# Module 17: Transactions

**Database System Concepts, 7th Ed.**

# 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

# 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.)

- **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 | T2 |
|---|---|
| 1. **read**(*A*) | |
| 2. *A* := *A* – 50 | |
| 3. **write**(*A*) | |
| | read(A), read(B), print(A+B) |
| 4. **read**(*B*) | |
| 5. *B* := *B* + 50 | |
| 6. **write**(*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

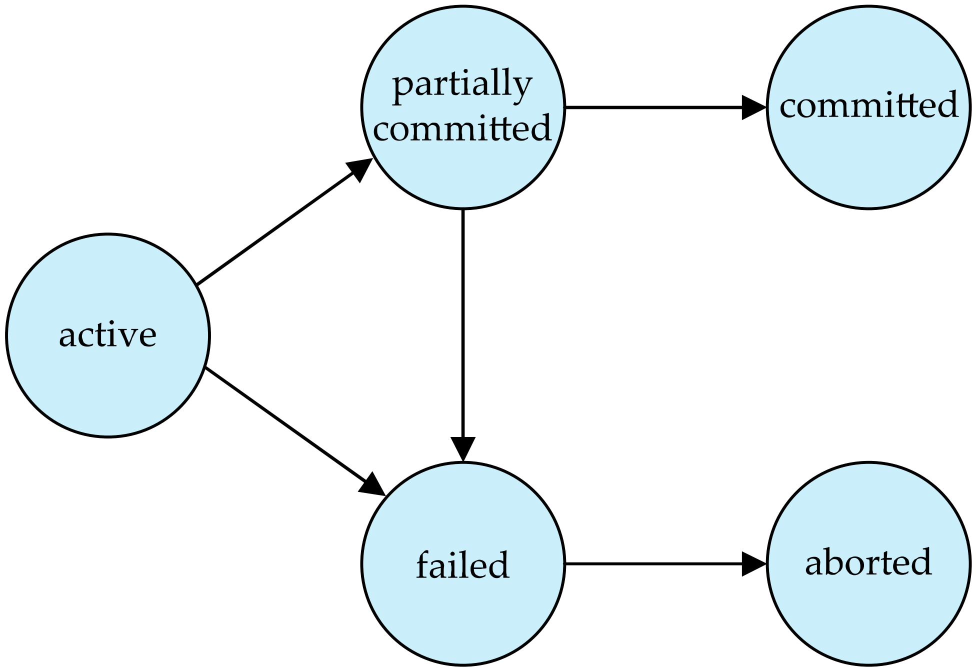
A **transaction** is a unit of program execution that accesses and possibly updates various data items. To preserve the integrity of data the database system must ensure:

- **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 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
  - **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 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.*
- 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 $T_1$

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

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 $l_i$ and $l_j$ of transactions $T_i$ and $T_j$ respectively, **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. $l_i$ = **read**($Q$), $l_j$ = **read**($Q$). $l_i$ and $l_j$ don't conflict.
  2. $l_i$ = **read**($Q$), $l_j$ = **write**($Q$). They conflict.
  3. $l_i$ = **write**($Q$), $l_j$ = **read**($Q$). They conflict
  4. $l_i$ = **write**($Q$), $l_j$ = **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 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 < $T_3$, $T_4$ >, or the serial schedule < $T_4$, $T_3$ >.

# 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**.

# Other Notions of Serializability

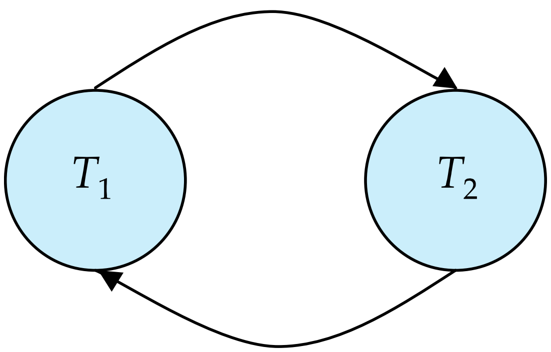
- The schedule below produces same outcome as the serial schedule $< T_1, T_5 >$, yet is not conflict equivalent or view equivalent to it.

| $T_1$ | $T_5$ |
|---|---|
| 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.

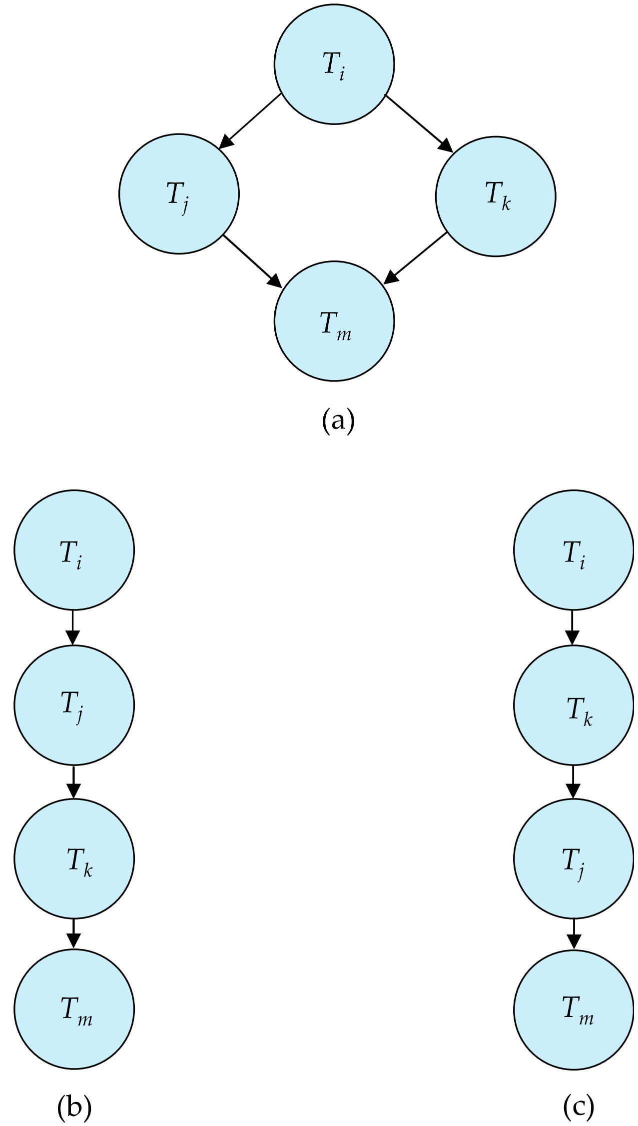
# Testing for Serializability

- Consider some schedule of a set of transactions $T_1$, $T_2$, ..., $T_n$
- **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**



# 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

| $T_8$ | $T_9$ |
|---|---|
| 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** — 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.)

- 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.

# 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 non-serializable 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.
  - Successive reads of record may return different (but committed) values.
- **Read uncommitted** — even uncommitted records may be read.

# Levels of Consistency

- 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 prior to version 9) by default support a level of consistency called snapshot isolation (not part of the SQL standard)

# Transaction Definition in SQL

- 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);
- Isolation level can be set at database level
- Isolation level can be changed at start of transaction
    - E.g. In SQL **set transaction isolation level serializable**
    - E.g. in JDBC -- connection.setTransactionIsolation( Connection.TRANSACTION_SERIALIZABLE)

# Implementation of Isolation Levels

Overview

- Locking
  - Lock on whole database vs lock on items
  - How long to hold lock?
  - Shared vs exclusive locks
- Timestamps
  - Transaction timestamp assigned e.g. when a transaction begins
  - Data items store two timestamps
    - Read timestamp
    - Write timestamp
  - Timestamps are used to detect out of order accesses
- Multiple versions of each data item
  - Allow transactions to read from a "snapshot" of the database

# Transactions as SQL Statements

- E.g. Transaction 1:
  **select** *ID, name* **from** *instructor* **where** *salary* > 90000
- Transaction 2:
  **insert into** *instructor* **values** ('11111', 'James', 'Marketing', 100000)
- Suppose
  - T1 starts, finds tuples salary > 90000 using index and locks them
  - And then T2 executes.
  - Do T1 and T2 conflict? Does tuple level locking detect the conflict?
  - Instance of the **phantom phenomenon**
- Also consider T3 below, with Wu's salary = 90000
  **update** *instructor*
  **set** *salary* = *salary* * 1.1
  **where** *name* = 'Wu'
- Key idea: Detect "**predicate**" conflicts, and use some form of "**predicate locking**"

# End of Chapter 17