Chapter 14: Transactions

Database System Concepts, 7th Ed.

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

- **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

- **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

ACID Properties

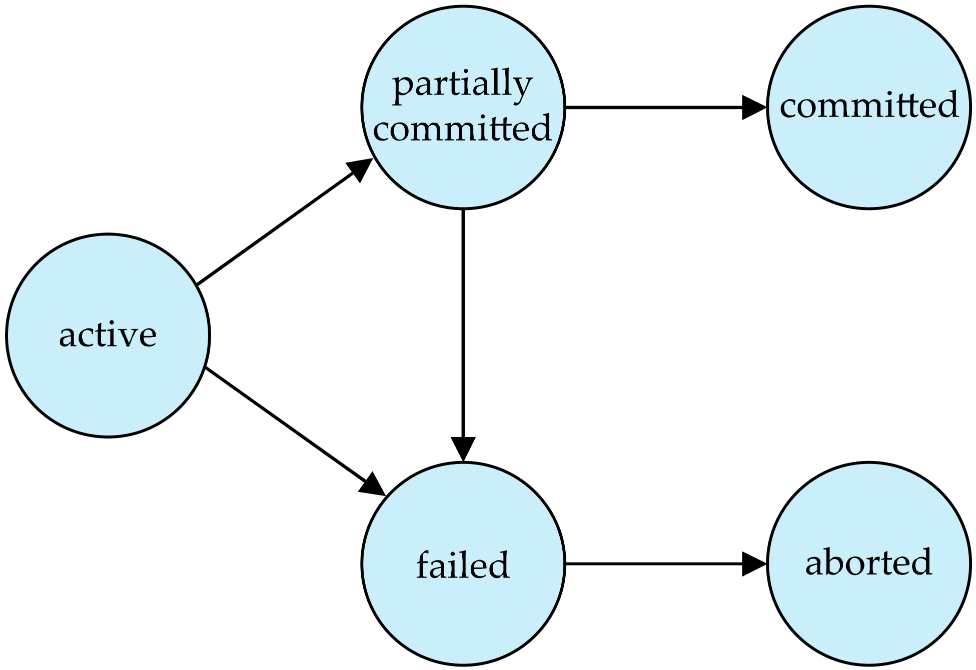
A **transaction** is a unit of program execution that accesses and possibly updates various data items. To preserve the integrity of data the database system must ensure:

- **Atomicity.** Either all operations of the transaction are properly reflected in the database, or none are (all or nothing)
- **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



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

The Lost Update Problem

(a)

Time

T_1	T_2
read_item(X);	
$X := X - N$;	
	read_item(X);
	$X := X + M$;
write_item(X);	
read_item(Y);	
	write_item(X);
$Y := Y + N$;	
write_item(Y);	

Item X has an incorrect value because its update by T_1 is *lost* (overwritten).

The Temporary Update Problem

(b)

Time

T_1	T_2

read_item(X);
$X := X - N$;
write_item(X);	

	read_item(X);
	$X := X + M$;
	write_item(X);

read_item(Y);	

Transaction T_1 fails and must change the value of X back to its old value; meanwhile T_2 has read the *temporary* incorrect value of X.

The Incorrect Summary Problem

(c)

T_1	T_3
	sum := 0;
	read_item(A);
	sum := *sum* + A;
	⋮
read_item(X);	
$X := X - N$;	
write_item(X);	
	read_item(X);
	sum := *sum* + X;
	read_item(Y);
	sum := *sum* + Y;
read_item(Y);	
$Y := Y + N$;	
write_item(Y);	

T_3 reads X after N is subtracted and reads Y before N is added; a wrong summary is the result (off by N).

The Unrepeatable Read Problem

- Transaction T reads the same item twice
- Value is changed by another transaction T′ between the two reads
- T receives different values for the two reads of the same item

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, a transaction is assumed to execute commit instruction as its last step

Schedule 1

- Let T_1 transfer \$50 from A to B, and T_2 transfer 10% of the balance of A 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 (i.e., T_1 followed by T_2)

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 is assumed correct if executed on its own
- Serial execution of a set of transactions is assumed correct
- **Criterion for correctness: every serial schedule is considered correct**
- A (possibly concurrent) schedule is serializable if it is equivalent to a serial schedule. Different forms of schedule equivalence give rise to the notion of **conflict 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* and *J* of transactions T_i and T_j respectively, **conflict** if and only if there exists some item *Q* accessed by both *I* and *J*, and at least one of these is a write instruction
  1. *I* = **read**(*Q*), *J* = **read**(*Q*). *I* and *J* don't conflict (the order of *I* & *J* does not matter)
  2. *I* = **read**(*Q*), *J* = **write**(*Q*). They conflict (the order of *I* & *J* matters: write before read and read before write gives different read results)
  3. *I* = **write**(*Q*), *J* = **read**(*Q*). They conflict (the order of *I* & *J* matters)
  4. *I* = **write**(*Q*), *J* = **write**(*Q*). They conflict (the order of *I* & *J* matters since it would affect the result of the next **read**(*Q*) instruction)
- Intuitively, a conflict between *I* and *J* forces a (logical) temporal order between them
- If *I* and *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**
- Or equivalently, two schedules are conflict equivalent if the relative order of any two conflicting instructions is the same in both schedules
- We say that a schedule *S* is **conflict serializable** if it is conflict equivalent to a serial schedule

Conflict Serializability

- Schedule 1 can be transformed into Schedule 2, a serial schedule where T_2 follows T_1, by series of swaps of non-conflicting instructions. Therefore Schedule 1 is conflict serializable

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

Schedule 1

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

Schedule 2

Conflict Serializability

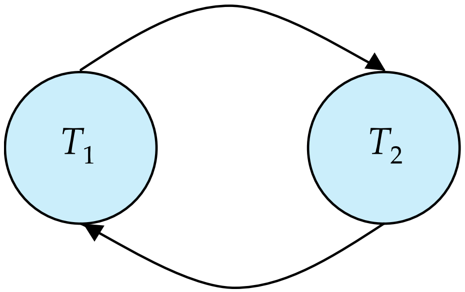
- Example of a schedule that is not conflict serializable:

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

- T_4's update is lost
- 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 >
- This is not conflict serializable since it is not equivalent to either the serial schedule < T_3, T_4 >, or the serial schedule < T_4, T_3 >

Testing for Serializability

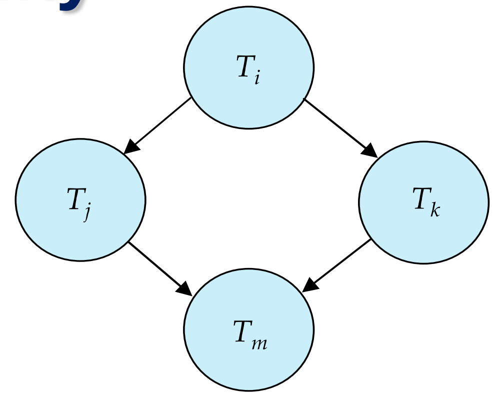
- Consider some schedule S of a set of transactions $T_1, T_2, ..., T_n$
- **Precedence graph** — a directed graph where the vertices are the transactions of a schedule S
- We draw an arc from T_i to T_j if one of three conditions holds:
  - T_i executes **write**(Q) before T_j executes **read**(Q)
  - T_i executes **read**(Q) before T_j executes **write**(Q)
  - T_i executes **write**(Q) before T_j executes **write**(Q)
- If an edge $T_i \rightarrow T_j$ exists in the precedence graph, then any serial schedule S' equivalent to S, T_i must appear before T_j
- Example of a precedence graph



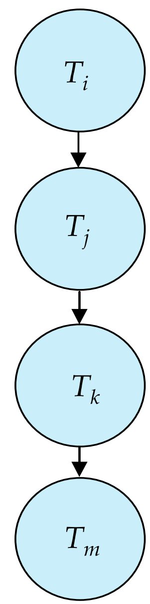
Test for Conflict Serializability

- 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
- 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 serializability order for Schedule (a) would be

$$T_i \rightarrow T_j \rightarrow T_k \rightarrow T_m$$



(a)



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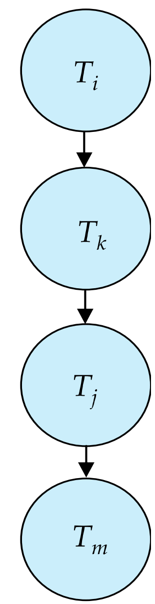

(c)

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)	

- If T_8 should abort, T_9 would have read an inconsistent database state but T_9 has already committed. 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. The read (A) in T_{11} and T_{12} is called **dirty read**

- 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

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
- Trade accuracy for performance

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

Transaction Support in SQL

- Isolation levels
  - **Dirty read** (reading of the update of an uncommitted transaction)
  - **Nonrepeatable read** (another transaction updates a data item between two reads so that the transaction sees two different values)
  - **Phantoms** (if another transaction inserts a new record *r* during the execution of the transaction, *r* was not there at the beginning of the transaction but was there at the end of the transaction; *r* is called a **phantom record**)

	Type of Violation		
Isolation Level	Dirty Read	Nonrepeatable Read	Phantom
READ UNCOMMITTED	Yes	Yes	Yes
READ COMMITTED	No	Yes	Yes
REPEATABLE READ	No	No	Yes
SERIALIZABLE	No	No	No