Table of Contents

Distributed Data Management

- Data objects
  - Files
  - Directories
- Data objects are dispersed and replicated
  - Unreplicated
  - Fully replicated
  - Partially replicated

Serializability Theory

Atomic execution

- A transaction is an "all or nothing" operation.
- The concurrent execution of several transactions affects the database as if executed serially in some order.
- The interleaved order of the actions of a set of concurrent transactions is called a *schedule*.

Example 22: Concurrent Transactions

T_1 **begin**

1 **read** A (obtaining *A_balance*)

2 **read** B (obtaining *B_balance*)

3 **write** *A_balance*-$10 to A

4 **write** *B_balance*+$10 to B

end

T_2 **begin**

1 **read** B (obtaining *B balance*)

2 **write** *B_balance*-$5 to B

end

Concepts

- Three types of **conflict**: *r-w* (read-write), *w-r* (write-read), and *w-w* (write-write).
- $r_j[x]$ *reads from* $w_i[x]$ iff
  - $w_i[x] < r_j[x]$.
  - There is no $w_k[x]$ such that $w_i[x] < w_k[x] < r_j[x]$.
- Two **schedules** are equivalent iff
  - Every read operation reads from the same write operation in both schedules.
  - Both schedules have the same final writes.
- When a non-serial schedule is equivalent to a serial schedule, it is called **serializable schedule**.

Transaction (step)	Action
$T_1(1)$	**read** A(obtaining *A_balance*)
$T_1(2)$	**read** B(obtaining *B_balance*)
$T_1(3)$	**write** *A_balance-$10* **to** A
$T_2(1)$	**read** B(obtaining *B_balance*)
$T_2(1)$	**write** *B_balance-$5* **to** B
$T_2(4)$	**write** *B_balance+$10* **to** B

(a)

Transaction (step)	Action
$T_1(1)$	**read** A(obtaining *A_balance*)
$T_2(1)$	**read** B(obtaining *B_balance*)
$T_2(1)$	**write** *B_balance-$5* **to** B
$T_1(2)$	**read** B(obtaining *B_balance*)
$T_1(3)$	**write** *A_balance-$10* **to** A
$T_1(4)$	**write** *B_balance+$10* **to** B

(b)

A nonserializable schedule (a) and serializable schedule (b) for Example 22.

Concurrency Control

Optimistic (assuming conflicts are less frequent)

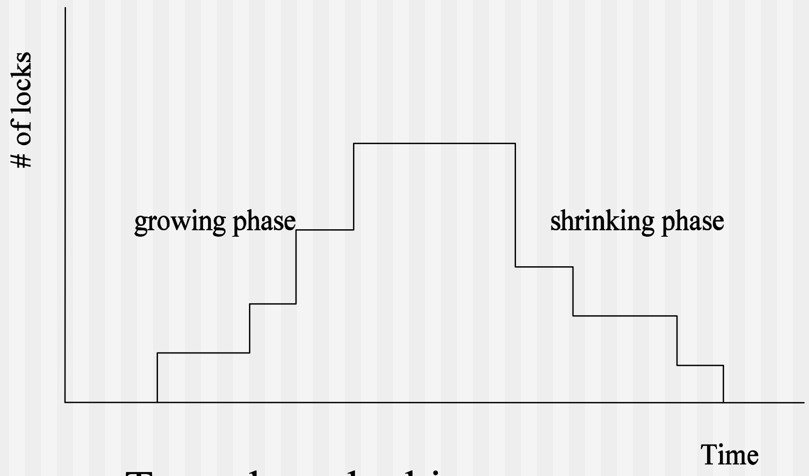
- Optimistic concurrency control
  - First tentatively perform updates locally
  - Then are made permanent and propagated if there are no conflicts

Conservative (assuming conflicts are frequent)

- Locking scheme
- Timestamp-based scheme

Focus 18: Two-Phase Locking

- A transaction is **well-formed** if it
  - locks an object before accessing it,
  - does not lock an object that is already locked, and
  - before it completes, unlocks each object it has locked.
- A schedule is **two-phase** if no object is unlocked before all needed objects are locked.



Two-phase locking

Example 23: Well-Formed, Two-Phase Transactions

T_1: **begin**
lock A
read A (obtaining A balance)
lock B
read B (obtaining B balance)
write A_balance-$10 to A
unlock A
write B_balance+$10 to B
unlock B
end

T_2: **begin**
lock B
read B (obtaining B balance)
write B_balance-$5 to B
unlock B
end

Different Looking Schemes

- *Centralized locking algorithm*: distributed transactions, but centralized lock management.
- *Primary-site locking algorithm*: each object has a single site designated as its primary site (as in INGRES).
- *Decentralized locking*: The lock management duty is shared by all the sites.

Focus 19: Timestamp-based Concurrency Control

Each request (transaction) is associated with timestamp: ts

$Time_r(x)$ ($Time_w(x)$): the largest timestamp of any read (write) processed thus far for object x.

Timestamp-based concurrency control:

- (Read) If $ts < Time_w(x)$ then the read request is rejected and the corresponding transaction is aborted; otherwise, it is executed and $Time_r(x)$ is set *to* $max\{Time_r(x), ts\}$.
- (Write) If $ts < Time_w(x)$ or $ts < Time_r(x)$, then the write request is rejected; otherwise, it is executed and $Time_w(x)$ is set to ts.

Example 24

- $Time_r(x) = 4$ and $Time_w(\text{x}) = 6$ initially.
- Sample:

  read(*x*,5), *write*(*x*,7), *read*(*x*,9), *read*(*x*, 8), *write*(x,8)
- First and last are rejected and $Time_r(x) = 7$, $Time_w(\text{x}) = 9$ when completed.

Conservative Timestamp Ordering

- Each site keeps a write queue (W-queue) and a read queue (R-queue).
  - A read (*x, ts*) request is executed if all W-queues are nonempty and the first write on each queue has a timestamp greater than *ts*; otherwise, the read request is buffered in the *R*-queue.
  - A write (*x, ts*) request is executed if all *R*-queues and *W*–queues are nonempty and the first read (write) on each *R*-queue (*W*-queue) has a timestamp greater than *ts*; otherwise, the write request is buffered in the *W*-queue.

Strict Consistency

- Any read returns the result of the most recent write.
- Impossible to enforce, unless
  - All writes are instantaneously visible to all processes.
  - All reads get the then-current values, no matter how quickly next writes are done.
  - An absolute global time order is maintained.

Weak Consistency

- **Sequential consistency**: All processes see all shared accesses in the same order.
- **Causal consistency**: All processes see causually-related shared accesses in the same order.
- **FIFO consistency**: All process see writes from each process in the order they were issued.

Example 25: Sample Consistent Models

P1	W(x,a)					
P2		W(x,b)				
P3			R(x,b)		R(x,a)	
P4				R(x, b)	R(x,a)	

sequentially-consistent

P1	W(x,a)					
P2		W(x,b)				
P3			R(x, b)		R(x,a)	
P4				R(x, a)	R(x,b)	

non-sequentially-consistent

Linearizable: sequentially-consistent, but taking ordering based on synchronized clocks

Example 25: Sample Consistent Models

P1	W(x,a)			W(x,c)		
P2		R(x,a)	W(x,b)			
P3			R(x,a)		R(x,c)	R(x,b)
P4			R(x,a)		R(x,b)	R(x,c)

causally-consistent

P1	W(x,a)					
P2		R(x,a)	W(x,b)			
P3					R(x,b)	R(x,a)
P4					R(x,a)	R(x,b)

non-causally-consistent

Example 25 (Cont'd)

P1	W(x,a)						
P2		R(x,a)	W(x,b)	W(x,c)			
P3					R(x,b)	R(x,a)	R(x,c)
P4					R(x,a)	R(x,b)	R(x,c)

FIFO-consistent

Weak Consistency (Cont'd)

- **Weak consistency**: Enforces consistency on a group of operations, not on individual reads and writes.
- **Release consistency**: Enforces consistency on a group of operations enclosed by acquire and release operations.
- **Eventual consistency**: All replicas will gradually become consistent. (Web pages with dominated read operations.)

Update Propagation for Multiple Copies

- **State** versus **Operations**
  - Propagate a notification of an update (such as invalidate signal)
  - Propagate data
  - Propagate the update operation
- **Pull** versus **Push**
  - Push-based approach (server-based)
  - Pull-based approach (client-based)
  - Lease-based approach (hybrid of push and pull)
- Consistency of duplicated data
  - **Write-invalidate** vs. **write-through**
  - **Quorum-voting** as an extension of single-write/multiple-read

Focus 20: Quorum-Voting

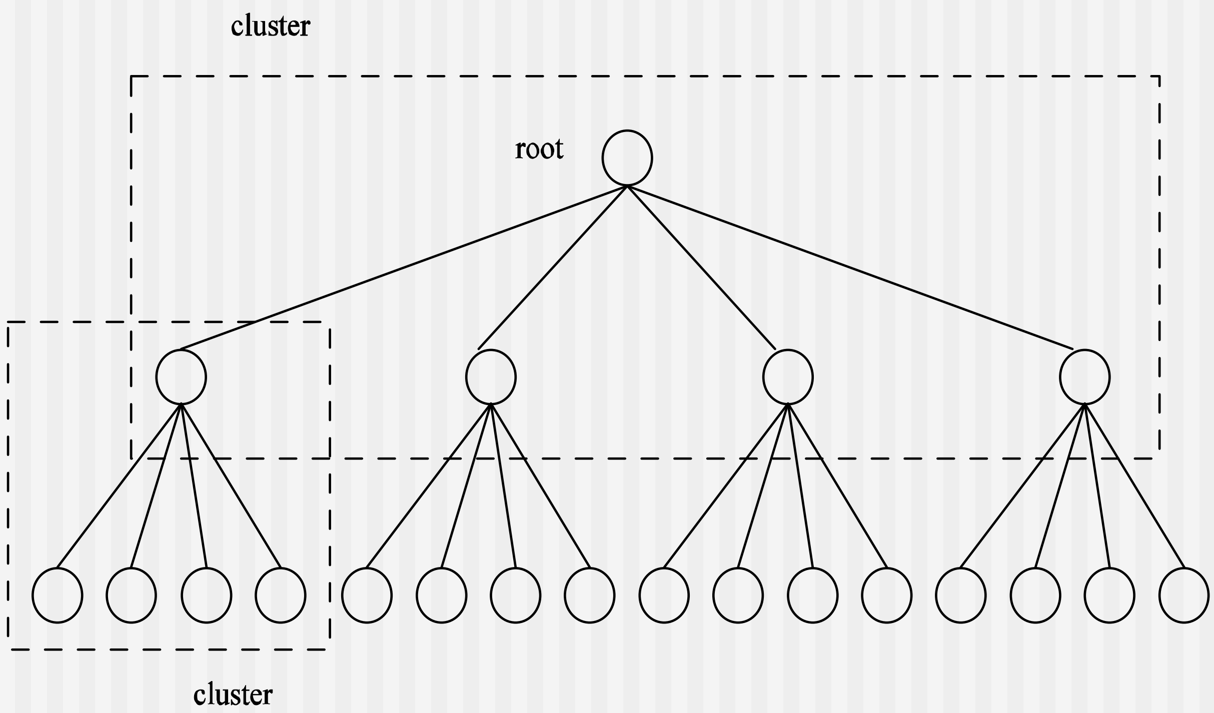
$$w > v/2 \text{ and } r + w > v$$

where *w* and *r* are write and read quorum and *v* is the total number of votes.

E.g., suppose v=9, there are the following possibilities:

(r, w): (5, 5), (4, 6), (3, 7), (2, 8), (1, 9)

Hierarchical Quorum Voting

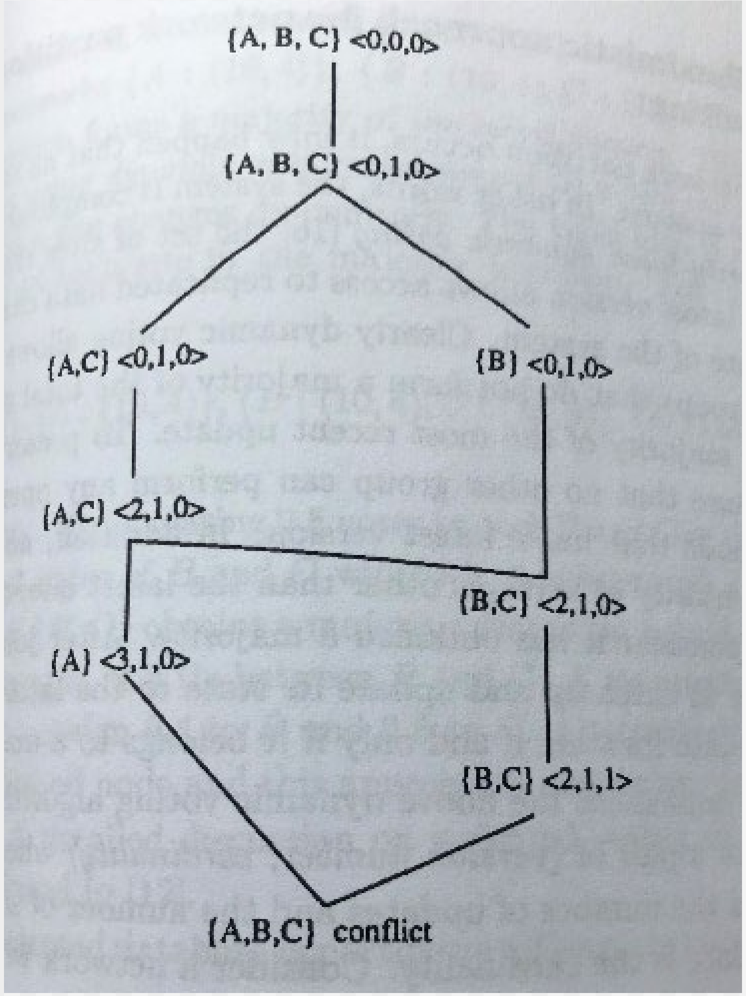


A 3-level tree in the hierarchical quorum voting with read quorum= 2 and write quorum = 3.

Network Partition

Optimistic approaches: version vectors used in LOCUS

$V=(v_1, v_2, \ldots, v_n)$, where n is the number of sites at which the file is stored. Version number v increases at each update.



Network Partition (cont’d)

Pessimistic approaches: Each site maintains a pair of *(version number, cardinality)*

Majority-based dynamic voting: *a majority of the most recent update*

Example: {A: (6, 5), B: (6, 5), C: (6, 5), D: (6, 5), E: (6, 5)} before partition

A partition: {A, B, C} and {D, E} and two updates at majority {A, B, C}

Another partition: {A: (8,3), D: (6,5)}, {B: (8,3), C: (8,3), E: (6,5)}

{B, C, E} has majority, but E needs a catch up (which is a new update)

Use *dynamic vote reassignment* to find a majority: different weights

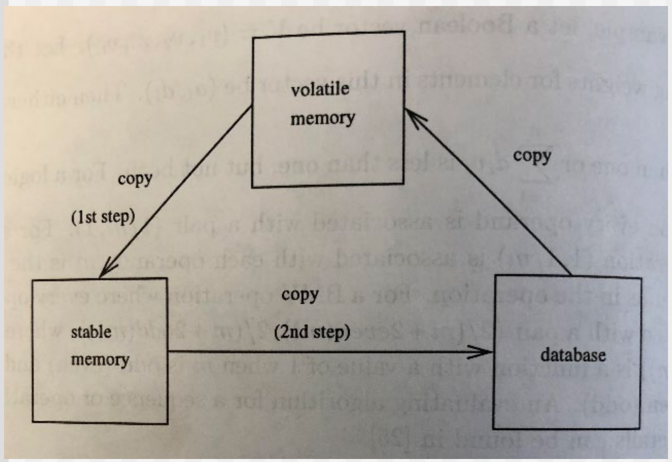
CAP Theorem

Brewer's CAP Theorem (2000):

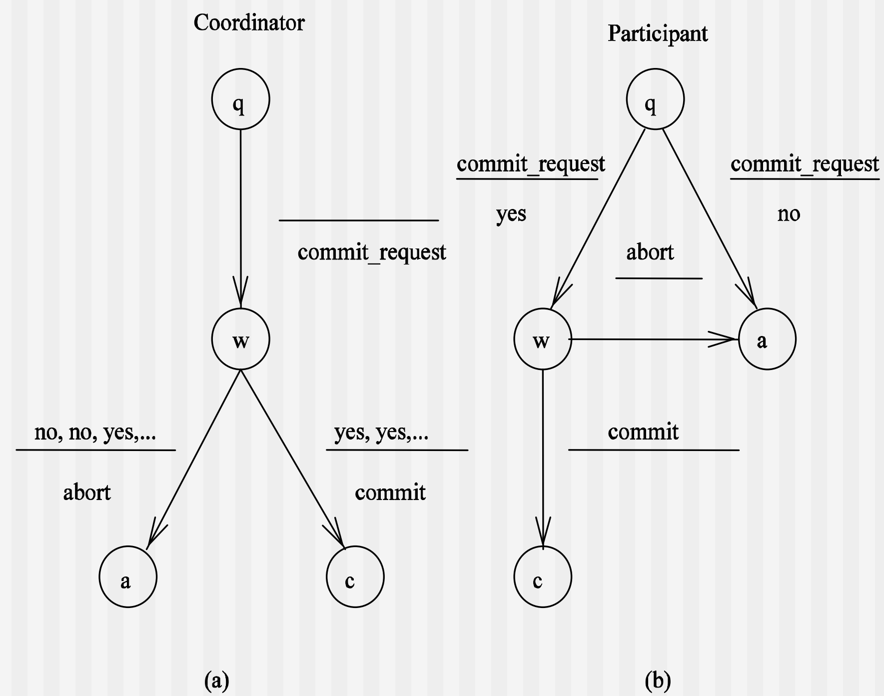
It is impossible for a web service to provide all three: *consistency, availability*, and *partition tolerance* (CAP)

Consistency: atomicity of transactions
Availability: any request to a non-faulty service leads to a response
Partition tolerance: service will be available during a partition

Distributed Atomic Transactions



Jim Gray’s Distributed Two-Phase Commitment:
One coordination with multiple participants



Two-step commit for one transaction:
(1) violate to stable and (2) stable
(2) to database

If an error occurs in (1), T is aborted; or in (2), it is rewritten to database and T is committed.

The finite state machine model for the two-phase commit protocol.

Phase 1

At the coordinator:

/*prec: initiate state (q) */

1. The coordinator sends a *commit_request* message to every participant and waits for replies from all the participants.

/*postc: waiting state (w) */

At participants:

/*prec: initiate state (q)*/

1. On receiving the *commit_request* message, a participant takes the following actions. If the transaction executing at the participant is successful, it writes *undo* and *redo* log, and sends a *yes* message to the coordinator; otherwise, it sends a *no* message.

/*postc: wait state (w) if *yes* or abort state (a) if *no**/

Phase 2

At the coordinator

/*prec: wait state (*w*)*/

1. If all the participants reply *yes* then the coordinator writes a *commit* record into the log and then sends a *commit* message to all the participants. Otherwise, the coordinator sends an *abort* message to all the participants.

/*postc: commit state (c) if *commit* or abort state (a) if *abort* */

2. If all the acknowledgments are received within a timeout period, the coordinator writes a *complete* record to the log; otherwise, it resends the commit/abort message to those participants from which no acknowledgments were received.

Phase 2 (Cont'd)

At the participants

/*prec: wait state (*w*) */

1. On receiving a *commit* message, a participant releases all the resources and locks held for executing the transaction and sends an acknowledgment.

/*postc: commit state (c) */

/*prec: abort state (a) or wait state (w) */

2. On receiving an *abort* message, a participant undoes the transaction using the *undo* log record, releases all the resources and locks held by it, and sends an acknowledgment.

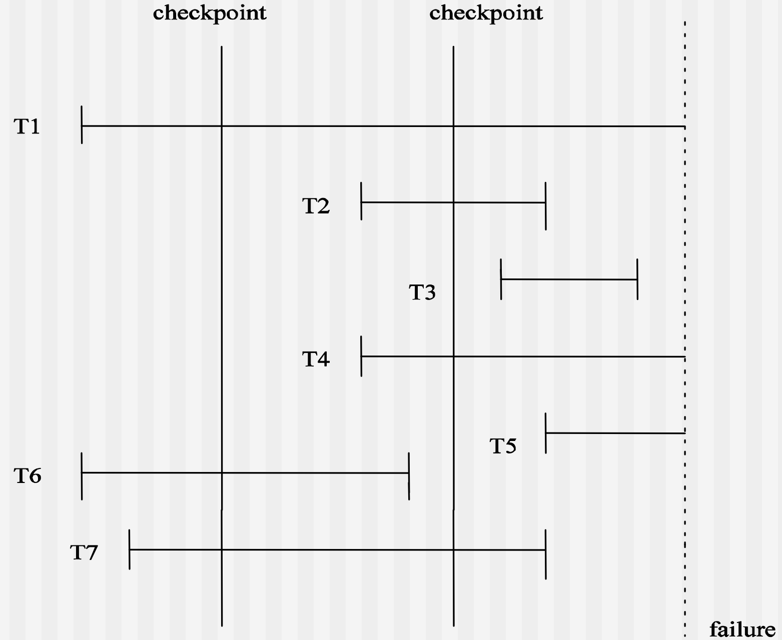
/*postc: abort state (a) */

Site/Message Failures and Recovery Actions

Location	Time of failure	Actions at coordi.	Actions at parti.
Coordi.	Before *commit*	Broadcasts *abort* on recovery	Committed parti. Undo the trans.
Coordi.	Before *complete* after *commit*	Broadcasts *commit* on recovery	__
Coordi.	After complete	--	--
Parti.	In Phase 1	Coordi. aborts the transaction	__
Parti.	In Phase 2	__	Commit/abort on recovery

Two Types of Logs

- *undo* log allows an uncommitted transaction to record in stable storage values it wrote. (T_1, T_4, and T_5 in the example)
- *redo* log allows a transaction to commit before all the values written have been recorded in stable storage. (T_2 and T_7)



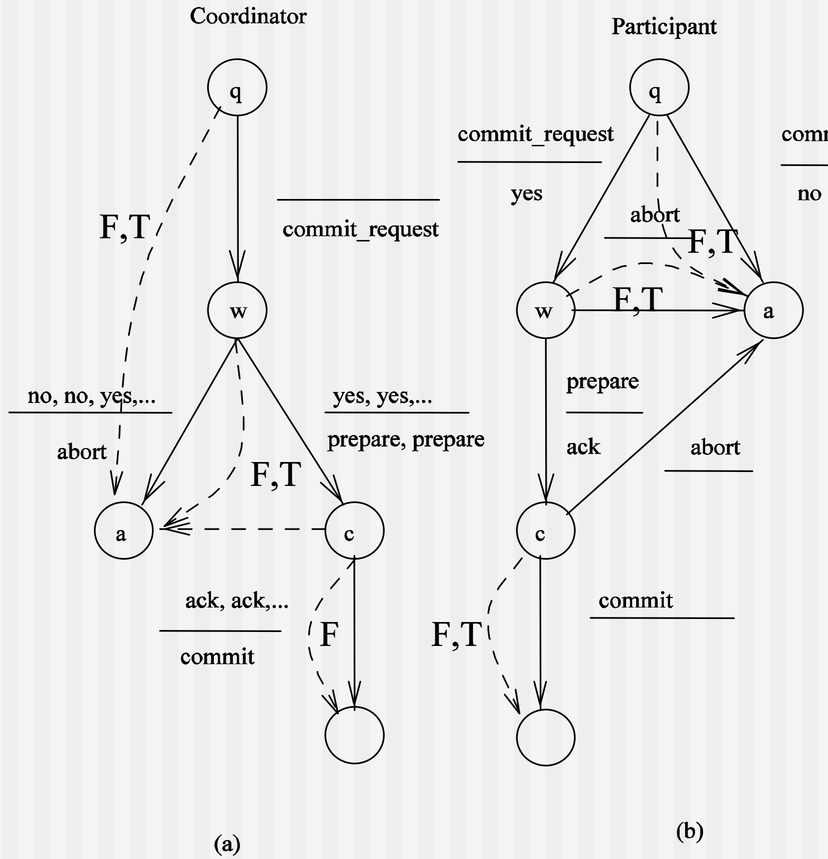
A recovery example.

Concepts

- If a participant fails in state w and its vote is *yes*, it can be either *commit* or *abort*, waiting is needed to contact coordinator. Therefore, two-phase commitment is blocking.

- Three-phase (non-blocking) commitment inserts a new state (precommit) to avoid a state containing both *abort* and *commit* options.

Skeen's Three-Phase Commitment Protocol



F: failure transition

T: timeout transition

Exercise 6

1. For the following two transactions:

   T1 **begin**

   1 **read** A (obtaining A balance)
   2 **write** A *balance*- $10 to A
   3 **read** B (obtaining B balance)
   4 **write** B *balance*+$10 to B

   end

   T2 **begin**

   1 **read** A (obtaining *A balance*)
   2 **write** A balance+$5 to *A*

   end

   (a) Provide all the interleaved executions (or schedules).
   (b) Find all the serializable schedules among the schedules obtained in (a).

Exercise 6 (Cont'd)

2. Point out serializable schedules in the following

L1 = w2(y)w1(y)r3(y)r1(y)w2(x)r3(x)r3(z)r2(z)
L2 = r3(z)r3(x)w2(x)r2(z)w1(y)r3(y)w2(y)r1(y)
L3 = r3(z)w2(y)w2(x)r1(y)r3(y)r2(z)r3(x)w1(y)
L4 = r2(z)w2(y)w2(x)w1(y)r1(y)r3(y)r3(z)r3(x)

3. A voting method called *voting-with-witness* replaces some of the replicas by witnesses. Witnesses are copies that contain only the version number but no data. The witnesses are assigned votes and will cast them when they receive voting requests. Although the witnesses do not maintain data, they can testify to the validity of the value provided by some other replica. How should a witness react when it receives a read quorum request? What about a write quorum request? Discuss the pros and cons of this method.