Today: Concurrency control

- Serial schedules and consistency.
- Conflict-serializability.
- Locking schemes:
  - 2-phase locking.
  - Lock modes and compatibility matrices.
- Optimistic concurrency control.
  - Timestamping.
  - Multi-version timestamps.

Today: Atomicity and isolation

- Later lecture deals with durability.
- This lecture is concerned with atomicity and isolation.
- Consistency is a consequence of atomicity and isolation + maintaining any declared DB constraint (not discussed in this course).

Problem session

- Come up with examples of undesired behaviour that could occur if several transactions run in parallel such that the actions interleave. Consider e.g.:
  - Transferring money and adding interest in a bank’s database.
  - Booking plane tickets.

ACID properties of transactions

- Atomicity: A transaction is executed either completely or not at all.
- Consistency: Database constraints must be kept.
- Isolation: Transactions must appear to execute one by one in isolation.
- Durability: The effect of a committed transaction must never be lost.

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Isolation and serializability

- We would like the DBMS to make transactions satisfy serializability:
  - The state of the database should always look as if the committed transactions were performed one by one in isolation (i.e., in a serial schedule).
  - The scheduler of the DBMS is allowed to choose the order of transactions:
    - It is not necessarily the transaction that is started first, which is first in the serial schedule.
    - The order may even look different from the viewpoint of different users.

A simple scheduler

- A simple scheduler would maintain a queue of transactions, and carry them out in order.
- Problems:
  - Transactions have to wait for each other, even if unrelated (e.g. requesting data on different disks).
  - Some transactions may take very long, e.g. when external input is needed during the transaction.

Interleaving schedulers

- Good DBMSs have schedulers that allow the actions of transactions to interleave.
- However, the result should be as if some serial schedule was used.
- Such schedules are called serializable.
- In practice schedulers do not recognize all serializable schedules, but allow just some. Today: Conflict serializable schedules.

Simple view on transactions

- We regard a transaction as a sequence of reads and writes of DB elements, that may interleave with sequences of other transactions.
- DB elements could be e.g. a value in a tuple, an entire tuple, or a disk block.
- r_t(X), shorthand for "transaction T reads database element X".
- w_t(X), shorthand for "transaction T writes database element X".

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Conflicts

- The order of some operations is of no importance for the final result of executing the transactions.
- Example: We may interchange the order of any two read operations without changing the behaviour of the transaction(s) doing the reads.
- In other cases, changing the order may give a different result - there is a conflict.

What operations conflict?

- By considering all cases, it can be seen that two operations can conflict only if:
  1. They involve the same DB element, and
  2. At least one of them is a write operation.
- Note that this is a conservative (but safe) rule.

Testing conflict serializability

- Suppose we have a schedule for the operations of current transactions.
- If there is a conflict between operations of two transactions, \( T_1 \) and \( T_2 \), we know which of them must be first in a conflict-equivalent serial schedule.
- This can be represented as a directed edge in a graph with transactions as vertices.

Problem session

- Find a criterion on the precedence graph which is equivalent to conflict-serializability, i.e.:
  - If the graph meets the criterion the schedule is conflict-serializable, and
  - If the schedule is conflict-serializable, the graph meets the criterion.

Enforcing serializability

- Knowing how to recognize conflict-serializability is not enough.
- We will now study mechanisms that enforce serializability:
  - Locking (pessimistic concurrency control).
  - Time stamping (optimistic concurrency control).

Locks

- In its simplest form, a lock is a right to perform operations on a database element.
- Only one transaction may hold a lock on an element at any time.
- Locks must be requested by transactions and granted by the locking scheduler.

Two-phase locking

- Commercial DB systems widely use two-phase locking, satisfying the condition:
  - In a transaction, all requests for locks precede all unlock requests.
  - If two-phase locking is used, the schedule is conflict-equivalent to a serial schedule in which transactions are ordered according to the time of their first unlock request. (Why?)

Lock modes

- The simple locking scheme we saw is too restrictive, e.g., it does not allow different transactions to read the same DB element concurrently.
- Idea: Have several kinds of locks, depending on what you want to do. Several locks on the same DB element may be ok (e.g. two read locks).
**Shared and exclusive locks**
- Locks needed for reading can be **shared (S)**.
- Locks needed for writing must be **exclusive (X)**.
- Compatibility matrix says which locks are granted:

<table>
<thead>
<tr>
<th>Lock held</th>
<th>Lock requested</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>S Yes No</td>
</tr>
<tr>
<td>X</td>
<td>X No No</td>
</tr>
</tbody>
</table>

**Update locks**
- A transaction that will eventually write to a DB element, may allow other DB elements to keep read locks until it is ready to write.
- This can be achieved by a special **update lock (U)** which can be upgraded to an exclusive lock.

**The locking scheduler**
- The locking scheduler is responsible for granting locks to transactions.
- It keeps lists of all current locks, and of all current lock requests.
- Locks are not necessarily granted in sequence, e.g., a request may have to wait until another transaction releases its lock.
- Efficient implementation in GUW.

**Compatibility for update locks**

<table>
<thead>
<tr>
<th>Lock held</th>
<th>S</th>
<th>X</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>X</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>U</td>
<td>No (1)</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

**Problem session**
- So far we did not discuss what DB elements to lock: Atomic values, tuples, blocks, relations?
- What are the advantages and disadvantages of fine-grained locks (such as locks on tuples) and coarse-grained locks (such as locks on relations)?
- Explain the following advice from Database Tuning: “Long transactions should use table locks, short transactions should use record locks”.

**Granularity of locks**
- Fine-grained locks allow a lot of concurrency, but may cause problems with deadlocks.
- Coarse-grained locks require fewer resources by the locking scheduler.
- We want to allow fine-grained locks, but use (or switch to) coarser locks when needed.
- Some DBMSs switch automatically - this is called **lock escalation**. The downside is that this easily leads to deadlocks.

**Warning locks**
- An exclusive lock on a tuple should prevent an exclusive lock on the whole relation.
- To implement this, all locks must be accompanied by **warning locks** at higher levels of the hierarchy of database elements.
- We denote shared/exclusive warning locks by IS/IX, where I stands for the intention to shared/exclusively lock database elements at a lower level.

**Compatibility of warning locks**

<table>
<thead>
<tr>
<th>Lock held</th>
<th>IS</th>
<th>IX</th>
<th>S</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>IX</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>S</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>X</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

**Phantom tuples**
- Suppose we lock tuples where A=42 in a relation, and subsequently another tuple with A=42 is inserted.
- For some transactions this may result in unserializable behaviour, i.e., it will be clear that the tuple was inserted during the course of a transaction.
- Such tuples are called **phantoms**.
**Avoiding phantoms**

- Phantoms can be avoided by putting an exclusive lock on a relation before adding tuples.
- However, this gives poor concurrency.
- In SQL, the programmer may choose to either allow phantoms in a transaction or insist they should not occur.

**Locks on indexes**

- When updating a relation, any indexes on the table also need to be updated.
- Again, we must use locks to ensure serializability.
- B-trees have a particular challenge: The root may be changed by any update, so it seems concurrent updates can’t be done using locks.

**SQL isolation levels**

A transaction in SQL may be chosen to have one of four isolation levels:
- **READ UNCOMMITTED:** “No locks are obtained.”
- **READ COMMITTED:** “Read locks are immediately released - read values may change during the transaction.”
- **REPEATABLE READ:** “2PL but no lock when adding new tuples.”
- **SERIALIZABLE:** “2PL with lock when adding new tuples.”

**Avoiding deadlocks by timestamp**

Two possible policies when T waits for U:
- **Wait-die.** If T is youngest it is rolled back.
- **Wound-wait.** If U is youngest it is rolled back.

In both cases there can be no waits-for cycles, because transactions only wait for younger (resp. older) transactions.

**Locks in B-trees**

- **Idea:**
  - Only put an exclusive lock on a B-tree node if there is a chance it may have to change.
  - Lock from top to bottom along the path.
  - Unlock from bottom to top as soon as nodes have been updated.
- More general scheme, the tree protocol, discussed in GUW.

**Locks and deadlocks**

- The DBMS sometimes must make a transaction wait for another transaction to release a lock.
- This can lead to deadlock if e.g. A waits for B, and B waits for A.
- In general, we have a deadlock exactly when there is a cycle in the waits-for graph.
- Deadlocks are resolved by aborting some transaction involved in the cycle.

**Problems with locking**

- Locking prevents transactions from engaging in non-serializable behaviour.
- However, it is sometimes a bit too strict and pessimistic, not allowing as much concurrency as we would like.
- Next we will consider an optimistic concurrency control that works better when transactions don’t conflict much.

**SQL implementation**

- Note that implementation is not part of the SQL standards - they specify only semantics.
- An SQL-DBMS designer may choose another implementation than the mentioned locking schemes, as long as the semantics conforms to the standard.
**Timestamps**

**Idea:**
- Associate a unique number, the **timestamp**, with each transaction.
- Transactions should behave as if they were executed in order of their timestamps.
- For each database element, record:
  - The highest timestamp of a transaction that read it.
  - The highest timestamp of a transaction that wrote it.
  - Whether the writing transaction has committed.

**Timestamp based scheduling**

If transaction T requests to:
- Read a DB element written by an uncommitted transaction, it must wait for it to commit or abort.
- Read a DB element with a higher write timestamp, it must be rolled back.
- Write a DB element with a lower read timestamp, it must be rolled back.

Rolling back means getting a **new** timestamp.

**Problem session**

- What should the scheduler do if a transaction requests to write a DB element with a higher write timestamp?

**Multiversion timestamps**

- In principle, all previous versions of DB elements could be saved.
- This would allow any read operation to be consistent with the timestamp of the transaction.
- Used in many systems for scheduling **read only** transactions. (In practice, only recent versions are saved.)

**Optimism vs pessimism**

- Pessimistic concurrency is best in high-conflict situations:
  - Smallest number of aborts.
  - No wasted processing.
- Optimistic concurrency control is best if conflicts are rare, e.g., if there are many read-only transactions.
  - Highest level of concurrency.
- Hybrid solutions often used in practice.

**Why this is useful knowledge**

- Knowledge on concurrency control of a DBMS is useful:
  - If you encounter concurrency problems, e.g., many deadlocks or long response times.
  - When choosing a suitable DBMS for a particular application (optimistic or pessimistic concurrency control?).

**Summary**

- Concurrency control is crucial in a DBMS.
- The schedule of operations of transactions should be **serializable**.
- The scheduler may use locks or timestamps.
  - Locks allow less concurrency, and may cause deadlocks.
  - Timestamps may cause more aborts.