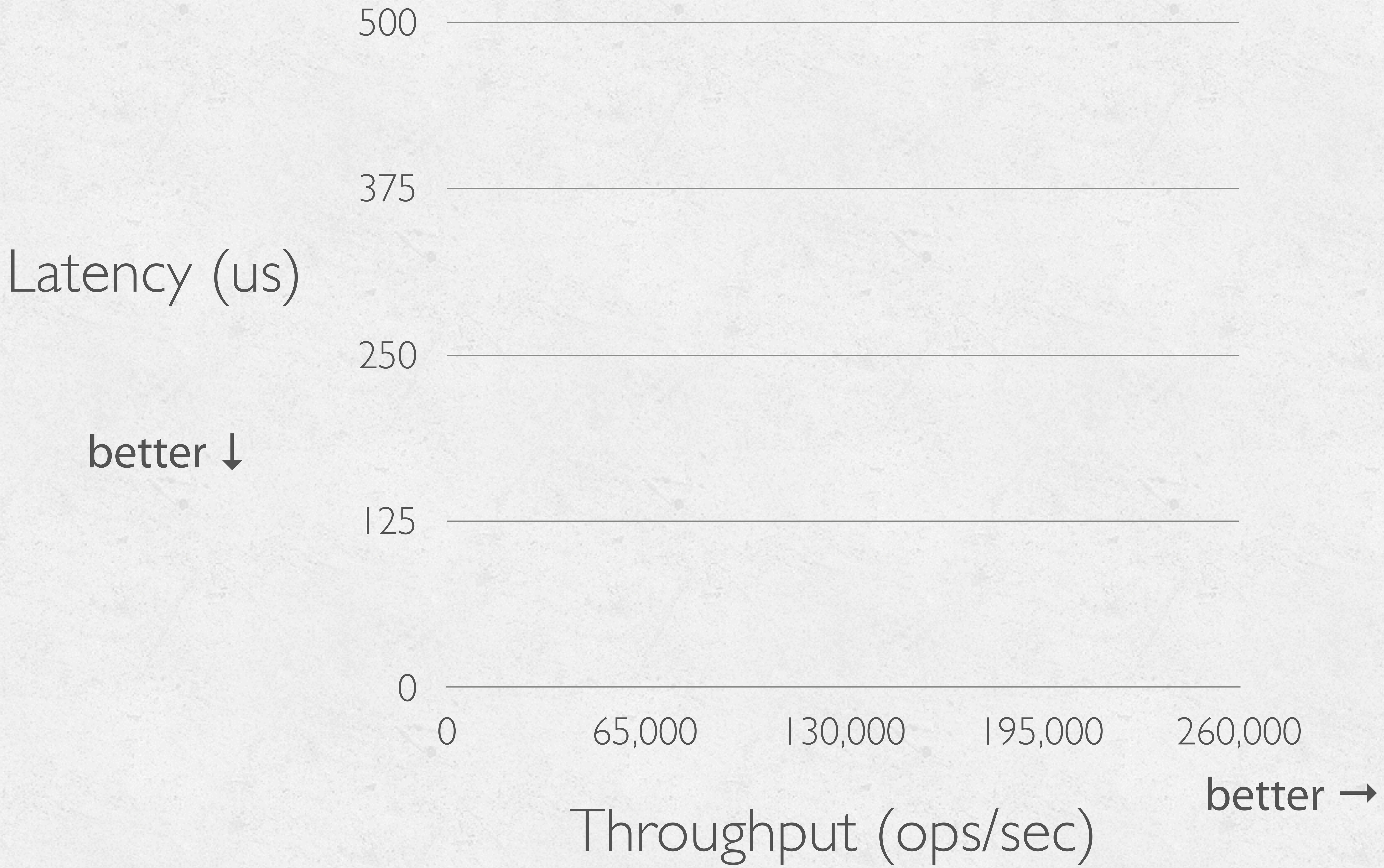


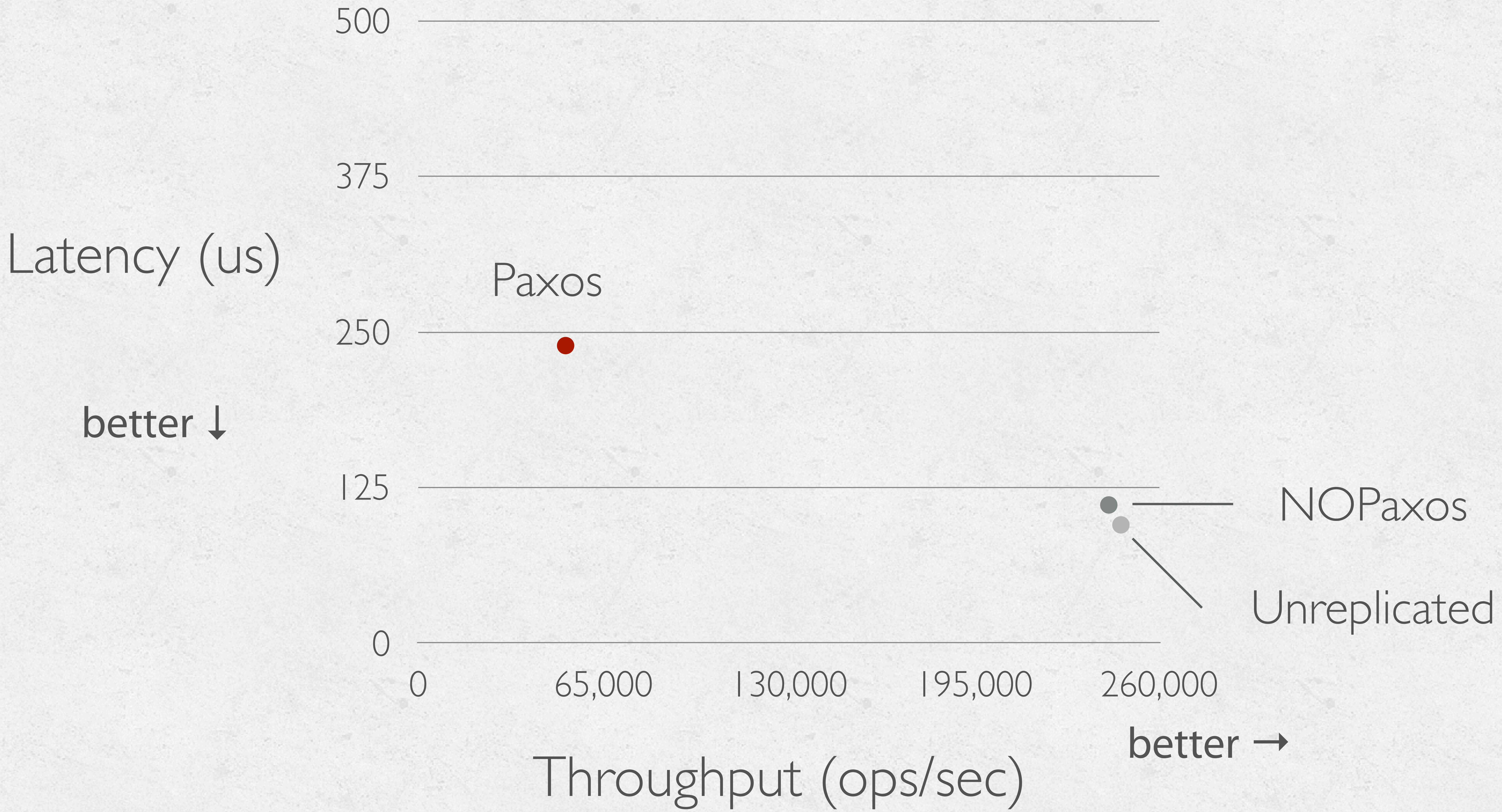
drops to 24% of maximum throughput

NOPaxos attains throughput within 2% of an unreplicated system

NOPAXOS ATTAINS THROUGHPUT WITHIN 2% OF AN UNREPLICATED SYSTEM



NOPaxos attains throughput within 2% of an unreplicated system



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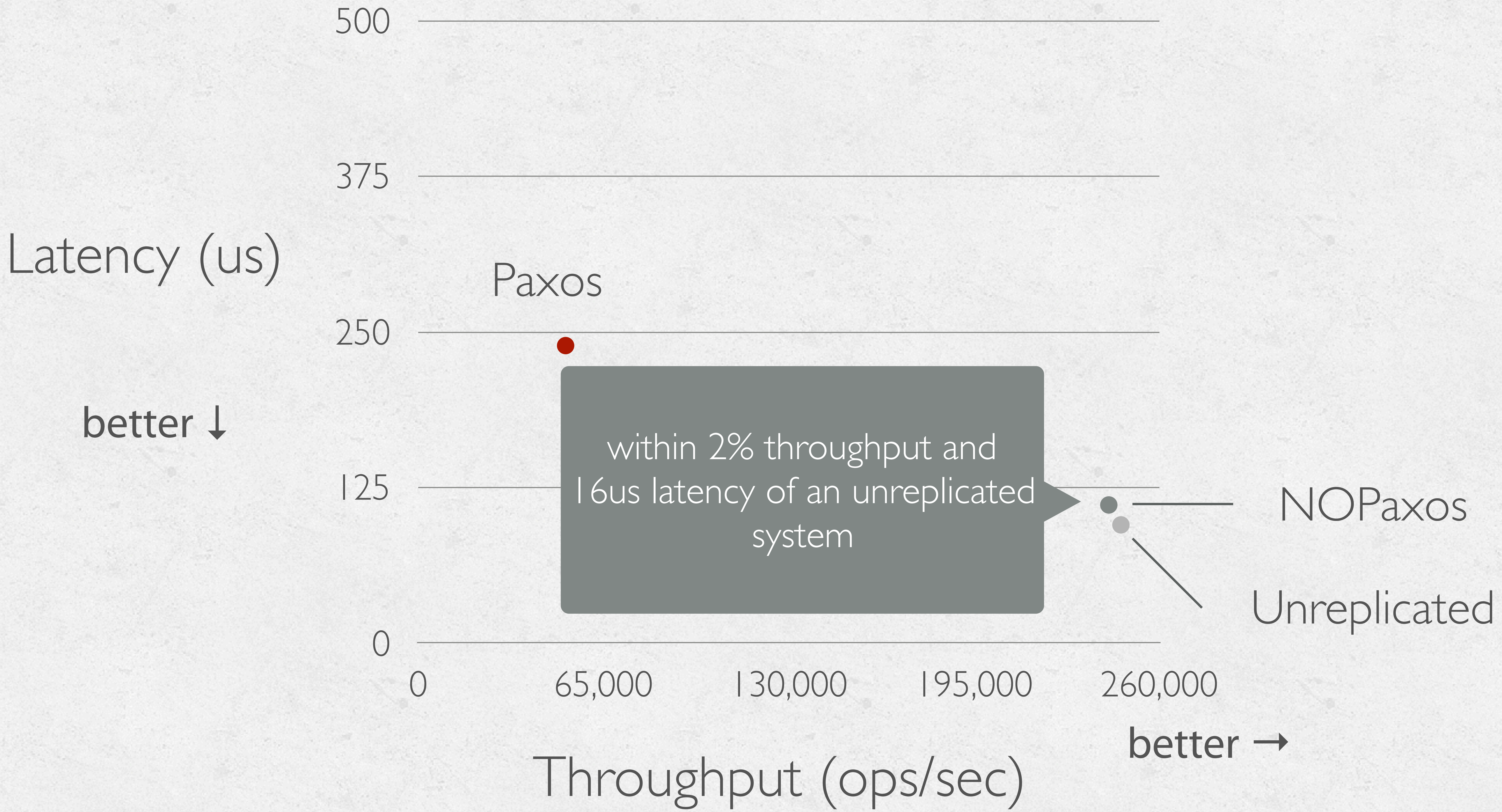
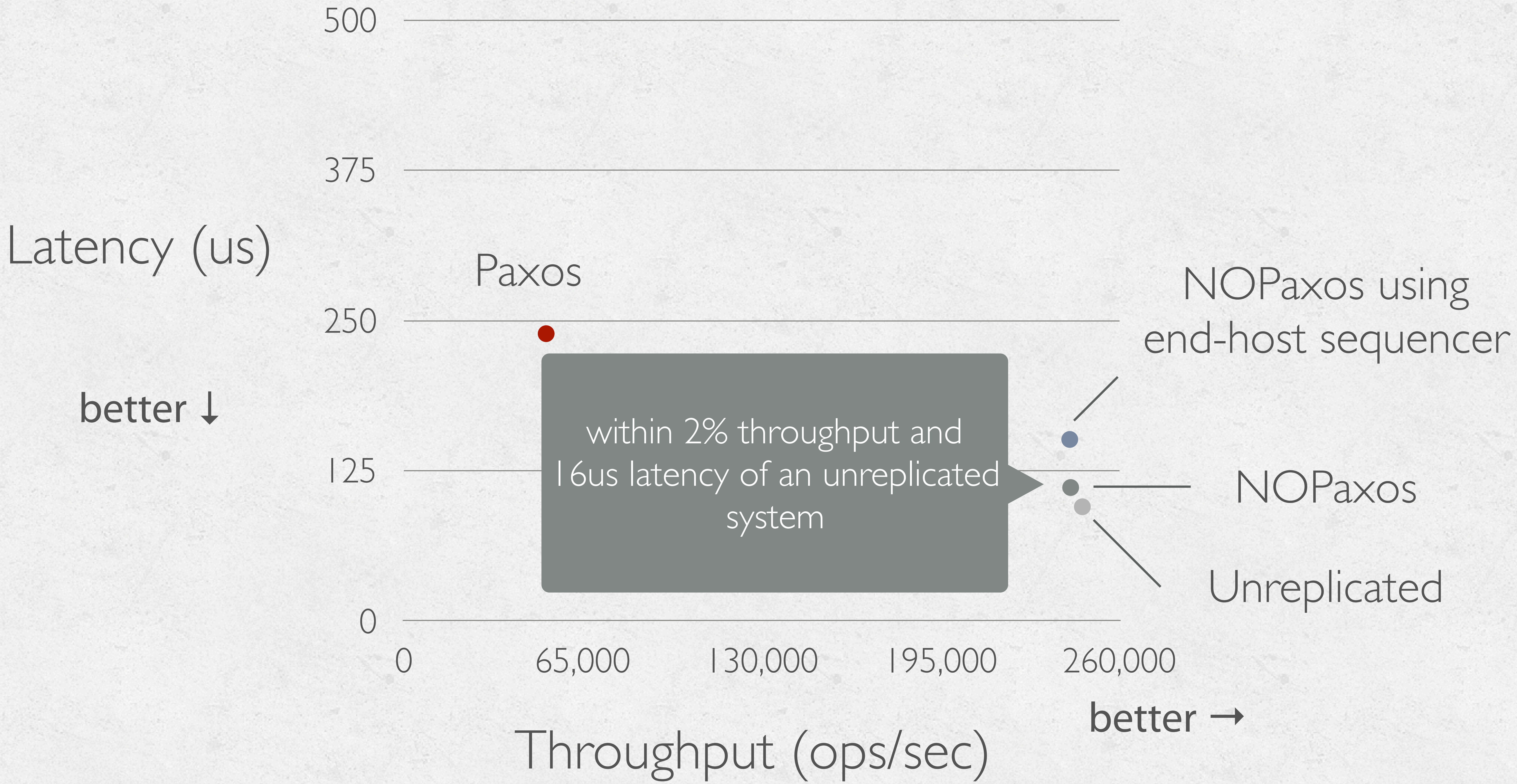


within 2% throughput and 16us latency of an unreplicated system

NOPaxos attains throughput within 2% of an unreplicated system



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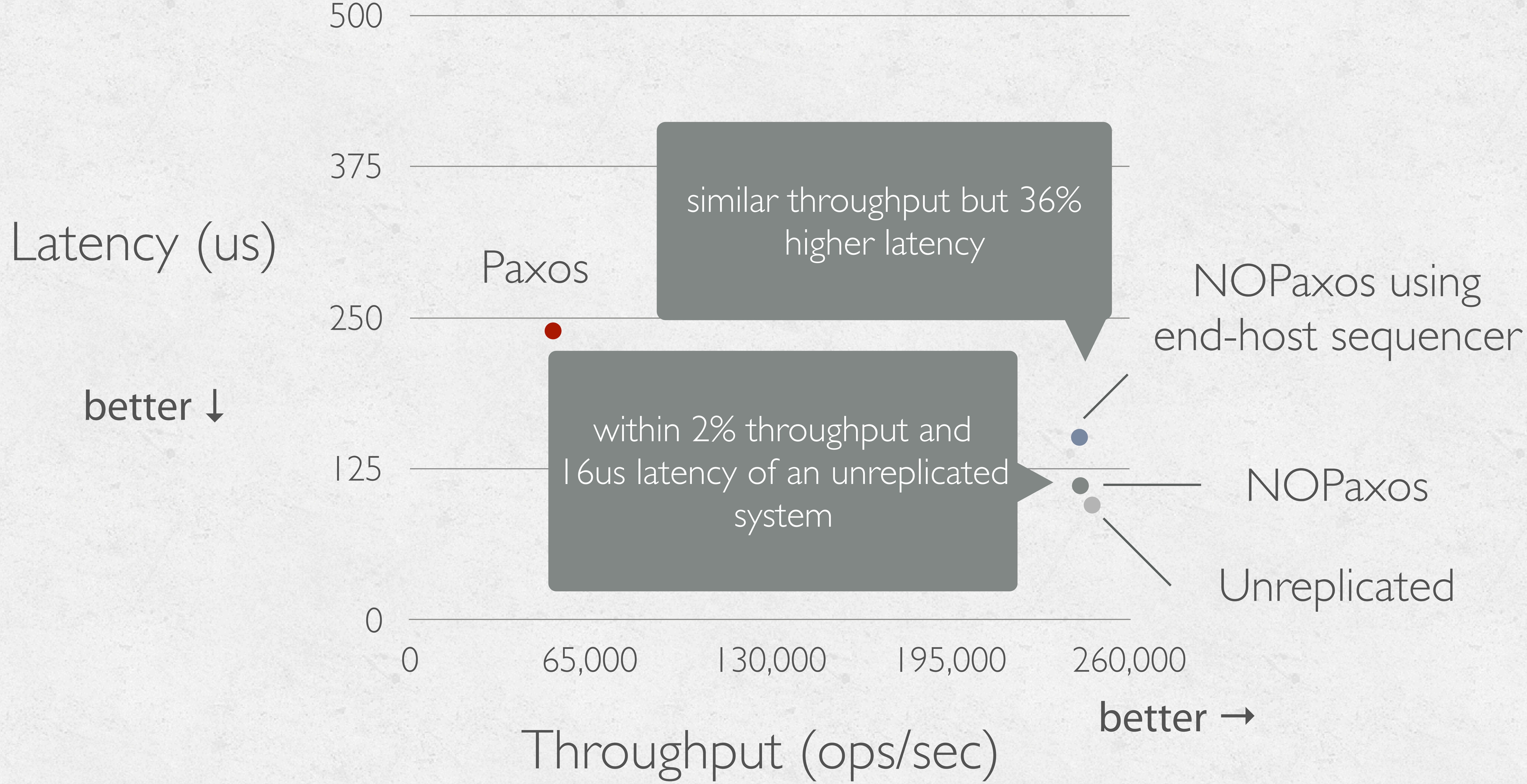


similar throughput but 36% higher latency

within 2% throughput and 16us latency of an unreplicated system

Summary

- Separate ordering from reliable delivery in state machine replication

- A network model OUM that provides ordered but unreliable message delivery

- A more efficient replication protocol NOPaxos that ensures reliable delivery

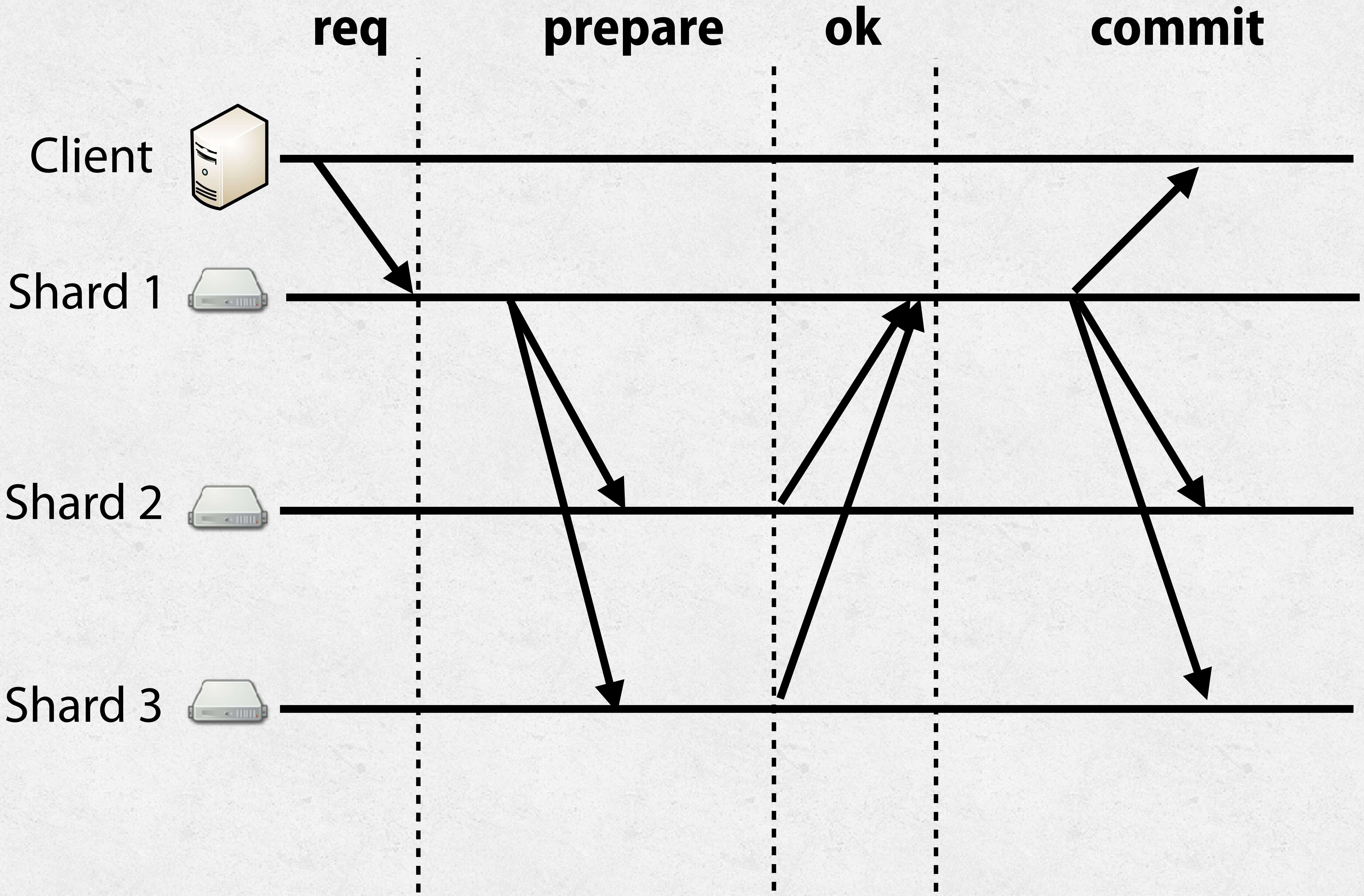
- The combined system achieves performance equivalent to an unreplicated system

The Eris Transaction Protocol

Existing transactional systems: extensive coordination

Client
Shard 1
Shard 2
Shard 3

EXISTING TRANSACTIONAL SYSTEMS: EXTENSIVE COORDINATION



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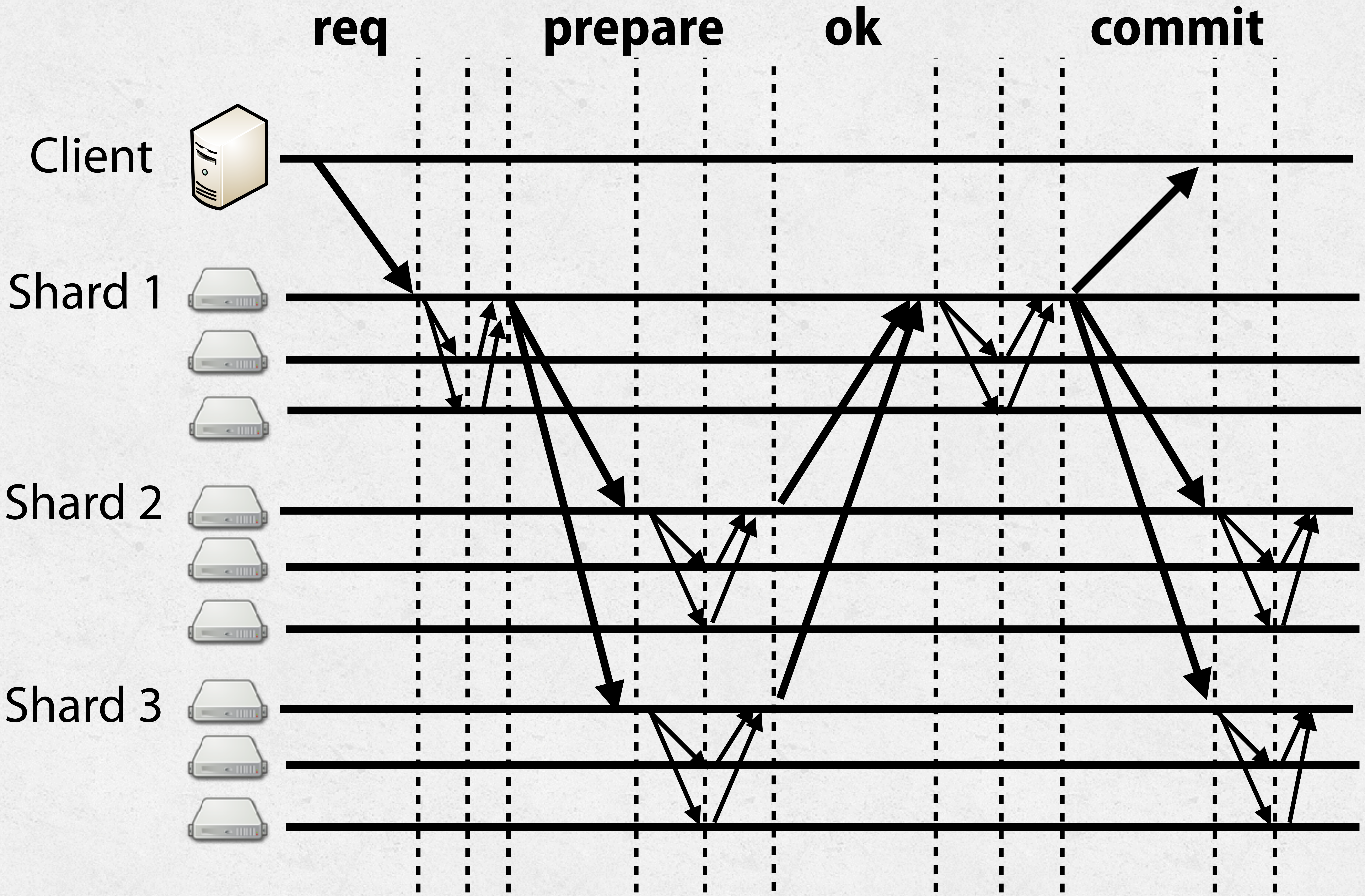

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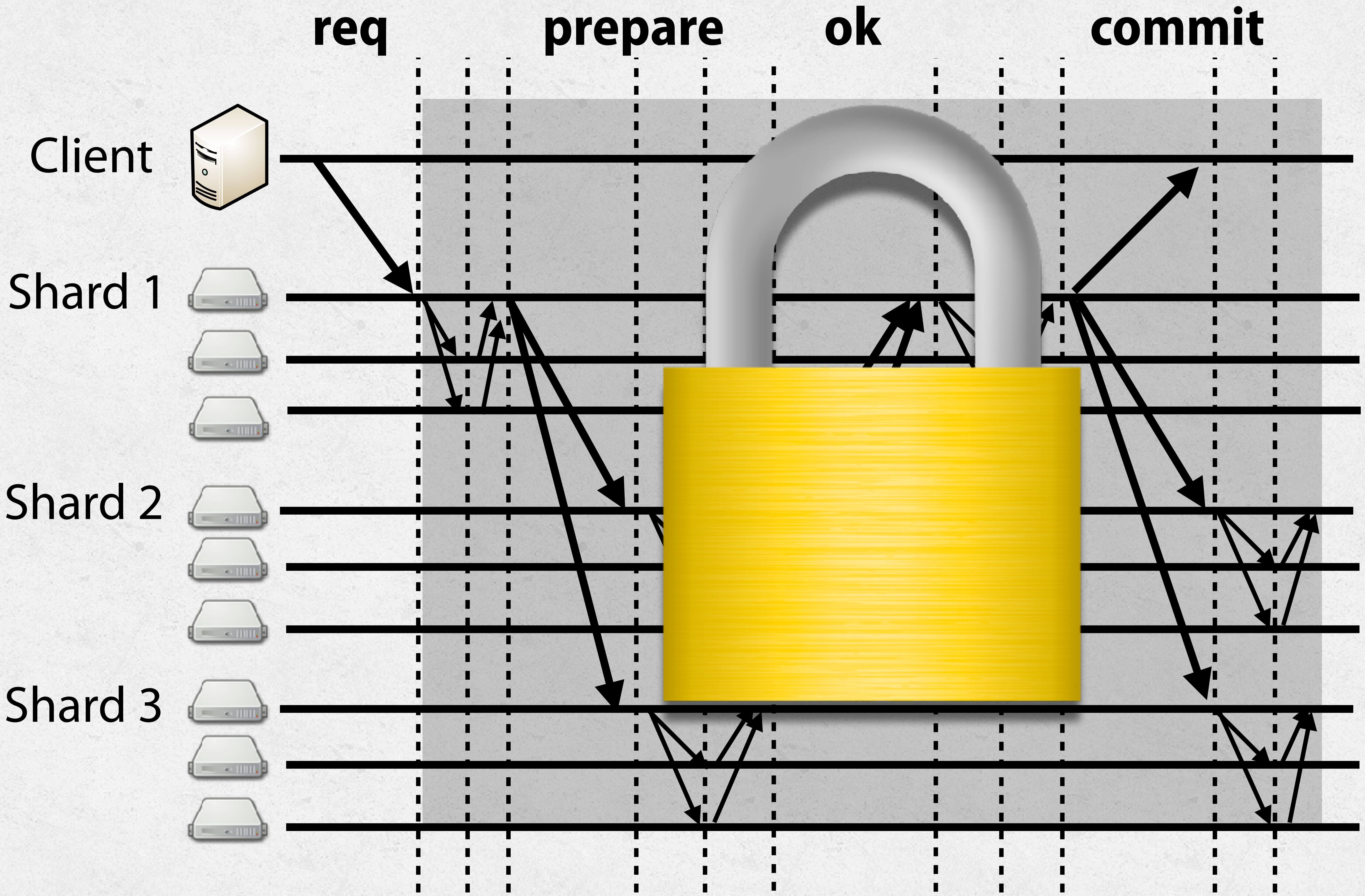


Eris

- Processes independent transactions **without coordination** in the normal case
- Performance within **3%** of a nontransactional, unreplicated system on TPC-C
- Strongly consistent, fault tolerant transactions with **minimal performance penalties**

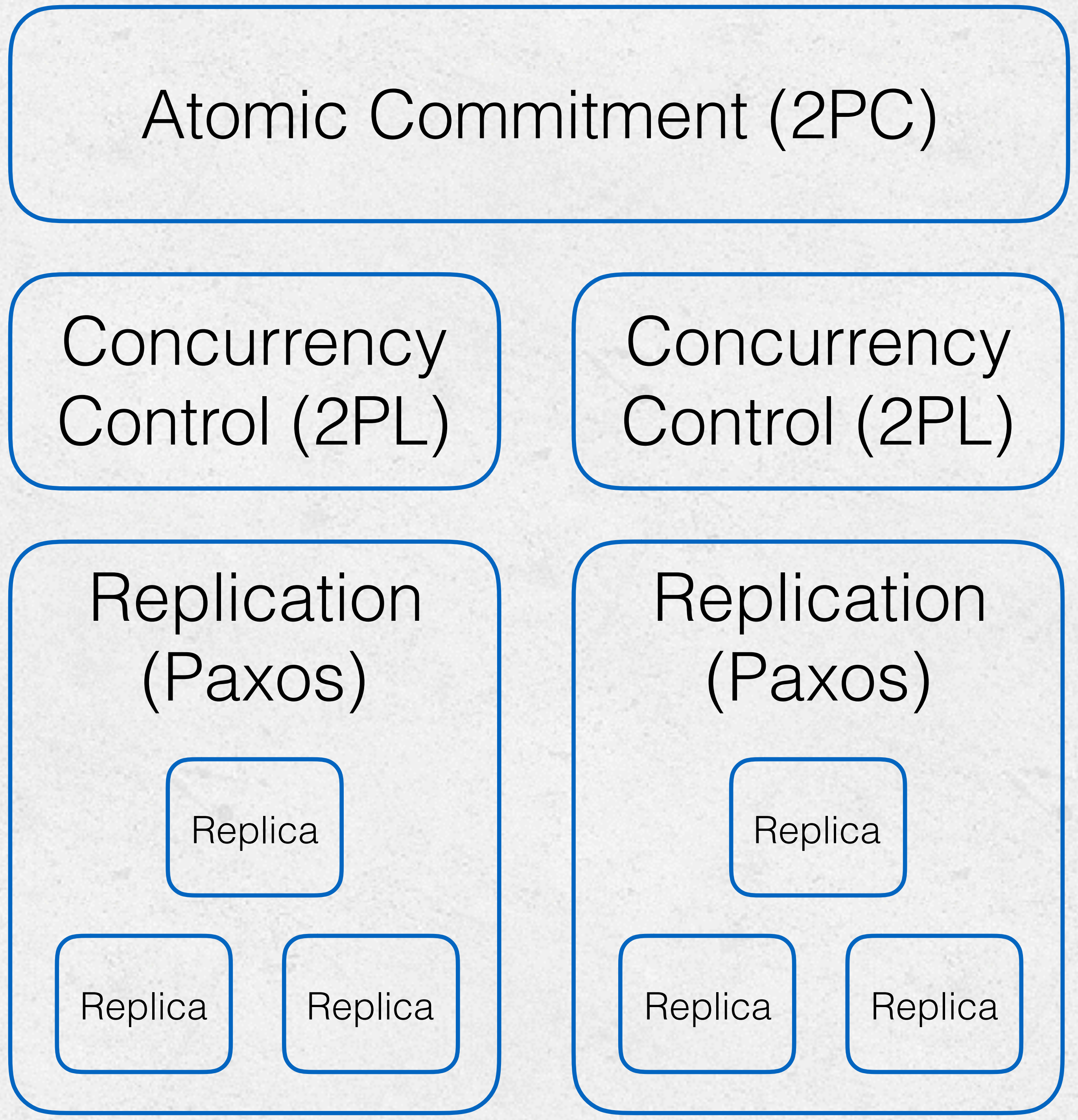
Key Contributions

A **new architecture** that divides the responsibility for transactional guarantees by

…leveraging the **datacenter network** to order messages within and across shards

…and a co-designed **transaction protocol** with minimal coordination.

Traditional Layered Approach



Atomic Commitment (2PC)

Concurrency Control (2PL)

Concurrency Control (2PL)

Replication (Paxos)

Replica

Replica

Replica

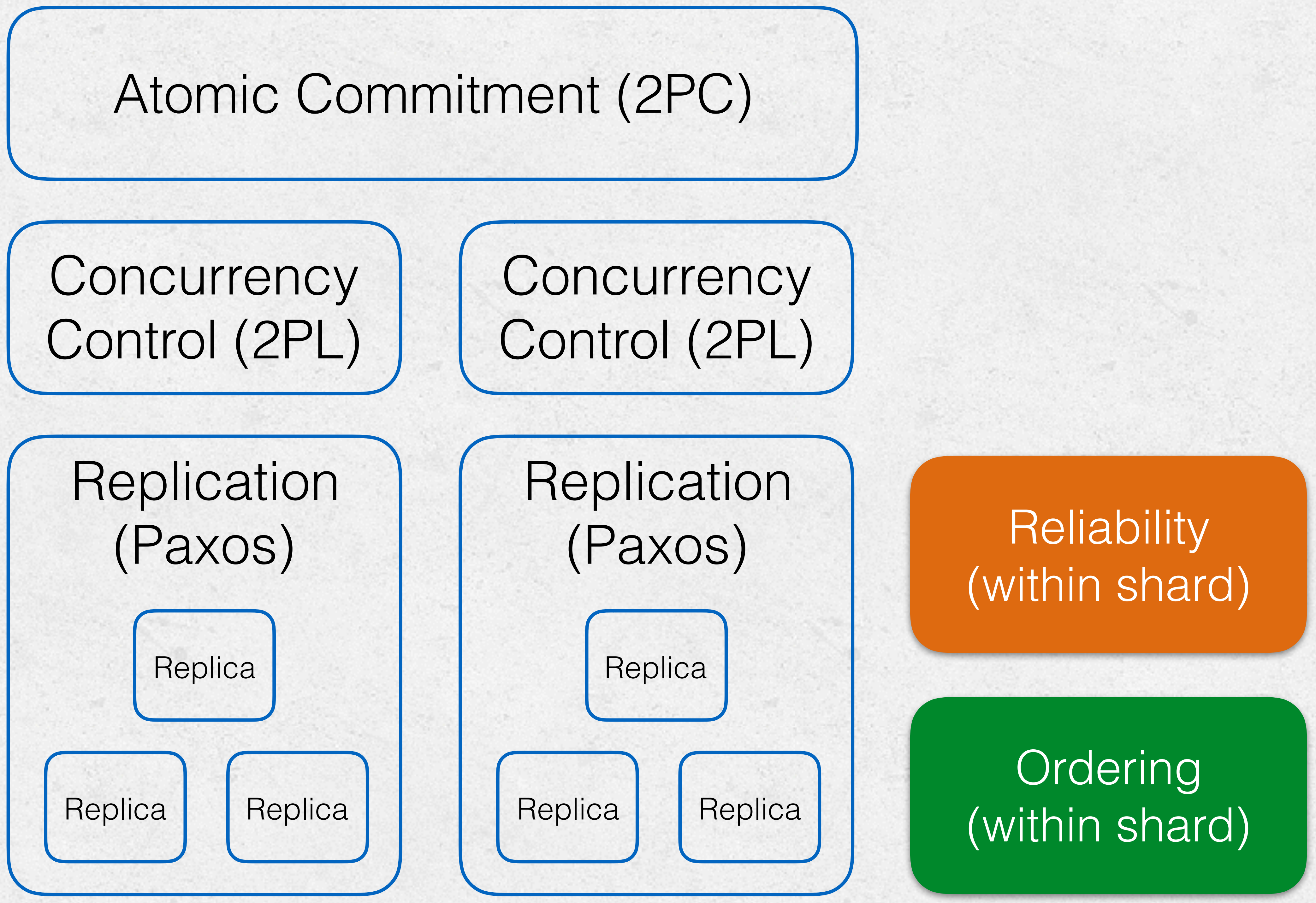
Replication (Paxos)

Replica

Replica

Replica

Traditional Layered Approach



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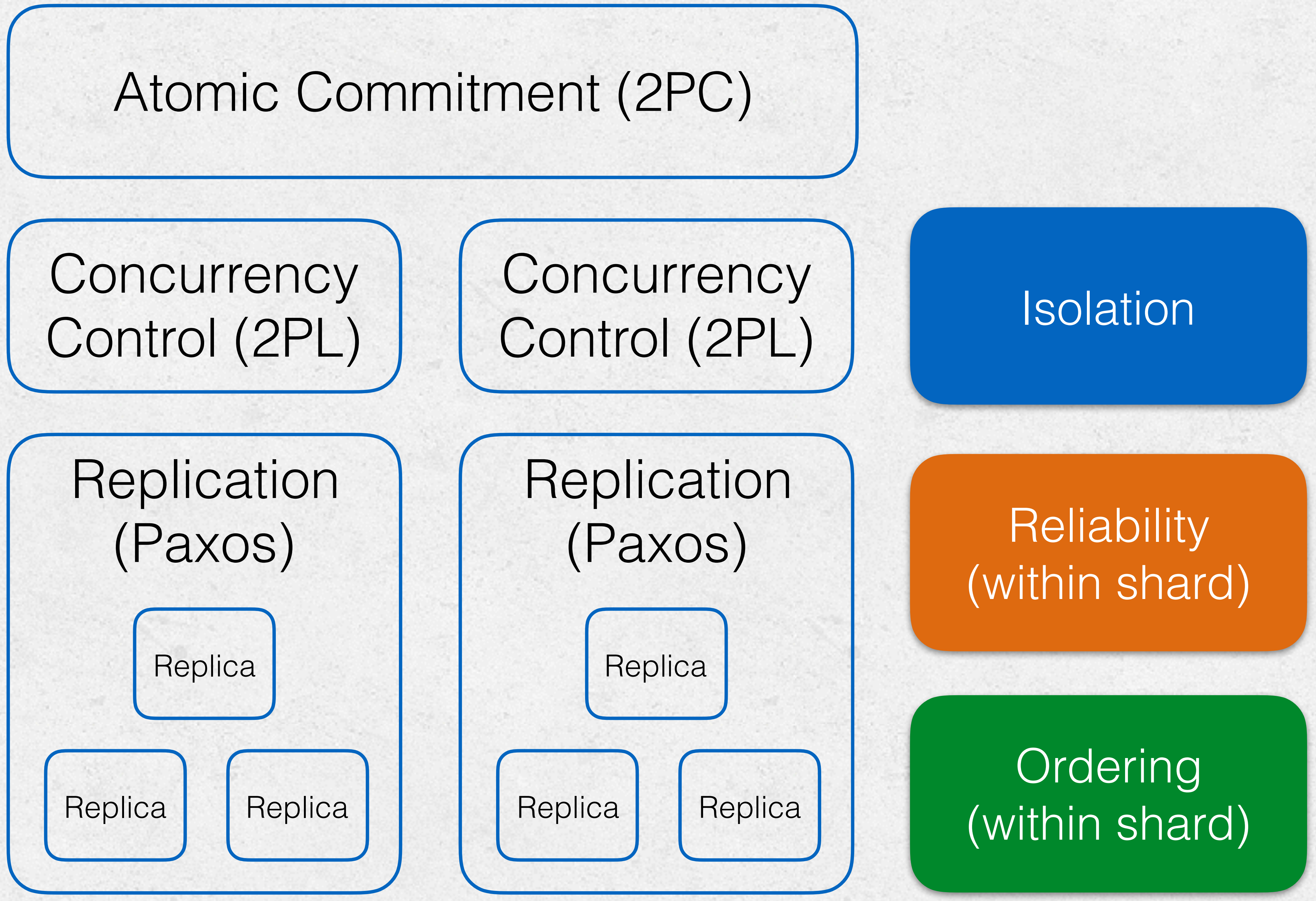
Replica

Reliability (within shard)

Ordering (within shard)

Traditional Layered Approach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Replica

Replica

Replica

Replication (Paxos)

Replica

Replica

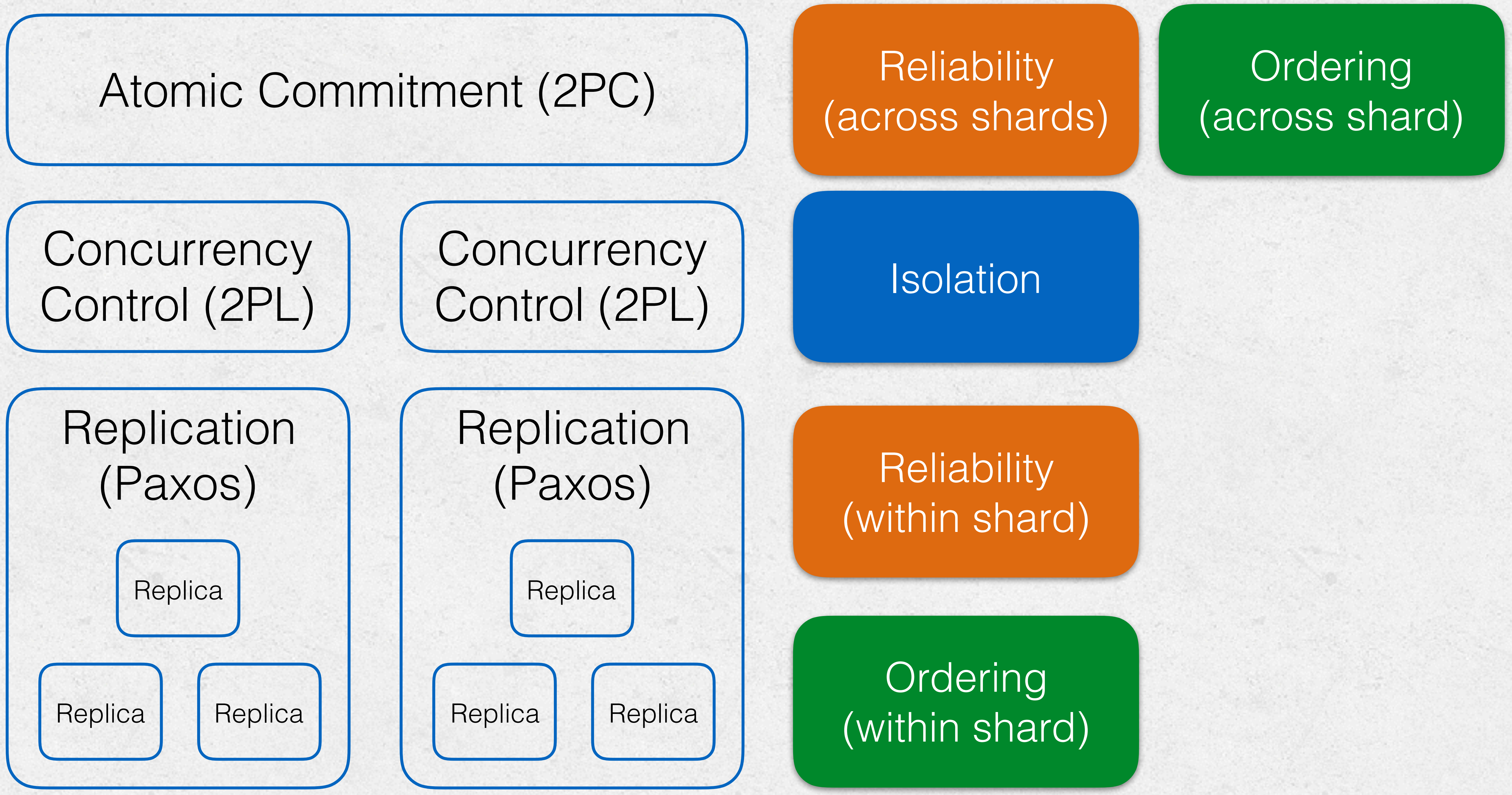
Replica

Isolation

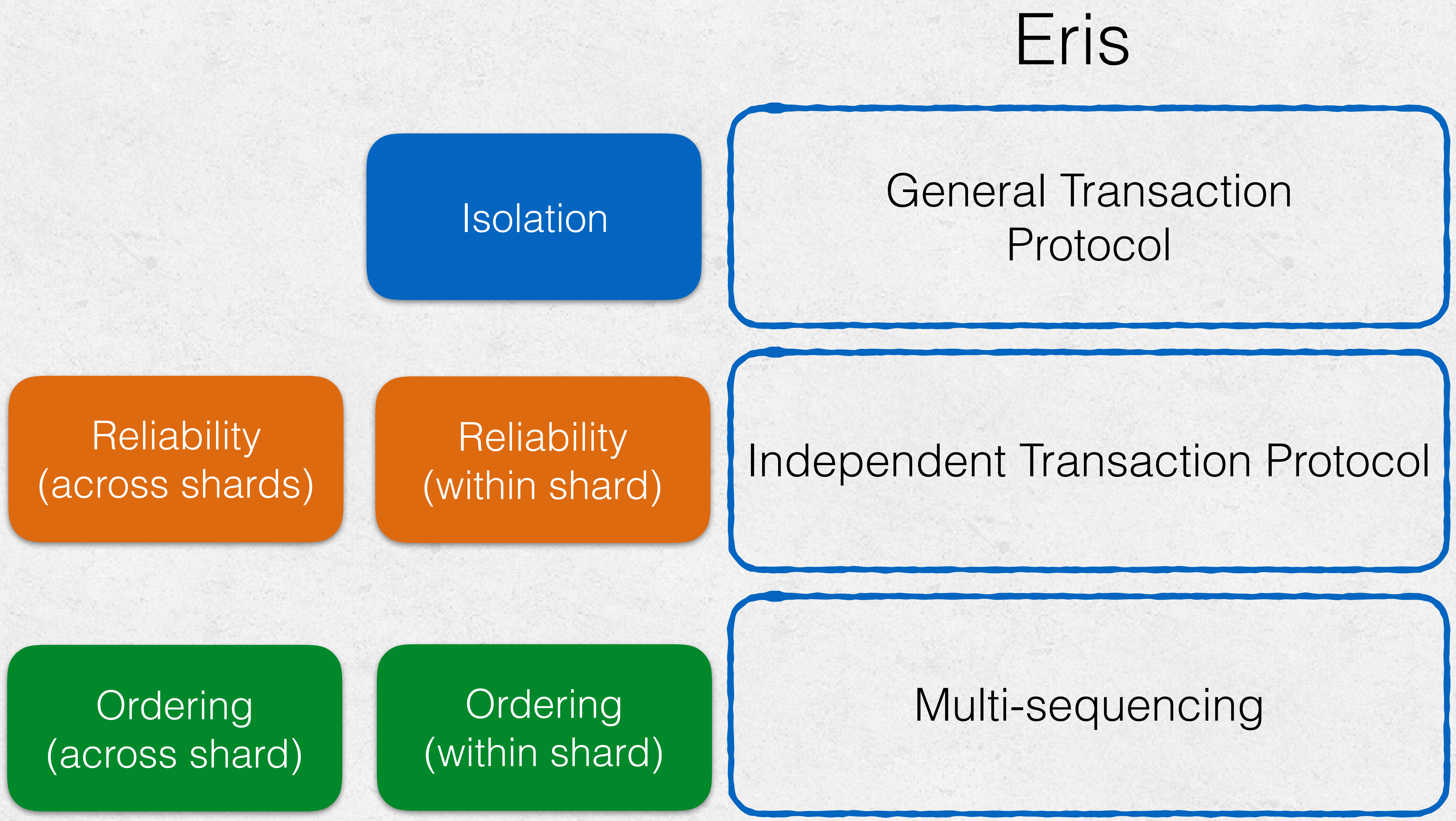
Reliability (within shard)

Ordering (within shard)

Traditional Layered Approach



A New Way to Divide Responsibilities


Eris

Isolation

General Transaction Protocol

Reliability (across shards)

Reliability (within shard)

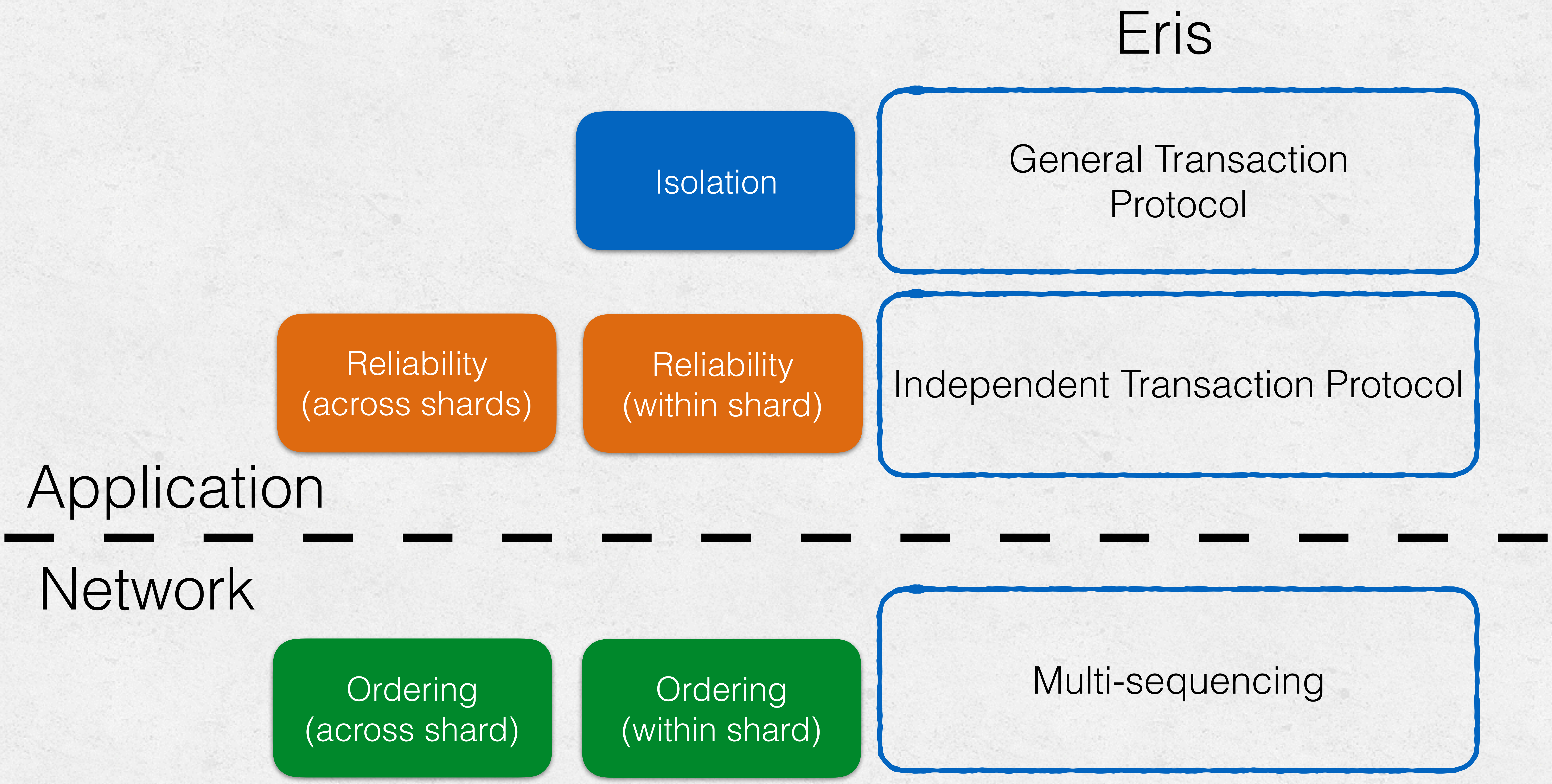
Independent Transaction Protocol

Ordering (across shard)

Ordering (within shard)

Multi-sequencing

A New Way to Divide Responsibilities



Eris

Isolation

General Transaction Protocol

Reliability (across shards)

Reliability (within shard)

Independent Transaction Protocol

Application

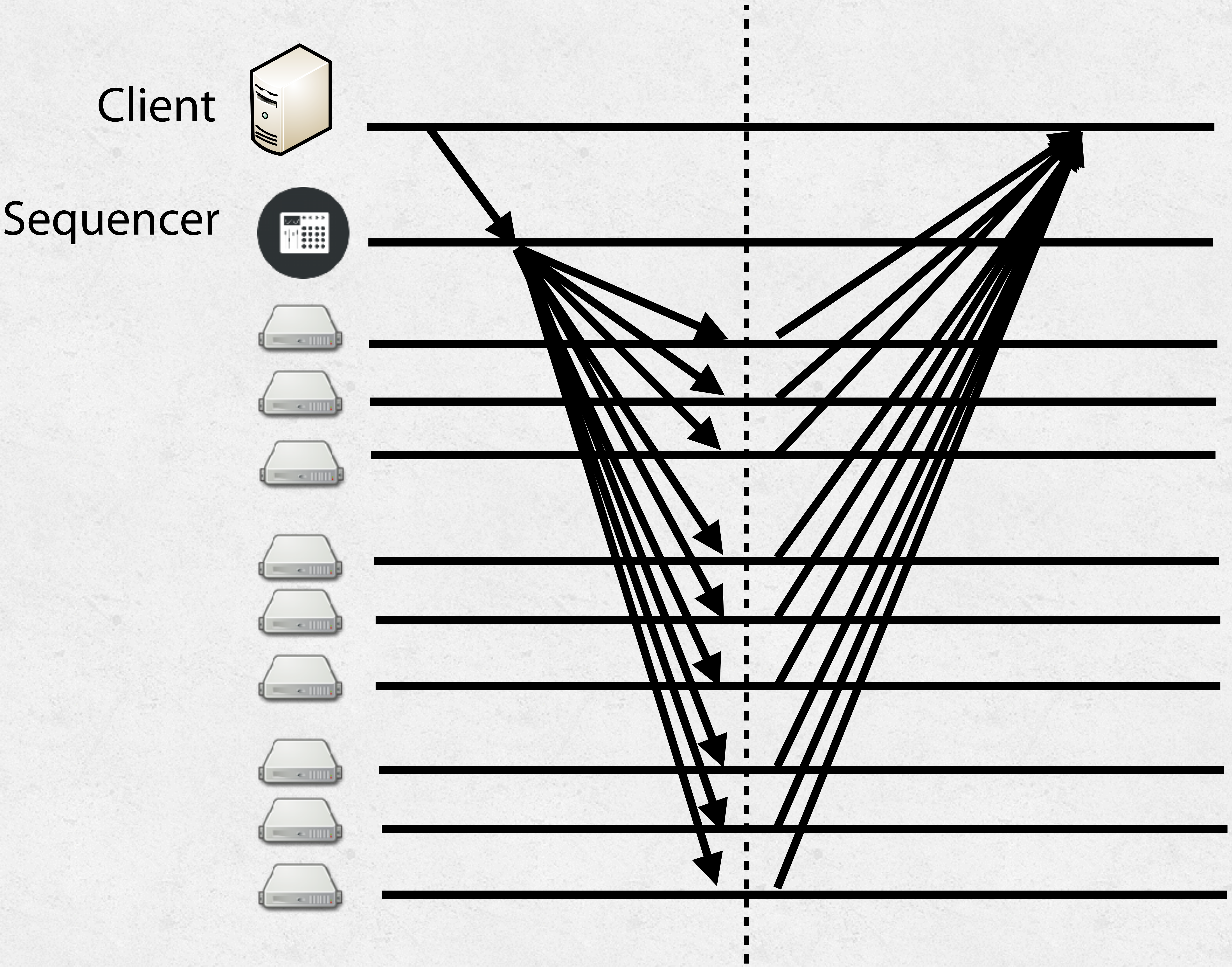
Network

Ordering (across shard)

Ordering (within shard)

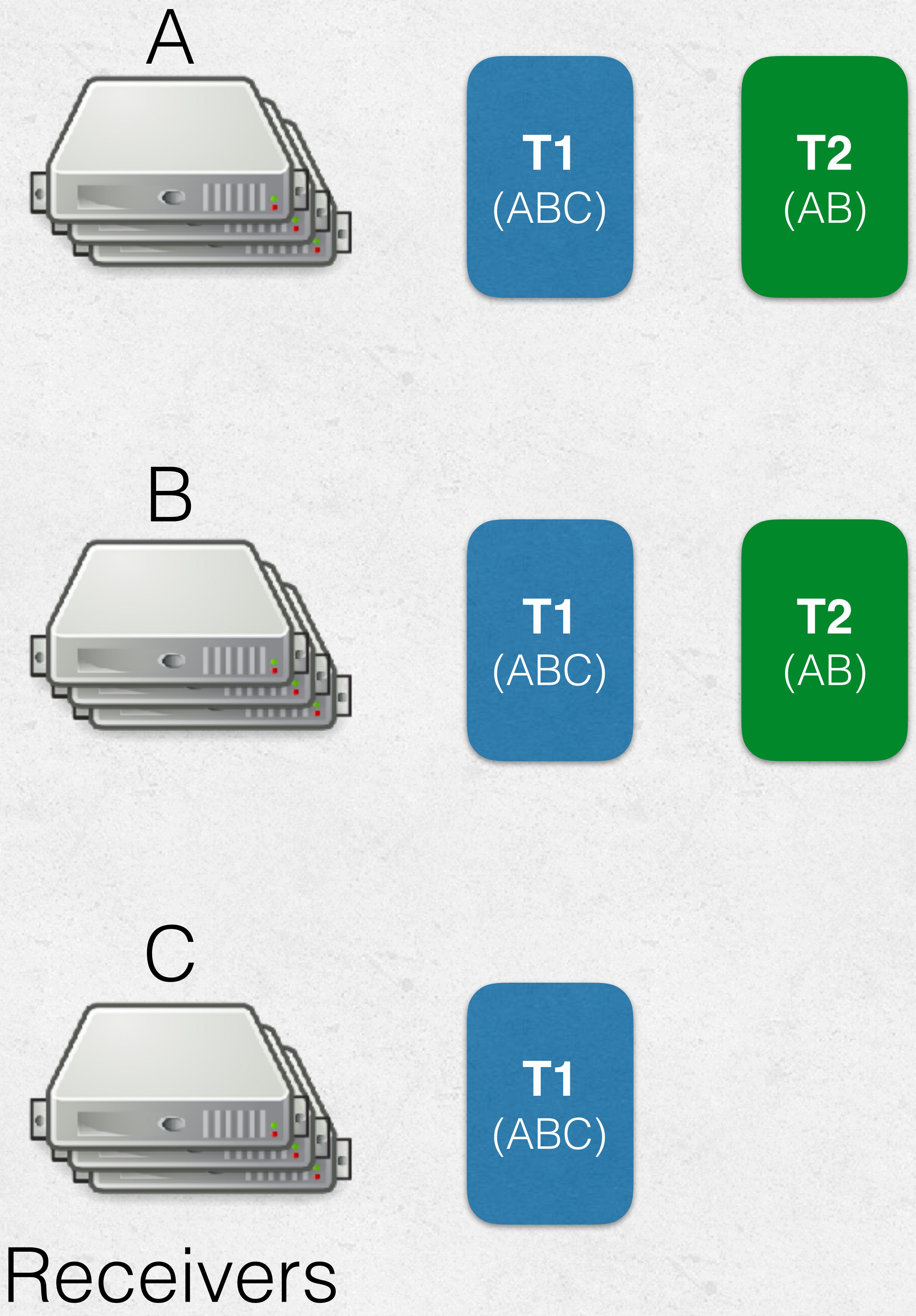
Multi-sequencing

Goal



In-Network Concurrency Control Goals

- **Globally consistent ordering** across messages delivered to multiple destination shards
- No reliable delivery guarantee
- Recipients can **detect dropped messages**



A

T1
(ABC)

T2
(AB)

B

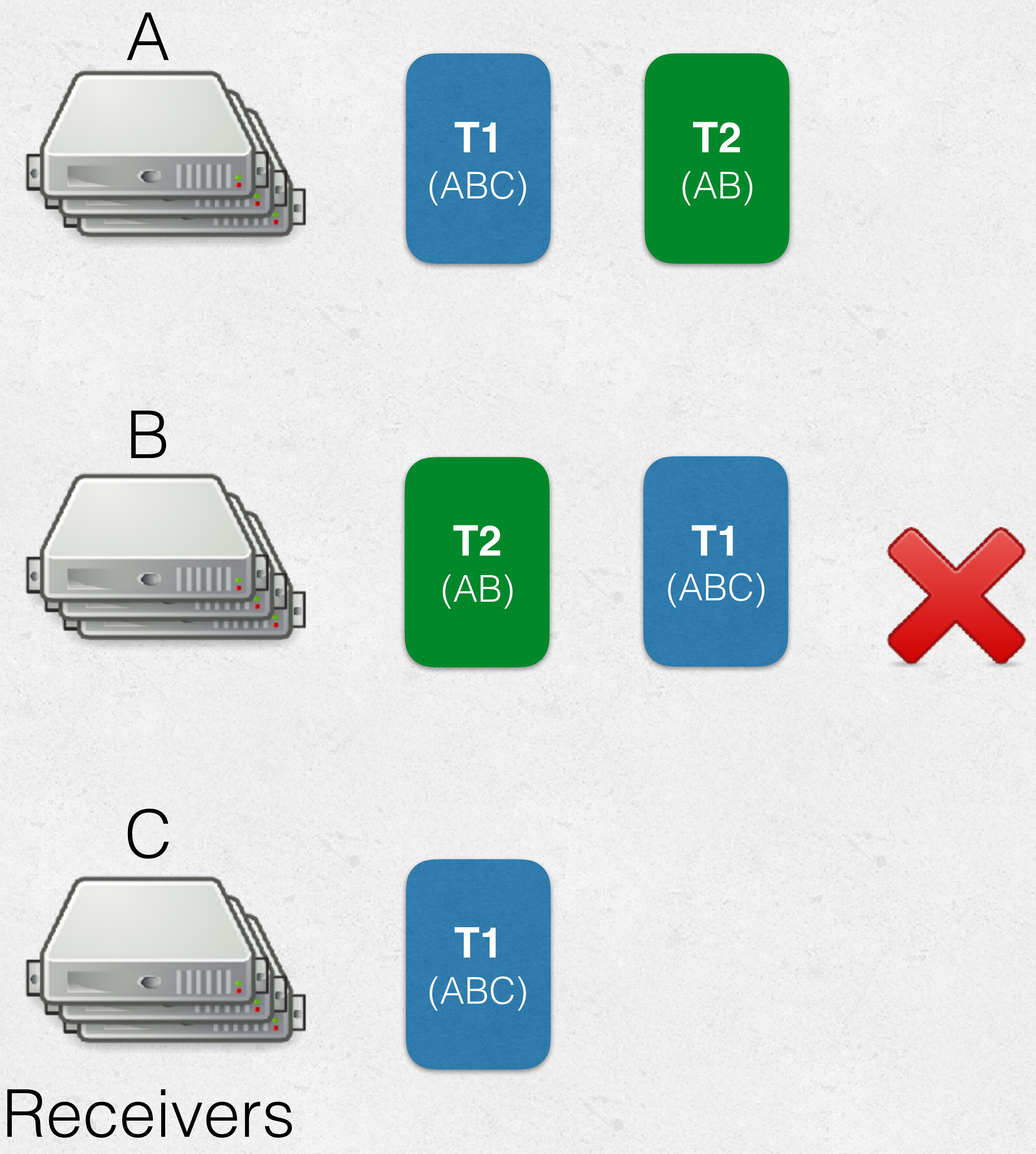
T1
(ABC)

T2
(AB)

C

T1
(ABC)

Receivers



A

T1 (ABC)

T2 (AB)

B

T2 (AB)

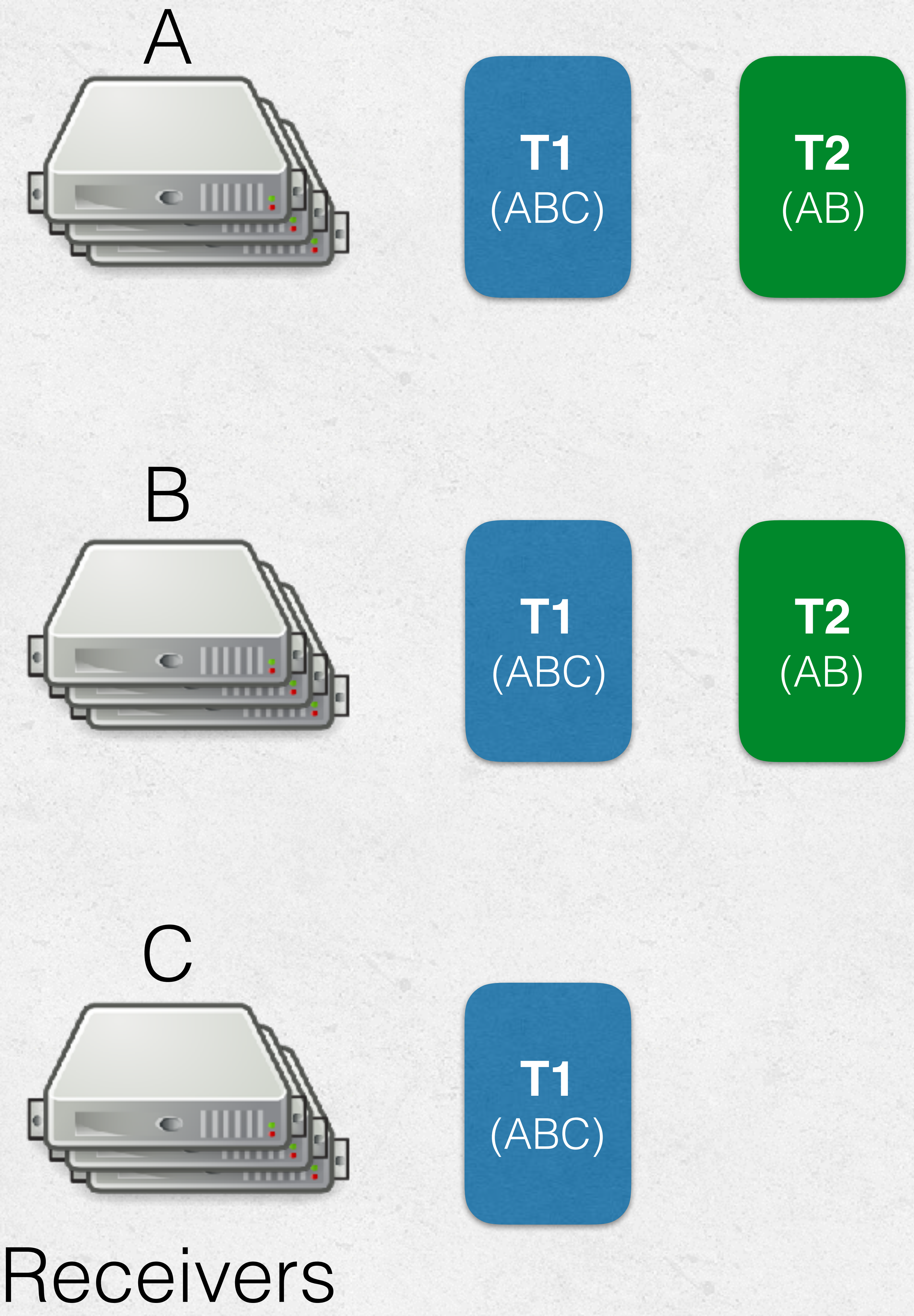
T1 (ABC)

✗

C

T1 (ABC)

Receivers



A

T1
(ABC)

T2
(AB)

B

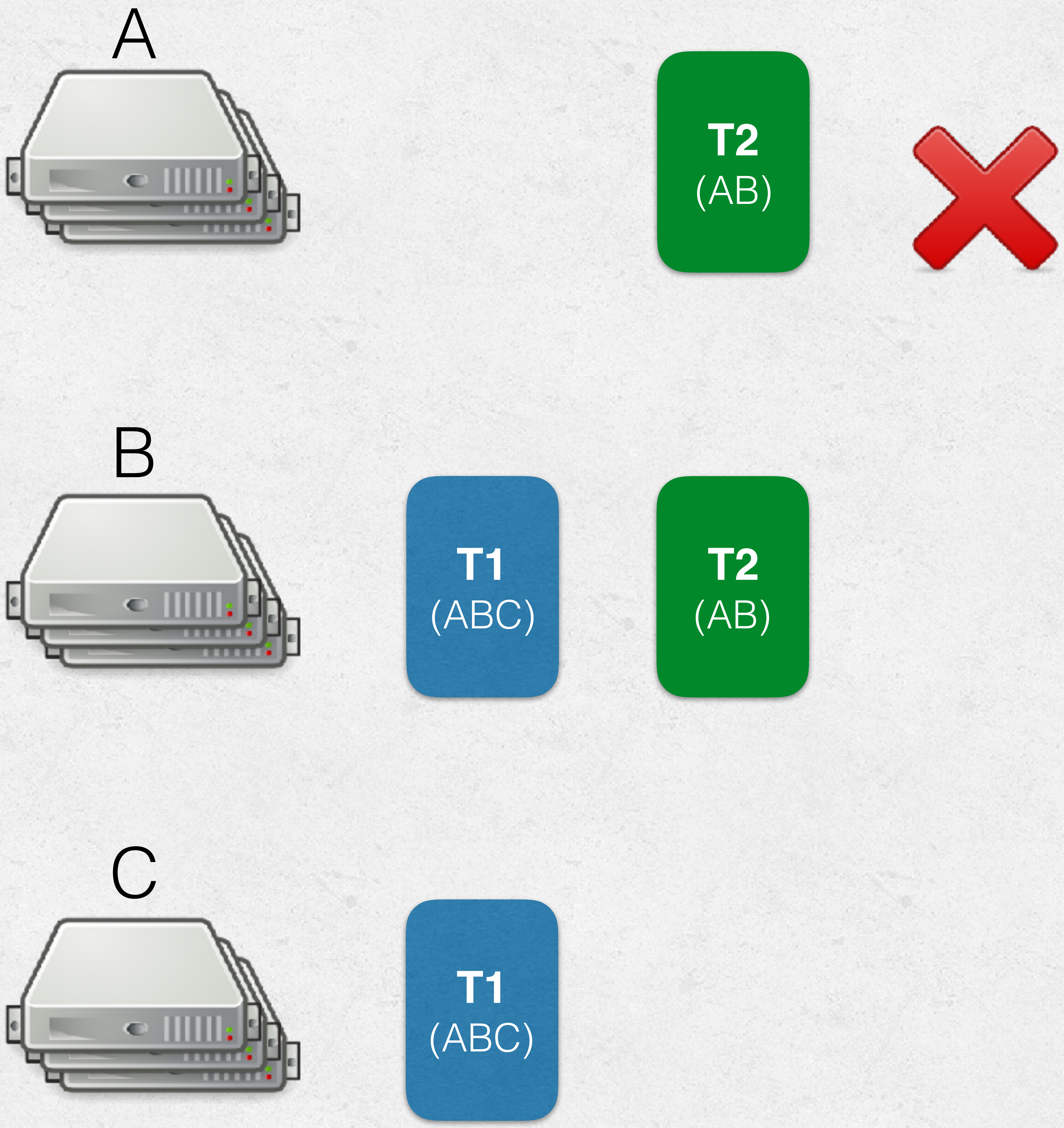
T1
(ABC)

T2
(AB)

C

T1
(ABC)

Receivers



A

T2
(AB)

✗

B

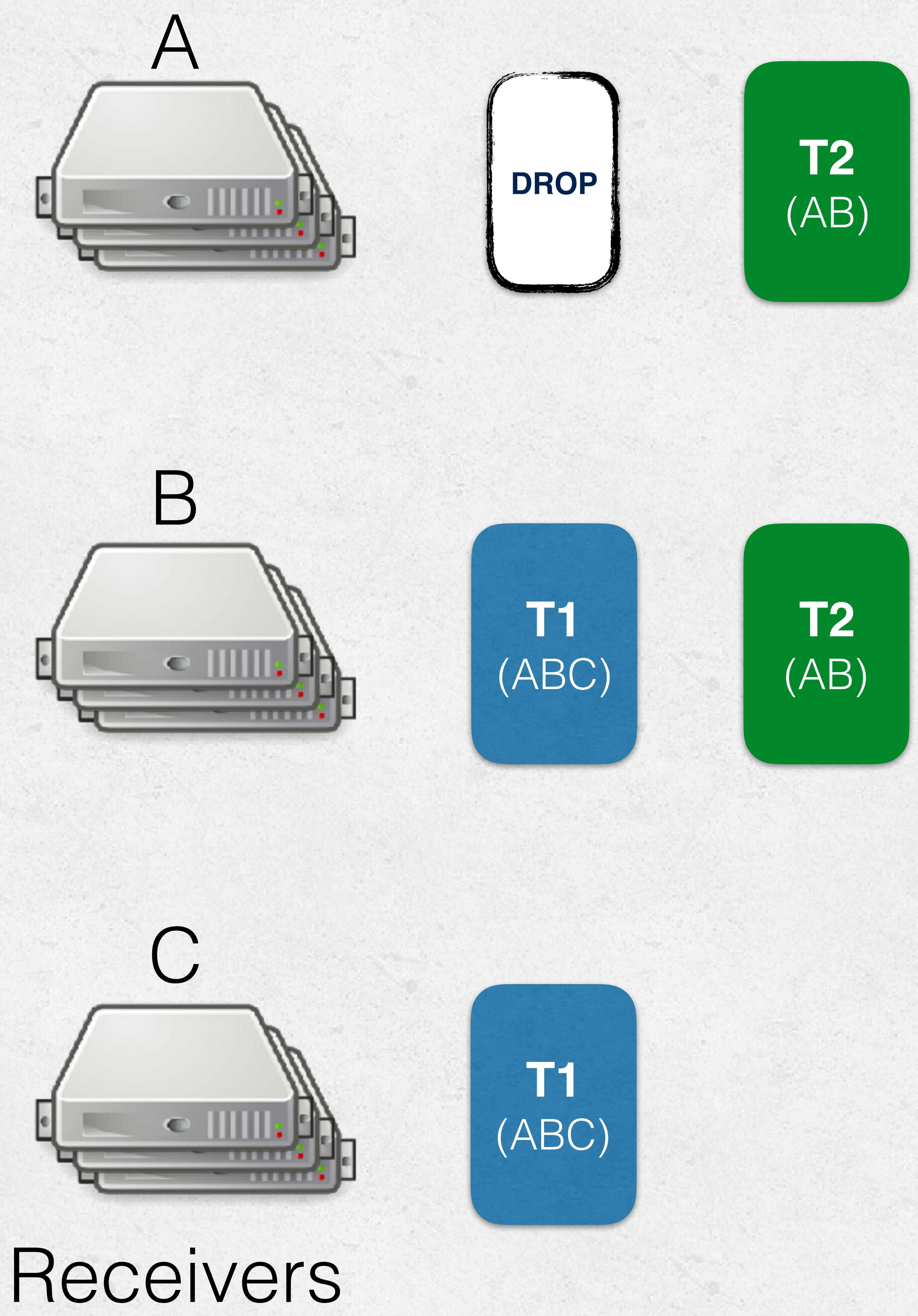
T1
(ABC)

T2
(AB)

C

T1
(ABC)

Receivers



A

DROP

T2 (AB)

B

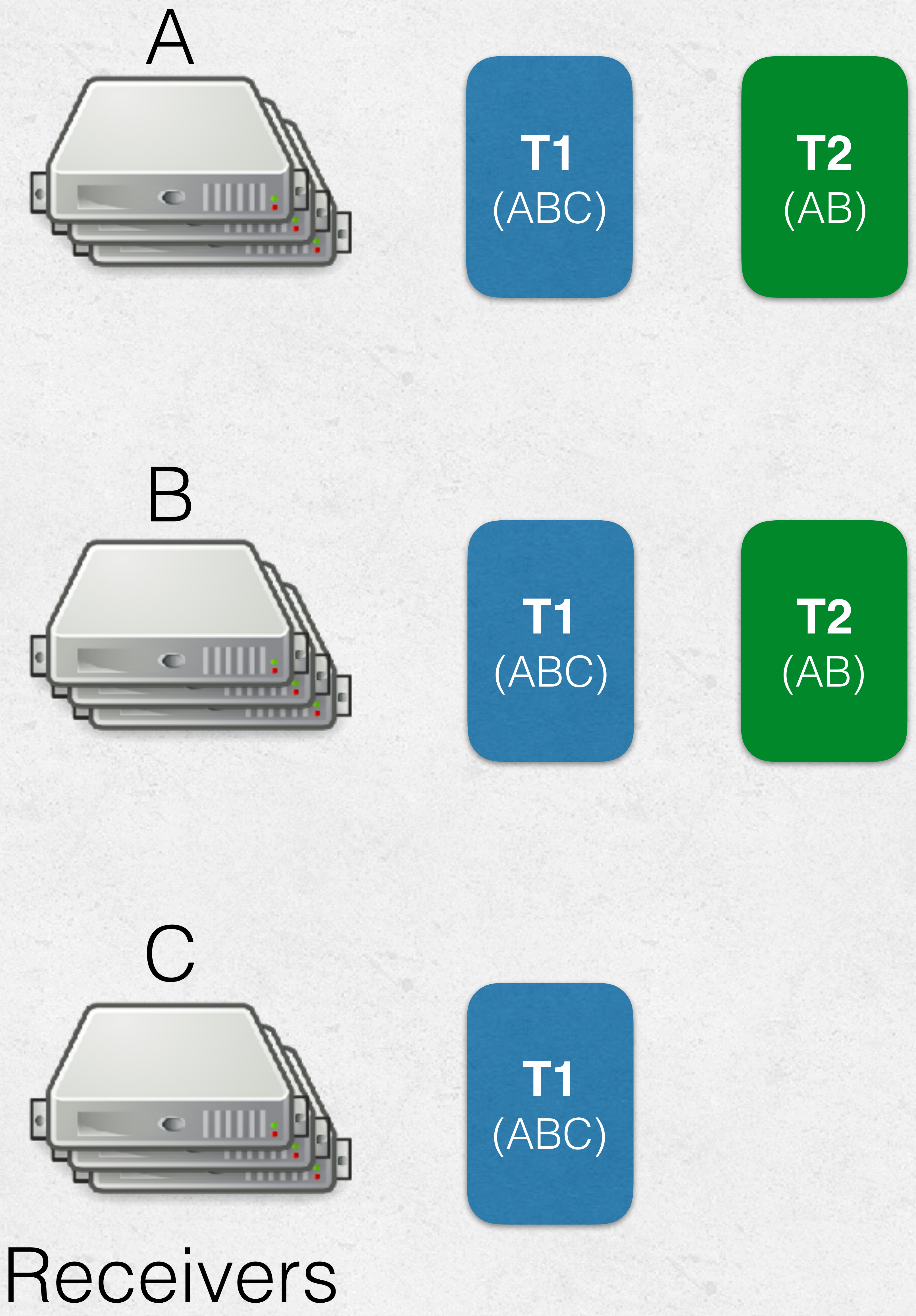
T1 (ABC)

T2 (AB)

C

T1 (ABC)

Receivers



A

T1
(ABC)

T2
(AB)

B

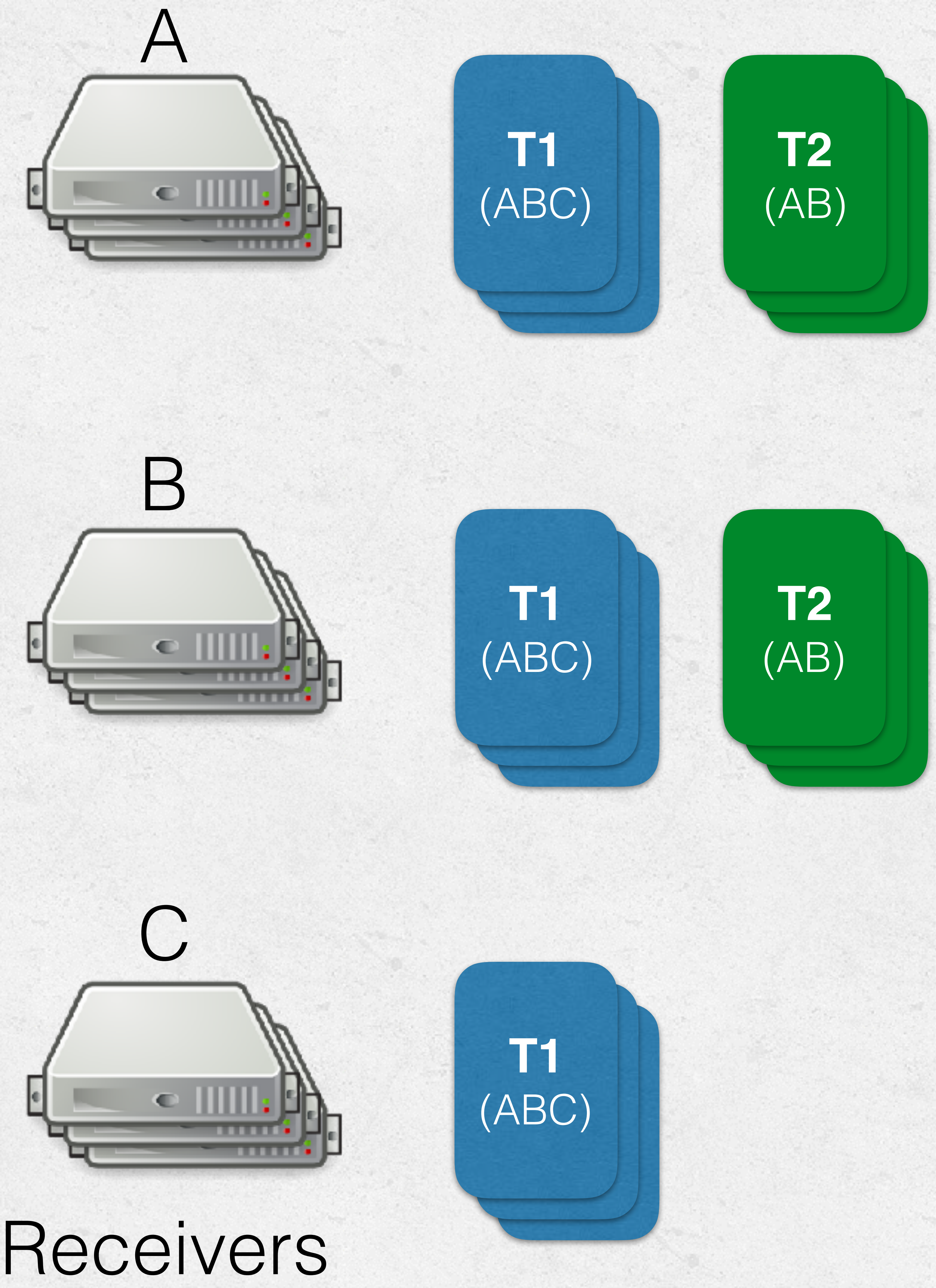
T1
(ABC)

T2
(AB)

C

T1
(ABC)

Receivers



A

T1
(ABC)

T2
(AB)

B

T1
(ABC)

T2
(AB)

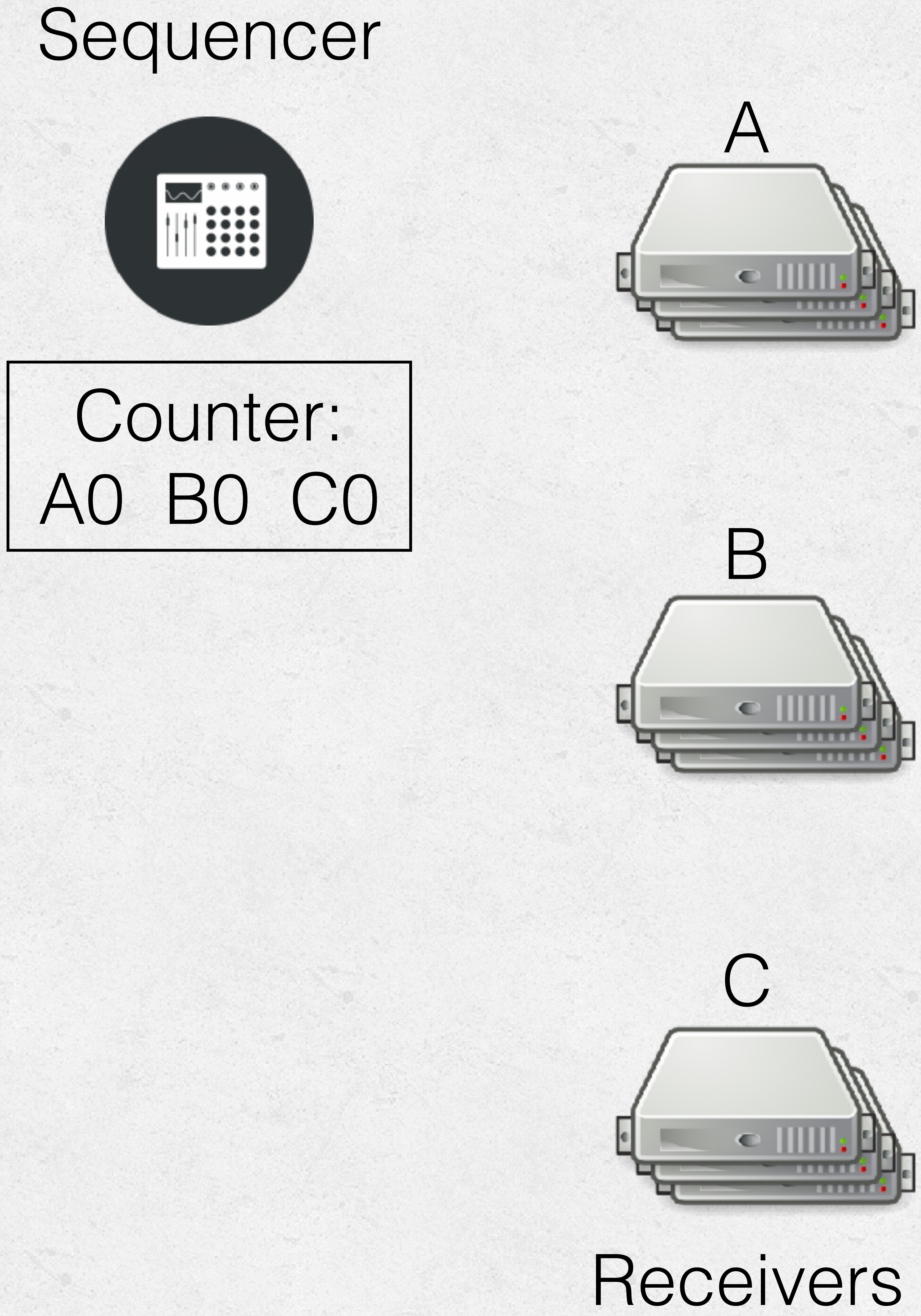
C

T1
(ABC)

Receivers

Multi-Sequenced Groupcast

- Groupcast: message header specifies a **set** of destination multicast groups
- Multi-sequenced groupcast: messages are sequenced **atomically** across all recipient groups
- Sequencer keeps a counter for each group
- Extends OUM in NOPaxos



Sequencer

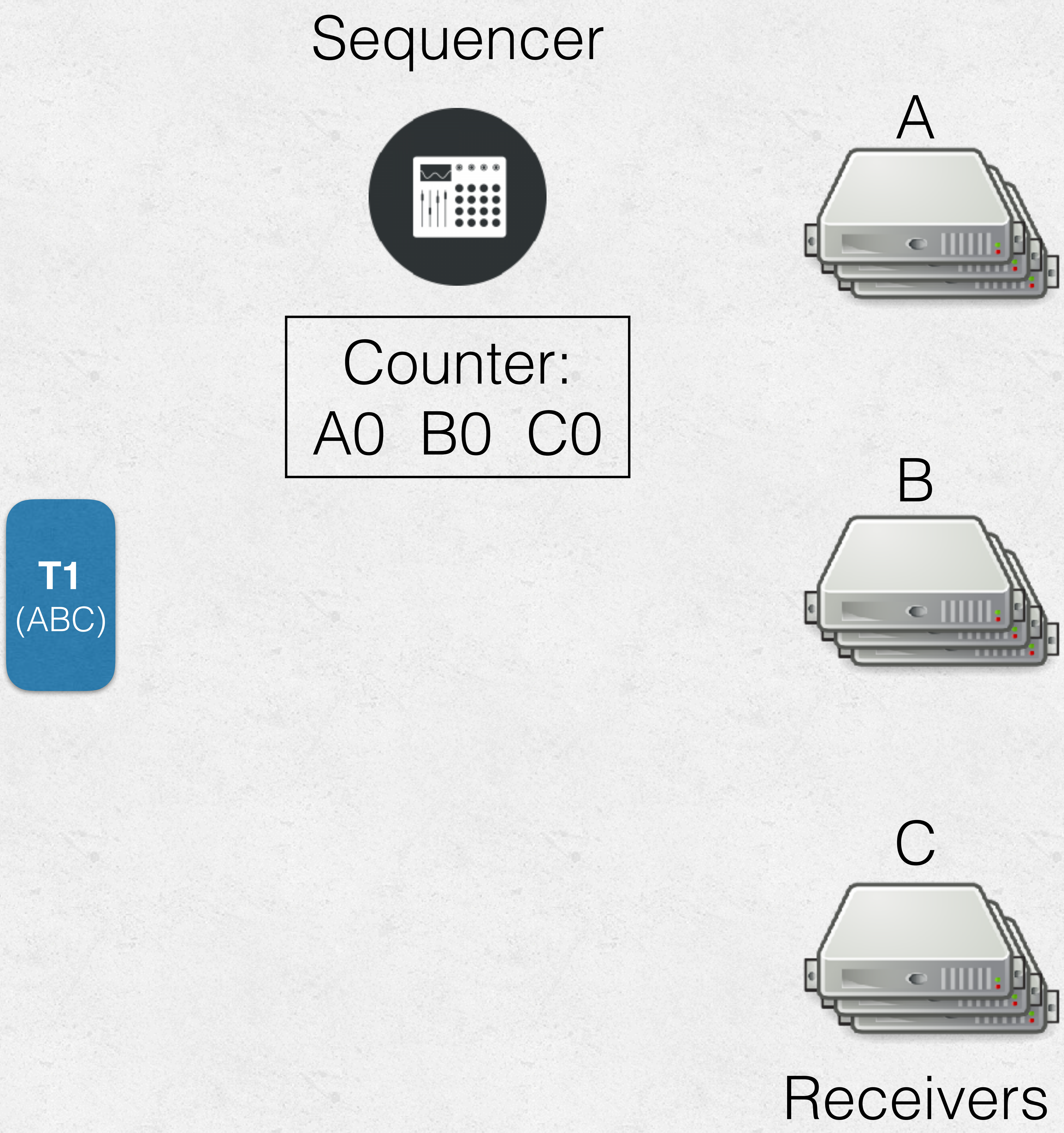
Counter:
A0 B0 C0

A

B

C

Receivers



Sequencer

Counter:
A0 B0 C0

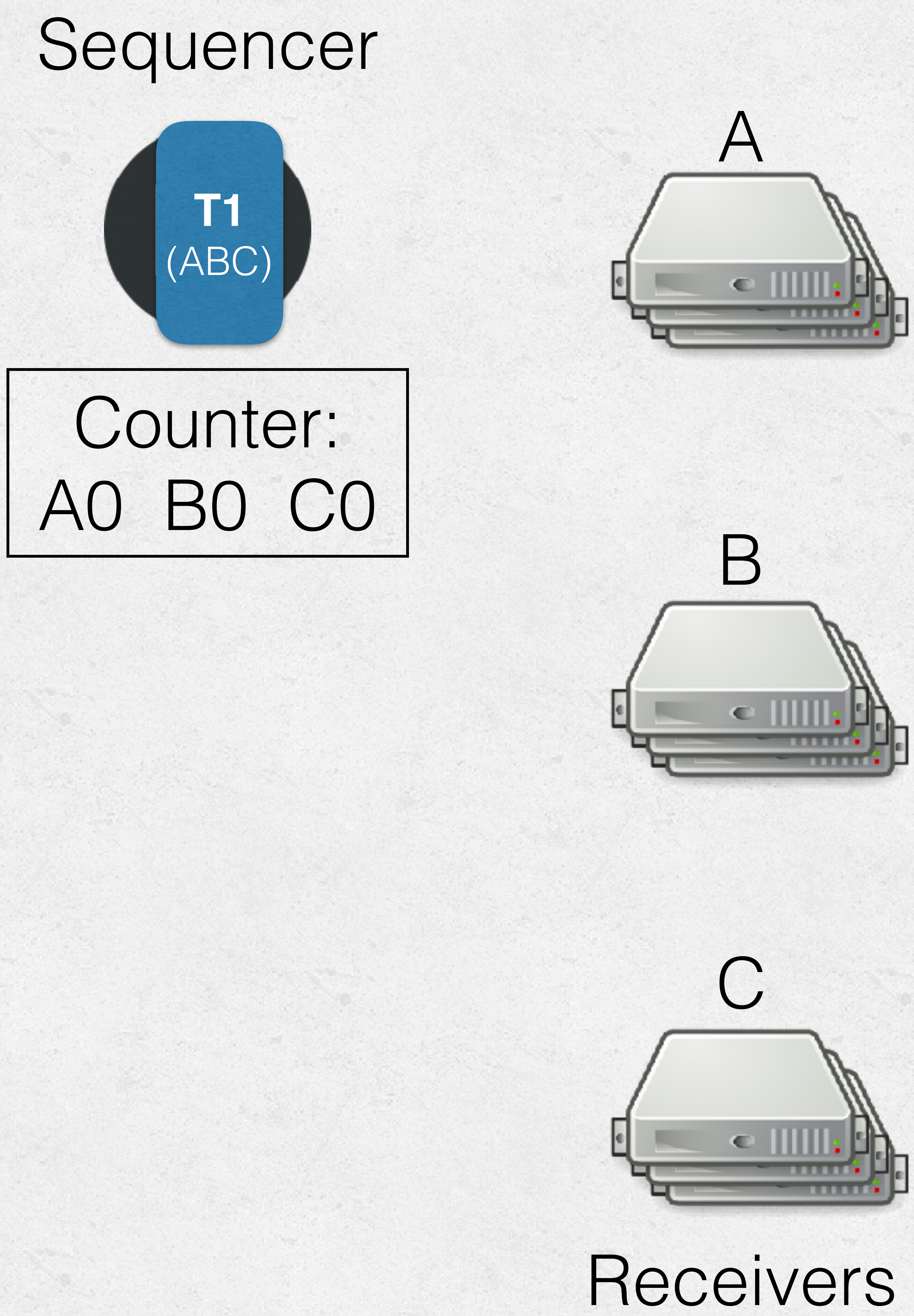
T1
(ABC)

A

B

C

Receivers



Sequencer

T1
(ABC)

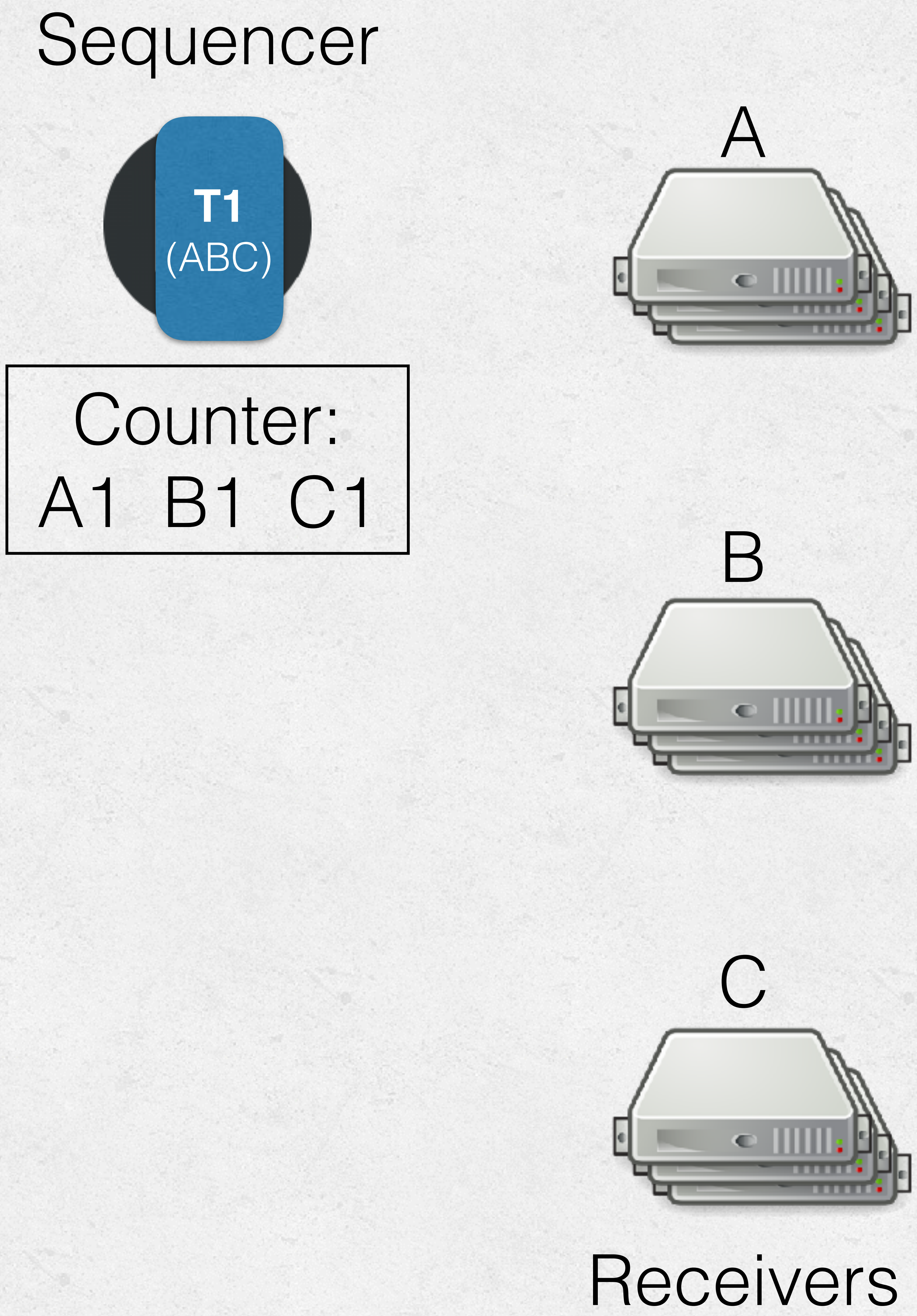
Counter:
A0 B0 C0

A

B

C

Receivers



Sequencer

T1
(ABC)

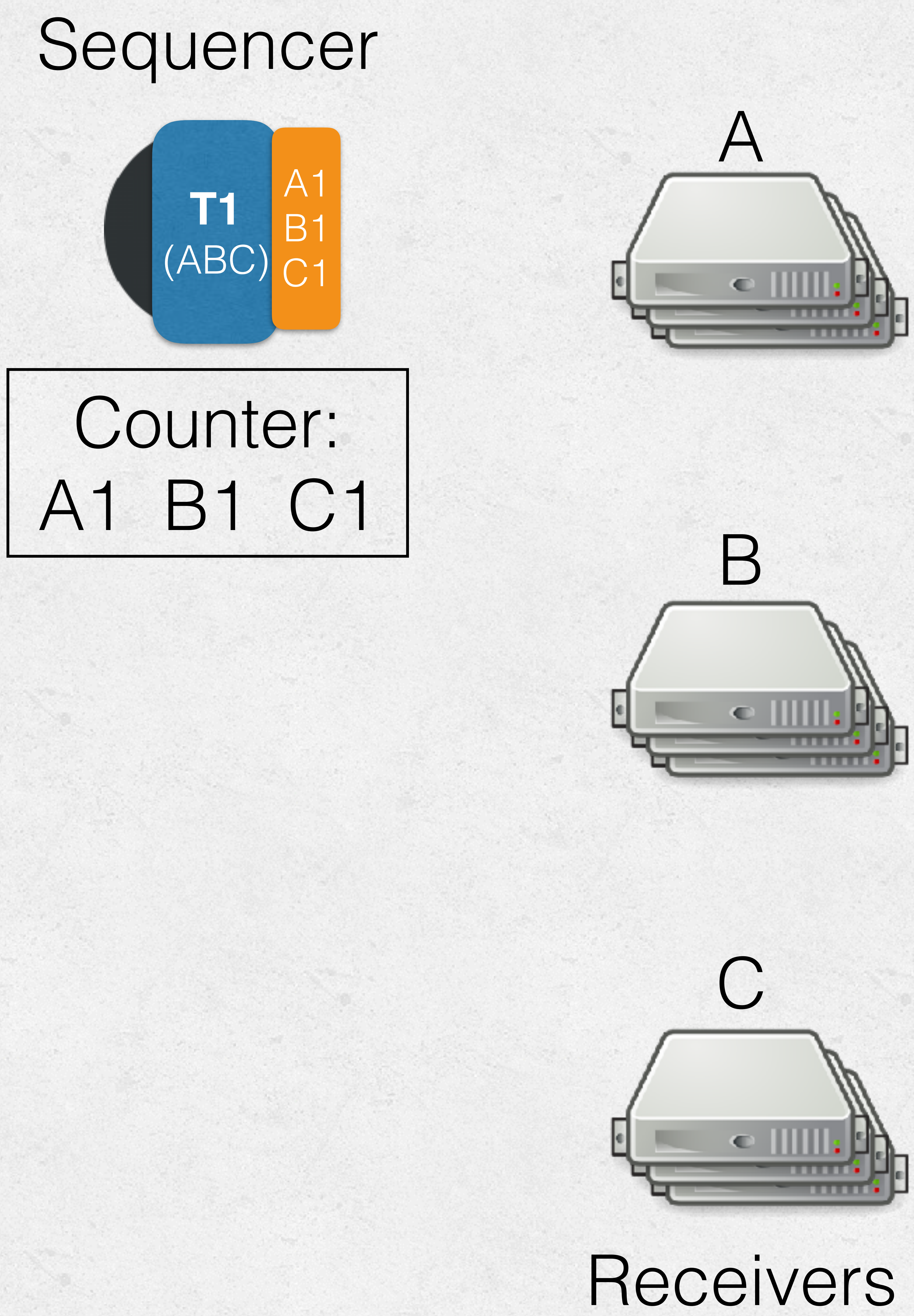
Counter:
A1 B1 C1

A

B

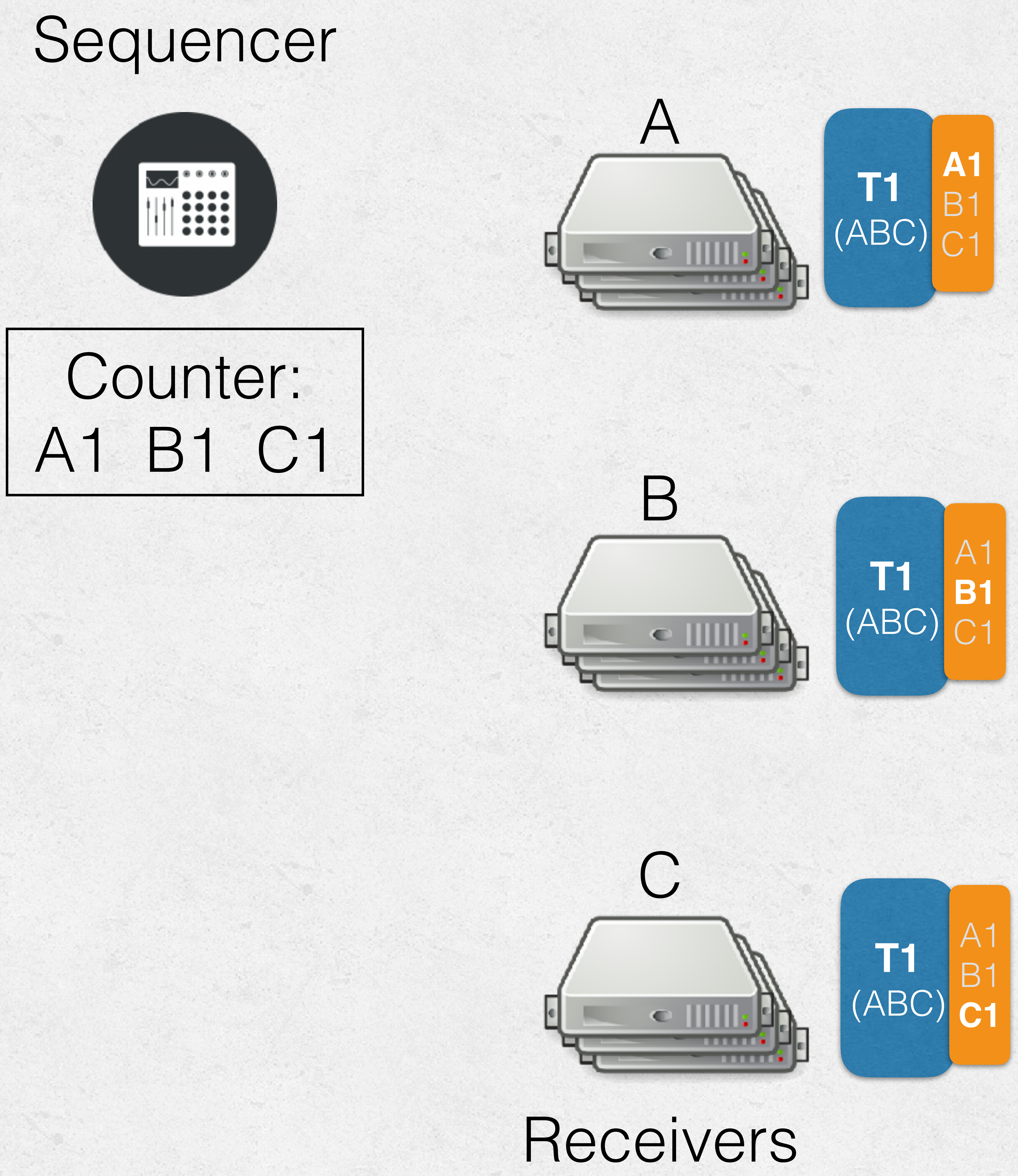
C

Receivers


Sequencer

Counter:
A1 B1 C1

Receivers



Sequencer

Counter:
A1 B1 C1

A

T1
(ABC)

A1
B1
C1

B

T1
(ABC)

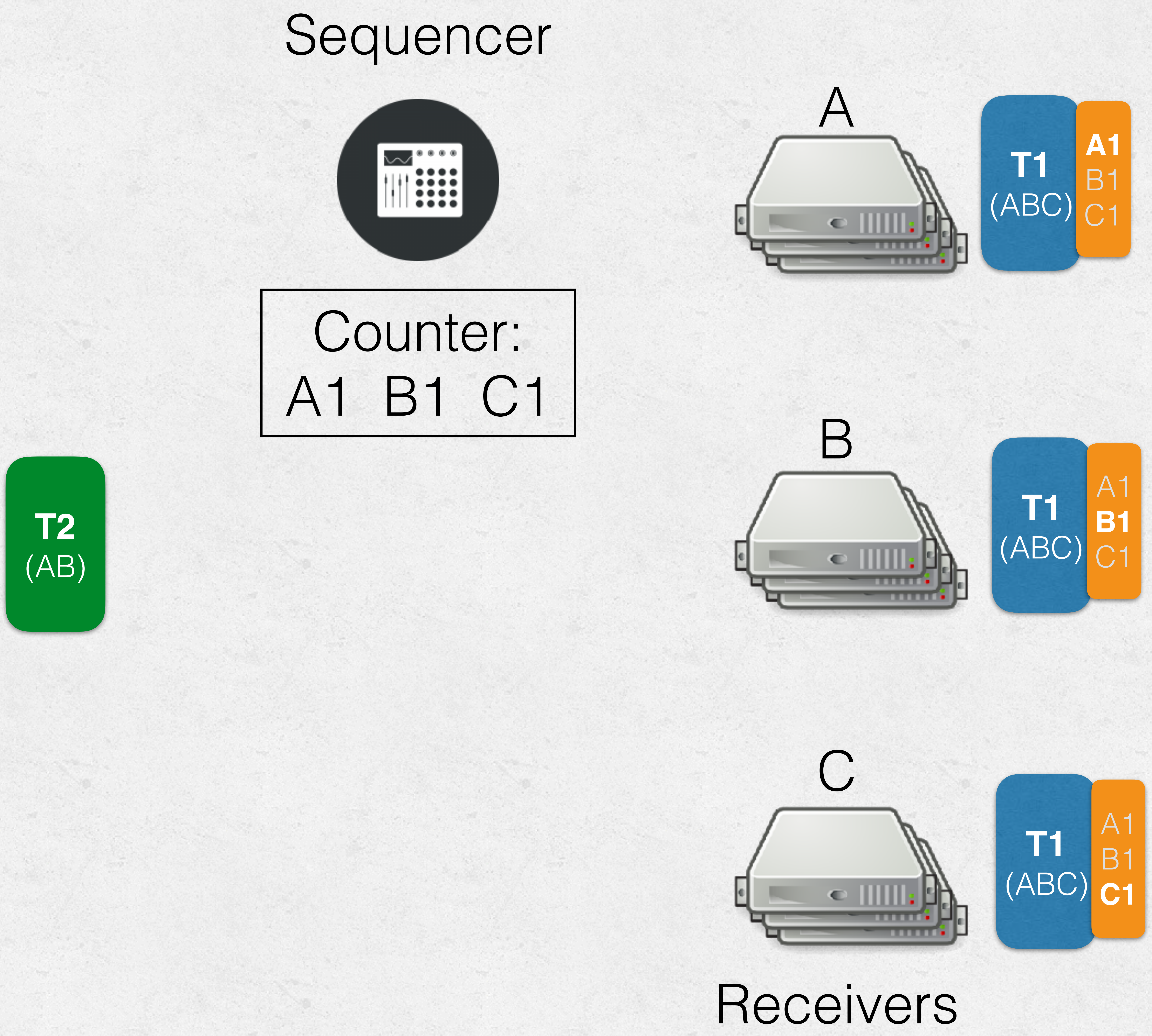
A1
B1
C1

C

T1
(ABC)

A1
B1
C1

Receivers



Sequencer

Counter:
A1 B1 C1

T2
(AB)

A

T1
(ABC)

A1
B1
C1

B

T1
(ABC)

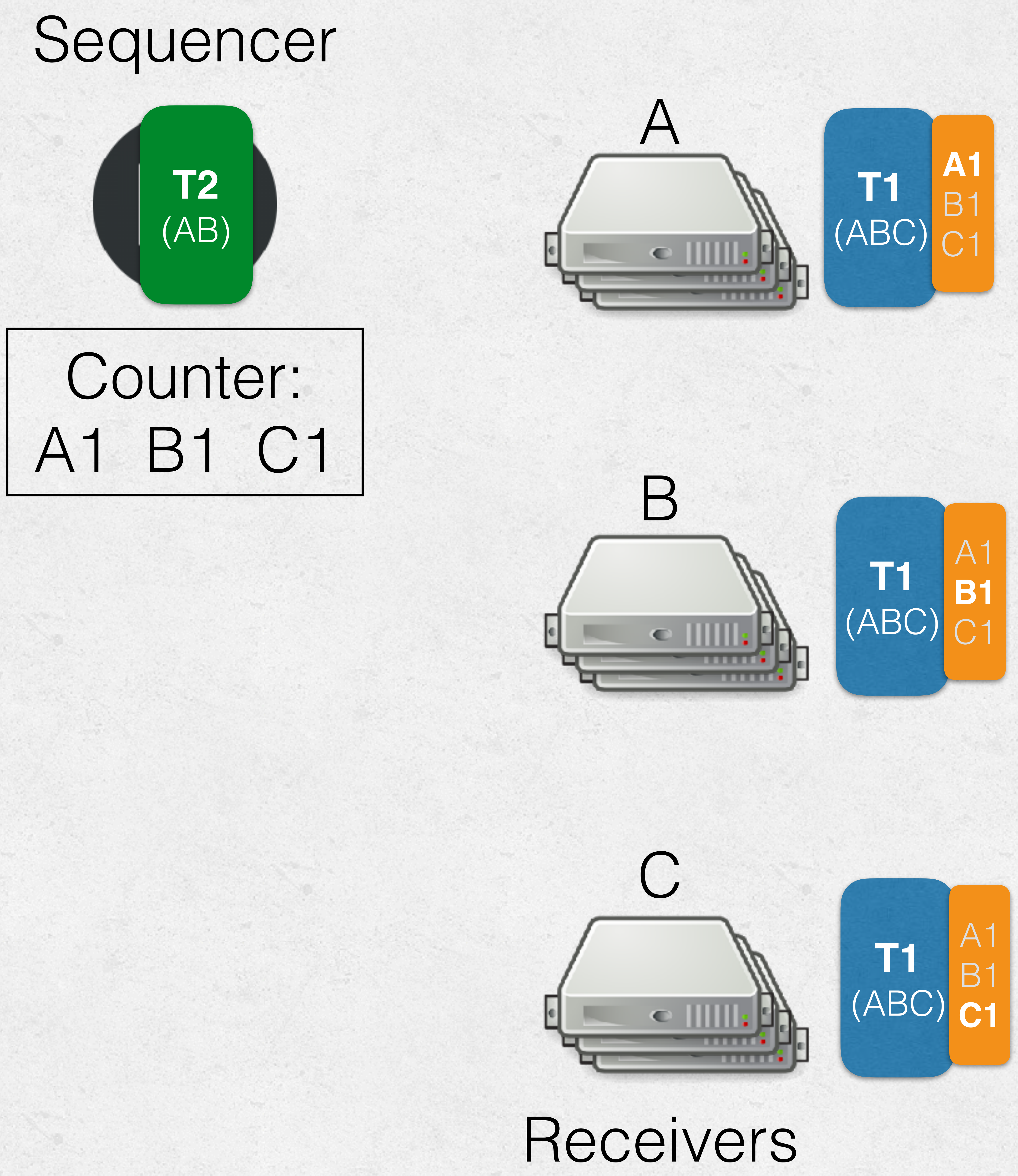
A1
B1
C1

C

T1
(ABC)

A1
B1
C1

Receivers



Sequencer

T2
(AB)

Counter:
A1 B1 C1

A

T1
(ABC)

A1
B1
C1

B

T1
(ABC)

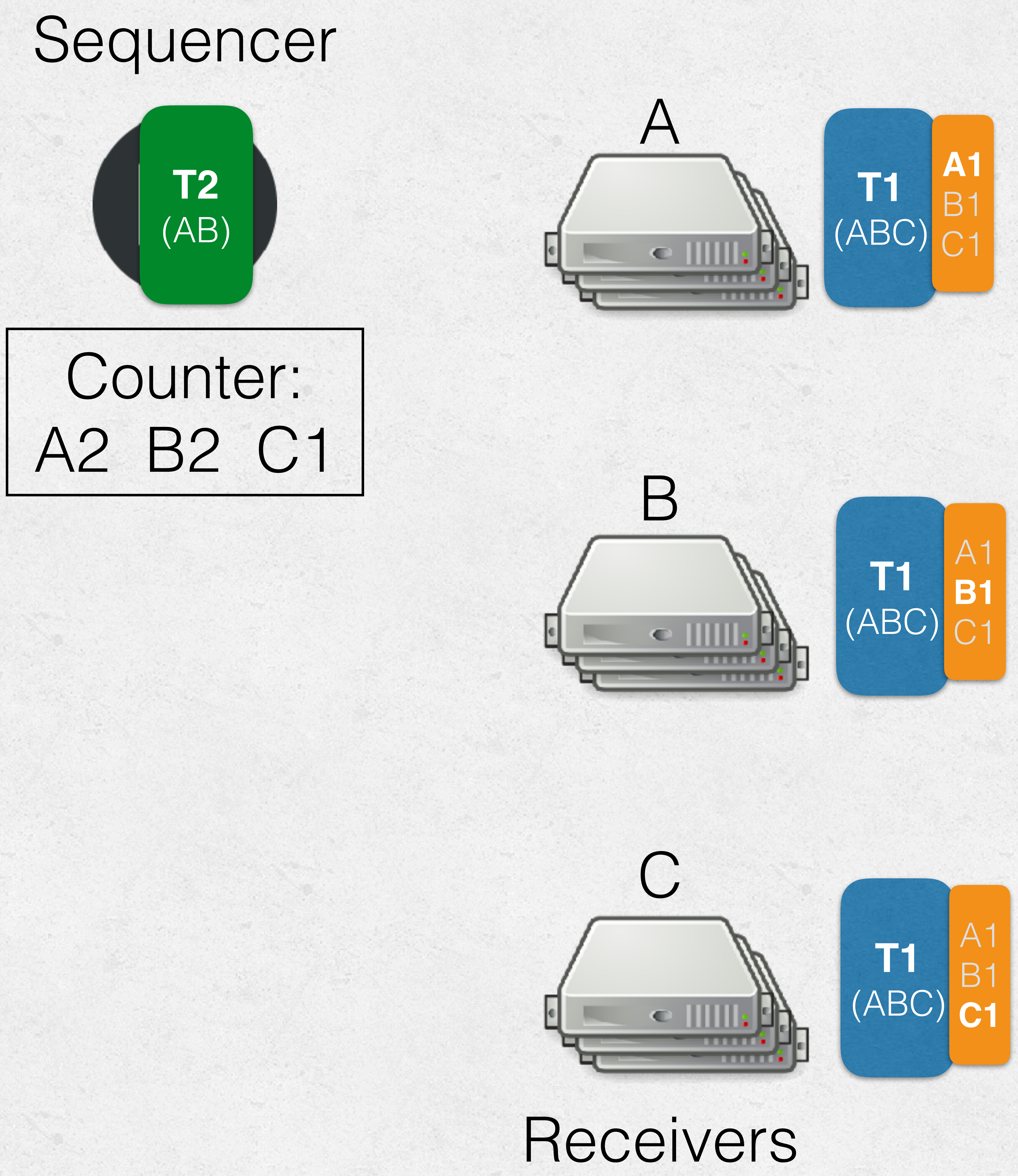
A1
B1
C1

C

T1
(ABC)

A1
B1
C1

Receivers



Sequencer

T2
(AB)

Counter:
A2 B2 C1

A

T1
(ABC)

A1
B1
C1

B

T1
(ABC)

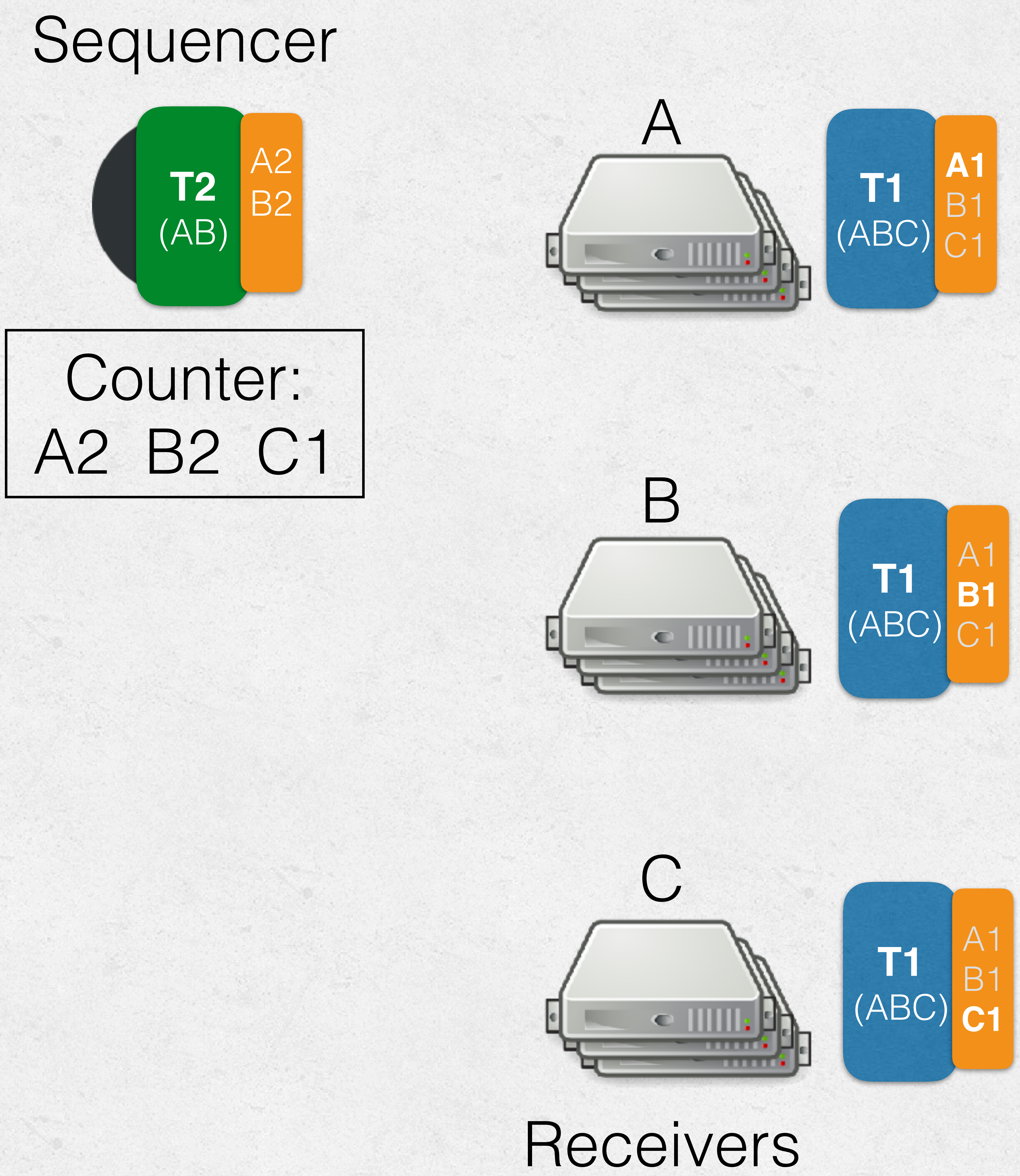
A1
B1
C1

C

T1
(ABC)

A1
B1
C1

Receivers



Sequencer

T2
(AB)
A2
B2

Counter:
A2 B2 C1

A

T1
(ABC)
A1
B1
C1

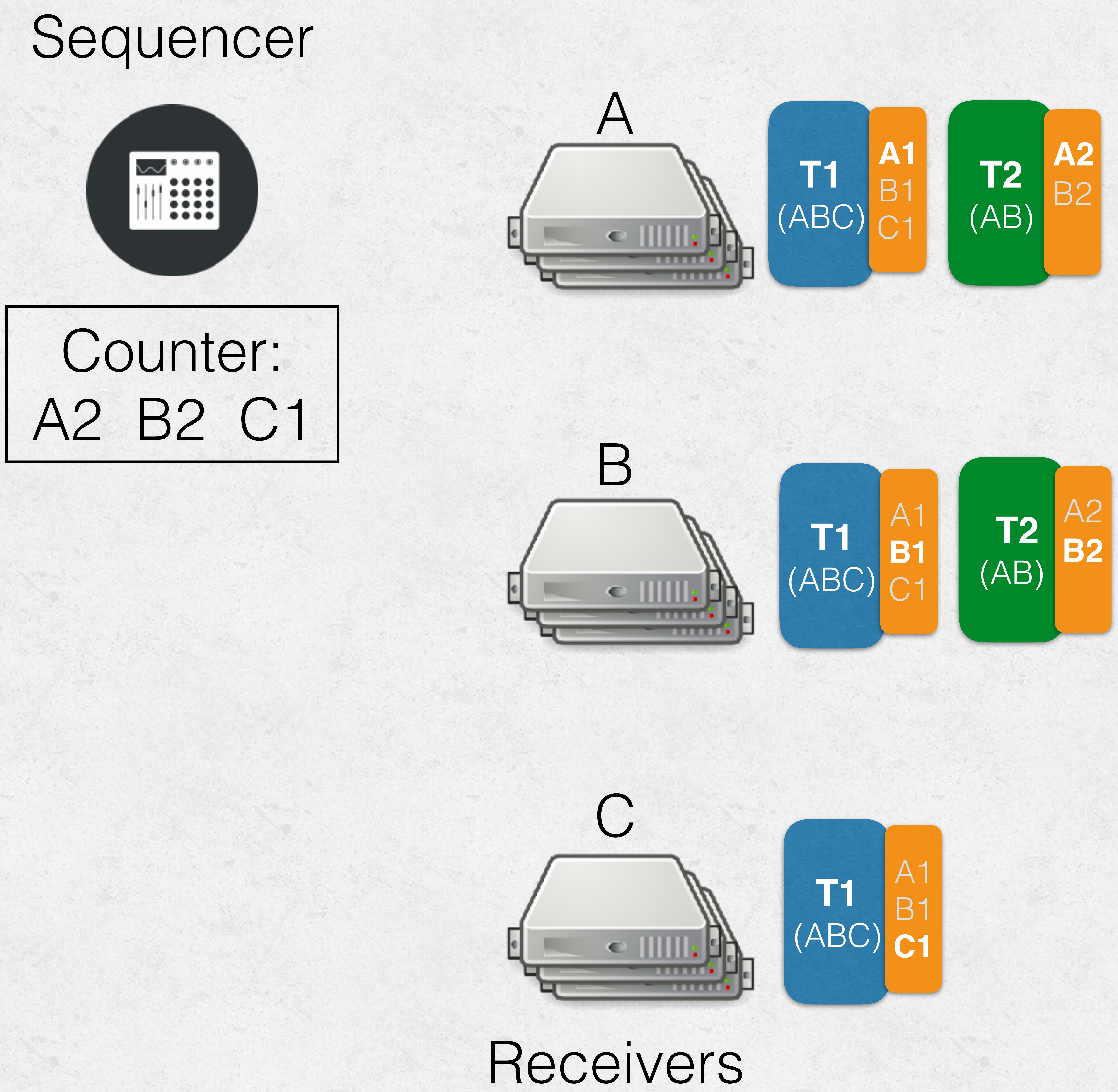
B

T1
(ABC)
A1
B1
C1

C

T1
(ABC)
A1
B1
C1

Receivers



Sequencer

Counter:
A2 B2 C1

A

T1 (ABC) | **A1** B1 C1

T2 (AB) | **A2** B2

B

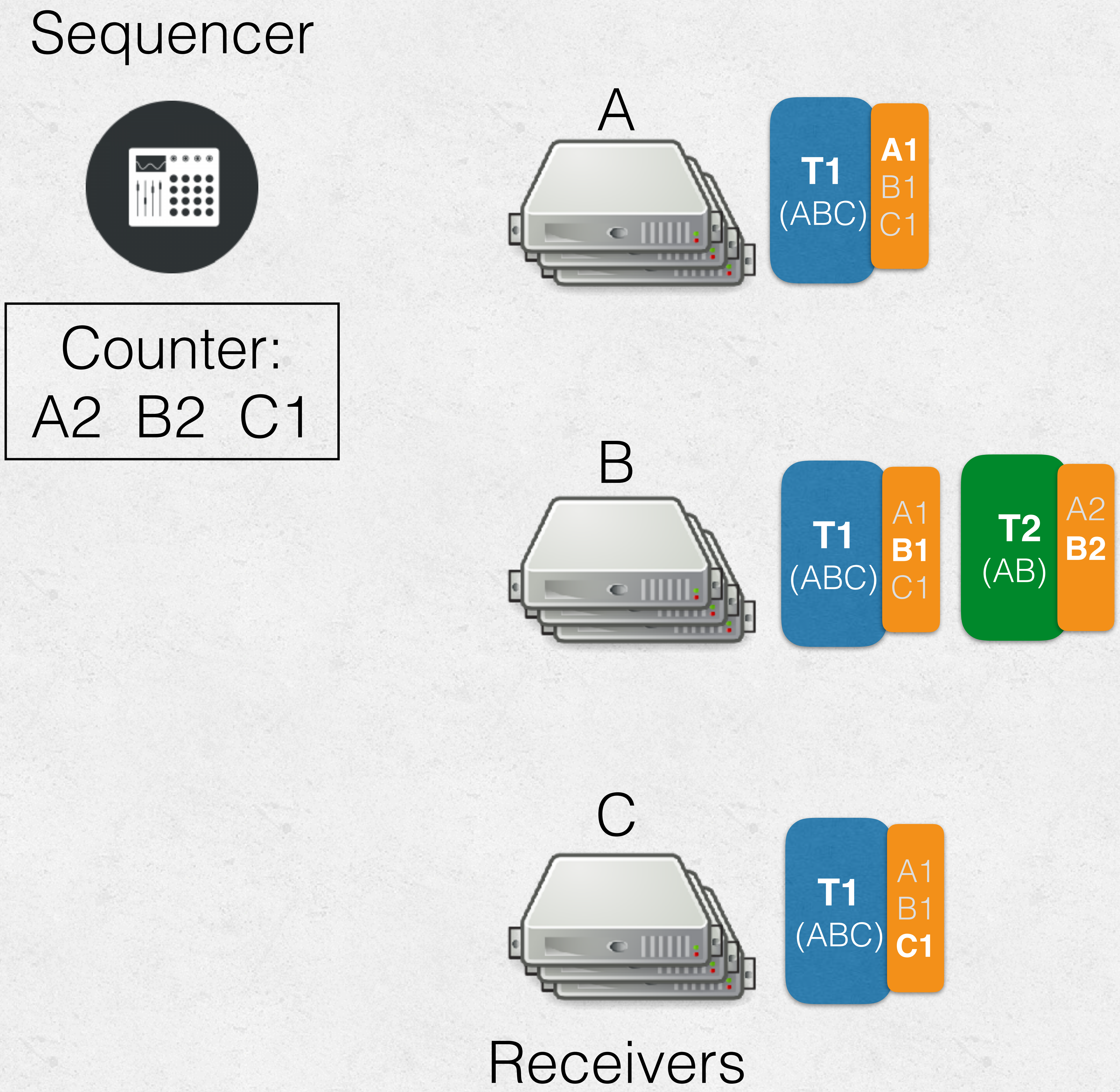
T1 (ABC) | A1 **B1** C1

T2 (AB) | A2 **B2**

C

T1 (ABC) | A1 B1 **C1**

Receivers



Sequencer

Counter:
A2 B2 C1

A

T1 (ABC) **A1** B1 C1

B

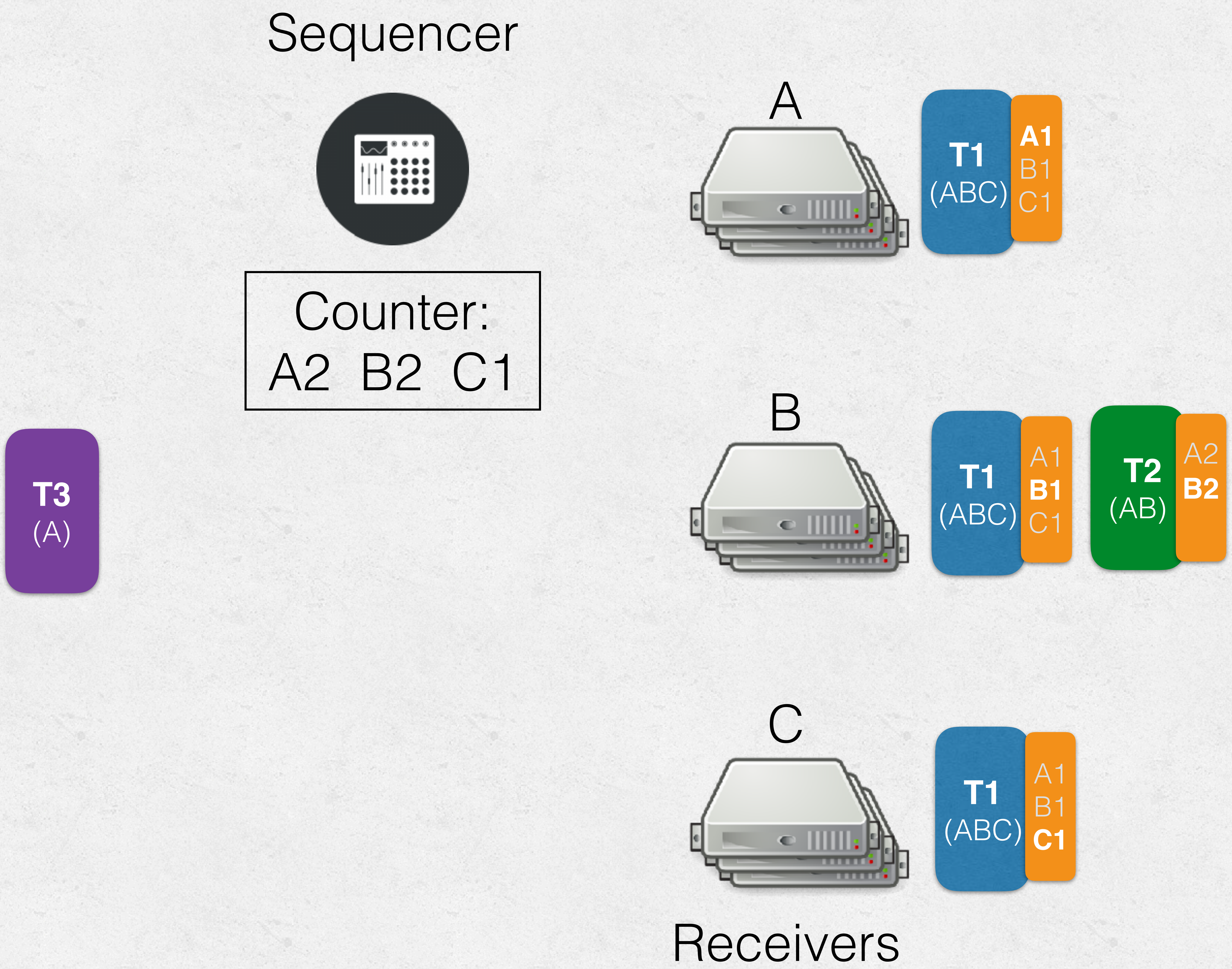
T1 (ABC) A1 **B1** C1

T2 (AB) A2 **B2**

C

T1 (ABC) A1 B1 **C1**

Receivers



Sequencer

Counter:
A2 B2 C1

T3
(A)

A

T1
(ABC)

A1
B1
C1

B

T1
(ABC)

A1
B1
C1

T2
(AB)

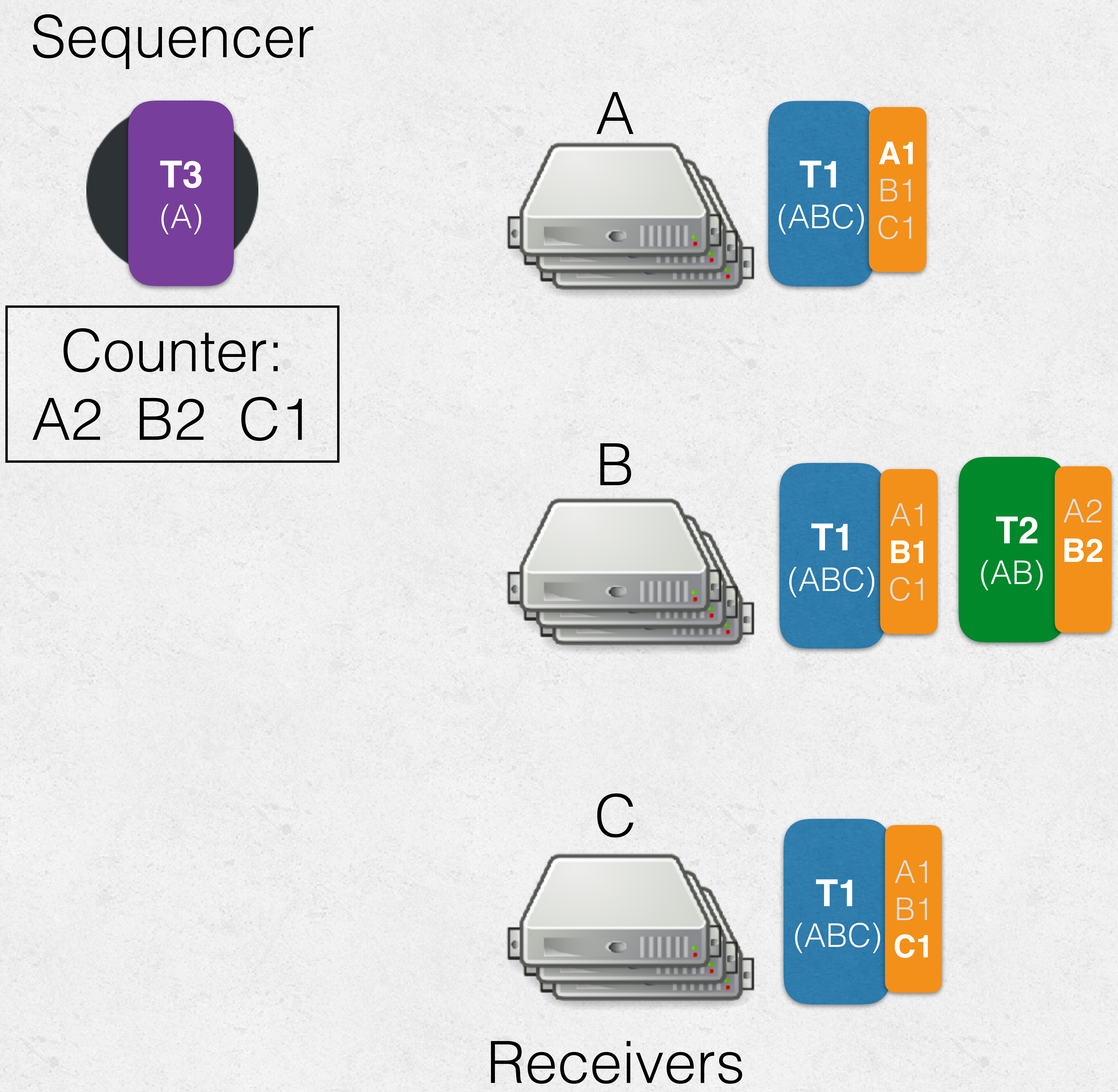
A2
B2

C

T1
(ABC)

A1
B1
C1

Receivers



Sequencer

T3
(A)

Counter:
A2 B2 C1

A

T1
(ABC)

A1
B1
C1

B

T1
(ABC)

A1
B1
C1

T2
(AB)

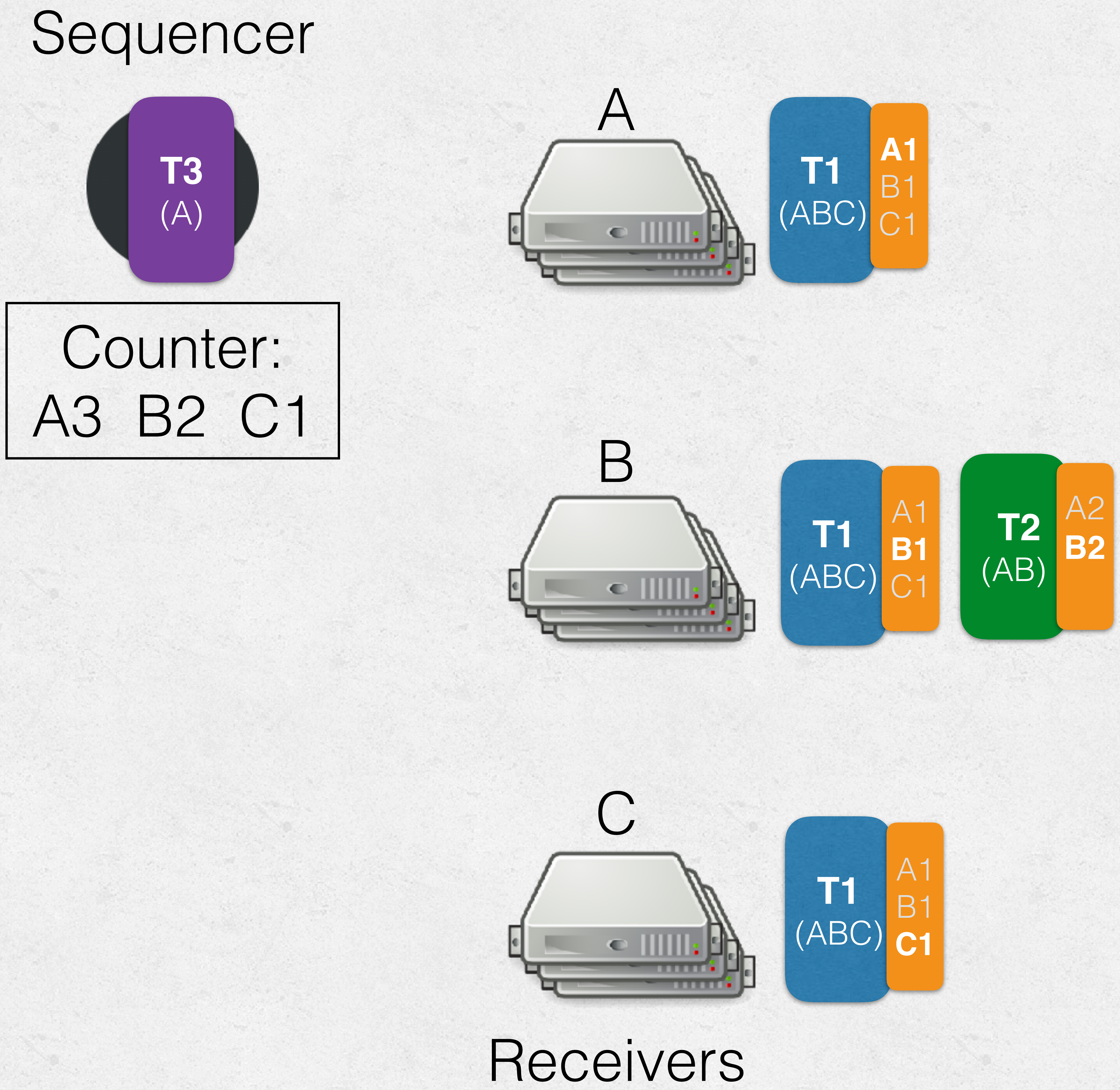
A2
B2

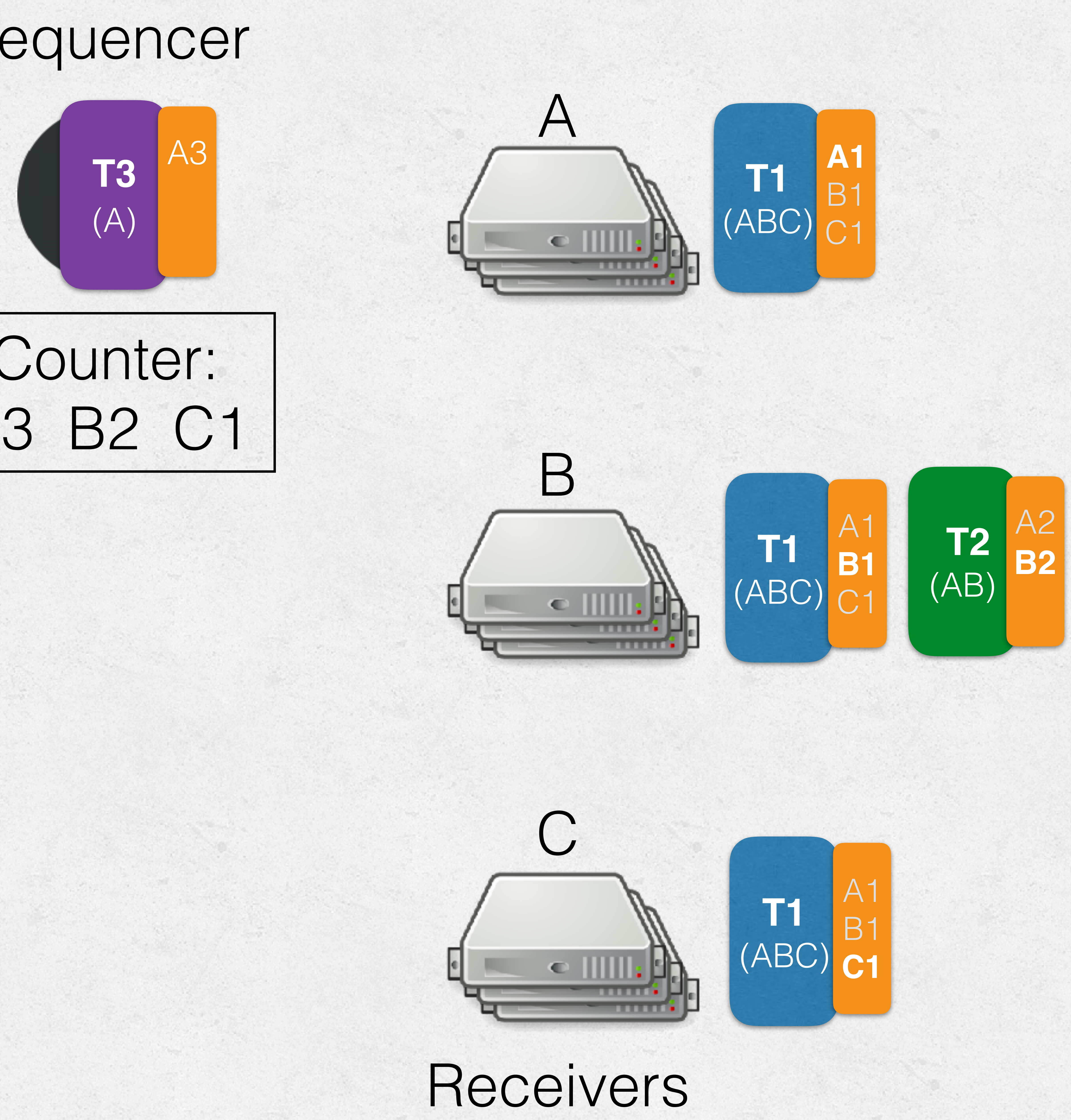
C

T1
(ABC)

A1
B1
C1

Receivers





Sequencer

T3
(A)
A3

Counter:
A3 B2 C1

A

T1
(ABC)
A1
B1
C1

B

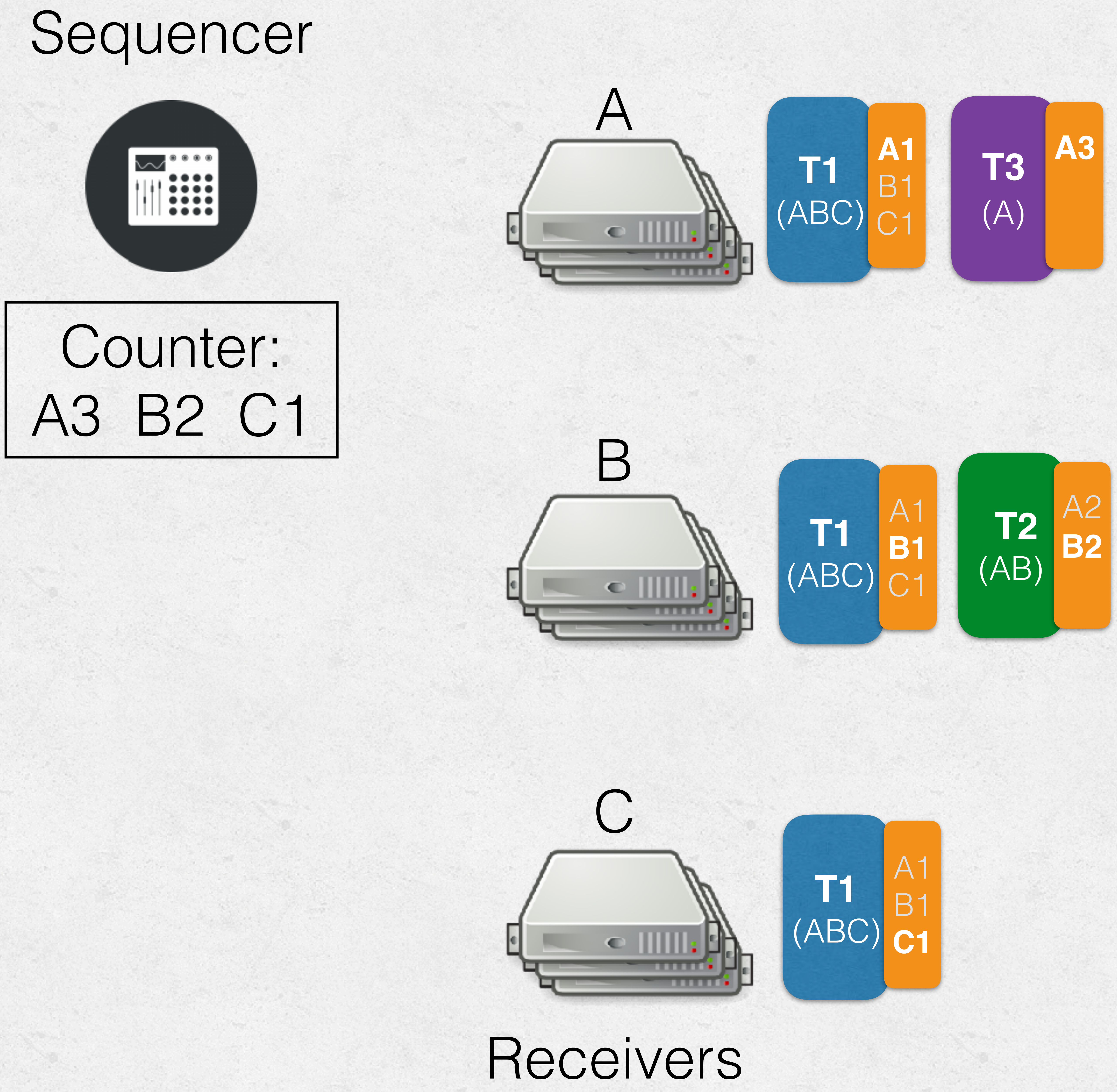
T1
(ABC)
A1
B1
C1

T2
(AB)
A2
B2

C

T1
(ABC)
A1
B1
C1

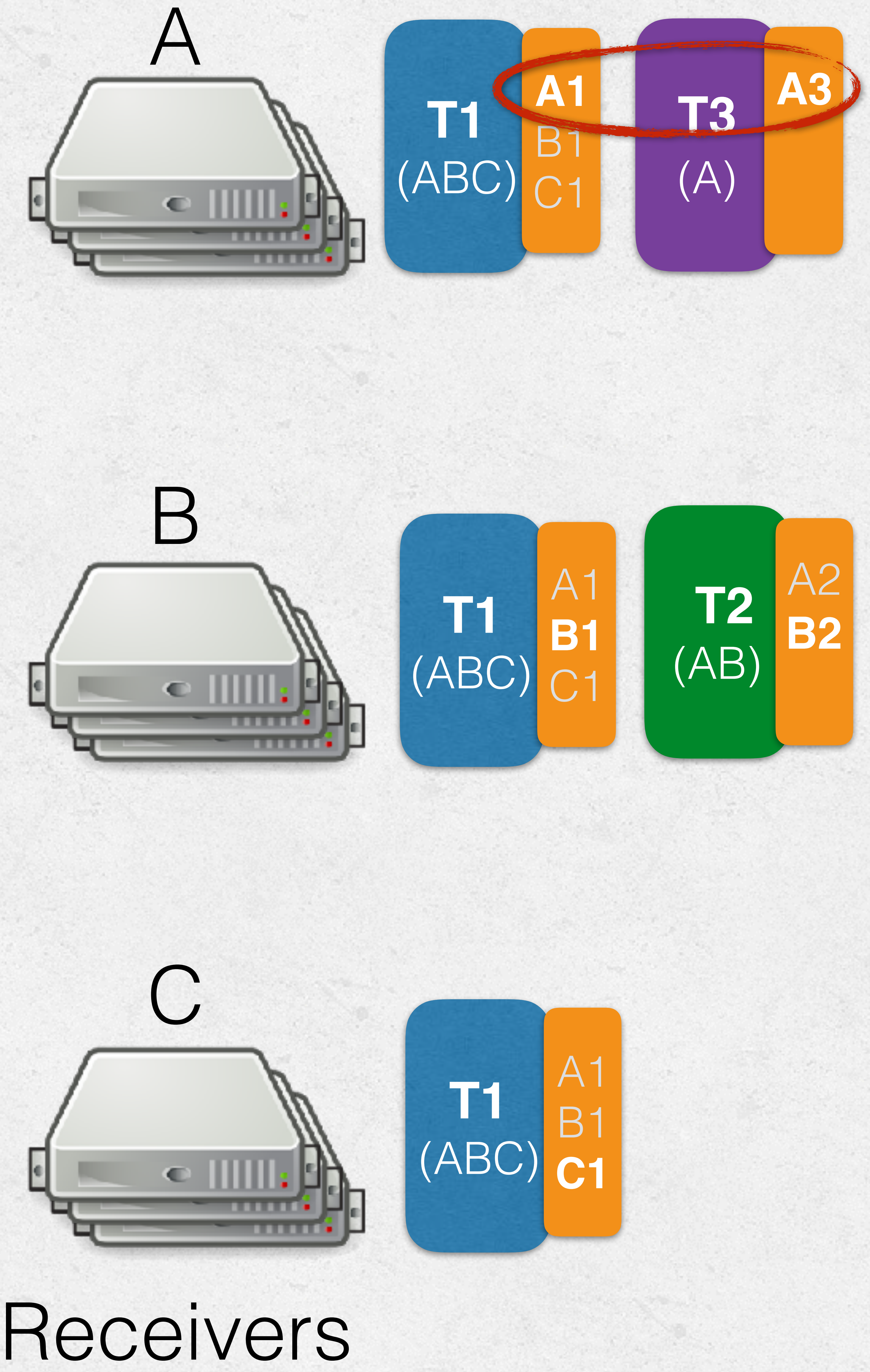
Receivers

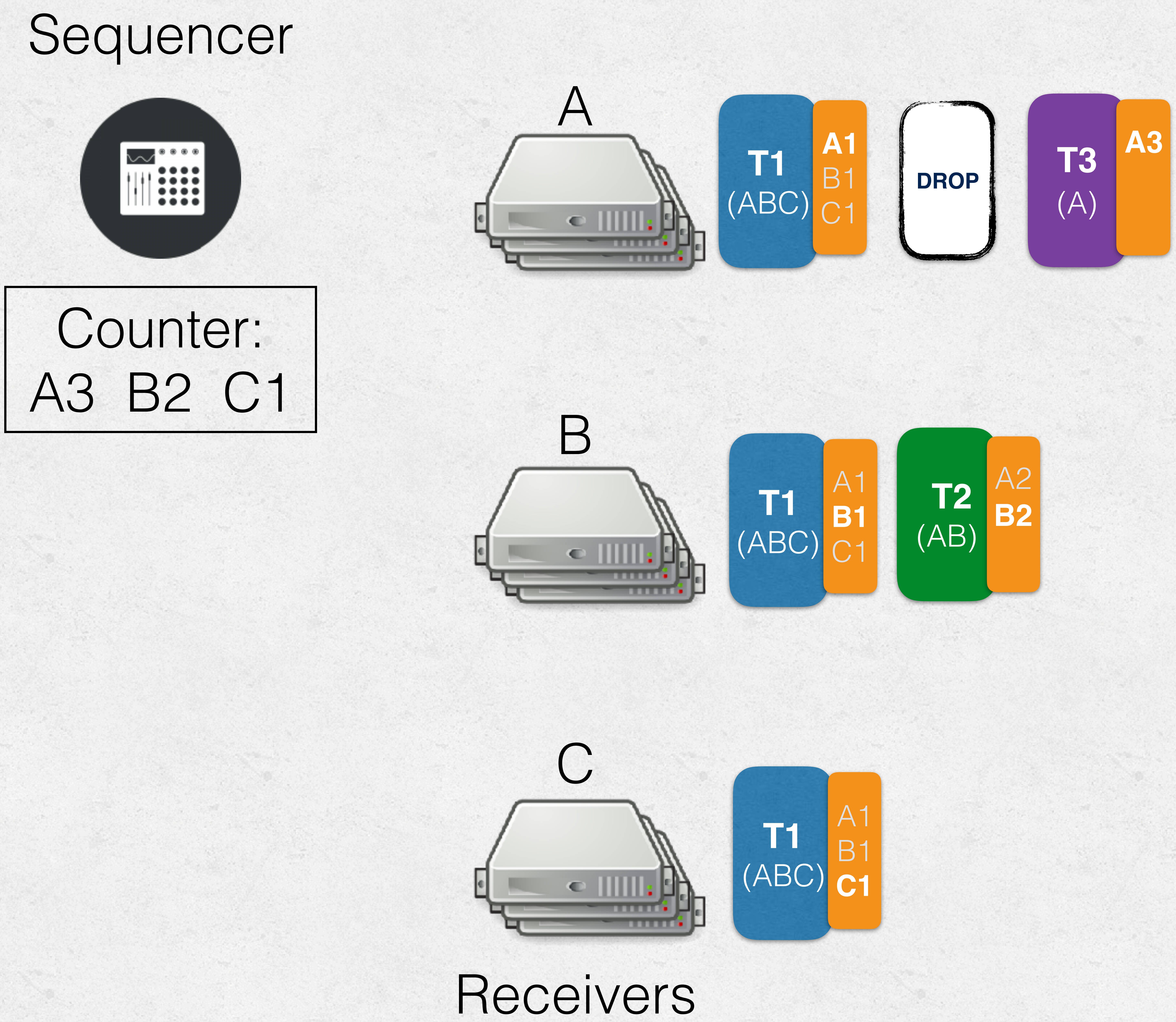


Sequencer
Counter:
A3 B2 C1
A
T1
(ABC)
A1
B1
C1
T3
(A)
A3
B
T1
(ABC)
A1
B1
C1
T2
(AB)
A2
B2
C
T1
(ABC)
A1
B1
C1
Receivers

Sequencer

Counter:
A3 B2 C1





What have we accomplished so far?

- Consistently ordered groupcast primitive with drop detection

- How do we go from multi-sequenced groupcast to transactions?

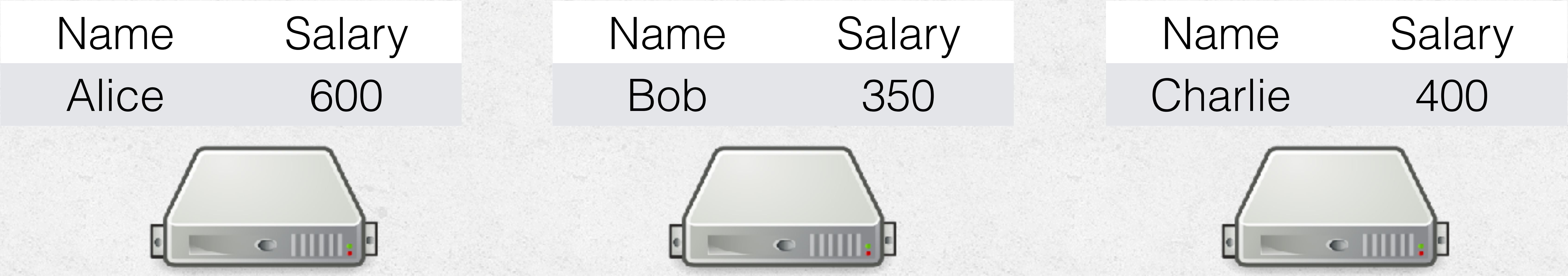
Transaction Model

Eris supports two types of transactions

- **Independent transactions**:
  - One-shot (stored procedures)
  - No cross-shard dependencies
  - Proposed by H-Store [VLDB ’07] and Granola [ATC ’12]
- Fully general transactions

INDEPENDENT TRANSACTION

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```



Name	Salary
Alice	600

Name	Salary
Bob	350

Name	Salary
Charlie	400

Independent Transaction

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Alice	600

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Bob	350

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Charlie	400

Independent Transaction

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Alice	600

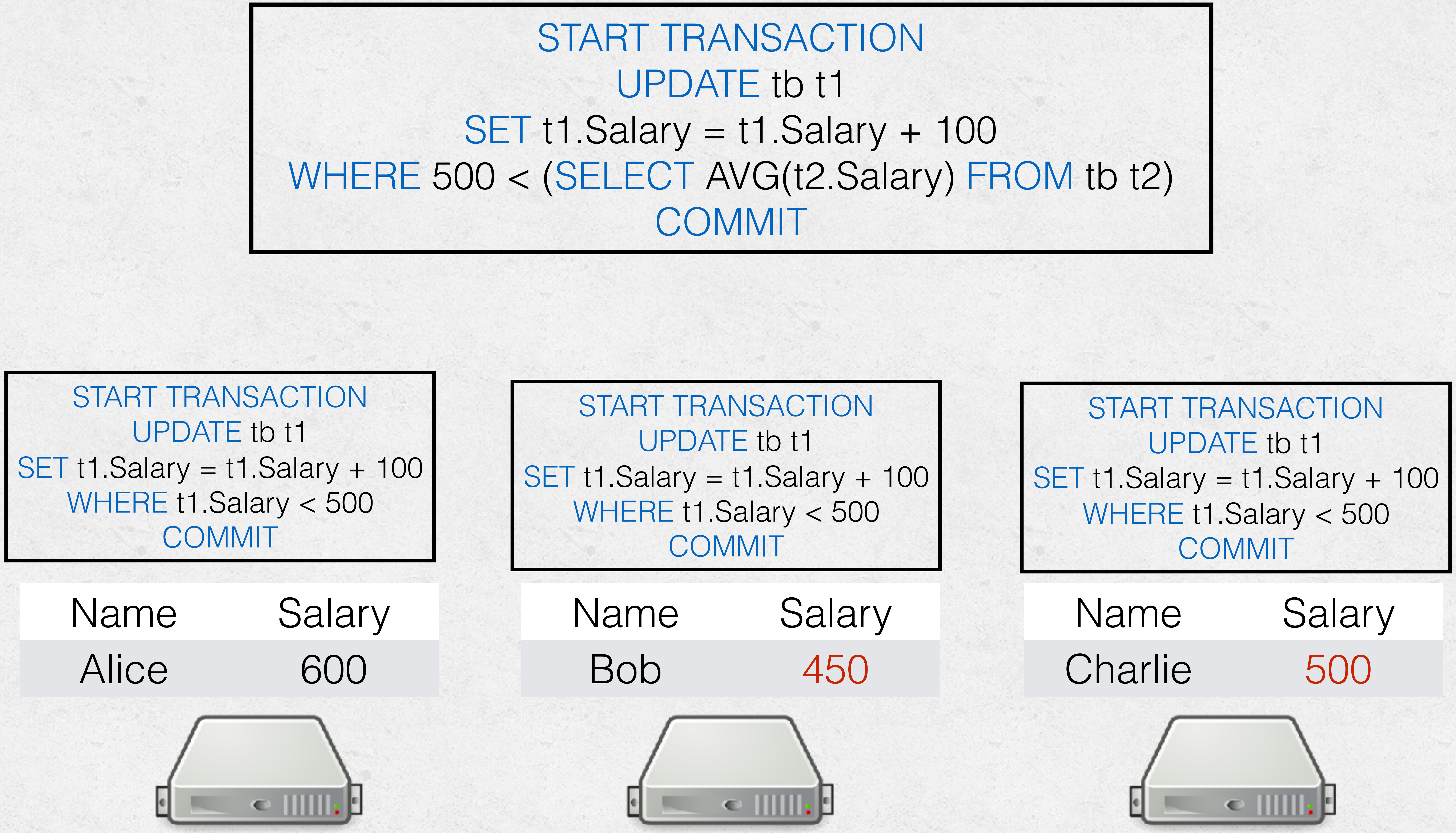
```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Bob	450

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Charlie	500

Independent Transaction



```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE 500 < (SELECT AVG(t2.Salary) FROM tb t2)
COMMIT
```

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Alice	600

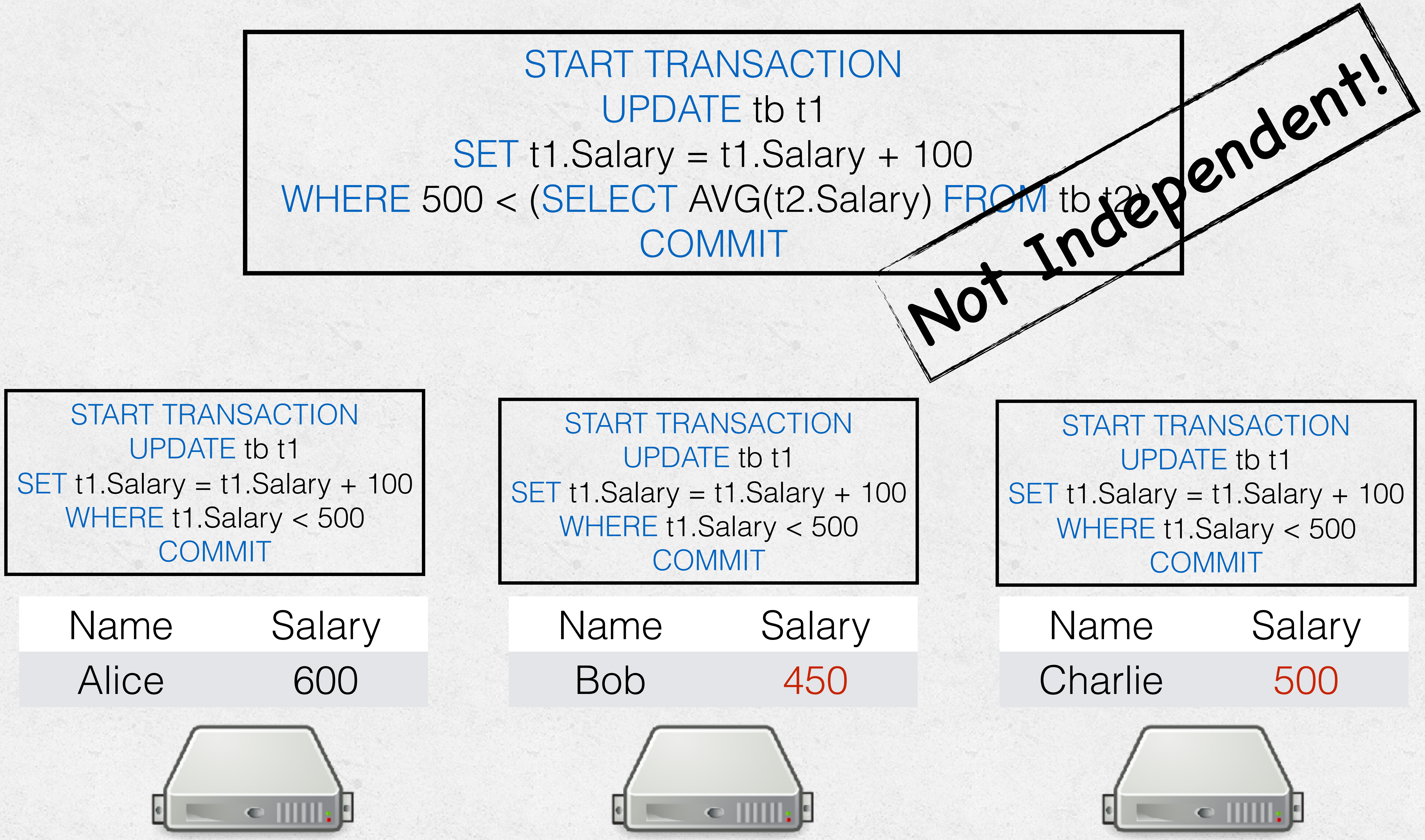
```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Bob	450

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Charlie	500

Independent Transaction



```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE 500 < (SELECT AVG(t2.Salary) FROM tb t2)
COMMIT
```

Not Independent!

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Alice	600

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Bob	450

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Charlie	500

Independent Transaction

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Alice	600

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

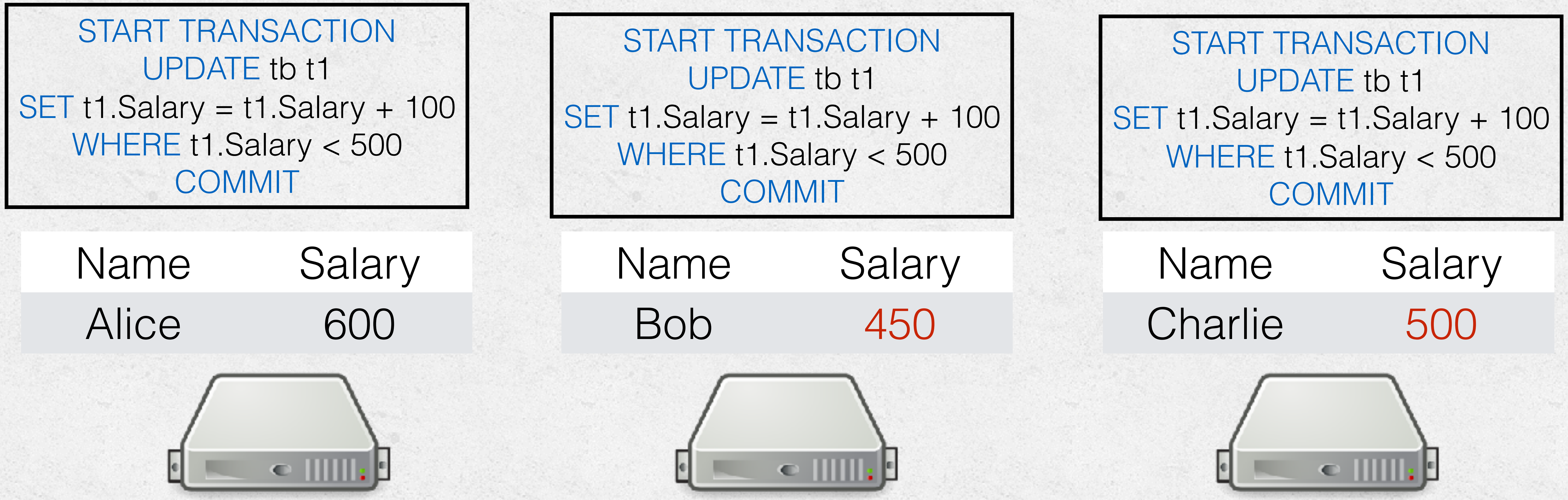
Name	Salary
Bob	450

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Charlie	500

Independent Transaction

Many applications consist **entirely** of independent transactions



```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Alice	600

```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Bob	450

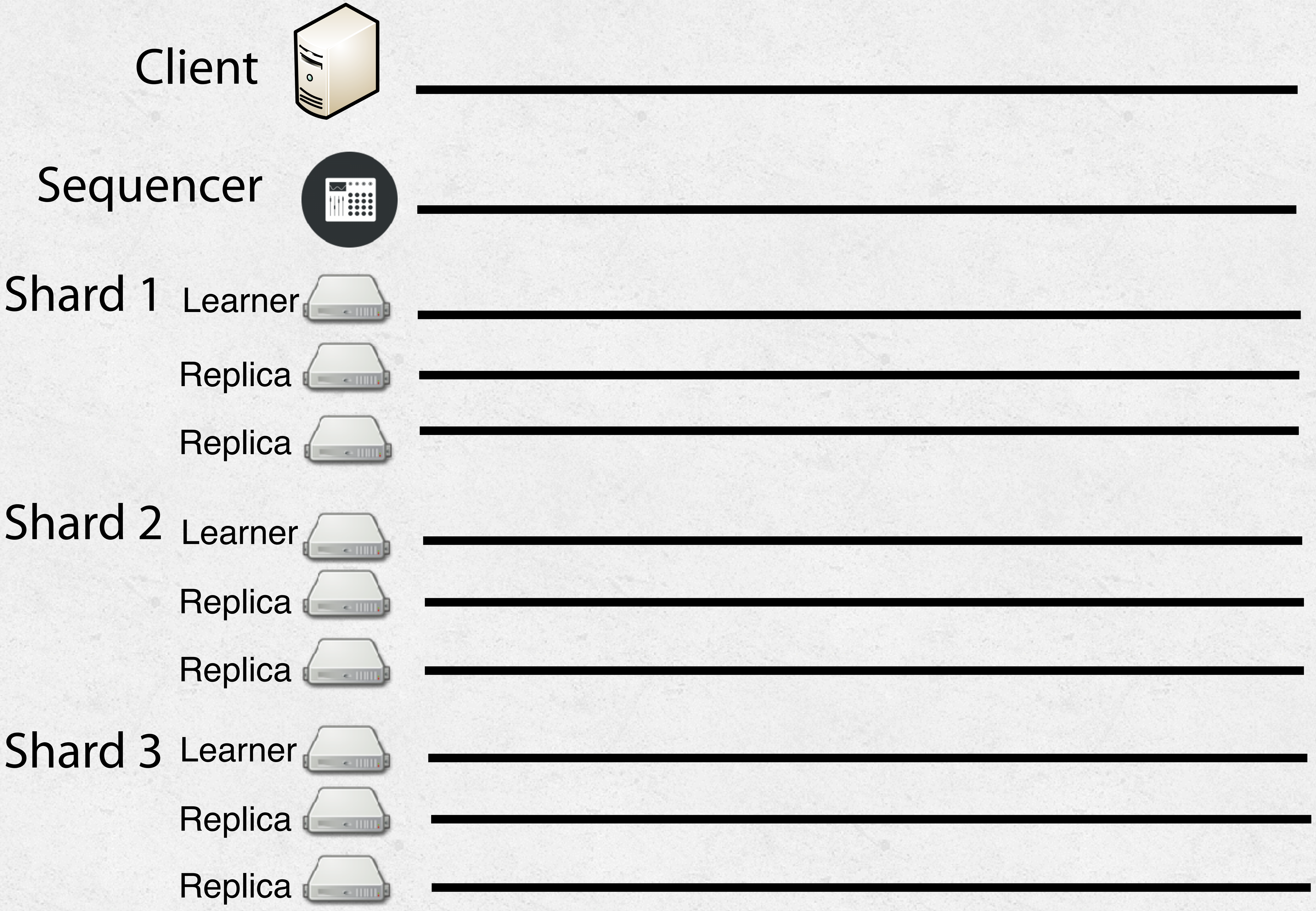
```
START TRANSACTION
UPDATE tb t1
SET t1.Salary = t1.Salary + 100
WHERE t1.Salary < 500
COMMIT
```

Name	Salary
Charlie	500

Why independent transactions?

- **No** coordination/communication across shards
- Executing them serially at each shard in a **consistent order** guarantees **serializability**
- Multi-sequenced groupcast establishes such an order
- How to handle **message drops** and sequencer/ server **failures**?

NORMAL CASE



Client

Sequencer

Shard 1 Learner

Replica

Replica

Shard 2 Learner

Replica

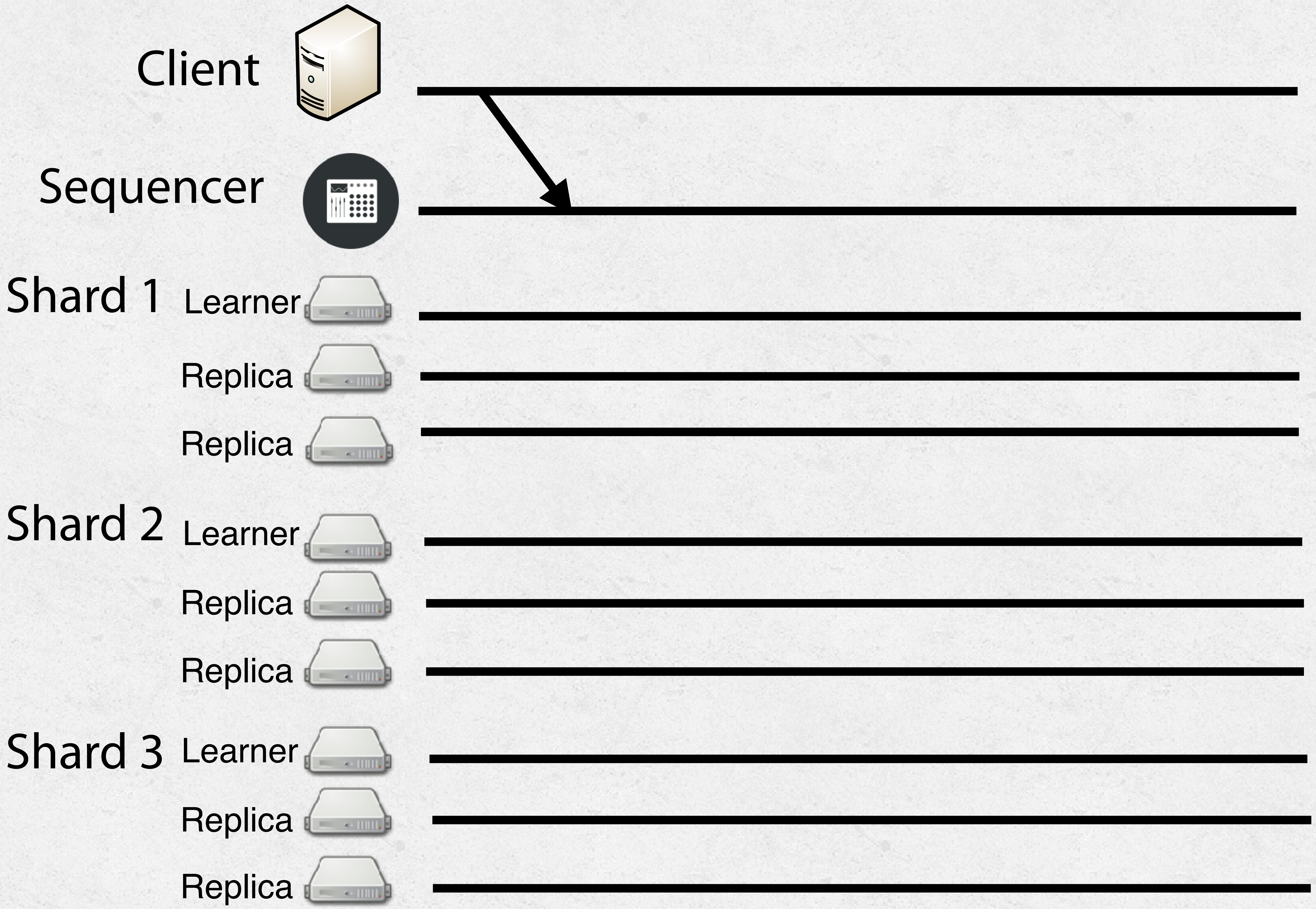
Replica

Shard 3 Learner

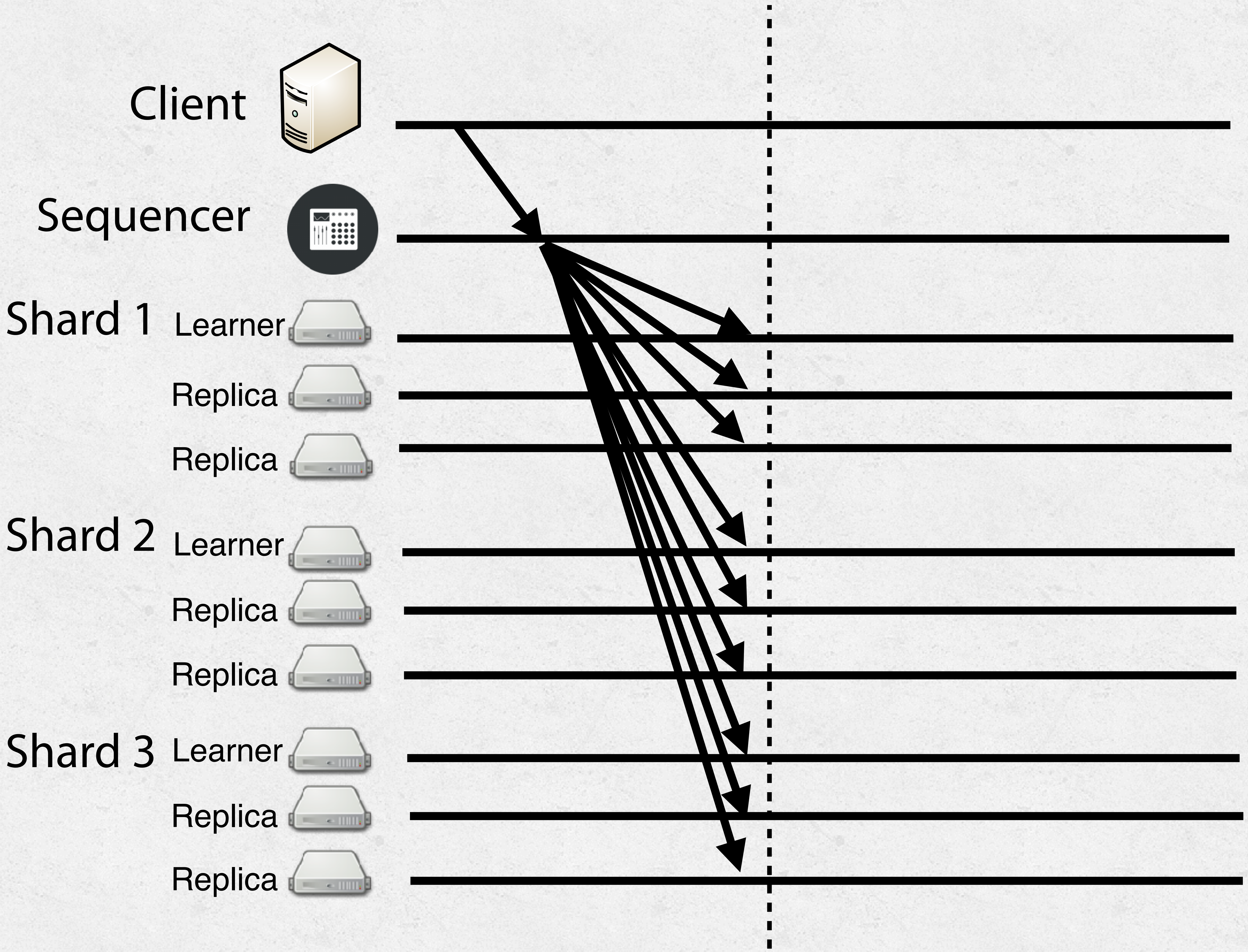
Replica

Replica

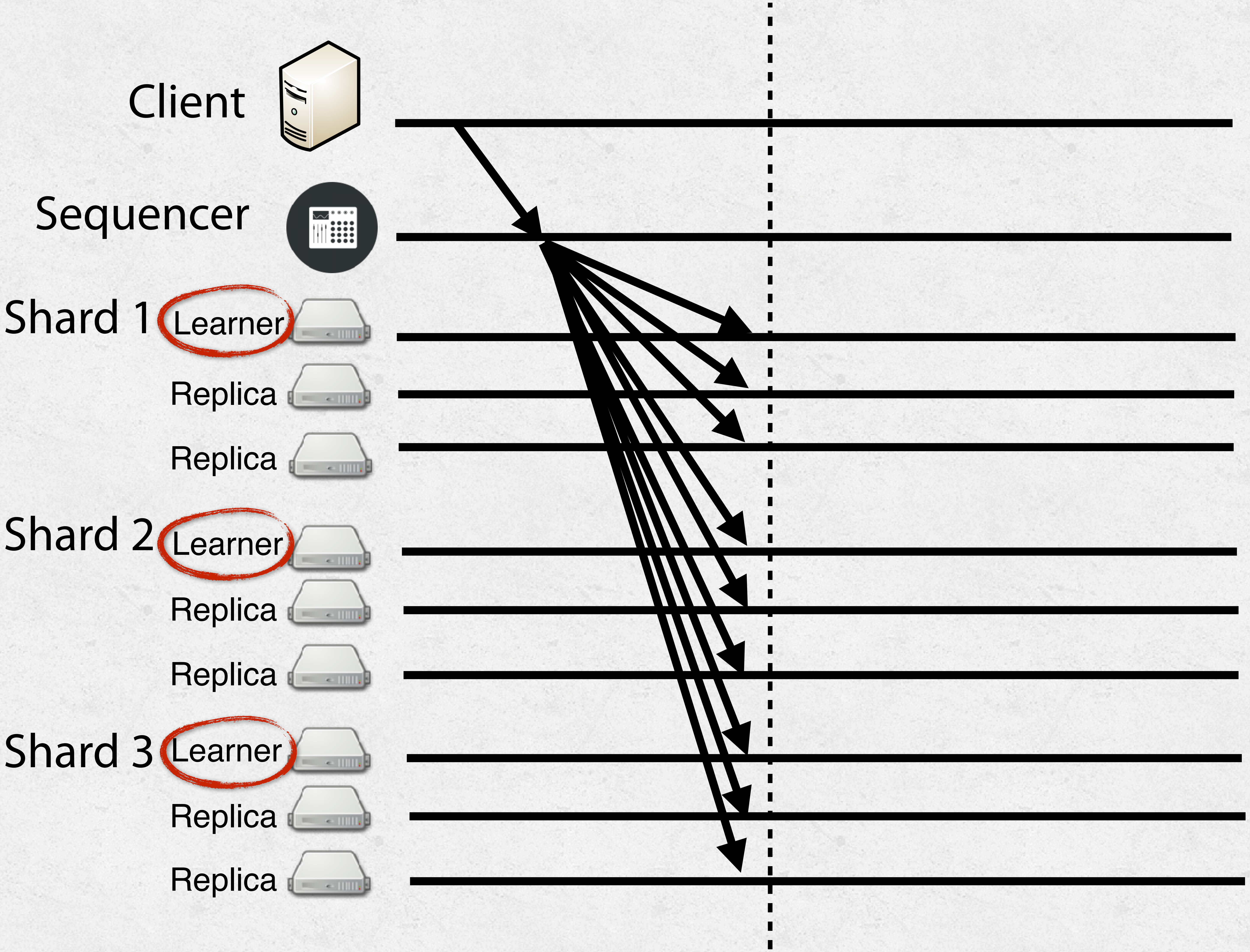
Normal Case


Client
Sequencer
Shard 1
Learner
Replica
Replica
Shard 2
Learner
Replica
Replica
Shard 3
Learner
Replica
Replica

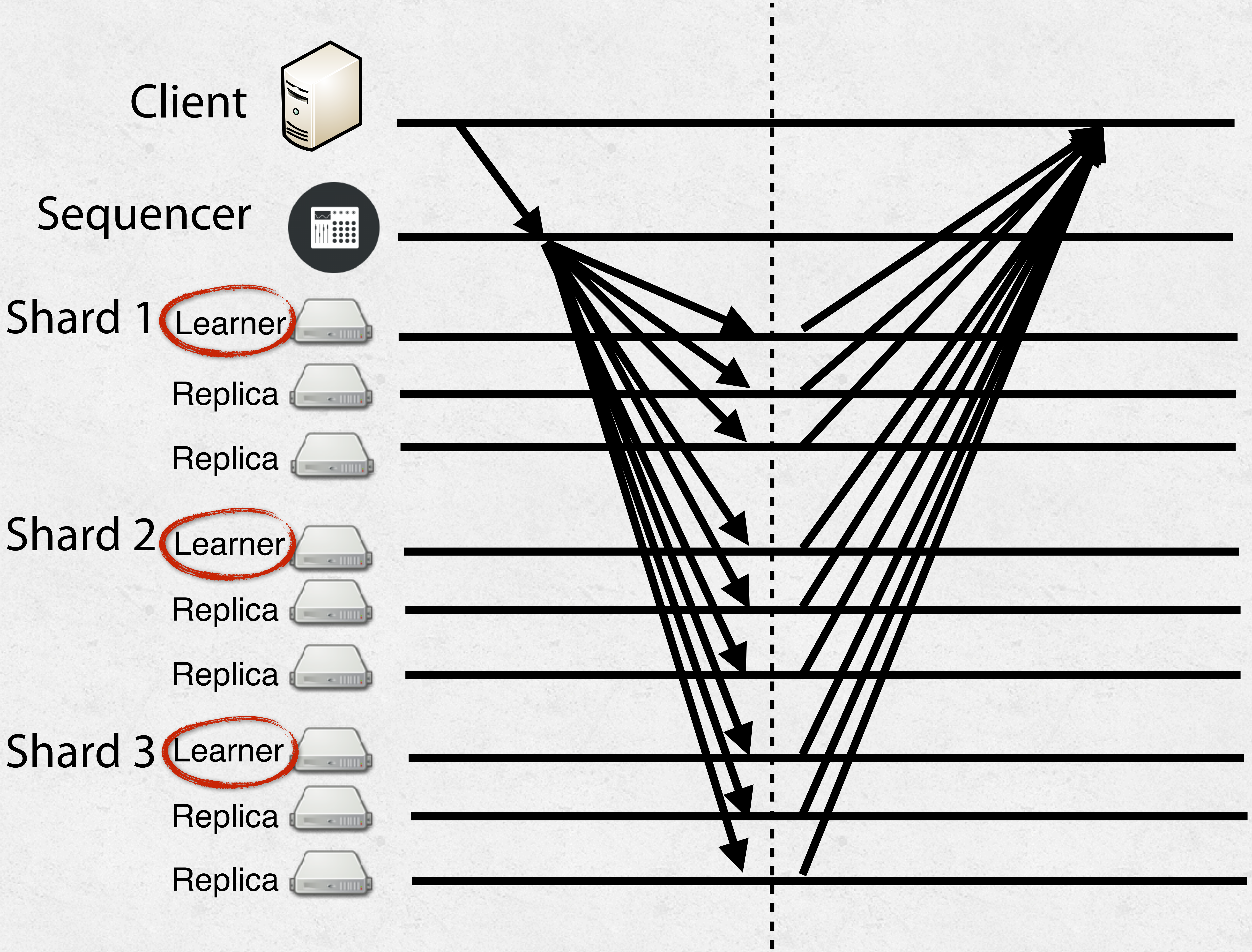
Normal Case


Client
Sequencer
Shard 1
Learner
Replica
Replica
Shard 2
Learner
Replica
Replica
Shard 3
Learner
Replica
Replica

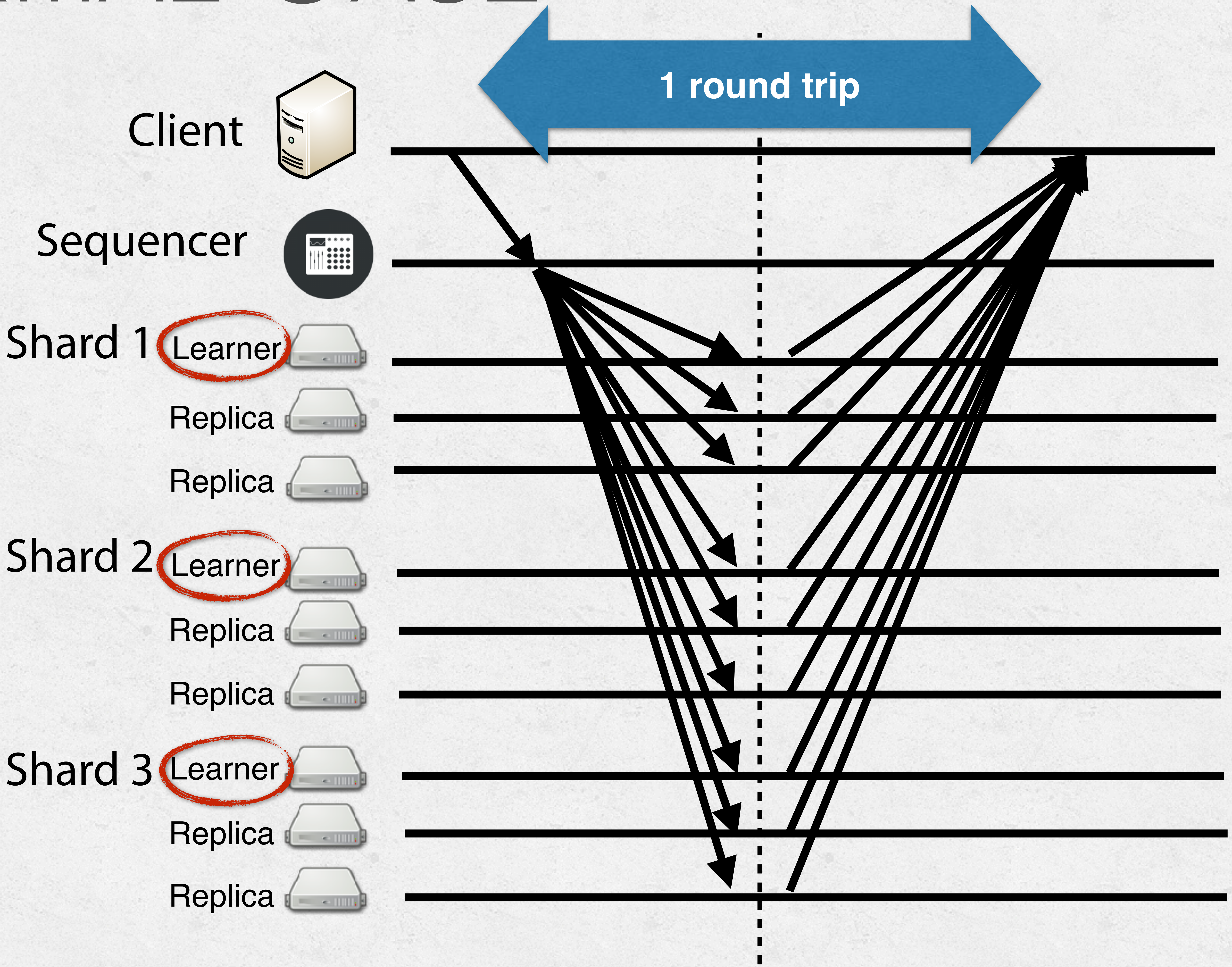
Normal Case


Client
Sequencer
Shard 1
Learner
Replica
Replica
Shard 2
Learner
Replica
Replica
Shard 3
Learner
Replica
Replica

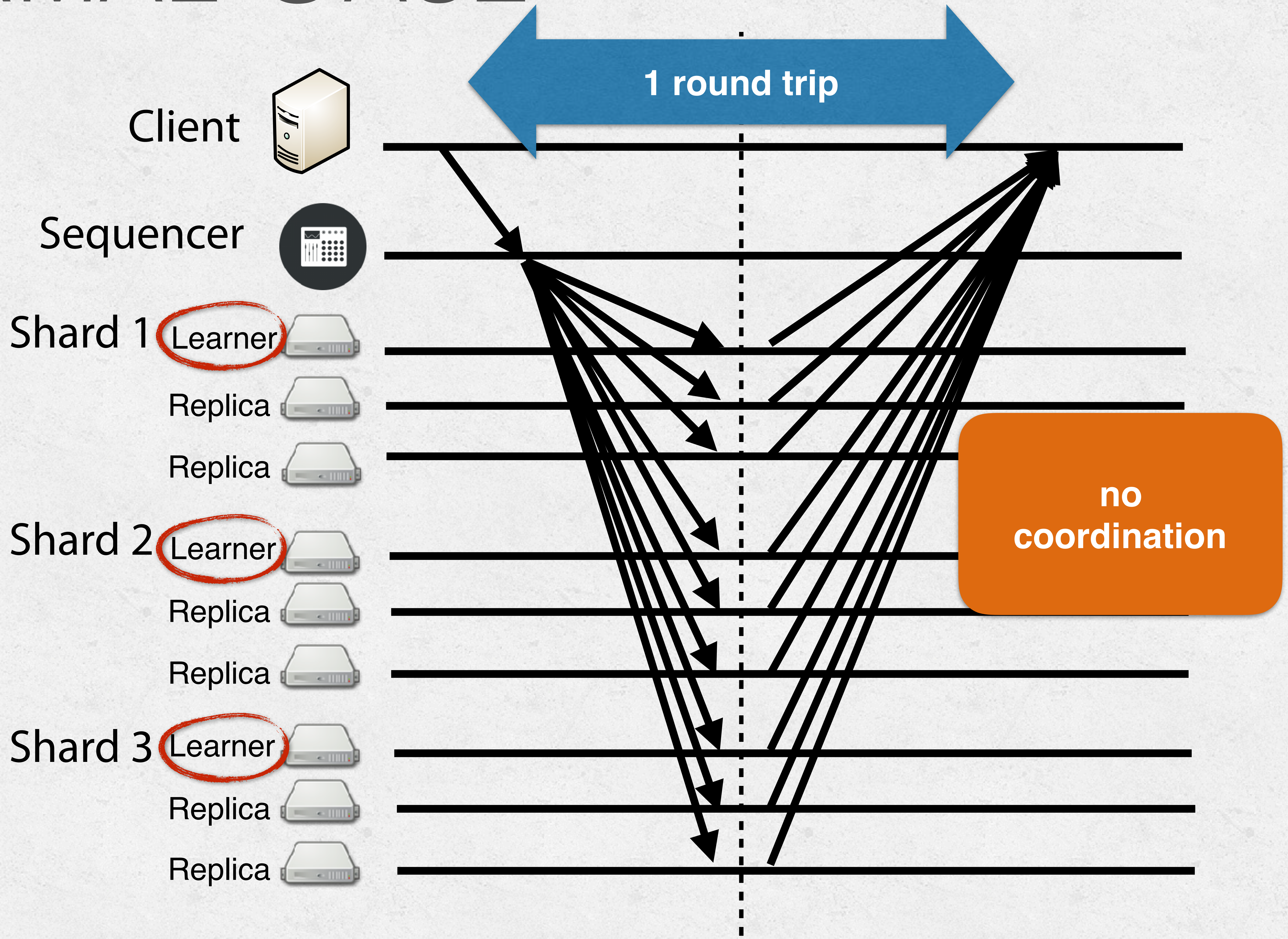
Normal Case


Client
Sequencer
Shard 1
Learner
Replica
Replica
Shard 2
Learner
Replica
Replica
Shard 3
Learner
Replica
Replica

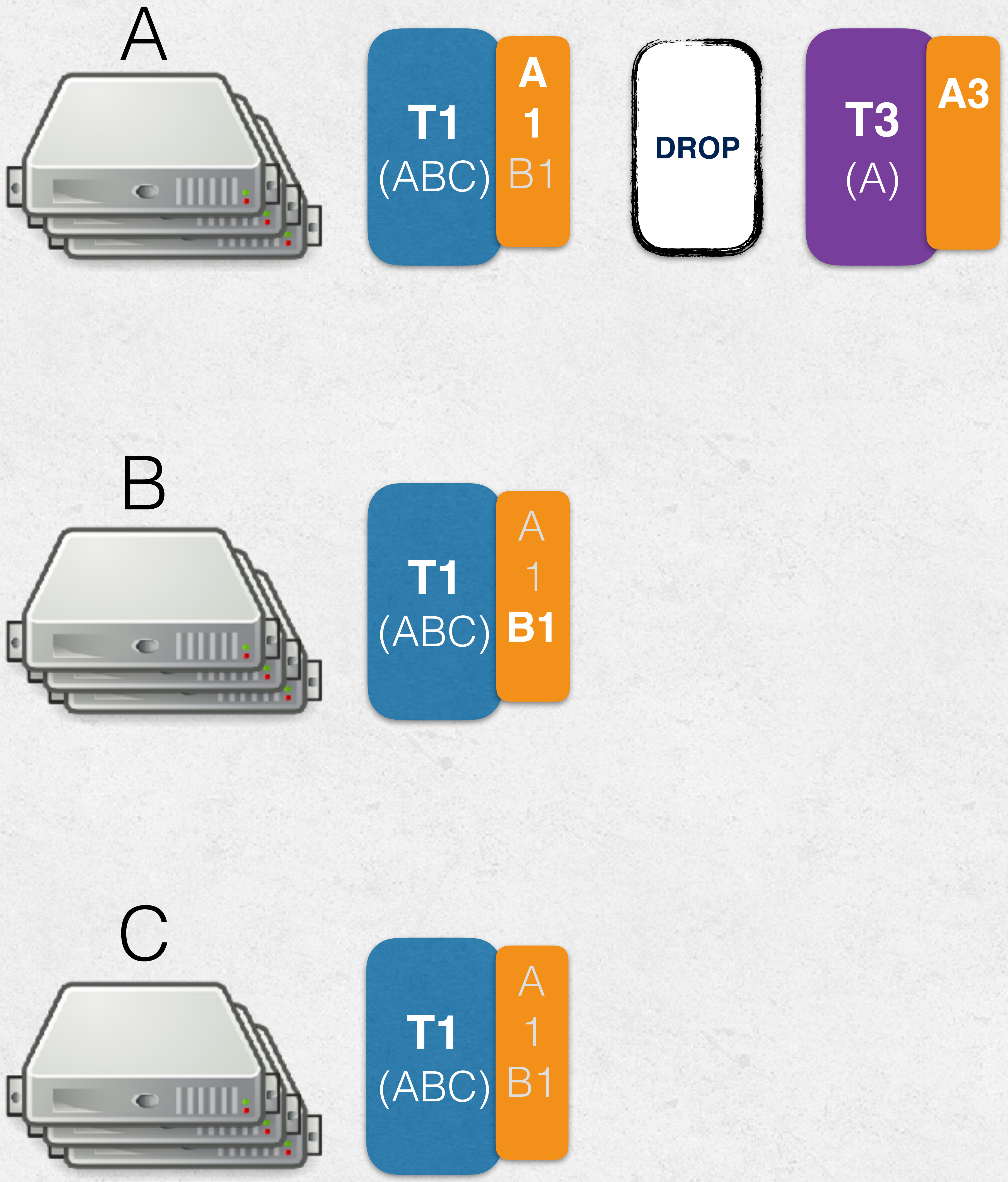
Normal Case


1 round trip
Client
Sequencer
Shard 1
Learner
Replica
Replica
Shard 2
Learner
Replica
Replica
Shard 3
Learner
Replica
Replica

Normal Case


1 round trip
Client
Sequencer
Shard 1
Learner
Replica
Replica
Shard 2
Learner
Replica
Replica
Shard 3
Learner
Replica
Replica
no coordination

How to handle dropped messages?



A

T1 (ABC) A 1 B1

DROP

T3 (A) A3

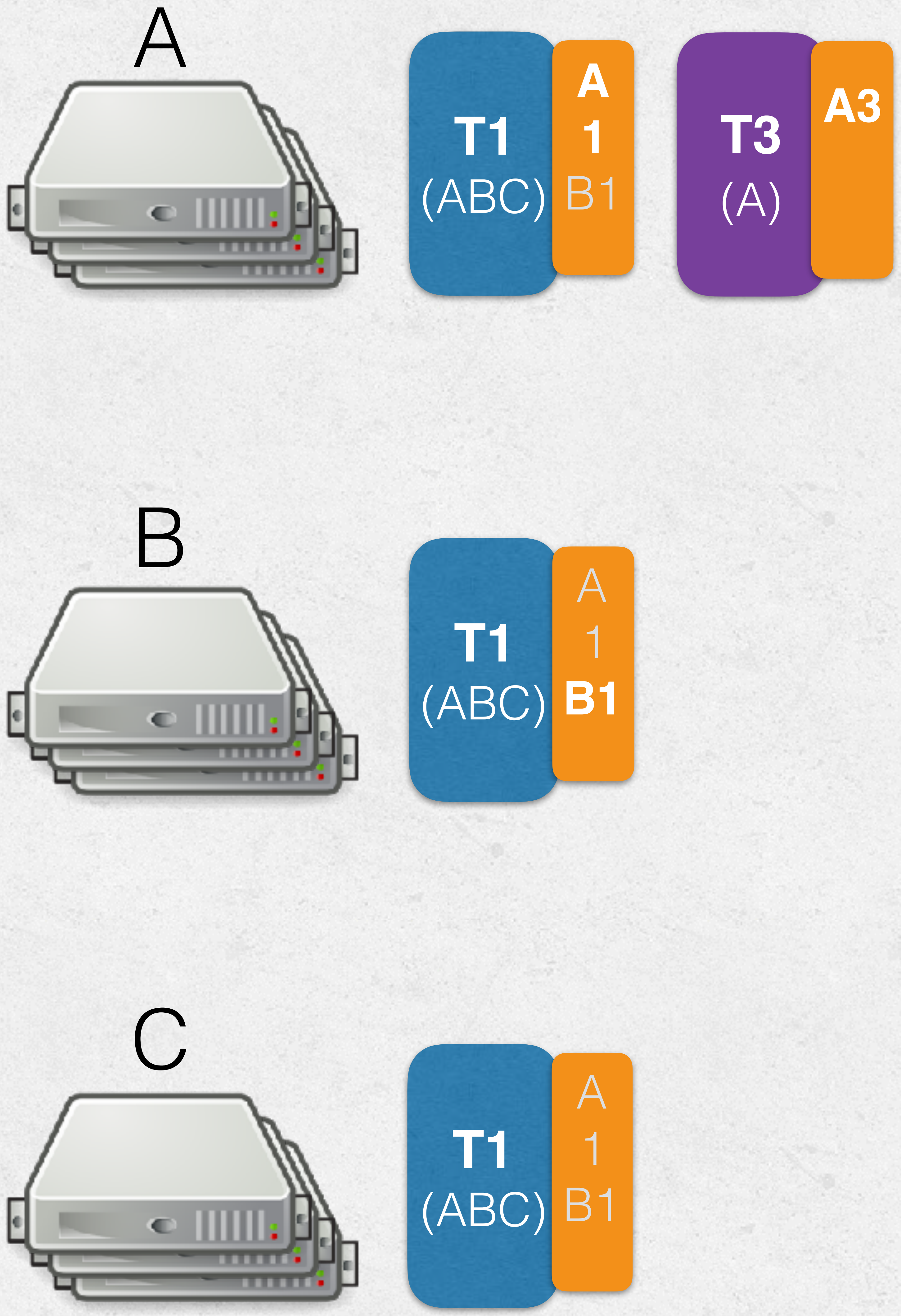
B

T1 (ABC) A 1 B1

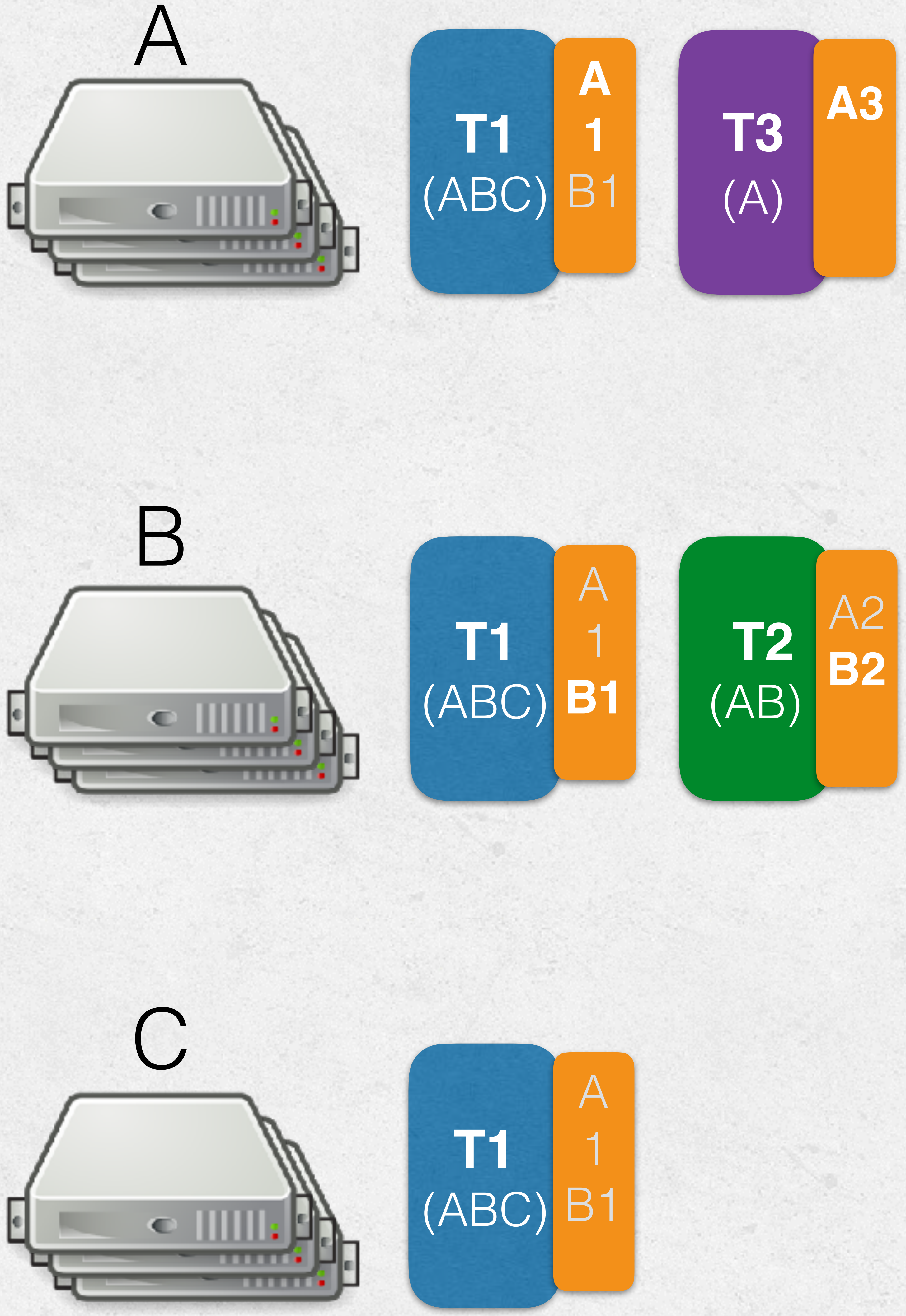
C

T1 (ABC) A 1 B1

How to handle dropped messages?



How to handle dropped messages?



A

T1 (ABC) **A** **1** B1

T3 (A) **A3**

B

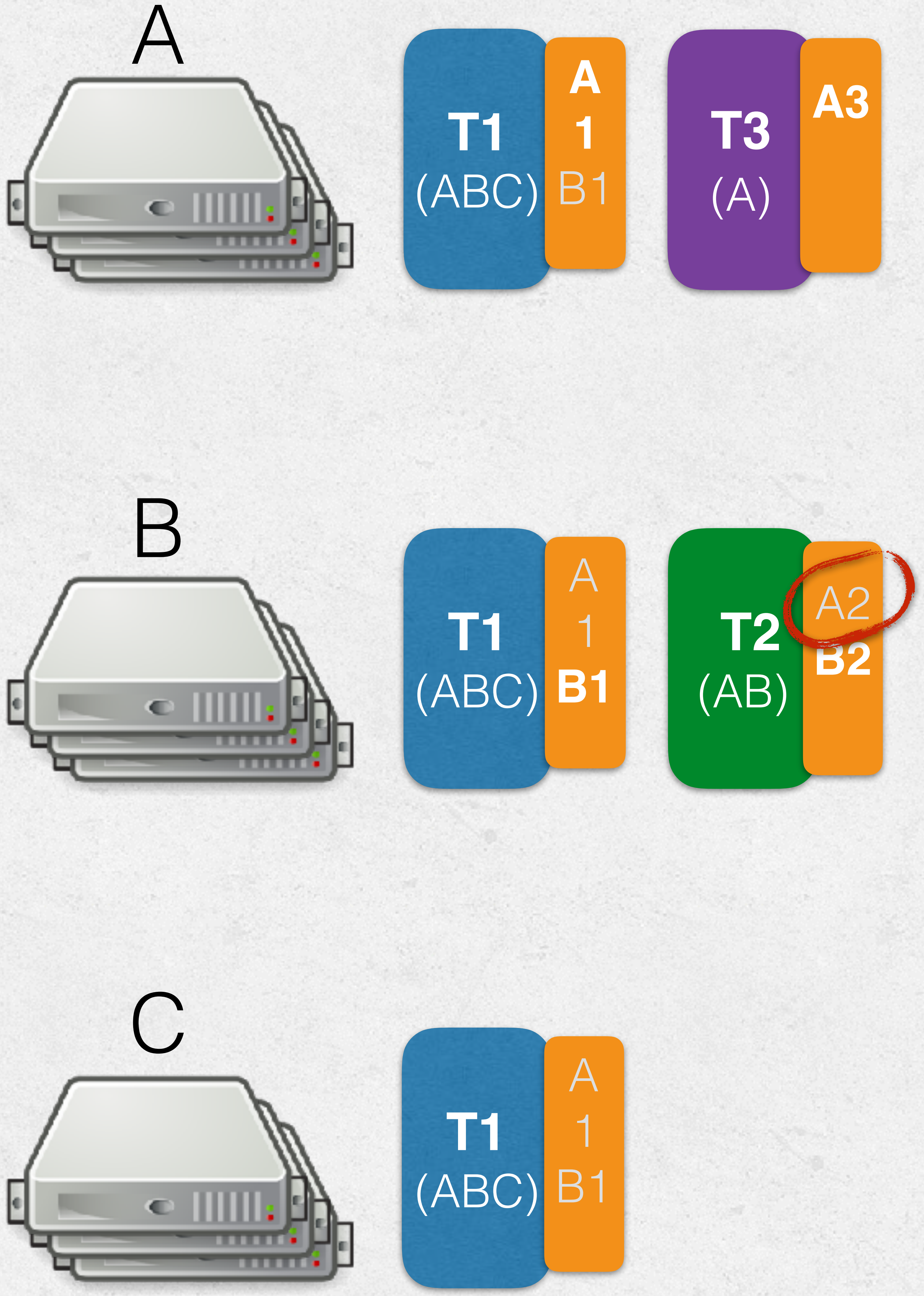
T1 (ABC) A 1 **B1**

T2 (AB) A2 **B2**

C

T1 (ABC) A 1 B1

How to handle dropped messages?



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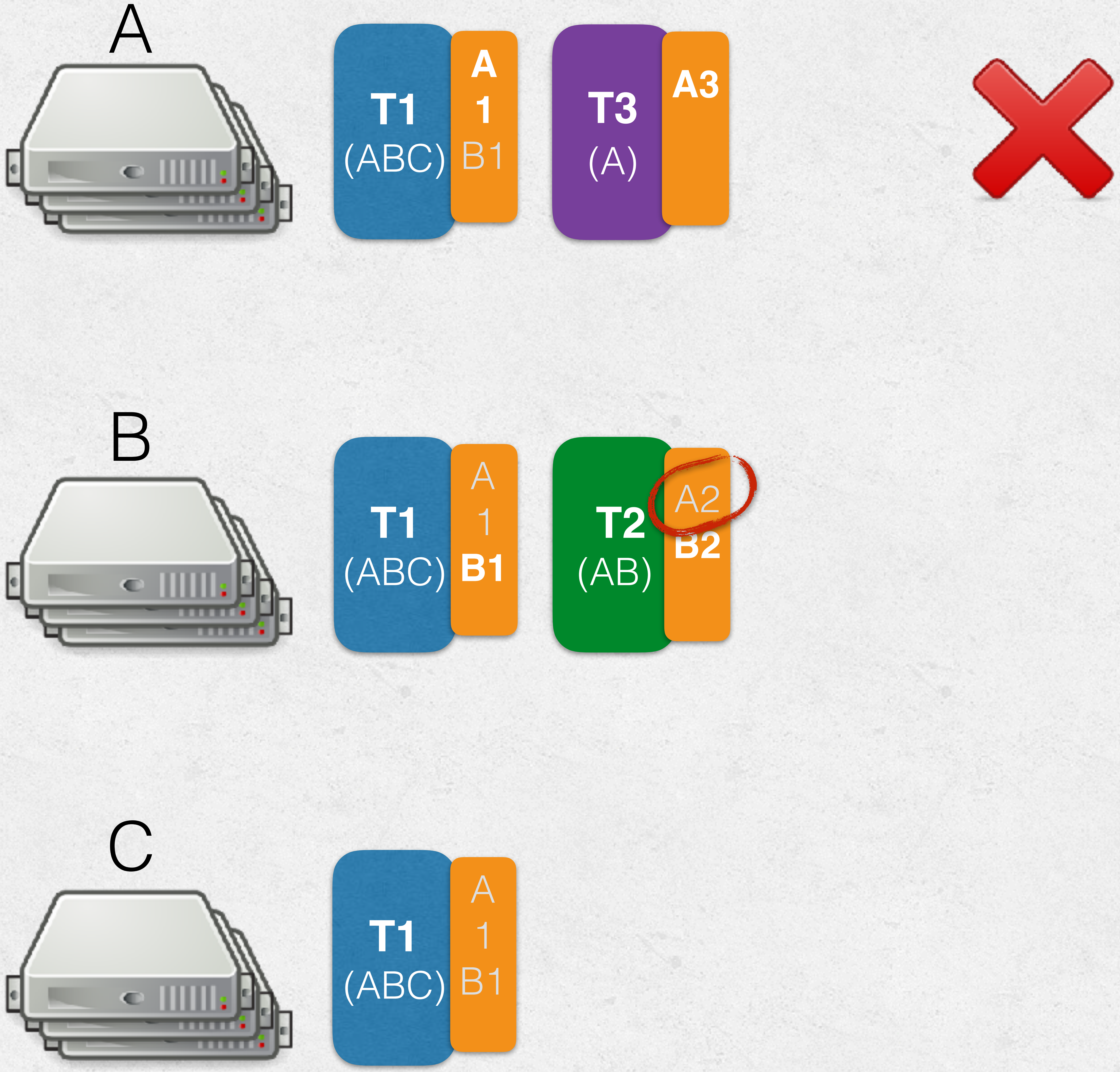
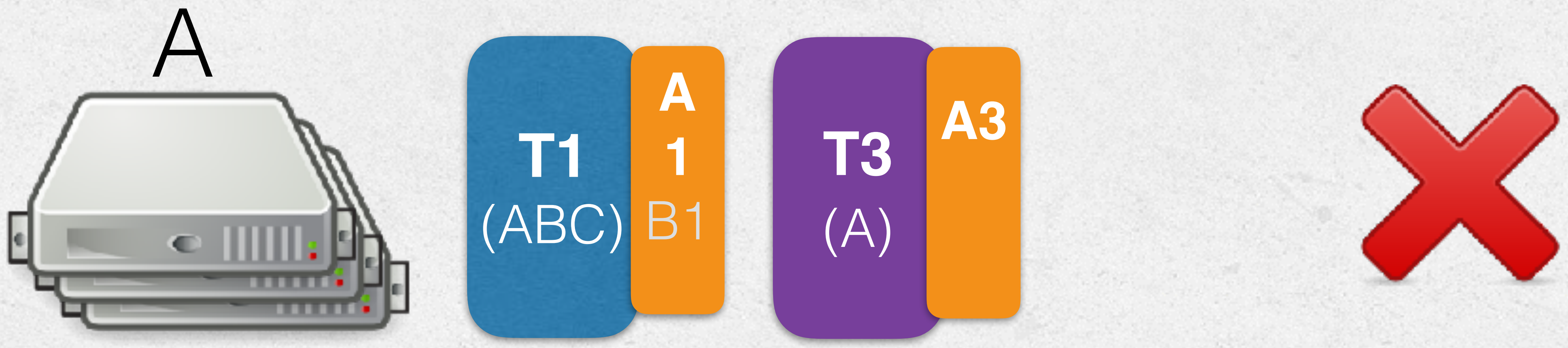
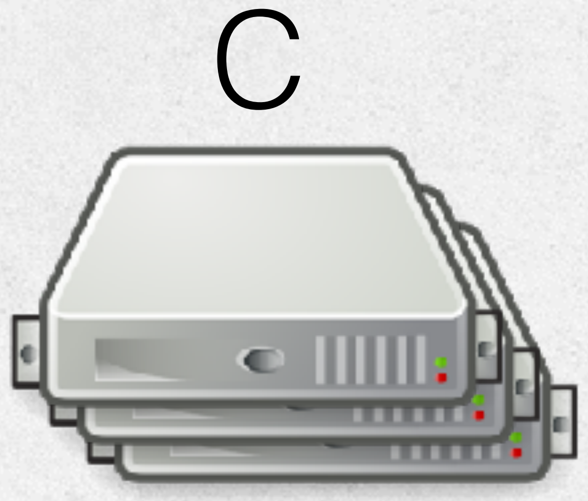


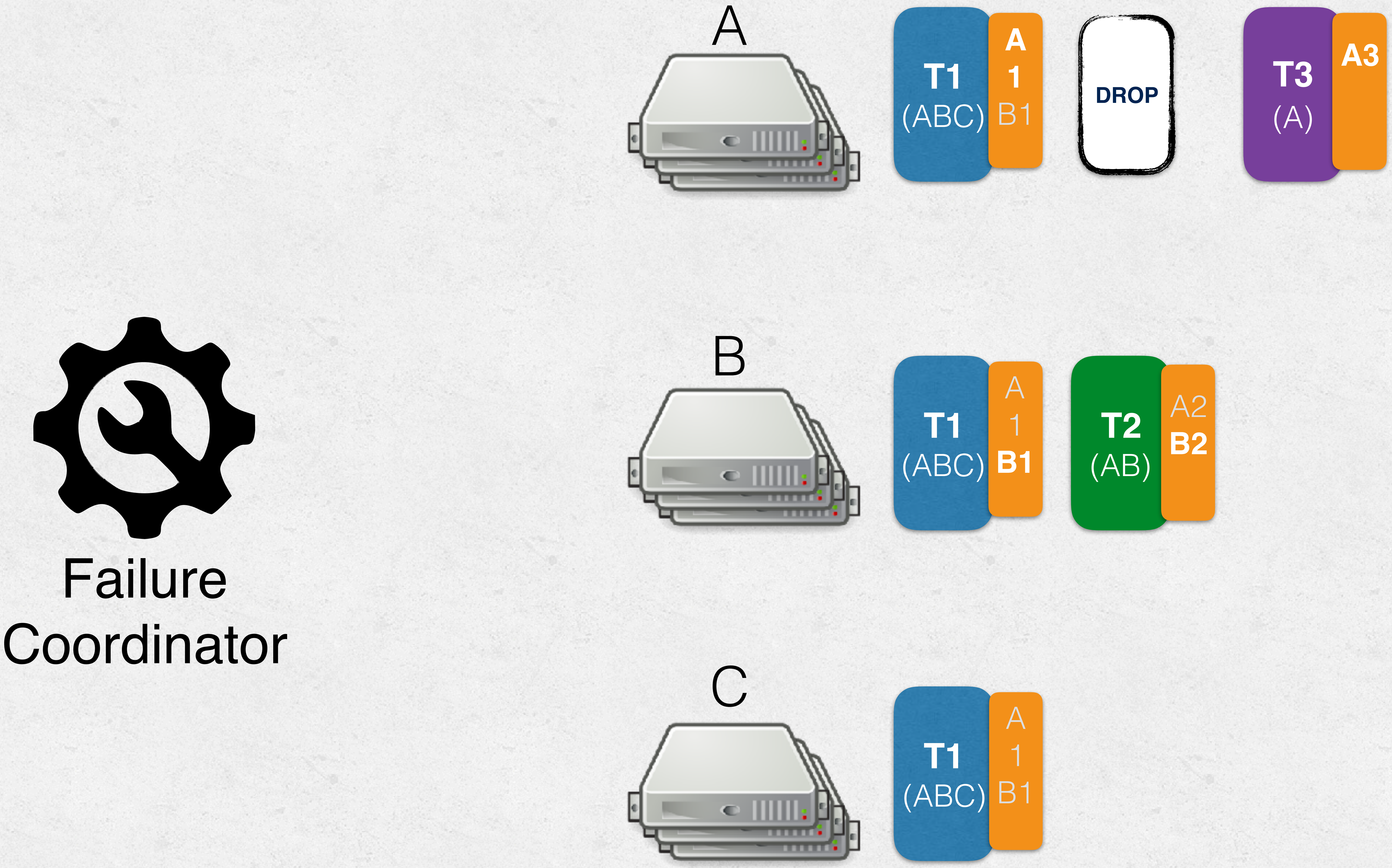
How to handle dropped messages?



Global coordination problem



The Failure Coordinator



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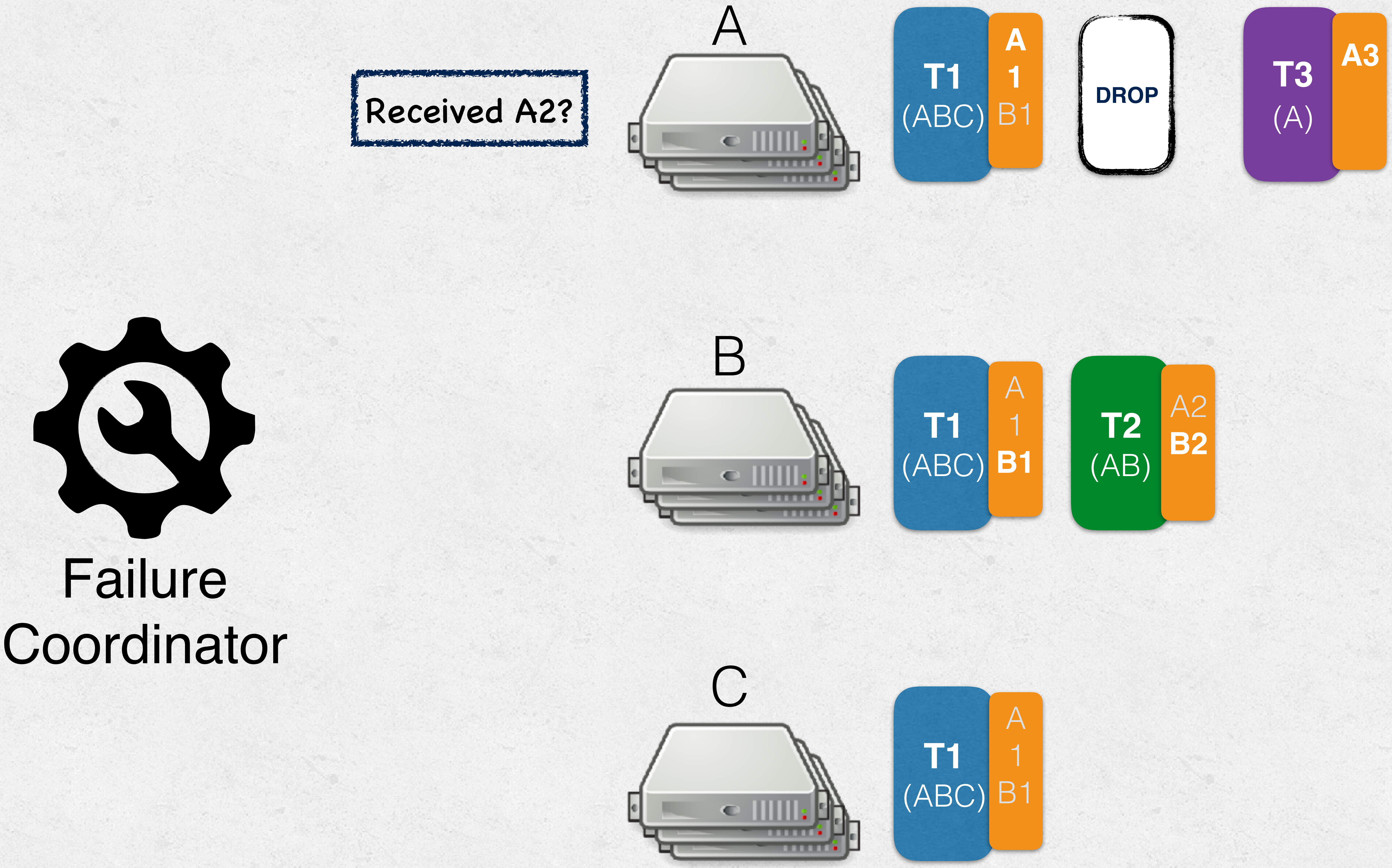

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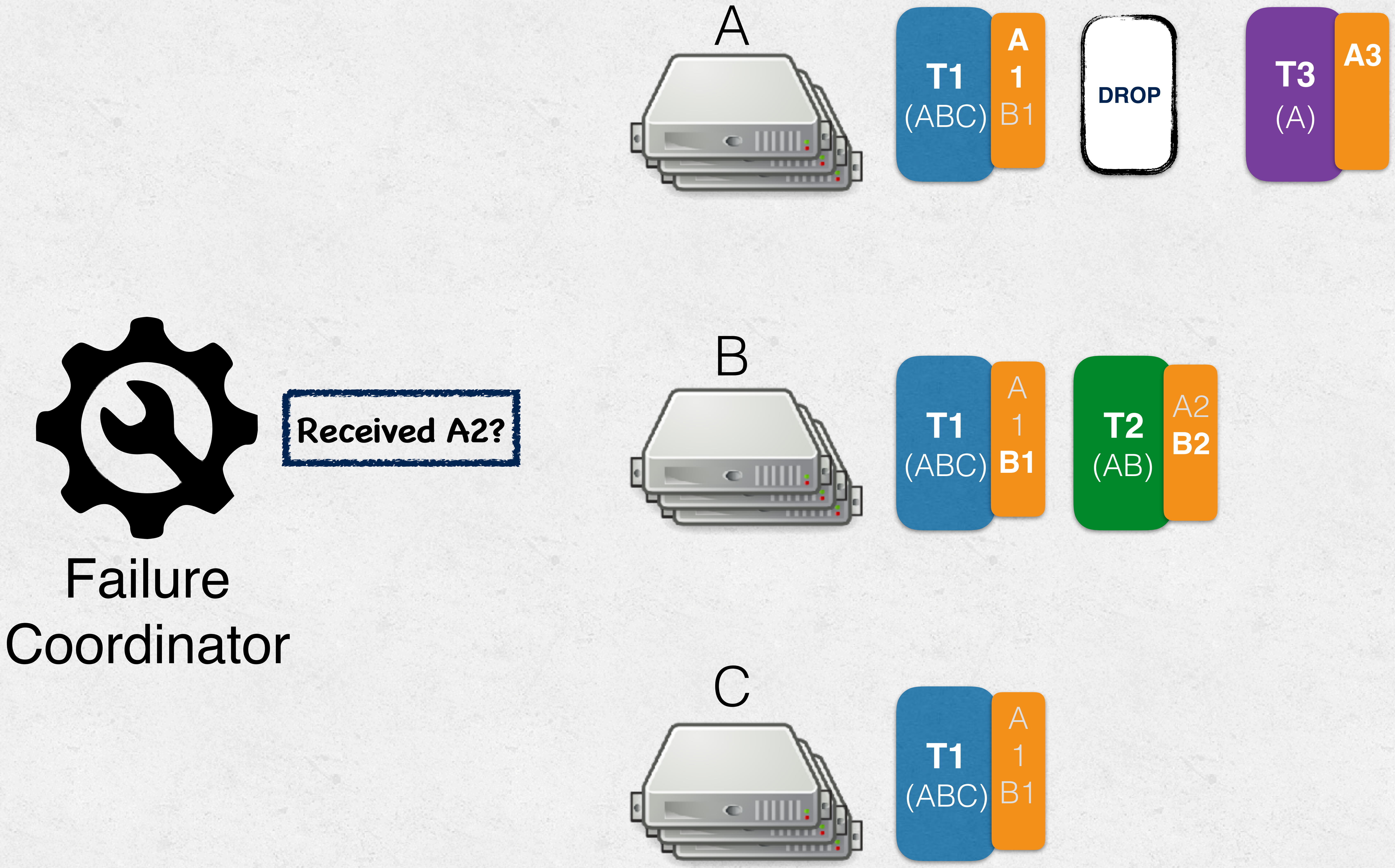
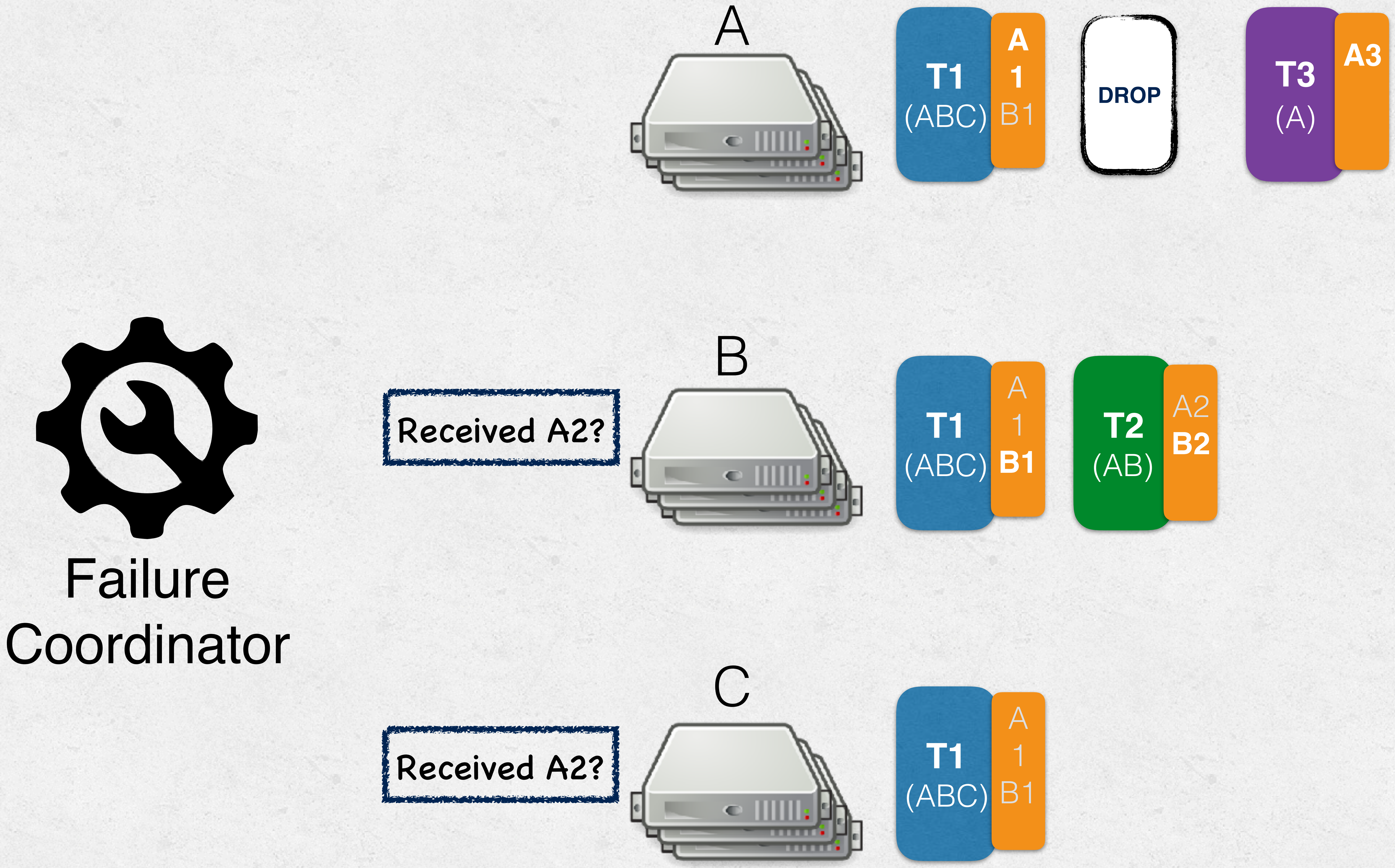


The Failure Coordinator



A

T1 (ABC) A 1 B1

DROP

T3 (A) A3

Failure Coordinator

Received A2?

B

T1 (ABC) A 1 B1

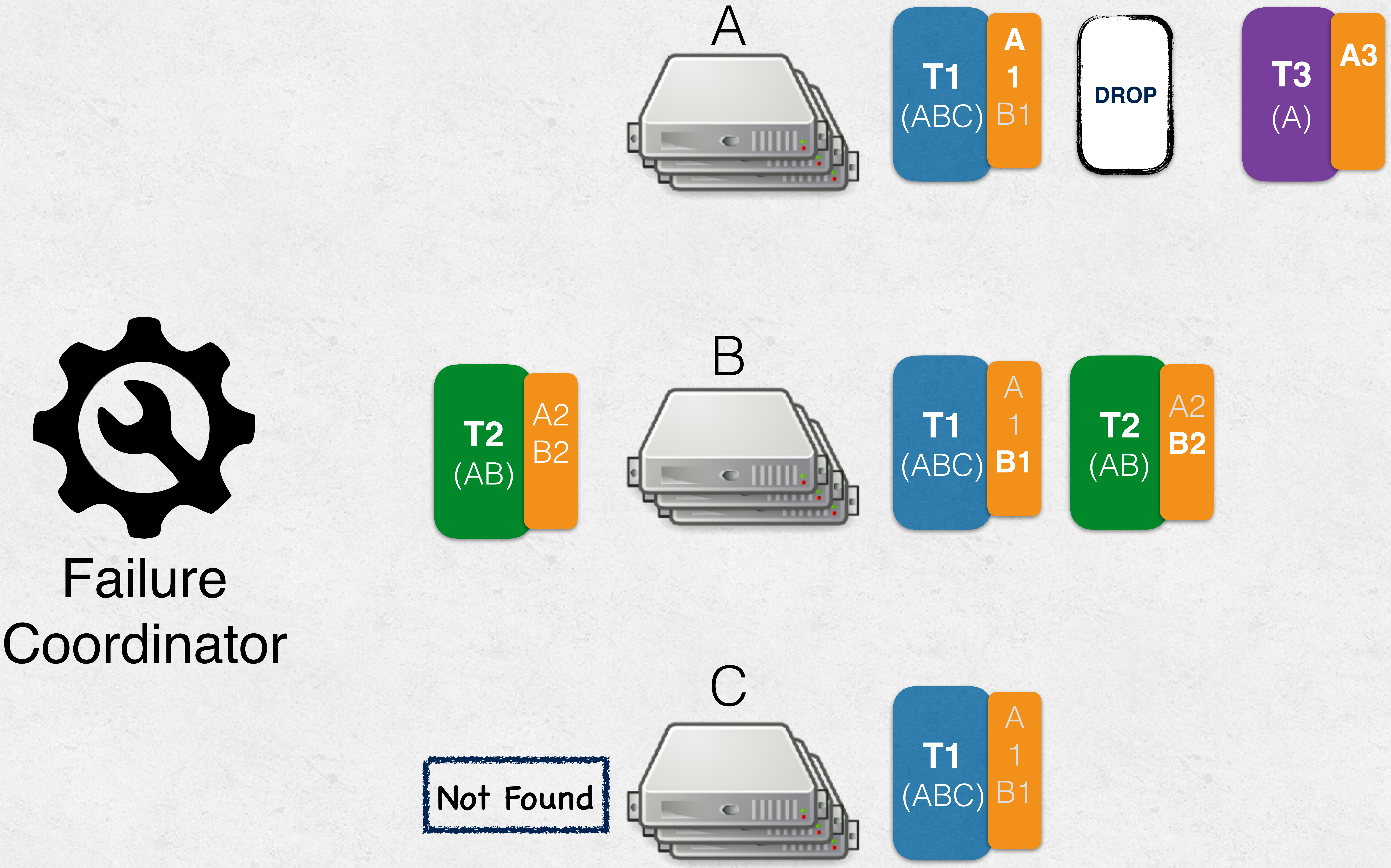
T2 (AB) A2 B2

Received A2?

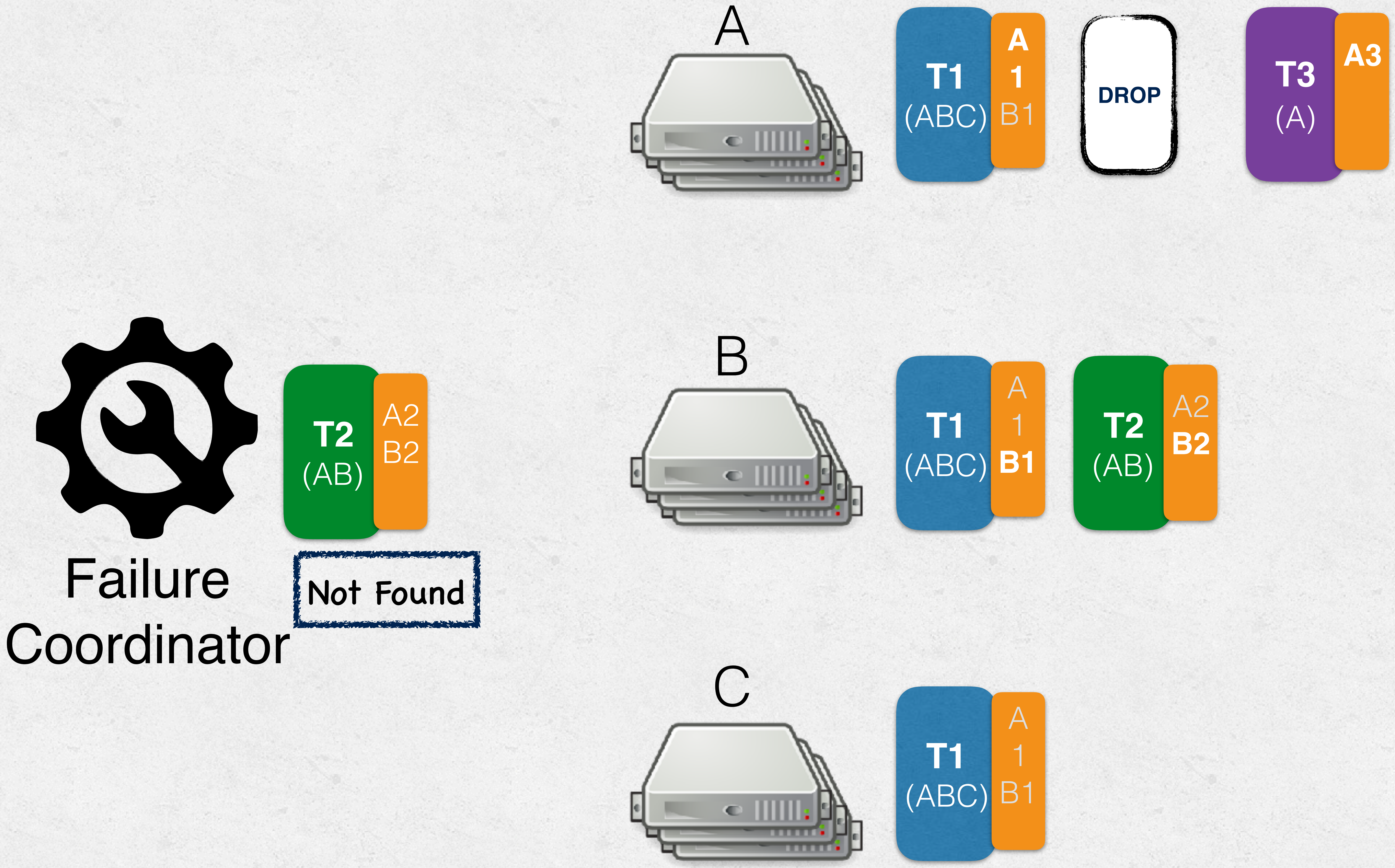
C

T1 (ABC) A 1 B1

The Failure Coordinator



THE FAILURE COORDINATOR



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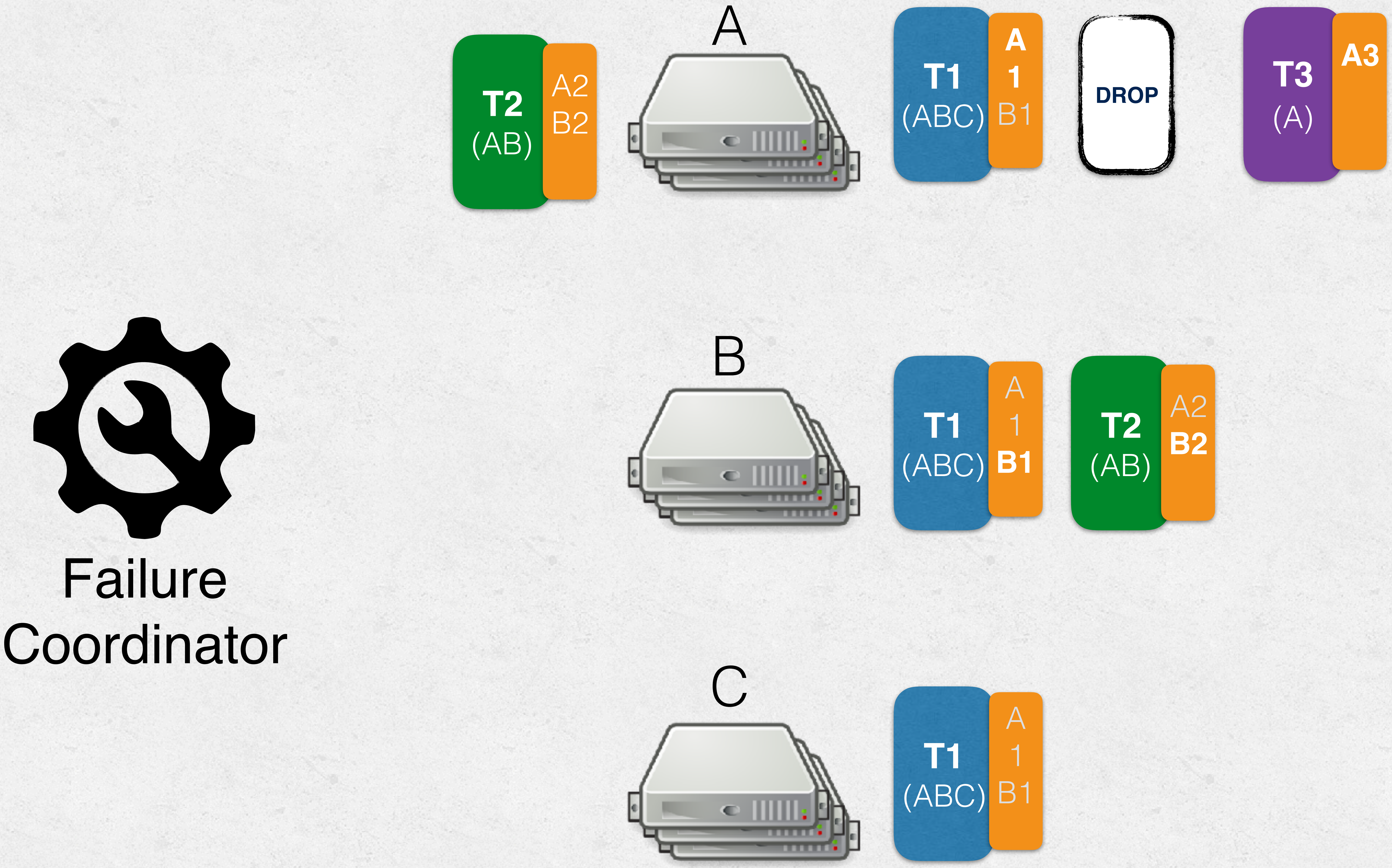

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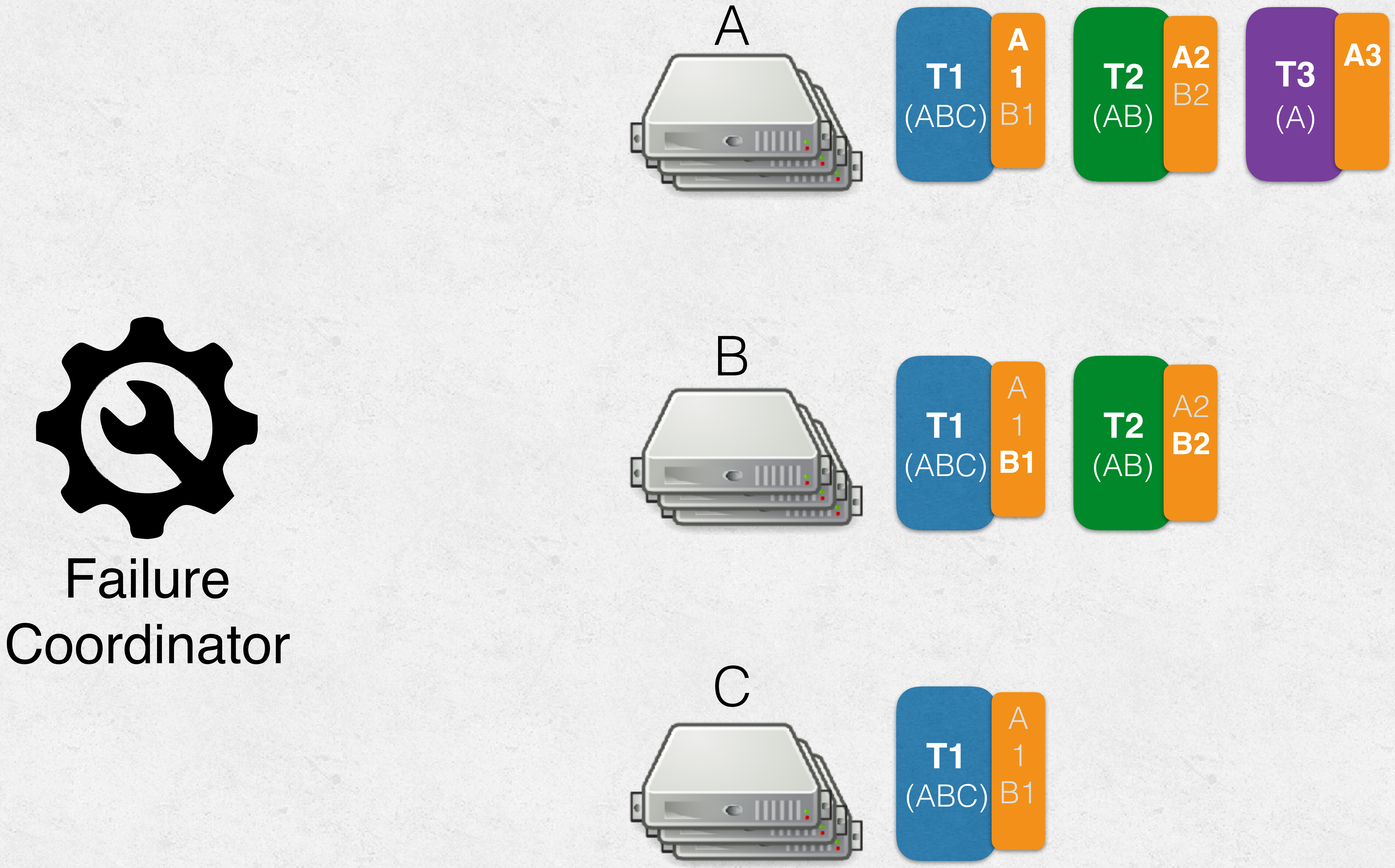


Failure Coordinator

A

T1 (ABC) **A 1** B1

T2 (AB) **A2** B2

T3 (A) **A3**

B

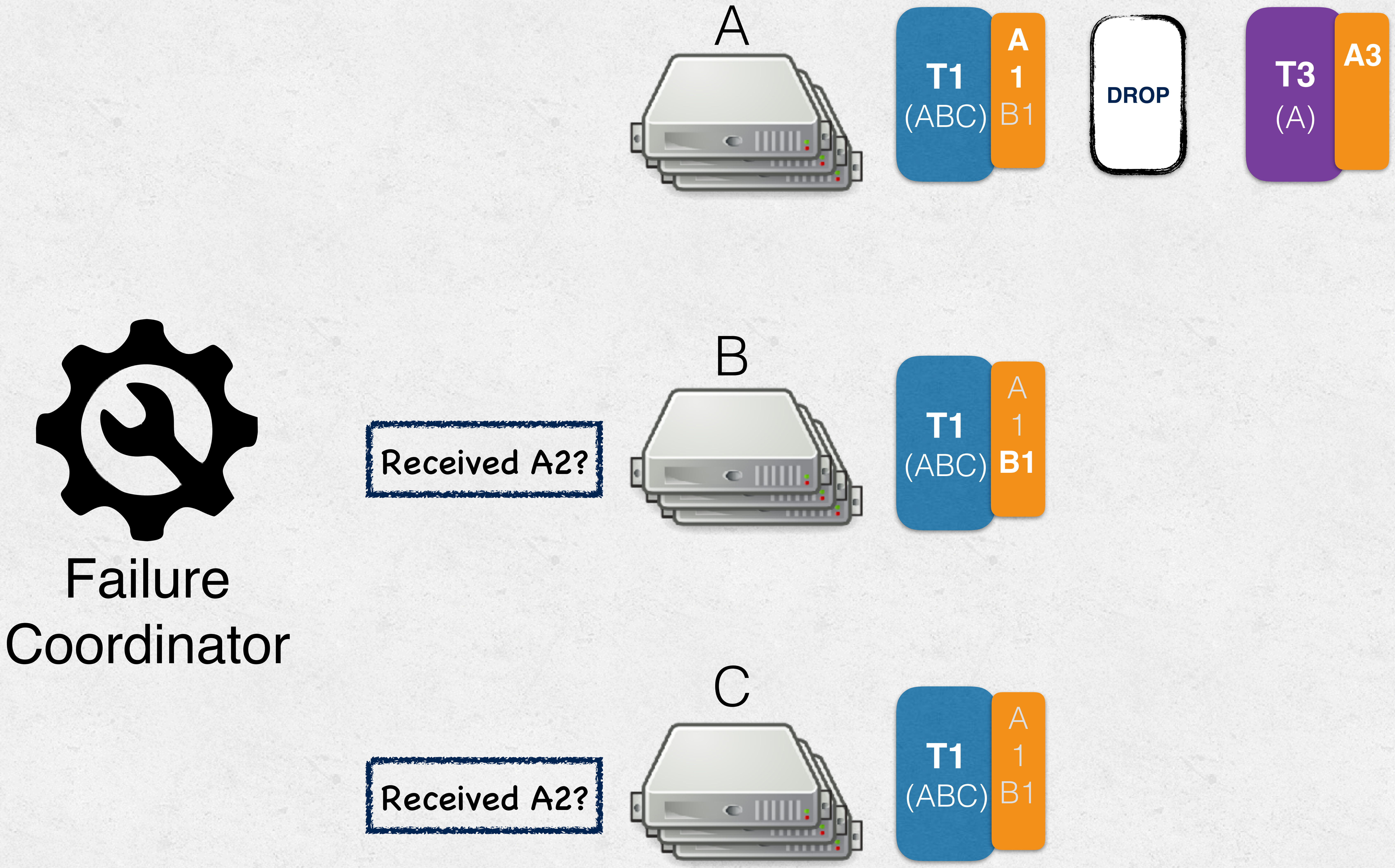
T1 (ABC) A 1 **B1**

T2 (AB) A2 **B2**

C

T1 (ABC) A 1 B1

The Failure Coordinator



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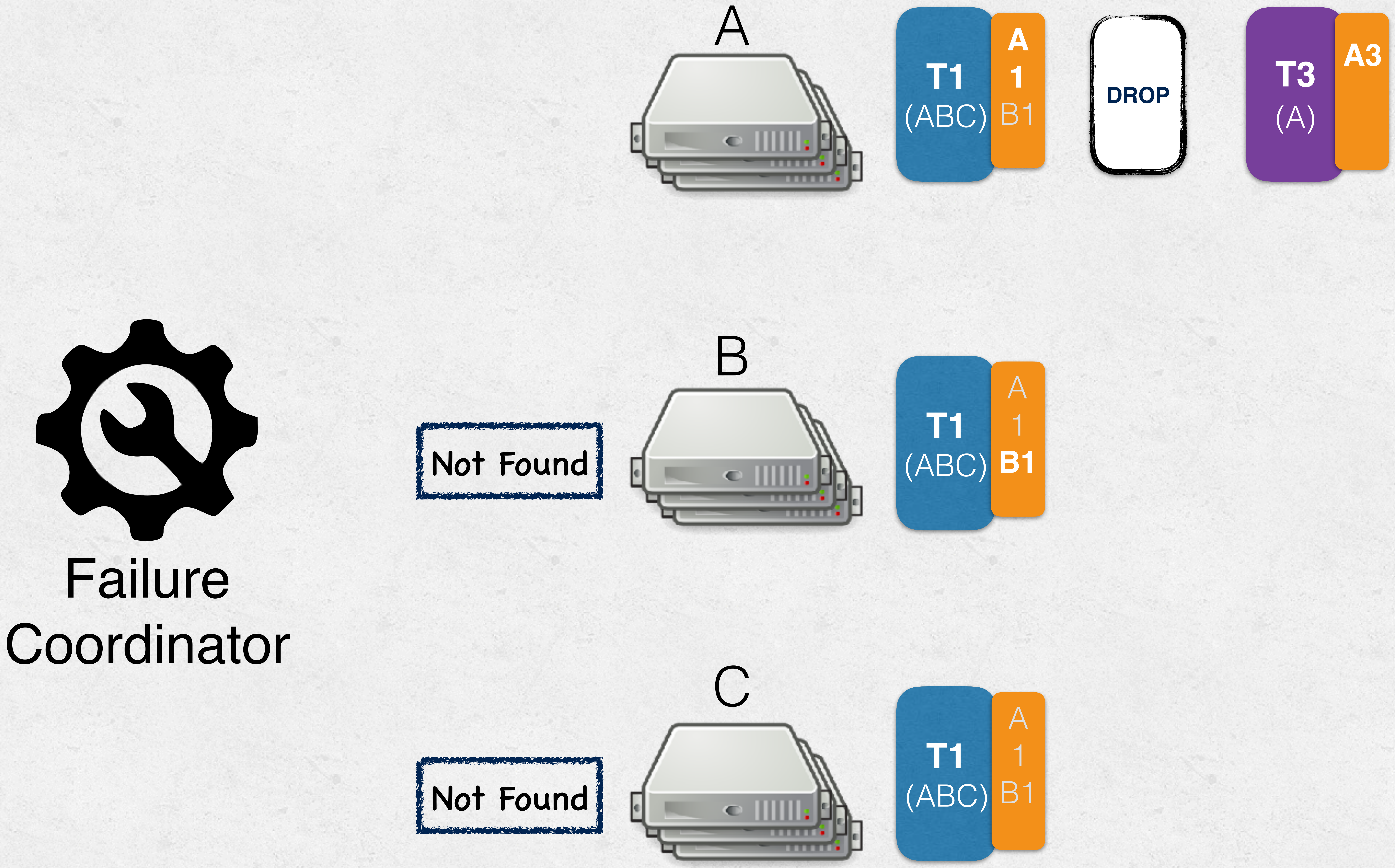

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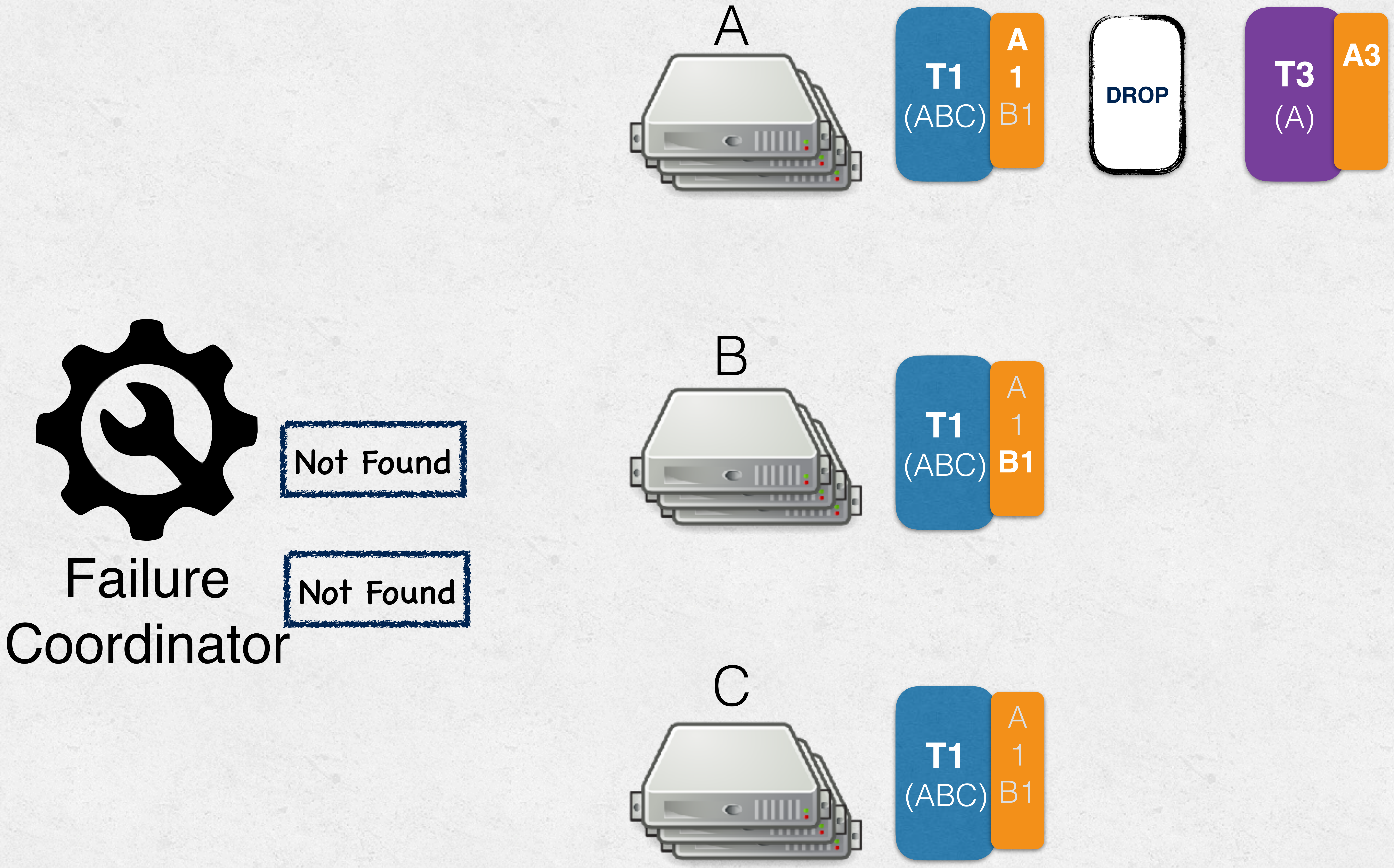

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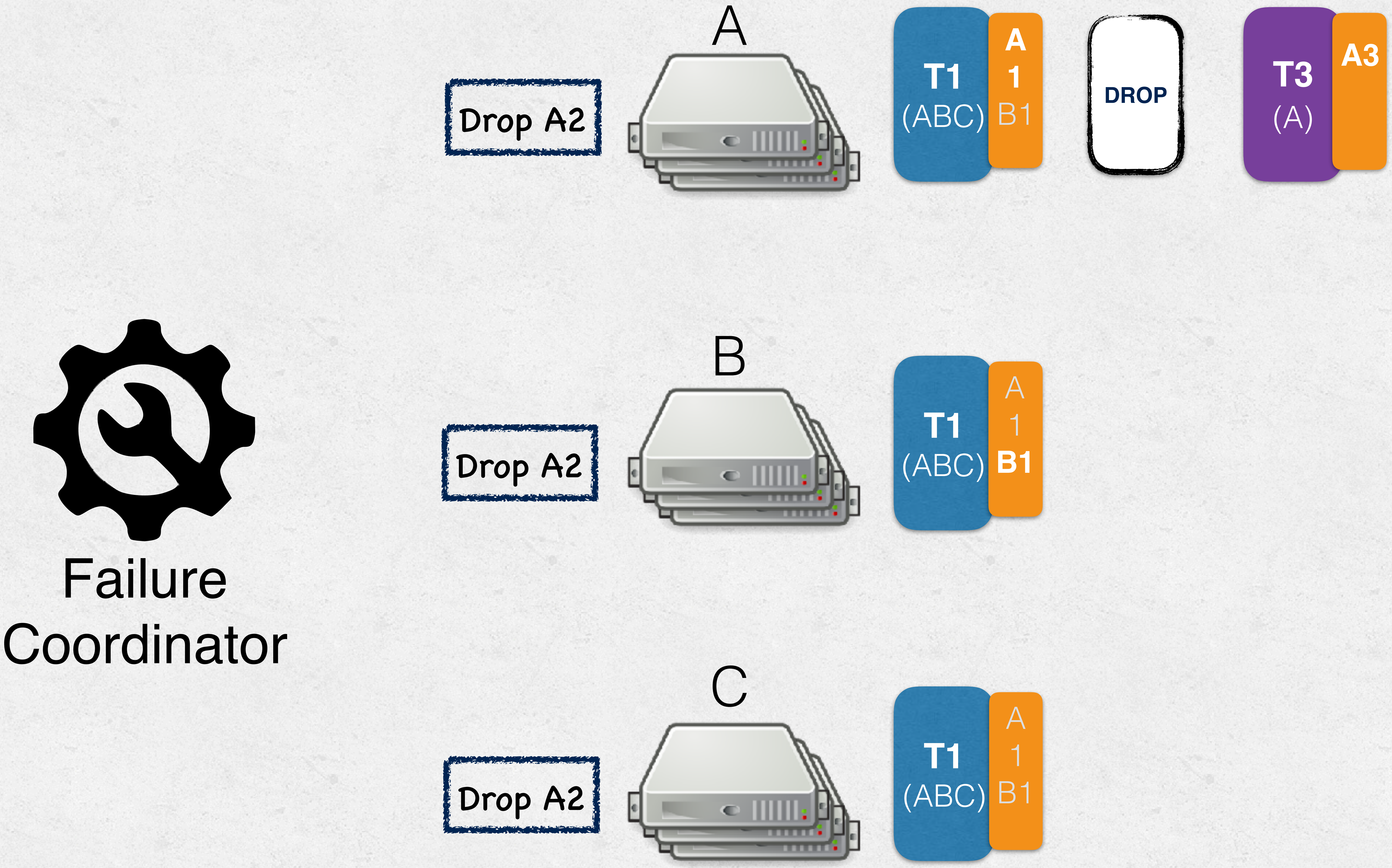
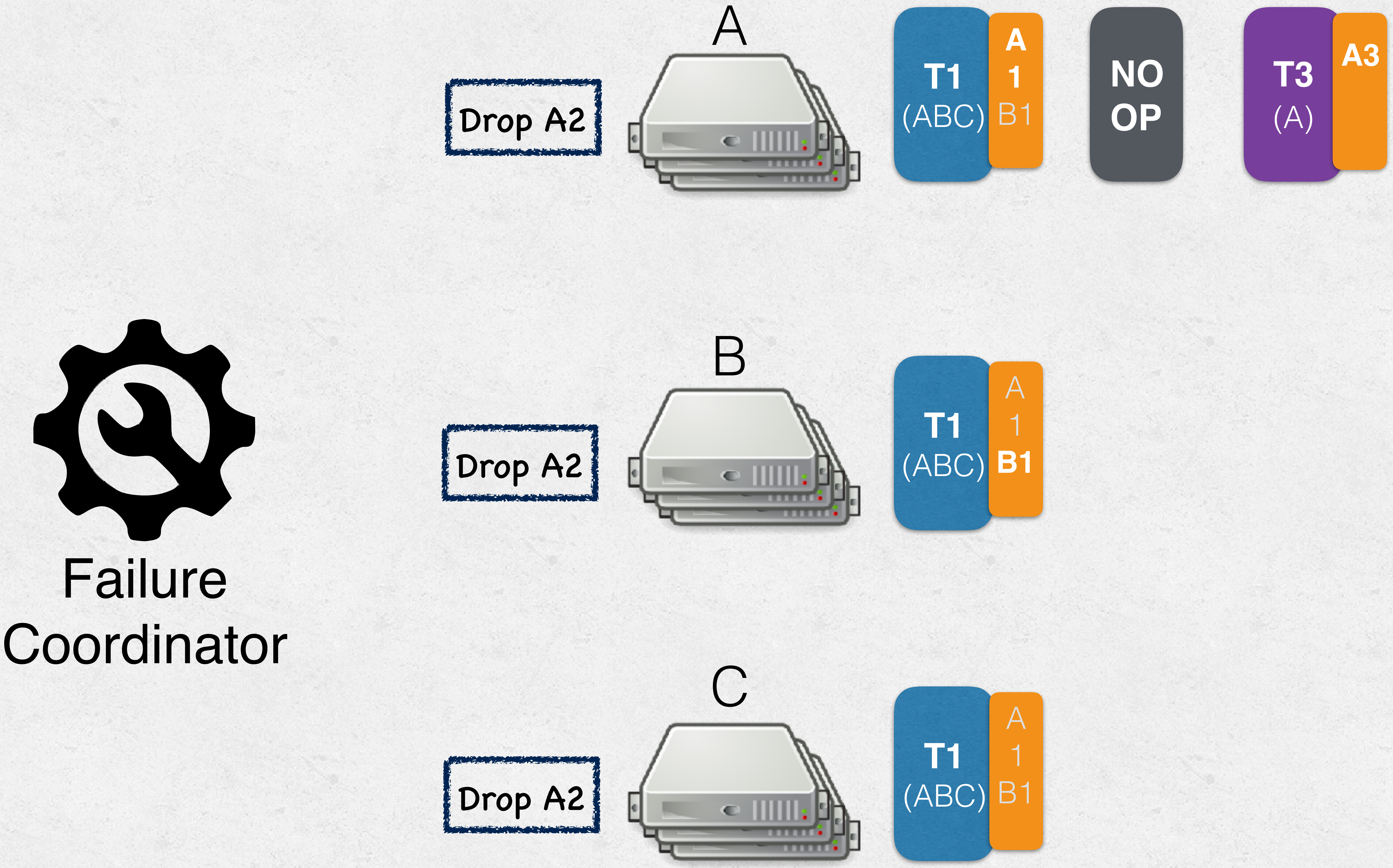
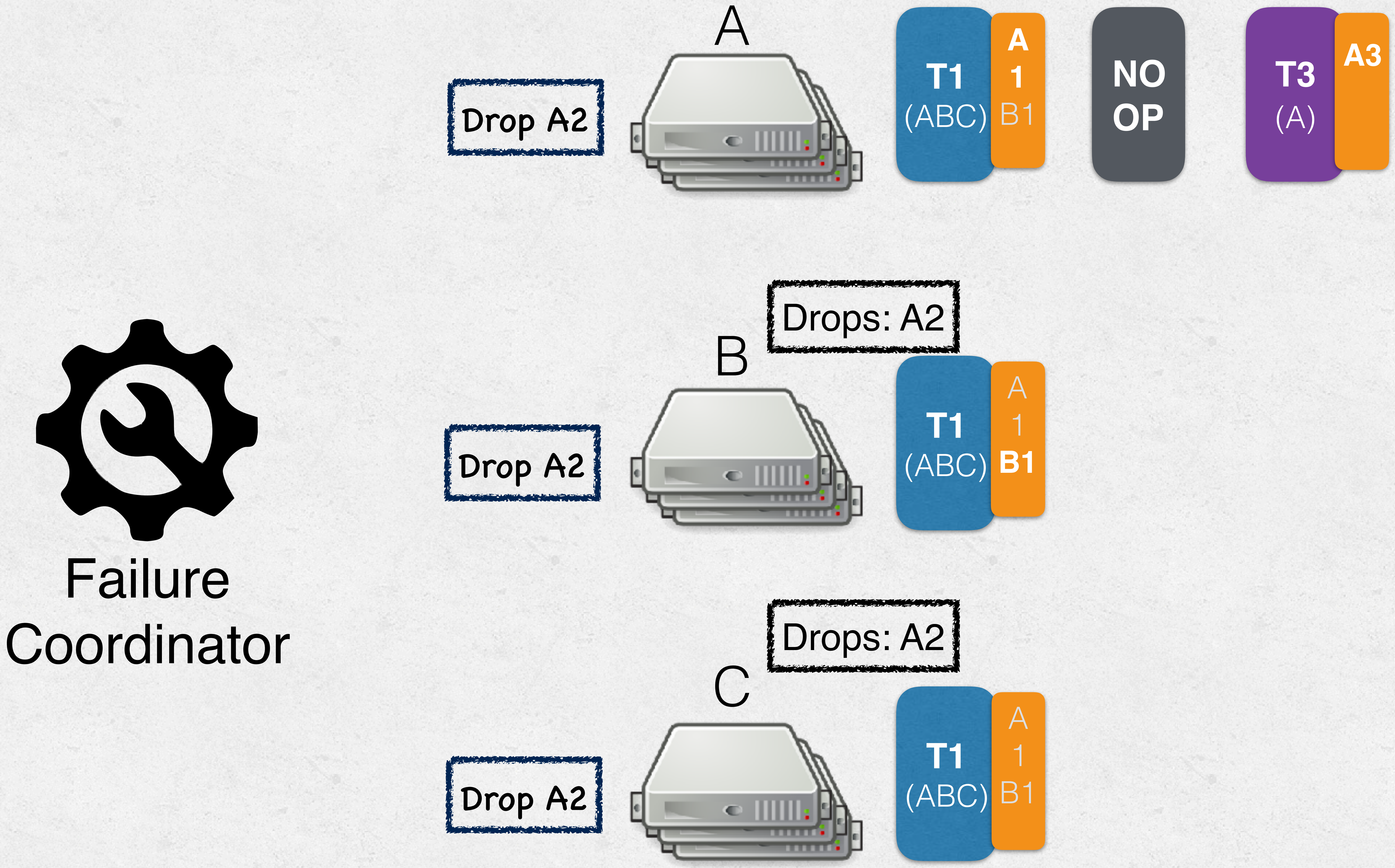


THE FAILURE COORDINATOR



THE FAILURE COORDINATOR



A

Drop A2

T1 (ABC) | A 1 B1 | NO OP | T3 (A) | A3

Drops: A2

B

Drop A2

T1 (ABC) | A 1 B1

Failure Coordinator

Drops: A2

C

Drop A2

T1 (ABC) | A 1 B1

Designated Learner and Sequencer Failures

Designated learner (DL) failure:

- View change based protocol
- Ensures new DL learns all **committed transactions** from previous views

Sequencer failure:

- Higher epoch number from the new sequencer
- Epoch change ensures all replicas across all shards start the new epoch in **consistent states**. They should all agree on the exact set of transactions completed in the previous epoch.

Can we process non-independent transactions efficiently?

Approach: Divide Into Independent Transactions

- Relies on the **linearizable execution** of independent transactions
- This means that we have the abstraction of a single, correct machine that processes independent transactions only.
- Uses **locks** to provide strong isolation
- Two phases:
  - Independent transaction 1: execute reads and acquire locks
  - Independent transaction 2: commit/abort changes and release locks

Benefits of our layered architecture

- Simple solution to handle client failures: if the client fails, any server can **unilaterally** send the abort command for its general transactions *as an independent transaction.*

- No deadlocks/deadlock detection. Locks are acquired in a single step.

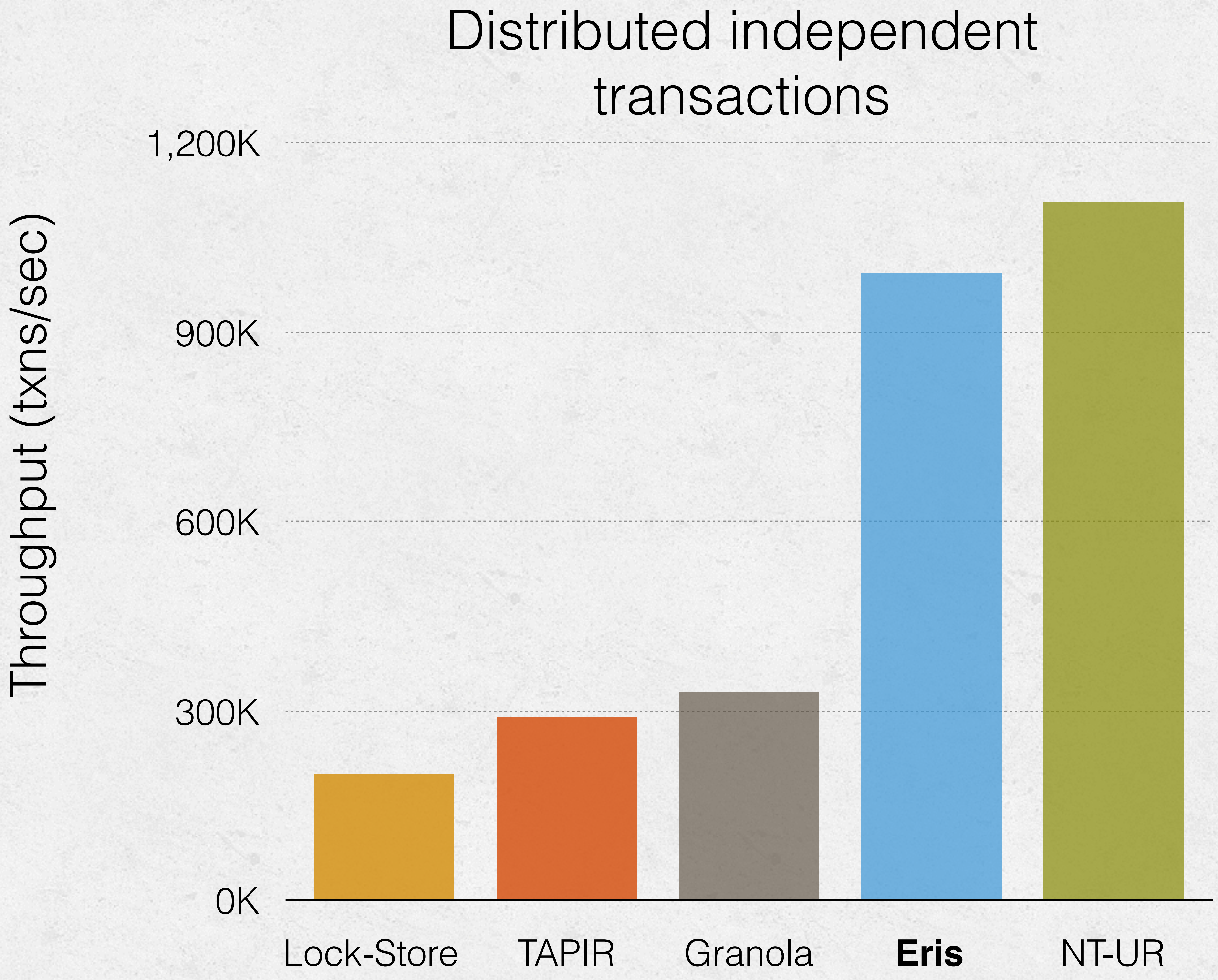
- Furthermore, we don't even need aborts! Wait queues are easy.

- Takes advantage of the efficient independent transaction processing layer. General transactions are processed in two round trips in the normal case.

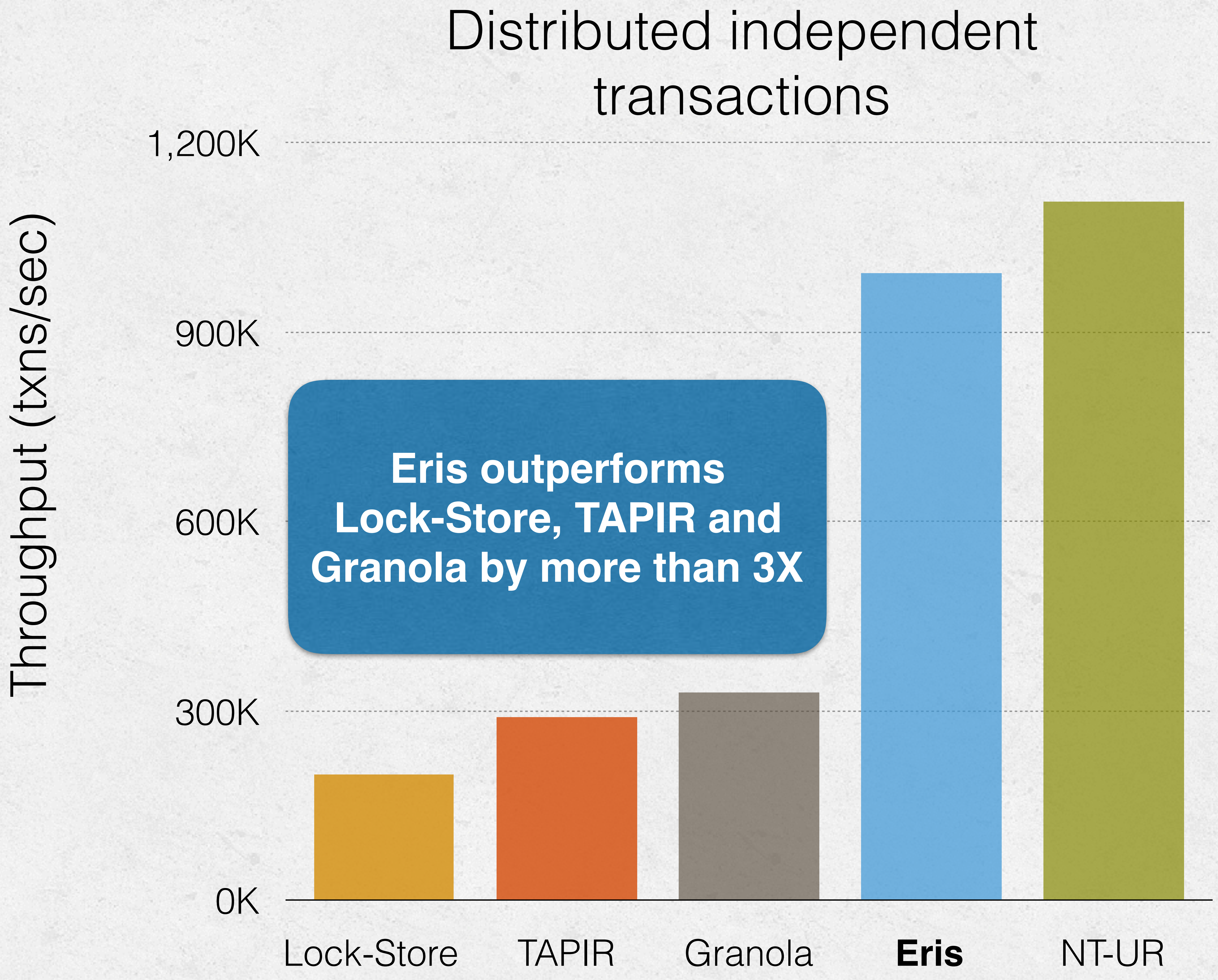
Evaluation Comparison Systems

- Lock-Store (2PC + 2PL + Paxos)
- TAPIR [SOSP ’15]
- Granola [ATC ‘12]
- Non-transactional, unreplicated (NT-UR)

Eris performs well on independent transactions



ERIS PERFORMS WELL ON INDEPENDENT TRANSACTIONS



Eris outperforms Lock-Store, TAPIR and Granola by more than 3X

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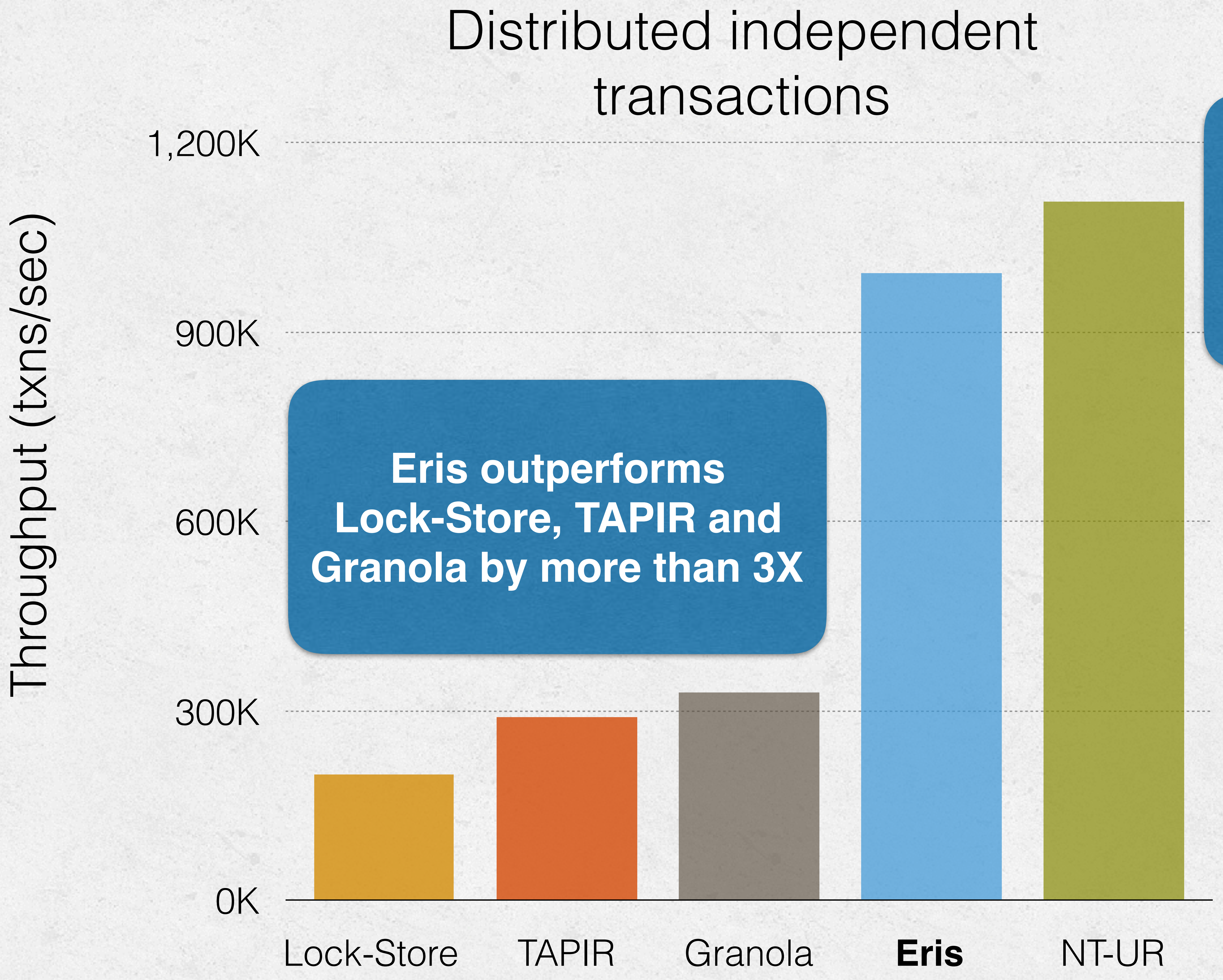
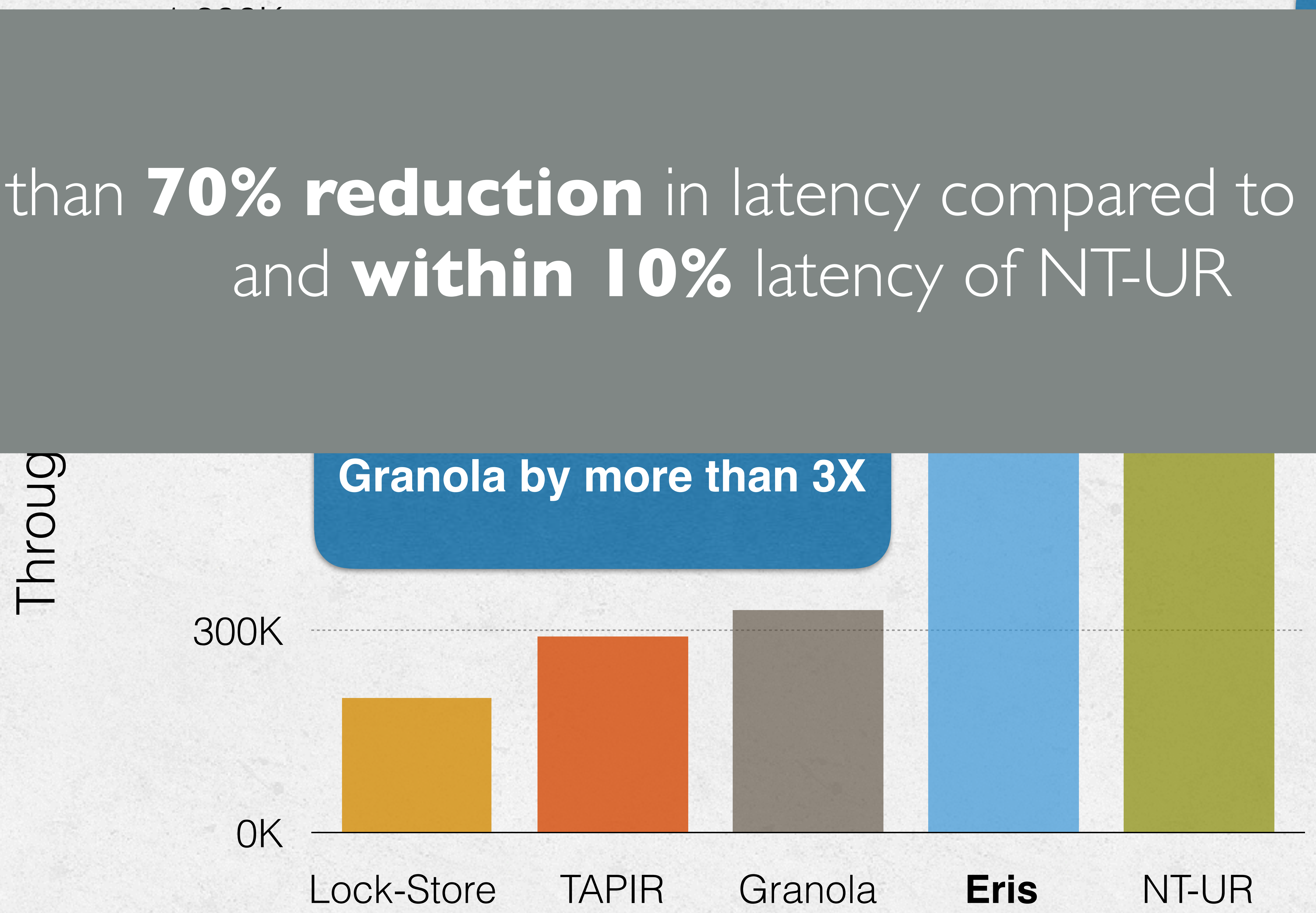


Eris outperforms Lock-Store, TAPIR and Granola by more than 3X

Eris achieves throughput within 10% of NT-UR

Eris performs well on independent transactions

Distributed independent transactions

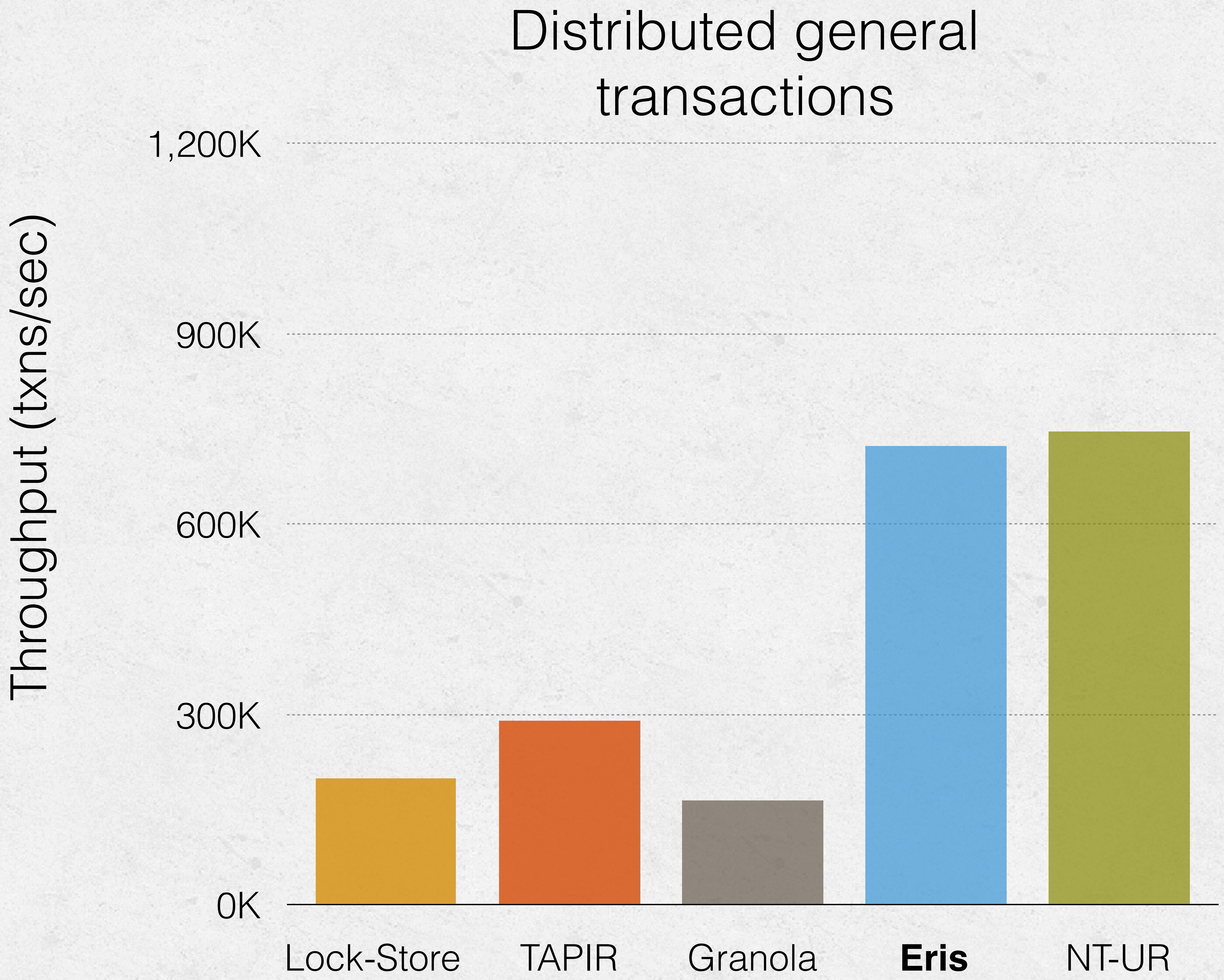


Granola by more than 3X

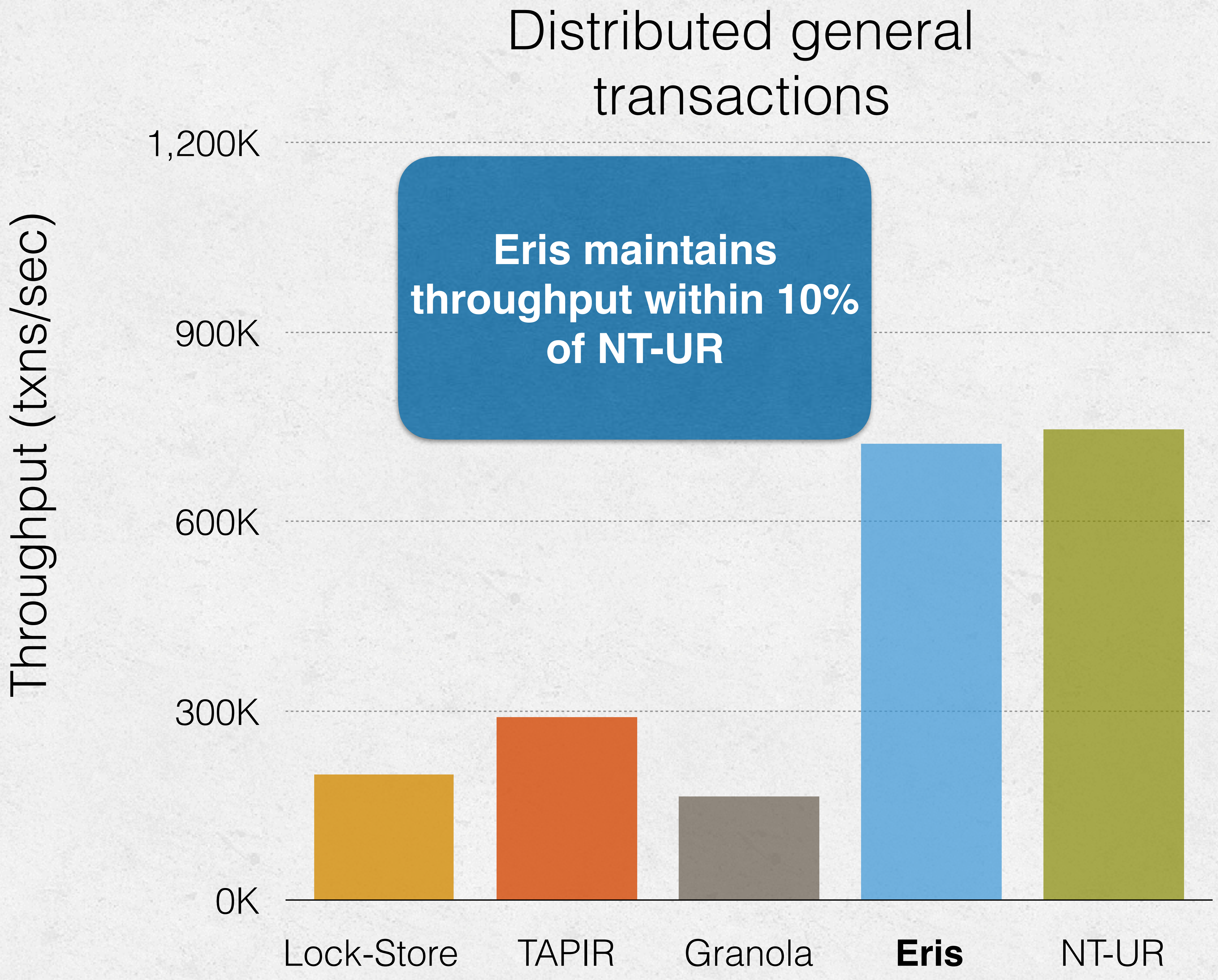
in

More than **70% reduction** in latency compared to Lock-Store, and **within 10%** latency of NT-UR

ERIS ALSO PERFORMS WELL ON GENERAL TRANSACTIONS

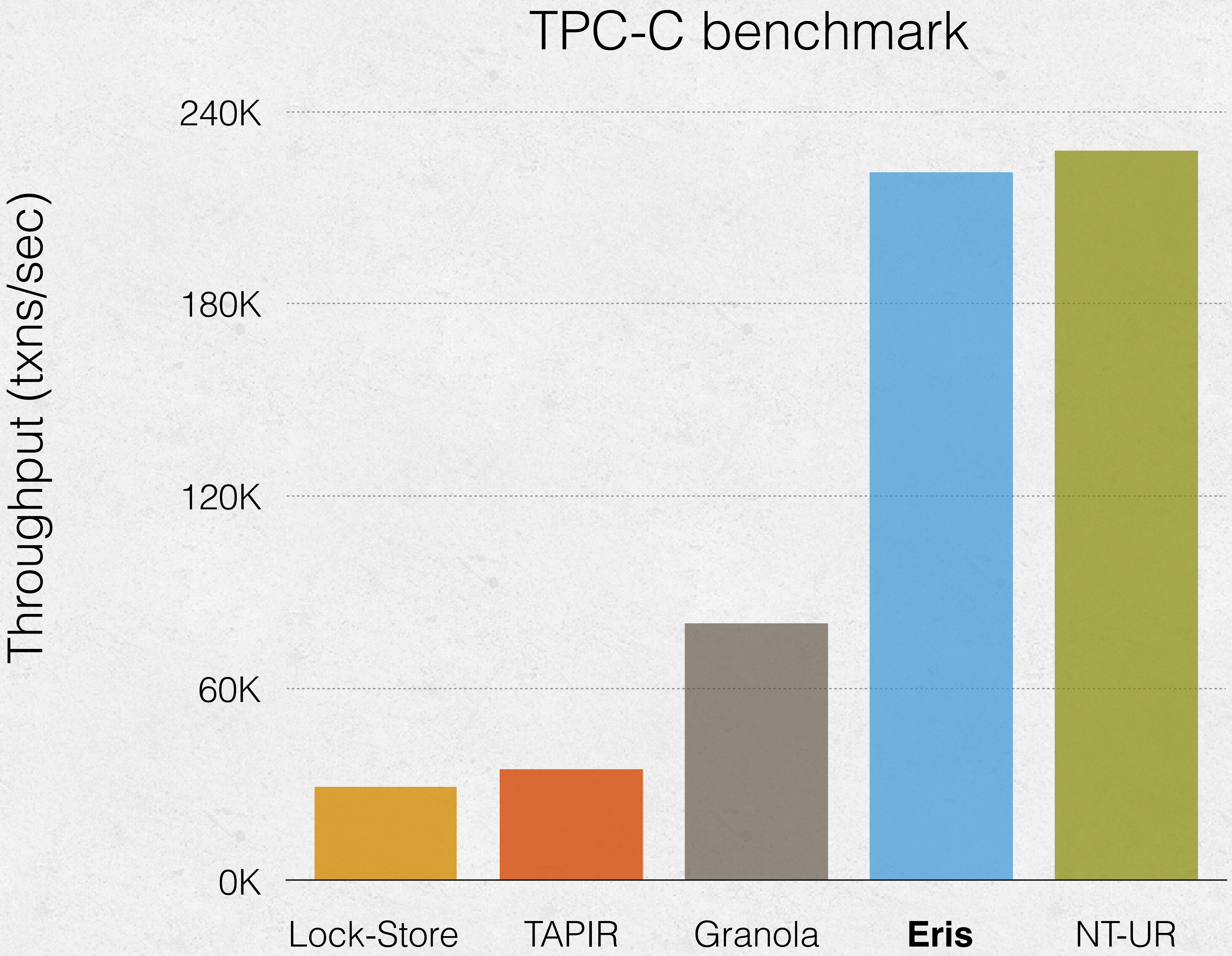


Eris also performs well on general transactions

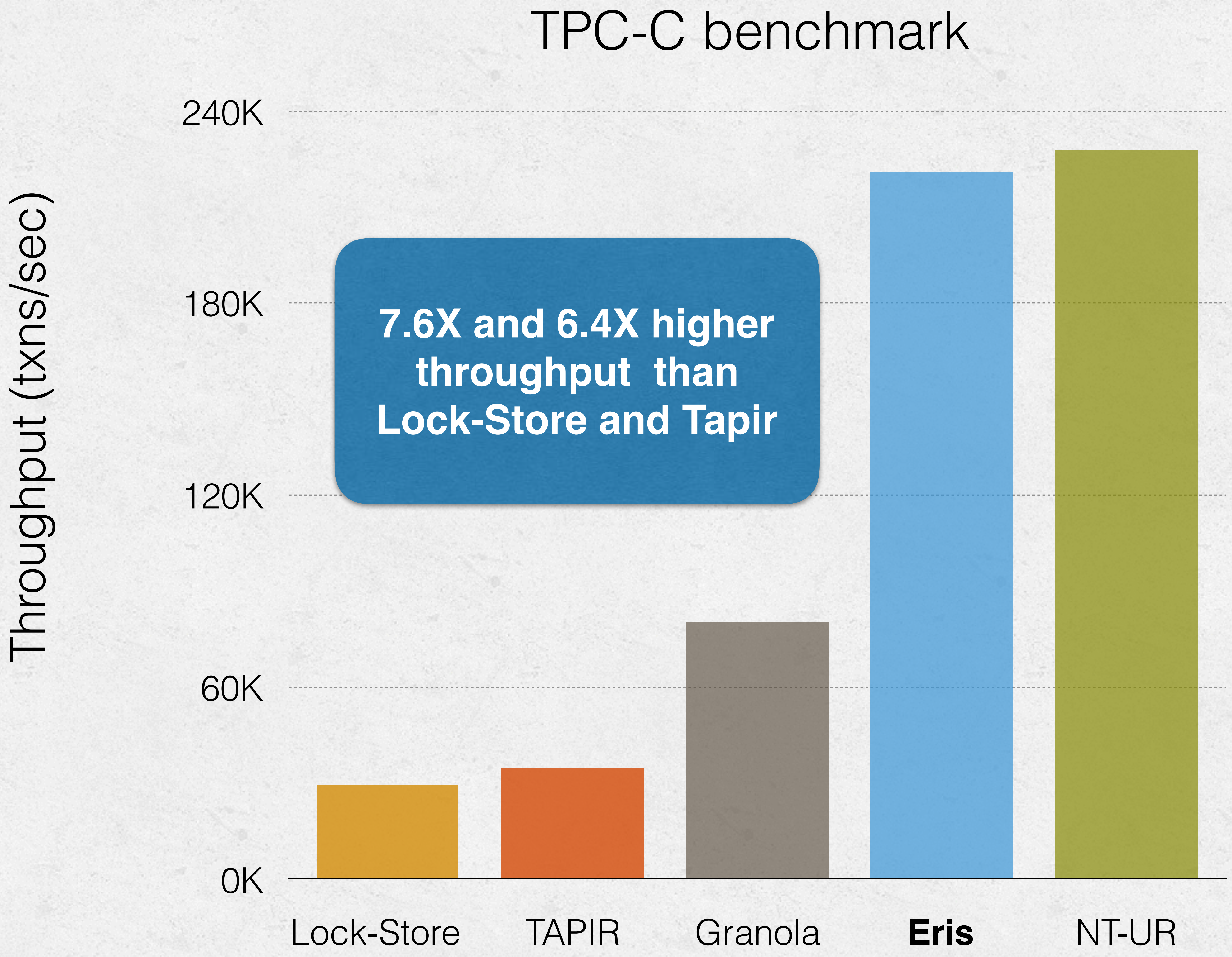


Eris maintains throughput within 10% of NT-UR

Eris excels at complex transactional applications

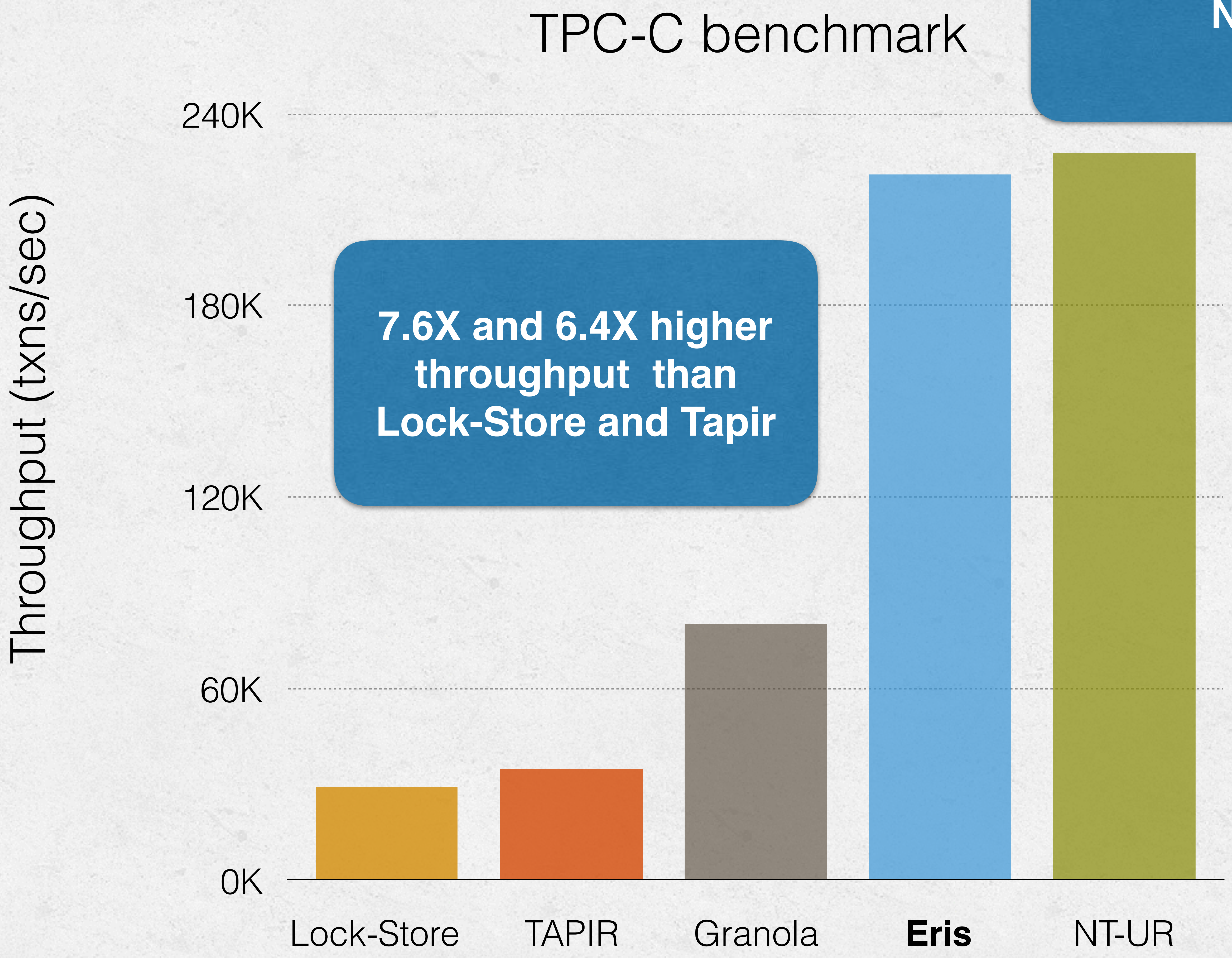


Eris excels at complex transactional applications



7.6X and 6.4X higher throughput than Lock-Store and Tapir

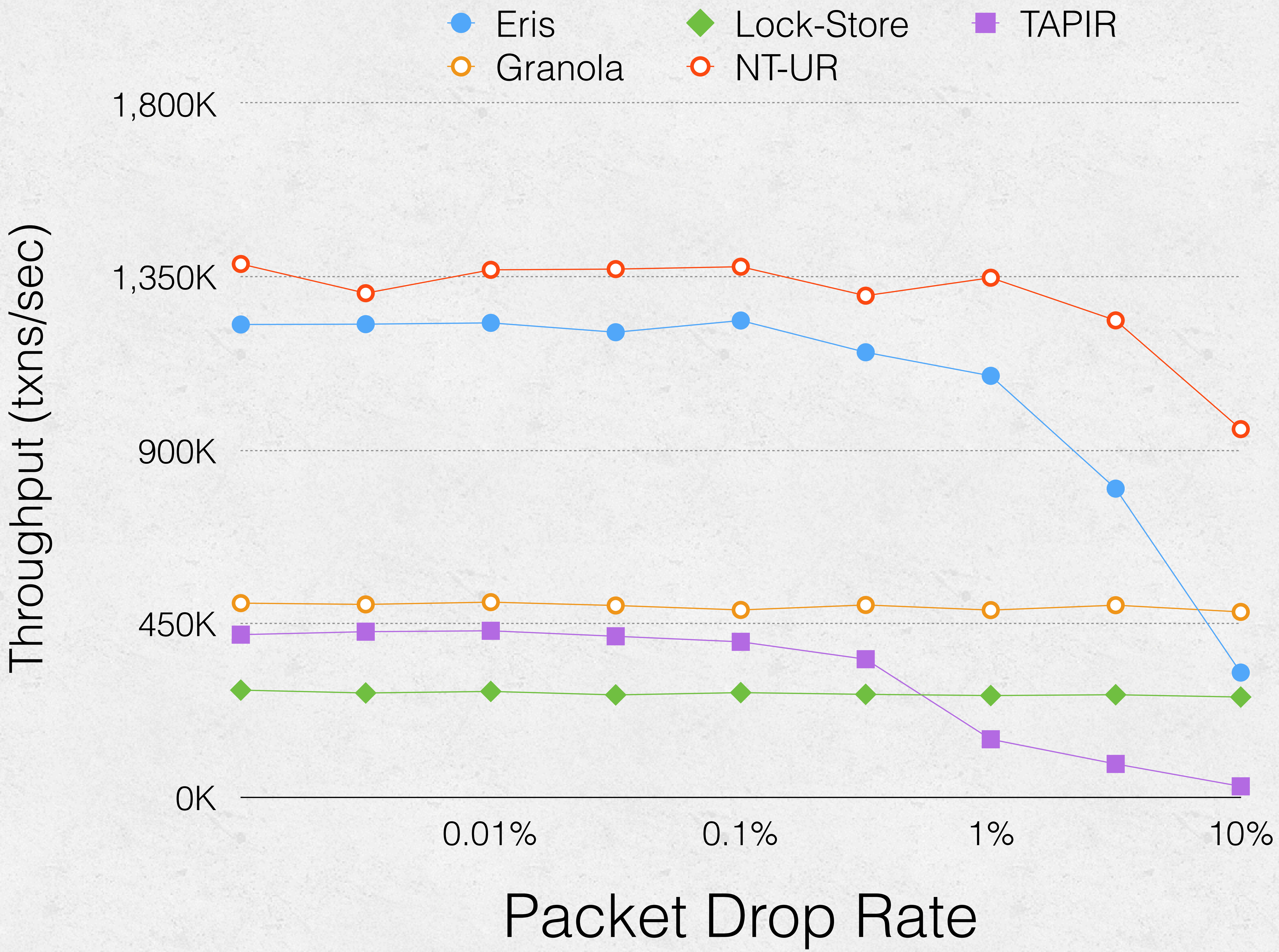
Eris excels at complex transactional applications



within 3% throughput of NT-UR

7.6X and 6.4X higher throughput than Lock-Store and Tapir

Eris is resilient to network anomalies



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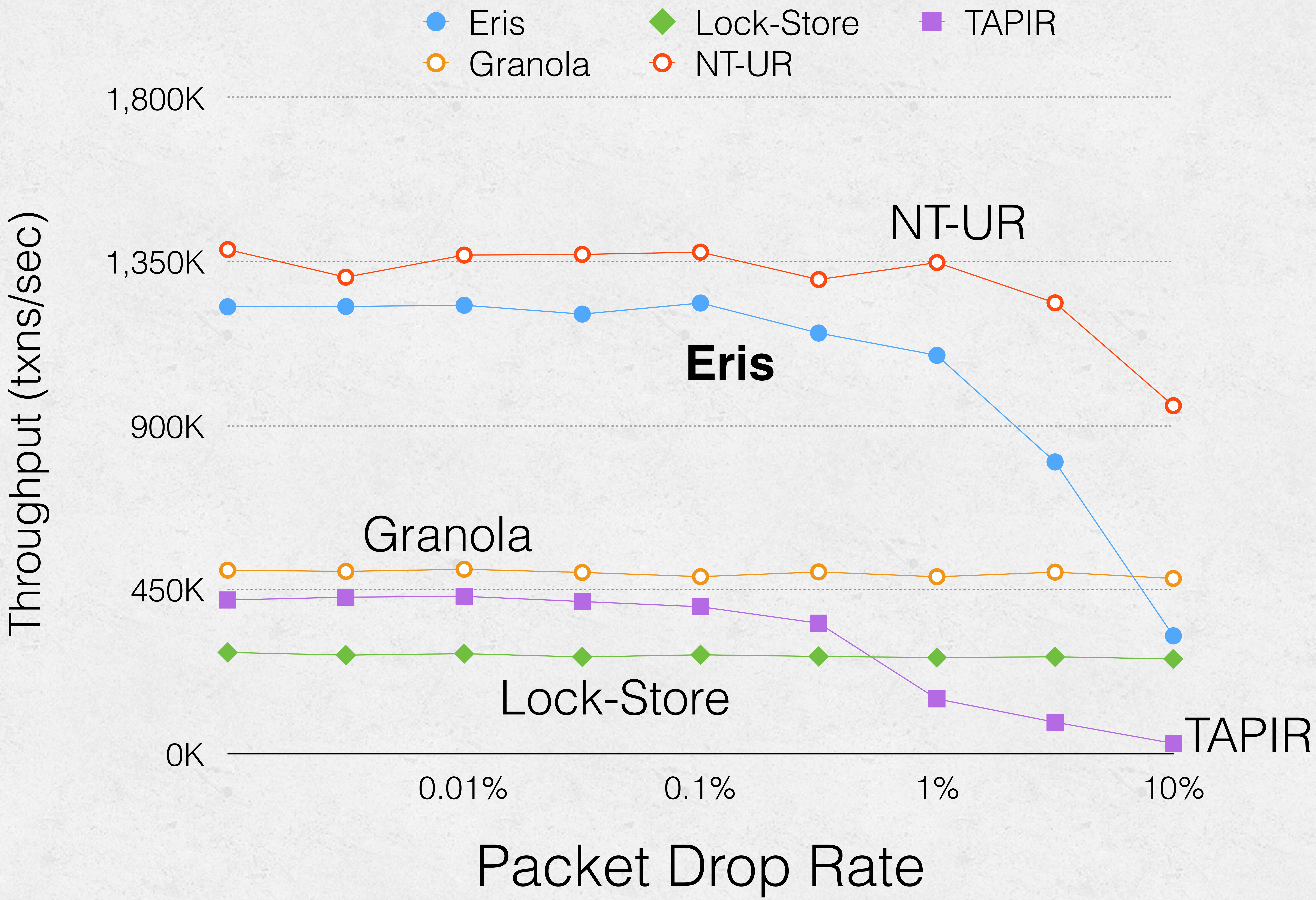

Eris Recap

- A new division of responsibility for transaction processing
  - An in-network concurrency control mechanism that establishes a **consistent order** of transactions across shards
  - An efficient protocol that ensures **reliable delivery** of independent transactions
  - A **general transaction** layer atop independent transaction processing
- Result: strongly consistent, fault-tolerant transactions with **minimal performance overhead**

Eris and NOPaxos Discussion

- Can we use an end-host sequencer for Eris? In NOPaxos, it's not a problem.

- What properties are important to NOPaxos's "scalability"?

- How deployable are these approaches?

- How scalable is Eris compared to two-phase commit?