CSE 486/586 Distributed Systems
Paxos

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Paxos

- A consensus algorithm
  - Known as one of the most efficient & elegant consensus algorithms
  - If you stay close to the field of distributed systems, you'll hear about this algorithm over and over.
- What? Consensus? What about FLP (the impossibility of consensus)?
  - Obviously, it doesn't solve FLP.
  - It relies on failure detectors to get around it.
- This lecture
  - Brief history (with a lot of quotes)
  - The protocol itself

Brief History

- Developed by Leslie Lamport (of the Lamport clock)
- *"A fault-tolerant file system called Echo was built at SRC in the late 80s. The builders claimed that it would maintain consistency despite any number of non-Byzantine faults, and would make progress if any majority of the processors were working."*
- *"I decided that what they were trying to do was impossible, and set out to prove it. Instead, I discovered the Paxos algorithm."*
- *"I decided to cast the algorithm in terms of a parliament on an ancient Greek island (Paxos)."*

Brief History

- The paper abstract:
  - *"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."*
- *"I gave a few lectures in the persona of an Indiana-Jones-style archaeologist."*
- *"My attempt at inserting some humor into the subject was a dismal failure. People who attended my lecture remembered Indiana Jones, but not the algorithm."*

Brief History

- People thought that Paxos was a joke.
- Lamport published it 8 years after it was written in 1990.
  - Title: *The Part-Time Parliament* [1]
- People did not understand the paper.
- Lamport gave up and wrote another paper that explains Paxos in simple English.
  - Title: *Paxos Made Simple* [2]
  - Abstract: “The Paxos algorithm, when presented in plain English, is very simple.”
- It’s still not the easiest algorithm to understand.
- People have written papers and lecture notes to explain *Paxos Made Simple*. (e.g., *Paxos Made Moderately Complex* [4], *Paxos Made Practical* [5], *etc.*)

Review: Consensus

- How do processes agree on something?
  - Q: should Ethan give an A to everyone taking CSE 486/586?
  - Input: everyone says either yes or no.
  - Output: an agreement of yes or no.
  - FLP: this is impossible with even one faulty process and arbitrary delays.
- Many distributed systems problems can be cast as a consensus problem
  - Mutual exclusion, leader election, total ordering, *etc.*
- Paxos
  - How do multiple processes agree on a value?
  - Under failures, network partitions, message delays, *etc.*

Review: Consensus

- People care about this!
- Real systems implement Paxos
  - Google Chubby
  - MS Bing cluster management
- Amazon CTO Werner Vogels (in his blog post "Job Openings in My Group", February 2, 2005)
  - "*What kind of things am I looking for in you?*"
  - "*You know your distributed systems theory: You know about logical time, snapshots, stability, message ordering, but also ACID and multi-level transactions. You have heard about the FLP impossibility argument. You know why failure detectors can solve it (but you do not have to remember which one diamond-w was). You have at least once tried to understand Paxos by reading the original paper.*"

Paxos Assumptions & Goals

Assumptions:

- The network is asynchronous, with message delays.
- Messages can be lost or duplicated, but not corrupted.
- Processes can crash.
- Processes are non-Byzantine (only crash-stop).
- Processes have permanent storage.
- Processes can propose values.

Goal:

- Every process agrees on a value from the set of proposed values.

Desired Properties

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

Roles of a Process

Three roles:

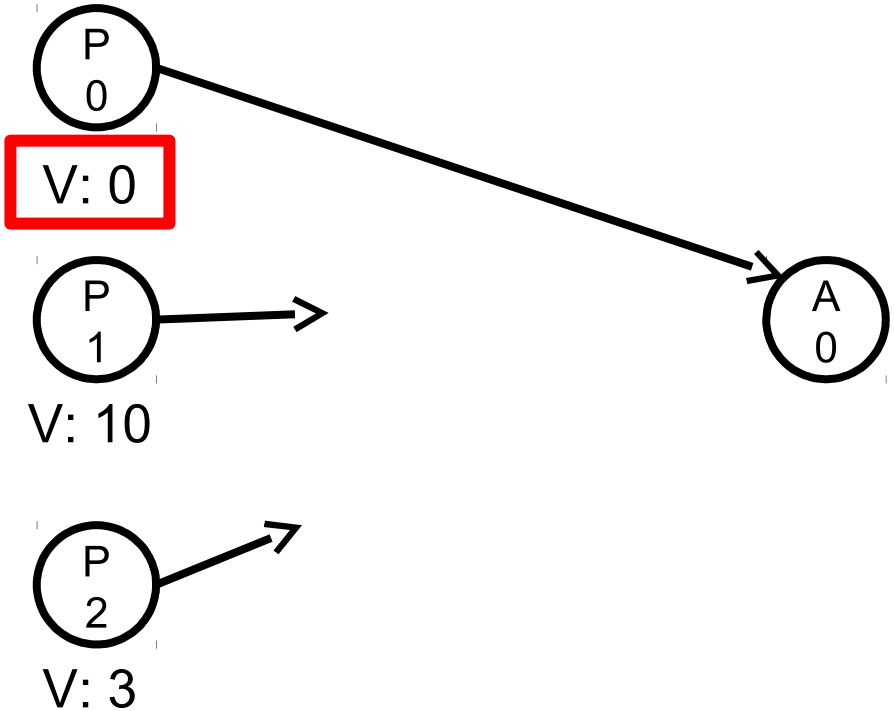
- Proposers: processes that propose values
- Acceptors: processes that accept (or *consider*) values
  - "Considering a value": the value is a candidate for consensus.
  - Majority acceptance → choosing the value
- Learners: processes that learn the outcome

Roles of a Process

- In reality, a process can inhabit any combination of roles.
- Important requirements
  - The protocol should work under process failures and with delayed and lost messages.
  - Consensus is reached via a majority (> ½).
- Example: a replicated state machine
  - All replicas agree on the order of execution for concurrent transactions
  - All replicas assume all roles, *i.e.*, they can each propose, accept, and learn.

First Attempt

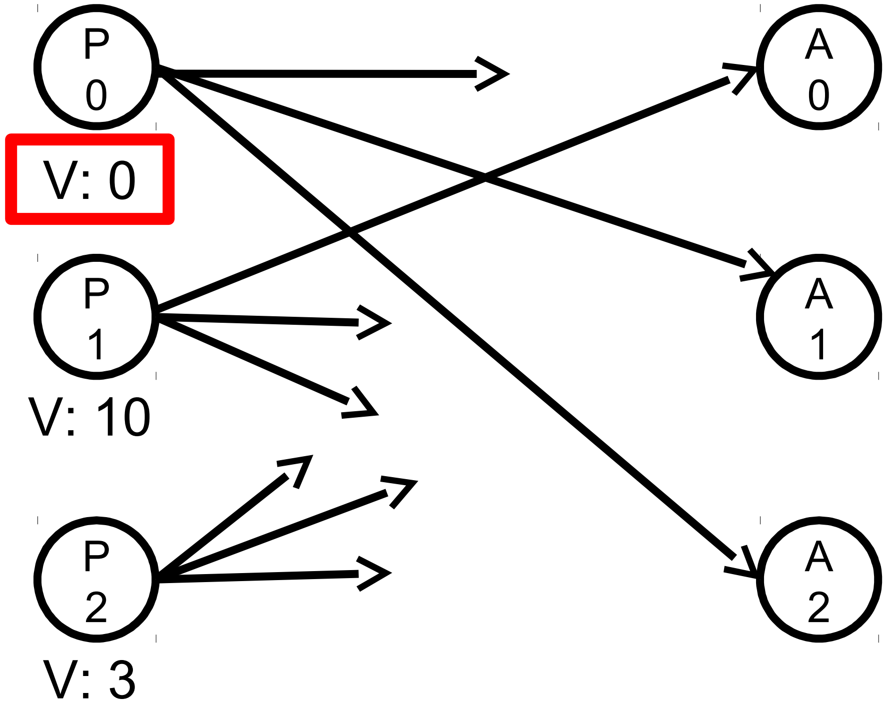
- Let's have just one acceptor, choose the first proposal that arrives, and tell the proposers about the outcome.



- What's wrong?
  - Single point of failure!

Second Attempt

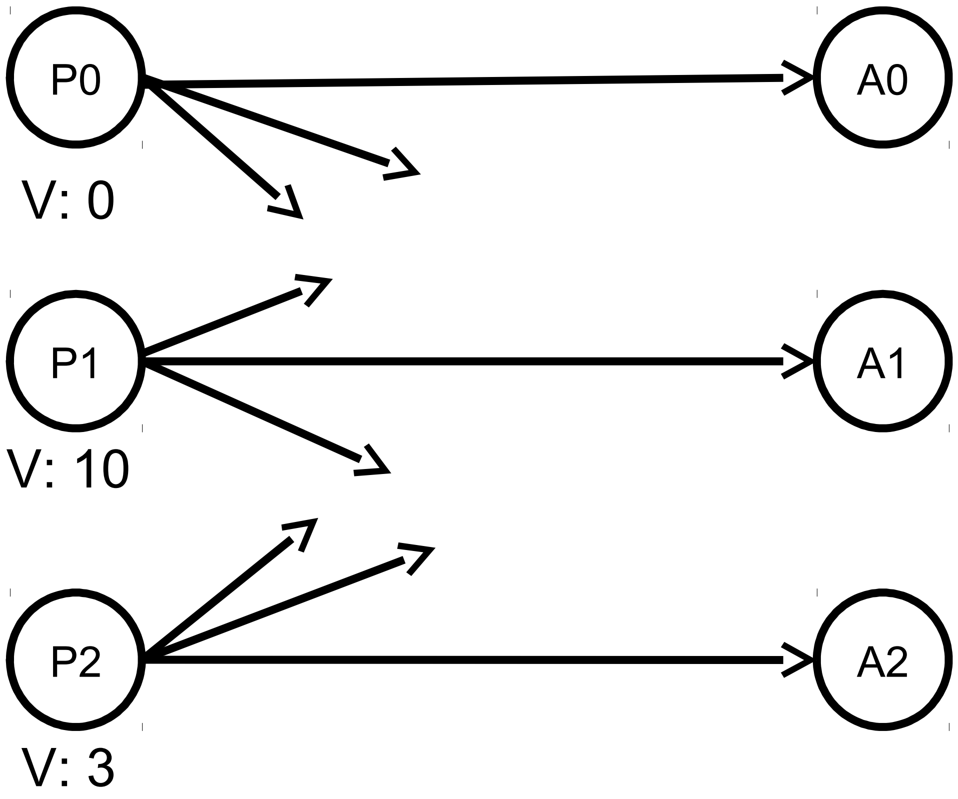
- Let's have multiple acceptors; each accepts the first one; then all choose the majority and tell the proposers about the outcome.



- What's wrong? (next slide)

Second Attempt

- One example, but many other possibilities



Paxos

- Let's have multiple acceptors each accept (*i.e.*, consider) multiple proposals.
  - An acceptor accepting a proposal doesn't mean it will be chosen. A majority must accept it to be chosen.
  - Make sure one of the multiple accepted proposals will have a vote from a majority (will get back to this later)
- Paxos: how do we select one value when there are multiple acceptors accepting multiple proposals?

Paxos Protocol Overview

- A proposal must have an ID (since there's multiple).
  - (proposal #, value) == (N, V)
  - The proposal # strictly increasing and globally unique across all proposers, *i.e.*, there should be no tie.
  - E.g., (per-process number).(process id) == 3.1, 3.2, 4.1, *etc.*
- Three phases
  - Prepare phase: a proposer learns previously-accepted proposals from the acceptors.
  - Propose phase: a proposer sends out a proposal.
  - Learn phase: learners learn the outcome.

Paxos Protocol Overview

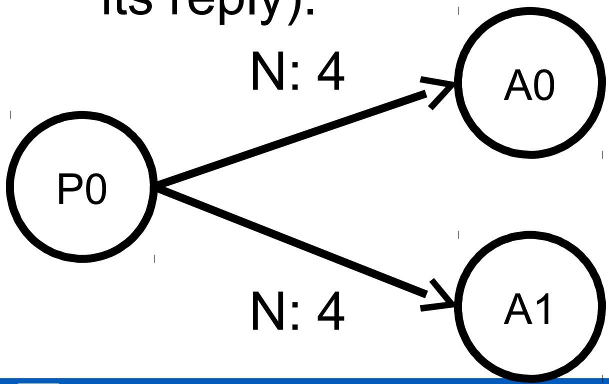
- Rough description of proposers
  - Before a proposer proposes a value, it will ask the acceptors if there is already any proposed value.
  - If there is, the proposer will propose the same value, rather than proposing another value.
  - Even with multiple concurrent proposals, each proposed value will be the same.
  - The behavior is altruistic: the goal is to reach consensus, rather than making sure that “my value” is chosen.

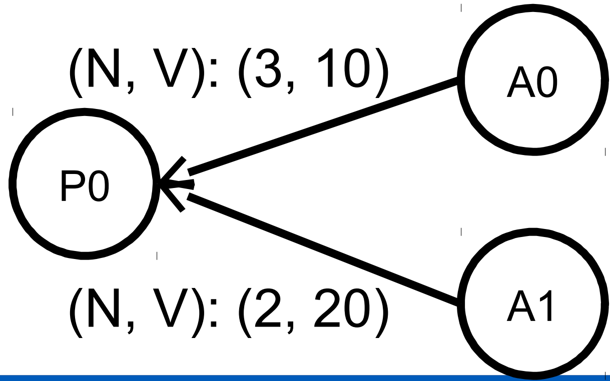
Paxos Protocol Overview

- Rough description of acceptors
  - The goal for acceptors is to accept the highest-numbered proposal from any proposer.
  - An acceptor tries to accept a value V with the highest proposal number N.
- Rough description of learners
  - All learners are passive and wait for the outcome.

Paxos Phase 1

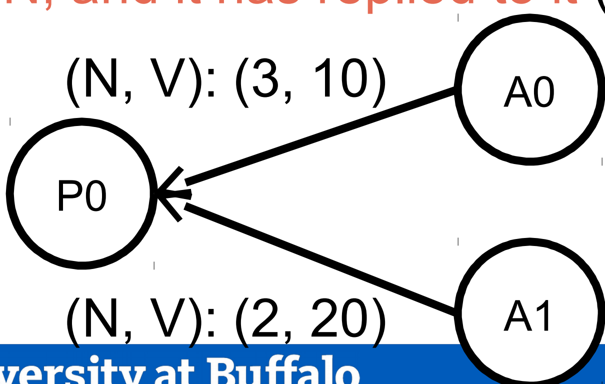
- A proposer chooses a proposal number N and sends a prepare request to acceptors.
  - "Hey, have you accepted any proposal yet?"
  - Note: Acceptors keep a history of proposals.
- If an acceptor has accepted anything, it replies with the accepted proposal and its value for the highest proposal number less than N.
- In addition, the acceptor will no longer accept any proposal numbered less than N (to make sure that it wouldn't alter the result of its reply).

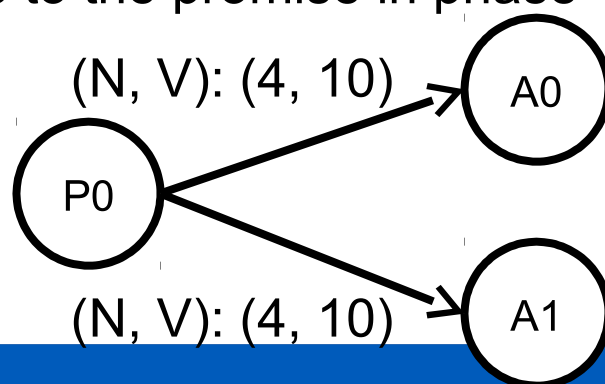




Paxos Phase 2

- If a proposer receives a reply from a majority of acceptors, it sends an accept request for proposal (N, V).
  - V is the value from the highest proposal number received.
- If no accepted proposal was returned in phase 1, it sends an accept request for the new proposal (N, V).
- Upon receiving (N, V), acceptors either:
  - Accept it
  - Reject it if there was another prepare request with N’ higher than N, and it has replied to it (due to the promise in phase 1).



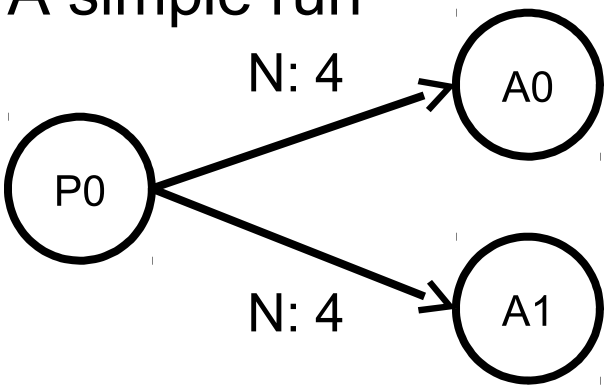


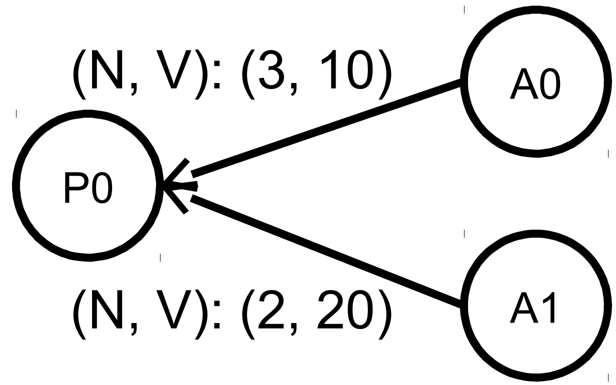
Paxos Phase 3

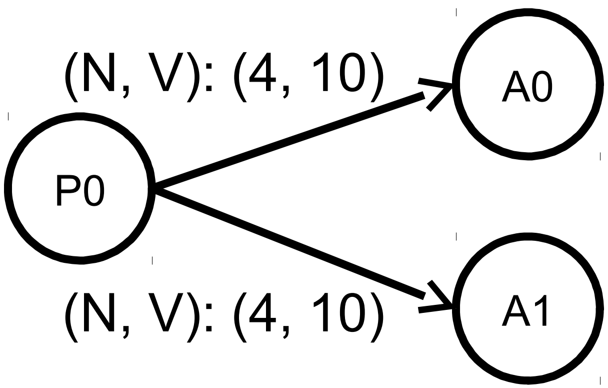
- Learners need to find out which value has been chosen.
- Many possibilities:
  - Have each acceptor notify all learners when it accepts a proposal:
    - Learners will know if a majority has accepted a proposal
    - May be effective, but will be expensive
  - Elect a distinguished learner:
    - Acceptors respond with their acceptances to this process
    - This distinguished learner informs other learners
    - Failure-prone
  - Mixing the two: a set of distinguished learners

Problem: Progress (Liveness)

- A simple run

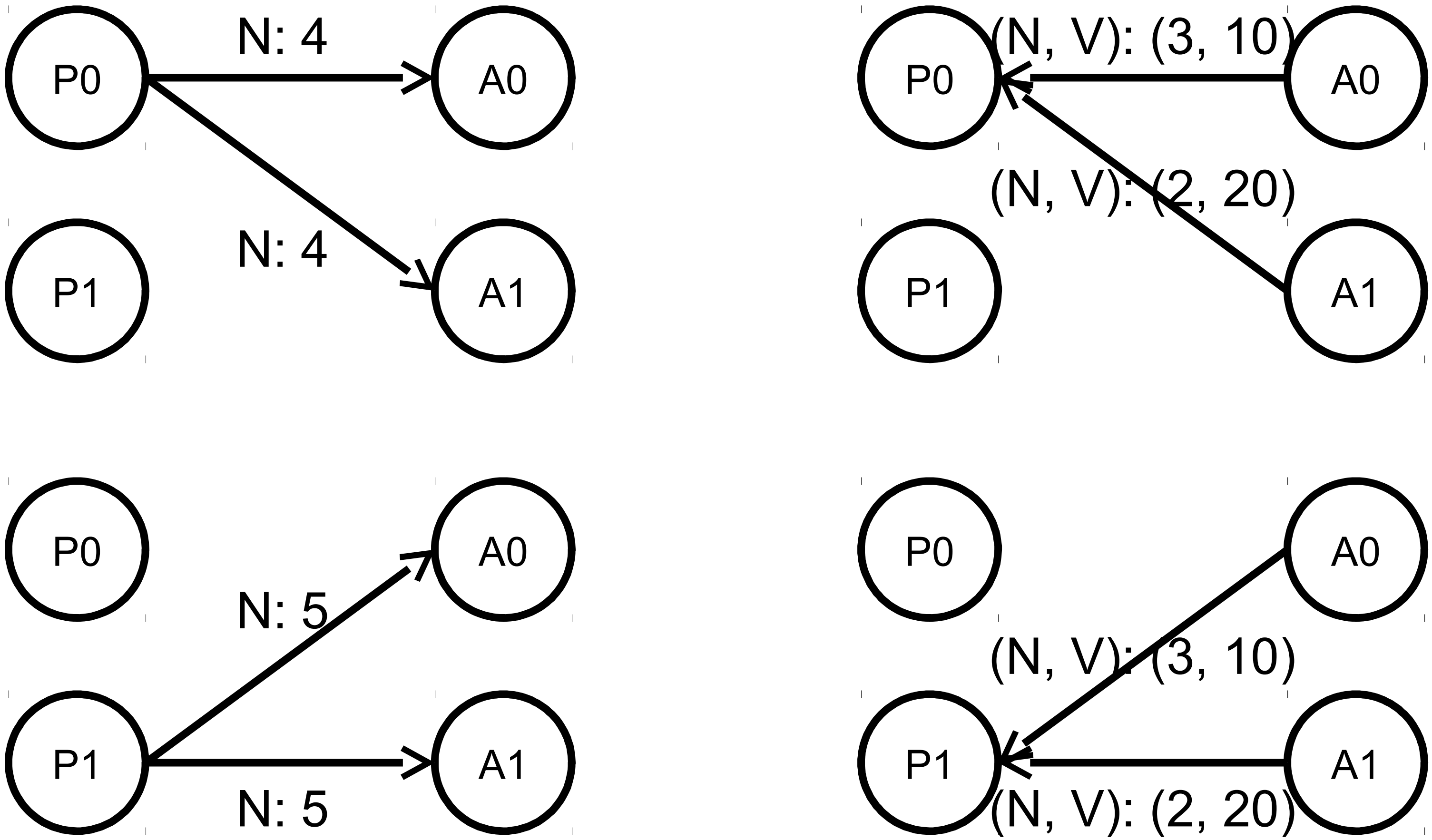






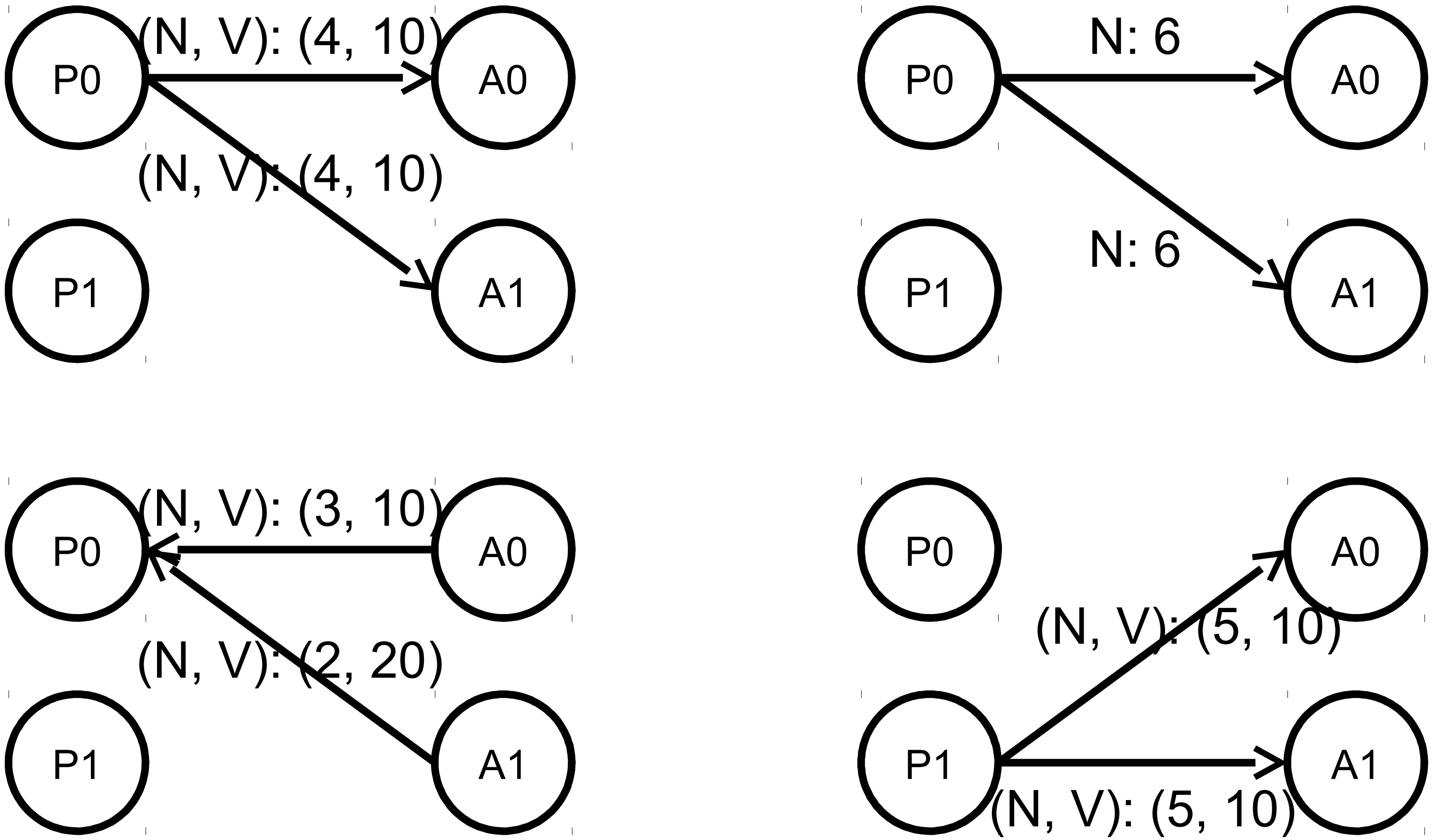
Problem: Progress (Liveness)

- A problematic run



Problem: Progress (Liveness)

- A problematic run (cont.)



Problem: Progress (Liveness)

- There's a race condition for proposals.
- P0 completes phase 1 with a proposal number N_0.
- Before P0 starts phase 2, P1 starts and completes phase 1 with a proposal number $N_1 > N_0$.
- P0 performs phase 2, acceptors reject.
- Before P1 starts phase 2, P0 restarts and completes phase 1 with a proposal number $N_2 > N_1$.
- P1 performs phase 2, acceptors reject.
- …(this can go on forever)

Providing Liveness

- Solution: elect a distinguished proposer
  - *I.e.*, have only one proposer at a time
- If the distinguished proposer can successfully communicate with a majority of acceptors, the protocol guarantees liveness.
  - *I.e.*, if a process plays all three roles, Paxos can tolerate f failures where $f < N/2$.
- Still needs to get around FLP for the leader election, *e.g.*, having a failure detector

Summary

- Paxos
  - A consensus algorithm
  - Handles crash-stop failures (f < N/2)
- Three phases
  - Phase 1: prepare request/reply
  - Phase 2: accept request/reply
  - Phase 3: learning of the chosen value

References

[1] Leslie Lamport. *The Part-Time Parliament.* ACM Transactions on Computer Systems. Vol. 16 No. 2. May 1998. *pp.* 133-169. **Required Reading.** **https://www.microsoft.com/en-us/research/uploads/prod/2016/12/The-Part-Time-Parliament.pdf**

[2] Leslie Lamport. *Paxos Made Simple.* White Paper. November 2001. **Required Reading.** https://www.microsoft.com/en-us/research/uploads/prod/2016/12/paxos-simple-Copy.pdf

[3] Textbook Section 21.5.2. **Required Reading.**

[4] Robbert van Renesse and Deniz Altinbuken. *Paxos Made Moderately Complex.* ACM Computing Surveys Vol. 47 No. 3, Article 42. February 2015. http://www.cs.cornell.edu/courses/cs7412/2011sp/paxos.pdf

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[5] David Mazières. *Paxos Made Practical.* White Paper. January 2007. http://www.scs.stanford.edu/~dm/home/papers/paxos.pdf

Acknowledgements

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