Consensus in Distributed Systems

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Presentation

1. Definition of the Problem
2. Paxos Made Simple
3. Paxos Made Moderately Complex
4. Different Types of Paxos
5. Discussion

Consensus Meaning

- **In Real World:** A group of people reaches an agreement after discussion.
- **In Distributed Systems:** A group of process agrees on a specific value.

Safety Requirements

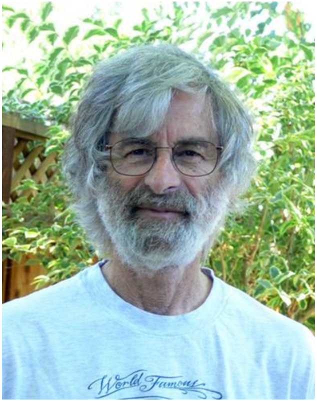
- Only a value that has been proposed may be chosen.
- Only a single value is chosen.
- The majority processes learn that the same value is chosen.

Assumptions

- Asynchronous environment
    - no bounds on timing characteristics
    - clocks run arbitrarily fast
    - message communication takes arbitrarily long
- Crash failures
    - processes just halt in case of failure
- Reliable links
    - messages will eventually be delivered
    - messages can be duplicated and reordered
    - communication is not corrupted

Paxos

Leslie Lamport: Researcher at Microsoft



Paxos Made Simple (2001): Simple description of Paxos protocol.

Classes of Agents

- **Proposers:** Propose values (possibly different) to acceptors.
- **Acceptors:** Choose a value amongst the proposed ones.
- **Learners:** Learn the correct chosen value from the acceptors.

* A process can act as a multi-agent.

Single Acceptor

- Proposers send proposals to a single Acceptor.
- The Acceptor chooses the first value it receives.
- **Problem:** If the Acceptor fails, further progress is impossible.
- **Solution:** Utilize multiple Acceptor agents.

Multi-Acceptors

- In a t fault-tolerant environment, 2t+1 Acceptors are needed.

- Proposers send their proposal to a set of processes, that consists of the majority of Acceptors.

- A value is chosen when at least t+1 Acceptors have accepted this value.

Proposal Format

- A proposal consists of a tuple (n, v), where n is a proposal id and v is the value assigned to this proposal.

- Each proposer has a unique set of proposal ids.

- Uniqueness is guaranteed for proposal ids.

Invariants

- **P1**: An Acceptor must accept the first proposal that it receives.

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$$\Uparrow$$

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Invariants

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$$\Uparrow$$

- **P2a**: If a proposal (n, v) is chosen, then for every proposal with id $n' > n$ accepted, the value must be v.

$$\Uparrow$$

- **P2b**: If a proposal (n, v) is chosen, then for every proposal with id $n' > n$ issued by any proposer the value must be v.

Invariants

- **P2c**: For any proposal (n, v), there is a set S consisting of a majority of Acceptors such that one of the following is true.
  (a) No Acceptor in S has accepted any proposal with number $n' < n$.
  (b) The value v is the value of the highest-numbered proposal among all proposals with number $n' < n$ accepted by the acceptors in S.

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$$\Downarrow$$

P2

Synod Algorithm

- Phase 1: Prepare
  - (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 the greatest proposal number it has ever responded to, then it doesn't respond to proposals with number less than *n* and replies with the highest-numbered proposal that it has accepted.

Synod Algorithm

- Phase 2: Accept
  (a) If the proposer receives a response from majority of acceptors, it sends an *accept request* with (n, v), where v is the highest value in the responses or any value if none responded with a value.

  (b) If an Acceptor receives a *accept request* with number n it accepts the proposal unless it received a *prepare request* with number $n' > n$.

Learners

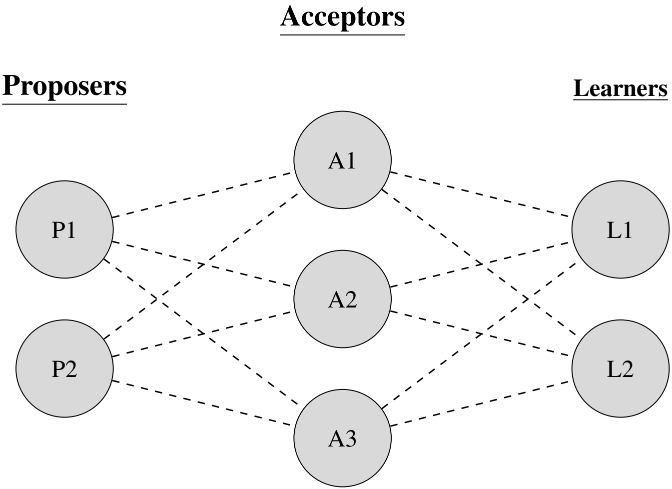
- Learners learn from Acceptors the accepted values and output the value that is proposed by the majority of them.

- In a t fault-tolerant environment, t+1 Learners are needed.

- **Broadcast:** All Acceptors forward to all Learners.

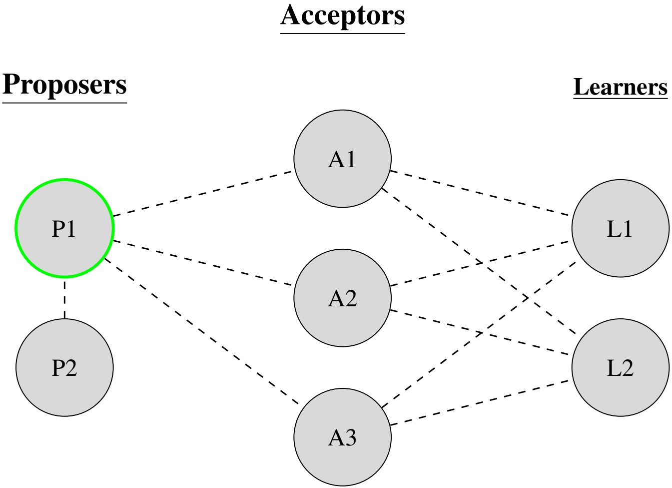
Optimizations

Basic Paxos



Optimizations

Basic Paxos with distinguished Proposer (Leader)



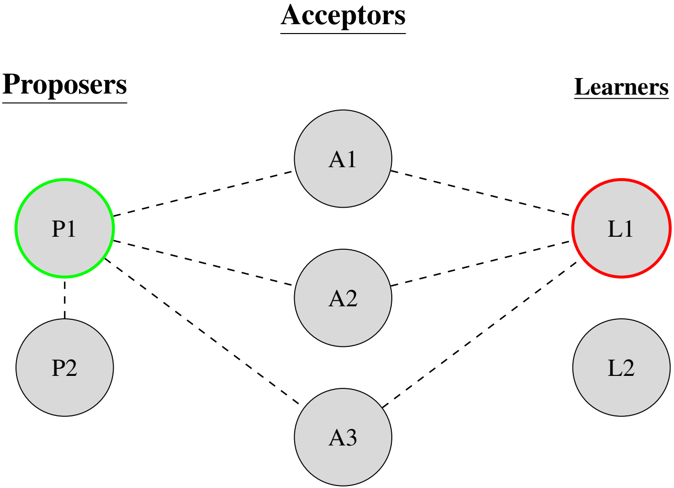
Optimizations

In case that Leader fails:

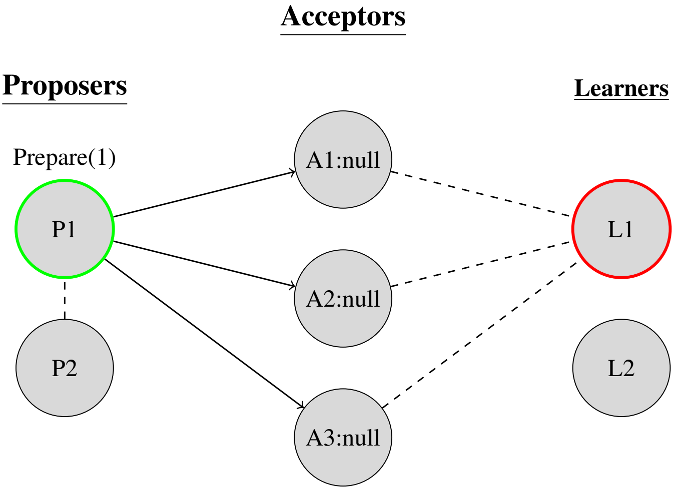
- The protocol must elect a new Leader. Is this another consensus problem?
- After the failed processor recovers it might continue to act as a Leader. This may lead to multiple Leaders.
- The protocol runs safely even with multiple Leaders

Optimizations

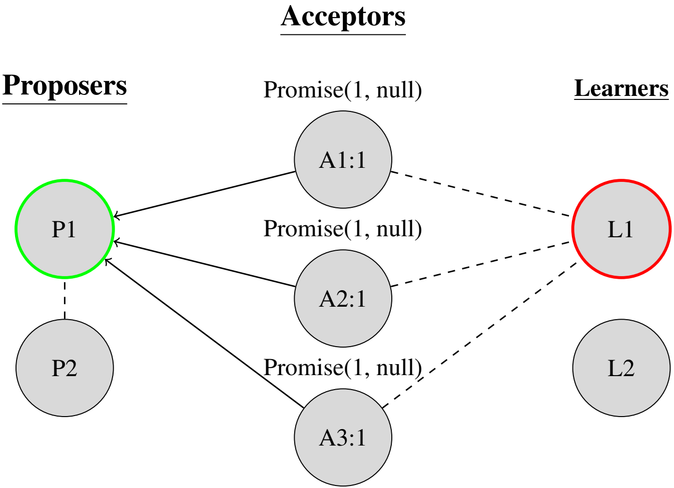
Basic Paxos with distinguished Learner (Leader)



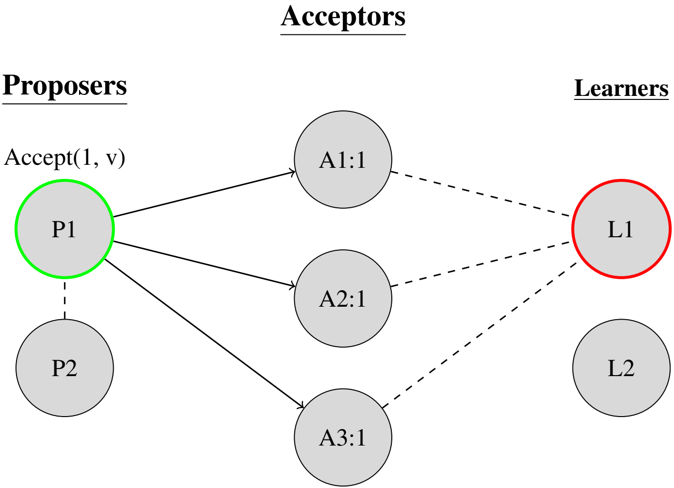
Example


Acceptors
Proposers
Learners
Prepare(1)
P1
P2
A1:null
A2:null
A3:null
L1
L2

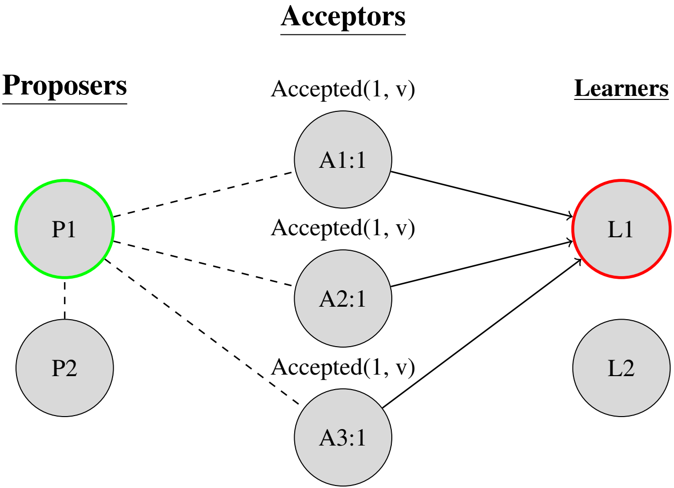
Example


Acceptors
Proposers
Learners
Promise(1, null)
Promise(1, null)
Promise(1, null)
P1
P2
A1:1
A2:1
A3:1
L1
L2

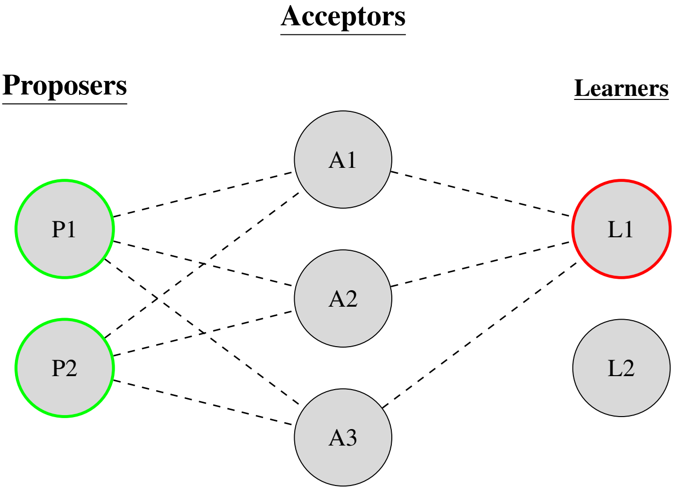
Example


Acceptors
Proposers
Learners
Accept(1, v)
P1
P2
A1:1
A2:1
A3:1
L1
L2

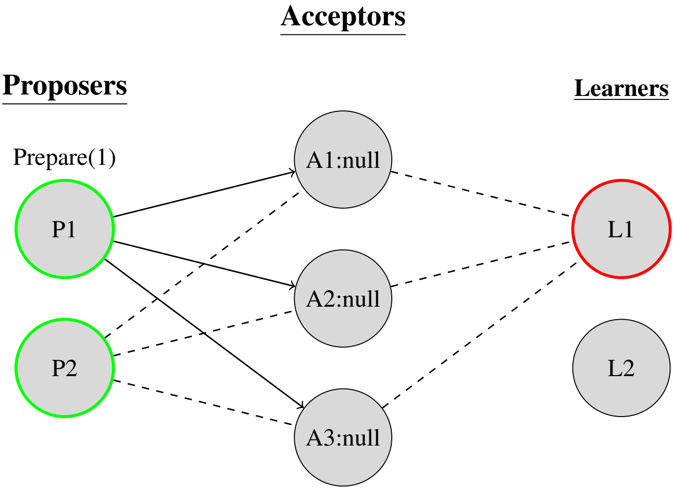
Example


Acceptors
Proposers
Accepted(1, v)
Learners
A1:1
P1
Accepted(1, v)
L1
A2:1
P2
Accepted(1, v)
L2
A3:1

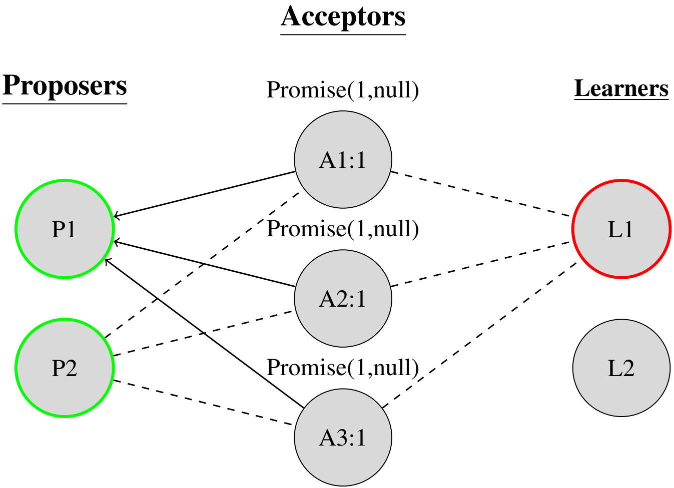
Progress



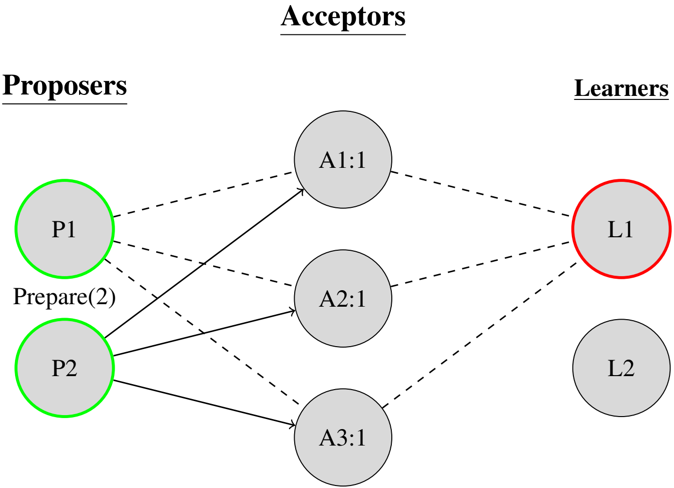
Progress


Acceptors
Proposers
Learners
Prepare(1)
P1
P2
A1:null
A2:null
A3:null
L1
L2

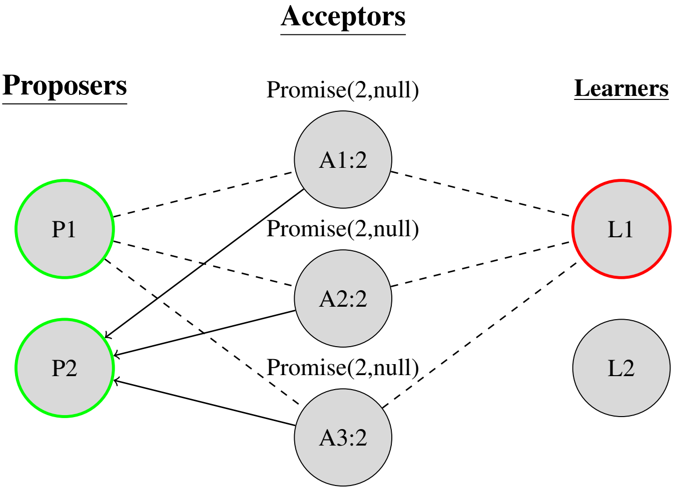
Progress


Acceptors
Proposers
Learners
Promise(1,null)
Promise(1,null)
Promise(1,null)
A1:1
A2:1
A3:1
P1
P2
L1
L2

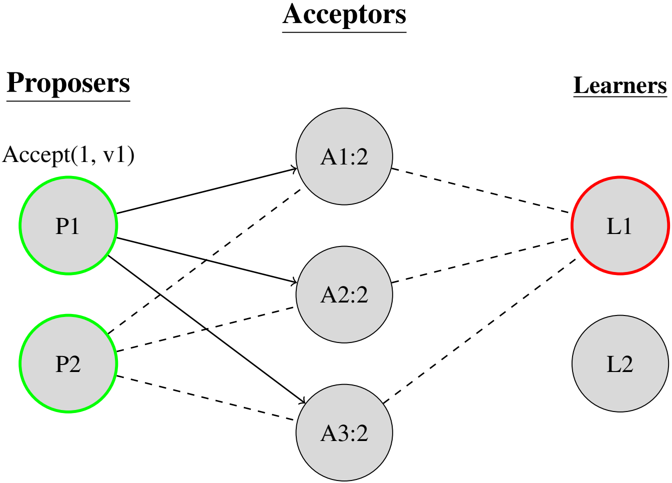
Progress


Acceptors
Proposers
Learners
A1:1
P1
L1
A2:1
Prepare(2)
P2
L2
A3:1

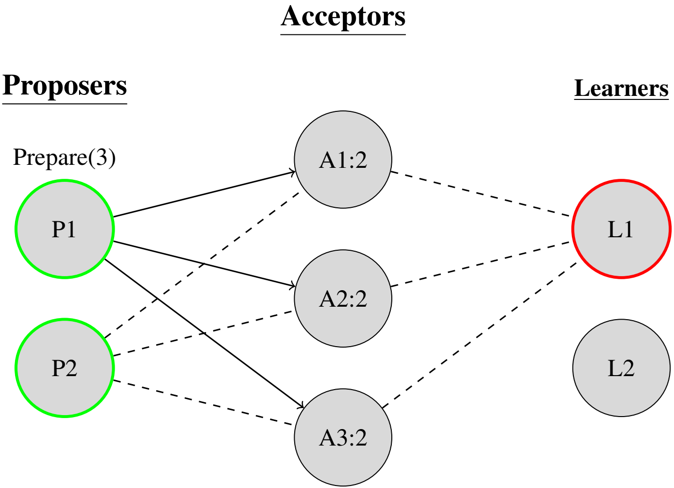
Progress


Acceptors
Proposers
Promise(2,null)
Learners
A1:2
P1
Promise(2,null)
L1
A2:2
P2
Promise(2,null)
L2
A3:2

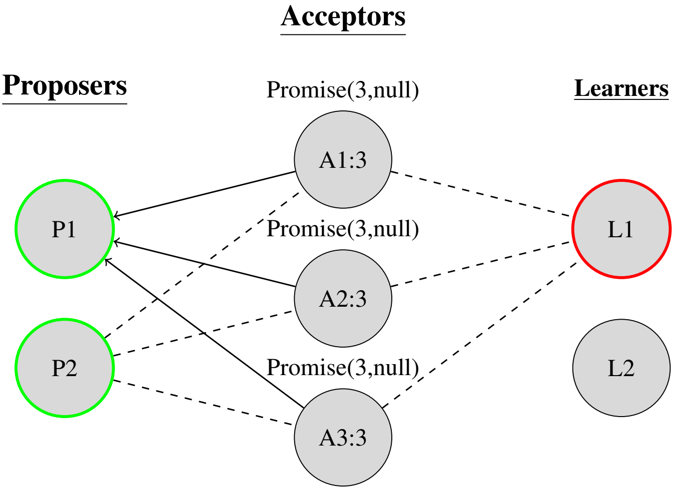
Progress


Acceptors
Proposers
Learners
Accept(1, v1)
P1
P2
A1:2
A2:2
A3:2
L1
L2

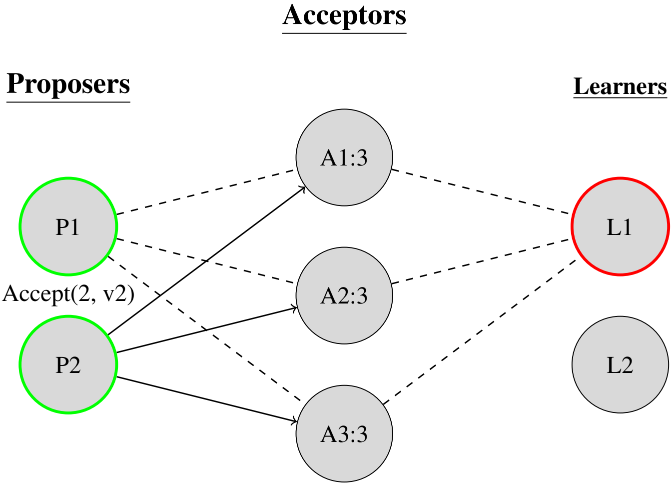
Progress


Acceptors
Proposers
Learners
Prepare(3)
P1
P2
A1:2
A2:2
A3:2
L1
L2

Progress


Acceptors
Proposers
Promise(3,null)
Learners
A1:3
P1
Promise(3,null)
L1
A2:3
P2
Promise(3,null)
L2
A3:3

Progress



Acceptors

Proposers

Learners

Progress

- **Theoretically:** Asynchronous environment and crash failure model lead to no Progress. *Impossibility of Distributed Consensus with One Faulty Process (1983)*
- **Practically:** Countermeasures can be taken to avoid this domino effect.
  - randomized timeouts
  - failure detection

Implementation of Paxos

- How the leaders are elected?
- What happens when multiple requests are spawned?
- How I get rid of redundant data?
- How do I achieve liveness requirement?

Paxos Made Moderately Complex

Robbert Van Renesse: Research Scientist at Cornell

Paxos Made Moderately Complex (2011): Difficulties in implementation of Paxos protocol.

State Machine

- Collection of states.
- Collection of transitions between states.
- Current state.

Deterministic: For any state and operation the transition is unique.

SMR: Masks failures via replication. It is assumed that at least one replica never crashes.

Problem

- Multiple clients

Problem

- Multiple clients

$$\Downarrow$$

- Multiple concurrent commands are executed with different order at the replicas.

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- Replicas make different transitions and are inconsistent with each other.

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- Replicas make different transitions and are inconsistent with each other.

Solution: Utilize Synod algorithm to agree on the order of commands.

Clients

- Clients make requests of type (k, cid, op).
  - *k* -> client unique id
  - *cid* -> command id
  - *op* -> operation to be performed
- They wait until they get a response.
- Clients should not be able to witness SMR model with failures. Instead, the system must behave like a single SM without failures.

Classes of agents

- **Replicas:** They are t+1 processes that guarantee t fault tolerance. They interact with the Clients.
- **Leaders:** They are placed between Replicas and Acceptors.
  - **Scouts:** execute first phase of Paxos.
  - **Commanders:** execute second phase of Paxos.
- **Acceptors:** They are 2t+1 processes. The majority is needed in order to reach a decision.

Slots and Ballots

Slots

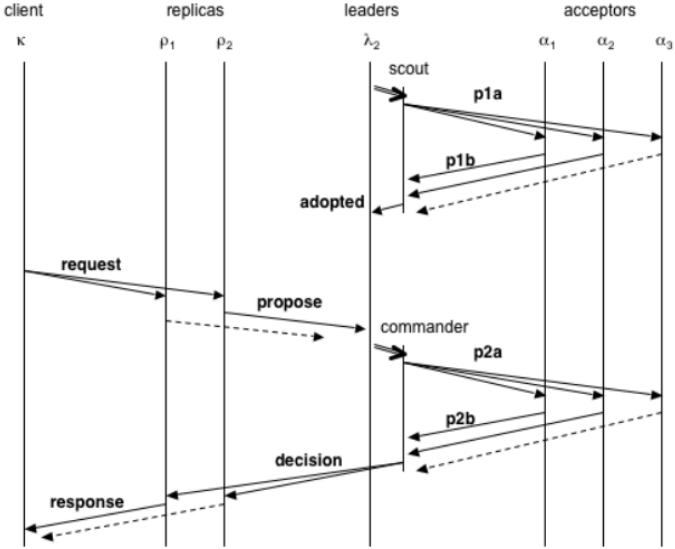
- contain commands in the order of execution
- each slot contains a unique command
- each command can be in multiple slots

Ballots

- there are tuples (λ, id) where λ is the Leader they belong to and id is a unique number for the ballot

PValues

- triple (b, s, p) where b is a ballot, s is a slot and p is the proposed command


client
replicas
leaders
acceptors
κ
ρ1
ρ2
λ2
α1
α2
α3
scout
p1a
p1b
adopted
request
propose
commander
p2a
p2b
decision
response

Liveness

- **Problem:** Liveness is not guaranteed.

- **Weaken Assumptions:** There is a bound
  - in clock drifts
  - in communication time between two non-faulty processes

- **Solutions:**
  - failure detection
  - TCP-like timeout mechanism

State Reduction

- Acceptors keep the highest PValues for each slot.
- Acceptors sent information only for slots that are undecided.
- Replicas can keep only the requests higher to their *slot_num*.
- Leaders spawn Commanders only for undecided slots.

Garbage Collection

- Acceptors do not need to keep PValues for slots that have been updated to all Replicas.

- A faulty Replica can stall the garbage collection.

- Have $2t + 1$ Replicas instead of $t + 1$. Acceptors erases the PValue when more than t Replicas have performed the corresponding command.

- A recovered Replica which is not able to learn a particular command will get a snapshot of the state of another Replica.

Co-location

- In practice, the Leaders are usually co-located with the Replicas.
- A Replica instead of broadcasting it sends the proposal to the local Leader. If Leader is active it spawns a Commander to handle the proposal. If not it sends the message to another active Leader (monitor).
- Avoid the expense of the Broadcast.
- Other scenarios of co-locations are possible, as well.

Read-only Commands

- Read operations do not change the state of Replicas. So, we don’t need consensus.
- Use leases mechanism in order to be certain that an update is not going to happen from the other Leader.
- If the Leader has the lease it can attach read-only commands to the highest slot number.

Multi-Paxos

- One Leader fairly stable.
- Skip prepare request after the first one.
- Instead of 4 messages delay we have 2 in the usual case.

Cheap-Paxos

- We have t+1 main Acceptors and t auxiliary Acceptors.
- Dynamic reconfiguration after failures.
- When system is stable the protocol is better.
- The system must halt when too many failures occur. (delay for reconfiguration)

Fast-Paxos

- Requests are made directly to all Acceptors.
- Response to requests goes to Learners and to a single Leader.
- The single Leader detects collisions and solves them with a new accept request.
- If there is not any collision, we have only 2 messages delay instead of 4.
- When collisions happen, we have 4 messages delay, which is the same with the basic Paxos.

Generalized-Paxos

- Partial order of events. Some operations can run concurrently.

- For some applications it is faster than Fast-Paxos algorithm.

Byzantine-Paxos

- Non-Byzantine processors assumption is erased.
- Extra replications are needed for guaranteed correctness.
- Fast-Paxos can be integrated to make it even faster (Fast-Byzantine-Paxos).

Many different versions of the protocol are proposed in literature.

Discussion

- Is Paxos implementation simple?
- Are there ways to weaken the assumptions realistically and obtain more performance gains?
- Is Paxos the only solution?

End of Presentation

Thank you!!!