Designing Distributed Systems using Approximate Synchrony in Data Center Networks

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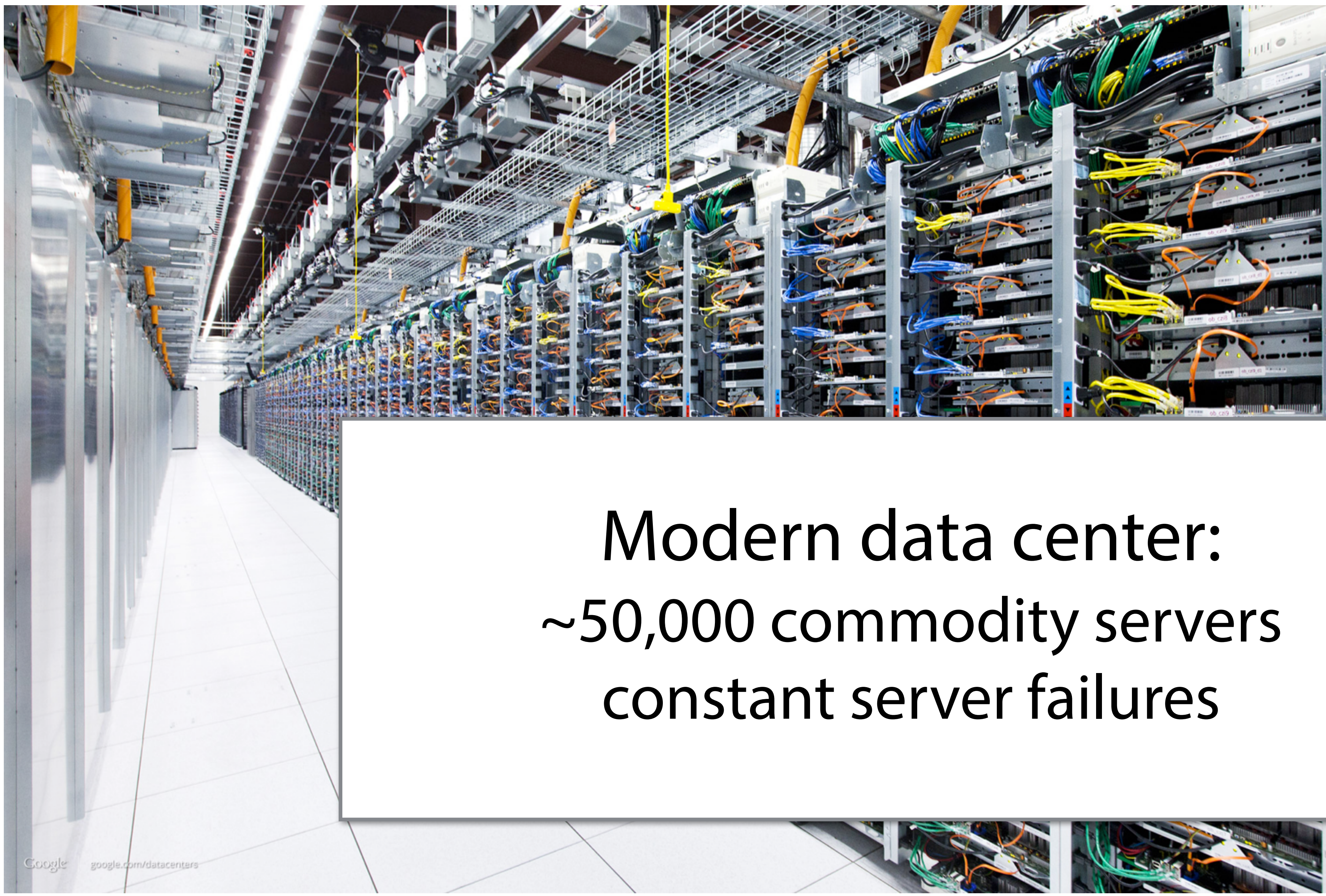


Modern data center:

~50,000 commodity servers

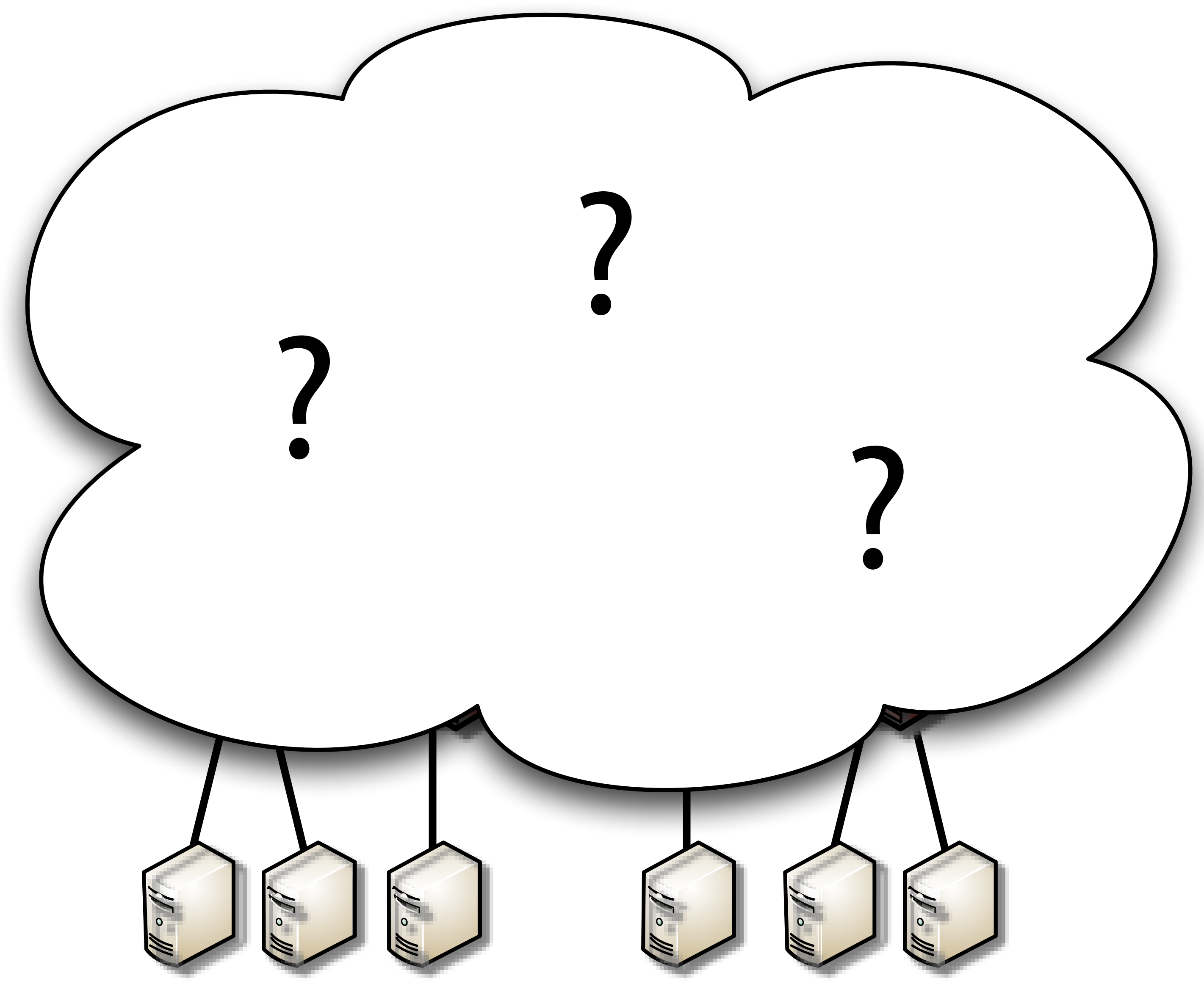
constant server failures

How do we program the data center?

Use distributed algorithms to tolerate failures, inconsistencies

Example: Paxos state machine replication

Distributed systems and networks are typically designed independently



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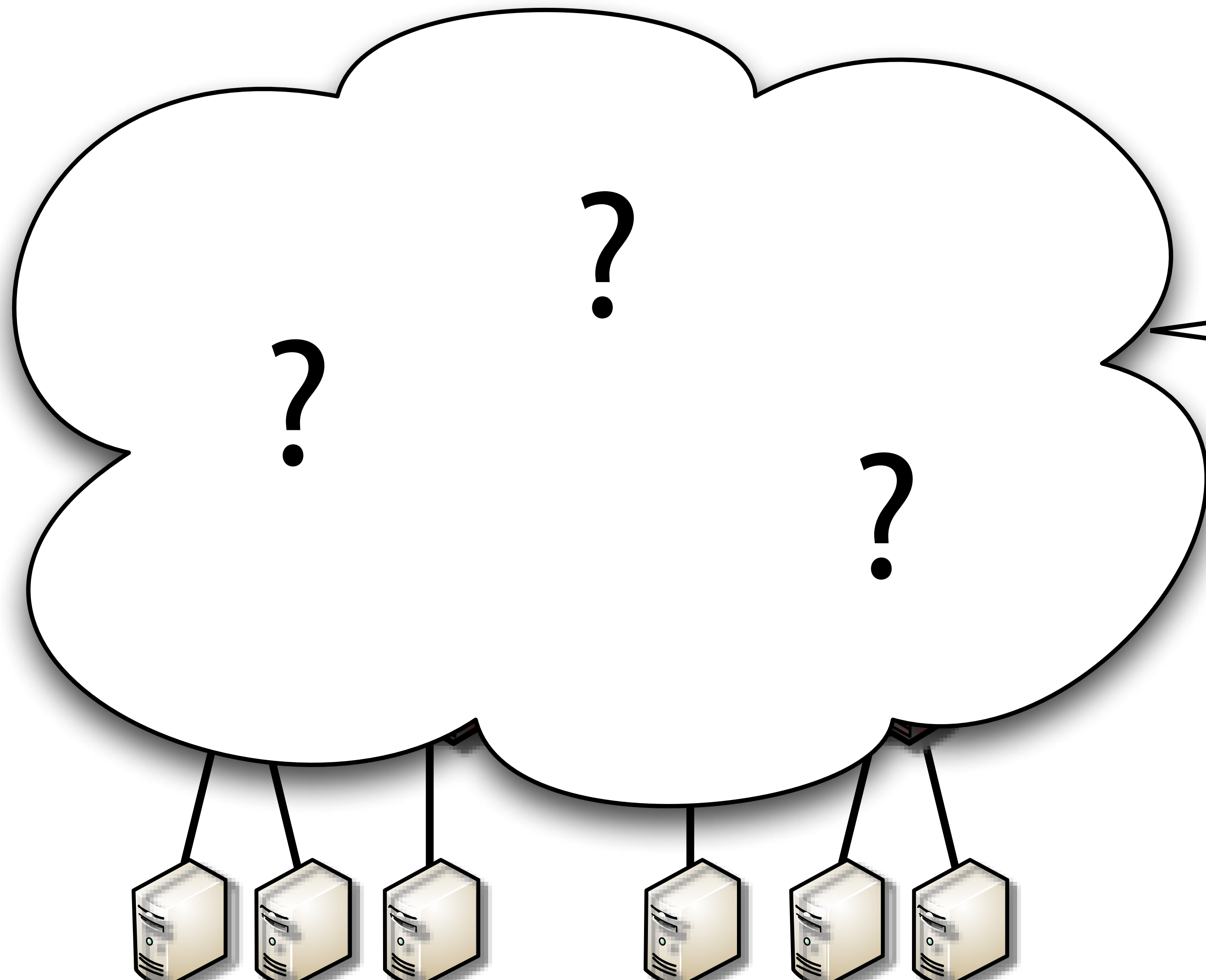

asynchronous network (Internet)

packets may be arbitrarily

- dropped
- delayed
- reordered

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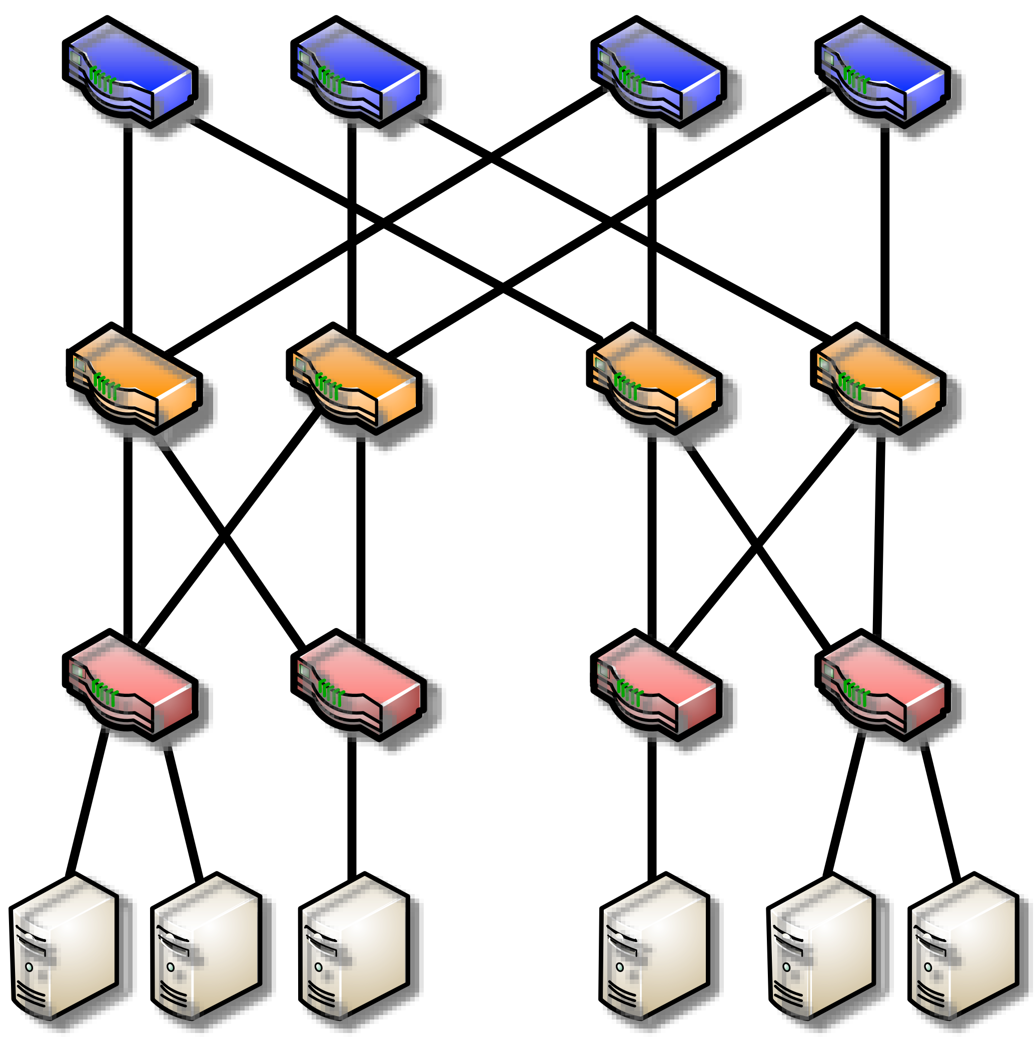

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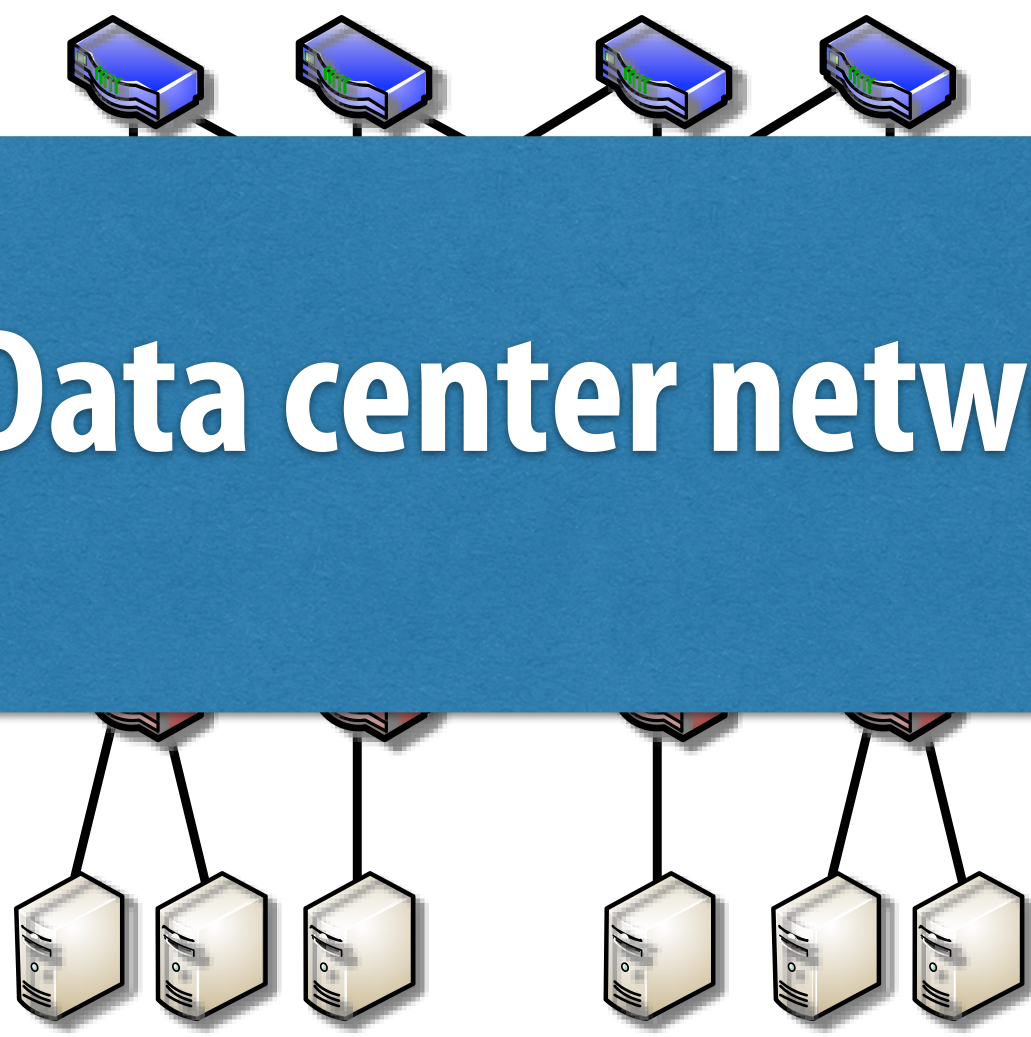

Data center networks are different!

Data Center Networks Are Different

Data center networks are more ***predictable***

- known topology, routes, predictable latencies

Data center networks are more ***reliable***

Data center networks are ***extensible***

- single administrative domain makes changes possible
- software-defined networking exposes sophisticated line-rate processing capability

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We should co-design distributed systems and data center networks!

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- software-defined networking exposes sophisticated line-rate processing capability

Co-Designing Networks and Distributed Systems

Design the ***data center network*** to support ***distributed applications***

Design ***distributed applications*** around the properties of the ***data center network***

This Talk

A concrete instantiation:

improving replication performance using
Speculative Paxos and ***Mostly-Ordered Multicast***

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new replication protocol

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A concrete instantiation:

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new replication protocol

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3x throughput and 40% lower latency than conventional approach

Outline

1. Co-designing Distributed Systems and Data Center Networks

2. **Background: State Machine Replication & Paxos**

3. Mostly-Ordered Multicast and Speculative Paxos

4. Evaluation

State Machine Replication

Used to tolerate failures in datacenter applications

- keep critical management services online
  (e.g., Google's Chubby, Zookeeper)
- persistent storage in distributed databases
  (e.g., Spanner, H-Store)

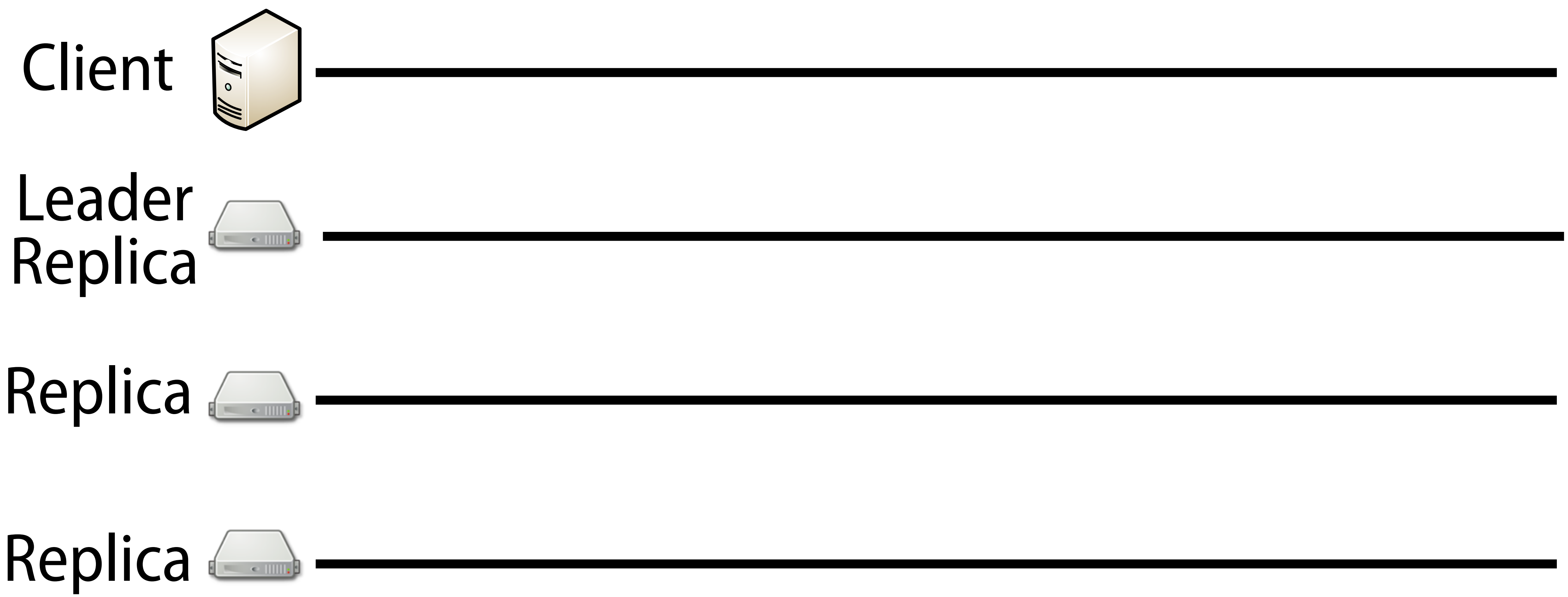
Strongly consistent (linearizable) replication, i.e.,

all replicas execute same operations in same order

. . . *even when up to half replicas fail*

. . . *even when messages are lost*

Example: Paxos



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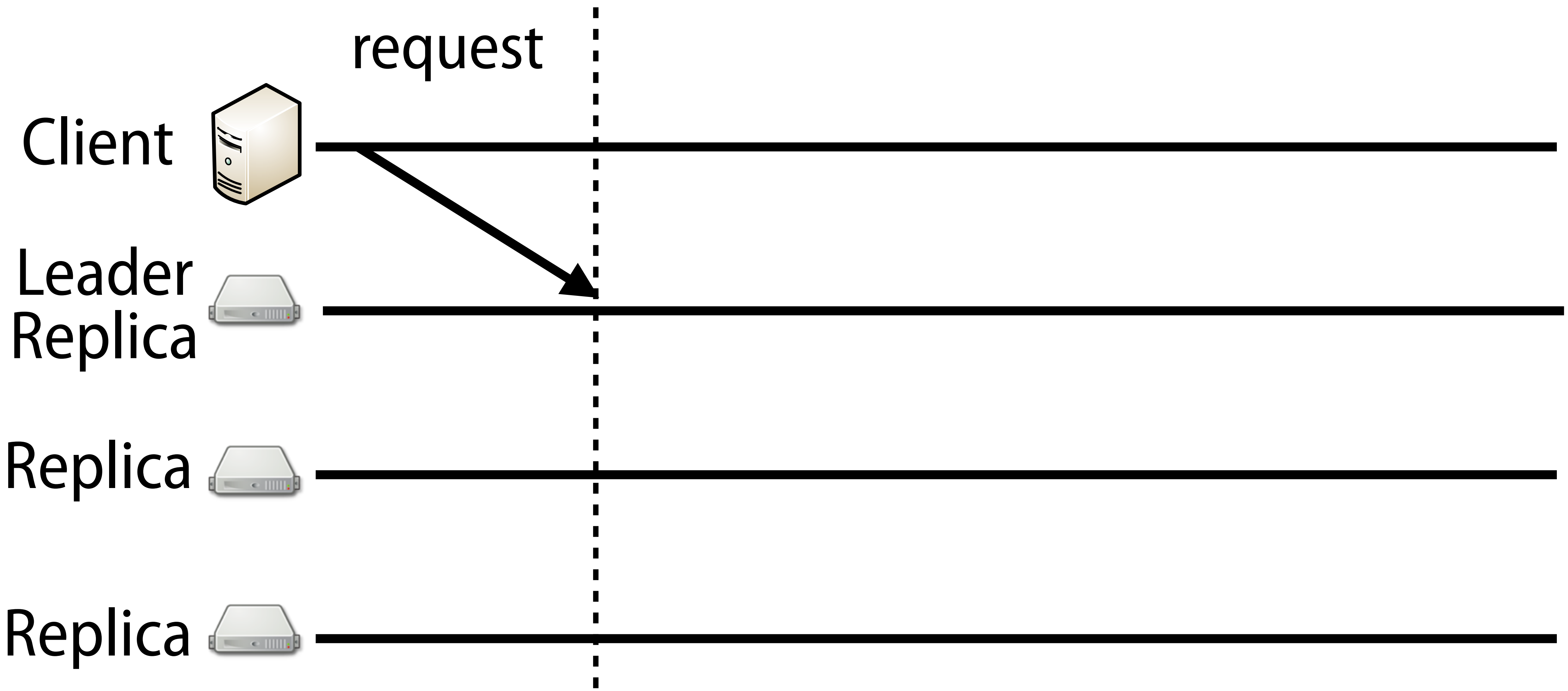

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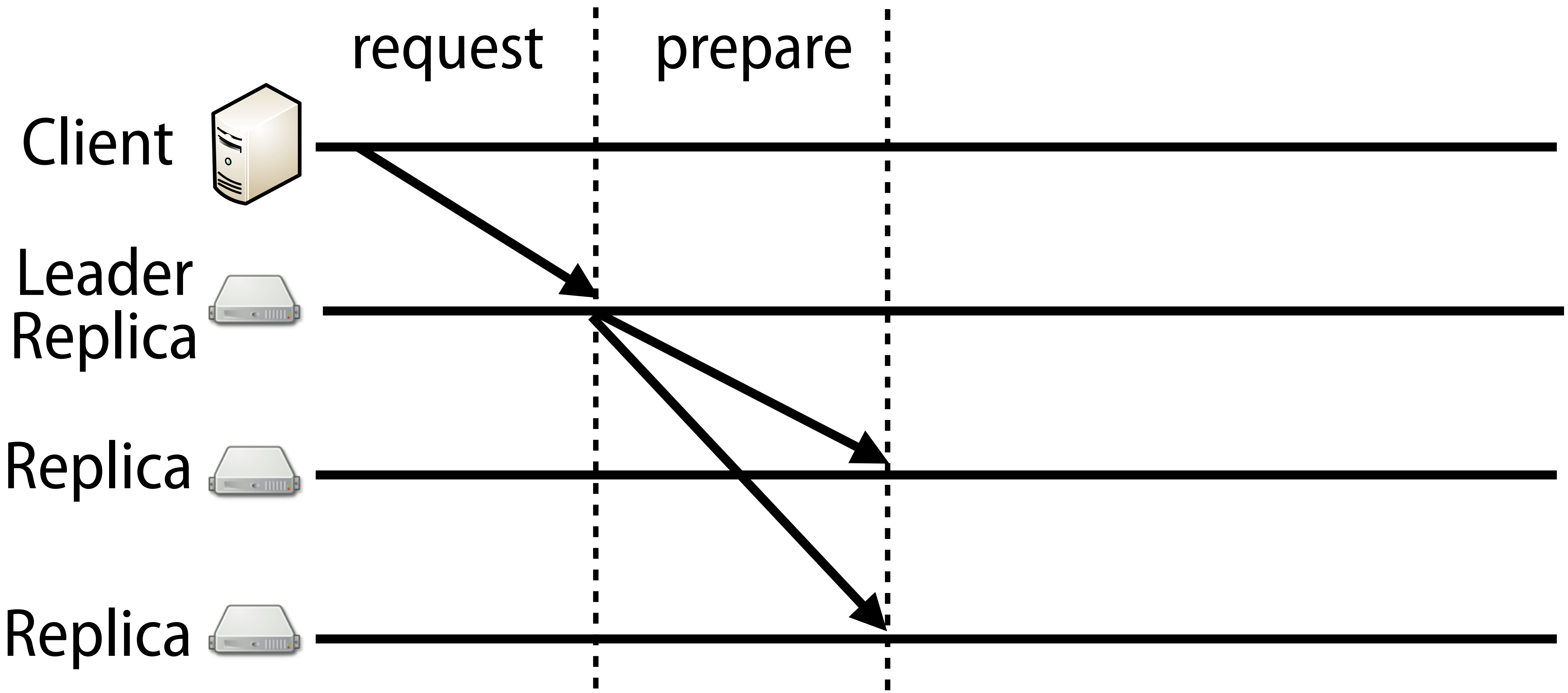

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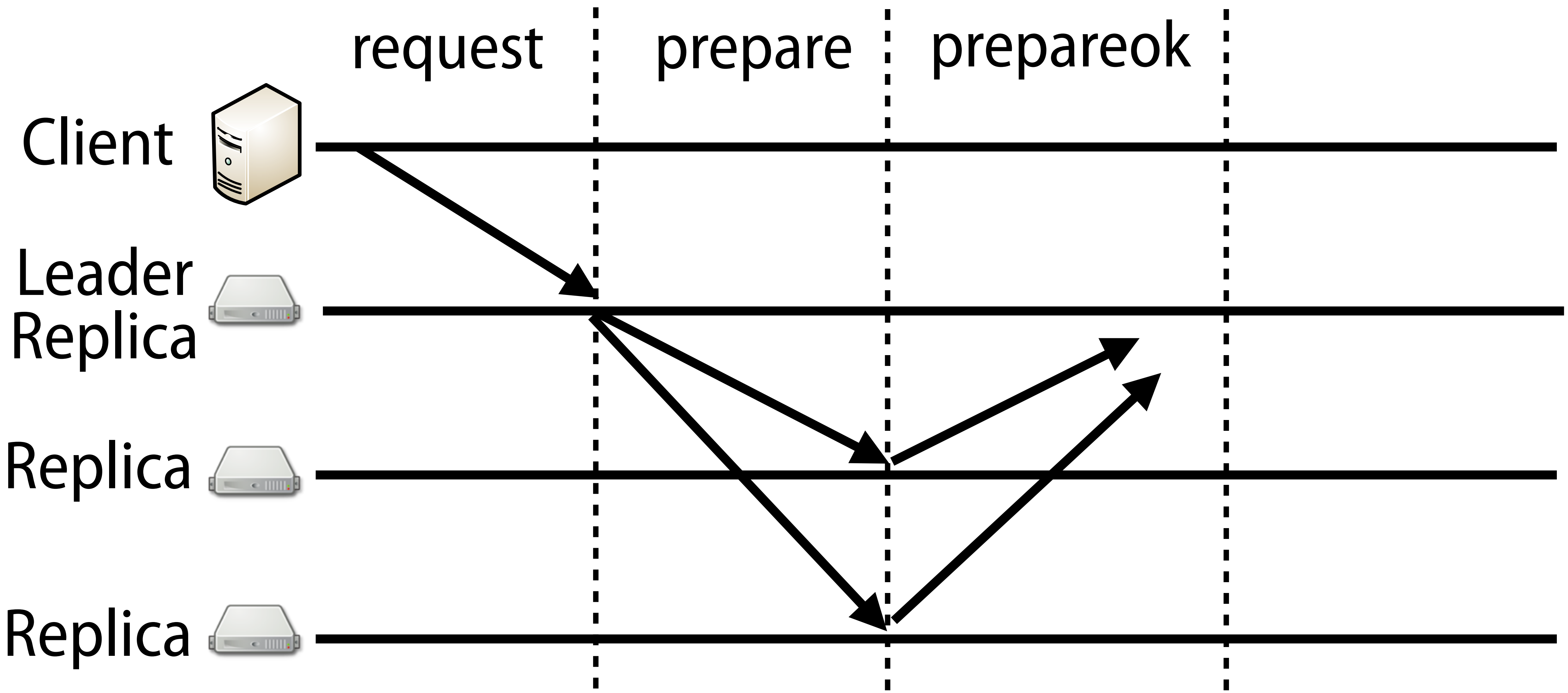

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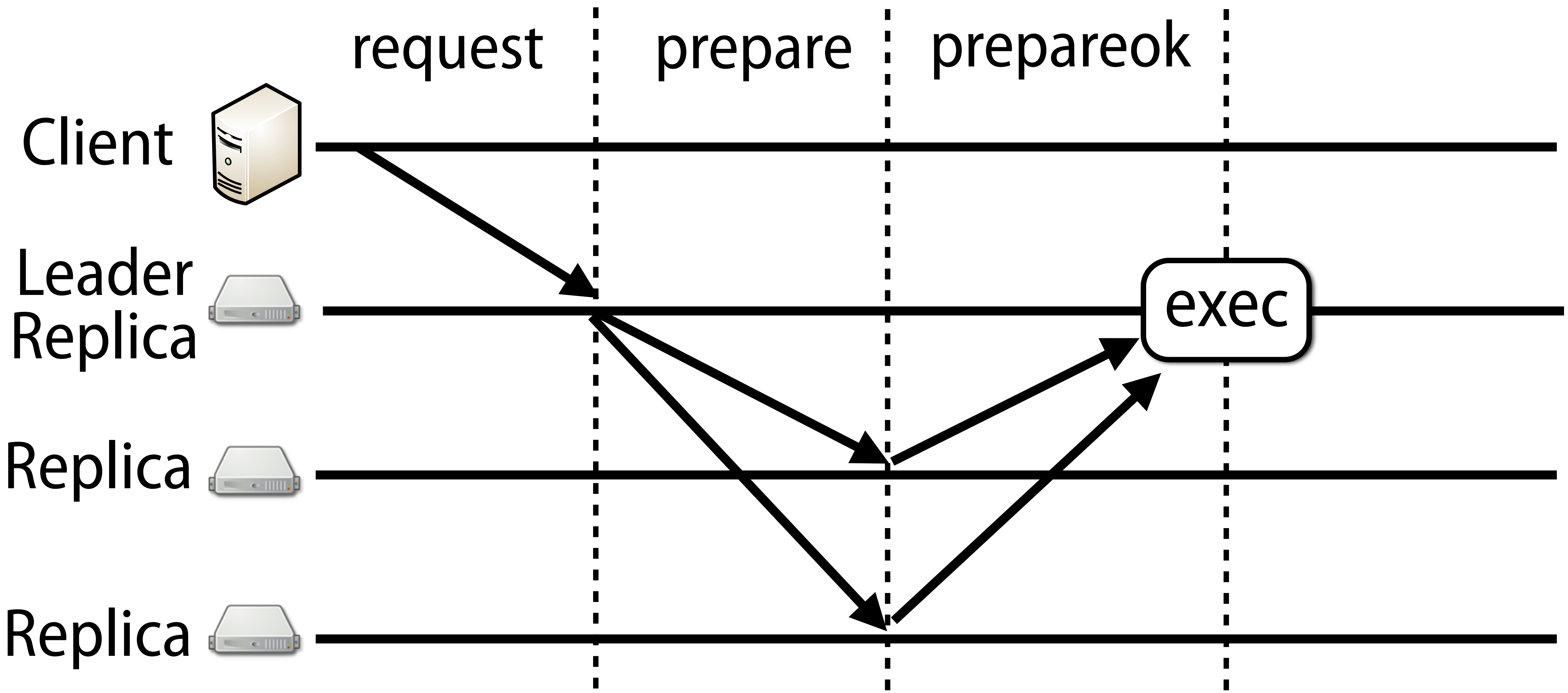

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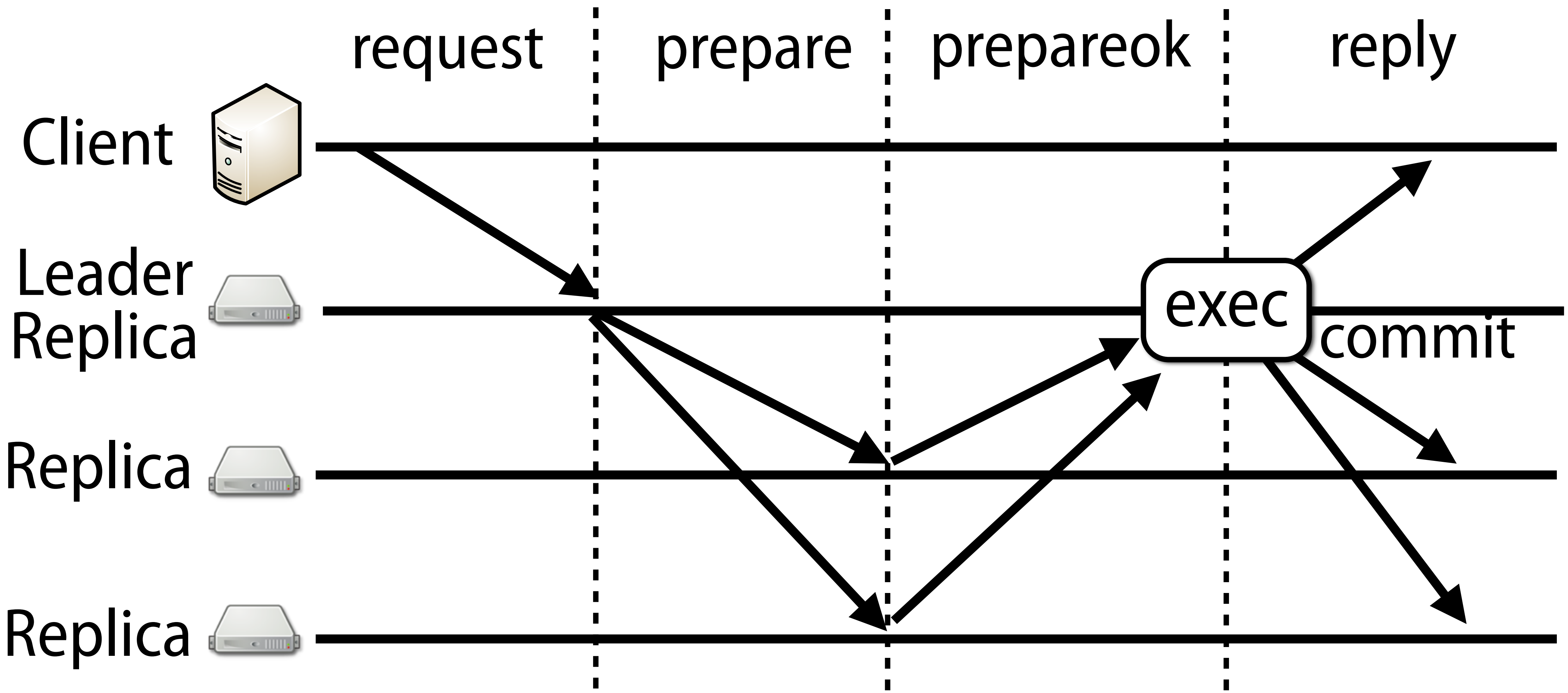

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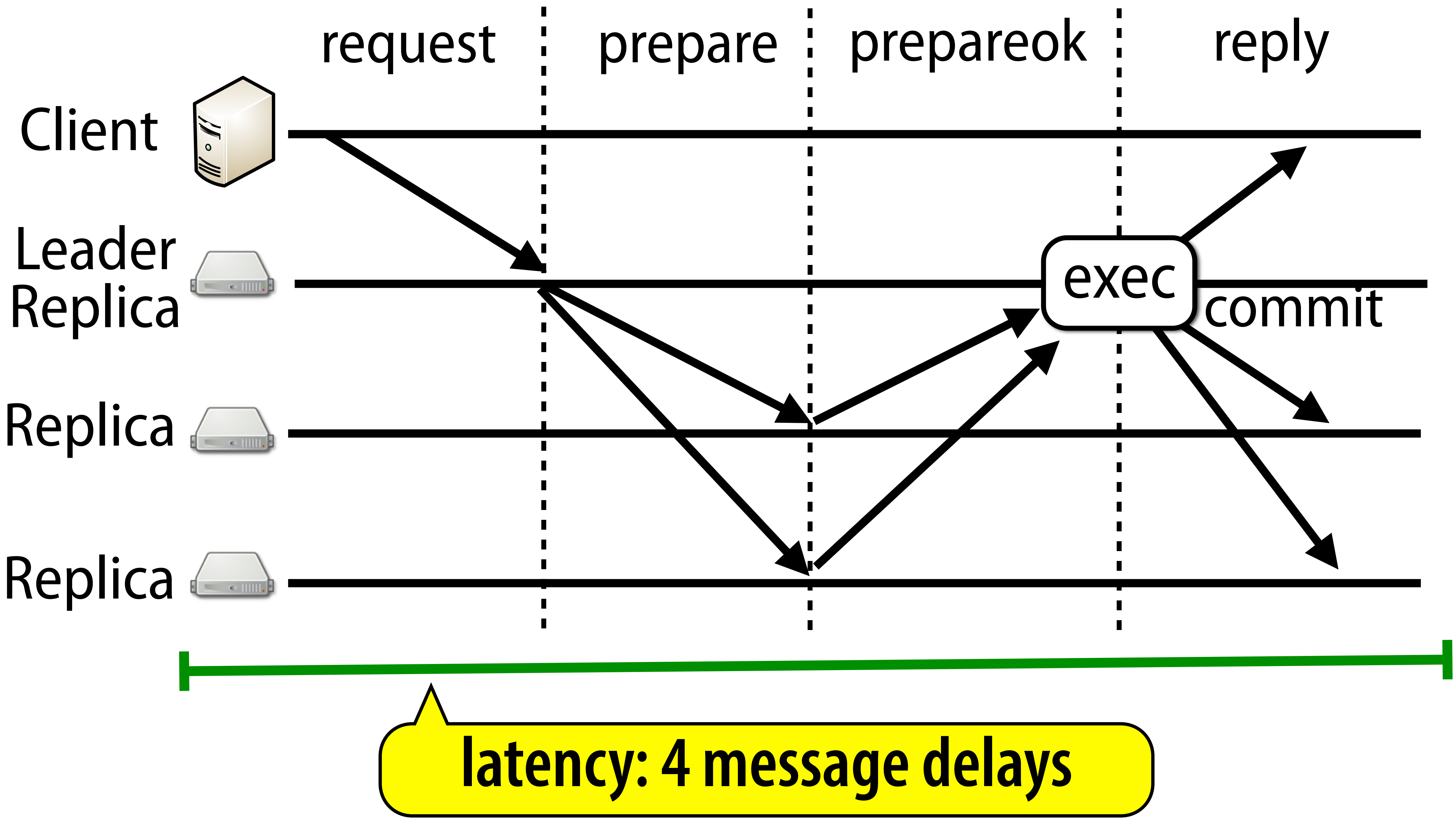

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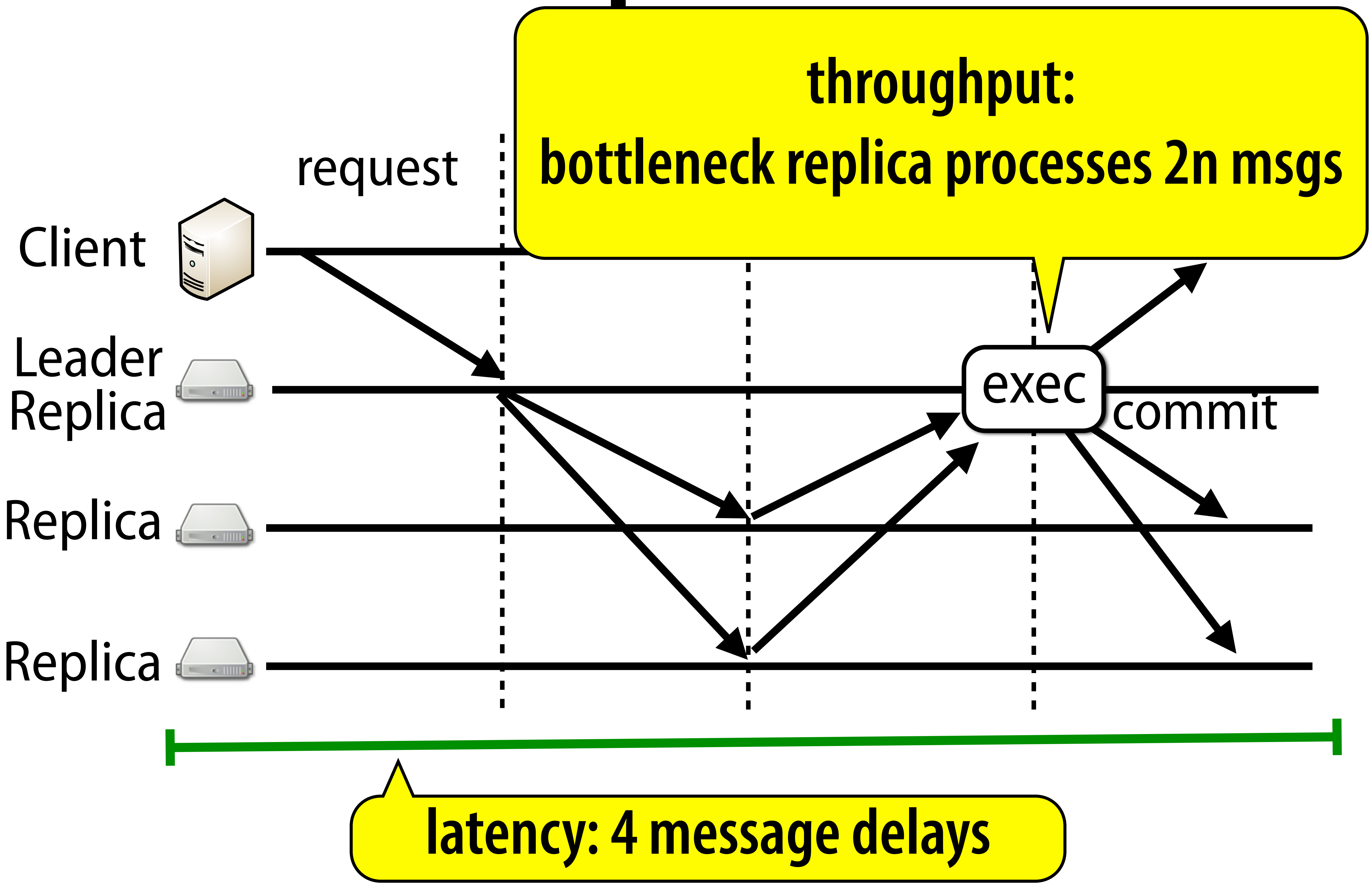

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1. Co-designing Distributed Systems and Data Center Networks
2. Background: State Machine Replication & Paxos
3. **Mostly-Ordered Multicast and Speculative Paxos**
4. Evaluation

Improving Paxos Performance

Paxos requires a leader replica to order requests

Can we use the network instead?

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Can we use the network instead?

Engineer the network to provide
Mostly-Ordered Multicast (MOM)

- best-effort ordering of multicasts

New replication protocol: **Speculative Paxos**

- commits most operations in a single round trip

Mostly-Ordered Multicast

Concurrent messages are ordered:

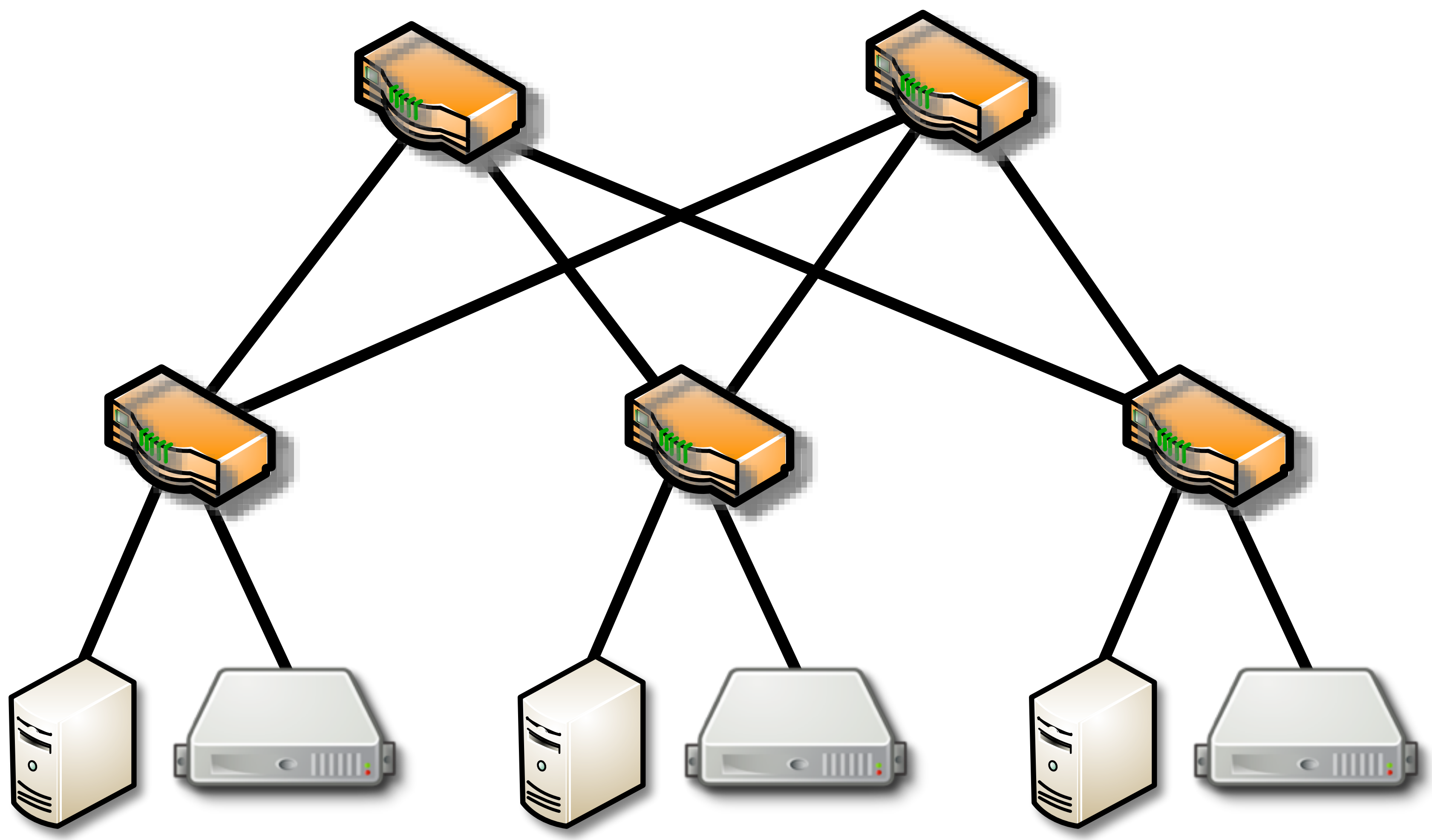
If any node receives message A then B, then
all other receivers process them ***in the same order***

- best effort — not guaranteed

Practical to implement

- can be violated in event of network failure
- but not satisfied by existing multicast protocols!

Mostly-Ordered Multicast



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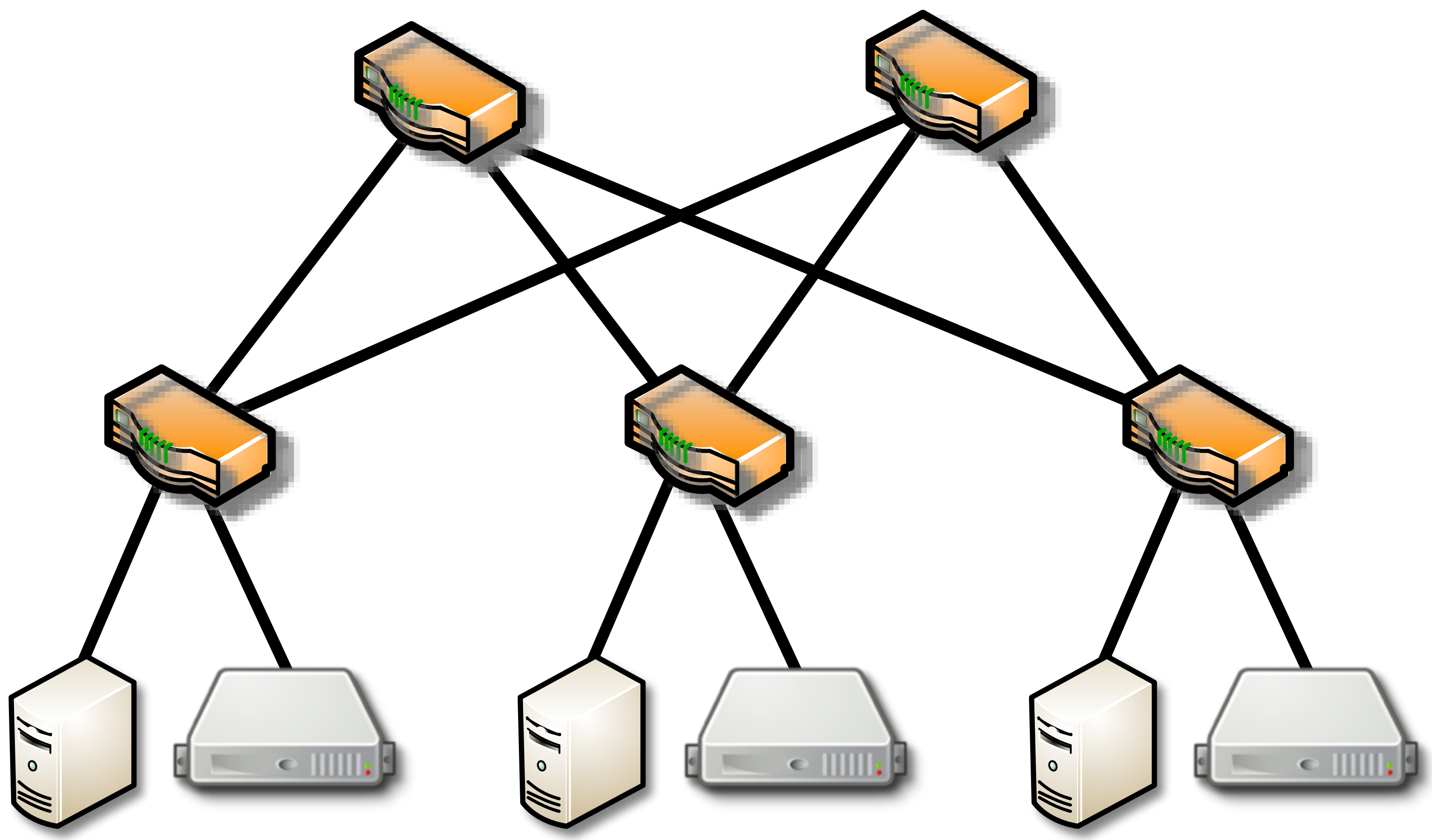

- Different path lengths, congestion cause reordering

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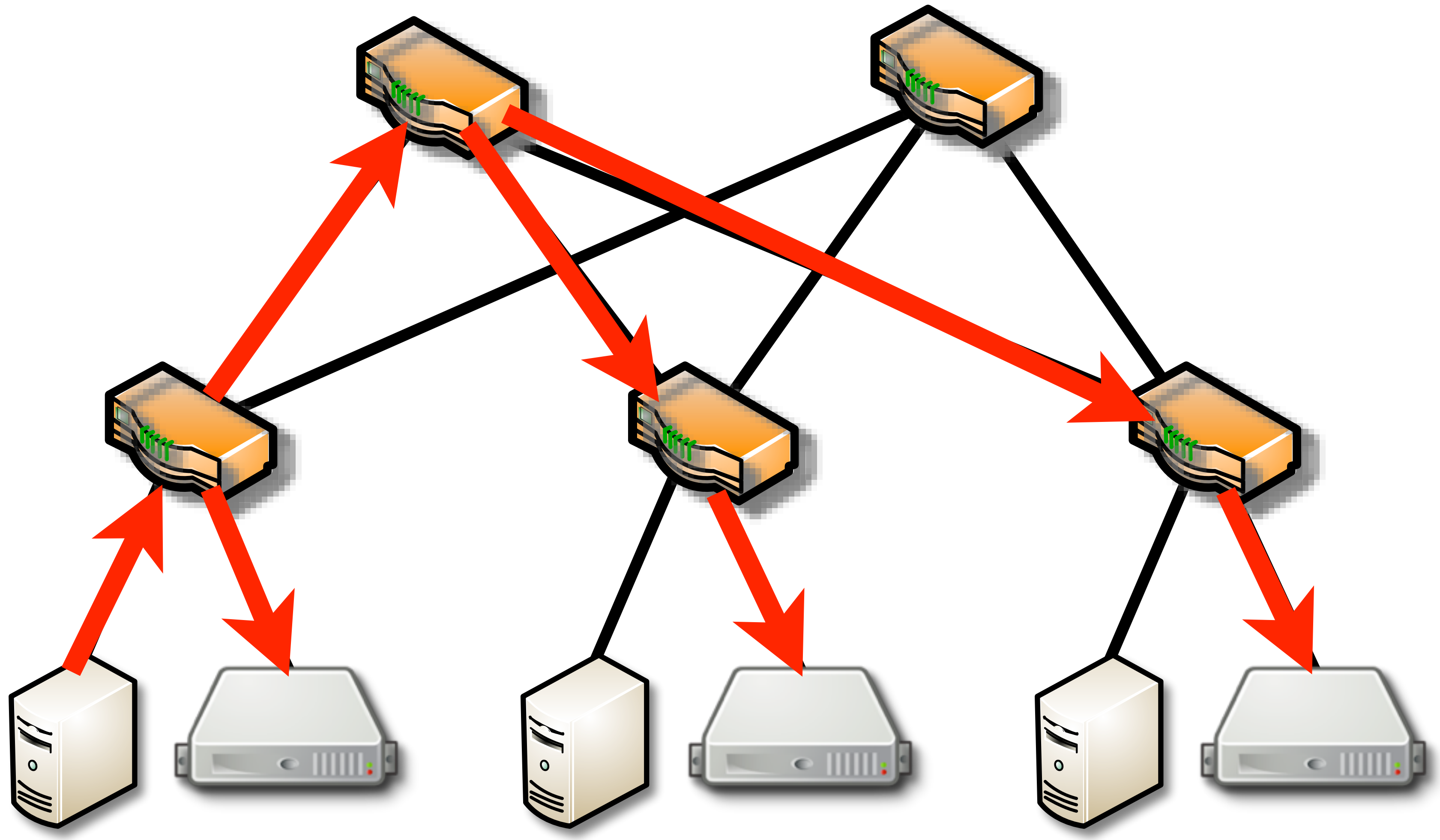

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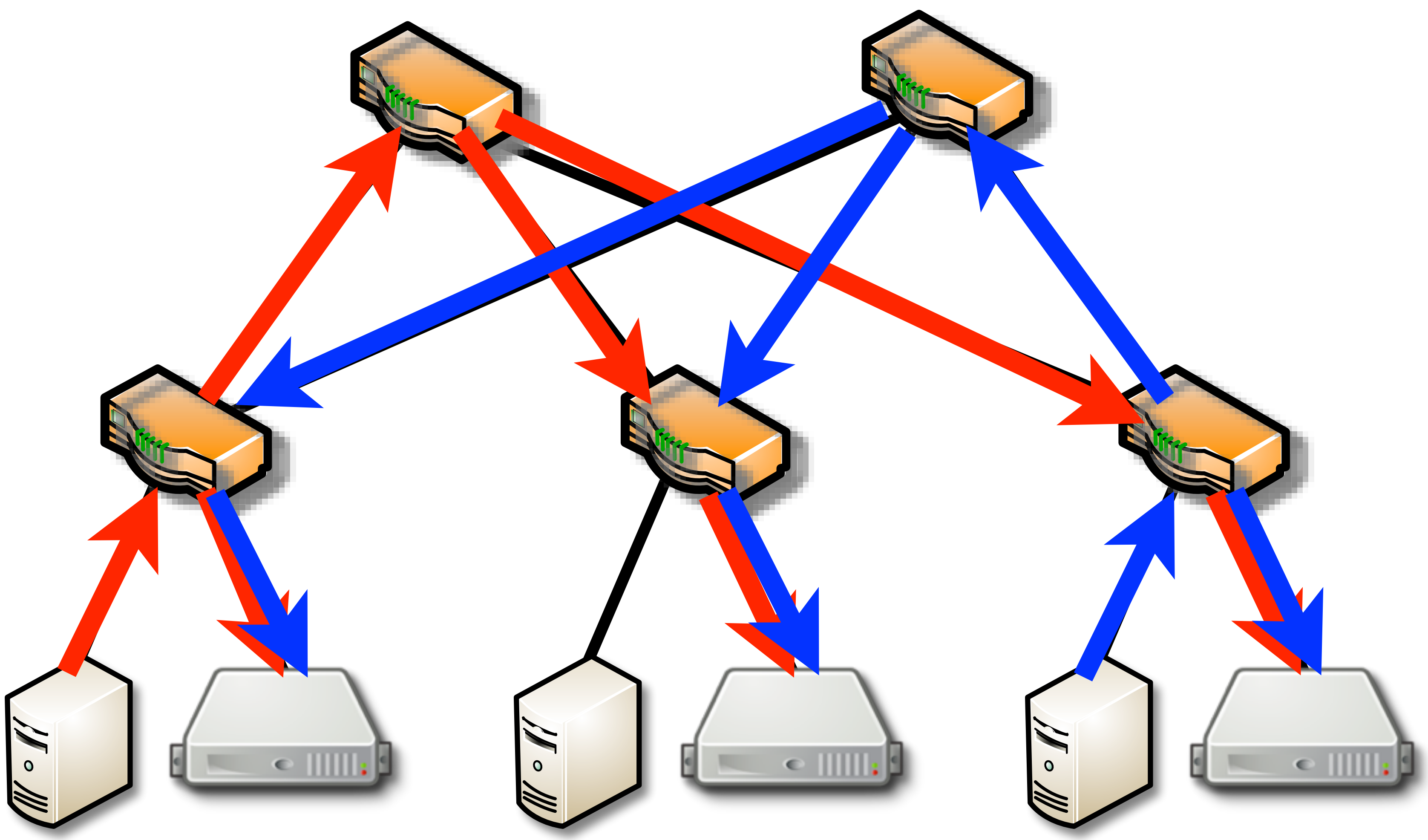

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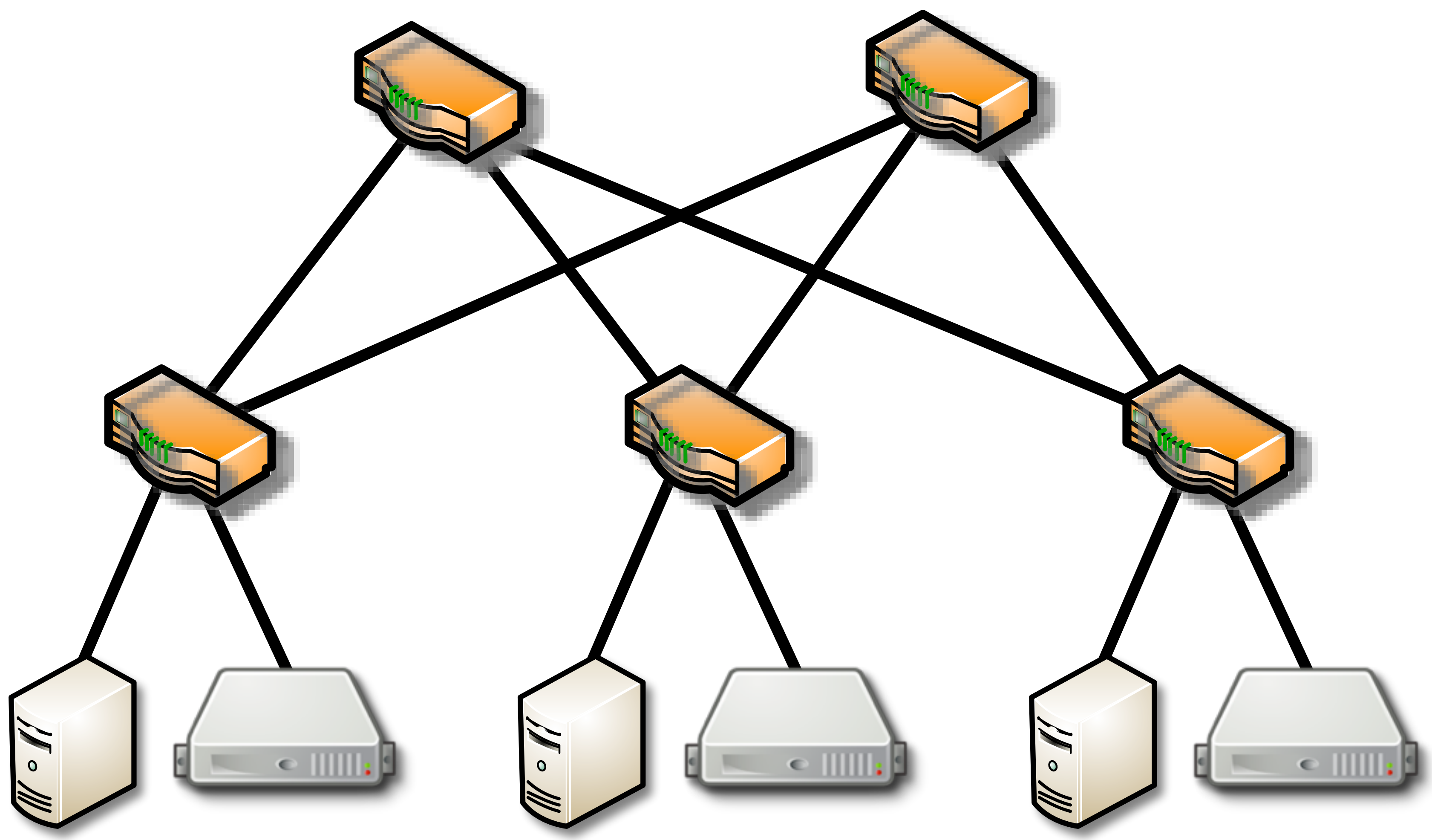

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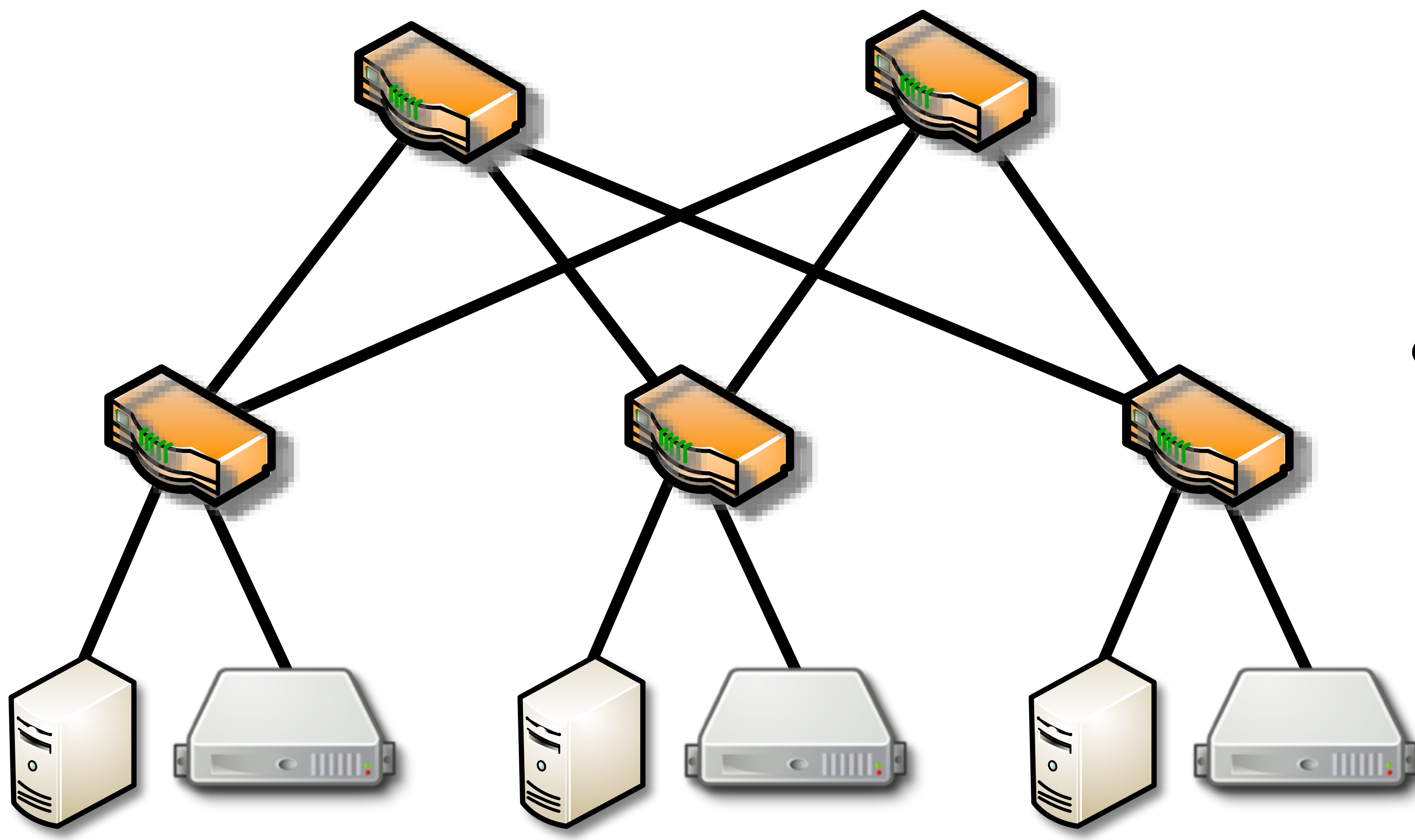

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- **MOM approach**: Route multicast messages to a root switch equidistant from receivers

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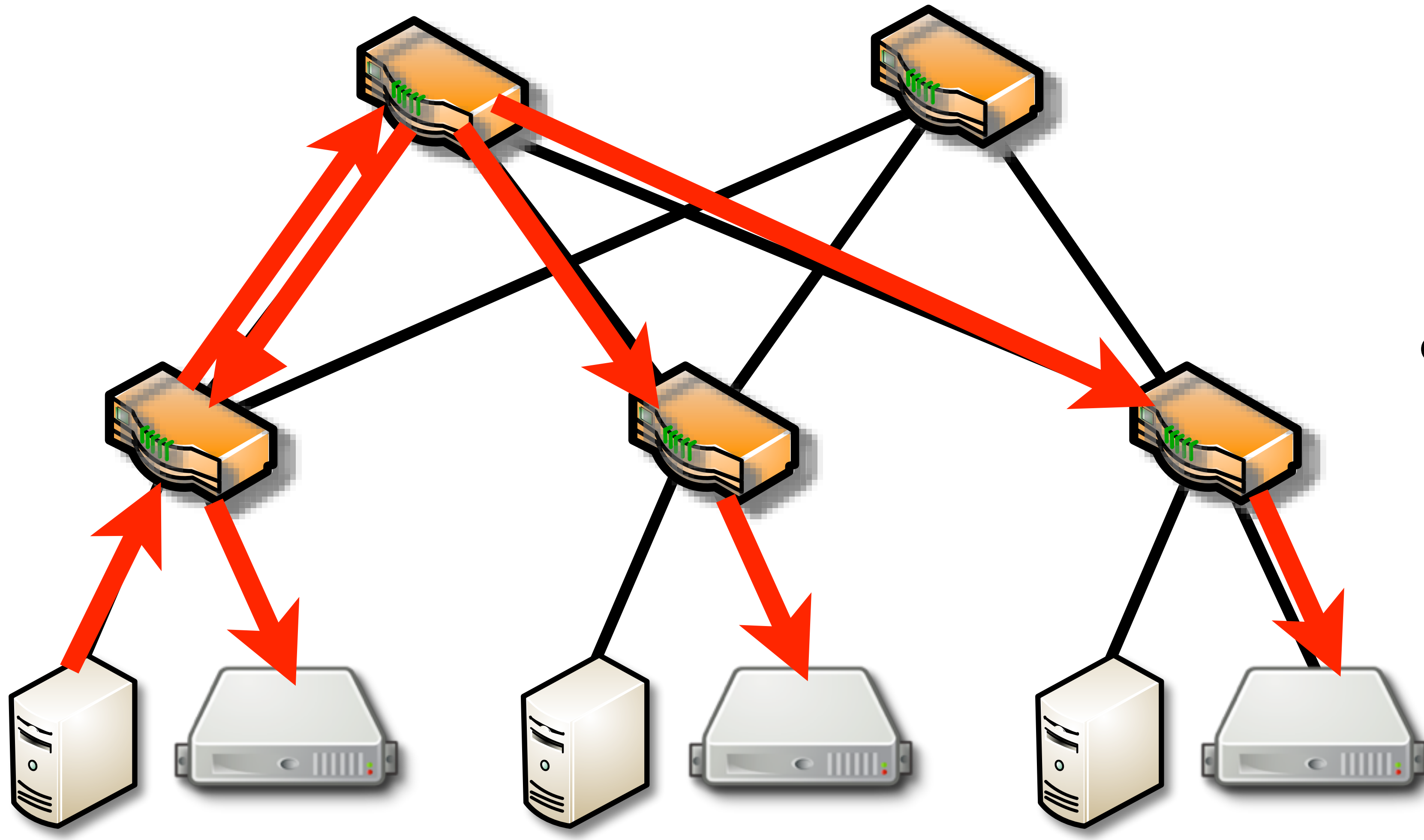

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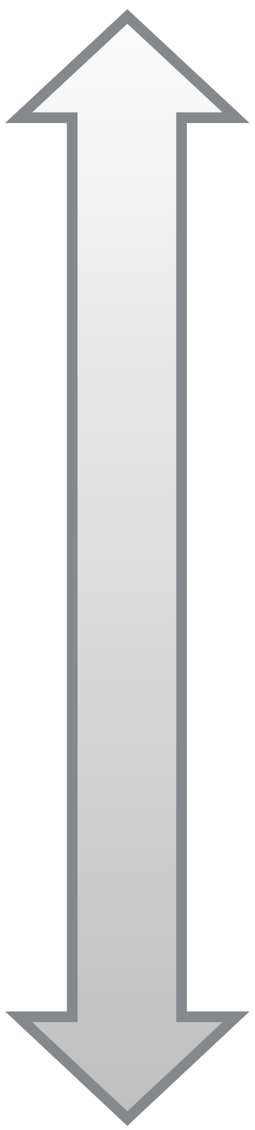
MOM Design Options

less network support



better ordering

MOM Design Options

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network support

1. Topology-Aware Multicast
   route packets to a randomly-chosen root switch

better ordering

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   use higher QoS priority to avoid link congestion

MOM Design Options

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1. Topology-Aware Multicast
   route packets to a randomly-chosen root switch
2. High-Priority Multicast
   use higher QoS priority to avoid link congestion
3. Network Serialization
   route packets through a *single* root switch

Speculative Paxos

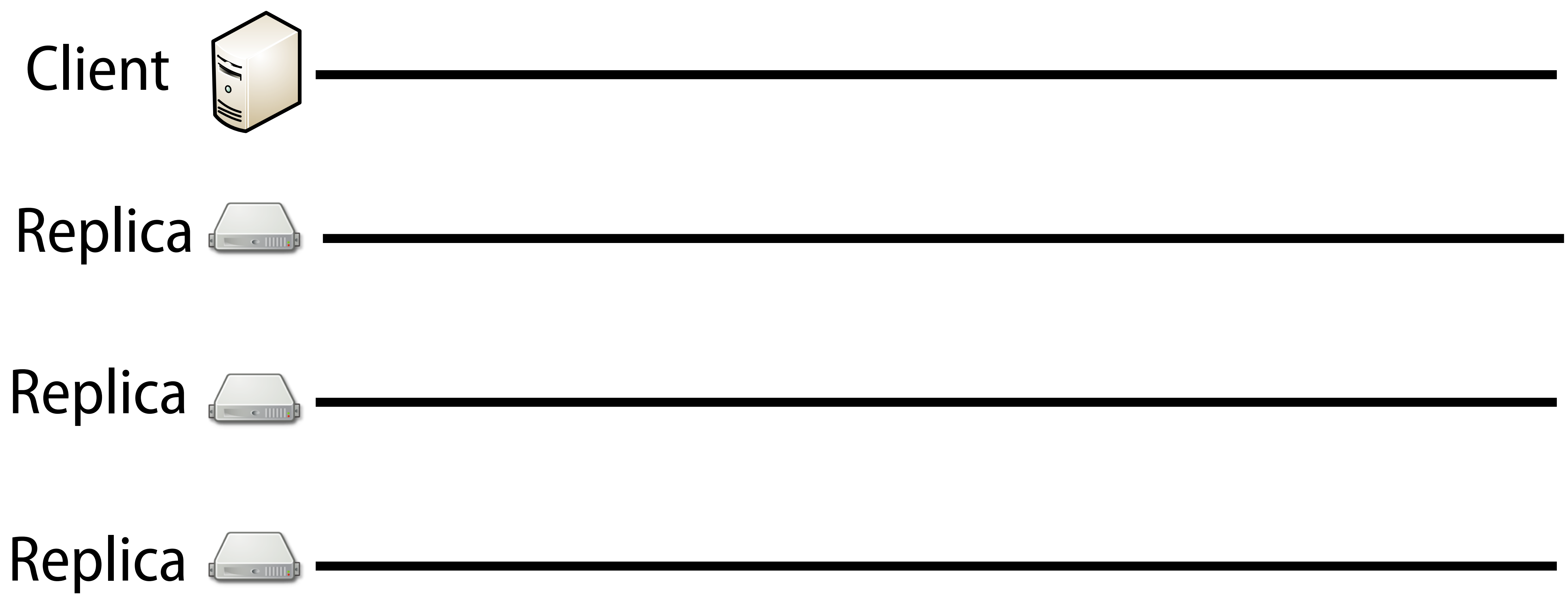
New state machine replication protocol

Relies on MOM to order requests
in the normal case

But not required:

- remains correct even with reorderings:
  safety + liveness under usual conditions

Speculative Paxos



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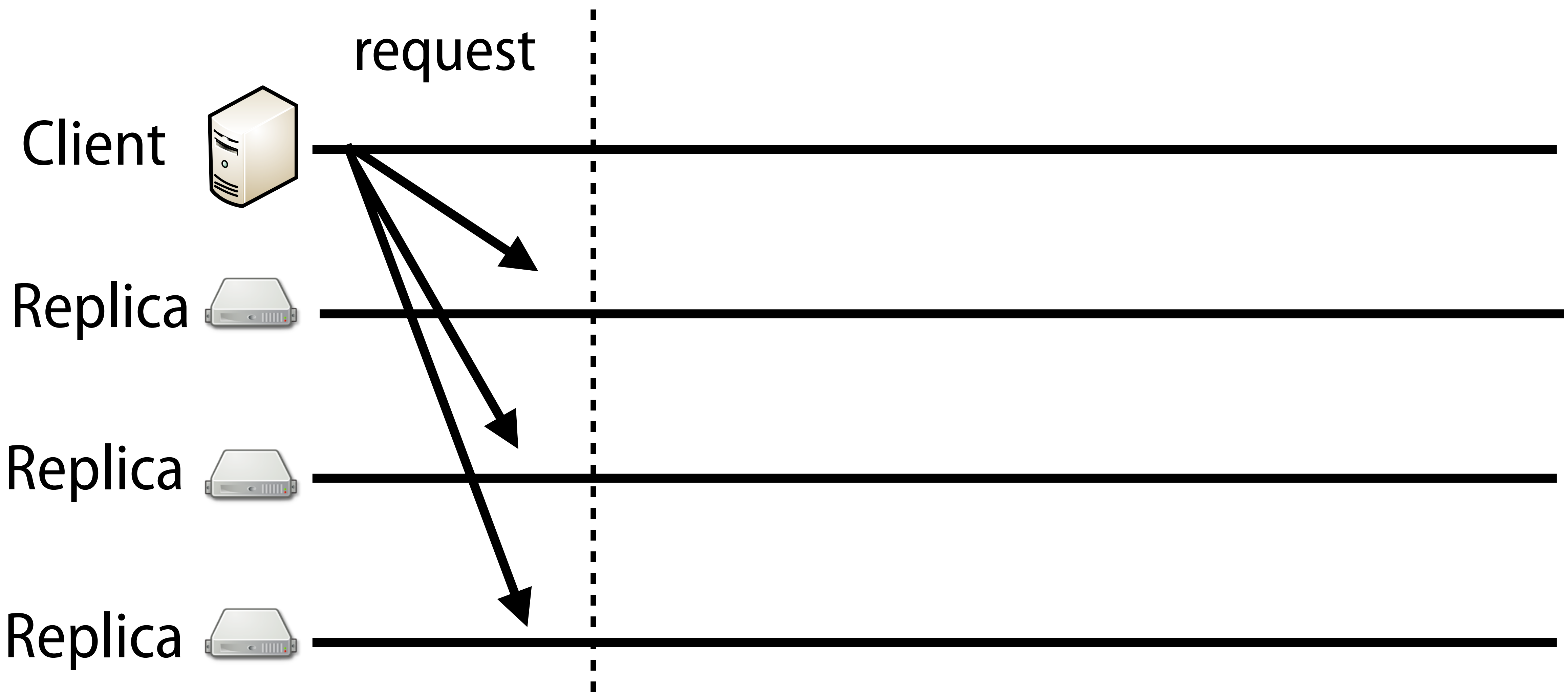
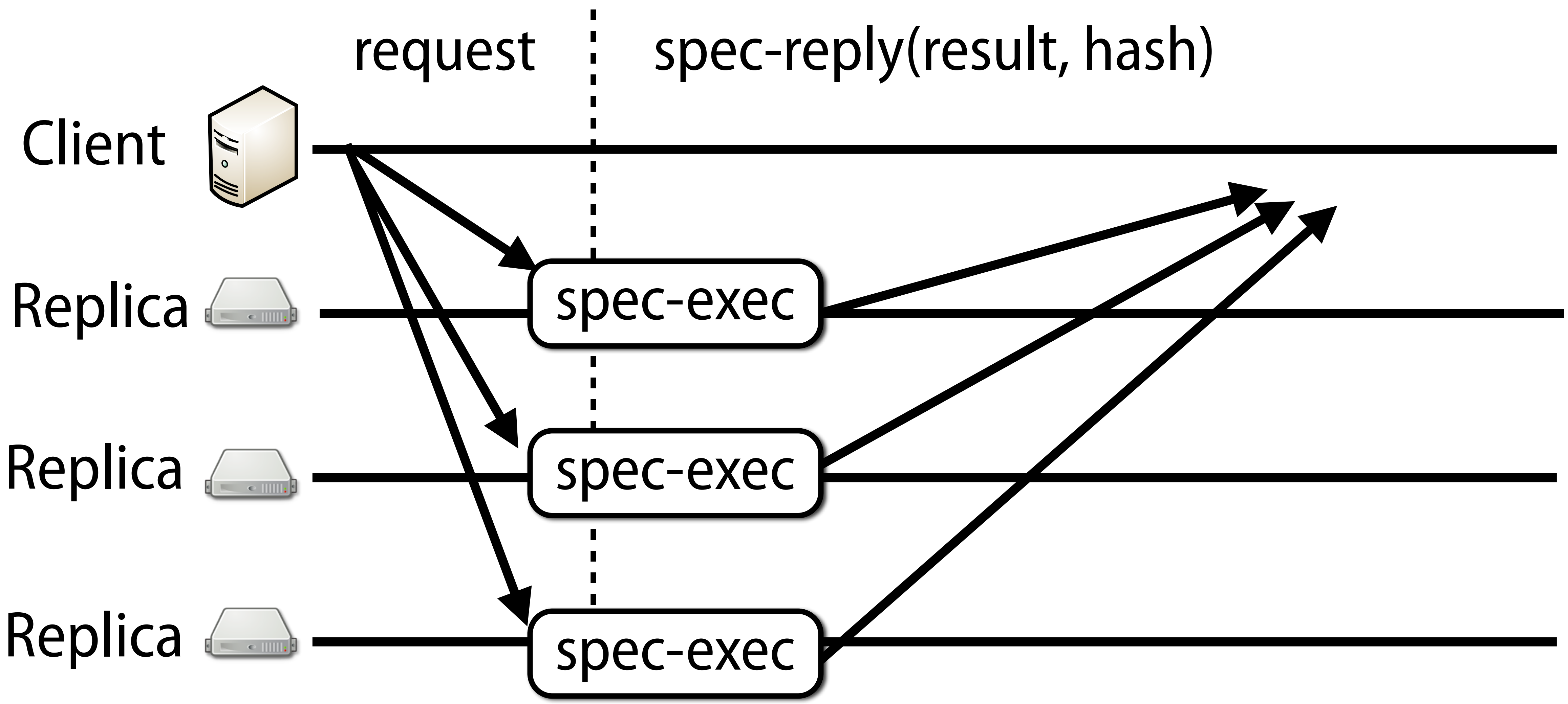


Speculative Paxos

replicas immediately speculatively execute request & reply!



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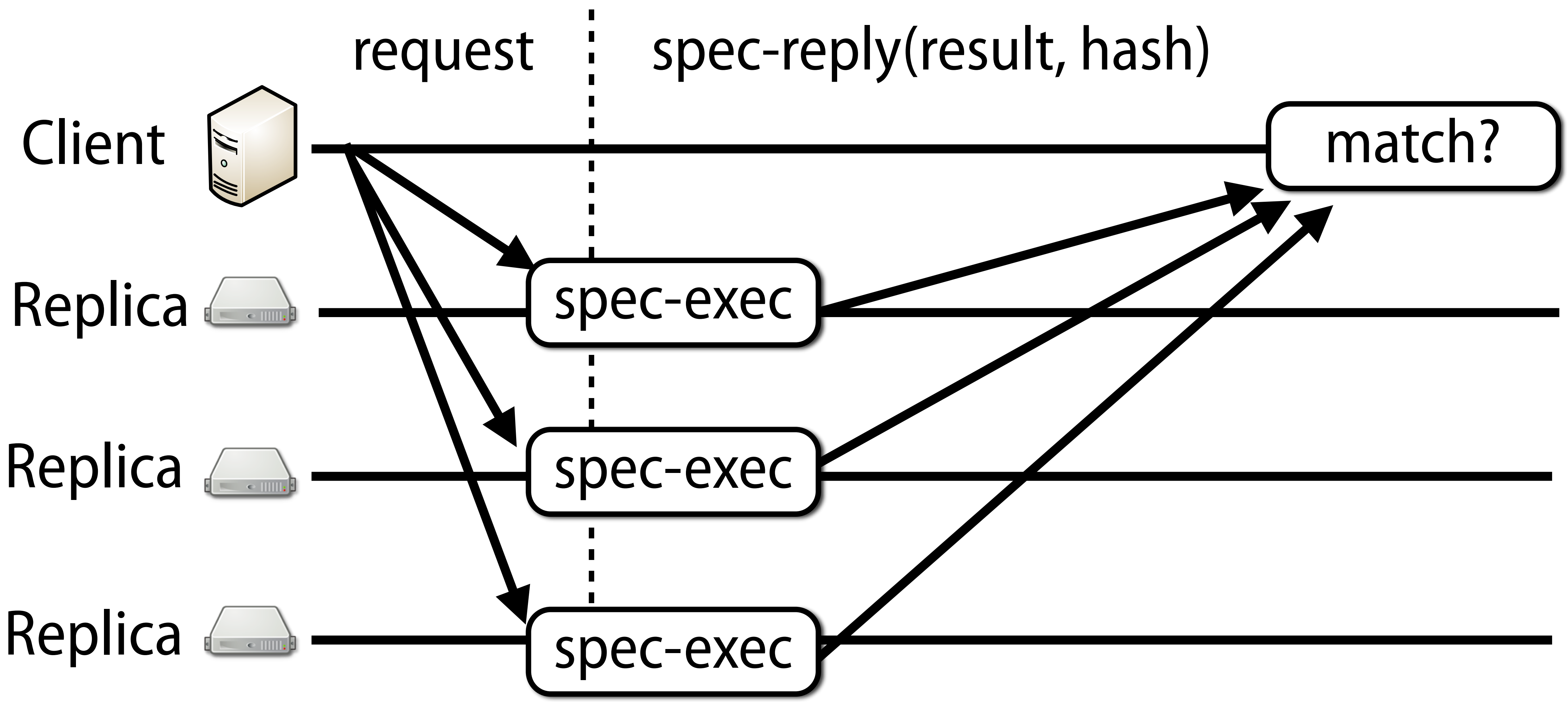
client checks for matching responses from 3/4 superquorum



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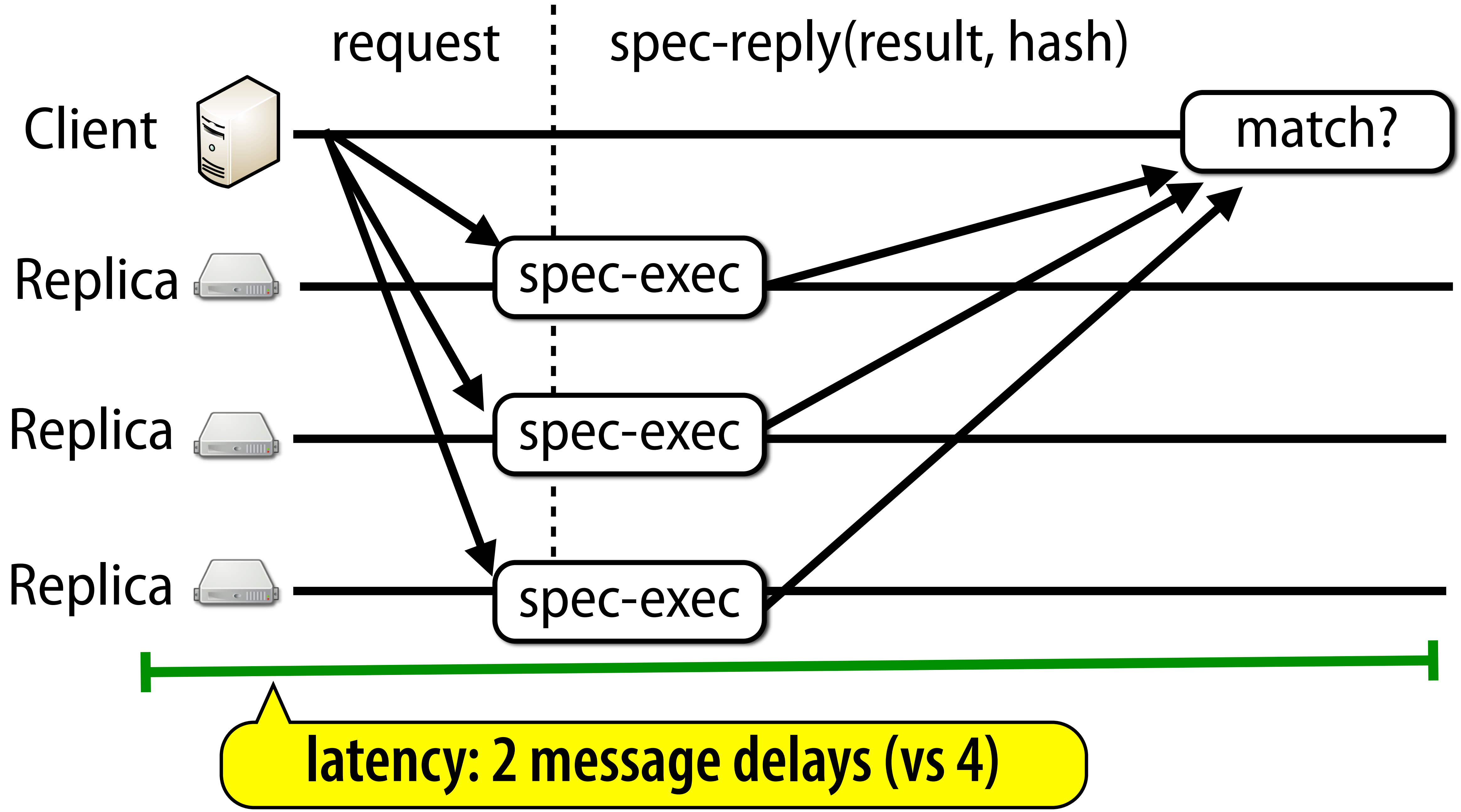

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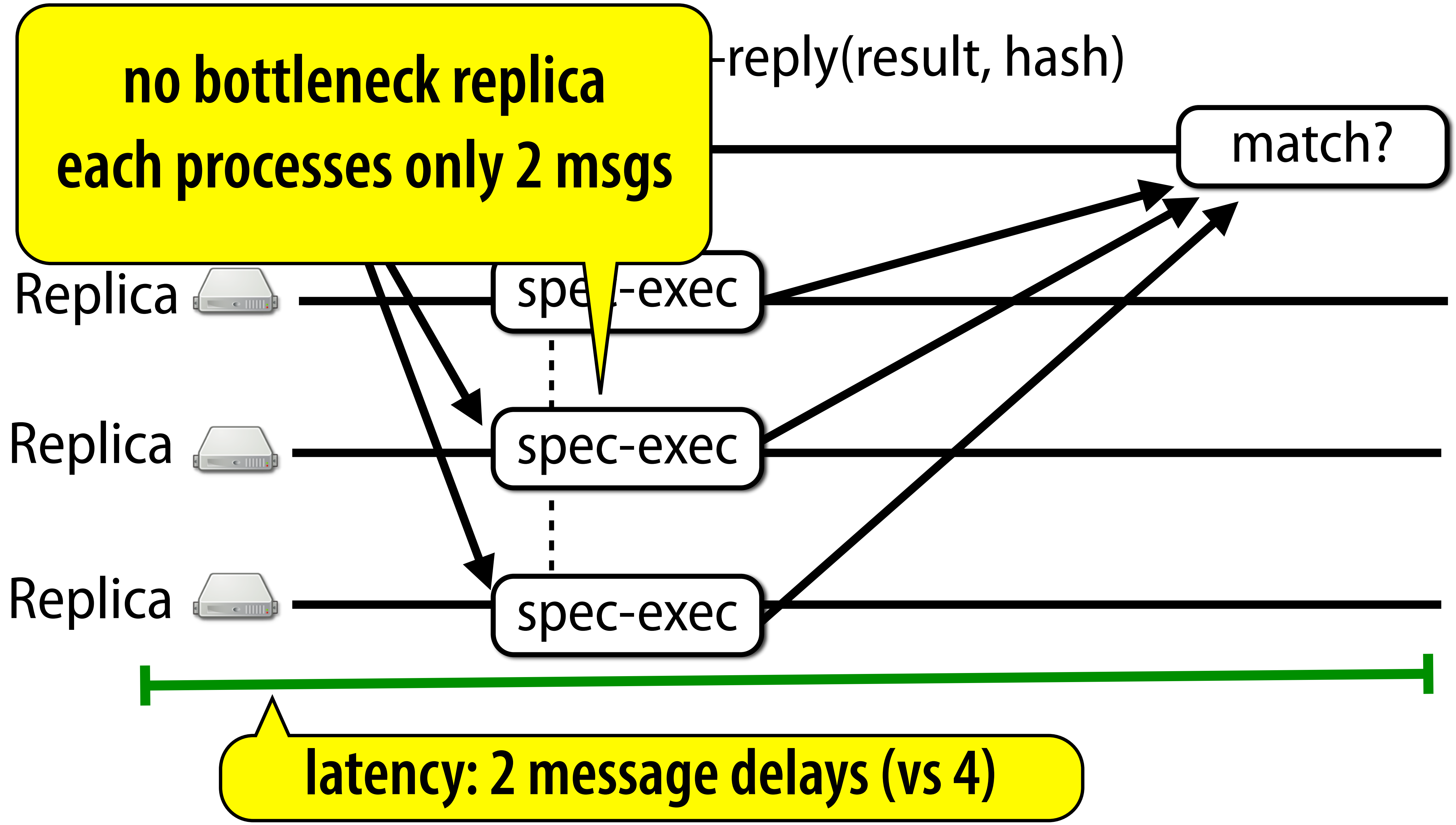

Speculative Execution

Replicas execute requests speculatively

- might have to roll back operations

Clients know their requests succeeded

- they check for matching hashes in replies
- means clients don't need to speculate

Similar to Zyzzyva [SOSP'07]

Handling Ordering Violations

What if replicas don’t execute requests in the same order?

Replicas periodically run ***synchronization*** protocol

If divergence detected: ***reconciliation***

- replicas pause execution, select leader, send logs
- leader decides ordering for operations and notifies replicas
- replicas rollback and re-execute requests in proper order

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What if replicas don't execute requests in the same order?

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Note: 3/4 superquorum requirement ensures new leader can always be sure which requests succeeded even if 1/2 fail. [cf. Fast Paxos]

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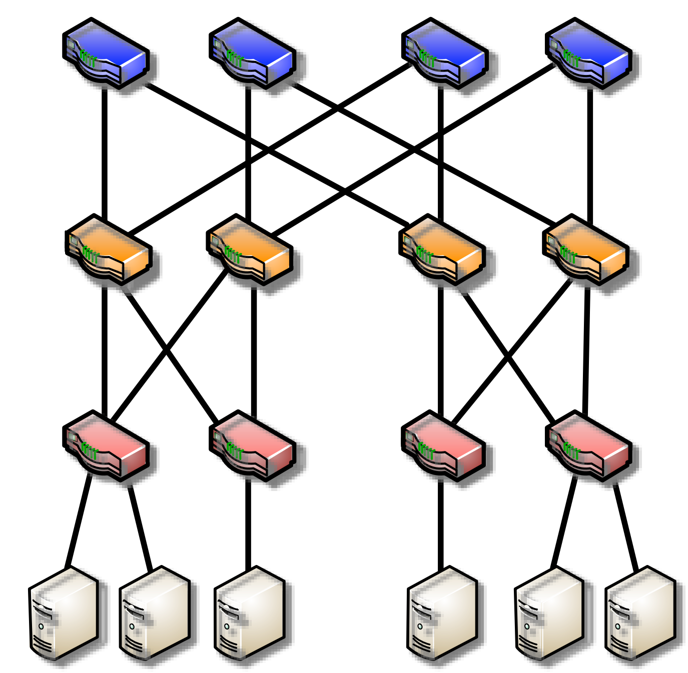
Evaluation Setup

12-switch fat tree testbed

1 Gb / 10 Gb ethernet

3 replicas (2.27 GHz Xeon L5640)



MOM scalability experiments:

2560-host simulated fat tree data center network

background traffic from Microsoft data center measurements

SpecPaxos Improves Latency and Throughput

(emulated datacenter network with MOMs)

better ↑

latency (us)

throughput (ops / second)

better →

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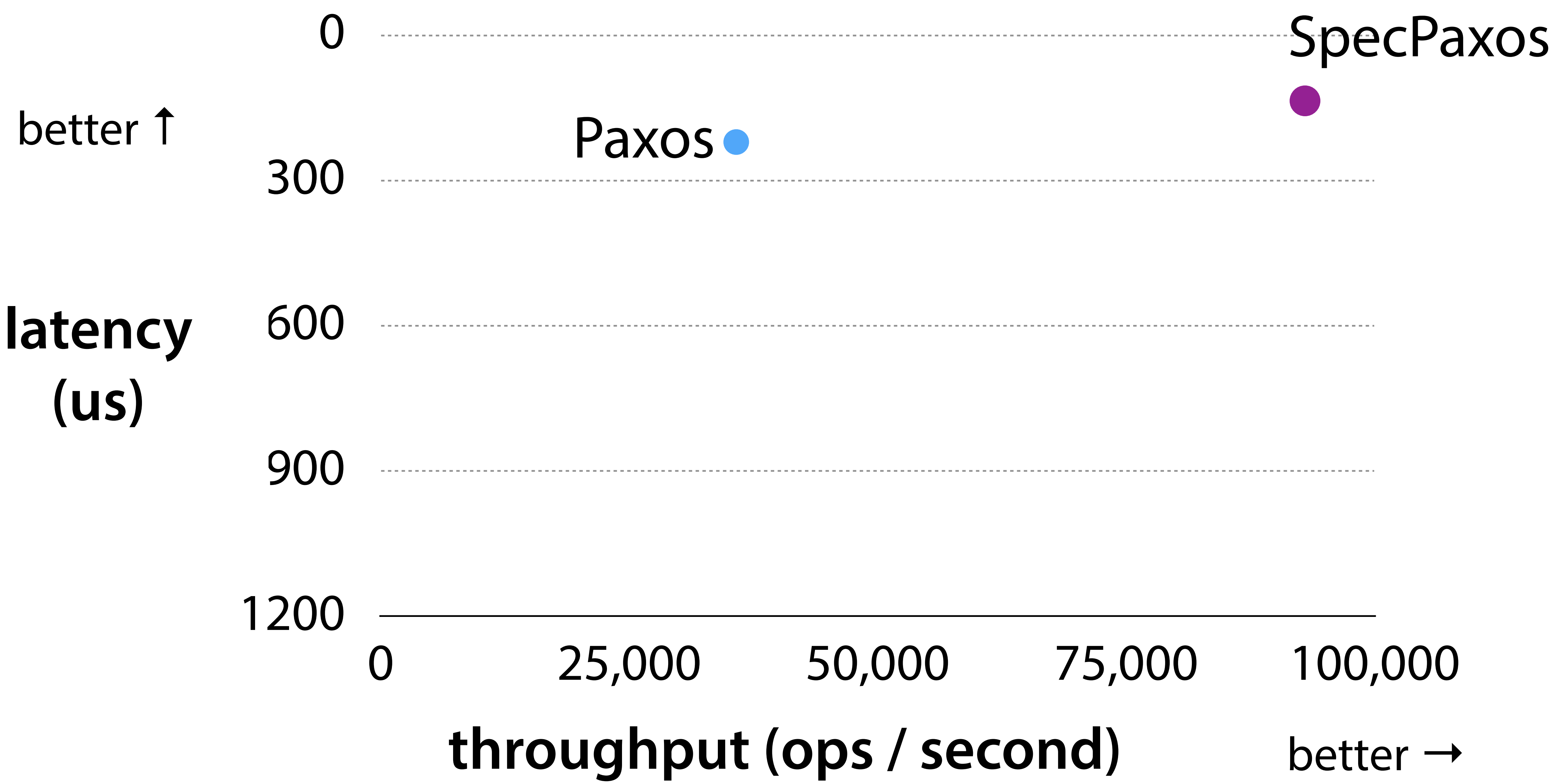

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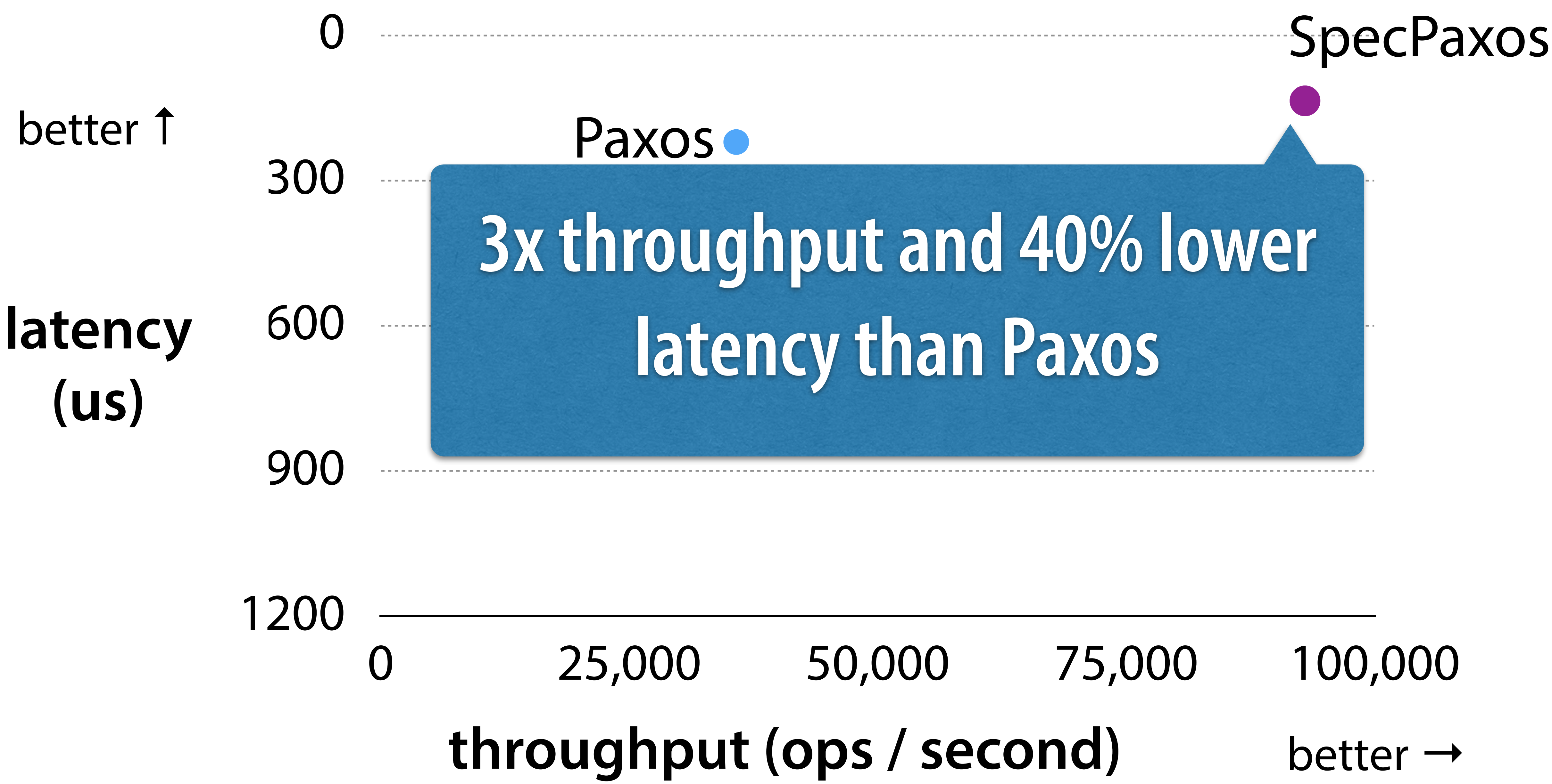

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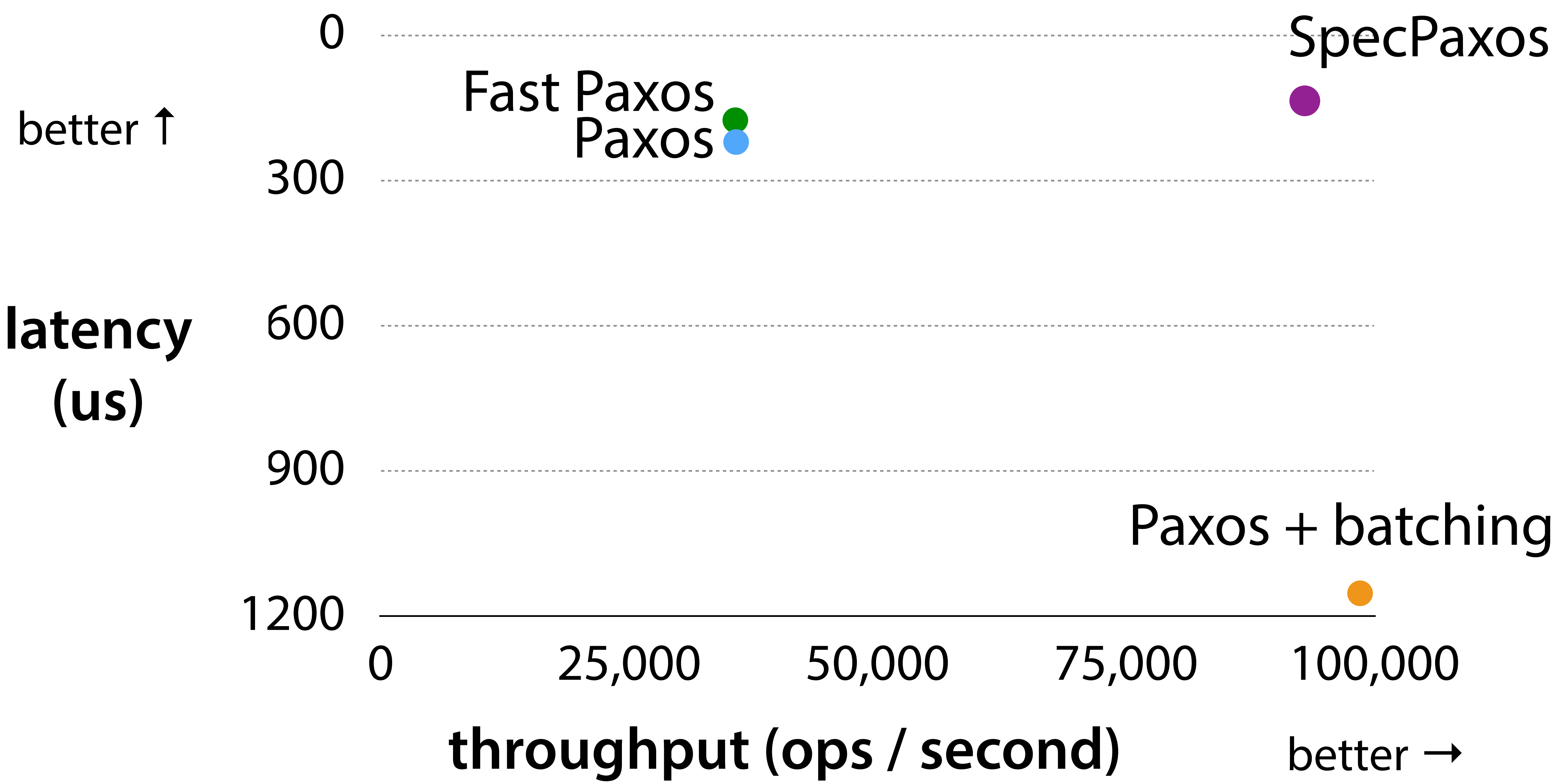

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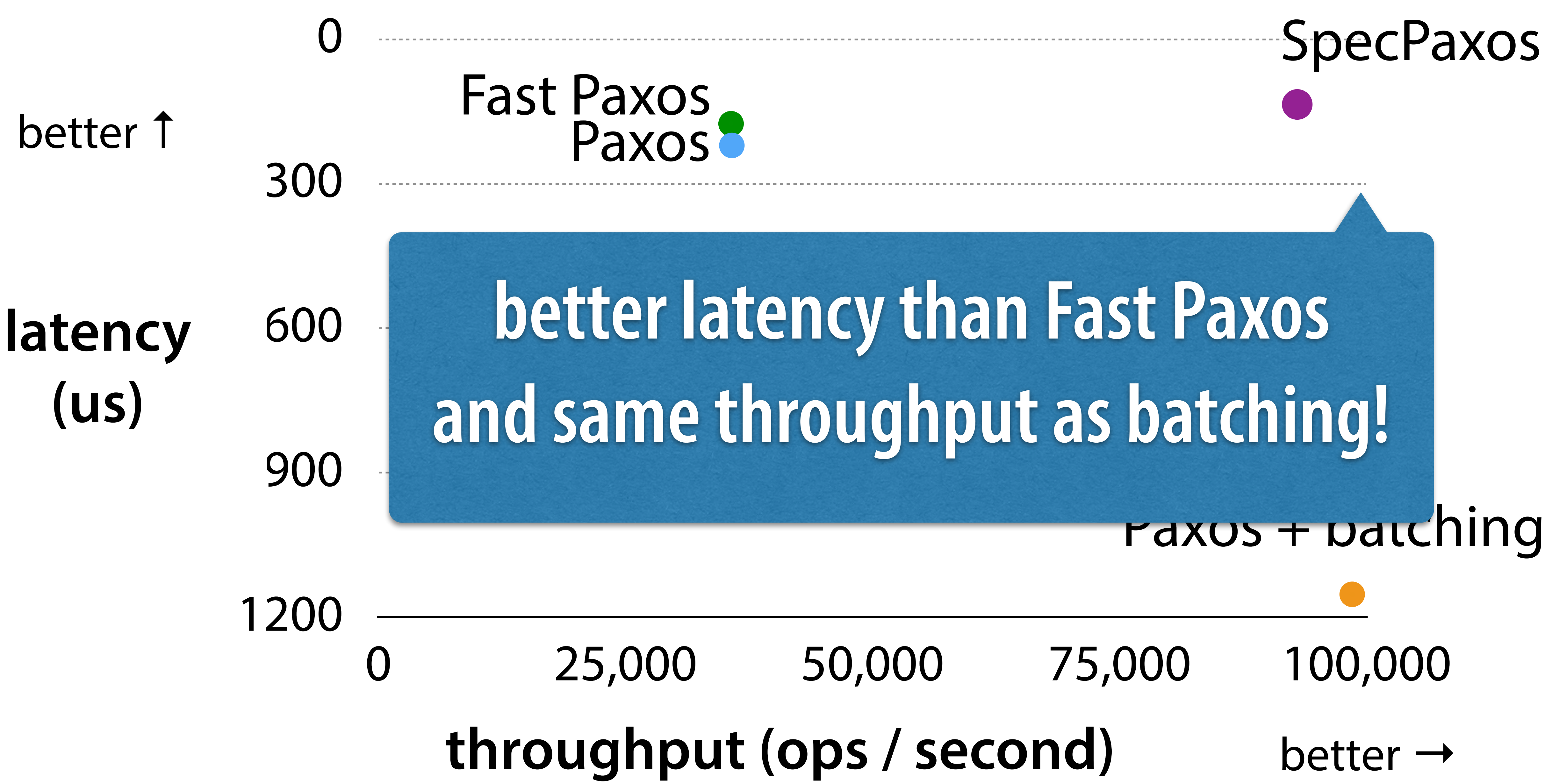
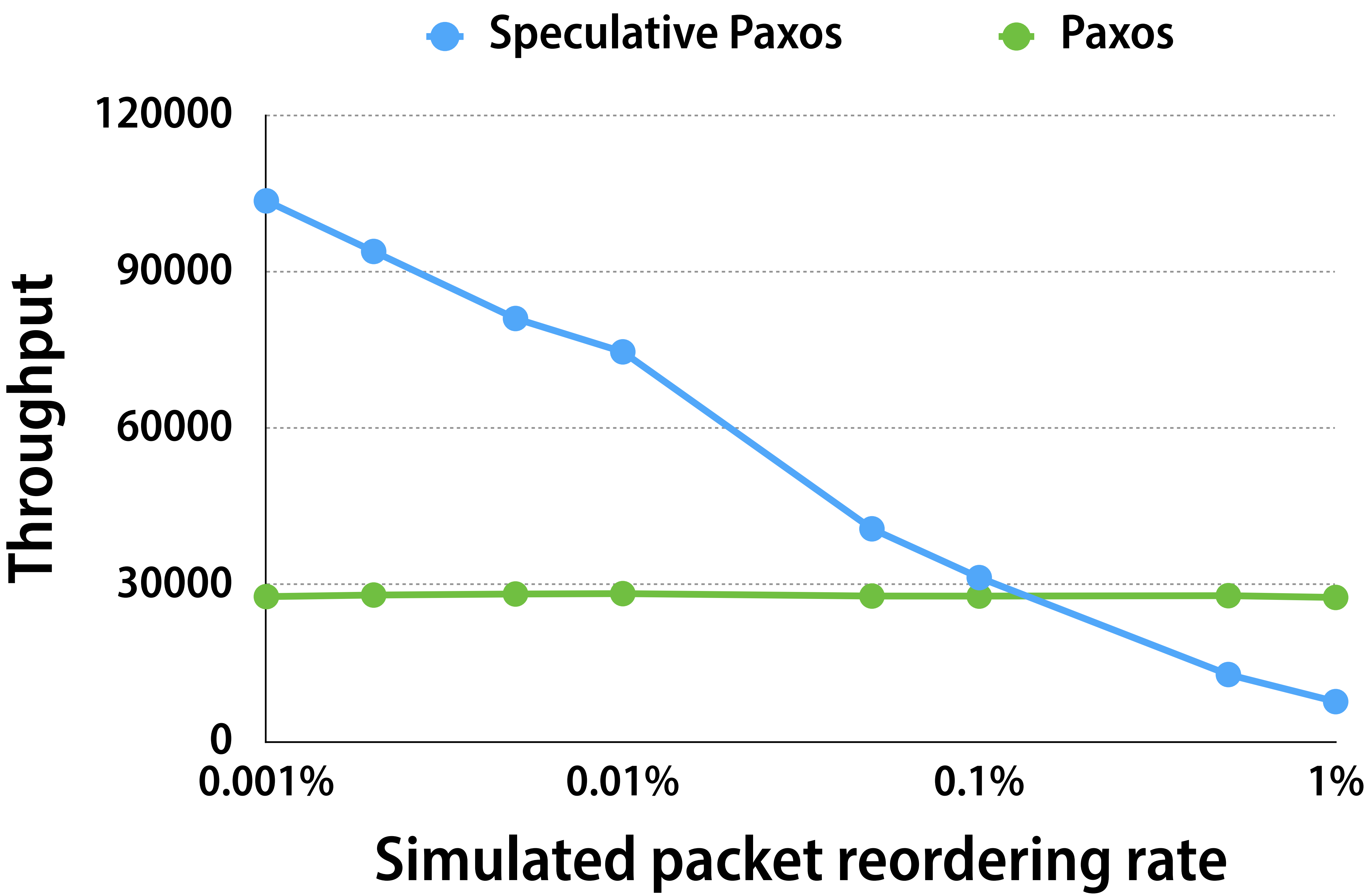


MOMs Provide Necessary Support



MOM Ordering Effectiveness

Ordering Violation Rates

	Testbed (12 switches)	Simulation (119 switches, 2560 hosts)
Regular Multicast	1-10%	1-2%
Topology-Aware MOM	0.001%-0.05%	0.01%-0.1%
Network Serialization	~0%	~0%

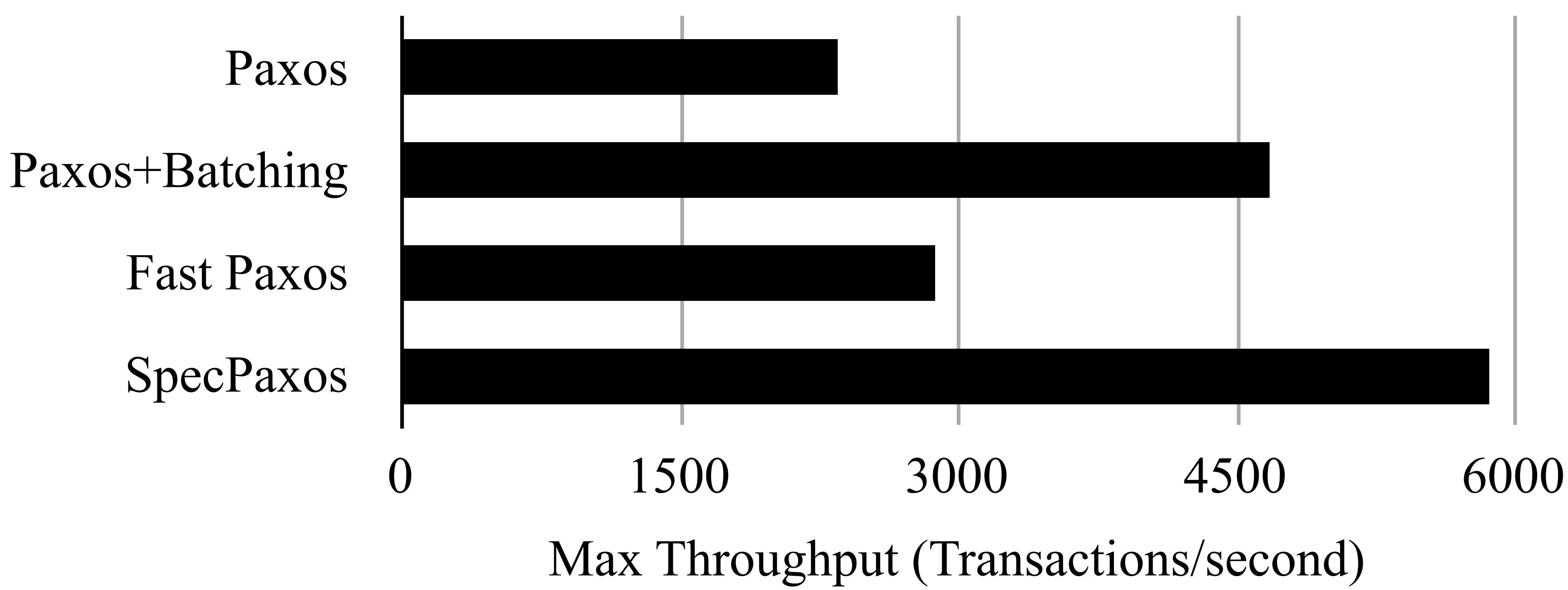
Application Performance

Transactional key-value store (2PC + OCC)

Synthetic workload based on Retwis Twitter clone

< 250 LOC required to implement rollback

Measured transactions/sec that meet 10 ms SLO



Summary

New approach to building distributed systems
based on co-designing with the data center network

Dramatic performance improvement for replication by combining

- MOM network primitive for best-effort ordering
- Speculative Paxos: efficient replication protocol

This is only the first step for co-designing distributed systems and data center networks!