Raft and Paxos Exam Rubric

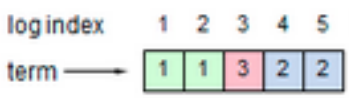
Grading

Where points are taken away for incorrect information, every section still has a minimum of 0 points.

Raft Exam

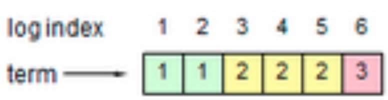
1. (4 points, easy) Each figure below shows a possible log configuration for a Raft server (the contents of log entries are not shown; just their indexes and terms). Considering each log in isolation, could that log configuration occur in a proper implementation of Raft? If the answer is "no," explain why not.

(a)



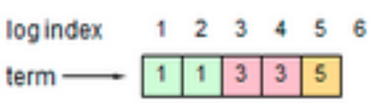
No: terms increase monotonically in a log.
Specifically, the leader that created entry <4,2> could only have received <3,3> from a leader with current term >= 3, so its current term would also be >= 3. Then it could not create <4,2>.

(b)



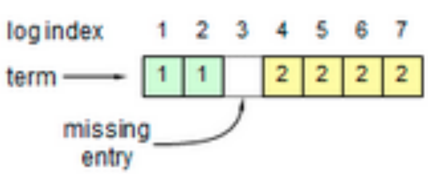
Yes

(c)



Yes

(d)



No: logs can not have holes.
Specifically, leaders only append to their logs, and the consistency check in AppendEntries never matches a hole.

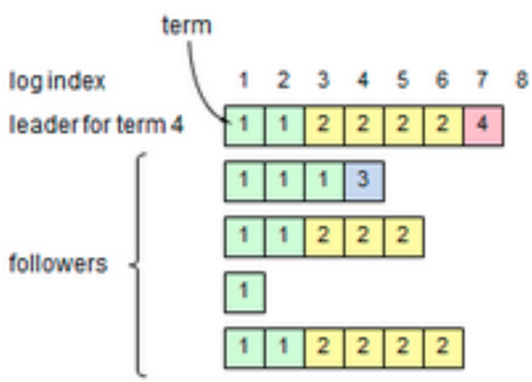
Grading: 4 points total

One point per part.

If the answer is yes, saying "yes" earns you 1 point. Saying "no" earns you no points. Any supporting explanations are ignored.

If the answer is no, saying "no" earns you half of the point, and a correct explanation earns you the other half. Not much supporting explanation is required. Saying "yes" earns you no points, and any accompanying explanation is ignored.

2. (6 points, medium) The figure below shows the state of the logs in a cluster of 5 servers (the contents of the entries are not shown). Which log entries may safely be applied to state machines? Explain your answer.



Entries <1,1> and <2,1> may be safely applied:

If an entry is not stored on a quorum, it can not be applied safely. This is because this minority can fail, and the other servers (which form a majority) can proceed with no knowledge of the entry.

Thus, we need only consider entries <1,1>, <2,1>, <3,2>, <4,2>, <5,2>.

We need to figure out which ones could be elected leader, and see if they could cause these entries to be removed.

Well, Server 2 can be elected leader because its log is at least as complete as S3, S4, and S5. It could then cause servers to remove entries <3,2>, <4,2>, and <5,2>, so those entries are not safe to apply.

So now we're left with entries <1,1>, <2,1> as possibly safe to apply.

Servers 3 and 4 can't be elected leader because their logs are not complete enough. Server 5 can be elected leader, but it contains <1,1> and <2,1>.

Therefore, only entries <1,1> and <2,1> are safe to apply.

Grading: 6 points total

3 points for saying "entries <1,1> and <2,1>" or "entries 1 and 2" (since there is no ambiguity). No partial credit is awarded for these 3 points, but responses with an incorrect answer may still be awarded partial credit for the explanation.

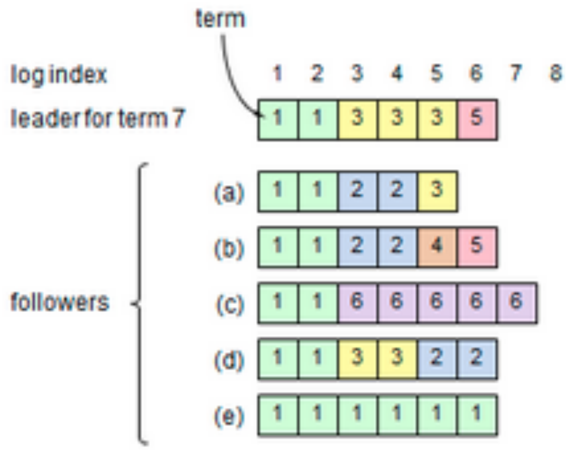
3 points for the explanation:
1 point for saying the entry must be stored on a quorum
2 point for saying that server 2 may be elected leader, which threatens entries past index 2

An answer that says "1 and 2 because entries from term 2 can't be committed until one of the entries from the leader's term reaches a majority of servers" receives 4.5 points (we got 3 answers like this; it's correct but not clear whether the participants understood why).

The incorrect answer of "entries 1-5 because they are stored on a majority" gets 1 point. The incorrect answer of "entries 1-6 because they are stored on a majority" gets 0 points (entry 6 is not).

3. (10 points, medium) Consider the figure below, which displays the logs in a cluster of 6 servers just after a new leader

has just been elected for term 7 (the contents of log entries are not shown; just their indexes and terms). For each of the followers in the figure, could the given log configuration occur in a properly functioning Raft system? If yes, describe how this could happen; if no, explain why it could not happen.



a) No. Entry <5,3> uniquely identifies a log prefix (by the AppendEntries consistency check), but this follower has entry <5,3> and a different log prefix before it than the leader.

b) No. Entry <6,5> uniquely identifies a log prefix (by the AppendEntries consistency check), but this follower has entry <6,5> and a different log prefix before it than the leader.

c) Yes. Since we can't say much about the other servers in the cluster, this server could have been leader in term 6 with a starting log of <1,1>, <2,1> and could have written a bunch of entries to its log and not communicated with our current leader of term 7. This assumes that entries <3,3>, <4,3>, <5,3>, and <6,5> were not committed in term 5, which is possible.

d) No. Terms increase monotonically in a log.
Specifically, the leader that created entry <5,2> could only have received <4,3> from a leader with current term >= 3, so its current term would also be >= 3. Then it could not create <5,2>.

e) Yes. For example, (e) is the leader for term 1 and commits entries <1,1> and <2,1>, then becomes partitioned from the other servers but continues processing client requests.

Grading: 10 points total
Two points per part.

1 for the boolean,
1 for a correct explanation.

If the boolean is incorrect, no points are awarded for the explanation.
If the boolean is correct, not much supporting explanation is required.

4. (5 points, medium) Suppose that a hardware or software error corrupts the nextIndex value stored by the leader for a particular follower. Could this compromise the safety of the system? Explain your answer briefly.

No.

If the nextIndex value is too small, the leader will send extra AppendEntries requests. Each will have no effect on the follower's log (they will pass the consistency check but not conflict with any entries in the follower's log or provide any entries to the follower that the follower didn't already have), and the successful response will indicate to the leader that it should increase its nextIndex.

If the nextIndex value is too large, the leader will also send extra AppendEntries requests. The consistency check will fail on these, causing the follower to reject the request and the leader to decrement nextIndex and retry.

Either way, this is safe behavior, as no critical state is modified in either case.

Grading: 5 points total
1 points for saying "no".
2 point for explaining what happens if nextIndex is too small.
2 point for explaining what happens if nextIndex is too large.

Answers that say a follower would truncate its log when nextIndex is too small receive -1 points, as that could result in a safety violation.

If the boolean is incorrect, partial credit may still be awarded for correct explanations.

5. (5 points, medium) Suppose that you implemented Raft and deployed it with all servers in the same datacenter. Now suppose that you were going to deploy the system with each server in a different datacenter, spread over the world. What changes would you need to make, if any, in the wide-area version of Raft compared to the single-datacenter version, and why?

We'd need to set the election timeouts higher: my expected broadcast time is higher, and the election timeout should be much higher than the broadcast time so that candidates have a chance to complete an election before timing out again. The rest of the algorithm does not require any changes, since it does not depend on timing.

Grading: 5 points total

For full credit, an answer needs to say to increase the election timeout and as justification mention increased latency or some sort of livelock.

Answers that talk about "increasing timeouts" without specifically mentioning elections receive up to 3.5 points (this affects 4 answers).

Unnecessary or optional changes (performance improvements) are ignored if correctly identified as such.
Negative points are awarded for other changes identified as required.

6. (10 points, hard) Each follower stores 3 pieces of information on its disk: its current term, its most recent vote, and all of the log entries it has accepted.

(a) Suppose that the follower crashes, and when it restarts, its most recent vote has been lost. Is it safe for the follower to rejoin the cluster (assuming no modifications to the algorithm)? Explain your answer.

No. This would allow a server to vote twice in the same term, which would then allow multiple leaders per term, which breaks just about everything.

For example, with 3 servers:
S1 acquires S1 and S2's votes and becomes leader of term 2.
S2 restarts and forgets it voted in term 2.
S3 acquires S2 and S3's votes and becomes the second leader of term 2.
Now S1 and S3 can commit distinct entries in term 2 with the same index and terms but different values.

(b) Now suppose that the follower's log is truncated during a crash, losing some of the entries at the end. Is it safe for the follower to rejoin the cluster (assuming no modifications to the algorithm)? Explain your answer.

No. This would allow a committed entry to not be stored on a quorum, which would then allow some other entry to be committed for the same index.

For example, with 3 servers.

S1 becomes leader in term 2 and apppends index=1, term=2, value=X on itself and S2.
S1 sets its committedIndex to 1 and returns to the client that X is committed.
S2 restarts and loses the entry from its log.

S3 (with an empty log) becomes leader in term 3, since its empty log is at least as complete as S2's.
S3 appends index=1, term=3, value=Y on itself and S2.
S3 sets its committedIndex to 1 and returns to the client that Y is committed.

Grading: 10 points total
5 points per part

1 point for the boolean,
4 points for a correct explanation (the detailed scenarios above are not required)

For full credit on part (a), answers needed to include that this would allow multiple leaders to be elected for the same term, not just that a follower could vote twice.

If the boolean is incorrect, no points are awarded for the explanation.

7. (10 points, hard) As described in the video, it's possible for a leader to continue operating even after other servers have decided that it crashed and elected a new leader. The new leader will have contacted a majority of the cluster and updated their terms, so the old leader will step down as soon as it communicates with any of these servers. However, in the meantime it can continue to act as leader and issue requests to followers that have not yet been contacted by the new leader; furthermore, clients may continue to send requests to the old leader. We know that the old leader cannot commit any *new* log entries it receives after the election has completed, since it would need to contact at least one of the servers in the electing majority to do this. But, is it possible for an old leader to execute a successful AppendEntries RPC that completes the commitment of an old log entry that was received before the election started? If so, explain how this could happen, and discuss whether or not this will cause problems for the Raft protocol. If this cannot happen, explain why.

Yes. This can only happen if the new leader also contains the entry being committed, so it will not cause problems.

Here's an example of this happening with 5 servers:
S1 with an empty log becomes leader for term 2 with votes S1, S2, and S3.
S1 completes appending index=1, term=2, value=X to itself and S2.
S2 with index=1, term=2, value=X in its log becomes leader for term 3 with votes S2, S4, S5.
S1 completes appending index=1, term=2, value=X to S3.
At this point, S1 has completed committment of index=1, term=2, value=X, even though it is no longer the current leader.

This behavior is safe because any new leader must also contain the entry, and so it will persist forever:
The entry must be stored on some server S that votes for the new leader L, and it must be stored on S *before* S votes for that new leader. The log completeness check says that S may only vote for L if:
L.lastLogTerm > S.lastLogTerm or
(L.lastLogTerm == S.lastLogTerm and L.lastLogIndex >= S.lastLogIndex)
If L is the first leader after S, we must be in the second case, and then L must contain every entry that S has, including the one we're worried about.
If L' is the second leader after S, L' could only have a larger last term than S if it received entries from L. But L must have replicated the entry we're worried about to L' prior to replicating any of its own entries to L', so this is also safe.
And this argument holds inductively for all future leaders.

Grading: 10 points total

4 points for showing this is possible
- 1 point for saying "Yes, it is possible"
- For the remaining 3 points, answers must include that the deposed leader completed an AppendEntries request to one of the voters of the new leader before that server voted.

6 points for arguing that it is not a problem
- 1 point for saying "It's not a problem."

- For the remaining 5 points, answers must include that because some voter must have the entry, the log completeness check guarantees that the new leader must also have the entry.

No points awarded for saying this cannot happen.
Credit for the scenario may be awarded even if the answer argues that this is a problem for Raft.

8. (10 points, hard) During configuration changes, if the current leader is not in C_{new}, it steps down once the log entry for C_{new} is committed. However, this means that there is a period of time when the leader is not part of the cluster it's leading (the current configuration entry stored on the leader is C_{new}, which does not include the leader). Suppose the protocol were modified so that the leader steps down as soon as it stores C_{new} in its log, if C_{new} doesn't include the leader. What's the worst that could happen with this approach?

Depending on the interpretation of the algorithm, there's two possible correct answers.

Answer 1 assumes a decent implementation -- that once a server is not part of its current configuration, it does not become candidate anymore. The problem is that another server in C_{old} could then be elected as leader, append C_{new} to its log, and immediately step down.

Worse yet, this could repeat for a majority of the servers C_{old}. It couldn't repeat more than that because once a majority of C_{old} stores the C_{new} entry, no server from C_{old} without this entry could be elected due to the log completeness check (a majority of C_{old}, required for $C_{old+new}$, would no longer grant its vote to this server).

After this, a server in C_{new} would have to get elected, and the cluster would continue. So the worst case is really just running through up to about $|C_{old}|/2$ extra elections and election timeouts.

Answer 2 assumes a naive implementation that allows a server that is not part of its current configuration to still become candidate. In this case, the worst thing that could happen is that the leader gets elected again as soon as it steps down (its log is still complete), then steps down again, then repeats infinitely.

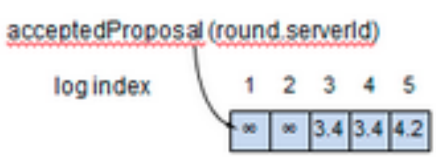
Grading: 10 points total

For full credit, an answer needs to identify that a server not in Cnew can be elected, that this can repeat, include a reasonable bound on this repetition, and mention that this causes an availability or liveness problem.

Paxos Exam

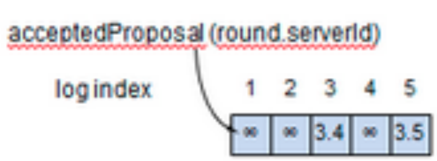
1. (4 points, easy) Each figure below shows a possible log configuration for a Multi-Paxos server (the number in each log entry gives its acceptedProposal value). Considering each log in isolation, could that log configuration occur in a proper implementation of Multi-Paxos?

(a)



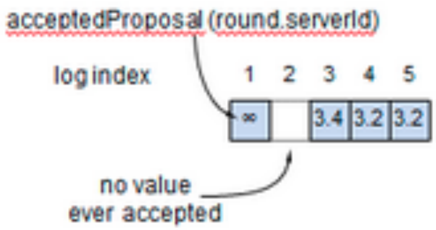
Yes

(b)



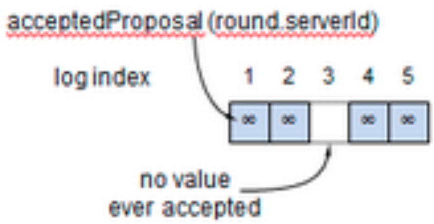
Yes

(c)



Yes

(d)



Yes

Grading: 4 points
1 point per boolean (no partial credit)

2. (6 points, medium) In Basic Paxos, suppose that a cluster contains 5 servers and 3 of them have accepted proposal 5.1 with value X. Once this has happened, is it possible that any server in the cluster could accept a different value Y? Explain your answer.

Yes. If it's S1, S2, and S3 that have accepted <5.1, X>, other servers could still accept Y if it has a stale proposal number.

For example, S4 could prepare 3.4 and discover no values. Then S1 could prepare 5.1 on just S1, S2, S3. Then S1 could complete accepts on just S1, S2, S3. And S4 can still complete accepts on S4 and S5 with <3.4, Y>.

Grading: 6 points total

2 points for saying "Yes", and 4 points for the accompanying explanation. The explanation must indicate that Y's proposal is concurrent with or numbered less than 5.1 (otherwise, -2 points).

The incorrect answer "No, because any new proposal must discover <5.1, X> in its prepare phase" receives 2 points. Other incorrect answers with "No" receive no credit.

3. (10 points, medium) Suppose that a server has just decided to act as leader in Multi-Paxos, and that no other servers are currently acting as leaders. Furthermore, assume that the server continues as leader for a period of time, arranging for many commands to be chosen for log entries, and that no other server attempts to act as leader during this period.

a) What is the lower bound on the number of rounds of Prepare RPCs that the server must issue during this period? Explain your answer, and be as precise as possible.

The lower bound is 1 round of Prepare RPCs, if a quorum of Prepare responses are returned right away that have noMoreAccepted=true.

b) What is the upper bound on the number of rounds of Prepare RPCs that the server must issue during this period? Explain your answer, and be as precise as possible.

The upper bound is one round of Prepare RPCs for each slot that is not chosen on the leader for which any acceptor has accepted any proposal. This can happen if every time the leader issues a prepare for one of its unchosen slots, it discovers an acceptor that has already accepted some value; then it needs to adopt this value for this slot and continue trying with the next slot.

Grading: 10 points total
5 points per part

For part a:

Just saying "1" is worth 2 points; the accompanying explanation is worth 3 points.

The explanation must include some mention of noMoreAccepted or the concept behind it.

For part b:

3 points for saying the number of entries a follower has accepted
2 points for subtracting out the ones that are chosen on the leader

An answer which is lacking precision that says "the upper bound is arbitrarily large" but which has a correct explanation as to why more than 1 is necessary receives 2 points.

Answers that just say "until noMoreAccepted is true for a majority" receive 2 points (true, but they could have gotten this off the slide without understanding).

Answers that are O(1) or O(Len(leader's log)) for part (b) are awarded no credit.

4. (5 points medium) When an acceptor is marking entries accepted using the firstUnchosenIndex provided by the proposer, it must first check the proposal number in the entries that it marks. Suppose it skipped this check: describe a scenario where the system would misbehave.

The question should have read "marking entries chosen" instead of "marking entries accepted". Oops.

The misbehavior that can arise is a server marking a value as chosen when a different value has been chosen. This requires a minimum of 2 competing proposals, 3 servers, and 2 log entries to show:

S1 completes a round of prepare for n=1.1, index=1 with S1, S2.
S1 completes only one accept for n=1.1, v=X, index=1 with S1 (itself).
S2 completes a round of prepare for n=2.2, index=1 with S2, S3 and gets back noMoreAccepted=true from both.
S2 completes a round of accept for n=2.2, v=Y, index=1 with S2, S3.
S2 marks index 1 as chosen.
S2 completes a round of accept for n=2.2, v=Z, index=2, firstUnchosenIndex=2 with S1, S2, and S3.
Here, S1 would have misbehaved by setting n=1.1, v=X as chosen and applying X to its state machine. This is incorrect, since in fact Y was chosen.

Grading: 5 points total

Unfortunately, most of the answers were not as specific as we would have liked for the scenario.

Full credit required identifying that the previously accepted *value* was different from the chosen value on the proposer, and not just that the proposal number was different. This helps separate people that regurgitated the material from people that had some understanding of why the algorithm is the way it is. Answers missing this component received up to 4 points (typically 2-3), depending on how well they showed understanding.

Since we messed up the wording in the question, no points were taken off on this question for confusing the words "accepted" and "chosen" in the answer (answers were read with these words exchanged in any way possible to give the answer the maximum number of points).

5. (5 points, medium) Suppose that the two parts of a proposal number (round number and unique server id) were exchanged, so that the server id is in the high-order bits.

a) Would this compromise the safety of Paxos? Explain your answer briefly.

No, since safety only requires proposals to be uniquely numbered (for a given index in Multi-Paxos). Because server IDs are unique to each server and round numbers still monotonically increase, this uniqueness is preserved.

b) Would this compromise the liveness of Paxos? Explain your answer briefly.

Yes, for example, the server with the largest ID could issue a Prepare RPC to every server in the cluster and then permanently fail. No other proposer would then be able to make any progress, since the remaining server's minProposal values would be too high for the remaining proposers.

Grading: 5 points total
2 points for safety, 3 points for liveness

For safety, saying "no" is worth 1 point, and a correct explanation is worth 1 point. Not much supporting explanation is required. Saying "yes" earns you no points, and any accompanying explanation is ignored.

For liveness, saying "yes" is worth 1 point, and a correct explanation is worth 2 points. Saying "no" earns you no points, and any accompanying explanation is ignored.

6. (10 points, hard) Suppose that a proposer executes the Basic Paxos protocol with an initial value of v1, but that it crashes at some (unknown) point during or after the execution of the protocol. Suppose that the proposer restarts and reexecutes the protocol from the beginning with the same proposal number used previously, but with a different initial value of v2. Is this safe? Explain your answer.

No. Different proposals must have distinct proposal numbers. Here's an example of something bad that can happen using 3 servers:

S1 completes Prepare(n=1.1) with S1, S2.
S1 completes Accept(n=1.1, v=v1) with S1.
S1 restarts.
S1 completes Prepare(n=1.1) with S2, S3 (and discovers no accepted proposals).
S1 completes Accept(n=1.1, v=v2) with S2, S3.
S1 responds to the client that v2 has been chosen.
S2 completes Prepare(n=2.2) with S1, S2 and gets back:
from S1: acceptedProposal=1.1, acceptedValue=v1,
from S2: acceptedProposal=1.1, acceptedValue=v2,
S2 chooses to use v1 arbitrarily.
S2 completes Accept(n=2.2, v=v1) with S1, S2, S3.
S2 responds to some client that v1 was chosen.

A different problem that can occur involves a request from before the crash being delivered after the crash:
S1 completes Prepare(n=1.1) with S1, S2.
S1 completes Accept(n=1.1, v=v1) with S1.
S1 sends Accept(n=1.1, v=v1) to S2 and S3, but they don't receive it yet.
S1 restarts.
S1 completes Prepare(n=1.1) with S2, S3 (and discovers no accepted proposals).
S1 completes Accept(n=1.1, v=v2) with S2, S3.
S1 responds to the client that v2 has been chosen.
Now S2 and S3 receive the Accept(n=1.1, v=v1) request and overwrite their acceptedValue to be v1.
The state of the cluster is now that v1 is chosen, even though a client has been told that v2 was chosen.

Grading: 10 points total

2 points for saying "no", and 8 points for a correct explanation

For full credit, answers needed to explain that v2's prepare phase did not discover v1 and include some violation of safety.

Saying "yes" earns you no points, and any accompanying explanation is ignored.

7. (10 points, hard) In a successful Accept RPC the acceptor sets its minProposal to n (the proposal number in the Accept RPC). Describe a scenario where this actually changes the value of minProposal (i.e., minProposal isn't already greater than or equal to n). Describe a scenario where the system would behave incorrectly without this code.

Working backwards, we need a server to receive an Accept that did not receive a Prepare, since otherwise its minProposal would be up to date. And for this to matter, a subsequent Accept needs to incorrectly not be rejected.

Using Basic Paxos and 5 servers.

S1 completes Prepare(n=1.1) with S1, S2, S3 (and discovers no accepted proposals).
S5 completes Prepare(n=2.5) with S3, S4, S5 (and discovers no accepted proposals).
S5 completes Accept(n=2.5, v=X) with S2, S3, S5. This is where S2's minProposal would be to 2.5 upon processing the Accept request.
S5 returns to the client that X is chosen.
S1 completes Accept(n=1.1, v=Y) with S2. This would normally be rejected, but would be accepted if S2's minProposal was not updated during Accept.
S3 completes Prepare(n=3.3) with S1, S2, S4 (and discovers n=1.1, v=Y).
S3 completes Accept(n=3.3, v=Y) with S1, S2, S3, S4, S5.
S3 returns to a client that Y is chosen.

Grading: 10 points total

4 points for the first three steps showing how minProposal can be set during Accept.
6 points for showing how the system misbehaves. For full credit, this must include a safety violation.

8. (10 points, hard) Consider a configuration change in Multi-Paxos, where the old configuration consists of servers 1, 2, and 3, and the new configuration consists of servers 3, 4, and 5. Suppose that the new configuration has been chosen for entry N in the log, and entries N through N+α (inclusive) have also been chosen. Suppose that at this point the old servers 1 and 2 are shut down because they are not part of the new configuration. Describe a problem that this could cause in the system.

This could cause a liveness problem for the new cluster because firstUnchosenIndex on those servers may be less than N+alpha.

For example in the worst case, server 3 might have failed permanently, and servers 1 and 2 would have made no attempt to transfer any values to servers 4 and 5 (using just the algorithm presented in the lecture). Then, try as they might, servers 4 and 5 will never be able to learn the chosen values for slots 1 through N+alpha-1 (inclusive), since they can't communicate with servers 1, 2, or 3. Server 4 and 5's state machines would never be able to advance beyond their initial state.

Grading: 10 points total

A complete answer must say that the new servers are missing chosen entries and dismiss server 3 as the solution.

Answers received up to 7 points if they implied server 3 must have all information (it can fail). Answers received up to 8 points if they implied server 3 having all information is sufficient (it can fail).

No points will be awarded for incorrectly saying there is no problem.

No points will be awarded for incorrectly saying that some slots in the range 1 through N - 1 (inclusive) may not have been chosen. That's because [N,N+alpha] chosen implies [1,N+alpha] chosen by the definition of alpha.