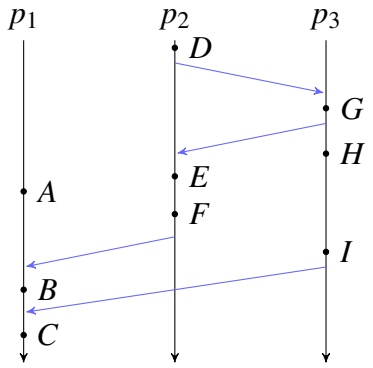
You are to work on the following questions *alone*. Typeset your answers and submit as a `PDF`.

1. (8 points) Recall the muddy forehead problem. There are n children, k of which get muddy foreheads at recess (which they cannot see). Suppose that, instead of announcing "someone has a muddy forehead" publicly, the teacher has the children line up outside when coming in from recess and tells each one "someone has a muddy forehead," before dismissing that child to return inside to the classroom. All children are facing forward and each can see: (1) the teacher telling the children ahead in line that someone has a muddy forehead, and (2) that the children ahead in line are *also* facing forward. No child has any knowledge of what goes on behind them in line (for all they know, all of the other children are looking away and have plugged their ears so they can't hear anything). Once all children have returned to the classroom, the teacher arranges them in a circle and tells the children, "I'm about to ask you infinitely many times to raise your hand if you know you have mud on your forehead." The teacher then repeatedly asks the children, "Raise your hand if you know you have mud on your forehead." The children are honest and logical; both of these facts are common knowledge.

   What happens? (Be as specific as possible.) Justify your answer.

2. (5 points) Consider an altered version of the coordinated attack problem. Scipio and Masinissa are trying to agree on when and whether to attack Carthage. In the original version, they could only communicate by messenger, and these messengers could get lost or captured. Suppose that Scipio also possessed a very loud battle horn, which can be heard for miles (certainly from Masinissa's position on the opposite side of Carthage). Can the generals now coordinate their attack? If so, briefly describe a strategy. If not, briefly explain why they can't.

3. Suppose we have the following space-time diagram describing an execution of a distributed system (time advances downwards).



   (a) (3 points) For event F, partition the other events (A, B, C, D, E, G, H, and I) into those that happen before F, those that happen after F, and those that are concurrent with F.

   (b) (3 points) Assume that each process maintains a logical clock. Each clock starts at 0 and is updated at each labeled event, at each message send, and at each message receive. Give the clock value corresponding to each event. (Hint: D has timestamp 1 and G has timestamp 4.)

(c) (3 points) Assume instead that each process maintains a vector clock. Give the clock values corresponding to each event. (Hint: G has timestamp $\{p_1 : 0, p_2 : 2, p_3 : 2\}$.)

4. In class, we suggested your solution to Lab 2 should obey certain constraints. In a sentence, explain why the constraint is needed; that is, why a violation of the constraint would cause a problem.

   (a) (4 points) State transfer from primary to backup must include metadata on which requests have received replies, and what the response was.

   (b) (4 points) The backup must accept a request forwarded by the primary if and only if the request and the backup have the same notion of the current view.

   (c) (4 points) Even on a read-only request, the primary must wait for the backup to accept the request before the primary can reply to the client.

5. Suppose we have set of servers, clients, and a view server all running a correct version of the primary/backup protocol from Lab 2. In particular, suppose there are exactly two clients, both of which send one command, `Append("foo", "x")`, and then halt. The network is completely asynchronous.

   (a) For each of the following predicates, indicate whether they could be true of a consistent global state in any possible execution.

      i. (2 points) Two different servers report currently being primary.

      ii. (2 points) The backup for view v reports having accepted a request from the primary in view v, while the primary has not yet entered view v (or any later view).

      iii. (2 points) One client has received a reply to its command, while the other has not.

      iv. (2 points) Both clients report receiving `AppendReply("x")`.

   (b) Now, instead consider a global state gathered by a monitor using the following procedure:

      – The monitor node sends a SNAPSHOT message to all other nodes.

      – Upon receiving SNAPSHOT, each node sends its state to the monitor.

      – After the monitor receives the states of all nodes, it combines them to form a global state of the system.

      For each of the following predicates, indicate whether they could be true of a global state gathered in this way.

      i. (2 points) Two different servers report currently being primary.

      ii. (2 points) The backup for view v reports having accepted a request from the primary in view v, while the view server has not yet received an acknowledgement for view v.

      iii. (2 points) One client has received a reply to its command, while the other has not.

      iv. (2 points) Both clients report receiving `AppendReply("x")`.