



# Chapter 9: Transactions



**Textbook: Chapter 14**



# Chapter 9: 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.
- 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:
  - **Recovery:** Failures of various kinds, such as hardware failures and system crashes
  - **Concurrent:** execution of multiple transactions



# 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, money will be “lost” leading to an inconsistent database state
  - ▶ 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.



# Example of Fund Transfer (Cont.)

- 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** in above example:
  - the sum of A and B is unchanged by the execution of the transaction
- In general, consistency requirements include
  - ▶ Explicitly specified integrity constraints such as primary keys and foreign keys
  - ▶ 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 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



# Example of Fund Transfer (Cont.)

- **Isolation requirement** — if between steps 3 and 6, 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
    - ▶ can be done only if no internal logical error
  - kill the transaction
- **Committed** – after successful completion.



# Transaction Model

## ■ Operations

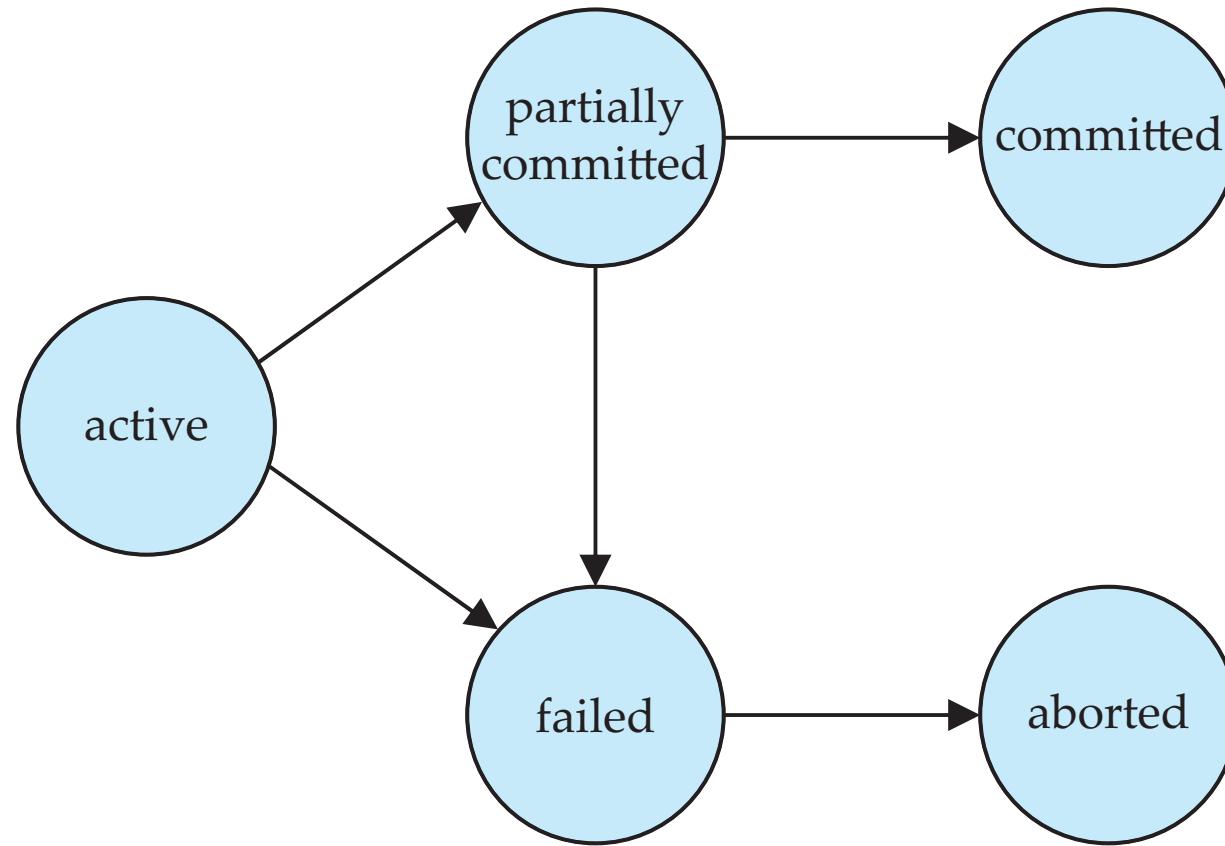
- Read(A) – read value of data item A
- Write(A) – write a new value of data item A
- Commit – commit changes of the transaction
- Abort – Revert changes made by the transaction

## ■ Data Items

- Objects in the data base
- Usually we consider tuples (rows) or disk pages



# 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*
    - ▶ E.g. one transaction can be using the CPU while another is reading from or writing to the disk
    - ▶ In multi-processor systems each statement can use one or more CPUs
  - **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



# Schedules

- **Schedule** – a sequence 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 instruction 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  $B$ .
- 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 where  $T_2$  is followed by  $T_1$

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



# 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

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

- 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**.
  - That is the order of each pair of conflicting operations in  $S$  and  $S'$  is the same
- 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**:



- 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, 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 (view serializable)?
- Every view serializable schedule that is not conflict serializable has **blind writes (write without read)**.



# 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.

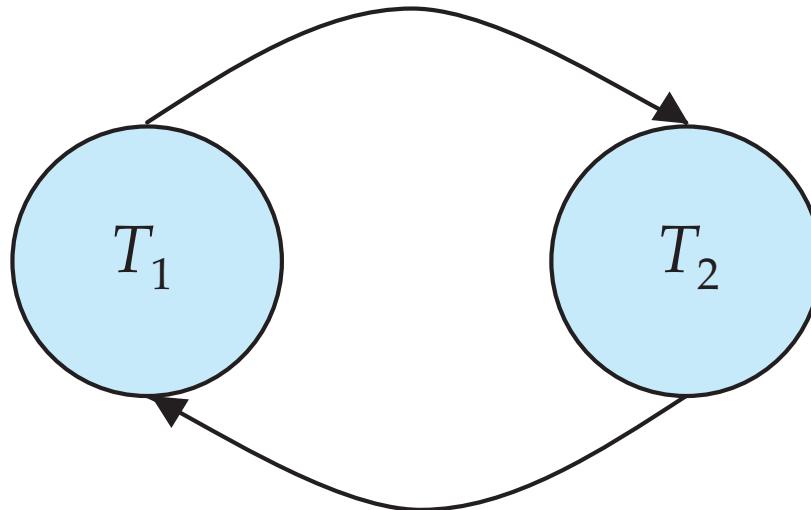
$T_1$	$T_5$
read ( $A$ ) $A := A - 50$ write ( $A$ )	read ( $B$ ) $B := B - 10$ write ( $B$ )
read ( $B$ ) $B := B + 50$ write ( $B$ )	read ( $A$ ) $A := A + 10$ write ( $A$ )

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



# Testing for Serializability

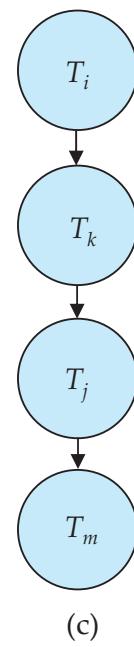
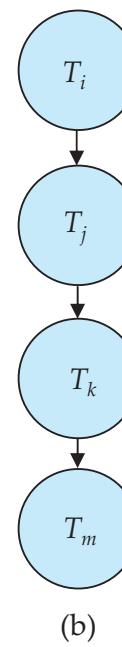
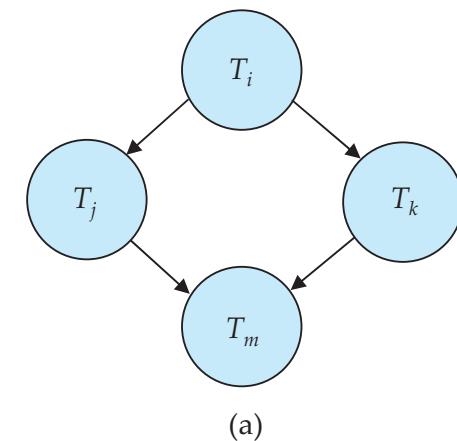
- Consider some schedule of a set of transactions  $T_1, T_2, \dots, T_n$
- **Precedence graph** — a directed graph where the vertices are the transactions (names).
- We draw an arc from  $T_i$  to  $T_j$  if the two transactions conflict, and  $T_i$  accessed the data item on which the conflict arose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





# 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.





# 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 ( $A$ ) 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 ( $A$ )	
abort		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 (Cont.)

- 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.



# 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 10.
- 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 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
- 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)



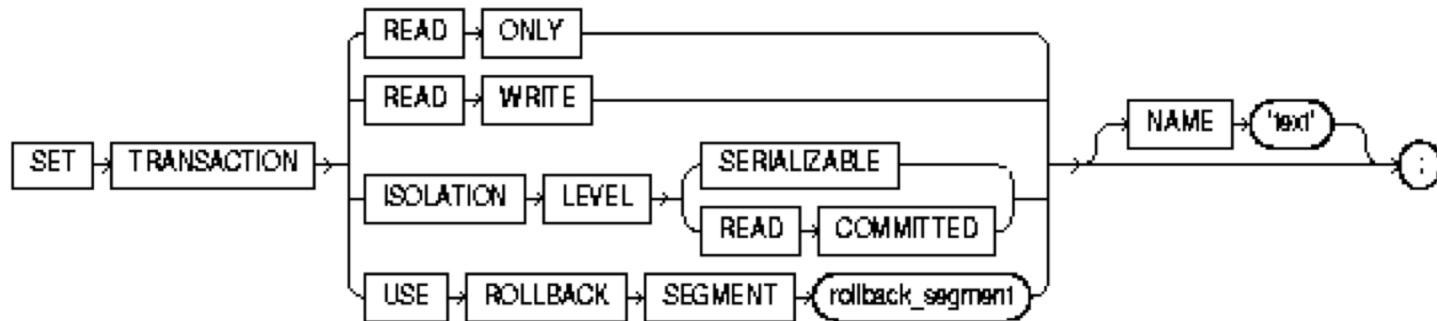
# Transaction Definition in SQL

- 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
    - ▶ E.g. in JDBC, `connection.setAutoCommit(false);`



# PL/SQL

- COMMIT;
- ROLLBACK;
- SAVEPOINT sp\_name;
- ROLLBACK TO sp\_name;
- SET AUTOCOMMIT ON/OFF/IMM/n;
- SET TRANSACTION READ ONLY (READ WRITE);
- SET TRANSACTION READ WRITE NAME 'tran\_name';
- SET TRANSACTION ISOLATION LEVEL SERIALIZABLE NAME 'tran\_name';





# End of Chapter 10

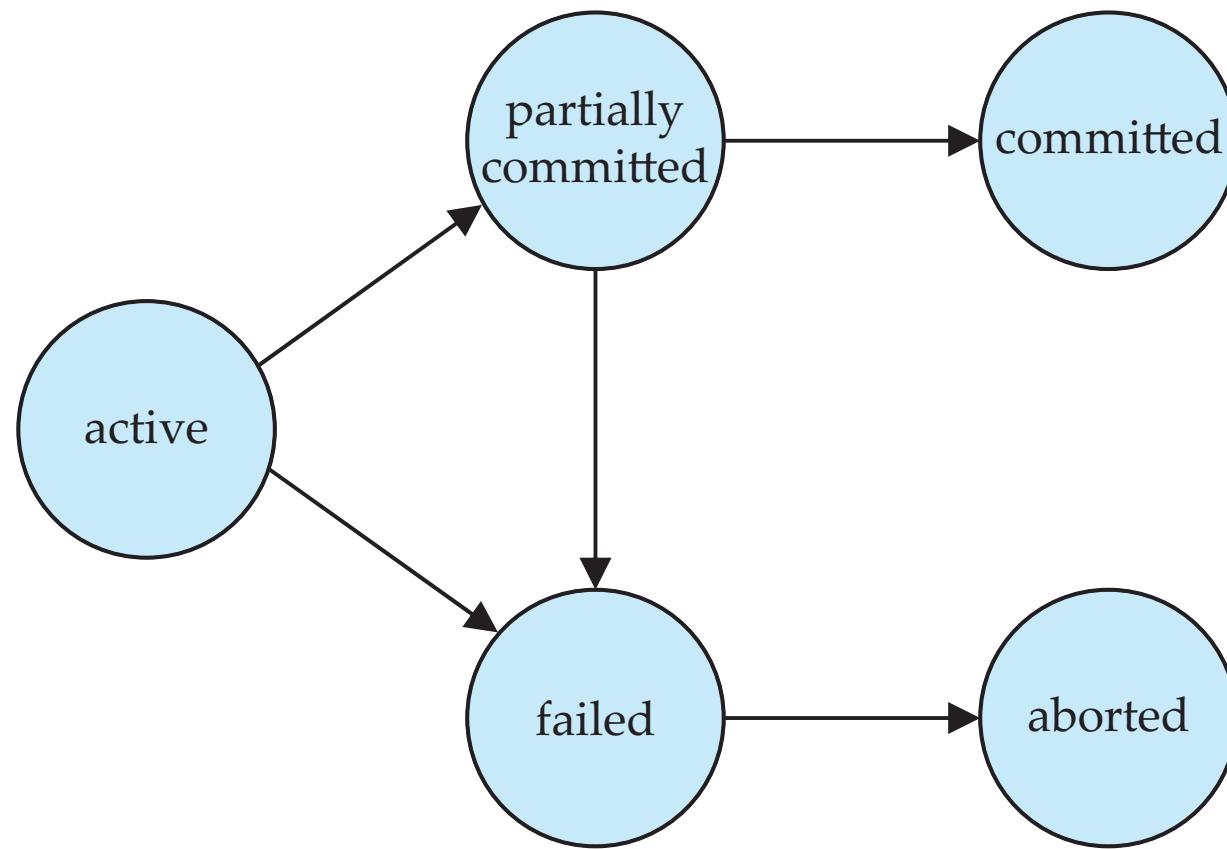


# Recap

- Transactions
  - ACID – Properties
- Schedules
  - Serial
  - Equivalence
    - ▶ Conflict-equivalent
    - ▶ View-equivalent
  - Serializability
    - ▶ = Equivalent to a serial schedule
  - Recoverable
  - Cascading Aborts
- Transactions in SQL



# Figure 14.01





# Figure 14.02

$T_1$	$T_2$
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



# Figure 14.03

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



# Figure 14.04

$T_1$	$T_2$
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



# Figure 14.05

$T_1$	$T_2$
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 ( $B$ ) commit	$B := B + temp$ write ( $B$ ) commit



# Figure 14.06

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



# Figure 14.07

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



# Figure 14.08

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

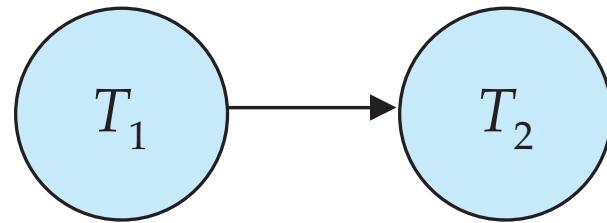


# Figure 14.09

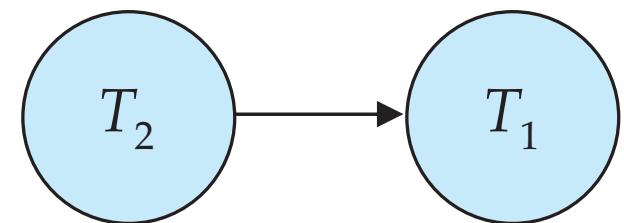




# Figure 14.10



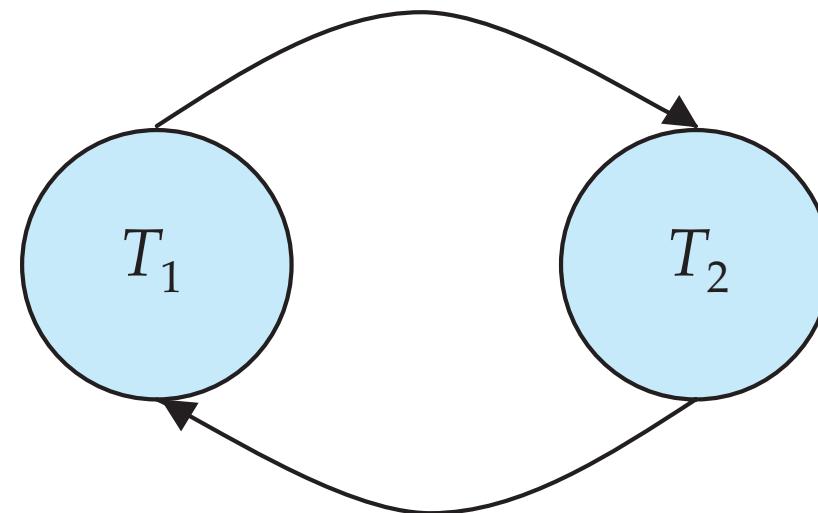
(a)



(b)

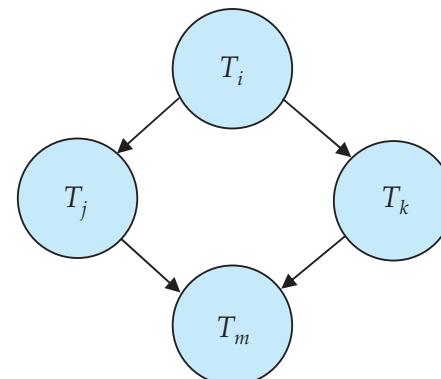


# Figure 14.11

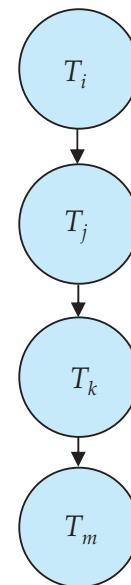




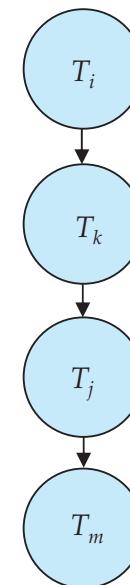
# Figure 14.12



(a)



(b)



(c)



# Figure 14.13

$T_1$	$T_5$
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 ( $A$ )



# Figure 14.14

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



# Figure 14.15

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



# Figure 14.16

