Tolerating Slowdowns in Replicated State Machines using Copilots

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Replicated State Machine (RSM)

- Fault tolerant group of replicas that acts like a single machine that does not fail
- RSMs are everywhere!
  - Distributed database, cloud storage, coordination services, …

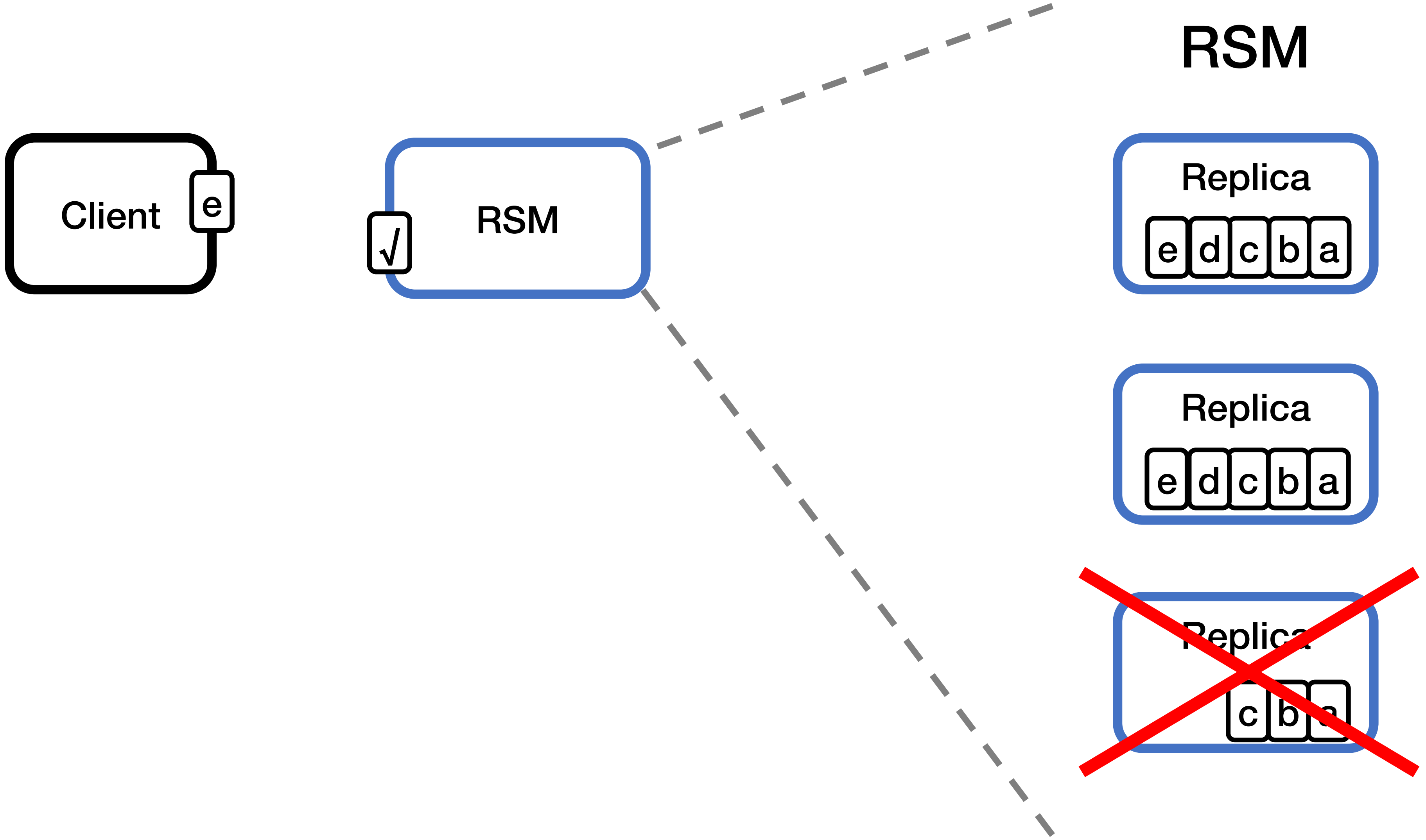
Azure

etcd

Cockroach DB

Cloud Spanner

Fault Tolerance for High Availability



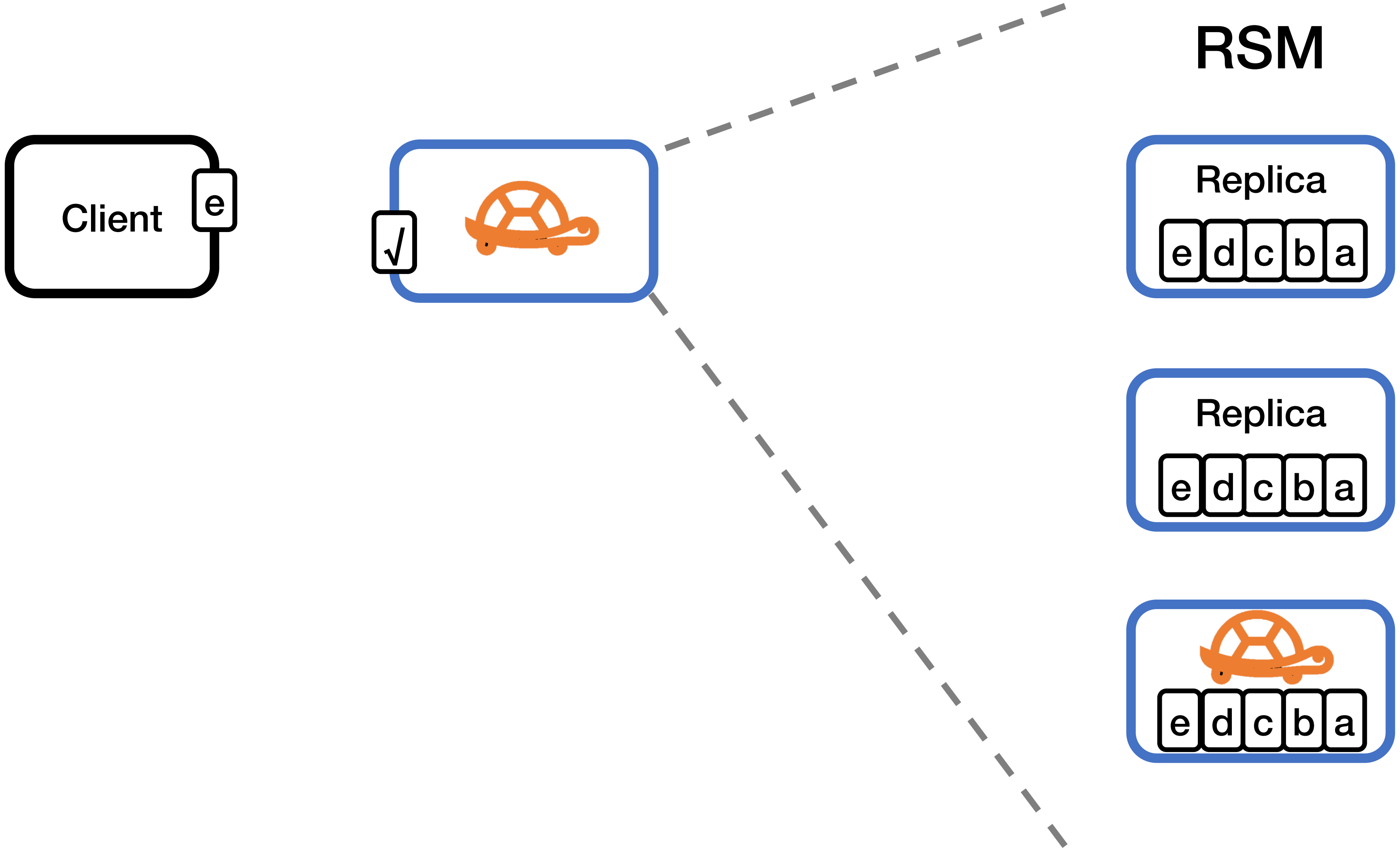
Replicas can Slowdown instead of Fail

- Many causes:
  - Misconfigurations
  - Partial hardware failures
  - Garbage collection events
  - …

- Effect: Replica takes longer than usual to send responses

RSMs tolerate failures, not slowdowns

Slowdowns Hurt Availability



We need slowdown tolerance!

Slowdowns Take Different Forms

- Duration
  - Transient slowdowns: not handled in general
  - Long-term slowdowns: eventually detected, but need to tolerate between onset and end of reconfiguration
- Severity
  - 10ms additional delay or 80ms?
- Scope
  - All processing paths or a subset?

Defining Slowdown Tolerance

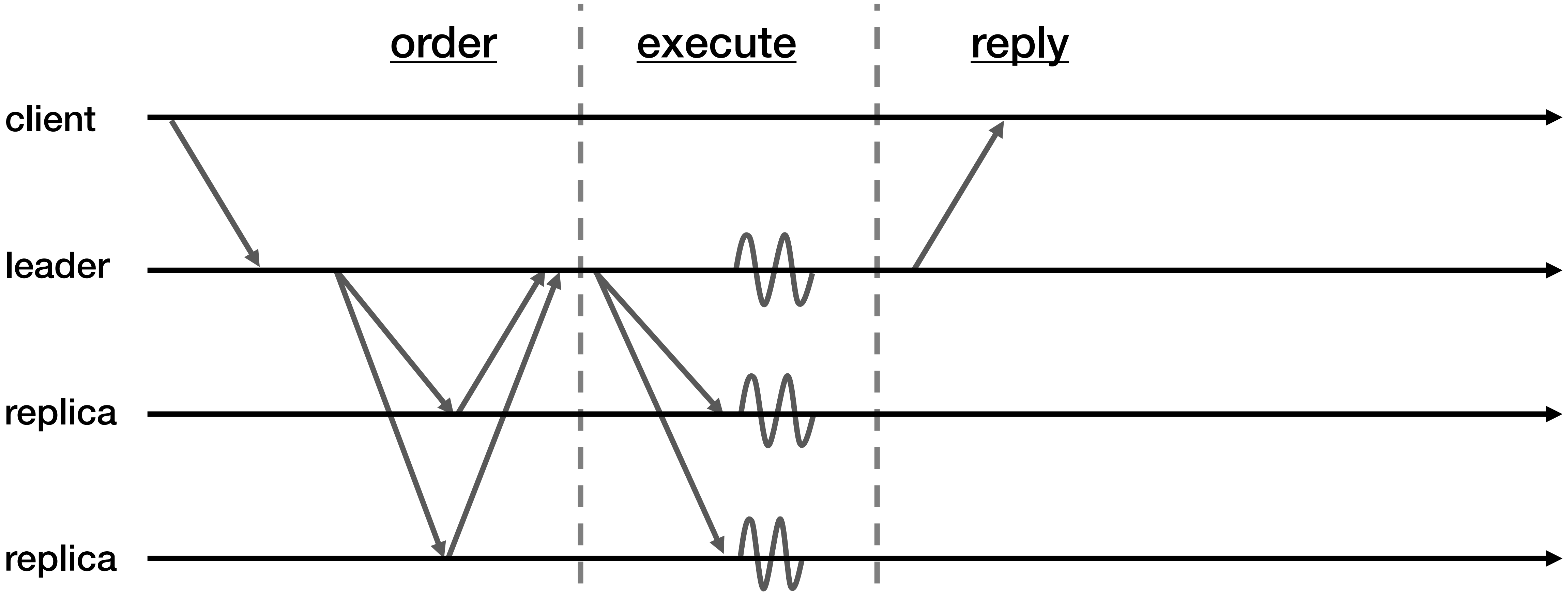
- “slow” replica = responses to messages take more than threshold time *t* over normal response time

- An RSM is *s*-slowdown-tolerant if it is not slow despite *s* slow replicas
    - Replacing the *s* slowest replicas with normal replicas should not change performance much

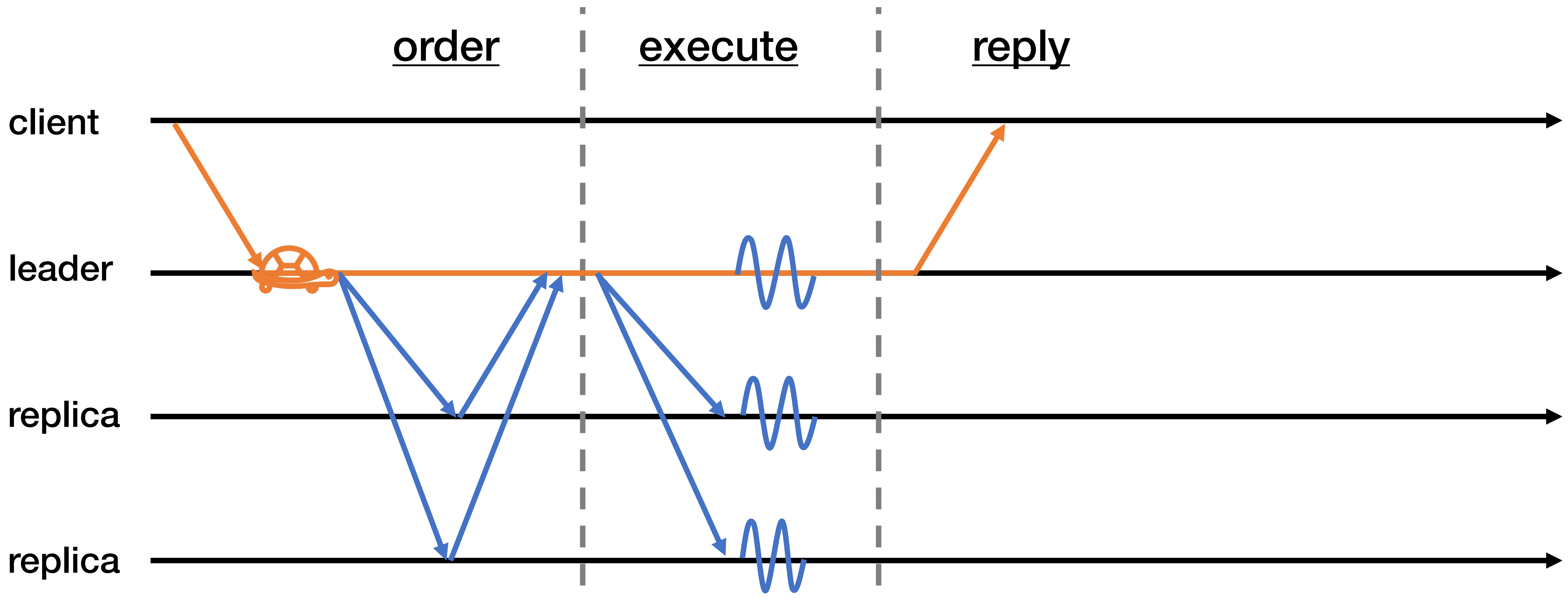
- This work’s focus: 1-slowdown-tolerance

No existing consensus protocol is 1-slowdown-tolerant

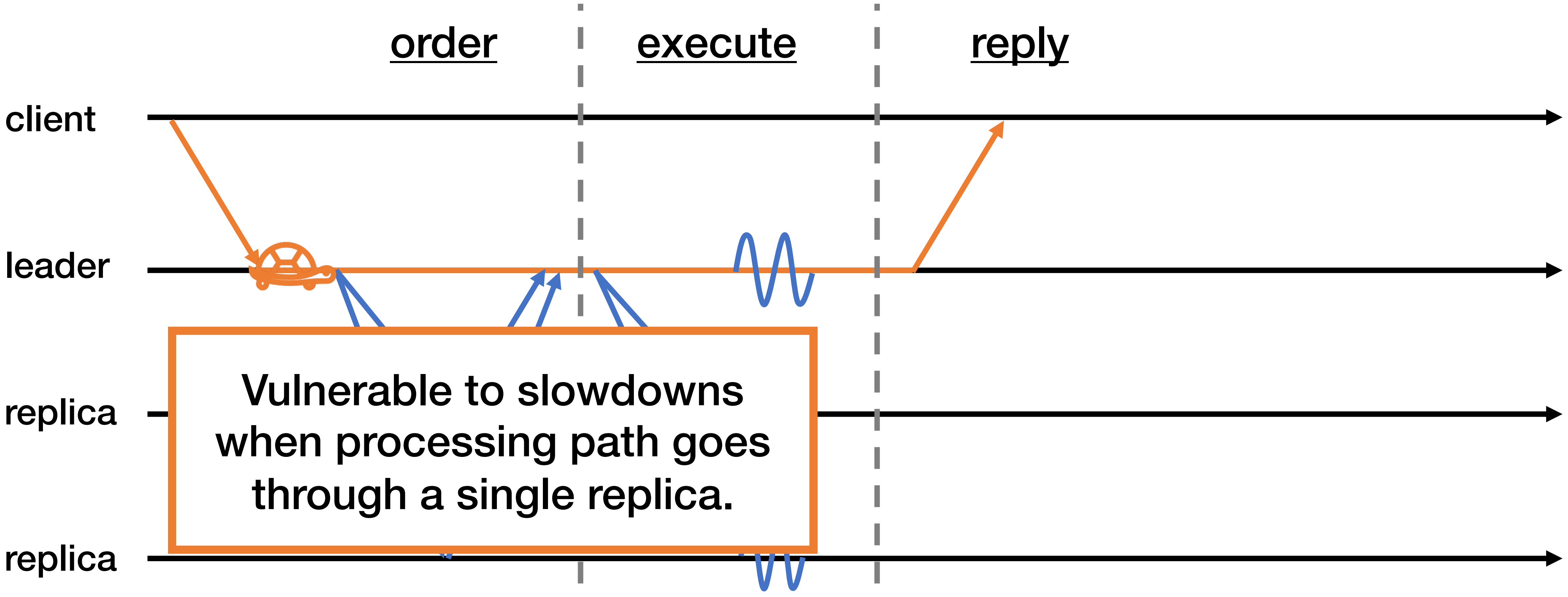
Multi-Paxos is Not 1-Slowdown-Tolerant



Multi-Paxos is Not 1-Slowdown-Tolerant

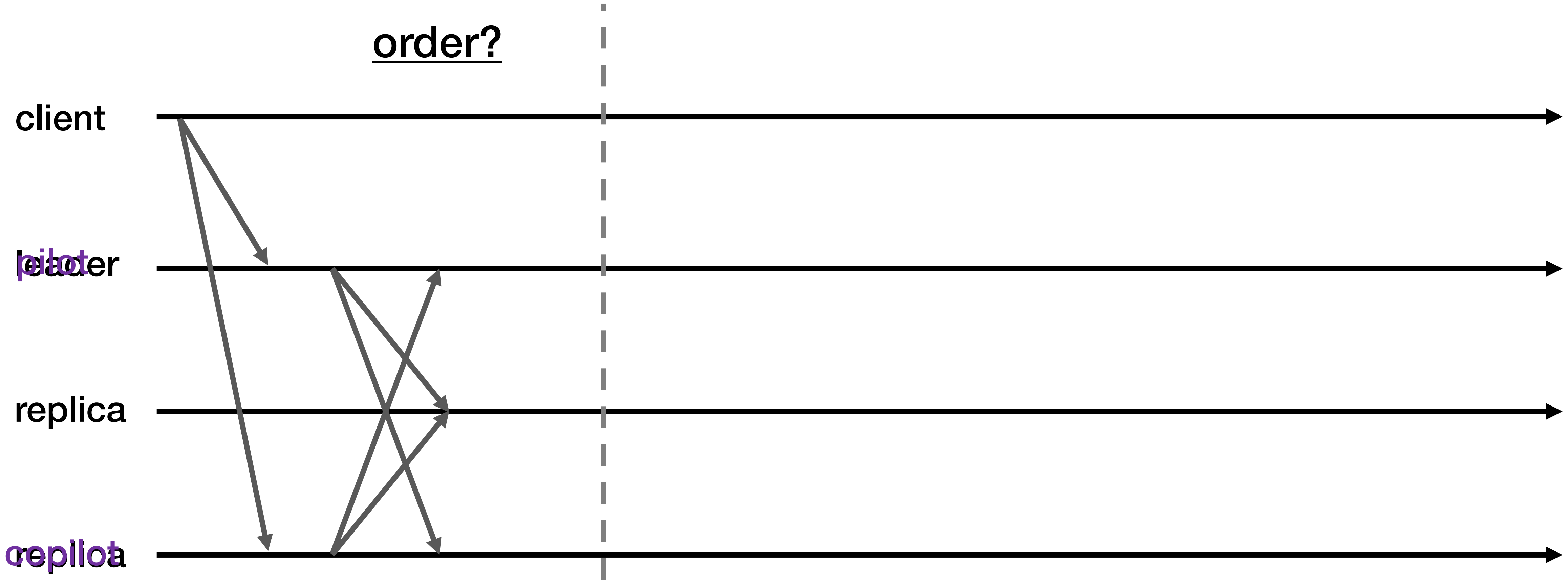


Multi-Paxos is Not 1-Slowdown-Tolerant

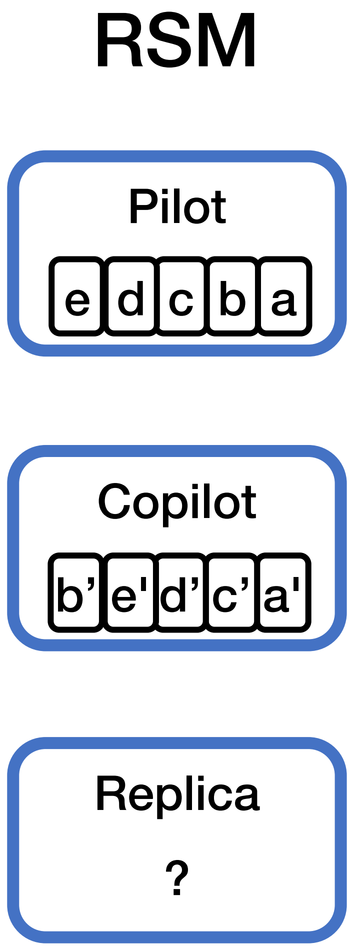


Vulnerable to slowdowns when processing path goes through a single replica.

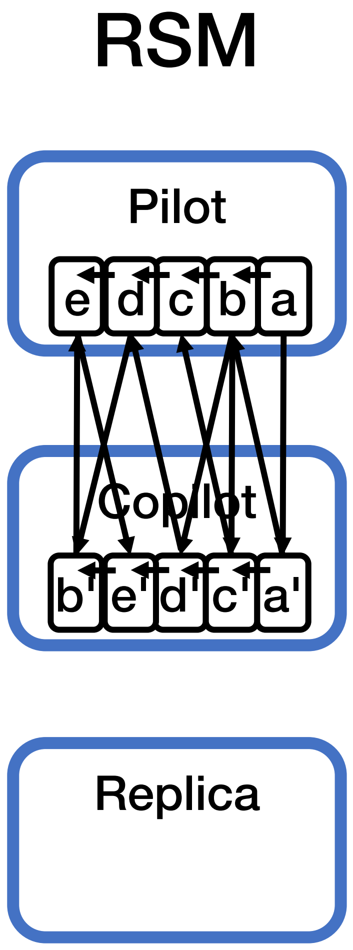
Copilot:
First 1-Slowdown-Tolerant Protocol



Ordering: Use Two Logs

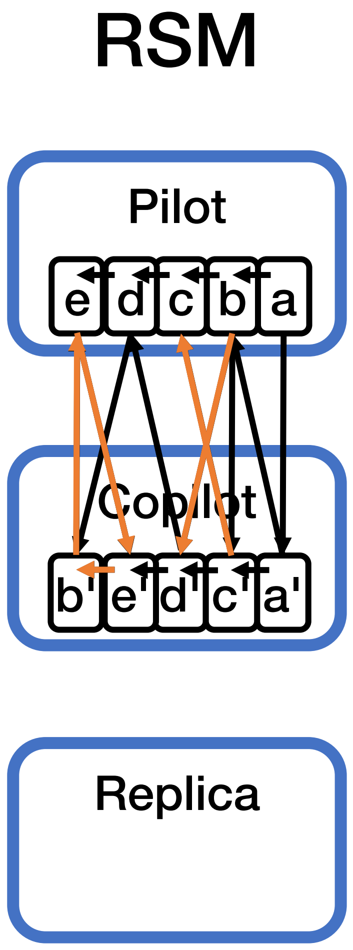


Ordering: Combine Logs with Dependencies

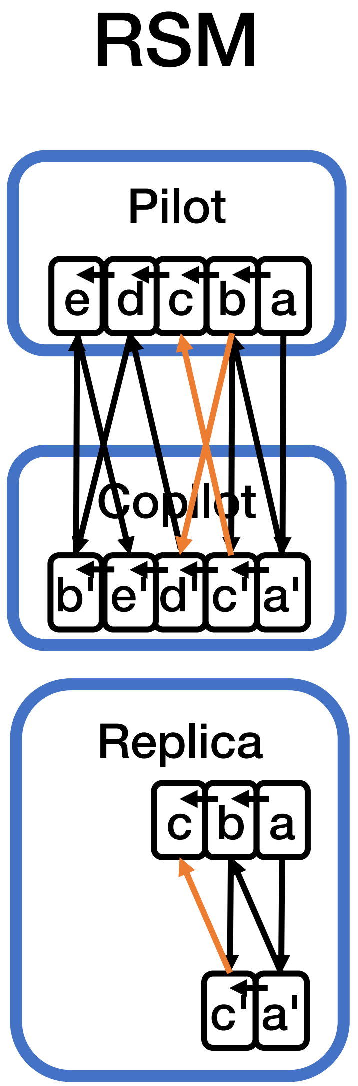


Ordering: Dependency Cycles

Break cycles deterministically



Ordering: A Tricky Case

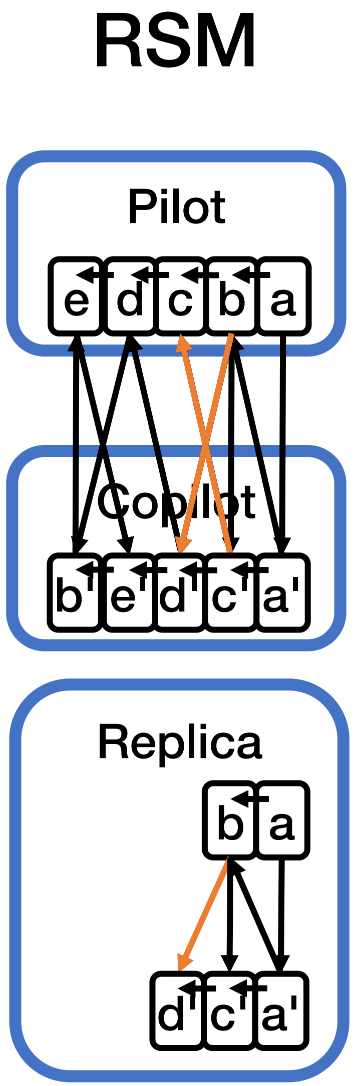


Possible ordering:
a, a’, b, c’, c

Ordering: A Tricky Case

~~Possible ordering: a, a’, b, c’, c~~

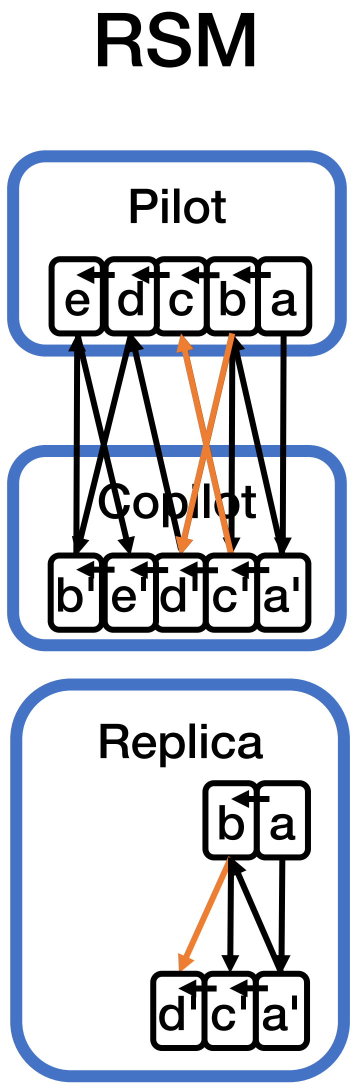
~~Possible ordering: a, a’, b, c’, d’~~



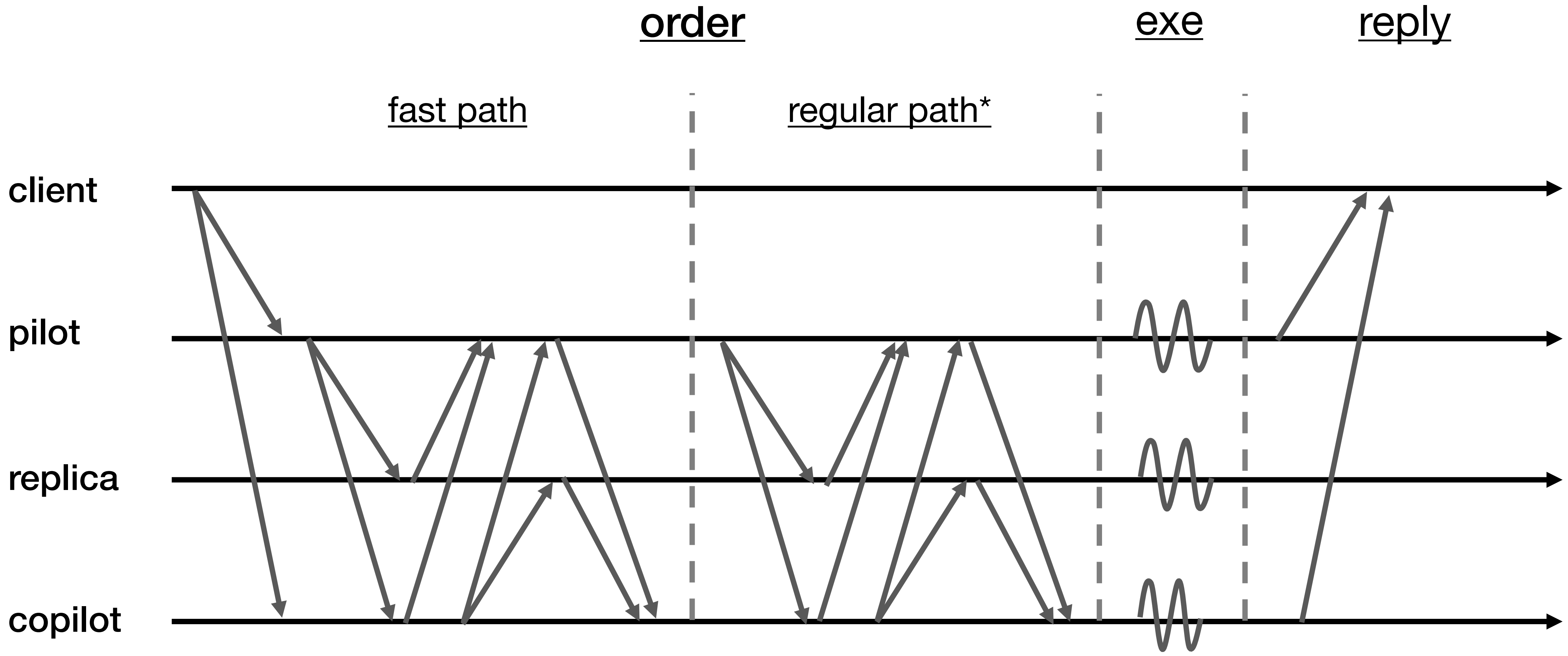
Ordering: Same on All Replicas

Compatibility check:
Only accept dependency if it cannot lead to multiple orders

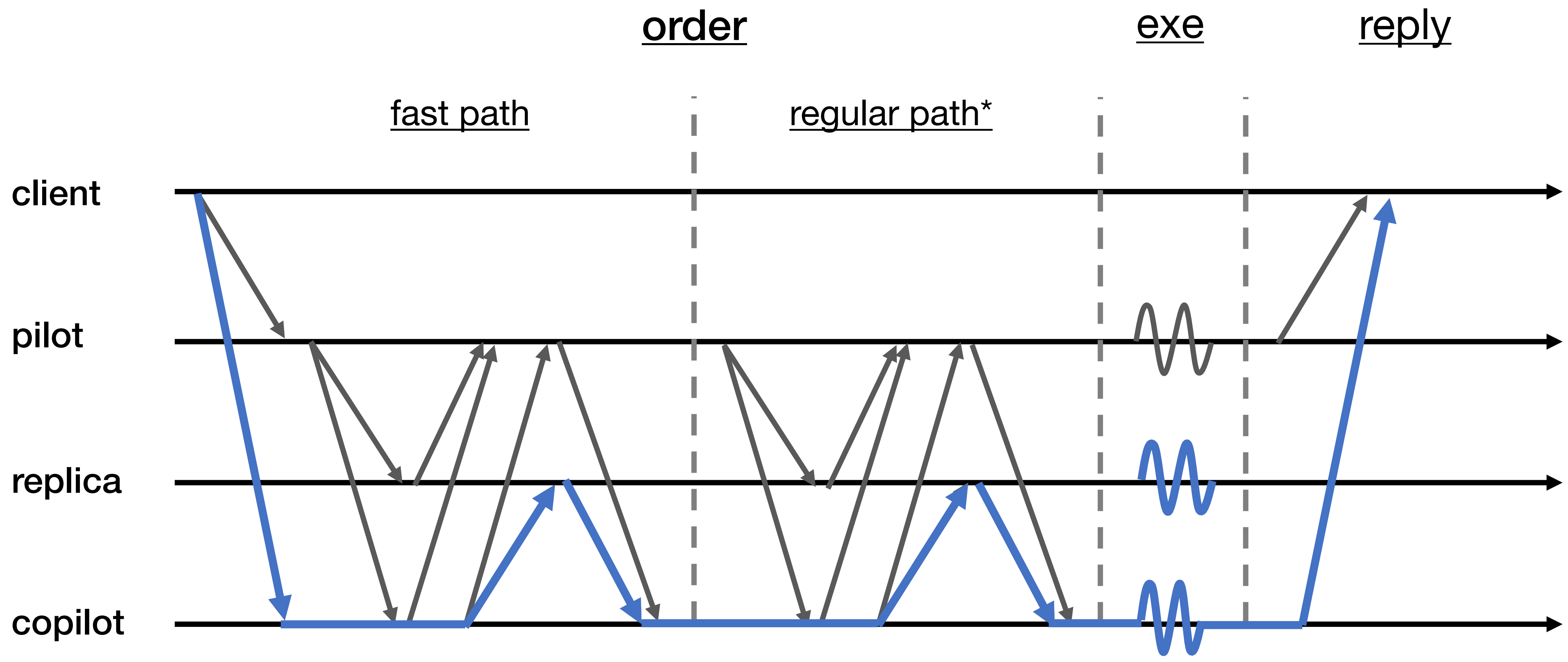
Break cycles deterministically



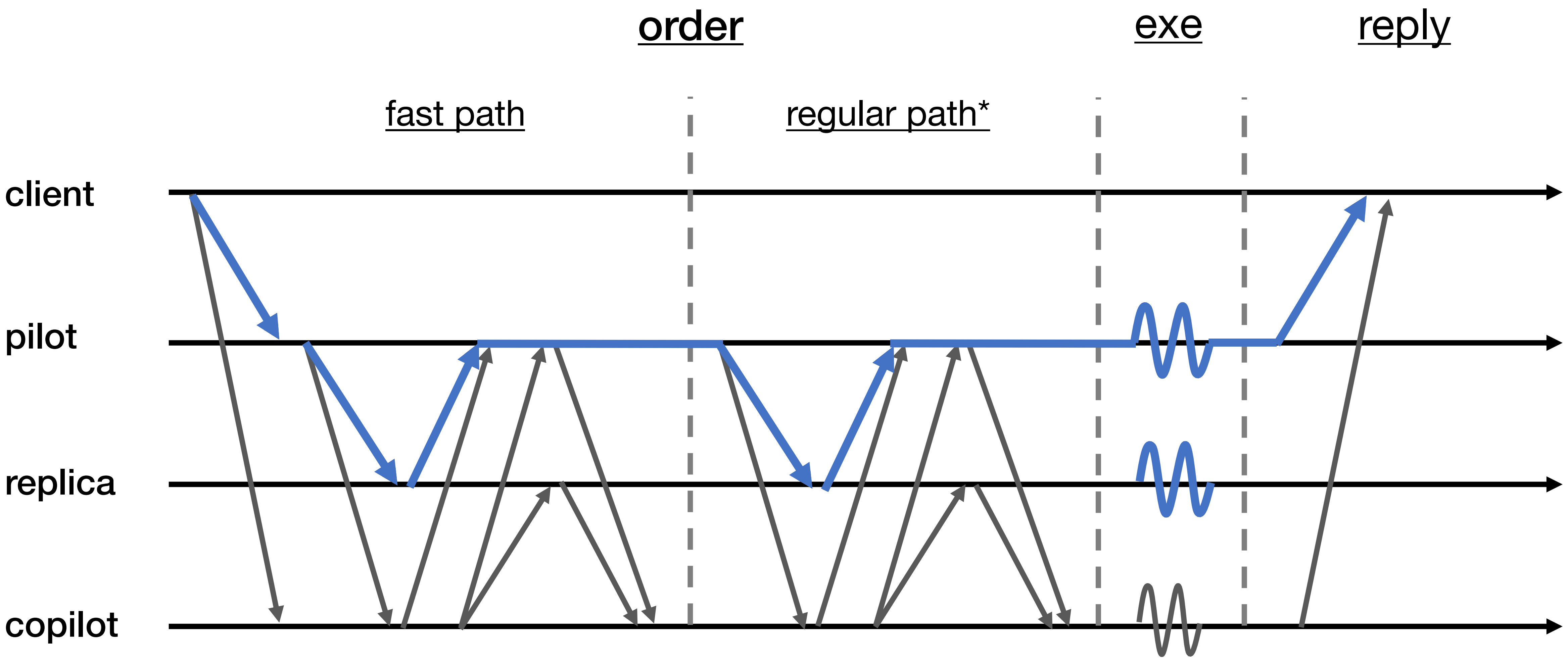
Copilot Protocol



Copilot Protocol

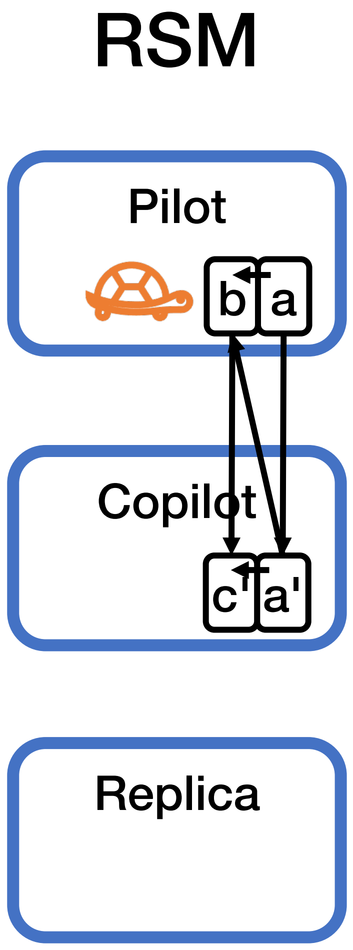


Copilot Protocol



Copilot Protocol: Dependencies?

Solution: **fast takeover** the slow pilot's ordering work!



Copilot Protocol: Summary

- Proactive redundancy: two pilots process all commands

- Use dependencies to combine ordering from two pilots
  - Compatibility check ensures same order on all replicas
  - Cycles broken by priority
  - Fast takeover to avoiding waiting on slow pilot

Optimizations

- Ping-Pong Batching
  - Improve Copilot’s performance when both pilots are fast
  - Pilots propose compatible orderings and commit on fast path
- Null Dependency Elimination
  - Improve Copilot’s performance when one pilot is slow
  - Allow a fast pilot to safely avoid waiting on commits from a continually slow pilot and thus avoid fast takeover

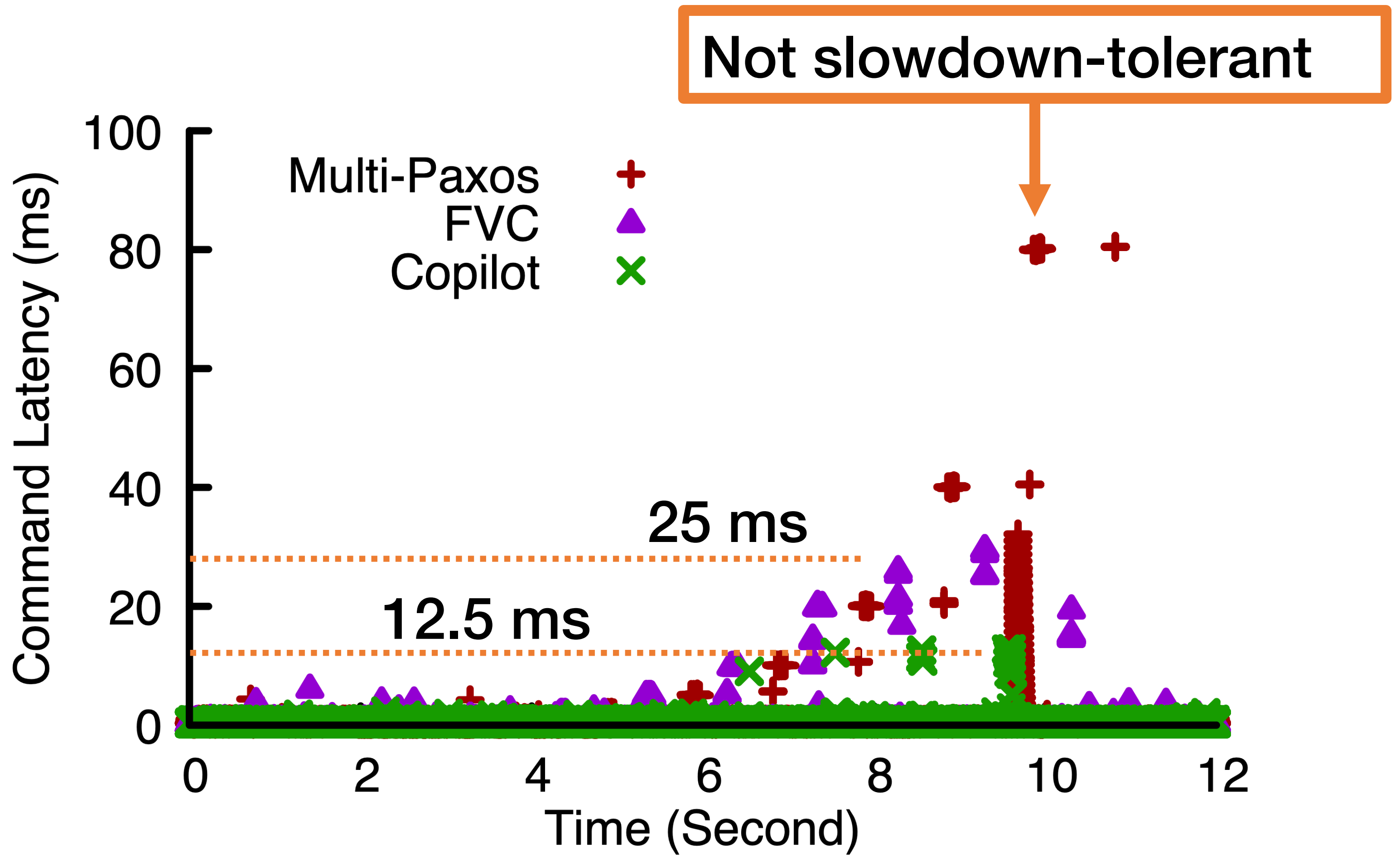
Evaluation

- Tolerate slowdowns that are transient, have varying manifestations, have varying severity?
- How does Copilot perform without slow replicas?

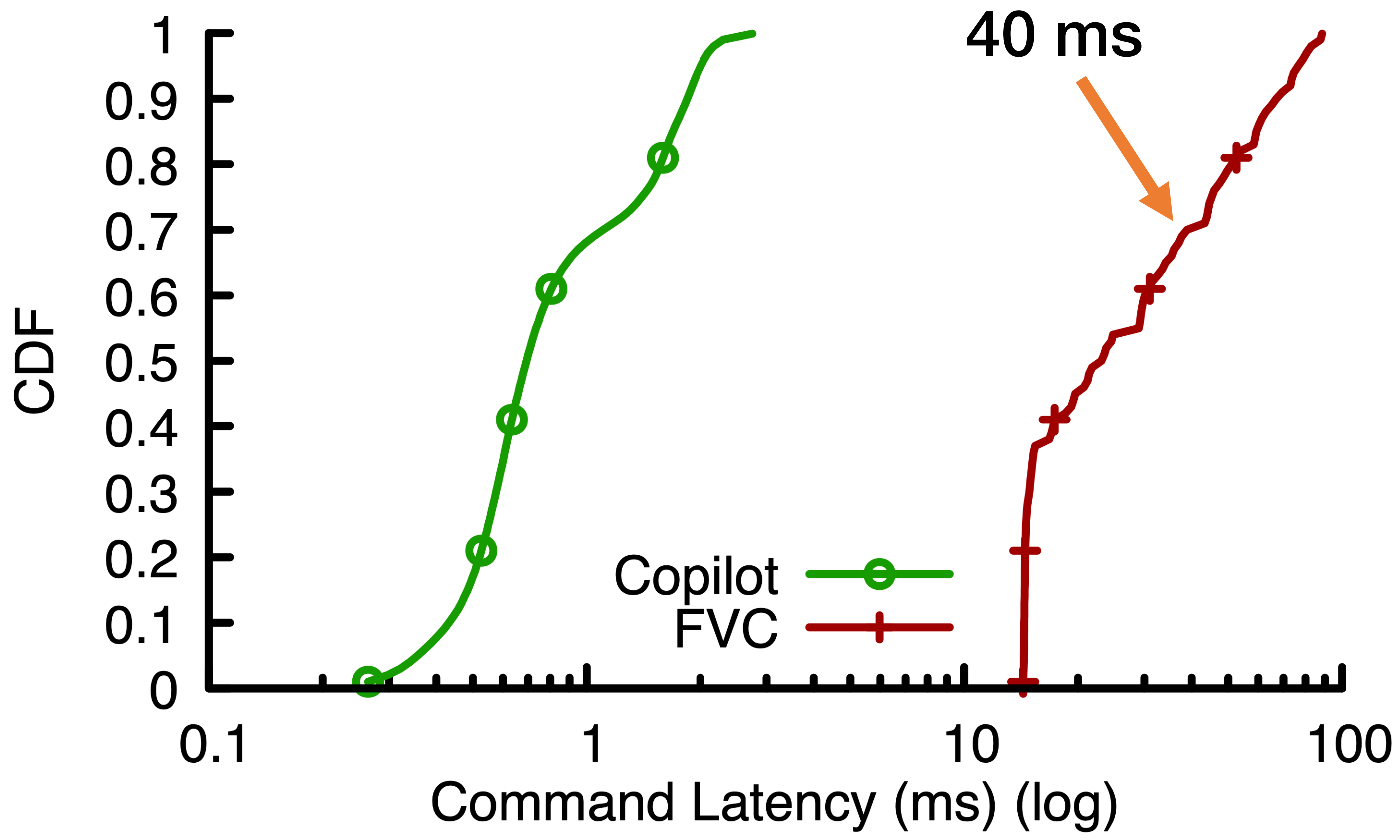
- 5-replica RSM, moderate load
- Replicas and clients in the same datacenter

- Baselines:
  - EPaxos
  - Multi-Paxos
  - Fast-View-Change (10 ms view-change timeout)

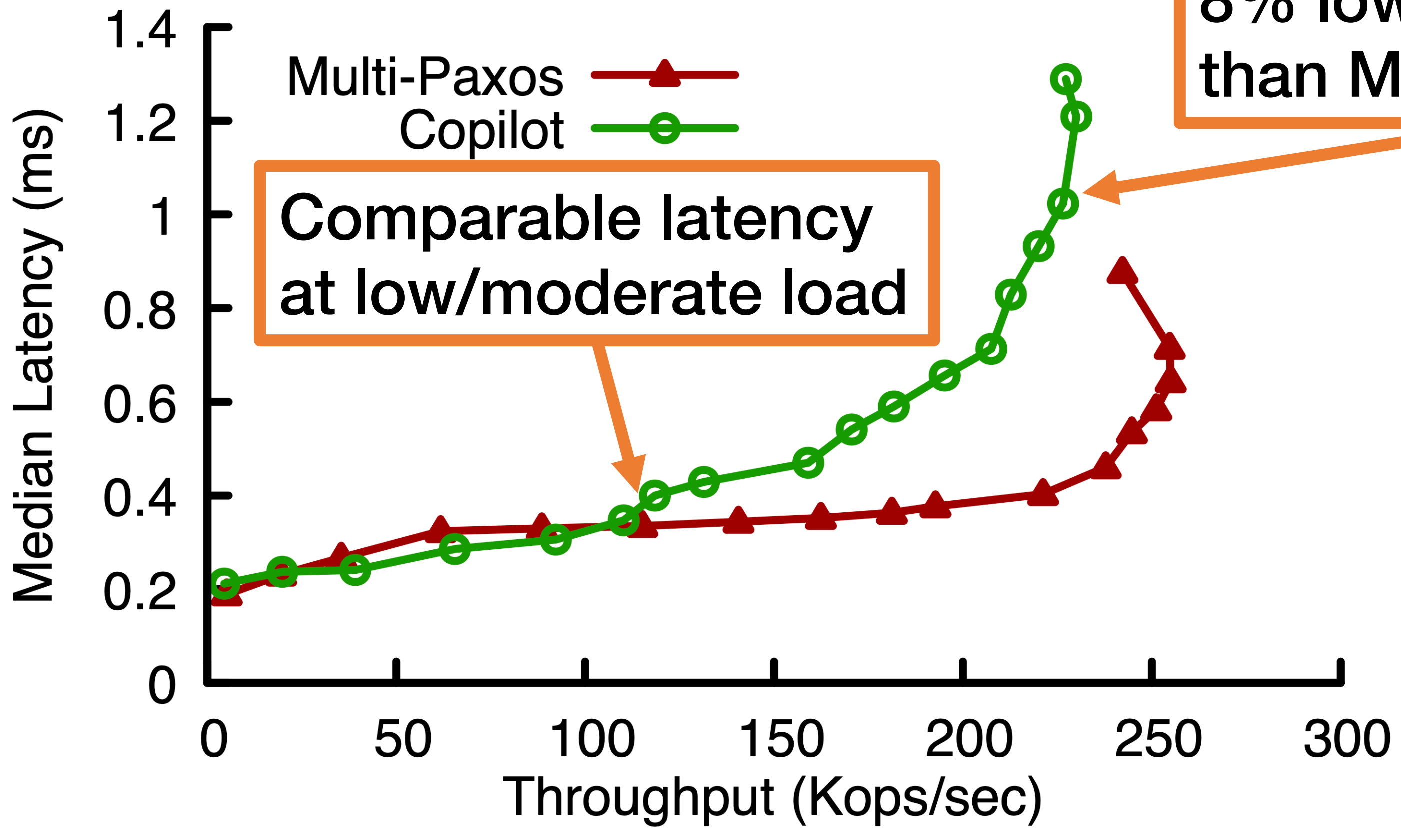
Transient Slowdowns



Gradual Slowdown



Performance Without Slow Replicas



Comparable latency at low/moderate load

8% lower throughput than Multi-Paxos

Conclusion

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- Slowdowns hurt availability, need s-slowdown-tolerant RSMs
- Copilot: first 1-slowdown-tolerant protocol
  - Slowdown tolerance: proactive redundancy and fast takeovers
  - Optimizations: ping-pong batching and null dependency elimination
- Copilot's performance without slow replicas is competitive
- Copilot is the only protocol that tolerates any one slowdown