Paxos

Arvind Krishnamurthy
University of Washington

The Part-Time Parliament

- Parliament determines laws by passing sequence of numbered decrees
- Legislators can leave and enter the chamber at arbitrary times
- No centralized record of approved decrees–instead, each legislator carries a ledger

Government 101

- No two ledgers contain contradictory information
- If a majority of legislators were in the Chamber and no one entered or left the Chamber for a sufficiently long time, then
  - any decree proposed by a legislator would eventually be passed
  - any passed decree would appear on the ledger of every legislator

Back to the future

- A set of processes that can propose values
- Processes can crash and recover
- Processes have access to stable storage
- Asynchronous communication via messages
- Messages can be lost and duplicated, but not corrupted

The Players

- Proposers
- Acceptors
- Learners

Overview

- Paxos is a protocol that enables replicated state machines
  - Consensus on command log (comprising of instances)

- Workflow terminology of a single Paxos instance:
  - Propose —> Accept —> Chosen —> Learnt
  - But have to "prepare" before issuing a proposal

The Game: Consensus

SAFETY

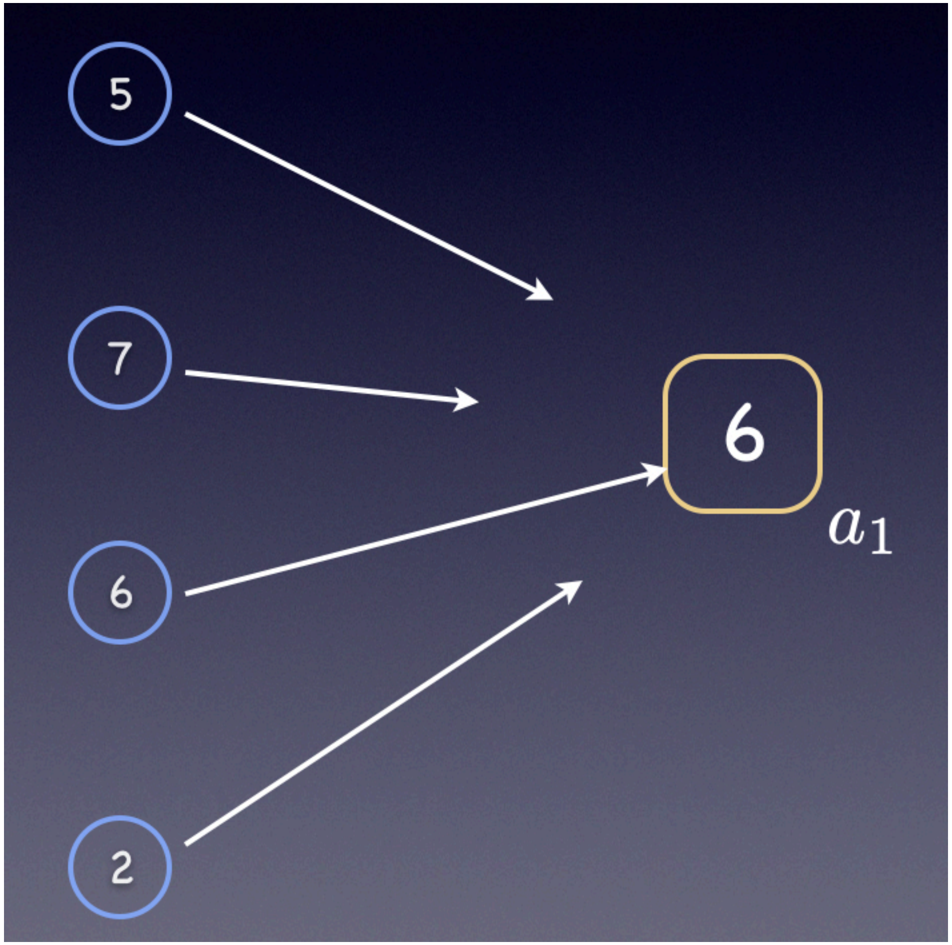
- Only a value that has been proposed can be chosen
- Only a single value is chosen
- A process never learns that a value has been chosen unless it has been

LIVENESS

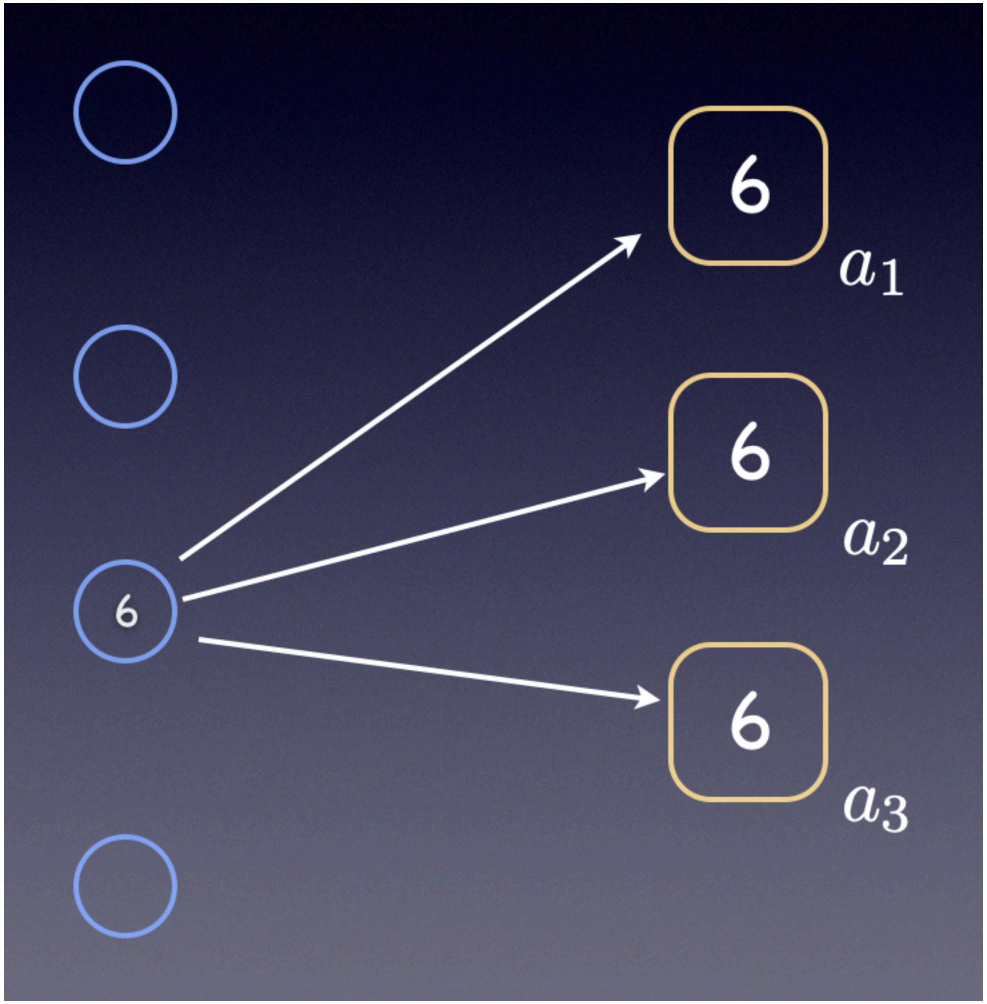
- Some proposed value is eventually chosen
- If a value is chosen, a process eventually learns it

Choosing a value

Use a single acceptor



What if the acceptor fails?



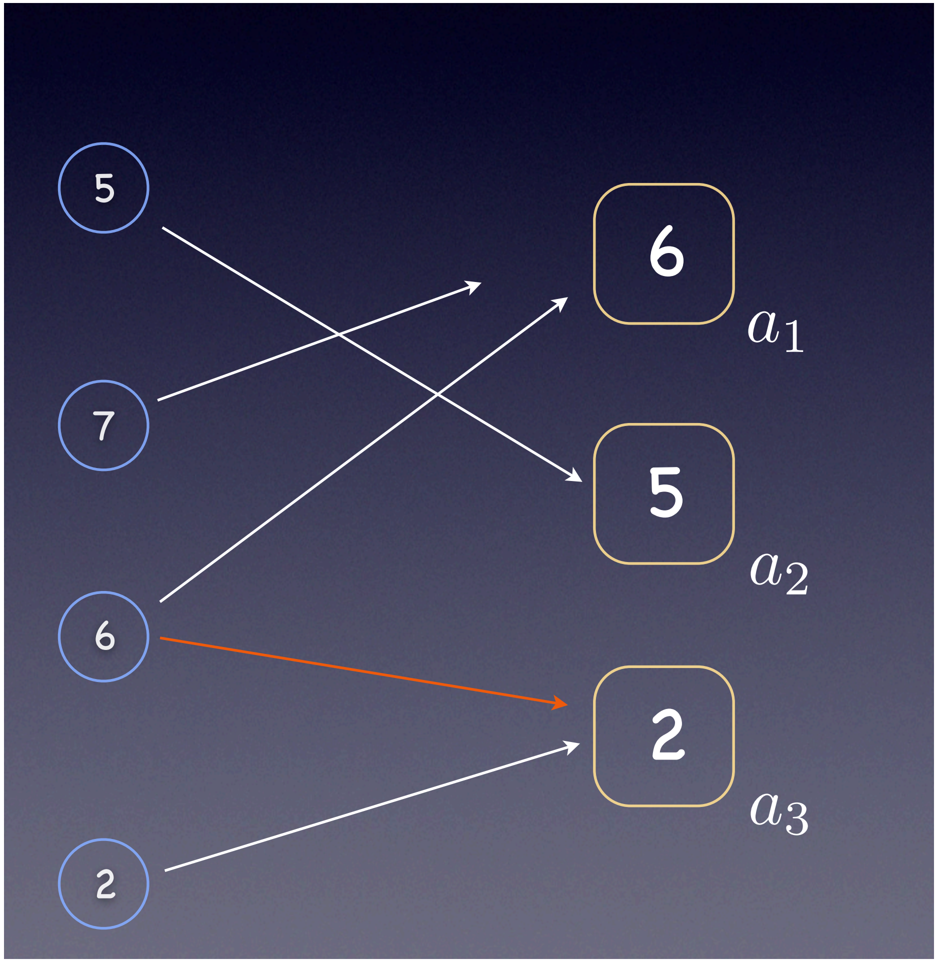
- Choose only when a "large enough" set of acceptors <u>accepts</u>
- Using a majority set guarantees that at most one value is chosen

Accepting a value

- Suppose only one value is proposed by a single proposer.
- That value should be chosen!
- First requirement:

  P1: An acceptor must accept the first proposal that it receives
- ...but what if we have multiple proposers, each proposing a different value?

P1 + multiple proposers



No value is chosen!

Handling multiple proposals

- Acceptors must accept more than one proposal
- To keep track of different proposals, assign a natural number to each proposal
  - A proposal is then a pair (psn, value)
  - Different proposals have different psn
  - A proposal is chosen when it has been accepted by a majority of acceptors
  - A value is chosen when a single proposal with that value has been chosen

Choosing a unique value

P2. If a proposal with value v is chosen, then every higher-numbered proposal that is chosen has value v

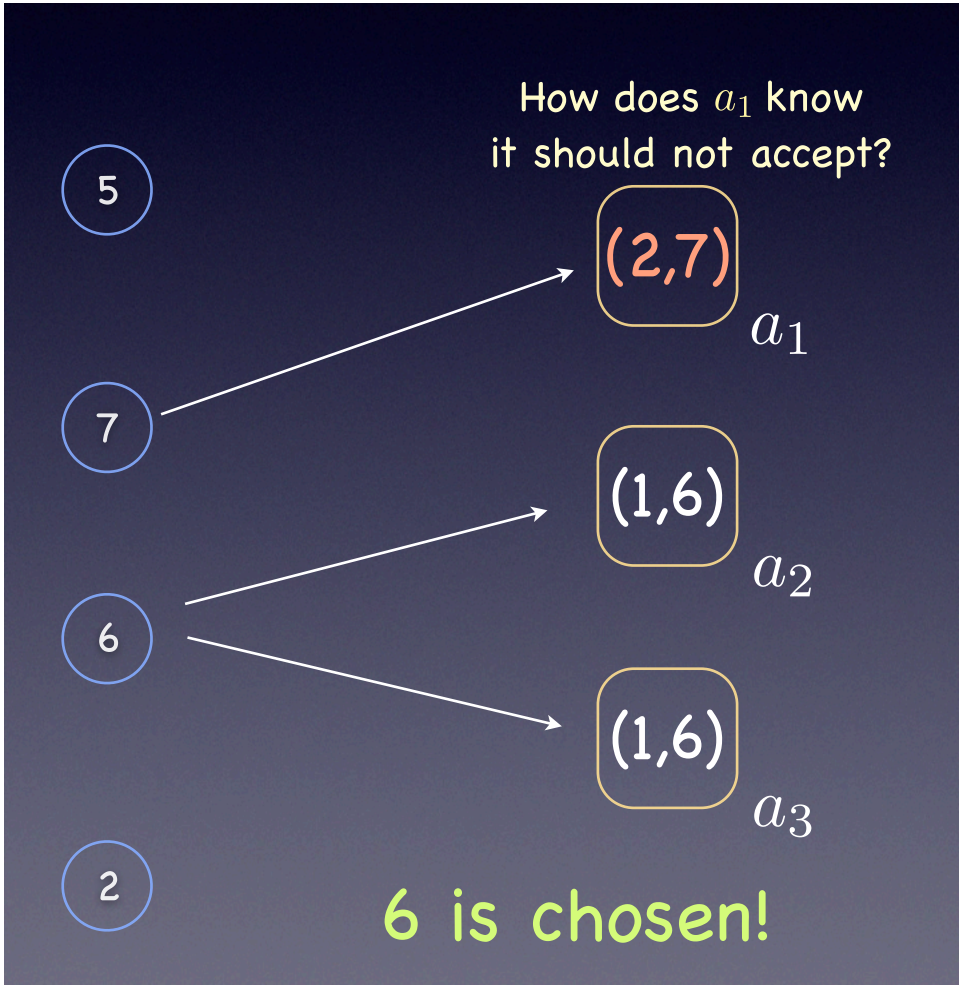
It's up to the Acceptors!

P2. If a proposal with value v is chosen, then every higher-numbered proposal that is chosen has value v

We strengthen it to:

P2a. If a proposal with value v is chosen, then every higher-numbered proposal accepted by any acceptor has value v

What about P1?



- Do we still need P1?

  YES, to ensure that some proposal is accepted

- How well do P1 and P2a play together?

  Asynchrony is a problem...

It's up to the Proposers!

Recall P2a:

P2a. If a proposal with value v is chosen, then every higher-numbered proposal accepted by any acceptor has value v

We strengthen it to:

P2b. If a proposal with value v is chosen, then every higher-numbered proposal issued by any proposer has value v

What to propose

P2b: If a proposal with value v is chosen, then every higher-numbered proposal issued by any proposer has value v

Suppose p wants to issue a proposal numbered n.

- If p can be certain that no proposal numbered $n' < n$ has been chosen then p can propose any value!
  - If a proposal numbered $n' < n$ has been chosen, then it has been accepted by a majority set S
  - Any majority set S' must intersect S
  - If p can find one S' in which no acceptors has accepted a proposal numbered $n' < n$, then no such proposal can have yet been chosen!
  - If no such S', a proposal numbered $n' < n$ may have been chosen…
  - *Then what?*

What to propose

P2b: If a proposal with value v is chosen, then every higher-numbered proposal issued by any proposer has value v

Suppose p wants to issue a proposal numbered n.

- If p can be certain that no proposal numbered n' < n has been chosen then p can propose any value!
- If not, p should propose the chosen value. But how?
  - Sometimes it cannot tell whether a proposal/value has been chosen
  - p should propose the highest numbered proposal among all proposals, numbered less than n, accepted by some majority set S

Example

It's up to an invariant!

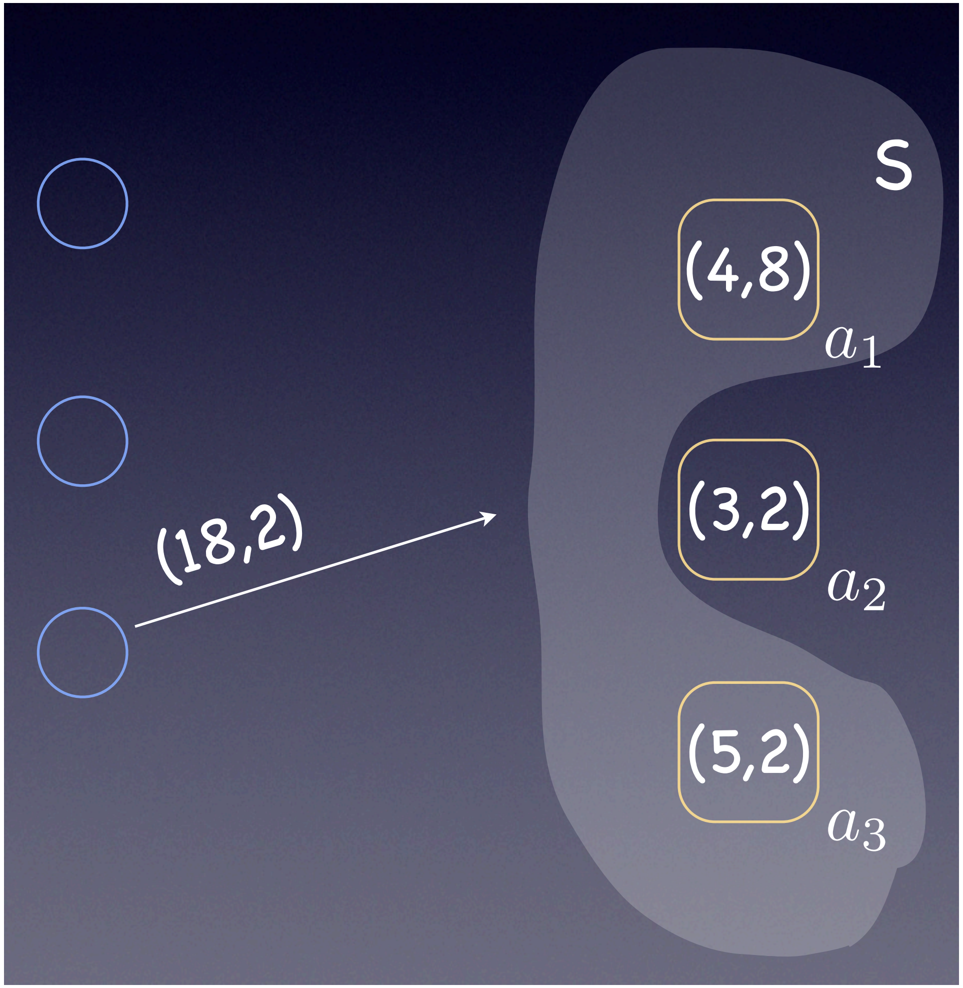
P2b: If a proposal with value v is chosen, then every higher-numbered proposal issued by any proposer has value v

Achieved by enforcing the following invariant

P2c: 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:

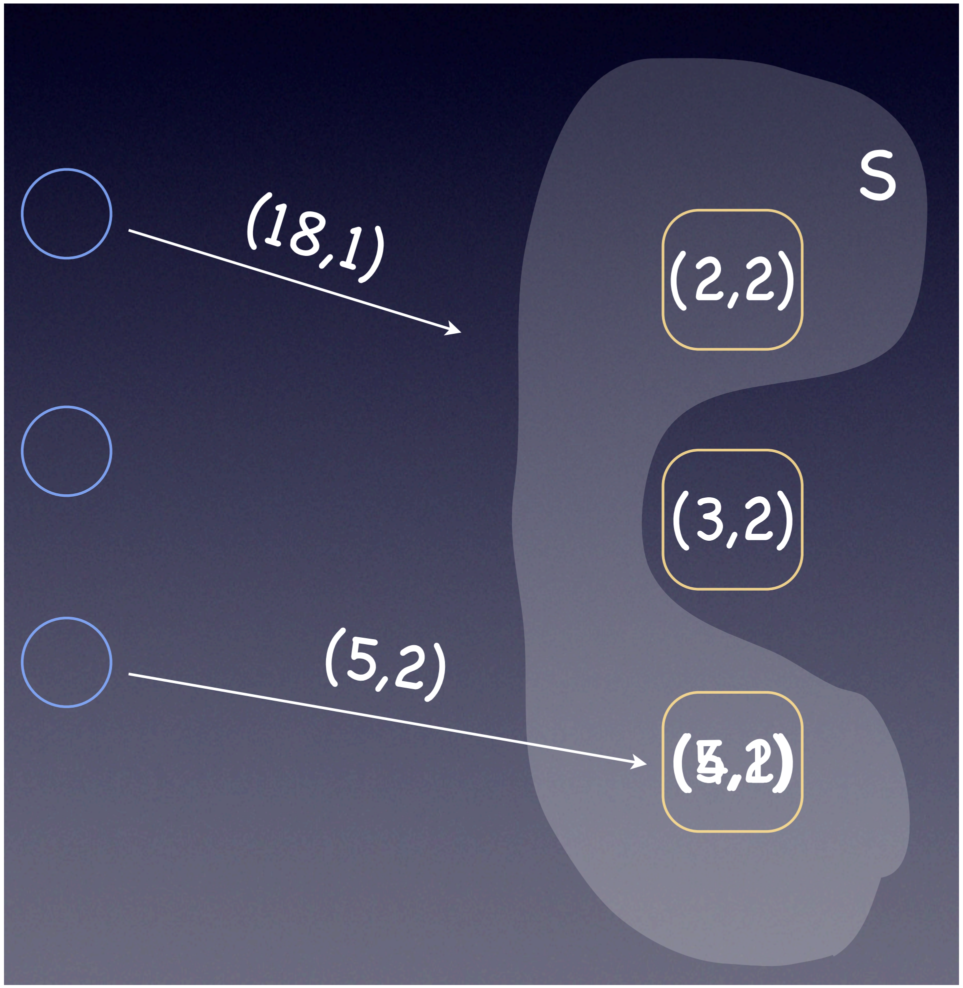
- no acceptor in S has accepted any proposal numbered less than n, or
- v is the value of the highest-numbered proposal among all proposals numbered less than n accepted by the acceptors in S

P2c in action



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

P2c in action



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

The invariant is violated

Future telling?

- p must learn the highest-numbered proposal with number less than n, if any, that has been or will be accepted by each acceptor in some majority of acceptors.
- Avoid predicting the future by extracting a promise from a majority of acceptors not to subsequently accept any proposals numbered less than n

The proposer's protocol (I)

- A proposer chooses a new proposal number n and sends a request to each member of some set of acceptors, asking it to respond with:

    a. A promise never again to accept a proposal numbered less than n, and
    b. The accepted proposal with highest number less than n if any.

...call this a prepare request with number n

The proposer's protocol (II)

- If the proposer receives a response from a majority of acceptors, then it can issue a proposal with number n and value v, where v is
  - the value of the highest-numbered proposal among the responses, or
  - is any value selected by the proposer if responders returned no proposals

A proposer issues a proposal by sending, to some set of acceptors, a request that the proposal be accepted.

...call this an accept request.

The acceptor's protocol

- An acceptor receives prepare and accept requests from proposers.
  - It can always respond to a prepare request
  - It can respond to an accept request, accepting the proposal, iff it has not promised not to, e.g.

P1a: An acceptor can accept a proposal numbered n iff it has not responded to a prepare request having number greater than n

...which subsumes P1.

Small optimizations

- If an acceptor receives a prepare request r numbered n when it has already responded to a prepare request for n' > n, then the acceptor can simply ignore r.

...so an acceptor needs only remember the highest numbered proposal it has accepted and the number of the highest-numbered prepare request to which it has responded.

Learning chosen values (I)

Once a value is chosen, learners should find out about it. Many strategies are possible:

i. Each acceptor informs each learner whenever it accepts a proposal.
ii. Acceptors inform a distinguished learner, who informs the other learners
iii. Something in between (a set of not-quite-as-distinguished learners)

Questions

- What are the liveness properties of Paxos? Why is Paxos not considered live?

Question

- What do you do when nodes fail? How is Paxos robust to failures?

Question

- Are there any advantages/disadvantages to having a designated leader?