CS 60002: Distributed Systems

T7:
Fault Tolerance

Department of Computer Science and Engineering

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Networks and Failures

- Synchronous vs Asynchronous Networks
  - **Synchronous**: I am sure that I'll get the message within a predefined time threshold
  - **Asynchronous**: I am not sure whether and when the message will arrive

- Failures in a network --
  - **Crash Fault**: A node stops responding
  - **Link Fault** (or Network Fault): A link fails to deliver the message
  - **Byzantine Fault**: A node starts behaving maliciously

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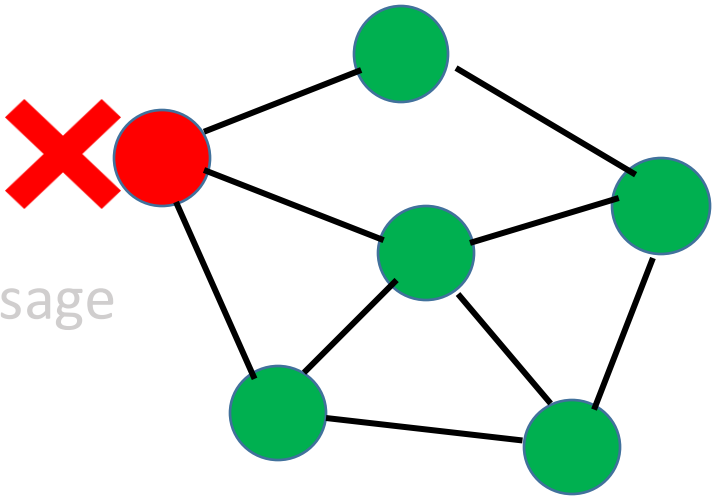

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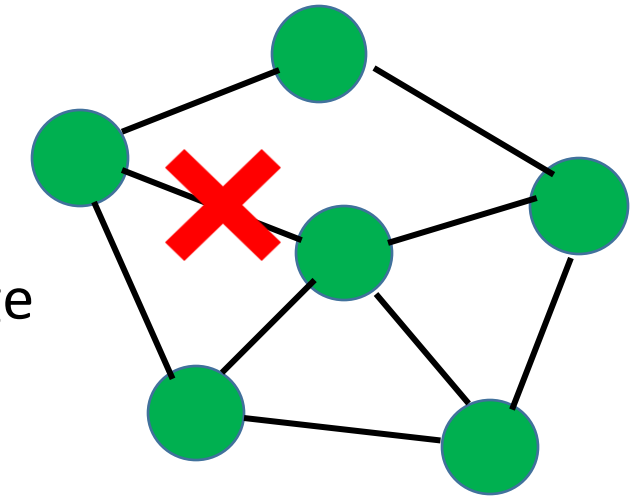

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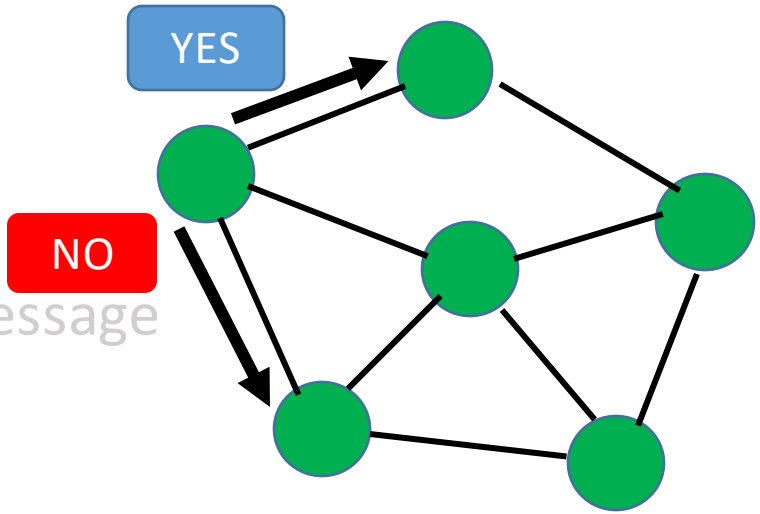

Dependability in the Presence of Failures

- A measure of how dependable a system is in the face of failures

These slides are taken from the Distributed Systems course by Prof. Arobinda Gupta, IIT Kharagpur

Dependability in the Presence of Failures

- A measure of how dependable a system is in the face of failures
  - Reliability
  - Availability
  - Safety

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Dependability in the Presence of Failures

- A measure of how dependable a system is in the face of failures
  - Reliability
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- **Reliability**
  - How often does the system fail?
  - What is the conditional probability that the system will work for the duration [0,t] given that it is working at time zero?
  - **Measured by**: **MTTF** (Mean Time To Failures), **MTTR** (Mean Time To Repair), **MTBF** (Mean Time Between Failures = MTTF + MTTR)

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Dependability in the Presence of Failures

- **Availability**
  - How available the system is
  - What is the probability that the system is up at time t?
  - Usually measured by uptime (ex. 99%, maximum downtime of 5 hours in 1 year, etc.)

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Dependability in the Presence of Failures

- **Availability**
  - How available the system is
  - What is the probability that the system is up at time t?
  - Usually measured by uptime (ex. 99%, maximum downtime of 5 hours in 1 year, etc.)

- **Safety**
  - How safe the system is, even if it fails
  - Does it always maintain some safety property?

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Reliability vs Availability

- A highly reliable system is also highly available
- A highly available system may or may not be highly reliable
  - Ex: If a system fails for 1 second every hour, it can still be considered highly available (99.97%) but not highly reliable
- The reliability of a system depends on the reliability of the components used to build the system
- Reliability/Availability can be of interest at different component levels
  - A memory chip
  - A disk controller with memory
  - A PC with disks
  - A cluster with a large number of PCs

Fault Tolerance

- The ability of a system to deliver desired services in spite of faults in its components

- Fault tolerance can be at the level of
  - A full service (specified behavior in fault-free state); ex. A primary-backup server system to tolerate one server failure
  - A degraded service (deviate from the specified behavior in fault-free state, but in a pre-defined manner); ex. A web service with multiple load balanced servers

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- Many modern distributed system needs to be highly available
  - Gmail
  - Facebook
  - Airline reservation system

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Types of Fault Tolerance

- **Masking:** Always behave as per specification even in the presence of faults in the system

- **Non-masking**: System may violate specification in presence of faults, but behave in a well-defined manner

- A fault tolerant system should specify
  - Class of faults tolerated (**Fault Model)**
  - What tolerance is given for each class (**Fault Tolerance**)

Primitive Operations for Fault Tolerance

- Building reliable storage from unreliable disks
  - RAID
  - Centralized network storage
- Reliable communication over unreliable links
  - Unicast, multicast, broadcast
- Agreement/Consensus
- Enforce atomic actions
- Checkpoint and Recovery

Agreement Problem

- A set of n processes, m of them may be faulty
- Non-faulty processes need to agree on some value(s) even in the presence of faulty processes

- One of the most studied problems in Distributed System
  - Agreement (Typically used for handling Byzantine faults, so use the term **Byzantine agreement** or **Byzantine Generals Problem**)
  - Consensus
  - Interactive Consistency

- All three problems are equivalent; solution of any one of them can be used to solve the other two

Agreement Protocol

- One process x broadcast a value v
- All non-faulty processes must agree on a common value (**agreement condition**)
- The agreed upon value must be v is x is non-faulty (**validity condition**)

- This idea is used to solve the **Byzantine Generals Problem** → **Byzantine Agreement Protocols**

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Byzantine Generals Problem

Commander

Lieutenant - 1

Lieutenant - 2

Byzantine Generals Problem

Attack

Attack

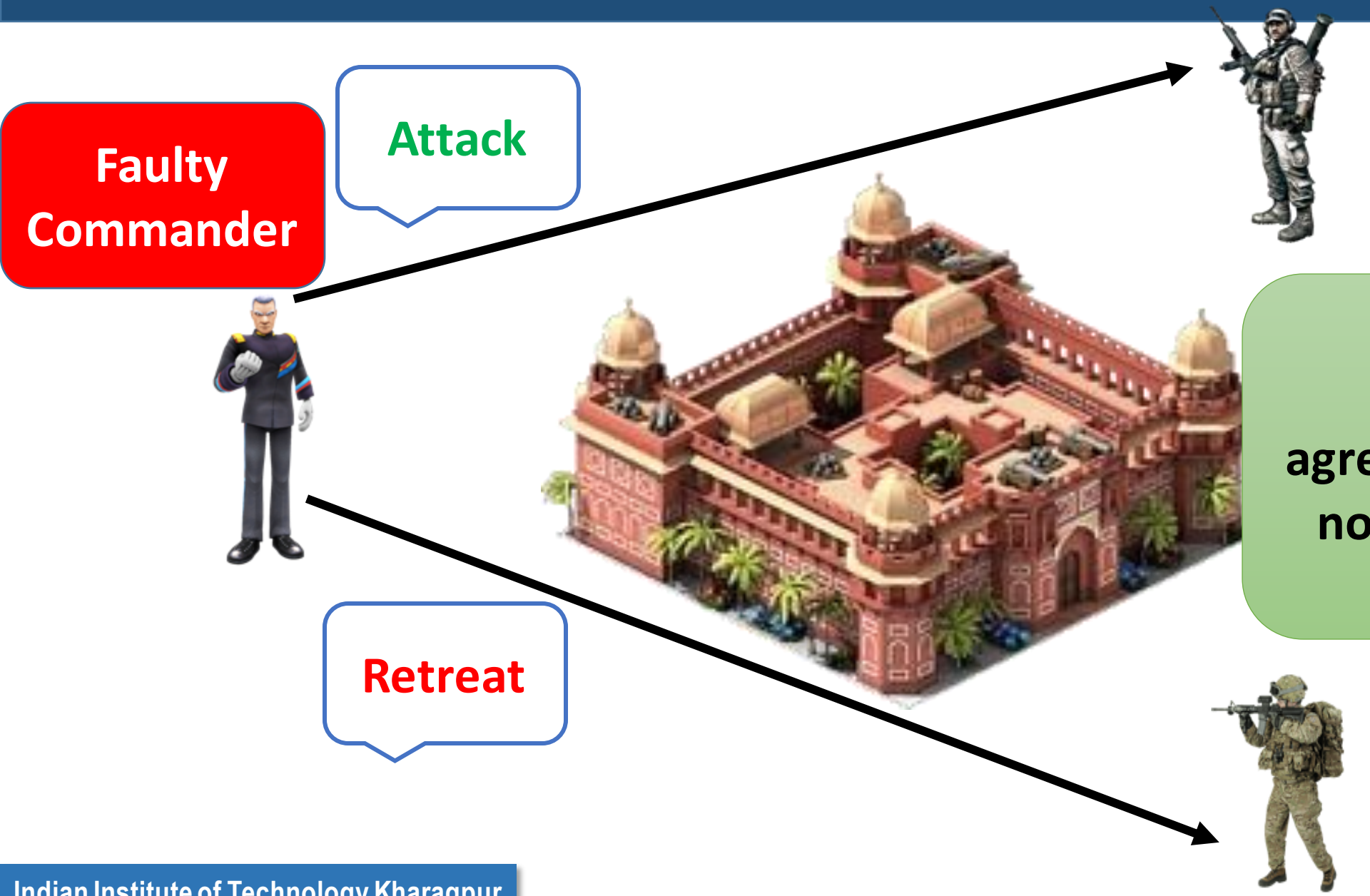
Byzantine Generals Problem

Faulty Commander

Attack

Retreat

Byzantine Generals Problem



We need an agreement among the non-faulty generals

Byzantine Generals Problem

Faulty Commander

Attack

Commander Said: Attack

Retreat

Byzantine Generals Problem

Faulty Commander

Attack

Retreat

Commander Said: Attack

Commander Said: Retreat

Byzantine Generals Problem

Faulty Commander

Attack

Retreat

Commander Said: Attack

Can we reach to an agreement?

Commander Said: Retreat

Byzantine Generals Problem

Good Commander

Attack

Attack

Byzantine Generals Problem

Good Commander

Attack

Attack

Commander Said: Attack

Commander Said: Retreat

Faulty Lieutenant

The agreement protocol solves this problem!

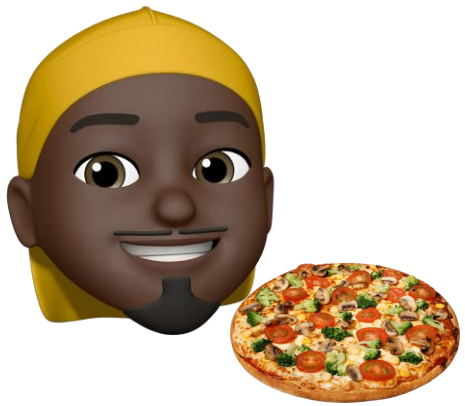
Consensus

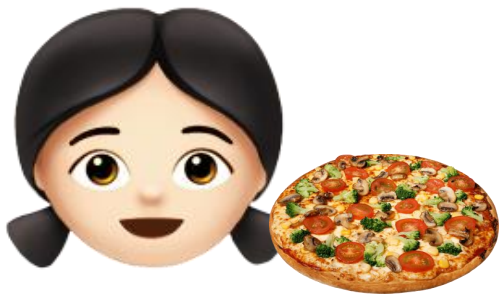
- Each process broadcast its initial value
  - Satisfy agreement condition
  - If initial value of all non-faulty processes is v, then the agreed upon value must be v

Distributed Consensus

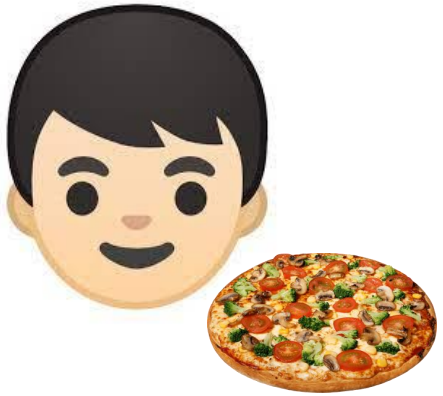
Distributed Consensus

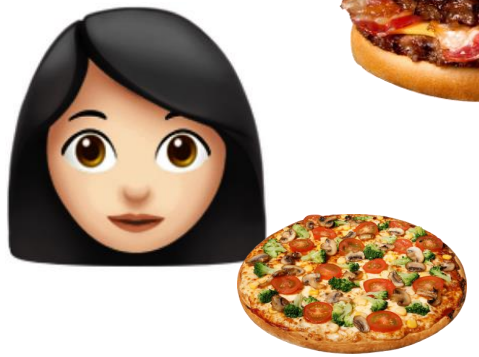
Distributed Consensus

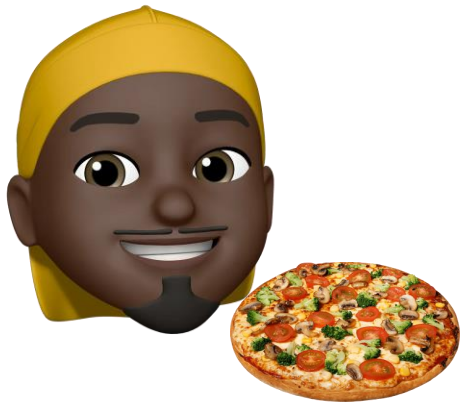


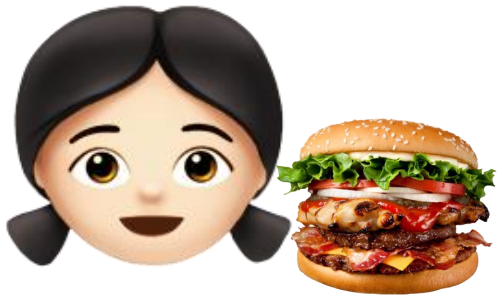


Distributed Consensus









Distributed Consensus





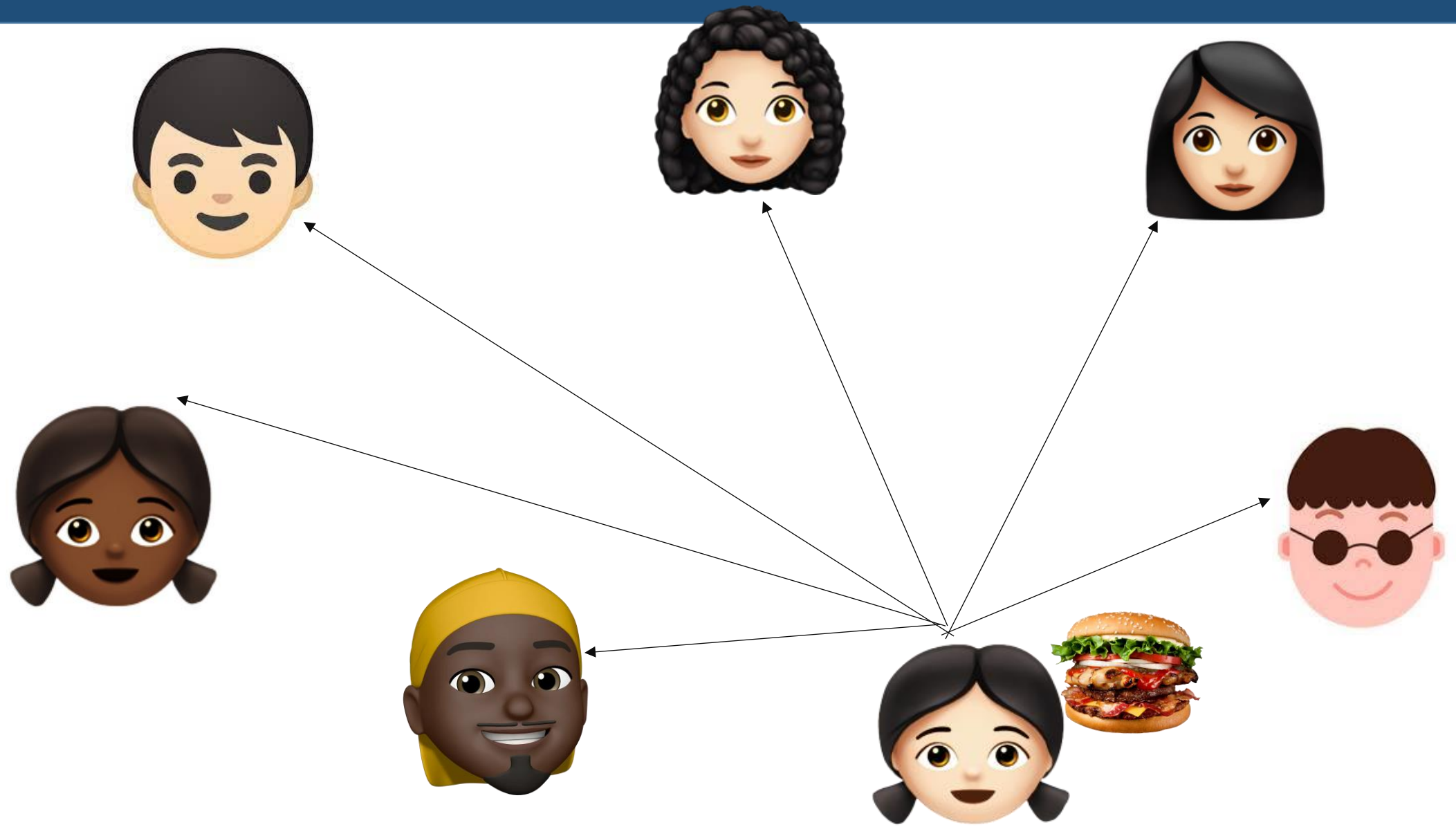




Distributed Consensus

How can we make this decision in a distributed way?

Distributed Consensus – Message Passing



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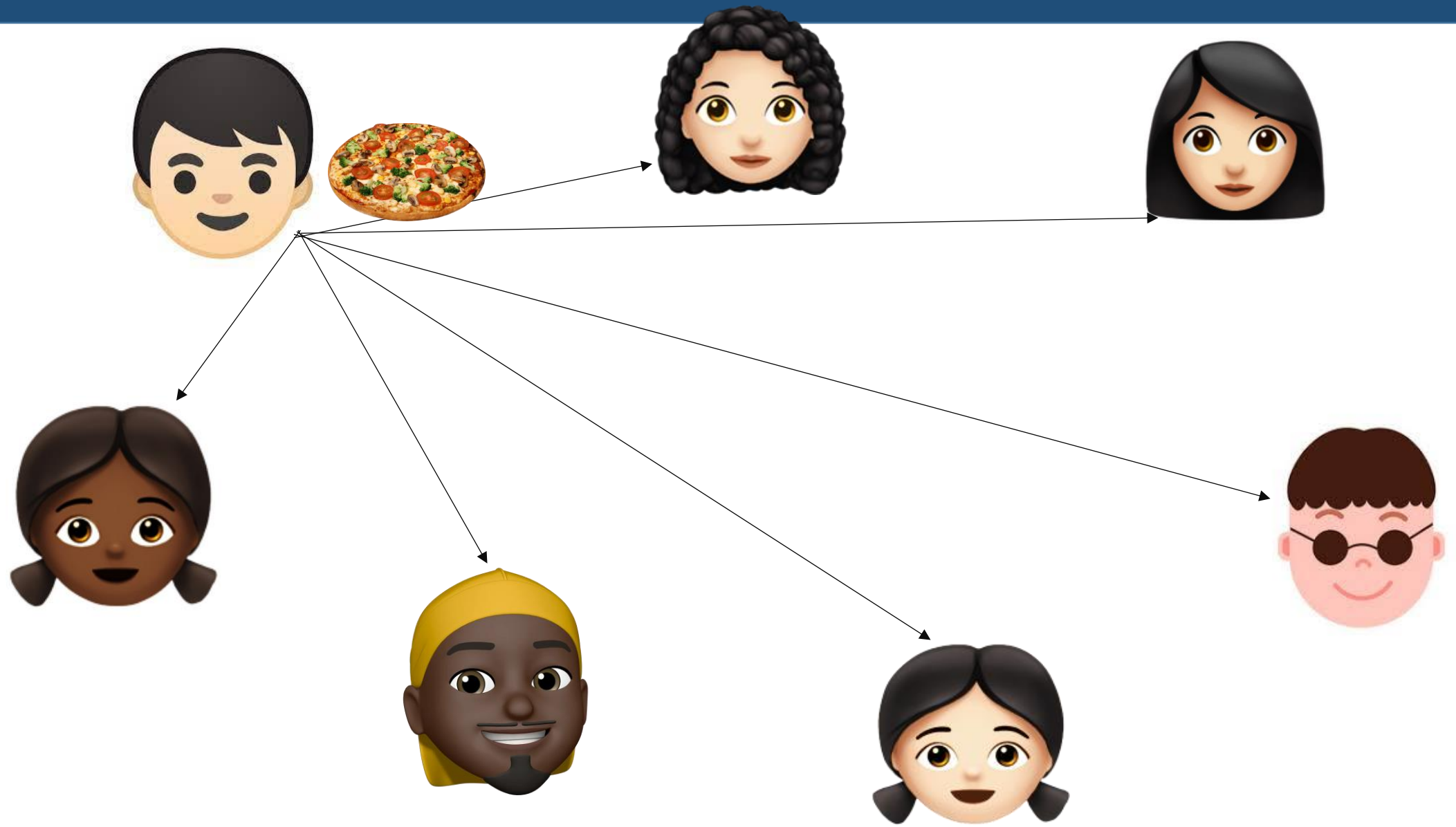

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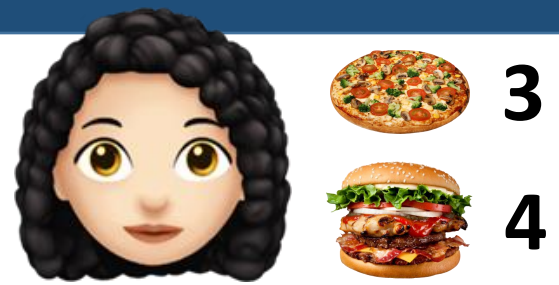
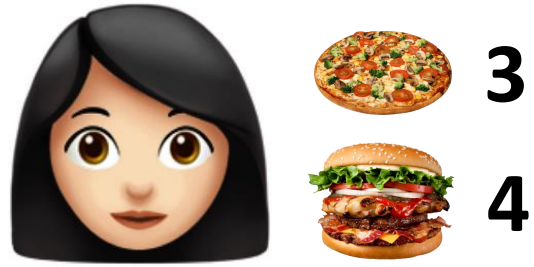
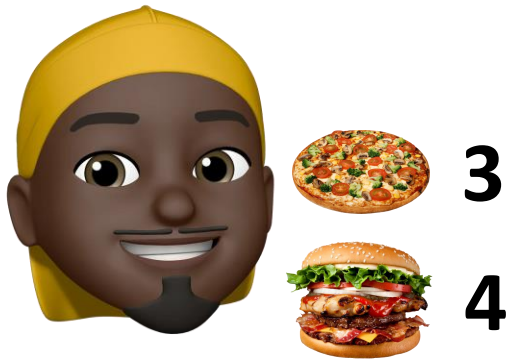
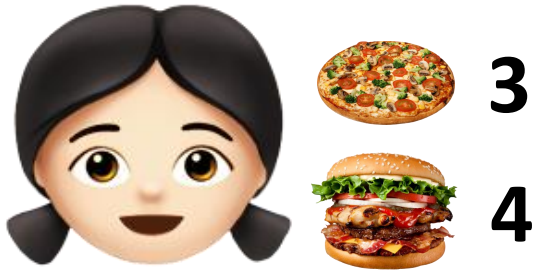




Count votes and decide!





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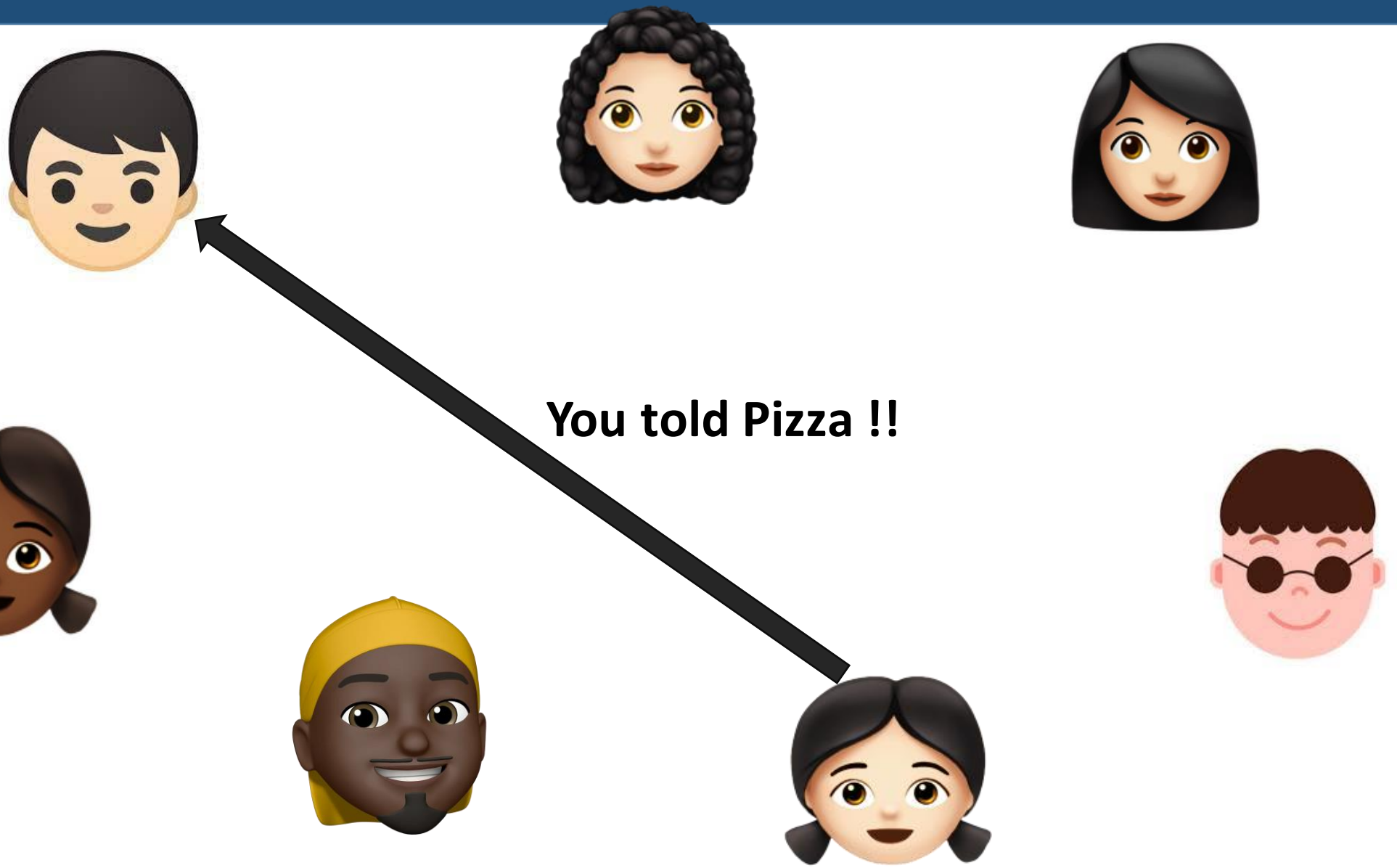

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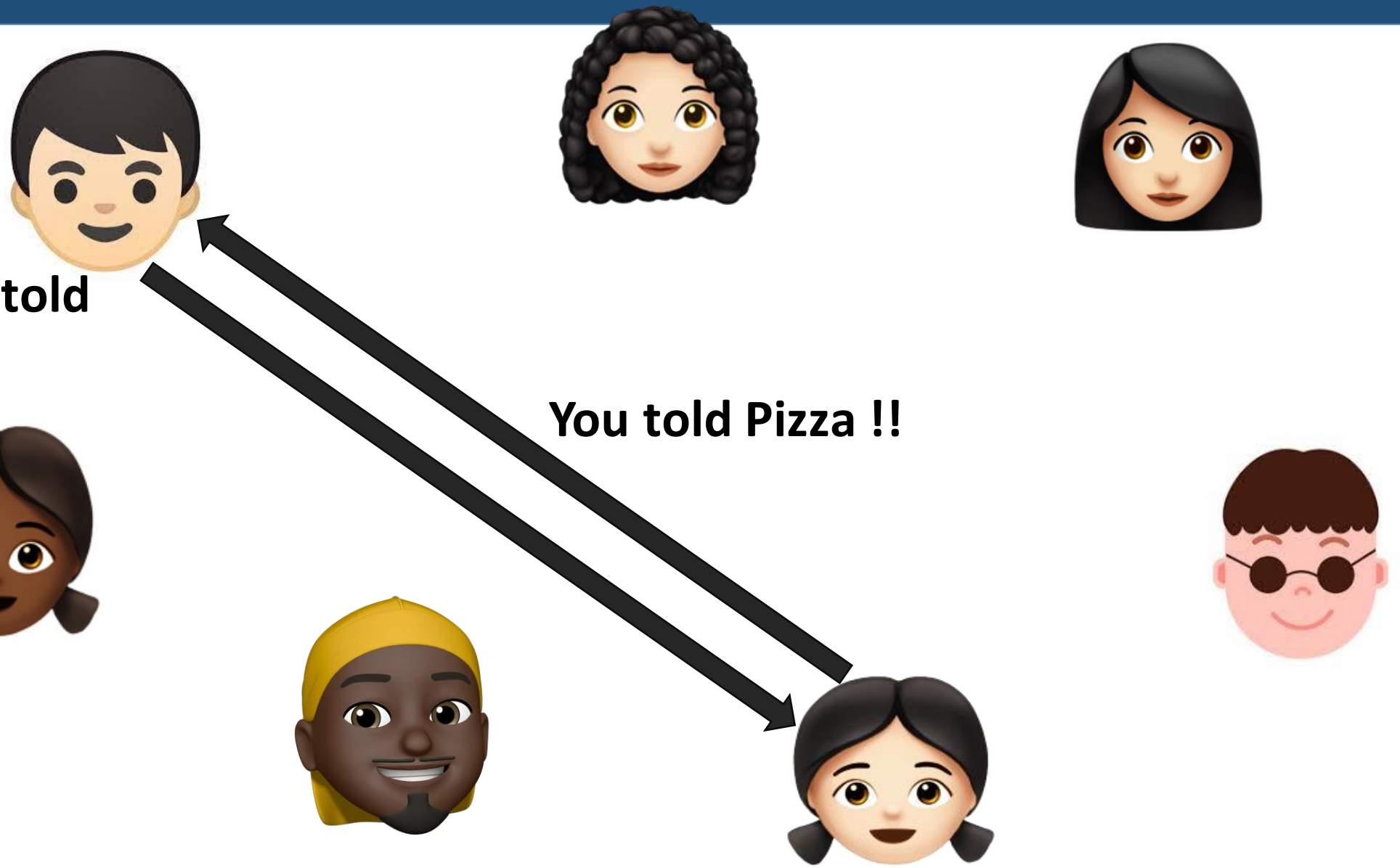

Interactive Consistency

- Each process i broadcasts its own value v_i
  - All non-faulty processes agree on a common vector $\{v_1, v_2, \ldots, v_n\}$
  - If i^{th} process is non-faulty, then the i^{th} value in the vector agreed upon by non-faulty processes must be v_i

Distributed Consensus

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Correct processes will yield the correct output

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The output will be produced within a finite amount of time (eventual termination)

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Distributed Consensus

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- 2009: Zookeeper released
  - Service for managing distributed applications
- 2010's onward: Different types of consensus algorithms released
  - Multi-Paxos
  - Raft
  - Byzantine Fault Tolerance
  - PBFT
  - ...

Another Interesting Impossibility Result

- [Santoro and Widmayer, 1989] **Even in a synchronous model, consensus is not possible even with a single link failure**.

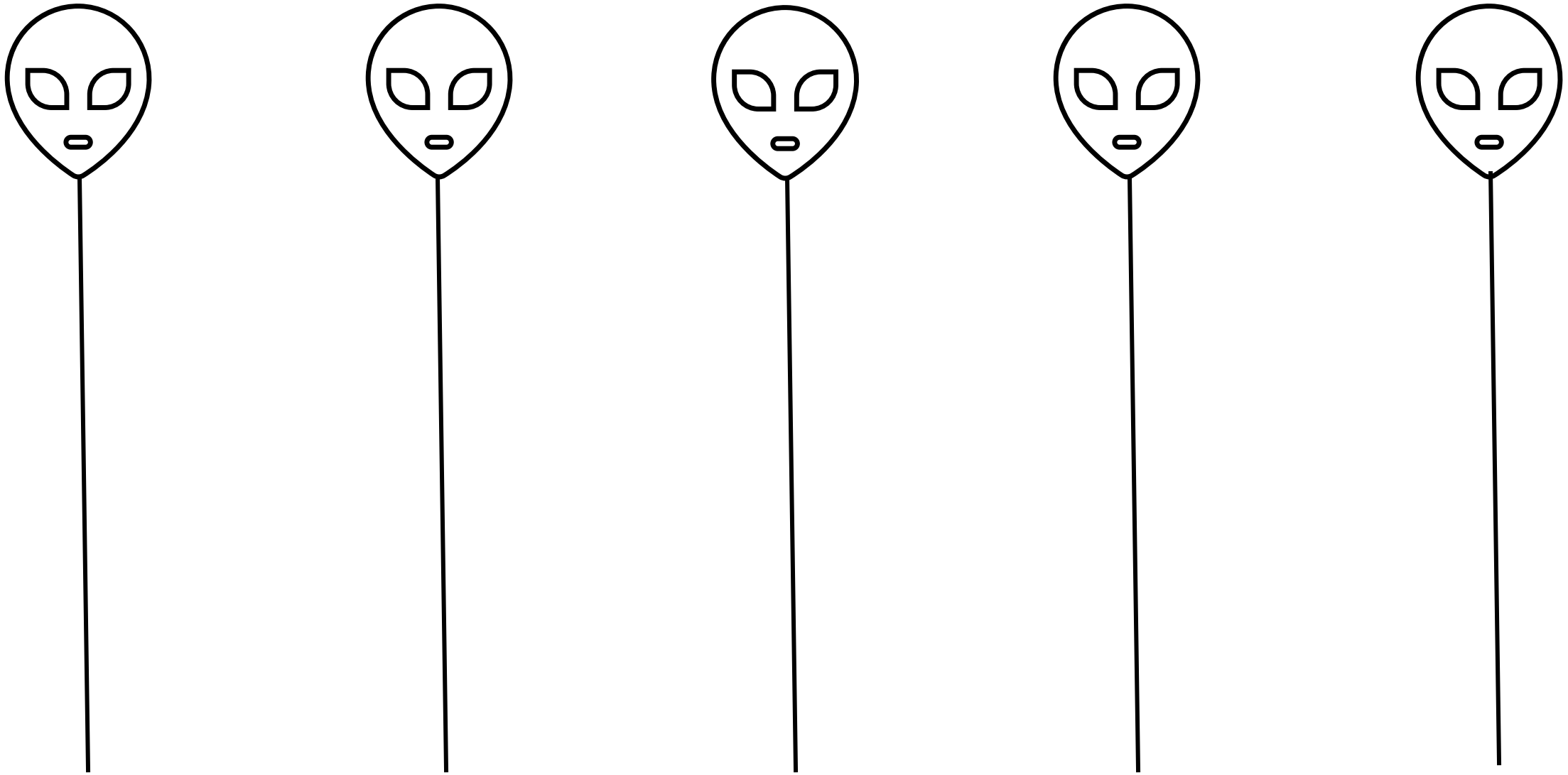
Santoro, Nicola, and Peter Widmayer. "Time is not a healer." *Annual Symposium on Theoretical Aspects of Computer Science*. Springer, Berlin, Heidelberg, 1989.

Asynchronous Consensus with Crash Faults

- Remember the **FLP Impossibility**
  - Give priority to safety over liveness

- Guarantees the followings --
  - **Validity**: If all correct process proposes the same value v, then any correct process decides v
  - **Agreement:** No two correct processes decide differently
  - **Termination**: Every correct process eventually decides

CFT Consensus in a Synchronous System



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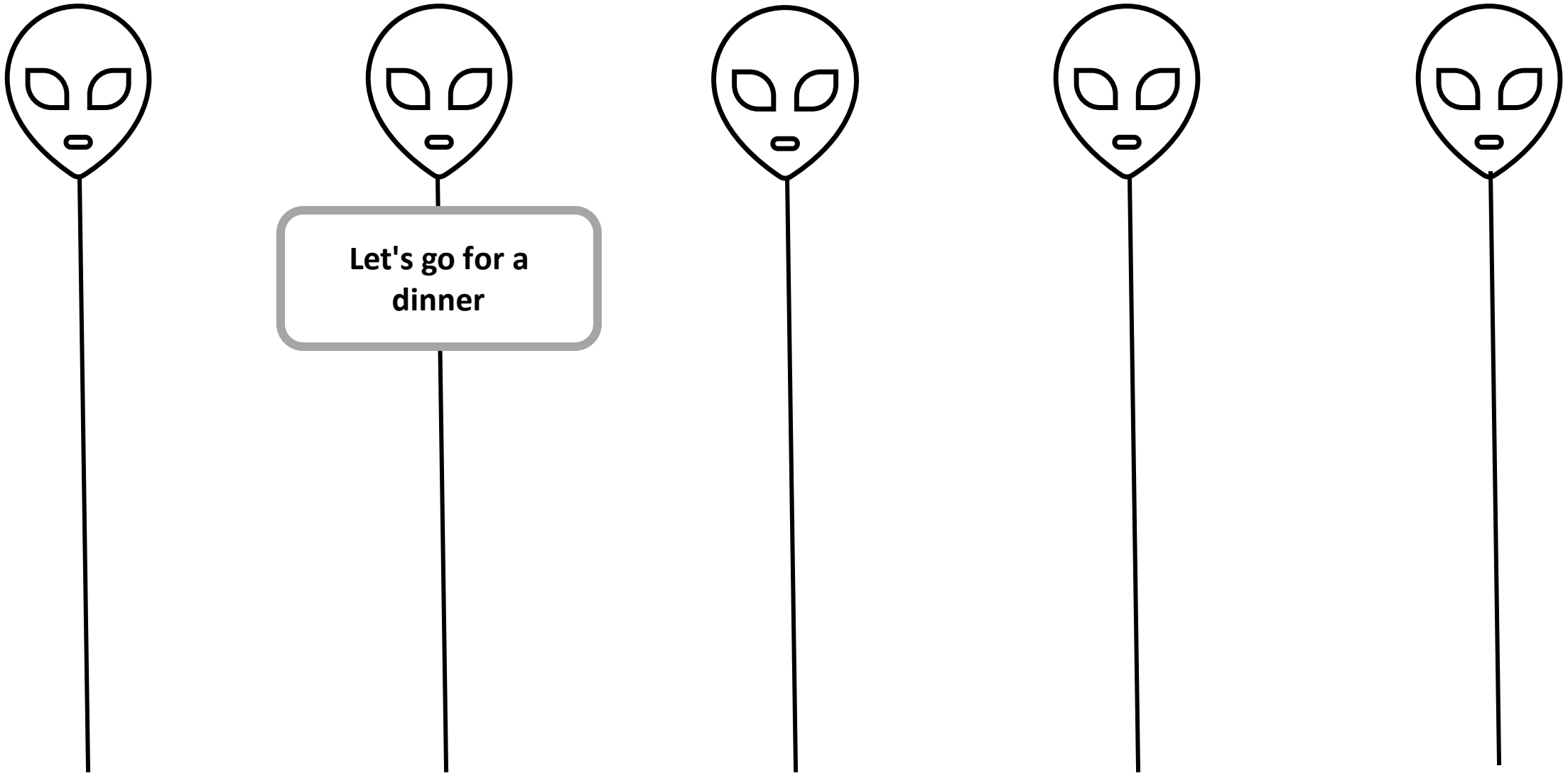

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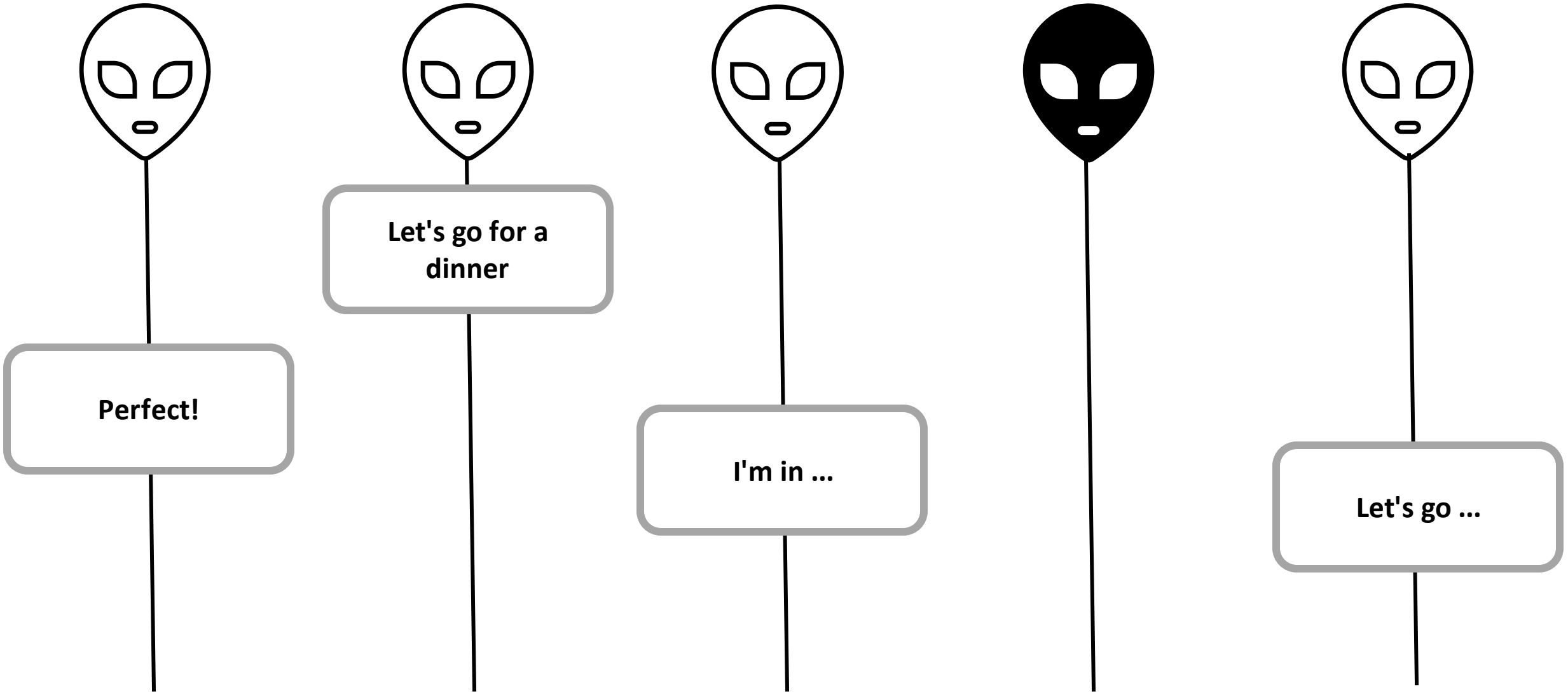

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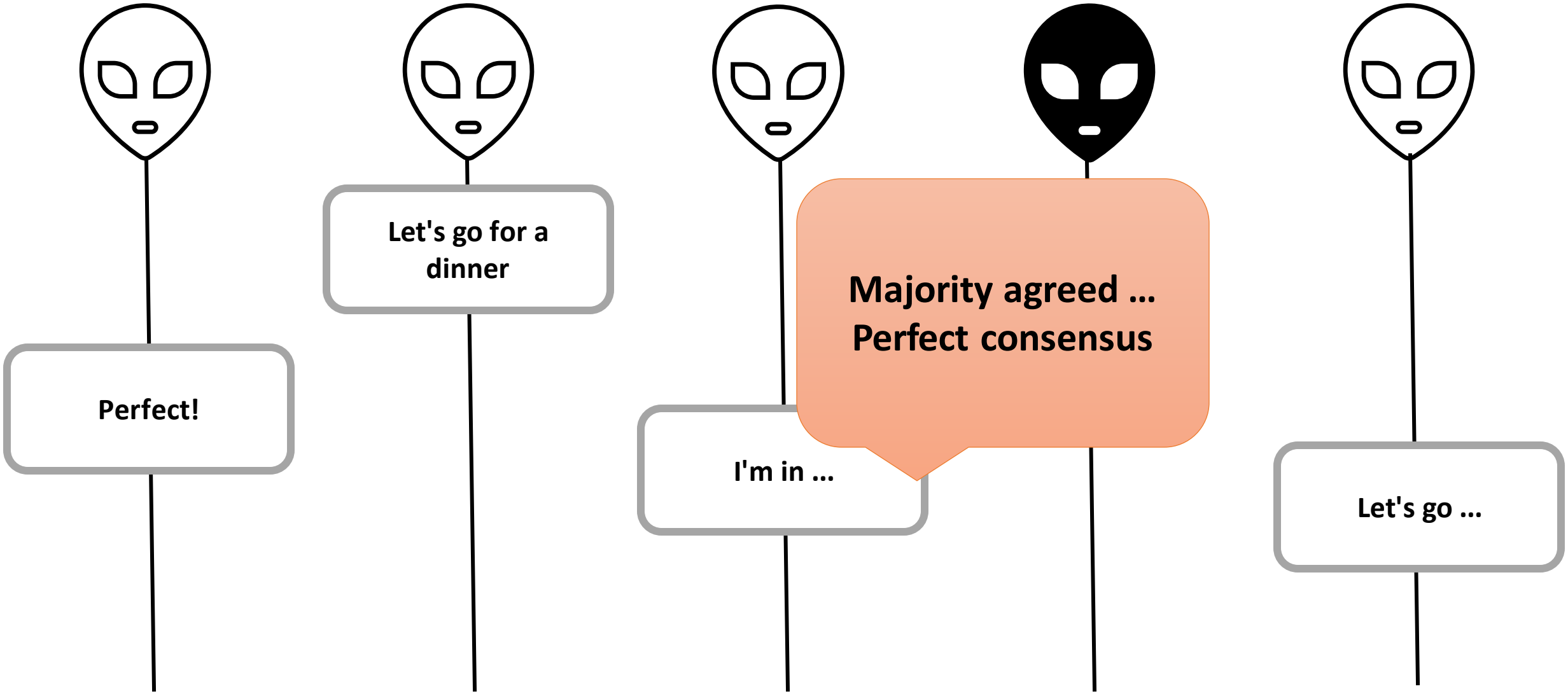

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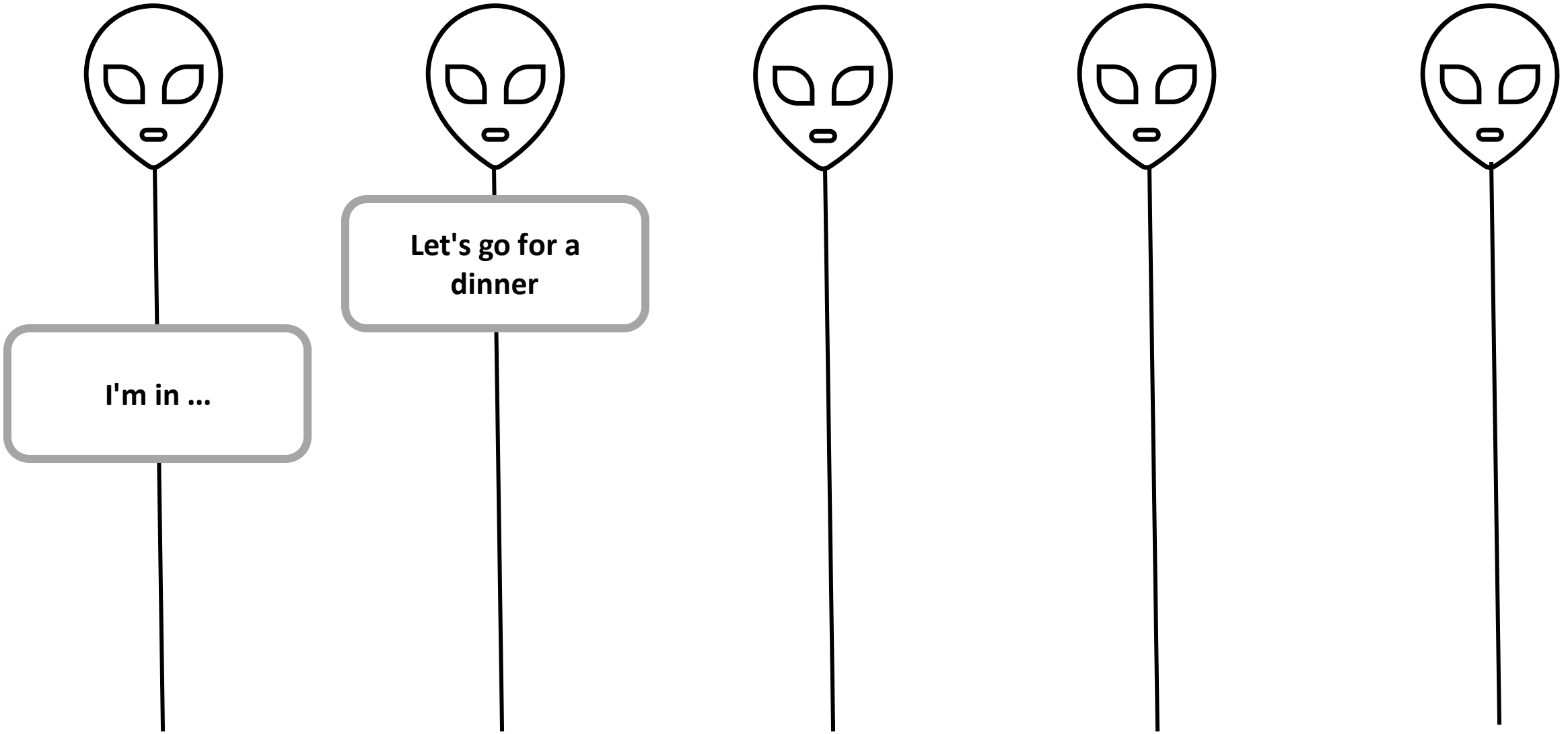

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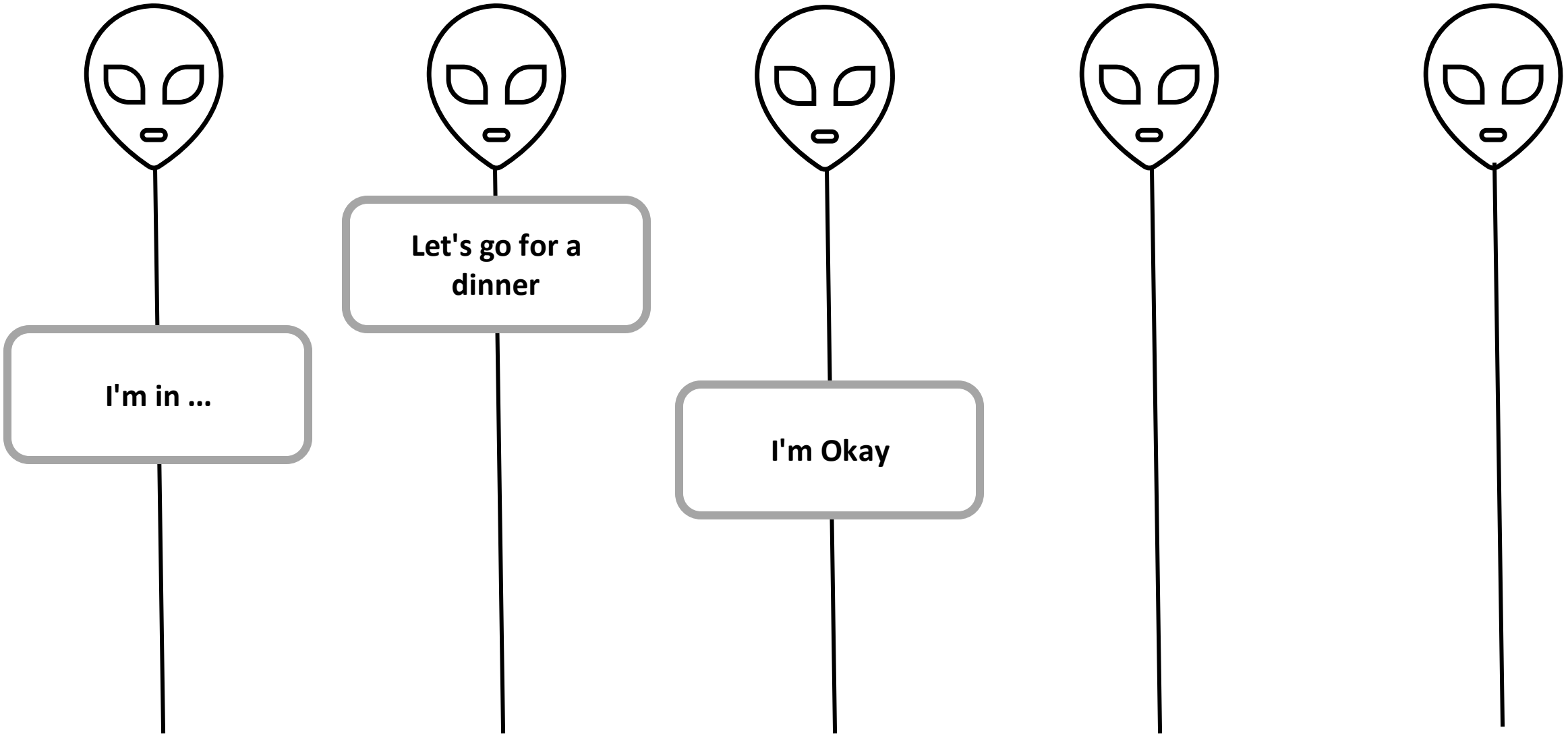

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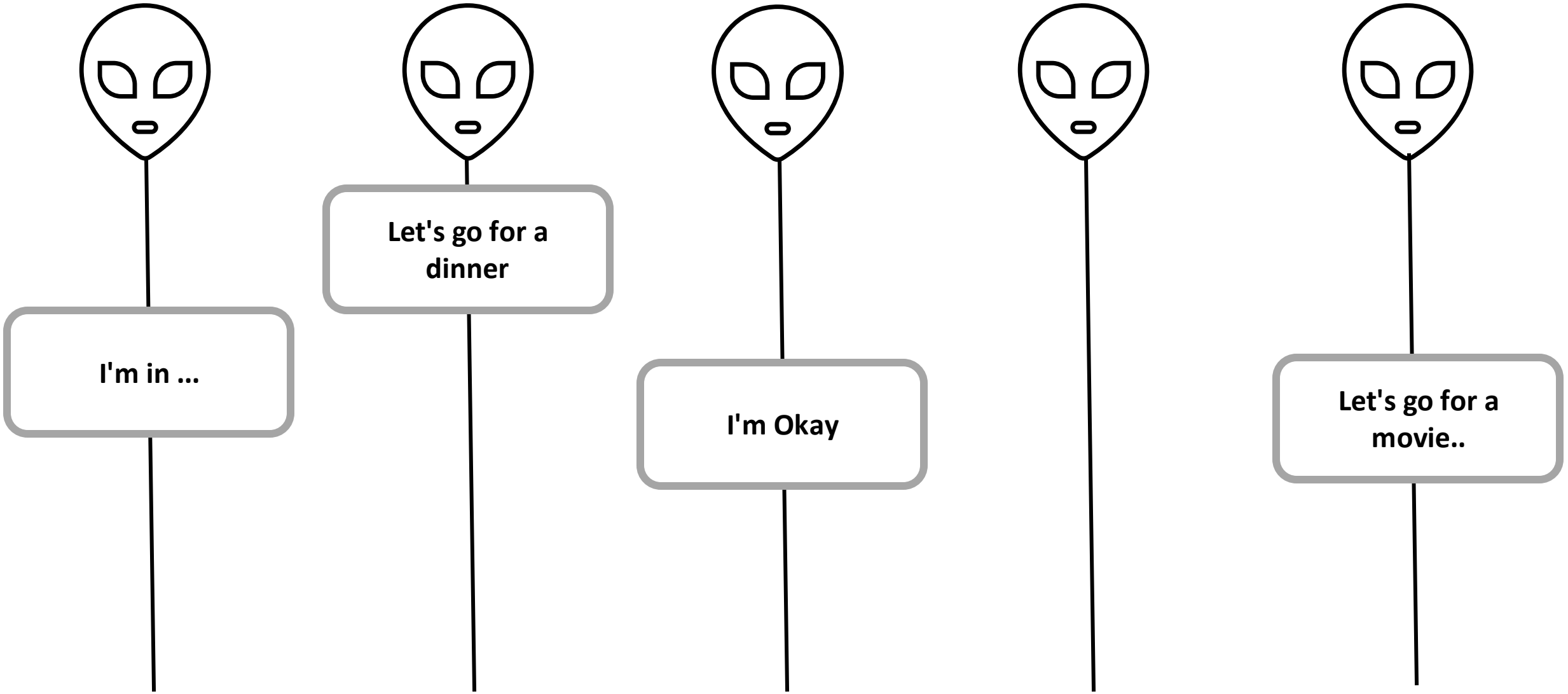

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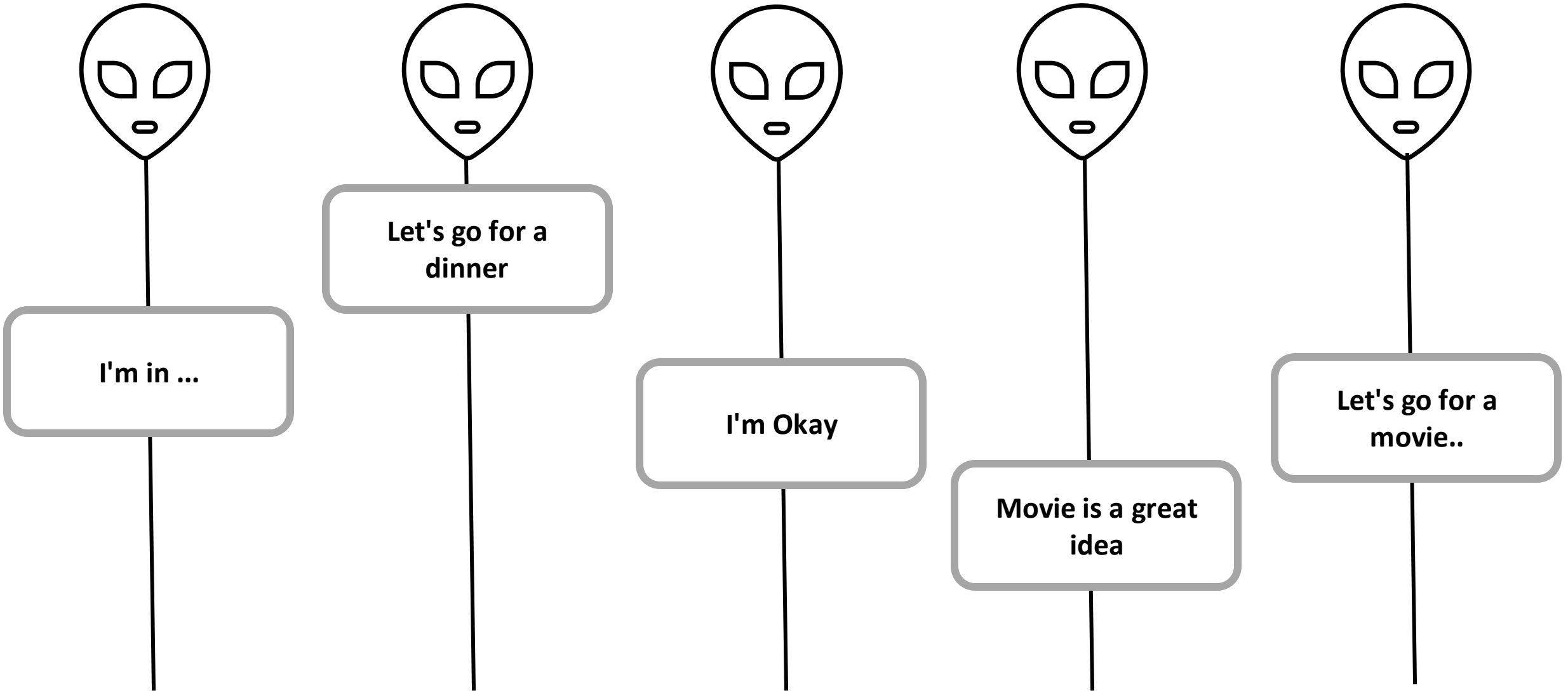

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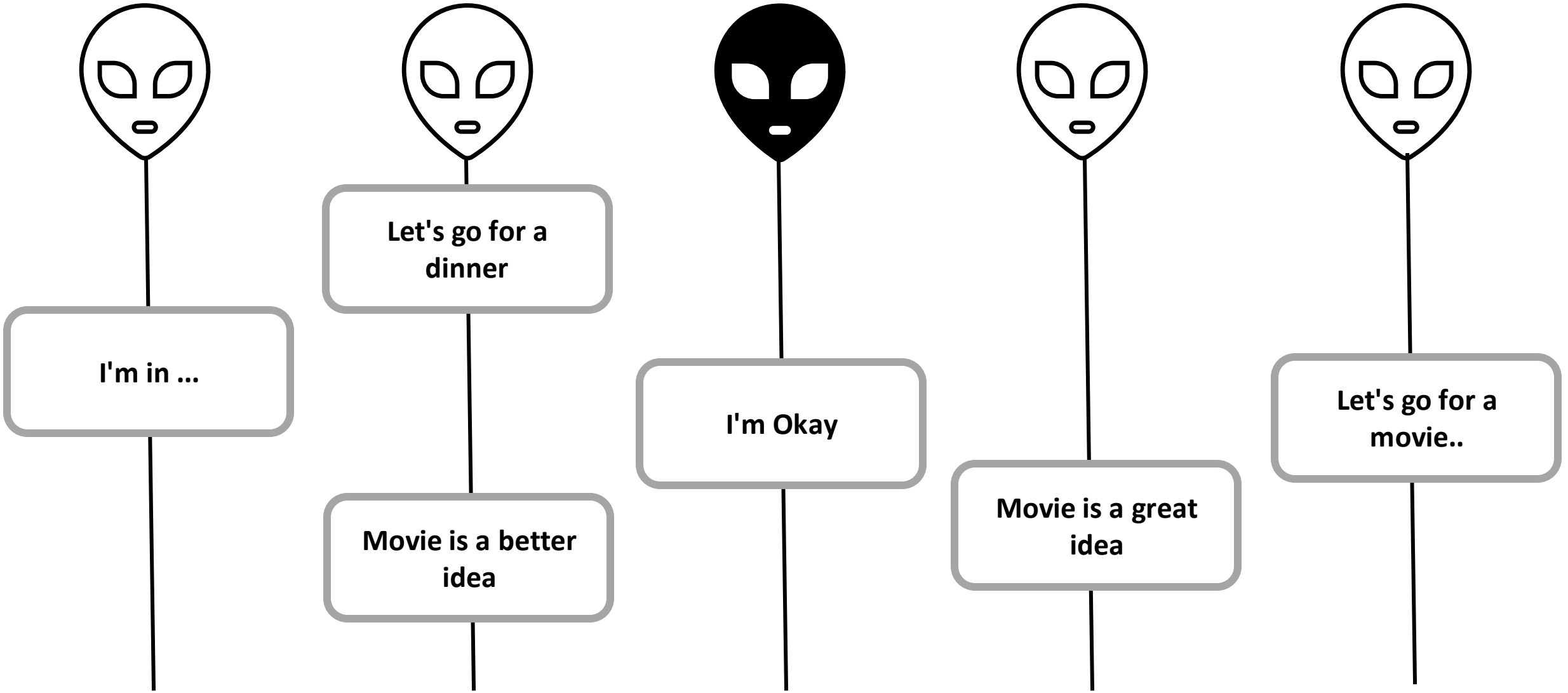

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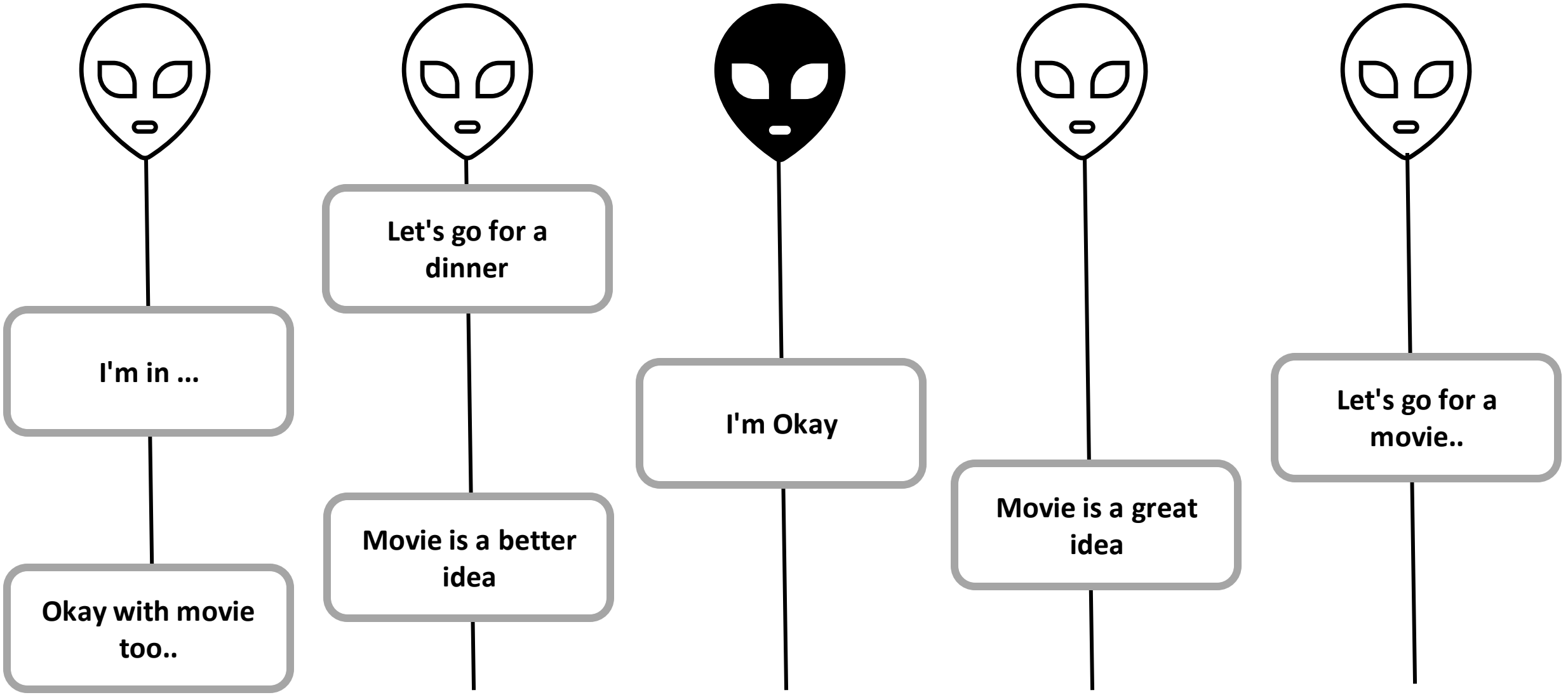

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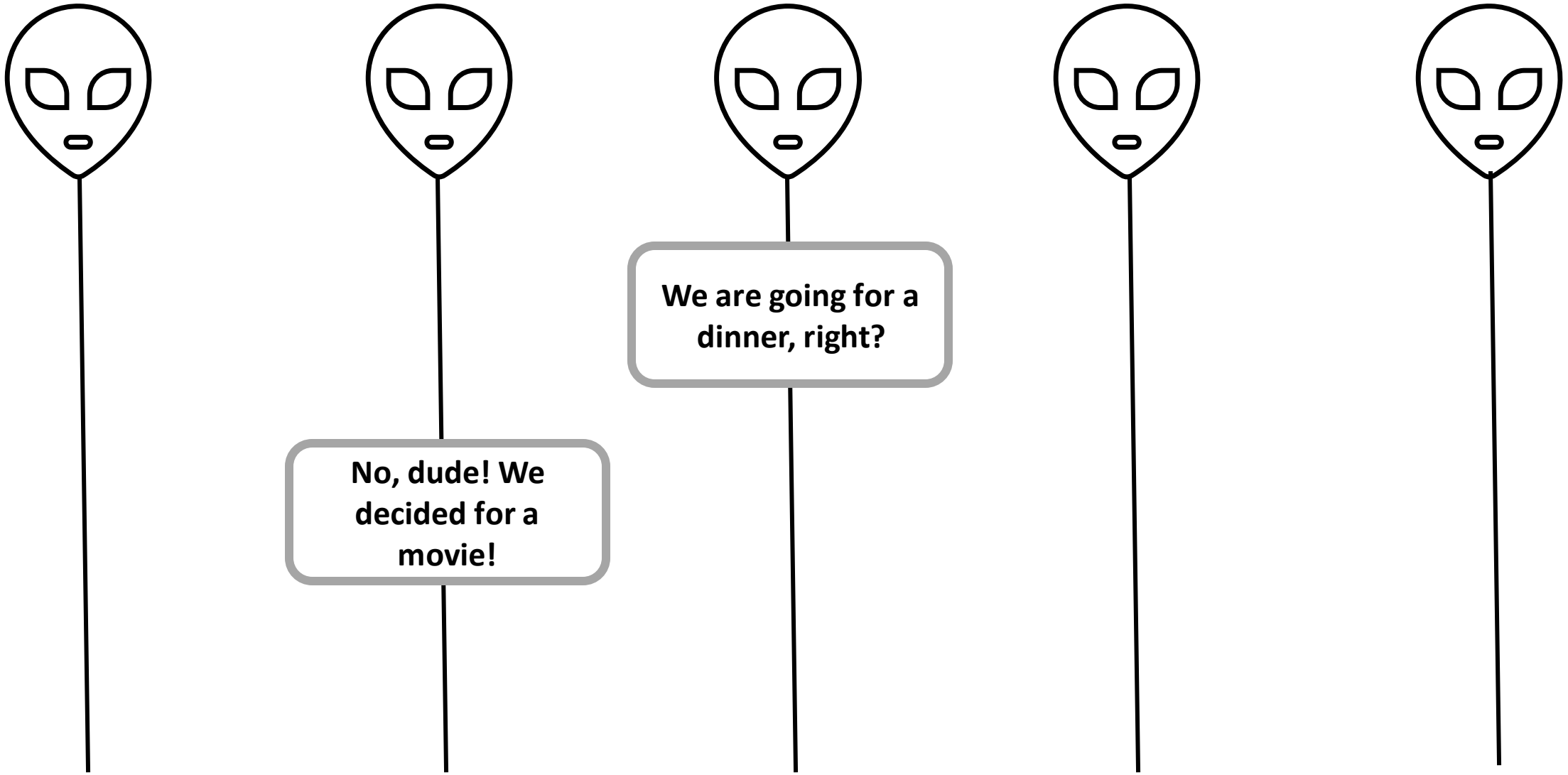

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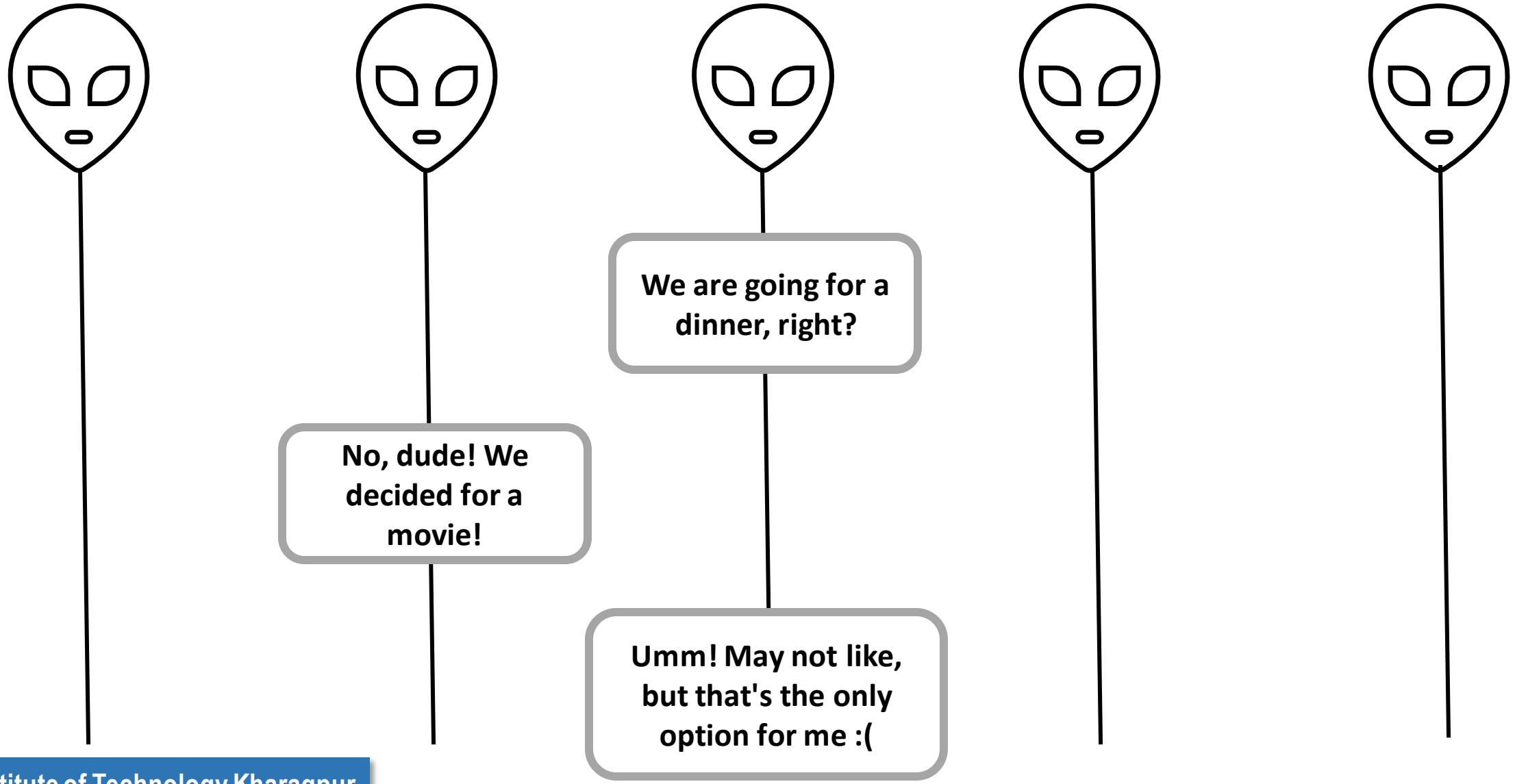

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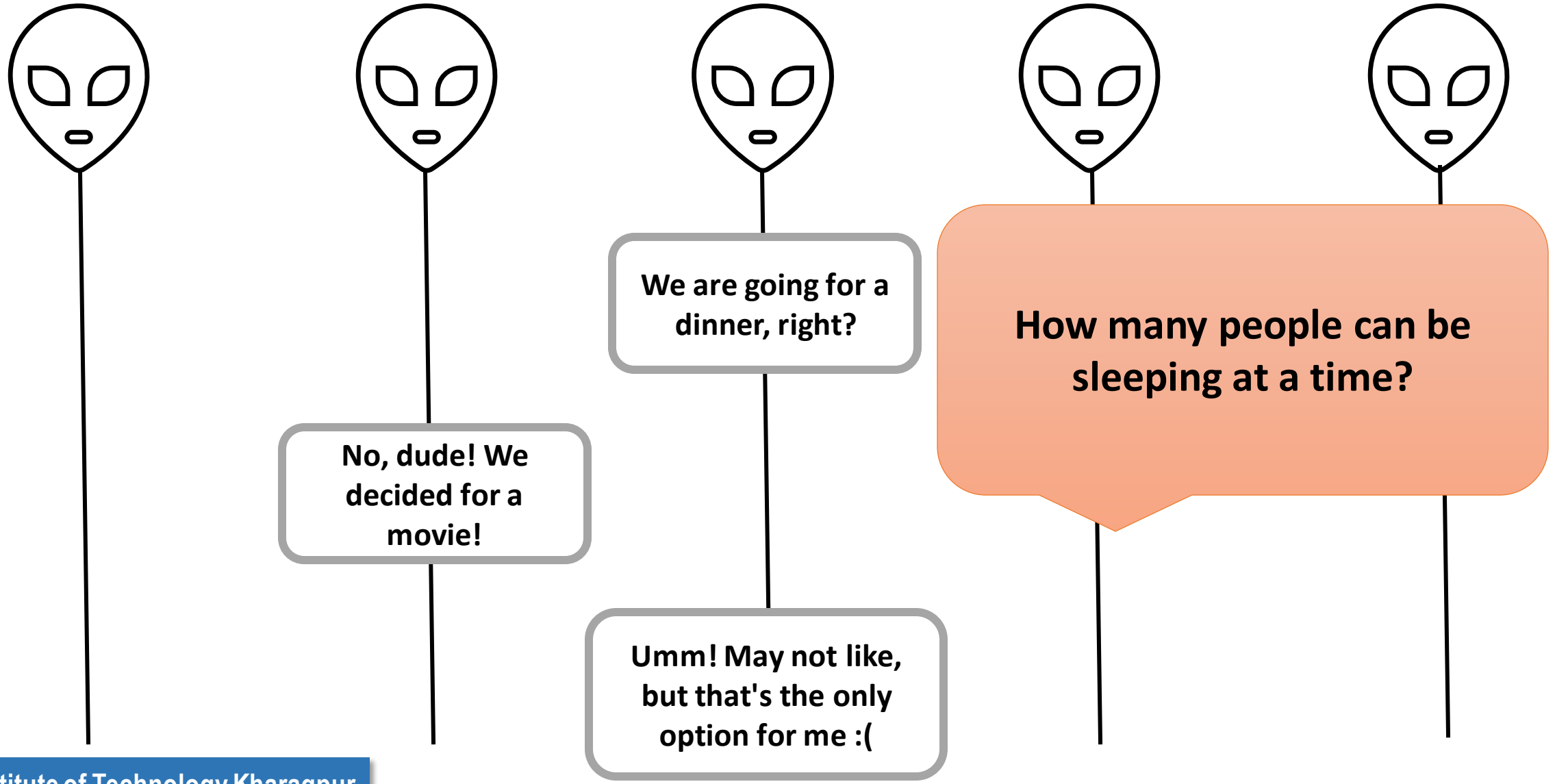

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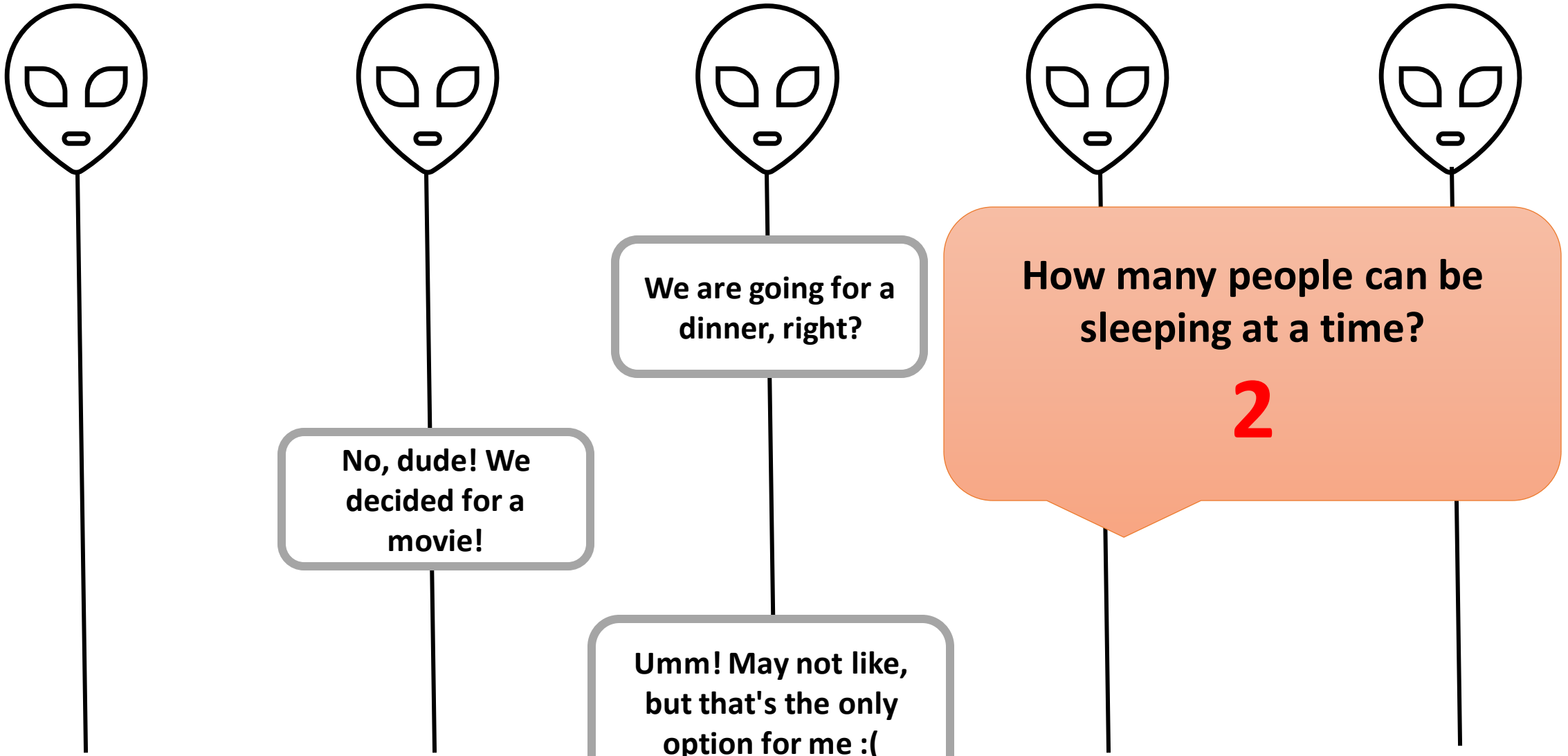


Asynchronous CFT

- If there are F faulty nodes (crash fault), we need at least 2F+1 nodes to reach consensus

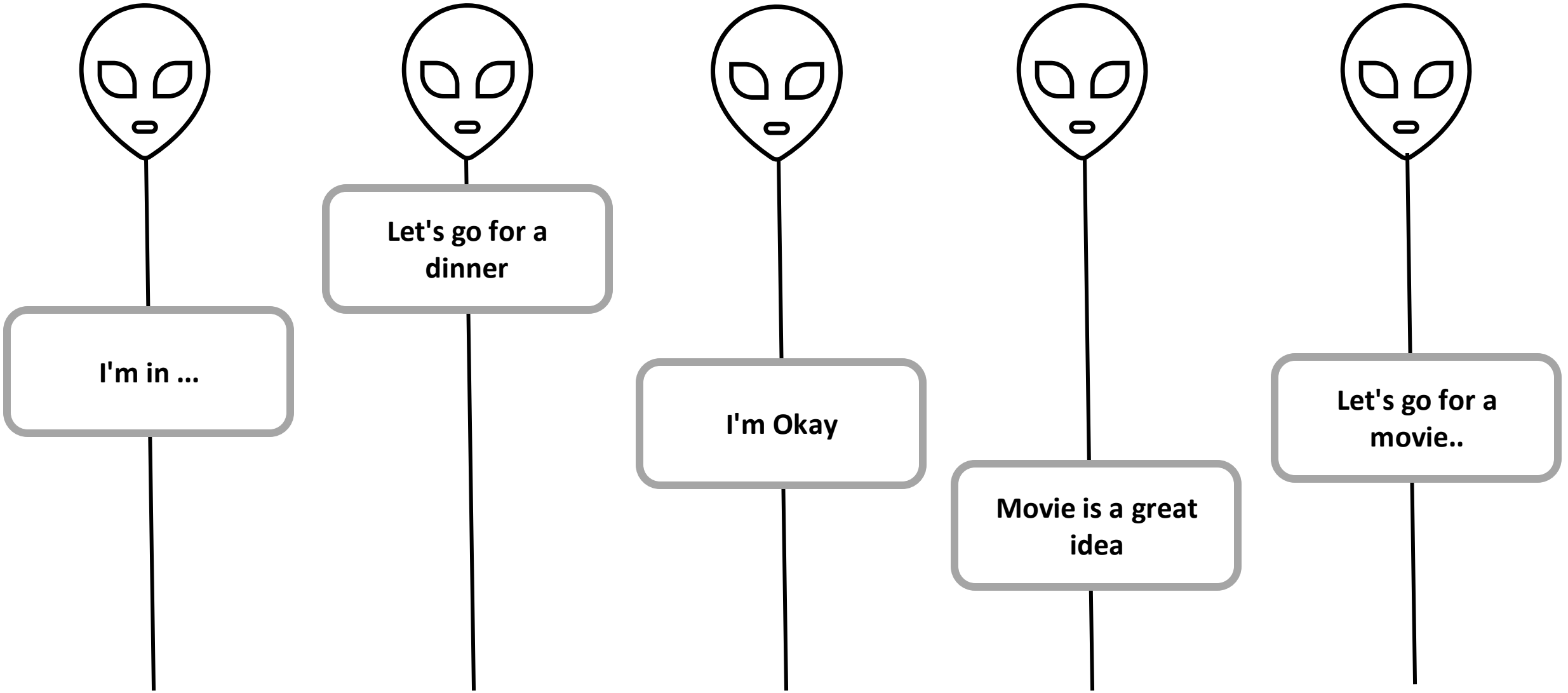
- **Paxos:** A family of distributed algorithms to reach consensus in an asynchronous CFT

Asynchronous CFT

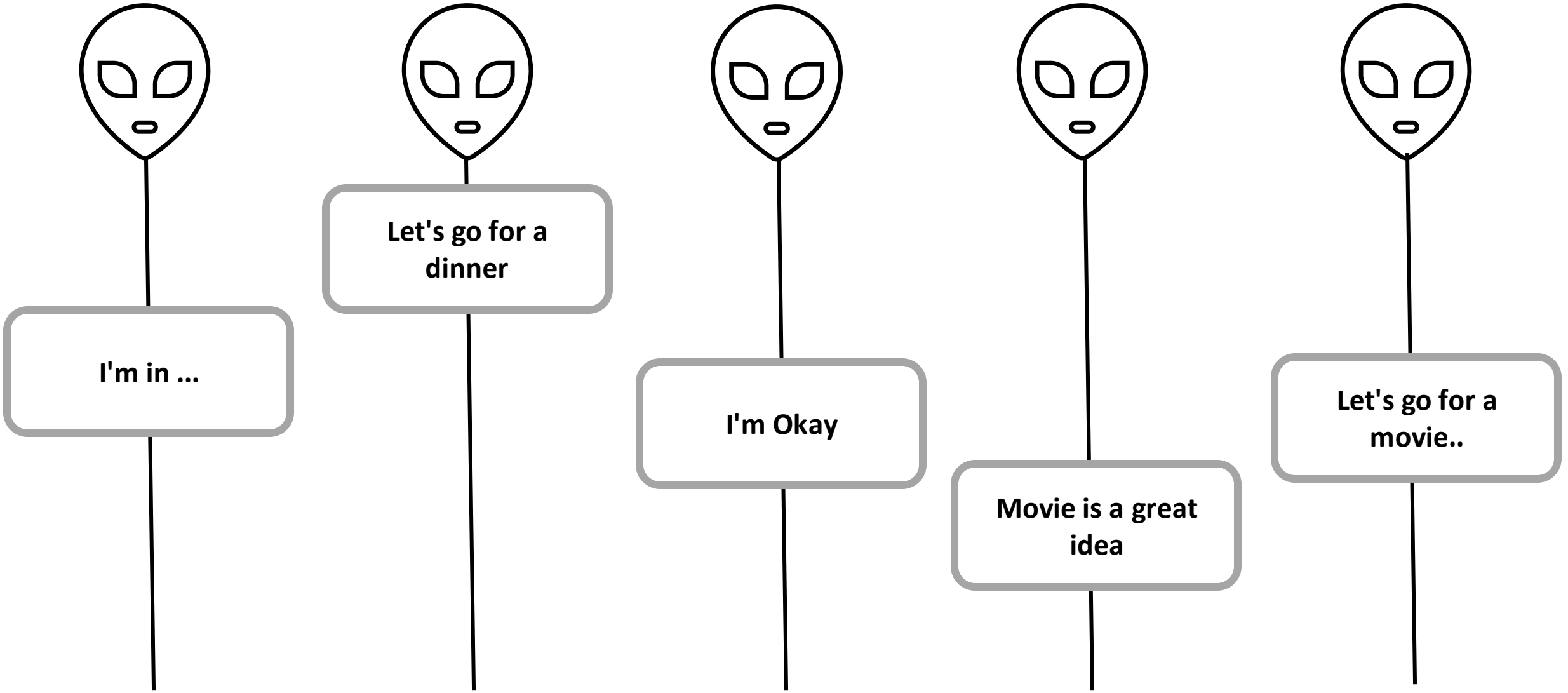
- If there are F faulty nodes (crash fault), we need at least 2F+1 nodes to reach consensus

- **Paxos:** A family of distributed algorithms to reach consensus in an asynchronous CFT
  - We'll discuss vanilla Paxos
  - Proposed by Lamport in 1989
  - Received a lot of criticism about its proof of correctness
  - Accepted in ACM Transactions on Computer Systems in 1998, titled *"The Part-time Parliament"*
  - Lamport received the Turing award in 2013

Paxos


I'm in ...
Let's go for a dinner
I'm Okay
Movie is a great idea
Let's go for a movie..

Paxos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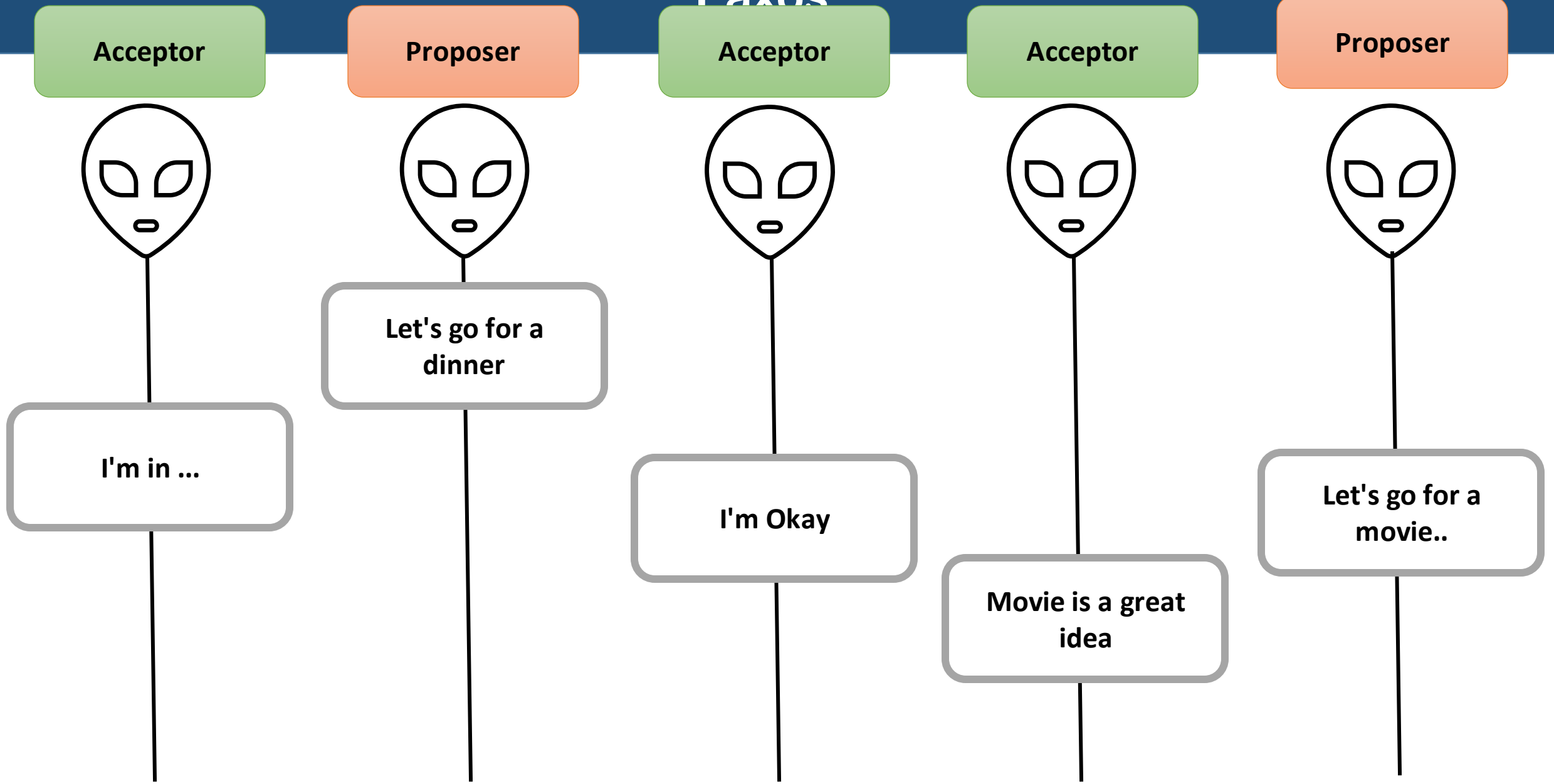
Let's go for a movie..

Paxos


Acceptor
Proposer
Acceptor
Acceptor
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I'm in ...
Let's go for a dinner
I'm Okay
Movie is a great idea
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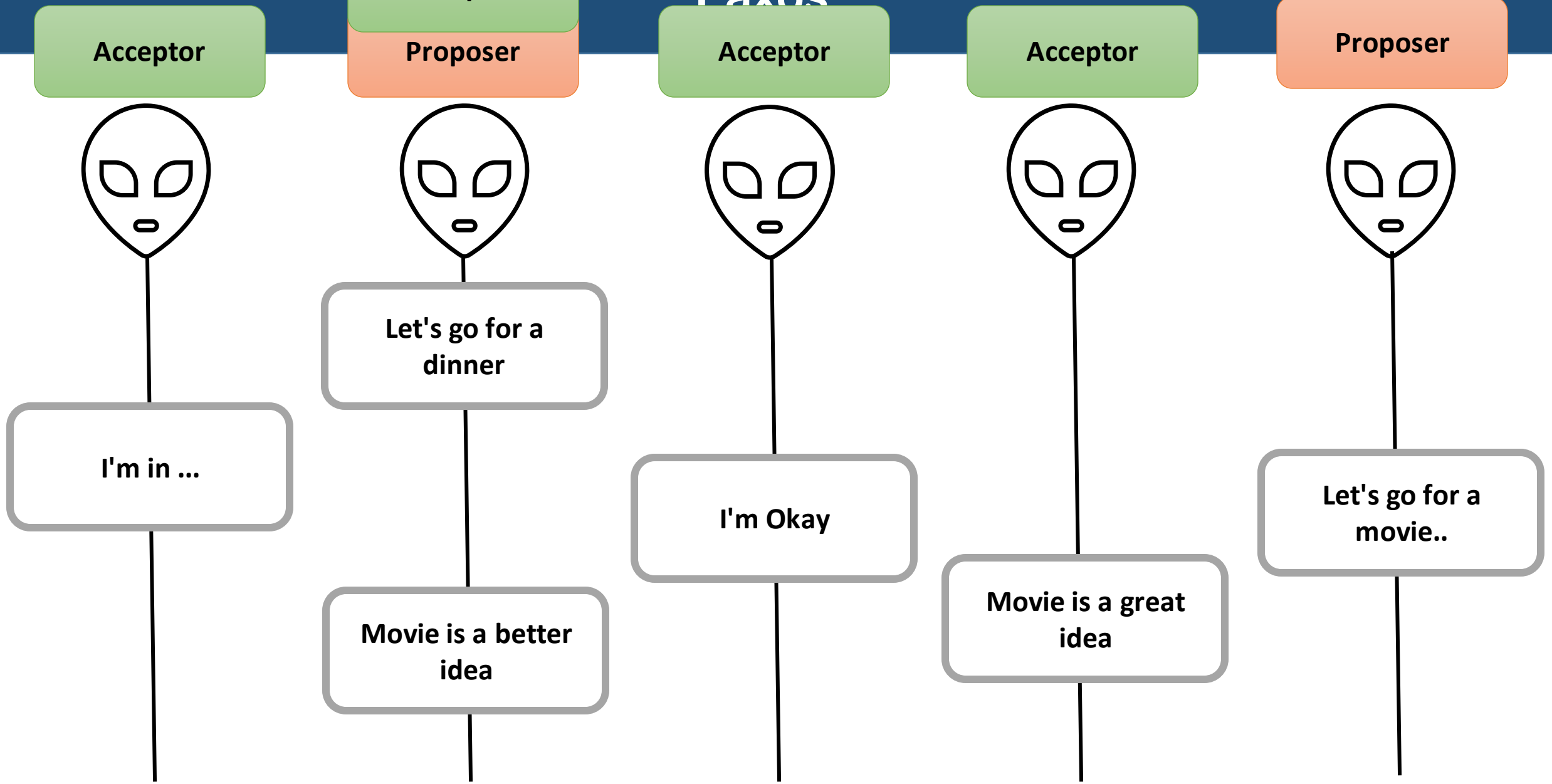
Paxos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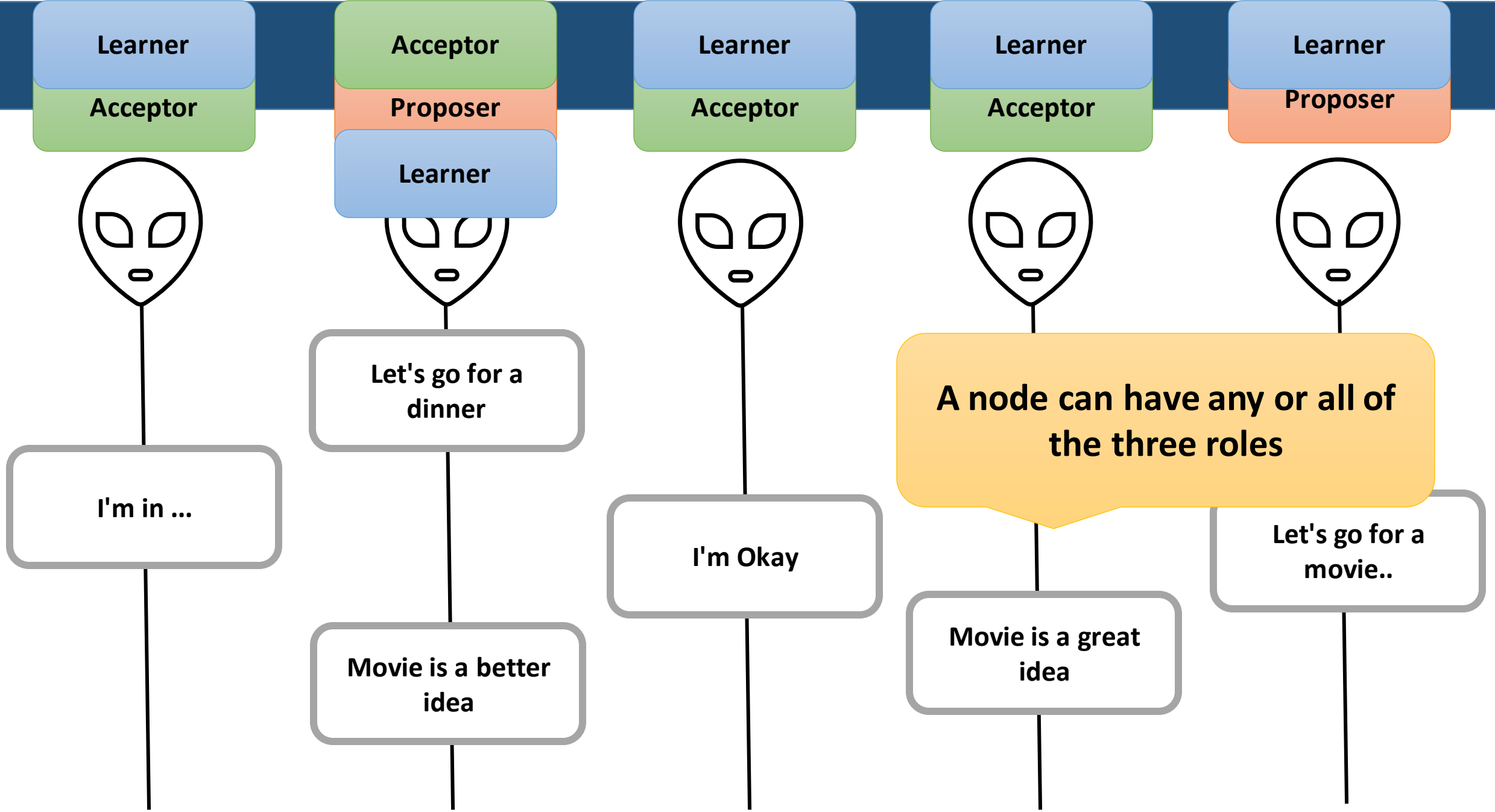
Learner
Acceptor
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A node can have any or all of the three roles
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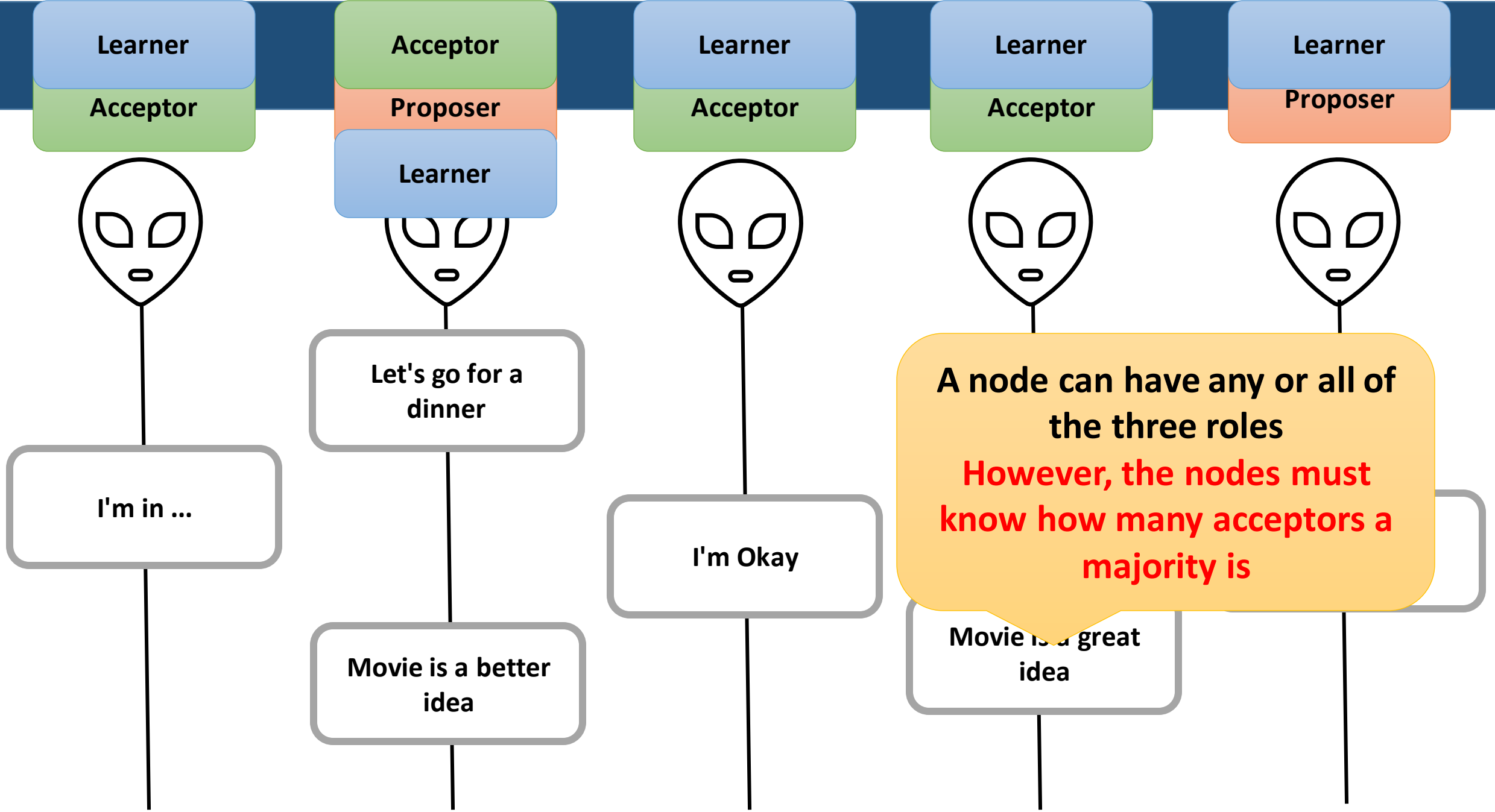
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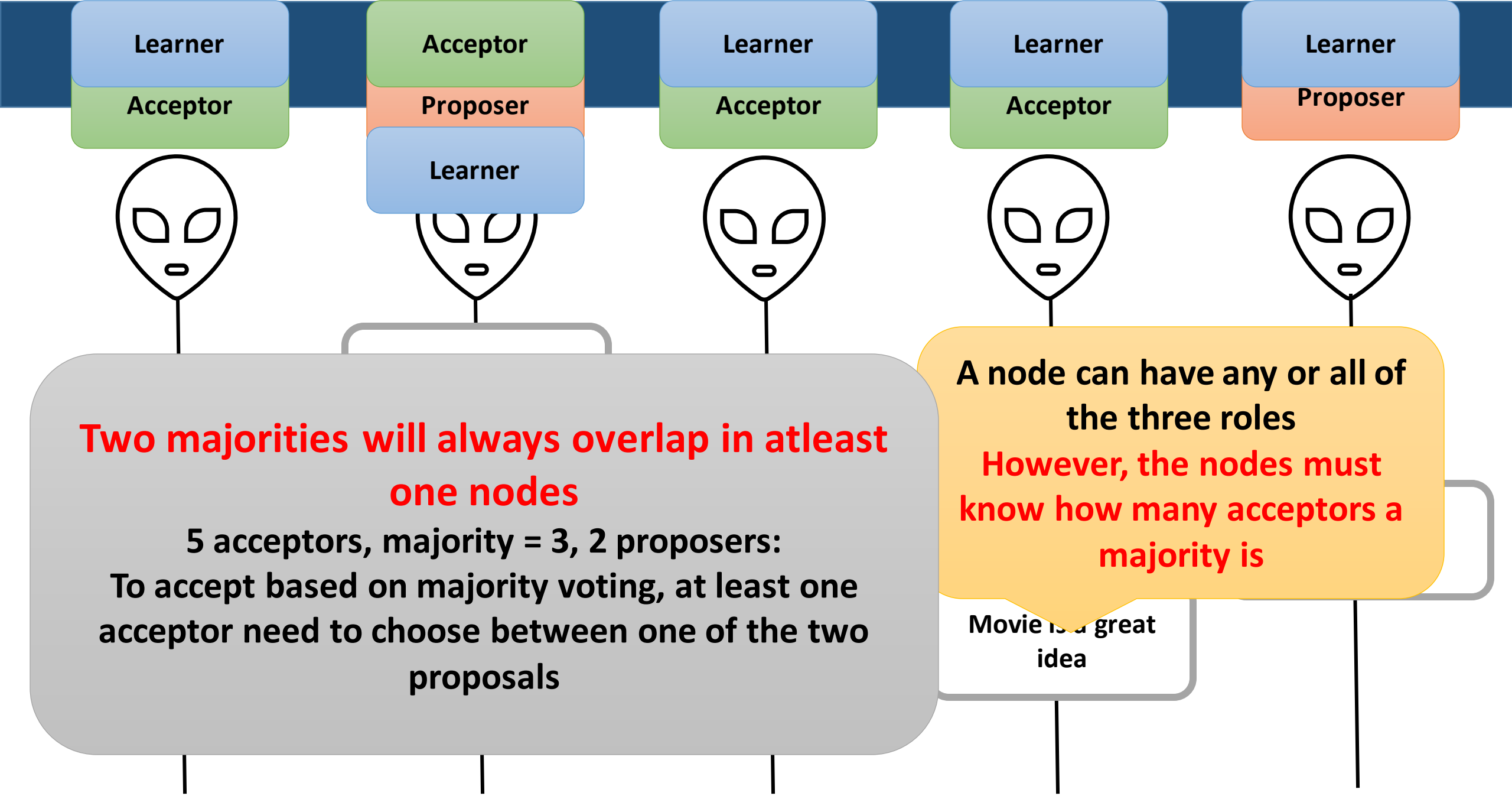
However, the nodes must know how many acceptors a majority is


Learner
Acceptor
Acceptor
Proposer
Learner
Learner
Acceptor
Learner
Acceptor
Learner
Proposer
Two majorities will always overlap in atleast one nodes
5 acceptors, majority = 3, 2 proposers:
To accept based on majority voting, at least one acceptor need to choose between one of the two proposals
A node can have any or all of the three roles
However, the nodes must know how many acceptors a majority is
Movie is a great idea

Paxos Basics

- Paxos is based on state-machine replication
  - Proposers and Acceptors maintain a state of the running epochs
  - Uses a variable IDp where p is an epoch number – maintains the state
  - **We'll see the concept of state-machine replication later in details**

- A Paxos run aims at reaching a **single consensus**
  - Once a consensus is reached, Paxos cannot progress to another consensus
  - To reach multiple consensus, you need to run Paxos in rounds (Multi-Paxos)

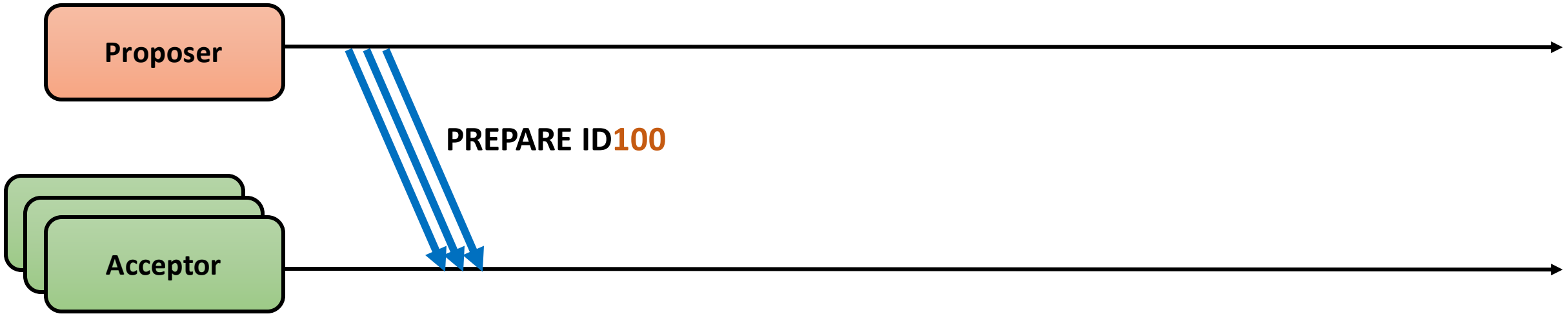
Paxos Algorithm

Paxos Algorithm

Proposer wants to propose its choice (values):

- Sends PREPARE IDp to a majority (or all) of the **acceptors**

Paxos Algorithm



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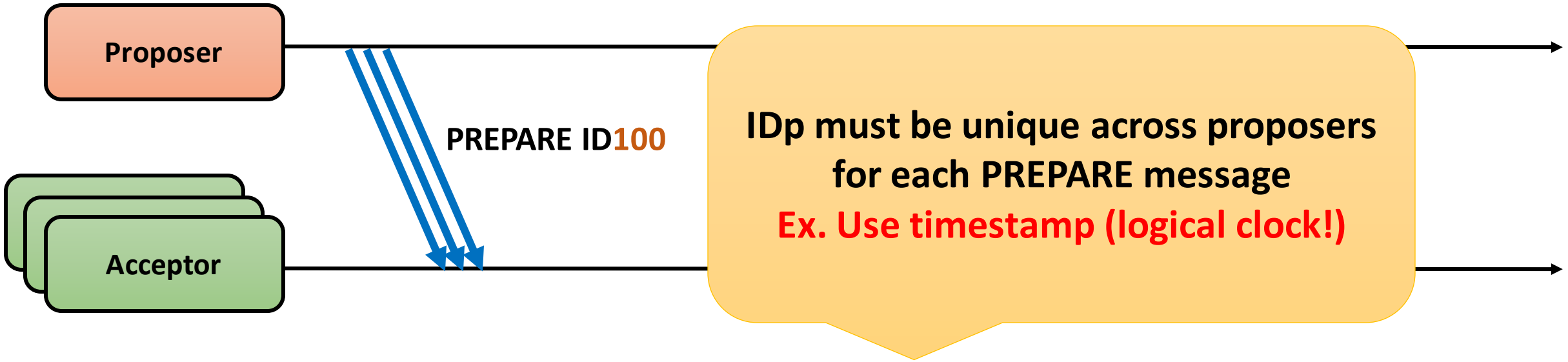

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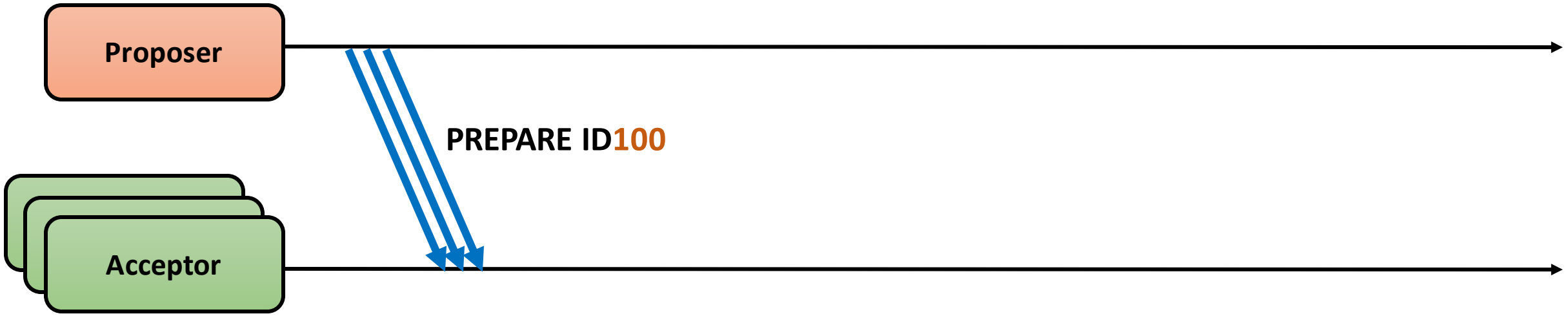

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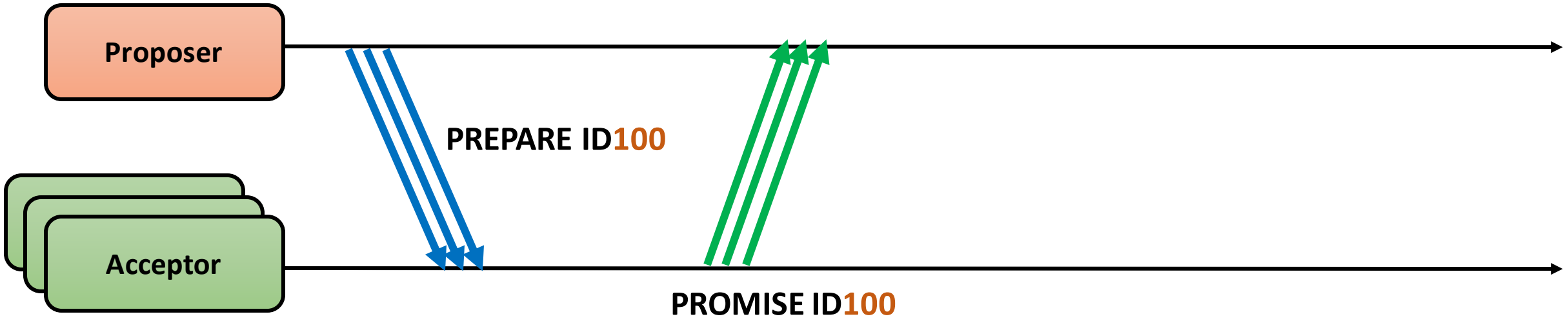

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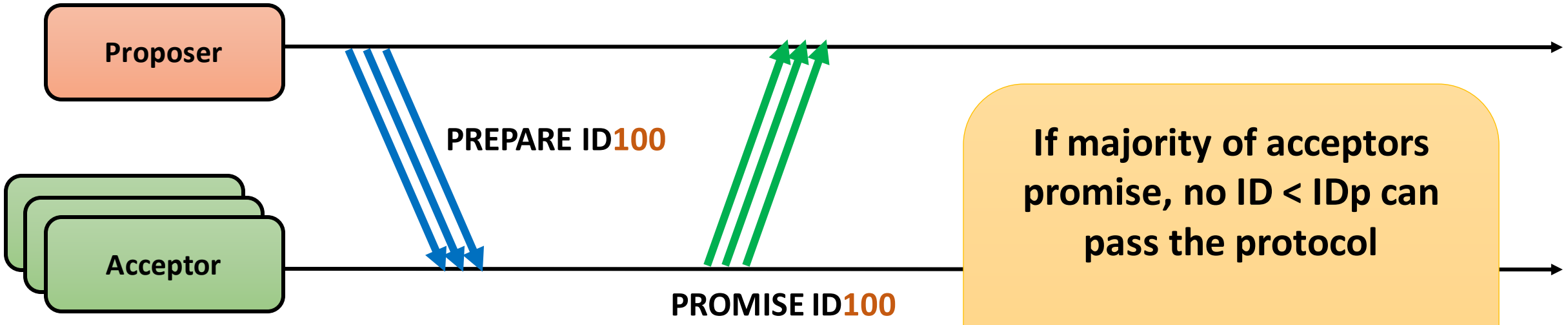

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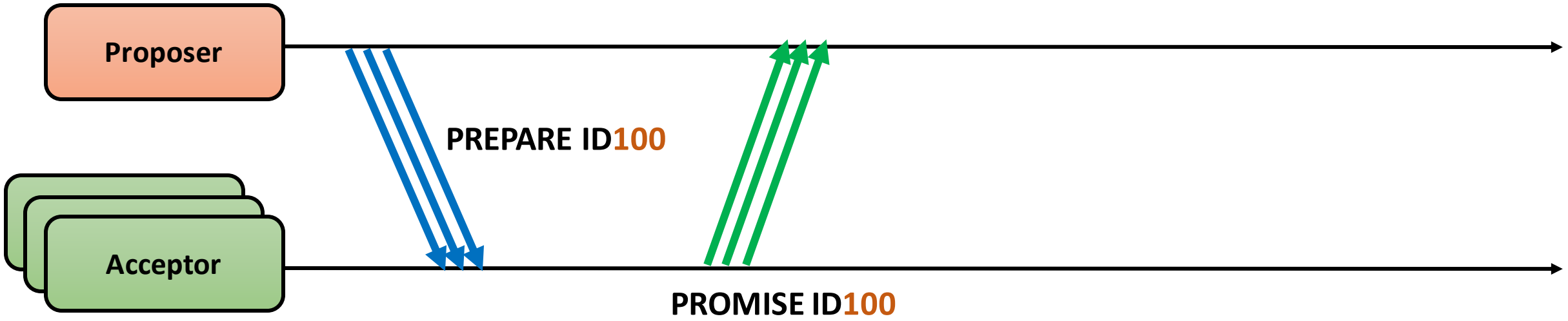

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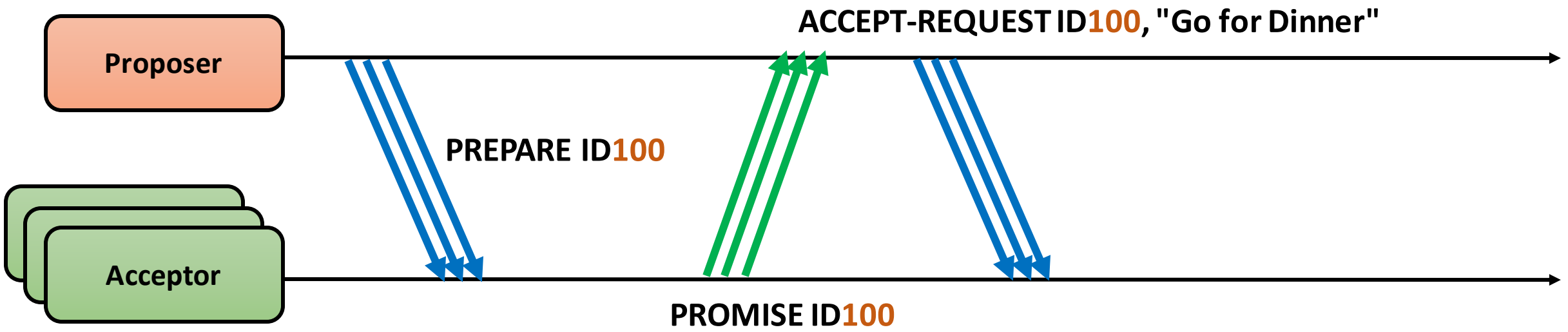

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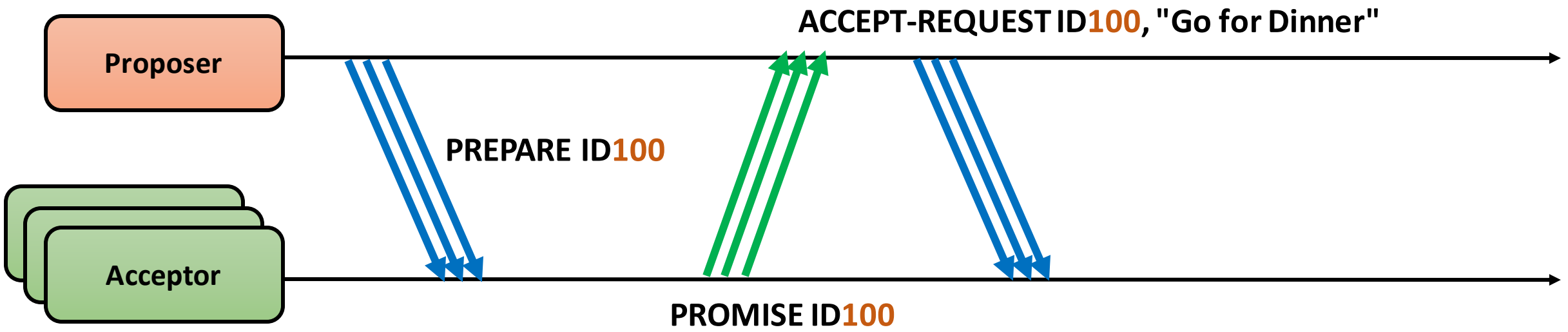
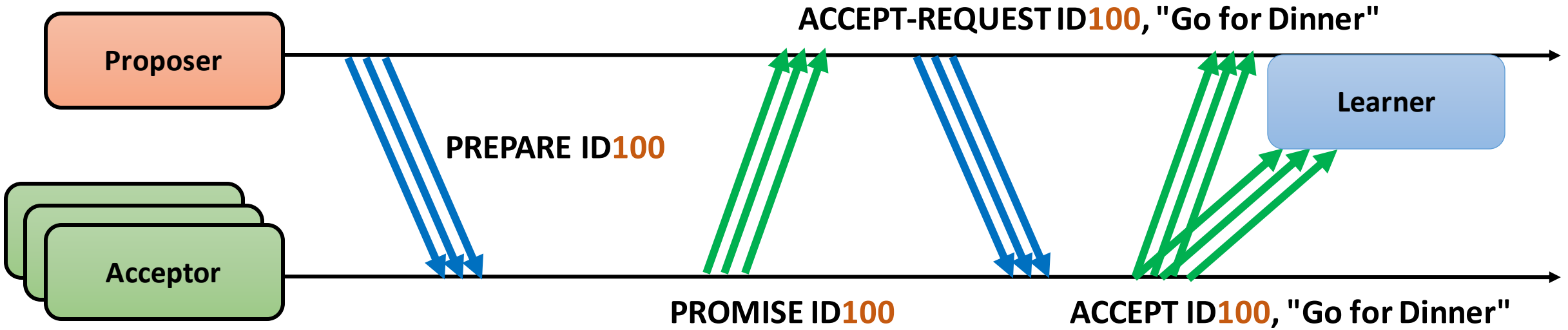


Acceptor receives an ACCEPT-REQUEST IDp, VALUE :

- Did it promised to ignore request with this IDp?
  - **YES:** Ignore
  - **NO:** Reply with **ACCEPT IDp, VALUE**; Also send it to all learners

Paxos Algorithm



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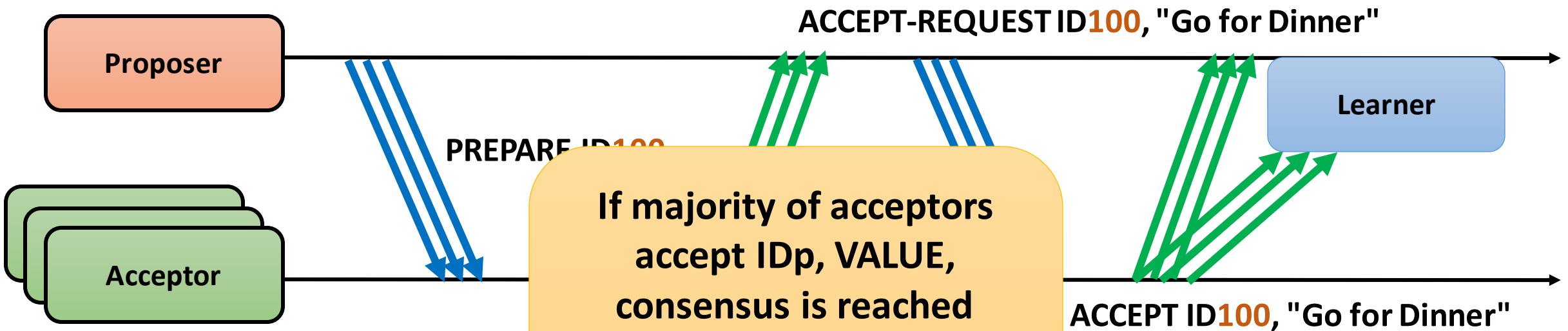

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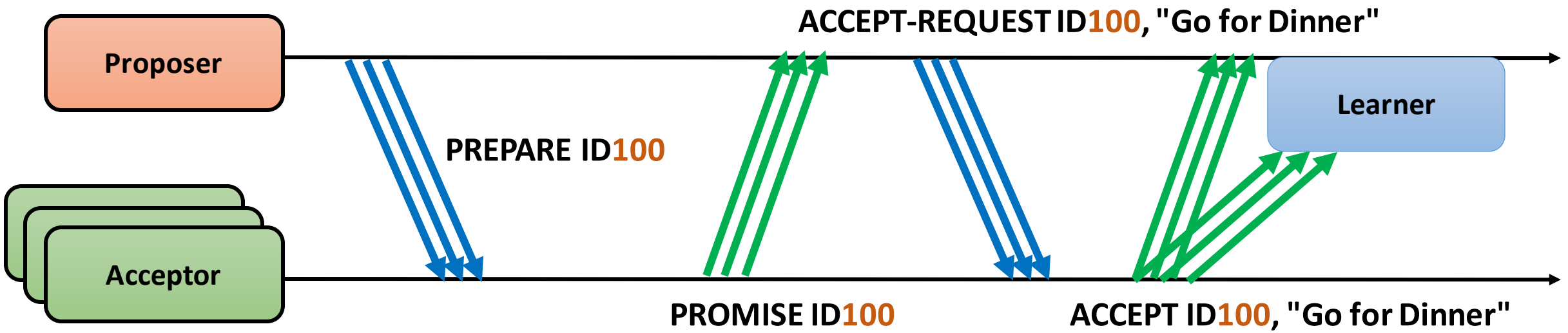
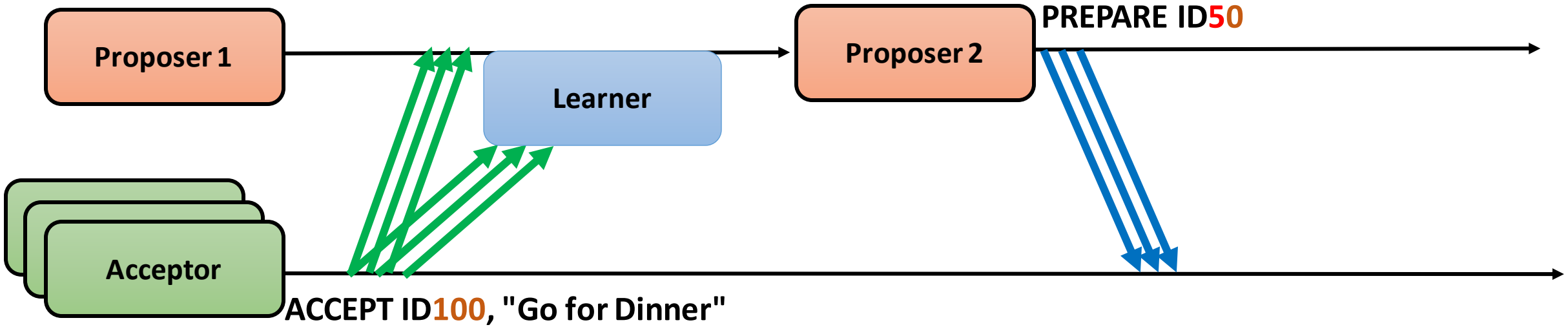


Proposer or **Learner** gets ACCEPT message with IDp, VALUE:

- If a proposer/learner gets majority of accept for a specific IDp, they know that consensus is reached for the value (not IDp).

Paxos Algorithm – Multiple Proposers



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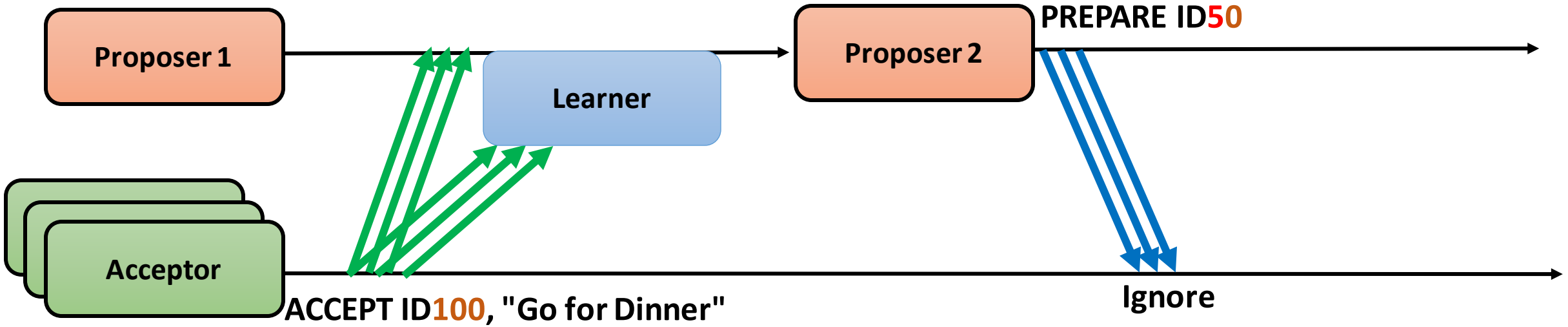

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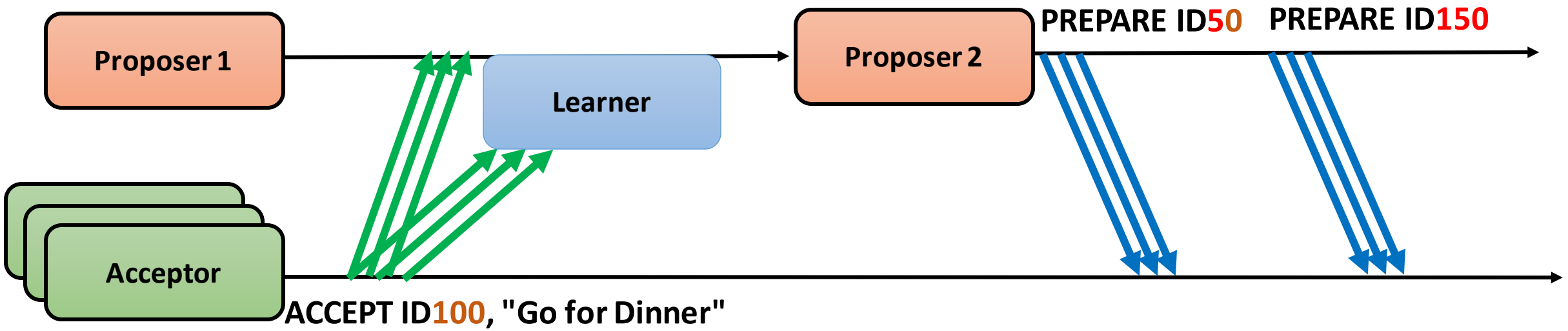

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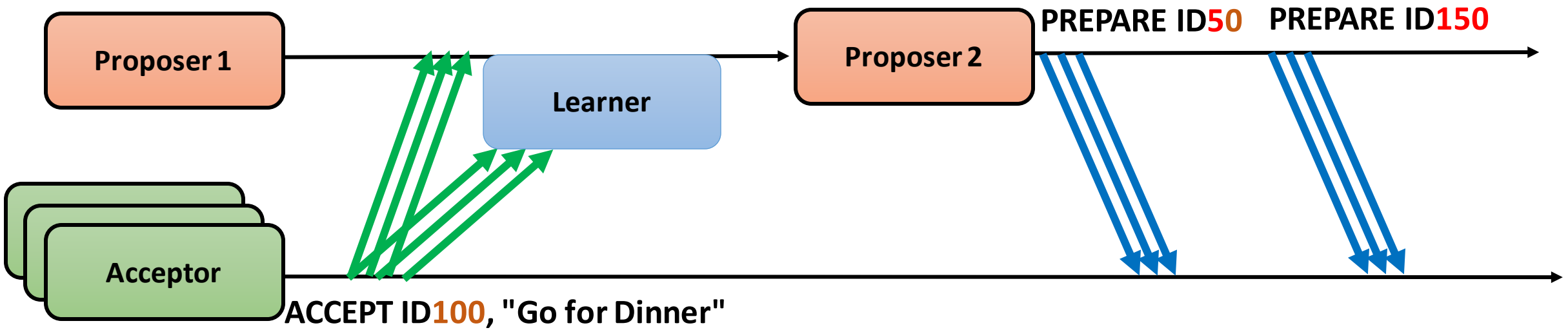

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  - **YES:** Ignore
  - **NO:** Will promise to ignore any request lower than IDp
    - Has it ever accepted anything? (Assume accepted ID = IDa)
      - **YES:** Reply with **PROMISE IDp accepted IDa, VALUE**
      - **NO:** Reply with **PROMISE IDp**

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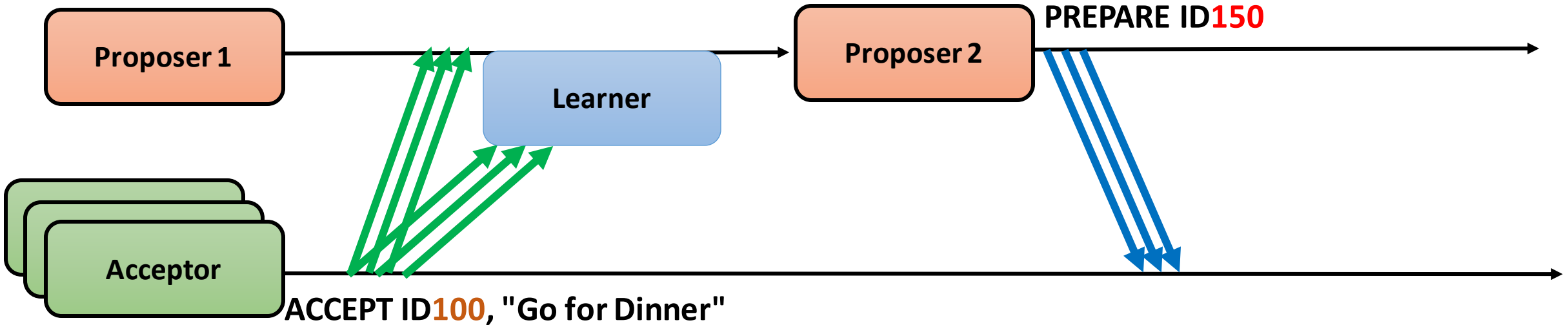

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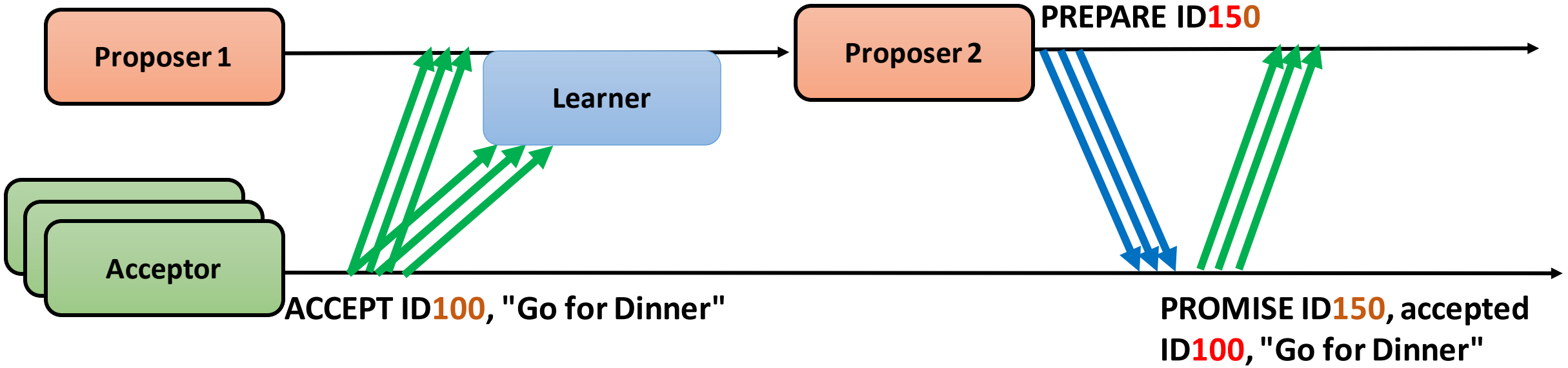
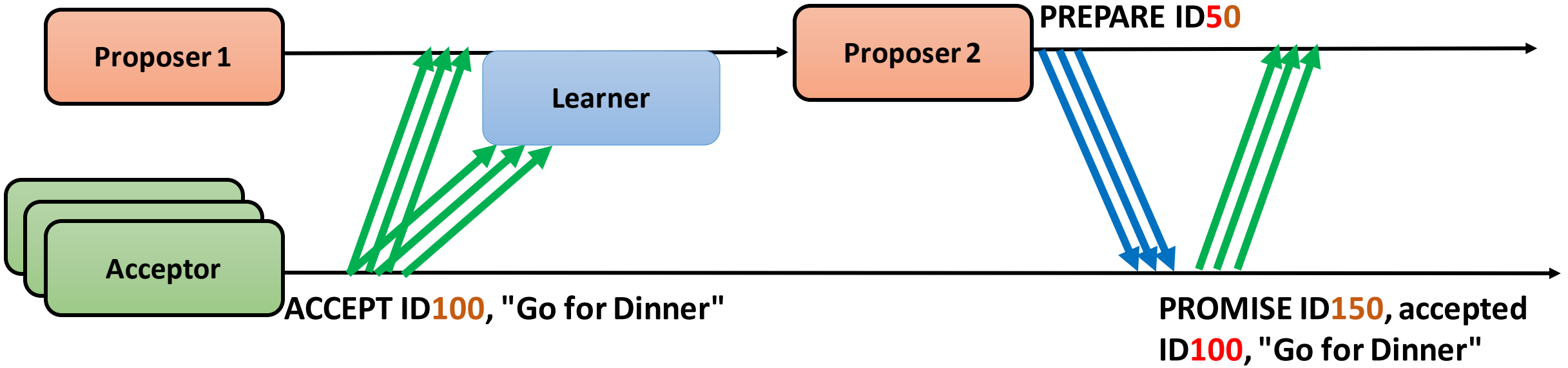


What the proposer will do?

Paxos Algorithm – Multiple Proposers



Proposer gets majority of PROMISE messages for a specific IDp:

- It sends **ACCEPT-REQUEST IDp**, **VALUE** to a majority (or all) of **Acceptors**
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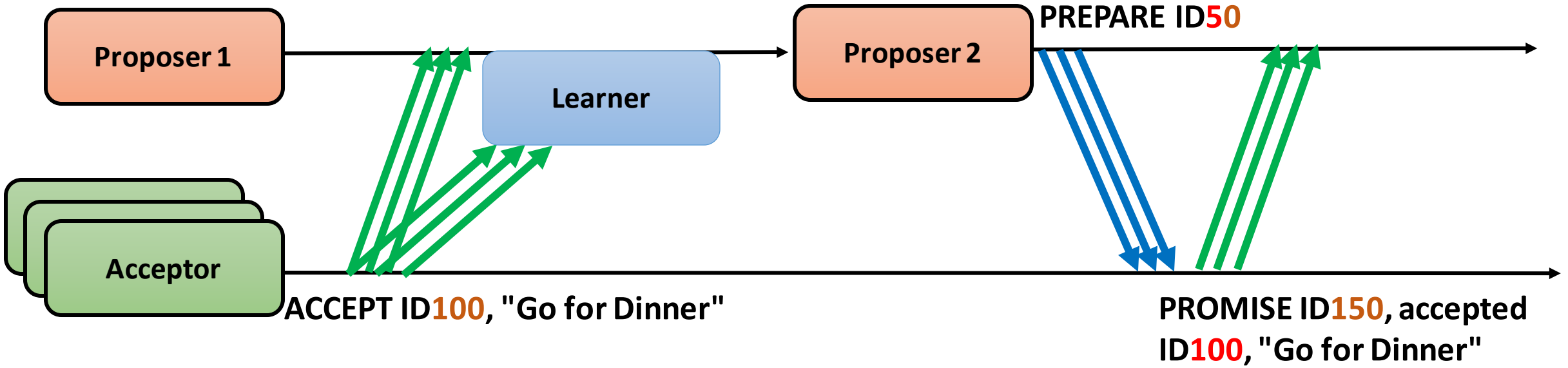

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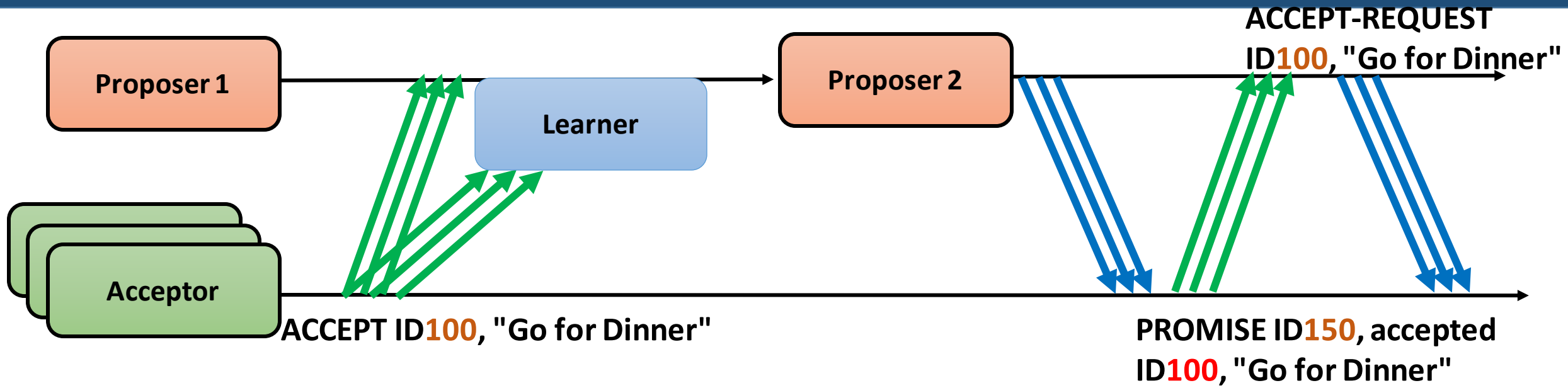
    - **YES:** Picks the value with the highest IDa
    - **NO:** Picks the value of its choice

Paxos Algorithm – Multiple Proposers



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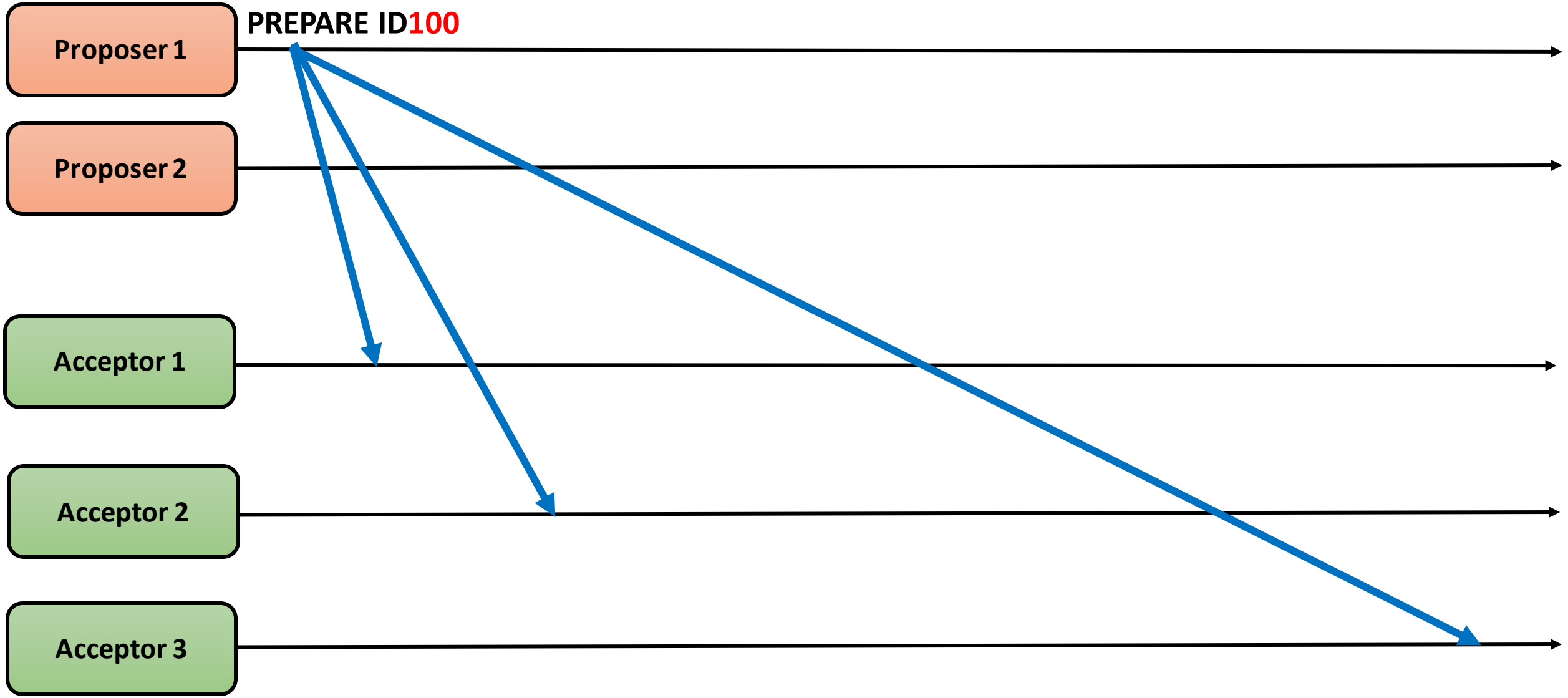
Paxos – How Majority Works



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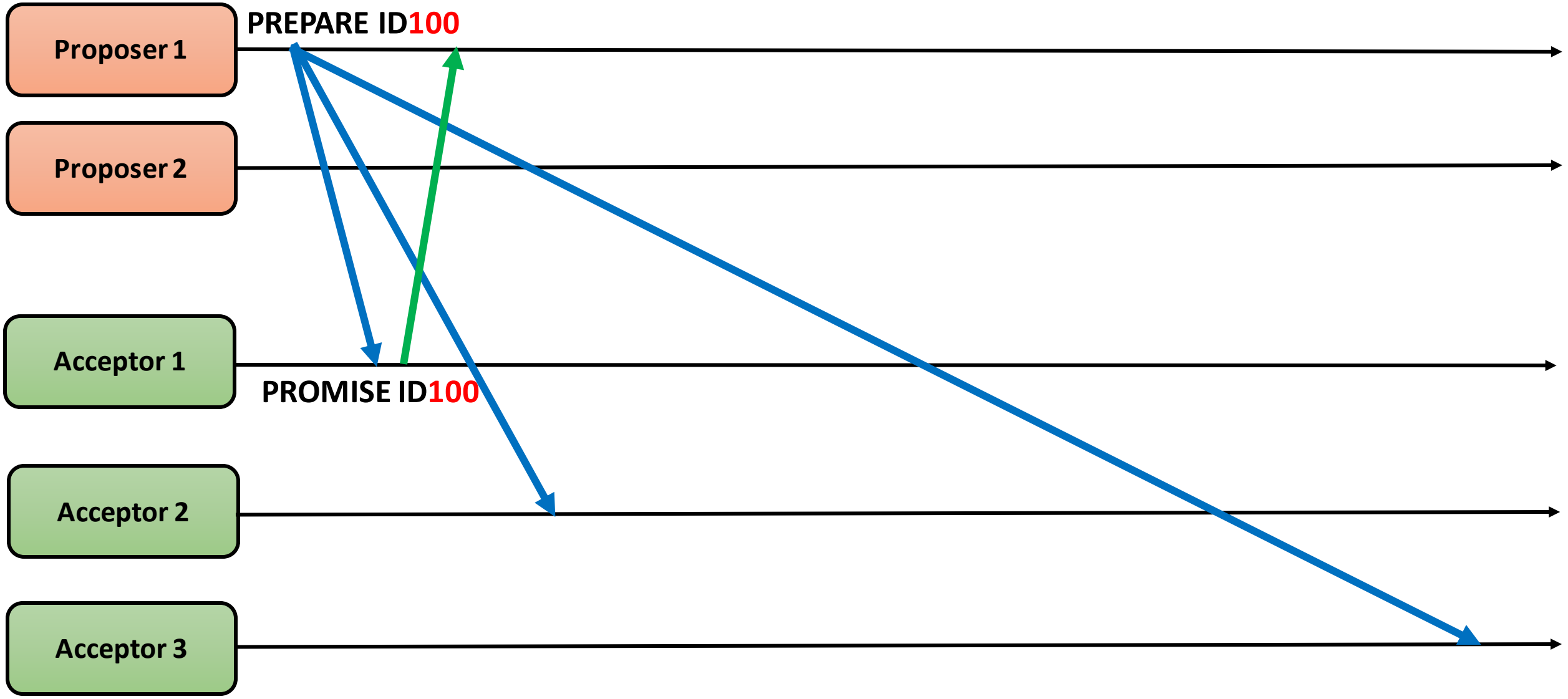

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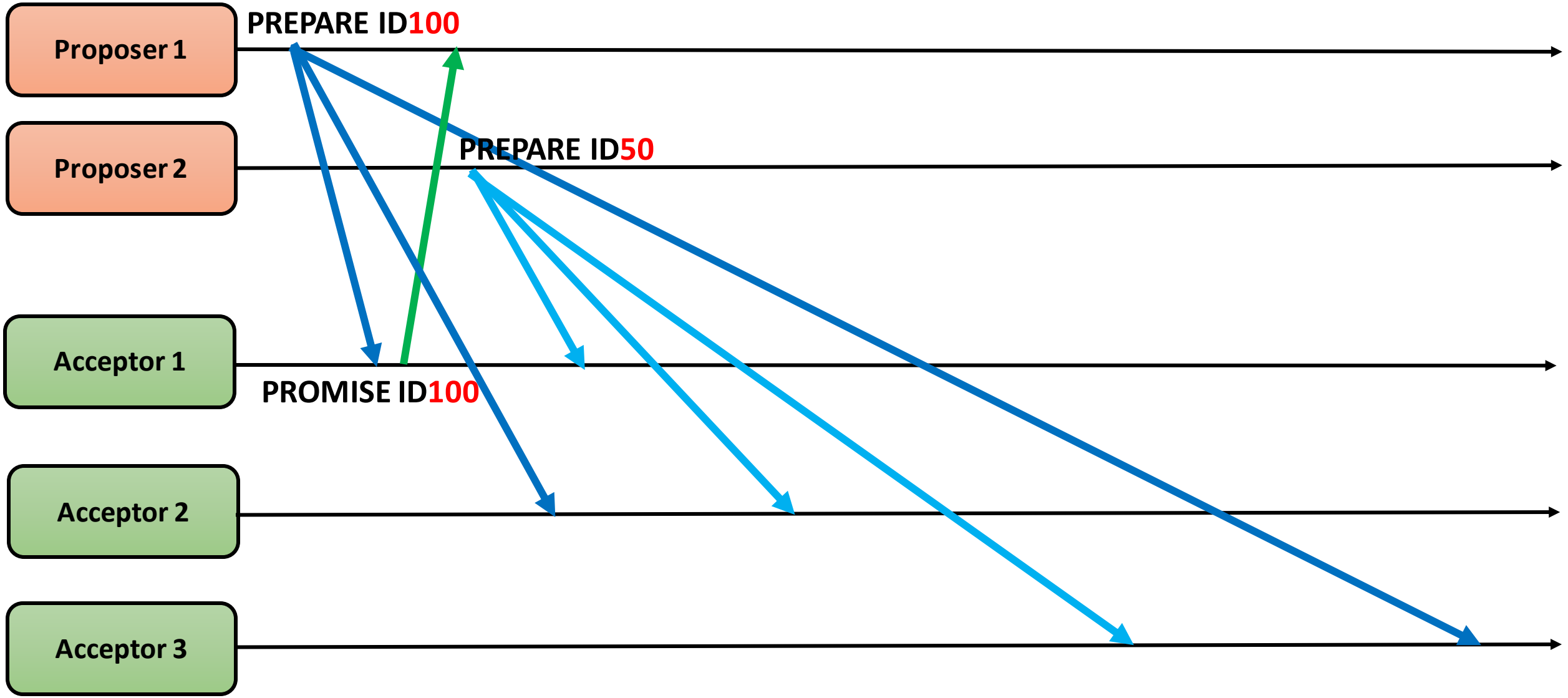

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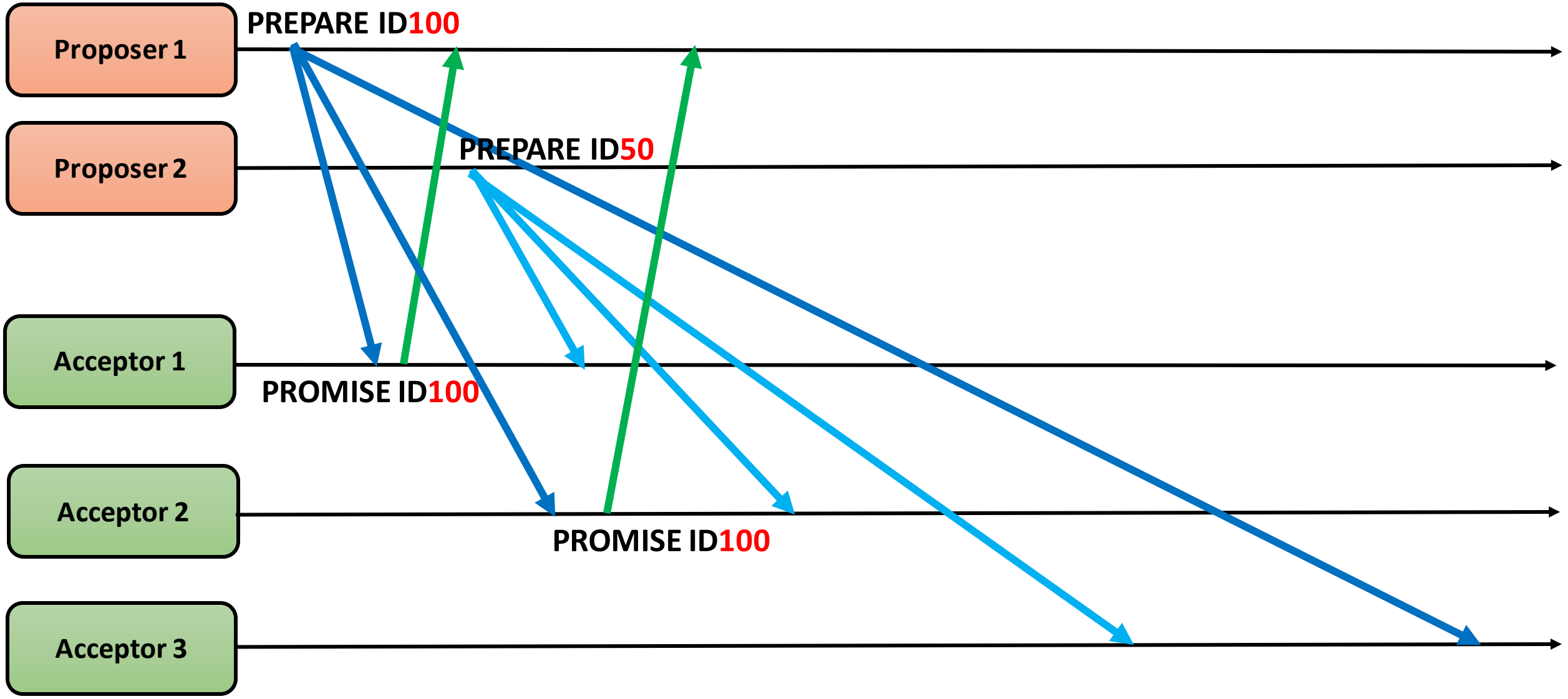

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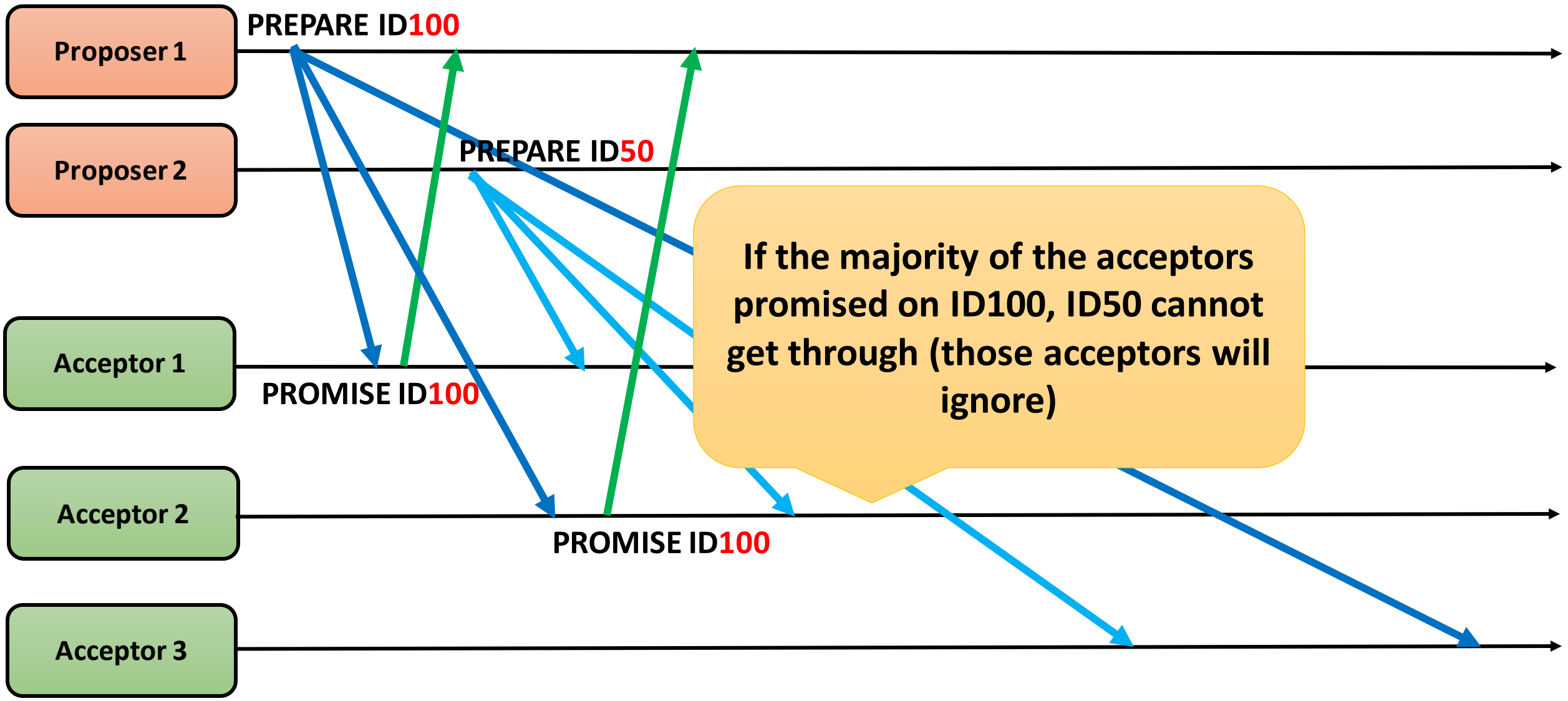

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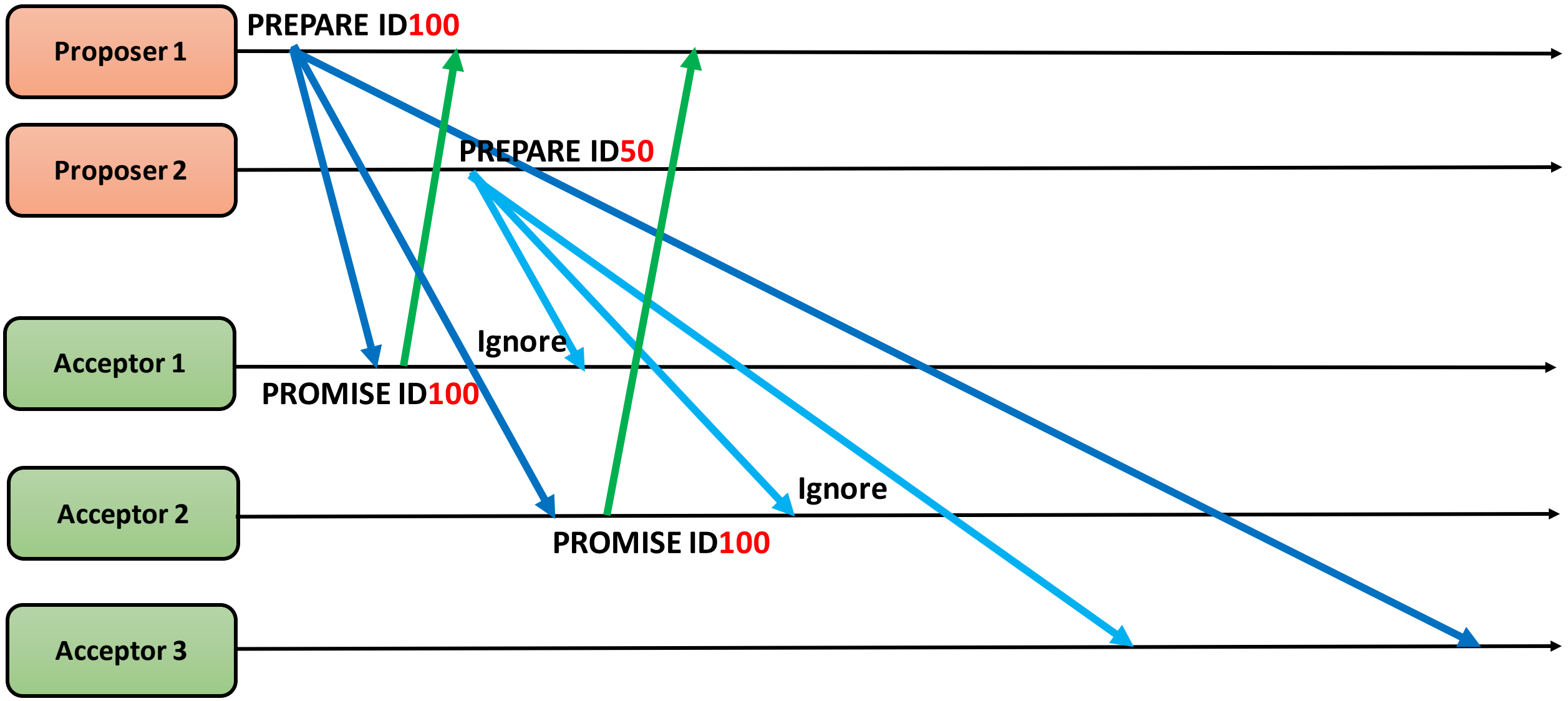
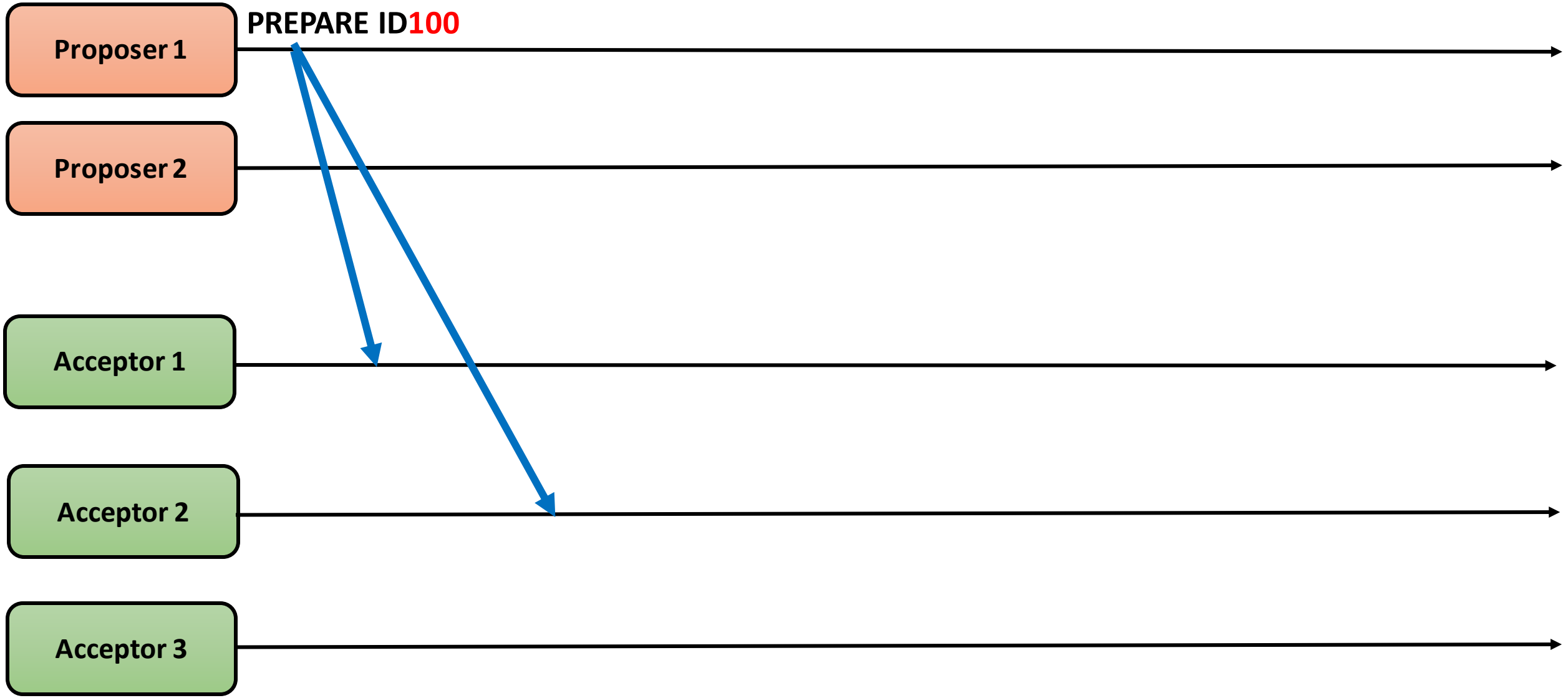


Paxos – Impact on Liveness



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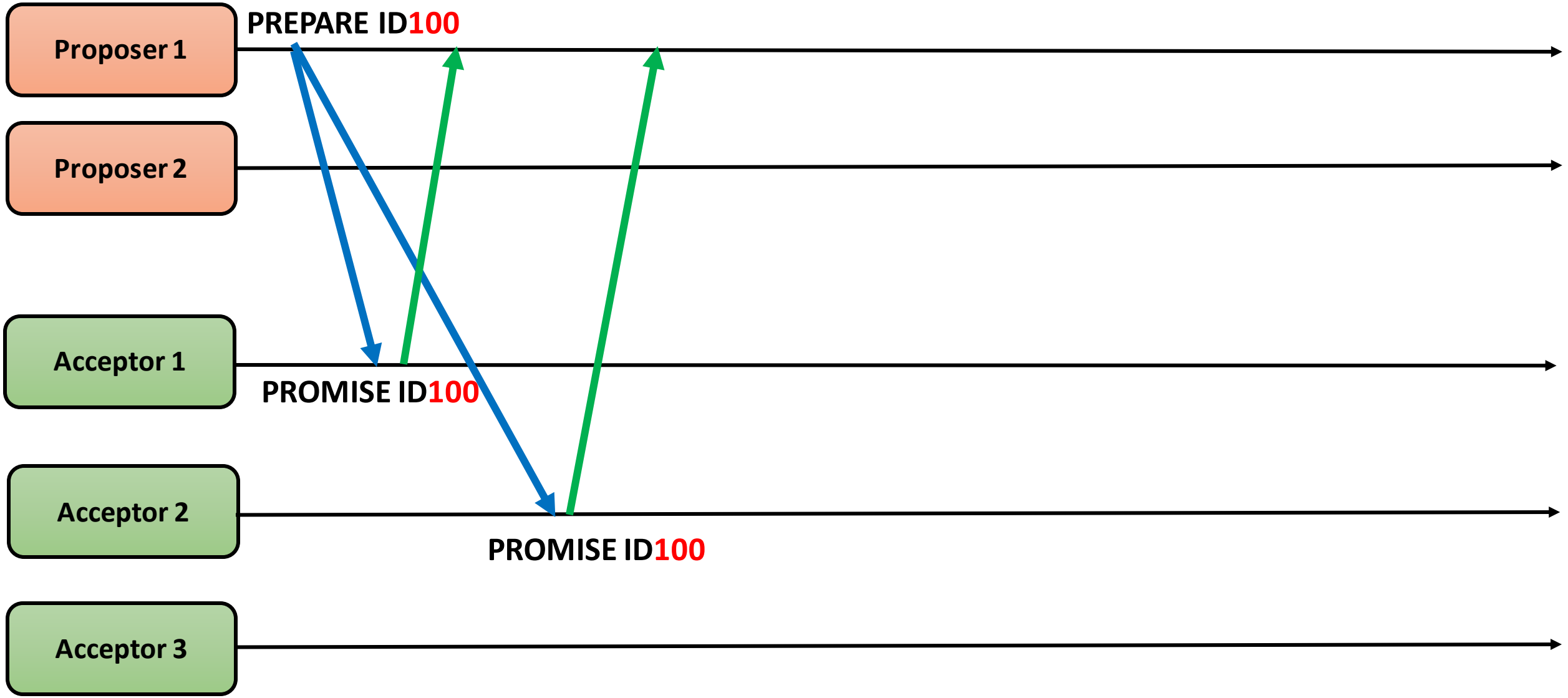

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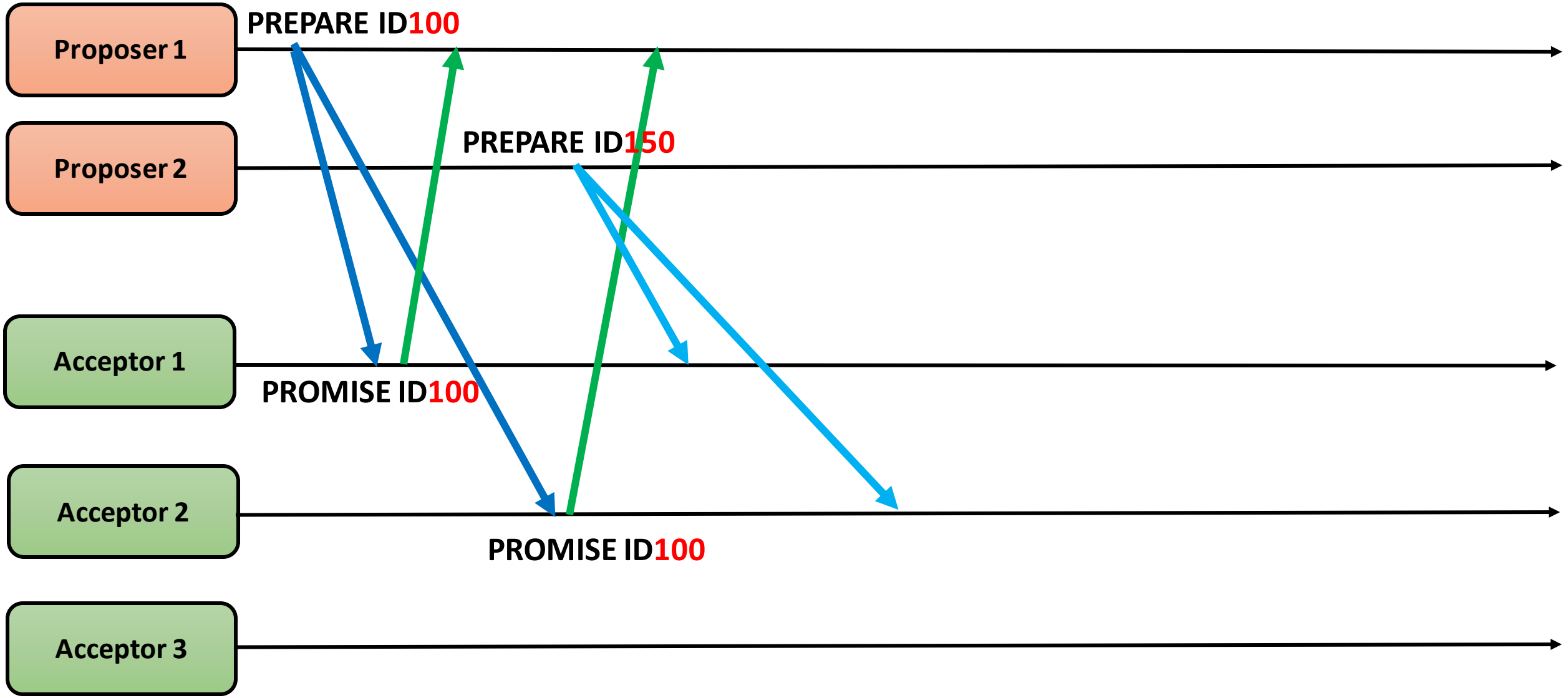

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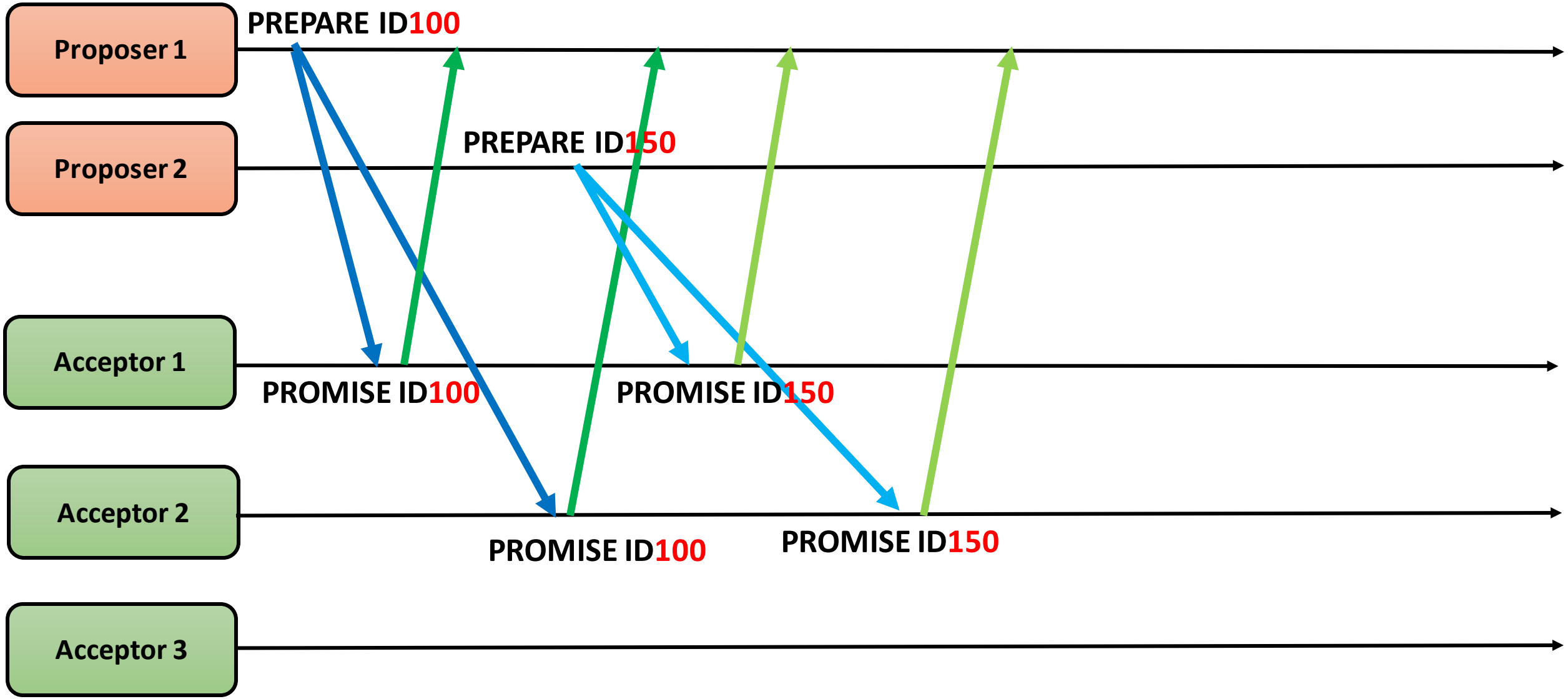

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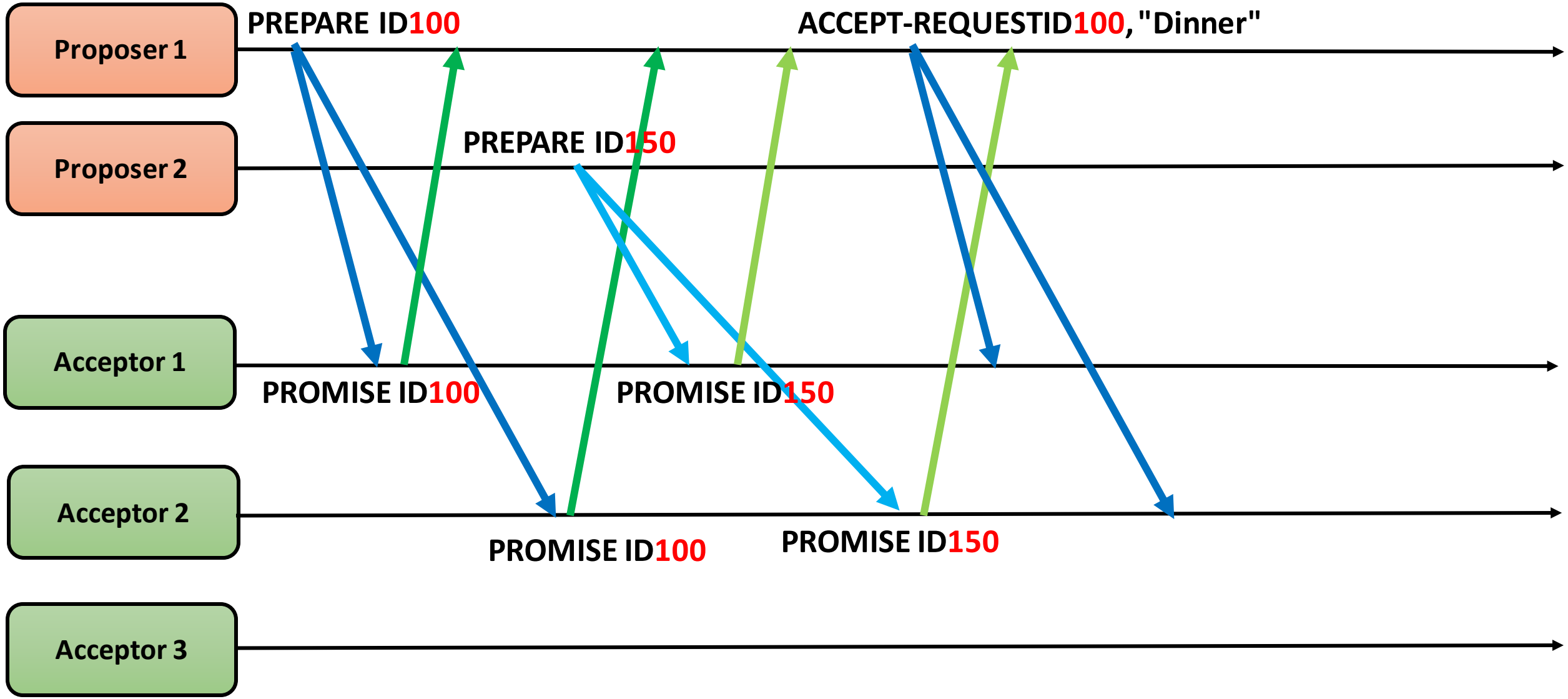

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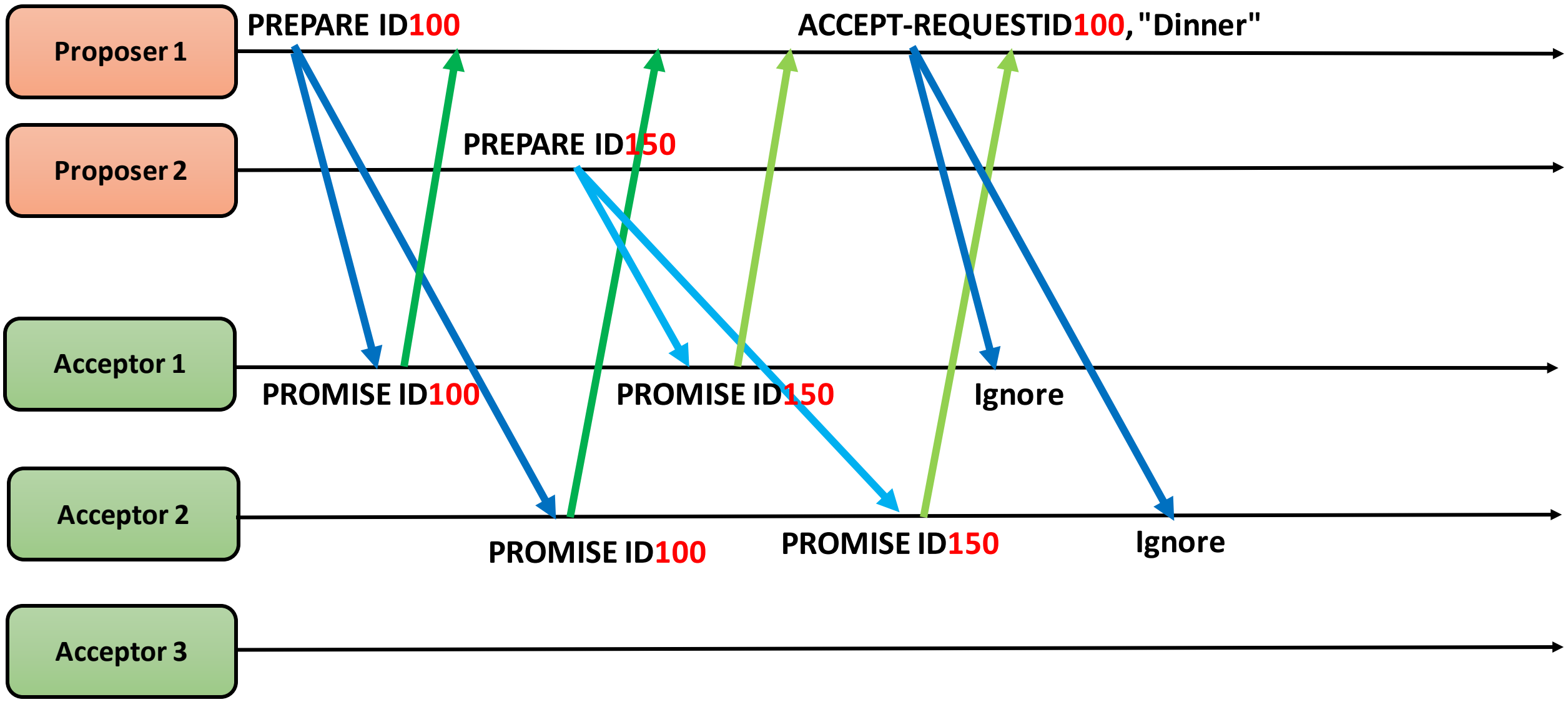

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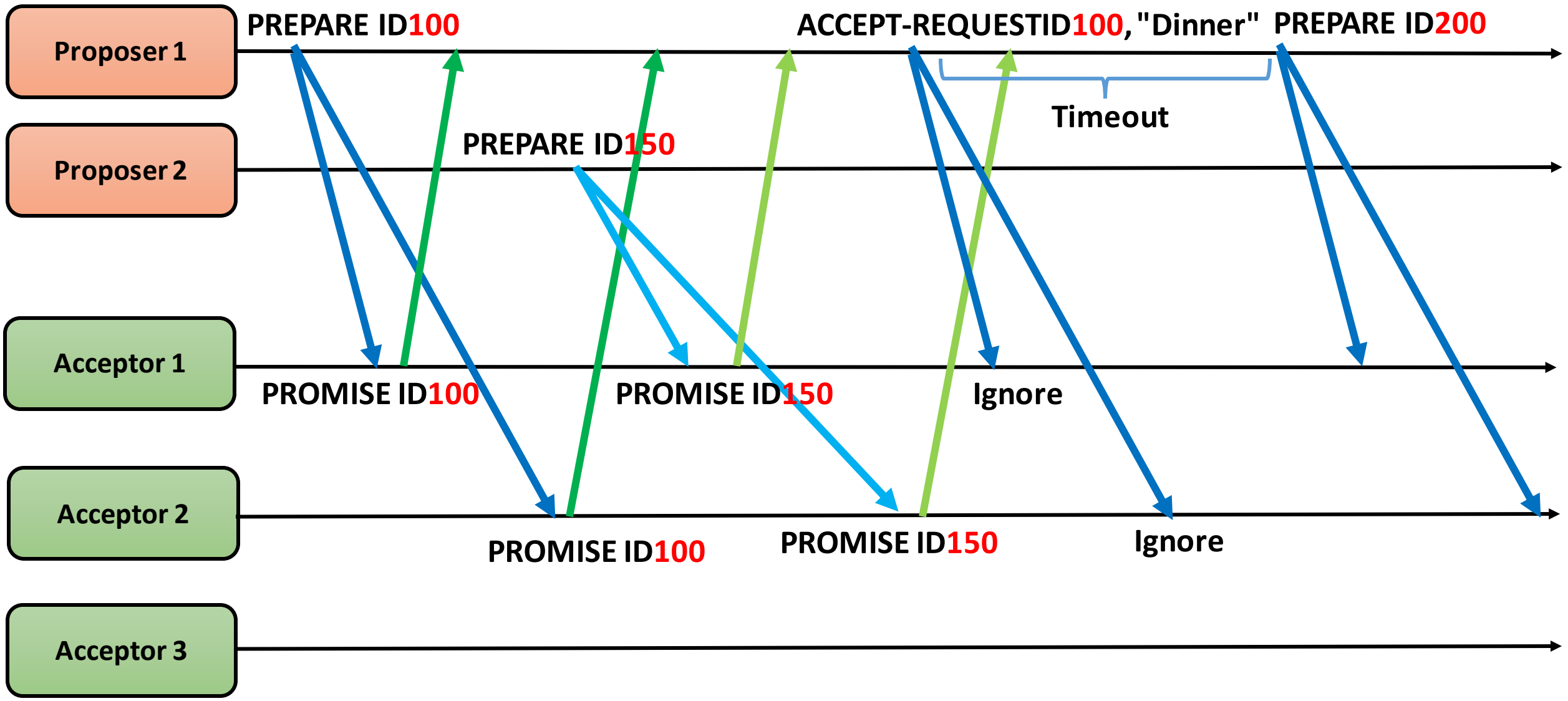

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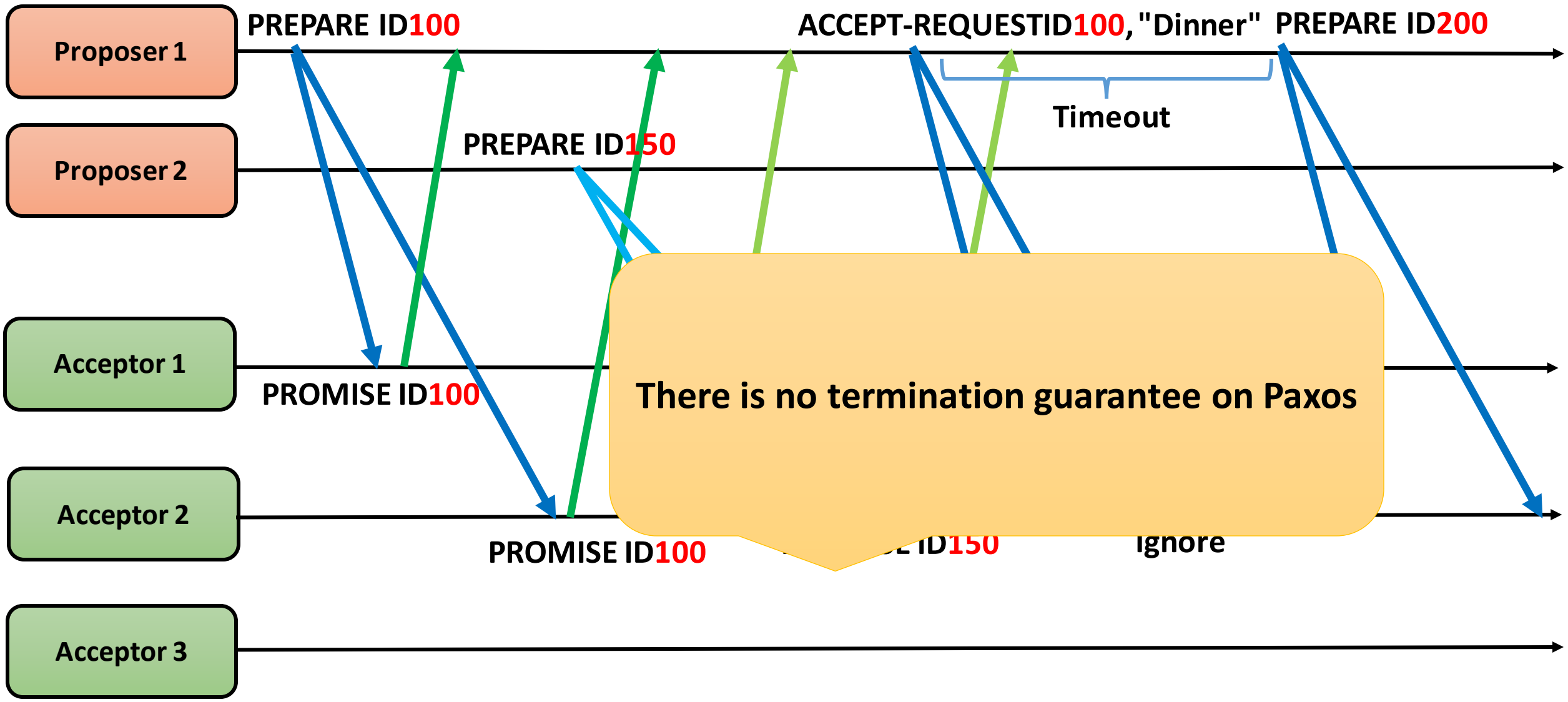

Majority of Accepts

- Majority of accepts accepts a request with an ID and a value
  - Consensus has been reached
  - The consensus is on the **value**

- Accept request with a lower ID
  - Will not be accepted by the majority (Would require majority of promises with the lower ID, but we got for a higher one, hence the accept request)

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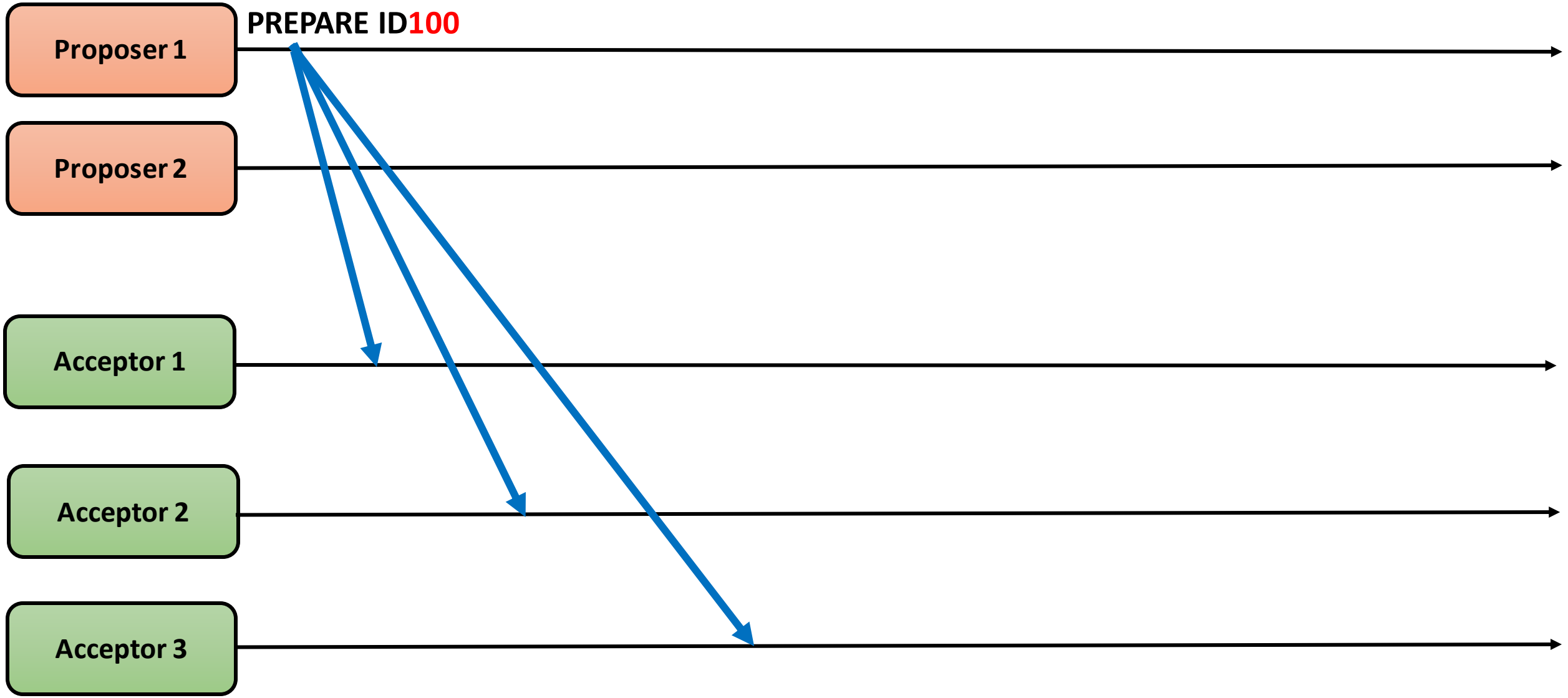
  - Consensus has been reached
  - The consensus is on the **value**
- Accept request with a lower ID
  - Will not be accepted by the major
    lower ID, but we got for a higher

So, the consensus is on the value

We need the ID to maintain the current state of promise and accept, so that multiple values does not propagate

- Accept request with a higher ID but a different value
  - Will not be accepted by the majority
  - At least one acceptor will piggyback the previously accepted value (Remember, two majority implies that there is a common node)

Paxos for Leader Election



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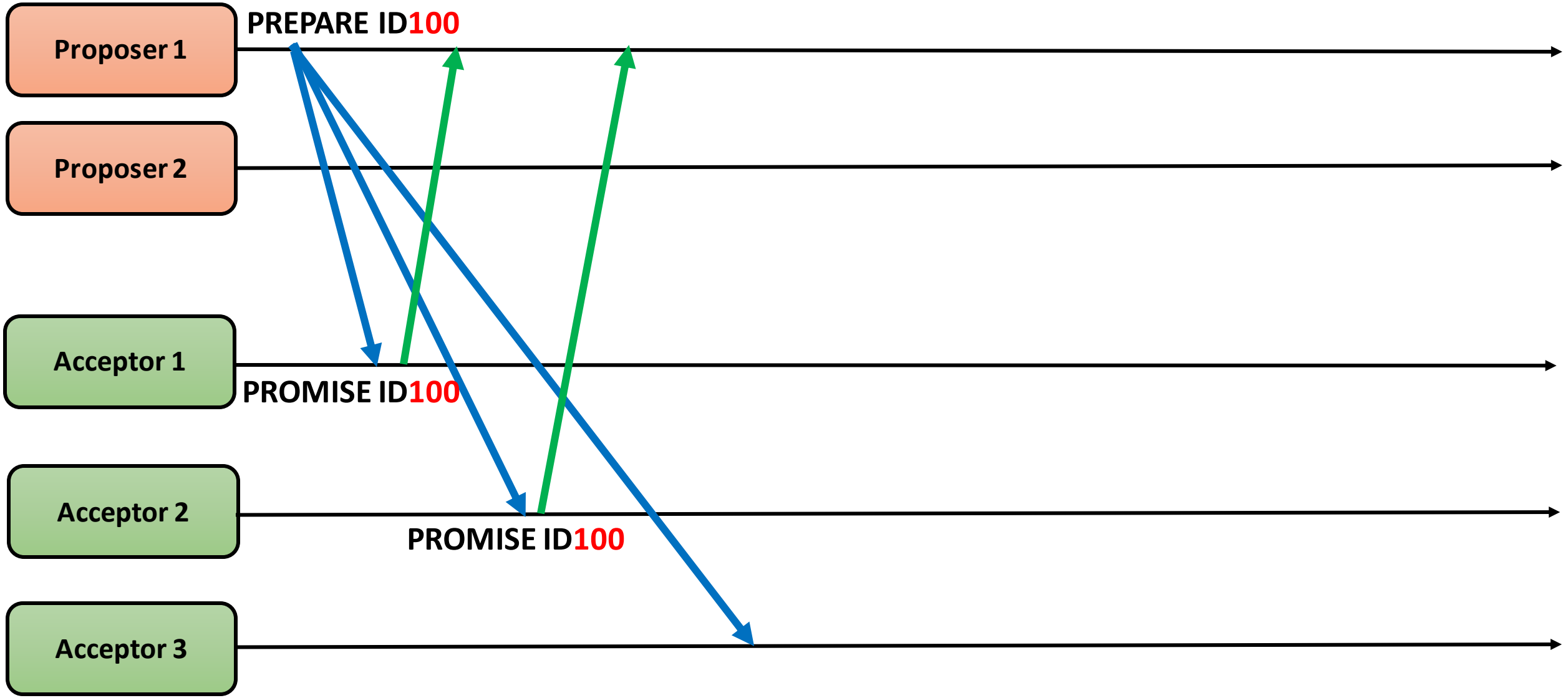

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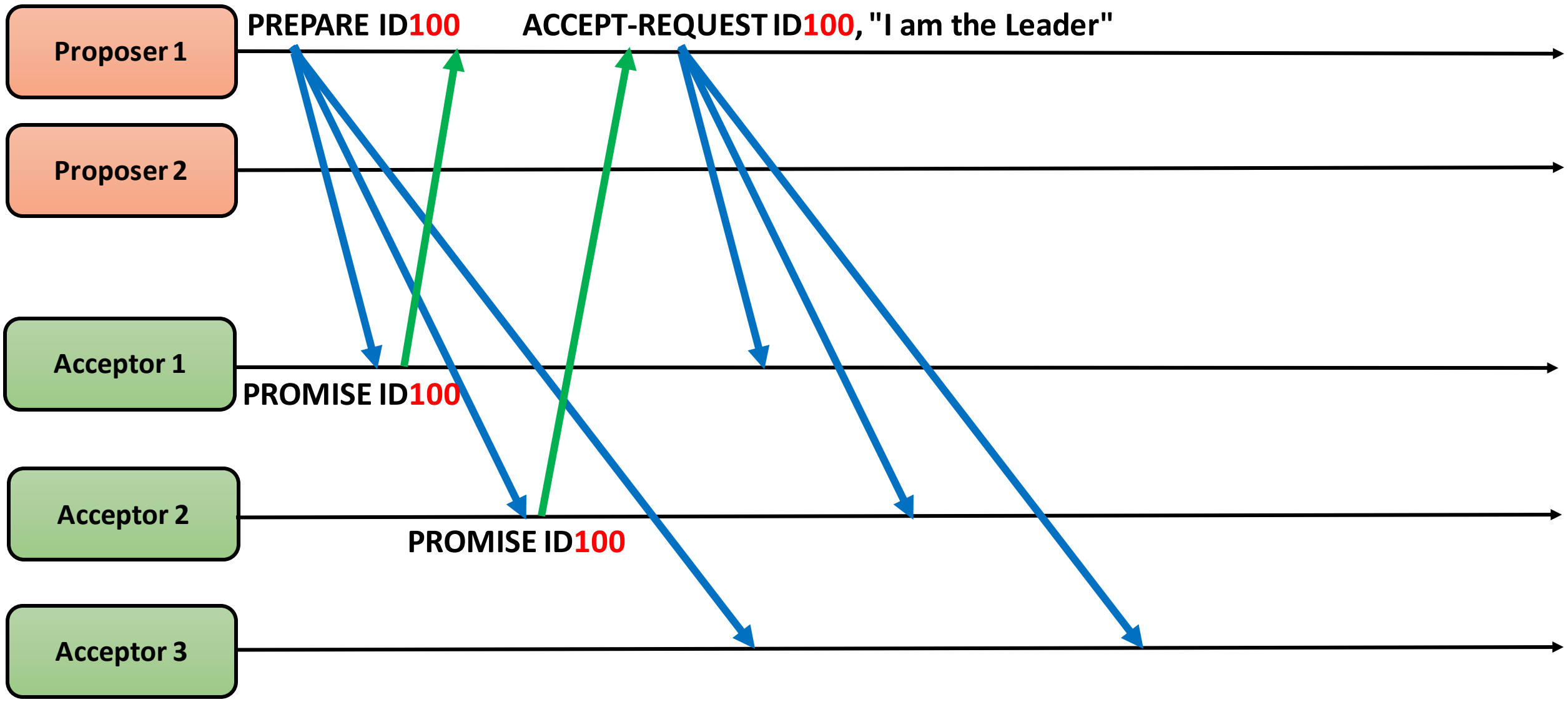

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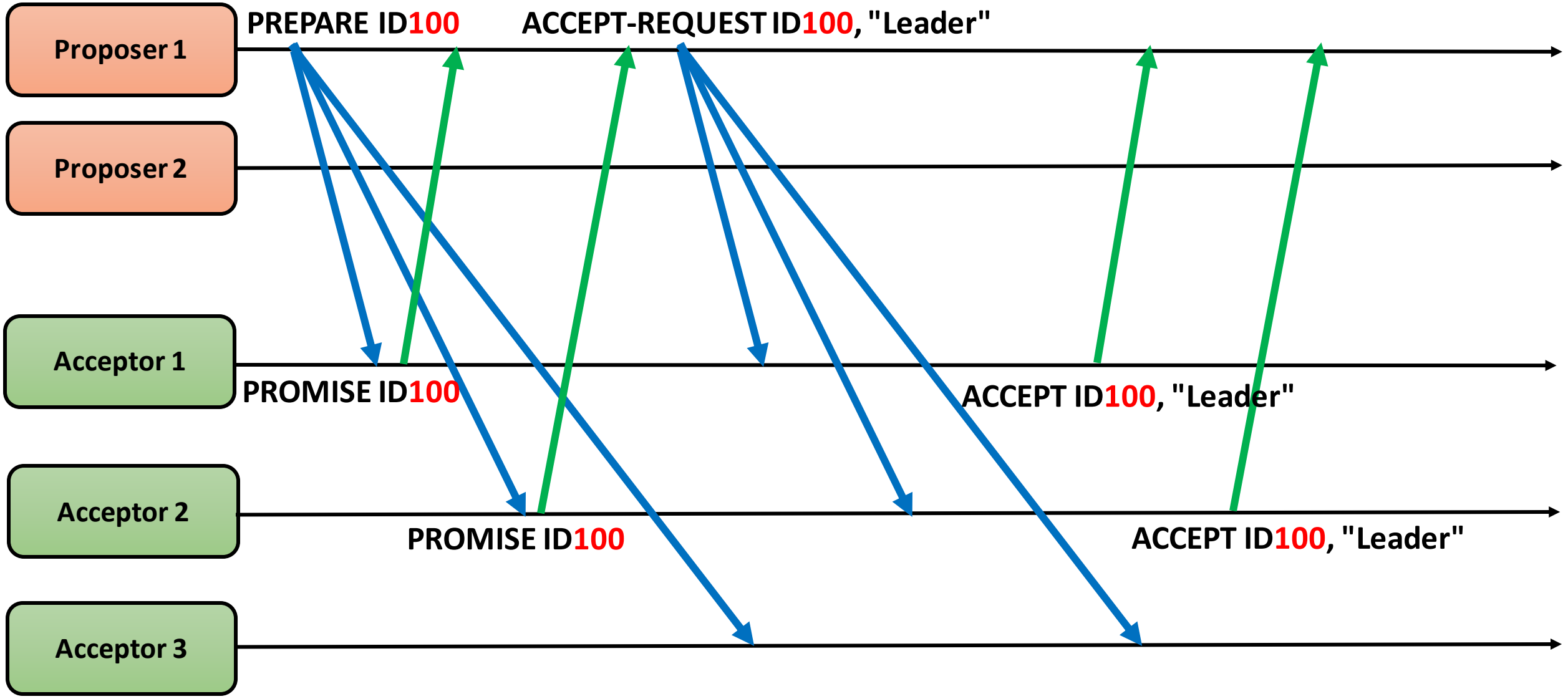

Multi-Paxos

- Applications often needs a continuous stream of agreed values
  - Commit the transactions in a replicated database – each transaction needs a consensus to be agreed upon by the replicas
- Run multiple instances of Paxos with different round numbers
  - Each value is associated with a round number
- If a value is already accepted for Round *n*, ignore the accept requests for a different value under Round *n*
  - Forward an ACCEPT IDp, (ROUNDn, VALUE) only when no value has been agreed upon for the Round *n*

Happy Learning