

# Lecture #17: Timestamp Ordering Concurrency Control

15-445/645 Database Systems (Spring 2024)  
<https://15445.courses.cs.cmu.edu/spring2024/>  
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## 1 Timestamp Ordering Concurrency Control

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Timestamp ordering (T/O) is an optimistic class of concurrency control protocols where the DBMS assumes that transaction conflicts are rare. Instead of requiring transactions to acquire locks before they are allowed to read/write to a database object, the DBMS instead uses timestamps to determine the serializability order of transactions.

Each transaction  $T_i$  is assigned a unique fixed timestamp  $TS(T_i)$  that is monotonically increasing. Different schemes assign timestamps at different times during the transaction. Some advanced schemes even assign multiple timestamps per transaction.

If  $TS(T_i) < TS(T_j)$ , then the DBMS must ensure that the execution schedule is equivalent to the serial schedule where  $T_i$  appears before  $T_j$ .

There are multiple timestamp allocation implementation strategies. The DBMS can use the system clock as a timestamp, but issues arise with edge cases like daylight savings. Another option is to use a logical counter. However, this has issues with overflow and with maintaining the counter across a distributed system with multiple machines. There are also hybrid approaches that use a combination of both methods.

## 2 Basic Timestamp Ordering (BASIC T/O)

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The basic timestamp ordering protocol (BASIC T/O) allows reads and writes on database objects without using locks. Instead, every database object  $X$  is tagged with timestamp of the last transaction that successfully performed a read (denoted as  $R-TS(X)$ ) or write (denoted as  $W-TS(X)$ ) on that object. The DBMS then checks these timestamps for every operation. If a transaction tries to access an object in a way which violates the timestamp ordering, the transaction is aborted and restarted. The underlying assumption is that violations will be rare and thus these restarts will also be rare.

### Read Operations

For read operations, if  $TS(T_i) < W-TS(X)$ , this violates timestamp order of  $T_i$  with regard to the previous writer of  $X$  (do not want to read something that is written in the “future”). Thus,  $T_i$  is aborted and restarted with a new timestamp. Otherwise, the read is valid and  $T_i$  is allowed to read  $X$ . The DBMS then updates  $R-TS(X)$  to be the max of  $R-TS(X)$  and  $TS(T_i)$ . It also has to make a local copy of  $X$  in a private workspace to ensure repeatable reads for  $T_i$ . Refer to slide 7 in the lecture slides.

### Write Operations

For write operations, if  $TS(T_i) < R-TS(X)$  or  $TS(T_i) < W-TS(X)$ ,  $T_i$  must be restarted (do not want to overwrite “future” change). Otherwise, the DBMS allows  $T_i$  to write  $X$  and updates  $W-TS(X)$ . Again, it needs to make a local copy of  $X$  to ensure repeatable reads for  $T_i$ . Refer to slide 8 in the lecture slides.

**Optimization: Thomas Write Rule**

An optimization for writes is if  $TS(T_i) < W-TS(X)$ , the DBMS can instead ignore the write and allow the transaction to continue instead of aborting and restarting it. This is called the *Thomas Write Rule*. Note that this violates timestamp order of  $T_i$  but this is okay because no other transaction will ever read  $T_i$ 's write to object X. If there are subsequent reads on object X by transaction  $T_i$ , it can read its own local copy of X. Refer to slide 38 for an example.

The Basic T/O protocol generates a schedule that is conflict serializable if it does not use Thomas Write Rule. It cannot have deadlocks because no transaction ever waits. However, long running transactions are more likely to starve as they are more likely to read objects from newer transactions.

It also permits schedules that are not recoverable. A schedule is *recoverable* if transactions commit only after all transactions whose changes they read, commit. Otherwise, the DBMS cannot guarantee that transactions read data that will be restored after recovering from a crash.

**Potential Issues (slide 40):**

- Every read of an object requires a timestamp write.
- High overhead from copying data to transaction's workspace and from updating timestamps.
- Long running transactions can get starved.
- Suffers from the timestamp allocation bottleneck on highly concurrent systems.
- Permits schedules that are not recoverable.

### 3 Optimistic Concurrency Control (OCC)

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Optimistic concurrency control (OCC) is another optimistic concurrency control protocol which also uses timestamps to validate transactions. OCC works best when the number of conflicts is low. This is when either all of the transactions are read-only or when transactions access disjoint subsets of data. If the database is large and the workload is not skewed, then there is a low probability of conflict, making OCC a good choice.

In OCC, the DBMS creates a *private workspace* for each transaction. All modifications of the transaction are applied to this workspace. Any object read is copied into workspace and any object written is copied to the workspace and modified there. No other transaction can read the changes made by another transaction in its private workspace.

When a transaction commits, the DBMS compares the transaction's workspace *write set* to see whether it conflicts with other transactions. If there are no conflicts, the write set is installed into the "global" database.

OCC consists of three phases:

1. **Read Phase:** Here, the DBMS tracks the read/write sets of transactions and stores their writes in a private workspace.
2. **Validation Phase:** When a transaction commits, the DBMS checks whether it conflicts with other transactions.
3. **Write Phase:** If validation succeeds, the DBMS applies the private workspace's changes to the database. Otherwise, it aborts and restarts the transaction.

**Validation Phase**

The DBMS assigns transactions timestamps when they enter the validation phase. To ensure only serializable schedules are permitted, the DBMS checks  $T_i$  against other transactions for RW and WW conflicts

and makes sure that all conflicts go one way.

- **Approach 1:** Backward validation (from younger transactions to older transactions, slide 69)
- **Approach 2:** Forward validation (from older transactions to younger transactions, slide 70)

In forward validation, the DBMS checks the timestamp ordering of the committing transaction with all other running transactions. Transactions that have not yet entered the validation phase are assigned a timestamp of  $\infty$ .

If  $TS(T_i) < TS(T_j)$ , then one of the following three conditions must hold:

1.  $T_i$  completes all three phases before  $T_j$  begins its execution (serial ordering) (slide 64).
2.  $T_i$  completes its Write phase before  $T_j$  starts its Write phase, and  $T_i$  does not write to any object read by  $T_j$  (slide 65).
  - $WriteSet(T_i) \cap ReadSet(T_j) = \emptyset$ .
3.  $T_i$  completes its Read phase before  $T_j$  completes its Read phase, and  $T_i$  does not write to any object that is either read or written by  $T_j$  (slide 66).
  - $WriteSet(T_i) \cap ReadSet(T_j) = \emptyset$ , and  $WriteSet(T_i) \cap WriteSet(T_j) = \emptyset$ .

In backward validation, the DBMS checks the timestamp ordering of the committing transaction with the Read/Write sets of transactions that have already committed, using the same three conditions as above.

#### Potential Issues:

- High overhead for copying data locally into the transaction's private workspace.
- Validation/Write phase bottlenecks.
- Aborts are potentially more wasteful than in other protocols because they only occur after a transaction has already executed.
- Suffers from timestamp allocation bottleneck.

## 4 Dynamic Databases and The Phantom Problem

In our previous discussions, we have considered transactions that operate on a static set of objects within the database. However, when transactions perform insertions, updates, and deletions, we encounter a new set of complications.

The phantom problem arises when transactions only lock existing records, neglecting those that are in the process of being created. This oversight can lead to non-serializable executions because the set of objects in the database is not fixed (slide 77). **Approaches to Address the Phantom Problem:**

### 1. Re-Execute Scans:

Transactions may re-run queries at commit time to check for different results, indicating missed changes due to new or deleted records. The DBMS keeps track of the WHERE clauses for all queries executed by the transaction. At commit time, it re-executes the scans to ensure that the results remain consistent (slide 80).

### 2. Predicate Locking:

This involves acquiring locks based on the predicates of the queries, ensuring that any data that satisfies the predicate cannot be modified by other transactions. Originally proposed in System R, this scheme is not widely implemented. However, systems like HyPer utilize a form of precision locking that is akin to predicate locking (slide 84).

### 3. Index Locking:

Utilizing index keys to protect ranges of data, preventing phantoms by ensuring that no new data can fall within the locked ranges. Different schemes are employed to prevent phantoms using index

locking:

- **Key-Value Locks:** Locks on individual key-values in an index, including virtual keys for non-existent values (slide 86).
- **Gap Locks:** Locks on the gap following a key-value, preventing insertion in these gaps (slide 89).
- **Key-Range Locks:** Locks on a range of keys, from one existing key to the next (slide 93).
- **Hierarchical Locking:** Allows transactions to hold broader key-range locks with different modes, reducing lock manager overhead (slide 97).

In the absence of a suitable index, transactions must lock every page in the table or the entire table itself to prevent changes that could lead to phantoms.

## 5 Isolation Levels

Serializability is useful because it allows programmers to ignore concurrency issues but enforcing it may allow too little parallelism and limit performance. We may want to use a weaker level of consistency to improve scalability.

Isolation levels control the extent that a transaction is exposed to the actions of other concurrent transactions.

**Anomalies:**

- **Dirty Read:** Reading uncommitted data.
- **Unrepeatable Reads:** Redoing a read retrieves a different result.
- **Phantom Reads:** Insertion or deletions result in different results for the same range scan queries.

**Isolation Levels (Strongest to Weakest):**

1. **SERIALIZABLE:** No Phantoms, all reads repeatable, and no dirty reads.
  - Possible implementation: Index locks + Strict 2PL.
2. **REPEATABLE READS:** Phantoms may happen.
  - Possible implementation: Strict 2PL.
3. **READ-COMMITTED:** Phantoms and unrepeatable reads may happen.
  - Possible implementation: Strict 2PL for exclusive locks, immediate release of the shared lock after a read.
4. **READ-UNCOMMITTED:** All anomalies may happen.
  - Possible implementation: Strict 2PL for exclusive locks, no shared locks for reads.

The isolation levels defined as part of SQL-92 standard only focused on anomalies that can occur in a 2PL-based DBMS. There are two additional isolation levels:

1. **CURSOR STABILITY**
  - Between repeatable reads and read committed.
  - Prevents Lost Update Anomaly.
  - Default isolation level in **IBM DB2**.
2. **SNAPSHOT ISOLATION**
  - Guarantees that all reads made in a transaction see a consistent snapshot of the database that existed at the time the transaction started.
  - A transaction will commit only if its writes do not conflict with any concurrent updates made since that snapshot.
  - Susceptible to write skew anomaly.