



# Chapter 14: Transactions

**Database System Concepts, 6<sup>th</sup> Ed.**

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# Outline

- Transaction Concept
- Transaction State
- Concurrent Executions
- Serializability
- Recoverability
- Implementation of Isolation
- Transaction Definition in SQL
- Testing for Serializability.



# Transaction Concept

- A **transaction** is a *unit* of program execution that accesses and possibly updates various data items.
- E.g., 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**( $B$ )
- Two main issues to deal with:
  - Failures of various kinds, such as hardware failures and system crashes
  - Concurrent execution of multiple transactions



# Required Properties of a Transaction

- Consider a 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**( $B$ )
- **Atomicity requirement**
  - If the transaction fails after step 3 and before step 6, money will be “lost” leading to an inconsistent database state
    - 4 Failure could be due to software or hardware
  - The system should ensure that updates of a partially executed transaction are not reflected in the database
- **Durability requirement** — once the user has been notified that the transaction has completed (i.e., the transfer of the \$50 has taken place), the updates to the database by the transaction must persist even if there are software or hardware failures.



# Required Properties of a Transaction (Cont.)

- **Consistency requirement** in above example:
  - The sum of A and B is unchanged by the execution of the transaction
- In general, consistency requirements include
  - 4 Explicitly specified integrity constraints such as primary keys and foreign keys
  - 4 Implicit integrity constraints
    - e.g., sum of balances of all accounts, minus sum of loan amounts must equal value of cash-in-hand
- A transaction, when starting to execute, must see a consistent database.
- During transaction execution the database may be temporarily inconsistent.
- When the transaction completes successfully the database must be consistent
  - Erroneous transaction logic can lead to inconsistency



# Required Properties of a Transaction (Cont.)

- **Isolation requirement** — if between steps 3 and 6 (of the fund transfer transaction), another transaction **T2** 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).

**T1**

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

**T2**

read( $A$ ), read( $B$ ), print( $A+B$ )

- Isolation 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 later.



# ACID Properties

A **transaction** is a unit of program execution that accesses and possibly updates various data items. To preserve the 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.



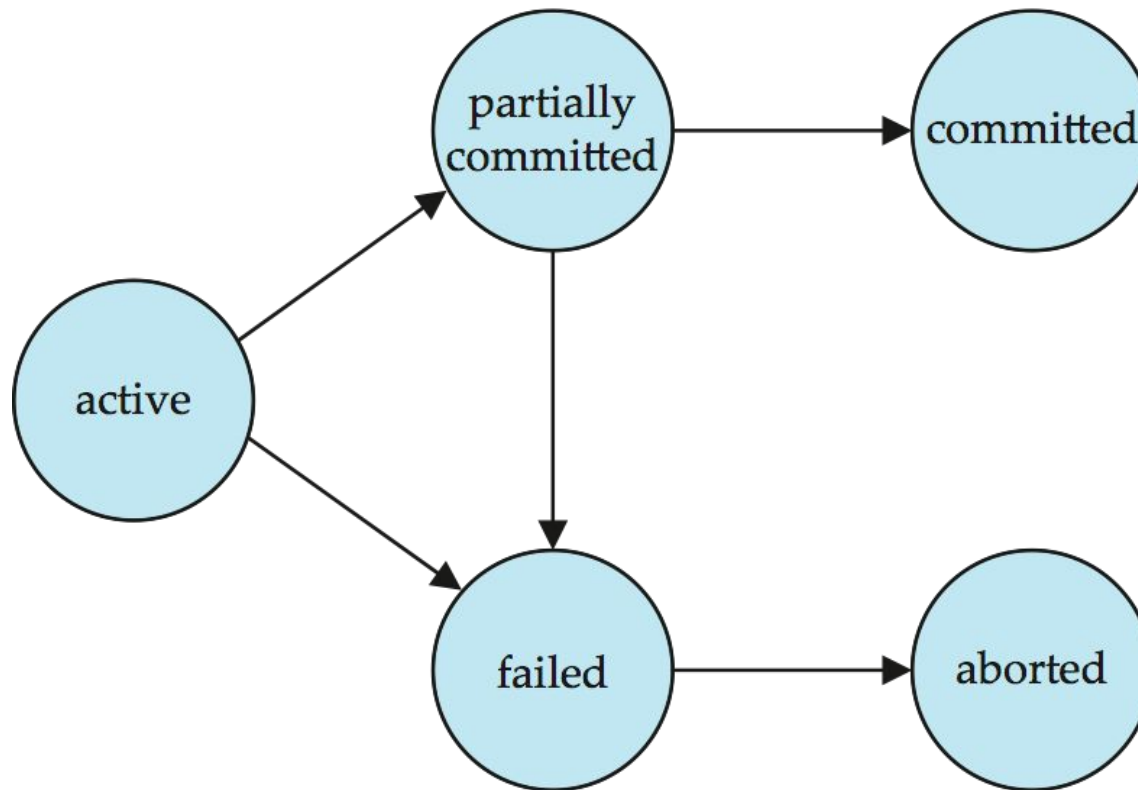
# Transaction State

- **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
    - 4 can be done only if no internal logical error
  - Kill the transaction
- **Committed** – after successful completion.





# Transaction State (Cont.)





# Concurrent Executions

- Multiple transactions are allowed to run concurrently in the system. Advantages are:
  - **Increased processor and disk utilization**, leading to better transaction *throughput*
    - 4 E.g. 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 achieve isolation
  - That is, to control the interaction among the concurrent transactions in order to prevent them from destroying the consistency of the database
    - 4 Will study in Chapter 15, after studying notion of correctness of concurrent executions.



# Schedules

- **Schedule** – a sequences of instructions that specify 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.
- A transaction that successfully completes its execution will have a **commit** instructions as the last statement
  - By default transaction assumed to execute commit instruction as its last step
- A transaction that fails to successfully complete its execution will have an **abort** instruction as the last statement



# Schedule 1

- Let  $T_1$  transfer \$50 from  $A$  to  $B$ , and  $T_2$  transfer 10% of the balance from  $A$  to  $B$ .
- An example of a **serial** schedule 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 ( $B$ ) commit	read ( $A$ ) $temp := A * 0.1$ $A := A - temp$ write ( $A$ ) read ( $B$ ) $B := B + temp$ write ( $B$ ) commit



# Schedule 2

- A **serial** schedule in which  $T_2$  is followed by  $T_1$  :

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



# Schedule 3

- Let  $T_1$  and  $T_2$  be the transactions defined previously. The following schedule 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) commit	
	read (B) $B := B + temp$ write (B) commit

Note -- In schedules 1, 2 and 3, the sum “A + B” is preserved.



- | $T_1$  | $T_2$   |
|--|---|
| read ( $A$ )<br>$A := A - 50$<br><br><br><br>write ( $A$ )<br>read ( $B$ )<br>$B := B + 50$<br>write ( $B$ )<br>commit | read ( $A$ )<br>$temp := A * 0.1$<br>$A := A - temp$<br>write ( $A$ )<br>read ( $B$ )<br><br><br><br>$B := B + temp$<br>write ( $B$ )<br>commit |



# 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 give rise to the notions of:
  1. **conflict serializability**
  2. **view serializability**





# Simplified view of transactions

- We ignore operations other than **read** and **write** instructions
- 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.



# Conflicting Instructions

- Let  $l_i$  and  $l_j$  be two Instructions of transactions  $T_i$  and  $T_j$  respectively. Instructions  $l_i$  and  $l_j$  **conflict** if and only if there exists some item  $Q$  accessed by both  $l_i$  and  $l_j$ , and at least one of these instructions wrote  $Q$ .
  1.  $l_i = \text{read}(Q)$ ,  $l_j = \text{read}(Q)$ .  $l_i$  and  $l_j$  don't conflict.
  2.  $l_i = \text{read}(Q)$ ,  $l_j = \text{write}(Q)$ . They conflict.
  3.  $l_i = \text{write}(Q)$ ,  $l_j = \text{read}(Q)$ . They conflict
  4.  $l_i = \text{write}(Q)$ ,  $l_j = \text{write}(Q)$ . They conflict
- Intuitively, a conflict between  $l_i$  and  $l_j$  forces a (logical) temporal order between them.
  - If  $l_i$  and  $l_j$  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

- 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



# Conflict Serializability (Cont.)

- Schedule 3 can be transformed into Schedule 6 -- 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)

Schedule 3

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

Schedule 6



# Conflict Serializability (Cont.)

- Example of a schedule that is not conflict serializable:

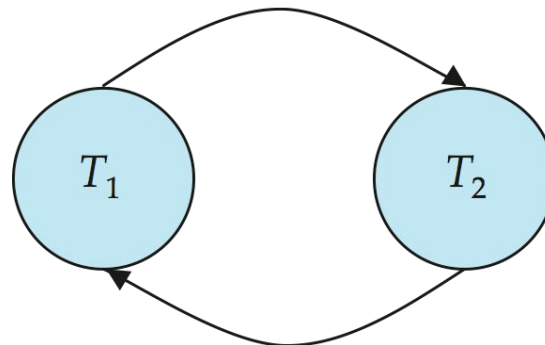
$T_3$	$T_4$
read (Q)	write (Q)
write (Q)	

- We are unable to swap instructions in the above schedule to obtain either the serial schedule  $\langle T_3, T_4 \rangle$ , or the serial schedule  $\langle T_4, T_3 \rangle$ .



# Precedence Graph

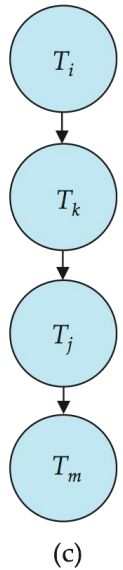
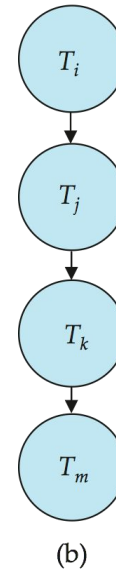
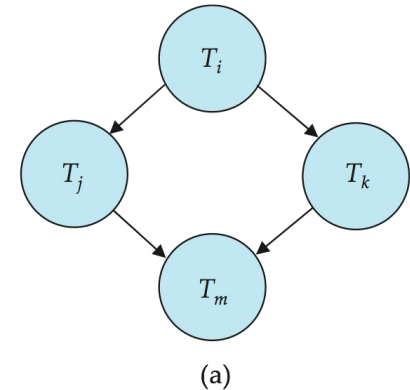
- Consider some schedule of a set of transactions  $T_1, T_2, \dots, T_n$
- **Precedence graph** — a direct graph where the vertices are the transactions (names).
- We draw an arc from  $T_i$  to  $T_j$  if the two transaction conflict, and  $T_i$  accessed the data item on which the conflict arose earlier.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





# Testing 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.
  - That is, a linear order consistent with the partial order of the graph.
  - For example, a serializability order for the schedule (a) would be one of either (b) or (c)





# Recoverable Schedules

- **Recoverable schedule** — if a transaction  $T_j$  reads a data item previously written by a transaction  $T_i$ , then the commit operation of  $T_i$  **must** appear before the commit operation of  $T_j$ .
- The following schedule is not recoverable if  $T_9$  commits immediately after the read(A) operation.

$T_8$	$T_9$
read (A)	
write (A)	
	read (A)
	commit
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.





# Cascading Rollbacks

- **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)
abort		

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



# Cascadeless Schedules

- **Cascadeless schedules** — 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
- Example of a schedule that is NOT cascadeless

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



# Concurrency Control

- A database must provide a mechanism that will ensure that all possible schedules are both:
  - Conflict serializable.
  - Recoverable 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
- Testing a schedule for serializability *after* it has executed is a little too late!
  - Tests for serializability help us understand why a concurrency control protocol is correct
- **Goal** – to develop concurrency control protocols that will assure serializability.



# Weak Levels of Consistency

- Some applications are willing to live with weak levels of consistency, allowing schedules that are not serializable
  - E.g., a read-only transaction that wants to get an approximate total balance of all accounts
  - E.g., database statistics computed for query optimization can be approximate (why?)
  - Such transactions need not be serializable with respect to other transactions
- Tradeoff accuracy for performance



# 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 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
  - Warning: some database systems do not ensure serializable schedules by default
    - E.g., Oracle and PostgreSQL by default support a level of consistency called snapshot isolation (not part of the SQL standard)



# 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.
- In almost all database systems, by default, every SQL statement also commits implicitly if it executes successfully
  - Implicit commit can be turned off by a database directive
    - 4 E.g. in JDBC, `connection.setAutoCommit(false);`



# Other Notions of Serializability



# 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, for each data item  $Q$ ,
  1. If in schedule  $S$ , transaction  $T_i$  reads the initial value of  $Q$ , then in schedule  $S'$  also transaction  $T_i$  must read the initial value of  $Q$ .
  2. If in schedule  $S$  transaction  $T_i$  executes **read**( $Q$ ), and that value was produced by transaction  $T_j$  (if any), then in schedule  $S'$  also transaction  $T_i$  must read the value of  $Q$  that was produced by the same **write**( $Q$ ) operation of transaction  $T_j$ .
  3. The transaction (if any) that performs the final **write**( $Q$ ) operation in schedule  $S$  must also perform the final **write**( $Q$ ) operation in schedule  $S'$ .
- As can be seen, view equivalence is also based purely on **reads** and **writes** 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.
- Below is a schedule which is view-serializable but *not* conflict serializable.

$T_{27}$	$T_{28}$	$T_{29}$
read ( $Q$ )	write ( $Q$ )	
write ( $Q$ )		write ( $Q$ )

- What serial schedule is above equivalent to?
- Every view serializable schedule that is not conflict serializable has **blind writes**.



# Test for View Serializability

- The precedence graph test for conflict serializability cannot be used directly to test for view serializability.
  - Extension to test for view serializability has cost exponential in the size of the precedence graph.
- The problem of checking if a schedule is view serializable falls in the class of *NP*-complete problems.
  - Thus, existence of an efficient algorithm is *extremely* unlikely.
- However, practical algorithms that just check some **sufficient conditions** for view serializability can still be used.



# More Complex Notions of Serializability

- The schedule below produces the same outcome as the serial schedule  $\langle T_1, T_5 \rangle$ , 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)

- If we start with  $A = 1000$  and  $B = 2000$ , the final result is 960 and 2040
- Determining such equivalence requires analysis of operations other than read and write.



# End of Chapter 14

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