



Chapter 15: Transactions

Database System Concepts, 5th Ed.

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Chapter 15: Transactions

- 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.
- A transaction must see a consistent database.
- During transaction execution the database may be temporarily inconsistent.
- When the transaction completes successfully (is committed), the database must be consistent.
- After a transaction commits, the changes it has made to the database persist, even if there are system failures.
- Multiple transactions can execute in parallel.
- Two main issues to deal with:
 - Failures of various kinds, such as hardware failures and system crashes
 - Concurrent execution of multiple transactions





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.





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)
- **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.
- **Consistency requirement** – the sum of A and B is unchanged by the execution of the transaction.





Example of Fund Transfer (Cont.)

- **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).
 - 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.
- **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 despite failures.





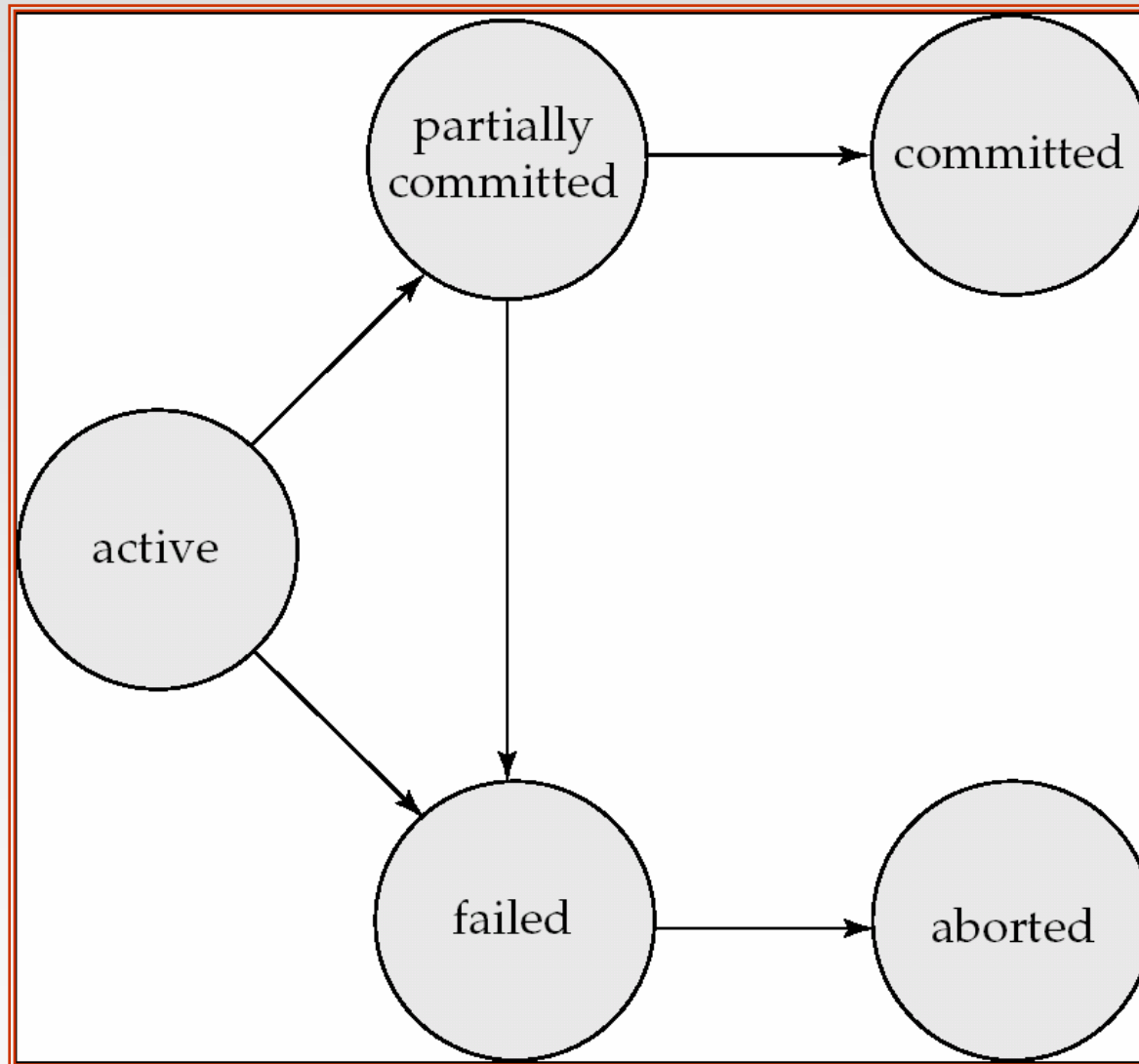
Transaction State

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





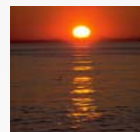
Transaction State (Cont.)





Implementation of Atomicity and Durability

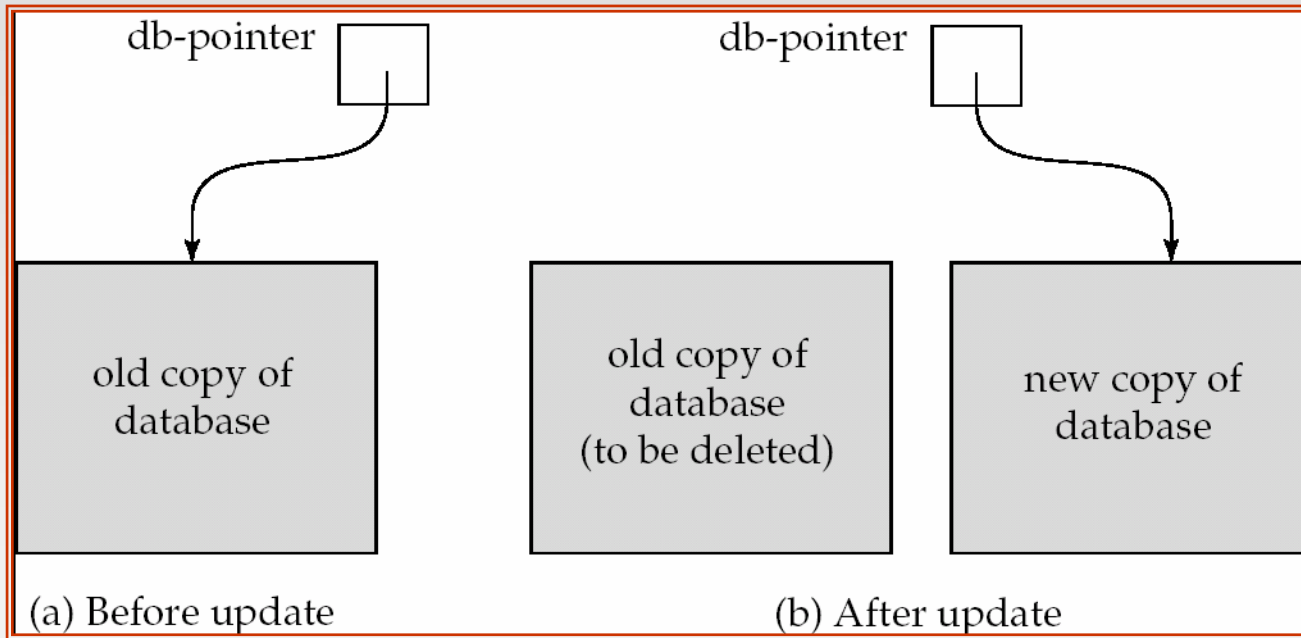
- The **recovery-management** component of a database system implements the support for atomicity and durability.
- The **shadow-database** scheme:
 - assume that only one transaction is active at a time.
 - a pointer called `db_pointer` always points to the current consistent copy of the database.
 - 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.





Implementation of Atomicity and Durability (Cont.)

The shadow-database scheme:



- Assumes disks do not fail
- Useful for text editors, but
 - extremely inefficient for large databases (why?)
 - Does not handle concurrent transactions
- Will study better schemes in Chapter 17.





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 achieve isolation; that is, to control the interaction among the concurrent transactions in order to prevent them from destroying the consistency of the database
 - Will study in Chapter 16, 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 (will be omitted if it is obvious)
- A transaction that fails to successfully complete its execution will have an abort instructions as the last statement (will be omitted if it is obvious)





Schedule 1

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





Schedule 2

- A serial schedule where 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)	read(A) $temp := A * 0.1$ $A := A - temp$ write(A) read(B) $B := B + temp$ write(B)





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)	read(B) $B := B + temp$ write(B)

In Schedules 1, 2 and 3, the sum $A + B$ is preserved.





Schedule 4

- The following concurrent schedule does not preserve the value of $(A + B)$.

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 give 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.





Conflicting Instructions

- 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. $I_i = \text{read}(Q)$, $I_j = \text{read}(Q)$. I_i and I_j don't conflict.
 2. $I_i = \text{read}(Q)$, $I_j = \text{write}(Q)$. They conflict.
 3. $I_i = \text{write}(Q)$, $I_j = \text{read}(Q)$. They conflict.
 4. $I_i = \text{write}(Q)$, $I_j = \text{write}(Q)$. 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

- 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 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 $\langle T_4, T_3 \rangle$.





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 **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_3	T_4	T_6
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**.





Other Notions of Serializability

- The schedule below produces 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)

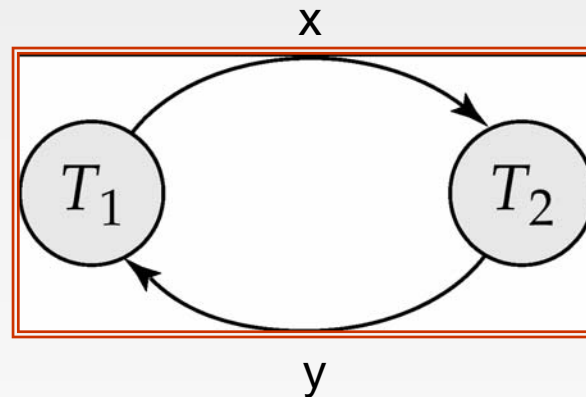
- Determining such equivalence requires analysis of operations other than read and write.





Testing for Serializability

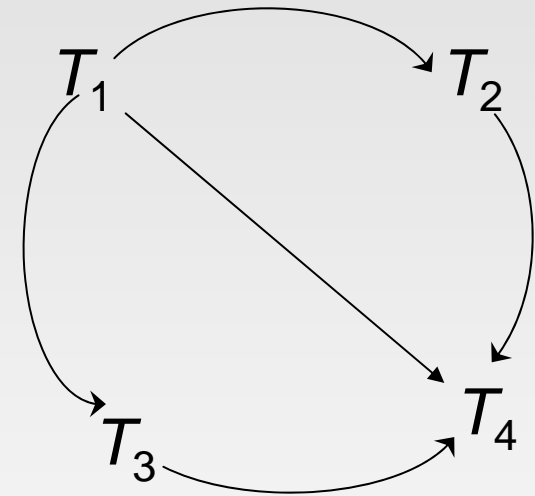
- Consider some schedule of a set of transactions T_1, T_2, \dots, T_n
- **Precedence graph** — a direct graph where the vertices are the transactions (names).
- We draw an arc from T_i to T_j if the two transaction conflict, and T_i accessed the data item on which the conflict arose earlier.
- We may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





Example Schedule (Schedule A) + Precedence Graph

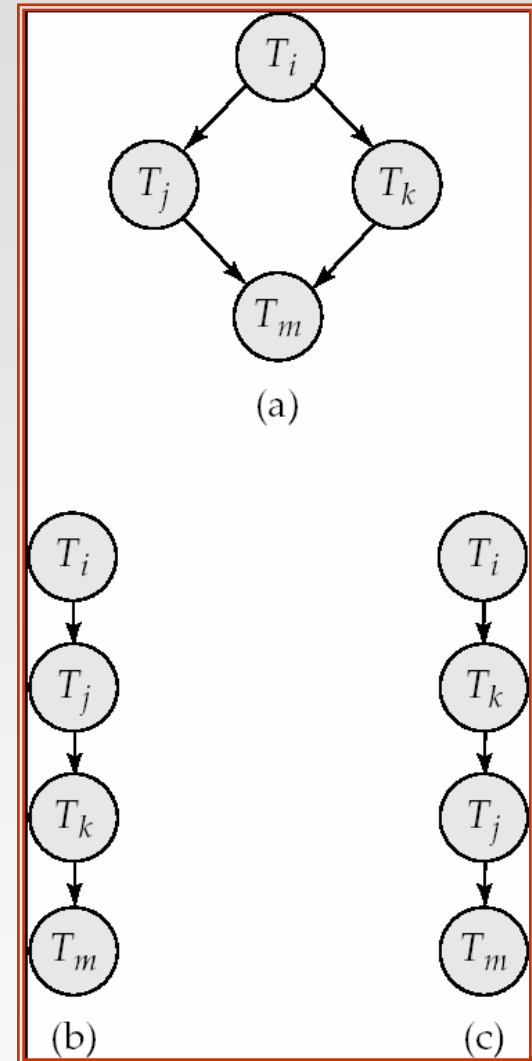
T_1	T_2	T_3	T_4	T_5
read(Y) read(Z)	read(X)			read(V) read(W) read(W)
	read(Y) write(Y)	write(Z)		
read(U)			read(Y) write(Y) read(Z) write(Z)	
read(U) write(U)				





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 $T_5 \rightarrow T_1 \rightarrow T_3 \rightarrow T_2 \rightarrow T_4$
 - ▶ Are there others?





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.





Recoverable Schedules

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

- **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 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.





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)

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** — 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





Concurrency Control

- A database must provide a mechanism that will ensure that all possible schedules are
 - either conflict or view serializable, and
 - are 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
 - Are serial schedules recoverable/cascadeless?
- Testing a schedule for serializability *after* it has executed is a little too late!
- **Goal** – to develop concurrency control protocols that will assure serializability.





Concurrency Control vs. Serializability Tests

- Concurrency-control protocols allow concurrent schedules, but ensure that the schedules are conflict/view serializable, and are recoverable and cascadeless.
- Concurrency control protocols generally do not examine the precedence graph as it is being created
 - Instead a protocol imposes a discipline that avoids nonserializable schedules.
 - We study such protocols in Chapter 16.
- Different concurrency control protocols provide different tradeoffs between the amount of concurrency they allow and the amount of overhead that they incur.
- Tests for serializability help us understand why a concurrency control protocol is correct.





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





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**

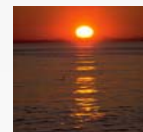




End of Chapter

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





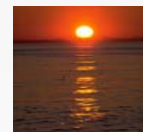
T_1	T_2
read(A)	
write(A)	
	read(A)
read(B)	
	write(A)
write(B)	
	read(B)
	write(B)





Schedule 7

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



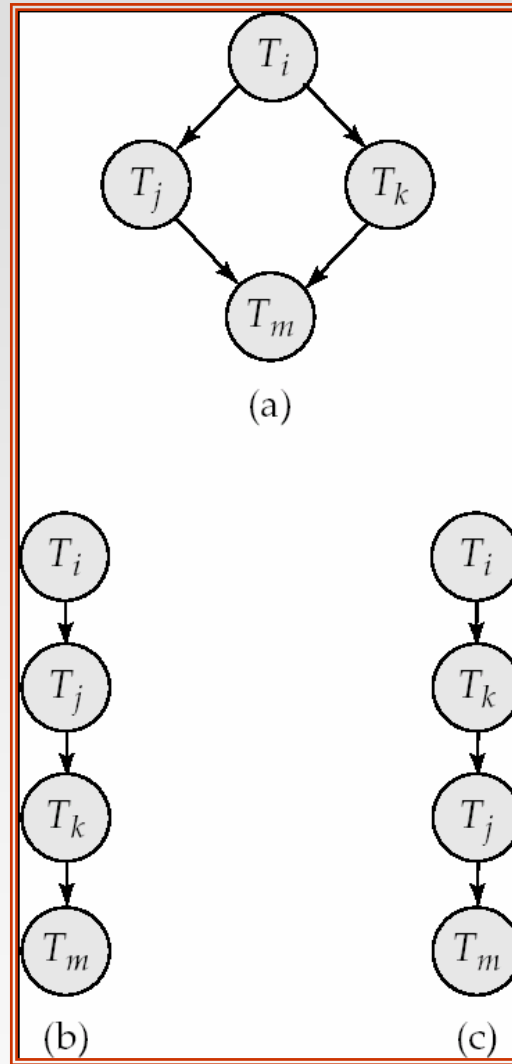


Precedence Graph for (a) Schedule 1 and (b) Schedule 2





Illustration of Topological Sorting





Precedence Graph

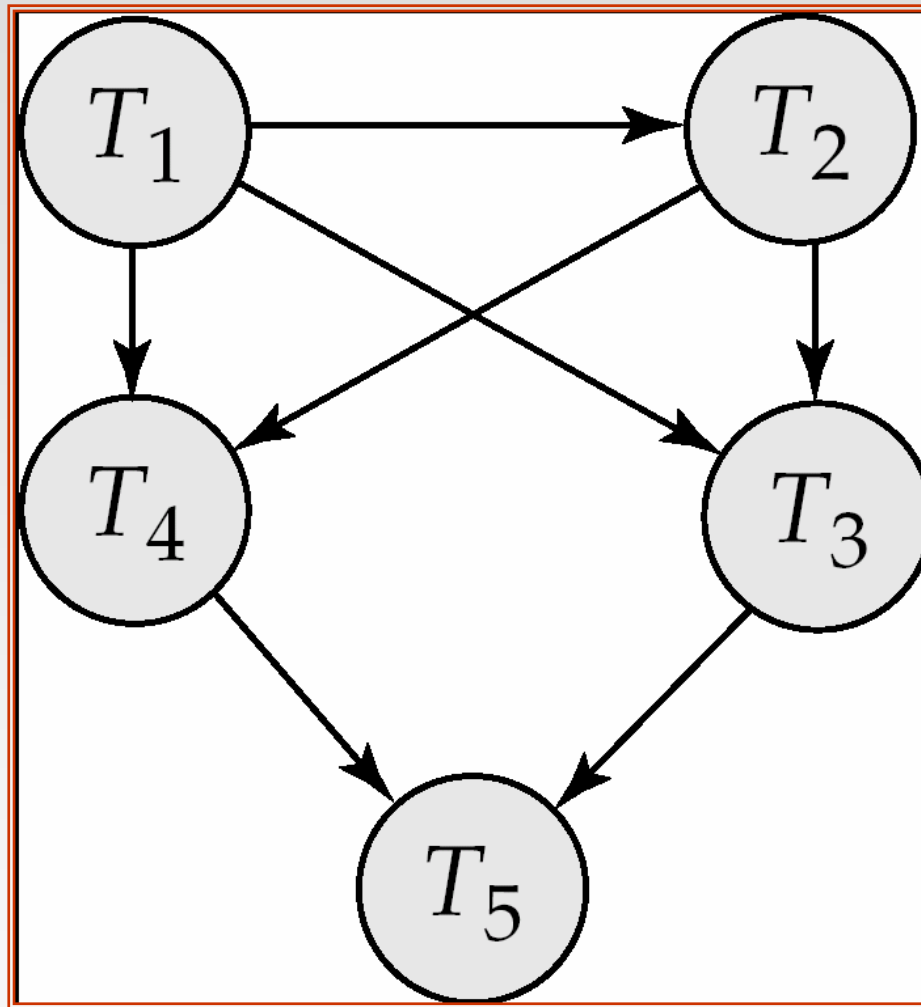




fig. 15.21

T_3	T_4	T_7
read(Q)	write(Q)	read(Q)
write(Q)		write(Q)





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.





Figure 15.6

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)



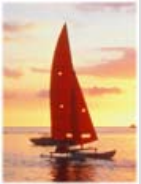


Figure 15.12

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

