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

(a) (4 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) (5 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) (5 points) Assume instead that each process maintains a vector clock. Give the clock values corresponding to each event. (Hint: $G$ has timestamp $\{p_1: 0, p_2: 2, p_3: 2\}$.)

2. 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.

3. 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, $\text{Append("foo", "x")}$, 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. (3 points) Two different servers report currently being primary.

ii. (3 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. (3 points) One client has received a reply to its command, while the other has not.

iv. (3 points) Both clients report receiving \texttt{AppendReply("x")}.

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

– The monitor node sends a \texttt{SNAPSHOT} message to all other nodes.
– Upon receiving \texttt{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. (3 points) Two different servers report currently being primary.

ii. (3 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. (3 points) One client has received a reply to its command, while the other has not.

iv. (3 points) Both clients report receiving \texttt{AppendReply("x")}. 