Department of Electrical Engineering and Computer Science

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

6.824 Distributed System Engineering: Spring 2016

Exam I

Write your name on this cover sheet. If you tear out any sheets, please write your name on them. You have 80 minutes to complete this quiz.

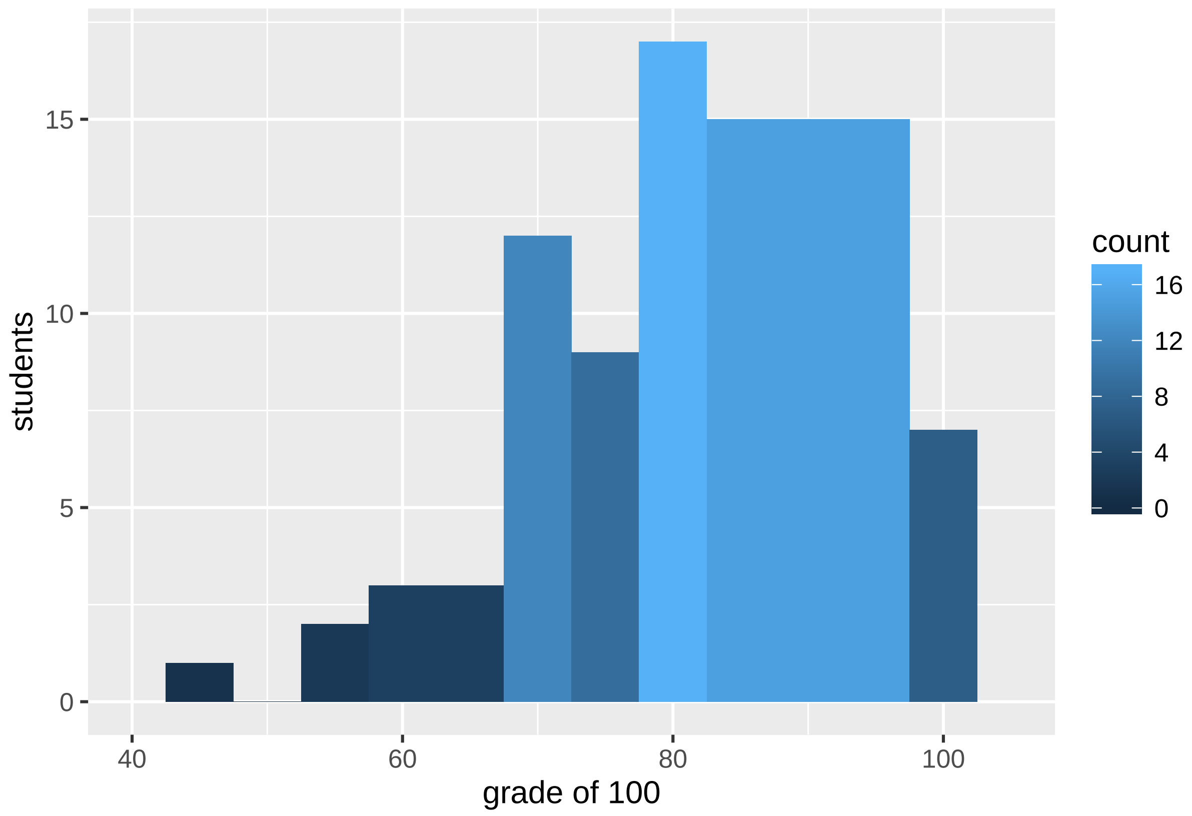
Some questions may be much harder than others. Read them all through first and attack them in the order that allows you to make the most progress. If you find a question ambiguous, write down any assumptions you make. Write neatly. In order to receive full credit you must answer each question as precisely as possible.

You may use class notes, papers, and lab material. You may read them on your laptop, but you are not allowed to use any network. For example, you may not look at web sites or communicate with anyone.

I (14)	**II (7)**	**III (7)**	**IV (21)**	**V (14)**	**VI (14)**	**VII (21)**	**VIII (2)**	**Total (100)**

Name:

Grade histogram for Exam 1



max	$=$	100
median	$=$	84
μ	$=$	82.4
σ	$=$	11.3

I Lab 1

Ben Bitdiddle is writing a simplified version of the schedule() function for the MapReduce lab. This function takes in an array of Tasks for a particular map or reduce phase and sends them to available workers. The function should return once all of the tasks in this phase have been completed.

```
func (mr *Master) schedule(tasks []Task) {
  done := 0

  for _, task := range tasks {
    go func(task Task) {

      // Get an available worker and give them the task to run.
      worker = <-mr.registerChannel
      call(worker, "Worker.DoTask", task)

      // Tell the master this task is done.
      done++

      // Reregister the worker as available.
      mr.registerChannel <- worker

    }(task)
  }

  // Wait for all of the jobs to return.
  for {
    if done == len(tasks) {
      break
    }
  }

  return
}
```

Ben notices that schedule() sometimes never finishes. However, he can see from looking at the output files that the workers have completed all of the tasks in the phase.

1. **[7 points]:** Identify a race in Ben's code that can cause schedule() to never return.

Answer: There is a race at line 12: if two threads update `done` concurrently, they increase by 1 instead of 2. Read/writes of done must be protected under a lock.

After fixing the race in the previous question, Ben's code passes all of the MapReduce tests. Now he hopes to make his implementation faster by returning an available worker to mr.registerChannel as soon as possible, that is, *before* incrementing `done`. He implements this by moving line 15 so it comes right after line 9. However, he notices that with this new plan schedule() never returns.

2. **[7 points]:** Why does this happen?

Answer: For the last few tasks, no go routine will be reading from the register channel, so the sends will block, preventing `done` from being updated, which prevents `schedule` from returning.

II GFS

Alice uses GFS (as described by Ghemawat *et al.*) to store the output of her MapReduce job. One task of the MapReduce job uses a single `write` call to write MapReduce records to a pre-existing "out.txt" file. That is, her job overwrites "out.txt", which was created by a previous run of her job (she doesn't care about any of the old content). Unfortunately, the GFS write call returns an error.

A check application runs on another machine while the MapReduce job is attempting to write. The check application opens "out.txt", reads it, and closes the file. To Alice's surprise the check application reads the bytes Alice's MapReduce job tried to write to "out.txt", even though the write reported an error to the MapReduce job. If she runs the check application again, however, it reads the old bytes.

3. [7 points]: Describe a scenario in which this can happen.

Answer: Client 1 opens a file, receives a list of chunk servers, and starts writing records. Client 2 also opens the file and receives a list of chunk servers. While client 1 is writing, the primary updates replica 1 for the chunk being written, but fails to update replica 2, perhaps due a network failure. Client 2 reads from replica 1 and reads the new bytes. The second read goes to replica 2 (reads can go to any replica), and thus reads the old bytes.

III VM-FT

After reading the VM-FT paper (by Scales *et al.*), Ben explores running the GFS master on VM-FT. He reasons that, without modifying the existing GFS master code, he can avoid the master being a single point of failure. Unfortunately, he finds that replicating the master with VM-FT results in much slower performance than with an unreplicated master: even GFS operations that merely fetch data from the master take significantly longer with the master running on VM-FT.

4. [7 points]: Explain what causes this decrease in performance.

Answer: The primary in VM-FT cannot respond to a client request (i.e., send a network packet) until the primary has received an acknowledgement from a backup for that event.

IV Lab 2

Ben is having trouble getting his Lab 2 to work. Here's the part of his code that sends out AppendEntries RPCs when a server acts as leader:

```
for {
  // ... omitted code that waits either for a new client
  // request or for a heartbeat interval.

  for i, p := range rf.peers {
    if i == rf.me {
      continue
    }
    rf.mu.Lock()
    if rf.state != LEADER {
      rf.mu.Unlock()
      break
    }
    n := rf.nextIndex[i]
    args := AppendEntriesArgs{
      // ...
      Term: rf.currentTerm,
      PrevLogIndex: n-1,
      PrevLogTerm: rf.log[n-1].Term,
      Entries: make([]LogEntry, len(rf.log[n:])),
    }
    copy(args.Entries, rf.log[n:])
    rf.mu.Unlock()

    var reply AppendEntriesReply
    ok := p.Call("Raft.AppendEntries", args, &reply)
    if ok && reply.Success {
      rf.mu.Lock()
      rf.nextIndex[i] = len(rf.log)
      rf.matchIndex[i] = rf.nextIndex[i] - 1
      rf.mu.Unlock()
    }
  }
  // update commitIndex based on rf.matchIndex
  // ...
}
```

5. [7 points]: Ben's implementation often fails tests because it commits too slowly. Describe a change to his code that will speed it up significantly when there are many Raft servers.

Answer: Send the RPCs asynchronously, and in parallel.

6. [7 points]: Ben discovers that his servers often commit different commands for the same index in the log. He discovers that this happens when the winner of an election was the leader in a previous term; in that situation the leader's matchIndex entries sometimes contain inexplicably large values shortly after the election, even though Ben's implementation sets nextIndex and matchIndex entries to zero when a server is elected leader. Explain how the code above can cause what Ben sees.

Answer: A delayed reply to an AppendEntries RPC may arrive after the re-election, causing matchIndex to be modified. The reply handling code should check that the term hasn't changed.

7. [7 points]: After fixing the problem identified in the previous question, Ben finds that a leader will sometimes commit a log entry that has not been accepted by a majority of servers. He finds that this is because the leader sets matchIndex too high after hearing a response from an AppendEntries RPC. Explain how Ben's code for updating nextIndex and matchIndex is wrong.

Answer: They should be updated to the log length as of when the AppendEntries was sent, not to the current log length.

V Zookeeper

In Zookeeper (as described by Hunt *et al.*), any server can respond to a read operation such as `GetData`. In lab 3, read operations such as `Get` are served by the Raft leader after committing the `Get` operation in Raft log. As a result, read operations in Zookeeper are fast and read operations in lab 3 are slow.

8. [7 points]: What does Zookeeper sacrifice compared to lab 3 by allowing each server to respond to a read operation? (Briefly explain your answer.)

Answer: ZooKeeper doesn't provide linearizable Get operations.

A Zookeeper client C_1 calls `setData("z", 27)` at server S_1 to change the value of znode `z` to 27 from its previous value of 0. No further `setData` calls happen after that one call. Another client C_2 calls `getData("z")` at server S_1 and reads 27. Now S_1 fails and client C_2 switches to server S_2.

9. [7 points]: If client C_2 calls `getData("z")` at server S_2 does Zookeeper guarantee that the client will observe 27 rather than 0? (Briefly explain your answer.)

Answer: Yes, Zookeeper will guarantee this thanks to the zxid included with all client requests. A Zookeeper server will ensure its state is at least as up to date as the client's zxid before responding.

VI FaRM

You're building a simple auction system using FaRM to store the bids (see the paper "No compromises: distributed transactions with consistency, availability, and performance"). Your application supports just one auction, with just two bidders. You store the two current bids in FaRM, in the bids[] array. Each user can bid any number of times with the bid() function, which returns a boolean indicating whether the bid is the highest so far. The function's who argument is 0 or 1, and indicates which user is bidding. The return value from commit_transaction() is true if the FaRM commit protocol committed the transaction, and false if it aborted.

```
// each user's bid is a distinct FaRM object.
type BidObject struct {
  value int
  // other stuff...
}

// bids are initialized to zero.
var bids [2]BidObject
bids[0].value = 0
bids[1].value = 0

bid(who, amount):
  start_transaction()
  if amount > bids[0].value && amount > bids[1].value:
    ret = true
    bids[who].value = amount
  else:
    ret = false
  if commit_transaction():
    return ret
  else:
    return false
```

Each bids[] array element is a separate FaRM object, with its own FaRM lock and version number.

10. [7 points]: Suppose the bids array starts out containing zeroes, and there are calls to bid(0,10) and bid(1,20) on different machines at roughly the same time (and no other activity). Could the bid(1,20) call return false? Explain your answer in terms of the commit protocol in the paper's Figure 4.

Answer: Yes. Both transactions read the initial values of the two bid objects. bid(0,10) commits first, changing the version number of bids[0]. bid(1,20) then tries to commit, but its VALIDATE for bids[0] sees that the version number has changed, so it aborts.

11. [7 points]: You can view FaRM's VALIDATE as an optimization of LOCK for objects that a transaction only reads. Suppose FaRM didn't have this optimization – suppose one were to eliminate the VALIDATE phase from Figure 4, and instead use LOCK for objects that are just read as well as for objects that are written. Explain why this would likely hurt performance.

Answer: Two reasons. First, concurrent commits involving just reads of the same object would cause conflicts and aborts with LOCK, but proceed in parallel with VALIDATE. Second, VALIDATE is implemented as a one-sided read, which is fast because the server CPU isn't involved. LOCK is a true RPC that has to be executed by the server CPU, so it's slower.

VII TreadMarks

Consider the following program with shared variables *x* and *y*:

```
int x = 0;
int y = 0;

int f() {
    x = 10;
}


int g() {
   y = 11;
}

int p() {
   print x, y
}
```

This is the entire program.

For these questions, please assume that the compiler generates instructions that preserve the program order of loads and stores on each processor.

Now consider the following scenario with time running from left to right:

```
Processor 1:     f();


Processor 2:                     g();


Processor 3:                                         p();
```

12. [7 points]: For a sequentially-consistent shared-memory system please list *all* possible outputs from Processor 3. (The stores to x and y complete as indicated by the time line. For example, by the time processor 2 updates y, x has been updated.)

Answer: 10, 11.

Consider the same program running on TreadMarks (as described by Keleher *et al.*):

13. [7 points]: For TreadMarks please list *all* possible outputs from Processor 3.

Answer: 10, 0; 0, 11; and 10, 11.

Consider the following slight modification: Processor 3 prints only *x* by calling `px` and Processor 4 prints only *y* by calling `py`.

```
int x = 0;
int y = 0;

int f() {
    acquire(x_lock); // answer
    x = 10;
    release(x_lock); // answer
}


int g() {
   acquire(y_lock); // answer
   y = 11;
   release(y_lock); // answer
}

int px() {
   acquire(x_lock); // answer
   print x;
   release(x_lock); // answer
}

int py() {
   acquire(y_lock); // answer
   print y;
   release(y_lock); // answer
}
```

```
Processor 1:     f();
Processor 2:                  g();
Processor 3:                              px();
Processor 4:                                      py();
```

14. [7 points]: Annotate `f`, `g`, `px`, and `py` in the above figure so that the program on TreadMarks generates the same result as on a sequentially-consistent memory, but minimizes communication overhead. (Briefly justify your annotations.)

Answer: See the lines marked "answer" added to the code above. The locks cause the readers to see the writes. Use of two different locks cause Processor 3 to only have to fetch the update to x, and Processor 4 to only have to fetch the update to y.

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15. [1 points]: Lab 2 turned out to be much harder than we anticipated. If you ran into significant difficulties, what were they?

Answer: 16x Synchronization/concurrency; 13x Not following details in fig2; 8x No significant difficulties; 8x Overall design; 6x Too much code (all-or-nothing); 6x Edge cases; 5x Leader election; 4x Test cases/testing; 4x The optimization/performance; 3x Started too late; 2x Logs out of sync
Debugging: 26x General (subtle bugs); 9x Locking; 7x Logging

16. [0.5 points]: Which papers should we definitely keep for future years?

Answer: 60x Raft; 33x FaRM; 32x ZooKeeper; 26x GFS; 20x Bayou; 20x PNUTS; 17x TreadMarks; 16x MapReduce; 10x Thor; 9x Dynamo; 4x VM-FT; 2x add Paxos; 1x add Spanner; 1x add FDS

17. [0.5 points]: Is there any paper that you think we should delete?

Answer: 26x TreadMarks; 15x FaRM; 14x PNUTS; 13x Bayou; 11x VM-FT; 9x GFS; 9x MapReduce; 8x Thor; 1x ZooKeeper; 1x Dynamo

End of Exam I