Large Scale Systems
CS 410 / 510

Lecture 13:

Speculation in Consensus

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Assignment 3 is Out!

- Assignment 3 is due on **May 18, 2026** at **11:59pm PST**.
- Please start working with your groups.

Last Class

- Last class we looked at:

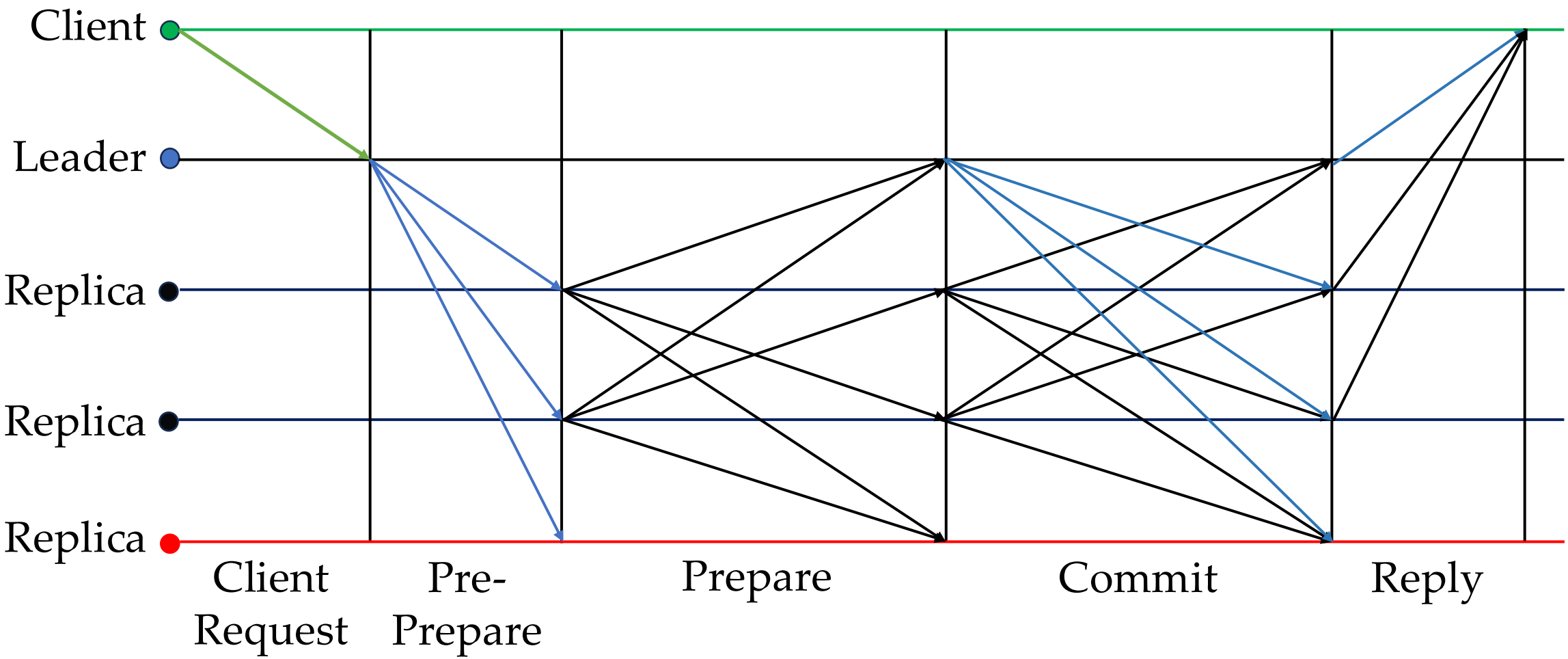
- PBFT Intricacies and view change

Optimizing PBFT

- Today, our goal is to optimize PBFT.

- How can we make PBFT more performant?

PBFT Protocol



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  - No, because we need to start separating the consensus from execution.

- How can out-of-order message processing help increase PBFT's throughput?
  - We can allow the leader to send the next Pre-prepare message without waiting for the previous message to reach the Commit.
  - Essentially, replicas will no longer be idle → parallel-pipelined architecture.

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- When the replica receives n-f Commit messages for the **k**-th Pre-Prepare message, it puts the transaction in an execution queue.

- The replica executes **k**-th transaction once it has executed (**k-1**)-th transaction.
  - Ex: Cannot execute 4^{th} transaction without executing the 3^{rd} transaction.

Execution and Reply under Out-of-Order Processing

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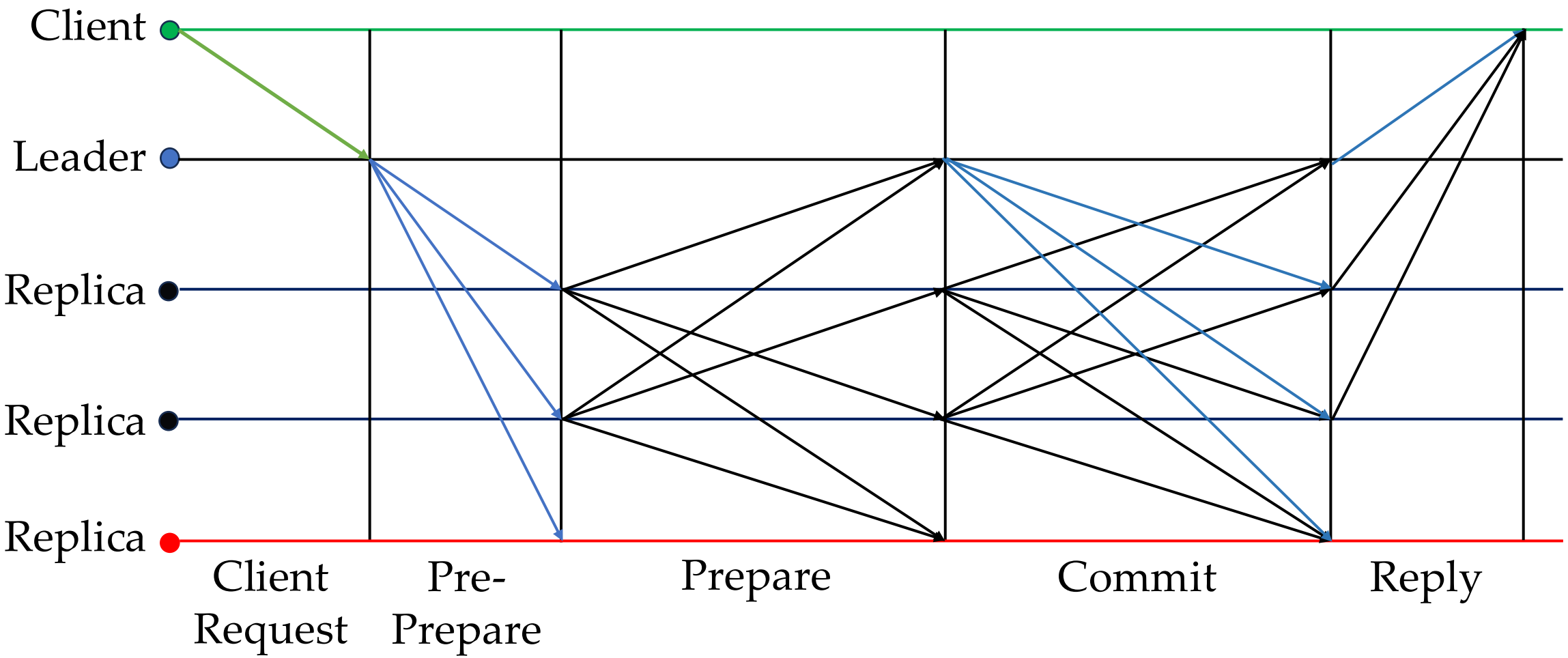

Execution and Reply under Out-of-Order Processing

- No changes in execution and client response procedures.

View Change under Out-of-Order Processing

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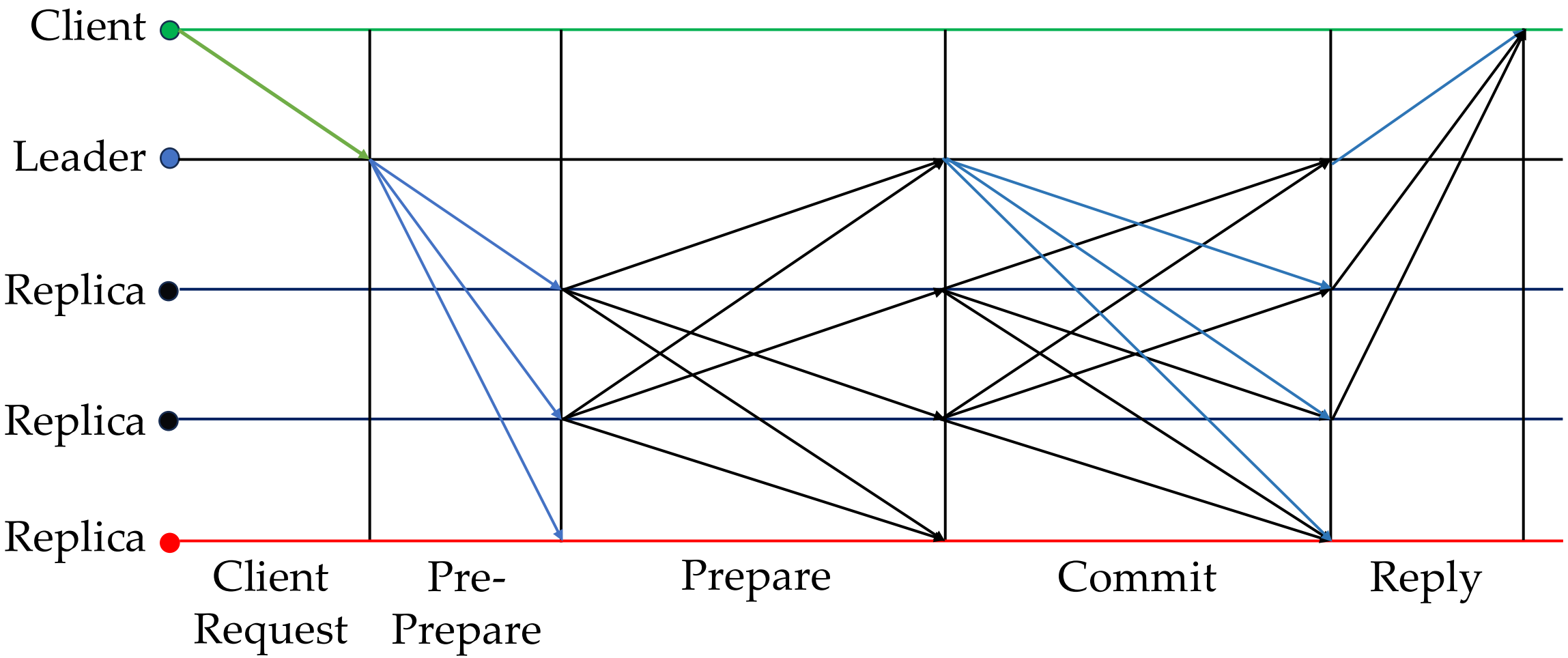

View Change under Out-of-Order Processing

- View change algorithm becomes trickier under out-of-order processing.

- A replica may have committed a message for the larger sequence number, while waiting for a request for a smaller sequence number.
  - Notice that the replica is keeping track of each sequence number now.

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- A replica may have committed a message for the larger sequence number, while waiting for a request for a smaller sequence number.
  - Notice that the replica is keeping track of each sequence number now.

- In its view change message, the replica may have **gaps**.
  - Gaps represent sequence numbers for which a replica does not have n-f Prepare messages or even Pre-prepare message.

- The new leader tries to fill all the gaps or ensure that everyone agrees on the gaps.

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- Where can we apply speculation in PBFT?

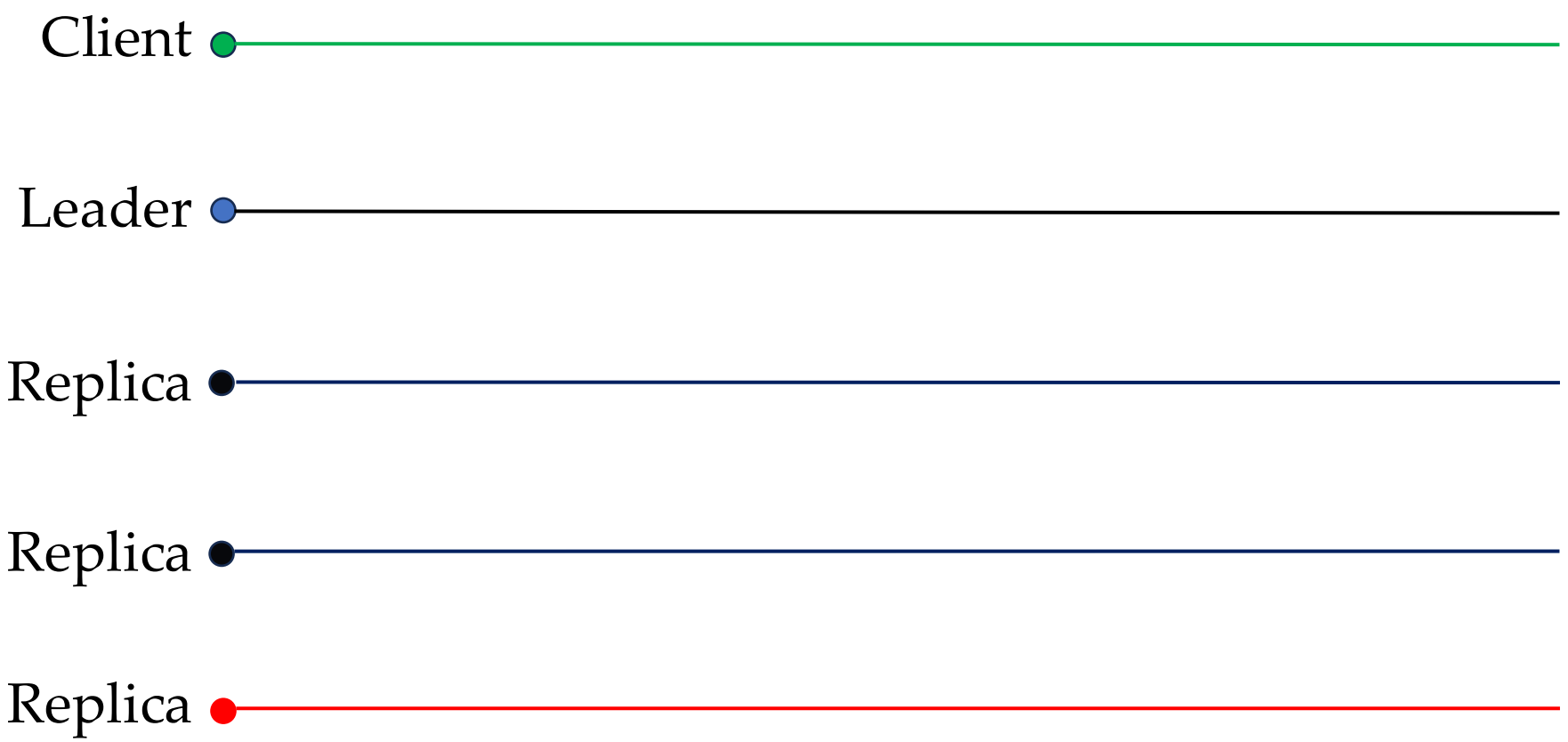
- We can speculate after the Prepare phase → Castro's Thesis and PoE [EDBT'22].

- We can speculate after the Pre-Prepare phase → Zyzzyva [SOSP'07].

Speculative Execution after Prepare Phase

- The safest route is to speculatively execute the transaction after the Prepare phase.
- This idea was first mentioned in Miguel Castro's thesis.
- **Proof-of-execution (PoE)** expanded this idea, illustrated its limitation, and presented a rigorous evaluation.

PoE Protocol



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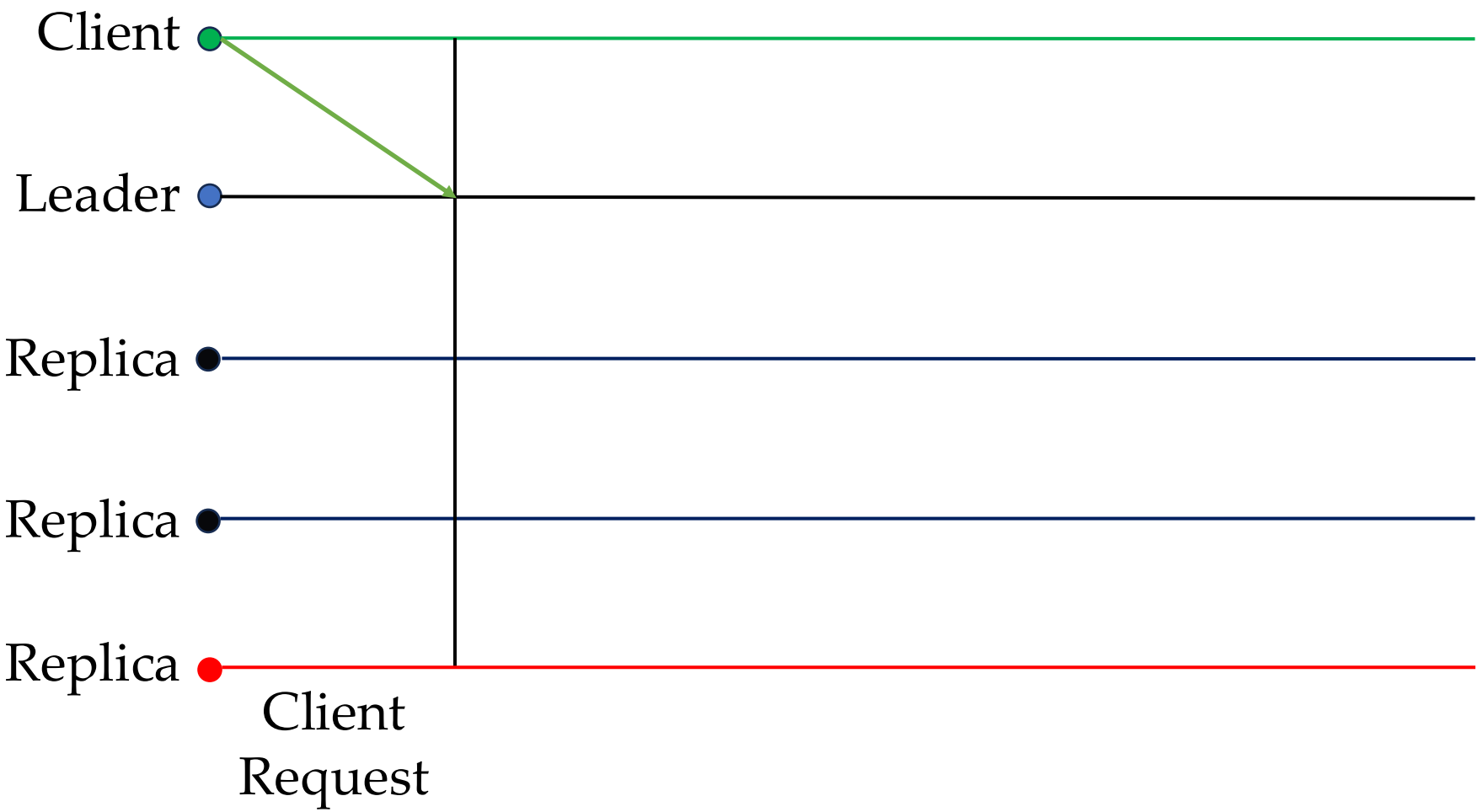

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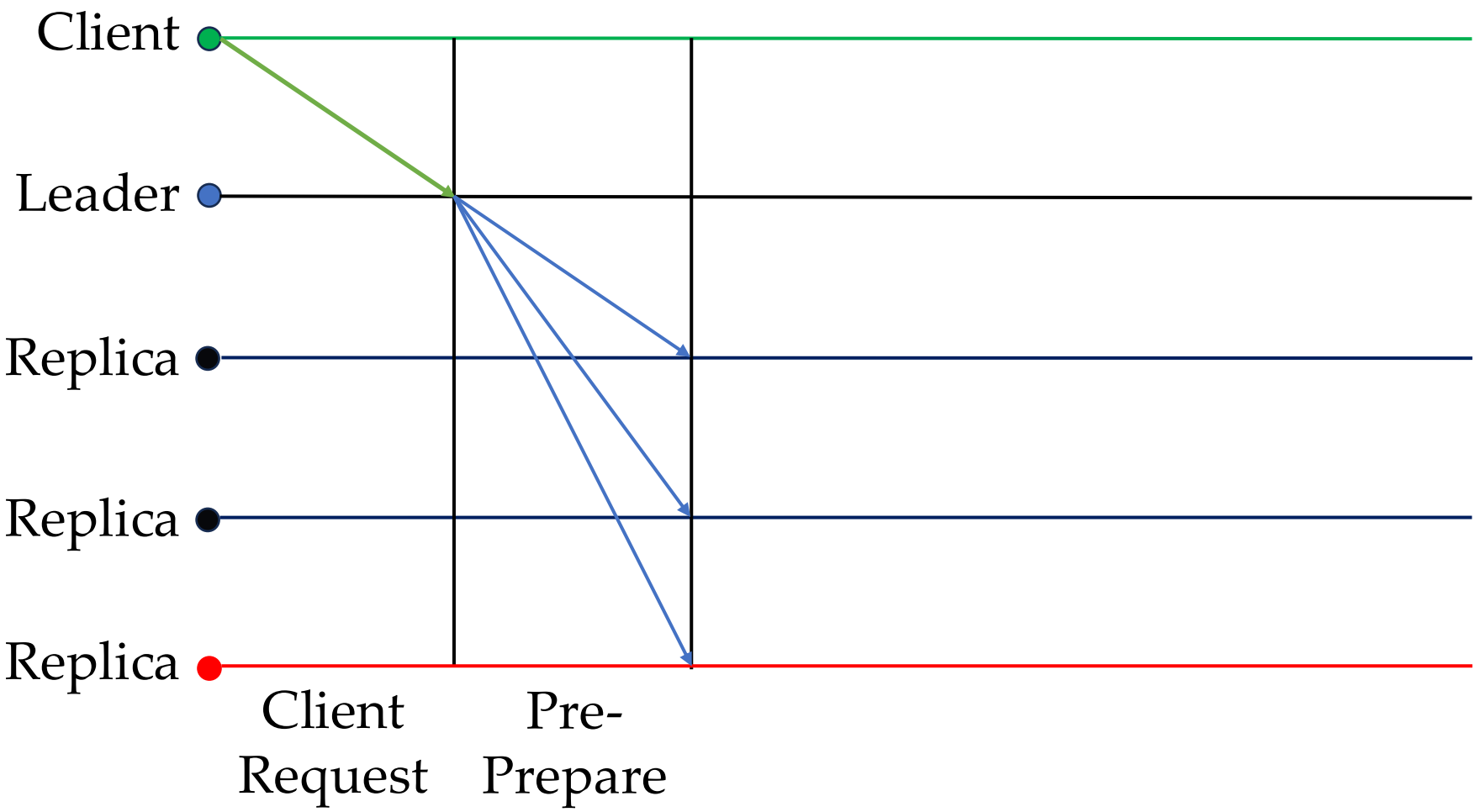

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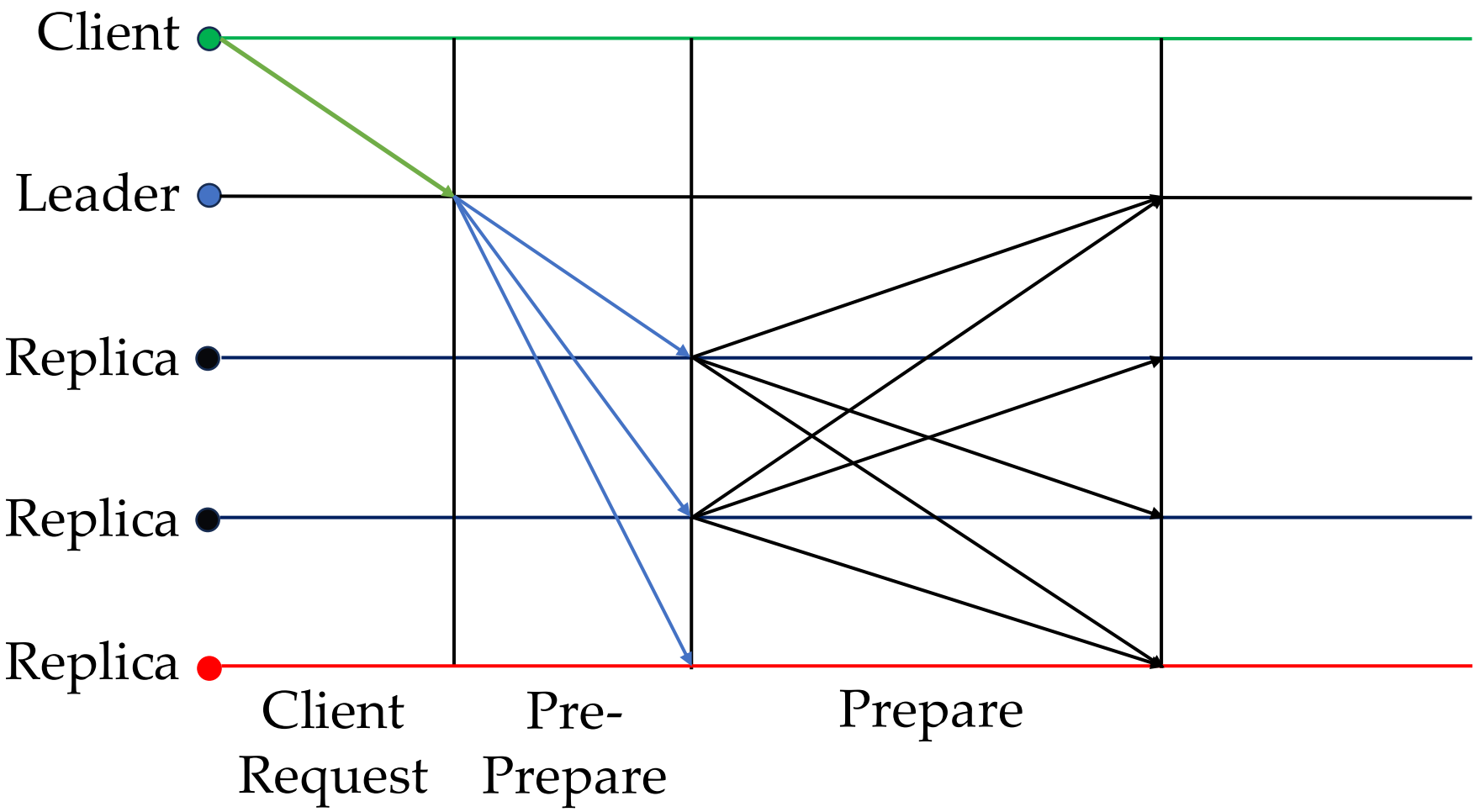

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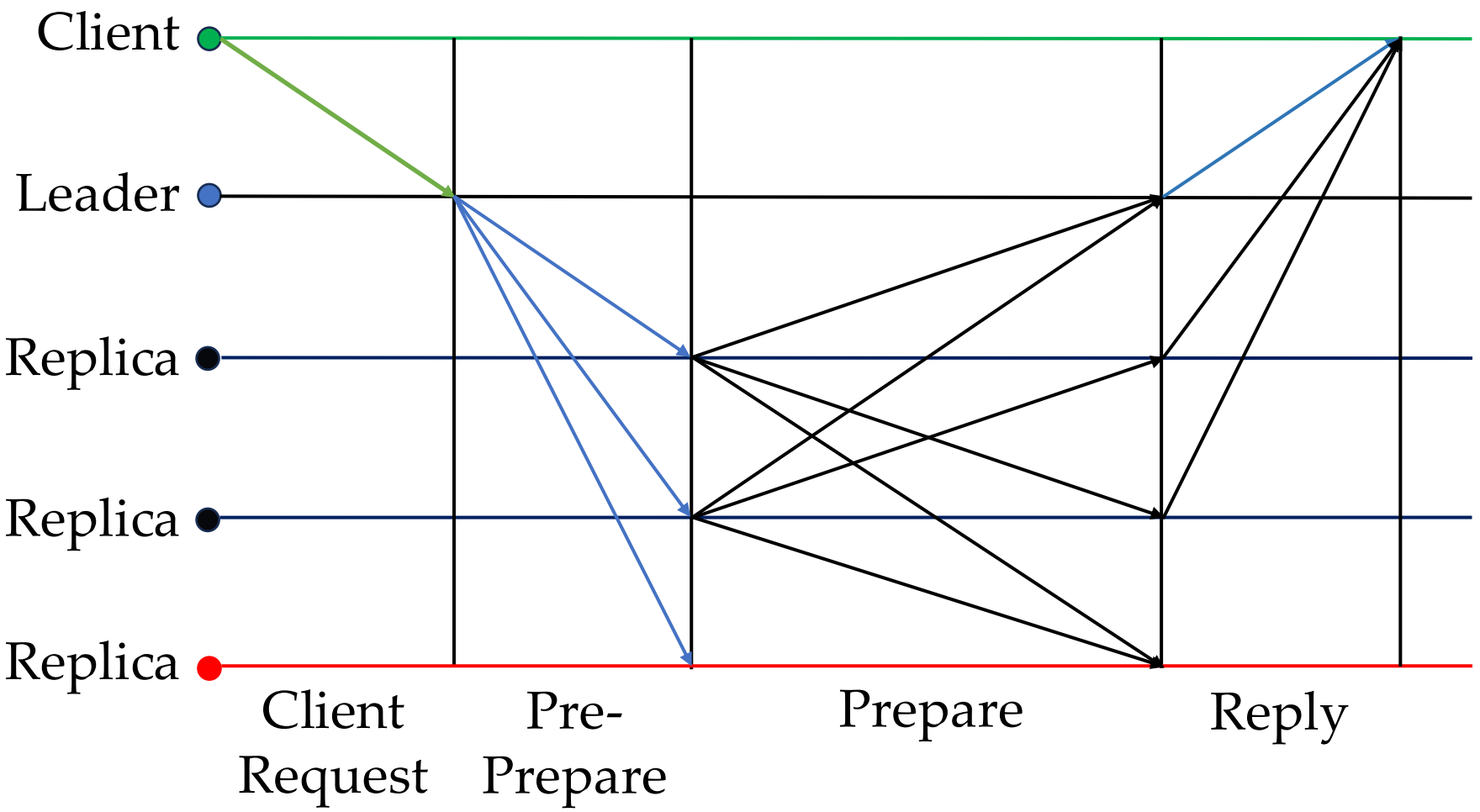

PoE Protocol

- **Key Points:**
  - Once a replica receives a Pre-Prepare message, it sends a corresponding Prepare message.
  - Once a replica receives n-f Prepare messages, it executes the request.
  - Finally, the replica replies to the client.

Key Challenges for PoE

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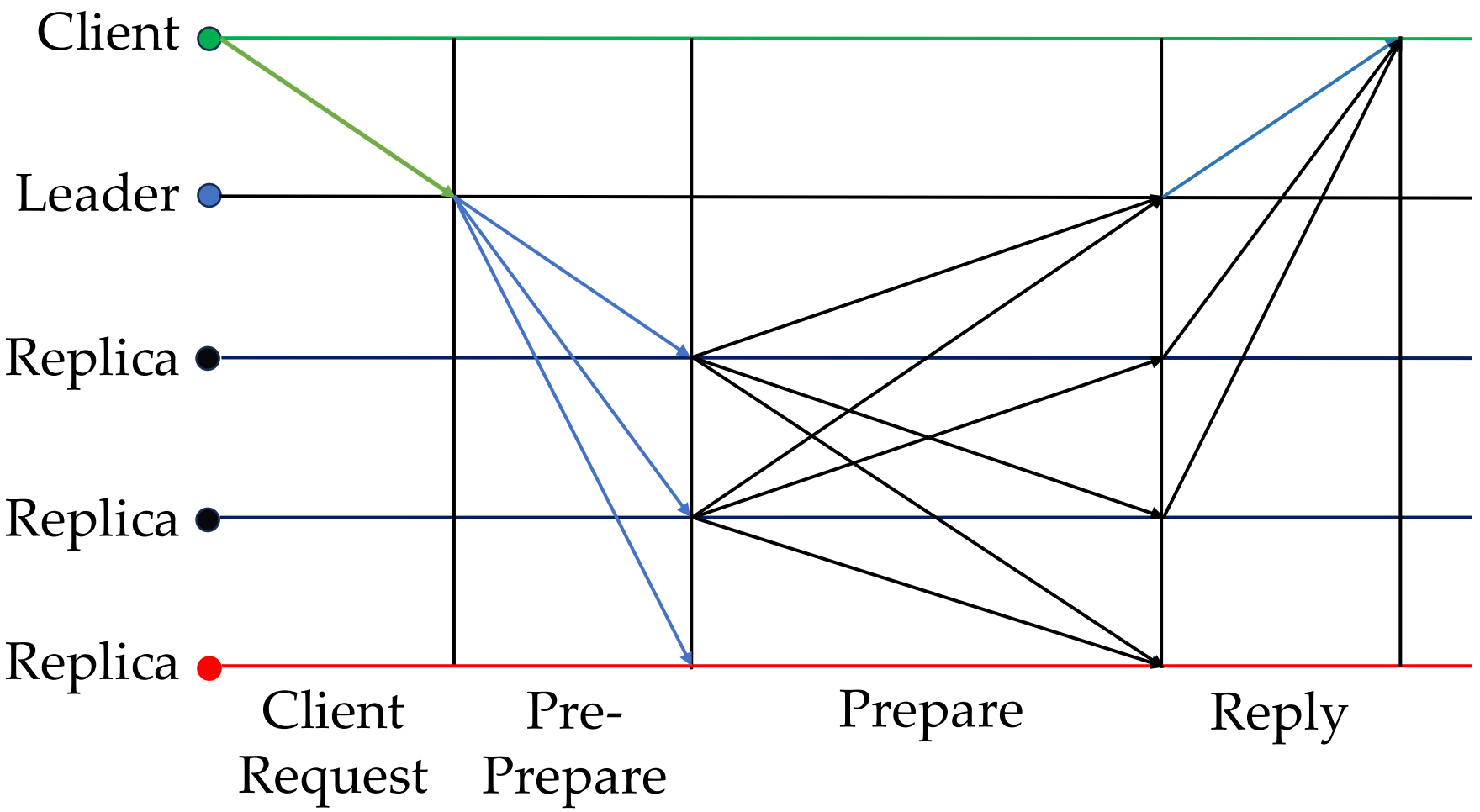
  - How can a replica know if the request is committed?
  - How can a client know if the request is committed?

Commit Information for Replica

PoE Protocol



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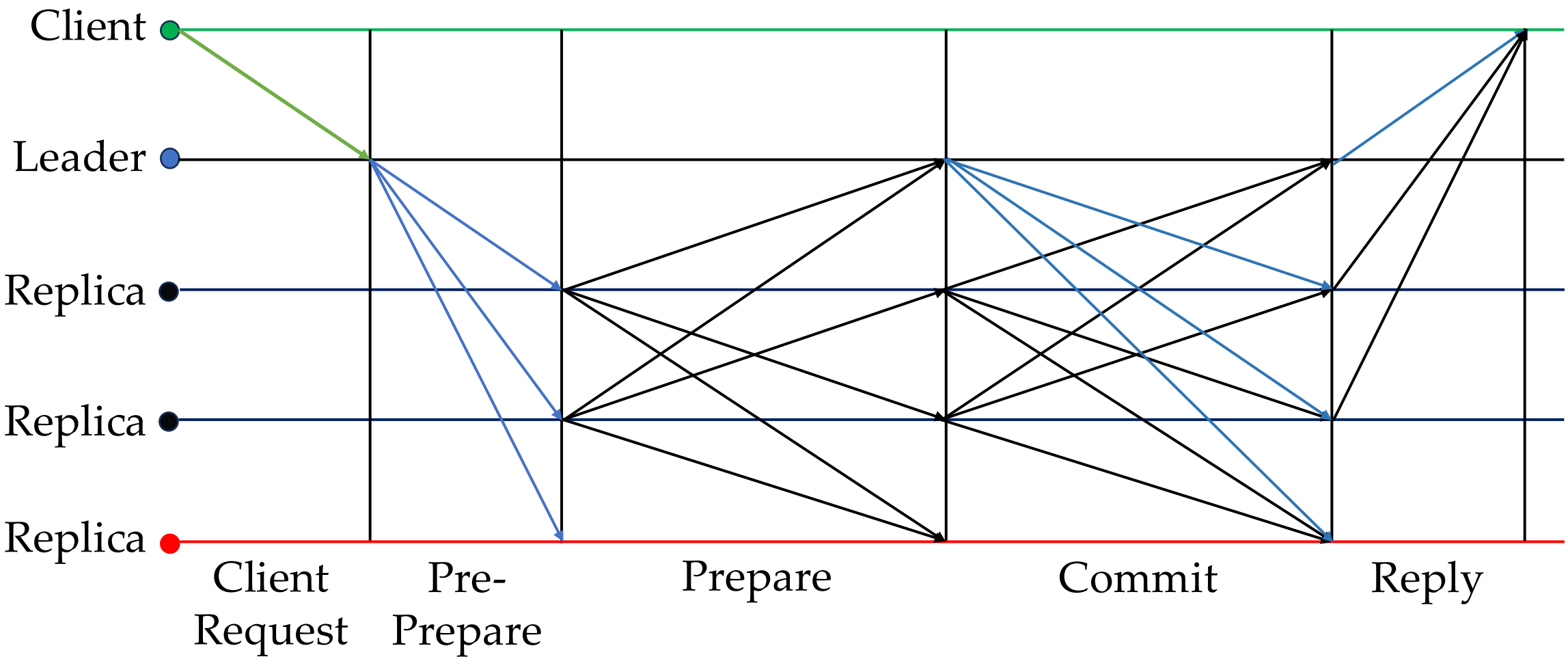

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- But what happens under out-of-order message processing?
  - It is possible that (**k+1**)-th request got prepared but **k**-th request did not arrive?
  - How to handle this?
  - Allow replicas to **rollback** their state.

Commit Information for Client

Commit Information for Replica

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- For clients, PoE sets the following rule:
  - Each client needs to wait for **n-f** responses instead of **f+1** responses.

  - If a client receives **n-f** responses, it has the guarantee that its request will eventually commit.

  - If a client does not receive **n-f** responses, then it does not have any information about the fate of the request.

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- When is it guaranteed that a replica's state will not be rollbacked.
  - When a request has been executed by at least f+1 replicas, it is guaranteed to persist.

PoE's Responsiveness Dilemma

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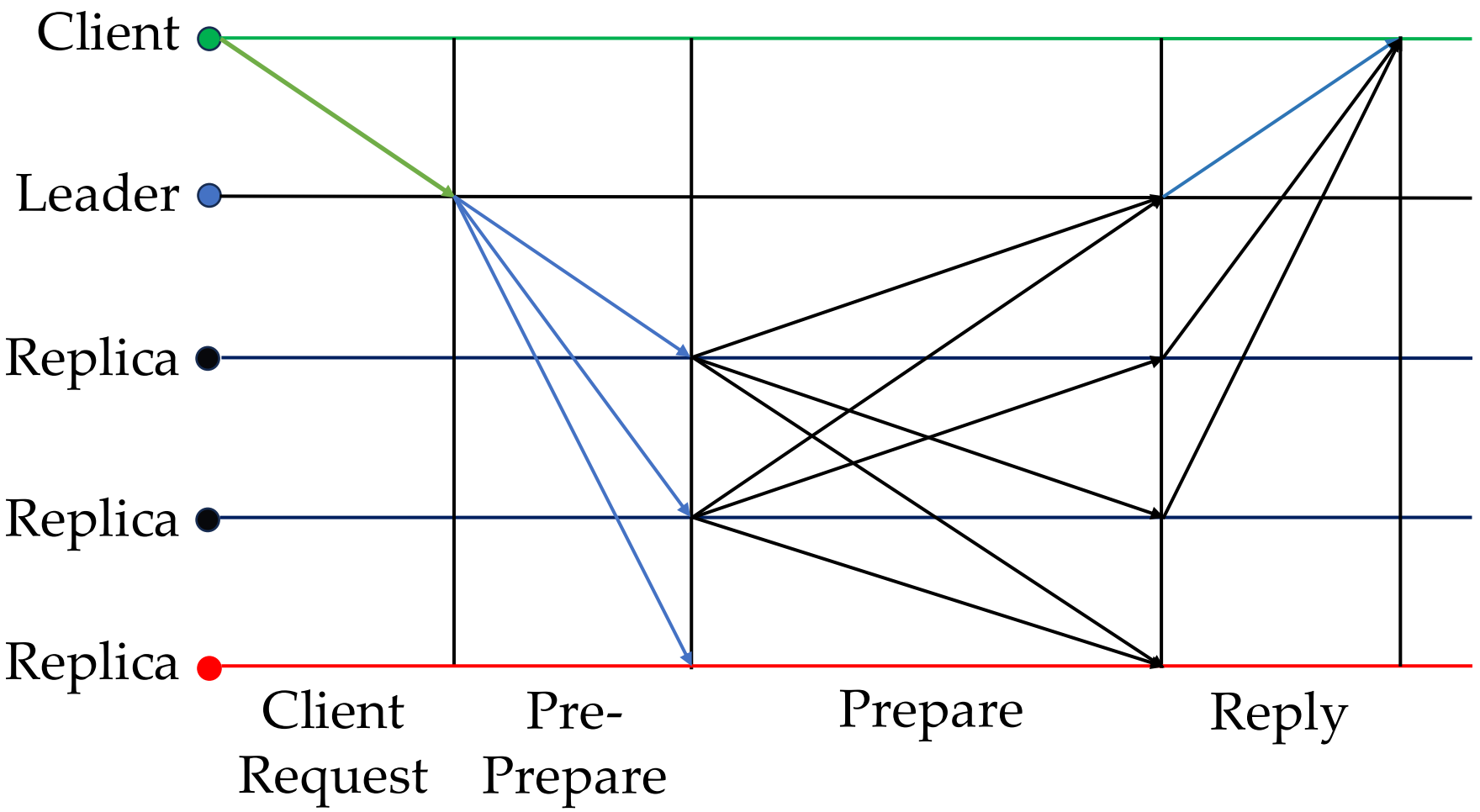

PoE's Responsiveness Dilemma

- PoE faces a responsiveness challenge:
  - The replicated system is both safe and live.
  - But clients do not receive n-f responses.
  - The leader cannot be replaced.

- Why?

PoE's Responsiveness Dilemma

- Recall that to replace the leader, support of **n-f** replicas is needed.
- The Byzantine leader plays cleverly, only includes **f+1** honest replicas in consensus.
- These **f+1** honest replicas will keep on preparing one request after another.
- However, client will never receive **n-f** responses because the **f** Byzantine replicas that helped to Prepare the requests will not send a response back to the client.
- Further, view change cannot take place as the **f+1** honest replicas have not observed any Byzantine behavior from the leader.