High Throughput Replication with Integrated Membership Management

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USENIX ATC 2022

NOVALINCS LABORATORY FOR COMPUTER SCIENCE AND INFORMATICS

NOVALINCS

FCT Fundação para a Ciência e a Tecnologia MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

NOVA SCHOOL OF SCIENCE & TECHNOLOGY

Outline

- Motivation and Related Work
- ChainPaxos
  - Writing
  - Local Linearizable Reads
  - Reconfiguration
- Evaluation

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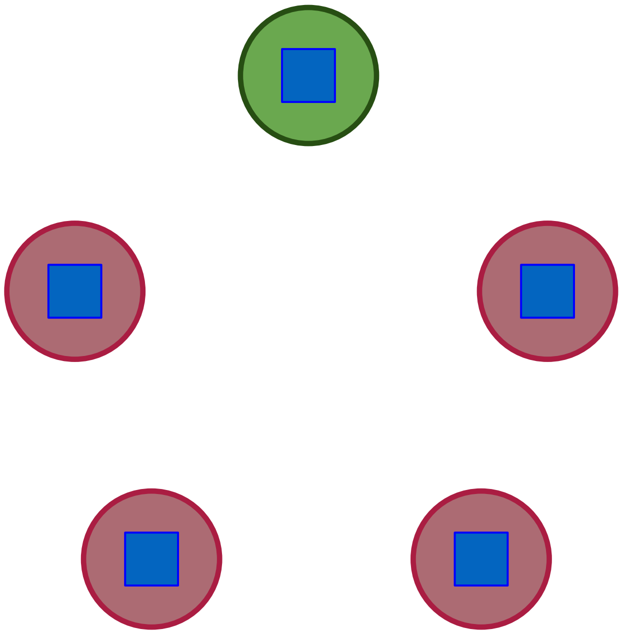
Related Work: Multi-Paxos



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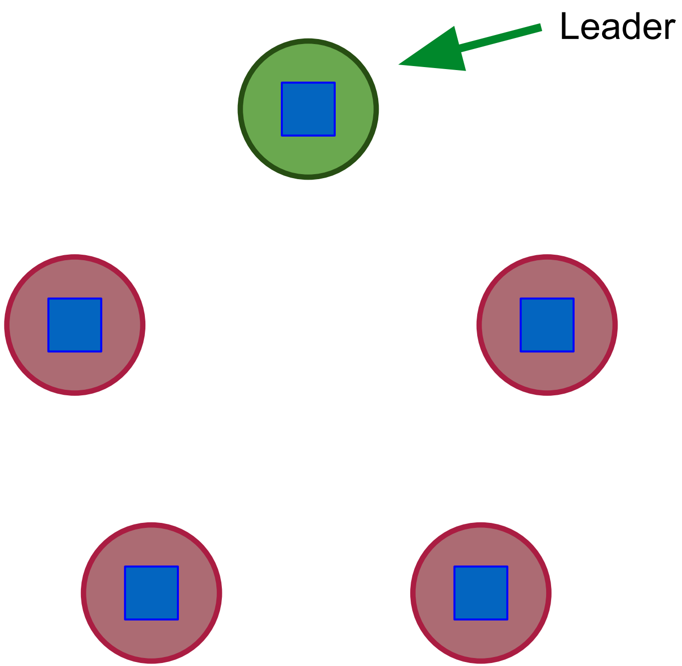

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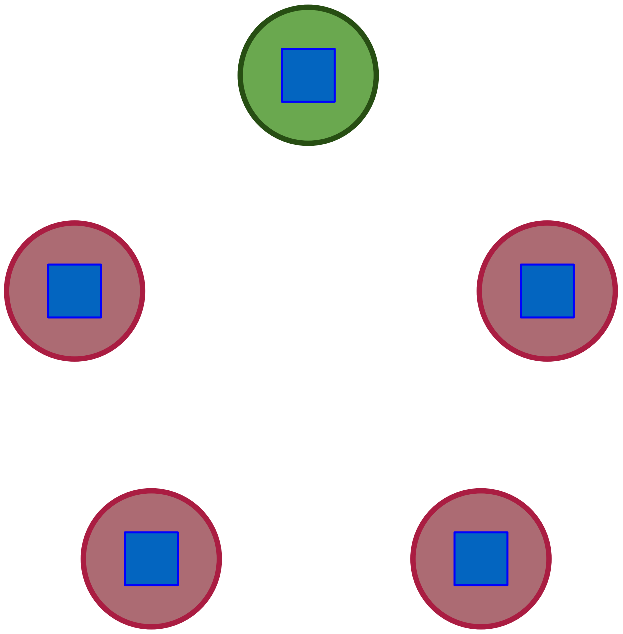
Classic Multi-Paxos



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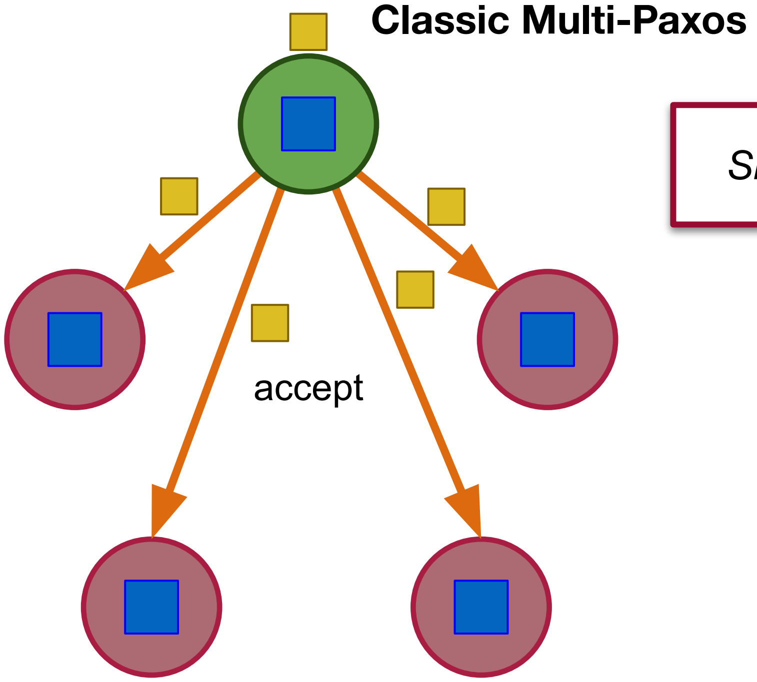

Skipping the first phase

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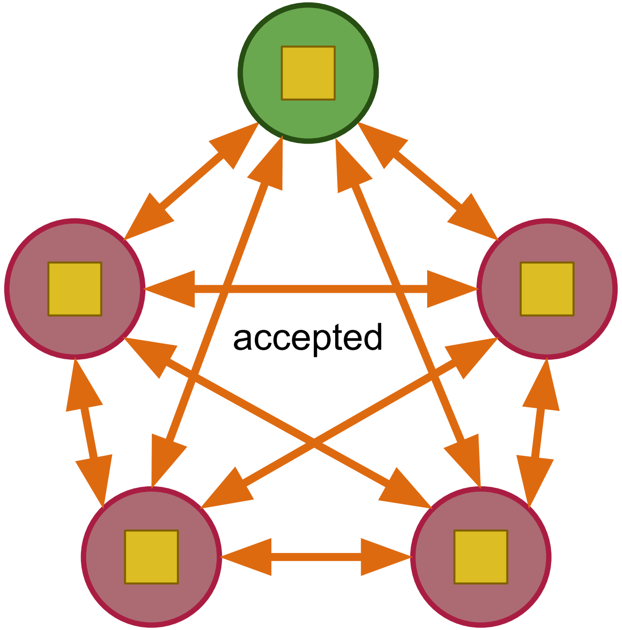

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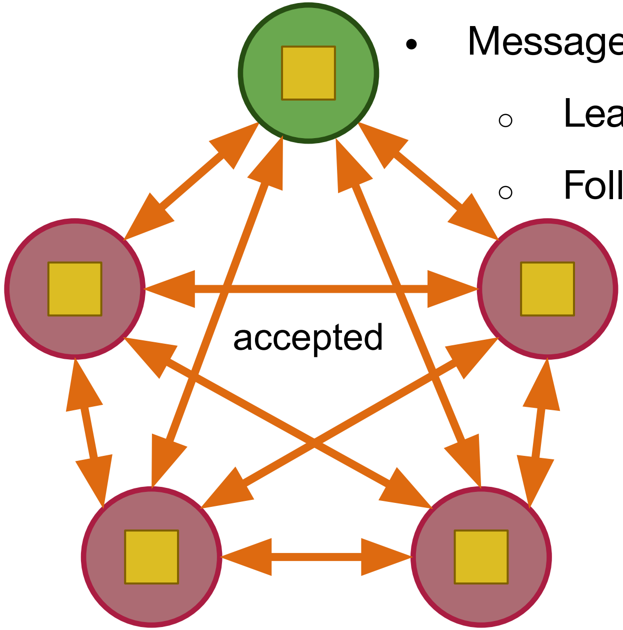

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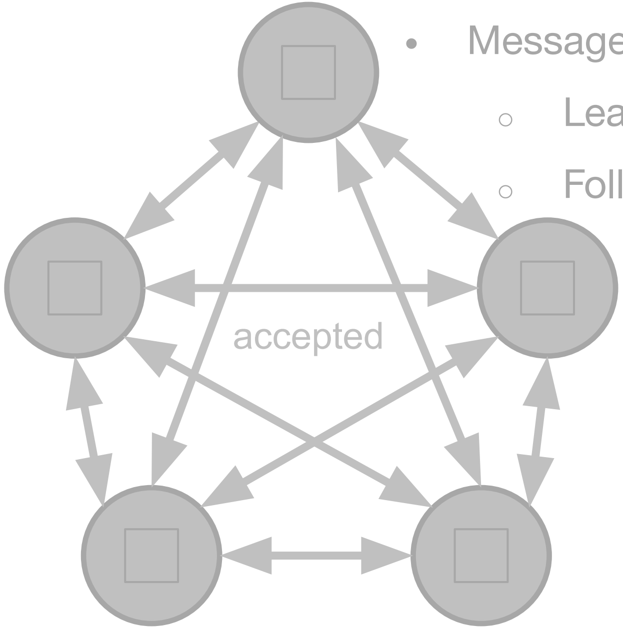

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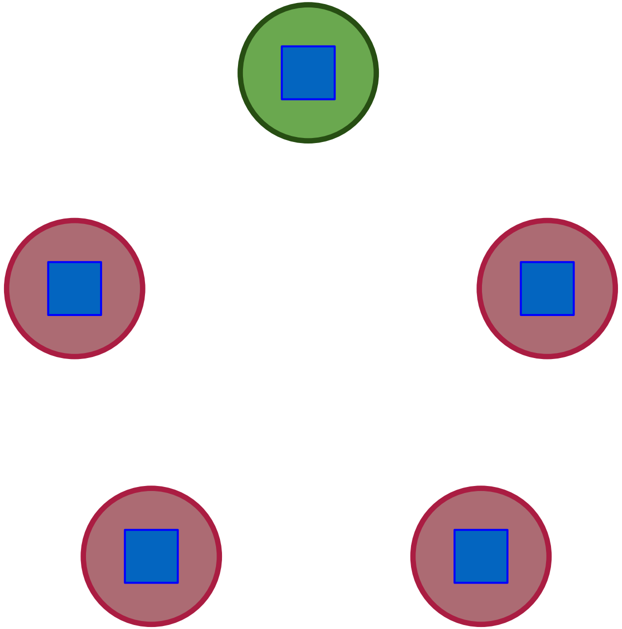
Distinguished Learner



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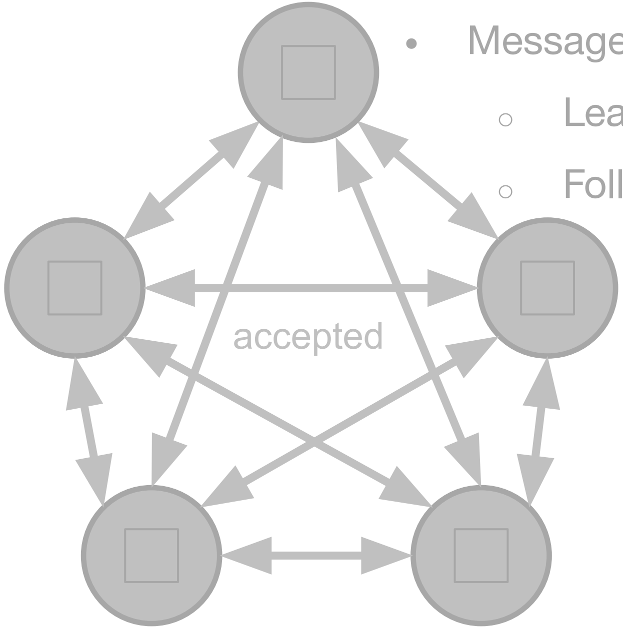

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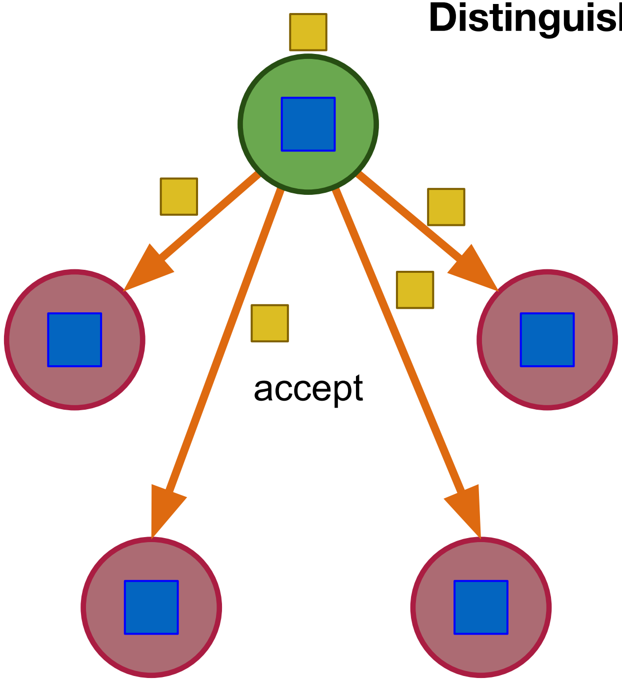

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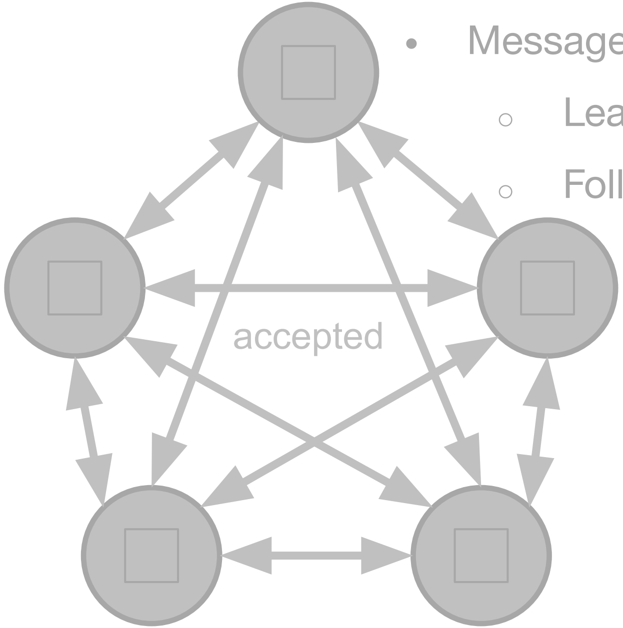

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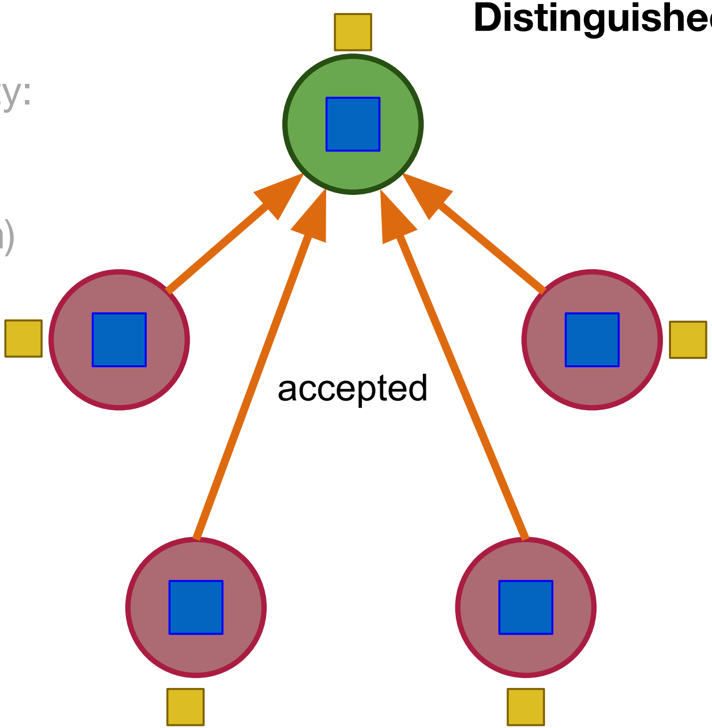

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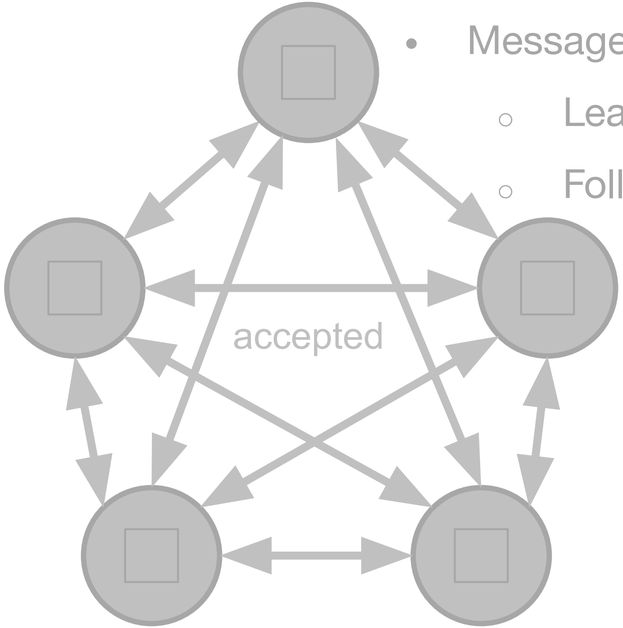

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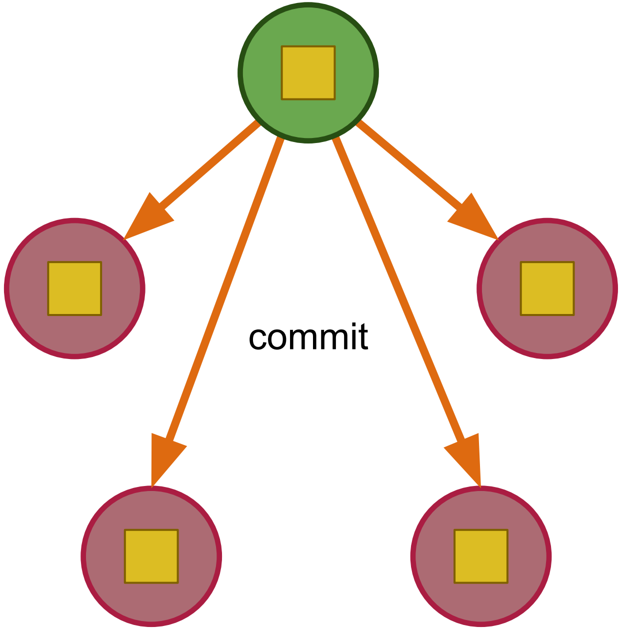

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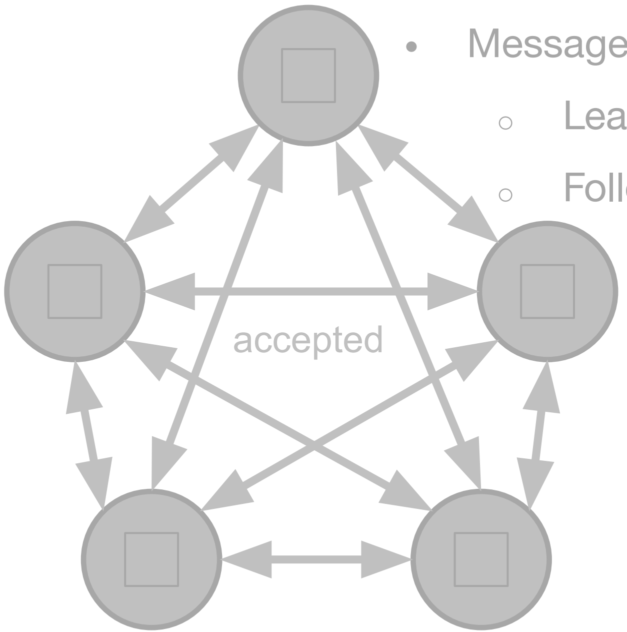

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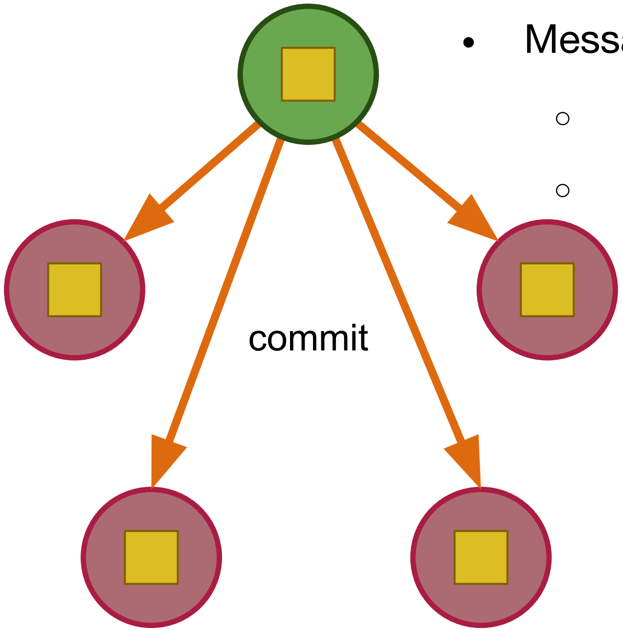

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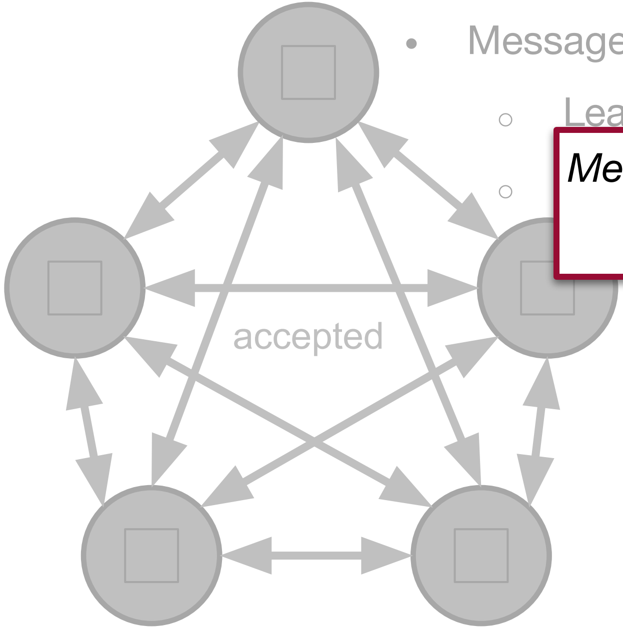

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  -

Message complexity proportional to the number of replicas

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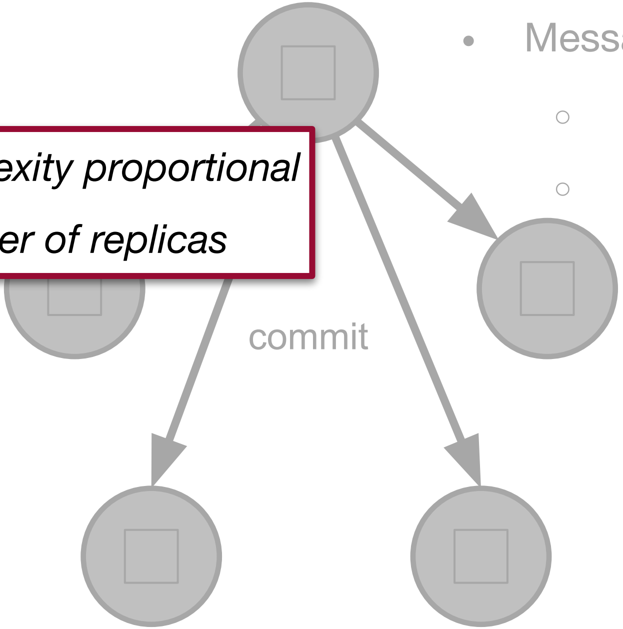

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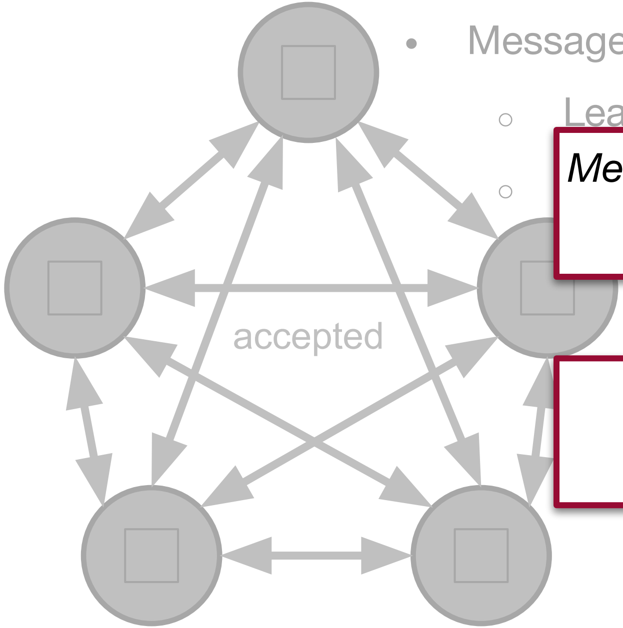

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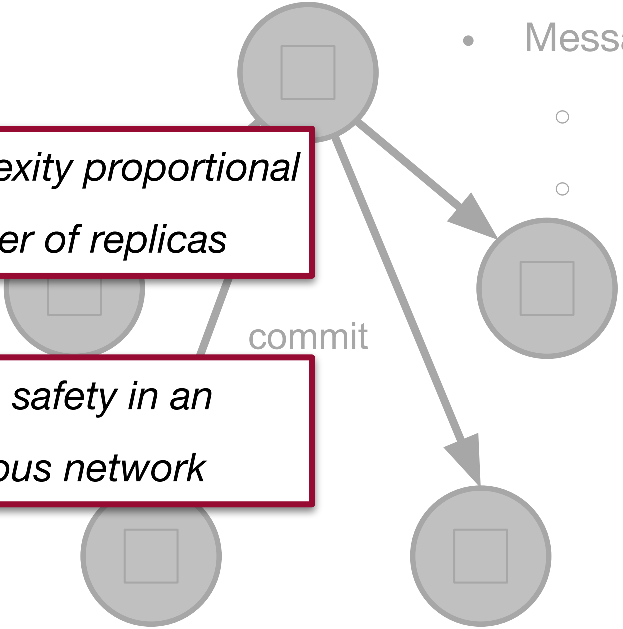

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Guarantees safety in an asynchronous network

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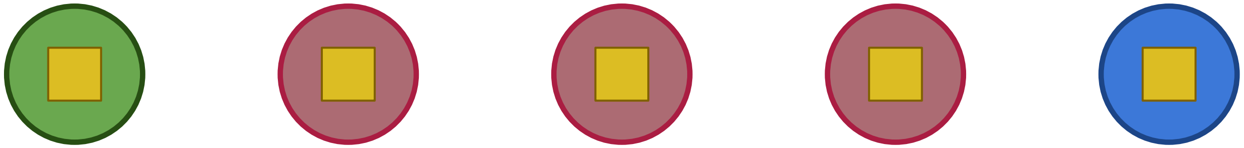

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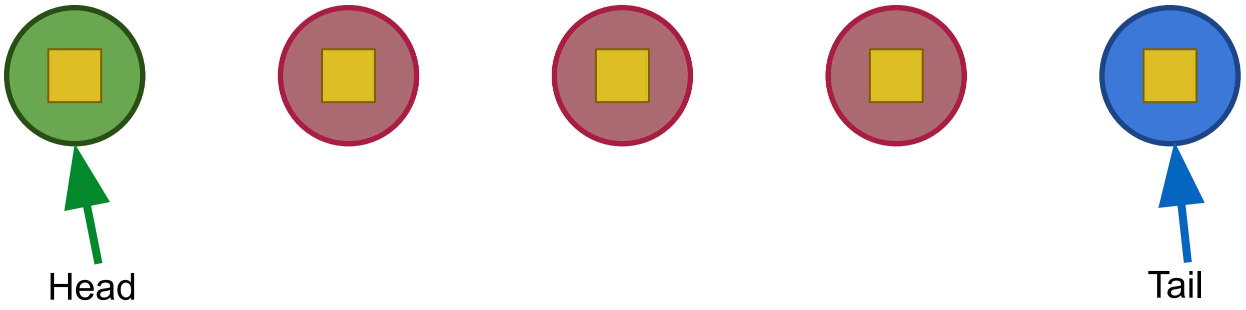

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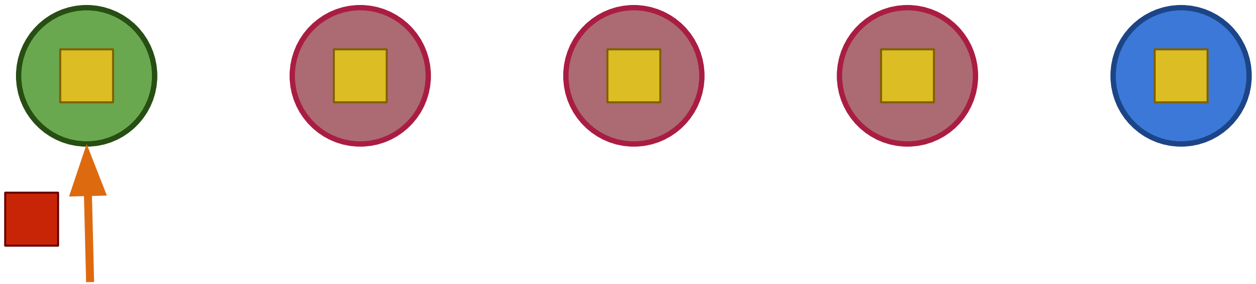

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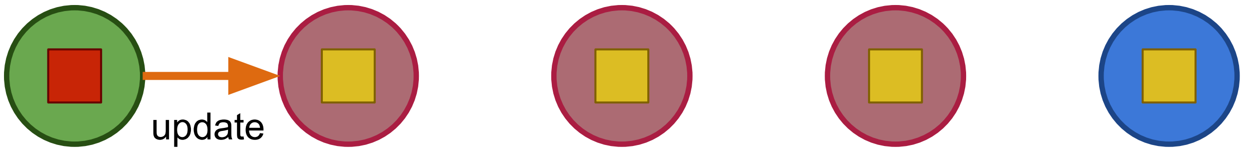

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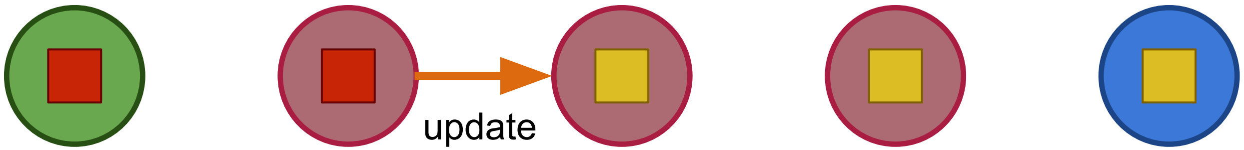

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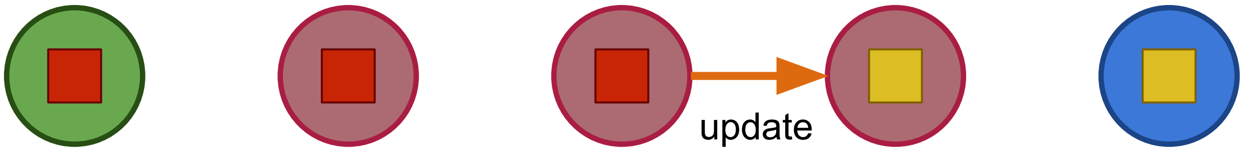

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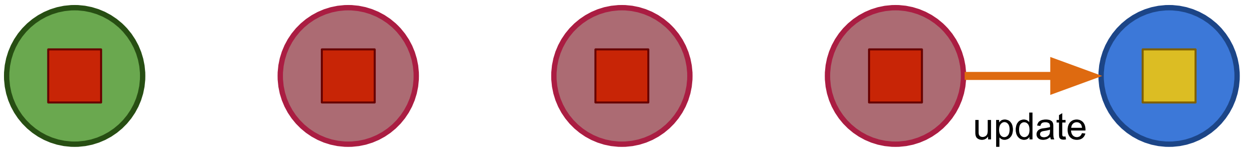

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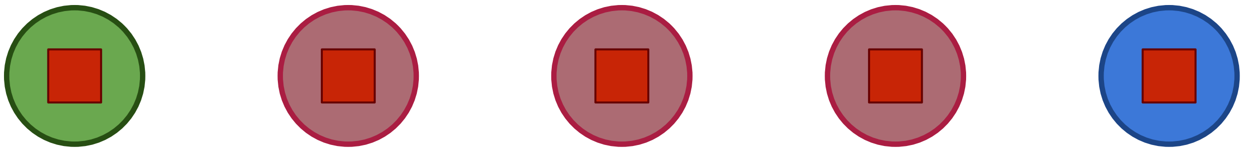

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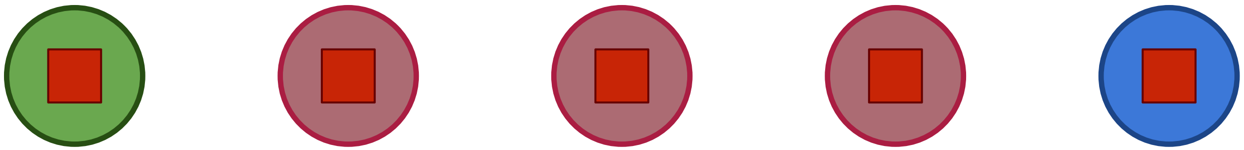

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However, it has its limitations…

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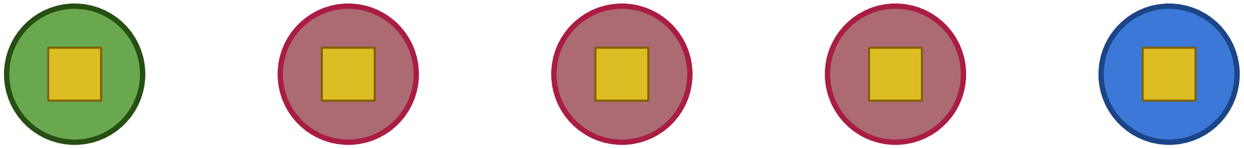

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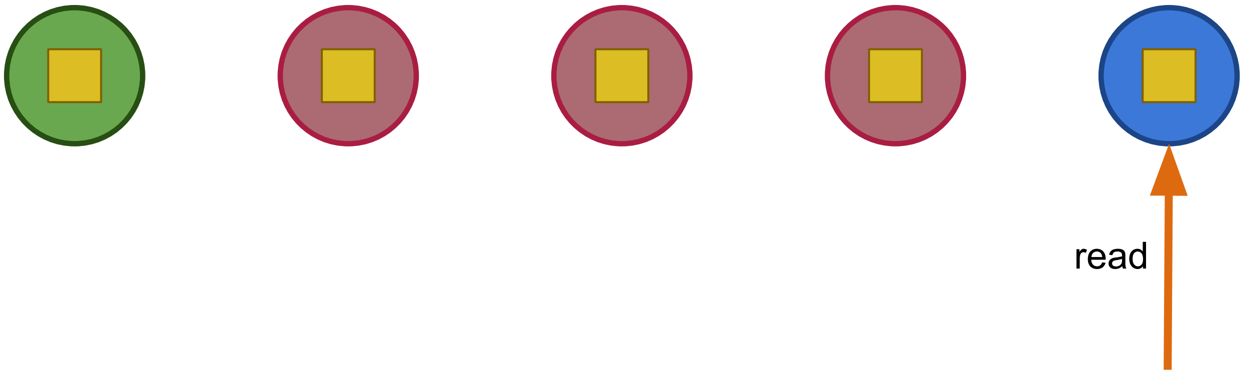

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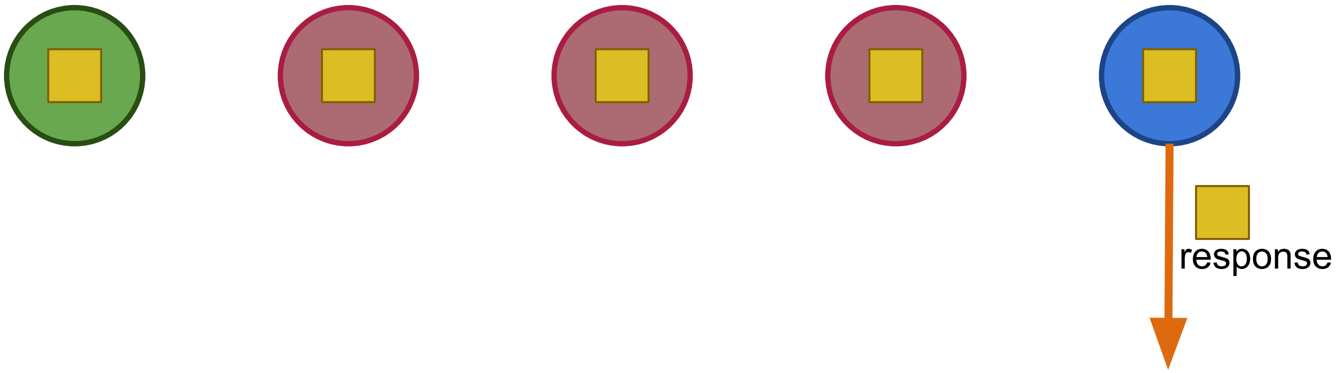

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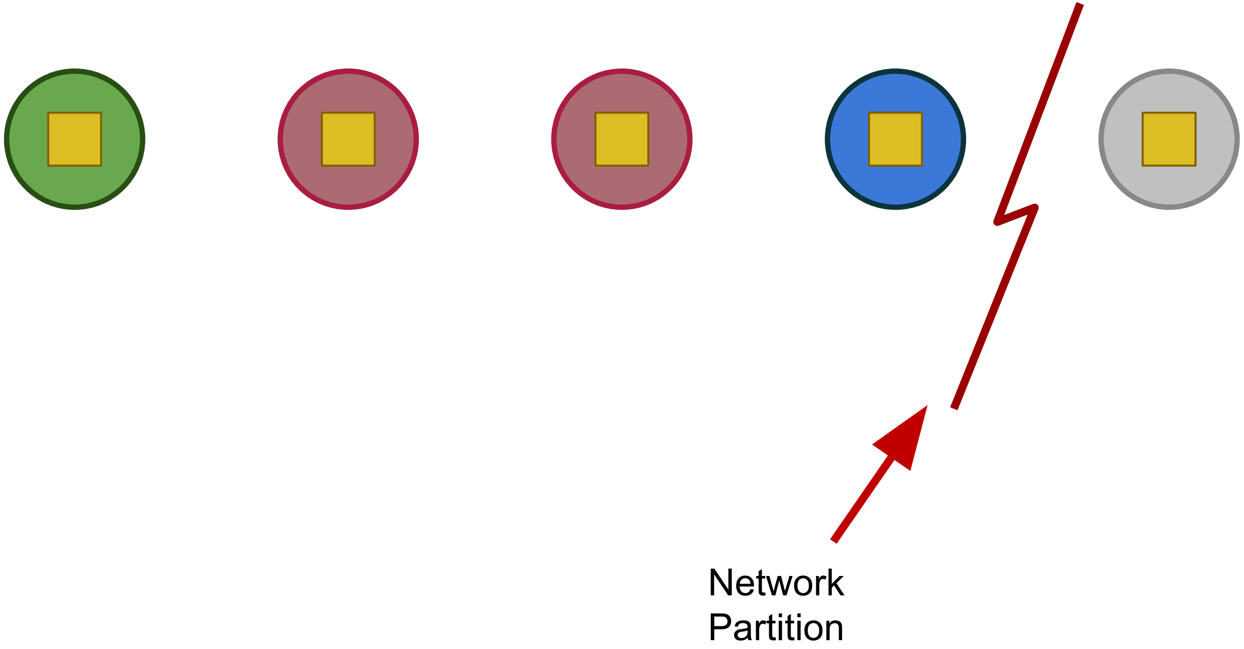

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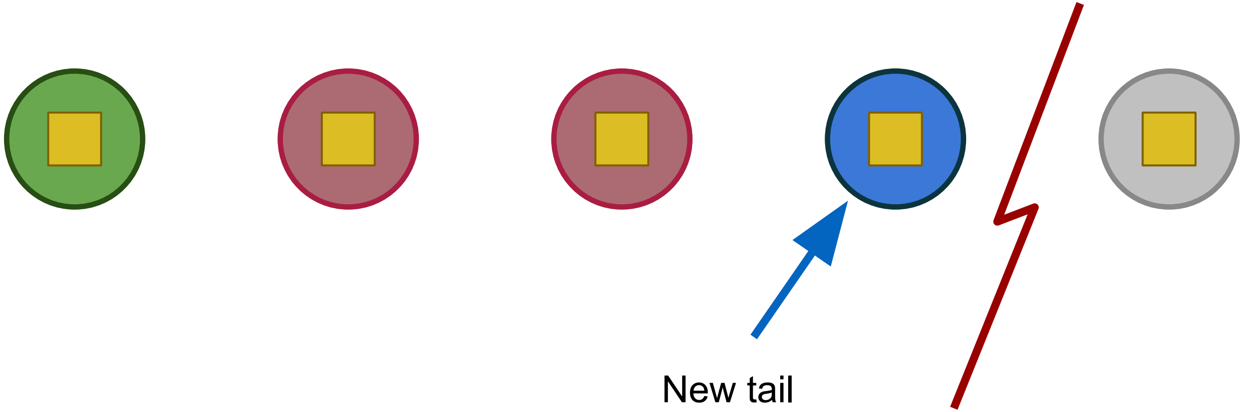

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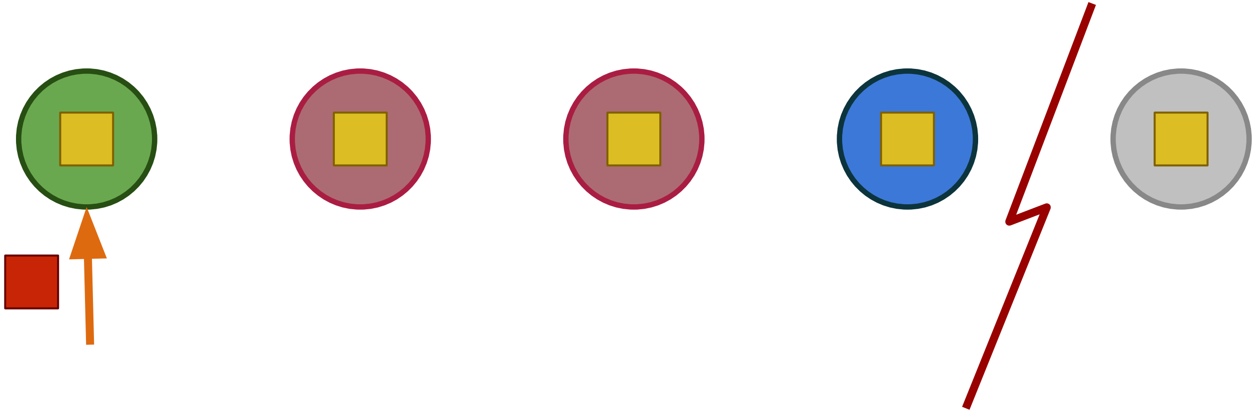

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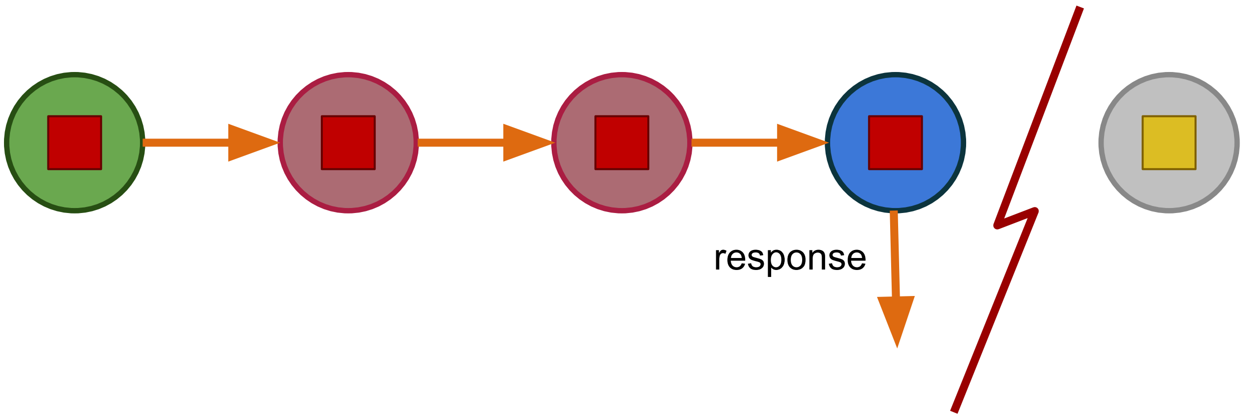

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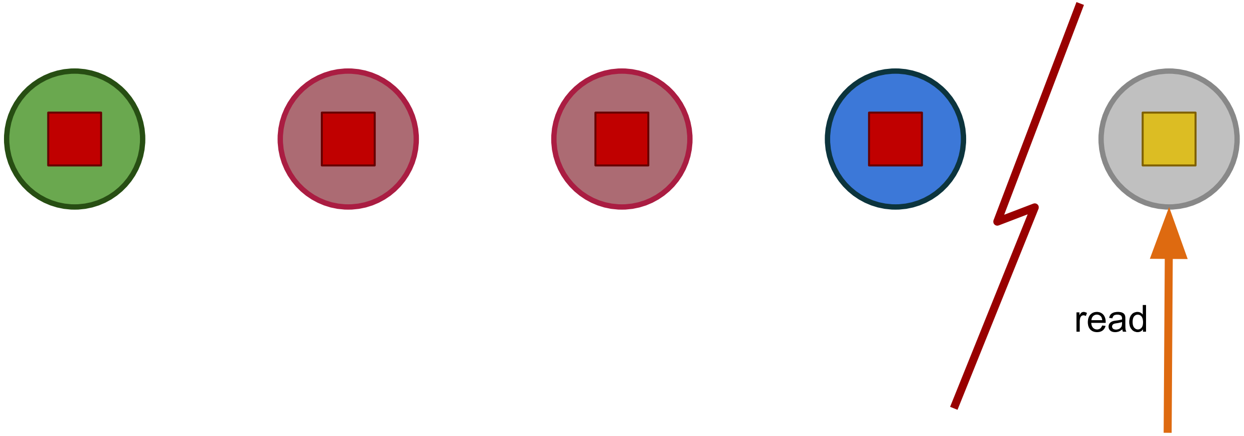

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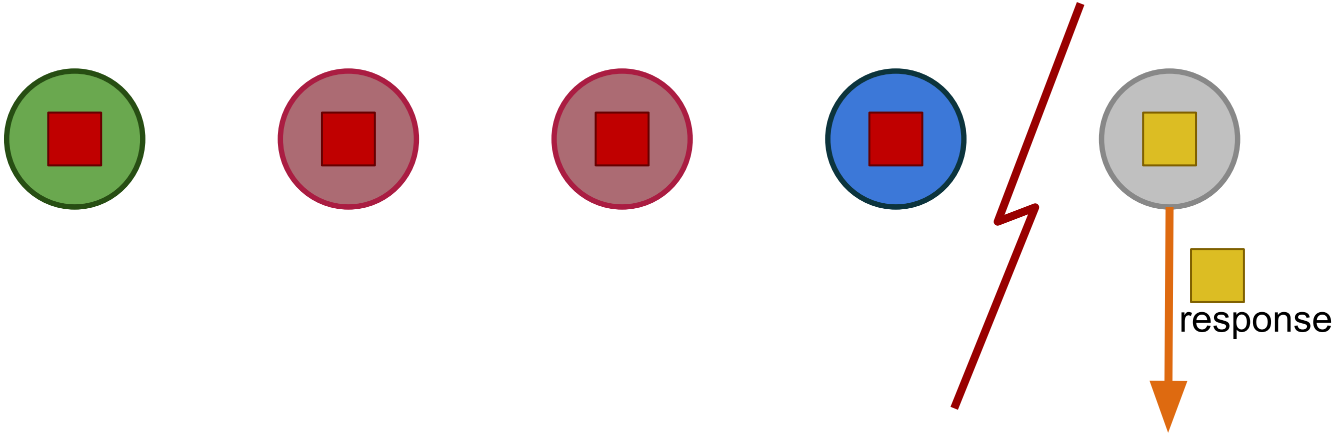

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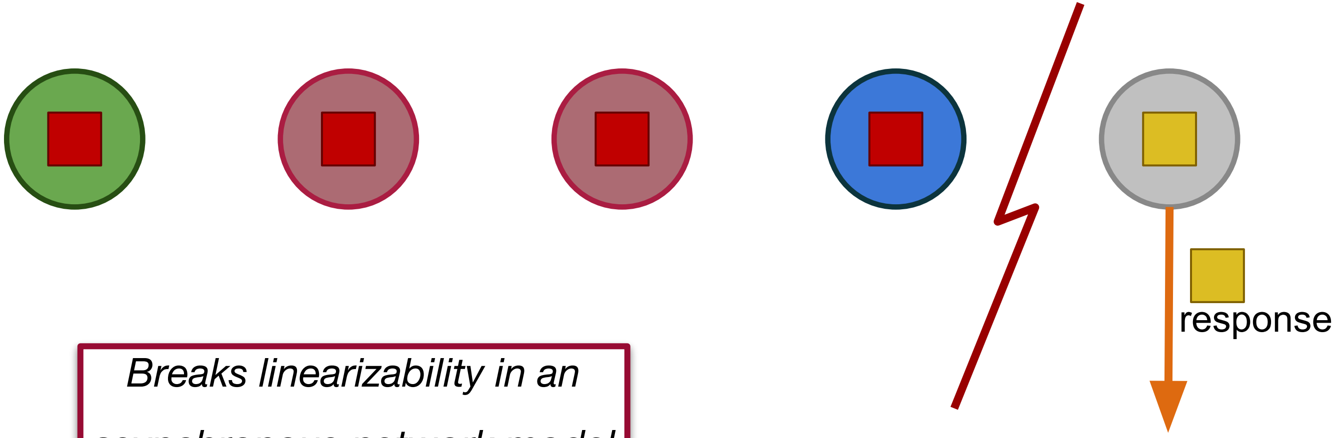

Breaks linearizability in an asynchronous network model

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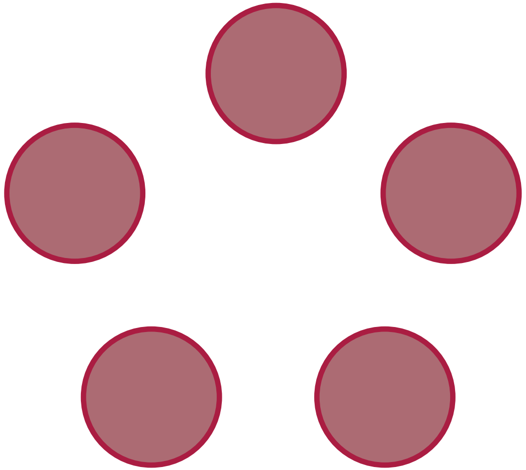

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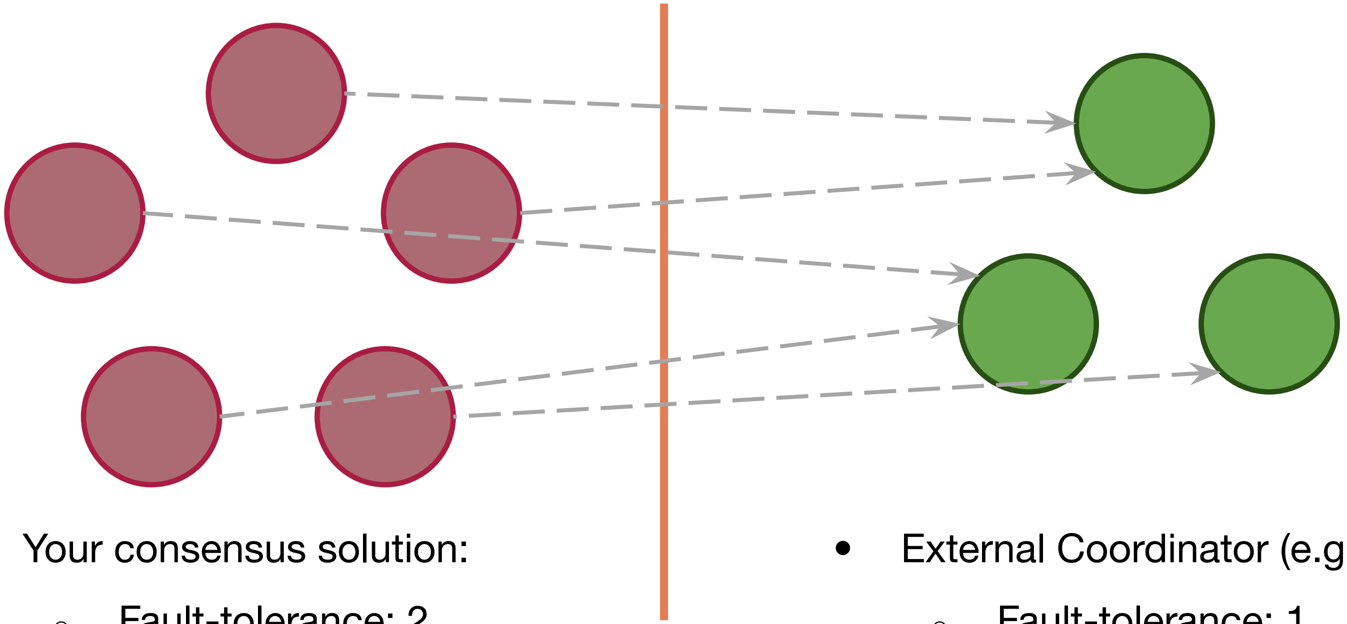

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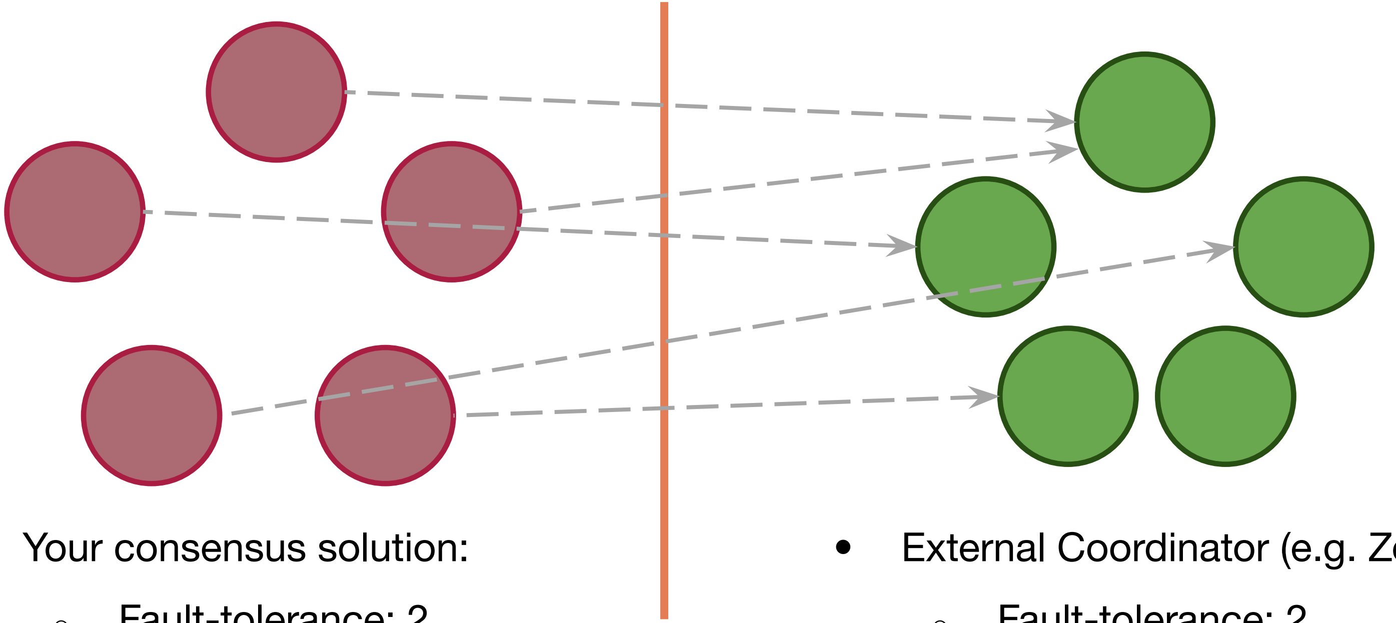

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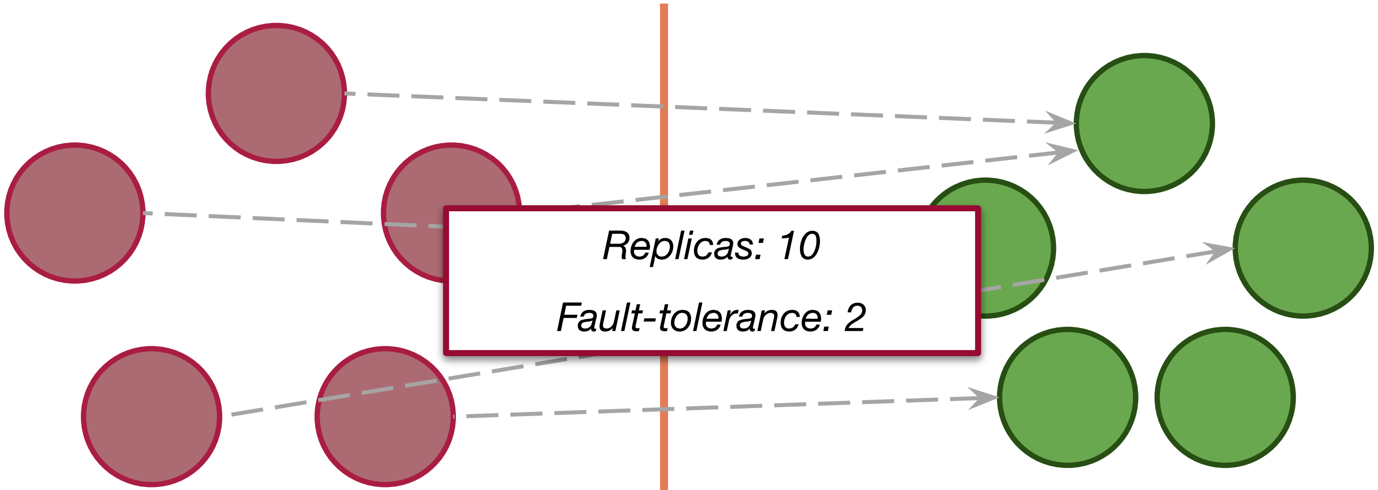

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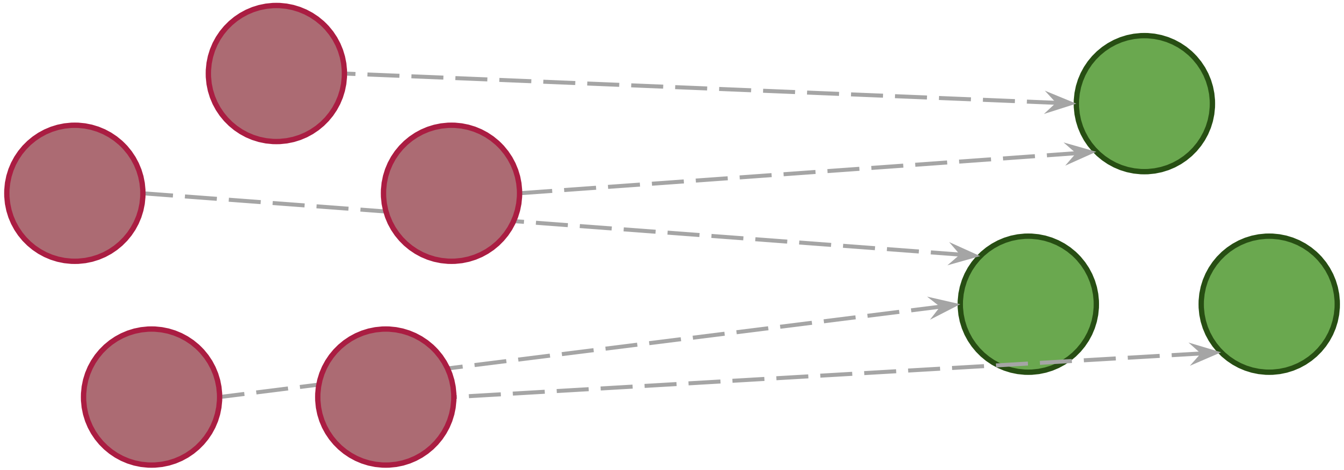

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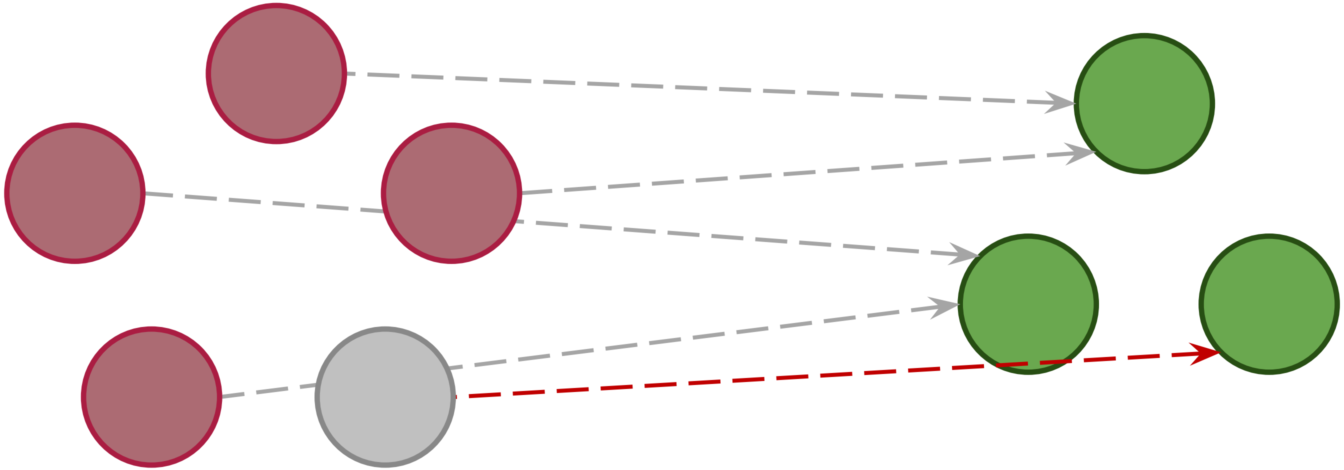

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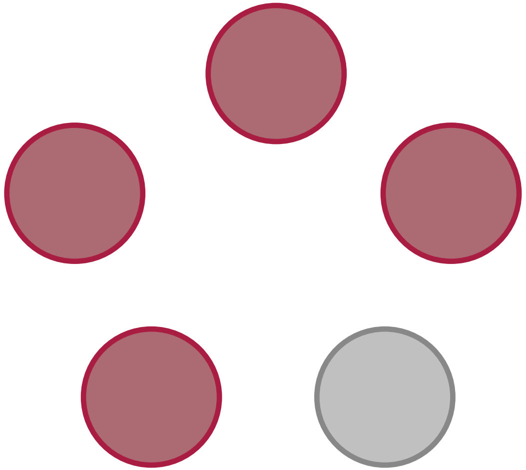
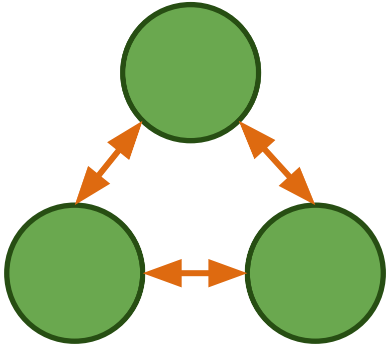
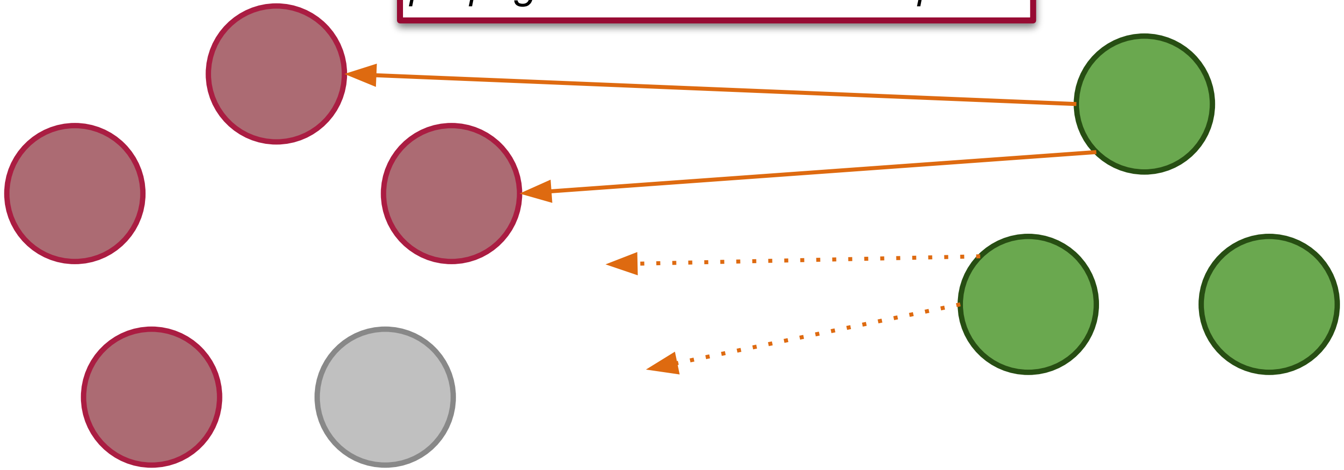




Consensus round to decide removal

Motivation: Membership Management

Asynchronous decision propagation to consensus replicas



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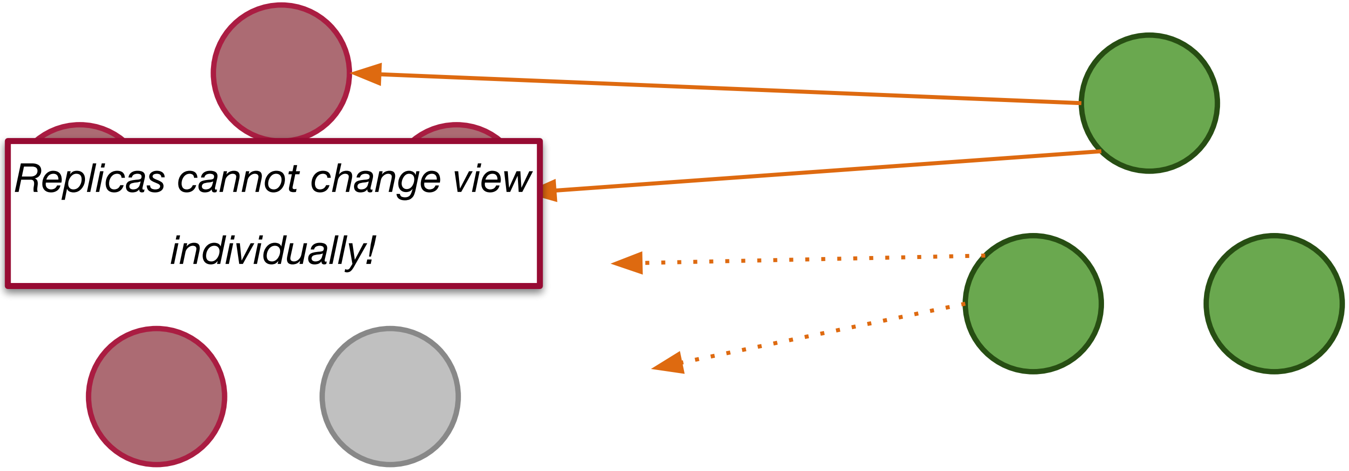
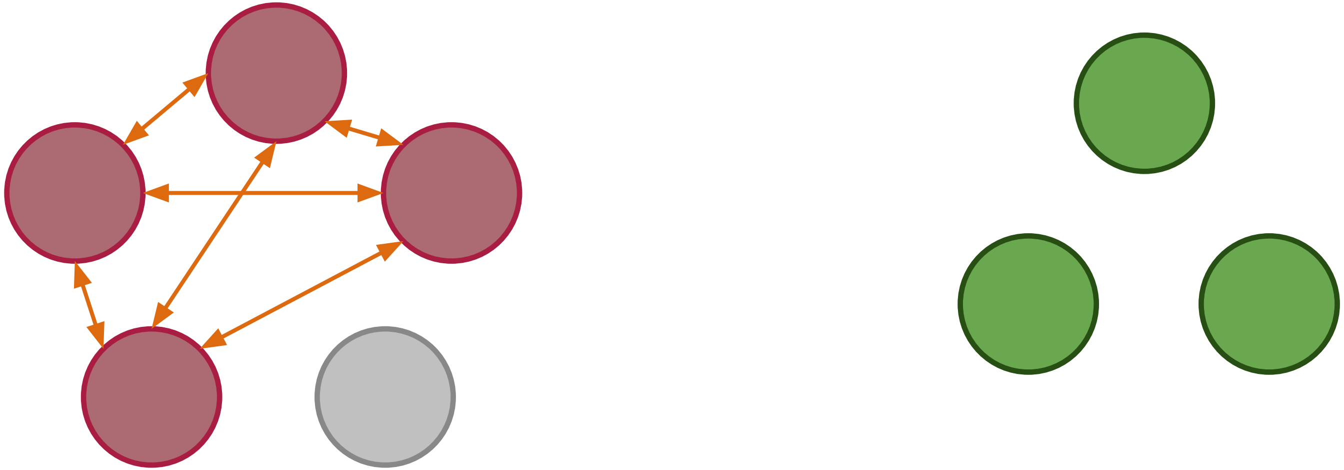


Motivation: Membership Management

Another (redundant)

consensus round is required



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- This is not the case:
  - **Fault-tolerance** becomes complex
  - **Complex (and redundant) integration** with consensus
  - More **vulnerable** to partial network partitions[1]

[1] *Alfatafta, Mohammed, et al. "Toward a generic fault tolerance technique for partial network partitioning." OSDI 2020.*

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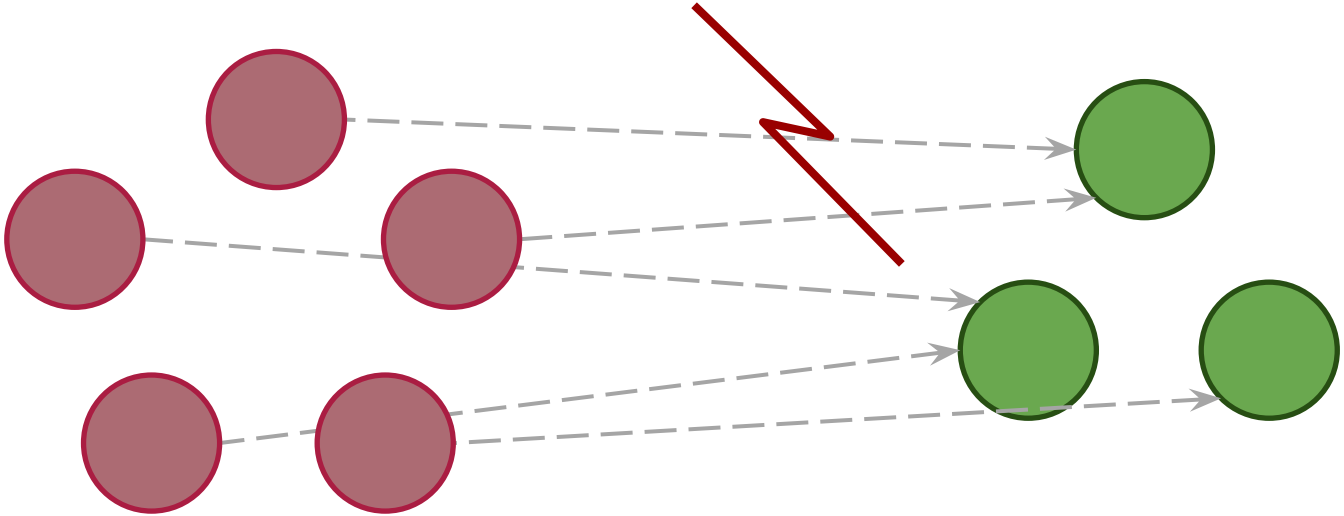

Partition between coordinator and consensus replicas

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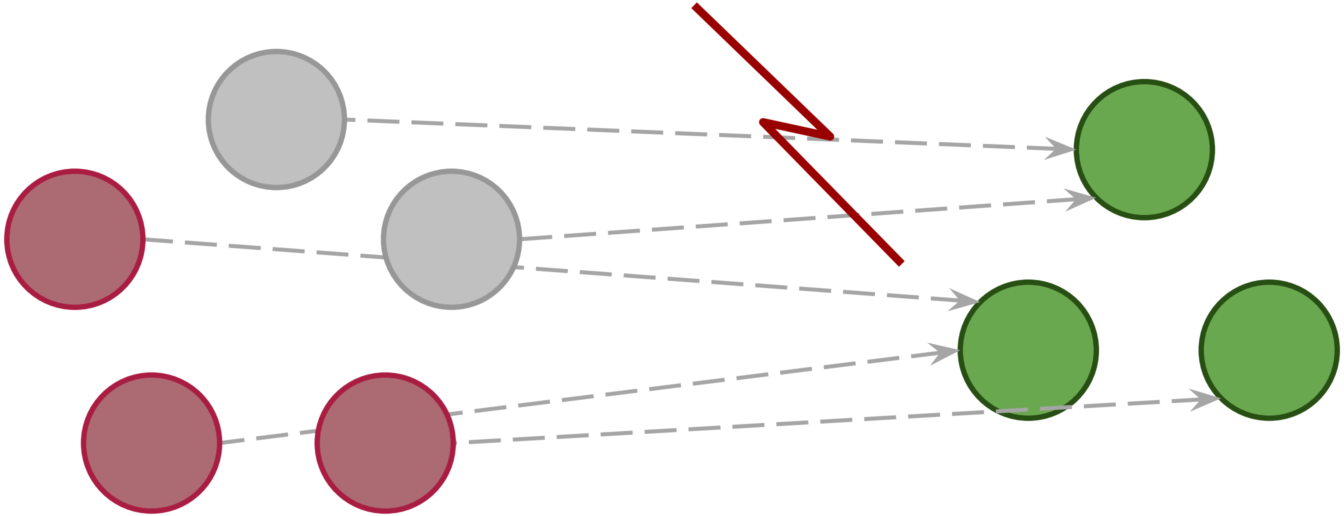

Correct replicas will be removed

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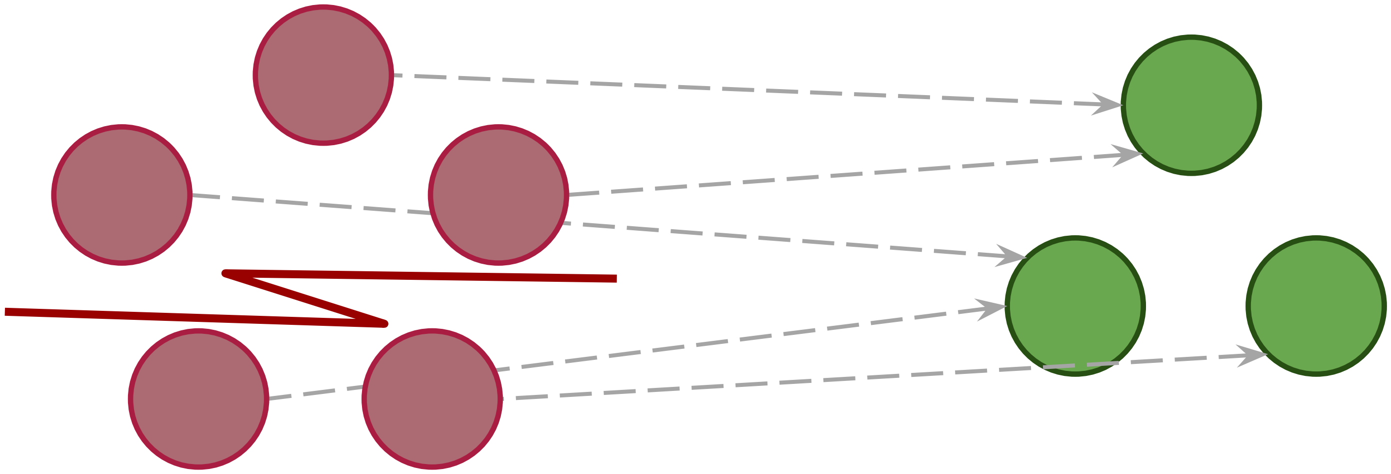
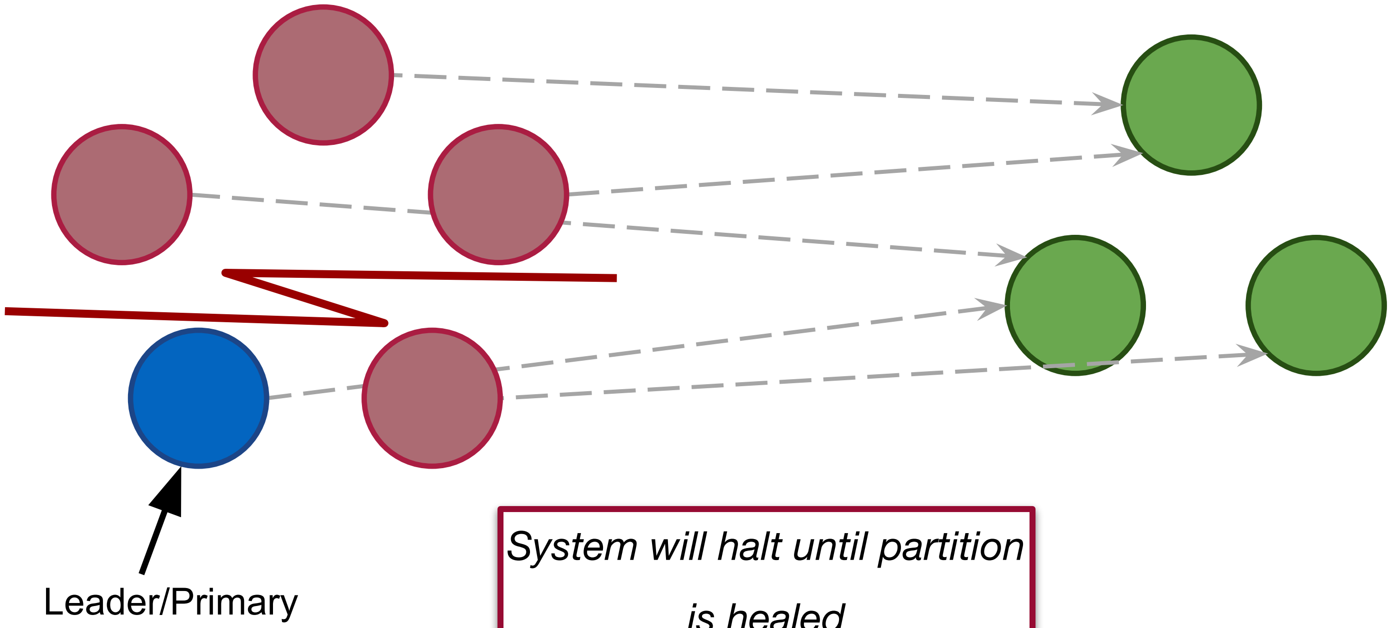


Partition between consensus replicas

Motivation: Membership Management



System will halt until partition is healed

Motivation: Consensus and SMR

- Building blocks of numerous practical replication systems
- Their performance is critical
- Many alternatives have been designed
- Two very relevant ones:
  - **(Multi-)Paxos**
  - **Chain Replication**
- Two aspects are often overlooked:
  - **Performant linearizable reads**
  - **Membership management and reconfiguration**

Proposal: ChainPaxos

Novel consensus algorithm:

- **Combining** the best properties of Multi-Paxos and Chain Replication
    - Correction in an **asynchronous network**
    - **Constant** message **complexity**

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Novel consensus algorithm:

- **Combining** the best properties of Multi-Paxos and Chain Replication
  - Correction in an **asynchronous network**
  - **Constant** message **complexity**

- Going beyond existing solutions:
  - **Maximizing throughput** of both read and write operations
  - Providing **local linearizable reads** in any replica
  - **Integrated reconfiguration** and fault-tolerance

Outline

- Motivation and Related Work
- ChainPaxos
    - Writing
    - Local Linearizable Reads
    - Reconfiguration
- Evaluation

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- Motivation and Related Work
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  - Writing (commits + garbage collection)
  - Local Linearizable Reads
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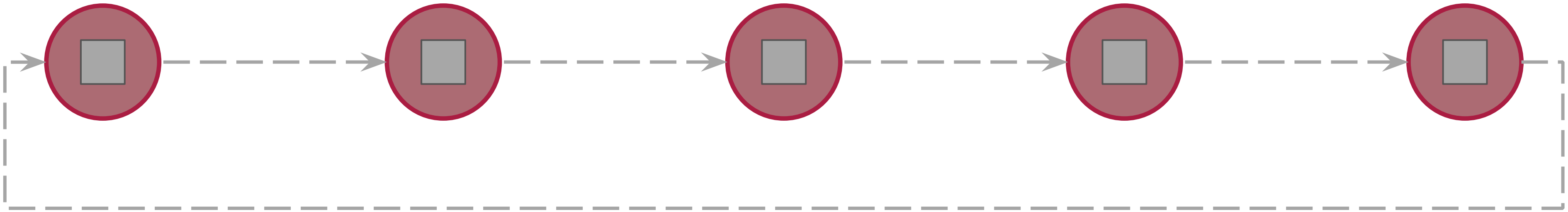
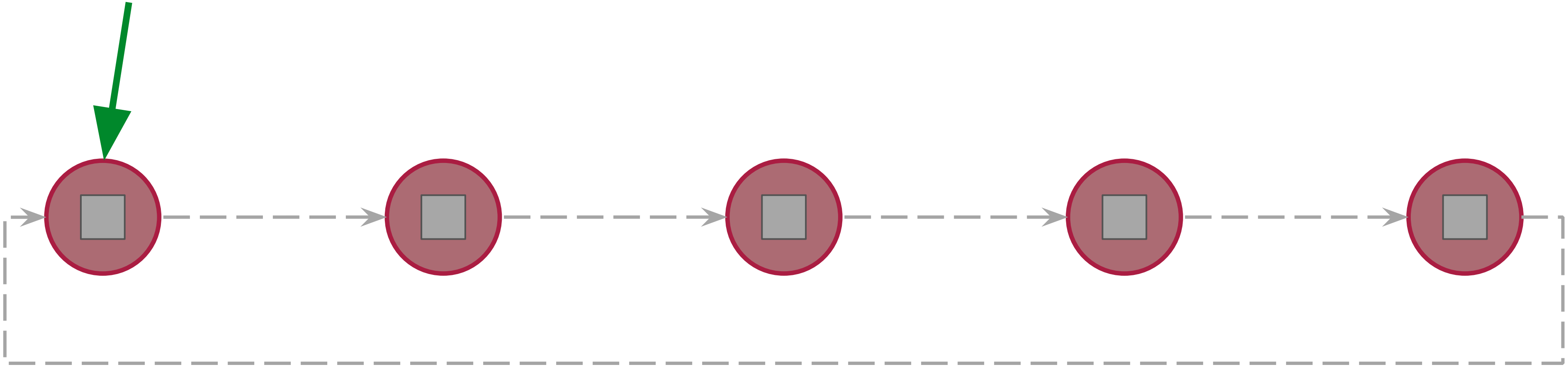
ChainPaxos: Write Path



ChainPaxos: Write Path

Leader (regular Multi-Paxos election)



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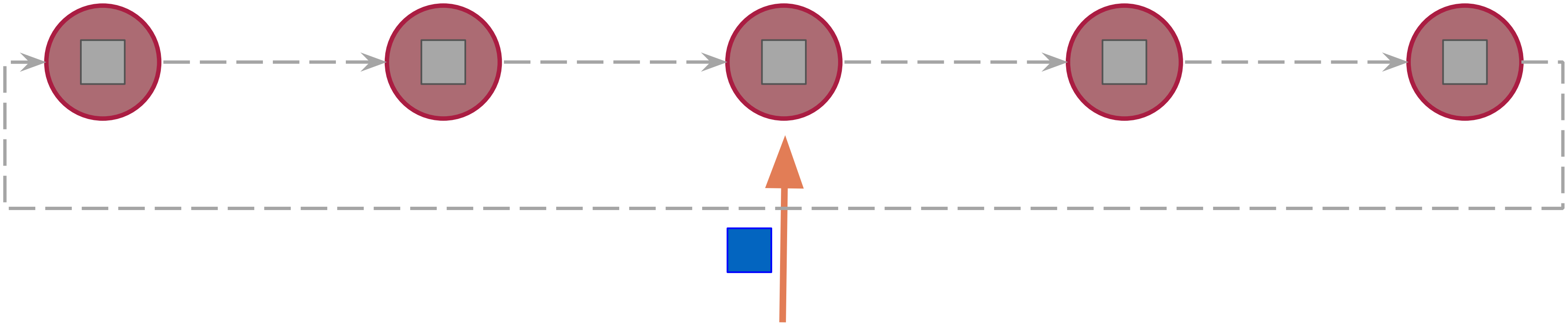

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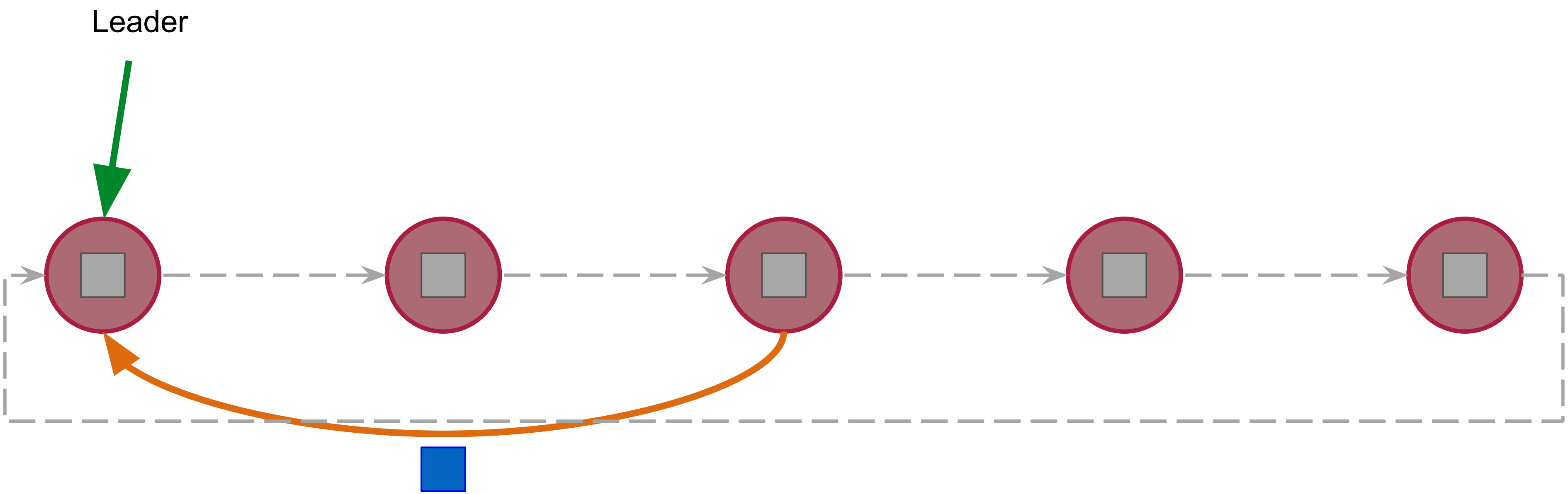

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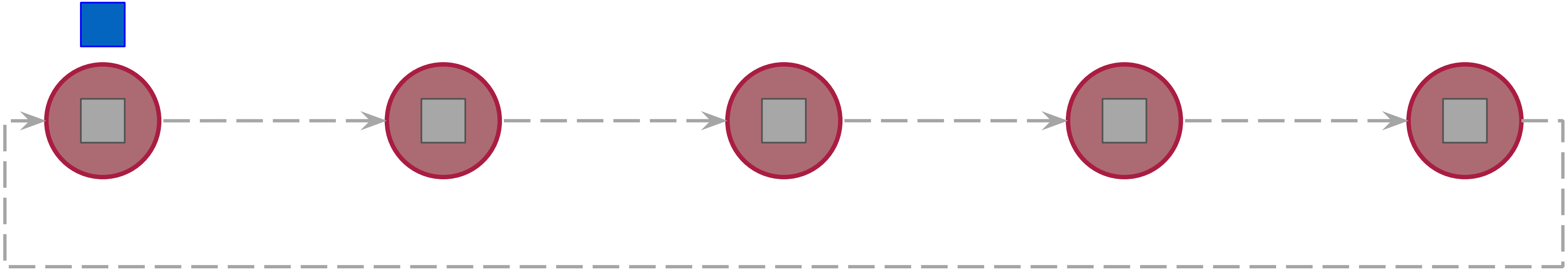

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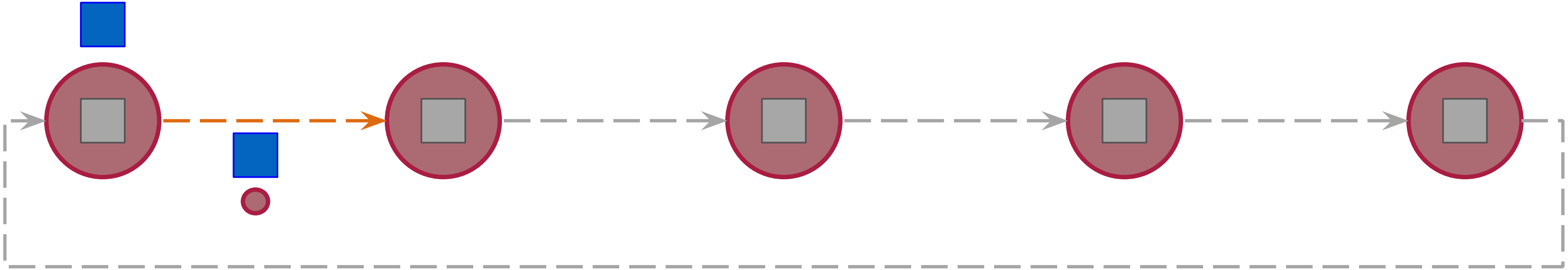
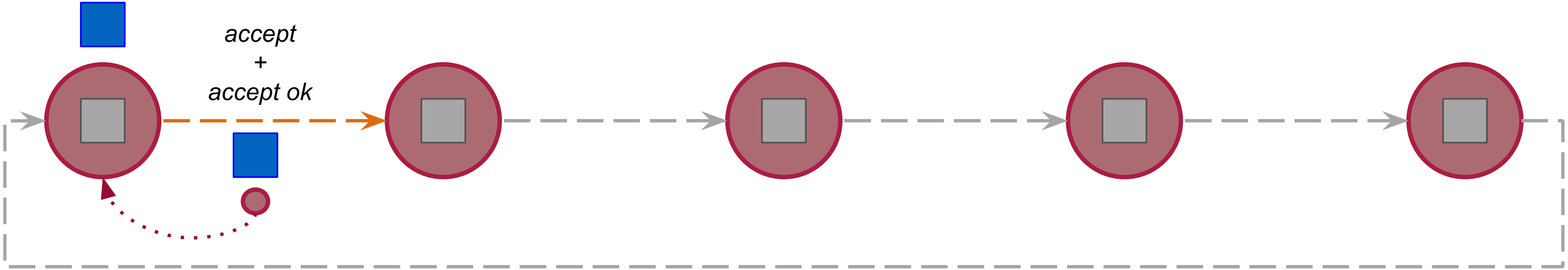


ChainPaxos: Write Path

Encapsulate multiple

Multi-Paxos messages



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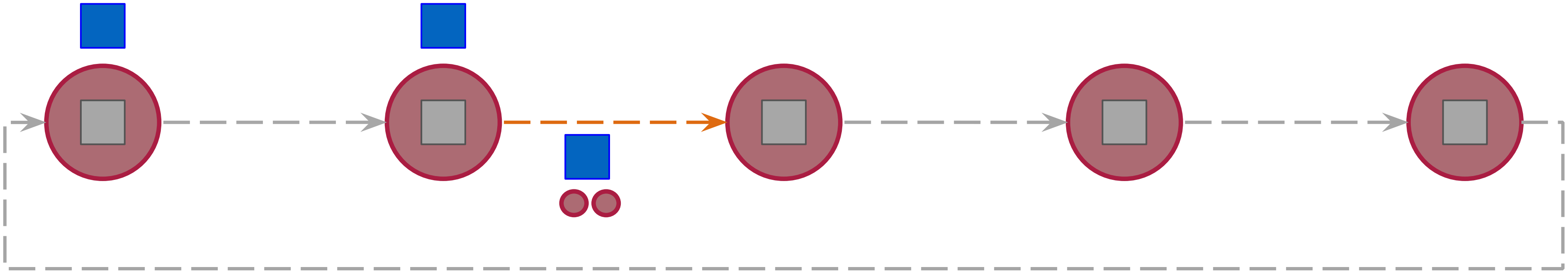

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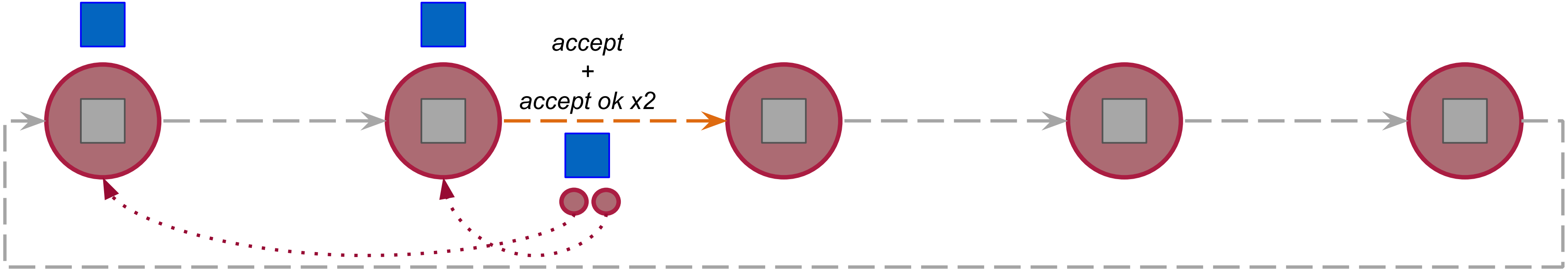
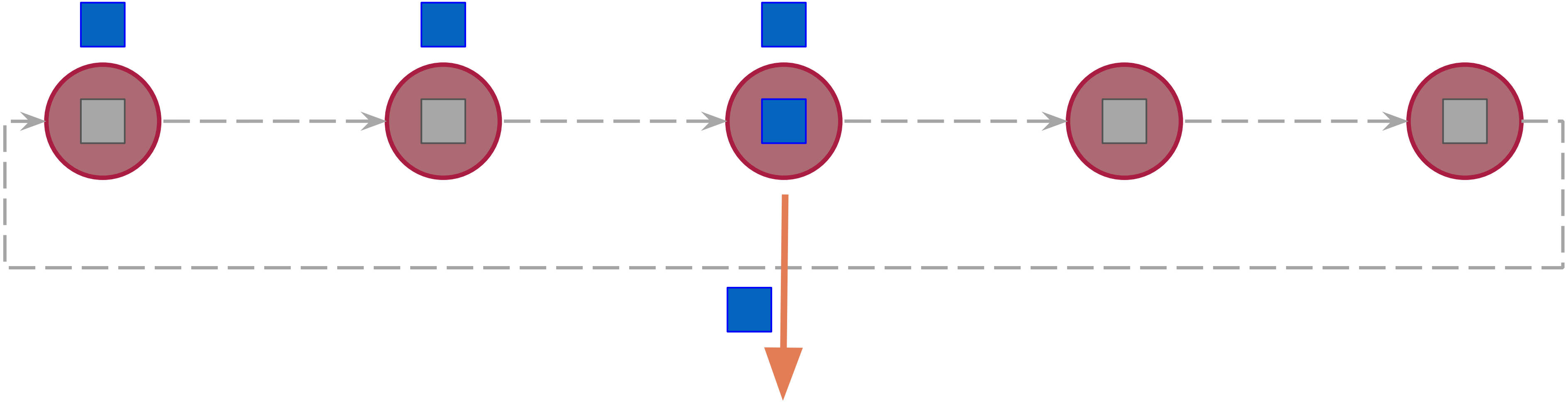


ChainPaxos: Write Path

Operation is "locked-in"



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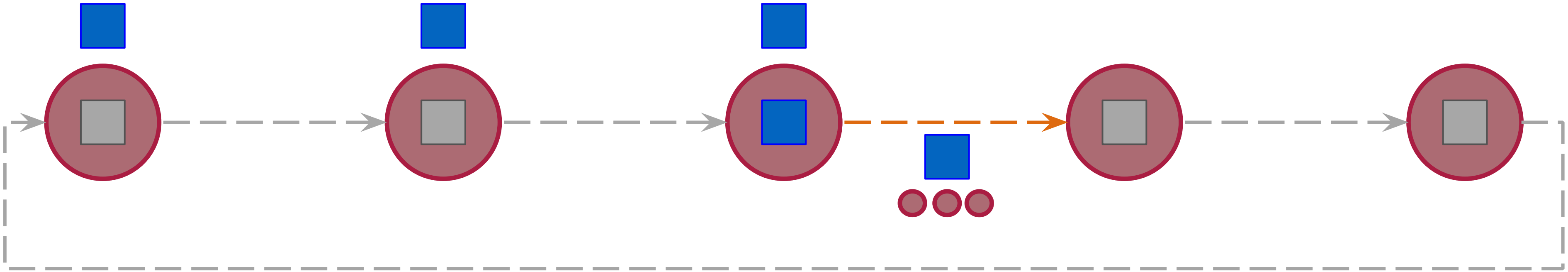

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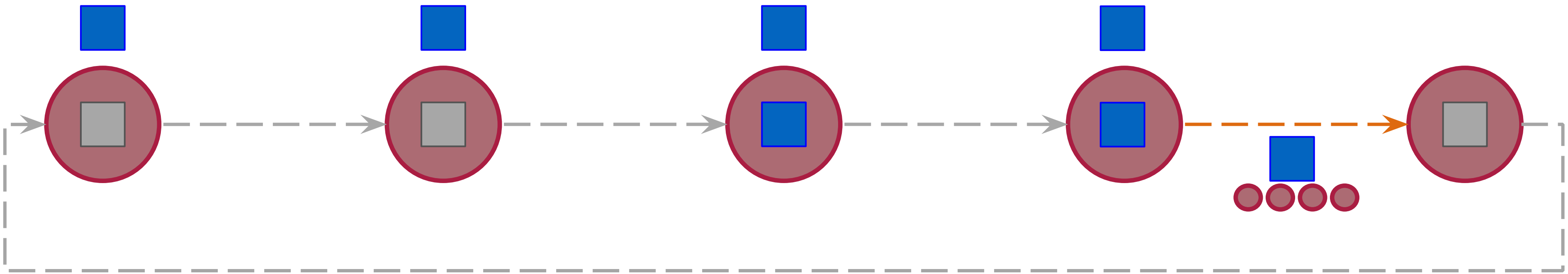

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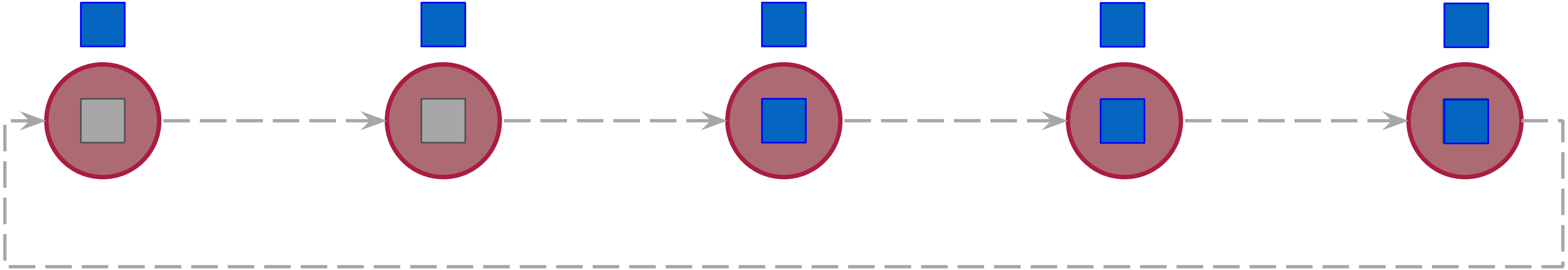
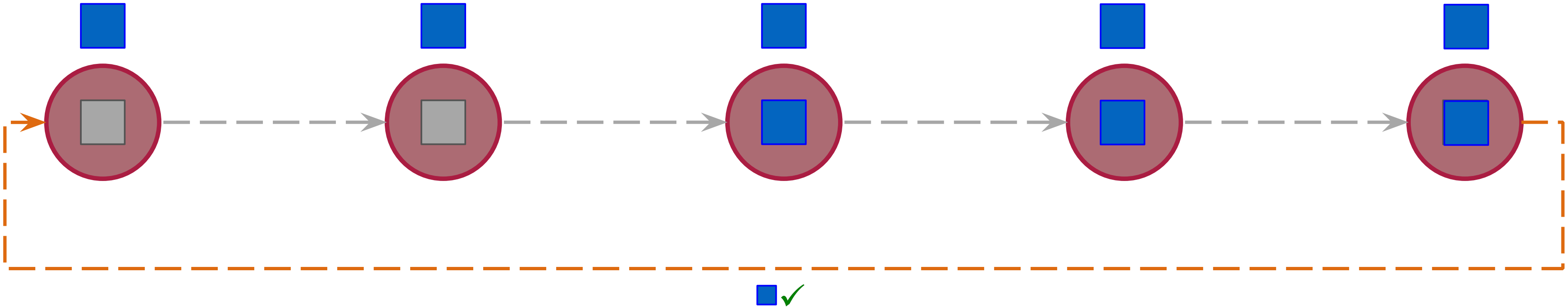


Need to garbage collect + execute on the first replicas

ChainPaxos: Write Path



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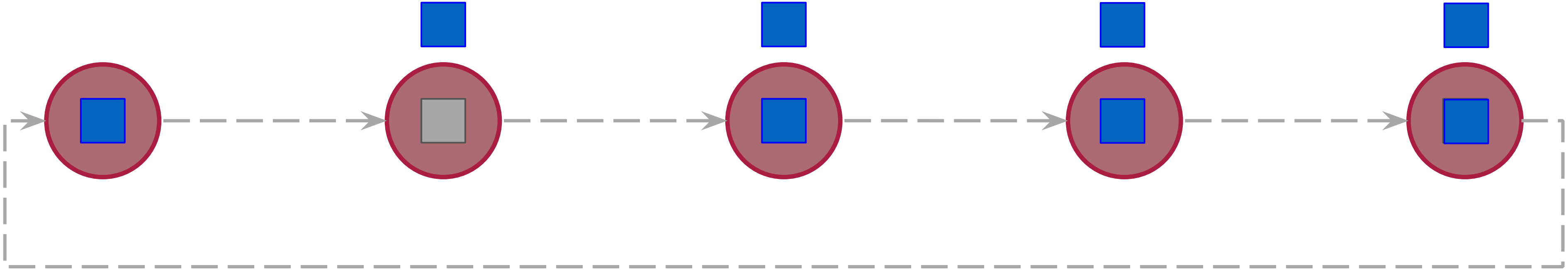

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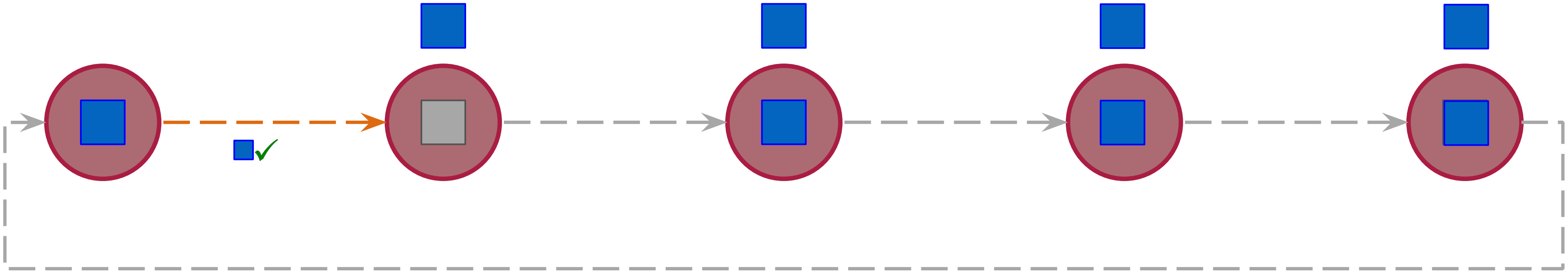

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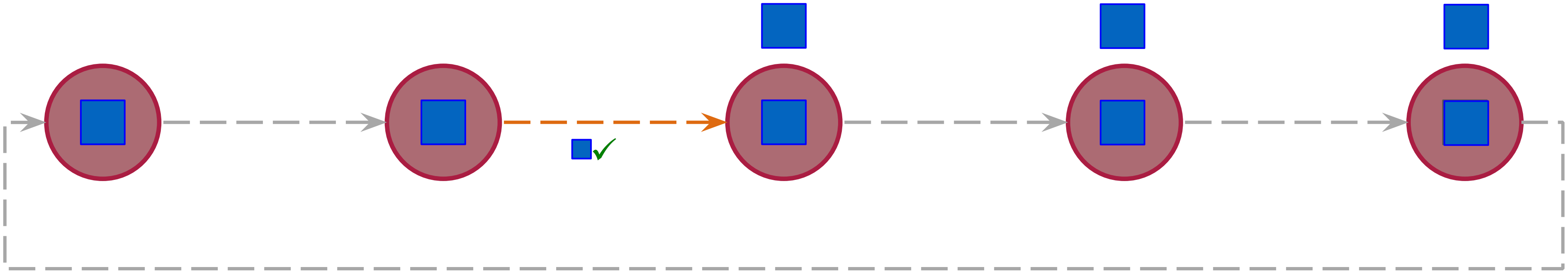

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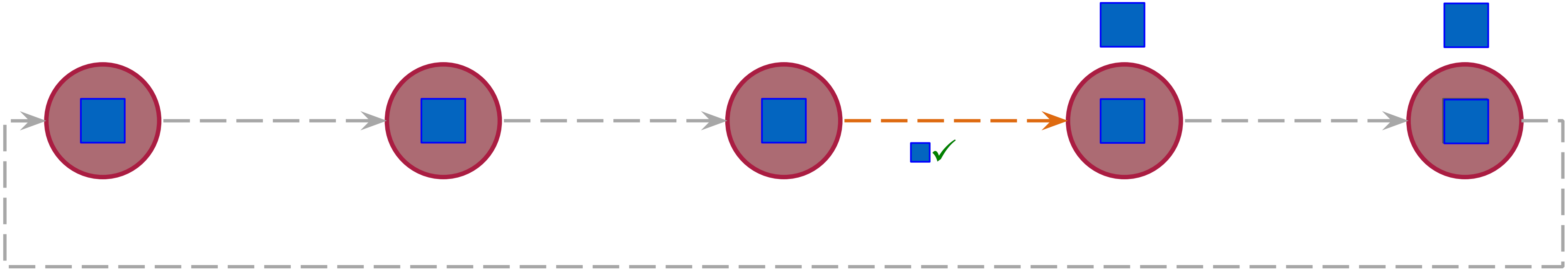

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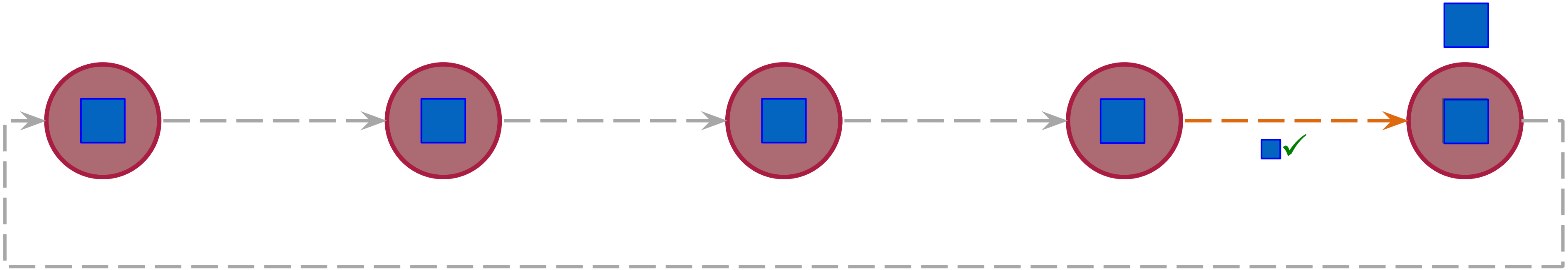

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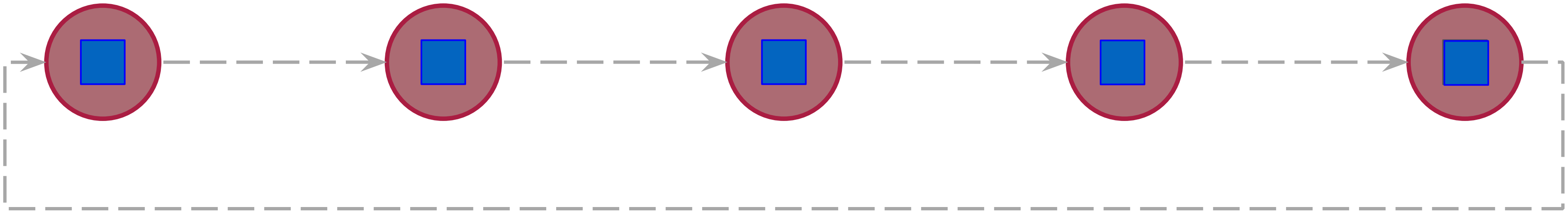

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  - Local Linearizable Reads
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Local Linearizable Reads

Requirements for linearizability:

- The result of a read must contain **all writes that completed** before it started
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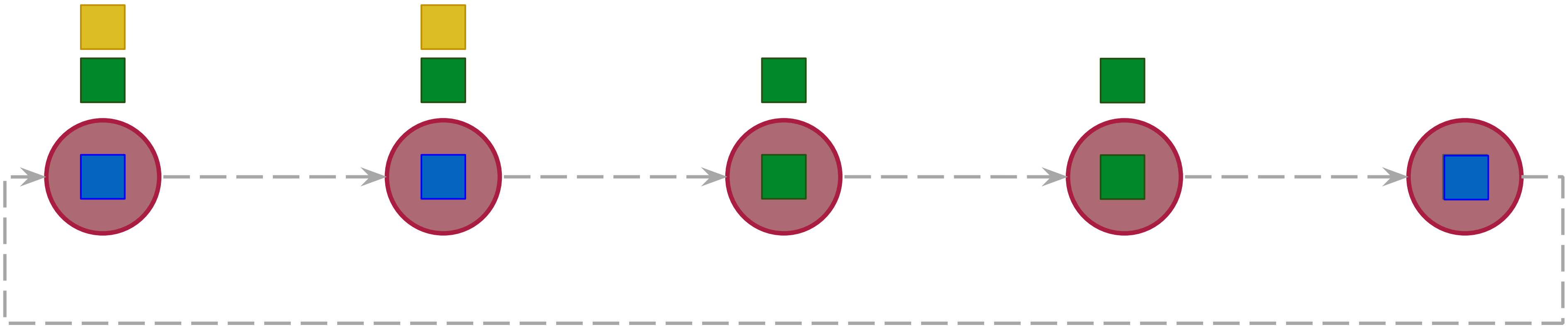
The chain topology is our friend!

Local Linearizable Reads



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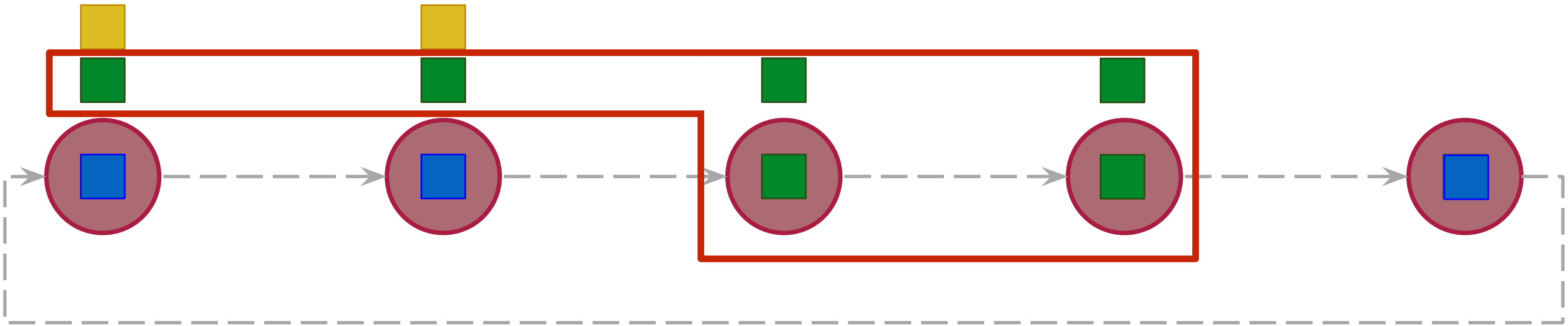

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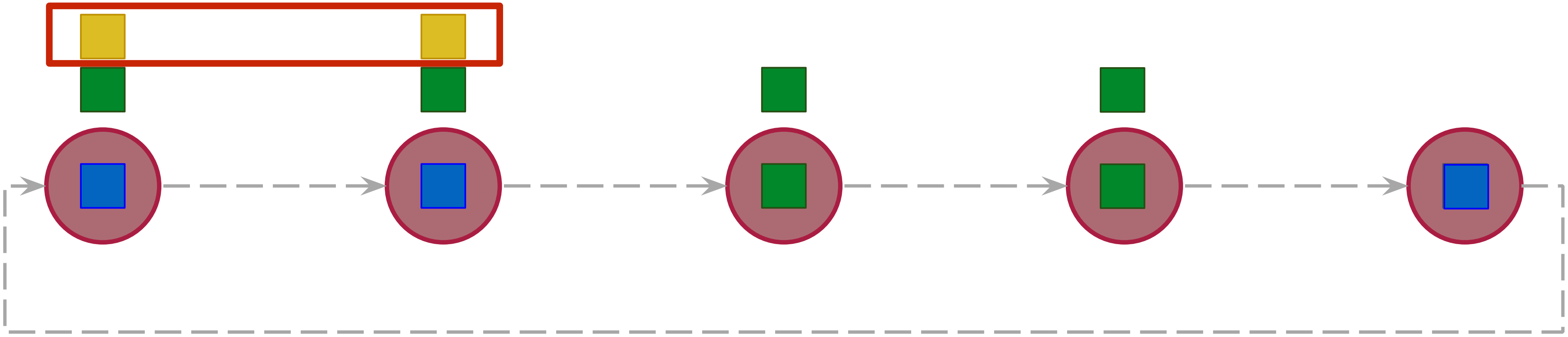

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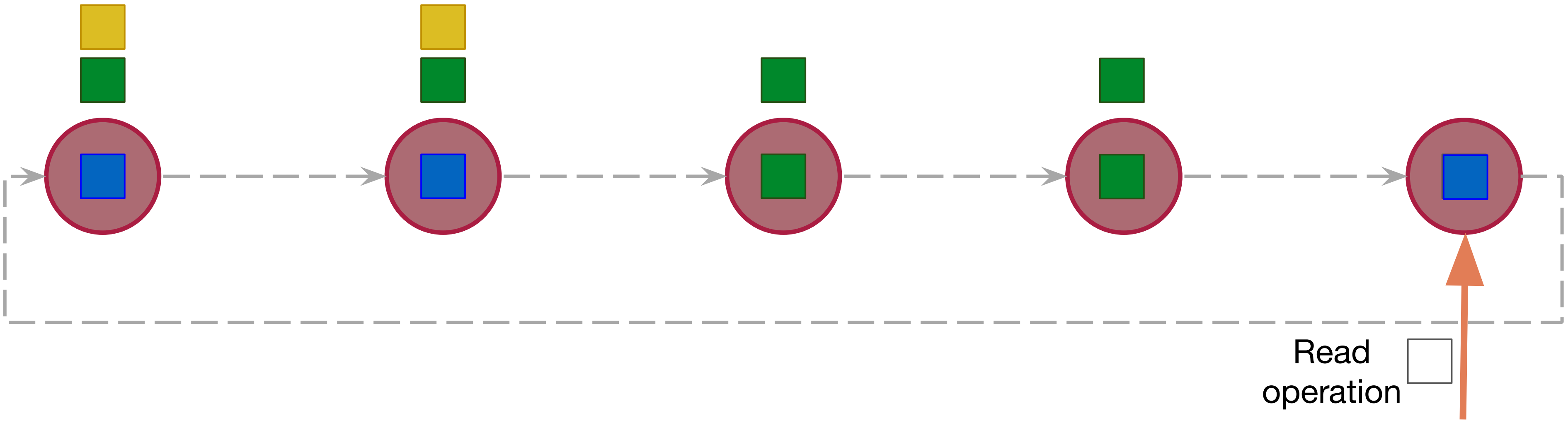

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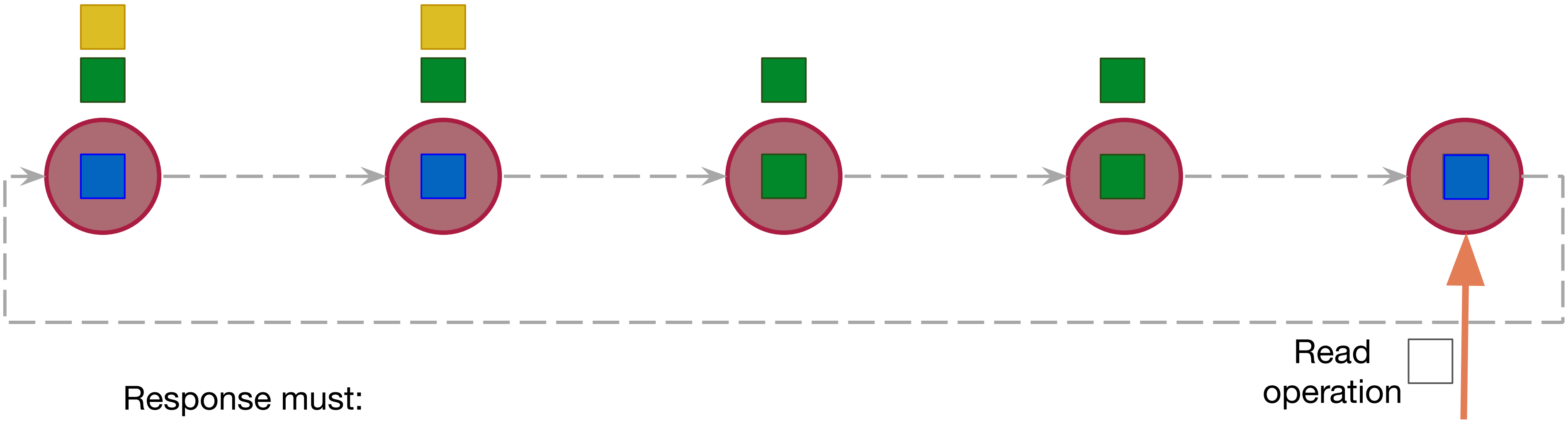

Response must:

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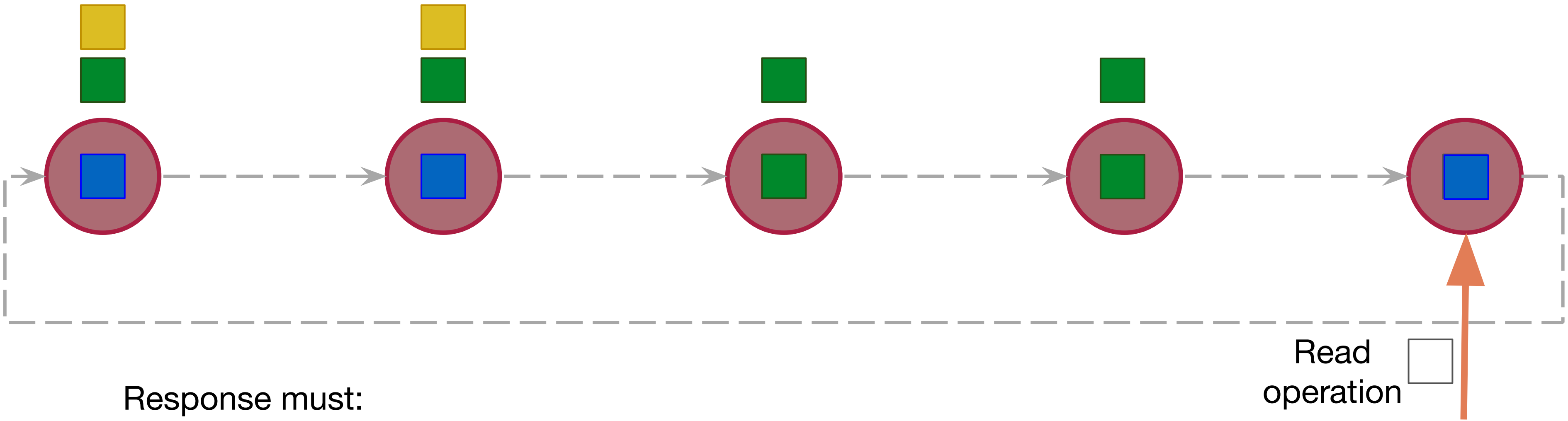
Local Linearizable Reads



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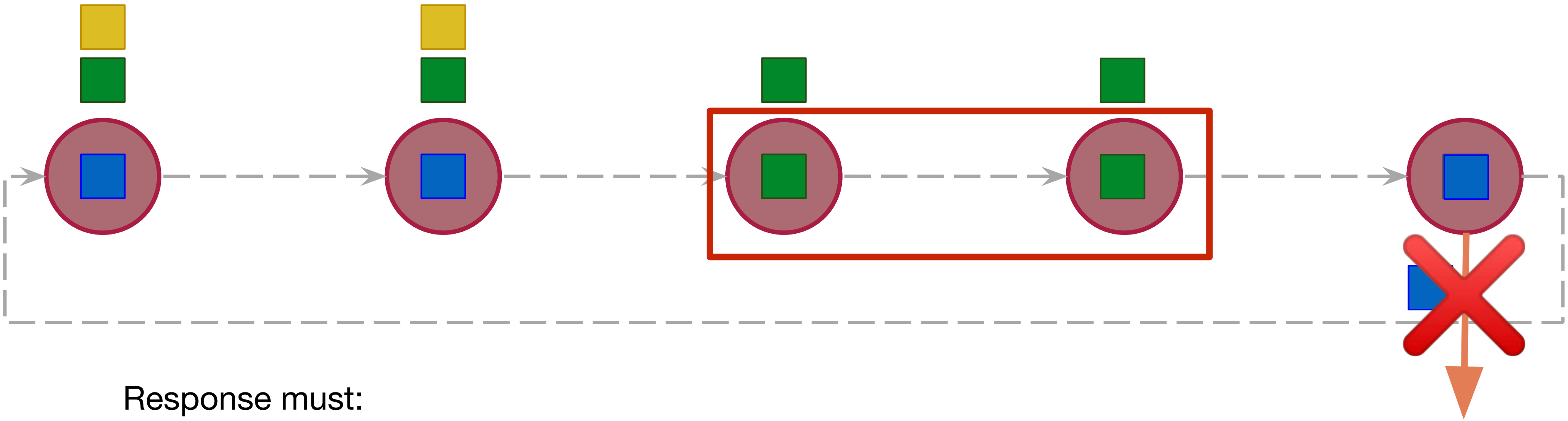

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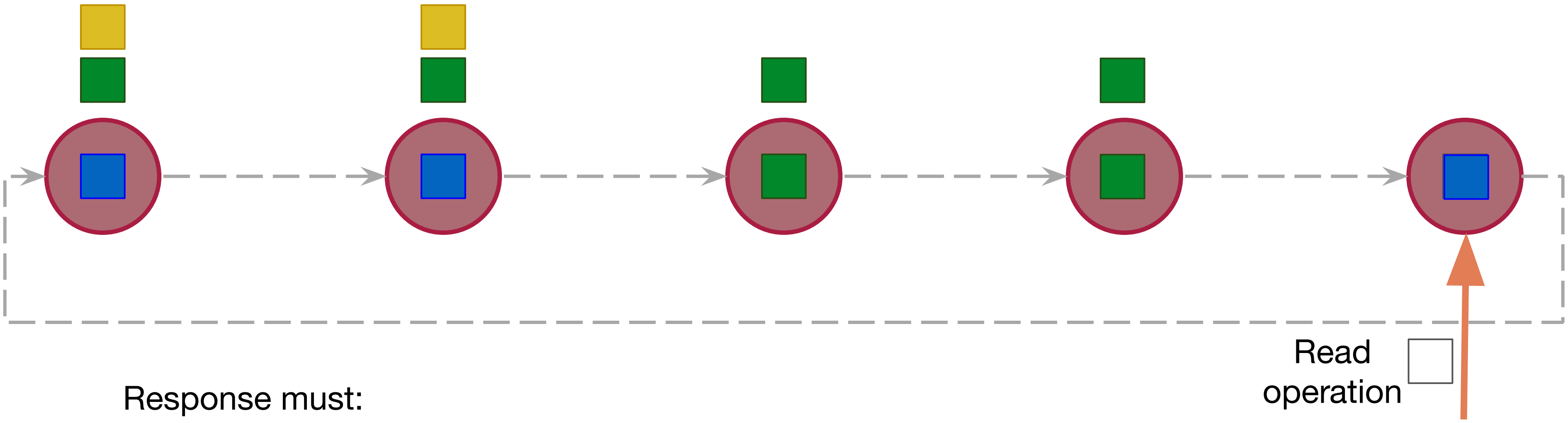
Local Linearizable Reads



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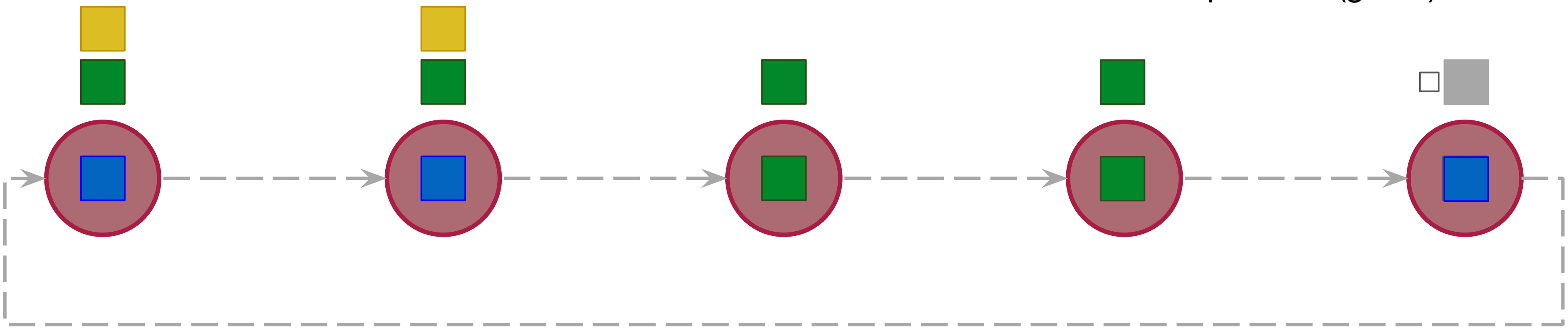
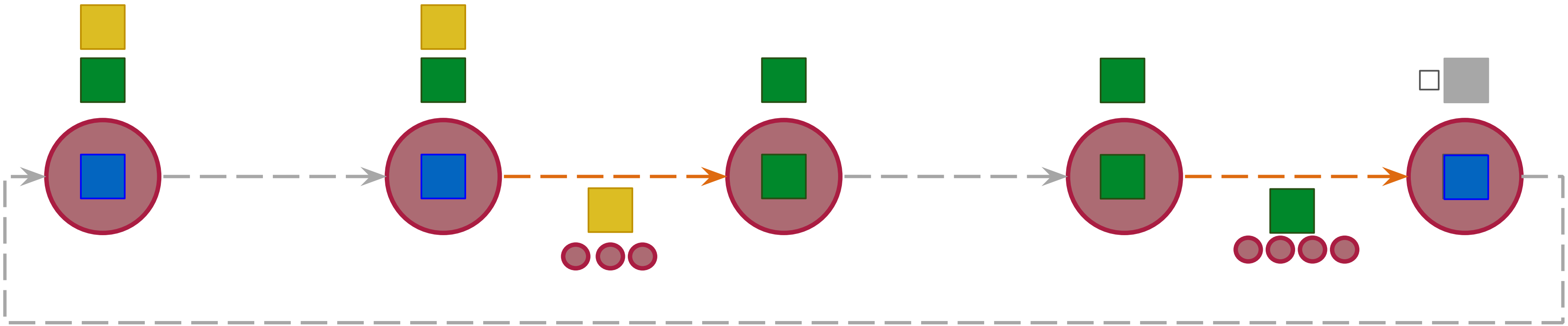
Local Linearizable Reads

Attach read to next unseen operation (green)

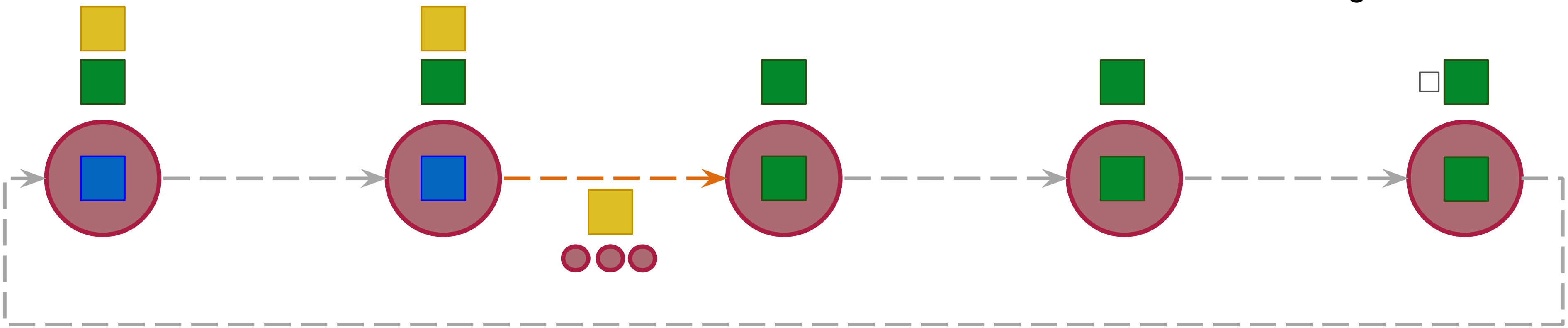


Local Linearizable Reads



Local Linearizable Reads

Read is now attached to green



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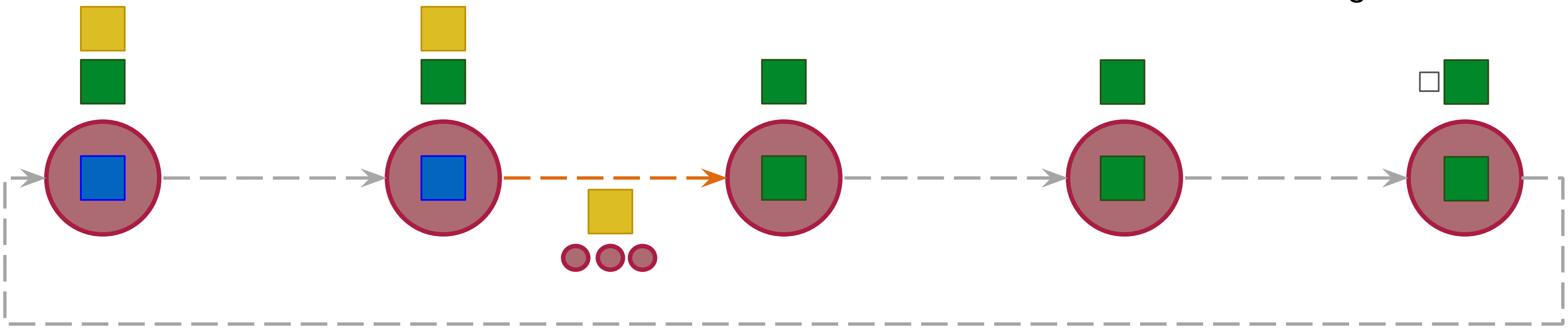

We now wait until the green ack goes around the chain

Local Linearizable Reads

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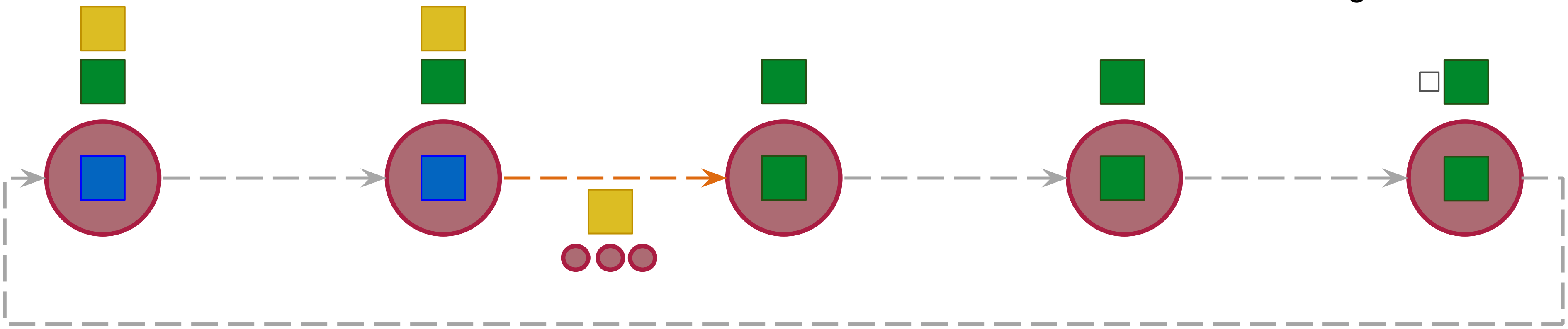

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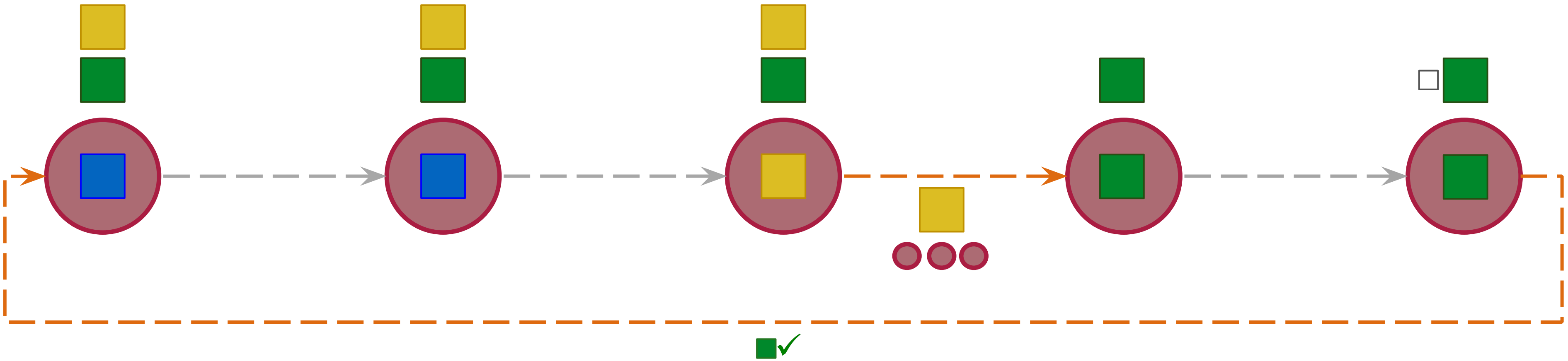

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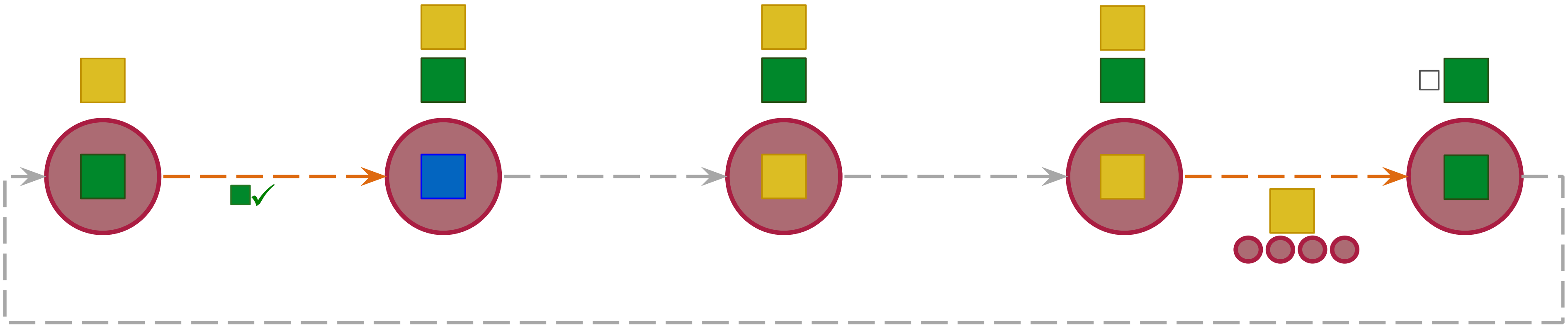

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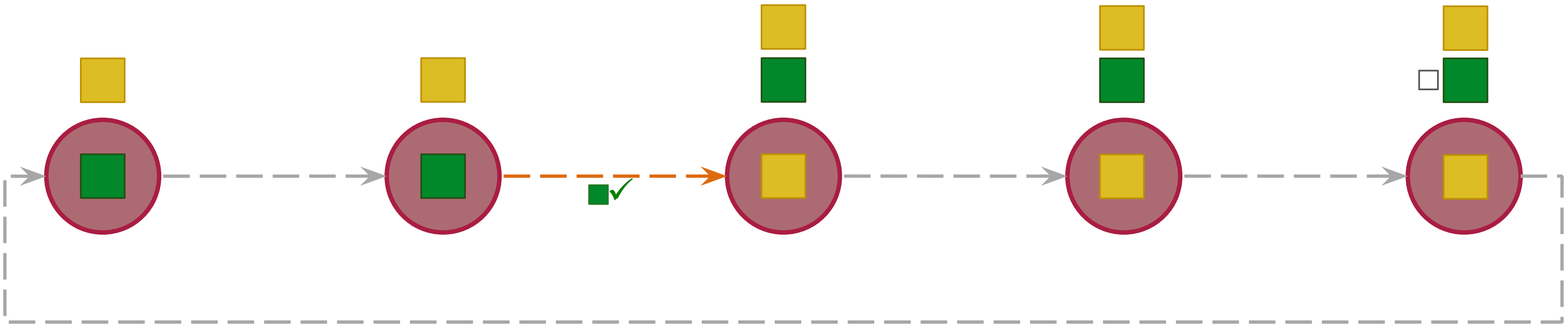

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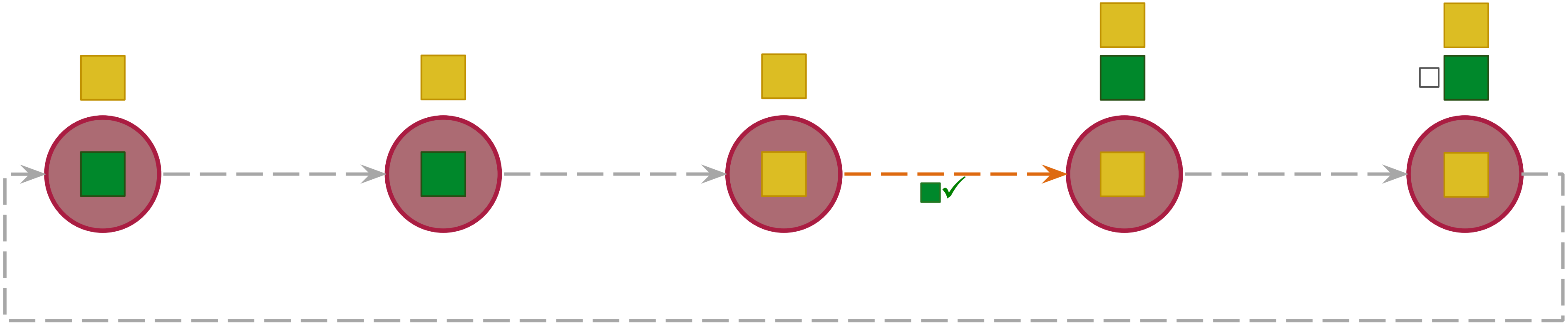

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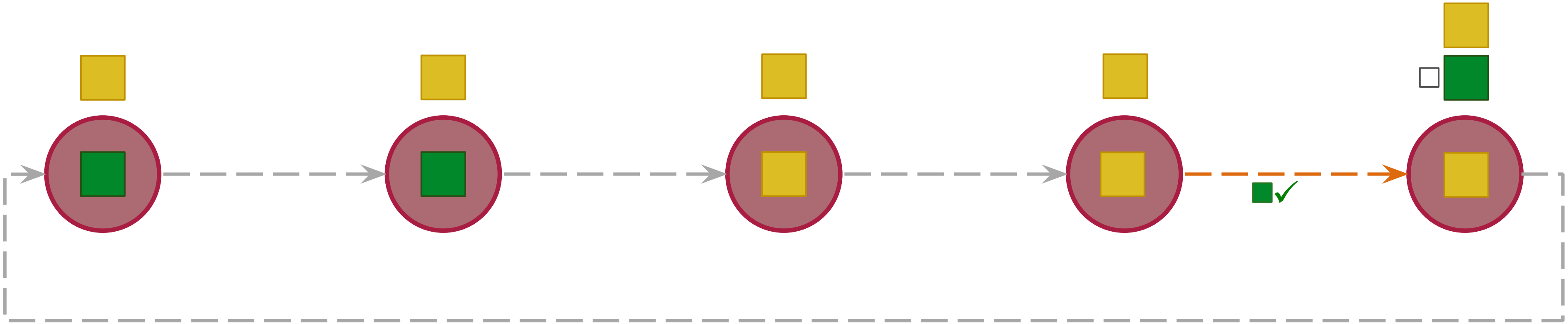

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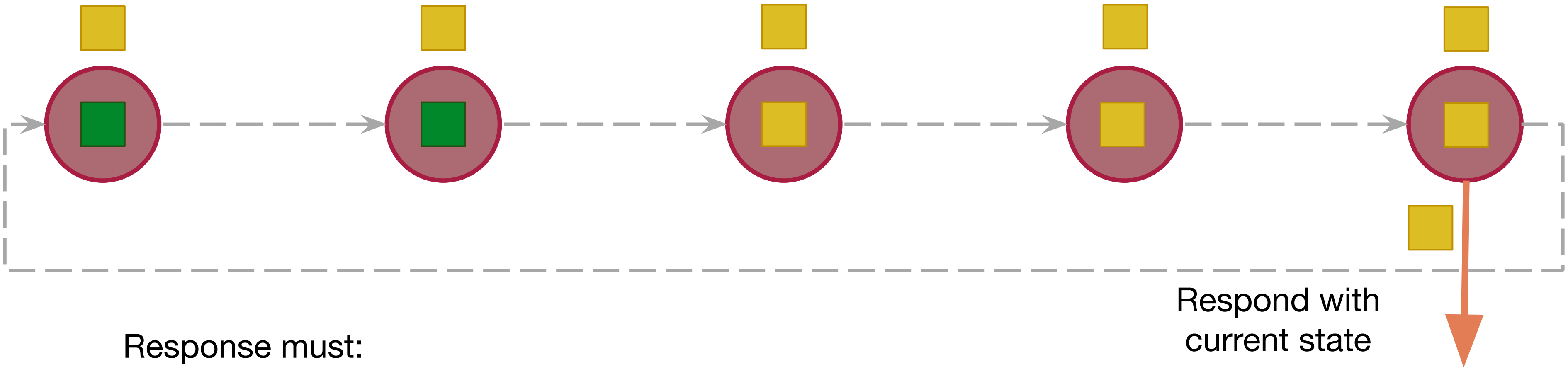

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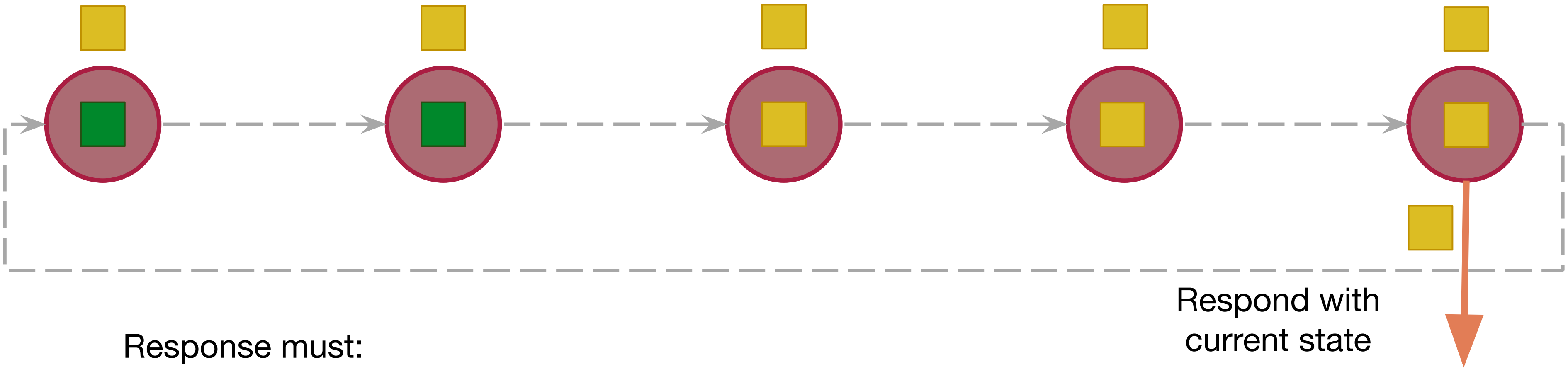
Local Linearizable Reads

Stronger than strictly required ( )

Best we can do without extra communication



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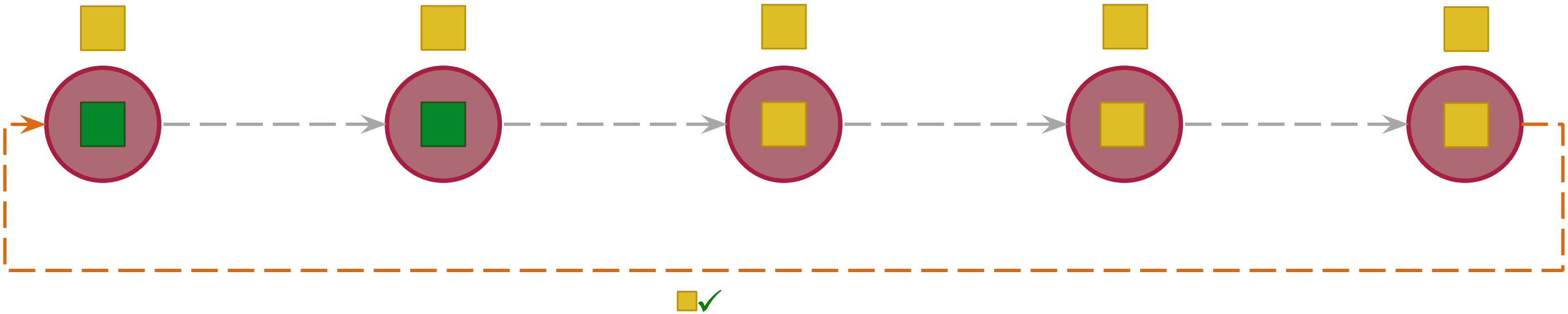

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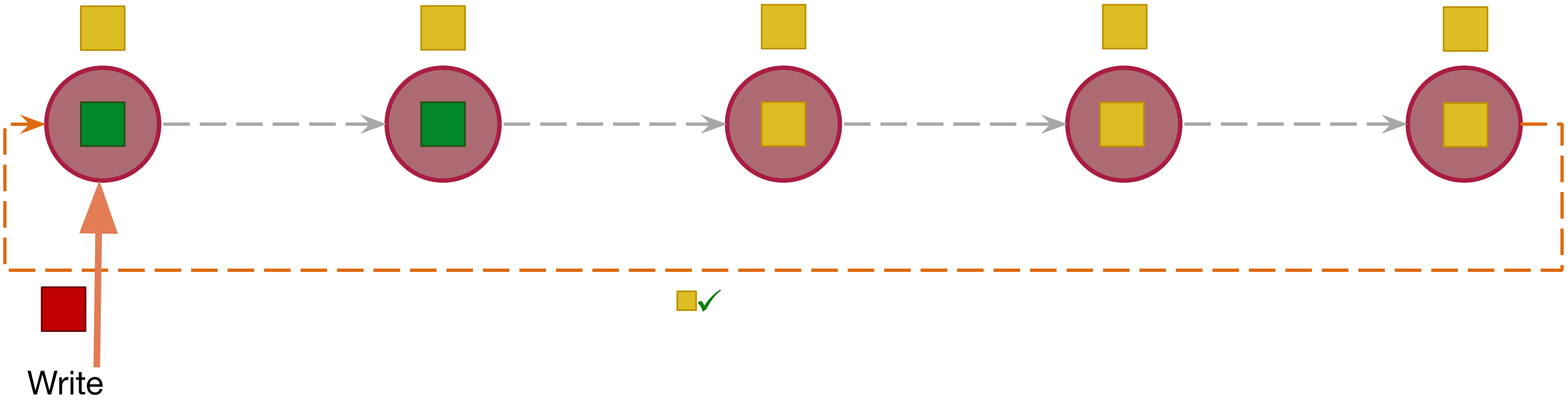

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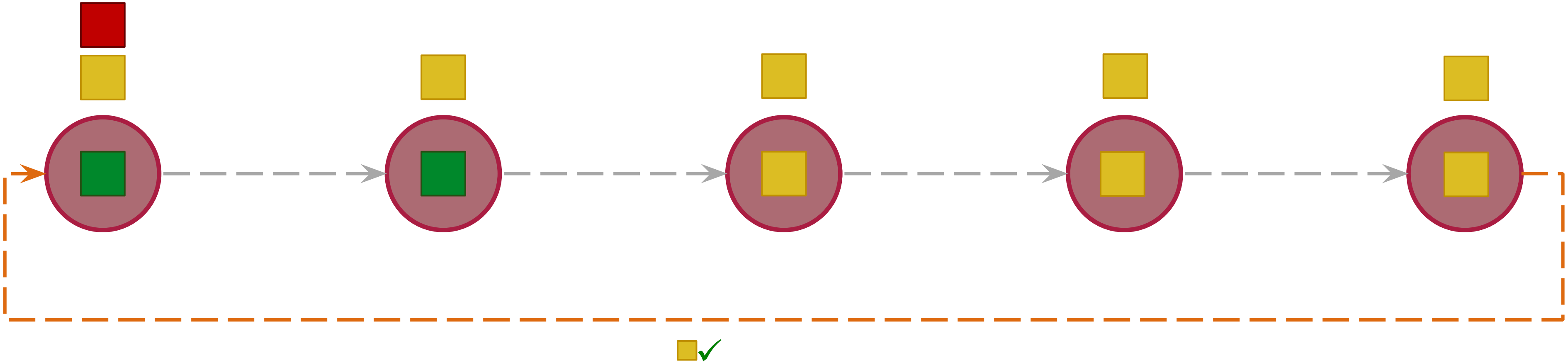

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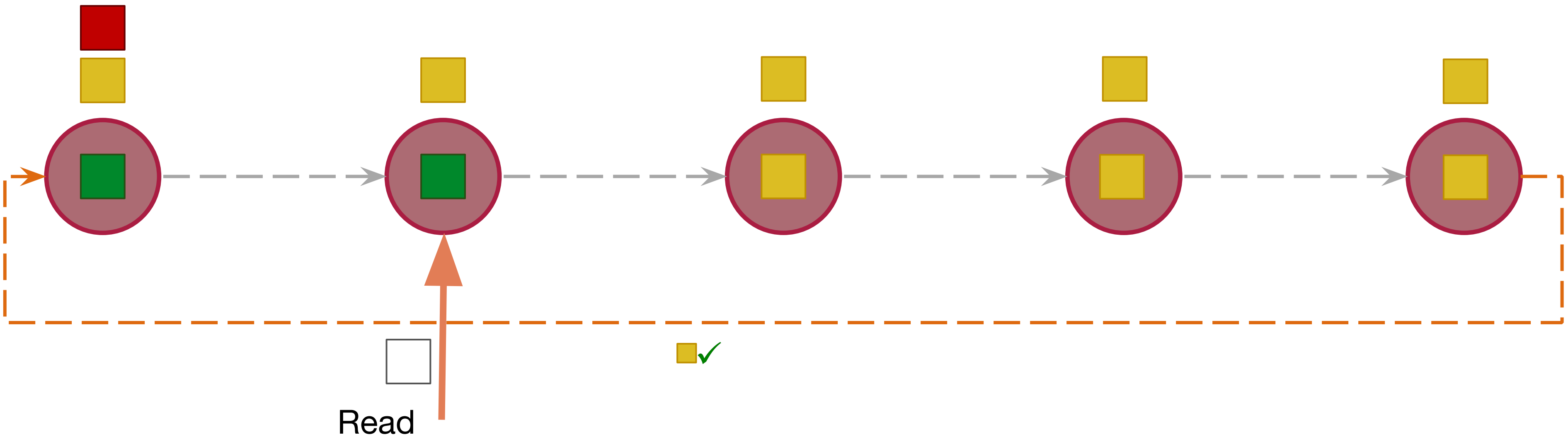

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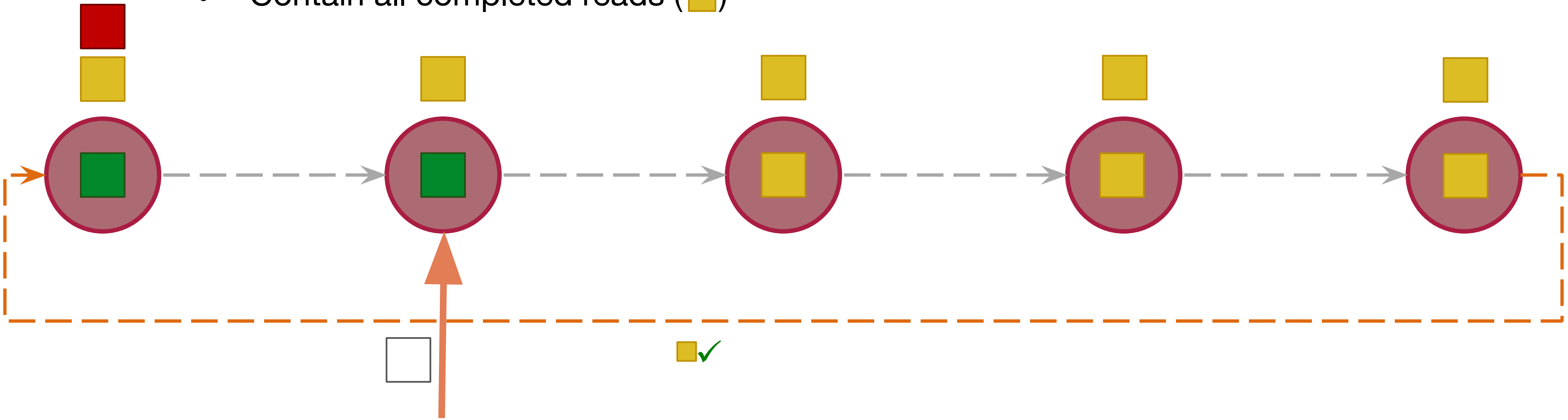

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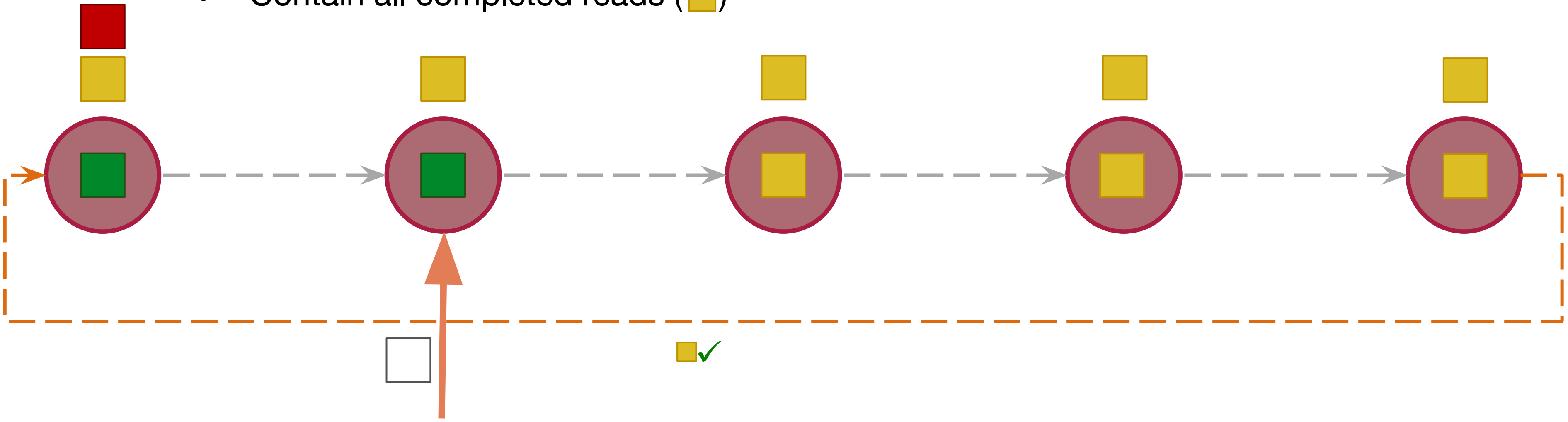

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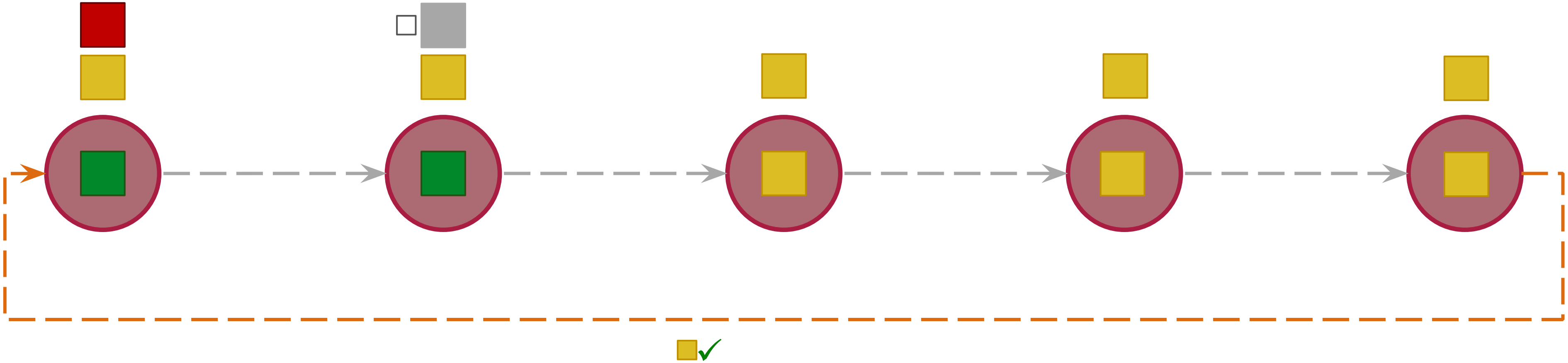

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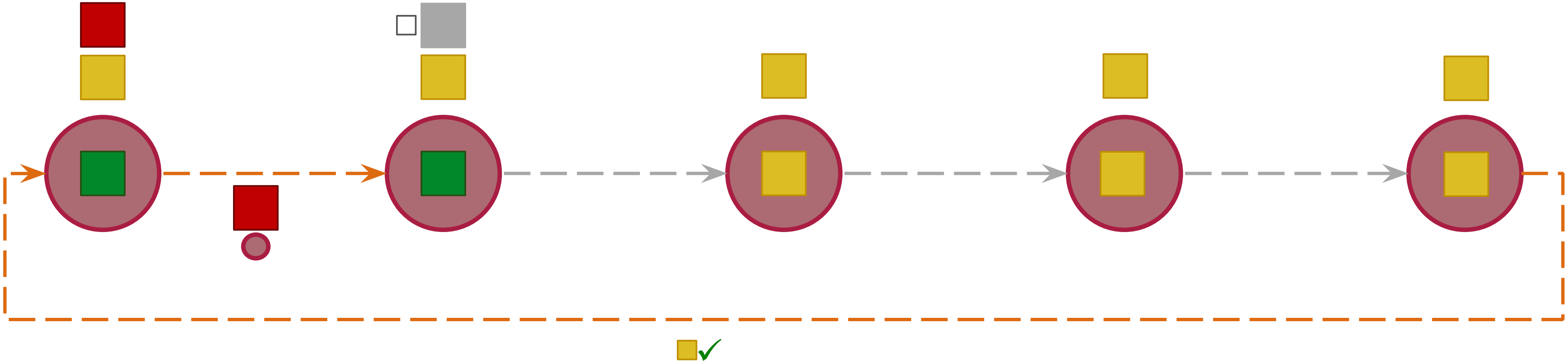

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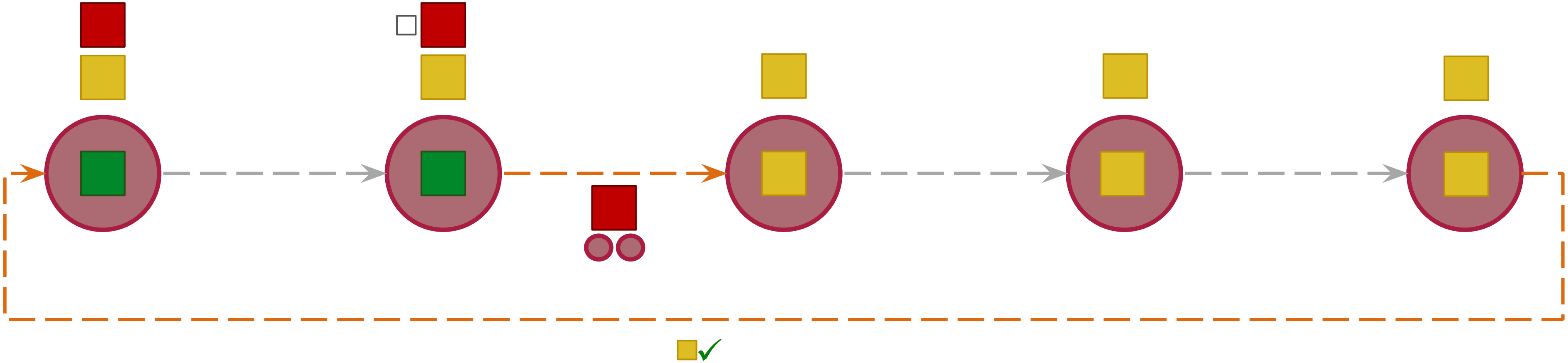
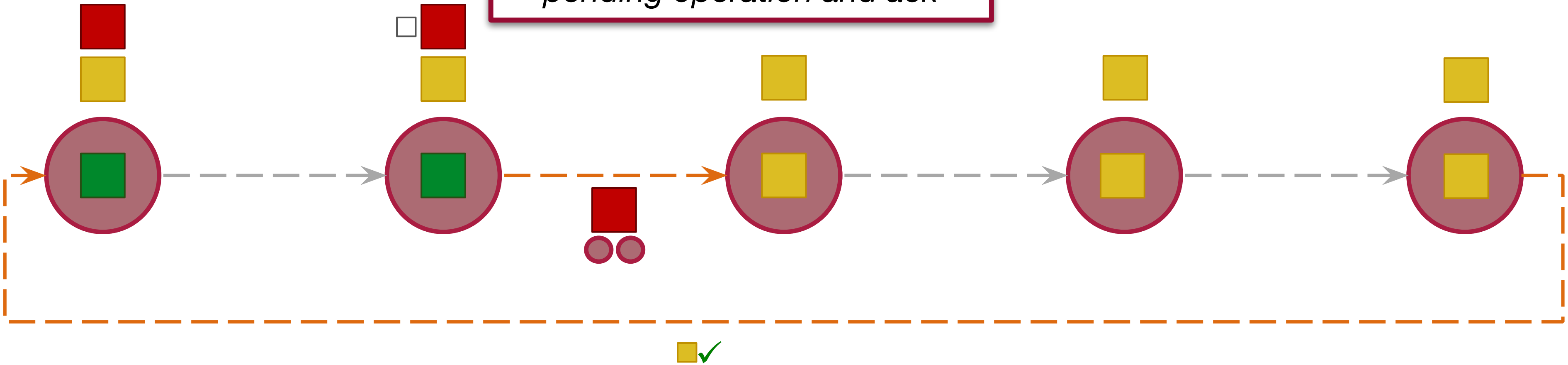


Local Linearizable Reads

Red operation will "push" every pending operation and ack



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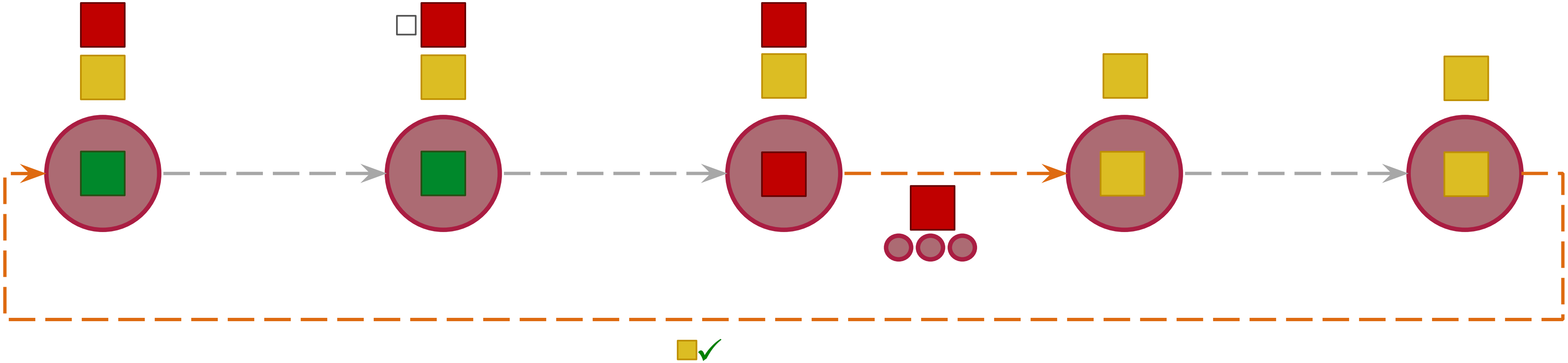

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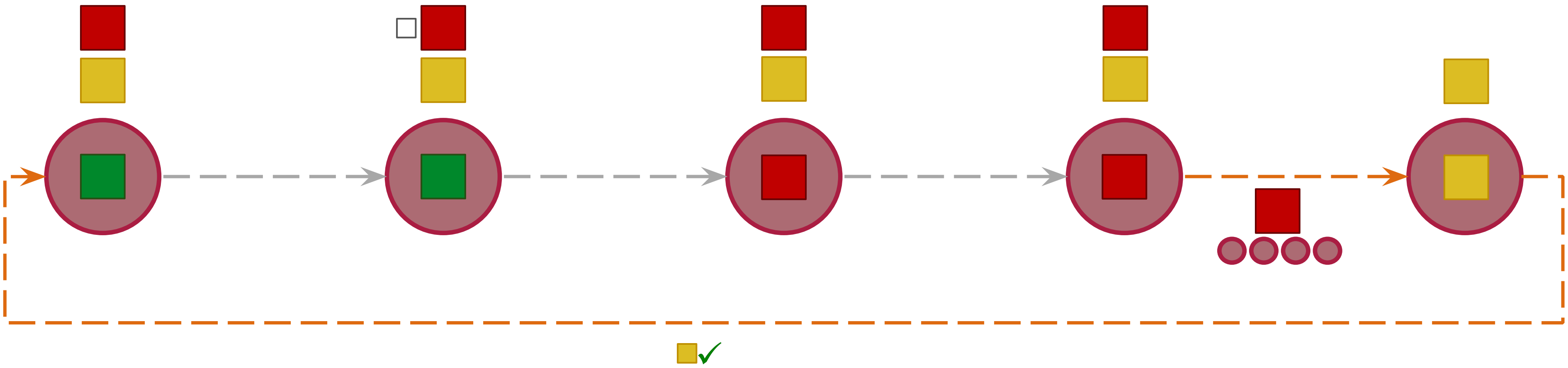

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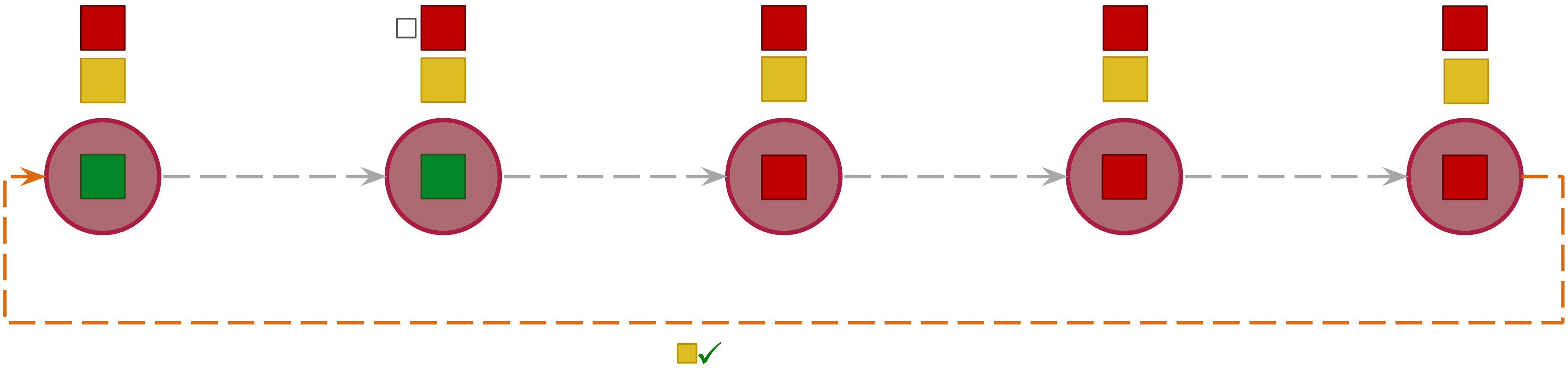

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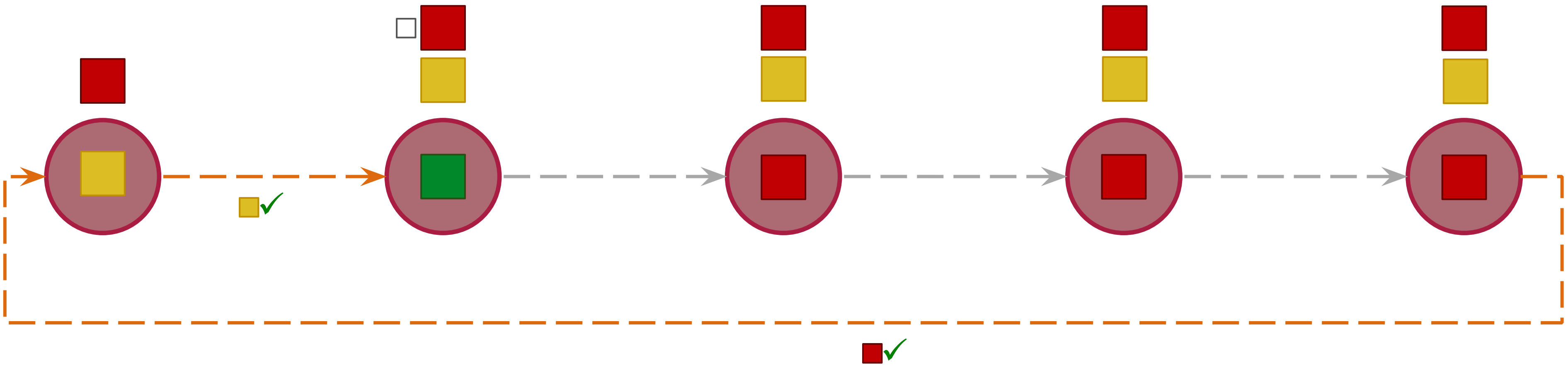

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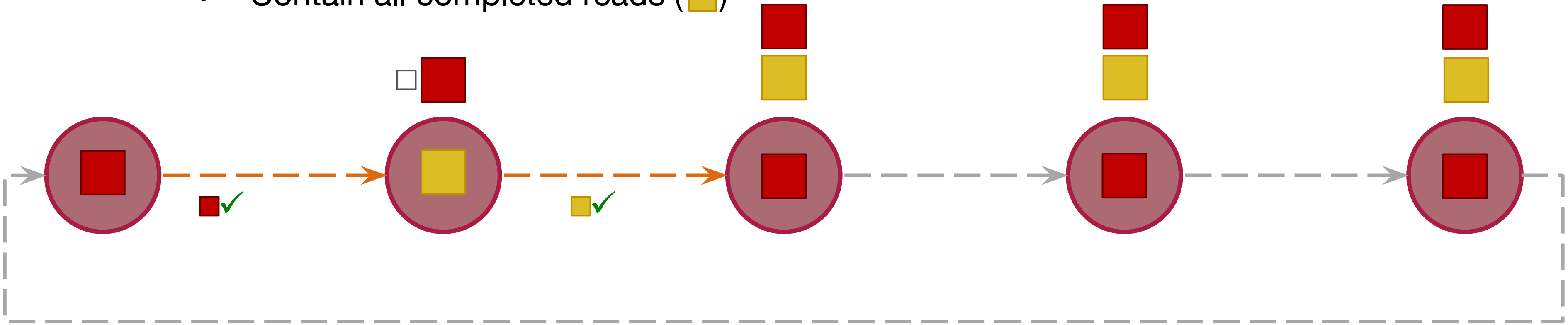

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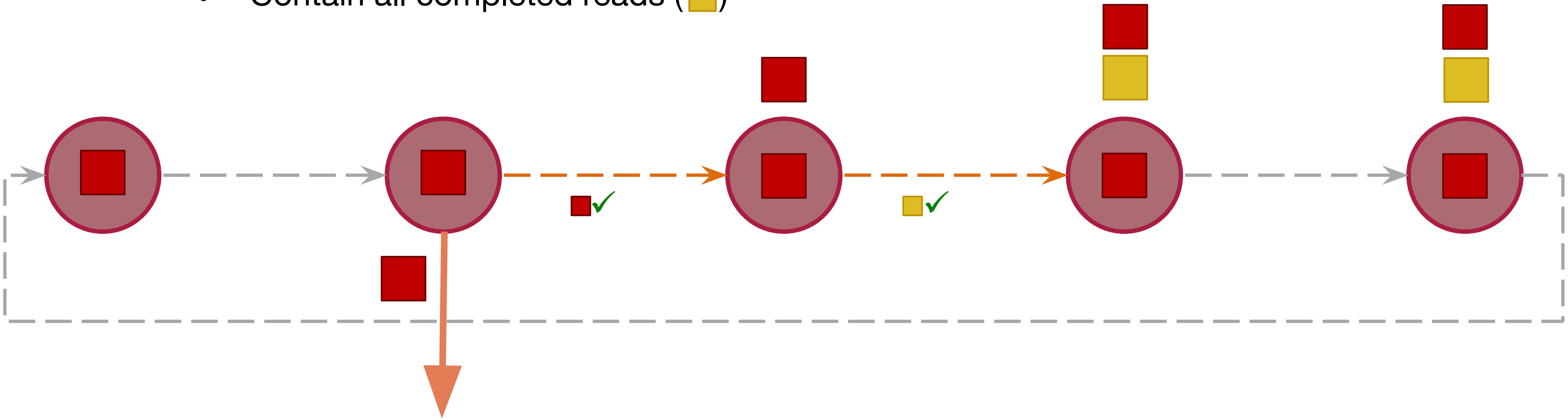

Local Linearizable Reads: Summary

- Read is dilated to guarantee linearizability:
  - Ensures all previously **completed reads and writes** are visible

- **No additional communication** steps are required
  - More **conservative** than required, but **unavoidable without coordination**

- Only possible due to **chain topology**

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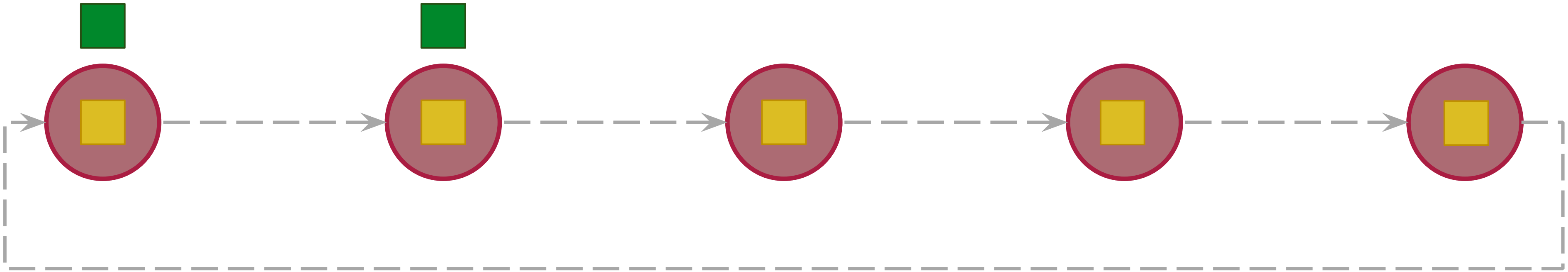
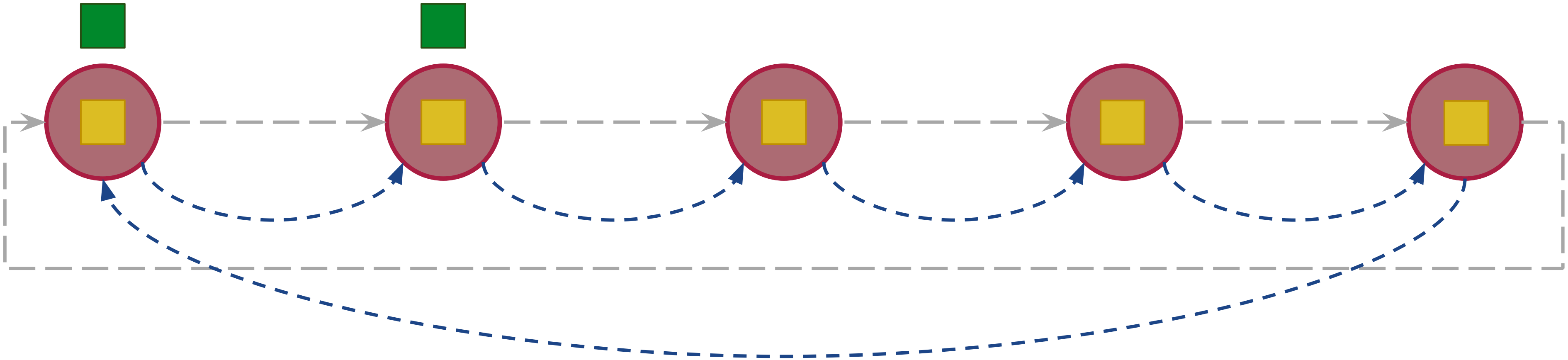
Membership Management: Removal



Membership Management: Removal

Replicas monitor the next replica in the chain



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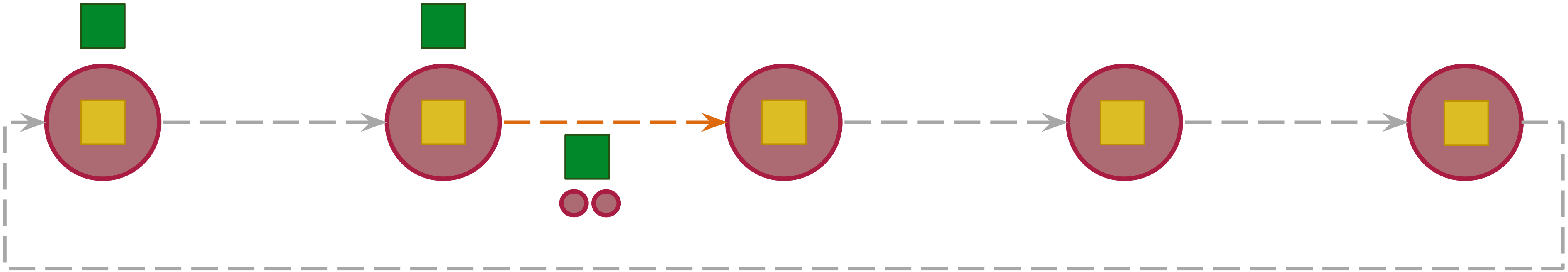

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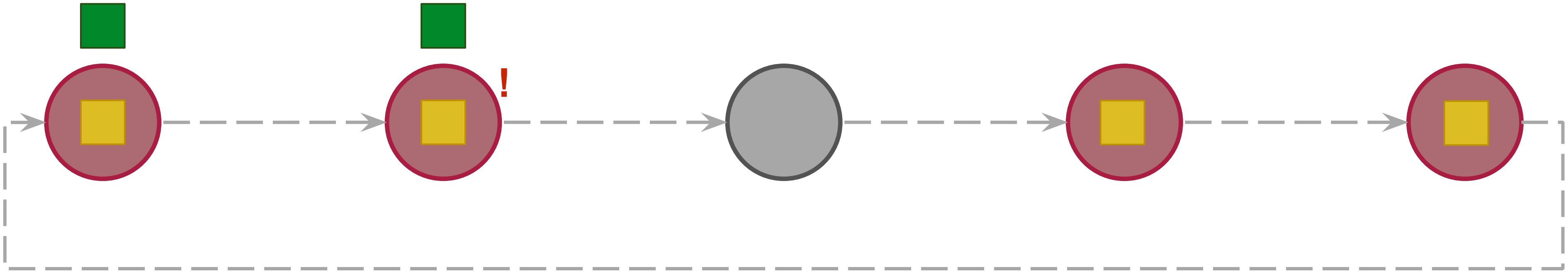

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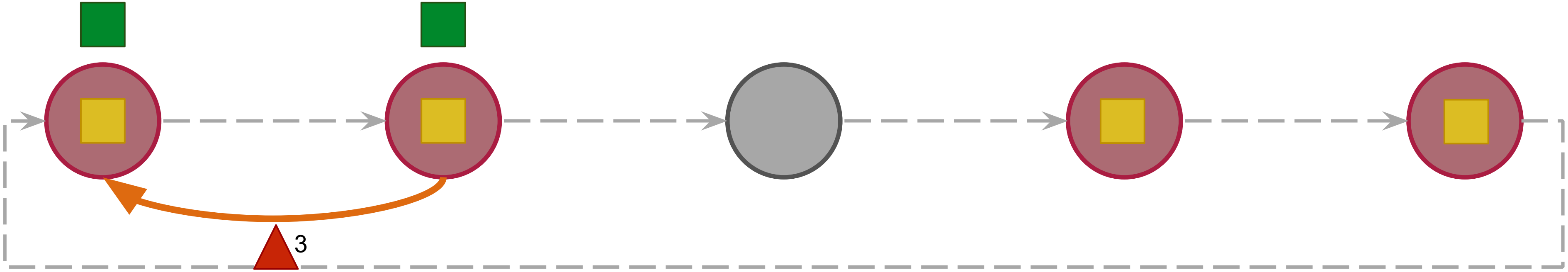
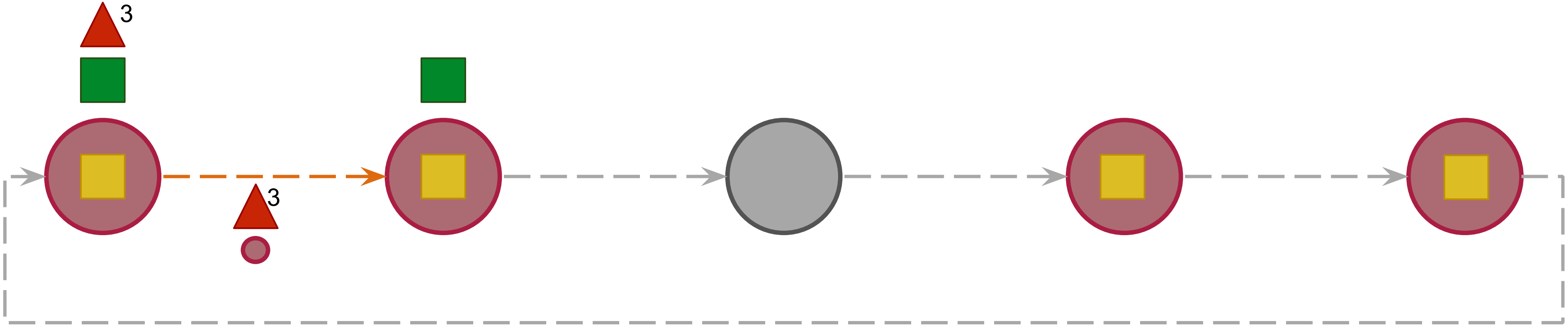


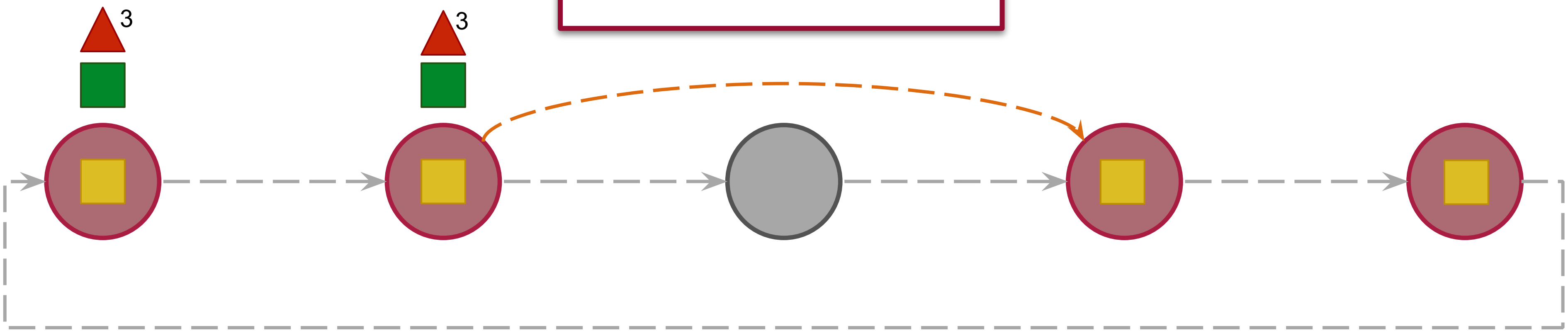
Removal requests are handled like regular operations

Membership Management: Removal



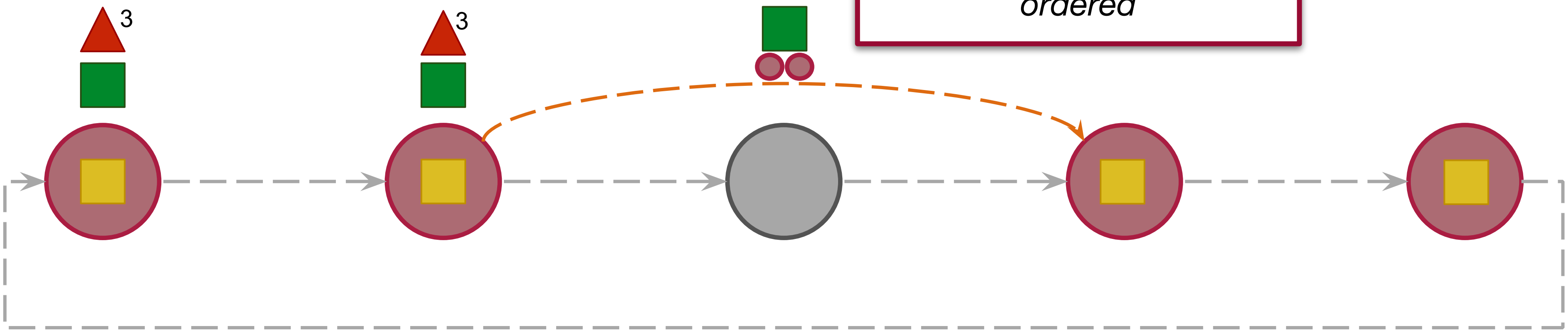
Membership Management: Removal

Skip suspected replica



Membership Management: Removal

Make sure operations are still ordered



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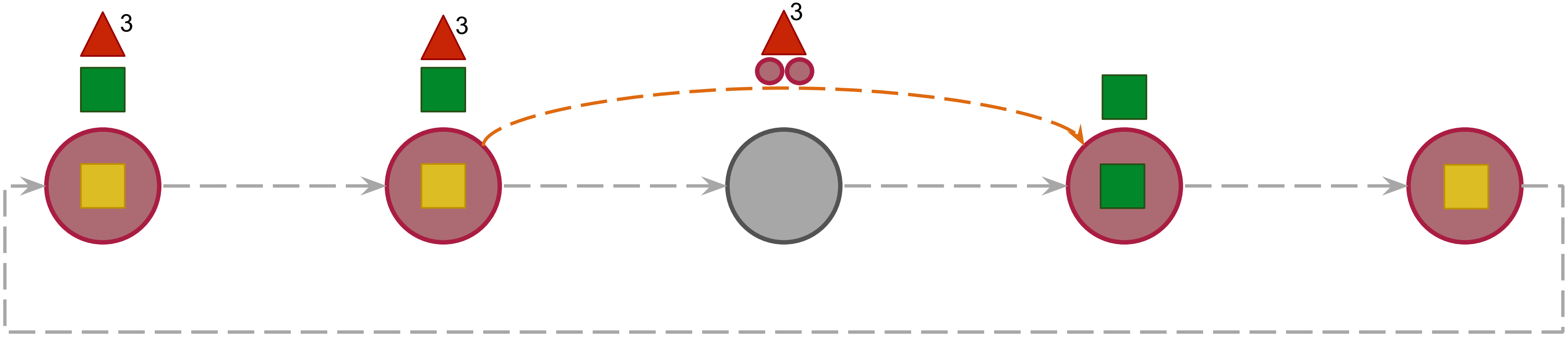

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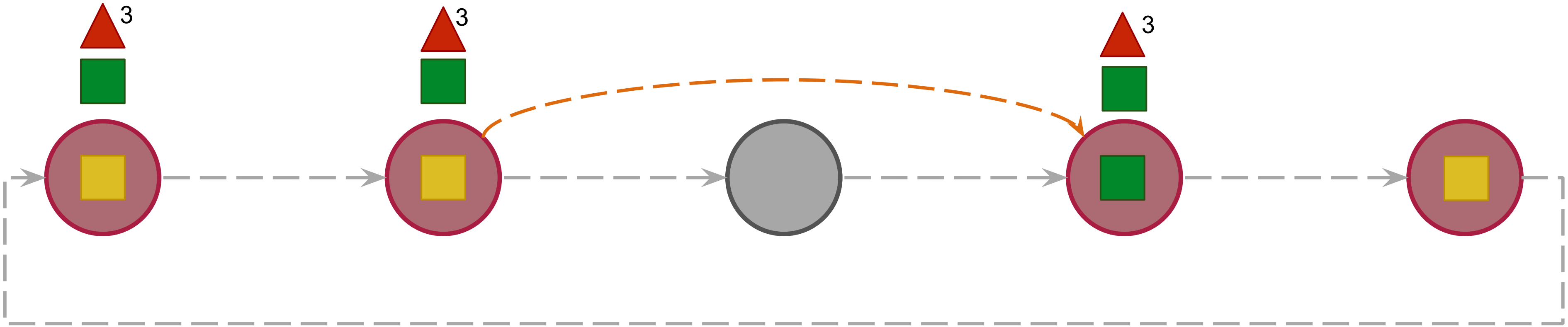

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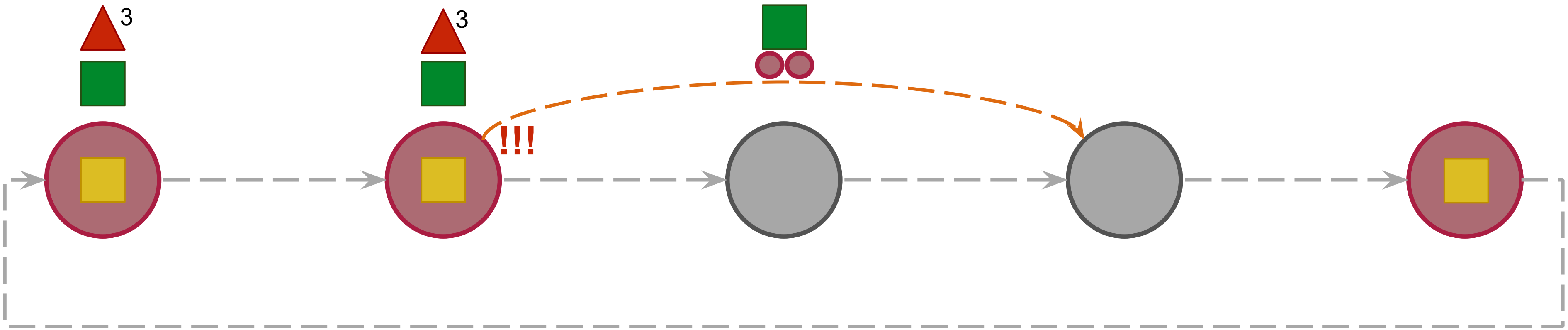

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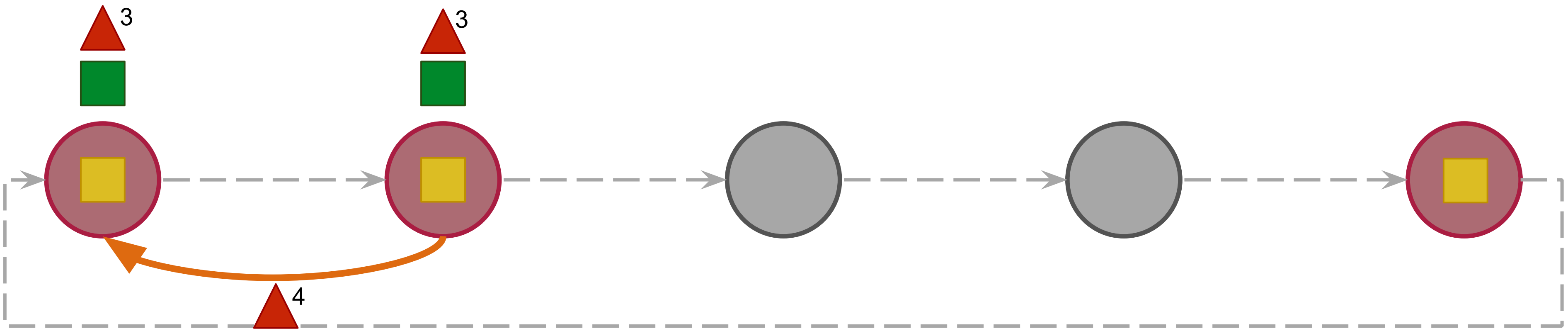

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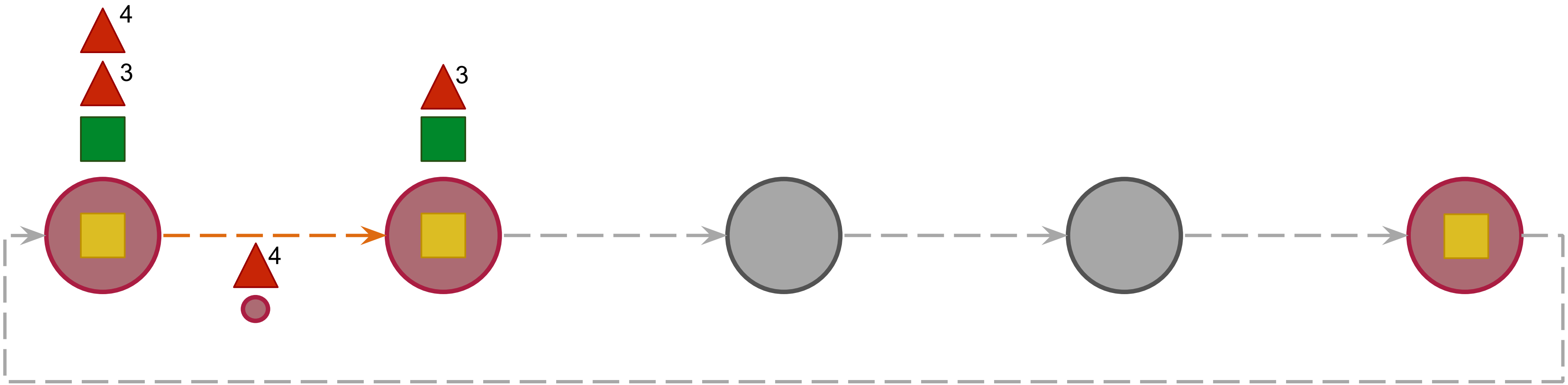

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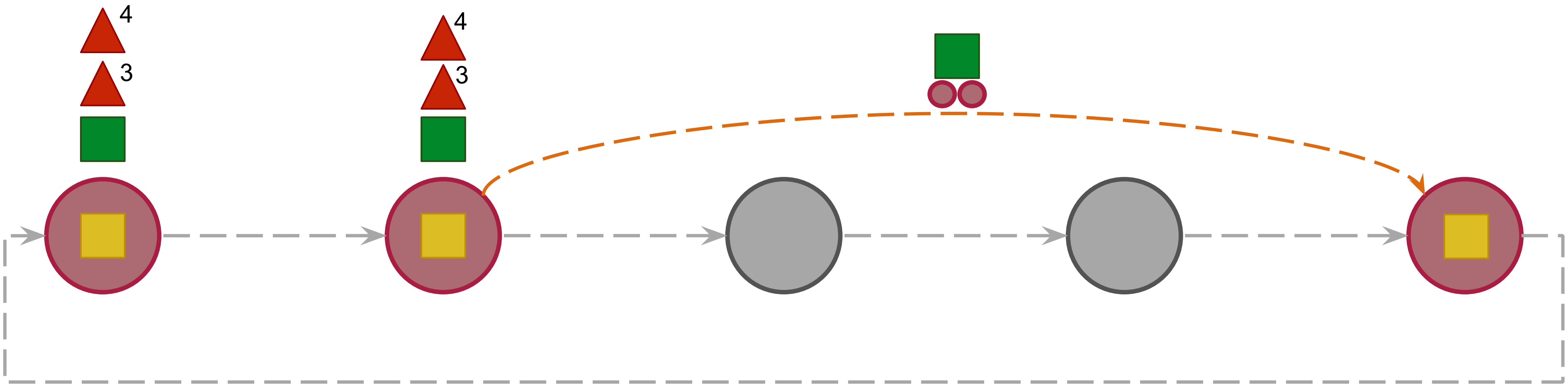

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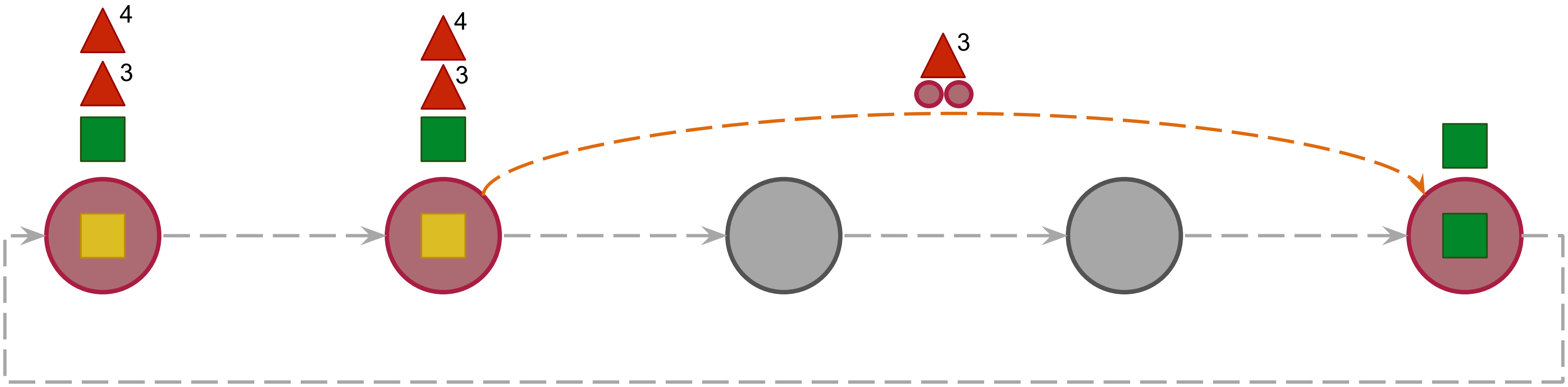

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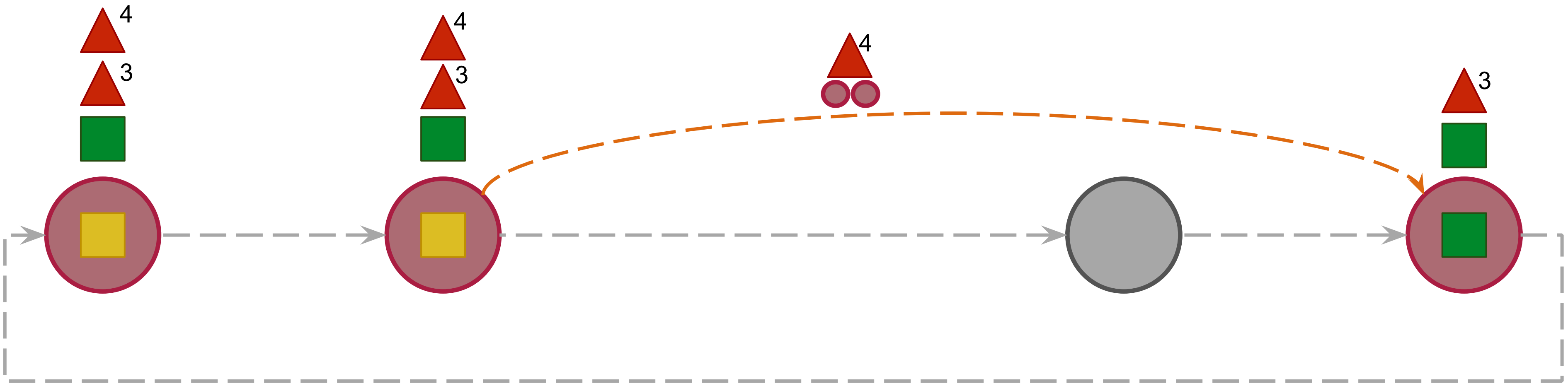

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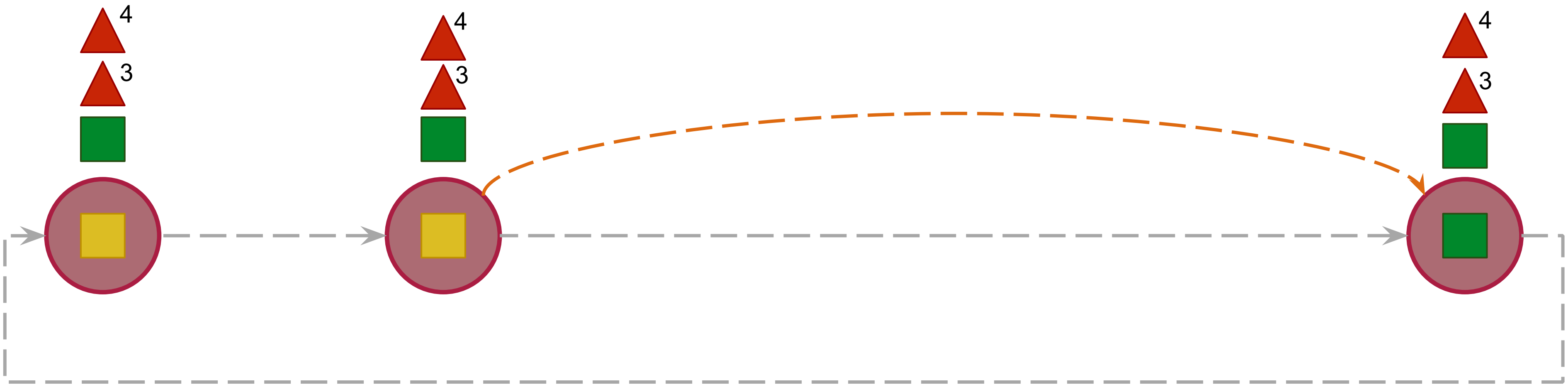

ChainPaxos: Summary

- Aggregates **Multi-Paxos messages for correction**
- **Minimizes communication cost** for write operations
- Provides **local linearizable reads** in any replica
    - With no additional communication
- **Integrated reconfiguration** and fault-tolerance
    - Avoiding external coordination services

Outline

- Motivation and Related Work
- ChainPaxos
  - Writing
  - Local Linearizable Reads
  - Reconfiguration
- Evaluation

Evaluation: Goals

- How does ChainPaxos' **performance** compare against the state-of-the-art?
- What is the **latency overhead** of the chain?
- How much do **local reads** improve on the performance?
- Is ChainPaxos adequate to be **used in a practical setting**?

Evaluation: Setup

Compare with state-of-the-art

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Evaluation: Methodology

Using Grid5000 testbed

Emulating clients with YCSB

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Measured:

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- Latency (as perceived by clients)

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Emulating clients with YCSB

Measured:

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- Latency (as perceived by clients)

Varying:

- Number of consensus replicas (3, 5, 7)
- Load on the system (YCSB clients)
- Workload (read/write ratio)

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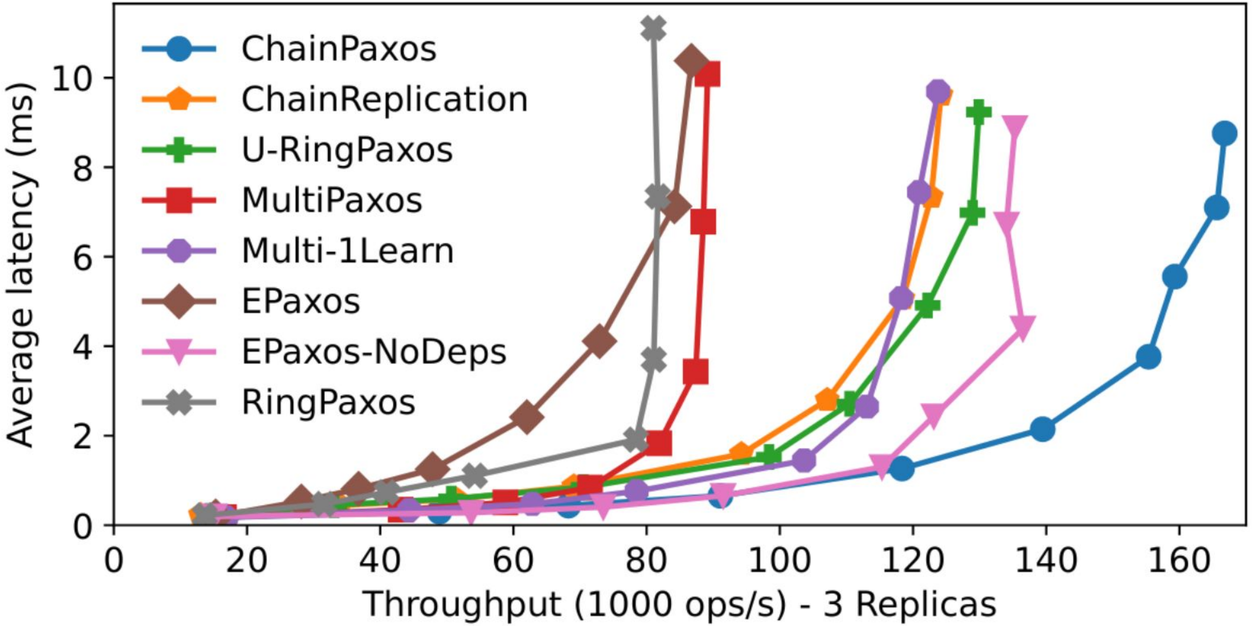

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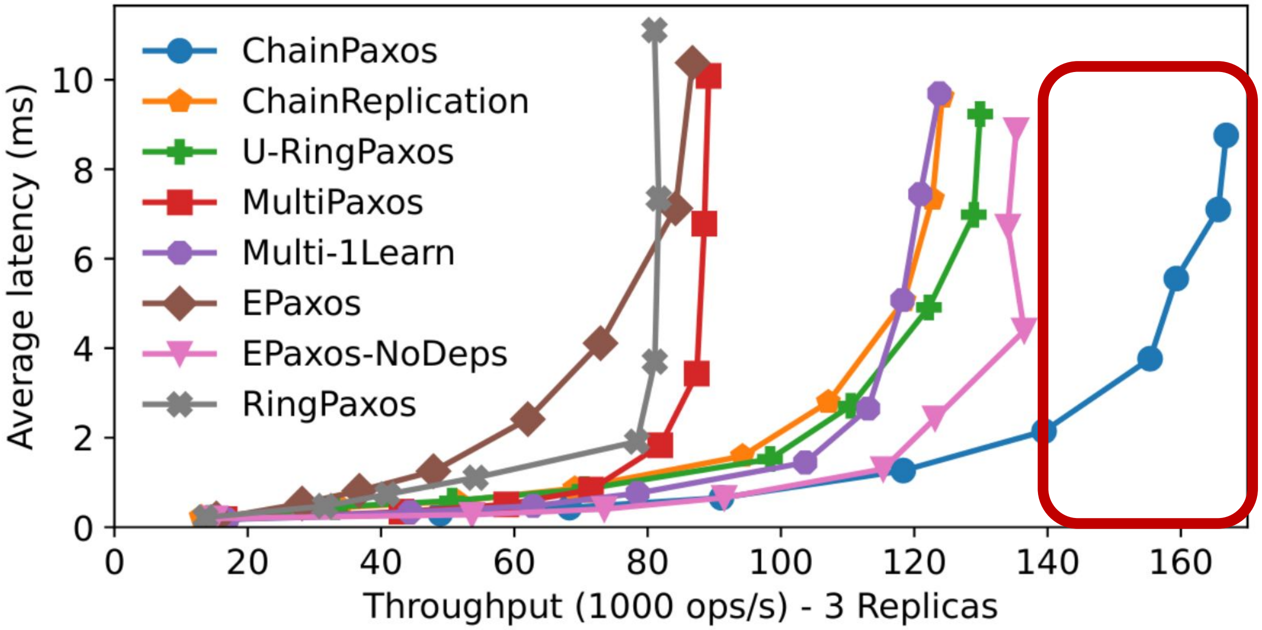

Minimizing the number of messages maximizes throughput

Evaluation: Results

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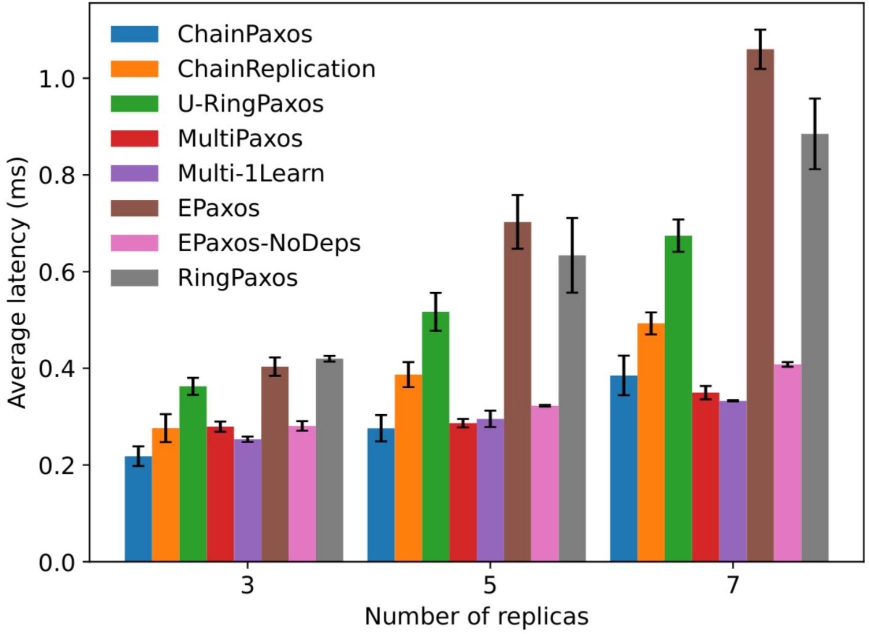

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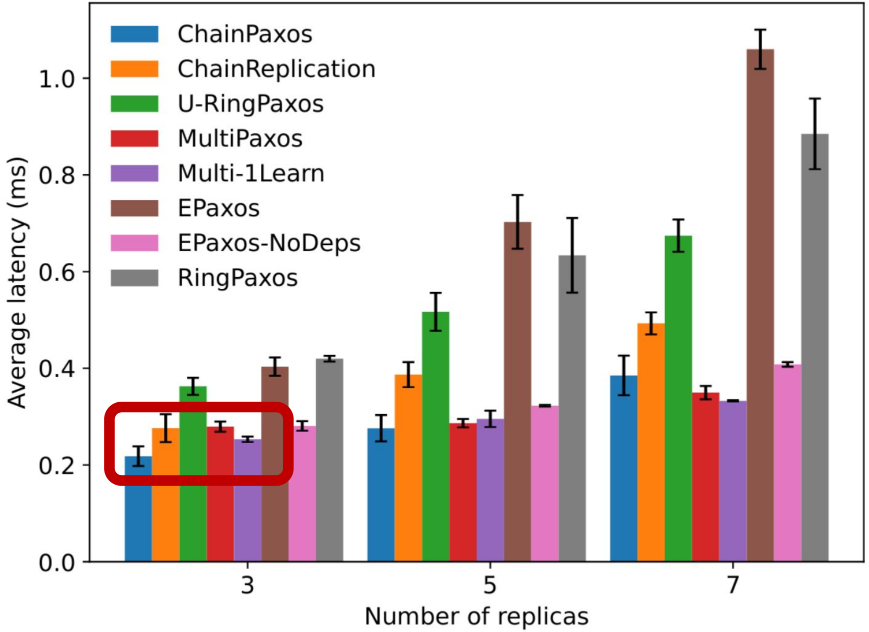

Latency is lower with a small number of replicas

Evaluation: Results

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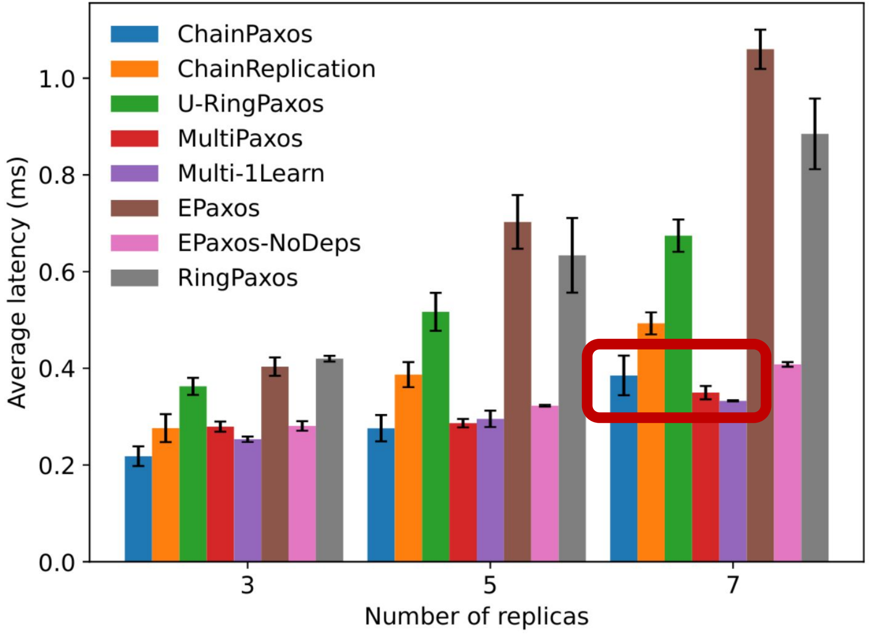

Latency is lower with a small number of replicas

Only starts being a problem with >7 replicas

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*How much do **local reads** improve on the performance?*

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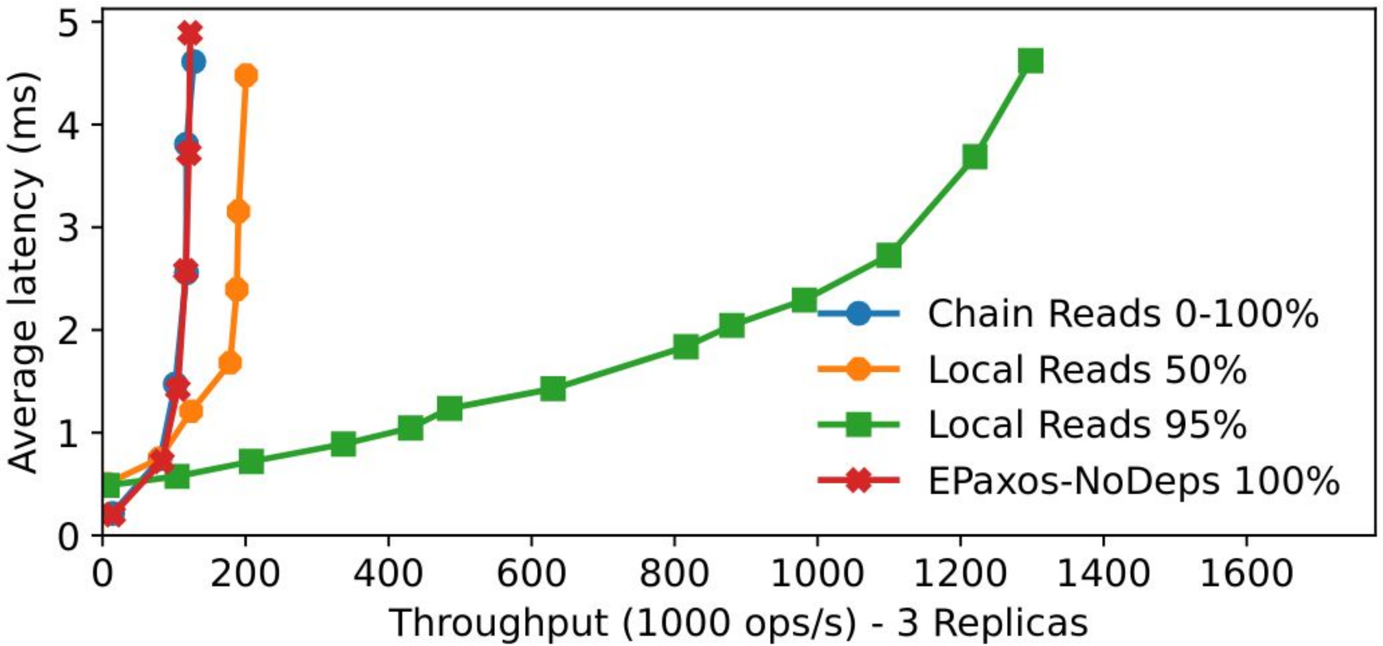

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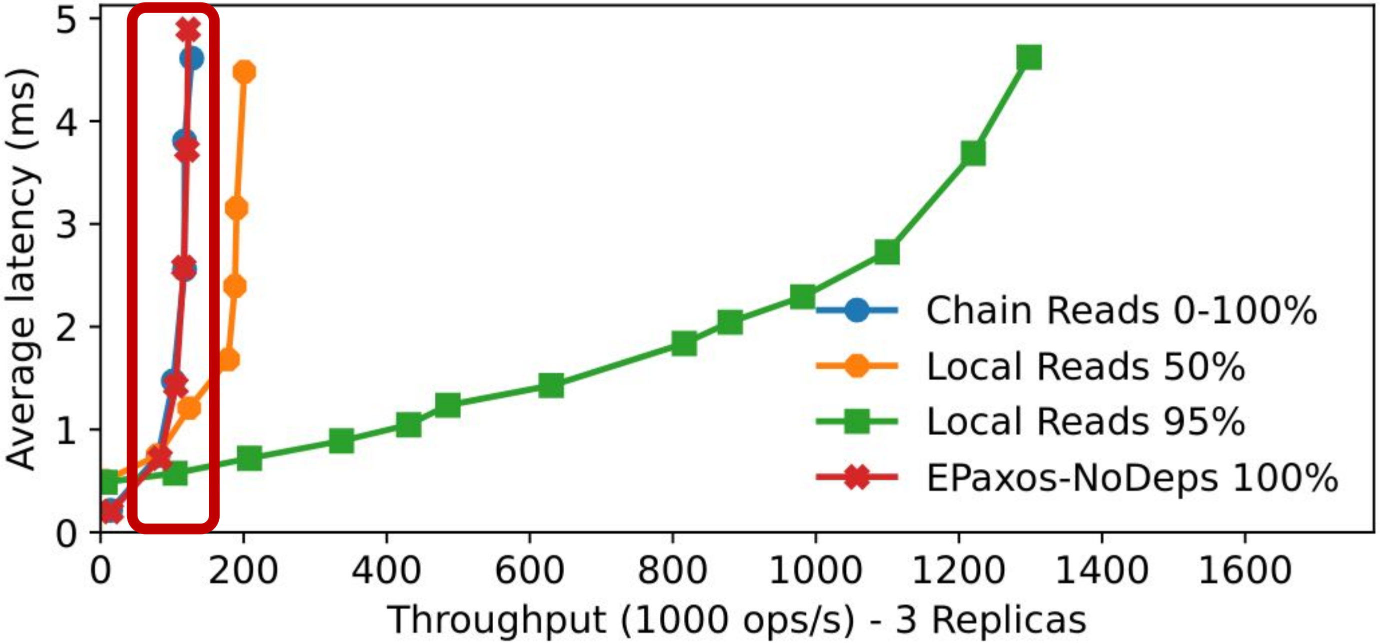

Reading through the chain is slow

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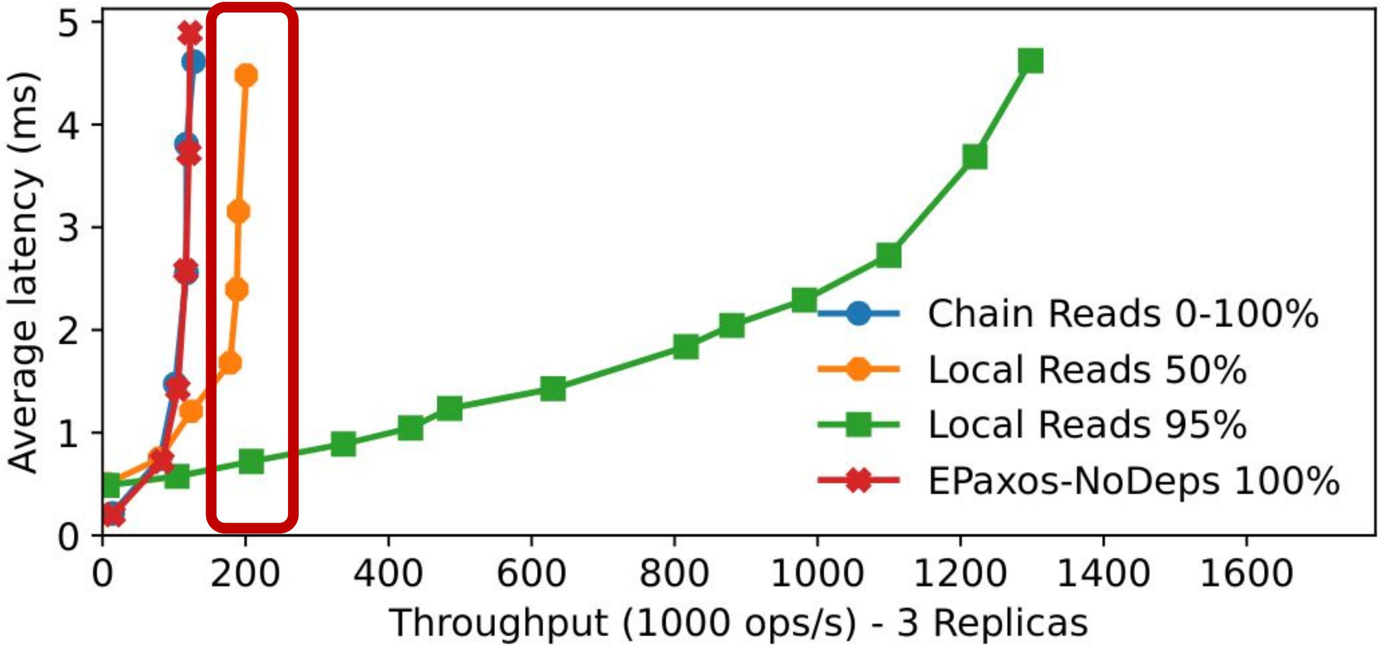

Reading through the chain is slow

Performance increases drastically with % of reads

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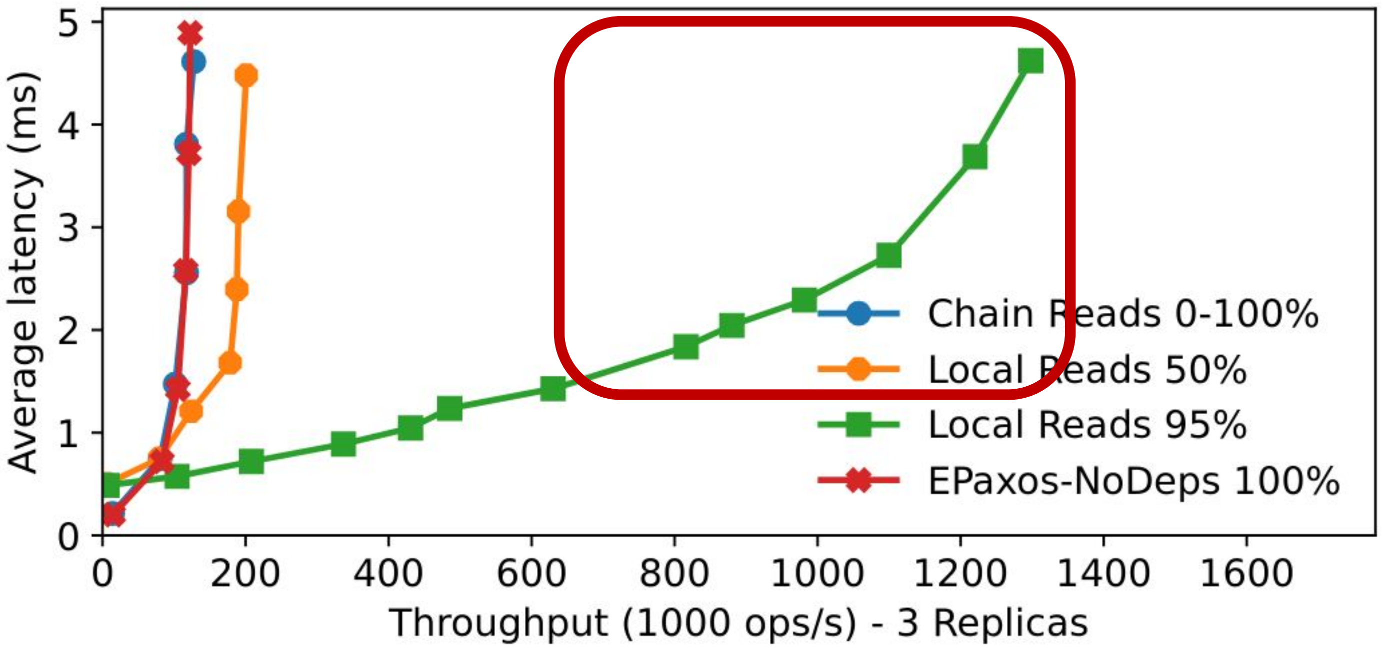

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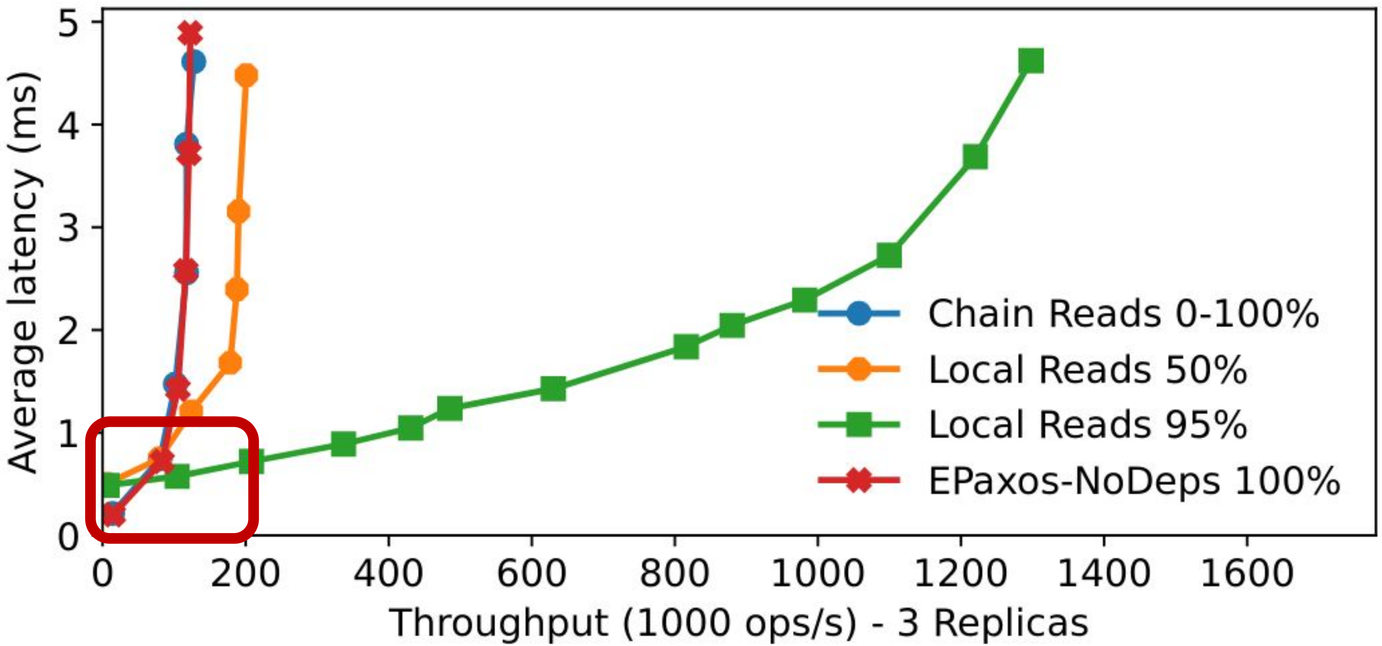

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Performance increases drastically with % of reads

Latency overhead is minimal

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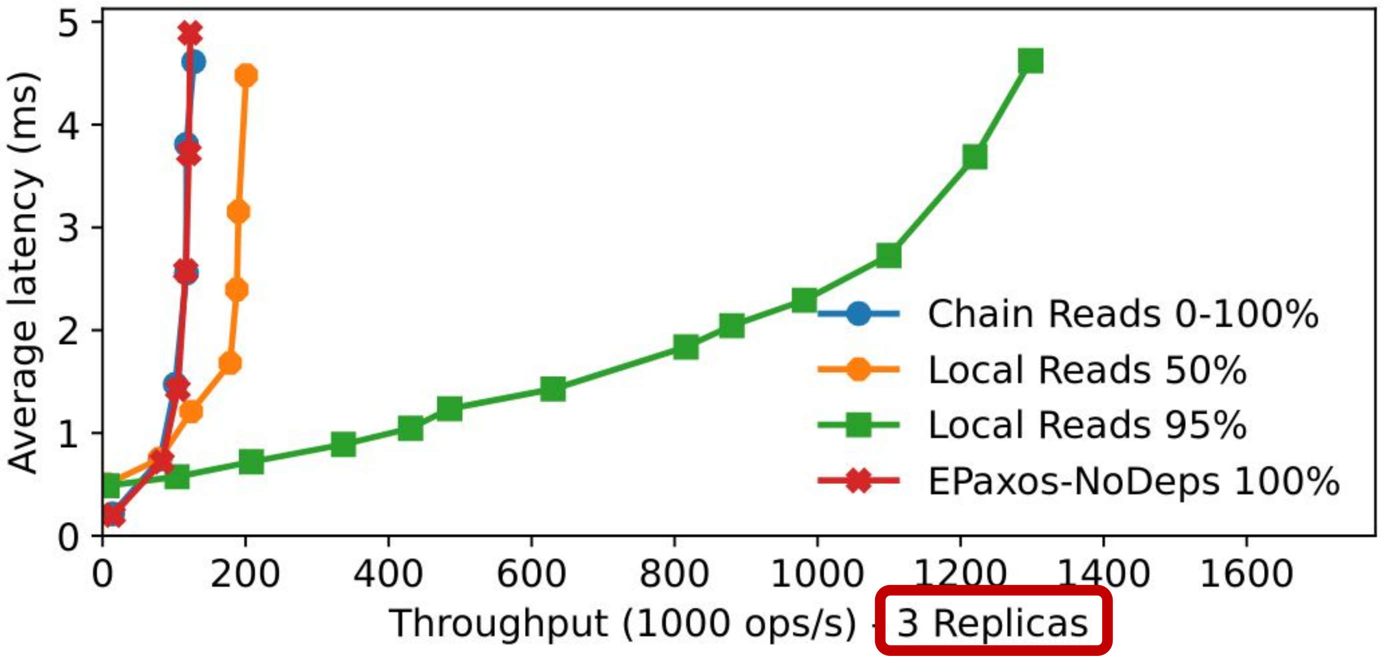

*Performance **increases** with number of replicas*

~1300 with 3 replicas

Evaluation: Results

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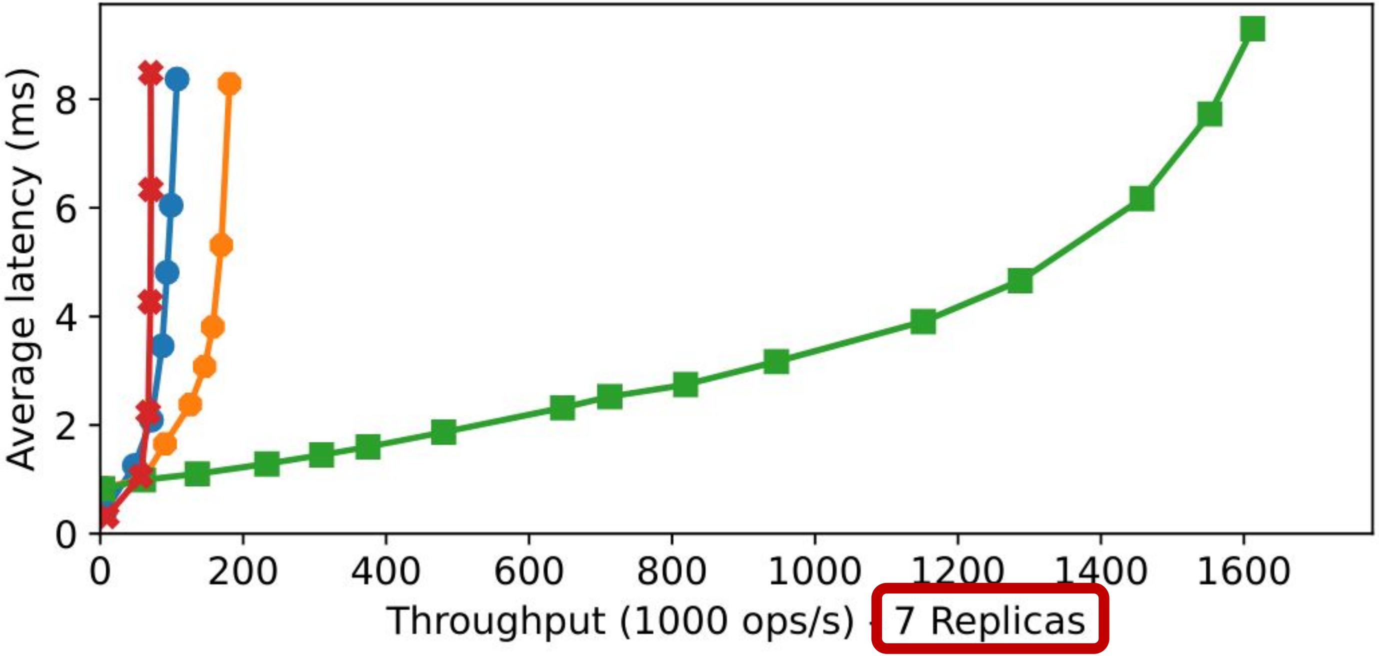

*Performance **increases** with number of replicas*

~1300 with 3 replicas
~1600 with 7 replicas

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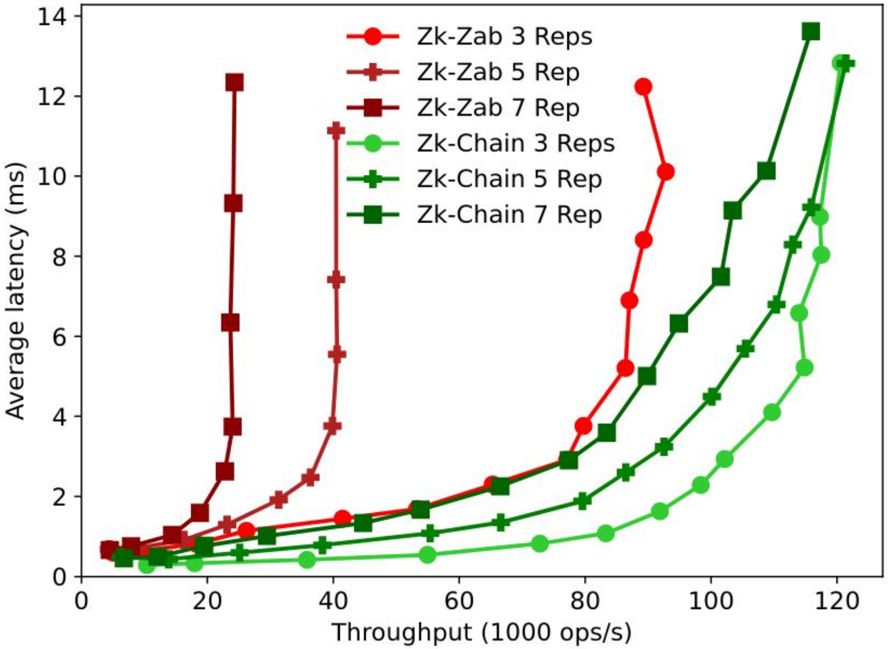

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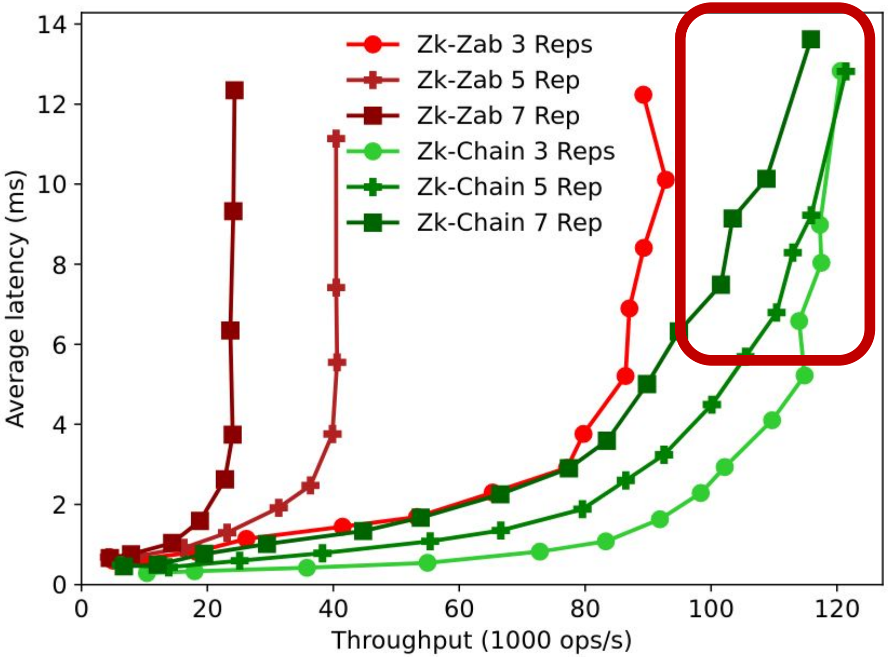

ChainPaxos shows higher throughput

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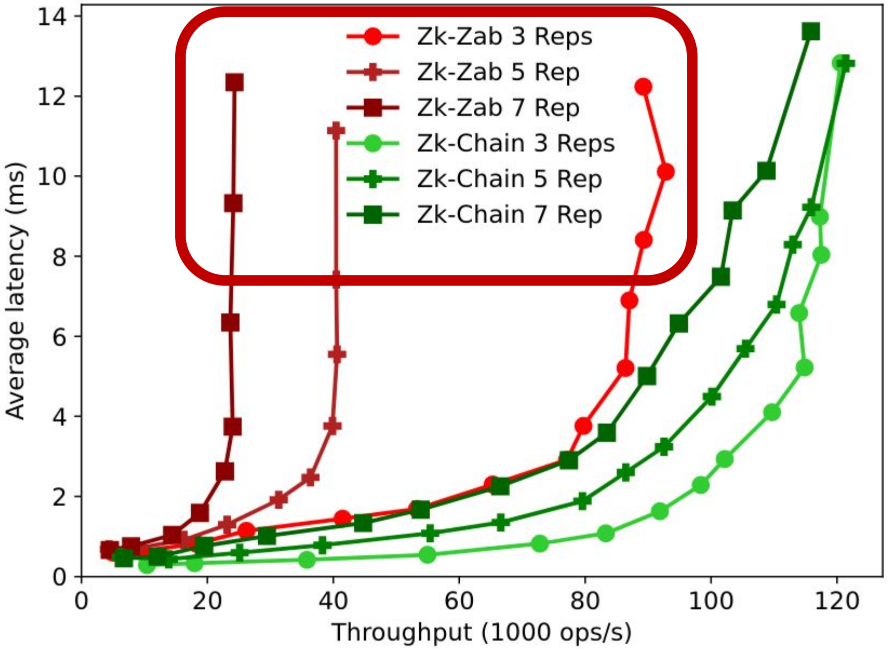

ChainPaxos shows higher throughput

Zab's throughput decreases with number of replicas

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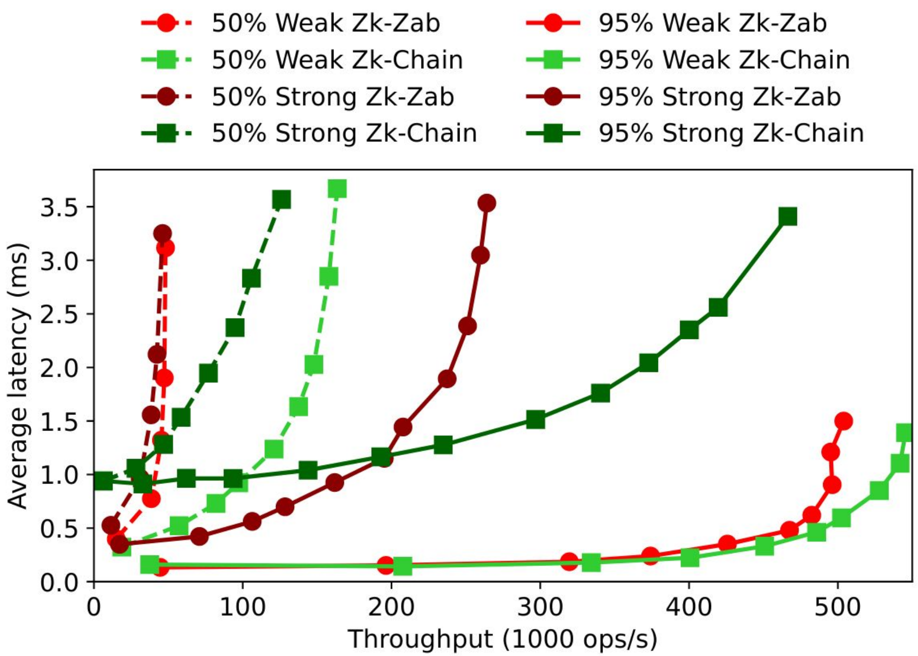

Mixed workload with 7 replicas

Evaluation: Results

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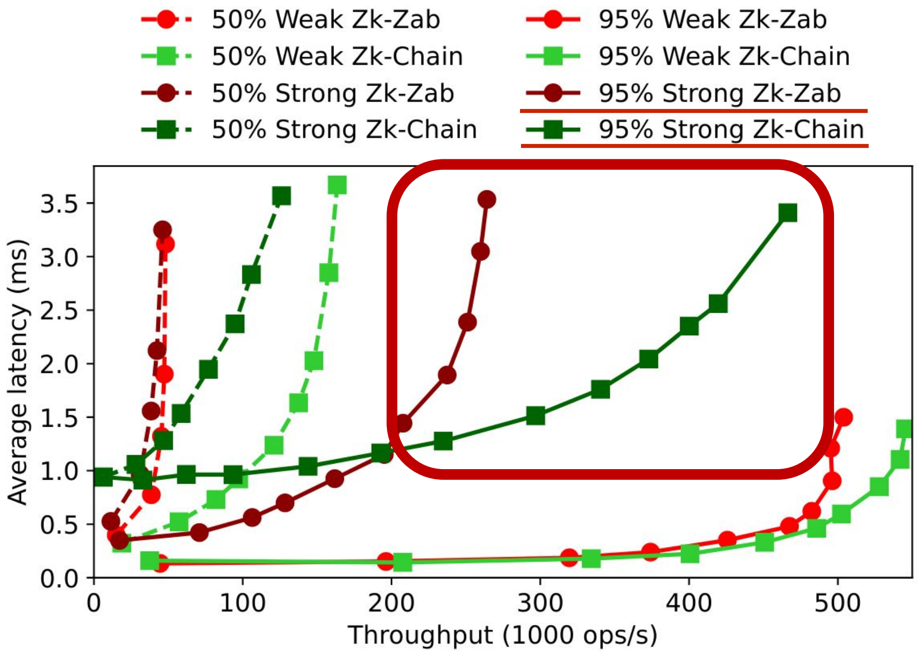

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ChainPaxos' linearizable reads show better performance

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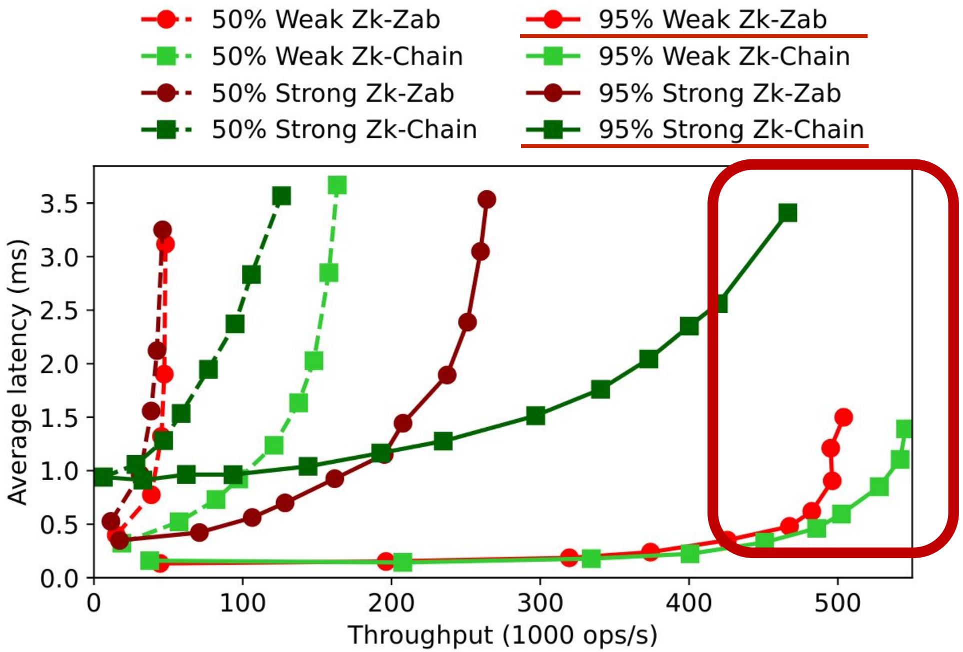

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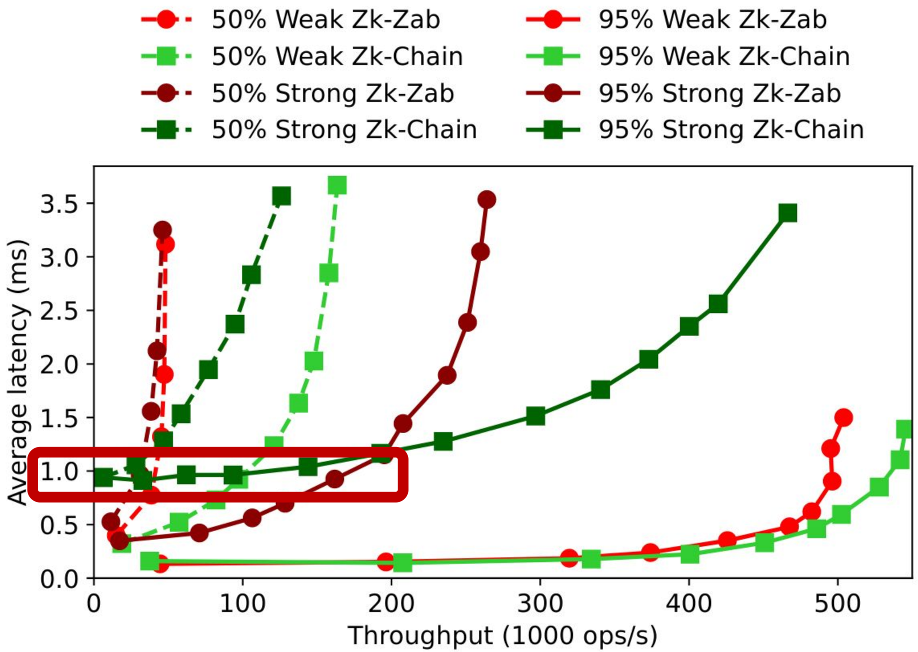

Mixed workload with 7 replicas

ChainPaxos' linearizable reads show better performance

Nearly match performance of weakly-consistent Zab reads

With minimal latency overhead

Recap: ChainPaxos

Novel consensus algorithm:

- **Combining** the best properties of Multi-Paxos and Chain Replication
    - Correction in an **asynchronous network**
    - **Constant** message **complexity**

- Going beyond existing solutions:
    - **Maximizing throughput** of both read and write operations
    - Providing **local linearizable reads** in any replica
    - **Integrated reconfiguration** and fault-tolerance

High Throughput Replication with Integrated Membership Management

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USENIX ATC 2022

NOVA LINCS
LABORATORY FOR COMPUTER SCIENCE AND INFORMATICS

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