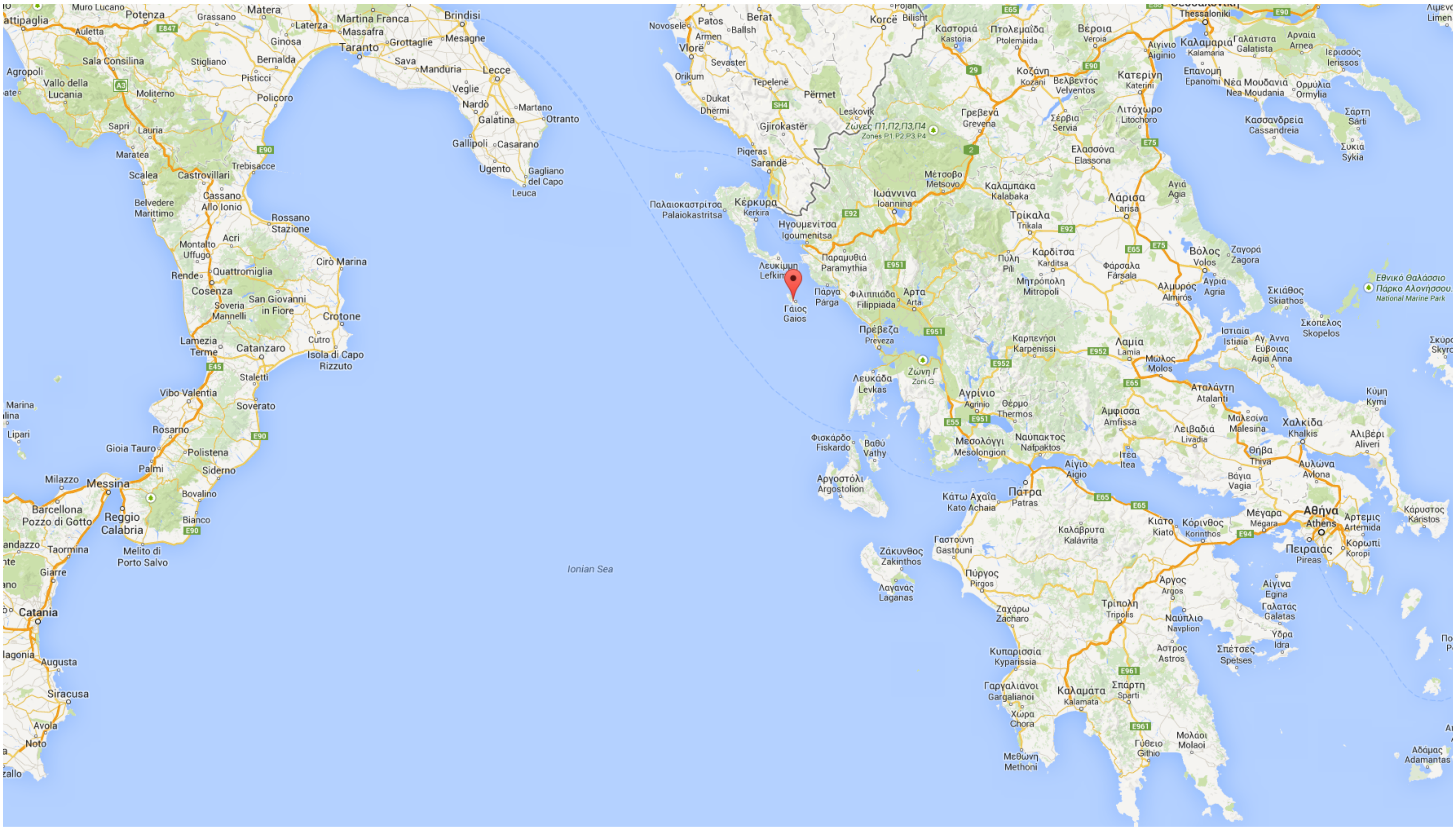
PAXOS


Γάιος
Gaios
Ionian Sea
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Ηγουμενίτσα
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Λευκάδα
Levkas
Αργοστόλι
Argostolion
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Πάτρα
Patras
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Athens
Λάρισα
Larisa
Βόλος
Volos
Καλαμάτα
Kalamata
Τρίπολη
Tripolis
Brindisi
Lecce
Taranto
Otranto
Sarandë
Vlorë
Gjirokastër
Messina
Reggio Calabria
Catanzaro
Cosenza
Crotone
Catania
Siracusa

PAXOS

- Leslie Lamport. **The part-time parliament**. ACM Transactions on Computer Systems, 16(2):133–169, May 1998.
- Leslie Lamport described in 1990 the algorithm as the solution to a problem of the parliament on a fictitious Greek island called Paxos (not Italy)
- Many readers were so distracted by the description of the activities of the legislators, they did not understand the meaning and purpose of the algorithm. The paper was rejected.
- Leslie Lamport refused to rewrite the paper. He later wrote that he "was quite annoyed at how humorless everyone working in the field seemed to be"
- After a few years, some people started to understand the importance of the algorithm
- After eight years, Leslie Lamport submitted the paper again, basically unaltered. It got accepted!

Leslie Lamport
ACM Turing Award 2014

Consensus (again)

- We have a collection of processes
- Each process can propose a value
- A single value among the proposed values is chosen
- If no value is proposed, no value should be chosen
- If a value has been chosen, processes should be able to learn the chosen value

System Model

- <u>Asynchronous</u> communications
- <u>Non-byzantine</u> failures:
  - Nodes crash
  - Messages can be lost, duplicated arbitrarily late
  - No corrupted messages
- <u>Fail-recover</u>: crashed nodes may recover later

Roles

- Each nodes has one or more of 3 roles
- Proposer: a node that can propose a certain value for acceptance
- Acceptor: a node that receives proposals from proposers and that can either accept or reject a proposal
- Learner: a node not involved in the decision process that wants to know the final result of the decision process
- We will assume all nodes act both as proposer and as acceptor

Acceptors

- A single acceptor (a.k.a. coordinator) can fail and block the whole procedure

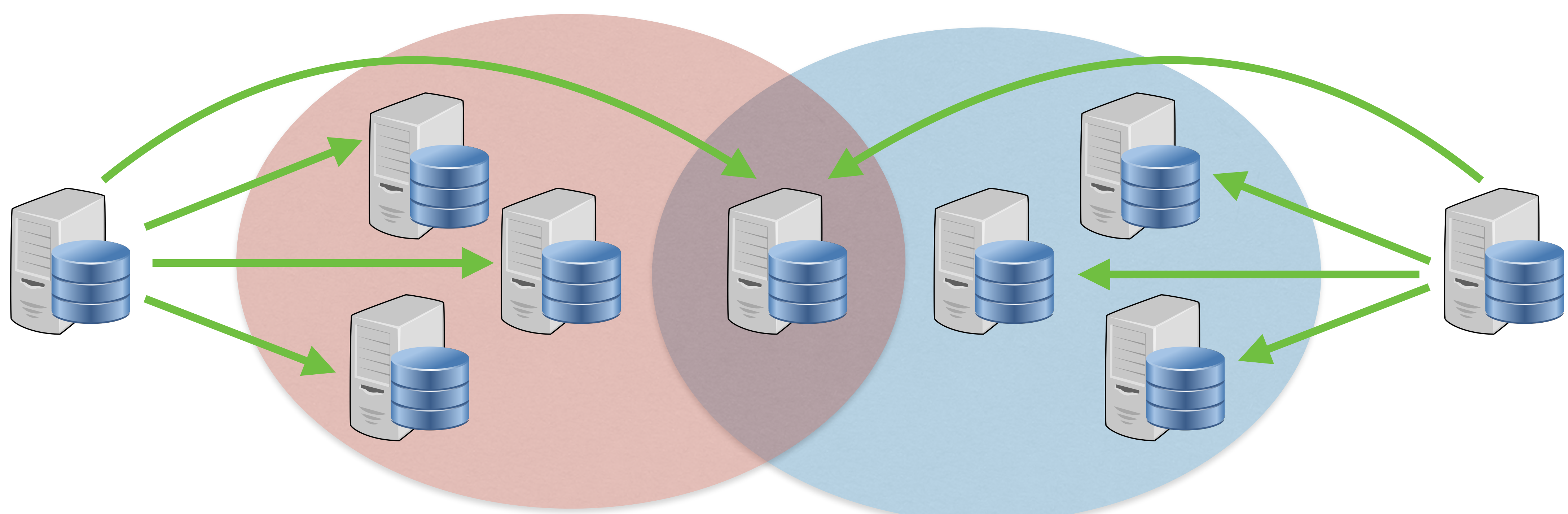
- There is not a coordinator, but multiple acceptors.

- An acceptor may **accept** a single value (e.g., express a single vote)

- How many acceptors do we need?

Majority

- To ensure that a single value is chosen, any majority (50% +1) of acceptors is enough
- The intersection of two majorities is not empty
- An acceptor may **accept** a single value
- A value is **chosen** when a majority of acceptors has accepted it
- If a majority choses a value, no other majority can chose a different value
- If an acceptor crashes, chosen value still available



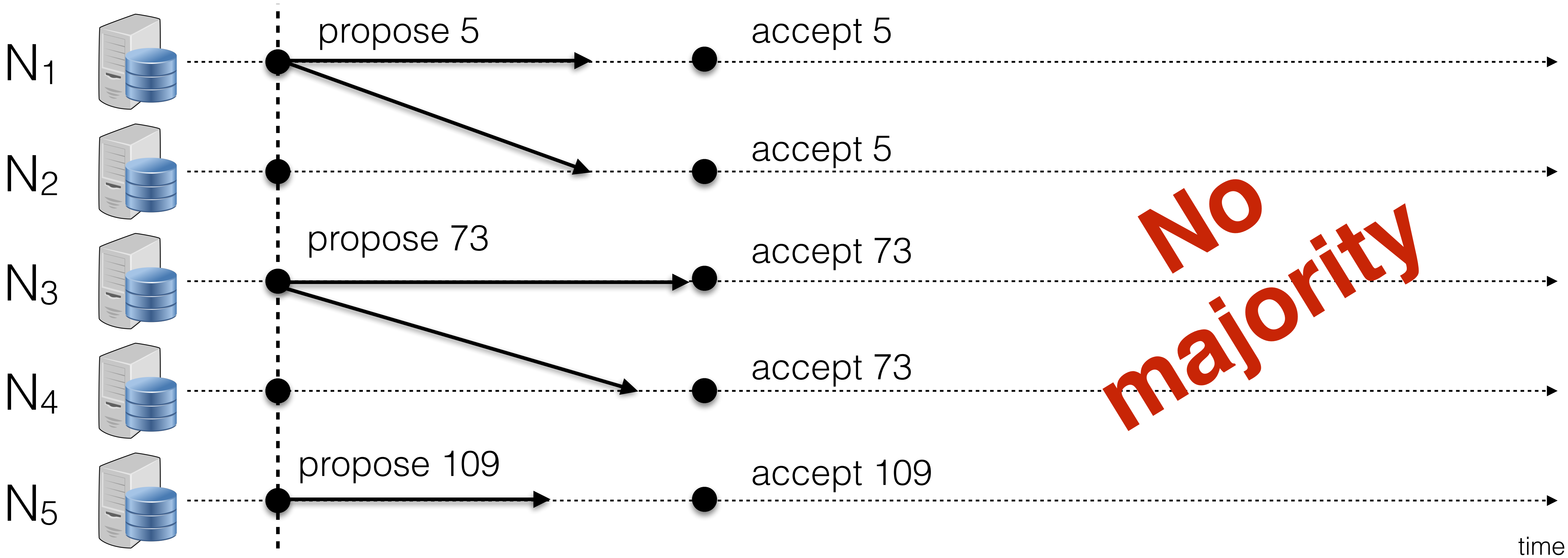
Acceptors

Since there can be a single proposer, the algorithm must guarantee that

P1: An acceptor must accept the first proposed value it receives

Since there can be a single proposer, the algorithm must guarantee that a single value is chosen only when it is accepted by a majority of acceptors

Split Votes



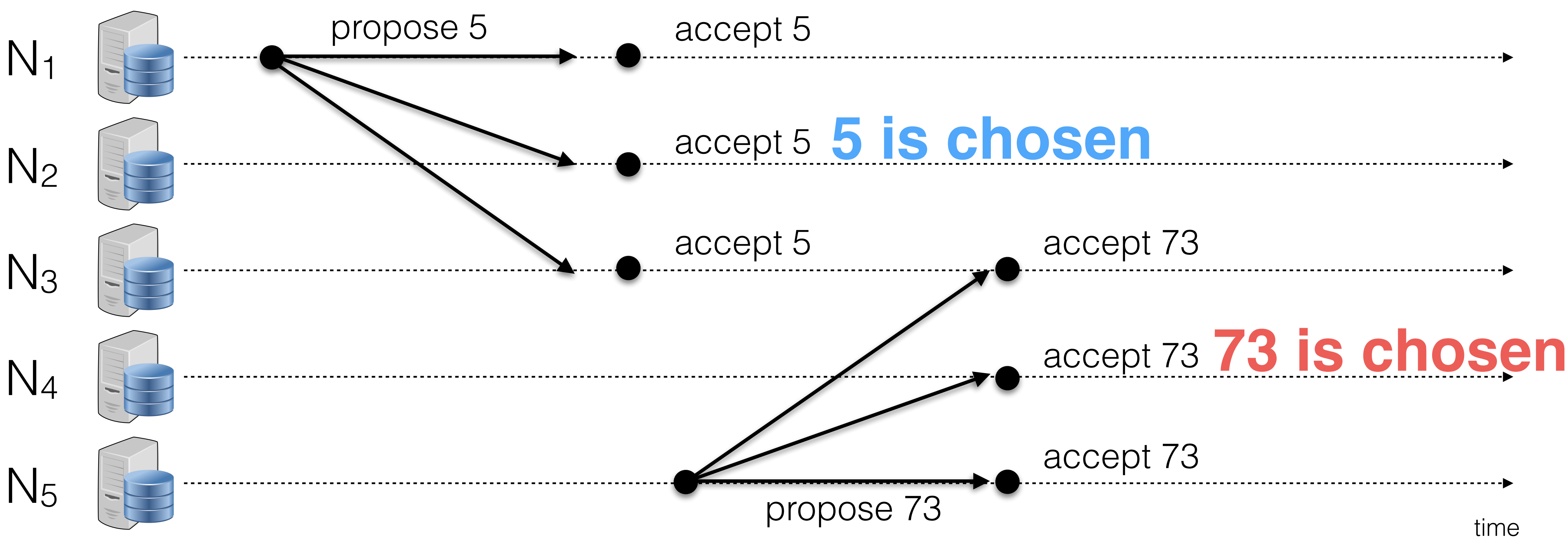
An acceptor must accept the first proposed value it receives

(and can accept more than one proposed value)

An acceptor can **accept** any number of proposed values, but an accepted proposed value may not necessarily be **chosen**.

Conflicting choices

Should acceptors accept every proposed value? No

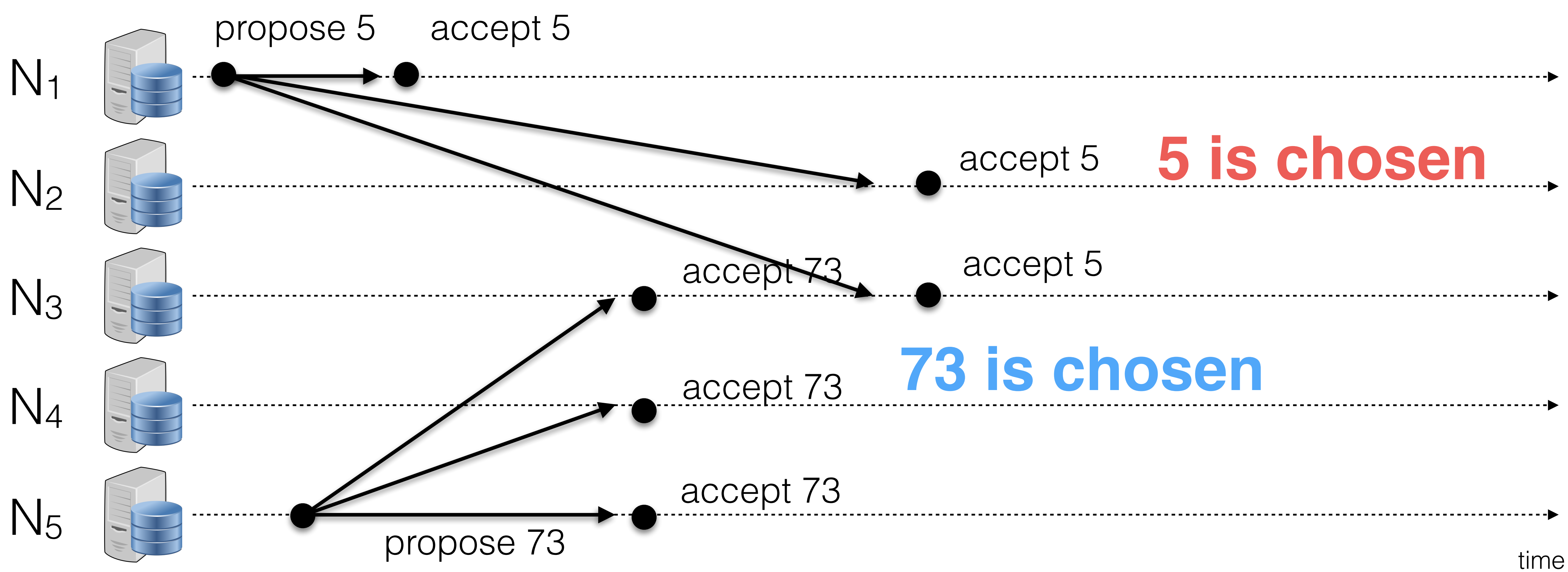


Once a value has been **chosen**, proposers must **propose** that same value

We need a two-phase protocol

Slides based on https://ramcloud.stanford.edu/~ongaro/userstudy/

Conflicting choices



Once a value has been **chosen**, older proposed values must be ignored

We need to order proposed values and reject old ones

Proposals

- A **proposal** *(v, n)* consists in the **proposed value** *v* and a **proposal number** *n*
- Whenever a proposer issues a new proposal, it chooses a strictly-increasing proposal number
- For a given proposer, a new proposal number must be greater than anything it has seen/used before
- Simple implementation

ROUNDNUMBER	NODEID

- Each server stores MAXROUND, i.e., the largest round number it has seen so far
- To generate a new proposal number: increment MAXROUND and concatenate with NODEID
- Proposers must persist MAXROUND on disk: must not reuse proposal numbers after crash/restart

Slides based on https://ramcloud.stanford.edu/~ongaro/userstudy/

Phase 1: PREPARE

- A proposer broadcasts a *prepare proposal (v, **n**)* with its own proposal value *v* and proposal number ***n***
- An acceptor receives a *prepare proposal (v, **n**)*:
    - if it has never received a *prepare proposal*:
        - it *promises* to never accept *proposal numbers* lesser than ***n*** (n_{min} = ***n***)
        - it returns (∅, *0*);
    - otherwise it checks its *promise*:
        - if ***n*** > n_{min} it sends its last *accepted proposal* (v_{last}, n_{last}); note that n_{last} < ***n***.
        - otherwise it does nothing

Phase 2: PROPOSE

- When a proposer receives a majority of responses, it broadcast to them a *propose proposal ($\boldsymbol{v'}$, n)*
    - If all acceptors returned ($\varnothing$, 0), $\boldsymbol{v'}$ is its own proposal value v
    - Otherwise $\boldsymbol{v'}$ is the v_{last} proposal value in the returned proposals with the greatest proposal number n_{last}
- If a majority of acceptors replies with **ACK**, the proposal is chosen
- Note that after a timeout, the proposer gives up and may send a new proposal

PAXOS Algorithm

Proposers	Acceptors

0) $n_p = 0$ highest prepare number seen
$n_a = 0$ highest accepted proposal number
$v_a = \varnothing$ highest accepted proposal value

These value must stably persist on disk

1) Choose new proposal number $\mathbf{n} > n_p$

2) Broadcast PREPARE(v, $\mathbf{n}$) to all nodes → 3) Handle PREPARE(v,$\mathbf{n}$):
   If ($\mathbf{n} > n_p$) then
      $n_p = \mathbf{n}$
      REPLY(v_a, n_a)

4) If REPLY(v_a, n_a) from majority: ←
   $\mathbf{v'} = v_a$ with greatest n_a
   If $\mathbf{v'} = \varnothing$ then
      $\mathbf{v'} = v$

5) Broadcast PROPOSE($\mathbf{v'}$, n) to all nodes → 6) Handle PROPOSE($\mathbf{v'}$, n):
   If ($n \geq n_p$) then
      $n_p = n$
      $(v_a, n_a) = (\mathbf{v'}, n)$
      ACCEPT($\mathbf{v'}$, n)

7) If ACCEPT($\mathbf{v'}$, n) from majority: ←
   Broadcast DECIDED($\mathbf{v'}$) to all nodes

Learning a decision

- After a proposal is chosen, only the proposer knows about it!
- How do the other nodes get informed?
  1. The proposer could inform all nodes directly
     - If the proposer fails, the others are not informed (directly)...
  2. The acceptors could broadcast every time they accept a proposal
     - Much more fault-tolerant
     - Many accepted proposals may not be chosen...
     - Moreover, choosing a value costs $O(n^2)$ messages without failures!
  3. The proposer could inform some nodes directly
     - They will broadcast the decision to other nodes

PAXOS is safe!

If a proposal *(v, n)* is **chosen**, then for every proposed proposal *(u, m)* for which $m > n$ it holds that $v = u$

- Assume that there is a proposed proposal *(u, m)* for which $m > n$ and $u \neq v$. Consider such a proposal with the smallest *m*.

- Consider the non-empty intersection *S* of the two majority sets of nodes that are acceptors for *(v, n)* and *(u, m)* proposals.

- Since proposal *(v, n)* has been accepted and $m > n$, nodes in *S* must have received PREPARE(*u, m*) after (*v, n*) has been accepted, thus returning REPLY(*v, n'*), with $n \leq n' < m$.

- As a consequence, the proposer of *(u, m)* should propose *(v, m)*, hence $u = v$, that is a contradiction.

PAXOS is correct!

If a value is chosen, all acceptors choose this value

- Once a proposal *(v, n)* is chosen, each following proposal *(u, m)* has the same proposal value, i.e., $u = v$, according to the previous theorem.

- Since every following proposal has the same value *v*, every proposal that is accepted after *(v, n)* is chosen will have the same proposal value *v*.

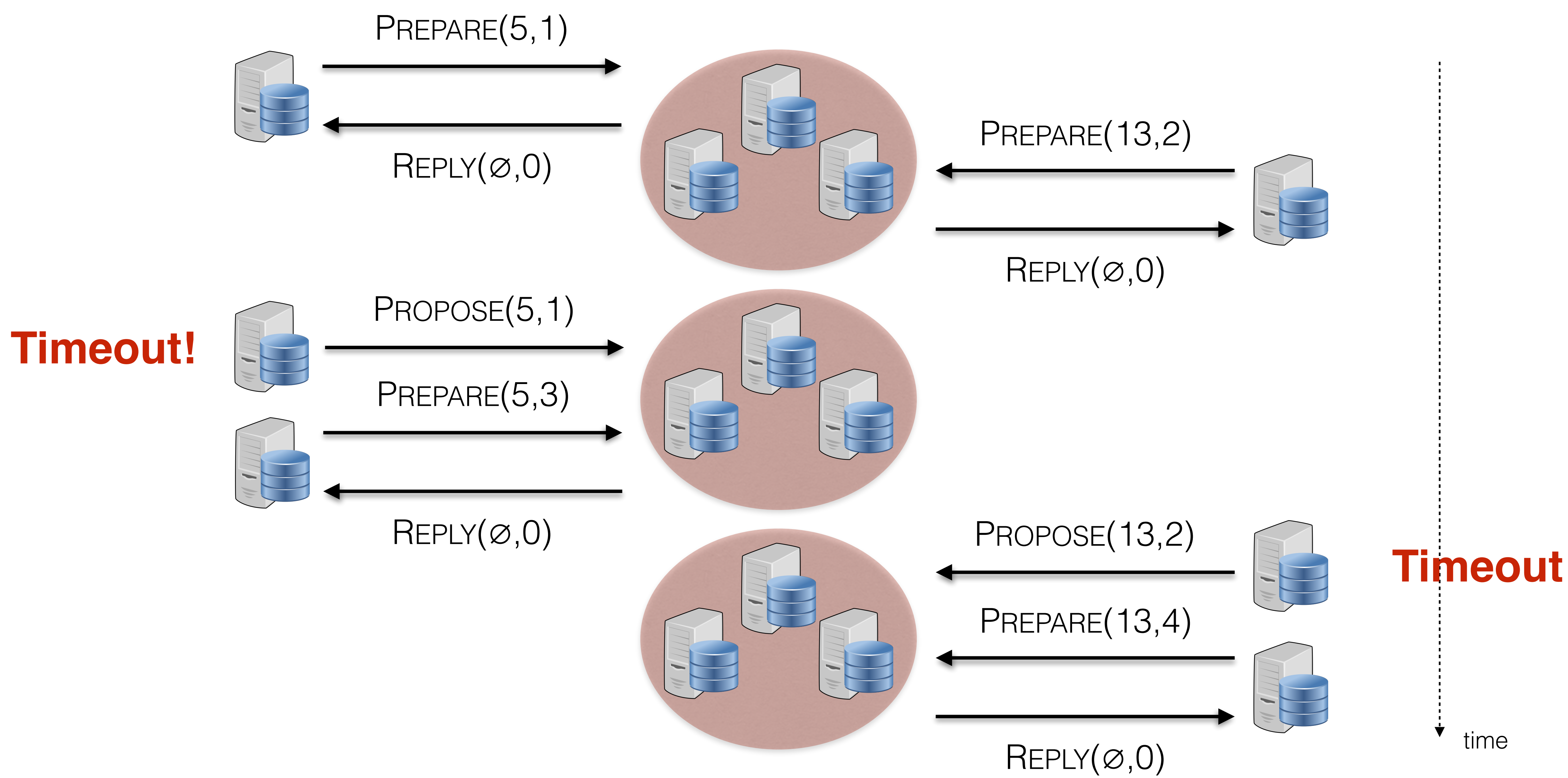
- Since no other value than *v* can be accepted, no other values can be chosen.

PAXOS is great?

- PAXOS is a deterministic algorithm working for asynchronous systems and tolerating ***f < n/2*** failures.
- Many optimizations exists (Multi-PAXOS, Disk-PAXOS, RAFT)
- **FLP Theorem** [1985]. No totally correct consensus algorithm exists (for the given system model).
- PAXOS disproves the FLP Theorem?

No Liveness Guarantees

- PAXOS only guarantees that if a value is chosen, the other nodes can only choose the same value
- PAXOS does not guarantee that a value is chosen!



Correctness vs. Termination

- In asynchronous systems, we cannot guarantee termination and correctness at the same time
- PAXOS is correct, so termination is not guaranteed
- PAXOS cannot guarantee that a consensus is reached in a finite number of steps
- In practice, PAXOS can be optimized to reduce probability of no termination
- For example, the acceptors could send NAK if they do not accept a prepare message or a proposal (this optimization increases the message complexity)
- PAXOS is used in Apache’s Zookeeper and Google’s Chubby