Motivating Paxos *by looking at consensus*

Assumptions (rather weak ones, and realistic)

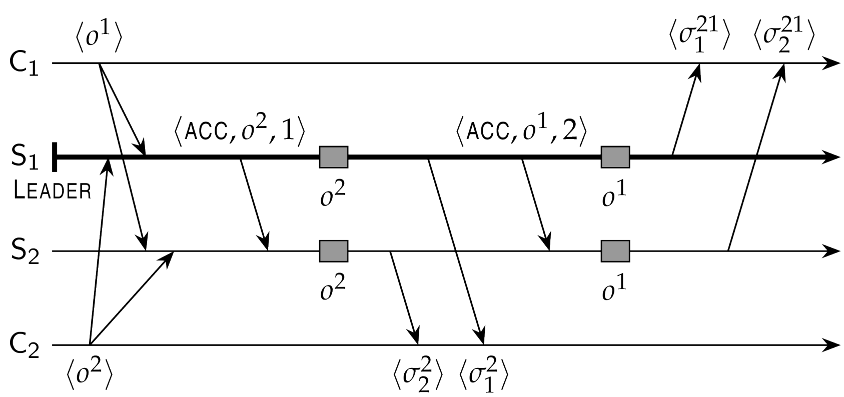
- System is *partially synchronous* (may even be *asynchronous*).
- *Communication* between processes may be *unreliable*:
  - messages may be lost, duplicated, or reordered.
- *Corrupted messages can be detected*
  - and thus subsequently ignored
- All *values are deterministic*:
  - once an execution is started, it is known exactly what it will do.
- Processes may exhibit *crash failures*, but *not arbitrary failures*.
- Processes *do not collude*.

Understanding Paxos

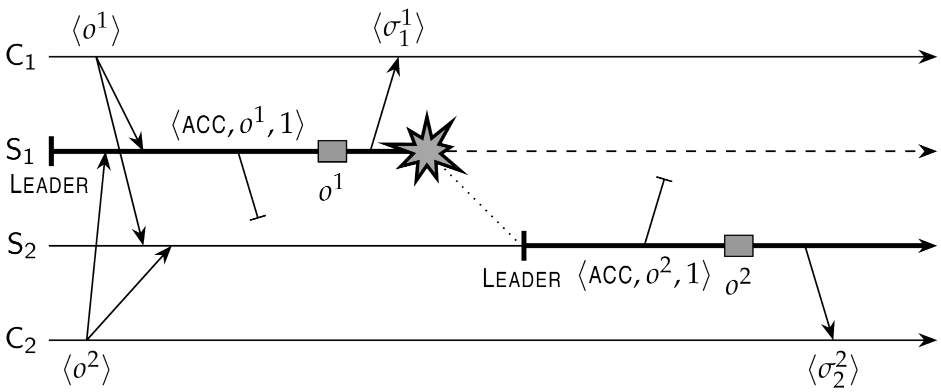
- We will build up to Paxos by looking at problems that occur.

Two Servers *leader + backup*

- The leader sends an *accept* message `ACCEPT(o,t)` to backups when assigning a timestamp *t* to command *o*.



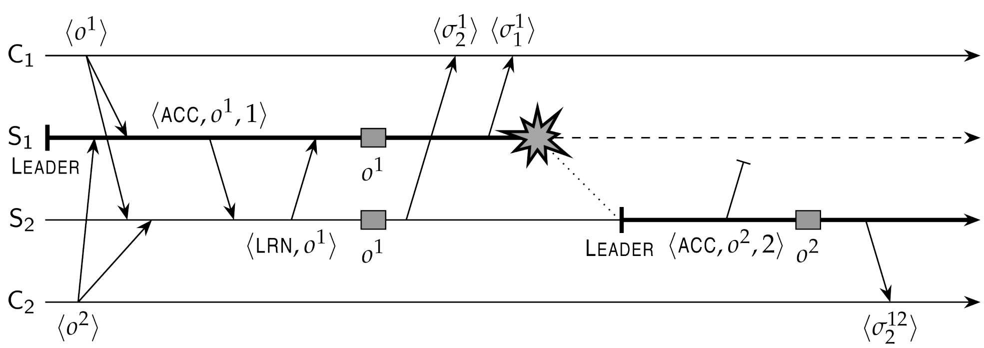
Two Servers *and a crash!*



Problem

Servers have diverged because primary crashes *after executing* an value, but the backup *never received* the accept message.

Two Servers *and a solution to the crash*

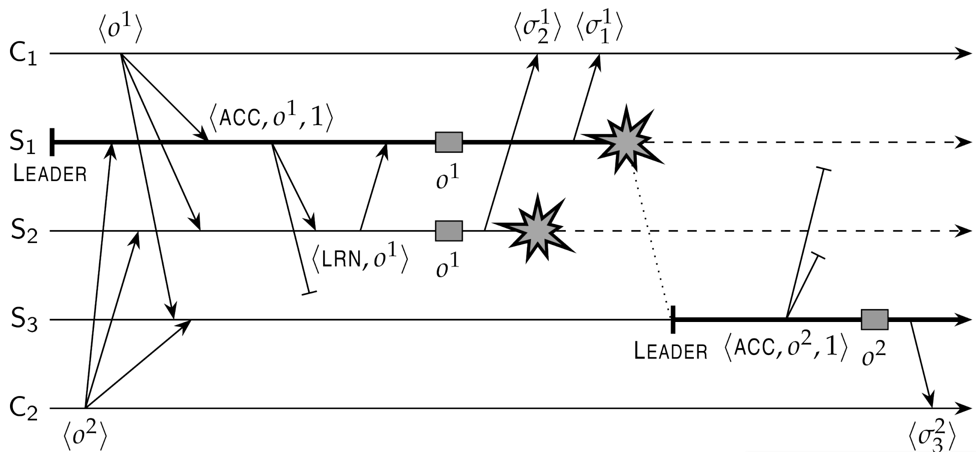


Solution

- A backup responds by sending a *learn* message: `LEARN(o,t)`
- When the leader notices that value *o* has not yet been learned, it retransmits `ACCEPT(o,t)` with the original timestamp.

Never commit an value before it is clear that is has been learned.

Three servers and two crashes: *still a problem?*



S_3 can commit because it knows *S_1* and *S_2* have failed. Sadly, it does not know about *o^1*

Scenario:

- Assume reliable fault detection.
- *S_1* is waiting for a majority before committing (and gets it when it hears from *S_2*)
- But if *S_1*, *S_2* crash there is no guarantee *S_3* knows anything…… and *S_3* commits o^2… *bad!*

One possible solution:

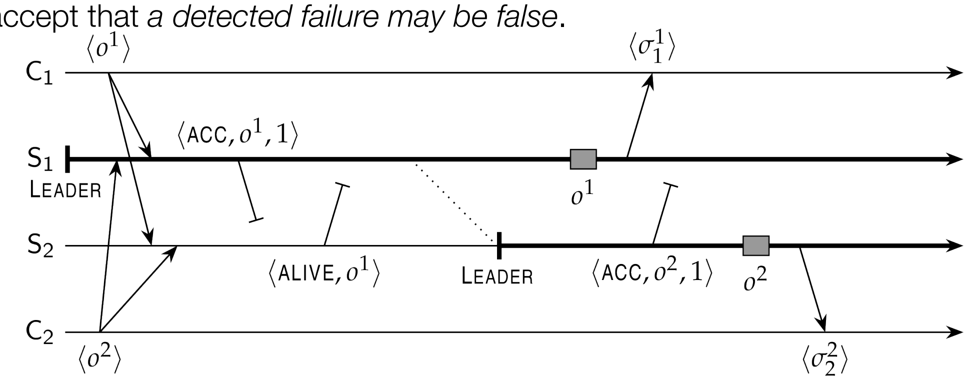
- No server should commit until it gets `learns` from all non-failed servers.
- However, this is a high bar, and reliable fault detection is impossible, so *need something else*.

Fundamental Rule

Another approach: a server *S* cannot commit an value *o* until it has received a `LEARN(o)` from a *majority of learners*.

Practice

Reliable failure detection is practically impossible. A solution is to set timeouts, but accept that *a detected failure may be false*.



S1, S2 opposite sides of a partition

Each think the other has crashed. Who's the real leader? (neither)

Majorities to commit values necessary:

Any two majorities are guaranteed to intersect - intersection property guarantees knowledge of past commits is never lost.

So Consensus Needs at Least Three Servers

Adapted fundamental rule

- With three servers, a server S cannot commit an value o until it has received at least one (other) `LEARN(o)` message, so that it knows that *a majority of servers will commit o*.

Assumptions before taking the next steps:

- Initially, S_1 is the leader.
- A server can *reliably detect it has missed a message*, and recover from that miss (timestamps, message IDs, ask for resends, etc.).
- When a new leader needs to be elected, the remaining servers follow a strictly deterministic algorithm, such as $S_1 \to S_2 \to S_3$.
- A client cannot be asked to help the servers to resolve a situation.

Observation:

If either one of the backups (S_2 or S_3) crashes, consensus still correct:

- values at nonfaulty servers are committed in the same order.

Example Failures *w/ correct recovery*

Leader crashes after executing o_1

S_3 is completely ignorant of any activity by S_1

S_2 received ACCEPT(o^1, 1), detects crash, and becomes leader. S_3 never received ACCEPT(o^1, 1)

If S_2 sends ACCEPT(o^2, 2), S_3 sees unexpected timestamp and tells S_2 that it missed timestamp 1. S_2 retransmits ACCEPT(o^1, 1), allowing S_3 to catch up.

S_2 missed ACCEPT(o^1, 1)

S_2 detects crash and becomes new leader

If S_2 sends ACCEPT(o^1, 1) $\Rightarrow$ S_3 retransmits LEARN(o^1).

If S_2 sends ACCEPT(o^2, 1) $\Rightarrow$ S_3 tells S_2 that it apparently missed ACCEPT(o^1, 1) from S_1, so that S_2 can catch up.

Example Failures

Leader crashes after sending ACCEPT(o^1, 1):

S_3 is completely ignorant of any activity by S_1

As soon as S_2 announces that o^2 is to be accepted, S_3 will notice that it missed an value and can ask S_2 to help recover.

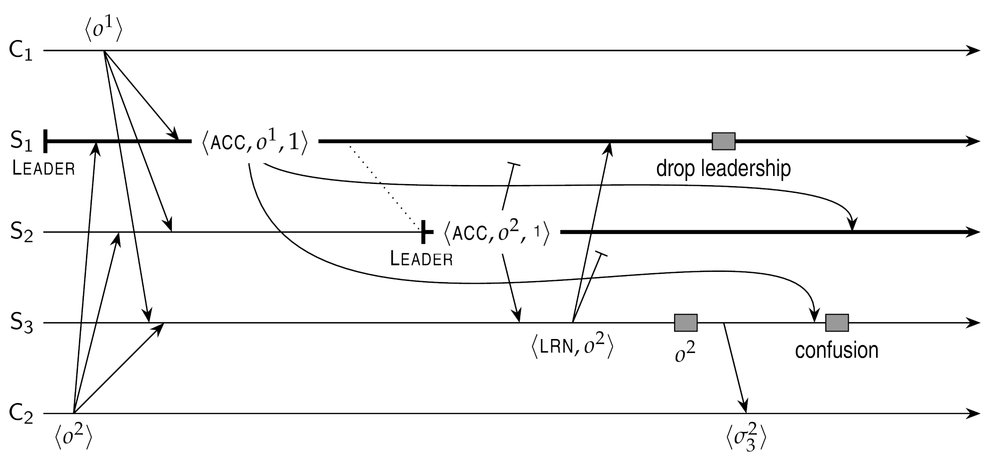
S_2 had missed ACCEPT(o^1, 1)

As soon as S_2 proposes an value, it will be using a stale timestamp, allowing S_3 to tell S_2 that it missed value o^1.

Observation

Consensus (with three servers) *behaves correctly* when a single server crashes, regardless of when that crash took place.

False Crash Detections

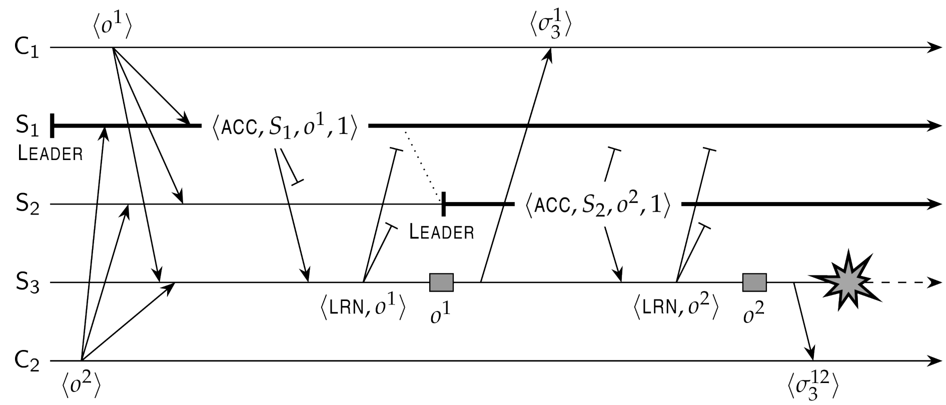


Problem and solution

S_3 receives ACCEPT(o^1, 1), but much later than ACCEPT(o^2, 1). If it knew who the current leader was, it could safely reject the delayed accept message

⇒ leaders should include their ID in messages.

But What About Progress?



Problem:
When S3 crashes no other server knows what it did

Essence of solution
When S_2 takes over, it needs to make sure that any outstanding values initiated by S_1 have been properly flushed, i.e., committed by enough servers. This requires an explicit leadership takeover by which other servers are informed before sending out new accept messages.

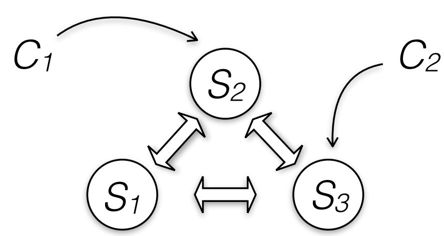
Terminology

- proposed *value* same as Steen's *operation*
- value *commit* same as Steen's *execute*

- *accept / learn* are second phase not first as we have seen

Paxos *original "single decree" Paxos*

- Server roles:
    - proposer: attempts *proposes* client's command
    - acceptor: *accepts* a proposed command
    - learner: *learns* of acceptances
    - Once a server learns a majority have accepted a proposal, it can be accepted and result sent to the client.
    - *All roles often played by each server*



Paxos *phases*

- A proposal has:
    - *timestamp*, or "proposal number", or "ID"
    - *value*, "value"
- We want correctness *and* liveness, so:
    - there can be concurrent proposals (by different servers)
    - phase 1: arbitrate between competing proposals
        - proposer sends a *prepare* msg w/ proposal number, *n*, and value o_n, to each acceptor
        - If the prepare's *n* is higher than any previously seen proposal, an acceptor *promises* to ignore later proposals with lower or same numbers
    - phase 2: decide on accepted value
        - proposer sends *accept* w/ its timestamp, and value from previously promise (or it's own value if none)
        - acceptors respond *accepted*, and tell all learners

proposer can time out and restart w/ higher proposal number

Paxos *single proposer*

```
Client   Proposer      Acceptor     Learner
   |         |          |  |  |       |  |
   X-------->|          |  |  |       |  |  Request(Va)
   |         X--------->|->|->|       |  |  Prepare(1,Va)
   |         |<---------X--X--X       |  |  Promise(1,null,null)
   |         X--------->|->|->|       |  |  Accept!(1,Va)
   |         |<---------X--X--x------>|->|  Accepted(1,Va)
   |<---------------------------------X--X  Response
```

- client sends proposal to random *proposer*
- proposer send *prepare* w/ bigger proposal number (ID) than previously seen
- acceptors:
  - do not respond if already promised w/ ID >= 1, or
  - respond with:
    - *promise* not to accept proposal w/ ID <= 1
      - value of highest proposal it has *promised* so far
      - this promise returns *null,null* because it is the first seen *prepare* msg
- if majority promises, proposer sends *accept* with:
  - ID and value from proposal w/ highest ID promised by an acceptor
- if learner gets *accepted* from majority of acceptors, proposal is *committed*

Paxos *proposer (server leader) failure*

```
Clients   Proposers      Acceptor     Learner
 C1 C2      P1 P2
 |  |       |  |          |  |  |       |  |
 X--------->|  |          |  |  |       |  |  Request(Va)
 |  |       X--|--------->|->|->|       |  |  Prepare(1,Va)
 |  |    FAIL!<-----------X--X--X       |  |  Promise(1,null,null)

 |  X------|->|           |  |  |       |  |  Request
 |  |       |  X--------->|->|->|       |  |  Prepare(2,Vb)
 |  |       |  |<---------X--X--X       |  |  Promise(2,Va,1)
 |  |       |  X--------->|->|->|       |  |  Accept!(2,Va)
 |  |       |  |<---------X--X--x------>|->|  Accepted(2,Va)
 |  |<----------------------------------X--X  Response
```

- P_1 fails, client request fails
- acceptors all append $V_a, 1$ to promises for proposal 2
- after gathering a majority, P_2 sends *accept* with:
  - new proposal ID of 2
  - value V_a from highest proposal promised by any acceptor
- P_2 is accepted, but value committed is actually from the earlier proposal (V_a from 1)

- single-decree Paxos can accept multiple proposals, but:
  all accepted values must be the same

Dueling Proposers *paxos*

```
Client   Proposer        Acceptor     Learner
X-|------|->|             |  |  |       |  |  !! NEW LEADER (knows last number was 1)
 | |      |  X--------->|->|->|       |  |  Prepare(2,Vb)
 | |      |  |<---------X--X--X       |  |  Promise(2,Va,1})

 | |      |  |            |  |  |       |  |  !! OLD LEADER continues, denied w/ ID 2
 | |      X------------>|->|->|       |  |  Prepare(2,Va)
 | |      |<------------X--X--X       |  |  Nack(2)

 | |      |  |            |  |  |       |  |  !! OLD LEADER tries 3
 | |      X------------>|->|->|       |  |  Prepare(3,Va)
 | |      |<------------X--X--X       |  |  Promise(3,Vb,2)

 | |      |  |            |  |  |       |  |  !! NEW LEADER tries accept, denied
 | |      |  X--------->|->|->|       |  |  Accept(2,Va)
 | |      |  |<---------X--X--X       |  |  Nack(3)

 | |      |  |            |  |  |       |  |  !! NEW LEADER tries 4
 | |      |  X--------->|->|->|       |  |  Prepare(4,Vb)
 | |      |  |<---------X--X--X       |  |  Promise(4,Va,3})

 | |      |  |            |  |  |       |  |  !! OLD LEADER proposes, denied
 | |      X------------>|->|->|       |  |  Accept(3,Vb)
 | |      |<------------X--X--X       |  |  Nack(4)
 | |      |  |            |  |  |       |  |  ... and so on ...
```

- progress not guaranteed…

derived from wikipedia

Multiple Single Decrees *paxos*

```
Client   Proposer       Acceptor     Learner
   |         |            |  |  |        |  |
   X-------->|            |  |  |        |  |  Request(Va)
   |         X--------->|->|->|        |  |  Prepare(1,Va)
   |         |<---------X--X--X        |  |  Promise(1,null,null)
   |         X--------->|->|->|        |  |  Accept!(1,Va)
   |         |<---------X--X--x------->|->|  Accepted(1,Va)
   |<---------------------------------X--X  Response
_____________________________________________________________________

   |         |            |  |  |        |  |
   X-------->|            |  |  |        |  |  Request(Vb)
   |         X--------->|->|->|        |  |  Prepare(1,Vb)
   |         |<---------X--X--X        |  |  Promise(1,null,null)
   |         X--------->|->|->|        |  |  Accept!(1,Vb)
   |         |<---------X--X--x------->|->|  Accepted(1,Vb)
   |<---------------------------------X--X  Response
```

completely separate

- each round takes two round trips (not counting client)
  - first identifies a leader
  - second gets value accepted
- maybe we can dispense w/ the first…

Multi-Paxos *chasing performance*

```
Multi-Paxos Collapsed Roles

Client      Servers
   |          |  |  | --- First Request ---
   X-------->|  |  |  Request(V0)
   |         X->|->|  Prepare(N,V0)
   |         |<-X--X  Promise(N})
   |         X->|->|  Accept!(N,0,V0)
   |         X<>X<>X  Accepted(N,0,V0)
   |<--------X  |  |  Response

   X-------->|  |  |  Request(V1)
   |         X->|->|  Accept!(N,1,V1)
   |         X<>X<>X  Accepted(N,1)
   |<--------X  |  |  Response

   X-------->|  |  |  Request(V2)
   |         X->|->|  Accept!(N, 2, V2)
   |         X<>X<>X  Accepted(N,2)
   |<--------X  |  |  Response
```

multi-paxos implementations usually do not change accepted values (*promise* only returns the proposal number)

- stable leader allows *one round per committed value*
- competing leader starts everything all over

derived from wikipedia