Motivating Paxos *by looking at consensus*

Assumptions (rather weak ones, and realistic)

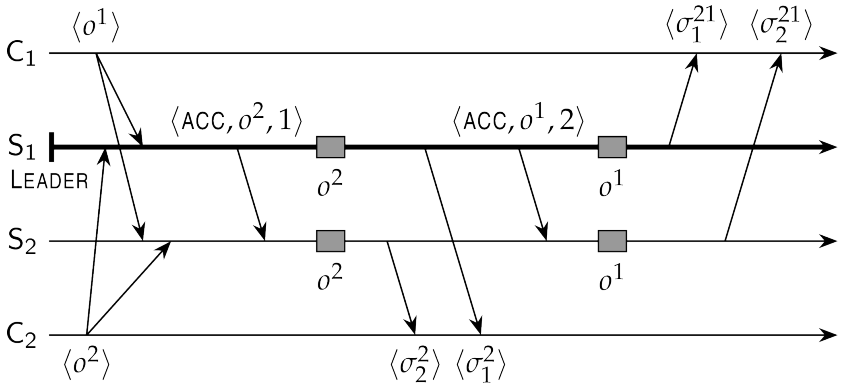
- System is *partially synchronous* (may even be *asynchronous*).
- *Communication* between processes may be *unreliable*:
  - messages may be lost, duplicated, or reordered.
- *Corrupted messages can be detected*
  - and thus subsequently ignored
- All *values are deterministic*:
  - once an execution 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

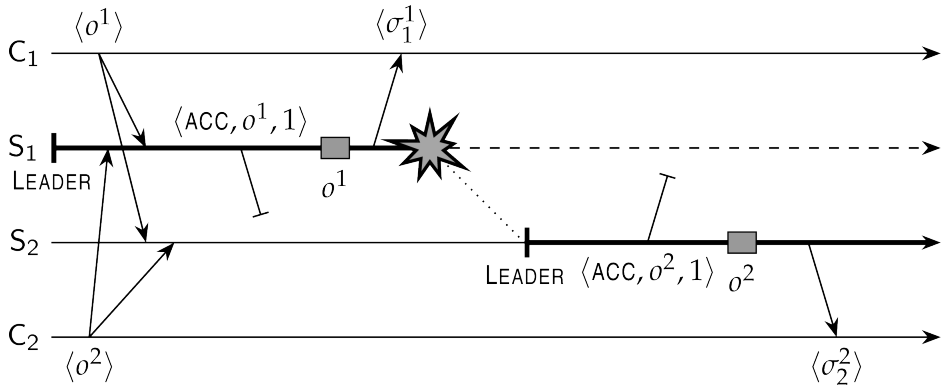
- We will build up to Paxos by looking at problems that occur.

Two Servers *leader + backup*

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



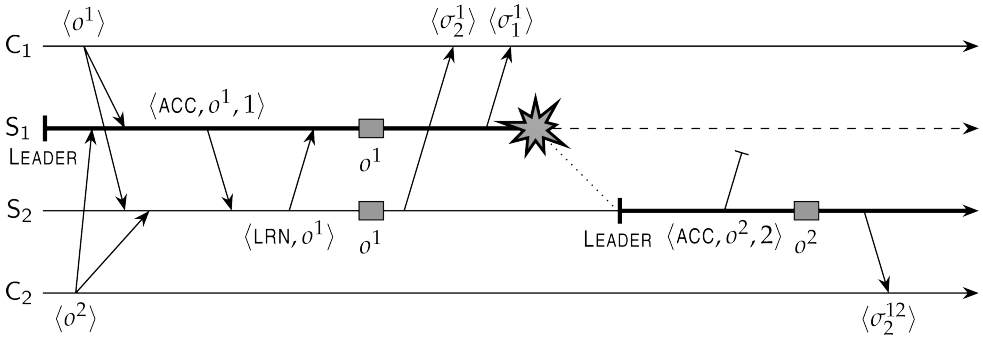
Two Servers *and a crash!*



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*

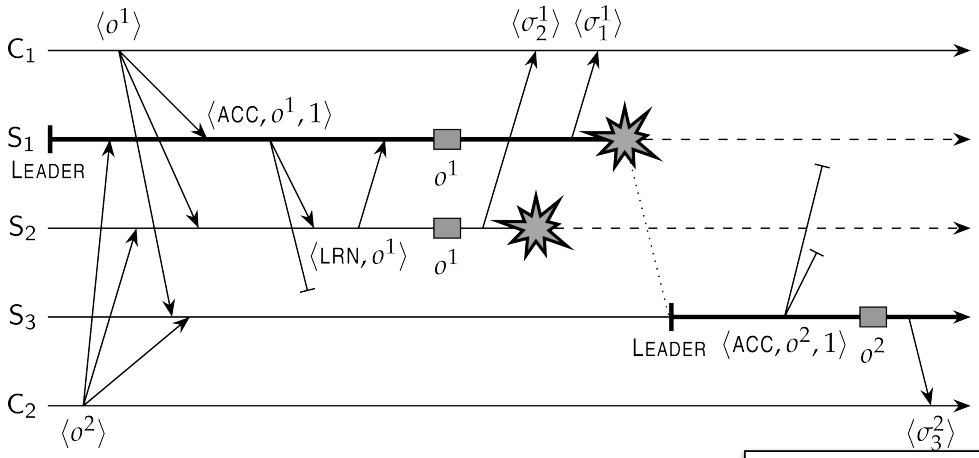


Solution

- 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?*



S₃ can commit because it knows *S₁* and *S₂* have failed. Sadly, it does not know about *o¹*

Scenario:

- Assume reliable fault detection.
- *S₁* is waiting for a majority before committing (and gets it when it hears from *S₂*)
- But if *S₁*, *S₂* crash there is no guarantee *S₃* knows anything…… and *S₃* commits *o²*… *bad!*

One possible solution:

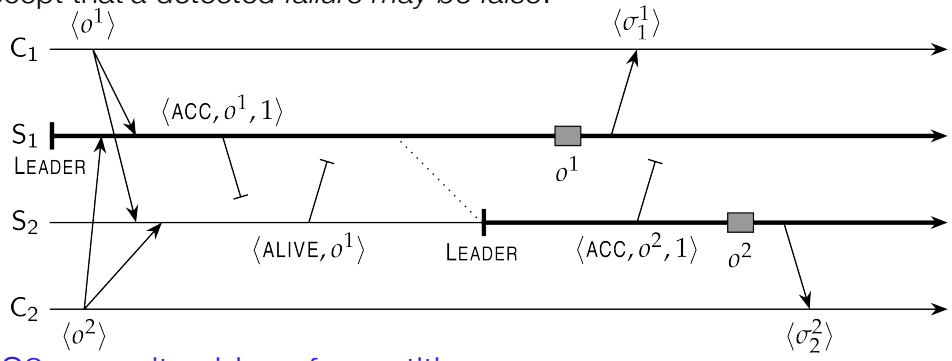
- No server should commit until it gets `learns` from all non-failed servers.
- However, this is a high bar, and reliable fault detection is impossible, so *need something else*.

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 $S_1 \rightarrow S_2 \rightarrow S_3$.
- 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) ⇒ S_3 retransmits LEARN(o^1).

If S_2 sends ACCEPT(o^2, 1) ⇒ 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.

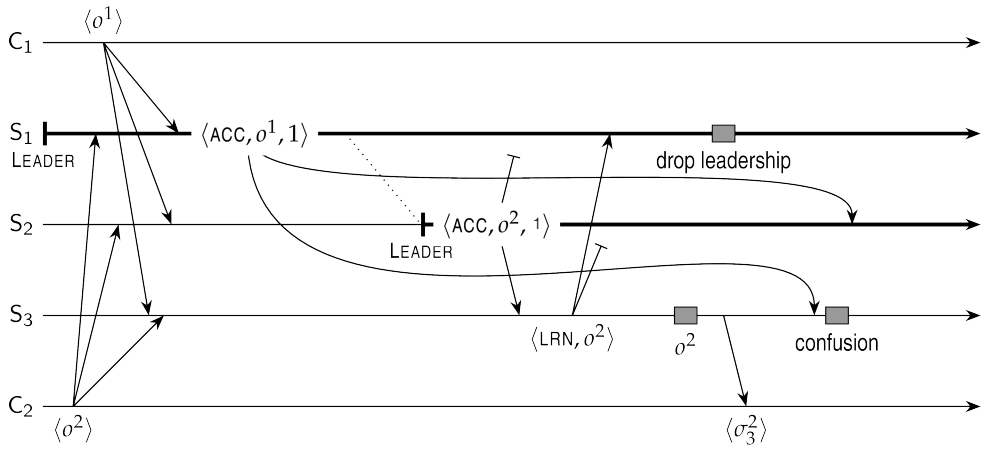
S_2 had missed ACCEPT(o^1, 1)

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

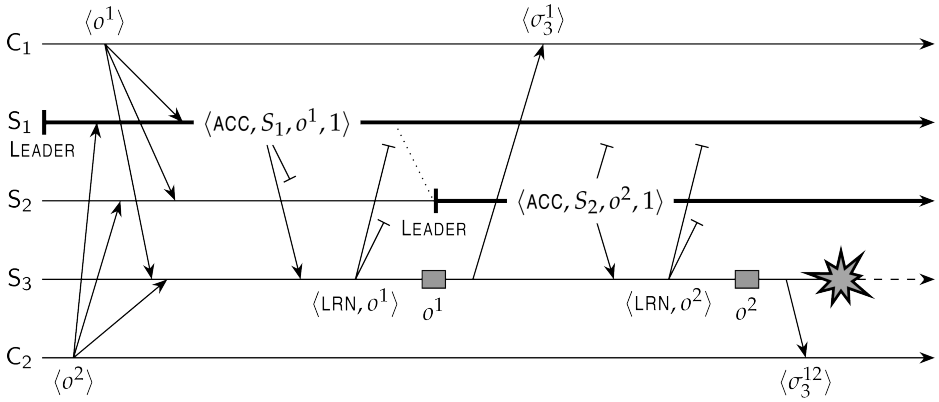


Problem and solution

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.

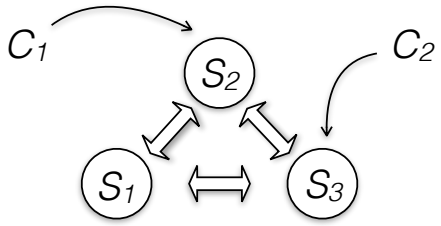
Terminology

- 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*

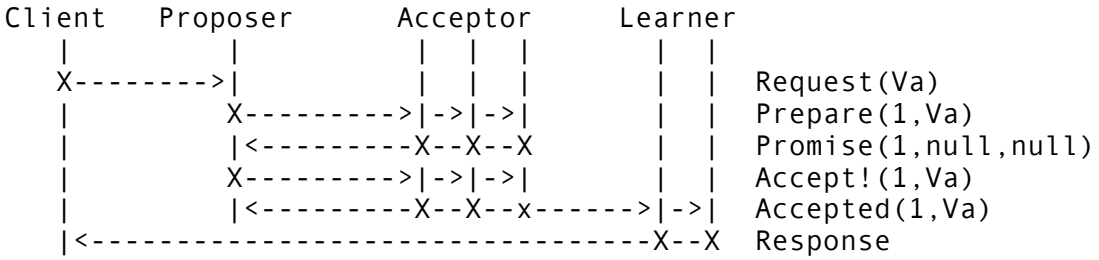


Paxos *phases*

- 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

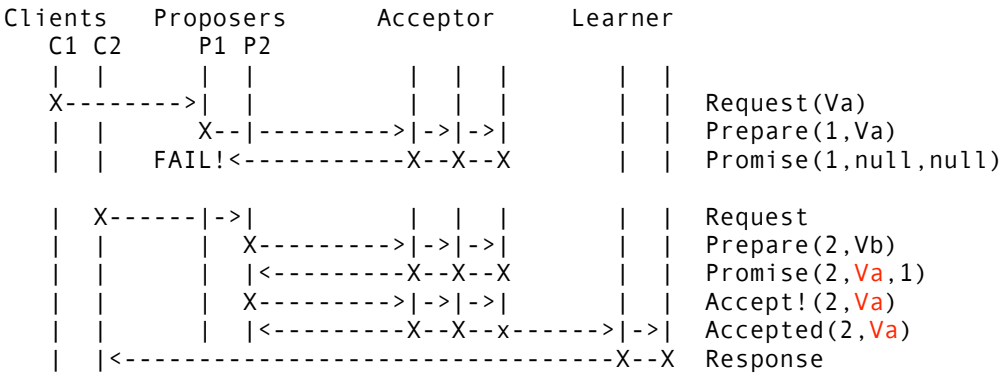
proposer can time out and restart w/ higher proposal number

Paxos *single proposer*



- client 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*

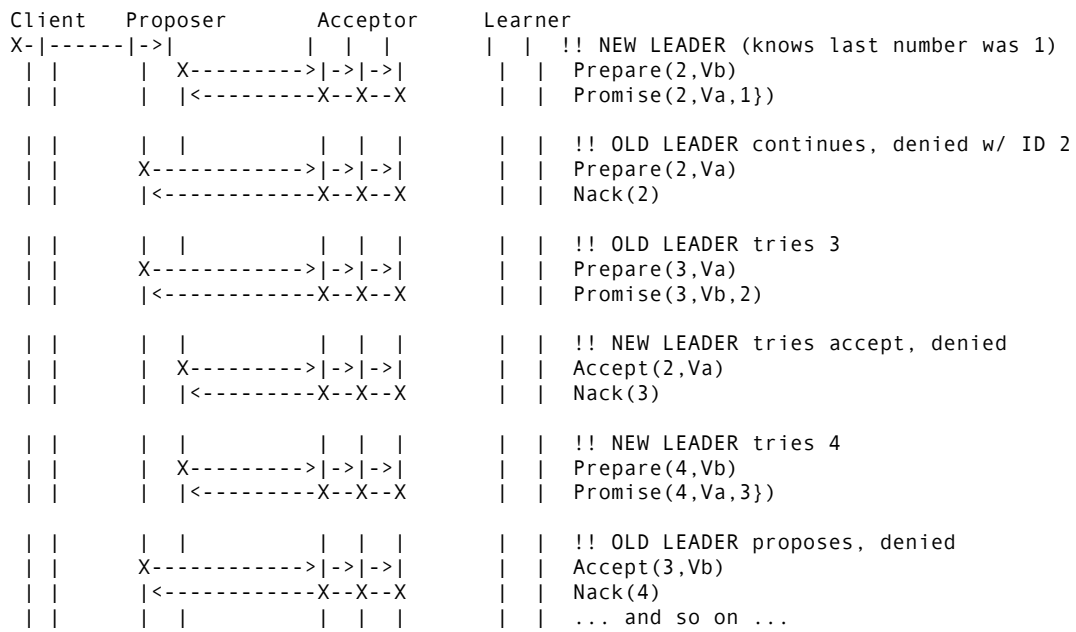
Paxos *proposer (server leader) failure*



- 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

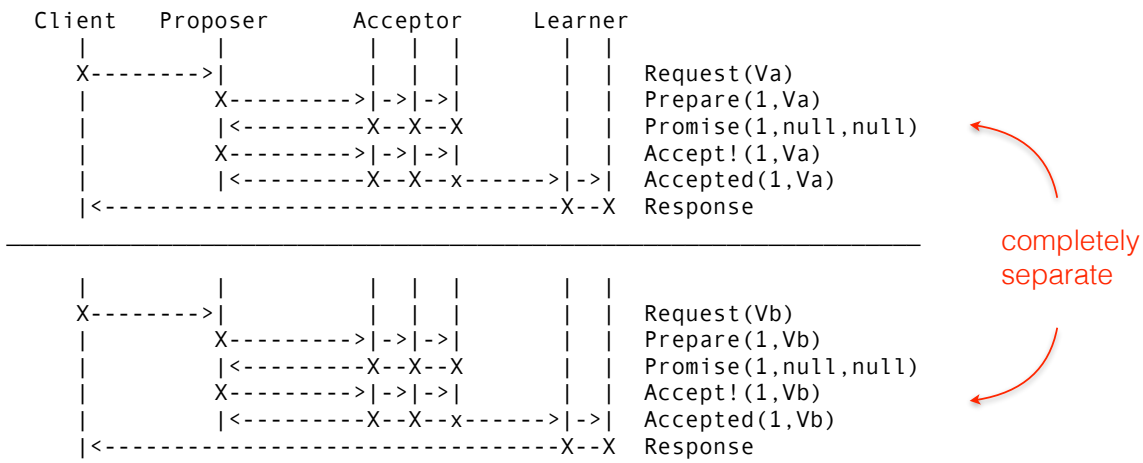
Dueling Proposers *paxos*



- progress not guaranteed…

derived from wikipedia

Multiple Single Decrees *paxos*



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

Multi-Paxos *interrupted!*

```
Client      S1 S2 S3
|  |         |  |  | --- 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(V99)
|  |         |<-X->|  Prepare(N+1,V99)
|  |         X->|<-X  Promise(N+1})
|  |         |<-X->|  Accept!(N+1,0,V99)
|  |         X->|<-X  Accepted(N+1,0,V99)
|<-|---------|--X  |  Response

|  X-------->|  |  |  Request(V1)
|  |         X->|->|  Accept!(N,2,V2)
|  |         X<>X<>X  no

|  X-------->|  |  |  Request(V2)
|  |         X->|->|  Prepare(N+2,V2)
|  |         |<-X--X  Promise(N+2})
|  |         X->|->|  Accept!(N+2,0,V2)
|  |         X<>X<>X  Accepted(N+2,0,V2)
|  |<--------X  |  |  Response

|  X-------->|  |  |  Request(V3)
|  |         X->|->|  Accept!(N+2,1,V3)
|  |         X<>X<>X  Accepted(N+2,1,V3)
|  |<--------X  |  |  Response
```

S_2 takes over

S_1 accept fails

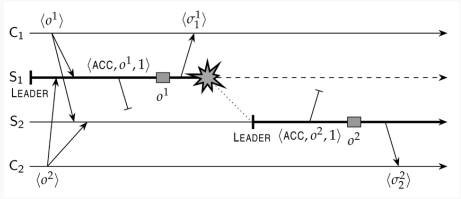
S_1 succeeds

S_1 back on track

derived from wikipedia

RH 11

Q1 Leader/backup
2 Points



Q1.1
1 Point

What issues make this example of a leader/backup system incorrect?

- (●) S_1 and S_2 commit different values first
- ( ) S_1's accept msg does not make it to S_2.
- ( ) S_2's accept msg does not make it to S_1.
- ( ) all of the above
- ( ) none of the above

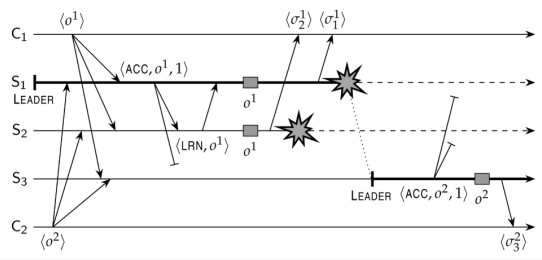
Q1.2
1 Point

How can it be fixed?

Explanation
wait for an acknowledgement of the `accept` message before committing the value.

RH 11

Q2 Leader/backup
3 Points



Q2.1
1 Point

Why did S_1/S_2 and S_3 diverge?

Explanation
It did not communicate with enough other servers to find out about the prior committed values.

Q2.2
1 Point

How to fix this?

Explanation
Require any leader to talk to a majority of all servers, including itself, before committing a value. Since all majority quorums overlap, at least one of the quorum members will have seen any prior value commits.

Q2.3
1 Point

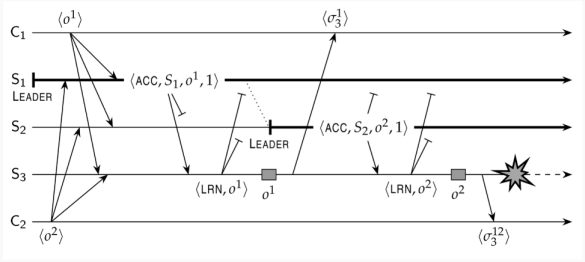
Will this example nonetheless give the correct answers?

Explanation
No. In more detail, committing value in different orders is expected to result in different final results, unless all the values *commute*.

RH 11

Q3 Leader/backup
1 Point

What's wrong w/ this example (still not paxos yet):



Explanation

S_3 replied to client before S_3 knew that any other servers knew about the choice.

Q4 Paxos!
4 Points

Q4.1
1 Point

Can an acceptor *promise* more than one proposal?

- (•) yes
- ( ) no

RH 11

Q4.3
1 Point

Now additionally assume that:

- all acceptors see this same sequence of *prepare* messages, and that
- all *prepare* and *promise* messages are received and processed before any *accept* messages are ever sent.

Which proposals are eventually *accepted* (w/ an *accepted* message)?

- [ ] $1/o_1$
- [ ] $5/o_2$
- [ ] $5/o_3$
- [ ] $4/o_4$
- [x] $8/o_5$

Explanation

All of the acceptors *promise* proposals 1,5, and then 8. Because of the last one, they cannot accept any *lower* ordered proposals.

Q4.2
1 Point

Assume a sequence of *prepare* messages with numbers/values, $1/o_1, 5/o_2, 5/o_3, 4/o_4, 8/o_5$, is seen by an acceptor. The proposals may have been sent by different proposers.

Which will of the following will be given *promises*?

- [x] $1/o_1$
- [x] $5/o_2$
- [ ] $5/o_3$
- [ ] $4/o_4$
- [x] $8/o_5$

Explanation

Acceptor will only promise an *n* if it has not received any prior proposals w/ number *n* or above.

Q4.4
1 Point

Which value is finally *accepted* and *committed*?

- [ ] o_1
- [x] o_2
- [ ] o_3
- [ ] o_4
- [ ] o_5

Explanation

A proposer only uses it's own value if no **promise** tells it of any prior **promise**d values. If it has seen such values, it chooses the value of the max previously promised proposal.

RH 11

Q5 Multi-Paxos!
4 Points

Assume:

- system of three servers
- all sent messages are received
- no failures (yet)

Q5.1
1 Point

How many communication roundtrip delays are required for a proposer to be ready to inform the client that a single value has been accepted?

A roundtrip is the duration observed by the proposer from when it sent a message until it received a reponse. Assume all messages sent in parallel arrive at the same time and do not consider the communication to and from the client.

- ○ 0
- ○ 1
- ◉ 2
- ○ 3
- ○ 4

Q5.2
1 Point

How many roundtrips will be observed to instead commit *three* values, assuming no interference from other proposers?

- ○ 0
- ○ 1
- ○ 2
- ○ 3
- ◉ 4
- ○ 5
- ○ 6

Explanation
First phase once, second phase all three times: $1 + 3 = 4$.

Q5.3
1 Point

Same as question 5.1, but for Paxos:

- ○ 0
- ○ 1
- ◉ 2
- ○ 3
- ○ 4
- ○ 5
- ○ 6

Q5.4
1 Point

Same as question 5.2, but for Paxos:

- ○ 0
- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ◉ 6

Final Exam

- 32 pts comprehensive
  - fill in the blank
- 36 pts GeekOS
  - should be straightforward if you worked through the projects
  - short answer
- 32 pts Paxos/MultiPaxos
  - 14 pts true/false
  - 6 pts fill-in-the-blanks
  - 12 pts short answer