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.
- Plan
  - Brief history (with a lot of quotes)
  - The protocol itself
  - ~~How to "discover" the protocol~~ (this is now optional in the schedule).

Brief History

- Developed by Leslie Lamport (from 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 finally published the paper 8 years later in 1998 after it was written in 1990.
  - Title: "The Part-Time Parliament"
- People did not understand the paper.
- Lamport gave up and wrote another paper that explains Paxos in simple English.
  - Title: "Paxos Made Simple"
  - Abstract: "The Paxos algorithm, when presented in plain English, is very simple."
- Still, it's not the easiest algorithm to understand.
- So people started to write papers and lecture notes to explain "Paxos Made Simple." (e.g., "Paxos Made Moderately Complex", "Paxos Made Practical", etc.)

Review: Consensus

- How do people agree on something?
  - Q: should Steve give an A to everybody taking CSE 486/586?
  - Input: everyone says either yes/no.
  - Output: an agreement of yes or no.
  - FLP: this is impossible even with one-faulty process and arbitrary delays.
- Many distributed systems problems can cast into 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
  - Etc.
- Amazon CTO Werner Vogels (in his blog post "Job Openings in My Group")
  - *"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."*

CSE 486/586 Administrivia

- Midterm grades will be posted soon.

Paxos Assumptions & Goals

- The network is *asynchronous* with message delays.
- The network can *lose or duplicate* messages, but *cannot corrupt* them.
- Processes can *crash*.
- Processes are *non-Byzantine* (only crash-stop).
- Processes have *permanent storage*.
- Processes can *propose* values.

- The goal: every process agrees on a value out of the 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 been
- Liveness
  - Some proposed value is eventually chosen
  - If a value is chosen, a process eventually learns it

Roles of a Process

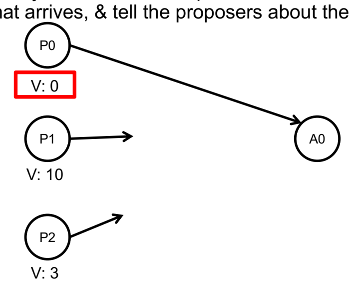
- Three roles
- Proposers: processes that propose values
- Acceptors: processes that accept (i.e., consider) values
  - "Considering a value": the value is a candidate for consensus.
  - Majority acceptance → choosing the value
- Learners: processes that learn the outcome (i.e., chosen value)

Roles of a Process

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

First Attempt

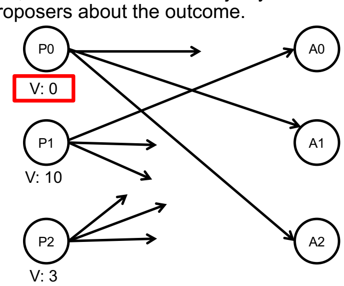
- Let's just have one acceptor, choose the first one that arrives, & tell the proposers about the outcome.



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

Second Attempt

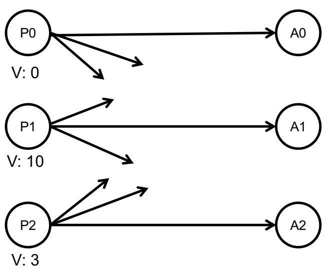
- Let's have multiple acceptors; each accepts the first one; then all choose the majority and tell the proposers about the outcome.



- 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 should accept it.
  - 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 should 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 the (logically) "latest" accepted proposal from each and every acceptor.
  - Propose phase: a proposer sends out a proposal.
  - Learn phase: learners learn the outcome.

Paxos Protocol Overview

- Rough description of the proposers
  - Before a proposer proposes a value, it will ask acceptors if there is any proposed value already.
  - If there is, the proposer will propose the same value, rather than proposing another value.
  - Even with multiple proposals, the value will be the same.
  - The behavior is altruistic: the goal is to reach a consensus, rather than making sure that "my value" is chosen.
- Rough description of the acceptors
  - The goal for acceptors is to accept the highest-numbered proposal coming from all proposers.
  - An acceptor tries to accept a value V with the highest proposal number N.
- Rough description of the learners
  - All learners are passive and wait for the outcome.

Paxos Phase 1

- A proposer chooses its proposal number N and sends a *prepare request* to acceptors.
  - "Hey, have you accepted any proposal yet?"
  - Note: Acceptors keep the history of proposals.
- An acceptor needs to reply:
  - If it accepted anything, the "latest" accepted proposal before N (the one with the highest proposal number less than N)
  - Extra action: The acceptor stops accepting any proposal numbered less than N any more (to make sure that it doesn't alter the result of the reply, i.e., the "latest" should be same).

Paxos Phase 2

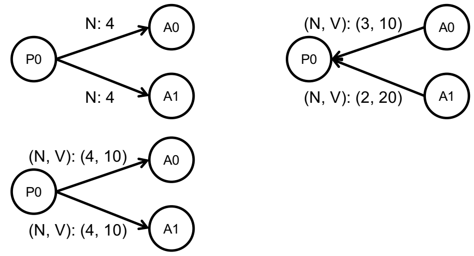
- If a proposer receives a reply from a majority, it sends an *accept request* with the proposal (N, V).
  - V: the value from the "latest" proposal among the replies
  - Or, if no accepted proposal was returned in phase 1, a new value to propose.
- Upon receiving (N, V), acceptors either:
  - Accept it
  - Or, reject it if there was another prepare request with N' higher than N, and it replied to it (due to the promise in phase 1).

Paxos Phase 3

- Learners need to know which value has been chosen.
- Many possibilities
- One way: have each acceptor respond to all learners, whenever it accepts a proposal.
  - Learners will know if a majority has accepted a proposal.
  - Might be effective, but expensive
- Another way: 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

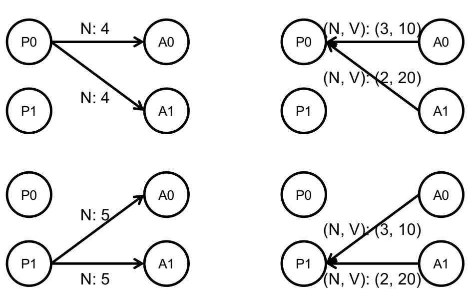
Problem: Progress (Liveness)

- A simple run



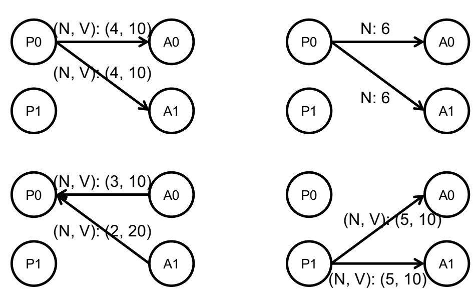
Problem: Progress (Liveness)

- 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 N0
- Before P0 starts phase 2, P1 starts and completes phase 1 with a proposal number N1 > N0.
- P0 performs phase 2, acceptors reject.
- Before P1 starts phase 2, P0 restarts and completes phase 1 with a proposal number N2 > N1.
- P1 performs phase 2, acceptors reject.
- …(this can go on forever)

Providing Liveness

- Solution: elect a distinguished proposer
  - I.e., have only one proposer
- If the distinguished proposer can successfully communicate with a majority, the protocol guarantees liveness.
  - I.e., if a process plays all three roles, Paxos can tolerate failures $f < 1/2 * N$.
  - *$N = 2f + 1$ (f is the maximum number of failed processes).*
- 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 < 1/2 * N)
- Three phases
  - Phase 1: prepare request/reply
  - Phase 2: accept request/reply
  - Phase 3: learning of the chosen value

Acknowledgements

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