Paxos Made Simple

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The Problem

- Reaching consensus on a proposed value, among a collection of processes

- Safety requirements:
  - Only a value that has been proposed may be chosen
  - Only a single value is chosen, and
  - A process never learns that a value has been chosen unless it actually has been.

Asynchronous, non-Byzantine model

- Processes communicate by sending messages
  - Processes operate at arbitrary speed
  - Processes may fail by stopping, and may restart
  - Information can be remembered by a process that has failed and restarted
- Messages are asynchronous
  - Might take arbitrarily long to be delivered
  - Might be duplicated and lost
  - Messages cannot be corrupted

Roles

- We have three different roles
  - Proposers
  - Acceptors
  - Learners

- A process may play one or more roles

Choosing a value

Two main requirements:

-P1

-P2

With extensions:

-$P2^a$

-$P2^b$

-$P2^c$

-$P1^a$

P1

An acceptor must accept the first proposal it receives

Ensures that paxos works even if there is only one proposal

P2

If a proposal with value *v* is chosen, then every higher-numbered proposal that is chosen has value *v*

Guarantees that only one value will be chosen

P2^{a}

If a proposal with value *v* is chosen, then every higher-numbered proposal accepted by any acceptor has value *v*

Ensures P2 will hold

$P2^b$

If a proposal with value *v* is chosen, then every higher-numbered proposal issued by any proposer has value *v*

Prevents proposers from ruining $P2^a$ by issuing proposals with values different from *v*

$P2^c$

For any *v* and *n*, if a proposal with value *v* and number *n* is issued, then there is a set S consisting of a majority of acceptors such that either:

a) no acceptor in S has accepted any proposal numbered less than *n*, or

b) *v* is the value of the highest-numbered proposal among all proposals numbered less than *n* accepted by the acceptors in S

Issuing proposals (1)

Algorithm for the proposer:

1. A proposer chooses a new proposal number *n* and sends a request to a set of acceptors, asking them to respond with:

  a) A promise to never accept a proposal numbered less than *n*, and

  b) The proposal with the highest number less than *n* that has been accepted, if any

Issuing proposals (2)

2. If the proposer receives the requested responses from a majority of the acceptors, it can issue a proposal with:

a) number *n* and value *v*, where *v* is the value of the highest-numbered proposal among the responses, or

b) any value if the responders reported no proposals

P1ª

An acceptor can accept a proposal numbered *n* if it has not responded to a *prepare* request having a number greater than n.

Responding to a prepare request includes promising not to accept any lower-numbered proposals. P1ª makes sure this promise is kept.

By enforcing P1ª we also implement P1

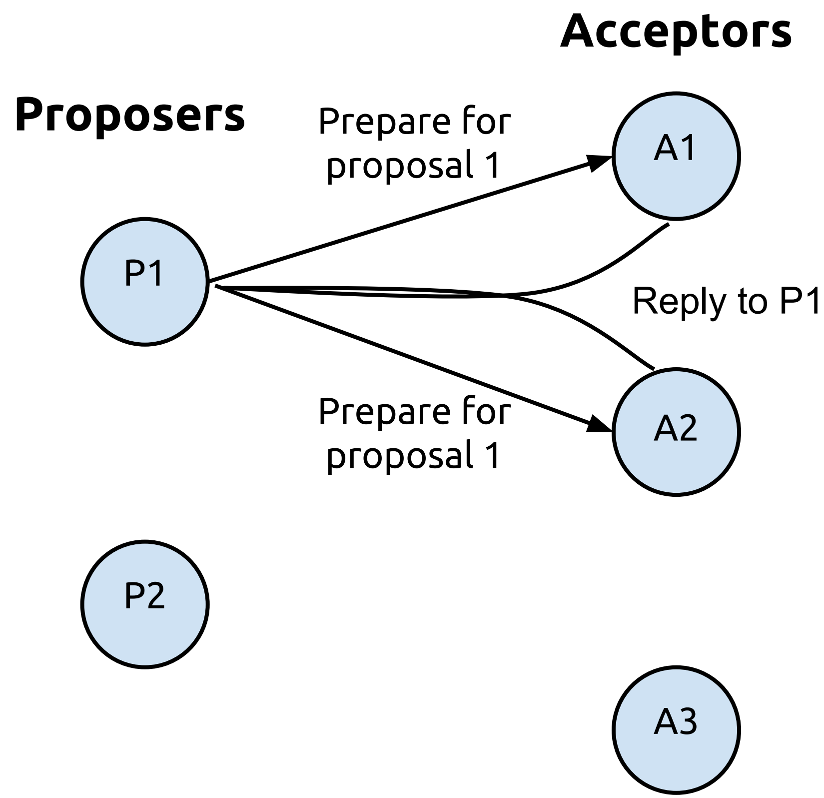
Consensus algorithm: Phase 1

A. A proposer selects a proposal number *n* and sends a prepare request with number *n* to a majority of acceptors
B. If an acceptor receives a prepare request with number *n* greater than that of any prepare request to which it has already responded, then it responds to the request with a promise not to accept any more proposals numbered less than *n* and with the highest-numbered proposal (if any) that it has accepted.

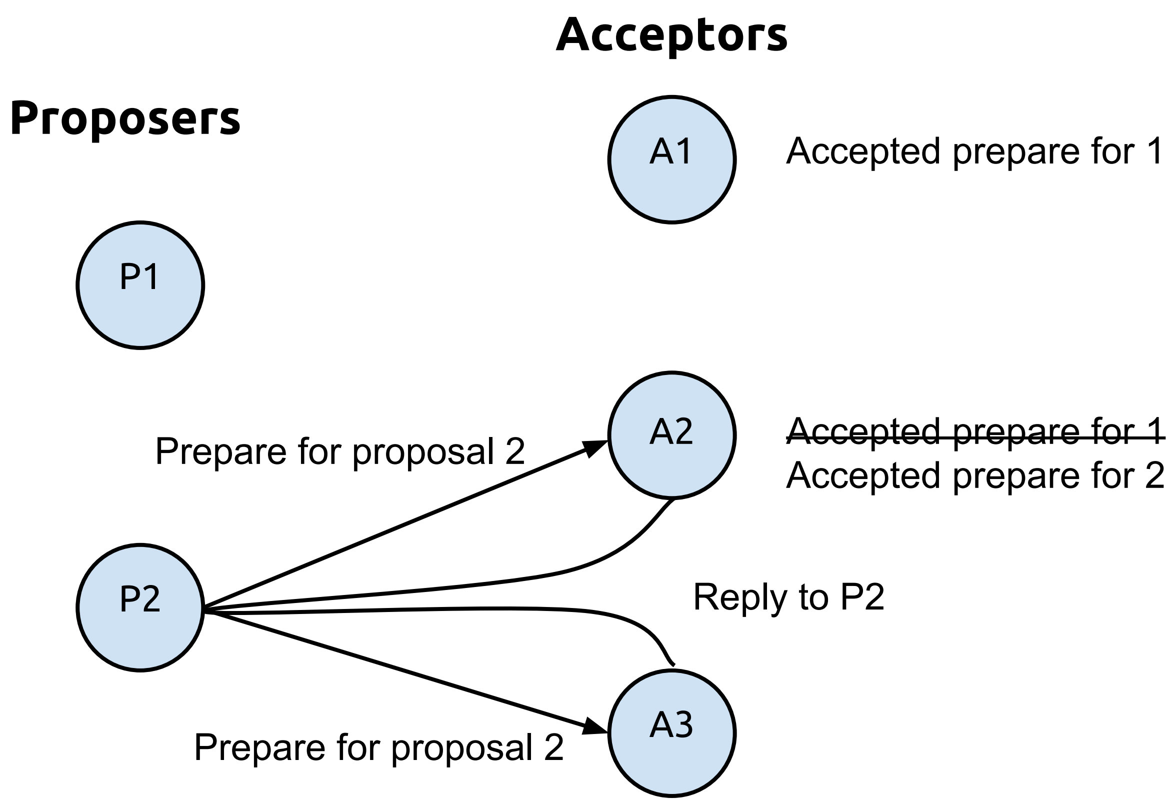
Consensus algorithm: Phase 2

A. If the proposer receives a response to its prepare request (numbered *n*) from a majority of acceptors, then it sends an accept request to each of those acceptors from a proposal numbered *n* with a value *v*, where *v* is the value of the highest-numbered proposal among the responses, or is any value if the responses reported no proposals.
B. If an acceptor receives an accept request for a proposal numbered *n*, it accepts the proposal unless it has already responded to a prepare request having a number greater than *n*.

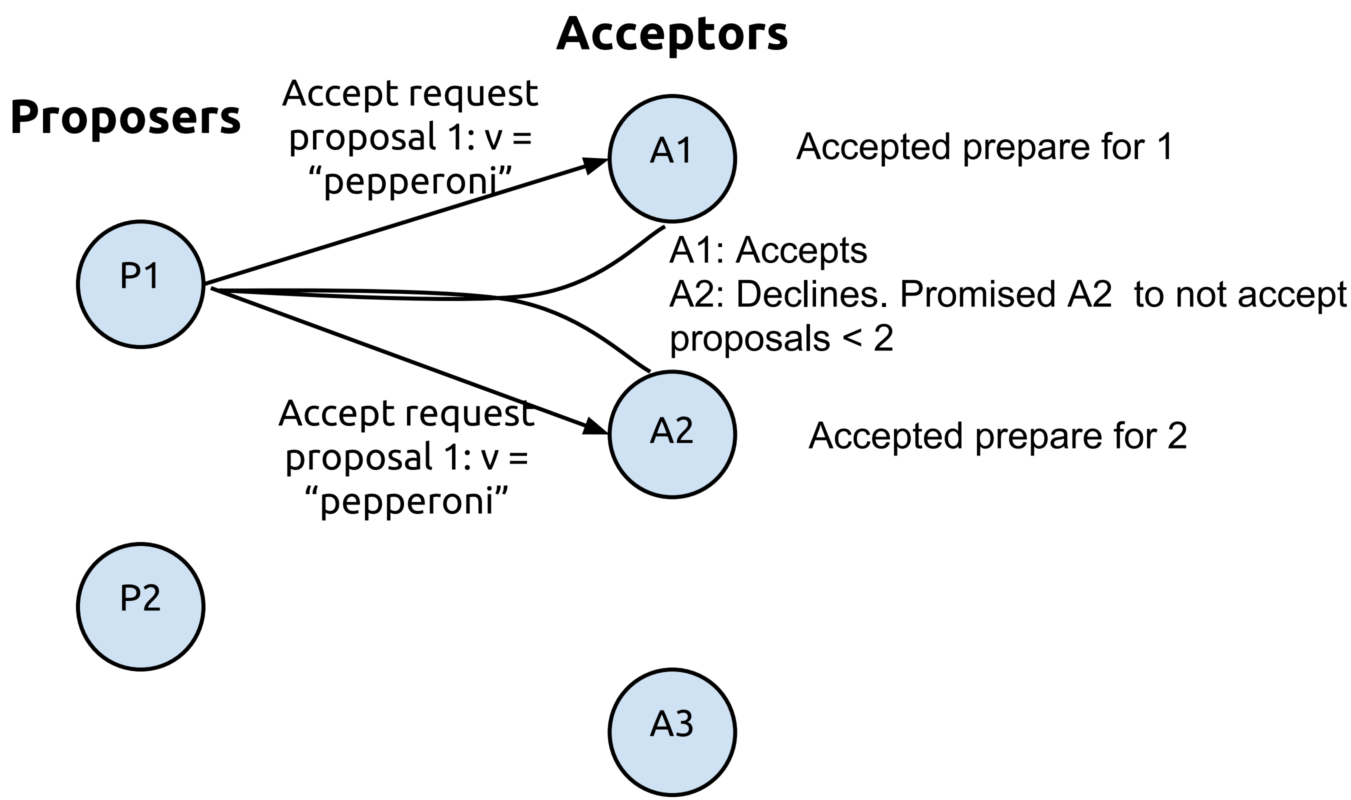
Example: Step 1



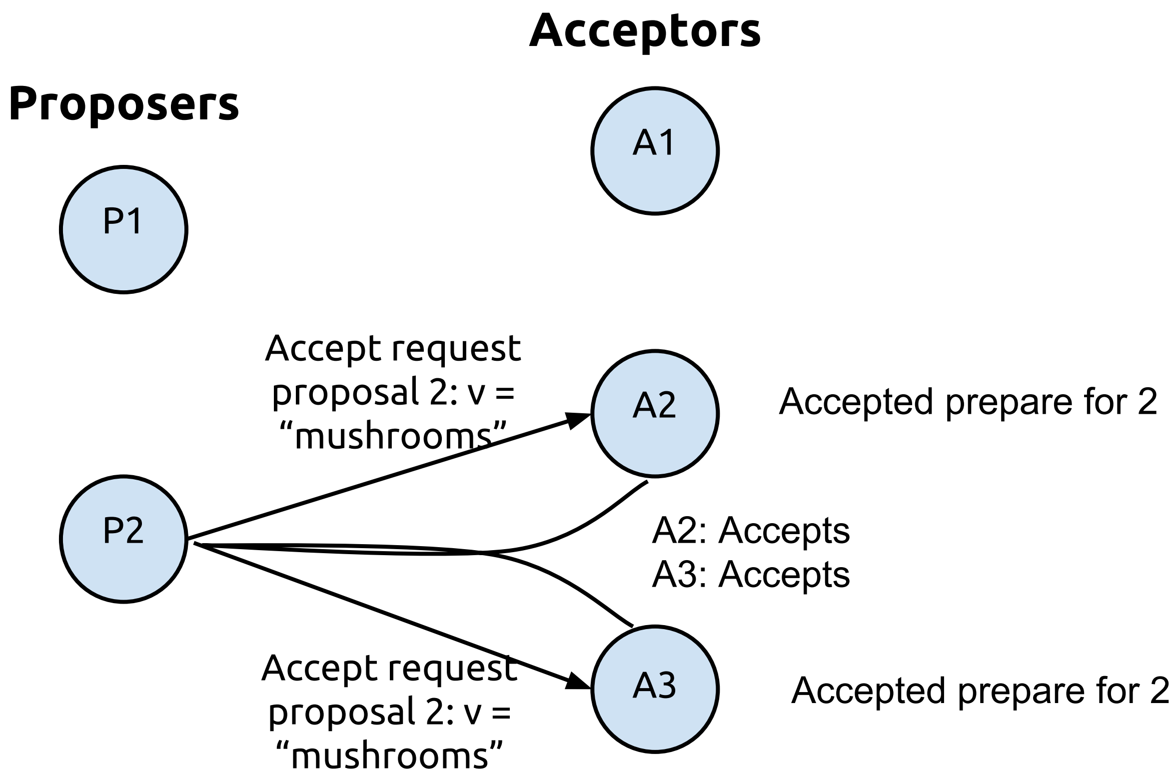
Example: Step 2



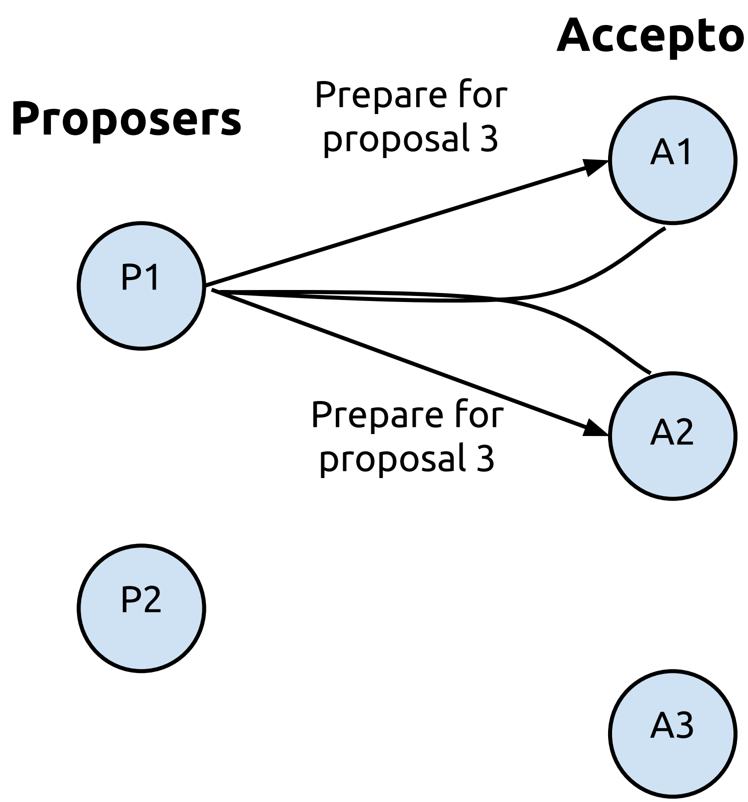
Example: Step 3



Example: Step 4 - The chosen value is “mushrooms”

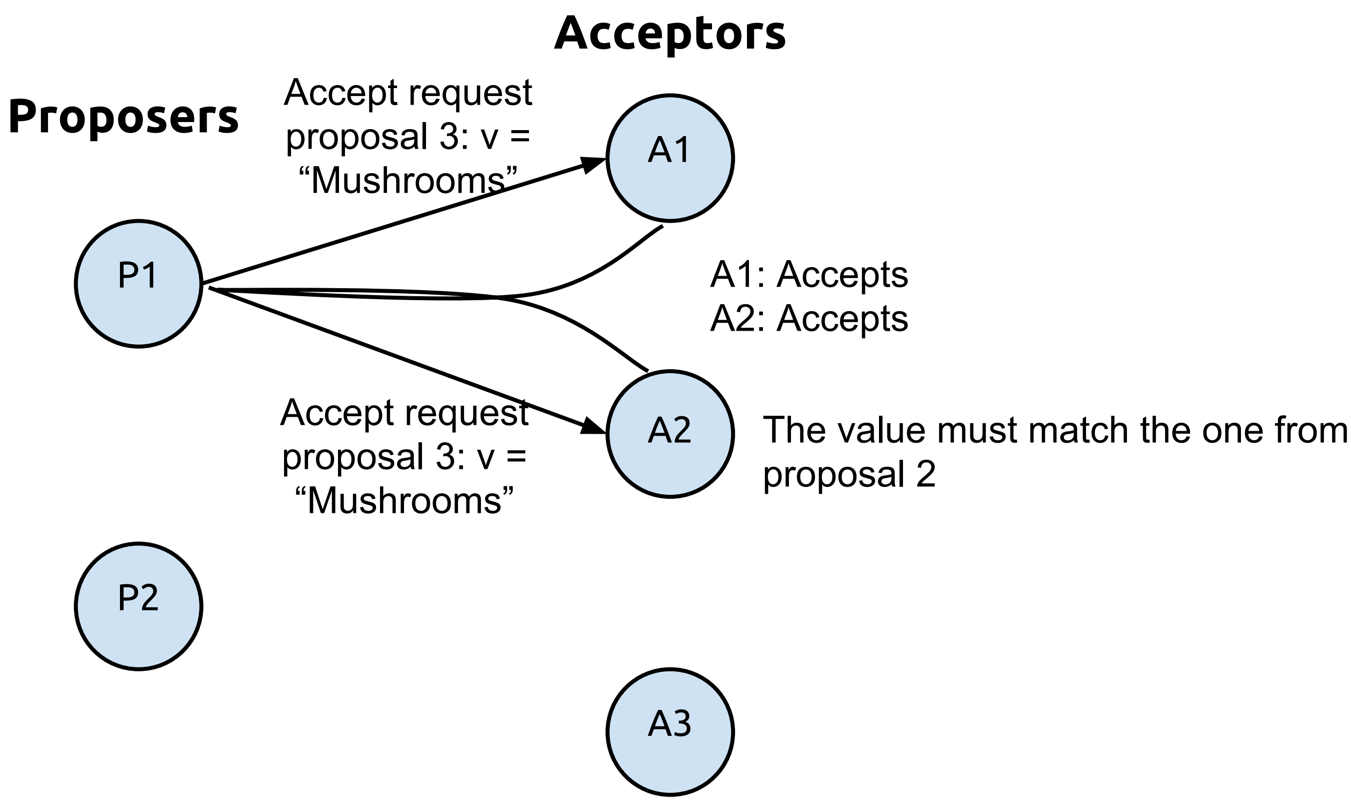


Example: Step 5



A1: Last accepted proposal 1: "Pepperoni"
A2: Last accepted proposal 2: "Mushrooms"

Example: Step 6



Learning a chosen value

- The learner must find out that a value has been accepted by a majority of acceptors
- Each acceptor informs each learner
  - Requires many messages to be sent
- Distinguished learner
  - Single point of failure
- Compromise with set of distinguished learners?
  - Greater reliability at the cost of greater communication complexity
  - All distinguished learners must fail in order to cause a problem

Progress Isn't Guaranteed!

- Easy to construct a scenario in which proposal never is chosen
  - Proposer p_1 sends prepare for 1
  - Proposer p_2 sends prepare for 2
  - p_1 sends accept request for 1; no replies
    - Sends prepare for 3
  - p_2 sends accept request 2; no replies
    - Sends prepare for 4
  - p_1 sends accept request 3; no replies
    - Sends prepare for 5

…

Guaranteeing progress

- Solution: allow only a distinguished proposer to prepare and issue proposals
  - Proposers send their proposals to the distinguished proposer, who organizes them.
- Can we avoid single-point of failure?
  - New distinguished proposer is elected if the current one fails
  - Many processes may believe they are leaders.

    However the safety properties are still preserved in that case
  - Little mention of how to do the election...

Implementing a state machine

- Paxos can be used to run a distributed set of state machines
  - Values are executable commands
  - One instance of paxos per command
  - Each process plays all roles
  - Elect one leader to be distinguished proposer and learner
  - An infinite (!) number of instances are executed simultaneously.

Summary

- Paxos is an algorithm for reaching consensus among processes
  - Simple
  - Robust
  - More or less optimal network use
  - Can be used to create distributed state machines