Paxos Explained from Scratch

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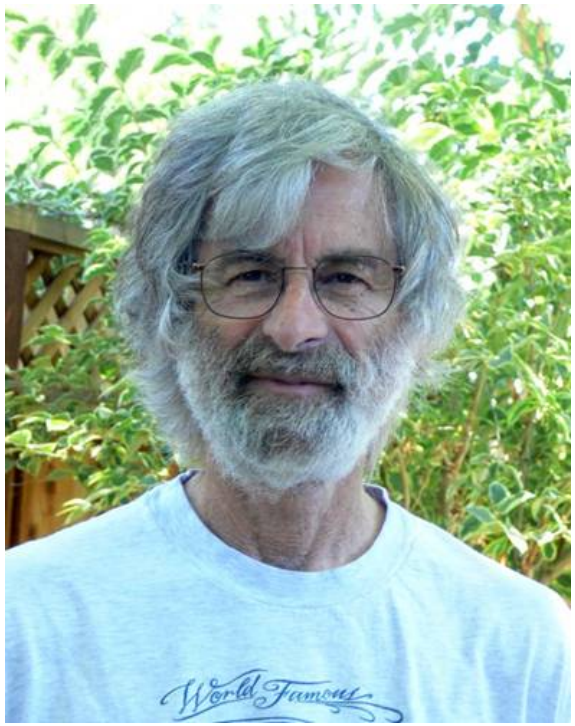
DAT520 Distributed Systems

Leslie Lamport

- Microsoft Research
- Many important contributions to distributed computing theory
- But most know for LaTeX



The Part-Time Parliament

LESLIE LAMPORT
Digital Equipment Corporation

Recent archaeological discoveries on the island of Paxos reveal that the parliament functioned despite the peripatetic propensity of its part-time legislators. The legislators maintained consistent copies of the parliamentary record, despite their frequent forays from the chamber and the forgetfulness of their messengers. The Paxon parliament's protocol provides a new way of implementing the state-machine approach to the design of distributed systems.

Categories and Subject Descriptors: C2.4 [**Computer-Communications Networks**]: Distributed Systems—*Network operating systems*; D4.5 [**Operating Systems**]: Reliability—*Fault-tolerance*; J.1 [**Administrative Data Processing**]: Government

General Terms: Design, Reliability

Additional Key Words and Phrases: State machines, three-phase commit, voting

Paxos for System Builders

Jonathan Kirsch and Yair Amir

Paxos Made Live - An Engineering Perspective

Tushar Chandra
Robert Griesemer
Joshua Redstone

June 20, 2007

Vertical Paxos and Primary-Backup Replication

Leslie Lamport, Dahlia Malkhi, Lidong Zhou
Microsoft Research

9 February 2009
corrected 26 August 2009

Paxos Made Moderately Complex

Robbert van Renesse
Cornell University
rvr@cs.cornell.edu

March 25, 2011

Paxos Made Simple

Leslie Lamport

01 Nov 2001

The Paxos Register

Harry C. Li, Allen Clement, Amitanand S. Aiyer, and Lorenzo Alvisi
The University of Texas at Austin
Department of Computer Sciences
{harry, aclement, anand, lorenzo}@cs.utexas.edu

In Search of an Understandable Consensus Algorithm

Diego Ongaro and John Ousterhout
Stanford University
(Draft of April 7, 2013, under submission to SOSP)

There Is More Consensus in Egalitarian Parliaments

Iulian Moraru, David G. Andersen, Michael Kaminsky
Carnegie Mellon University and Intel Labs

Cheap Paxos

Leslie Lamport and Mike Massa
Microsoft

Fast Paxos

Leslie Lamport

When You Don't Trust Clients: Byzantine Proposer Fast Paxos

Hein Meling*, Keith Marzullo†, and Alessandro Mei‡
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†Department of Computer Science and Engineering, University of California San Diego, USA
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- Used in production systems: Chubby, ZooKeeper, and Spanner
- It is always safe

Objectives and Approach

- Explain Paxos
  - Using visual aids
  - In a step-wise manner
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  - Understand why it works and why the solution is necessary
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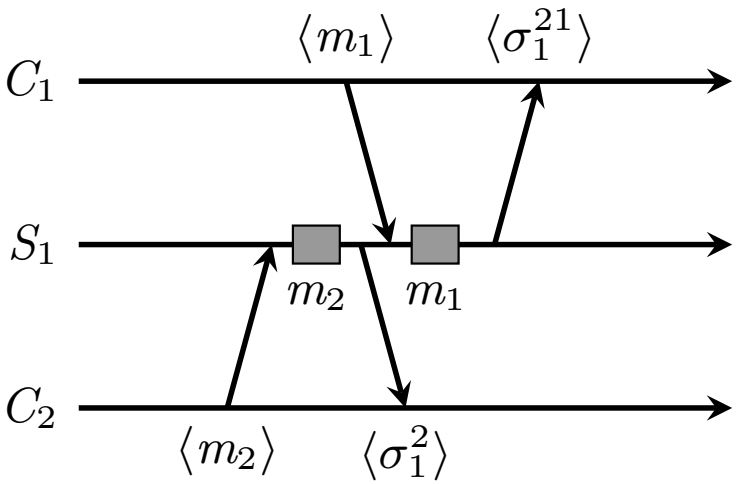
- Approach
  - Use a simple client/server system as base
  - To build fault tolerant server (replicated state machine)
  - Construct Multi-Paxos
  - Decompose Multi-Paxos into Paxos

A Stateful Service: *SingleServer*



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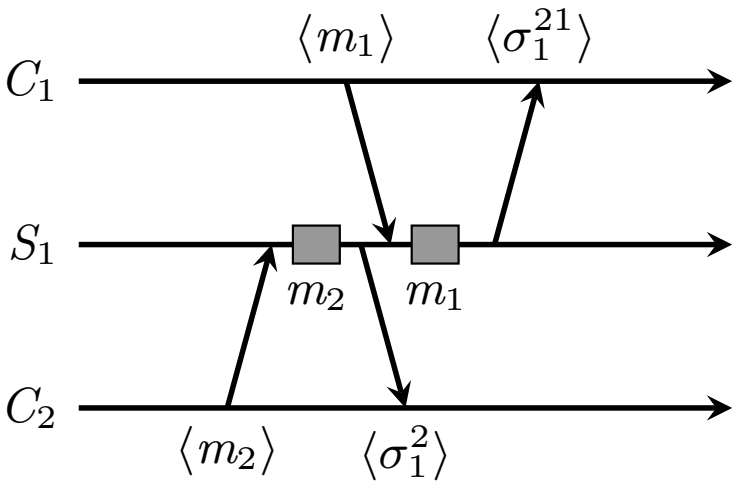
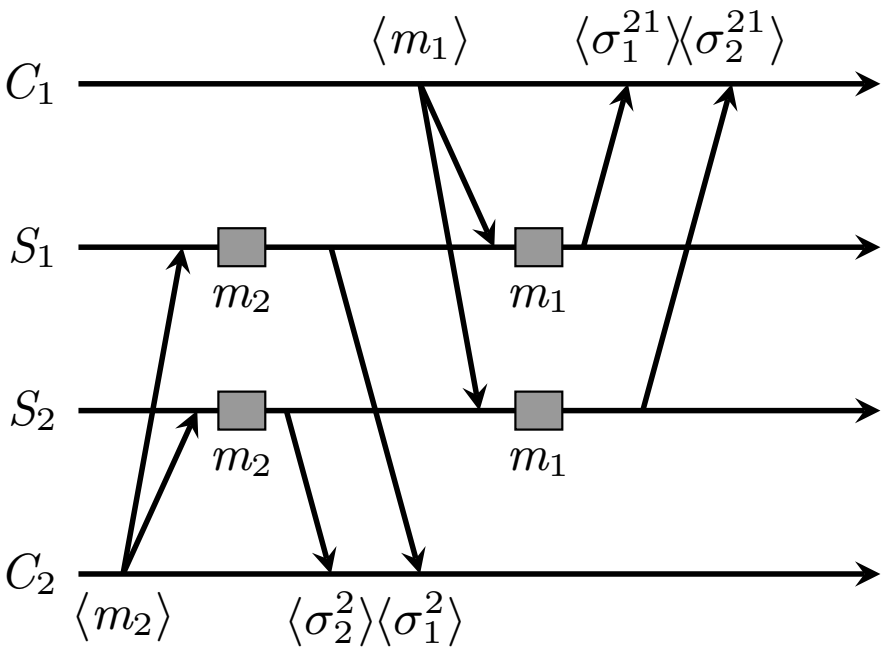


- Client C_2 sees: σ^2
- Client C_1 sees: σ^{21}
- Corresponds to execution sequence: $m_2 m_1$

We Want to Make the Service Fault Tolerant!

Fault Tolerance with Two Servers



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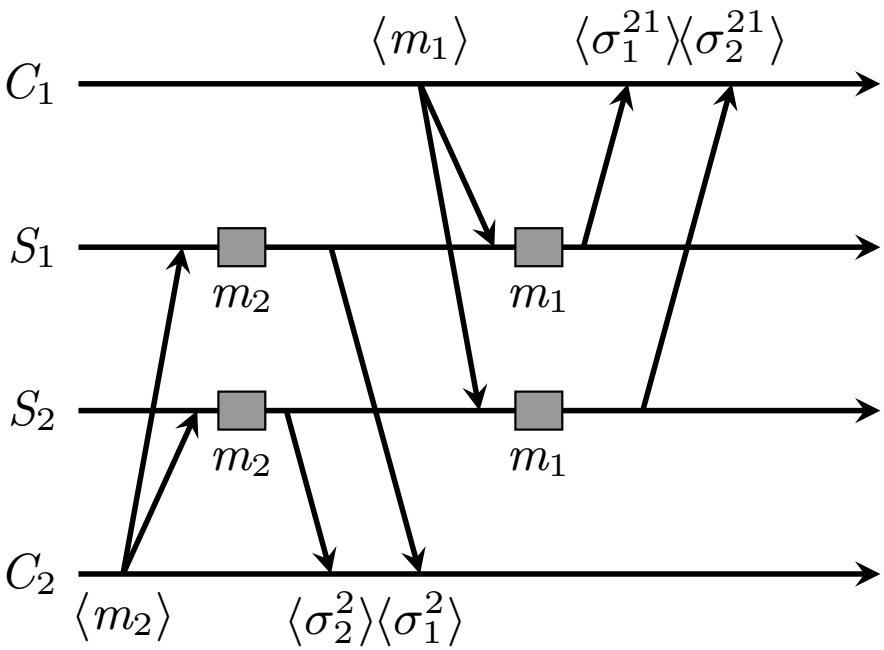

- Client C_2 sees: σ^2
- Client C_1 sees: σ^{21}
  - σ^2 is a prefix of σ^{21}
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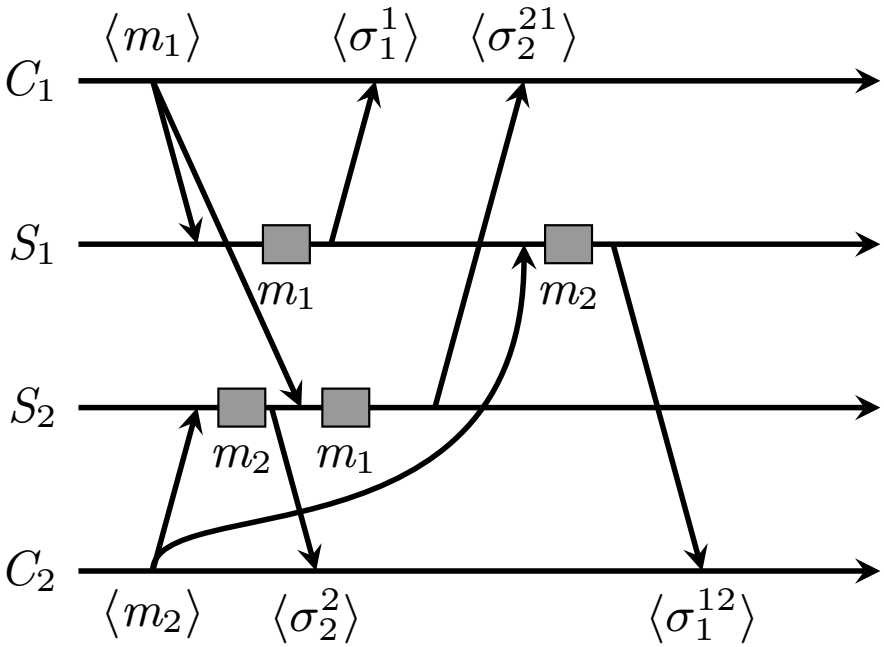
Deterministic State Machine

- The service is implemented as a deterministic state machine
- Thus processing requests results in unique state transitions:
  - Therefore $\sigma_1^2 = \sigma_2^2$ and $\sigma_1^{21} = \sigma_2^{21}$.
- Clients can detect and suppress identical replies

Fault Tolerance with Two Servers: Whoops!



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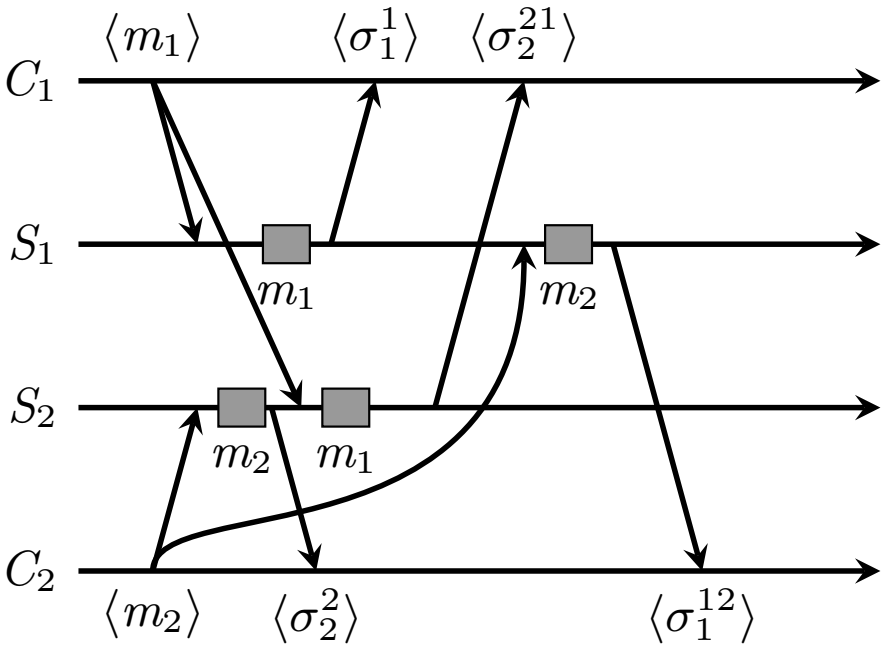
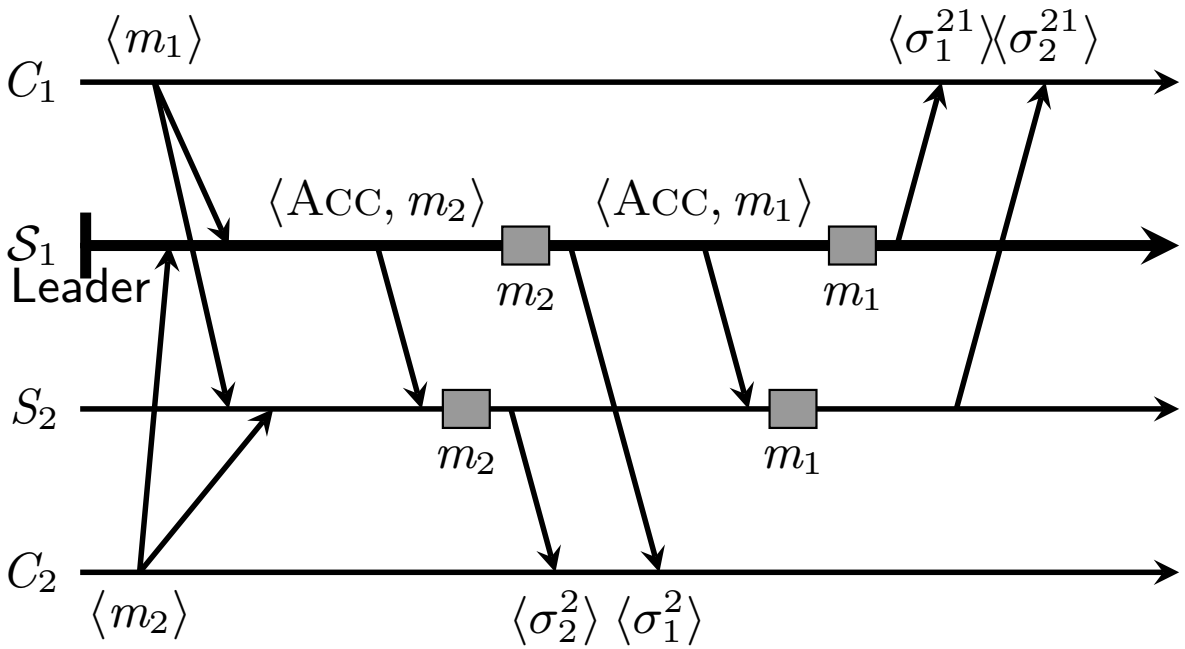


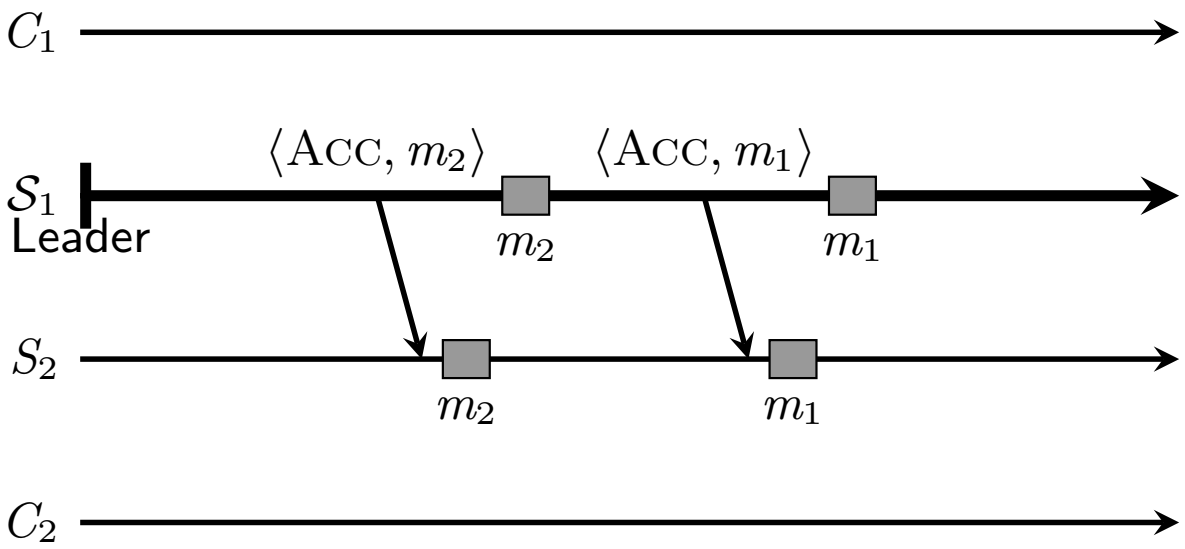
- Client C_2 sees: $\sigma^2\sigma^{12}$
  - σ^2 is not a prefix of σ^{12}
- Client C_1 sees: $\sigma^1\sigma^{21}$
  - σ^1 is not a prefix of σ^{21}
- Corresponds to execution sequence at
  - S_1: $m_1 m_2$
  - S_2: $m_2 m_1$

We Need to Order Client Requests!

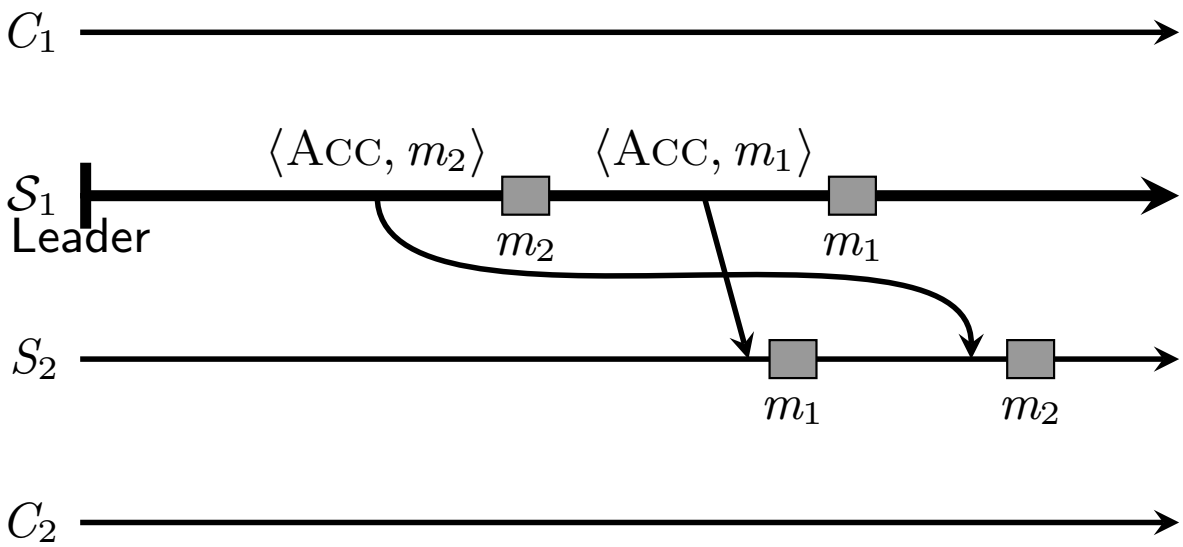
Let's Designate a Leader to Order Requests



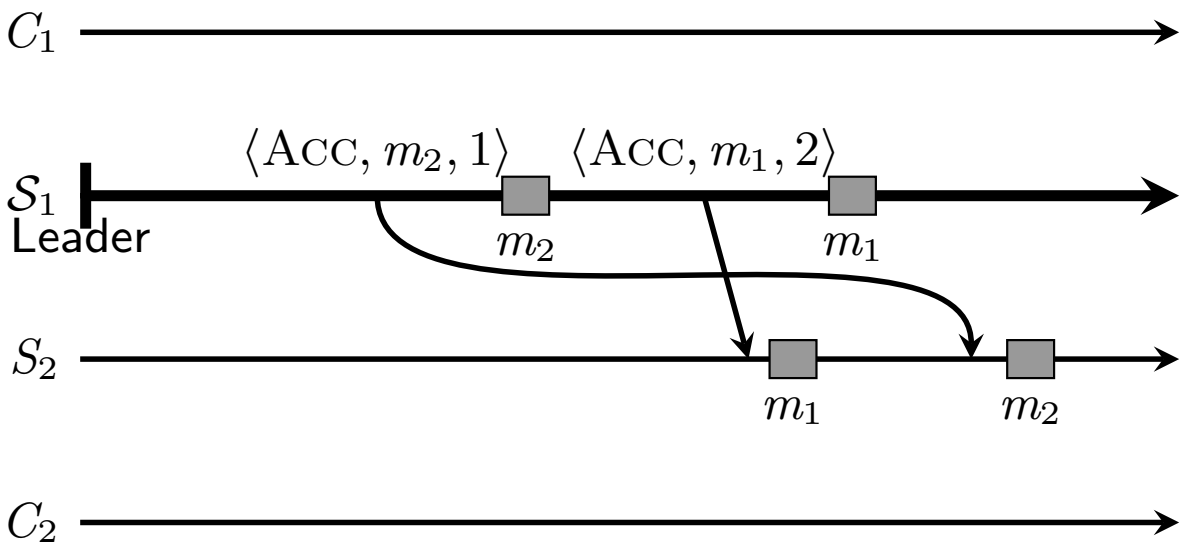
Without Clients



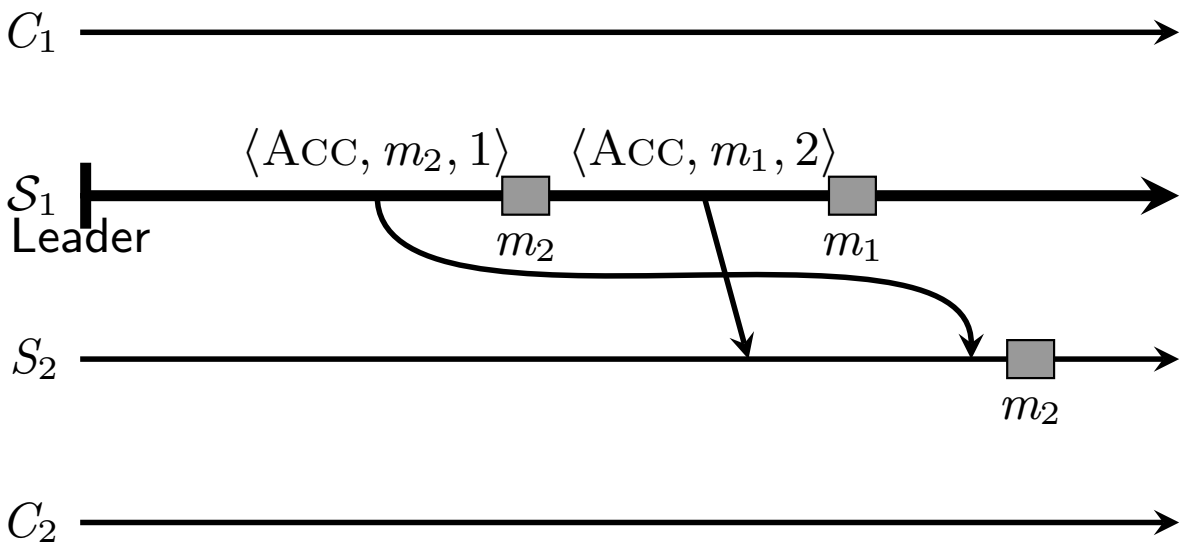
Problem: Also Accept Messages can be Reordered



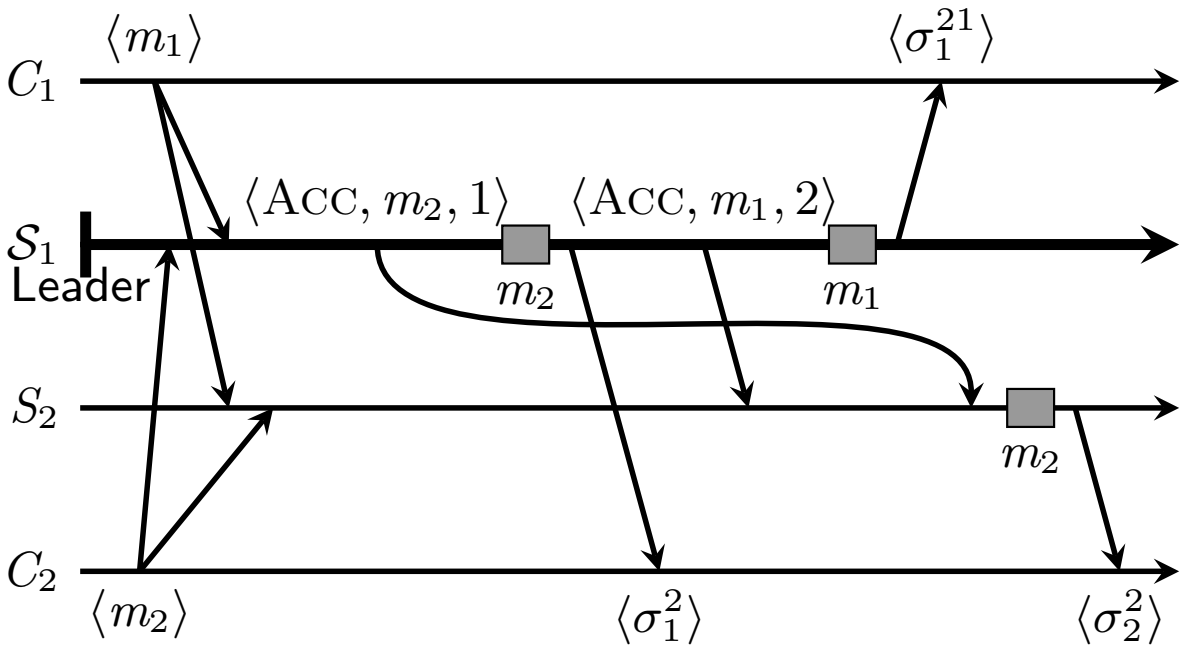
Add Sequence Numbers



Discard Out-of-Order Messages



Now with Clients



Clients Observe The Same Server States as Before

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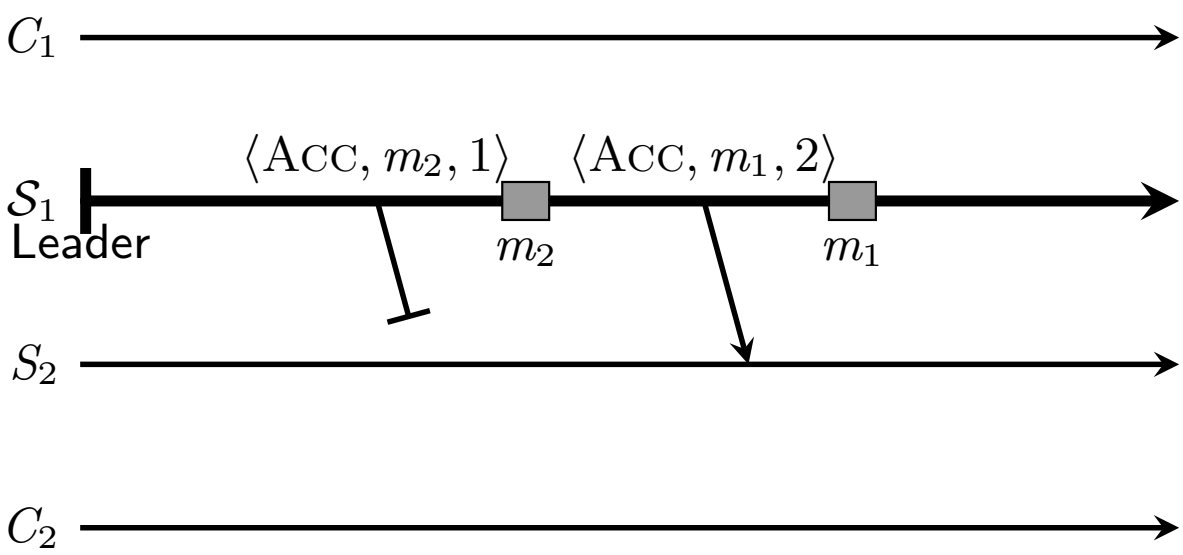
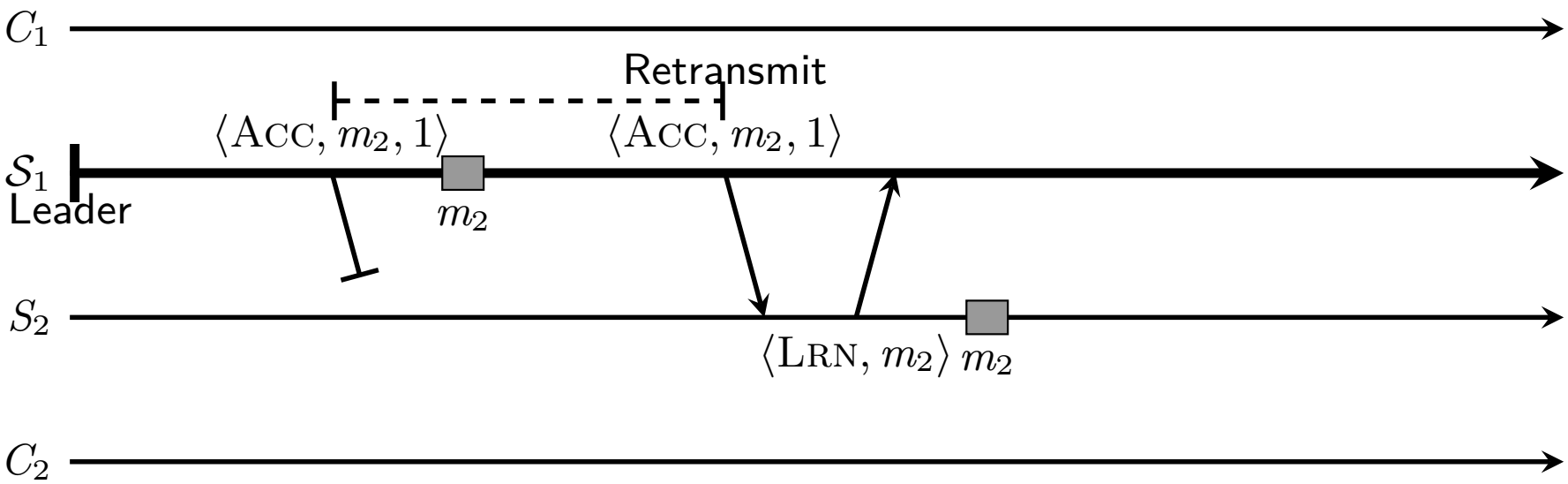
  - A2: Retransmission mechanism

Problem: Message Loss – S_2 Won't Execute Anything

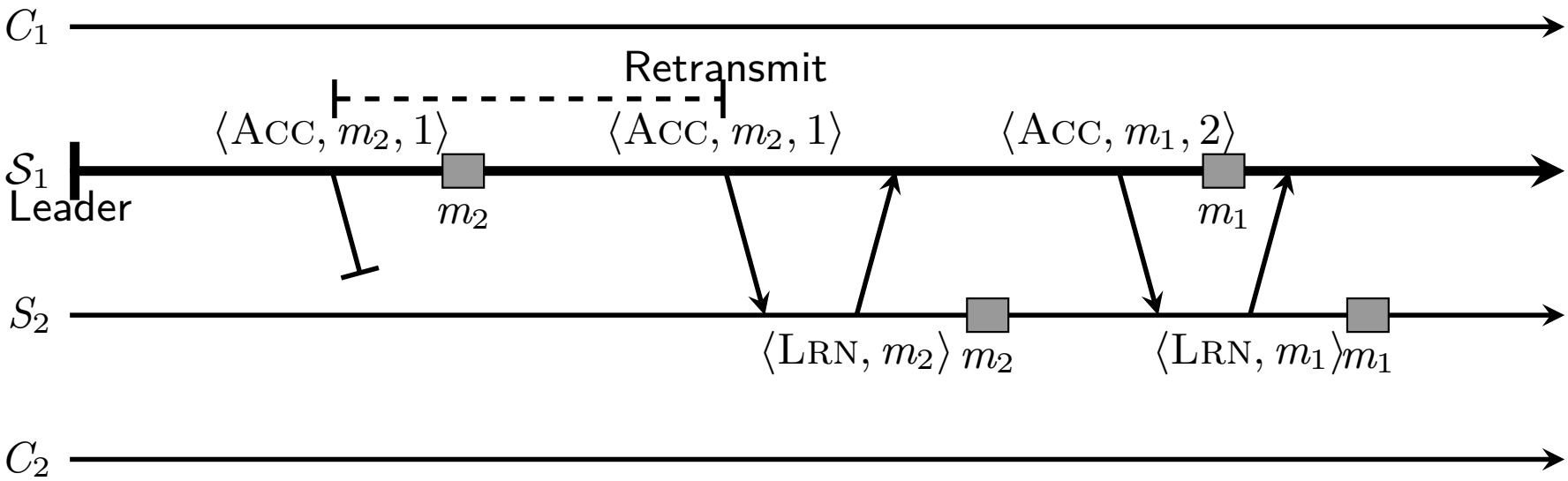


We Need a Retransmission Mechanism!

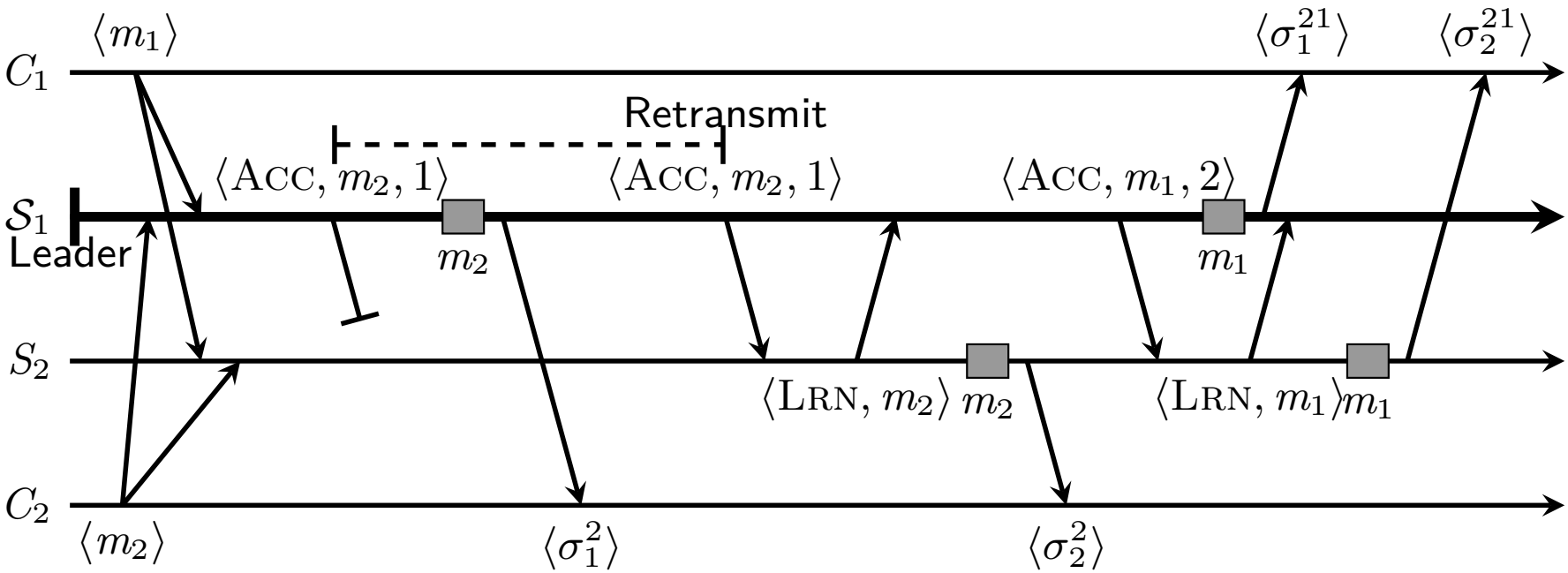
A Learn Stops Retransmission



Don't Send New Accept Until Learn



With Clients



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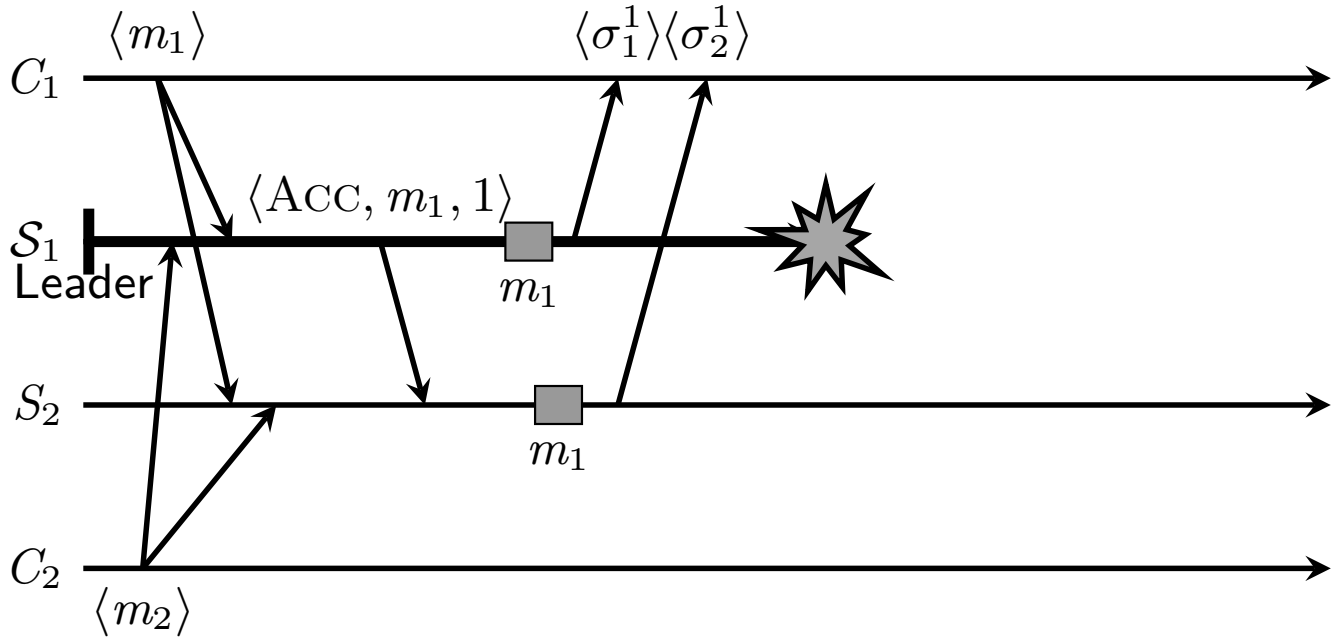
Combination of mechanisms:

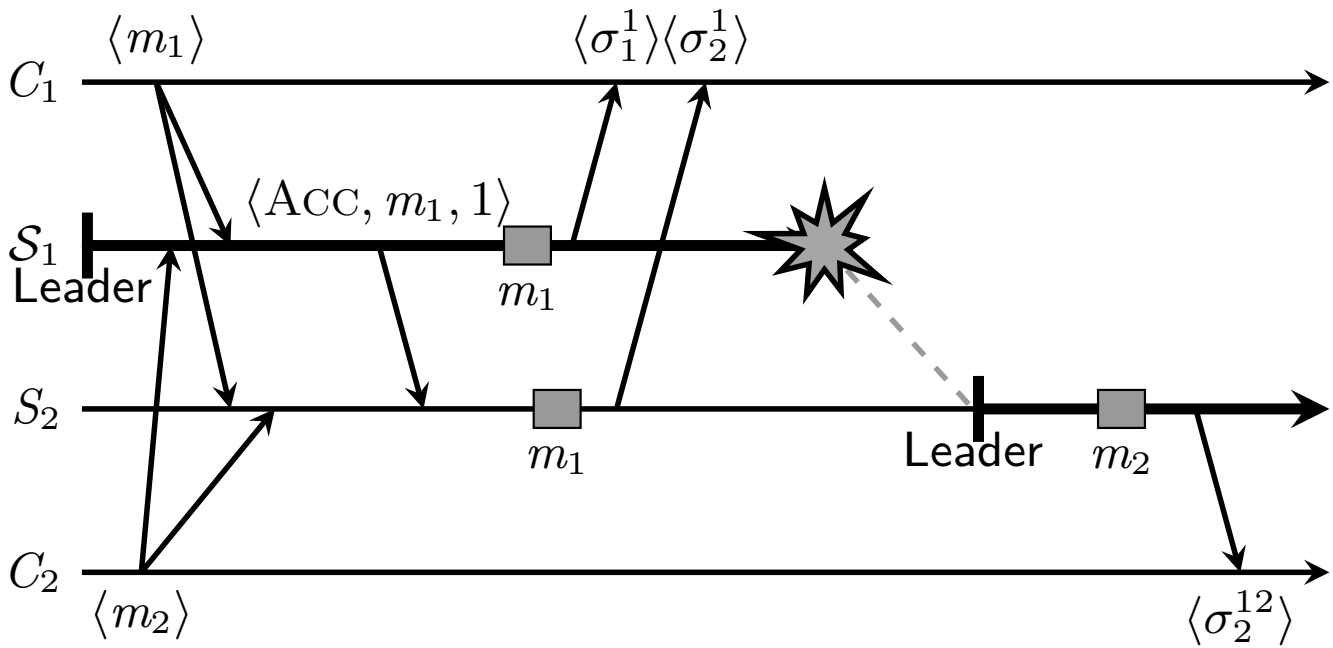
RetransAccept protocol

What About Server Crashes?

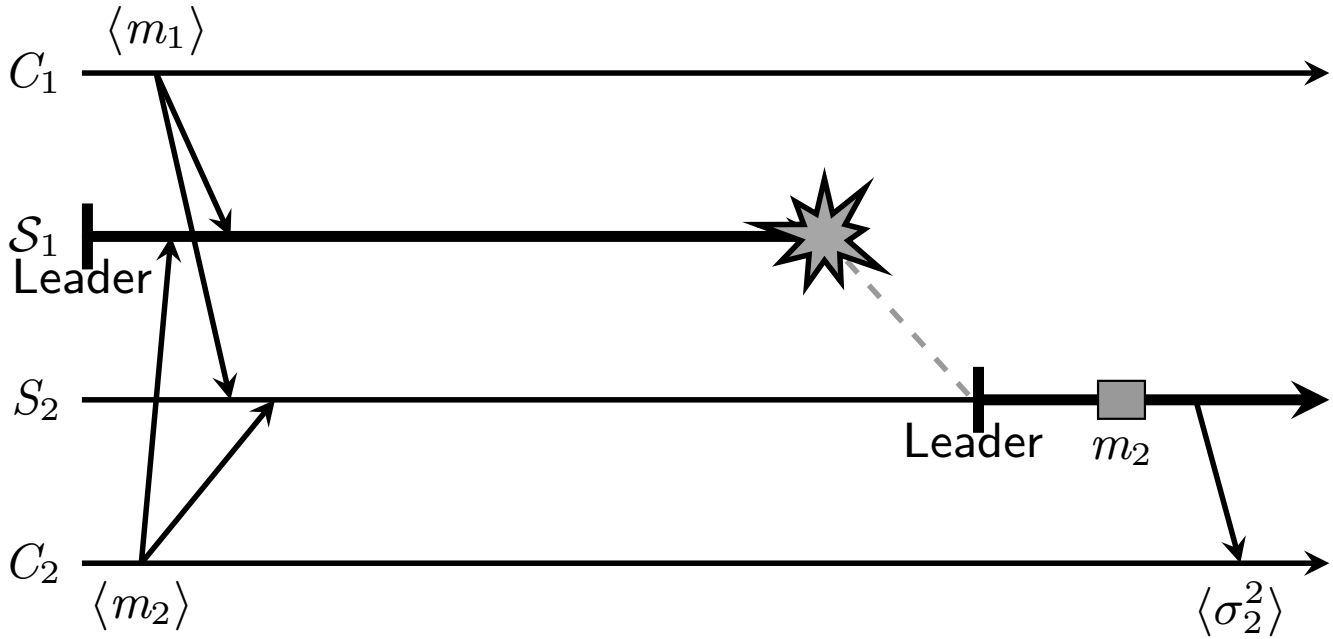
Crash


$\langle m_1 \rangle$
$\langle \sigma_1^1 \rangle \langle \sigma_2^1 \rangle$
C_1
$\langle \text{Acc}, m_1, 1 \rangle$
$\mathcal{S}_1$
Leader
m_1
S_2
m_1
C_2
$\langle m_2 \rangle$

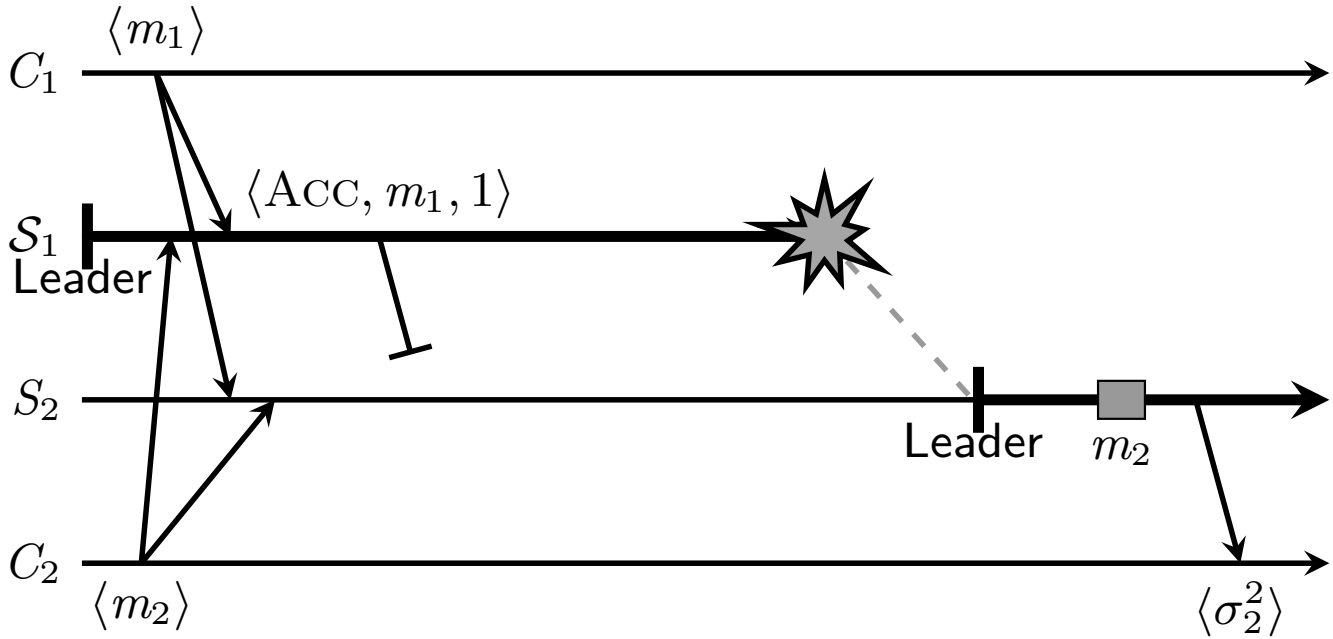
Crash: Leader Takeover



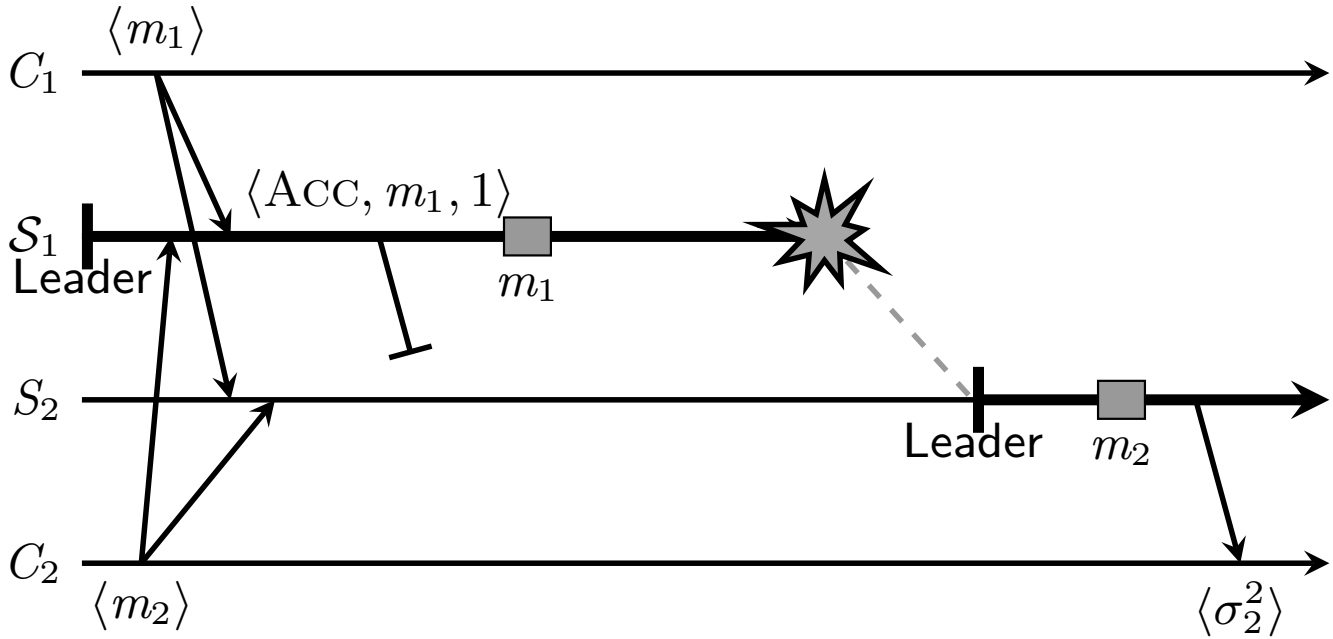
Single Server Rule: Case 1



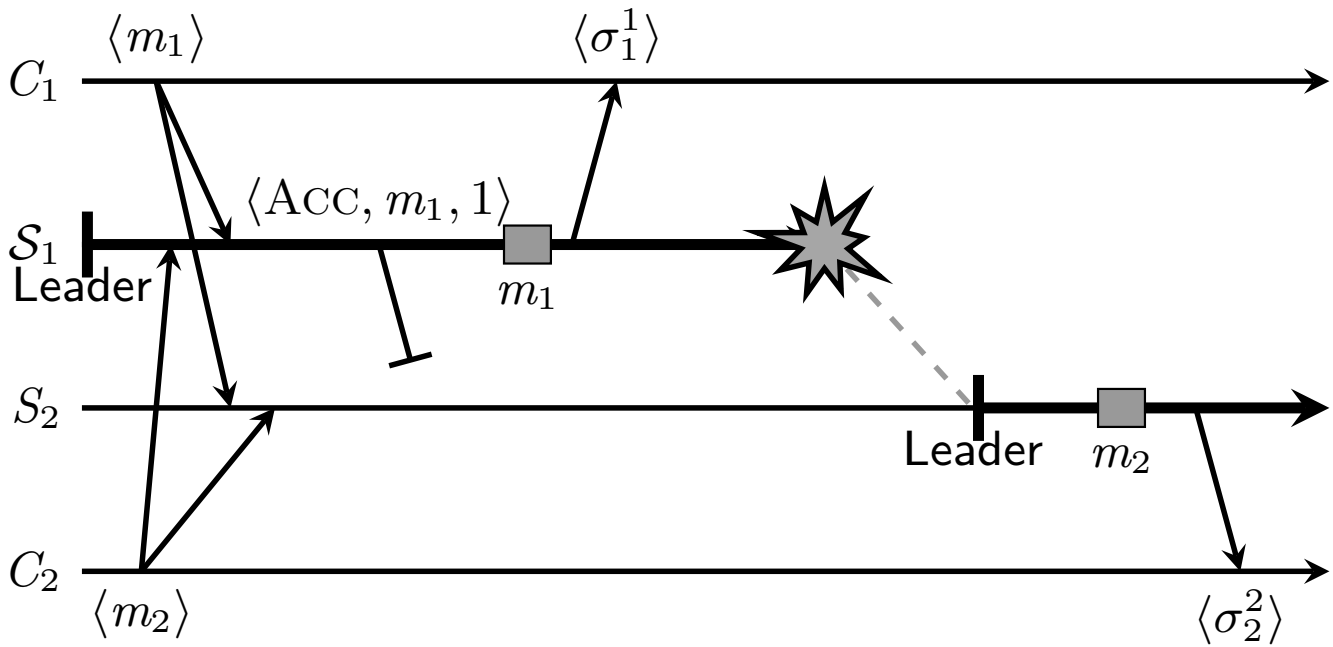
Single Server Rule: Case 2



Single Server Rule: Case 3



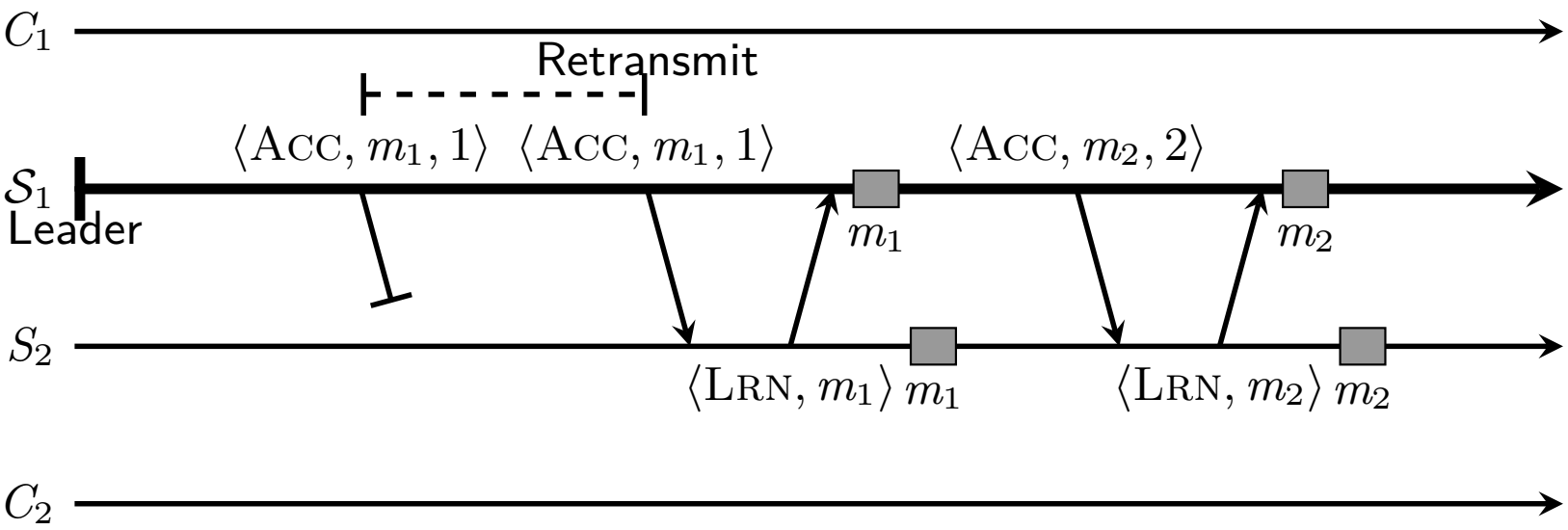
Single Server Rule: Case 4 – A Problem



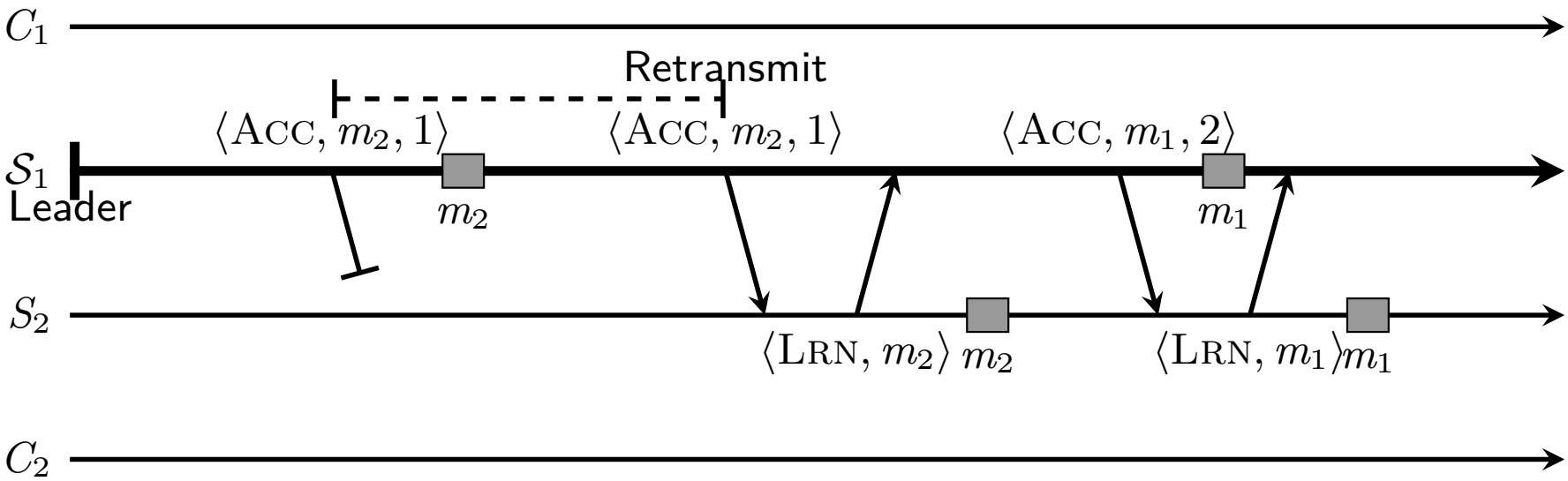
Single Server Rule: Case 4 – A Problem

- Imagine that (S_1, S_2) implements a fault tolerant resource manager, e.g. a lock service
- Both clients could have gotten the lock

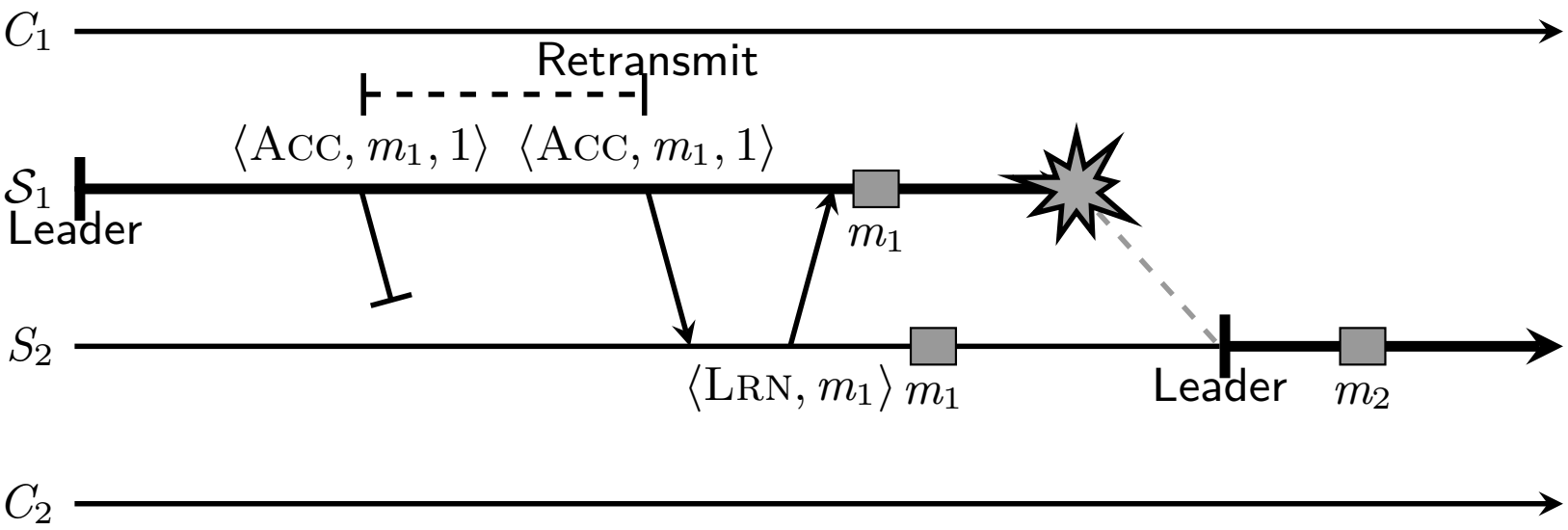
Solution: Leader Waits for Learn Before Executing



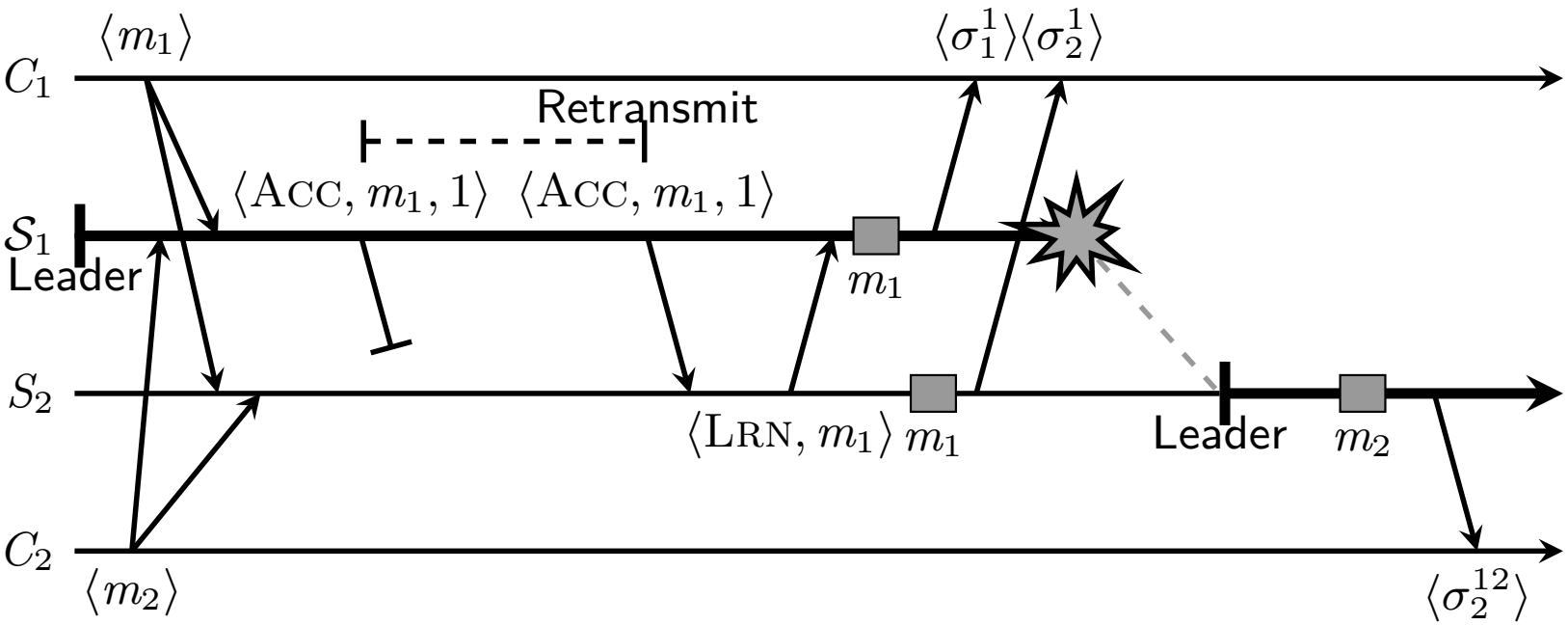
Recall Earlier Version



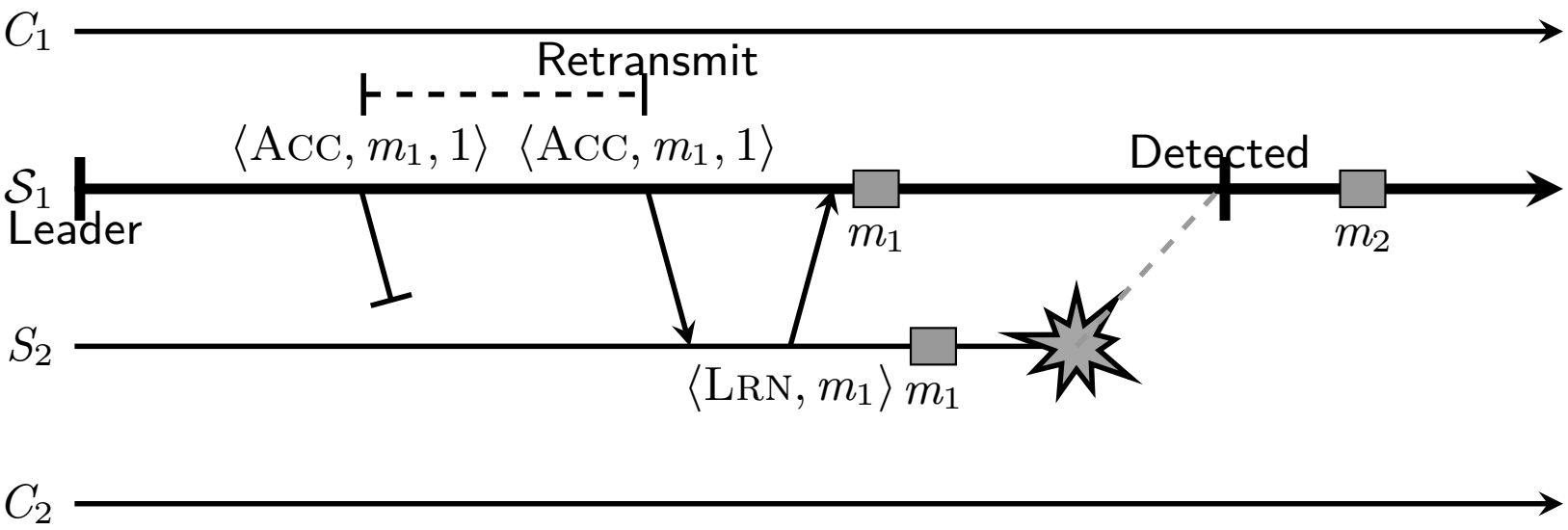
Now Leader Takeover is Safe



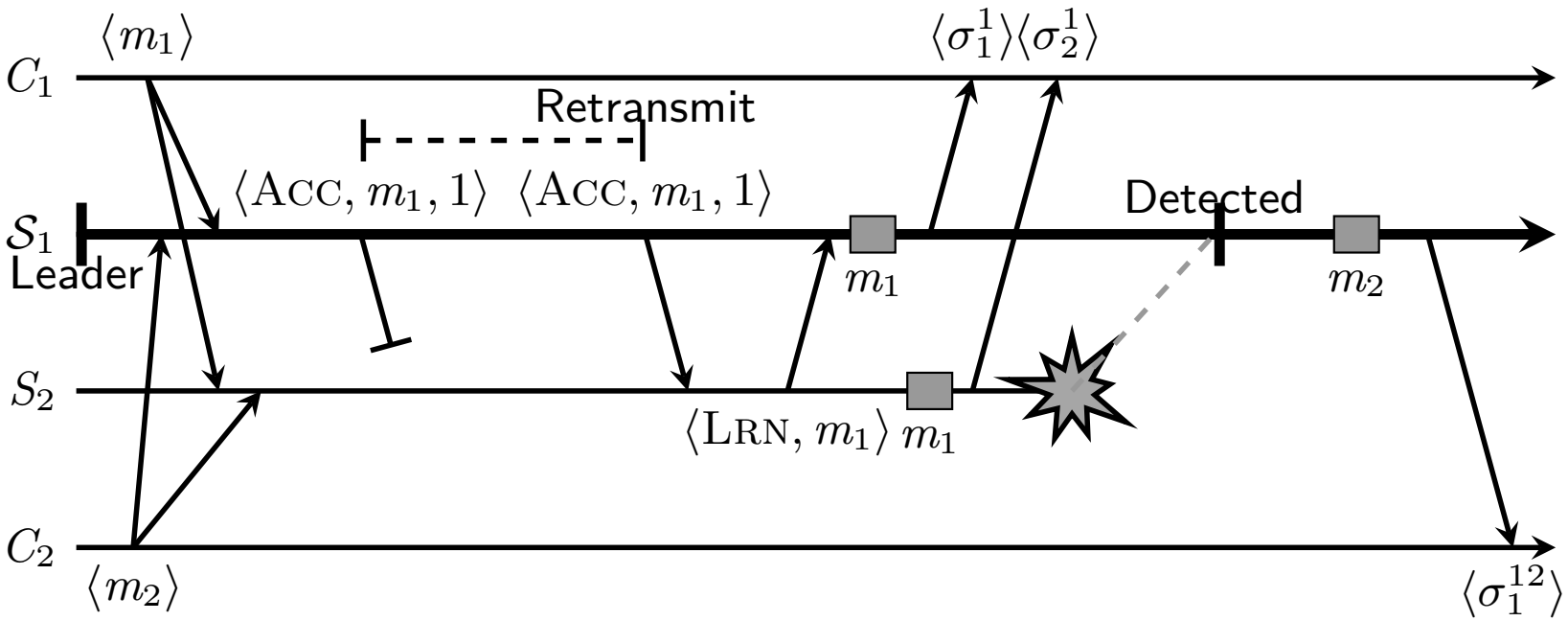
Let's Add Client Messages



Leader Remain in Control when S_2 Crash



Let's Add Client Messages Again



Recap: The Problem

- When we detect a server crash
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- When we detect a server crash
  - Adopt the *SingleServer* protocol
- Problem with our *RetransAccept* protocol:
  - The leader might have replied to a client and then crashed, without ensuring that S_2 saw the accept
  - S_2 takes over and may execute a different request in *SingleServer* mode

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- Q: What happens if the learn message to the leader is lost?
- A: The leader uses *RetransAccept*; the accept will be retransmitted. So no need for another retransmit protocol.

Somewhat Rougher Road Ahead!

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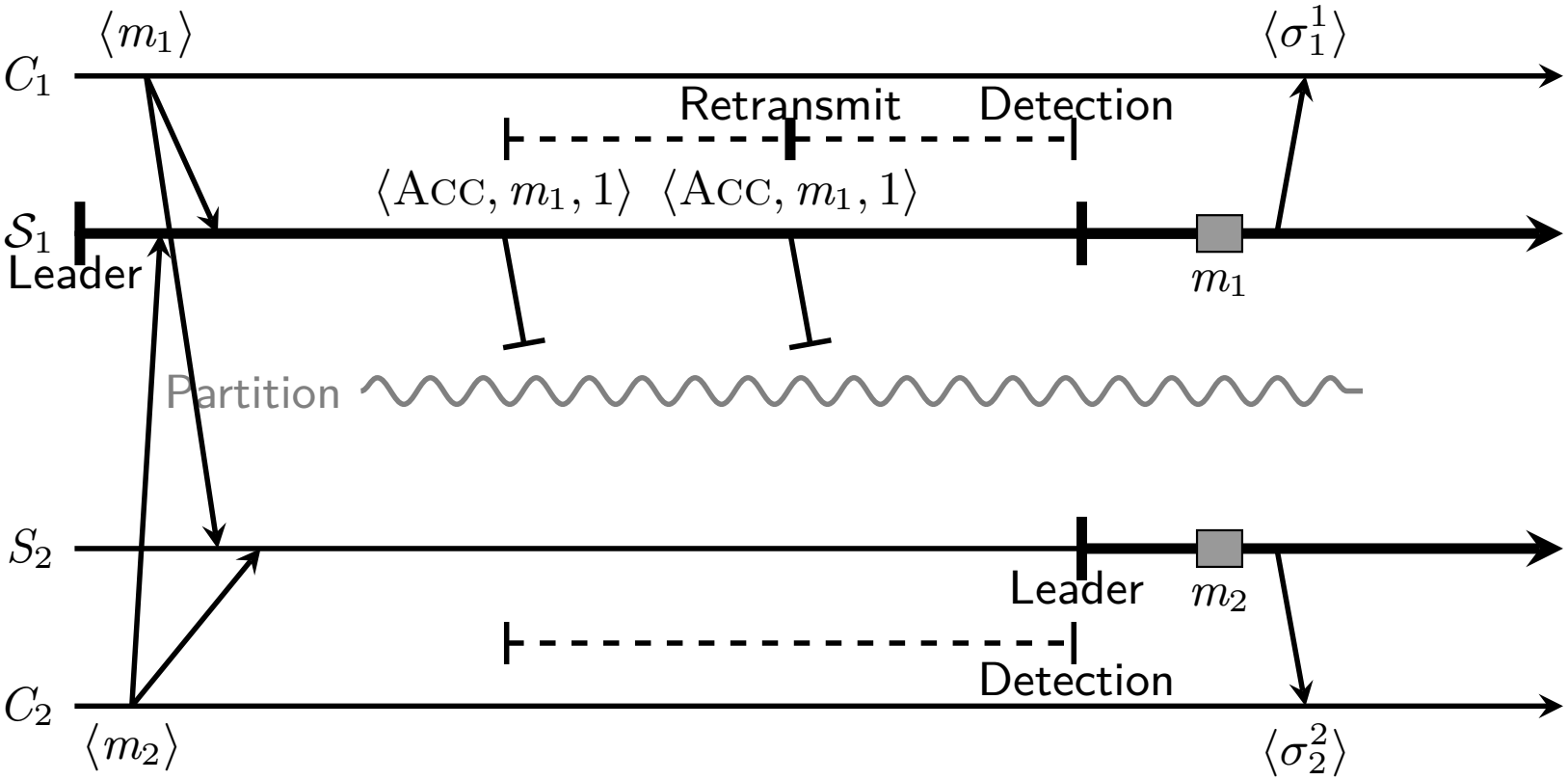
  - There is always a chance of false detection
  - Because it is impossible to pick the right timeout delay
- We now consider false detection in the context of network partitions

Problem: Network Partitions



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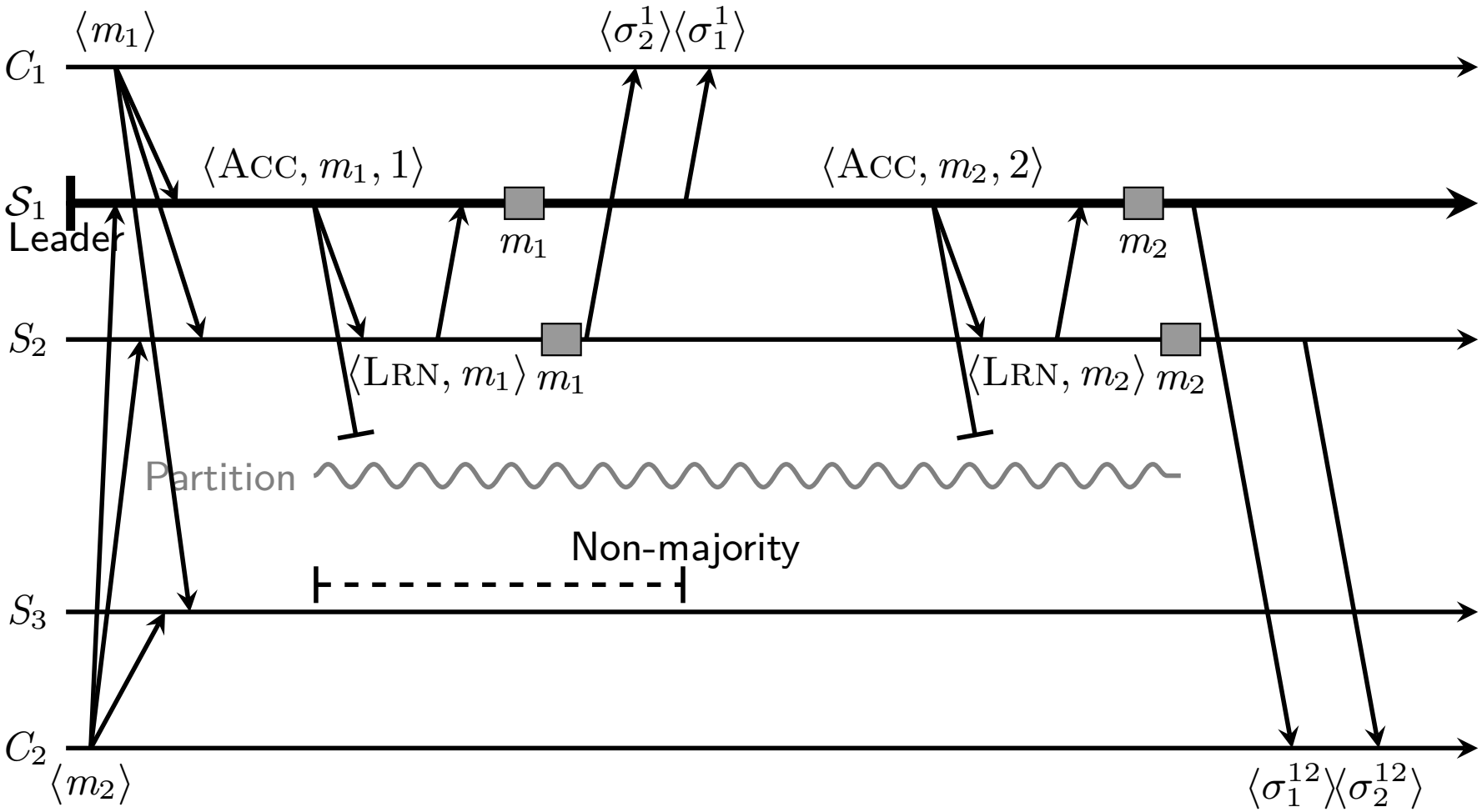
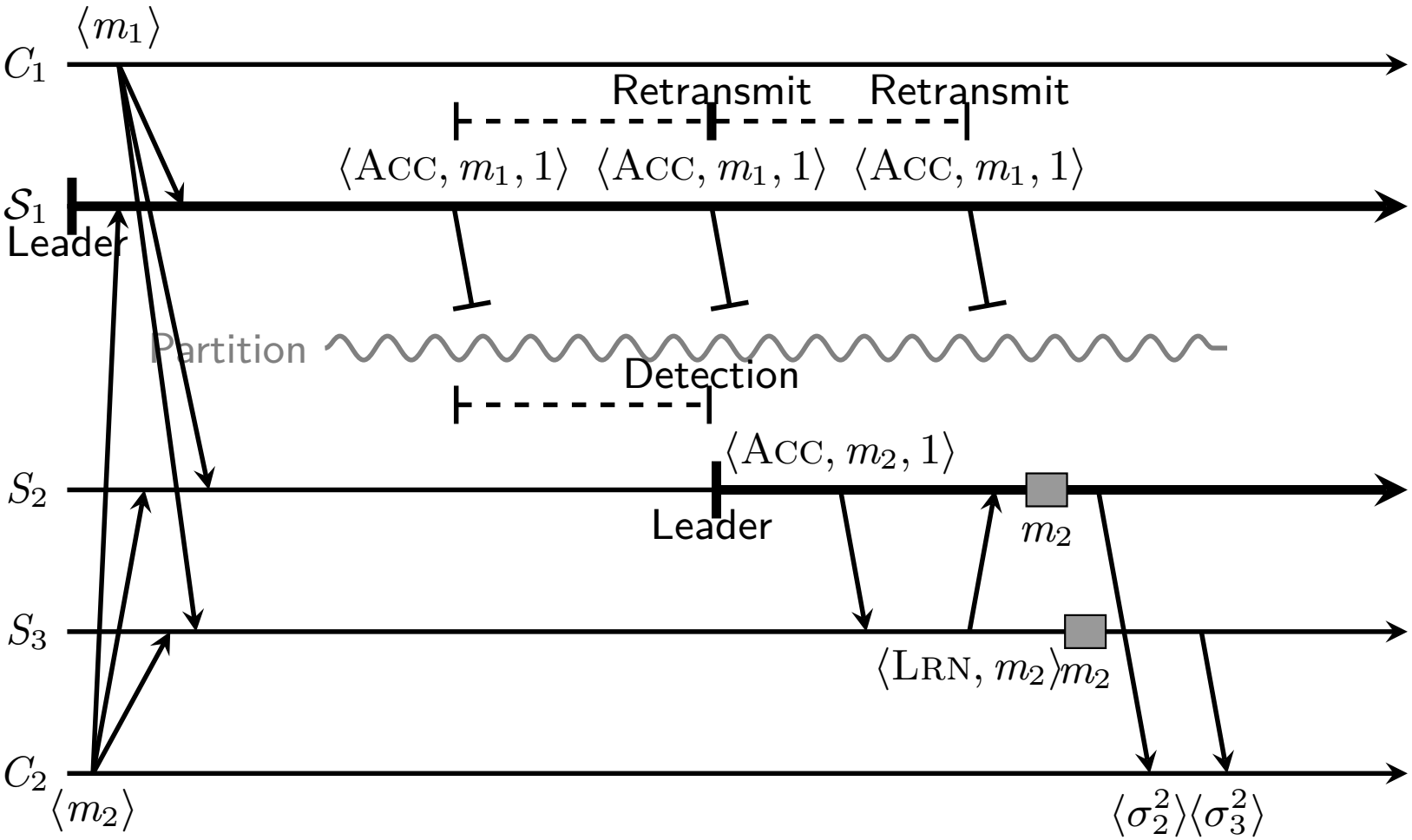
  - Involves rollback on multiple clients
  - Quickly becomes unmanageable

We Want to Avoid Relying on Clients!

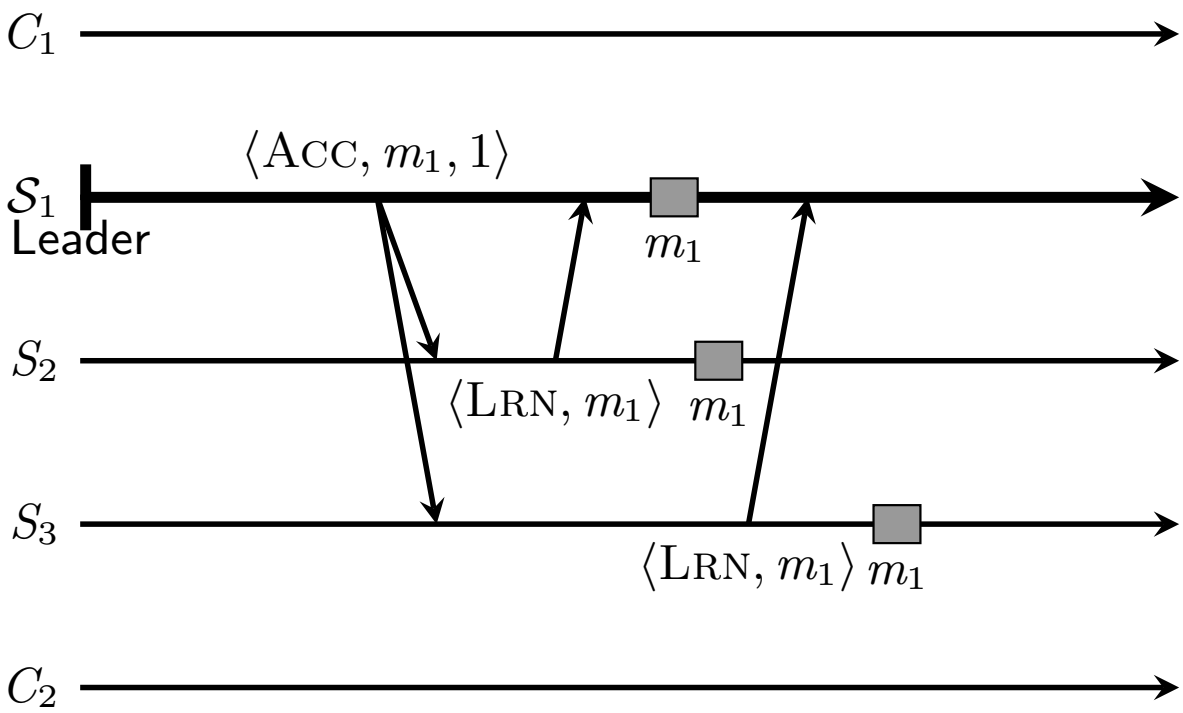
Add Another Server; Make Progress in Majority Partition



New Leader in Majority Partition



WaitForLearn Without Partition



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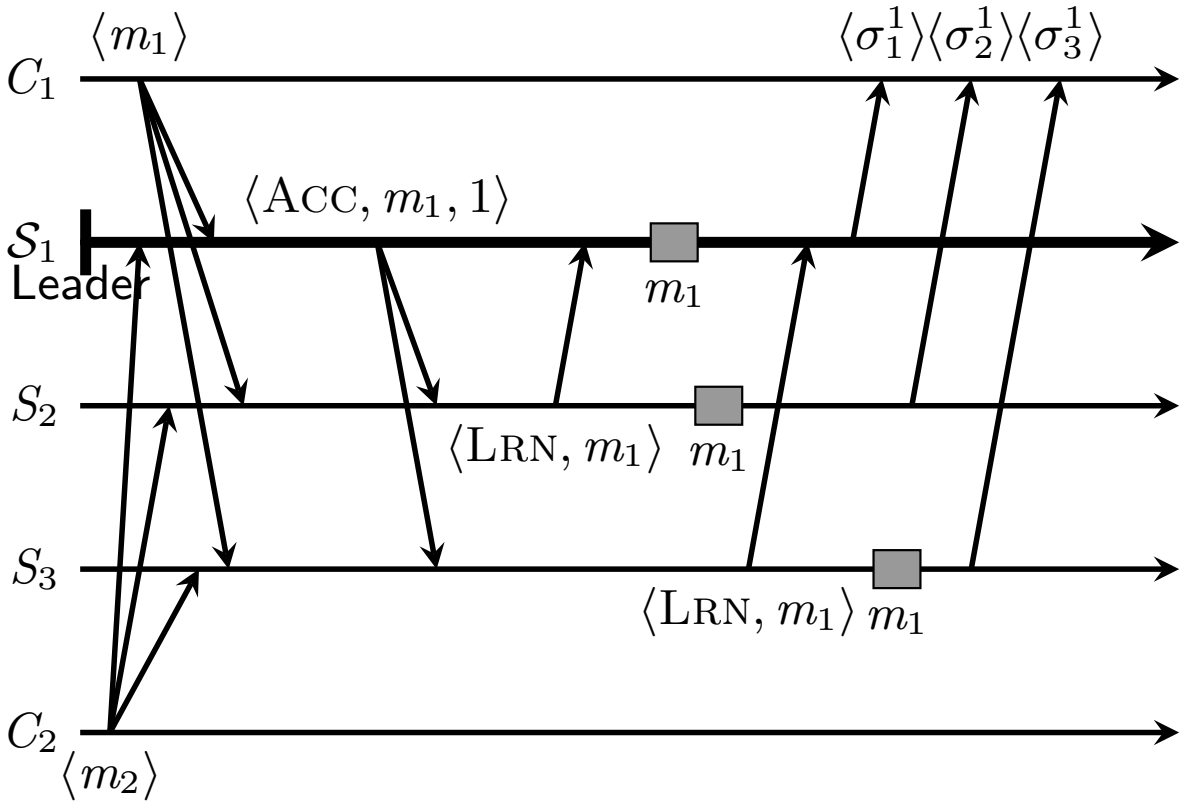

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- Leader only needs to wait for *one* learn before executing the request
  - Allows the leader to make progress,
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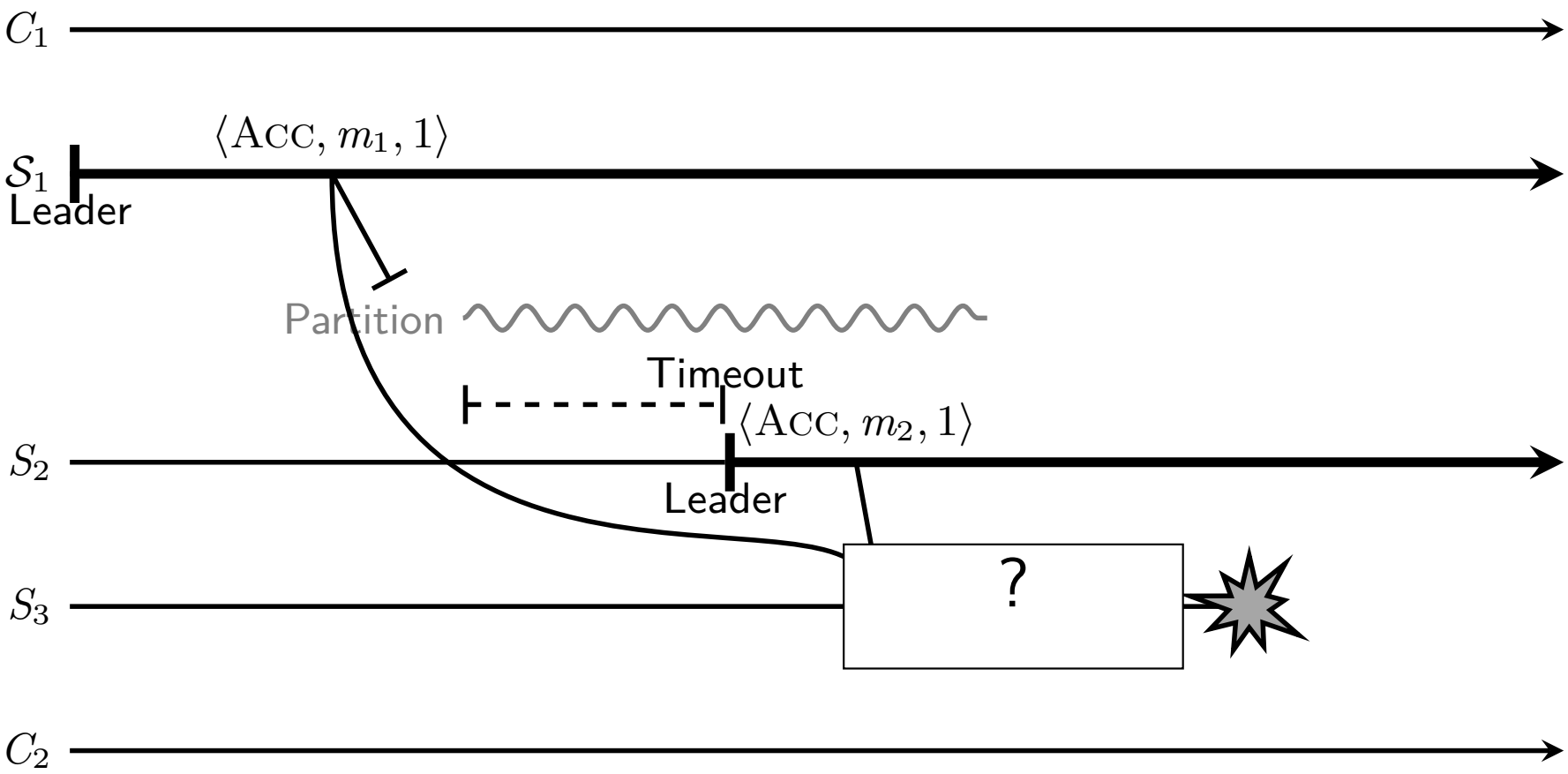
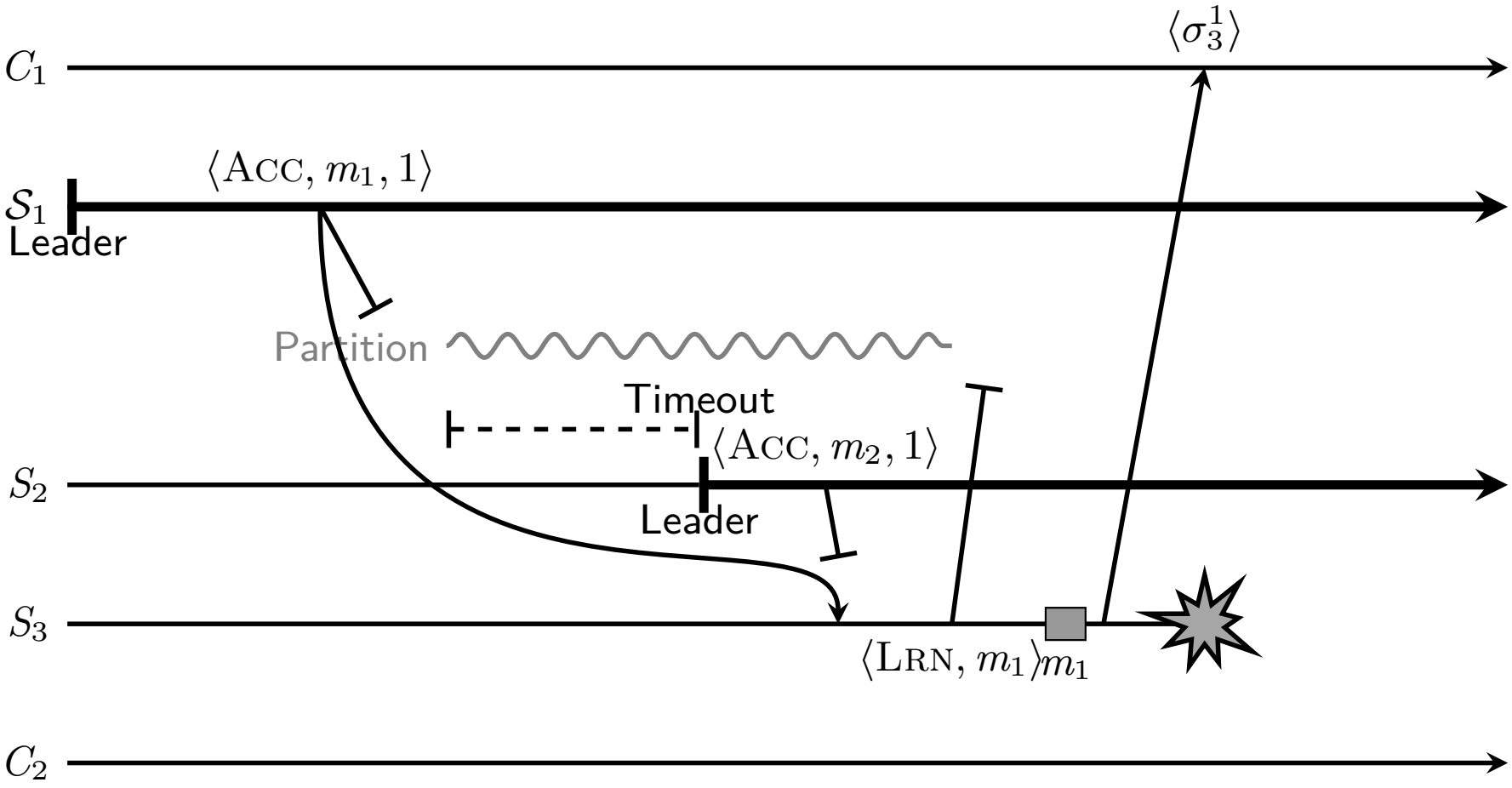
- But we still only tolerate one concurrent failure
  - Either a crash or a network partition

What can go Wrong: Concurrent Crash and Partition

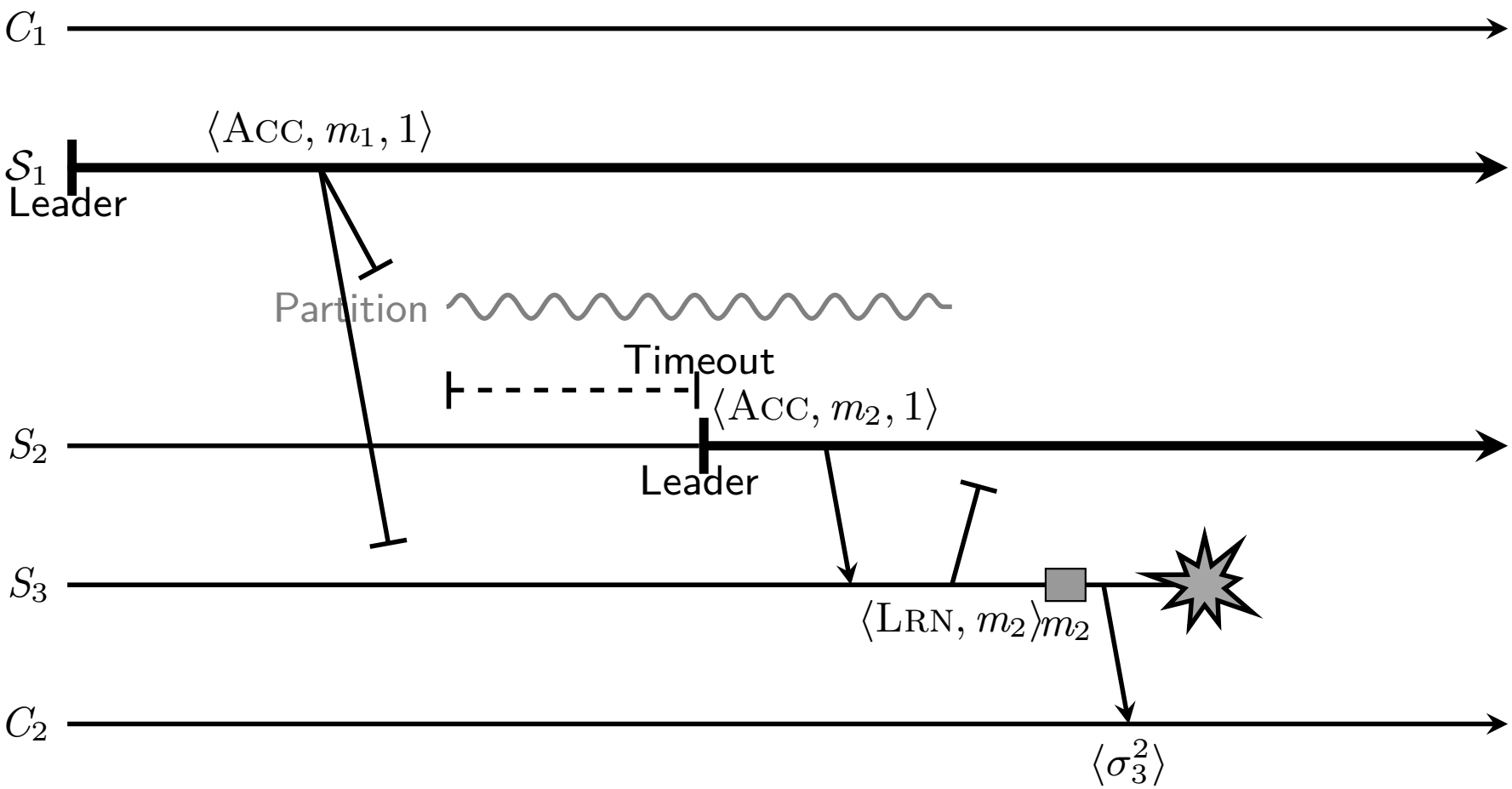
Concurrent Crash and Partition



Crash and Partition: Outcome 1 – m_1 Executed



Crash and Partition: Outcome 2 – m_2 Executed



Recap: Crash and Partition

- S_3 crashed
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- S_3 crashed
  - But *it could* have executed either m_1 or m_2
  - And replied to a client
- Other servers cannot determine which message, if any, was executed
  - Maybe we could talk to clients?
  - We don't want to rely on clients!

Explicit Leader Change Mechanism

- Above problem is rooted in possibility of false detection
  - Can lead to several servers thinking they are leaders
  - And sending accept messages concurrently

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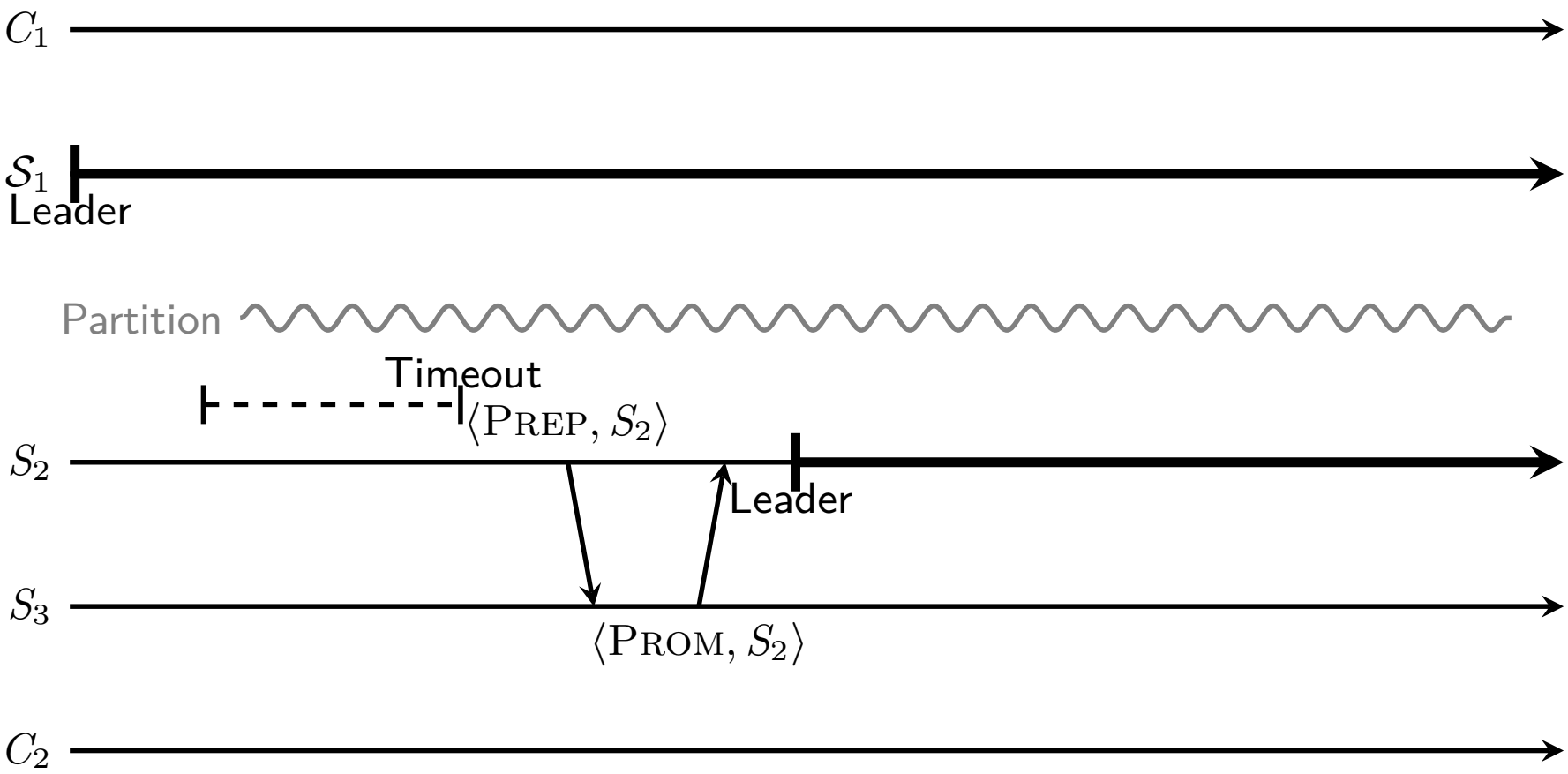
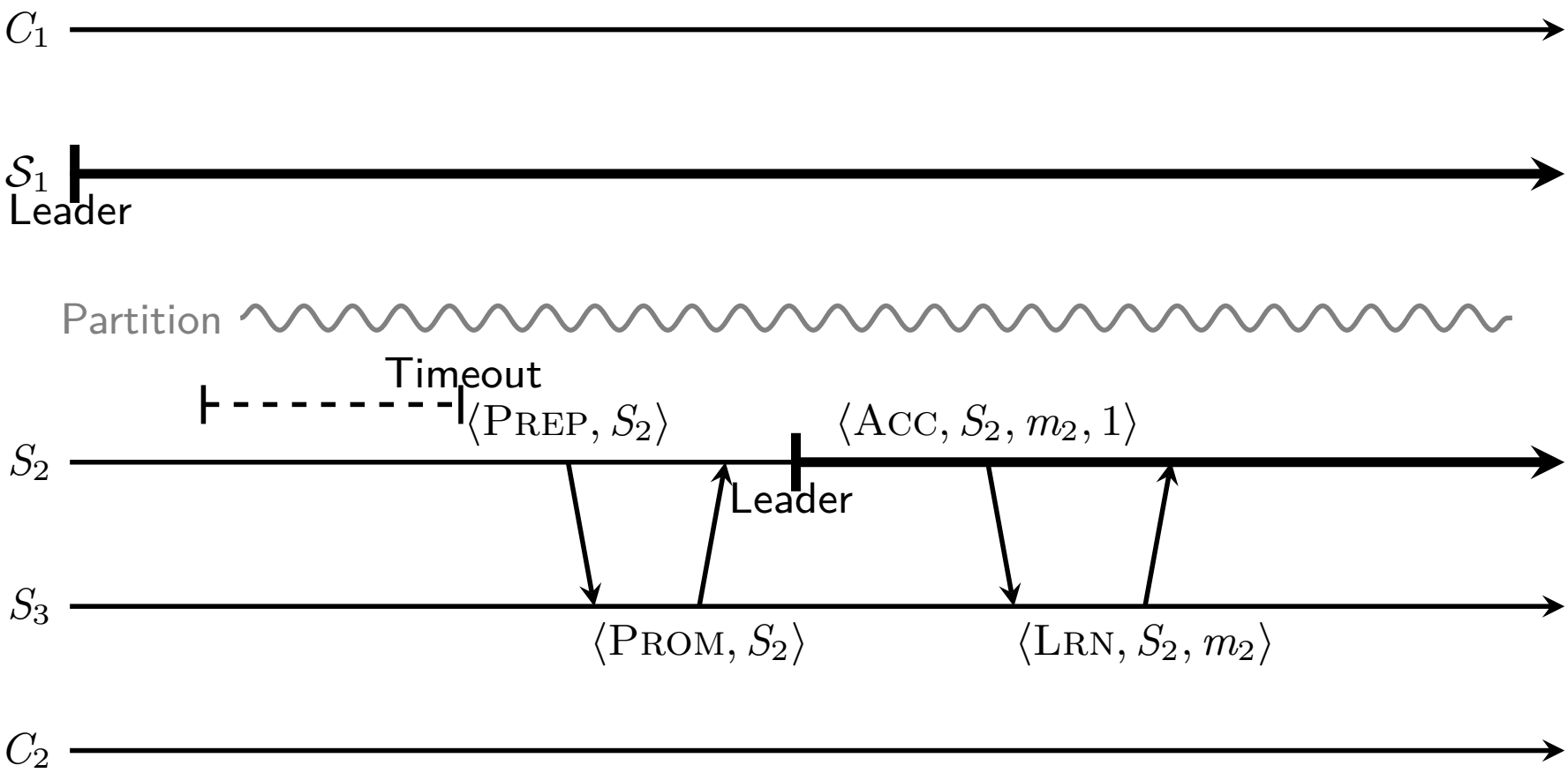
  - Can lead to several servers thinking they are leaders
  - And sending accept messages concurrently
- It can be solved by an explicit leader takeover protocol
- We need a way to
  - Distinguish messages from different leaders
  - Change the leader

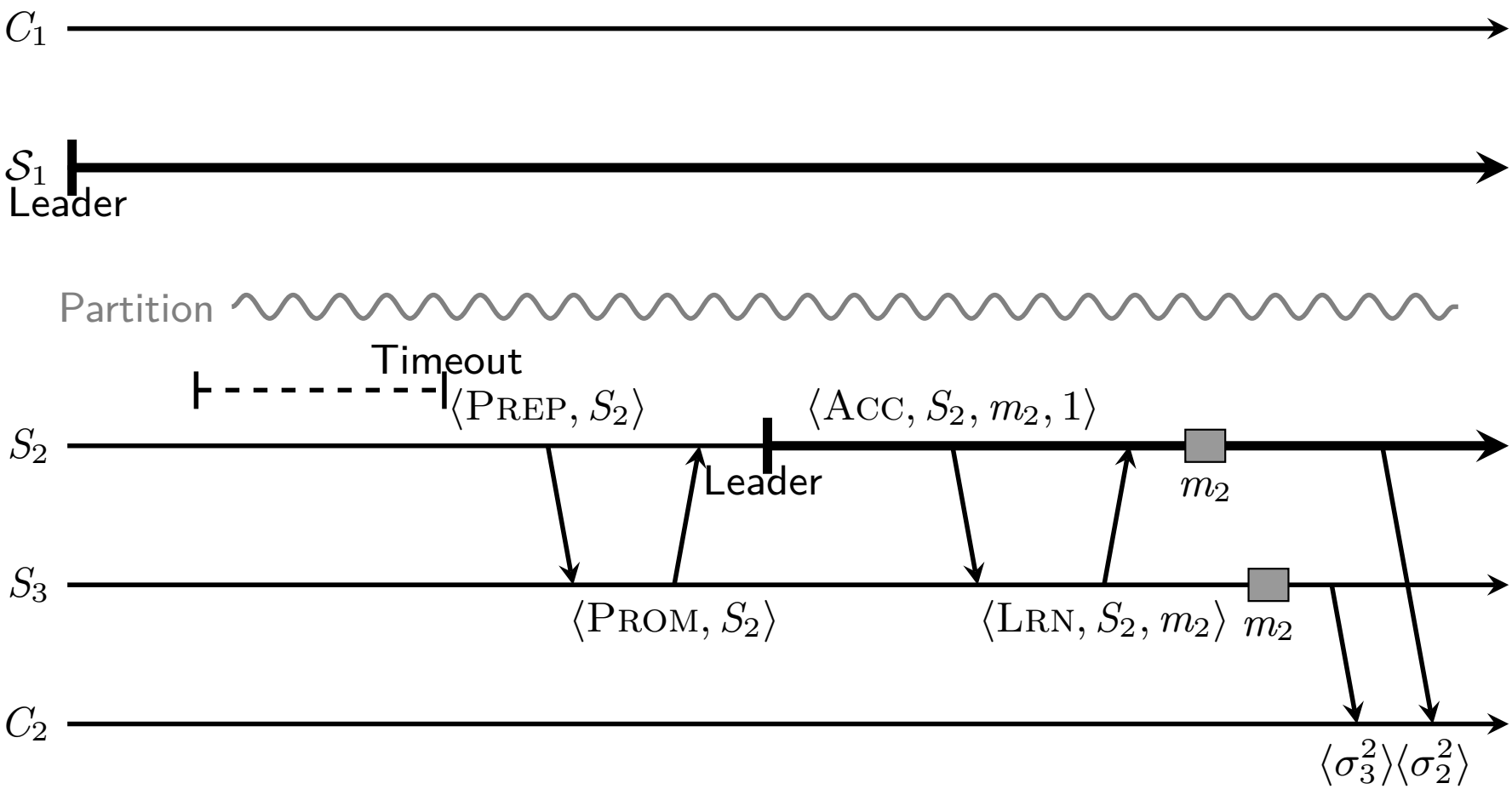
Explicit Leader Change



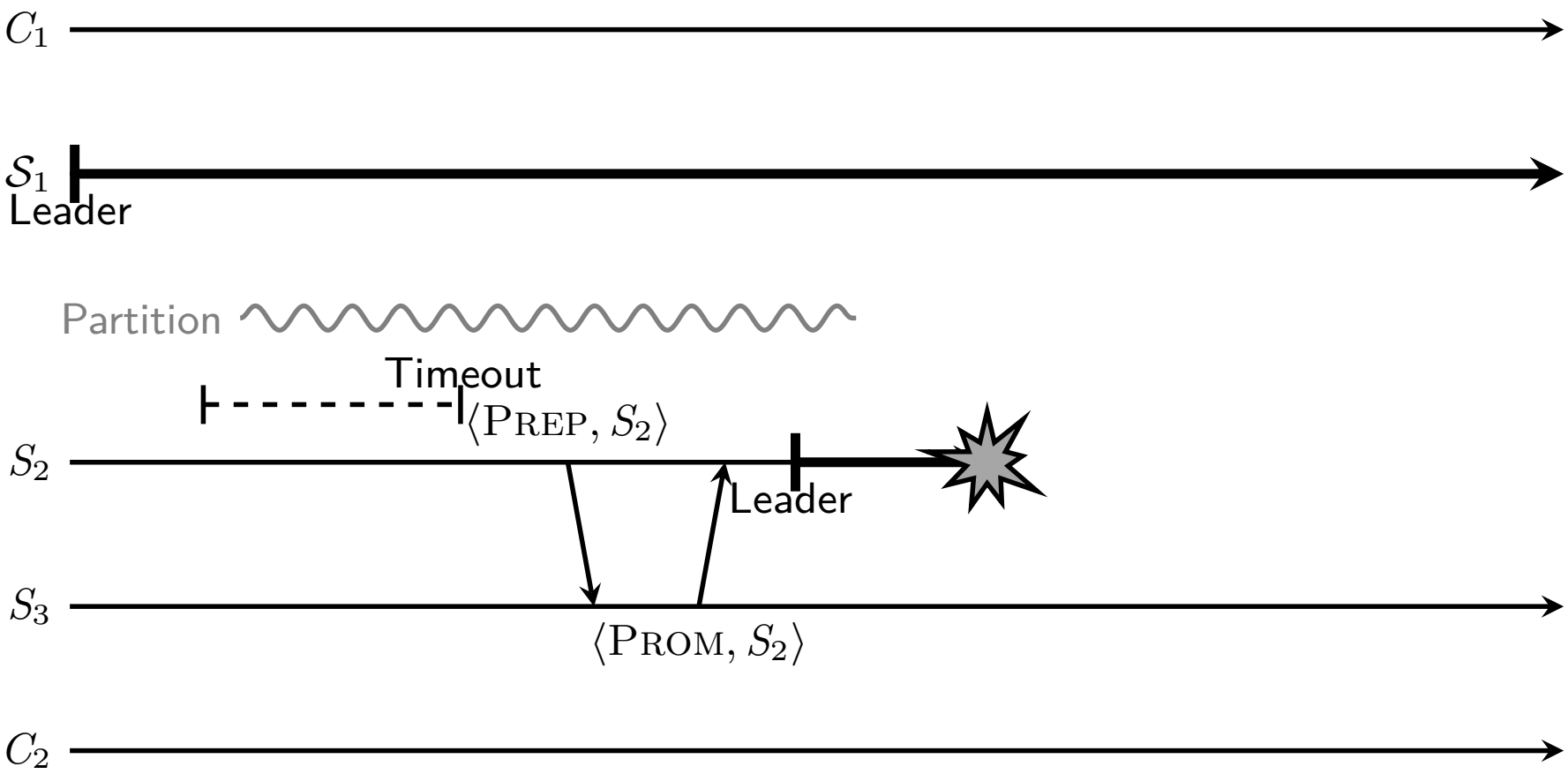
Leader Identifiers in Accept and Learn Messages



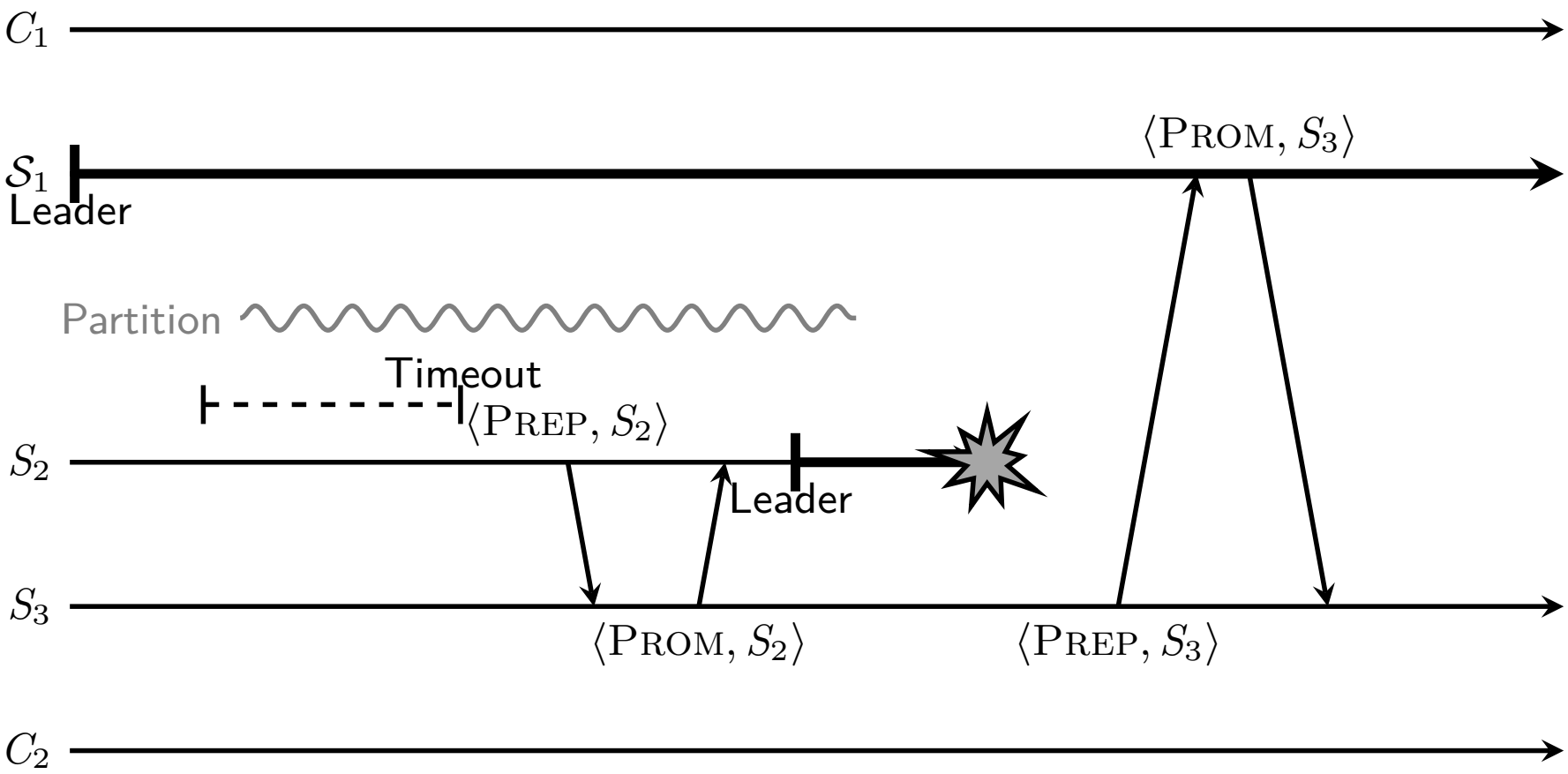
With Client Replies



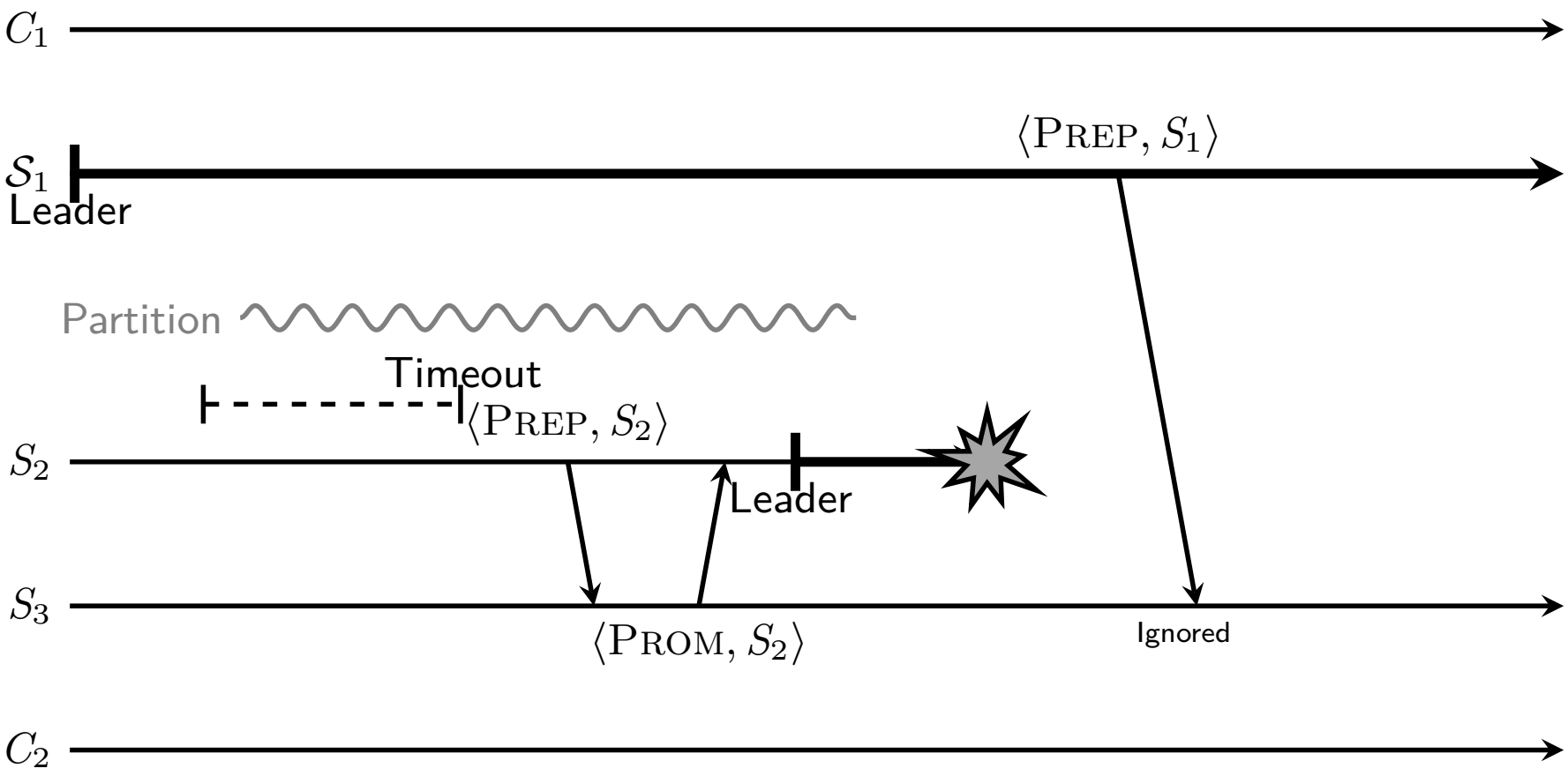
What Happens Now?



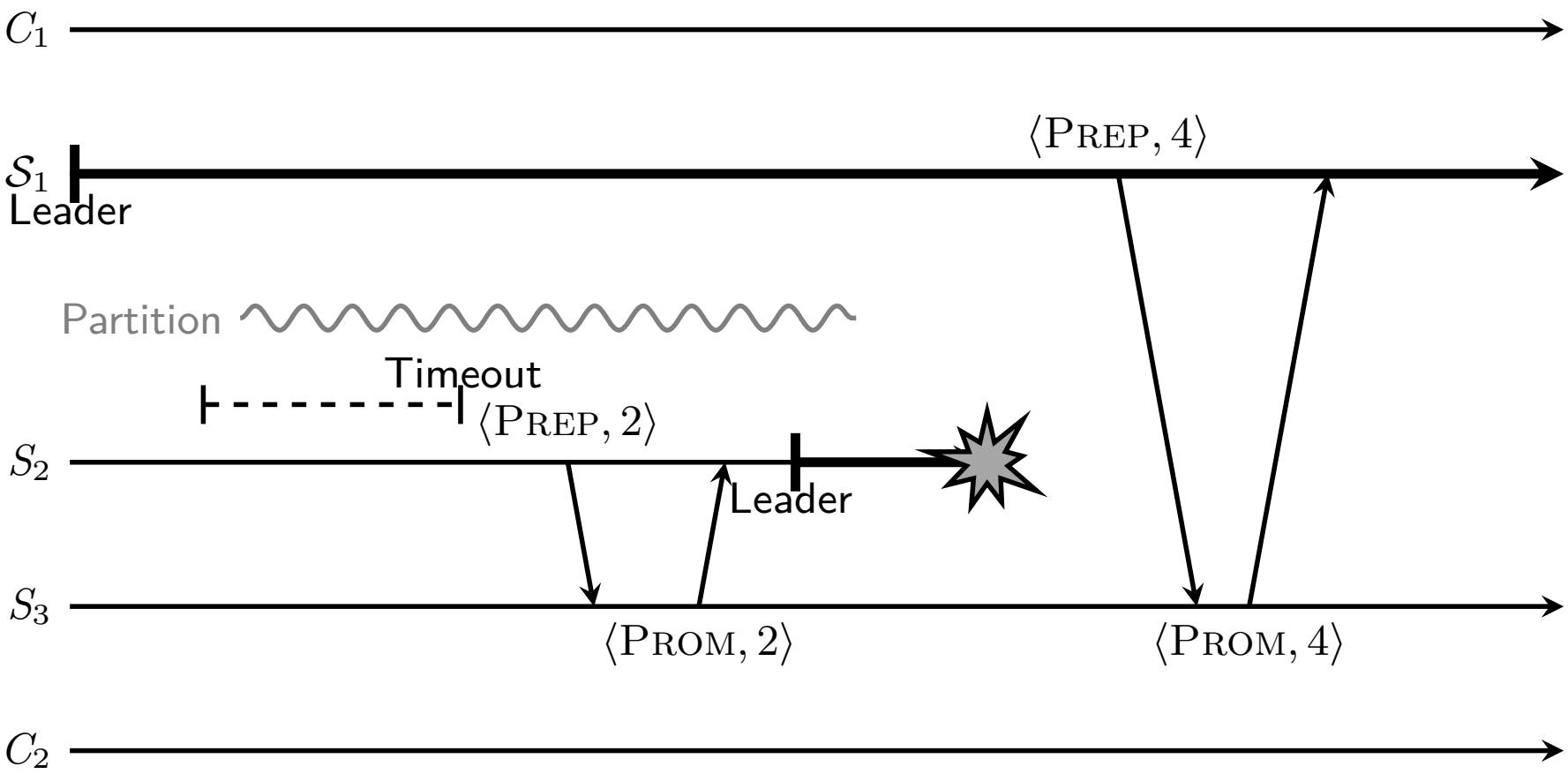
S_3 Takes Over?



S_1 Takes Over Again?



Replace Leader Identifiers With Round Numbers



Recap: Leader Change

- Added round number rnd in messages
  - To identify the leader
    - $\langle \textsc{Acc}, rnd, m, seqno \rangle$: Sent by leader of round rnd
    - $\langle \textsc{Lrn}, rnd, m \rangle$: Sent to leader of round rnd

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  - Round numbers are assigned:
    - S_1: $1, 4, 7, \ldots$
    - S_2: $2, 5, 8, \ldots$
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  - Skipping rounds is possible

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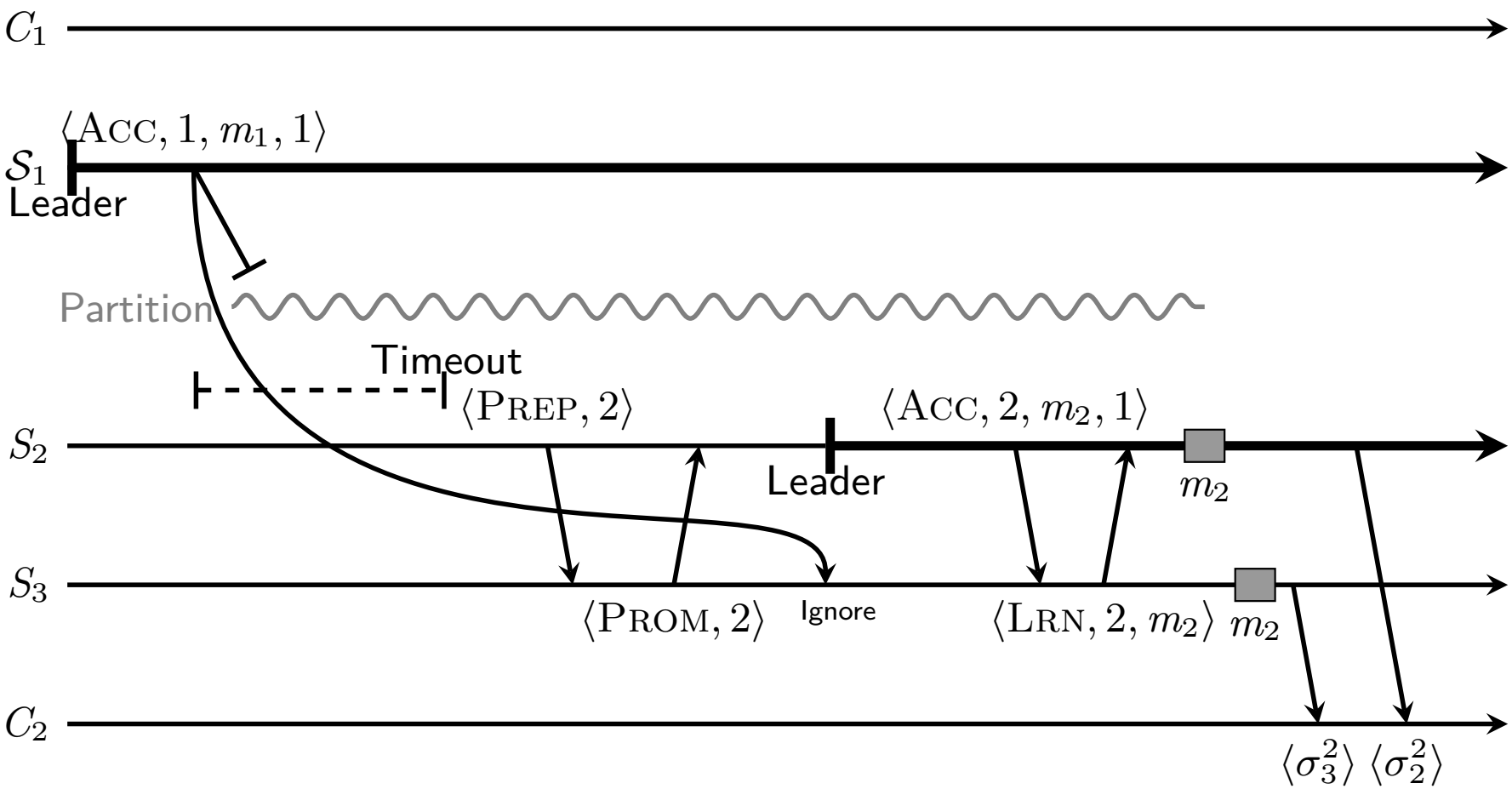
    - S_3: $3, 6, 9, \ldots$
  - Skipping rounds is possible
- Added two new messages
  - $\langle \text{PREP}, rnd \rangle$: Request to become leader for round rnd
  - $\langle \text{PROM}, rnd \rangle$: Promise not to accept messages from a lower round than rnd (i.e. an older leader)

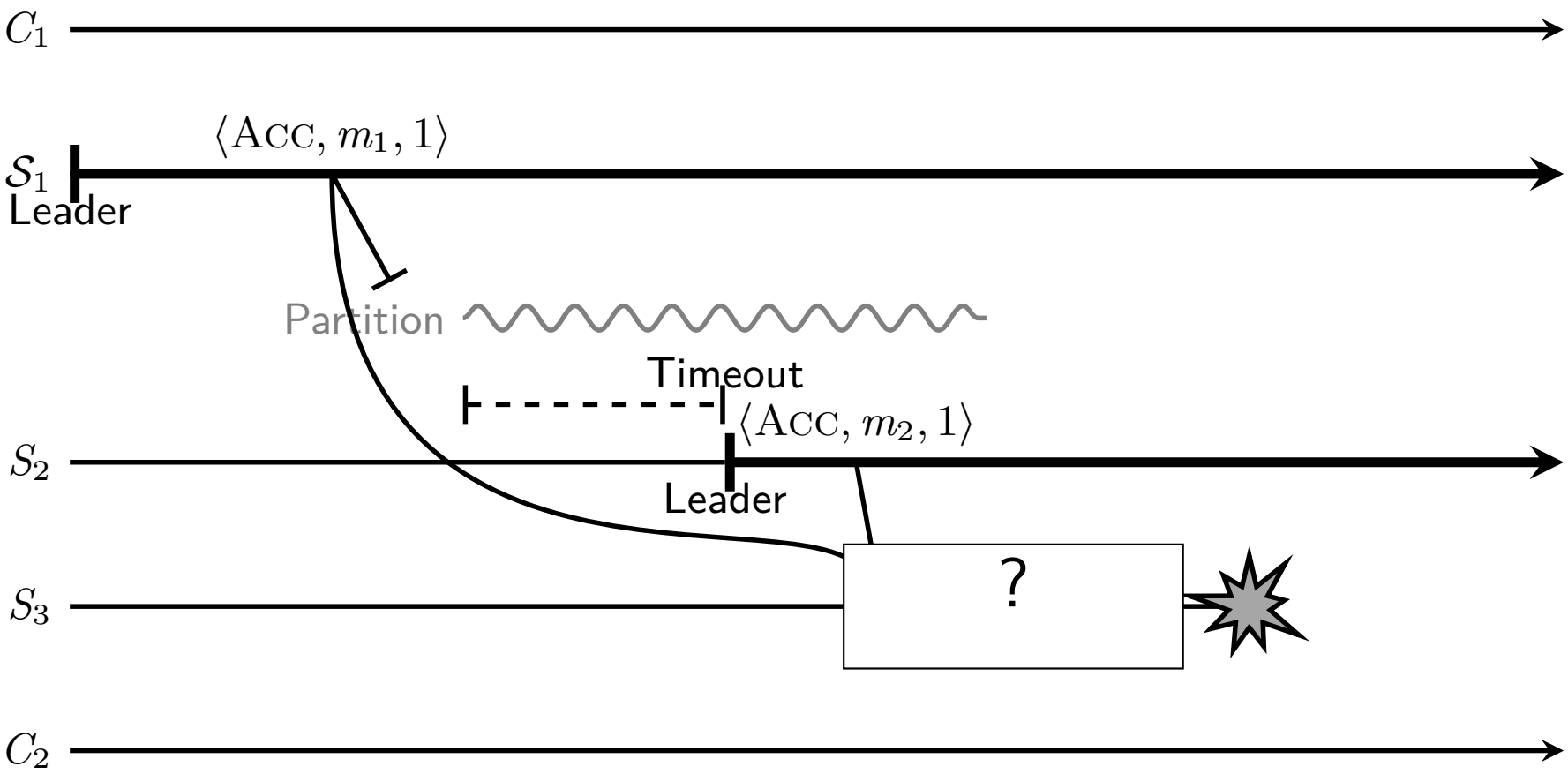
Let's Apply This Together With Accept and Learn

S_3 Ignores Accept Message From Old Leader

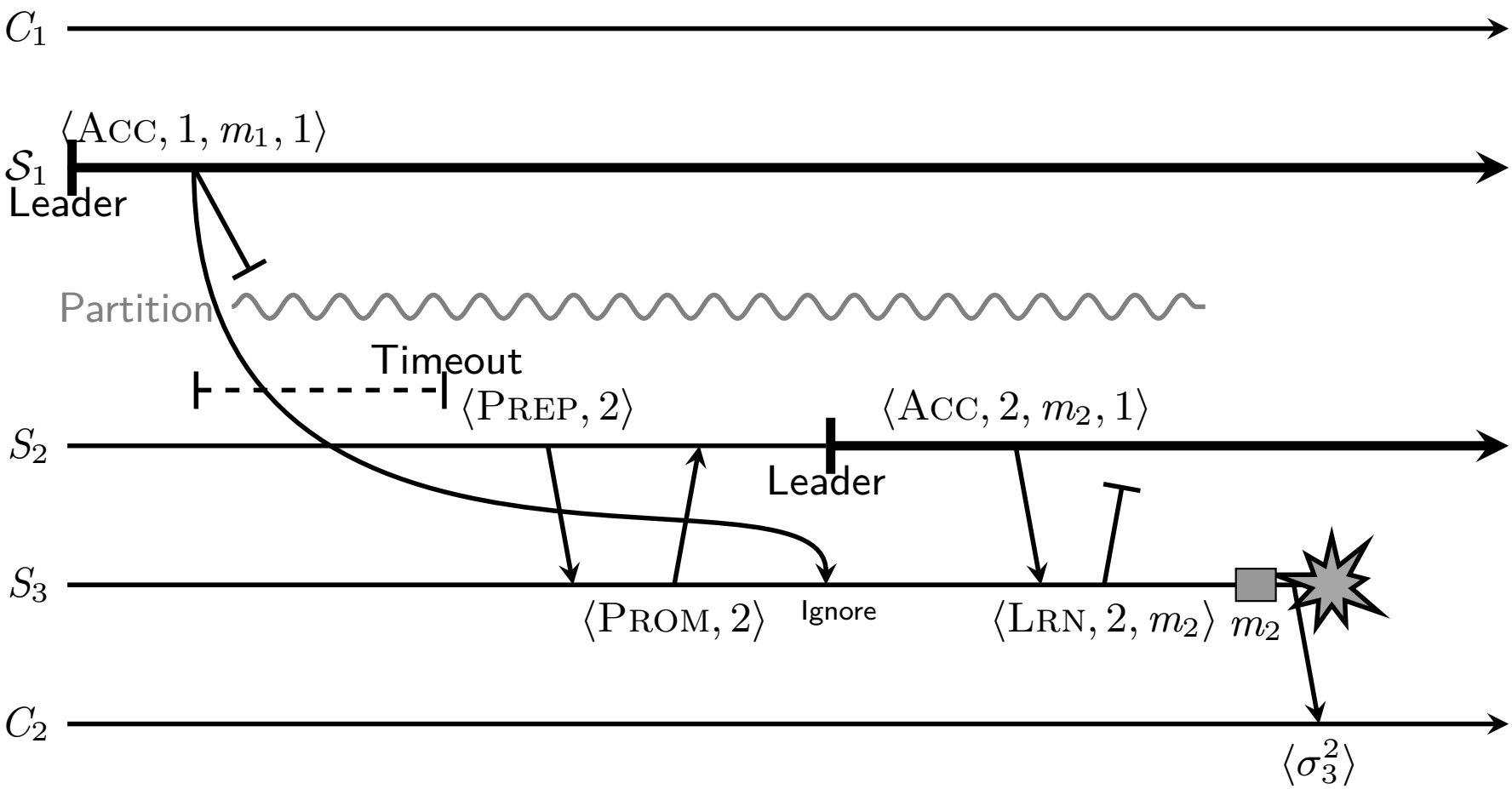


Let's Recall the Problem we are Trying to Solve

We Don't Know What S_3 Did Before Crashing



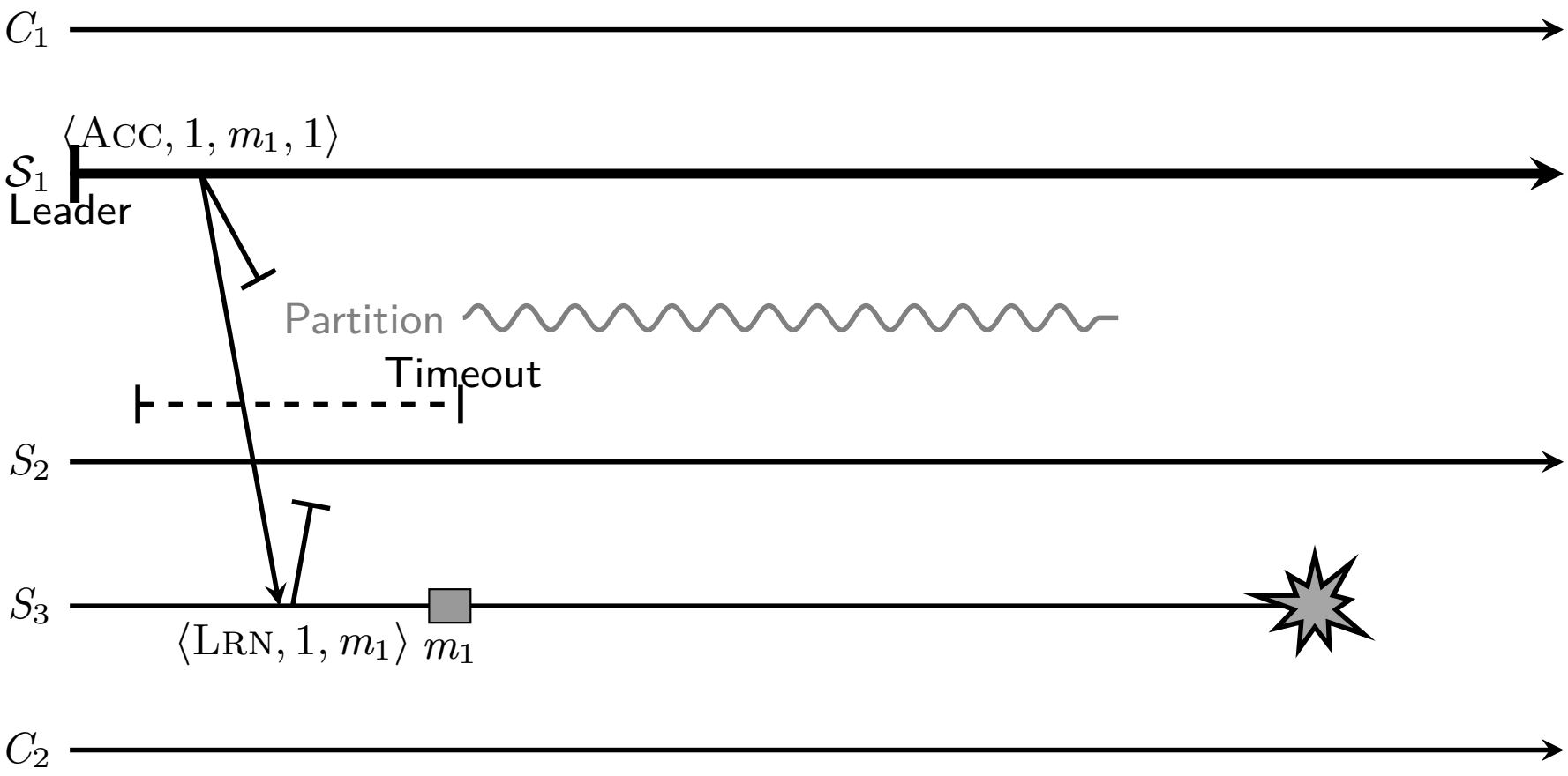
Do We Know Now?



No we don't!

But it is Safe to Continue as If m_2 Had Been Executed

What Happens If S_3 Learn m_1?



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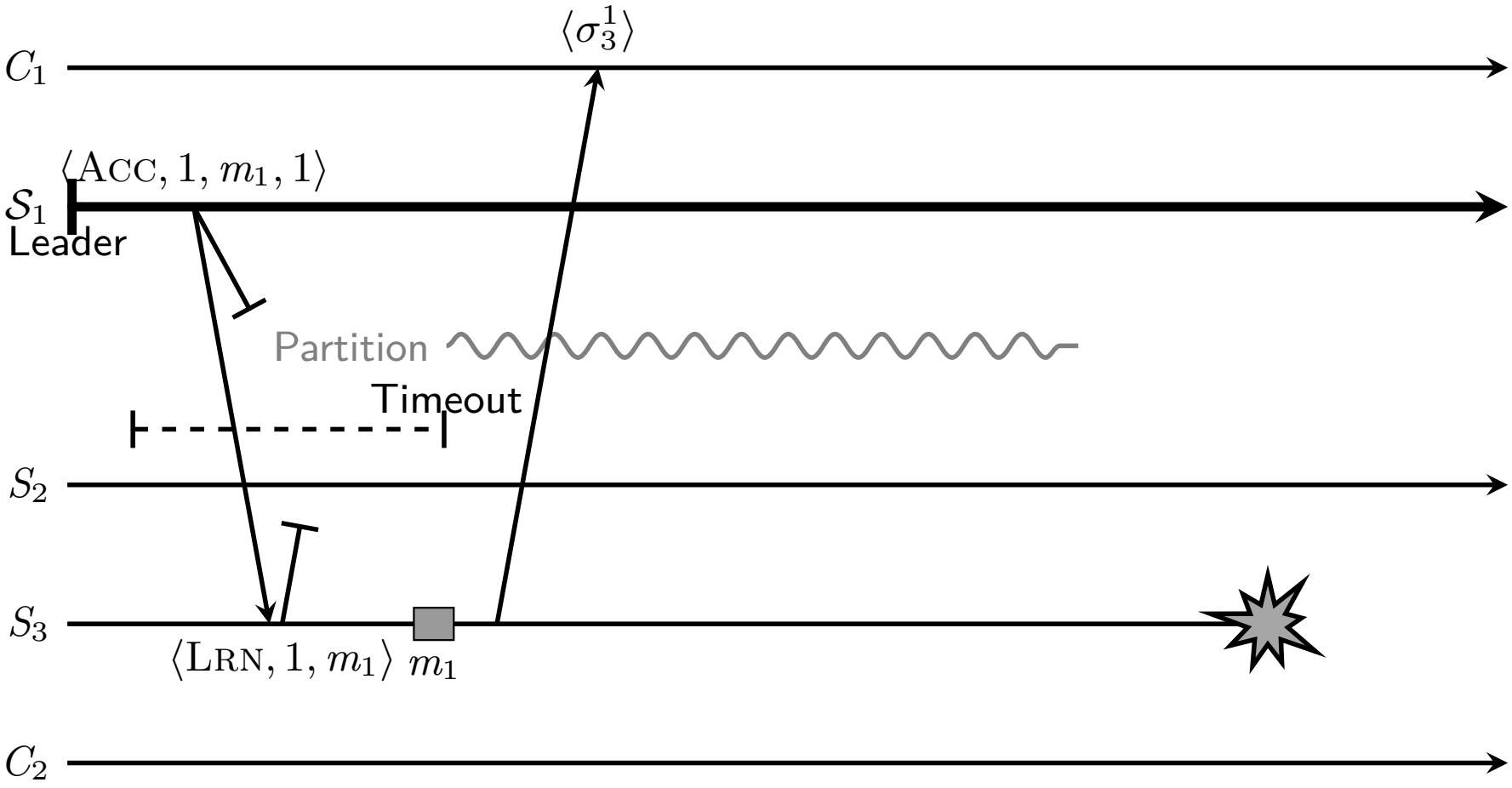
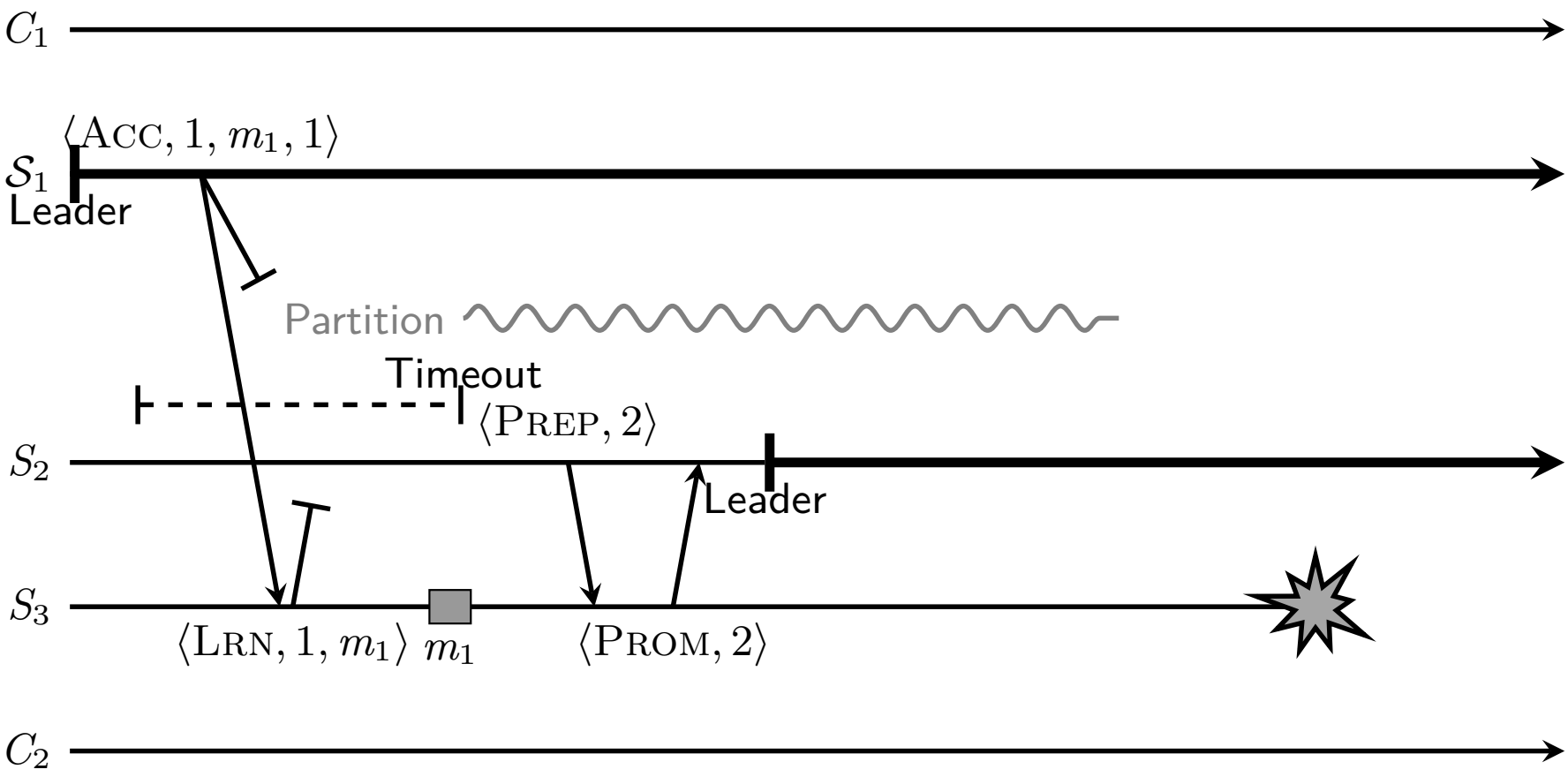


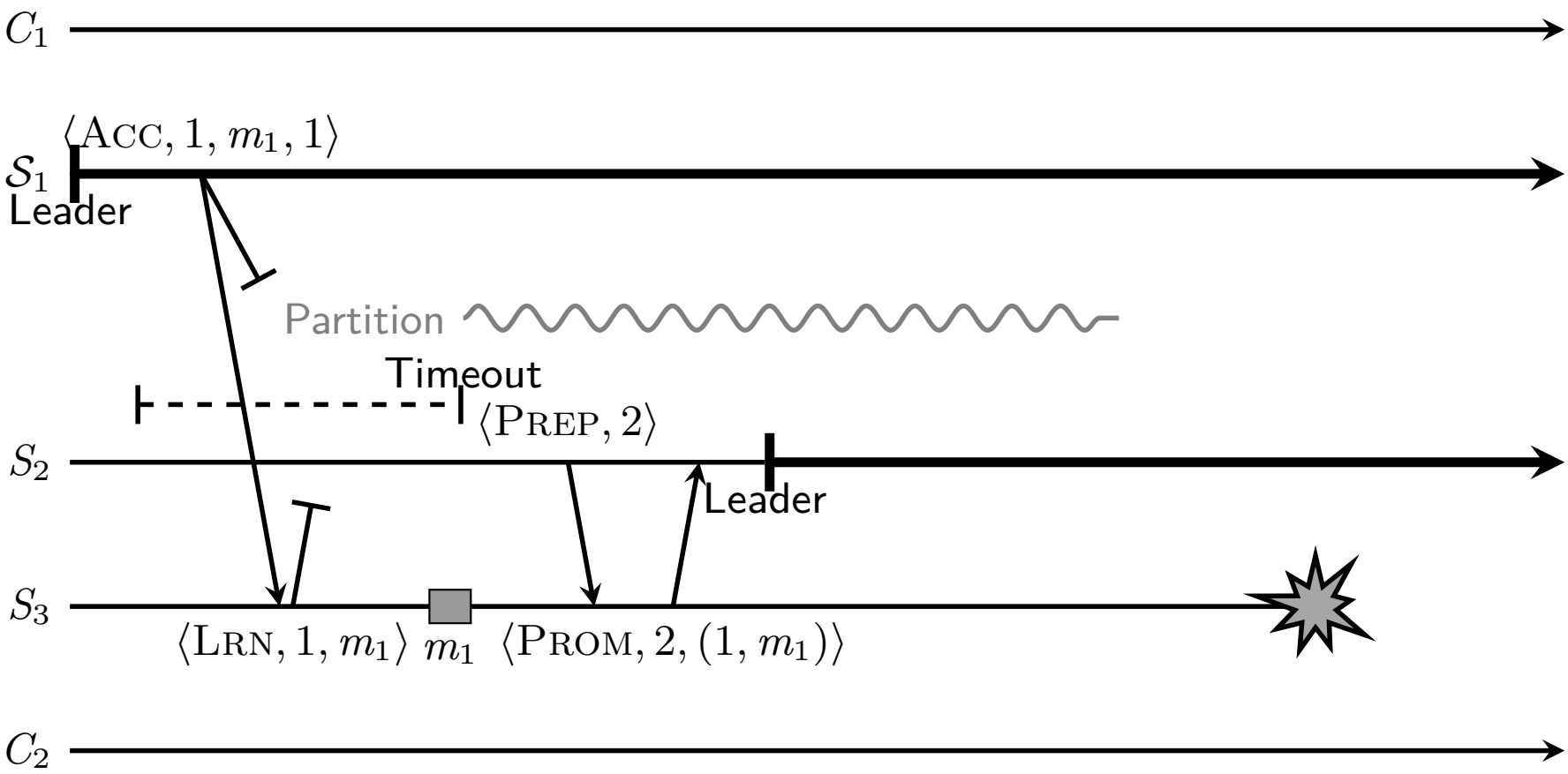
Does Leader Change Help?



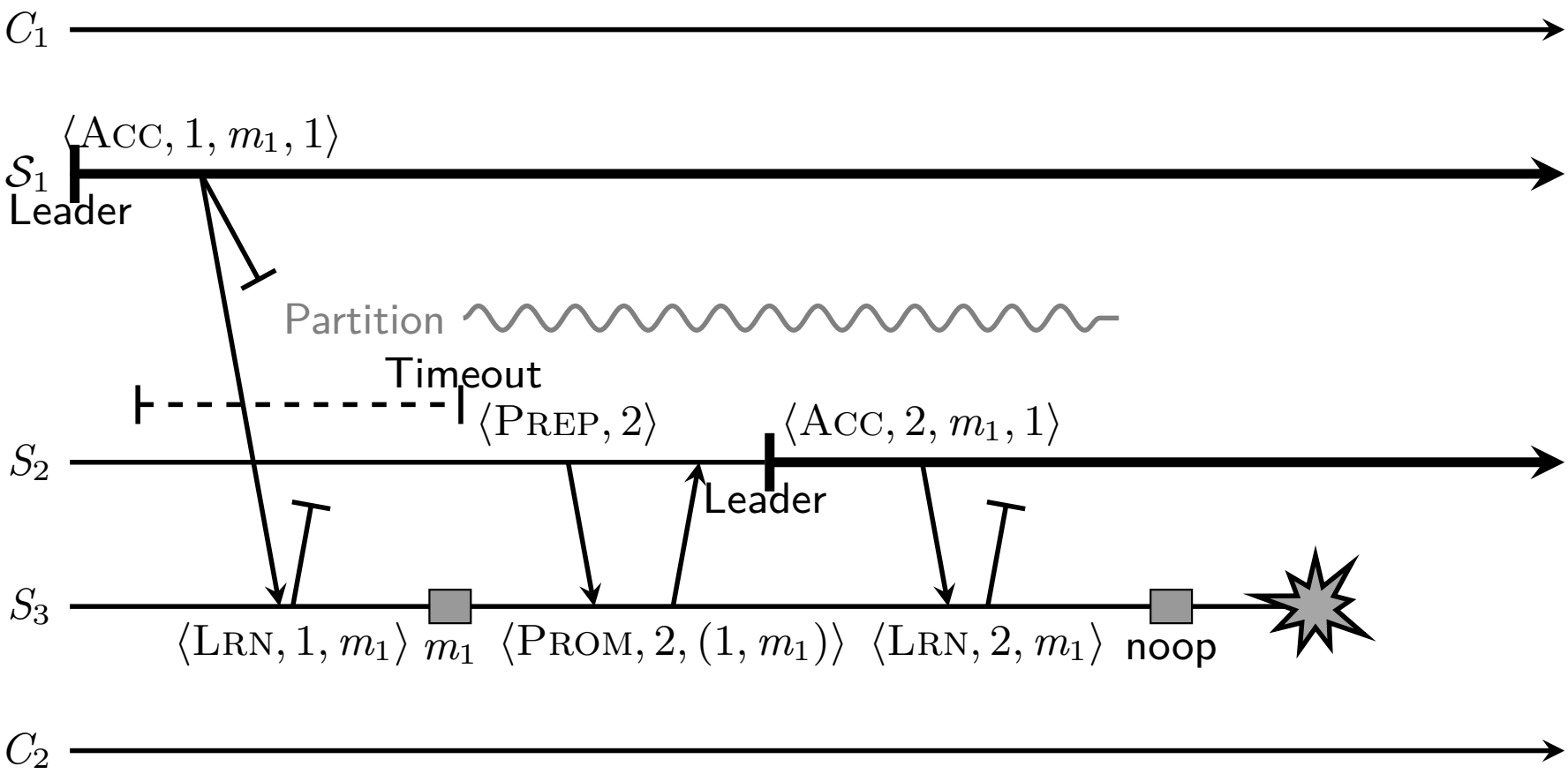
No!
We Still don't Know What
S_3 Did Before Crashing.

But the fix is Easy!

Tell new Leader About Accepted Messages

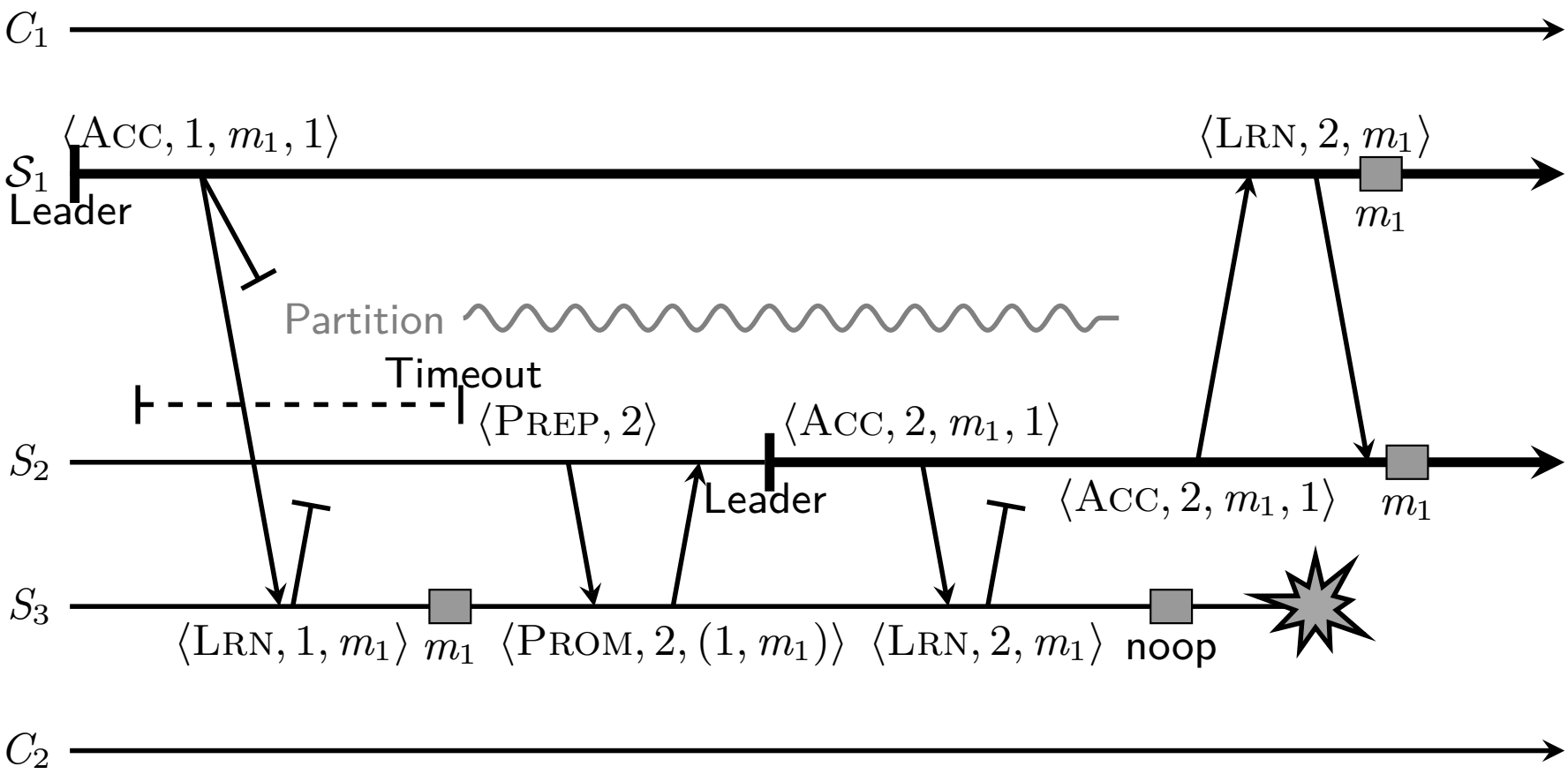


The new Leader Resends Accept for Those Messages

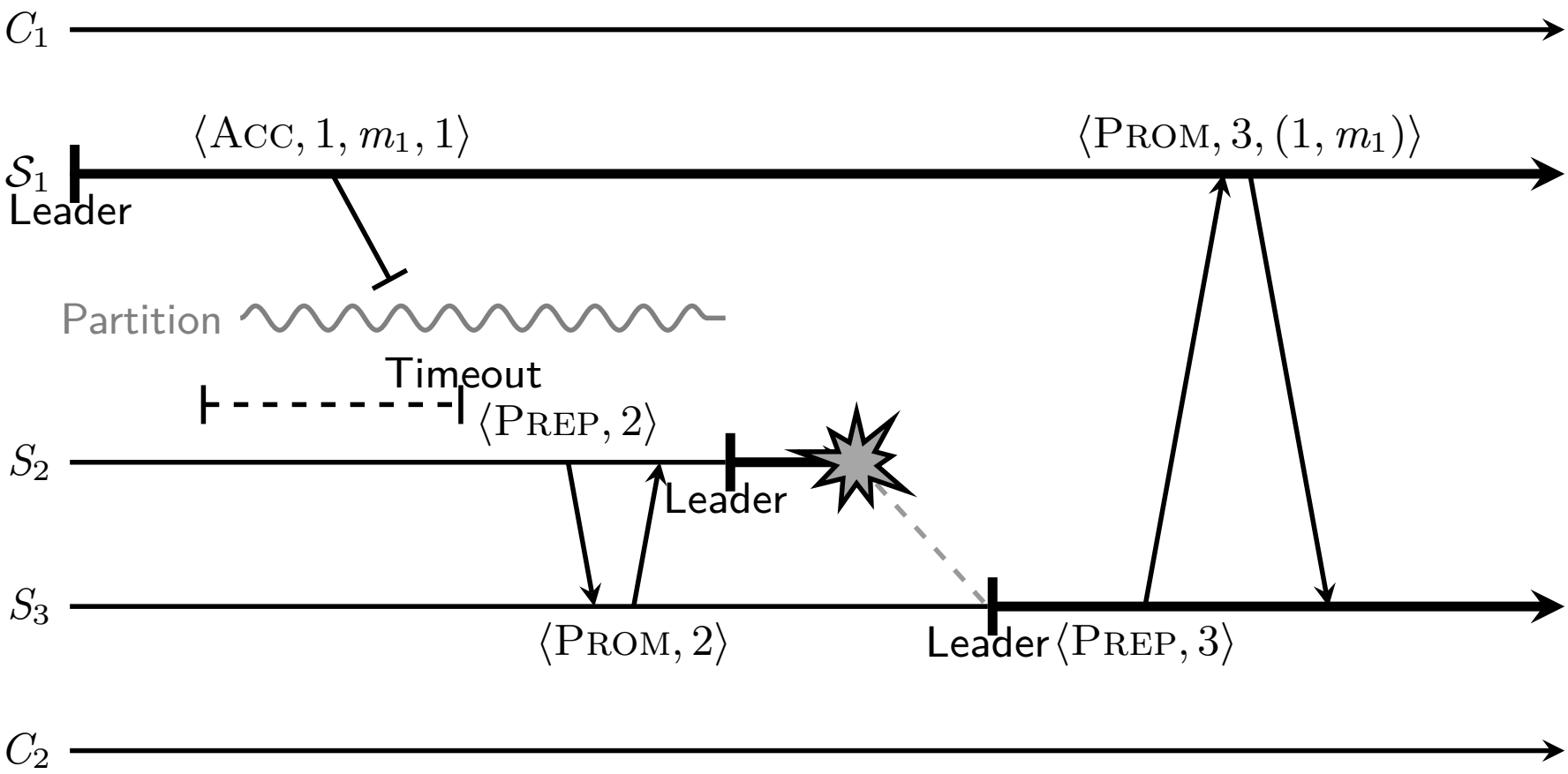


Learn was Lost and S_3 Crashed.
Leader Still can't Execute m_1.

Leader Also Resends Accept After Merge



Promise from old Leader Includes Accepted Messages



Recap: Leader Change 2

- Added information about accept from previous leader: $\langle \text{PROM}, rnd, (1, m_1) \rangle$
  - Promise not to accept messages from a lower round than rnd
  - Last leader did send m_1 in round 1
  - Typical naming: $\langle \text{PROM}, rnd, (vrnd, vval) \rangle$

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  - Typical naming: $\langle \text{PROM}, rnd, (vrnd, vval) \rangle$
- Leader resends accept for messages identified in the promise message
  - After receiving the promise
  - After a partition merge

What About More Than one Crash?

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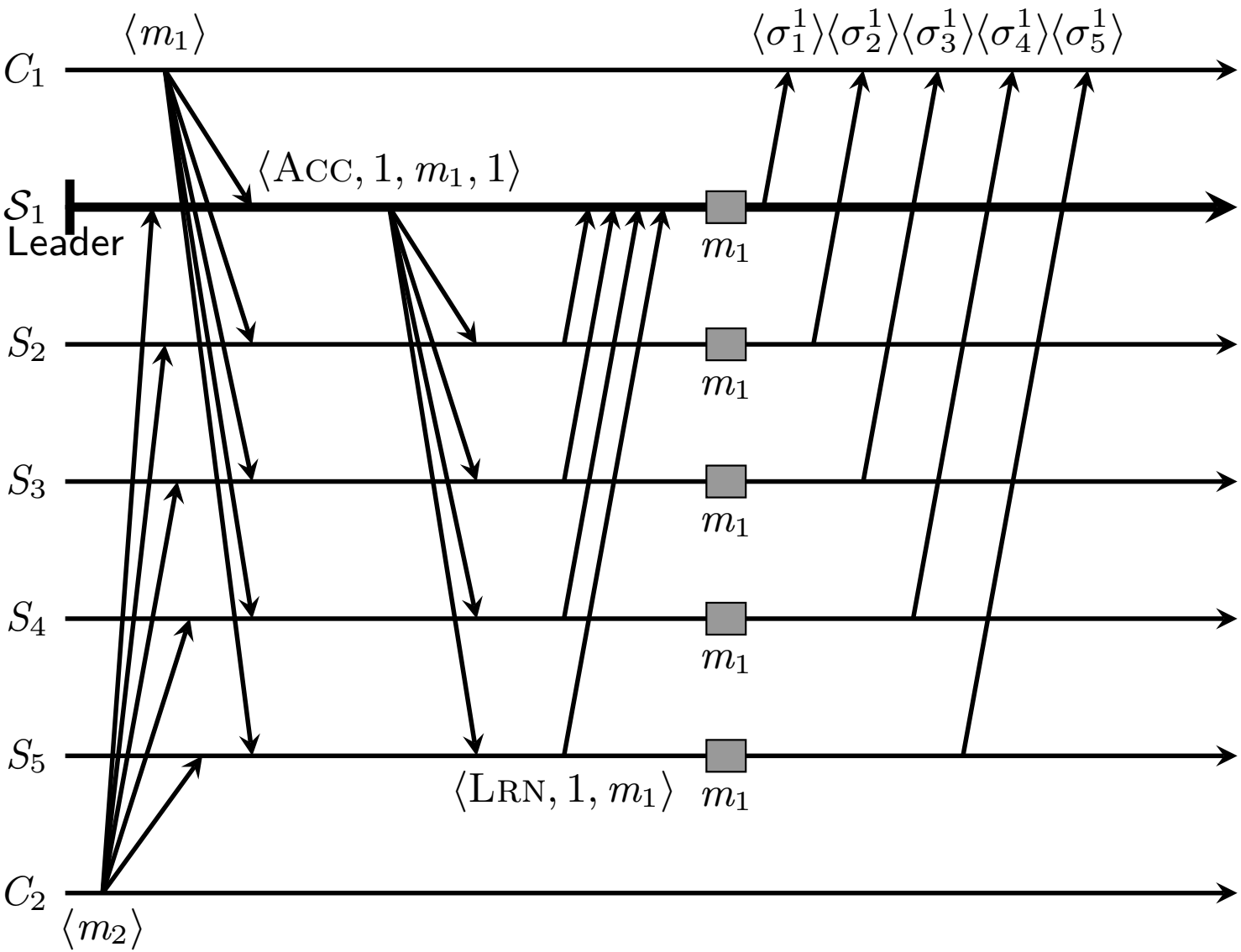
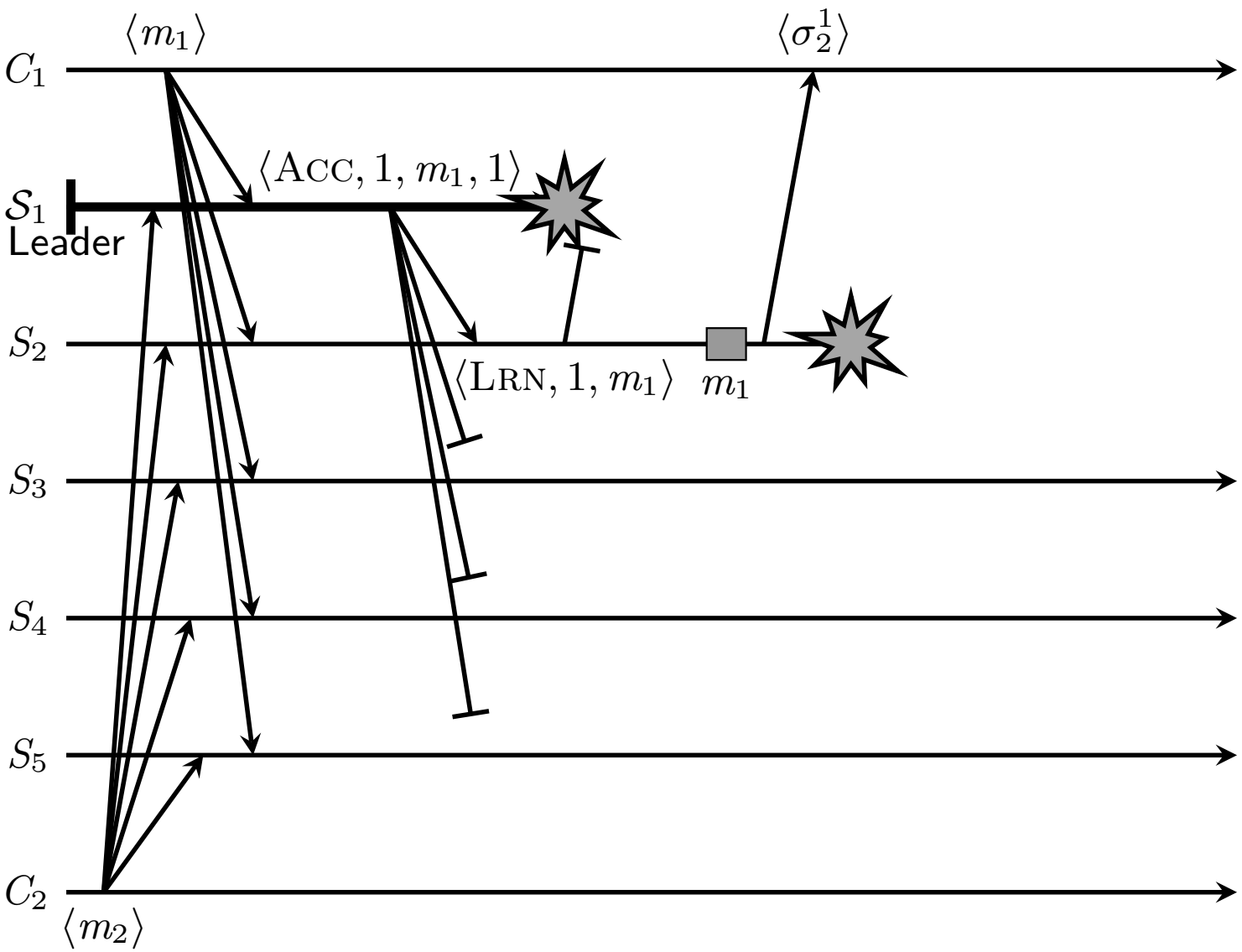
- Increase the number of servers
- To limit progress to a majority partition:
  - We can only tolerate fewer than half of the servers fail
  - To tolerate f crashes, we need at least $2f + 1$

With Five Servers



With Five Servers, S_2 Cannot Execute After Accept



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  - Prevent non-leader servers from executing after receiving an accept
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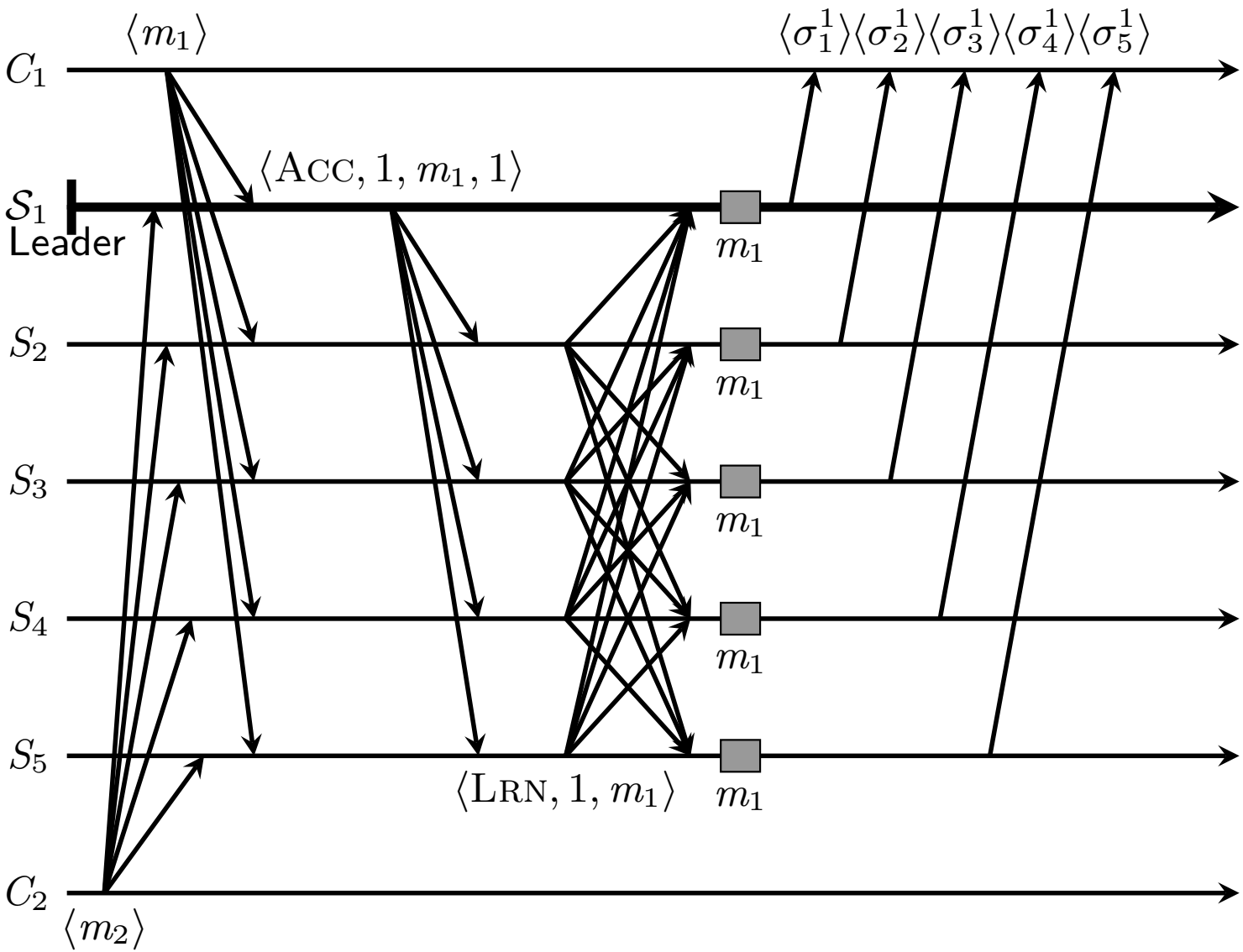
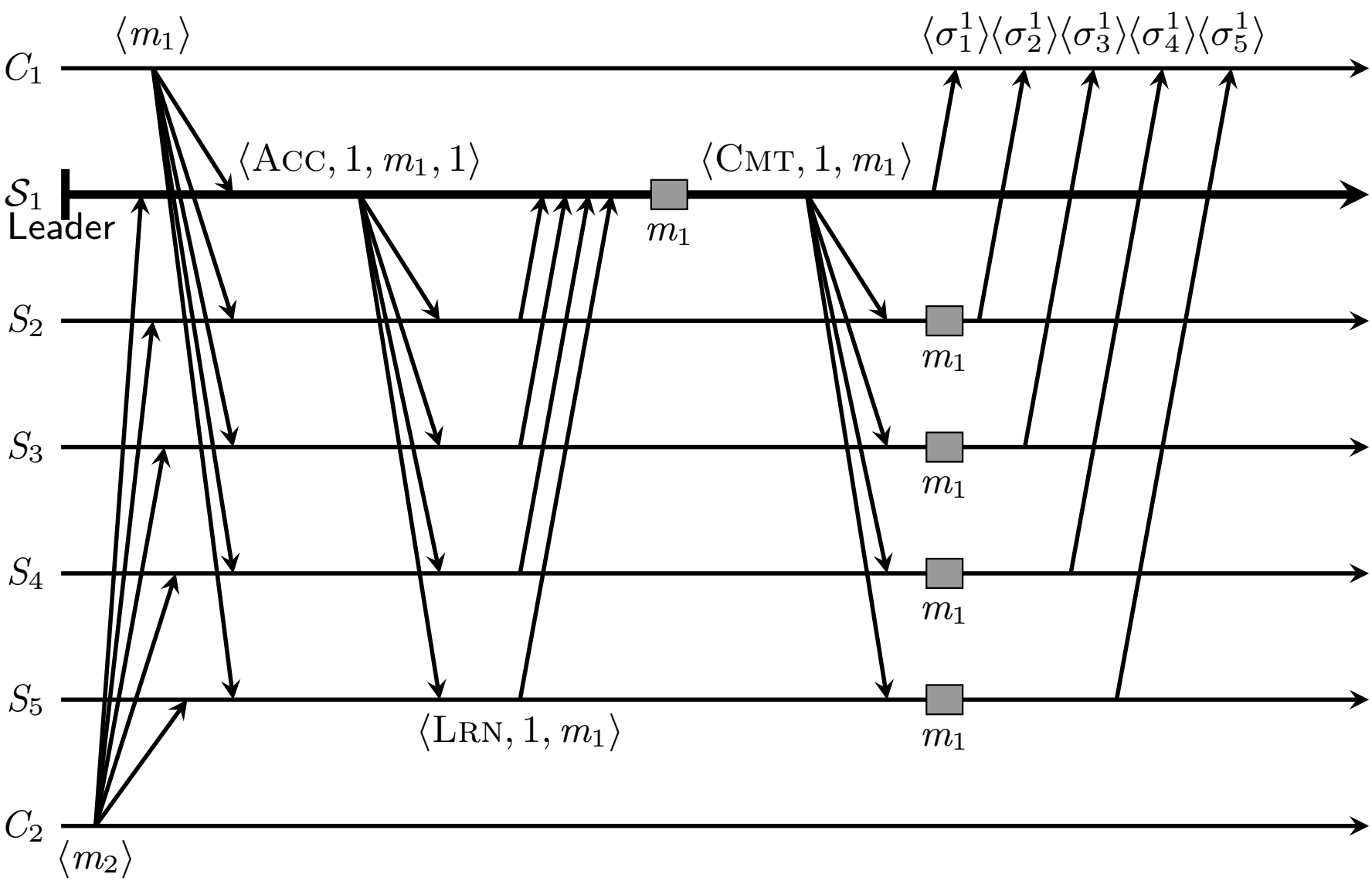
- There are two solutions:
  - Wait for all-to-all learn
  - Wait for commit from leader

All-to-All Learn Before Execute

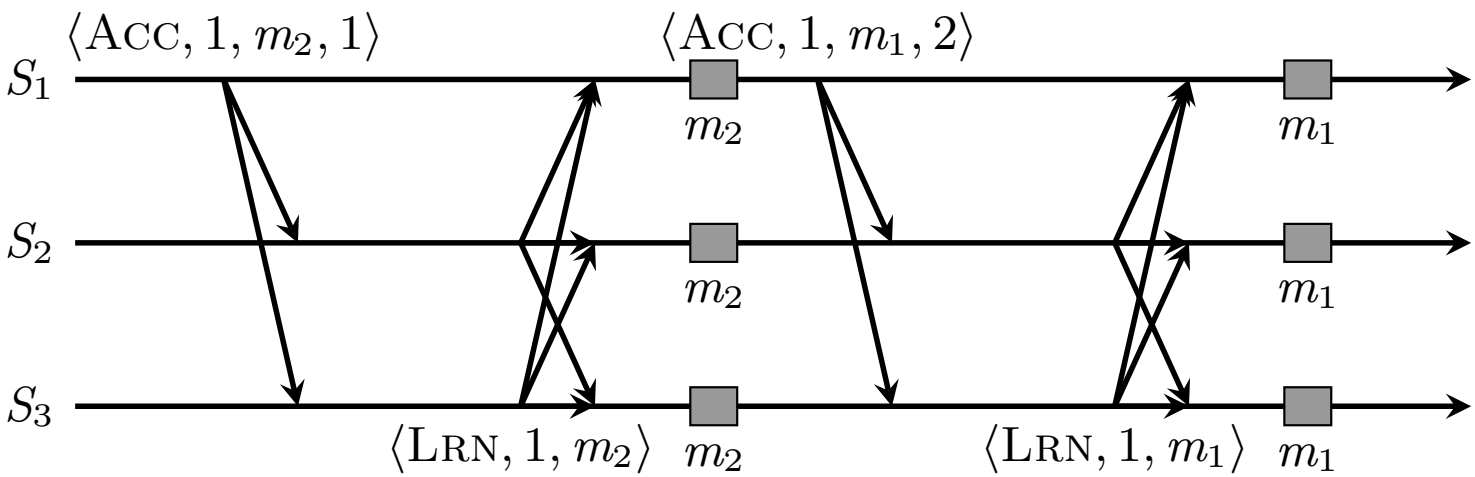


Await Commit Before Execute

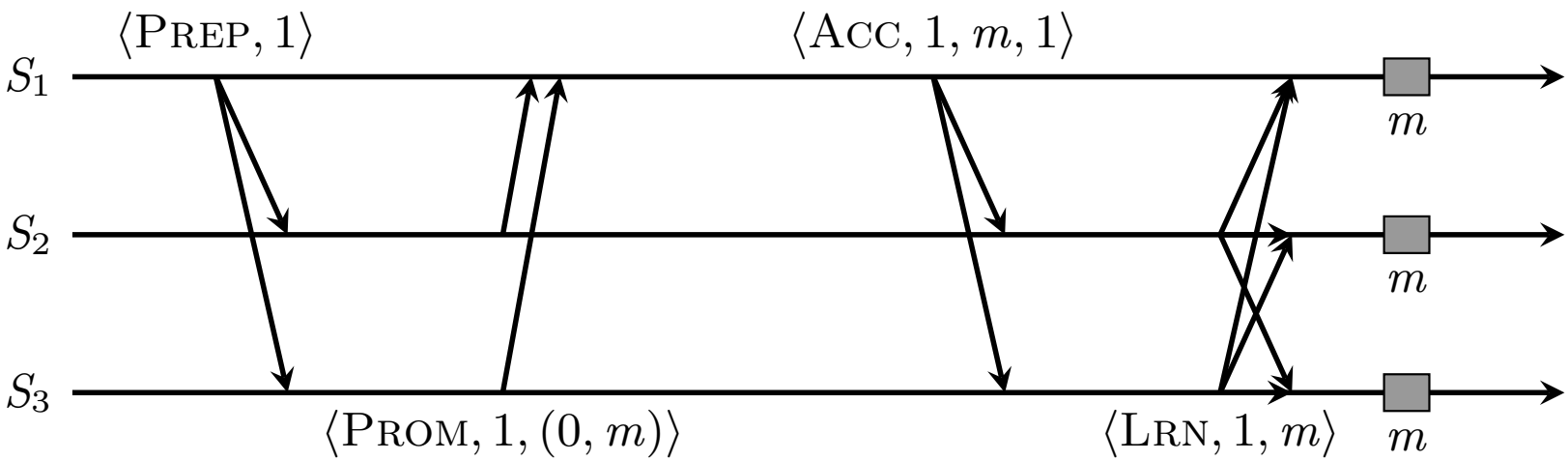


Wrapping it up!

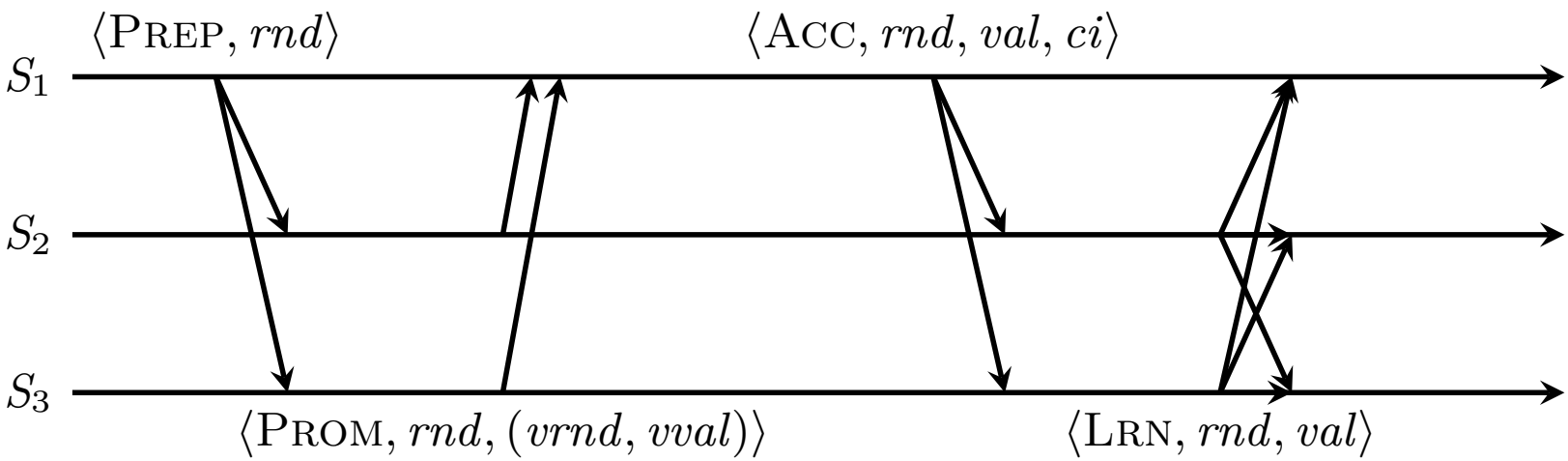
Multi-Paxos


$\langle \text{ACC}, 1, m_2, 1 \rangle$
$\langle \text{ACC}, 1, m_1, 2 \rangle$
S_1
S_2
S_3
m_2
m_2
m_2
m_1
m_1
m_1
$\langle \text{LRN}, 1, m_2 \rangle$
$\langle \text{LRN}, 1, m_1 \rangle$

Paxos



Paxos



Paxos Agents

- Proposer = Leader
  - Sends prepare and accept messages
  - Receive promise messages
- Acceptor
  - Receive accept messages
  - Sends learn messages
- Learner
  - Receive learn messages

That's It! Thank You!