Advanced Databases

Transactions

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Adapted from slides for textbook "Database System Concepts"
by Silberschatz, Korth, Sudarshan
http://codex.cs.yale.edu/avi/db-book/db6/slide-dir/index.html

Outline

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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

Required Properties of a Transaction/1

- 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)
- 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.

Required Properties of a Transaction/2

- 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

Required Properties of a Transaction/3

- 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.
- However, executing multiple transactions concurrently has significant benefits.

ACID Properties

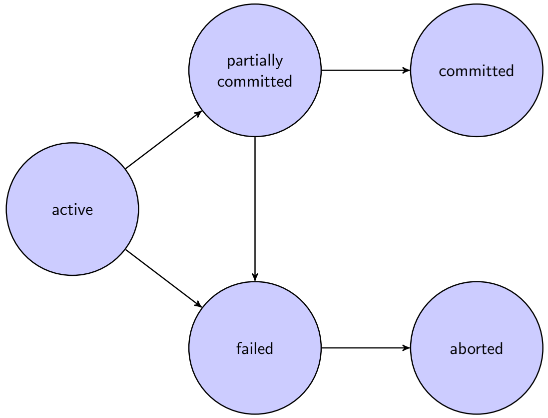
A transaction is a unit of program execution that accesses and possibly updates various data items. To preserve the integrity of data the database system must ensure:

- Atomicity. Either all operations of the transaction are properly reflected in the database or none are.
- 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/1

- 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/2



Outline

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 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.
- 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.
- An example of a serial schedule in which T_1 is followed by T_2:

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

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 "$A + B$"

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

Outline

Concurrent Executions

- **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:
    - conflict serializability
    - view serializability

Simplified model 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.

I_i	I_j	
read(Q)	read(Q)	no conflict
read(Q)	write(Q)	conflict
write(Q)	read(Q)	conflict
write(Q)	write(Q)	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/1

- If a schedule S can be transformed into a schedule S' by a series of swaps of non-conflicting instructions, then S and S' are conflict equivalent.
- A schedule S is conflict serializable if and only if it is conflict equivalent to a serial schedule.

Conflict Serializability/2

- Schedule 3 and (serial) Schedule 6 are conflict equivalent, therefore Schedule 3 is conflict serializable.

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

Table: Schedule 3

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

Table: Schedule 6

Conflict Serializability/3

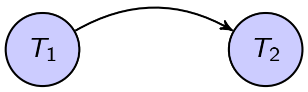
- Example of a schedule that is not conflict serializable:

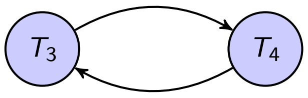
T_3	T_4
$read(Q)$	
	$write(Q)$
$read(Q)$	

- We are unable to swap non-conflicting instructions in the above schedule to obtain either the serial schedule $< T_3, T_4 >$, or the serial schedule $< T_4, T_3 >$.

Precedence Graph

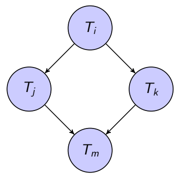
- Consider some schedule of a set of transactions $T_1, T_2, \dots, T_n$
- Precedence graph: a direct graph where the vertices are the transactions (names).
- We draw an arc from T_i to T_j if the two transaction conflict, and T_i accessed the data item on which the conflict arose earlier.
- We may label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



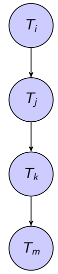


Testing for Conflict Serializability

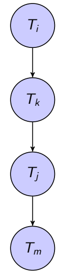
- A schedule is conflict serializable if and only if its precedence graph is acyclic.
- Cycle detection: depending on the algorithm, cycle detection takes
  - order n^2 runtime, where n is the number of vertices in the graph, or
  - order $n + e$ runtime, where e is the number of edges.
- Serializability order: is obtained by a topological sorting of the acyclic graph, i.e., a linear order consistent with the partial order of the graph.
- Example: a serializability order for the schedule (a) would be one of either (b) or (c)



(a)



(b)



(c)

View Serializability/1

- 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 also in schedule S' 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 also in schedule S' 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'.
- Like conflict equivalence, view equivalence is based purely on reads and writes.

View Serializability/2

- 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 the schedule above equivalent to?
- Every view serializable schedule that is not conflict serializable has blind writes.

Test for View Serializability

- The precedence graph test for conflict serializability cannot be used directly to test for view serializability.
- The so-called polygraph is used to test for view serializability:
  - some of the edges in the polygraph form mutale exclusive pairs, i.e., only one of the two edges in a pair is required;
  - if there is a choice of edges such that the resulting graph is asyclic, then the corresponding schedule is view serializable.
- The problem of checking if a schedule is view serializable falls in the class of NP-complete problems, i.e., it is assumed to be intractable.
- However, practical algorithms that just check some sufficient conditions for view serializability can still be used.

More Complex Notions of Serializability

- The following schedule produces the same result as the serial schedule <T1,T5>, yet is neither conflict equivalent nor view equivalent to it.

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

- Example: If we start with $A = 1000$ and $B = 2000$, the final result is $A = 960$ and $B = 2040$ as for the serial schedule <T1,T5>.
- Such equivalences cannot be derived by analysing reads and writes alone: in the example, the commutativity of the operations is relevant.

Outline

Recoverable Schedules

- 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.
- The following schedule is not recoverable: T_9 reads A written by T_8 but commits before T_8.

T_8	T_9
$read(A)$	
$write(A)$	
	$read(A)$
	$C \leftarrow A$
	$write(C)$
	$commit$
$read(B)$	

- If T_8 aborts, T_9 has read and copied an inconsistent database state.
- 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 — 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.
- 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		

- It is *desirable* to restrict the schedules to those that are cascadeless.

Outline

Concurrency Control and Recoverability

- 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.
- Protocols that assure serializability and recoverability are required:
  - testing a schedule for serializability after it has executed (e.g., cycle detection in precedence graphs) is too late!
  - serializability tests help us to 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 computes an approximate total balance of all accounts
  - database statistics computed for query optimization can be approximate
- Such transactions need not be serializable with respect to other transactions.
- Tradeoff: accuracy for performance

Undesirable Phenomena of Concurrent Transactions

- Dirty read
  - transaction reads data written by concurrent uncommitted transaction
  - problem: read may return a value that was never in the database because the writing transaction aborted
- Non-repeatable read
  - different reads on the same item within a single transaction give different results (caused by other transactions)
  - e.g., concurrent transactions T_1: $x = R(A)$, $y = R(A)$, $z = y - x$ and T_2: $W(A = 2 * A)$, then z can be either zero or the initial value of A (should be zero!)
- Phantom read
  - repeating the same query later in the transaction gives a different set of result tuples
  - other transactions can insert new tuples during a scan
  - e.g., "Q: get accounts with $balance > 1000$" gives two tuples the first time, then a new account with $balance > 1000$ is inserted by an other transaction; the second time Q gives three tuples

Isolation Guarantees (SQL Standard)

- Read uncommitted: dirty, non-repeatable, phantom
  - reads may access uncommitted data
  - writes do not overwrite uncommitted data
- Read committed: non-repeatable, phantom
  - reads can access only committed data
  - cursor stability: in addition, read is repeatable within single `SELECT`
- Repeatable read: phantom
  - phantom reads possible
- Serializable:
  - none of the undesired phenomenas can happen

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.
  - BEGIN [TRANSACTION ISOLATION LEVEL ...]
  - Isolation levels: read committed, read uncommitted, repeatable read, serializable
- A transaction in SQL ends by:
  - COMMIT commits current transaction and begins a new one.
  - ROLLBACK causes current transaction to abort.
- Typicallly, an SQL statement commits implicitly if it executes successfully
  - Implicit commit can be turned off by a database directive, e.g. in JDBC, connection.setAutoCommit(false);