Database Management Systems

Concurrency Control

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Basics

Concurrency control is the way to preserve isolation of transactions while managing concurrent execution

Assumption: No failure occurs during concurrent execution.

We know that serializability ensures the consistency of a database.

So, concurrency control schemes are mostly based on the serializability property.

Note: Serializable concurrency control might have adverse effects on long-duration transactions.

Lock-based protocols – Basics

A lock is a mechanism to control concurrent access to a data item in a mutually exclusive manner

The two most common lock modes are:

- Exclusive (**X**) – Data item can be both read as well as written
- Shared (**S**) – Data item can only be read

Lock requests are made to the concurrency control manager and a transaction can proceed only after its *request* is granted.

Note: A lock held by a transaction on an item may be granted another lock requested by another transaction.

Lock-based protocols – Basics

Definition (Lock compatibility)

If a transaction can be granted a lock A on an item immediately, in spite of the presence of another lock B on the same data item, then it is said that A is compatible with B.

The lock compatibility relations:

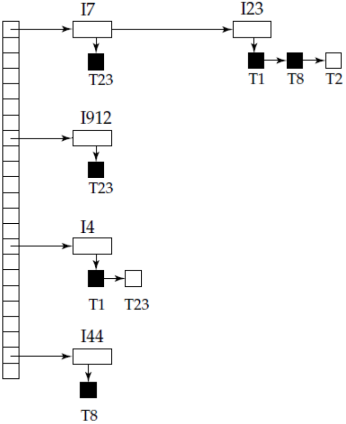
	S	X
S	True	False
X	False	False

Definition (Locking protocol)

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.

Implementation of locking

The lock manager uses a hash table indexed on the name of a data item. It finds the linked list, in the order in which the requests arrived, for a currently locked data item.



A lock table

- A blackbox denotes an approved lock request
- A whitebox denotes a waiting lock request
- The type of lock gets recorded
- New lock requests get added to the end of the queue
- Unlock requests or abort deletes the corresponding requests

Lock-based protocols – Managing serializability

The following protocol does not guarantee serilizability:

Transaction T_1	
lock-S(ISI$_{PC}$)	
read (ISI$_{PC}$)	
unlock(ISI$_{PC}$)	Updates on IISc$_{PC}$ is not admissible!!!
lock-S(IISc$_{PC}$)	Updates on IISc$_{PC}$ is not admissible!!!
read (IISc$_{PC}$)	
unlock(IISc$_{PC}$)	
display(ISI$_{PC}$+IISc$_{PC}$)	

Note: If IISc$_{PC}$ (or ISI$_{PC}$) gets updated in-between the reads of ISI$_{PC}$ and IISc$_{PC}$ (or IISc$_{PC}$ and ISI$_{PC}$), then the sum will be displayed wrong.

Lock-based protocols – Managing serializability

The following protocol guarantees serilizability:

Transaction T_1
lock-S(ISI$_{PC}$)
read (ISI$_{PC}$)
lock-S(IISc$_{PC}$)
read (IISc$_{PC}$)
display(ISI$_{PC}$+IISc$_{PC}$)
unlock(ISI$_{PC}$)
unlock(IISc$_{PC}$)

Lock-based protocols – Drawbacks

Transaction T_1	Transaction T_2
lock-X(ISI$_{PC}$)	
read(ISI$_{PC}$)	
ISI$_{PC}$ $\leftarrow$ ISI$_{PC}$ - 10	
write(ISI$_{PC}$)	
	lock-S(IISc$_{PC}$)
	read(IISc$_{PC}$)
	lock-S(ISI$_{PC}$)
lock-X(IISc$_{PC}$)	

Deadlock – lock-S(ISI$_{PC}$) causes T_2 to wait for T_1 to release its lock on ISI$_{PC}$, whereas lock-X(IISc$_{PC}$) causes T_1 to wait for T_2 to release its lock on $IISc_{PC}$.

Solution: T_1 or T_2 must be rolled back and the corresponding lock should be released.

Lock-based protocols – Drawbacks

Transaction T_1	Transaction T_2	Transaction T_3
lock-X(IISc$_{PC}$)		
lock-S(ISI$_{PC}$)		
read(ISI$_{PC}$)		
ISI$_{PC}$ $\leftarrow$ ISI$_{PC}$ - 10		
		lock-S(ISI$_{PC}$)
write(IISc$_{PC}$)		
		read(ISI$_{PC}$)
	lock-X(ISI$_{PC}$)	

Starvation – lock-X(ISI$_{PC}$) causes T_2 to wait for both T_1 and T_3 to release their locks on ISI$_{PC}$, and T_2 is repeatedly rolled back due to deadlocks.

Solution: Concurrency control manager should be designed appropriately.

Two-phase locking protocols – Basics

Working principle:

1. **Phase 1 (Grow)** – A transaction may obtain locks, but may not release any lock.
2. **Phase 2 (Shrink)** – A transaction may release locks, but may not obtain any new locks.

Two-phase locking protocols ensure conflict serializability.

Note: The serialization is determined based on the order of transaction *lock points* (where a transaction acquires its final lock).

Two-phase locking protocols – Implementation

Two-phase locking with lock conversions:

- **Phase 1**
  - can acquire a lock-S on the data item
  - can acquire a lock-X on the data item
  - can convert a lock-S to a lock-X (upgrade)
- **Phase 2**
  - can release a lock-S
  - can release a lock-X
  - can convert a lock-X to a lock-S (downgrade)

Two-phase locking protocols – An example

Transaction T_1	Transaction T_2
lock-S(IISc$_{PC}$)	
	lock-S(IISc$_{PC}$)
lock-S(ISI$_{PC}$)	
	lock-S(ISI$_{PC}$)
lock-S(IITK$_{PC}$)	
lock-S(IITD$_{PC}$)	
	unlock(IISc$_{PC}$)
	unlock(ISI$_{PC}$)
lock-S(IITB$_{PC}$)	
upgrade(IISc$_{PC}$)	
write(IISc$_{PC}$)	

Note: Avoiding lock-X on IISc$_{PC}$ at the beginning provides more concurrency to schedules. The lock can be upgraded as and when required (not via unlock followed by a lock-X).

Two-phase locking protocols – Drawbacks

Deadlock: In two-phase locking protocol, two transactions might wait for each other to release their corresponding locks on two different items.

Solution: Rollback any of the transactions causing the deadlock.

Cascading rollback: A single transaction failure leads to a series of transaction rollbacks.

Solution: Either use *strict two-phase locking protocol* (a transaction must hold all its exclusive locks till it commits/aborts) or *rigorous two-phase locking protocol* (all locks are held till commit/abort).

Dirty reads

A *dirty read* (or *uncommitted dependency*) occurs when a transaction is allowed to read a data item that has been updated by another running transaction and not yet committed. It causes cascading rollback (rollback in T_1 causes rollbacks in T_2, T_3).

Transaction T_1	**Transaction T_2**	**Transaction T_3**
	lock-X($IISc_{PC}$)	
lock-X(ISI_{PC})		
read(ISI_{PC})		
$ISI_{PC} \leftarrow ISI_{PC}$ - 10		
write(ISI_{PC}) ↑ *rollback*		
unlock(ISI_{PC})		
	lock-X(ISI_{PC})	
	read(ISI_{PC})	
	write(ISI_{PC})	
	unlock(ISI_{PC})	
		lock-S(ISI_{PC})
		read(ISI_{PC})

Insertion and deletion under two-phase locking

It can be used with two-phase locking protocol.

Working principle:

1. A delete operation may be performed only if the transaction deleting the tuple has an exclusive lock on the tuple to be deleted.
2. A transaction that inserts a new tuple into the database is given an exclusive lock on the tuple.

Insertion and deletion under two-phase locking – Drawback

Phantom phenomenon: A transaction that scans a relation and a transaction that inserts a tuple in the relation might conflict in spite of not accessing any tuple in common.

Solution: Associate a data item with the relation to represent the information about what tuples the relation contains.

Graph-based protocols – Basics

Working principle:

1. Graph-based protocols impose a partial ordering $\rightarrow$ on the set of all items $I = I_1, I_2, ..., I_n$.
2. It also includes the constraint that if $I_i \rightarrow I_j$ then any transaction accessing both I_i and I_j must access I_i before accessing I_j.

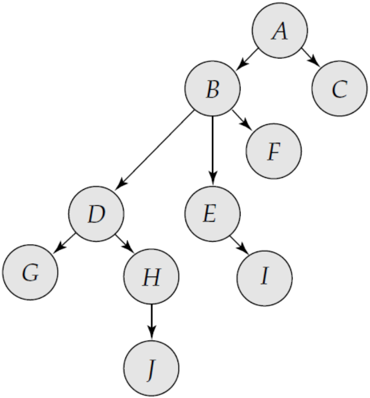
It implies that the set I may now be viewed as a directed acyclic graph that is known as database graph.

Graph-based protocols – An example

Tree protocol:

- Only exclusive locks are allowed.
- The first lock by T_i may be on any item. Subsequently, an item Q can be locked by T_i only if the parent of Q is currently locked by T_i.
- Data items may be unlocked at any time.
- A data item that has been locked and unlocked by T_i cannot subsequently be relocked by T_i

Graph-based protocols – Visualization



Visualizing a tree protocol

Timestamp-based protocols – Basics

In concurrency control, timestamps are implemented either with the *system clock* or using a *logical counter*.

Working principle:

1. Each transaction (say T_i) obtains a timestamp (say $\mathcal{TS}(T_i)$) on entering the system.
2. If an old transaction T_i has timestamp $\mathcal{TS}(T_i)$, a new transaction T_j is assigned a timestamp $\mathcal{TS}(T_j)$ such that $\mathcal{TS}(T_i) < \mathcal{TS}(T_j)$.

This ensures concurrent execution and the timestamps determine the serializability order.

Implementation schemes:

1. W-timestamp(Q) – The timestamp of a transaction that has executed the last write(Q) successfully.
2. R-timestamp(Q) – The timestamp of a transaction that has executed the last read(Q) successfully.

Timestamp-based protocols – Implementation

Timestamp-ordering protocol:

if Transaction T_i issues read(Q) **then**
    if $\mathcal{TS}(T_i) <$ W-timestamp(Q) **then**
        Reject read(Q) and roll back T_i. // T_i needs to read a value of Q already overwritten
    else
        Execute read(Q) and set R-timestamp(Q) $=$ max{R-timestamp(Q), $\mathcal{TS}(T_i)$}.
    end if
end if
if Transaction T_i issues write(Q) **then**
    if $\mathcal{TS}(T_i) <$ R-timestamp(Q) **then**
        Reject write(Q) and roll back T_i. // The value of Q that T_i is producing was needed previously, so it is assumed that it would never be produced
    end if
    If $\mathcal{TS}(T_i) <$ W-timestamp(Q), reject write(Q) and roll back T_i. // T_i is attempting to write an obsolete value of Q
    Otherwise, execute the write operation and set W-timestamp(Q) $= \mathcal{TS}(T_i)$.
end if

Note: Transactions arriving earlier cannot read/write later.

Timestamp-based protocols – Example I

See below an implementation of the timestamp-ordering protocol on five transactions (T_1, T_2, T_3, T_4 and T_5) having timestamps 3, 2, 4, 10 and 1, respectively.

T_1	T_2	T_3	T_4	T_5
				read(ISI_{PC})
	read($IISc_{PC}$)			
read($IISc_{PC}$)				
		write($IISc_{PC}$)		
		write(ISI_{PC})		
				read(ISI_{PC})
	read(ISI_{PC})			
	abort			
read(ISI_{PC})				
			write($IISc_{PC}$)	
		write($IISc_{PC}$)		
		commit		
				write($IISc_{PC}$)
				write(ISI_{PC})

Timestamp-based protocols – Revised implementation

Thomas' write rule:

if Transaction T_i issues read(Q) **then**
    if $\mathcal{TS}(T_i) <$ W-timestamp(Q) **then**
        Reject read(Q) and roll back T_i.
    else
        Execute read(Q) and set R-timestamp(Q) $=$ max{R-timestamp(Q), $\mathcal{TS}(T_i)$}.
    end if
end if
if Transaction T_i issues write(Q) **then**
    if $\mathcal{TS}(T_i) <$ R-timestamp(Q) **then**
        Reject write(Q) and roll back T_i.
    end if
    If $\mathcal{TS}(T_i) <$ W-timestamp(Q), ignore write(Q). // T_i is not rolled back*
    Otherwise, execute the write operation and set W-timestamp(Q) $= \mathcal{TS}(T_i)$.
end if

*It ensures view serializability for schedules that are not conflict serializable.

Timestamp-based protocols – Advantages and drawbacks

Serializability guaranteed: Timestamp-ordering protocol ensures serializability since all the arcs in the precedence graph do not form any cycle in the precedence graph.

Freedom from deadlock: Timestamp-ordering protocol ensures freedom from deadlock because no transaction ever waits.

Cascading rollback problem: A single transaction failure leads to a series of transaction rollbacks.

Recoverability problem: A transaction may not be recoverable.

Validation-based protocols – Basics

It is also called *optimistic concurrency control* since transaction executes fully in the hope that all will go well during validation.

Working principle:

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.

Each transaction must go through the three aforementioned phases in the same order.

Validation-based protocols – Basics

Implementation schemes:

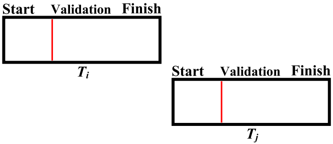
1. Timestamp Start(T_i) – The time when T_i started its execution
2. Timestamp Validation(T_i) – The time when T_i entered its validation phase
3. Timestamp Finish(T_i) – The time when T_i finished its write phase

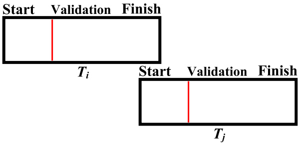
to increase concurrency, serializability order is determined by the timestamp given at validation time i.e. $\mathcal{TS}(T_i)$ is set to Validation(T_i).

Validation-based protocols – An example

Validation test: To ensure one of the following things:

- There is no overlapped execution
- Writes of T_i and T_j do not affect reads of T_j and T_i, respectively.





for T_j with $\mathcal{TS}(T_i) < \mathcal{TS}(T_j)$ **do**
    if (Finish(T_i) $<$ Start(T_j)) or (Start(T_j) $<$ Finish(T_i) $<$ Validation(T_j) and the set of data items written by T_i does not intersect with the set of data items read by T_j) **then**
        Commit T_j.
    else
        Abort T_j.
    end if
end for

Validation-based protocols – An example

Transaction T_1	**Transaction** T_2
read(IISc$_{PC}$)	
	read(IISc$_{PC}$)
	IISc$_{PC}$ $\leftarrow$ IISc$_{PC}$ - 10
	read(ISI$_{PC}$)
	ISI$_{PC}$ $\leftarrow$ ISI$_{PC}$ $+$ 10
read(ISI$_{PC}$)	
$<$ Validate $>$	
display(ISI$_{PC}$ $+$ IISc$_{PC}$)	
	write(IISc$_{PC}$)
	write(ISI$_{PC}$)

Multiple granularity – Basics

It allows data items to be of various sizes and define a hierarchy of data granularities, where the small granularities are nested within larger ones.

Working principle:

1. It is represented graphically as a tree.
2. When a transaction locks a node in the tree explicitly, it implicitly locks all the node's descendants in the same mode.

Granularity of locking can be at two levels:

- Fine granularity (lower in tree) – ensures high concurrency and locking overhead
- Coarse granularity (higher in tree) – ensures low concurrency and locking overhead.

Multiple granularity – Basics

Different locking modes:

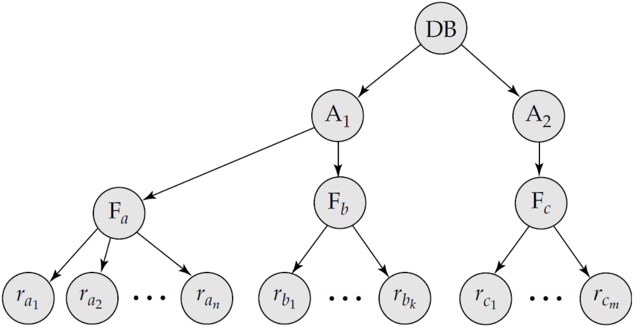
- **IS** – Intention-shared lock that indicates explicit locking at a lower level of the tree but only with shared locks.
- **IX** – Intention-exclusive lock that indicates explicit locking at a lower level with exclusive or shared locks.
- **S** – Shared lock as used conventionally.
- **SIX** – Shared and intention-exclusive lock in which the root node (of the subtree) is S-locked and explicit locking is being done at a lower level with exclusive locks.
- **X** – Exclusive lock as used conventionally.

Multiple granularity – Basics

The lock compatibility relations:

	IS	IX	S	SIX	X
IS	True	True	True	True	False
IX	True	True	False	False	False
S	True	False	True	False	False
SIX	True	False	False	False	False
X	False	False	False	False	False

Multiple granularity – Visualization



Hierarchy of granularity

Levels from the top to bottom: database (DB), area (A_1, A_2), file (F_a, F_b, F_c) and record ($r_{a_1}, r_{a_2}, \ldots, r_{a_n}, r_{b_1}, \ldots, r_{b_k}, r_{c_1}, \ldots, r_{c_m}$)

Multiple granularity – Implementation

Transaction T_i can lock a node Q, using the following rules:

1. The lock compatibility matrix must be observed.
2. The root of the tree must be locked first, and may be locked in any mode.
3. A node Q can be locked by T_i in S or IS mode only if the parent of Q is currently locked by T_i in either IX or IS mode.
4. A node Q can be locked by T_i in X, SIX, or IX mode only if the parent of Q is currently locked by T_i in either IX or SIX mode.
5. T_i can lock a node only if it has not previously unlocked any node i.e. T_i is two-phase.
6. T_i can unlock a node Q only if none of the children of Q are currently locked by T_i.

Multiversion schemes – Timestamp ordering

Each data item Q has a sequence of versions $< Q_1, Q_2, \ldots, Q_m >$.
Each version Q_k contains three data fields:

- Content – The value of version Q_k.
- W-timestamp(Q_k) – The timestamp of the transaction that wrote (created) version Q_k.
- R-timestamp(Q_k) – The largest timestamp of a transaction that successfully read version Q_k.

Working principle:

1. When a transaction T_i creates a new version Q_k of Q, set W-timestamp(Q_k) $= \mathcal{TS}(T_i)$ and R-timestamp(Q_k) $= \mathcal{TS}(T_i)$.
2. Update R-timestamp(Q_k) with $\mathcal{TS}(T_j)$ whenever a transaction T_j reads Q_k, and $\mathcal{TS}(T_j) >$ R-timestamp(Q_k).

Multiversion schemes – Two-phase Locking

Differentiates between read-only transactions and update transactions.

Working principle:

1. Update transactions acquire read and write locks, and hold all locks up to the end of the transaction. That is, update transactions follow rigorous two-phase locking.
2. Read-only transactions are assigned a timestamp by reading the current value of *timestamp counter* before they start execution; they follow the multiversion timestamp-ordering protocol for performing reads.

Concurrency in indexes – Basics

This approach can solve the phantom phenomenon.

Working principle:

1. Every relation must have at least one index.
2. A transaction can access tuples only after finding them through one or more indices on the relation.
3. A transaction T_i that performs a read (lookup) must lock all the index leaf nodes that it accesses in shared mode, even if the leaf node does not contain any tuple satisfying the index lookup.
4. A transaction T_i that inserts, updates or deletes a tuple t_i in a relation r must update all indices to r and must obtain exclusive locks on all index leaf nodes affected by the insert/update/delete.
5. The rules of the two-phase locking protocol must be observed.