Chapter 17: Transactions

Edited by Radhika Sukapuram

Database System Concepts, 6th Ed.

Transaction

- 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

Read and write operations

- Transactions access data using two operations:
  - read(*X*), which transfers the data item *X* **from the database to a variable**, also called *X*
  - *X is* in a buffer in main memory belonging to the transaction that executed the read operation.
  - write(*X*), which transfers the value in the variable *X* in the main-memory buffer of the transaction that executed the write **to the data item *X* in the database**.
- A write operation does not necessarily result in the immediate update of the data on the disk – **for now we assume it does**

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
    - 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
  - Ensuring atomicity is the **responsibility of the database system**

Required Properties of a Transaction (Cont.)

- **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.

- To ensure durability the database must ensure that either:
  - The updates carried out by the transaction have been written to disk **before the transaction completes**

  OR

  - **Information about the updates** carried out by the transaction is written to disk
  - and such information is sufficient to enable the database to reconstruct the updates when the database system is restarted after the failure
  - The above is the job of the recovery system of a DBMS

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
  - 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, 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
- Ensuring consistency is **the responsibility of the application programmer** who codes the transaction. This task may be facilitated by automatic testing of integrity constraints

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	**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.
- Ensuring the isolation property is the responsibility of a component of the database system called the concurrency-control system

ACID Properties

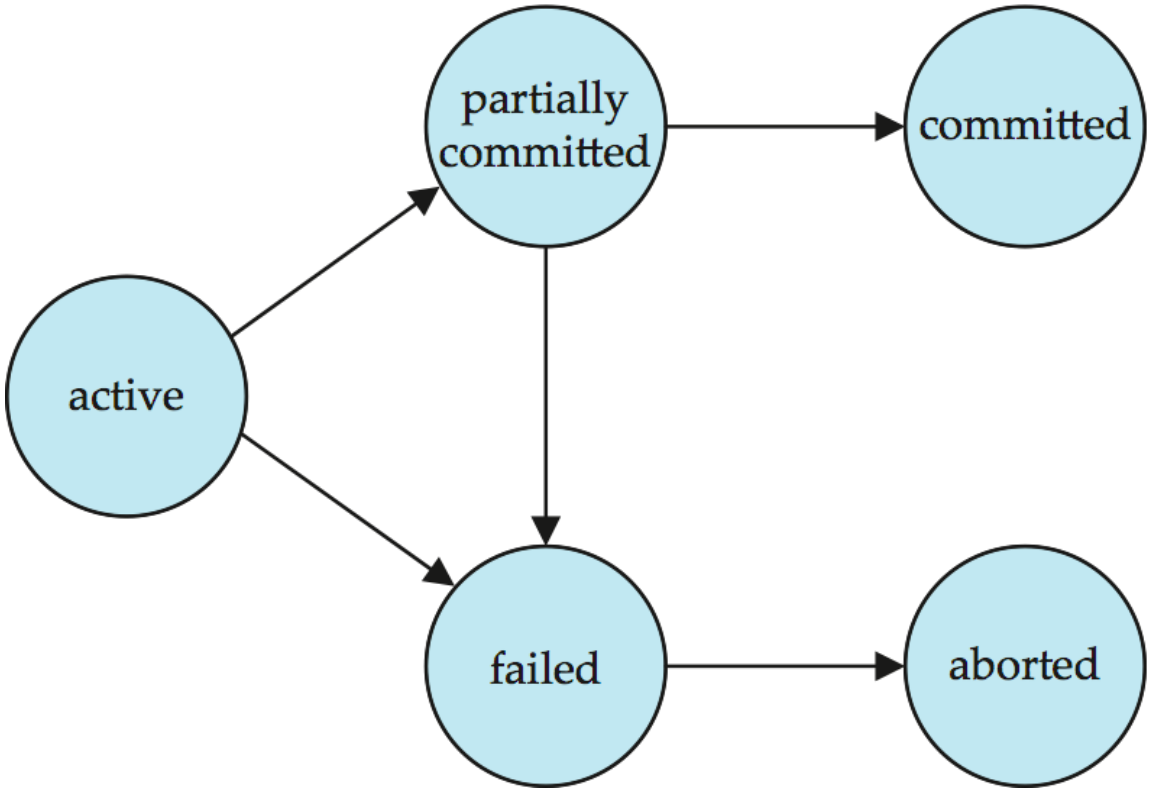
A **transaction** is a unit of program execution that accesses and possibly updates various data items. To preserve the integrity of data the database system must ensure:

- **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.)



Observable external writes

- Observable external writes
  - Examples: writes to a user's screen, or sending email
  - Allow them to take place only after the transaction is committed
  - If the system restarts after a commit, perform the external write after restart
- More complex situations may require compensating transactions
  - Example: Dispensing cash in an ATM

Concurrent Executions

- Multiple transactions are allowed to run concurrently
  - **Increased processor and disk utilization**, leading to better transaction *throughput*
    - E.g. one transaction can use 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.
- we present the concept of **schedules** to help identify those executions that are guaranteed to ensure the isolation property

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

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 a 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

A serial schedule

- A serial schedule
  - consists of a sequence of instructions from various transactions,
  - where the instructions belonging to a transaction appear together in that schedule
- Any schedule that is executed must leave the database system in a consistent state

Concurrency control

- **Concurrency control schemes** – mechanisms to achieve **isolation**
  - That is, to control the interaction among concurrent transactions
    - in order to prevent them from destroying the consistency of the database
    - Will study later

Schedule 2

- A **serial** schedule in which 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

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

Schedule 4

- The following concurrent schedule does not preserve the sum of "$A + B$"

A=1000, B=2000

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

Assume that T1 and T2 run in separate processes. What are the values of A and B at the end?

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 I_i and I_j be two Instructions of transactions T_i and T_j respectively.
- Instructions I_i and I_j **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 = **read**(Q), I_j = **read**(Q). I_i and I_j don't conflict.
  2. I_i = **read**(Q), I_j = **write**(Q). They conflict.
  3. I_i = **write**(Q), I_j = **read**(Q). They conflict
  4. I_i = **write**(Q), I_j = **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 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

Are schedules 1 and 2 conflict equivalent?

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 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 2

Conflict Serializability (Cont.)

- Example of a schedule that is not conflict serializable:

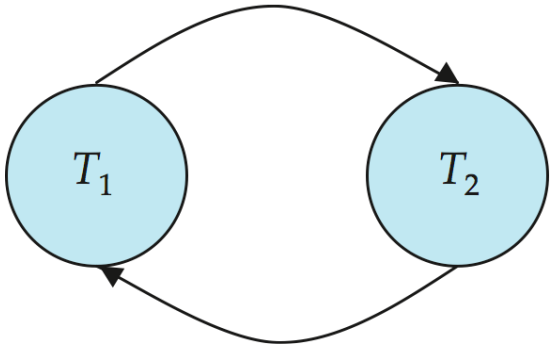
T_3	T_4
read (Q)	
	write (Q)
write (Q)	

- 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 >.
- How to efficiently determine conflict serializability of a schedule ?

Precedence Graph

- Consider some schedule of a set of transactions T_1, T_2, ..., 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 accesses the data item first on which the conflict arose (RW, WR, WW)
- We may label the arc by the item that was accessed.

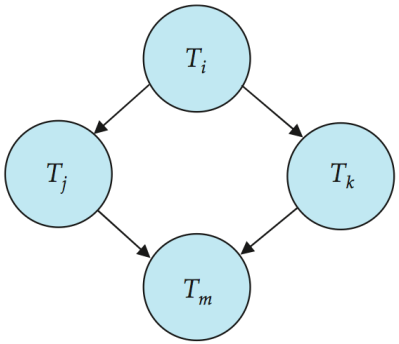
Precedence graph cont.



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

Testing for Conflict Serializability

- A schedule is conflict serializable if and only if its precedence graph is acyclic.
- Cycle-detection algorithms exist
  - (order (*n* + *e)* where *e* is the number of edges, n the number of vertices.)
- 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)



(a)

Transaction failures

- The discussion on serializability assumes that there are no transaction failures
- Suppose there are transaction failures
  - The effect must be undone
  - A dependent transaction must also be aborted
- What is the impact of this ?

Recoverable Schedules

- 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, a database must ensure that schedules are recoverable.
- **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

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 schedule** — one where 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)	
		read (A)
abort		

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
- Tests for serializability help us understand why a concurrency control protocol is correct
- **Goal** – to develop concurrency control protocols that will ensure 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
  - Such transactions need not be serializable with respect to other transactions
- Tradeoff accuracy for performance

Weak levels of consistency cont.

- Dirty read : A transaction T_j reads an uncommitted data item previously written by T_i
- Dirty write : A transaction T_j writes an uncommitted data item previously written by T_i

Weak levels of consistency cont.

- Phantom read: A transaction T_j reads a data item (a phantom) that was inserted into the database by T_i
- T_{30}: **select** *ID*, *name*

  from *instructor*

  where *salary* > 90000;
- T_{31} : **insert into** *instructor*
  values (1111, 'Feynman', 'Physics', 94000);
  - If T_{30} reads the value written by T_{31}, in a serializable schedule, T_{30} must come afterT_{31}. Else T_{30} must come beforeT_{31}
  - Conflict is on predicates, not on the data item itself
    - Information used to find tuples must also be considered for concurrency control
  - If concurrency is performed at tuple granularity, the inserted tuple may go undetected – this is called the phantom phenomenon

Levels of Consistency in SQL-92

- **Serializable** — default [may result in non-serializable executions in some DBMSs]
- **Repeatable read** —
  - only committed records to be read, (no dirty reads)
  - repeated reads of same record must return same value. (between two reads of a data item by a transaction, no other transaction is allowed to update it : no non-repeatable reads)
  - However, a transaction may not be serializable – it may find some records inserted by a transaction but not find others (phantoms allowed).
    - T1 may see some records inserted by T2, but may not see others inserted by T2
- **Read committed** — only committed records can be read (no dirty reads), but successive reads of record may return different (but committed) values (non-repeatable reads and phantom reads allowed).
- **Read uncommitted** — even uncommitted records may be read.
- **All the levels above additionally disallow dirty writes**
- Syntax: **set transaction isolation level <isolation_level >;**

Transaction Definition in SQL

- Data manipulation languages must include a construct for specifying the set of actions that comprise a transaction.
- In SQL99, a transaction begins with **begin**
- 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);

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'.*

S1

T1	T2
R(X)	
W(X)	
	R(X)
	W(X)
R(Y)	
W(Y)	
	R(Y)
	W(Y)

S2

T1	T2
R(X)	
W(X)	
R(Y)	
W(Y)	
	R(X)
	W(X)
	R(Y)
	W(Y)

View Serializability (Cont.)

- Conditions 1 and 2 ensure that each transaction reads the same values in both schedules and, therefore, performs the same computation
- Condition 3, coupled with conditions 1 and 2, ensures that both schedules result in the same final system state.
- 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? <T27, T28, T29>
- Every view serializable schedule that is not conflict serializable has **blind writes (writes without prior reads)**
- The problem of checking if a schedule is view serializable falls in the class of *NP*-complete problems.

More Complex Notions of Serializability

- The schedule below produces the 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)

- 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, ie analysis of what computations are performed.
- Conclusion : There are less stringent definitions of schedule equivalence than conflict/view equivalence

End of Chapter 17

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