Database Systems
Lecture18 – Chapter 17: Transactions

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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*)

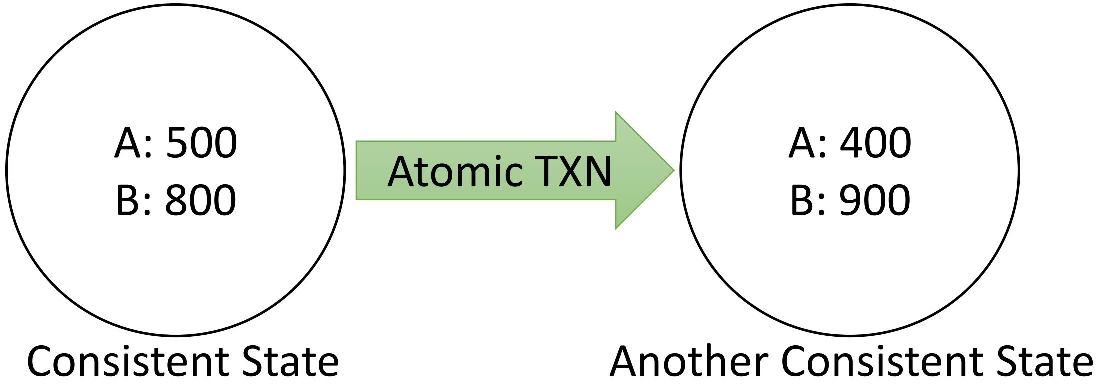
- Two main issues to deal with:
  - Failures of various kinds, such as hardware failures and system crashes
  - Concurrent execution of multiple transactions

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
  - 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
  - Explicit 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.

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**, i.e., one after the other.
- However, executing multiple transactions sequentially has performance problems.

ACID Principles

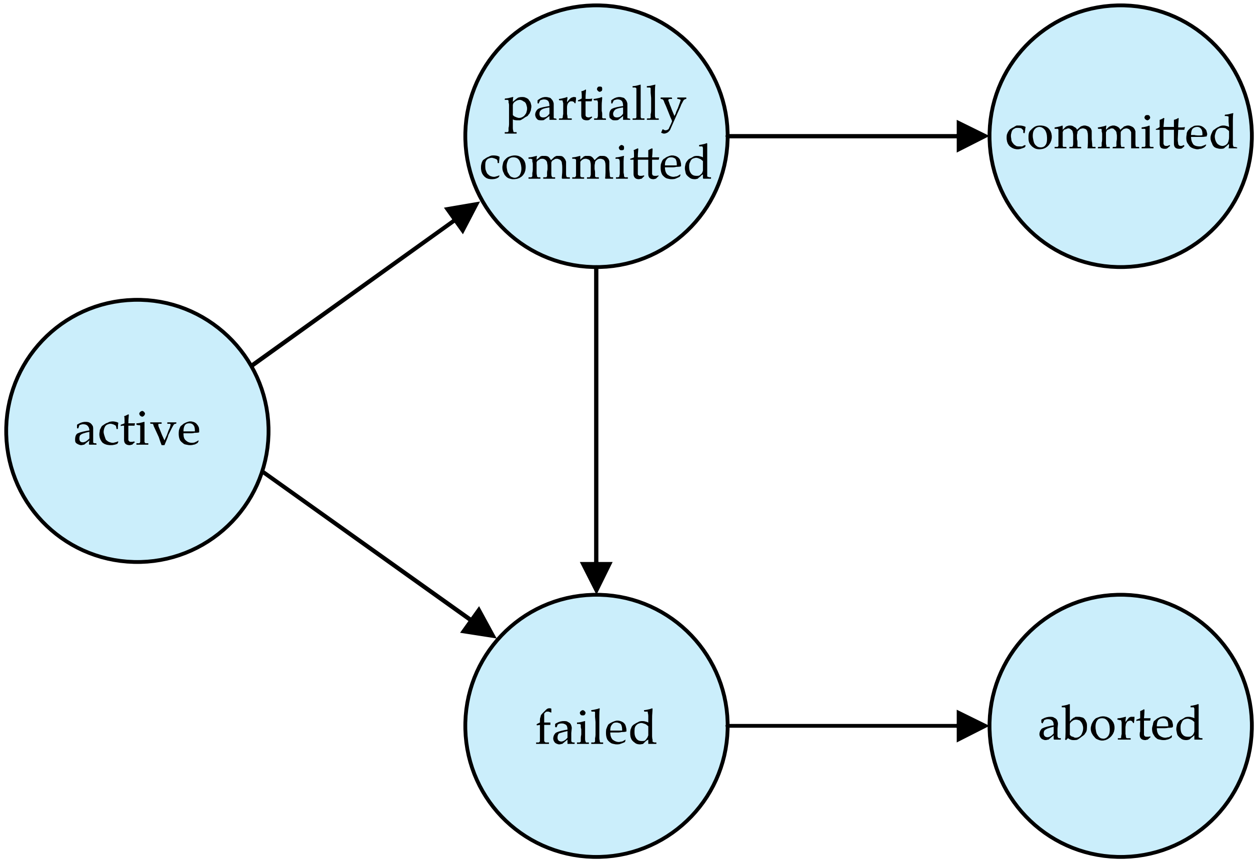
- To preserve the integrity of data the database system must ensure:

- **Atomicity.** Either all operations of the transaction are properly reflected in the database or none are. All or Nothing.
- **Consistency.** Atomic 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** – state after the final statement has been executed.
- **Failed** – state after the discovery that normal execution can no longer proceed.
- **Aborted** – state 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** – state after successful completion.

Transaction State Transition Diagram



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
  - control the interaction among the concurrent transactions
  - prevent from destroying the consistency of the database
    - Will study in Chapter 18

Schedules

- **Schedule** –specify the 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 of instructions that appear in each individual transaction.

- A transaction that successfully completes its execution will have a commit instruction as the last statement

- A transaction that fails to complete its execution will have an abort instruction as the last statement

Serial 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

Serial 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	

Serializable 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.

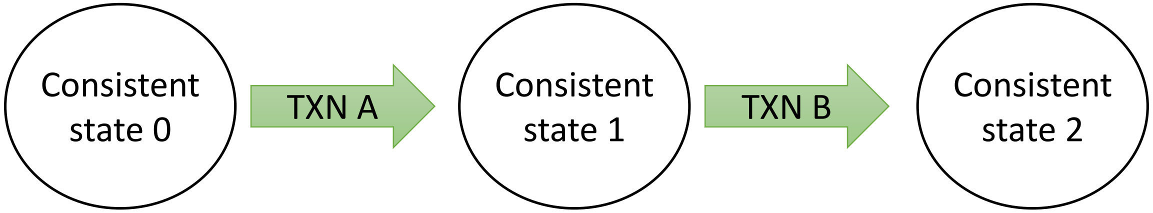
Schedule 4

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

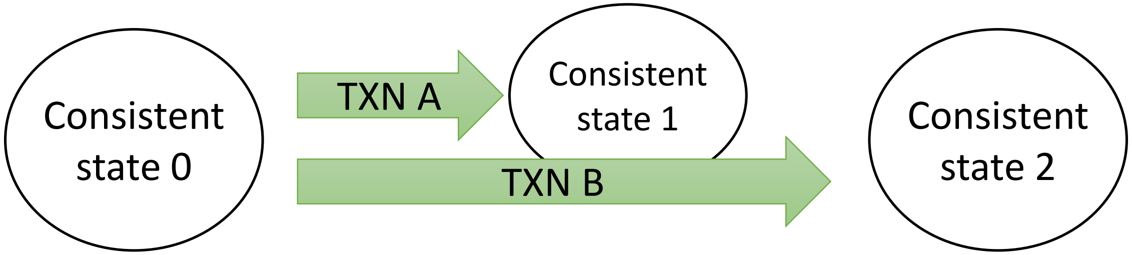
T_1	T_2
read (A)	
$A := A - 50$	
	read (A)
	$temp := A * 0.1$
	$A := A - temp$
	write (A)
	read (B)
write (A)	
read (B)	
$B := B + 50$	
write (B)	
commit	
	$B := B + temp$
	write (B)
	commit

Serializability

- **Basic Assumption**:
  - We assume each transaction preserves database consistency.
- Thus, serial execution of a set of transactions preserves database consistency.



- A schedule is ***serializable*** if it is equivalent to a serial schedule.



- Different forms of serializability:
  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 **conflict** if and only if at least one of these instructions write a shared data item *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

- Note: a conflict forces an order between them.
- If *instructions* are consecutive in a schedule and they do not conflict, their results would remain the same even if we interchange them 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

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'.*

- 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

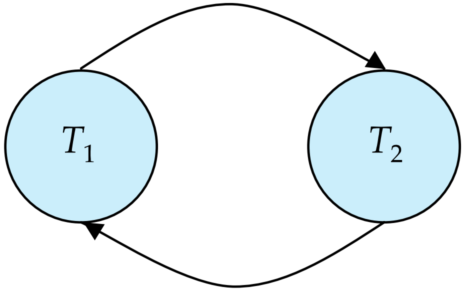
- The schedule below produces same outcome as the serial schedule < T_1, T_5 >, yet is not conflict equivalent or view equivalent to it.

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.

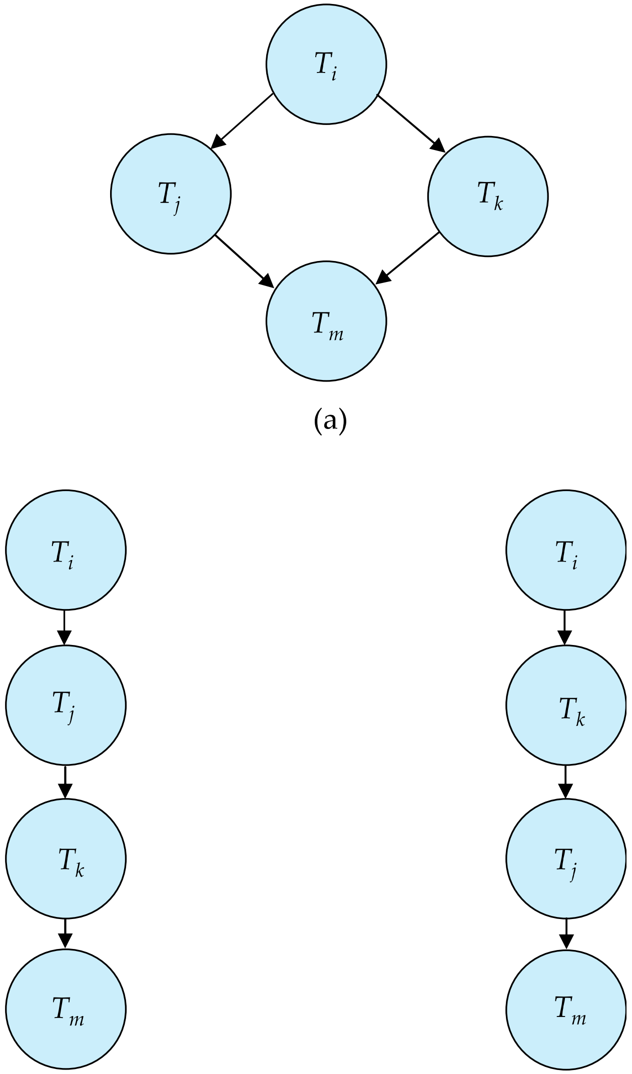
Testing for Serializability

- 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 transactions conflict, and T_i accessed the conflicting data item earlier than T_j.
- We may label the arc by the item that was accessed.
- Example of a precedence graph



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.



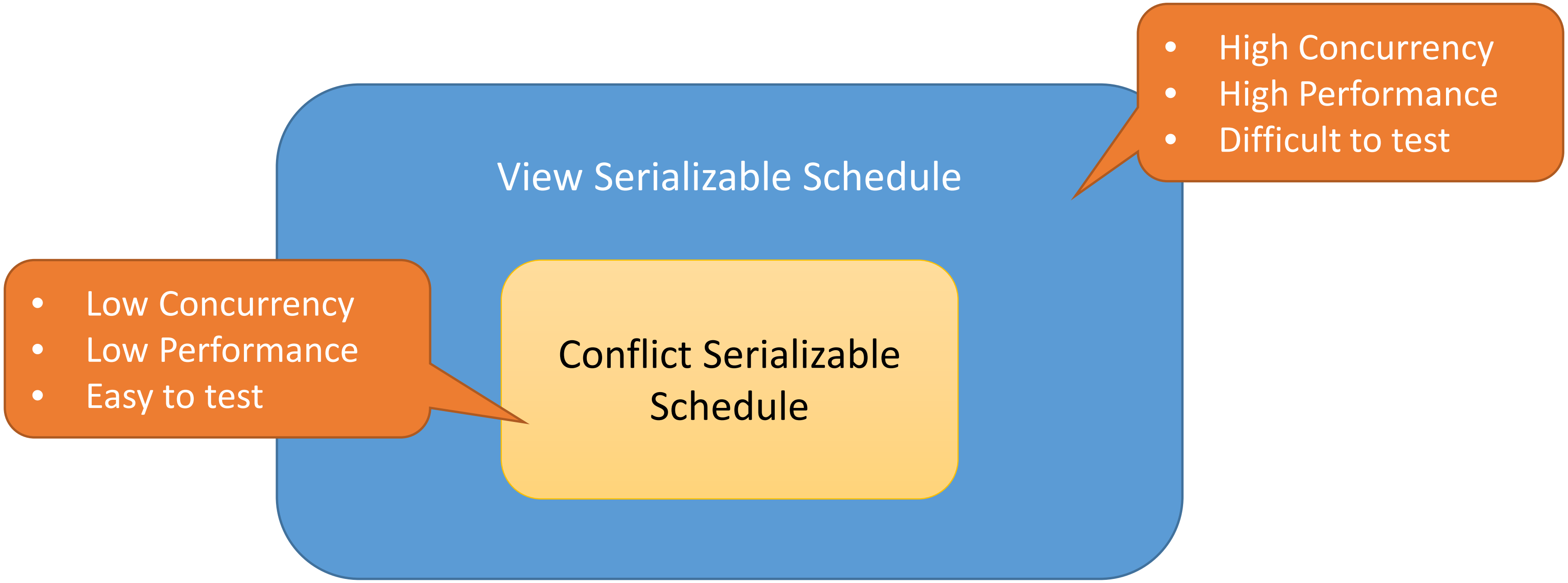
(a) (b) (c)

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.

Conflict Serializability vs. View Serializability

- Conflict serializability is more popular in DBMS in practice
- But, conflict serializability actually permit only a subset of serializable schedules that do not have consistency problems.
- The general form of view serializability is very expensive to test, and only a very restricted form of it is used for concurrency control.



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 is not recoverable

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

- 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.
  - Read committed data only!
- Every Cascadeless schedule is also recoverable
- It is desirable to restrict the schedules to those that are cascadeless

Concurrency Control

- Goal: A DBMS must make scheduling decisions that are
  - either conflict or view serializable, and
  - recoverable and preferably cascadeless

- DBMS scheduler should provide a high degree of concurrency
  - 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.
  - We study concurrency control protocols in Chapter 18.

Weak Levels of Consistency

- Some applications (OLAP) are willing to live with weak levels of consistency, allowing schedules that are not serializable
  - Tradeoff accuracy for performance
- On Line Transaction Processing –OLTP
  - Maintains a database that is an accurate model of some real-world enterprise
    - Short simple transactions
    - Transactions access only a small fraction of the database
- On Line Analytic Processing –OLAP
  - Uses database to guide strategic decisions.
    - Complex queries
    - Transactions access a large fraction of the database
    - Data need not be up-to-date
    - E.g., A bank CEO wants to get an approximate total balance of all customers' accounts
  - OLAP transactions need not be serializable with respect to other OLTP transactions

Phenomena caused by Concurrent Transactions

- **dirty read**
  - A transaction reads data written by a concurrent uncommitted transaction.
- **nonrepeatable read**
  - A transaction runs the same query twice and finds that a data has been modified by another transaction.
- **phantom read**
  - A transaction runs the same query twice and finds that the result set has new records due to another recently-committed transaction.
- **serialization anomaly**
  - The result of successfully committing a group of transactions is inconsistent with all possible orderings of running those transactions one at a time.

Phantom Phenomenon

- E.g., Transaction 1:
  select *ID, name* **from** *instructor* **where** *salary* > 90000
- E.g., 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**

Transaction Isolation 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.

Isolation Level	Dirty Read	Nonrepeatable Read	Phantom Read	Serialization Anomaly
Read uncommitted	Allowed, but not in PG	Possible	Possible	Possible
Read committed	Not possible	Possible	Possible	Possible
Repeatable read	Not possible	Not possible	Allowed, but not in PG	Possible
Serializable	Not possible	Not possible	Not possible	Not possible

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

- 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