1 2007 Paper 4 Question 1

https://www.cl.cam.ac.uk/teaching/exams/pastpapers/y2007p4q1.pdf

(a) What is meant by a *serialisable* order for two or more transactions?

A serialisable order o_s for two transactions T_1, T_2 is an order containing all operations in both transactions such that there exists a serial order where all conflicting operations in o_s are ordered in the same way as in the serial order.

(b) Explain how *timestamp ordering* enforces isolation.

Under timestamp ordering, the system decides on a serial order in which each transaction executes. If any transaction discovers that one of its conflicting operations is out-of-order then the transaction aborts (potentially causing cascading aborts). This means that transactions only commit if the order their conflicting operations took effect in is the same as some serial order – the definition of serialisable. Notice that the converse is not true – if the system chooses a suboptimal serial order then some transactions may abort even though there was a valid serial order.

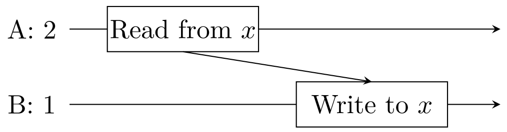
This is implemented by assigning each process a timestamp – these timestamps must be globally unique and totally ordered. We must be able to compare two timestamps and determine which process is first in the serial order which we are attempting to fulfil. Each shared data has two timestamps associated with it – the timestamp of the last transaction to read from it and the timestamp of the last transaction to write to it. Before any transaction reads shared data it must check whether any process with a higher timestamp has written to this data. If so, the transaction cannot fulfil the serial order and so must abort (potentially causing a cascading abort).

Before any transaction writes to data, it must check if any transaction with a higher timestamp has read from the data. If it has, then writing to this data would be out of order and break isolation. Therefore the transaction cannot write to data and must abort. If no transaction with a higher ID has read from the data, the transaction must *then* check whether any transaction with a higher timestamp has written to the data. If it has then we return. Notice that we return *if and only if* the data has been written to after us but was not read by any transactions with timestamps between the first transaction and the transaction that successfully wrote. Therefore this does not break isolation. If none of those conditions are met then the transaction can write to the data.

(c) Draw and explain a history graph for two transactions whose invocations of a set of conflicting operations are serialisable but who are rejected by TSO .

If TSO assigns A the timestamp 2 and B the timestamp 1 then this serialisable order will be rejected. As discussed earlier, TSO decides on a serial ordering when each transaction is issued – this may not be optimal and therefore many valid orderings will not be subsets of the serial order the decided at the start.

A will read from x, B will then attempt to write to x but see that A, which has a higher timestamp than B has already read from x and therefore writing to it could break isolation. Therefore B will abort even though the order is serialisable.



(d) Considering Optimistic Concurrency Control (OCC):

(i) State the properties of a transaction's set of shadow copies that must be verified at commit time.

- All versions of data read by the transaction were concurrently correct at some point in time. The set of times for which all versions of data held the values read by the transaction is its set of possible start times.
- There does not exist a committed transaction T which read from any data the new transaction wishes to write to such that the start time of T is greater than all possible start times for the new transaction.

(ii) Carefully explain the algorithm used by a single-threaded commit-time validator.

- Firstly check that both the properties stated above hold.

  We can check there exists a time when all data read by the transaction was concurrently correct by comparing the timestamp associated with the shadow copy (the last-written timestamp when we read the copy) with the times the data was written to. If there is a time between when the last data was read and any were overwritten then this predicate is true. Else it is false and we must abort/rollback the transaction. Aborting/rollback in OCC means disregarding the shadow-copies and restarting the transaction.

  We then check there does not exist any committed transaction which read from data we propose writing to that has a timestamp greater than all possible start times of the new transaction. We do this by checking that for each data the new transaction is writing to, that the "last read" timestamp is smaller than the last possible start time – that all data reads are serialisable. If there is a transaction which is not serialisable then the new transaction must abort/rollback. Otherwise we should set the start time to be the smallest valid start time as this places the least restrictions on the order.

- Now we need to commit the data. This can be split into two parts – writing the data and updating the data's read and write timestamps.

  The shadow copies must be swapped in individually atomically to prevent reads while data structures are in an inconsistent state. We can implement this by taking out a lock on the data structure while writing to it – note there is no "hold-and-wait" and so this is fast. Before releasing the lock we update the list "last written to" timestamp to include the timestamp of the new transaction.

  However, if the data has been written to by a transaction with a larger timestamp then we should not write to it (but should still update the data with the record that the transaction did). Notice that this is only the case if the transaction with a larger timestamp never read from the data.

  We must then update the list of "last read" timestamps associated with the data that the transaction read.

  Since the validator is single-threaded, I assume validating our transaction cannot be preempted by validating another transaction and therefore assume validation-validation race conditions are nonexistent.

(e) Consider a system in which the transactions cause updates to objects which are not all located on a single server but which are distributed widely around the Internet. What factors would influence your choice of using TSO or OCC to enforce isolation?

- The rarity of conflicts

  OCC aborts only when it is certain there is no serialisable ordering. This works well under the assumption that conflicts are sufficiently rare that occasionally doing additional work is more efficient than frequently aborting safe transactions.

  TSO implements a fail-fast mechanism to abort when it is no longer certain that an order is serialisable. This means that it wastes no work but frequently aborts transactions which are safe to serialise.

If conficts are common then the underlying assumptions of OCC are broken, which means OCC will have poor performance. In situations like this, TSO may be better.

Therefore OCC usually performs better than TSO when conflicts are rare.

- The proportion of operations which are reads or writes

  If there is a high number of reads and a low number of writes then TSO will frequently abort – it will attempt to write however transactions with a lower timestamp will have read from the data we wish to write to and therefore the transaction will be unsafe and will be forced to abort. However, in these situations OCC will find a safe serialisation which places the writes are after the reads.

- The size of data we operate on

  OCC has to make a shadow copy of the data it operates on. If the data that transactions operate on is large, this may mean that OCC will make copy of large sections of the database. This is inviable in many situations and therefore in cases like this, TSO would be preferable.

- Whether transactions can go idle or fail midway through

  Under TSO, transactions can partially complete. If transactions can also fail or idle they would cause a memory leak or massive cascading abort. In the first case we assume it will resume at some point and must keep track of all transactions performed and their inverse operations; while in the second at some point we assume the transaction has failed and abort all transactions with higher timestamps or when the transaction resumes and aborts. We may have to abort thousands of transactions. On a large system this disadvantage alone makes TSO unusable.

  In OCC an idle or failed transaction will not commit. Therefore rest of the system is unaffected and so there is no problem.

- The network bandwidth

  If the network bandwidth is low then it may be problematic to transfer enough data for OCC to make shadow copies and swap them back in. This may make TSO preferable.

- The network latency

  When TSO aborts it has to make a large number of reads and writes to each server it has communicated with to undo its transactions. This means that on abort, the transaction has to communicate with every server its read from or written to. If network latency is high then this may take significant amounts of time and OCC may be preferable.

2 2011 Paper 5 Question 7

https://www.cl.cam.ac.uk/teaching/exams/pastpapers/y2011p5q7.pdf

Database concurrency control enables multiple transactions to proceed simultaneously against a shared database.

(a) Give an example of *conflicting* and *non-conflicting* operations on objects in a database.

Conflicting transactions are non-commutative while conflicting operations are commutative.

An example of a conflicting operation is a read and a write to the same entry in the database.

An example of a non-conflicting operation is writing to different entries in the database.

(b) Explain how timestamp ordering (TSO) works, and how it responds to conflicts between transactions.

Under TSO, the server decides on a serial order which it will attempt to fulfil. Transactions are then assigned a unique, totally ordered timestamp such that two transactions can compare timestamps and determine which transaction occurs first in the serial order. The timestamps can be logical timestamps or timestamps from the system clock.

Data has two labels – the largest timestamp of any transaction that read from the data and the largest timestamp transaction that wrote to the data. This is sufficient to provide safety.

Before a transaction reads from data, it checks to see that no transaction with a higher timestamp has written to the data – if so the read would not match the serial order and therefore cannot take place. So the transaction would abort; causing all transactions which read from data it had written to to abort. Notice that if the data has been read by a transaction with a higher timestamp then the transaction can still read – reads do not conflict with other reads.

Before a transaction writes to data it must check both the read and write timestamps associated with the data. If a transaction with a larger timestamp has read from the data, then writing to it would be out of the serial order and is therefore unsafe. So the transaction will abort, potentially causing a cascading abort. If a transaction with a higher timestamp has written to the data then the write should return without writing to the data. This in itself does not break serialisability and therefore should not cause an abort.

(c) Explain cascading aborts and use an example to show how they can occur with TSO .

Cascading aborts occur when a transaction is forced to abort, however this transaction has written to data which was then read by other transactions. This forces these other transactions to abort. This can lead to long chains of aborts.

Consider the transactions A,B,C executing concurrently with $V(A) < V(B) < V(C)$:

A	B	C
write ℓ_1	write ℓ_2	
		read ℓ_1
read ℓ_2		

When A reads from ℓ_2, it will abort. However, A wrote to ℓ_1 and C has read from ℓ_1 – therefore C is now incorrect and must be aborted. So B causes A to abort and A aborting causes C to abort. This is a cascading abort.

(d) Why is TSO not subject to deadlock?

There are four requirements that a system must meet for it to deadlock:

- Cyclic Dependency
- Hold-and-wait
- No preemption
- Mutual Exclusion

A system will deadlock if and only if it meets all four of these criteria simultaneously. TSO does not have hold-and-wait – under TSO if a transaction is going to read or write then it will either do it immediately after acquiring the first lock or it will abort. Since TSO cannot meet all four of the criteria; TSO cannot deadlock.

(e) Explain why TSO distributes well, compared with two-phase locking.

Transactions in TSO do not take out locks meaning transactions never block. This allows for good concurrency. Two-phase locking takes out locks and holds them to ensure serialisability – however often two-phase locking holds locks longer than is strictly necessary. Therefore two-phase locking often overly-serialises execution. Two-phase locking is very good at preventing unnecessary work – this is important if conflicts are common. However, as systems scale there become more and more data proportional to the number of transactions and so the probability of conflicts reduces. Therefore as systems scale, TSO becomes more effective and 2PL becomes less effective.

(f) Construct a workload that performs badly under TSO, and explain why it does so. What could you do to improve its performance.

The following workload will livelock on a system which does not have any mitigations:

- A reads from ℓ_1, then performs 5s of compute and writes to ℓ_2.
- B does 1s of compute, then reads from ℓ_2 and immediately writes to ℓ_1.

The only serialisable order is are one transaction committing before the other starts. If both transactions start at the same time, they will abort repeatedly until one commits before the other has started. Since both processes are long-running, it is unlikely that one will be able to commit before the other starts – therefore if both transactions are started at the same time, they will lead to livelock with high probability.

Assume B starts between 1s before and 4s after A starts – such that on the first attempt at execution, A reads ℓ_1 before B writes to ℓ_1 and B reads ℓ_2 before A writes to ℓ_2.

Consider both possible timestamp orderings:

- $V(A) < V(B)$:

  A writes to ℓ_1, then B writes to ℓ_2 and reads from ℓ_1 and terminates. Later, A will read from ℓ_2 – however B has written to ℓ_2 – so A will abort which causes B to abort and the cycle restarts.

- $V(B) < V(A)$:

  A writes to ℓ_1 and B writes to ℓ_2 (the order of these operations does not matter) B then reads from ℓ_1 – however the read ℓ_1 is out of order (as $V(B) < V(A)$ and A has written to ℓ_1) and so B will abort and restart. A has already started, so when B restarts it will be given a timestamp higher than $V(A)$. Note that this case only happens if B starts before A does – therefore when B aborts, there will be at least 4s before A attempts to write to ℓ_1. This gives B sufficient time to finish before A attempts to write. This reverts to the case $V(A) < V(B)$.

This livelock can only be resolved by allowing one task to commit before the other task starts.

We could hold a graph of transactions which have aborted and not terminated. An edge $t_1 \rightarrow t_2$ means that transaction t_1 caused t_2 to abort. When a transaction commits, we remove it from this graph. If a transaction t aborts, we update the graph adding t and attempt to find a path from t to t (a cycle). If there is a cycle then we remove t from the graph and do not restart t until at least one transaction in the cycle finishes. Note that in a cascading abort, we should add transactions one-by-one to ensure we only remove one transaction from a cycle.

t will only be held back if there is a nontrivial risk of livelock. In most TSO systems, aborting is rare – if a transaction does not abort or cause an abort then its performance will be unaffected by this livelock detection – if a transaction aborts once or causes an abort then the impact on this threads performance will be very small.