Databases 2

Transactions

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Outline

Inhalt

What is a Transaction?

- A transaction is a unit of program execution that accesses and possibly updates various data items.
- Example: transfer $50 from account A to account B
  1. $R(A)$
  2. $A \leftarrow A - 50$
  3. $W(A)$
  4. $R(B)$
  5. $B \leftarrow B + 50$
  6. $W(B)$
- Two main issues:
  1. concurrent execution of multiple transactions
  2. failures of various kind (e.g., hardware failure, system crash)

ACID Properties

- Database system must guarantee ACID for transactions:
  - Atomicity: either all operations of the transaction are executed or none
  - 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 the other concurrent transactions.
  - Durability: After a transaction completes successfully, changes to the database persist even in case of system failure.

Atomicity

- Example: transfer \$50 from account A to account B
  1. $R(A)$
  2. $A \leftarrow A - 50$
  3. $W(A)$
  4. $R(B)$
  5. $B \leftarrow B + 50$
  6. $W(B)$
- What if failure (hardware or software) after step 3?
  - money is lost
  - database is inconsistent
- Atomicity:
  - either all operations or none
  - updates of partially executed transactions not reflected in database

Consistency

- Example: transfer \$50 from account A to account B
  1. $R(A)$
  2. $A \leftarrow A - 50$
  3. $W(A)$
  4. $R(B)$
  5. $B \leftarrow B + 50$
  6. $W(B)$
- Consistency in example: sum $A + B$ must be unchanged
- Consistency in general:
  - explicit integrity constraints (e.g., foreign key)
  - implicit integrity constraints (e.g., sum of all account balances of a bank branch must be equal to branch balance)
- Transaction:
  - must see consistent database
  - during transaction inconsistent state allowed
  - after completion database must be consistent again

Isolation – Motivating Example

- Example: transfer \$50 from account A to account B
  1. $R(A)$
  2. $A \leftarrow A - 50$
  3. $W(A)$
  4. $R(B)$
  5. $B \leftarrow B + 50$
  6. $W(B)$
- Imagine second transaction T_2:
  - $T_2 : R(A), R(B), print(A + B)$
  - T_2 is executed between steps 3 and 4
  - T_2 sees an inconsistent database and gives wrong result

Isolation

- Trivial isolation: run transactions serially
- Isolation for concurrent transactions: For every pair of transactions T_i and T_j, it appears to T_i as if either T_j finished execution before T_i started or T_j started execution after T_i finished.
- Schedule:
  - specifies the chronological order of a sequence of instructions from various transactions
  - equivalent schedules result in identical databases if they start with identical databases
- Serializable schedule:
  - equivalent to some serial schedule
  - serializable schedule of $T1$ and $T2$ is either equivalent to $T1, T2$ or $T2, T1$

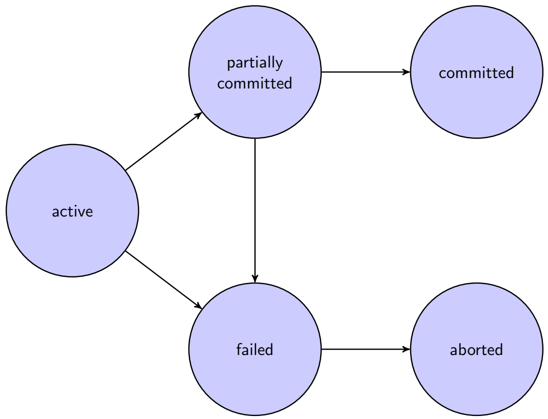
Durability

- When a transaction is done it commits.
- Example: transaction commits too early
  - transaction writes A, then commits
  - A is written to the disk buffer
  - then system crashes
  - value of A is lost
- Durability: After a transaction has committed, the changes to the database persist even in case of system failure.
- Commit only after all changes are permanent:
  - either written to log file or directly to database files
  - database must recover in case of a crash

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



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Concurrent Executions

- Multiple transactions are allowed to run concurrently in the system.
- Advantages of concurrent transactions:
  - 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.
- Concurrent transactions require concurrency control protocol:
  - 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:
  - must consist of all instructions of the concurrent 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
$read(A)$	
$A := A - 50$	
	$read(A)$
	$temp := A * 0.1$
	$A := A - temp$
	$write(A)$
	$read(B)$
$write(A)$	
$read(B)$	
$B := B + 50$	
$write(B)$	
$commit$	
	$B := B + temp$
	$write(B)$
	$commit$

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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

- Conflicts of read and write instructions:

$T_i \downarrow \quad T_j \rightarrow$	$I_j =$ read	$I_j =$ write
$I_i =$ read	no conflict	conflict
$I_i =$ write	conflict	conflict

- Intuitively, a conflict between two instructions 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 it is conflict equivalent to a serial schedule.

Conflict Serializability/2

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

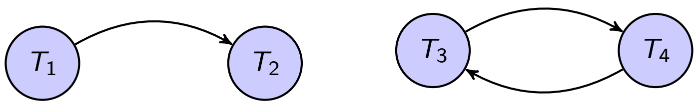
- Example of a schedule that is not conflict serializable:

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

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

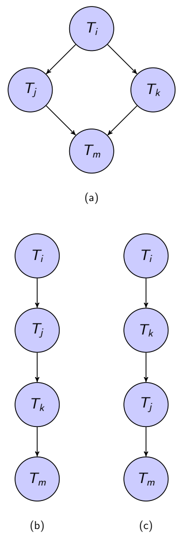
Precedence Graph

- Consider some schedule of a set of transactions $T_1, T_2, \ldots, T_n$
- 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 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 the 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)



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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.

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Concurrency Protocols

- A database must provide a mechanism that will ensure that all possible schedules are both:
  - serializable
  - recoverable and preferably cascadeless
- A concurrency protocol is a policy to guarantees serializable schedules.
- Serial schedule: A policy in which only one transaction can execute at a time provides a poor degree of concurrency.
- Various protocols allow concurrent schedules that are serializable:
  - lock-based protocols
  - timestamp ordering protocols
  - validation-based protocols
  - multi-version concurrency control

Lock-Based Protocols/1

- A lock is a mechanism to control concurrent access to a data item.
- Data items can be locked in two modes:
  1. exclusive (X) mode. Data item can be both read as well as written. X-lock is requested using **lock-X** instruction.
  2. shared (S) mode. Data item can only be read. S-lock is requested using **lock-S** instruction.
- Lock requests are made to the concurrency-control manager by the programmer. Transaction can proceed only after request is granted.

Lock-Based Protocols/2

- A lock on an item is granted to a transaction if the requested lock is compatible with locks already held on the item by other transactions.
- Lock-compatibility matrix:

	S	*X*
S	*true*	*false*
X	*false*	*false*

  - Any number of transactions can hold a shared lock on an item.
  - If any transaction holds an exclusive lock on the item, no other transaction may hold any lock on the item.
- If a lock cannot be granted, the requesting transaction is made to wait till all incompatible locks held by other transactions have been released. The lock is then granted.

Lock-Based Protocols/3

- Example of a transaction performing locking:

  T_2: **lock-S**(A)
  read(A)
  unlock(A)
  lock-S(B)
  read(B)
  unlock(B)
  display($A + B$)

- Locking is not sufficient to guarantee serializability: if A gets updated in-between the read of A and B, the displayed sum is wrong.
- A locking protocol is a set of rules followed by all transactions while requesting and releasing locks. Locking protocols restrict the set of possible schedules.

The Two-Phase Locking Protocol/1

- In the Two-Phase Locking (2PL) protocol, each transaction must go through two phases that restrict the order in which locks can be granted and released.
- Phase 1: Growing Phase
  - transaction may obtain locks
  - transaction may not release locks
- Phase 2: Shrinking Phase
  - transaction may release locks
  - transaction may not obtain locks

The Two-Phase Locking Protocol/2

- The 2PL protocol guarantees conflict serializability.
- The transactions can be serialized in the order of their lock points (i.e., the point where a transaction acquired its final lock).
- The set of 2PL schedules is a subset of conflict serializable schedules, i.e., there can be conflict serializable schedules that cannot be obtained with 2PL.
- 2PL is necessary: In the absence of extra information (e.g., ordering of access to data) a locking protocol that does not follow 2PL cannot guarantee conflict serializability.

Timestamp Ordering Protocols

- Each transaction gets a timestamp when it enters the system.
- The protocol manages concurrent execution such that the time-stamps determine the serializability order.
- Each data item Q gets two timestamp values:
  - Write timestamp: timestamp of youngest transaction that wrote Q.
  - Read timestamp: timestamp of youngest transaction that read Q.
- The timestamp ordering protocol ensures that any conflicting operations are executed in timestamp order.

Validation-Based Protocols

- Optimistic approach: Execute transaction first and check for serializability problems at the end.
- Execution of transaction T_i is done in three phases:
  1. Read and execution phase: Transaction T_i writes only to temporary local variables.
  2. Validation phase: Transaction T_i performs a validation test to determine if local variables can be written without violating serializability.
  3. Write phase: If T_i is validated, the updates are applied to the database; otherwise, T_i is rolled back.

Multiversion Concurrency Control (MVCC)

- MVCC schemes keep old versions of data item to increase concurrency.
- Each successful write results in the creation of a new version of the written data item.
- Readers are never blocked: an appropriate version of the data item is returned based on the timestamp of the reading transaction.
- Snapshot Isolation: MVCC scheme implemented e.g. in PostgreSQL.
  - each transaction gets a snapshot (conceptually a copy) of the database at its start
  - transaction operates on its snapshot and does not see updates of other transactions
  - conflicting updates are dealed with at time of update (first updater wins) or commit (first committer wins)

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Deadlocks/1

- Consider the partial schedule

T_3	T_4
lock-x(B)	
read(B)	
$B := B - 50$	
write(B)	
	lock-s(A)
	read(A)
	lock-s(B)
lock-x(A)	

- Neither T_3 nor T_4 can make progress — executing **lock-S**(B) causes T_4 to wait for T_3 to release its lock on B, while executing **lock-X**(A) causes T_3 to wait for T_4 to release its lock on A.
- Such a situation is called a deadlock.
- To handle the deadlock, one of T_3 or T_4 must be aborted and its locks released.

Deadlocks/2

- Two-phase locking does not ensure freedom from deadlocks.
- In addition to deadlocks, there is a possibility of starvation.
- Starvation occurs if the concurrency control manager is badly designed. For example:
  - The same transaction is repeatedly rolled back due to deadlocks.
  - A transaction waits for an X-lock on an item, while a sequence of other transactions request and are granted an S-lock on the same item.
- Concurrency control manager can be designed to prevent starvation.

Deadlocks/3

- The potential for deadlock exists in most locking protocols. Deadlocks are a necessary evil.
- When a deadlock occurs there is a possibility of cascading rollbacks.
- Cascading roll-back is possible under two-phase locking. To avoid this, follow a modified protocol called strict two-phase locking — a transaction must hold all its exclusive locks till it commits/aborts.
- Rigorous two-phase locking is even stricter. Here, all locks are held till commit/abort. In this protocol, transactions can be serialized in the order in which they commit.

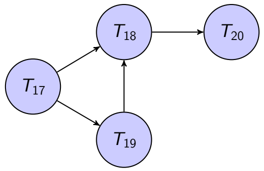
Deadlock Handling

- A system is deadlocked if there is a set of transactions such that every transaction in the set is waiting for another transaction in the set.
- How to deal with deadlocks?
  1. Detection & Recovery: allow deadlocks to happen and recover from the deadlock state.
  2. Prevention: ensure that the system will never enter into a deadlock state.

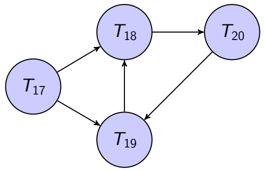
Deadlock Detection/1

- Deadlocks can be described as a wait-for graph, which consists of a pair $G = (V, E)$,
  - V is a set of vertices (all the transactions in the system)
  - E is a set of edges; each element is an ordered pair $T_i \rightarrow T_j$.
- If $T_i \rightarrow T_j$ is in E, then there is a directed edge from T_i to T_j, implying that T_i is waiting for T_j to release a data item.
- When T_i requests a data item currently being held by T_j, then the edge $T_i \rightarrow T_j$ is inserted in the wait-for graph. This edge is removed only when T_j is no longer holding a data item needed by T_i.
- The system is in a deadlock state if and only if the wait-for graph has a cycle. Must invoke a deadlock-detection algorithm periodically to look for cycles.

Deadlock Detection/2



Wait-for graph without a cycle



Wait-for graph with a cycle

Deadlock Recovery

- To recover from a deadlock state, some transaction must be aborted.
- How to pick a victim (transaction to be aborted)?
  - Select a transaction as victim that will incur minimum cost.
  - Starvation happens if same transaction is always chosen as victim.
  - Include the number of rollbacks into the cost factor to avoid starvation.
- How far to roll back victim transaction?
  - total rollback: abort the transaction and then restart it
  - more efficient to roll back transaction only as far as necessary to break deadlock

Deadlock Prevention Strategies/1

1. Predeclaration: Require that each transaction locks all its data items before it begins execution.
   - Problem: need to know data items to be locked upfront.
2. Lock Order: Impose order on all data items. Transaction can lock only in the specified order.
   - Easy to implement on top of existing 2PL implementation.
   - Problem: need to know data items to be locked upfront.
3. Timeout-Based schemes:
   - A transaction waits for a lock only for a specified amount of time.
   - Roll back and restart transaction if lock cannot be granted within timeout interval.
   - Problem: difficult to determine good value of the timeout interval.

Deadlock Prevention Strategies/2

4. Preemptive and non-preemptive scheme based on timestamps:
   - Transactions have a timestamps: Older transactions (smaller timestamp) have precedence over younger transactions.
   - Preemptive: Younger transaction is aborted if it holds a lock required by an older one (called wound-wait scheme).
   - Non-preemptive: Younger transaction is aborted if it request a lock held by and older one (called wait-die scheme)
   - A rolled back transactions is restarted with its original timestamp.

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Weak Levels of Consistency

- Concurrency control protocols make a trade-off between the amount of concurrency they allow and the amount of overhead they impose.
- Trade off accuracy for performance: Some applications are willing to live with weak levels of consistency, allowing schedules that are not serializable.
- SQL defines three undesired phantomena of concurrent transactions and isolation levels to avoid them.

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);