Department of Electrical Engineering and Computer Science

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

6.824 Distributed System Engineering: Spring 2009

Quiz II Solutions

All problems are open-ended questions. In order to receive credit you must answer the question as precisely as possible. The quiz is designed to take 80 minutes, but you have two hours to complete it. (If you finish early, we included some light additional reading.)

Write your name on this cover sheet AND at the bottom of each page of this booklet.

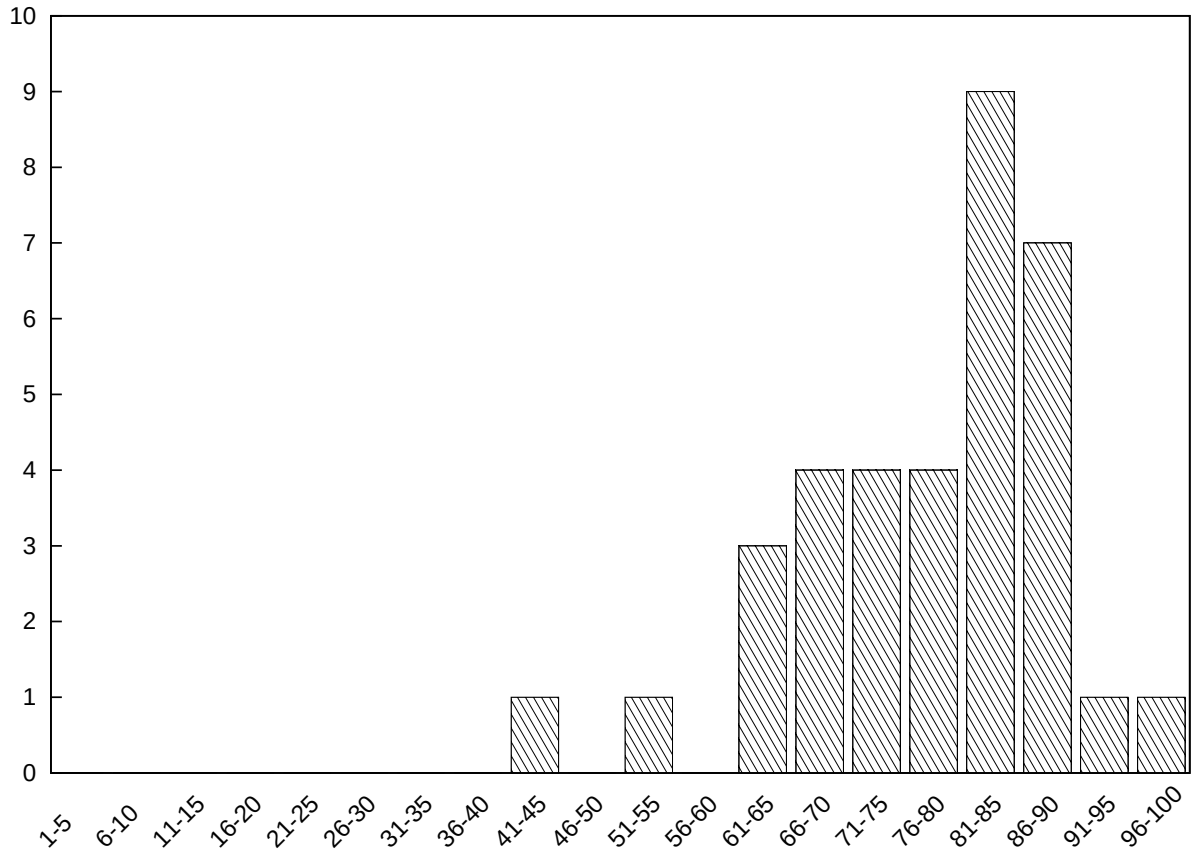
Some questions may be much harder than others. Read them all through first and attack them in the order that allows you to make the most progress. If you find a question ambiguous, be sure to write down any assumptions you make. Be neat. If we can't understand your answer, we can't give you credit!

THIS IS AN OPEN BOOK, OPEN NOTES QUIZ.

I (xx/40)	II (xx/16)	III (xx/25)	IV (xx/12)	V (xx/7)	Total (xx/100)

Name:

Grade histogram for Quiz 2



$$\begin{aligned} \text{max} &= 99 \\ \text{median} &= 81 \\ \mu &= 77.3 \\ \sigma &= 11.3 \end{aligned}$$

I Short Questions

1. [8 points]: The Storm authors, tired of pesky researchers infiltrating their botnet, want to prevent it from being subverted in the future. They propose two defenses to address the attacks used by the Spamalytics authors, and hire you to evaluate their designs. (For the purposes of this problem, assume that you have no scruples.) Assume that the Storm authors have a secure way to distribute keys to proxies and workers.

Which of the following changes would address the attack described in the Spamalytics paper? Circle all that apply. For each proposal that won't work, explain why not. If they both work, identify the one you think is better (for the Storm authors) and give a specific argument why it is superior.

(a) Each master adds a MAC to messages for each proxy using a key it shares with that proxy. Each proxy adds a MAC to messages for each worker using a key it shares with that worker. Proxies and workers verify the MACs on messages they receive.

(b) The masters use their private keys to sign the tasks intended for each worker. Workers verify the signatures on messages they receive.

Both changes address the attack described in the paper, wherein the researchers run the unmodified proxy and only intercept and rewrite network traffic.

So which one is better? You could have argued that MACs are better because they solve the problem and are much cheaper than signatures, which reduces the load on the master. Alternatively, you could have argued that signatures are better because they would prevent more sophisticated attacks where the proxies themselves are modified.

2. [8 points]: After seeing the 6.824 Lab 9 demos, Ben Bitdiddle decides to implement his extent service on top of Chord for better scalability. He implements Chord as described in the paper. He uses the extent numbers as keys, and stores each extent at the Chord node that is responsible for the extent's key. He notices that when a new node is joining, `gets` sometimes fail and report that extents are missing. Give a specific example to illustrate the problem, and describe a simple way to fix it. Assume that there are no failures, network partitions, or multiple concurrent joins.

This can happen when a new node joins the ring but has not yet transferred the extents from its successor. Several fixes are possible, but the simplest is probably the one suggested by the paper, where clients retry periodically if Chord can't find the requested extent.

3. [8 points]: Suppose we took a system that uses SUNDR and made it extra secure by replicating the SUNDR server with BFT. In what ways does this provide stronger security than just using SUNDR alone?

One answer is that if between 1 and f replicas are compromised, BFT + SUNDR provides sequential consistency instead of fork consistency. Another possible answer is that BFT + SUNDR provides availability when between 1 and f replicas are compromised, whereas with SUNDR alone, a single compromised server can prevent clients from making progress.

4. [8 points]: Consider the application described in Example 1 in the PNUTS paper. Describe how you would write this application with the PNUTS primitives (`read-any`, `read-critical`, `read-latest`, `write`, and `test-and-set-write`.) You only need to discuss the two operations in the example: publishing photos and updating the access control list. Explain why your implementation would avoid the problem discussed in the example.

One possible solution:

```
(acl, photos) = read-any();
latest_version = write(acl - 'mom');
while (!test-and-set-write(latest_version, photos + new_photo))
 (latest_version, photos) = read-latest(photos);
```

This ensures that the ACL update is applied before the photo is published. Since PNUTS only guarantees per-row consistency, the photo list and the ACL must also be in the same row.

5. [8 points]: Ben is designing a new web browser, Chromium, and considering which features to include to achieve world domination. After reading the Coral paper, he wonders if he could add something to the browser to simplify the design of the Coral CDN and reduce latency for users. Describe the additional functionality the web browser should have to achieve Ben's goals, and explain how it achieves them.

A good strategy is for the browser to do the measurement and proxy selection itself, rather than relying on a layer of indirection (the resolver) to do it. This simplifies the resolver and results in more accurate measurement; the system no longer needs the assumption that proxies that are close to the resolver are close to the client. It also means that dnssrv does not need to verify that HTTP proxies are live before returning them. (See the last paragraph of Section 3.1.)

II Paxos

Recall the following snippets from the Paxos pseudocode in lab 7:

```
if node receives prepare(instance, n):
  if instance <= instance_h:
    return oldinstance(instance, values[instance])
[...]
if node gets accept(instance, n, v):
  if instance <= instance_h:
    return oldinstance(instance, values[instance])
```

6. [8 points]: Many students noticed that the return type of `acceptreq()` was an integer and couldn't encode an `oldinstance` response. It was claimed on the mailing lists that it was okay to simply reject the `accept` message in the above scenario instead of modifying the return type of `acceptreq()` to return an `oldinstance` response. Explain why this modification is correct.

If a quorum of nodes are in a later view and reject the `accept` message, the leader will fail to get a majority, abort, and try again starting from the prepare phase. When it sends out the new `prepare`s, it will get an `oldinstance` response. (Even though it does not affect correctness, allowing `accept` to return an `oldinstance` response might improve performance marginally.)

Recall the `rsm_tester`'s test 6, which kills the fourth server, then kills the primary after the accept phase of Paxos but before the decide phase. Finally, it restarts the fourth server.

A student asked the following question on the discussion list:

> When I try test 6, nodes 2/3/4 all manage to agree on the view (2,3,4) in the end, but they don't first agree on the view originally proposed by the first node (that is, (1,2,3)), so the test fails. I don't see what's wrong with what my implementation does – why should nodes 2/3/4 agree on (1,2,3) before moving on to (2,3,4)?

7. [8 points]: Provide a succinct answer to the student's question:

Once an instance of Paxos has chosen a particular value, no other value should be chosen. Otherwise, different nodes might disagree about the membership of the new view, which is exactly the problem Paxos is designed to prevent. Hence, when the coordinator fails after a quorum has accepted the value `(1,2,3)`, the new coordinator must commit `(1,2,3)`.

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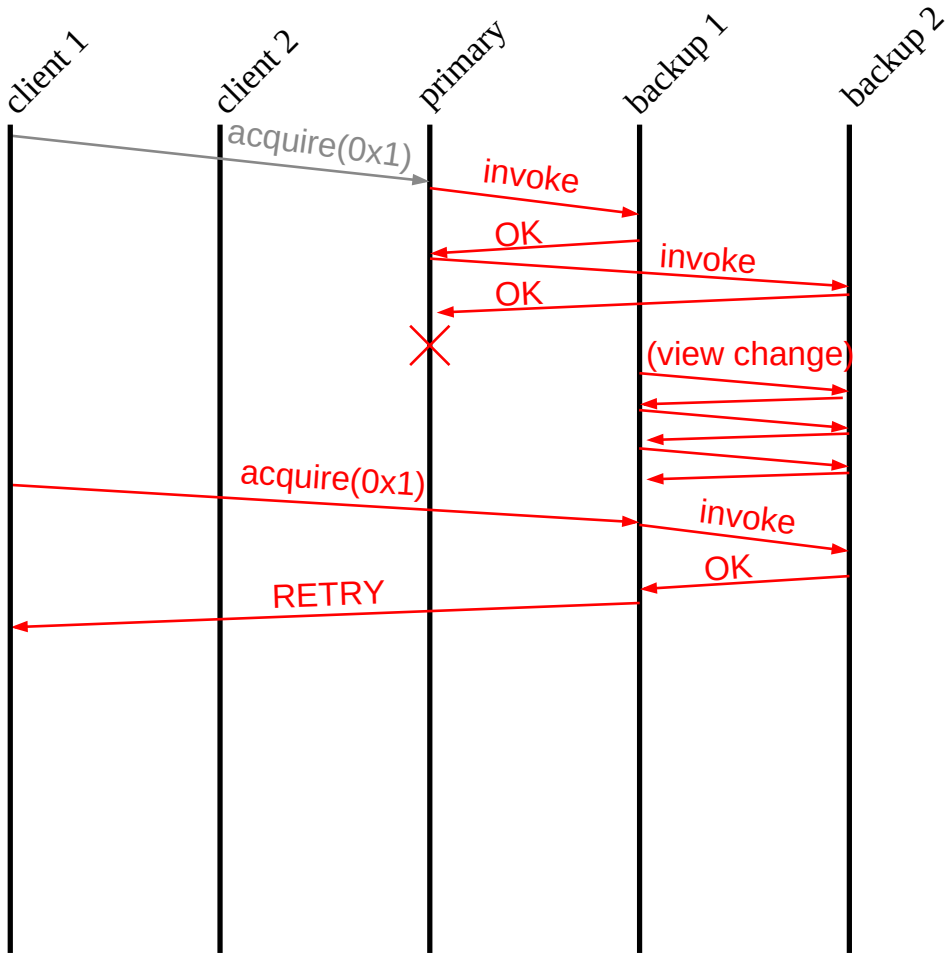
III Replicated State Machines

Lem E. Tweakitt completes all the 6.824 labs as suggested by the course staff. However, he isn't sure why his lock service needs to add sequence numbers to `acquire` and `release` requests. He reasons that the RPC code already attaches sequence numbers to requests and provides at-most-once semantics, and it appears that the additional sequence numbers are redundant.

8. [8 points]: Use the timing diagram below to show what would go wrong if Lem omitted these sequence numbers (and related code) from the lock service, and made no other changes. Assume that the clients do not crash and failed replicas do not re-join. ~~Hint: The scenario must involve two clients.~~



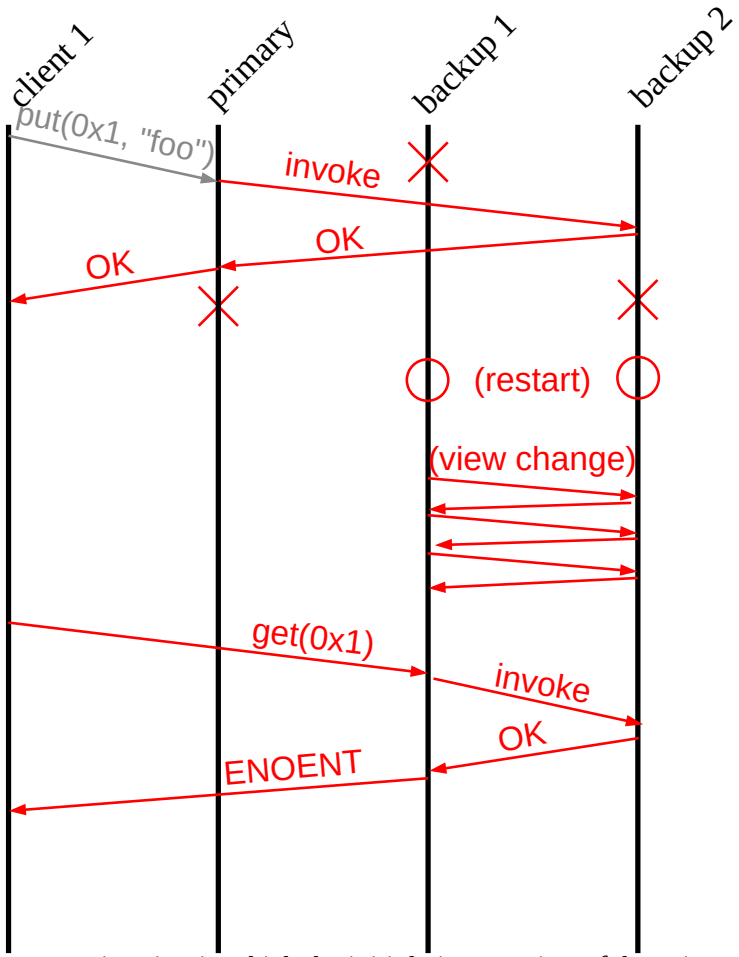
The diagram illustrates a scenario where the primary sends the `acquire` *operation to the backups, then crashes before it can reply to the client. A view change occurs, and the client retries the request on the new primary. However, the new primary's state indicates that the lock is already held, so it incorrectly replies with* `RETRY`*.*

In principle, Lem could modify his lock server to address the above problem by looking at which client sent the `acquire` *request. However, it's possible to construct a scenario where sequence numbers are needed regardless. Suppose the* `rsm_client` *times out and retransmits a* `release` *request. The original request is delayed by the network and delivered much later, after the lock has been acquired again. This confuses the lock server into granting the lock to two different clients.*

Lem observes that the extent service loses all its state if the extent server crashes. He modifies the extent service to keep its state on disk. When a `put` writes an extent, the extent service writes the modified extent to the disk before returning an `OK` response. For high availability, he replicates this extent service using his correctly working RSM code. As with the lock service, his extent service adds sequence numbers to `puts` and `gets` and handles duplicates appropriately.

Since the extent service stores state on disk, Lem also wants the RSM to recover correctly after nodes fail and re-join the RSM. In particular, Lem wants to make it possible for all nodes of the RSM to fail, restart, re-join, and continue correctly when a majority of the nodes is back up.

9. [8 points]: Alyssa argues that the YFS RSM design is insufficient for correct recovery of Lem's service. She suggests that Lem should modify the extent service to write the view stamp (view #, sequence #) of the last RSM operation on disk before acknowledging the operation to primary. The primary writes the view stamp on disk before responding to a client. Use the timing diagram below to construct a scenario that shows what might go wrong without Alyssa's fix.



The diagram illustrates a situation in which the initial view consists of the primary and backup 2. All the replicas crash at a point where backup 2 has extent `0x1`. The two backups restart and recover, and backup 1 becomes the new primary. However, the backups' states differ: backup 2 has extent `0x1` and backup 1 does not. Without knowing the last viewstamp each replica committed, it's uncertain which replica has the most up-to-date state. If the recovery procedure guesses wrong, then sequential consistency is violated, as illustrated in the diagram.

Name:

After implementing Alyssa's suggestion, Lem observes that his RSM handles failures well. However, Lem's naïve recovery protocol (based on the Lab 8 framework) is inefficient when there are many extents because primary and backups transfer all the extents over the network to synchronize their state. For instance, in Lem's system, if a node crashes and immediately re-joins, it will download all of the extents from the primary, even if most of the extents on the recovering node's disk are already up to date.

10. [9 points]: Ben Bitdiddle tells Lem that he may be able to speed up recovery in some cases by using redo-only logs. Propose a design that uses redo logs for recovery. You may need to change both the replication protocol and the recovery protocol.

The key challenge in this problem is that if a failure occurs, some of the backups may have received an operation from the primary that will not commit. For instance, suppose extent `0x1` *initially contains* `foo`*, and a backup receives* `put(0x1, "bar")` *from the primary. It writes the new value to disk and logs it, but becomes partitioned from the network before it can reply. The primary aborts the operation and initiates a view change to remove the partitioned backup. The other replicas, which all agree that extent* `0x1` *contains* `foo`*, continue to process requests. When the excluded backup rejoins, its log and the contents of extent* `0x1` *will be inconsistent with the other replicas.*

Replication protocol: A simple solution to this problem is to use a two-phase replication protocol. The backups log and acknowledge `invoke` *requests, but not execute the operations right away. When the primary replies to the client, it also multicasts a* `commit` *message to the backups, informing them that they can execute the requests. (Since the replication protocol we use does not allow multiple concurrent requests, the primary can implicitly tell the backups to commit request r when it sends request $r + 1$.)*

Recovery protocol: Instead of doing full state transfer, nodes send only the needed log entries. A backup that rejoins and is n operations behind needs the last n committed log entries. Additionally, if the new primary logged an `invoke` *in the old view, it should re-send the request in the new view and ensure that the backups commit it (since a replica that failed in the old view might have committed it already.)*

An alternative solution is to have the primary ask the backups to checkpoint their logs periodically, which effectively provides an "undo" mechanism. (To address the problem described above, the checkpoint must cover up to the most recently committed operation.) In recovery, nodes send log entries as described above and roll forward from the most recent checkpoint.

IV Byzantine Fault Tolerance

For each of the following changes to BFT, explain what can go wrong with the resulting protocol. If nothing can go wrong, explain why not. (Focus on correctness, not performance.)

11. [4 points]: Reducing the number of messages: Instead of having every replica broadcast prepare and commit messages ($O(n^2)$ messages in total) as described in the paper, replicas send these messages to the primary. The primary collects $2f + 1$ `prepare` (or `commit`) messages and then broadcasts a prepared (or committed) certificate to the replicas ($O(n)$ messages in total).

This change is fine. BFT does not trust the network and signs all messages, so a malicious primary can't trick replicas into accepting bogus messages. The primary can try to prevent the replicas for making progress, but the replicas will eventually notice this and request a view change.

This is the version of the protocol that was presented in lecture.

12. [4 points]: Read-only optimization: When replicas receive a `pre-prepare` for a read-only request, they reply to the client immediately, and the client accepts $f + 1$ matching replies as the answer.

This change sacrifices serializability. Of the $f + 1$ replies the client receives, up to f could be from liars, and up to f could be from non-faulty replicas that are behind. For a concrete example, consider the setup described in Question 13. Suppose A, B, and C commit request $r1$ from client 1, which changes the value x from 1 to 2. Then client 2 sends request $r2$, which reads x. A lies and says that x is 1, and D is behind and also says x is 1, so client 2 believes that x is still 1.

The paper describes a similar optimization, but points out that it is necessary to wait for $2f + 1$ replies.

Suppose we have a BFT deployment with 4 replicas: A, B, C, and D. The malicious primary A, gets request $r1$ from client 1 and $r2$ from client 2.

13. [4 points]: A tries to get B and C to prepare request $r1$, and then tries to get D to prepare request $r2$ with the same sequence number. Explain in one or two sentences sentence what feature of BFT prevents the attack and how.

Replicas do not prepare requests unless $2f + 1$ other replicas agree to the ordering proposed by the primary.

Name:

V 6.824

14. [3 points]: Many have speculated that had the authors of AnalogicFS actually implemented their system completely, they would have discovered that using lambda calculus to manage the lookaside buffer is harder in practice than it looks on paper. Think back about all the labs you implemented. What was the biggest challenge you faced and what made it difficult?

Most common answers:

16 fault tolerance (labs 7 and 8)
10 concurrency / distributed debugging
1 implementing Paxos while on flight to Paris
6 other

15. [4 points]: If you could change one thing in 6.824, what would it be? (If you think 6.824 is perfect already, unbridled praise for the course staff is an acceptable answer.)

Most common answers:

9 cleaner staff code
4 more time/emphasis on the final project
3 official answers to reading questions
2 unbridled praise
17 other

End of Quiz II