Chapter 13: Transactions

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Transaction Concept

- A *transaction* is a *unit* of program execution that accesses and possibly updates various data items.
- A transaction must see a consistent database.
- During transaction execution the database may be inconsistent.
- When the transaction is committed, the database must be consistent.
- Two main issues to deal with:
  - Failures of various kinds, such as hardware failures and system crashes
  - Concurrent execution of multiple transactions

ACID Properties

To preserve integrity of data, the database system must ensure:

- **Atomicity.** Either all operations of the transaction are properly reflected in the database or none are.
- **Consistency.** Execution of a transaction in isolation preserves the consistency of the database.
- **Isolation.** Although multiple transactions may execute concurrently, each transaction must be unaware of other concurrently executing transactions. Intermediate transaction results must be hidden from other concurrently executed transactions. That is, for every pair of transactions T_i and T_j, it appears to T_i that either T_j finished execution before T_i started, or T_j started execution after T_i finished.
- **Durability.** After a transaction completes successfully, the changes it has made to the database persist, even if there are system failures.

Example of Fund Transfer

- Transaction to transfer \$50 from account A to account B :

  1. **read**(A)
  2. $A := A - 50$
  3. **write**(A)
  4. **read**(B)
  5. $B := B + 50$
  6. **write**(B)

- Consistency requirement — the sum of A and B is unchanged by the execution of the transaction.
- Atomicity requirement — if the transaction fails after step 3 and before step 6, the system should ensure that its updates are not reflected in the database, else an inconsistency will result.

Example of Fund Transfer (Cont.)

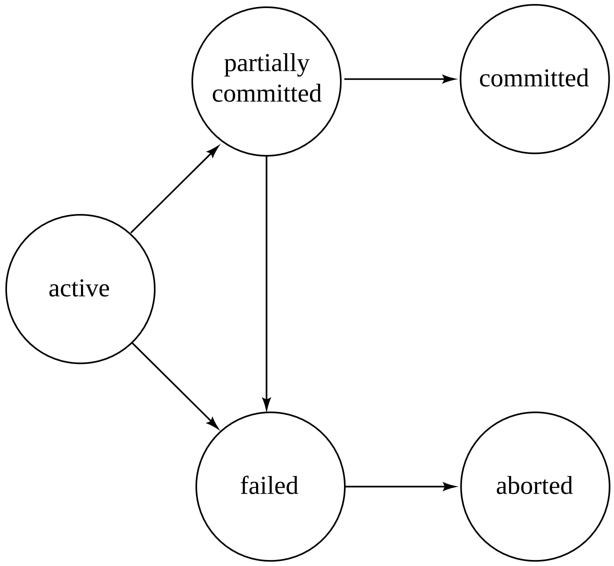
- Durability requirement — once the user has been notified that the transaction has completed (ie. the transfer of the $50 has taken place), the updates to the database by the transaction must persist despite failures.
- Isolation requirement — if between steps 3 and 6, another transaction is allowed to access the partially updated database, it will see an inconsistent database (the sum $A + B$ will be less than it should be).

  Can be ensured trivially by running transactions *serially*, that is, one after the other. However, executing multiple transactions concurrently has significant benefits, as we will see.

Transaction State

- **Active**, the initial state; the transaction stays in this state while it is executing
- **Partially committed**, after the final statement has been executed.
- **Failed**, after the discovery that normal execution can no longer proceed.
- **Aborted**, after the transaction has been rolled back and the database restored to its state prior to the start of the transaction. Two options after it has been aborted :
  - restart the transaction – only if no internal logical error
  - kill the transaction
- **Committed**, after *successful completion*.

Transaction State (Cont.)

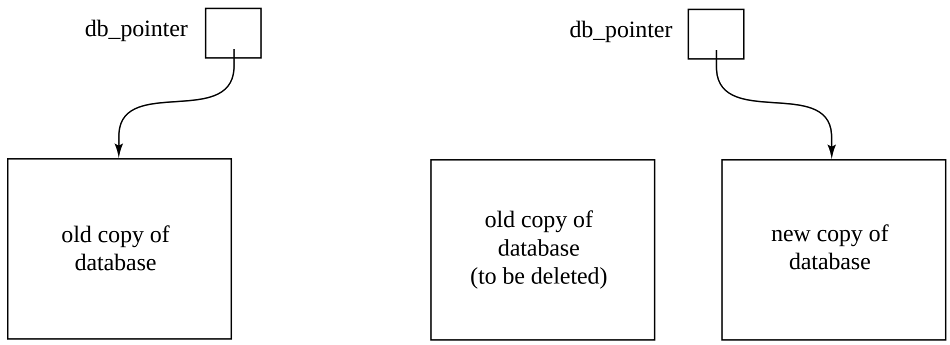


Implementation of Atomicity and Durability

- The recovery-management component of a database system implements the support for atomicity and durability.
- The *shadow-database* scheme:
  - assume that only one transaction is active at a time.
  - a pointer called **db_pointer** always points to the current consistent copy of the database.
  - all updates are made on a *shadow copy* of the database, and **db_pointer** is made to point to the updated shadow copy only after the transaction reaches partial commit and all updated pages have been flushed to disk.
  - in case transaction fails, old consistent copy pointed to by **db_pointer** can be used, and the shadow copy can be deleted.

Impl. of Atomicity and Durability (Cont.)

The shadow-database scheme:



(a) Before update (b) After update

- Assumes disks do not fail
- Useful for text editors, but extremely inefficient for large databases: executing a single transaction requires copying the *entire* database. Will see better schemes in Chapter 15.

Concurrent Executions

- Multiple transactions are allowed to run concurrently in the system. Advantages are :
  - increased processor and disk utilization, leading to better transaction *throughput*: one transaction can be using the CPU while another is reading from or writing to the disk
  - reduced *average response time* for transactions: short transactions need not wait behind long ones
- *Concurrency control* schemes – mechanisms to control the interaction among the concurrent transactions in order to prevent them from destroying the consistency of the database
  - Will study in Chapter 14, after studying notion of correctness of concurrent executions.

Schedules

- *Schedules* – sequences that indicate the chronological order in which instructions of concurrent transactions are executed
  - a schedule for a set of transactions must consist of all instructions of those transactions
  - must preserve the order in which the instructions appear in each individual transaction

Example Schedules

- Let T_1 transfer \$50 from A to B, and T_2 transfer 10% of the balance from A to B. The following is a serial schedule (Schedule 1 in the text), in which T_1 is followed by T_2.

T_1	T_2
read(A)	
$A := A - 50$	
write(A)	
read(B)	
$B := B + 50$	
write(B)	
	read(A)
	$temp := A * 0.1;$
	$A := A - temp$
	write(A)
	read(B)
	$B := B + temp$
	write(B)

Example Schedules (Cont.)

- Let T_1 and T_2 be the transactions defined previously. The following schedule (Schedule 3 in the text) is not a serial schedule, but it is *equivalent* to Schedule 1.

T_1	T_2
read(A)	
$A := A - 50$	
write(A)	
	read(A)
	$temp := A * 0.1;$
	$A := A - temp$
	write(A)
read(B)	
$B := B + 50$	
write(B)	
	read(B)
	$B := B + temp$
	write(B)

- In both Schedules 1 and 3, the sum $A + B$ is preserved.

Example Schedules (Cont.)

- The following concurrent schedule (Schedule 4 in the text) does not preserve the value of the sum $A + B$.

T_1	T_2
read(A)	
$A := A - 50$	
	read(A)
	$temp := A * 0.1;$
	$A := A - temp$
	write(A)
	read(B)
write(A)	
read(B)	
$B := B + 50$	
write(B)	
	$B := B + temp$
	write(B)

Serializability

- Basic Assumption – Each transaction preserves database consistency.
- Thus serial execution of a set of transactions preserves database consistency
- A (possibly concurrent) schedule is serializable if it is equivalent to a serial schedule. Different forms of schedule equivalence gives rise to the notions of :
  1. conflict serializability
  2. view serializability
- We ignore operations other than **read** and **write** instructions, and we assume that transactions may perform arbitrary computations on data in local buffers in between reads and writes. Our simplified schedules consist of only **read** and **write** instructions.

Conflict Serializability

- Instructions I_i and I_j, of transactions T_i and T_j respectively, *conflict* if and only if there exists some item Q accessed by both I_i and I_j, and at least one of these instructions wrote Q.
- 1. I_i = **read**(Q), I_j = **read**(Q). I_i and I_j don't conflict.
  2. I_i = **read**(Q), I_j = **write**(Q). They conflict.
  3. I_i = **write**(Q), I_j = **read**(Q). They conflict.
  4. I_i = **write**(Q), I_j = **write**(Q). They conflict.
- Intuitively, a conflict between I_i and I_j forces a (logical) temporal order between them. If I_i and I_j are consecutive in a schedule and they do not conflict, their results would remain the same even if they had been interchanged in the schedule.

Conflict Serializability (Cont.)

- If a schedule S can be transformed into a schedule S' by a series of swaps of non-conflicting instructions, we say that S and S' are *conflict equivalent*.
- We say that a schedule S is *conflict serializable* if it is conflict equivalent to a serial schedule.
- Example of a schedule that is not conflict serializable :

T_3	T_4
read(Q)	
	write(Q)
write(Q)	

  We are unable to swap instructions in the above schedule to obtain either the serial schedule $< T_3, T_4 >$, or the serial schedule $< T_4, T_3 >$.

Conflict Serializability (Cont.)

- Schedule 3 below can be transformed into Schedule 1, a serial schedule where T_2 follows T_1, by a series of swaps of non-conflicting instructions. Therefore Schedule 3 is conflict serializable.

T_1	T_2
read(A)	
write(A)	
	read(A)
	write(A)
read(B)	
write(B)	
	read(B)
	write(B)

View Serializability

- Let S and S' be two schedules with the same set of transactions. S and S' are *view equivalent* if the following three conditions are met:
  1. For each data item Q, if transaction T_i reads the initial value of Q in schedule S, then transaction T_i must, in schedule S', also read the initial value of Q.
  2. For each data item Q, if transaction T_i executes **read**(Q) in schedule S, and that value was produced by transaction T_j (if any), then transaction T_i must in schedule S' also read the value of Q that was produced by transaction T_j.
  3. For each data item Q, the transaction (if any) that performs the final **write**(Q) operation in schedule S must perform the final **write**(Q) operation in schedule S'.
- As can be seen, view equivalence is also based purely on **read**s and **write**s alone.

View Serializability (Cont.)

- A schedule S is *view serializable* if it is view equivalent to a serial schedule.
- Every conflict serializable schedule is also view serializable.
- Schedule 9 (from text) — a schedule which is view-serializable but *not* conflict serializable.

T_3	T_4	T_6
read(Q)		
	write(Q)	
write(Q)		
		write(Q)

- Every view serializable schedule which is not conflict serializable has *blind writes*.

Other Notions of Serializability

- Schedule 8 (from text) given below produces same outcome as the serial schedule $< T_1, T_5 >$, yet is not conflict equivalent or view equivalent to it.

T_1	T_5
read(A)	
$A := A - 50$	
write(A)	
	read(B)
	$B := B - 10$
	write(B)
read(B)	
$B := B + 50$	
write(B)	
	read(A)
	$A := A + 10$
	write(A)

- Determining such equivalence requires analysis of operations other than read and write.

Recoverability

Need to address the effect of transaction failures on concurrently running transactions.

- *Recoverable* schedule — if a transaction T_j reads a data items previously written by a transaction T_i, the commit operation of T_i appears before the commit operation of T_j.
- The following schedule (Schedule 11) is not recoverable if T_9 commits immediately after the read

T_8	T_9
read(A)	
write(A)	
	read(A)
read(B)	

If T_8 should abort, T_9 would have read (and possibly shown to the user) an inconsistent database state. Hence database must ensure that schedules are recoverable.

Recoverability (Cont.)

- Cascading rollback – a single transaction failure leads to a series of transaction rollbacks. Consider the following schedule where none of the transactions has yet committed (so the schedule is recoverable)

T_{10}	T_{11}	T_{12}
read(A)		
read(B)		
write(A)		
	read(A)	
	write(A)	
		read(A)

  If T_{10} fails, T_{11} and T_{12} must also be rolled back.

- Can lead to the undoing of a significant amount of work

Recoverability (Cont.)

- *Cascadeless* schedules — cascading rollbacks cannot occur; for each pair of transactions T_i and T_j such that T_j reads a data item previously written by T_i, the commit operation of T_i appears before the read operation of T_j.
- Every cascadeless schedule is also recoverable
- It is desirable to restrict the schedules to those that are cascadeless.

Implementation of Isolation

- Schedules must be conflict or view serializable, and recoverable, for the sake of database consistency, and preferably cascadeless.
- A policy in which only one transaction can execute at a time generates serial schedules, but provides a poor degree of concurrency.
- Concurrency-control schemes tradeoff between the amount of concurrency they allow and the amount of overhead that they incur.
- Some schemes allow only conflict-serializable schedules to be generated, while others allow view-serializable schedules that are not conflict-serializable.

Transaction Definition in SQL

- Data manipulation language must include a construct for specifying the set of actions that comprise a transaction.
- In SQL, a transaction begins implicitly.
- A transaction in SQL ends by:
  - **Commit work** commits current transaction and begins a new one.
  - **Rollback work** causes current transaction to abort.
- Levels of consistency specified by SQL-92:
  - **Serializable** — default
  - **Repeatable read**
  - **Read committed**
  - **Read uncommitted**

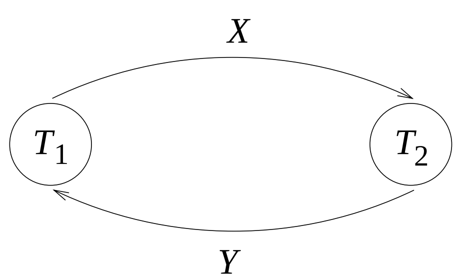
Levels of Consistency in SQL-92

- **Serializable** — default
- **Repeatable read** — only committed records to be read, repeated reads of same record must return same value. However, a transaction may not be serializable – it may find some records inserted by a transaction but not find others.
- **Read committed** — only committed records can be read, but successive reads of a record may return different (but committed) values.
- **Read uncommitted** — even uncommitted records may be read.

Lower degrees of consistency useful for gathering approximate information about the database, e.g. statistics for query optimizer.

Testing for Serializability

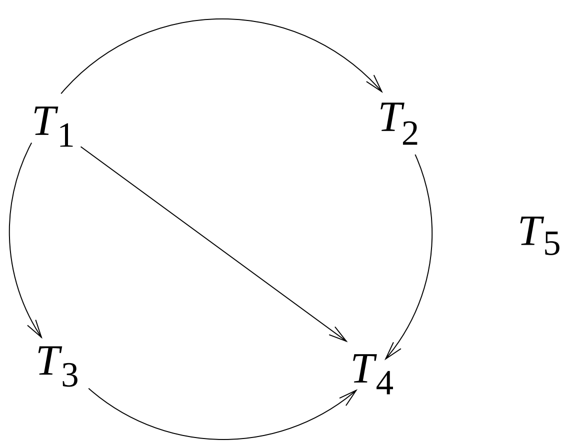
- Consider some schedule of a set of transactions $T_1, T_2, \ldots, T_n$
- *Precedence graph* — a directed graph where the vertices are the transactions (names).
- We draw an arc from T_i to T_j if the two transactions conflict, and T_i accessed the data item on which the conflict arose earlier.
- We may label the arc by the item that was accessed.
- **Example 1**



Example Schedule (Schedule A)

T_1	T_2	T_3	T_4	T_5
	read(X)			
read(Y)				
read(Z)				
				read(V)
				read(W)
				write(W)
	read(Y)			
	write(Y)			
		write(Z)		
read(U)				
			read(Y)	
			write(Y)	
			read(Z)	
			write(Z)	
read(U)				
write(U)				

Precedence Graph for Schedule A



Test for Conflict Serializability

- A schedule is conflict serializable if and only if its precedence graph is acyclic.
- Cycle-detection algorithms exist which take order n^2 time, where n is the number of vertices in the graph. (Better algorithms take order $n + e$ where e is the number of edges.)
- If precedence graph is acyclic, the serializability order can be obtained by a *topological sorting* of the graph. This is a linear order consistent with the partial order of the graph.

  For example, a serializability order for Schedule A would be $T_5 \rightarrow T_1 \rightarrow T_3 \rightarrow T_2 \rightarrow T_4$.

Test for View Serializability

- The precedence graph test for conflict serializability must be modified to apply to a test for view serializability.
- Construct a *labeled precedence graph*. Look for an acyclic graph which is derived from the labeled precedence graph by choosing one edge from every pair of edges with the same non-zero label. Schedule is view serializable if and only if such an acyclic graph can be found.
- The problem of looking for such an acyclic graph falls in the class of *NP*-complete problems. Thus existence of an efficient algorithm is unlikely.

  However practical algorithms that just check some *sufficient conditions* for view serializability can still be used.

Concurrency Control vs. Serializability Tests

- Testing a schedule for serializability *after* it has executed is a little too late!
- Goal – to develop concurrency control protocols that will assure serializability. They will generally not examine the precedence graph as it is being created; instead a protocol will impose a discipline that avoids nonserializable schedules.
  Will study such protocols in Chapter 14.
- Tests for serializability help understand why a concurrency control protocol is correct.