Week 10 Lecture 1

Class	BSCCS2001
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Materials	
Module #	46
Type	Lecture
Week #	10

Transactions

Transaction Concept

- A transaction is a unit of program execution that accesses and possibly updates various data items
- For example: transaction to transfer $50 from account A to account B
    - read(A)
    - A := A - 50
    - write(A)
    - read(B)
    - B := B + 50
    - write(B)
- Two main issue to deal with:
    - Failures of various kinds, such as hardware failure and system crash
    - Concurrent execution of multiple transactions

Required properties of a Transaction: ACID: Atomicity

- **Atomicity Requirement**
    - If the transaction fails after step 3 and before step 6, money will be "lost" leading to an inconsistent database state
        - Failure could be due to software or hardware
    - The system should ensure that updates of a partially executed transaction are not reflected in the database

Required properties of a Transaction: ACID: Consistency

- **Consistency Requirement**
  - A + B must be unchanged by the execution of the transaction
  - In general, consistency requirements include
    - Explicitly specified integrity constraints
      - primary keys and foreign keys
    - Implicit integrity constraints
      - sum of balances of all accounts, minus sum of loan amounts must equal value of cash-in-hand
  - A transaction, when starting to execute, must see a consistent database
  - During transaction execution the database may be temporarily inconsistent
  - When the transaction completes successfully the database must be consistent
    - Erroneous transaction logic can lead to inconsistent

Required properties of a Transaction: ACID: Isolation

- **Isolation Requirement**
  - If between steps 3 and 6 (of the fund transfer transaction), another transaction T2 is allowed to access the partially updated database, it will see an inconsistent database (the sum A + B will be less than it should be)

T1	T2
1. **read**(A)	
2. $A := A - 50$	
3. **write**(A)	
	read(A), **read**(B), **print**$(A + B)$
4. **read**(B)	
5. $B := B + 50$	
6. **write**(B)	

  - Isolation can be ensured trivially by running transactions serially
    - That is, one after the other
  - However, executing multiple transactions concurrently has significant benefits

Required properties of a Transaction: ACID: Durability

- **Durability Requirement**
  - Once the user has been notified that the transaction has completed (that is, the transfer of $50 has taken place), the updates to the database by the transaction must persist even if there are software or hardware failures

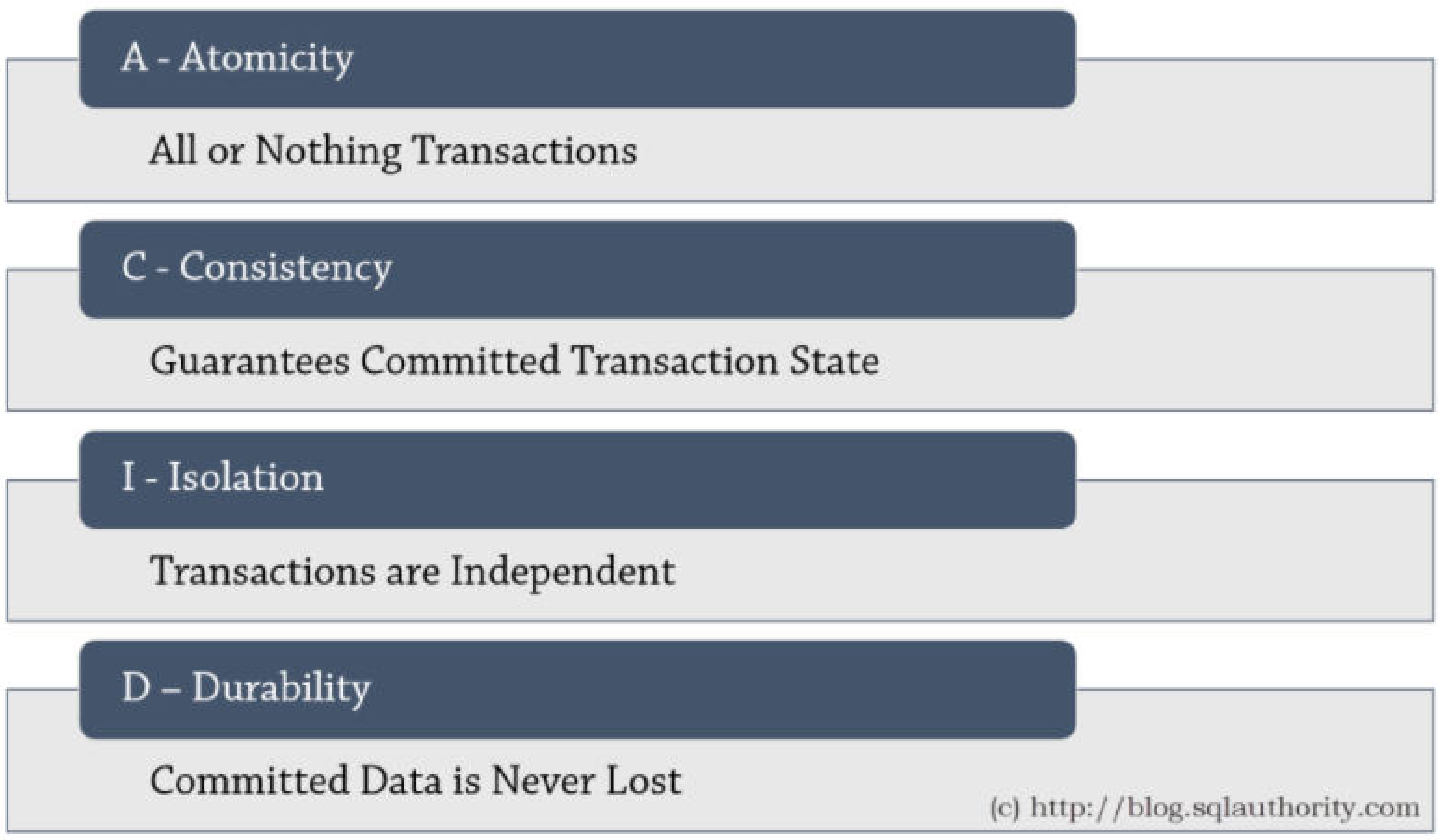
ACID Properties

A **transaction** is a unit of program execution that accesses and possibly updates various data items

- **Atomicity:** Atomicity guarantees that each transaction is treated as a single unit, which either succeeds completely or fails completely
  - If any of the statements constituting a transactions fails to complete, the entire transaction fails and the database is left unchanged
  - Atomicity must be guaranteed in every situation, including power failures, errors and crashes
- **Consistency:** Consistency ensures that a transaction can only bring the database from one valid state to another, maintaining database invariants
  - Any data written to the database must be valid according to all defined rules, including constraints, cascades, triggers and any combination thereof

    - **Isolation:** Transactions are often executed concurrently (multiple transactions reading and writing to a table at the same time)
        - Isolation ensures that concurrent execution of transactions leaves the database in the same state that would have been obtained if the transactions were executed sequentially
- **Durability:** Durability guarantees that once a transactions has been committed, it will remain committed even in the case of a system failure (like power outage or crash)
    - This usually means that completed transactions (or their effects) are recorded in non-volatile memory

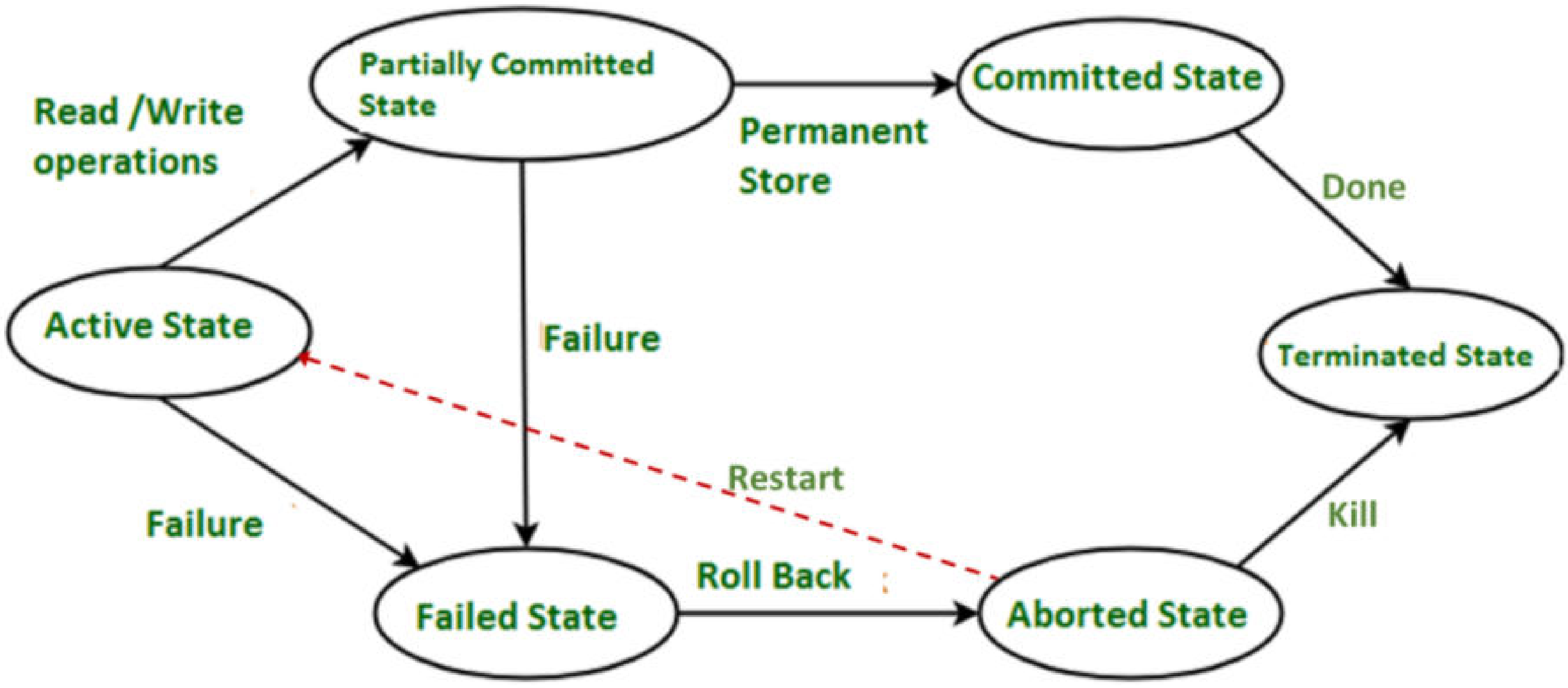
ACID Properties: Quick Reckoner



Transaction States

- Every transaction can be in one of the following states (like Process States in OS)
    - **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
    - **Terminated**
        - After it has been committed or aborted (killed)

Transitions for Transaction states



Concurrent Executions

- Multiple transactions are allowed to run concurrently in the system
  - Advantages are:
    - **Increased processor and disk utilization**, leading to better transaction throughput
      - For example, 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
- **Concurrency Control Schemes:** Mechanisms to achieve isolation
  - To control the interaction among the concurrent transactions in order to prevent them from destroying the consistency of the database

Schedules

- **Schedules:** A sequence of instructions that specify the chronological order in which instructions of concurrent transactions are executed
  - A scheduled for a set of transactions must consists for all instructions of those transactions
  - Must preserve the order in which the instructions appear in each individual transactions
- A transactions that successfully completes its execution will have a commit instruction as the last statement
  - By default, transaction assumed to execute commit instruction as its last step
- 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

A	B	A+B	Transaction	Remarks
100	200	300	@ Start	
50	200	250	T1, write A	
50	250	300	T1, write B	@ Commit
45	250	295	T2, write A	
45	255	300	T2, write B	@Commit

Consistent @ Commit

Inconsistent @ Transit

Inconsistent @ 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	

A	B	A+B	Transaction	Remarks
100	200	300	@ Start	
90	200	290	T2, write A	
90	210	300	T2, write B	@ Commit
40	210	250	T1, write A	
40	260	300	T1, write B	@Commit

Consistent @ Commit

Inconsistent @ Transit

Inconsistent @ Commit

Values of A & B are different from Schedule 1 – yet consistent

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

Schedule 3

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

Schedule 1

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

A	B	A+B	Transaction	Remarks
100	200	300	@ Start	
50	200	250	T1, write A	
45	200	245	T2, write A	
45	250	295	T1, write B	@ Commit
45	255	300	T2, write B	@Commit

Consistent @ Commit

Inconsistent @ Transit

Inconsistent @ 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

A	B	A+B	Transaction	Remarks
100	200	300	@ Start	
90	200	290	T2, write A	
50	200	250	T1, write A	
50	250	300	T1, write B	@ Commit
50	210	260	T2, write B	@ Commit

Consistent @ Commit

Inconsistent @ Transit

Inconsistent @ Commit

Week 10 Lecture 2

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Transactions: Serializability

Serializability

- **Assumption:** *Each transaction preserves database consistency*
- Thus, serial execution of a set of transactions preserves database consistency
- A (possible 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

Recap Schedule 3: Serializable

- 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

Schedule 3

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

Schedule 1

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

A	B	A+B	Transaction	Remarks
100	200	300	@ Start	
50	200	250	T1, write A	
45	200	245	T2, write A	
45	250	295	T1, write B	@ Commit
45	255	300	T2, write B	@Commit

Consistent @ Commit

Inconsistent @ Transit

Inconsistent @ Commit

Note: In schedules 1, 2 and 3, the sum "$A + B$" is preserved

Recap Schedule 4: Not Serializable

- 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

A	B	A+B	Transaction	Remarks
100	200	300	@ Start	
90	200	290	T2, write A	
50	200	250	T1, write A	
50	250	300	T1, write B	@ Commit
50	210	260	T2, write B	@ Commit

Consistent @ Commit

Inconsistent @ Transit

Inconsistent @ Commit

Simplified View of Transactions

- We ignore operations other than read and write instructions
  - Other operations happen in memory (are temporary in nature) and (mostly) do not affect the state of the database
  - This is a simplifying assumption for analysis
- 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

- Let I_i and I_j be 2 instructions from transactions T_i and T_j respectively
- Instructions I_i and I_j conflict if and only if there exists some item Q accessed by both I_i and I_j and at least one of these instructions write to Q
  - I_i = read(Q), I_j = read(Q) → I_i and I_j don't conflict
  - I_i = read(Q), I_i = write(Q) → They conflict
  - I_i = write(Q), I_j = read(Q) → They conflict
  - I_i = write(Q), I_j = write(Q) → They conflict
- Intuitively, a conflict between 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

- If a schedule S can be transformed into a schedule S' by a series of swaps of non-conflicting instructions, we say that S and S' are conflict equivalent
- We say that a schedule S is conflict serializable if it is conflict equivalent to a serial schedule

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- Schedule 3 can be transformed into Schedule 6, a serial schedule where T_2 follows T_1 by a series of swaps of non-conflicting instructions:
    - Swap T1.read(B) and T2.write(A)
    - Swap T1.read(B) and T2.read(A)
    - Swap T1.write(B) and T2.write(A)
    - Swap T1.write(B) and T2.read(A)

  These swaps do not conflict as they work with different items (A or B) in different transactions

T_1	T_2
read (A)	
write (A)	
	read (A)
	write (A)
read (B)	
write (B)	
	read (B)
	write (B)

Schedule 3

T_1	T_2
read(A)	
write(A)	
	read(A)
read(B)	
	write(A)
write(B)	
	read(B)
	write(B)

Schedule 5

T_1	T_2
read (A)	
write (A)	
read (B)	
write (B)	
	read (A)
	write (A)
	read (B)
	write (B)

Schedule 6

- Example of a schedule that is not conflict serializable

T_3	T_4
read (Q)	
	write (Q)
write (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 $< T_4, T_3 >$

Example: Bad Schedule

Consider two transactions:

Transaction 1

UPDATE accounts

SET balance = balance - 100

WHERE acct_id = 31414

Transaction 2

UPDATE accounts

SET balance = balance * 1.005

	A	B
(initial:)	200.00	100.00
$r_1(A)$:		
$r_2(A)$:		
$w_1(A)$:	100.00	
$w_2(A)$:	201.00	
$r_2(B)$:		
$w_2(B)$:		100.50

Schedule S

- In terms of read/write, ~~we have no read/write~~, we can write this as:

Transaction 1: $r_1(A), w_1(A) // A$ is the balance for *acct_id* = 31414

Transaction 2: $r_2(A), w_2(A), r_2(B), w_2(B) // B$ is the balance of other accounts

- Consider schedule S:
  - Schedule S: $r_1(A), r_2(A), w_1(A), w_2(A), r_2(B), w_2(B)$
  - Suppose: A starts with $200 and account B starts with $100
- Schedule S is very bad!
  - We withdrew $100 from account A, but somehow the database has recorded that our account now holds $201

- Ideal schedule is serial:

  Serial schedule 1:

  $r_1(A), w_1(A), r_2(A), w_2(A), r_2(B), w_2(B)$

  Serial schedule 2:

  $r_2(A), w_2(A), r_2(B), w_2(B), r_1(A), w_1(A)$
- We call a schedule ***serializable*** if it has the same effect as some serial schedule regardless of the specific information in the database
- As an example, consider Schedule T, which has swapped the third and fourth operations from S:
  - Schedule S: $r_1(A), r_2(A), w_1(A), w_2(A), r_2(B), w_2(B)$
  - Schedule T: $r_1(A), r_2(A), w_2(A), w_1(A), r_2(B), w_2(B)$
- By first example, the outcome is the same as Serial schedule 1
  - But that's just a peculiarity of the data, as revealed by the second example, where the final value of A can't be the consequence of either of the possible serial schedules
- So, neither S nor T are serializable

T1	Schedule 1: T1-T2		Schedule 2: T2-T1	
T2	A	B	A	B
Initial Value	200.00	100.00	200.00	100.00
Final Value	100.00	100.00	201.00	100.50
Initial Value	100.00	100.00	201.00	100.50
Final Value	100.50	100.50	101.00	100.50

A is $100 initially	*A*	*B*	*A* is $200 initially	*A*	*B*
(initial:)	100.00	100.00	(initial:)	200.00	100.00
$r_1(A)$:			$r_1(A)$:		
$r_2(A)$:			$r_2(A)$:		
$w_2(A)$:	100.50		$w_2(A)$:	201.00	
$w_1(A)$:	0.00		$w_1(A)$:	100.00	
$r_2(B)$:			$r_2(B)$:		
$w_2(B)$:		100.50	$w_2(B)$:		100.50

Schedule T

Example: Good Schedule

- What's a non-serial example of serializable schedule?
  - We could credit interest to A first then withdraw the money, then credit interest to B:
  - Schedule U: $r_2(A), w_2(A), r_1(A), w_1(A), r_2(B), w_2(B)$
    - Initial: A = 200, B = 100
    - Final: A = 101, B = 100.50

- Schedule U is conflict serializable to Schedule 2:

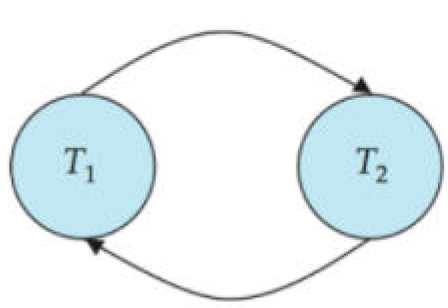
Schedule U:	$r_2(A), w_2(A), r_1(A), w_1(A), r_2(B), w_2(B)$
swap $w_1(A)$ and $r_2(B)$:	$r_2(A), w_2(A), r_1(A), r_2(B), w_1(A), w_2(B)$
swap $w_1(A)$ and $w_2(B)$:	$r_2(A), w_2(A), r_1(A), r_2(B), w_2(B), w_1(A)$
swap $r_1(A)$ and $r_2(B)$:	$r_2(A), w_2(A), r_2(B), r_1(A), w_2(B), w_1(A)$
swap $r_1(A)$ and $w_2(B)$:	$r_2(A), w_2(A), r_2(B), w_2(B), r_1(A), w_1(A)$: Schedule 2

Serializability

- Are all serializable schedules conflict-serializable? No
- Consider the following schedule for a set of three transactions
    - $w_1(A), w_2(A), w_2(B), w_1(B), w_3(B)$
- We can perform no swaps to this:
    - The first 2 operations are both on A and at least one is a write
    - The second and third operations are by the same transaction
    - The third and fourth are both on B at least one is a write and
    - So are the fourth and fifth
    - So this schedule is not conflict-equivalent to anything - and certainly not any serial schedules
- However, since nobody ever reads the values written by the $w_1(A), w_2(B)$ and $w_1(B)$ operations, the schedule has the same outcome as the serial outcome
    - $w_1(A), w_1(B), w_2(A), w_2(B), w_3(B)$

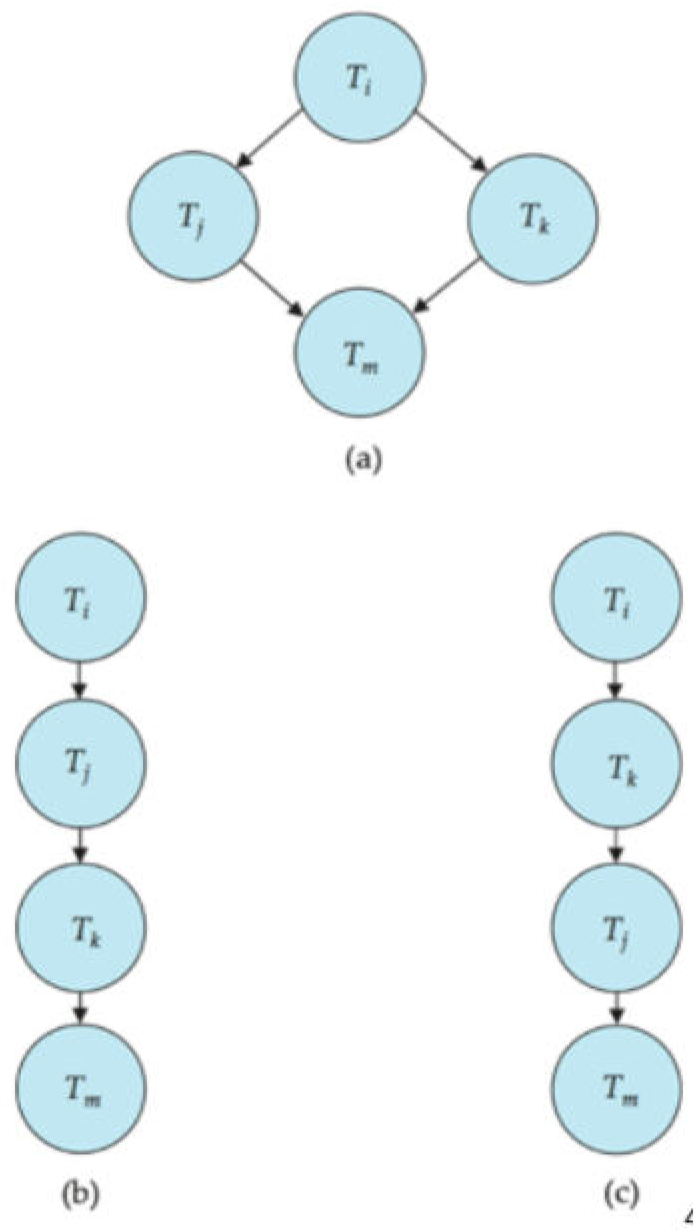
Precedence Graph

- Consider some schedule of a set of transactions $T_1, T_2, ..., T_n$
- **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 transactions 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 precedence graph is acyclic, the serializability order can be obtained by a topological sorting of the graph
    - That is, 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)



- Build a directed graph, with a vertex for each transaction
- Go through each operation of the schedule
  - If the operation is of the form $w_i(X)$, find each subsequent operation in the schedule also operating on the same data element X by a different transaction: that is, anything of the form $r_j(X)$ or $w_j(X)$
    - For each subsequent operation, add a directed edge in the graph from T_i to T_j
  - If the operation is of the form $r_i(X)$, find each subsequent write to the same data element X by a different transaction: that is, anything of the form $w_j(X)$
    - For each such subsequent write, add a directed edge in the graph from T_i to T_j
- The schedule is conflict-serializable if and only if the resulting directed graph is acyclic
- Moreover, we can perform a topological sort on the graph to discover the serial schedule to which the schedule is conflict-equivalent

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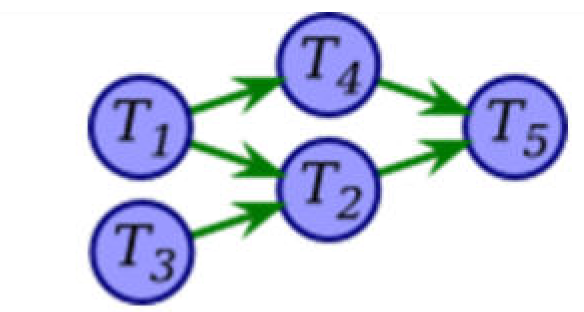
- Consider the following schedule:
  - $w_1(A), r_2(A), w_1(B), w_3(C), r_2(C), r_4(B), w_2(D), w_4(E), r_5(D), w_5(E)$
- We start with an empty graph with five vertices labeled T_1, T_2, T_3, T_4, T_5
- We go through each operation in the schedule:

$w_1(A)$: A is subsequently read by T_2, so add edge $T_1 \to T_2$
$r_2(A)$: no subsequent writes to A, so no new edges
$w_1(B)$: B is subsequently read by T_4, so add edge $T_1 \to T_4$
$w_3(C)$: C is subsequently read by T_2, so add edge $T_3 \to T_2$
$r_2(C)$: no subsequent writes to C, so no new edges
$r_4(B)$: no subsequent writes to B, so no new edges
$w_2(D)$: C is subsequently read by T_2, so add edge $T_3 \to T_2$
$w_4(E)$: E is subsequently written by T_5, so add edge $T_4 \to T_5$
$r_5(D)$: no subsequent writes to D, so no new edges
$w_5(E)$: no subsequent operations on E, so no new edges

- We end up with a precedence graph



- This graph has no cycles, so the original schedule must be serializable
  - Moreover, since one way to topologically sort the graph is $T_3 - T_1 - T_4 - T_2 - T_5$, one serial schedule that is conflict-equivalent is

    $w_3(C), w_1(A), w_1(B), r_4(B), w_4(E), r_2(A), r_2(C), w_2(D), r_5(D), w_5(E)$

Week 10 Lecture 3

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Transactions: Recoverability

What is Recovery?

- Serializability helps to ensure Isolation and Consistency of a schedule
- Yet, the Atomicity and Consistency may be compromised in the face of system failures
- Consider a schedule comprising of a single transaction (serial):
    - read(A)
    - A := A - 50
    - write(A)
    - read(B)
    - B := B + 50
    - write(B)
    - commit // Make the changes permanent; show the results to the user
- What if system fails after step 3 and before step 6?
    - Leads to inconsistent state
    - Need to rollback update of A
- This is known as Recovery

Recoverable Schedules

- 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 if T_9 commits immediately after the read(A) operation

T_8	T_9
read (A)	
write (A)	
	read (A)
	commit
read (B)	

- If T_8 should abort, T_9 would have read (and possibly shown to the user) an inconsistent database state
  - Hence, the 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
- It is desirable to restrict the schedules to those that are cascadeless
- 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		

Example: Irrecoverable Schedule

T1	T1's Buffer	T2	T2's Buffer	Database
				A = 5000
R(A);	A = 5000			A = 5000
A = A – 1000;	A = 4000			A = 5000
W(A);	A = 4000			A = 4000
		R(A);	A = 4000	A = 4000
		A = A + 500;	A = 4500	A = 4000
		W(A);	A = 4500	A = 4500
		Commit;		
Failure Point				
Commit;				

Rollback is possible only till the end (commit) of T2

So, the computation of A (4000) and write in T1 is lost

Example: Recoverable Schedule with Cascading Rollback

T1	T1's Buffer	T2	T2's Buffer	Database
				A = 5000
R(A);	A = 5000			A = 5000
A = A – 1000;	A = 4000			A = 5000
W(A);	A = 4000			A = 4000
		R(A);	A = 4000	A = 4000
		A = A + 500;	A = 4500	A = 4000
		W(A);	A = 4500	A = 4500
Failure Point				
Commit;				
		Commit;		

Rollback is possible as T2 has not committed yet

But, T2 also need to be rolled back for rolling back T1

Example: Recoverable Schedule without Cascading Rollback

T1	T1's Buffer	T2	T2's Buffer	Database
				A = 5000
R(A);	A = 5000			A = 5000
A = A – 1000;	A = 4000			A = 5000
W(A);	A = 4000			A = 4000
Commit;				
		R(A);	A = 4000	A = 4000
		A = A + 500;	A = 4500	A = 4000
		W(A);	A = 4500	A = 4500
		Commit;		

Rollback is possible without cascading - wherever failure occurs

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
  - A transaction in SQL ends by:
    - **Commit work**
      - Commits current transaction and begins a new one
    - **Rollback work**
      - Causes current transaction to abort
  - In almost al database systems, by default, every SQL statement also commits implicitly if it executes successfully
    - Implicit commit can be turned off by a database directive
      - For example in JDBC, `connection.setAutoCommit(false);`

Transaction Control Language (TCL)

- The following commands are used to control transactions
  - **COMMIT**
    - To save the changes
  - **ROLLBACK**
    - To roll back the changes
  - **SAVEPOINT**
    - Creates points within the groups of transactions in which to ROLLBACK
  - **SET TRANSACTION**
    - Places a name on a transaction
- Transactional control commands are only used with the DML Commands such as
  - INSERT, UPDATE and DELETE only
  - They cannot be used while creating tables or dropping them because these operations are automatically committed to the database

TCL: COMMIT Command

- COMMIT is the transactional command used to save changes invoked by a transaction to the database
- COMMIT saves all the transactions to the database since the last COMMIT or ROLLBACK command
- The syntax for the COMMIT command is as follows:

- `SQL> DELETE FROM Customers WHERE AGE = 25;`
- `SQL> COMMIT;`

```
SQL> SELECT * FROM Customers;
```

Before DELETE

ID	NAME	AGE	ADDRESS	SALARY
1	Ramesh	32	Ahmedabad	2000
2	Khilan	25	Delhi	1500
3	kaushik	23	Kota	2000
4	Chaitali	25	Mumbai	6500
5	Hardik	27	Bhopal	8500
6	Komal	22	MP	4500
7	Muffy	24	Indore	10000

```
SQL> SELECT * FROM Customers;
```

After DELETE

ID	NAME	AGE	ADDRESS	SALARY
1	Ramesh	32	Ahmedabad	2000
3	kaushik	23	Kota	2000
5	Hardik	27	Bhopal	8500
6	Komal	22	MP	4500
7	Muffy	24	Indore	10000

TCL: ROLLBACK Command

- The ROLLBACK is the command used to undo transactions that have not been already saved to the database
- This can only be used to undo transactions since the last COMMIT or ROLLBACK command was issued
- The syntax for a ROLLBACK command is as follows:
  - `SQL> DELETE FROM Customers WHERE AGE = 25;`
  - `SQL> ROLLBACK;`

```
SQL> SELECT * FROM Customers;
```

Before DELETE

ID	NAME	AGE	ADDRESS	SALARY
1	Ramesh	32	Ahmedabad	2000
2	Khilan	25	Delhi	1500
3	kaushik	23	Kota	2000
4	Chaitali	25	Mumbai	6500
5	Hardik	27	Bhopal	8500
6	Komal	22	MP	4500
7	Muffy	24	Indore	10000

```
SQL> SELECT * FROM Customers;
```

After DELETE

ID	NAME	AGE	ADDRESS	SALARY
1	Ramesh	32	Ahmedabad	2000
2	Khilan	25	Delhi	1500
3	kaushik	23	Kota	2000
4	Chaitali	25	Mumbai	6500
5	Hardik	27	Bhopal	8500
6	Komal	22	MP	4500
7	Muffy	24	Indore	10000

TCL: SAVEPOINT/ROLLBACK Command

- A SAVEPOINT is a point in a transaction when you can roll the transaction back to a certain point without rolling back the entire transaction
- The syntax for a SAVEPOINT command is
  - `SAVEPOINT SAVEPOINT_NAME;`
- This command serves only in the creation of a SAVEPOINT among all the transactional statements
- The ROLLBACK command is used to undo a group of transactions
- The syntax for rolling back to a SAVEPOINT is:
  - `ROLLBACK TO SAVEPOINT_NAME;`

Example:

- `SQL> SAVEPOINT SP1;`
  - Savepoint created.
- `SQL> DELETE FROM Customers WHERE ID=1;`
  - 1 row deleted.
- `SQL> SAVEPOINT SP2;`
  - Savepoint created.
- `SQL> DELETE FROM Customers WHERE ID=2;`
  - 1 row deleted.
- `SQL> SAVEPOINT SP3;`
  - Savepoint created.
- `SQL> DELETE FROM Customers WHERE ID=3;`
  - 1 row deleted.

- Three records deleted
- Undo the deletion of last two
- `SQL> ROLLBACK TO SP2;`
  - Rollback complete

```
SQL> SAVEPOINT SP1;
SQL> DELETE FROM Customers WHERE ID=1;
SQL> SAVEPOINT SP2;
SQL> DELETE FROM Customers WHERE ID=2;
SQL> SAVEPOINT SP3;
SQL> DELETE FROM Customers WHERE ID=3;
```

`SQL> SELECT * FROM Customers`

At the beginning

ID	NAME	AGE	ADDRESS	SALARY
1	Ramesh	32	Ahmedabad	2000
2	Khilan	25	Delhi	1500
3	kaushik	23	Kota	2000
4	Chaitali	25	Mumbai	6500
5	Hardik	27	Bhopal	8500
6	Komal	22	MP	4500
7	Muffy	24	Indore	10000

`SQL> SELECT * FROM Customers;`

After ROLLBACK

ID	NAME	AGE	ADDRESS	SALARY
2	Khilan	25	Delhi	1500
3	kaushik	23	Kota	2000
4	Chaitali	25	Mumbai	6500
5	Hardik	27	Bhopal	8500
6	Komal	22	MP	4500
7	Muffy	24	Indore	10000

TCL: RELEASE SAVEPOINT Command

- The RELEASE SAVEPOINT command is used to remove a SAVEPOINT that you have created
- The syntax for a RELEASE SAVEPOINT command is as follows
  - `RELEASE SAVEPOINT SAVEPOINT_NAME;`
- Once a SAVEPOINT has been released, you can no longer use the ROLLBACK command to undo transactions performed since the last SAVEPOINT

TCL: SET TRANSACTION Command

- The SET TRANSACTION command can be used to initiate a database transaction
- This command is used to specify a characteristics for the transactions that follows
  - For example, you can specify a transaction to be read-only or read-write
- The syntax for a SET TRANSACTION command is as follows:

- `SET TRANSACTION [READ WRITE | READ ONLY];`

View Serializability

- Let S and S' be two schedules with the same set of transactions
- S and S' are view equivalent if the following 3 conditions are met, for each data item Q
  - **Initial Read:** If in schedule S, transaction T_i reads the initial value of Q, then in schedule S' also transaction T_i must read the initial value of Q
  - **Write-Read Pair:** If in schedule S transaction T_i executed **read**(Q) and that value was produced by transaction T_j (if any), then in schedule S" also transaction T_i must read the value of Q that was produced by the same **write**(Q) operation of transaction T_j
  - **Final Write:** The transaction (if any) that performs the final **write**(Q) operation in schedule S must also perform the final **write**(Q) operation in schedule S'
- As can be seen, view equivalence is also based purely on reads and writes alone

---

- A schedule S is view serializable if it is view equivalent to a serial schedule
- Every conflict serializable schedule is also view serializable
- Below is a schedule which is view-serializable but not conflict serializable

T_{27}	T_{28}	T_{29}
read (Q)		
	write (Q)	
write (Q)		
		write (Q)

- What serial schedule is above equivalent to?
  - $T_{27} - T_{28} - T_{29}$
  - The one **read**(Q) instruction reads the initial value of Q in both schedules and
  - T_{29} performs the final write of Q in both schedules
- T_{28} and T_{29} perform **write**(Q) operations called blind writes, without having performed a **read**(Q) operation
- Every view serializable schedule that is not conflict serializable has blind writes

Test for View Serializability

- The %age graph test for conflict serializability cannot be used directly to test for view serializability
  - Extension to test for view serializablilty has cost exponential in the size of the precedence graph
- The problem of checking if a schedule is view serializable falls in the case of NP-complete problems
  - Thus, existence of an efficient algorithm is extremely unlikely
- However, practical assignments that just check some sufficient conditions for view serializability can still be used

View Serializability: Example 1

- Check whether the schedule is view serializable or not?
  - $S : R2(B); R2(A); R1(A); R3(A); W1(B); W2(B); W3(B)$
- Solution:
  - With 3 transactions, total number of schedules possible $= 3! = 6$
    - $< T_1 T_2 T_3 >$
    - $< T_1 T_3 T_2 >$
    - $< T_2 T_3 T_1 >$
    - $< T_2 T_1 T_3 >$
    - $< T_3 T_1 T_2 >$

        - $< T_3 T_2 T_1 >$
- Solution #2
    - Final update on data items:
        - A :- (No write on A)
        - B : T_1, T_2, T_3 (All 3 transactions write B)
        - As the final update on B is made by $T_3 (T_1, T_2) \rightarrow T_3$
            - Now, removing those schedules in which T_3 is not executing at last:
                - $< T_1 T_2 T_3 >$
                - $< T_2 T_1 T_3 >$
- Solution #3
    - Initial Read + Which transaction updates after read?
        - A : T_2, T_1, T_3 (initial read)
        - B : T_2 (initial read); T_1 (update after read)
        - The transaction T_2 reads B initially which is updated by T_1
            - So, T_2 must execute before T_1
            - Hence, $T_2 \rightarrow T_1$
            - So, only one schedule survives:
        - $< T_2 T_1 T_3 >$
    - Write Read Sequence (WR)
        - No need to check here
    - Hence, view equivalent serial schedule is:
        - $T_2 \rightarrow T_1 \rightarrow T_3$

View Serializability: Example 2

- Check whether S is Conflict serializable and / or view serializable or not?
    - $S : R1(A); R2(A); R3(A); R4(A); W1(B); W2(B); W3(B); W4(B)$

More Complex Notions of Serializability

- The schedule below produces the same outcome as the serial schedule $< T1, T5 >$, yet is not conflict equivalent or view equivalent to it

T_1	T_5
read (A) $A := A - 50$ write (A)	
	read (B) $B := B - 10$ write (B)
read (B) $B := B + 50$ write (B)	
	read (A) $A := A + 10$ write (A)

- If we start with A = 1000 and B = 2000, the final result is 960 and 2040
- Determining such equivalence requires analysis of operations other than read and write

Week 10 Lecture 4

Class	BSCCS2001
Created	@November 8, 2021 7:30 PM
Materials	
Module #	49
Type	Lecture
Week #	10

Concurrency Control

- A database must provide a mechanism that will ensure that all possible schedules are both:
    - Conflict serializable
    - Recoverable and, preferably, Cascadeless
- A policy in which only one transaction can execute at a time generates serial schedules, but provides a poor degree of concurrency
- Concurrency-control schemes tradeoff between the amount of concurrency they allow and the amount of overhead that they incur
- Testing a schedule for serializability after it has executed is a little too late!
    - Tests for serializability help us understand why a concurrency control protocol is correct
- **Goal:** *To develop concurrency control protocols that will assure serializability*
- One way to ensure isolation is to require that data items be accessed in a mutually exclusive manner, that is, while one transaction is accessing a data item, no other transactions can modify that data item
    - Should a transaction hold a lock on the whole database
        - Would lead to strictly serial schedules - very poor performance
- The most common method used to implement locking requirement is to allow a transaction to access a data item only if it is currently holding a lock on that item

Lock-based Protocols

- A lock is a mechanism to control concurrent access to a data item

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

Lock-based Protocols: Lock Compatibility Matrix

- Lock-Compatibility Matrix: A lock compatibility matrix is used which states whether a data item can be locked by two transactions at the same time
- Full compatibility matrix

State of the lock	Lock request type → Shared	Exclusive
Unlock	Yes	Yes
Shared	Yes	No
Exclusive	No	No

- Abbreviated compatibility matrix

State of the lock	Lock request type → Shared	Exclusive
Shared	Yes	No
Exclusive	No	No

- Requesting for / Granting of a Lock
  - A transaction may be granted a lock on an item if the requested lock is compatible with locks already held on the item by other transactions
- Sharing a Lock
  - Any number of transactions can hold shared locks on an item
  - But if any transaction holds an exclusive lock on the item no other transaction may hold any lock on the item
- Waiting for a Lock
  - If a lock cannot be granted, the requesting transaction is made to wait till all incompatible locks held by other transactions have been released
- Holding a Lock
  - A transaction must hold a lock on a data item as long as it accesses that item
- Unlocking / Releasing a Lock
  - Transaction T_i may unlock a data item that it had locked at some earlier point
  - It is not necessarily desirable for a transaction to unlock a data item immediately after its final access of that data item, since serializability may not be ensured

Lock-Based Protocols: Example → Serial Schedule

- Let A and B be 2 accounts that are accessed by transactions T_1 and T_2
  - Transaction T_1 transfers $50 from account B to account A
  - Transaction T_2 displays the total amount of money in accounts A and B, that is, the sum A + B
- Suppose that the values of accounts A and B are $100 and $200, respectively
- If these transactions are executed serially, either as T_1, T_2 or the order T_2, T_1 then transaction T_2 will display the value $300

```
T1:                       T2:
    lock-X(B);                lock-S(A);
    read(B);                  read(A);
    B := B – 50;              unlock(A);
    write(B);                 lock-S(B);
    unlock(B);                read(B);
    lock-X(A);                unlock(B);
    read(A);                  display(A + B)
    A := A + 50;
    write(A);
    unlock(A);
```

Lock-Based Protocols: Example → Concurrent Schedule: Bad

- If, however, these transactions are executed concurrently, then schedule 1 is possible
- In this case, transaction T_2 displays $250, which is incorrect
  - The reasons are ...
    - the transaction T_1 unlocked data item B too early, as a result of which T_2 saw an inconsistent state
  - Suppose we delay unlocking till the end

T1	T2	Concurrency Control Manager
lock-X(B)		
		grant-X(B, T_1)
read(B) $B := B - 50$ write(B) unlock(B)		
	lock-S(A)	
		grant-S(A, T_2)
	read(A) unlock(A) lock-S(B)	
		grant-S(B, T_2)
	read(B) unlock(B) display($A + B$)	
lock-X(A)		
		grant-X(A, T_1)
read(A) $A := A - 50$ write(A) unlock(A)		

Schedule 1

```
T1:                       T2:
    lock-X(B);                lock-S(A);
    read(B);                  read(A);
    B := B – 50;              unlock(A);
    write(B);                 lock-S(B);
    unlock(B);                read(B);
    lock-X(A);                unlock(B);
    read(A);                  display(A + B)
    A := A + 50;
    write(A);
    unlock(A);
```

Lock-Based Protocols: Example → Concurrent Schedule: Good

- Delaying unlocking till the end, T_1 becomes T_3 & T_2 becomes T_4

```
T3:                       T4:
    lock-X(B);                lock-S(A);
    read(B);                  read(A);
    B := B – 50;              lock-S(B);
    write(B);                 read(B);
    lock-X(A);                display(A + B);
    read(A);                  unlock(A);
    A := A + 50;              unlock(B)
    write(A);
    unlock(B);
    unlock(A)
```

T_1	T_2	concurrency control manager
lock-X(B)		
		grant-X(B, T_1)
read(B) $B := B - 50$ write(B) unlock(B)		
	lock-S(A)	
		grant-S(A, T_2)
	read(A) unlock(A) lock-S(B)	
		grant-S(B, T_2)
	read(B) unlock(B) display($A + B$)	
lock-X(A)		
		grant-X(A, T_1)
read(A) $A := A - 50$ write(A) unlock(A)		

Schedule 1

- Hence, sequence of reads and writes as in Schedule 1 is no longer possible
- T_4 will correctly display $300

Lock-Based Protocols: Example → Concurrent Schedule: Deadlock

- Given T_3 and T_4 consider Schedule 2 (partial)
- Since T_3 is holding an exclusive mode lock on B and T_4 is requesting a shared-mode lock on B, T_4 is waiting for T_3 to unlock B
- Similarly, since T_4 is holding a shared-mode lock on A and T_3 is requesting an exclusive-mode lock on A, T_3 is waiting for T_4 to unlock A
- Thus, we have arrived at a state where neither of these transactions can ever proceed with its normal execution
- This situation is called a **deadlock**
- When deadlock occurs, the system must roll back one of the two transactions
- Once a transaction has been rolled back, the data items that were locked by that transaction are unlocked
- These data items are then available to the other transaction which can continue with its execution

```
T3:                      T4:
    lock-X(B);               lock-S(A);
    read(B);                 read(A);
    B := B − 50;             lock-S(B);
    write(B);                read(B);
    lock-X(A);               display(A + B);
    read(A);                 unlock(A);
    A := A + 50;             unlock(B)
    write(A);
    unlock(B);
    unlock(A)
```

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)	

Schedule 2

Lock-Based Protocols

- If we do not use locking, or if we unlock data items too soon after reading or writing them, we may get inconsistent states
- On the other hand, if we do not unlock a data item before requesting a lock on another data item, deadlocks may occur
- Deadlocks are a necessary evil associated with locking, if we want to avoid inconsistent states
- Deadlocks are definitely preferable to inconsistent states, since they can be handled by rolling back transactions, whereas inconsistent states may lead to real-world problems that cannot be handled by the database system
- 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 set of all such schedules is a proper subset of all possible serializable schedules
- We present locking protocols that allow only conflict-serializable schedules, and thereby ensure isolation

Two-Phase Locking Protocol

- This protocol ensures conflict-serializable schedules
- 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 protocol assures serializability
    - It can be proved that the transactions can be serialized in the order of their lock points
        - That is, the point where a transaction acquires its final lock
- There can be conflict serializable schedules that cannot be obtained if two-phase locking is used
- However, in the absence of extra information (that is, ordering of access to data), two-phase locking is needed for conflict serializability in the following sense:
    - Given a transaction T_i that does not follow two-phase locking, we can find a transaction T_j that uses two-phase locking, and a schedule for T_i and T_j that is not conflict serializable

Lock Conversions

- Two-phase locking with lock conversions
    - First Phase
        - can acquire a lock-S on item
        - can acquire a lock-X on item
        - can convert a lock-S to a lock-X (upgrade)
    - Second Phase
        - can release a lock-S
        - can release a lock-X
        - can convert a lock-X to a lock-S (downgrade)
- This protocol assures serializability
    - But still relies on the programmer to insert the various locking instructions

Automatic Acquisition of Locks: Read

- A transaction T_i issues the standard read/write instruction, without explicit locking calls
- The operation **read**(D) is processed as:

if T_i has a lock on D

    then

        read(D)

    else begin

        if necessary, wait until no other transaction has a **lock-X** on D

        grant T_i a **lock-S** on D;

        read(D)

    end

Automatic Acquisition of Locks: Write

- **write**(D) is processed as:

if T_i has a **lock-X** on D

    then

        write(D)

    else begin

        if necessary, wait until no other transaction has any lock on D

        if T_i has a **lock-S** on D

            then

upgrade lock on D to **lock-X**

else

grant T_i a **lock-X** on D

write(D)

end;

- All locks are released after commit or abort

Deadlocks

- Two-phase locking does not ensure freedom from deadlocks

```
T3:                       T4:
    lock-X(B);                lock-S(A);
    read(B);                  read(A);
    B := B − 50;              lock-S(B);
    write(B);                 read(B);
    lock-X(A);                display(A + B);
    read(A);                  unlock(A);
    A := A + 50;              unlock(B)
    write(A);
    unlock(B);
    unlock(A)
```

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)	

- Observe that transactions T_3 and T_4 are two phase, but, in deadlock

Starvation

- In addition to deadlocks, there is a possibility of **Starvation** (wot)
- **Starvation** occurs if the concurrency control manager is badly designed
    - For example:
        - A transaction may be waiting for an X-lock on an item, while a sequence of other transactions request and are granted an S-lock on the same item
        - The same transaction is repeatedly rolled back due to deadlocks
- Concurrency control manager can be designed to prevent starvation
- Starvation is also loosely referred to as **Livelock**

Cascading Rollback

- The potential for deadlock exists in most locking protocols
    - Deadlocks are necessary evil
- When a deadlock occurs there is a possibility of cascading roll-backs
- Cascading roll-back is possible under two-phase locking
- In the schedule here, each transaction observes the two-phase locking protocol, but the failure of T5 after the read(A) step of T7 leads to cascading rollback of T6 and T7

T_5	T_6	T_7
lock-X(A)		
read(A)		
lock-S(B)		
read(B)		
write(A)		
unlock(A)		
	lock-X(A)	
	read(A)	
	write(A)	
	unlock(A)	
		lock-S(A)
		read(A)

More Two Phase Locking Protocols

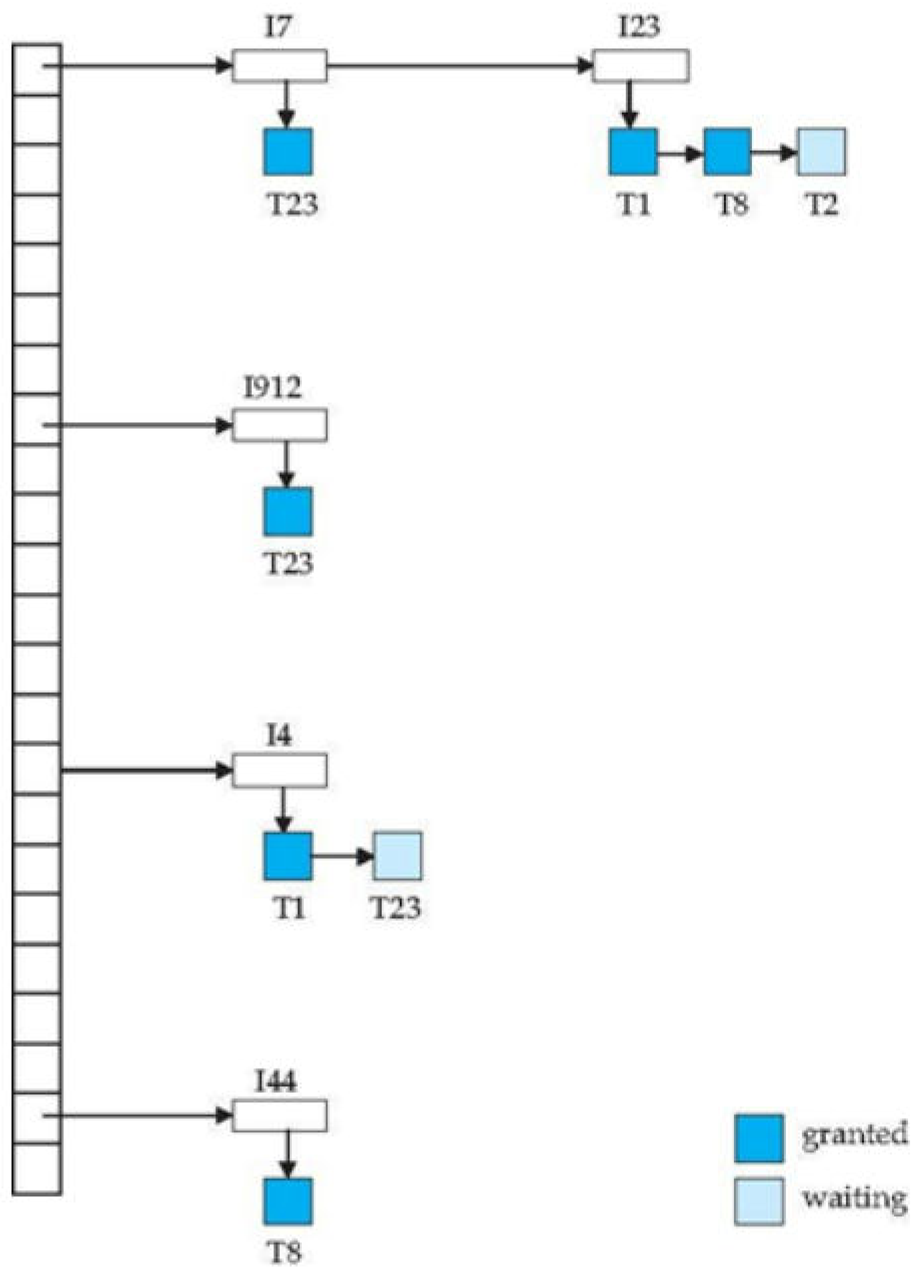
- To avoid Cascading roll-back, follow a modified protocol called strict two-phase locking
  - A transaction must hold all its exclusive locks till it commits/aborts
- Rigorous two-phase locking is even stricter
  - All locks are held till commit/abort
    - In this protocol, transactions can be serialized in the order in which they commit
- Note that concurrency goes down as we move to more and more strict locking protocol

Implementation of Locking

- A lock manager can be implemented as a separate process to which transactions send lock and unlock requests
- The lock manager replies to a lock request by sending a lock grant messages (or a message asking the transaction to roll back, in case of a deadlock)
- The requesting transaction waits until its request is answered
- The lock manager maintains a data-structure called a lock table to record granted locks and pending requests
- The lock table is usually implemented as an in-memory hash table indexed on the name of the data item being locked

Lock Table

- Dark blue rectangle indicate granted locks; light blue indicate waiting requests
- Lock table also records the type of lock granted or requested
- New request is added to the end of the queue of requests for the data item, and granted if it is compatible with all earlier locks
- Unlock requests result in the request being deleted, and later requests are checked to see it they can now be granted
- If transaction aborts, all waiting or granted requests of the transaction are deleted
  - Lock manager may keep a list of locks held by each transaction, to implement this efficiently


I7
I23
T23
T1
T8
T2
I912
T23
I4
T1
T23
I44
T8
granted
waiting

Week 10 Lecture 5

Class	BSCCS2001
Created	@November 9, 2021 4:41 PM
Materials	
Module #	50
Type	Lecture
Week #	10

Concurrency Control (part 2)

Deadlock Handling

- 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
- Deadlock Prevention protocols ensure that the system will never enter into a deadlock state
    - Some prevention strats:
        - Require that each transaction locks all its data items before it beings execution (pre-declaration)
        - Impose partial ordering of all data items and require that a transaction can lock data items in the order specified by the partial order

Deadlock Prevention

- **Transaction Timestamp:** Timestamp is a unique identifier created by the DBMS to identify the relative starting time of a transaction
    - Timestamping is a method of concurrency control in which each transaction is assigned a transaction timestamp
- Following schemes use transaction timestamps for the sake of deadlock prevention alone
    - **wait-die** scheme: non-preemptive
        - Older transaction may wait for younger one to release data item (here, older means smaller timestamp)
            - Younger transactions never wait for older ones; they are rolled back instead
        - A transaction may die several times before acquiring needed data item
    - **wound-wait scheme:** preemptive

        - Older transaction wounds (forces rollback) of younger transaction instead of waiting for it
            - Younger transactions may wait for older ones
        - May be fewer rollbacks than wait-die schemes

Deadlock Prevention: Wait-Die Scheme

- It is a **non-preemptive** technique for deadlock prevention
- When transaction T_n requests a data item currently held by T_k, T_n is allowed to wait only if it has a timestamp smaller than that of T_k (That is, T_n is older than T_k), otherwise T_n is killed ("die")
- If a transaction requests to lock a resource (data item), which is already held with a conflicting lock by another transaction, then one of the two possibilities may occur:
    - **Timestamp**$(T_n) <$ **Timestamp**(T_k)**:** T_n which is requesting a conflicting lock, is older than T_k, then Tn is allowed to "wait" until the data-item is available
    - **Timestamp**(T_k) **> Timestamp**(T_k)**:** T_n is younger than T_k, then T_n is killed ("dies")
        - *Tn is restarted later with a random delay but with the same timestamp(n)*
- This scheme allows the older transaction to "wait" but kills the younger one ("die")
- Example:
    - Suppose that transaction T_5, T_{10}, T_{15} have timestamps 5, 10 and 15 respectively
    - If T_5 requests a data item held by T_{10} then T_5 will "wait"
    - If T_{15} requests a data item held by T_{10}, then T_{15} will be killed ("die")

Deadlock Prevention: Wound-Wait Scheme

- It is a preemptive technique for deadlock prevention
- When transaction T_n requests a data item currently held by T_k, T_n is allowed to wait only if it has a timestamp larger than that of T_k, otherwise T_k is killed (wounded by T_n)
- If a transaction requests to lock a resource (data item), which is already held with a conflicting lock by another transaction, then one of the two possibilities may occur:
    - **Timestamp**$(T_n) <$ **Timestamp**(T_k)**:** T_n forces T_k to be killed ("wounds")
        - T_k is restarted later with a random delay but with the same timestamp(k)
        - **Timestamp**$(T_n) >$ **Timestamp**(T_k)**:** T_n "wait"s until the resource is free
- This scheme allows the younger transaction requesting a lock to "wait" if the older transaction already holds a lock, but forces the younger one to be suspended ("wound") if the older transaction requests a lock on an item already held by the younger one
- Example:
    - Suppose that transaction T_5, T_{10}, T_{15} have time-stamps 5, 10 and 15 respectively
    - If T_5 requests a data item held by T_{10}, then it will be preempted from T_{10} and T_{10} will be suspended ("wounded")
    - If T_{15} requests a data item held by T_{10}, then T_{15} will "wait"

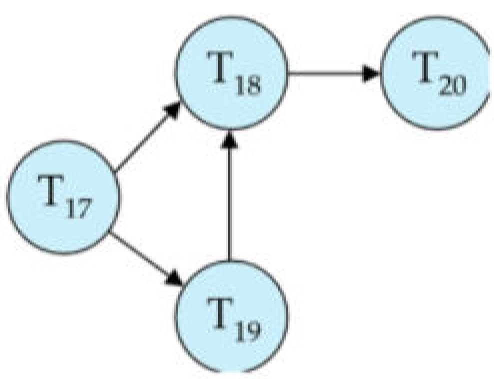
Deadlock prevention

- Both in wait-die and in wound-wait schemes, a rolled back transaction is restarted with its original timestamp
    - Older transactions thus have precedence over newer ones, and starvation is hence avoided
- **Timeout-Based Schemes**
    - A transaction waits for a lock only for a specified amount of time
        - If the lock has not been granted within that time, the transaction is rolled back and restarted
    - Thus, deadlocks are not possible
    - Simple to implement; but starvation is possible
        - Also difficult to determine good value of the timeout interval

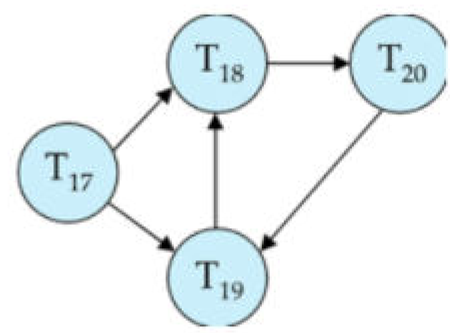
Deadlock Detection

- 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_i 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: Example



Wait-for graph without a cycle



Wait-for graph with a cycle

Deadlock Recovery

- When deadlock is detected:
  - Some transaction will have to rolled back (made a victim) to break deadlock
    - Select that transaction as victim that will incur minimum cost
  - Rollback – determine how far to roll back transaction
    - ***Total rollback:*** Abort the transaction and then restart it
    - More effective to roll back transaction only as far as necessary to break deadlock
  - Starvation happens if same transaction is always chosen as victim
    - Include the number of rollbacks in the cost factor to avoid starvation

Timestamp-based Protocols

- Each transaction is issued a timestamp when it enters the system
  - If an old transaction T_i has time-stamp $TS(T_i)$, a new transaction T_i is assigned time-stamp $TS(T_j)$ such that $TS(T_i) < TS(T_j)$
- The protocol manages concurrent execution such that the time-stamps determine the serializability order
- In order to assure such behavior, the protocol maintains for each data Q two timestamp values:
  - **W-timestamp(Q)** is the largest time-stamp of any transaction that executed write(Q) successfully
  - **R-timestamp(Q)** is the largest time-stamp of any transaction that executed read(Q) successfully
- The timestamp ordering protocol ensures that any conflicting read and write operations are executed in timestamp order
- Suppose a transaction T_i issues a **read**(Q)
  - If $TS(T_i) \leq$ **W**-timestamp(Q), then T_i needs to read a value of Q that was already overwritten
    - Hence, the read operation is rejected, and T_i is rolled back

- If $TS(T_i) \geq$ **W**-timestamp(Q), then the read operation is executed, and **R**-timestamp(Q) is set to **max**(**R**-timestamp(Q), $TS(T_i)$)
- Suppose that transaction T_i issues **write**(Q)
  - If $TS(T_i) <$ **R**-timestamp(Q), then the value of Q that T_i is producing was needed previously, and the system assumed that that value would never be produced
    - Hence, the **write** operation is rejected, and T_i is rolled back
  - If $TS(T_i) <$ **W**-timestamp(Q), then T_i is attempting to write an obsolete value of Q
    - Hence, the **write** operation is rejected, and T_i is rolled back
  - Otherwise, the **write** operation is executed, and **W**-timestamp(Q) is set to $TS(T_i)$

Example use of the Protocol

A partial schedule for several data items for transactions with timestamps 1, 2, 3, 4, 5

T_1	T_2	T_3	T_4	T_5
				read (X)
	read (Y)			
read (Y)				
		write (Y)		
		write (Z)		
				read (Z)
	read (Z)			
	abort			
read (X)				
			read (W)	
		write (W)		
		abort		
				write (Y)
				write (Z)

Correctness of Timestamp-Ordering Protocol

- The timestamp-ordering protocol guarantees serializability since all the arcs in the precedence graph are of the form:

  Thus, there will be no cycles in the precedence graph
- Timestamp protocol ensures freedom from deadlock as no transaction ever waits ~~*(TATAKAE)*~~
- But the schedule may not be cascade-free, may not even be recoverable