



# Transaction Management

## Introduction

Database System Concepts, 7<sup>th</sup> Ed.

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# Outline

- Transaction Concept
- Transaction State
- Concurrent Executions
- Serializability
- Recoverability
- Implementation of Isolation
- Transaction Definition in SQL
- Testing for Serializability.



# Transaction Concept

- A **transaction** is a *unit* of program execution that accesses and possibly updates various data items.
- E.g., transaction to transfer \$50 from account A to account B:
  1. **read(A)**
  2.  $A := A - 50$
  3. **write(A)**
  4. **read(B)**
  5.  $B := B + 50$
  6. **write(B)**
- Two main issues to deal with:
  - Failures of various kinds, such as hardware failures and system crashes
  - Concurrent execution of multiple transactions



# Example of Fund Transfer

- Transaction to transfer \$50 from account A to account B. **t=0, A=B=100**
  1. **read(A)**
  2.  $A := A - 50$
  3. **write(A)**
  4. **read(B)**
  5.  $B := B + 50$
  6. **write(B)**
- **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
- **Durability requirement** — once the user has been notified that the transaction has completed (i.e., the transfer of the \$50 has taken place), the updates to the database by the transaction must persist even if there are software or hardware failures.



# Example of Fund Transfer (Cont.)

- **Consistency requirement** in above example:
  - The **sum of A and B is unchanged** by the execution of the transaction **(A+B=200)**
- In general, consistency requirements include
  - **Explicitly specified integrity constraints** such as primary keys and foreign keys
  - **Implicit integrity constraints**
    - e.g., **sum of balances of all accounts**, minus sum of loan amounts must equal value of cash-in-hand
  - A transaction 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 inconsistency



## Example of Fund Transfer (Cont.)

- **Isolation requirement** — if between steps 3 and 6, 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

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

T2

read(A), read(B), print(A+B)

- Isolation can be ensured trivially by running transactions **serially**
  - That is, one after the other.
- However, executing multiple transactions concurrently has significant benefits, as we will see later.



# ACID Properties

A **transaction** is a unit of program execution that accesses and possibly updates various data items. To preserve the integrity of data the database system must ensure:

- **Atomicity.** Either all operations of the transaction are properly reflected in the database or none are.
- **Consistency.** Execution of a transaction in isolation preserves the consistency of the database.
- **Isolation.** Although multiple transactions may execute concurrently, each transaction must be unaware of other concurrently executing transactions. Intermediate transaction results must be hidden from other concurrently executed transactions.
  - That is, for every pair of transactions  $T_i$  and  $T_j$ , it appears to  $T_i$  that either  $T_j$  finished execution before  $T_i$  started, or  $T_j$  started execution after  $T_i$  finished.
- **Durability.** After a transaction completes successfully, the changes it has made to the database persist, even if there are system failures.

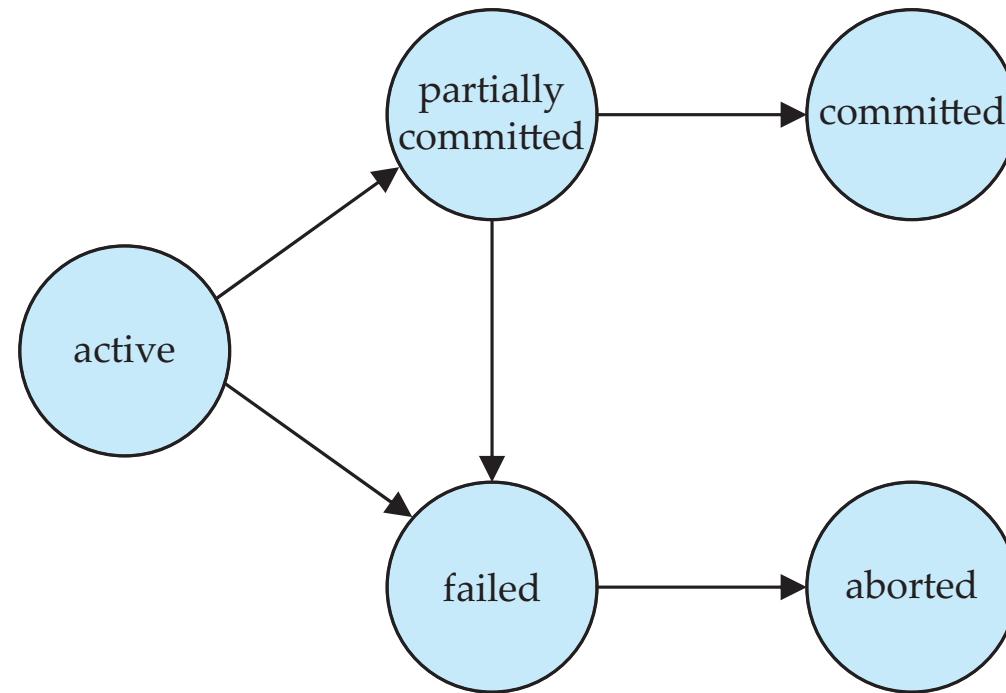


# Transaction State

- **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.



# Transaction State (Cont.)





# Concurrent Executions

- Multiple transactions are allowed to run concurrently in the system.  
Advantages are:
  - **Increased processor and disk utilization**, leading to better transaction *throughput*
    - E.g., 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
  - That is, to control the interaction among the concurrent transactions in order to prevent them from destroying the consistency of the database



# Disk Structure

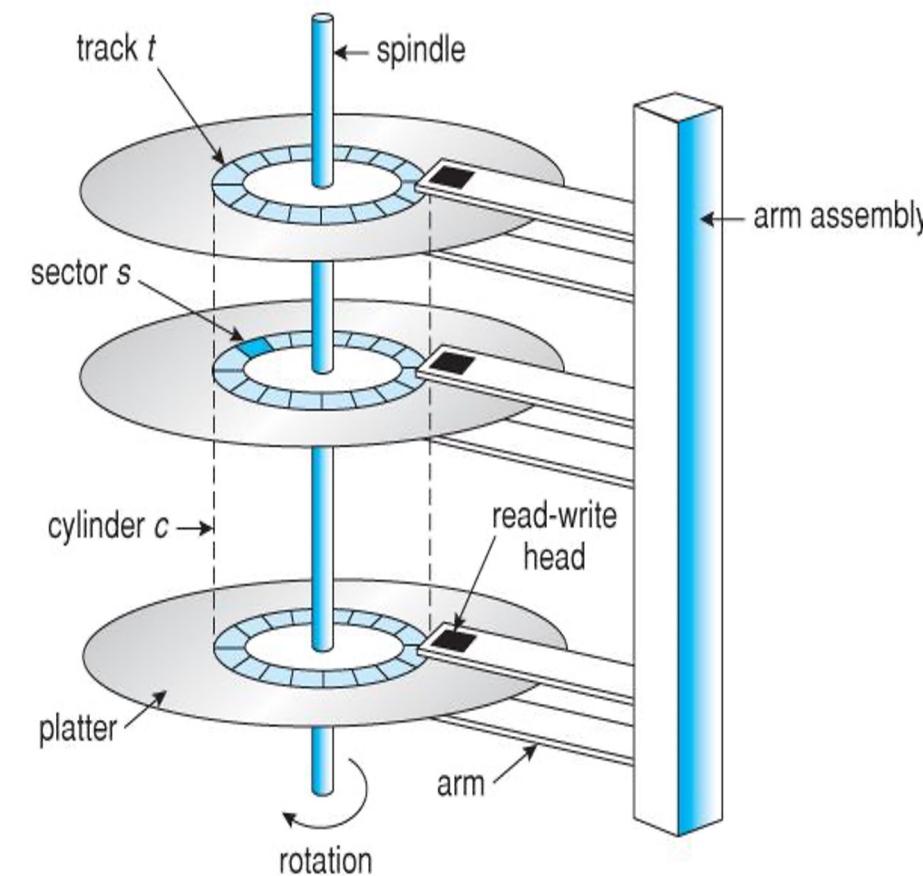


Figure 3. Disk Structure



# Schedules

- **Schedule** – a sequences of instructions that specify the chronological order in which instructions of concurrent transactions are executed
  - A schedule for a set of transactions must consist of all instructions of those transactions
  - Must preserve the order in which the instructions appear in each individual transaction.
- A transaction that successfully completes its execution will have a commit instructions 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  $B$ .
- At t=0, A=B=100, A+B= 200, A=45, B=155**
- 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



## Schedule 2

- A serial schedule where  $T_2$  is followed by  $T_1$
- At t=0, A=B=100, A+B= 200, A=40, B=160

$T_1$	$T_2$
	<pre>read (A) temp := A * 0.1 A := A - temp write (A) read (B) B := B + temp write (B) commit</pre> <pre>read (A) A := A - 50 write (A) read (B) B := B + 50 write (B) commit</pre>



# 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

$T_1$	$T_2$
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

- In Schedules 1, 2 and 3, the sum  $A + B$  is preserved.



## Schedule 4

- The following concurrent schedule does not preserve the value 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



# Serializability

- **Basic Assumption** – Each transaction preserves database consistency.
- Thus, serial execution of a set of transactions preserves database consistency.
- A (possibly concurrent) **schedule** is serializable if it is equivalent to a **serial schedule**. Different forms of schedule equivalence give rise to the notions of:
  1. **Conflict serializability**
  2. **View serializability**



## ***Simplified view of transactions***

- We ignore operations other than **read** and **write** instructions
  - 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.
- 
- $\text{read}(X)$ , which transfers the data item  $X$  from the database to a variable, also called  $X$ , in a buffer in main memory belonging to the transaction that executed the read operation.
  - •  $\text{write}(X)$ , which transfers the value in the variable  $X$  in the main-memory buffer of the transaction that executed the write to the data item  $X$  in the database.



# Conflicting Instructions

- Instructions  $I_i$  and  $I_j$  of transactions  $T_i$  and  $T_j$  respectively, **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 wrote  $Q$ .
  1.  $I_i = \text{read}(Q)$ ,  $I_j = \text{read}(Q)$ .  $I_i$  and  $I_j$  don't conflict.
  2.  $I_i = \text{read}(Q)$ ,  $I_j = \text{write}(Q)$ . They conflict.
  3.  $I_i = \text{write}(Q)$ ,  $I_j = \text{read}(Q)$ . They conflict
  4.  $I_i = \text{write}(Q)$ ,  $I_j = \text{write}(Q)$ . 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



# Conflict Serializability (Cont.)

- Schedule 3 can be transformed into Schedule 6, a serial schedule where  $T_2$  follows  $T_1$ , by series of swaps of non-conflicting instructions. Therefore Schedule 3 is conflict serializable.

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

Schedule 3

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

Schedule 6



# Conflict Serializability (Cont.)

- 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  $\langle T_3, T_4 \rangle$ , or the serial schedule  $\langle T_4, T_3 \rangle$ .



# View Serializability

- Let  $S$  and  $S'$  be two schedules with the same set of transactions.  $S$  and  $S'$  are **view equivalent** if the following three conditions are met, for each data item  $Q$ ,
  1. 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  $Q$ .
  2. If in schedule  $S$  transaction  $T_i$  executes **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  $T_j$ .
  3. 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.



# View Serializability (Cont.)

- 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?
- Every view serializable schedule that is not conflict serializable has **blind writes**.



# Other Notions of Serializability

- The schedule below produces same outcome as the serial schedule  $< T_1, T_5 >$ , yet is not conflict equivalent or view equivalent to it.

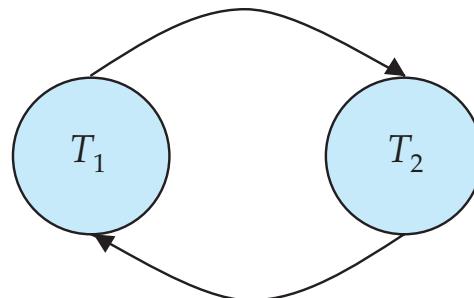
$T_1$	$T_5$
read ( $A$ ) $A := A - 50$ write ( $A$ )	read ( $B$ ) $B := B - 10$ write ( $B$ )
read ( $B$ ) $B := B + 50$ write ( $B$ )	read ( $A$ ) $A := A + 10$ write ( $A$ )

- Determining such equivalence requires analysis of operations other than read and write.



# Testing for Serializability

- Consider some schedule of a set of transactions  $T_1, T_2, \dots, T_n$
- **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 transaction 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 of a precedence graph



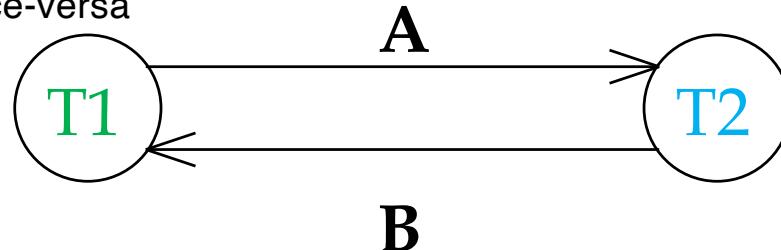


# Example

- A schedule that is not conflict serializable:

T1:	R(A), W(A),	R(B), W(B)
T2:		R(A), W(A), R(B), W(B)

- One node per Xact; edge from  $T_i$  to  $T_j$  if actions of  $T_i$  precedes and conflicts with one of  $T_j$ 's actions
- The cycle in the graph  $G(V, E)$  reveals the problem. The output of  $T_1$  depends on  $T_2$ , and vice-versa

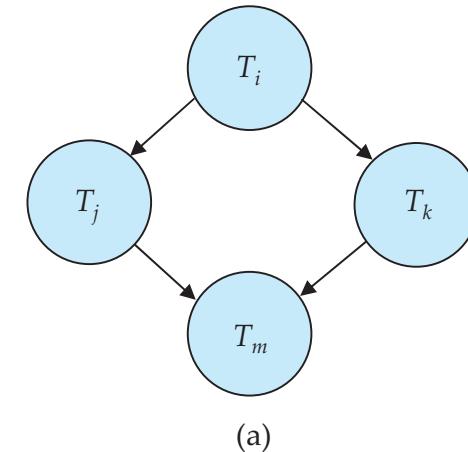


- **Schedule is conflict serializable if and only if its precedence graph is acyclic**

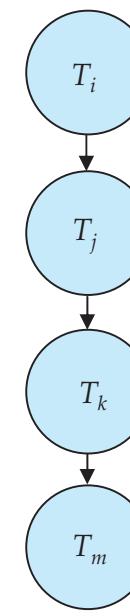


# Test for Conflict Serializability

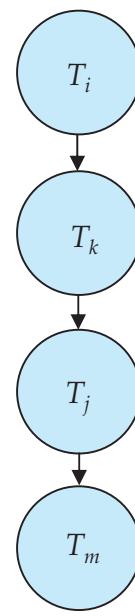
- A schedule is conflict serializable if and only if its precedence graph is acyclic.
- Cycle-detection algorithms exist which take order  $n^2$  time, where  $n$  is the number of vertices in the graph.
  - (Better algorithms take order  $n + e$  where  $e$  is the number of edges.)
- If precedence graph is acyclic, the serializability order can be obtained by a *topological sorting* of the graph.
  - This is a linear order consistent with the partial order of the graph.
  - For example, a serializability order for Schedule A would be  
 $T_5 \rightarrow T_1 \rightarrow T_3 \rightarrow T_2 \rightarrow T_4$ 
    - Are there others?



(a)



(b)



(c)



# Test for View Serializability

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



# Recoverable Schedules

Need to address the effect of transaction failures on concurrently running transactions.

- **Recoverable schedule** — if a transaction  $T_j$  reads a data item previously written by a transaction  $T_i$ , then the commit operation of  $T_i$  appears before the commit operation of  $T_j$ .
- The following schedule (Schedule 11) is not recoverable

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

- If  $T_8$  should abort,  $T_9$  would have read (and possibly shown to the user) an inconsistent database state. Hence, 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 ( $A$ )  abort	read ( $A$ ) write ( $A$ )	read ( $A$ )

- 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** — cascading rollbacks cannot occur:
  - 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



# Concurrency Control

- A database must provide a mechanism that will ensure that all possible schedules are
  - **serializable**, and
  - are 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
  - Are serial schedules recoverable/cascadeless?
- Testing a schedule for serializability *after* it has executed is a little too late!
- **Goal** – to develop concurrency control protocols that will assure serializability.



# Concurrency Control (Cont.)

- Schedules must be conflict or view serializable, and recoverable, for the sake of database consistency, 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.
- Some schemes allow only conflict-serializable schedules to be generated, while others allow view-serializable schedules that are not conflict-serializable.



# Concurrency Control vs. Serializability Tests

- Concurrency-control protocols allow concurrent schedules, but ensure that the schedules are conflict/view serializable, and are recoverable and cascadeless .
- Concurrency control protocols (generally) do not examine the precedence graph as it is being created
  - Instead a protocol imposes a discipline that avoids non-serializable schedules.
  - We study such protocols in Chapter 16.
- Different concurrency control protocols provide different tradeoffs between the amount of concurrency they allow and the amount of overhead that they incur.
- Tests for serializability help us understand why a concurrency control protocol is correct.



# Weak Levels of Consistency

- Some applications are willing to live with weak levels of consistency, allowing schedules that are not serializable
  - E.g., a read-only transaction that wants to get an approximate total balance of all accounts
  - E.g., database statistics computed for query optimization can be approximate (why?)
  - Such transactions need not be serializable with respect to other transactions
- Tradeoff accuracy for performance



# Levels of Consistency in SQL-92

- **Serializable** — default
- **Repeatable read** — only committed records to be read.
  - Repeated reads of same record must return same value.
  - However, a transaction may not be serializable – it may find some records inserted by a transaction but not find others.
- **Read committed** — only committed records can be read.
  - Successive reads of record may return different (but committed) values.
- **Read uncommitted** — even uncommitted records may be read.



# Levels of Consistency

- Lower degrees of consistency useful for gathering approximate information about the database
- Warning: some database systems do not ensure serializable schedules by default
- E.g., Oracle (and PostgreSQL prior to version 9) by default support a level of consistency called snapshot isolation (not part of the SQL standard)



# Transaction Definition in SQL

- 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 all database systems, by default, every SQL statement also commits implicitly if it executes successfully
  - Implicit commit can be turned off by a database directive
    - E.g., in JDBC -- `connection.setAutoCommit(false);`
- Isolation level can be set at database level
- Isolation level can be changed at start of transaction
  - E.g. In SQL **set transaction isolation level serializable**
  - E.g. in JDBC -- `connection.setTransactionIsolation(`  
`Connection.TRANSACTION_SERIALIZABLE)`



# Implementation of Isolation Levels

- Locking
  - Lock on whole database vs lock on items
  - How long to hold lock?
  - Shared vs exclusive locks
- Timestamps
  - Transaction timestamp assigned e.g. when a transaction begins
  - Data items store two timestamps
    - Read timestamp
    - Write timestamp
  - Timestamps are used to detect out of order accesses
- Multiple versions of each data item
  - Allow transactions to read from a “snapshot” of the database



# Transactions as SQL Statements

- E.g., Transaction 1:  
`select ID, name from instructor where salary > 90000`
- E.g., Transaction 2:  
`insert into instructor values ('11111', 'James', 'Marketing', 100000)`
- Suppose
  - T1 starts, finds tuples salary > 90000 using index and locks them
  - And then T2 executes.
  - Do T1 and T2 conflict? Does tuple level locking detect the conflict?
  - Instance of the **phantom phenomenon**
- Also consider T3 below, with Wu's salary = 90000  
`update instructor  
set salary = salary * 1.1  
where name = 'Wu'`
- Key idea: Detect “**predicate**” conflicts, and use some form of “**predicate locking**”



# End of Chapter 17



## Module 17: Transactions

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- Two main issues to deal with:
  - Failures of various kinds, such as hardware failures and system crashes
  - Concurrent execution of multiple transactions



# Example of Fund Transfer

- Transaction to transfer \$50 from account A to account B. **t=0, A=B=100**
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  - 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
- **Durability requirement** — once the user has been notified that the transaction has completed (i.e., the transfer of the \$50 has taken place), the updates to the database by the transaction must persist even if there are software or hardware failures.



## Example of Fund Transfer (Cont.)

- **Consistency requirement** in above example:
  - The sum of A and B is unchanged by the execution of the transaction  
**(A+B=200)**
- In general, consistency requirements include
  - Explicitly specified integrity constraints such as primary keys and foreign keys
  - Implicit integrity constraints
    - e.g., sum of balances of all accounts, minus sum of loan amounts must equal value of cash-in-hand
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## Example of Fund Transfer (Cont.)

- **Isolation requirement** — if between steps 3 and 6, 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

1. **read(A)**
2.  $A := A - 50$
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6. **write(B)**

T2

read(A), read(B), print(A+B)

- Isolation can be ensured trivially by running transactions **serially**
  - That is, one after the other.
- However, executing multiple transactions concurrently has significant benefits, as we will see later.



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A **transaction** is a unit of program execution that accesses and possibly updates various data items. To preserve the integrity of data the database system must ensure:

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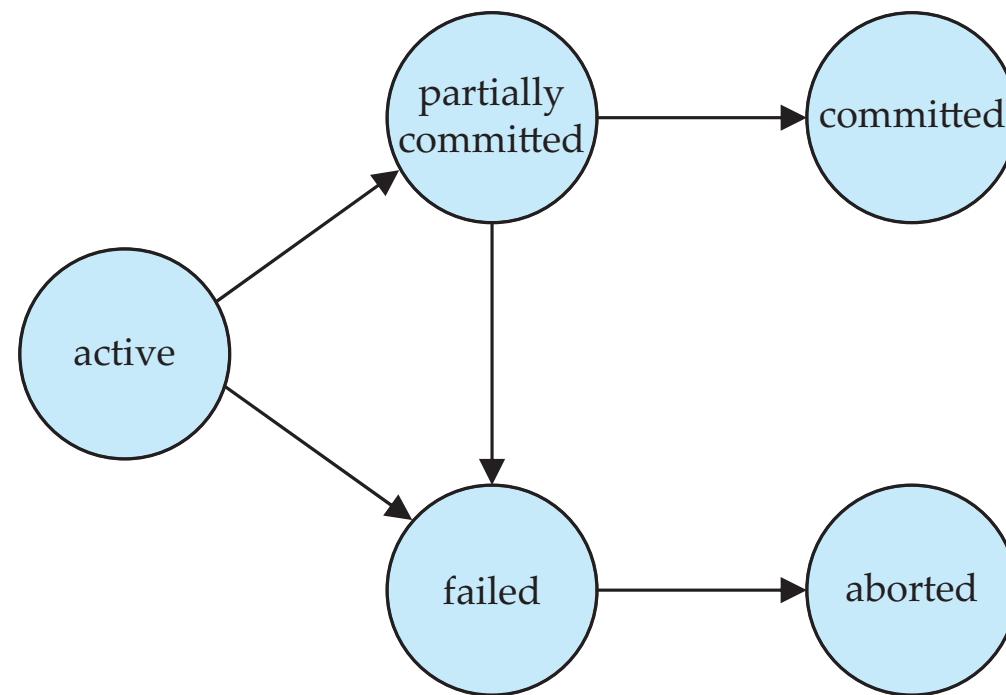


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- **Failed** -- after the discovery that normal execution can no longer proceed.
- **Aborted** – after the transaction has been rolled back and the database restored to its state prior to the start of the transaction. Two options after it has been aborted:
  - Restart the transaction
    - Can be done only if no internal logical error
  - Kill the transaction
- **Committed** – after successful completion.



# Transaction State (Cont.)





# Concurrent Executions

- Multiple transactions are allowed to run concurrently in the system.  
Advantages are:
  - **Increased processor and disk utilization**, leading to better transaction *throughput*
    - E.g., 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
  - That is, to control the interaction among the concurrent transactions in order to prevent them from destroying the consistency of the database



## Disk Structure<sup>[1]</sup>

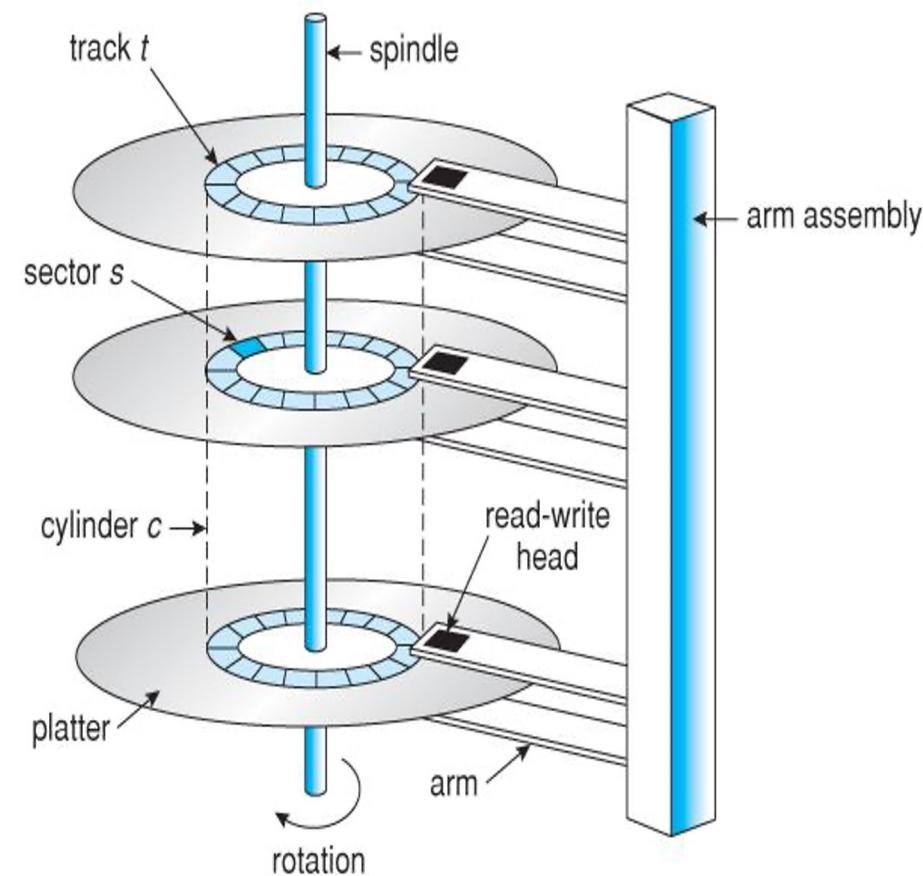


Figure 3. Disk Structure



# Schedules

- **Schedule** – a sequences of instructions that specify the chronological order in which instructions of concurrent transactions are executed
  - A schedule for a set of transactions must consist of all instructions of those transactions
  - Must preserve the order in which the instructions appear in each individual transaction.
- A transaction 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  $B$ .
- At t=0, A=B=100, A+B= 200, A=45, B=155**
- 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



# Schedule 2

- A serial schedule where  $T_2$  is followed by  $T_1$
- At t=0, A=B=100, A+B= 200, A=40, B=160

$T_1$	$T_2$
	<pre>read (A) temp := A * 0.1 A := A - temp write (A) read (B) B := B + temp write (B) commit</pre> <pre>read (A) A := A - 50 write (A) read (B) B := B + 50 write (B) commit</pre>



# 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

$T_1$	$T_2$
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

- In Schedules 1, 2 and 3, the sum  $A + B$  is preserved.



# Schedule 4

- The following concurrent schedule does not preserve the value 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



# Serializability

- **Basic Assumption** – Each transaction preserves database consistency.
- Thus, serial execution of a set of transactions preserves database consistency.
- A (possibly concurrent) schedule is serializable if it is equivalent to a serial schedule. Different forms of schedule equivalence give rise to the notions of:
  1. **Conflict serializability**
  2. **View serializability**



## ***Simplified view of transactions***

- We ignore operations other than **read** and **write** instructions
  - 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.
- 
- **read( $X$ )**, which transfers the data item  $X$  from the database to a variable, also called  $X$ , in a buffer in main memory belonging to the transaction that executed the read operation.
  - • **write( $X$ )**, which transfers the value in the variable  $X$  in the main-memory buffer of the transaction that executed the write to the data item  $X$  in the database.



# Conflicting Instructions

- Instructions  $I_i$  and  $I_j$  of transactions  $T_i$  and  $T_j$  respectively, **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 wrote  $Q$ .
  1.  $I_i = \text{read}(Q)$ ,  $I_j = \text{read}(Q)$ .  $I_i$  and  $I_j$  don't conflict.
  2.  $I_i = \text{read}(Q)$ ,  $I_j = \text{write}(Q)$ . They conflict.
  3.  $I_i = \text{write}(Q)$ ,  $I_j = \text{read}(Q)$ . They conflict
  4.  $I_i = \text{write}(Q)$ ,  $I_j = \text{write}(Q)$ . 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



# Conflict Serializability (Cont.)

- Schedule 3 can be transformed into Schedule 6, a serial schedule where  $T_2$  follows  $T_1$ , by series of swaps of non-conflicting instructions. Therefore Schedule 3 is conflict serializable.

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

Schedule 6



# Conflict Serializability (Cont.)

- 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  $\langle T_3, T_4 \rangle$ , or the serial schedule  $\langle T_4, T_3 \rangle$ .



# View Serializability

- Let  $S$  and  $S'$  be two schedules with the same set of transactions.  $S$  and  $S'$  are **view equivalent** if the following three conditions are met, for each data item  $Q$ ,
  1. 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  $Q$ .
  2. If in schedule  $S$  transaction  $T_i$  executes **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  $T_j$ .
  3. 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.



# View Serializability (Cont.)

- 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?
- Every view serializable schedule that is not conflict serializable has **blind writes**.



# Other Notions of Serializability

- The schedule below produces same outcome as the serial schedule  $< T_1, T_5 >$ , yet is not conflict equivalent or view equivalent to it.

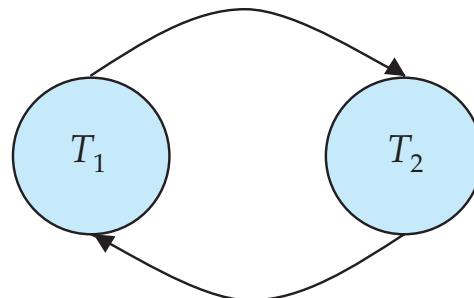
$T_1$	$T_5$
read ( $A$ ) $A := A - 50$ write ( $A$ )	read ( $B$ ) $B := B - 10$ write ( $B$ )
read ( $B$ ) $B := B + 50$ write ( $B$ )	read ( $A$ ) $A := A + 10$ write ( $A$ )

- Determining such equivalence requires analysis of operations other than read and write.



# Testing for Serializability

- Consider some schedule of a set of transactions  $T_1, T_2, \dots, T_n$
- **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 transaction 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 of a precedence graph



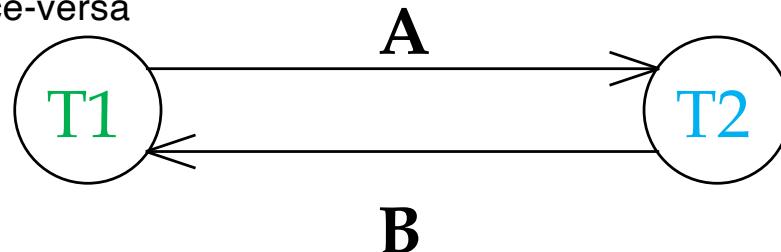


# Example

- A schedule that is not conflict serializable:

T1:	R(A), W(A),	R(B), W(B)
T2:		R(A), W(A), R(B), W(B)

- One node per Xact; edge from  $T_i$  to  $T_j$  if actions of  $T_i$  precedes and conflicts with one of  $T_j$ 's actions
- The cycle in the graph  $G(V, E)$  reveals the problem. The output of  $T_1$  depends on  $T_2$ , and vice-versa

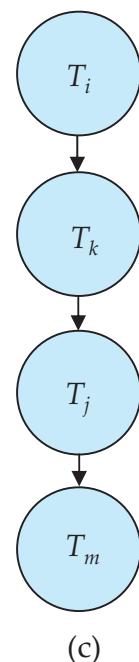
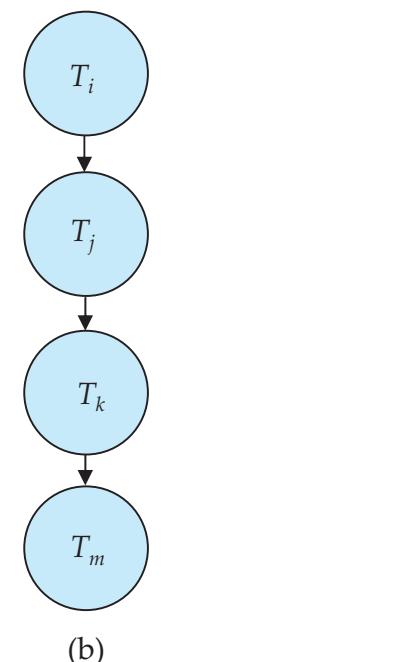
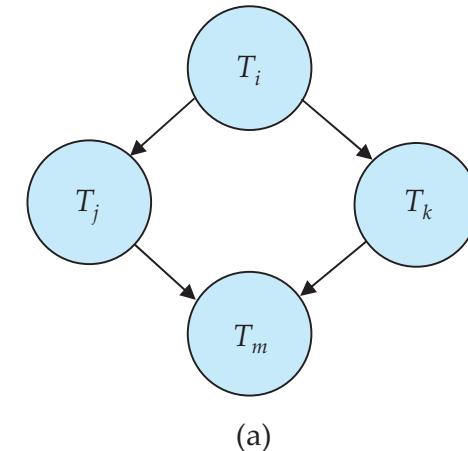


- **Schedule is conflict serializable if and only if its precedence graph is acyclic**



# Test 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.
  - This is a linear order consistent with the partial order of the graph.
  - For example, a serializability order for Schedule A would be  
 $T_5 \rightarrow T_1 \rightarrow T_3 \rightarrow T_2 \rightarrow T_4$ 
    - Are there others?





# Test for View Serializability

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



# Recoverable Schedules

Need to address the effect of transaction failures on concurrently running transactions.

- **Recoverable schedule** — if a transaction  $T_j$  reads a data item previously written by a transaction  $T_i$ , then the commit operation of  $T_i$  appears before the commit operation of  $T_j$ .
- The following schedule (Schedule 11) is not recoverable

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

- If  $T_8$  should abort,  $T_9$  would have read (and possibly shown to the user) an inconsistent database state. Hence, 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 ( $A$ )  abort	read ( $A$ ) write ( $A$ )	read ( $A$ )

- 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** — cascading rollbacks cannot occur:
  - 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



# Concurrency Control

- A database must provide a mechanism that will ensure that all possible schedules are
  - **serializable**, and
  - are 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
  - Are serial schedules recoverable/cascadeless?
- Testing a schedule for serializability *after* it has executed is a little too late!
- **Goal** – to develop concurrency control protocols that will assure serializability.



# Concurrency Control

- 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.



# Concurrency Control Protocols

- Lock-Based Protocols
- Timestamp-Based Protocols
- Validation-Based Protocols
- Multiple Granularity
- Multiversion Schemes
- Insert and Delete Operations
- Concurrency in Index Structures



# Lock Based CC

- Only serializable, recoverable schedules are allowed, no actions of committed transactions are lost while undoing aborted transactions
- Use of locks
- Locking protocol is a set of rules to be followed by each transaction to ensure that net effect of interleaved transactions is identical to some serial execution



# Lock-Based Protocols

- A lock is a mechanism to control concurrent access to a data item
- Data items can be locked in two modes :
  1. **exclusive (X) mode**. Data item can be both read as well as written. X-lock is requested using **lock-X** instruction.
  2. **shared (S) mode**. Data item can only be read. S-lock is requested using **lock-S** instruction.
- Lock requests are made to concurrency-control manager. Transaction can proceed only after request is granted.



# Lock-Based Protocols

## ■ Lock-compatibility matrix

	S	X
S	true	false
X	false	false

- 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.
- 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.
- If a lock cannot be granted, the requesting transaction is made to wait till all incompatible locks held by other transactions have been released. The lock is then granted.



# Lock-Based Protocols

- Example of a transaction performing locking:

```
 $T_2$ : lock-S(A);  
read (A);  
unlock(A);  
lock-S(B);  
read (B);  
unlock(B);  
display(A+B)
```

- Locking as above is not sufficient to guarantee serializability — if  $A$  and  $B$  get updated in-between the read of  $A$  and  $B$ , the displayed sum would be wrong.
- 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.



# Deadlock

- Consider the partial schedule

$T_3$	$T_4$
lock-X( $B$ )	
read( $B$ )	
$B := B - 50$	
write( $B$ )	
	lock-S( $A$ )
	read( $A$ )
	lock-S( $B$ )
lock-X( $A$ )	

- Neither  $T_3$  nor  $T_4$  can make progress — executing **lock-S( $B$ )** causes  $T_4$  to wait for  $T_3$  to release its lock on  $B$ , while executing **lock-X( $A$ )** causes  $T_3$  to wait for  $T_4$  to release its lock on  $A$ .
- Two-phase locking does *not* ensure freedom from deadlock. Observe that transactions  $T_3$  and  $T_4$  are two phase
- Such a situation is called a **deadlock**.
  - To handle a deadlock one of  $T_3$  or  $T_4$  must be rolled back and its locks released.



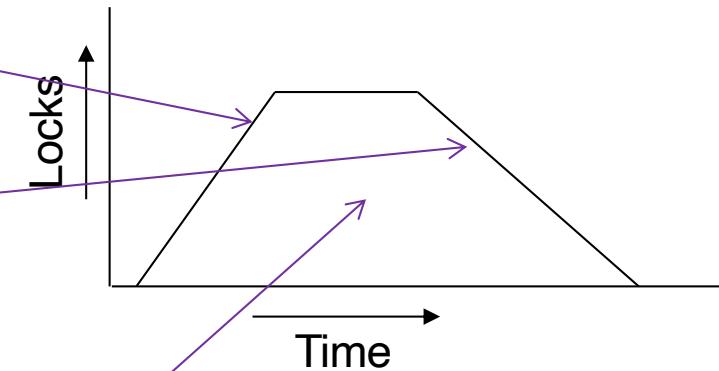
# Deadlock (Cont.)

- The potential for deadlock exists in most locking protocols. Deadlocks are a necessary evil.
- **Starvation** is also possible if 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.



# The Two-Phase Locking Protocol

- A protocol which 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** (i.e., the point where a transaction acquired its final lock).





# The Two-Phase Locking Protocols

- Two-phase locking *does not* ensure freedom from deadlocks.
- Cascading roll-back is possible under two-phase locking. To avoid this, follow a modified protocol called strict two-phase locking. Here a transaction must hold all its exclusive locks till it commits/aborts.
- Rigorous two-phase locking is even stricter: here *all* locks are held till commit/abort. In this protocol transactions can be serialized in the order in which they commit.



# The Two-Phase Locking Protocols (Cont.)

- Two-phase locking *does not* ensure freedom from deadlocks
- Extensions to basic two-phase locking needed to ensure recoverability of freedom from cascading roll-back
  - **Strict two-phase locking:** a transaction must hold all its exclusive locks till it commits/aborts.
    - Ensures recoverability and avoids cascading roll-backs
  - **Rigorous two-phase locking/ Two-phase locking:** a transaction must hold *all* locks till commit/abort.
    - Transactions can be serialized in the order in which they commit.
- Most databases implement rigorous two-phase locking, *but refer to it as simply two-phase locking*



# Locking in Commercial Databases

- When a transaction  $T_i$  issues a  $\text{read}(Q)$  operation, the system issues a lock-S( $Q$ ) instruction followed by the  $\text{read}(Q)$  instruction.
- When  $T_i$  issues a  $\text{write}(Q)$  operation, the system checks to see whether  $T_i$  already holds a shared lock on  $Q$ . If it does, then the system issues an upgrade( $Q$ ) instruction, followed by the  $\text{write}(Q)$  instruction. Otherwise, the system issues a lock-X( $Q$ ) instruction, followed by the  $\text{write}(Q)$  instruction.
- All locks obtained by a transaction are unlocked after that transaction commits or aborts.



# Lock Management

- Lock and unlock requests are handled by the lock manager
- Maintains Lock table entry:
  - Number of transactions currently holding a lock
  - Type of lock held (shared or exclusive)
  - Pointer to queue of lock requests
- Locking and unlocking have to be atomic operations
- Lock upgrade: transaction that holds a shared lock can be upgraded to hold an exclusive lock
- Descriptive entry in transaction table for each transaction
- Entry contains pointer to a list of locks held by the transaction
- This list is checked before requesting a lock to ensure that a transaction does not request the same lock twice



# Concurrency Control vs. Serializability Tests

- Concurrency-control protocols allow concurrent schedules, but ensure that the schedules are conflict/view serializable, and are recoverable and cascadeless .
- Different concurrency control protocols provide different tradeoffs between the amount of concurrency they allow and the amount of overhead that they incur.



# Weak Levels of Consistency

- Some applications are willing to live with weak levels of consistency, allowing schedules that are not serializable
  - E.g., a read-only transaction that wants to get an approximate total balance of all accounts
  - E.g., database statistics computed for query optimization can be approximate
  - Such transactions need not be serializable with respect to other transactions
- Tradeoff accuracy for performance



# Levels of Consistency

- Lower degrees of consistency useful for gathering approximate information about the database
- Warning: some database systems do not ensure serializable schedules by default
- E.g., Oracle (and PostgreSQL prior to version 9) by default support a level of consistency called snapshot isolation (not part of the SQL standard)



## Pitfalls of Lock-Based Protocols

- Starvation is also possible if 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.



# Deadlocks

- Deadlock: Cycle of transactions waiting for locks to be released by each other.
- Two ways of dealing with deadlocks:
  - Deadlock prevention
  - Deadlock detection
- Identification of deadlocks using timeout mechanism: transaction waiting for too long...assuming it is a deadlock ...abort it
- Blocking : blocked transactions may hold other locks that force other transactions to wait
- Aborting and restarting: wastes the work done



# Deadlock prevention

- protocols ensure that the system will *never* enter into a deadlock state. Some prevention strategies:
  - **Require that each transaction locks all its data items before it begins execution** (predeclaration).
  - **Impose partial ordering of all data items and require that a transaction can lock data items only in the order specified by the partial order** (graph-based protocol).



# Deadlock Prevention Strategies

- Following schemes use transaction timestamps for the sake of deadlock prevention alone.
- $TS(T_1) < TS(T_2)$
- wait-die scheme —
  - older transaction may wait for younger one to release data item. 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 —
  - 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* scheme



## Deadlock Prevention

- Assign priorities based on timestamps. Assume  $T_i$  wants a lock that  $T_j$  holds.  
Two policies are possible:
    - Wait-Die: If  $T_i$  has higher priority,  $T_i$  waits for  $T_j$ ; otherwise  $T_i$  aborts
    - Wound-wait: If  $T_i$  has higher priority,  $T_j$  aborts; otherwise  $T_i$  waits
  - Fewer rollbacks in wound-wait
- 
- If a transaction re-starts, make sure it has its original timestamp



## Wait-Die

- Lower the timestamp, higher the priority
- If  $T_i$  has higher priority,  $T_i$  waits for  $T_j$ ; otherwise  $T_i$  aborts
- Lower priority transactions can never wait for higher priority transactions
- To ensure that no transaction is repeatedly aborted, when a transaction is aborted and hence restarted, it will be given the original timestamp it had
- Only a transaction requesting a lock can be aborted
- As the transaction grows older, it tends to wait for more and more younger transactions. The conflicting younger transaction may be repeatedly aborted. But a transaction having all the locks will never be aborted.



## Wound-Wait

- If  $T_i$  has higher priority,  $T_j$  aborts; otherwise  $T_i$  waits
- A transaction that has all the locks it needs may get aborted



# 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, thus starvation is avoided
- **Timeout-Based Schemes:**
  - a transaction waits for a lock only for a specified amount of time. After that, the wait times out and the transaction is rolled back.
  - thus deadlocks are not possible
  - simple to implement; but starvation is possible. Also difficult to determine good value of the timeout interval.



# Deadlock Detection

- Create a **wait-for graph**:
  - Nodes are transactions
  - There is an **edge from  $T_i$  to  $T_j$  if  $T_i$  is waiting for  $T_j$  to release a lock**
- Periodically **check for cycles in the waits-for graph**



# Schedule

T1: S(A), R(A),            S(B)

T2:                            X(B), W(B)                            X(C)

T3:                            S(C), R(C)                            X(A)

T4:                            X(B)

- S1(A), R1(A), X2(B), S1(B), W2(B), S3(C), R3(C), X2(C), X4(B), X3(A)

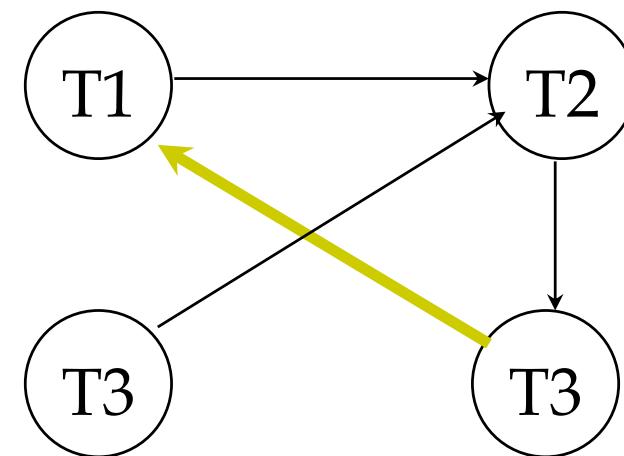
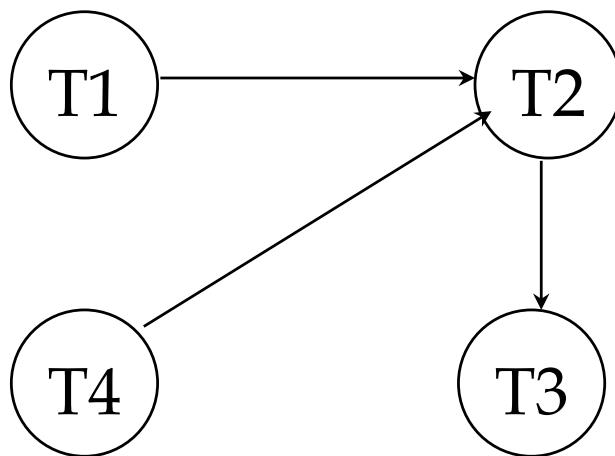


# Deadlock Detection (Continued)

Example:

T1: S(A), R(A),            S(B)  
T2:                        X(B), W(B)  
T3:  
T4:

                            X(C)  
S(C), R(C)                                    X(A)  
    X(B)





## 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  $T_j$  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 Recovery

When deadlock is detected: Selection of victim, rollback, starvation

■ **Selection of victim:** Some transaction will have to be rolled back (made a victim) to break deadlock. **Select that transaction as victim that will incur minimum cost.**

- How long it has computed and how long is still to go?
- Number of data items already used by it
- Number of data items to be used further by it
- Number of transactions involved in rollback



# Deadlock Recovery

- **Rollback** -- determine how far to roll back transaction

**Total rollback:** Abort the transaction and then restart it.

**Partial rollback:** More effective to roll back transaction only as far as necessary to break deadlock.

- Needs to keep additional information like state of all running , sequence of lock request/grants and updates performed by transactions
- Detection mechanism should decide which locks the selected transactions needs to release to break the deadlock
- The selected transaction must be rolled back to the point where it obtained first of these locks, undoing all actions it took after that point

- **Starvation**

- happens if same transaction is always chosen as victim.
- Include the number of rollbacks in the cost factor to avoid starvation



# Multiple Granularity

- Allow data items to be of various sizes and define a hierarchy of data granularities, where the small granularities are nested within larger ones.
- Can be represented graphically as a tree (but don't confuse with tree-locking protocol)
- 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** (level in tree where locking is done):
  - **fine granularity** (lower in tree): high concurrency, high locking overhead
  - **coarse granularity** (higher in tree): low locking overhead, low concurrency



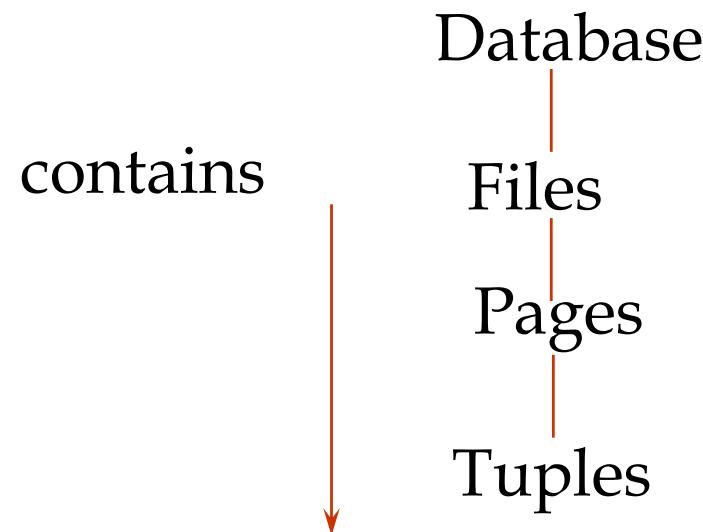
# Granularity

- Data items are of various sizes
- Defining hierarchy of data granularities where small granularities are nested within larger ones
- Tree
- A nonleaf node of multi granularity tree represents data associated with its descendants



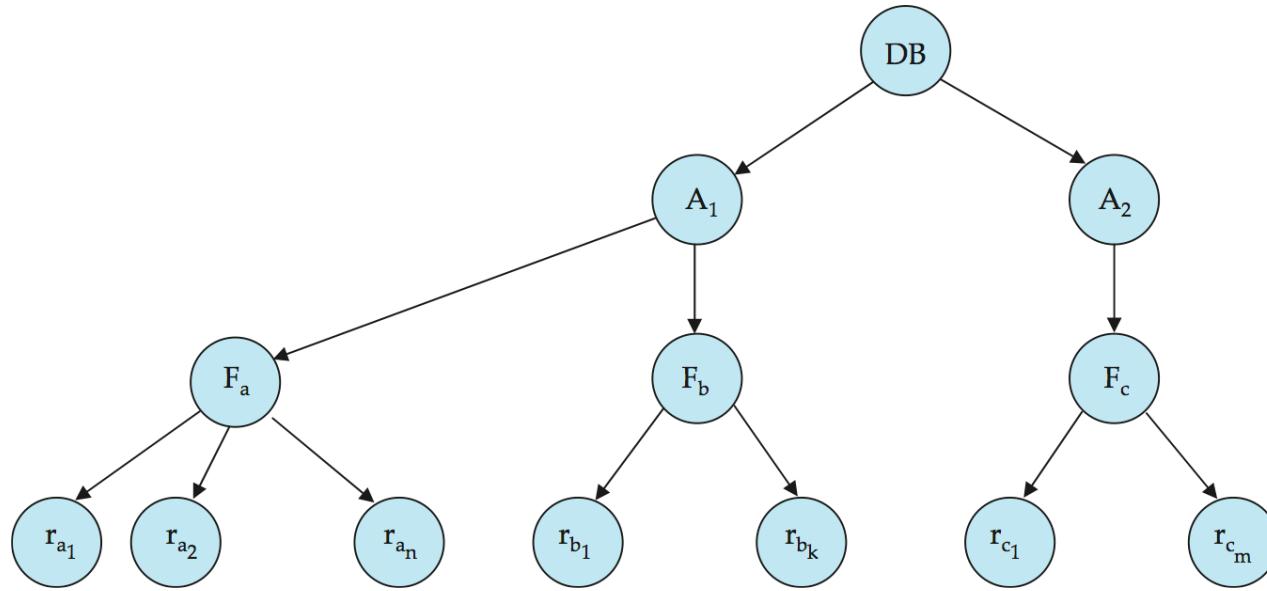
# Multiple-Granularity Locks

- Hard to decide what granularity to lock (tuples vs. pages vs. tables).
- Shouldn't have to decide!
- Data “containers” are nested:





# Example of Granularity Hierarchy



The levels, starting from the coarsest (top) level are:

- *database*
- *file*
- *record*



## Writer Starvation Problem

- If several READ requests are compatible, immediately grant the lock request. Such policy may cause writer starvation problem if there are a large number of read requests. If a reader was granted a read lock, then fellow readers can immediately join in. However, writers will be blocked out, until all readers have finished. In fact, some unlucky writers may get blocked indefinitely.
- A solution is to use FIFO (first in, first out) policy to queue up the requests. Only requests at the front of the queue can try to get the lock. However, concurrency and efficiency may be negatively impacted. Some opportunities for parallel access will be lost as queue processing is serial in nature.



# Optimistic CC

- Locking is a conservative approach in which conflicts are prevented.  
Disadvantages:
  - Lock management overhead
  - Deadlock detection/resolution
  - Lock contention for heavily used objects
- If conflicts are rare, we might be able to gain concurrency by not locking, and instead checking for conflicts before the transaction commits



# Timestamp-Based Protocols

- Each transaction is issued a timestamp when it enters the system. If an old transaction  $T_i$  has time-stamp  $\text{TS}(T_i)$ , a new transaction  $T_j$  is assigned time-stamp  $\text{TS}(T_j)$  such that  $\text{TS}(T_i) < \text{TS}(T_j)$ .
- 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.



## Timestamp-Based Protocols (Cont.)

- 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)**:
  1. If  $TS(T_i) \leq W\text{-timestamp}(Q)$ , 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.
  2. If  $TS(T_i) \geq W\text{-timestamp}(Q)$ , then the **read** operation is executed, and  $R\text{-timestamp}(Q)$  is set to  $\max(R\text{-timestamp}(Q), TS(T_i))$ .



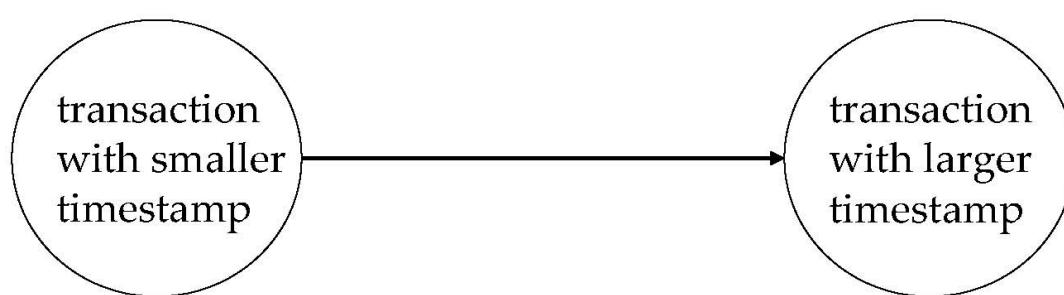
## Timestamp-Based Protocols (Cont.)

- Suppose that transaction  $T_i$  issues **write** ( $Q$ ).
  1. If  $TS(T_i) < R\text{-timestamp } (Q)$ , 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.
  2. If  $TS(T_i) < W\text{-timestamp } (Q)$ , then  $T_i$  is attempting to write an obsolete value of  $Q$ .
    - ▶ Hence, this **write** operation is rejected, and  $T_i$  is rolled back.
  3. Otherwise, the **write** operation is executed, and  $W\text{-timestamp}(Q)$  is set to  $TS(T_i)$ .



## 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.
- But the schedule may **not be cascade-free**, and **may not even be recoverable**.



# Recoverability and Cascade Freedom

- Problem with timestamp-ordering protocol:
  - Suppose  $T_i$  aborts, but  $T_j$  has read a data item written by  $T_i$
  - Then  $T_j$  must abort; if  $T_j$  had been allowed to commit earlier, the schedule is not recoverable.
  - Further, any transaction that has read a data item written by  $T_j$  must abort
  - This can lead to cascading rollback --- that is, a chain of rollbacks
- Solution 1:
  - A transaction is structured such that its writes are all performed at the end of its processing
  - All writes of a transaction form an atomic action; no transaction may execute while a transaction is being written
  - A transaction that aborts is restarted with a new timestamp
- Solution 2: Limited form of locking: wait for data to be committed before reading it
- Solution 3: Use commit dependencies to ensure recoverability



## Thomas' Write Rule

- Modified version of the timestamp-ordering protocol in which obsolete **write** operations may be ignored under certain circumstances.
- When  $T_i$  attempts to write data item  $Q$ , if  $TS(T_i) < W\text{-timestamp}(Q)$ , then  $T_i$  is attempting to write an obsolete value of  $\{Q\}$ .
  - Rather than rolling back  $T_i$  as the timestamp ordering protocol would have done, this **{write}** operation can be ignored.
- Otherwise this protocol is the same as the timestamp ordering protocol.
- Thomas' Write Rule allows greater potential concurrency.



## Multiversion Timestamp Protocol

- Multiversion schemes keep old versions of data item to increase concurrency.
- Each successful **write** results in the creation of a new version of the data item written.
- Use **timestamps** to label versions.
- When a **read(Q)** operation is issued, **select an appropriate version of Q based on the timestamp of the transaction, and return the value of the selected version.**
- **reads** never have to wait as an appropriate version is returned immediately.



## Multiversion Timestamp Ordering

- Each data item  $Q$  has a sequence of versions  $\langle Q_1, Q_2, \dots, Q_m \rangle$ . Each version  $Q_k$  contains three data fields:
  - **Content** -- the value of version  $Q_k$ .
  - **W-timestamp( $Q_k$ )** -- timestamp of the transaction that created (wrote) version  $Q_k$
  - **R-timestamp( $Q_k$ )** -- largest timestamp of a transaction that successfully read version  $Q_k$
- when a transaction  $T_i$  creates a new version  $Q_k$  of  $Q$ ,  $Q_k$ 's W-timestamp and R-timestamp are initialized to  $TS(T_i)$ .
- **R-timestamp of  $Q_k$  is updated whenever a transaction  $T_j$  reads  $Q_k$ , and  $TS(T_j) > R\text{-timestamp}(Q_k)$ .**



## Multiversion Timestamp Ordering (Cont)

- Suppose that transaction  $T_i$  issues a **read(Q)** or **write(Q)** operation. Let  $Q_k$  denote the version of Q whose write timestamp is the largest write timestamp less than or equal to  $TS(T_i)$ .
  1. If transaction  $T_i$  issues a **read(Q)**, then the value returned is the content of version  $Q_k$ .
  2. If transaction  $T_i$  issues a **write(Q)**
    1. if  $TS(T_i) < R\text{-timestamp}(Q_k)$ , then transaction  $T_i$  is rolled back.
    2. if  $TS(T_i) = W\text{-timestamp}(Q_k)$ , the contents of  $Q_k$  are overwritten
    3.  $TS(T_i) > R\text{-timestamp}(Q_k)$ , a new version of Q is created.
- Observe that
  - Reads always succeed.
  - A write by  $T_i$  is rejected if some other transaction  $T_j$  that (in the serialization order defined by the timestamp values) should read  $T_i$ 's write, has already read a version created by a transaction older than  $T_i$ .
- Protocol guarantees serializability.



## MVCC: Implementation Issues

- Reading of data items also requires the updating of R-timestamp field (2 disk accesses)
- Conflicts are resolved through rollbacks rather than through waits (expensive)
- Creation of multiple versions increases storage overhead
  - Extra tuples
  - Extra space in each tuple for storing version information
- Versions can, however, be garbage collected
  - E.g., if Q has two versions  $Q_k$  and  $Q_j$ , and both versions have W-timestamp less than the timestamp of the oldest transaction in the system. Then the older of the 2 versions ( $Q_k, Q_j$ ) will not be used again and can be deleted
  - the oldest active transaction has timestamp  $> 9$ , then  $Q_5$  will never be required again

# CC Protocols

# Locking Policies

- Several locking policies consider efficiency and fairness
- writer starvation problem, deadlock problem

# Writer Starvation Problem

- If several READ requests are compatible, immediately grant the lock request. Such policy may cause writer starvation problem if there are a large number of read requests. If a reader was granted a read lock, then fellow readers can immediately join in. However, writers will be blocked out, until all readers have finished. In fact, some unlucky writers may get blocked indefinitely.
- A solution is to use FIFO (first in, first out) policy to queue up the requests. Only requests at the front of the queue can try to get the lock. However, concurrency and efficiency may be negatively impacted. Some opportunities for parallel access will be lost as queue processing is serial in nature.

# Deadlock Problem

- lock granting priority must be given to the parties who already own some kind of locks
- Time-out followed by rollback of the transaction would cause the release of the locks responsible for the deadlock

# Optimistic CC

- Locking is a conservative approach in which conflicts are prevented.  
Disadvantages:
  - Lock management overhead.
  - Deadlock detection/resolution.
  - Lock contention for heavily used objects.
- If conflicts are rare, we might be able to gain concurrency by not locking, and instead checking for conflicts before Xacts commit.

# Validation-Based Protocol

- Execution of transaction  $T_i$  is done in three phases.

**Read and execution phase** Transaction  $T_i$  writes only to temporary local variables

## Validation phase

Transaction  $T_i$  performs a ``validation test'' When transaction wants to commit, DBMS checks whether transaction would possibly have conflicted with any other concurrently running transactions. If there is a possible conflict, transaction is aborted,

Private workspace is cleared and it is restarted

**Write phase** In case of no conflict, changes to the data item made in private workspace are copied to the database

## Validation-based protocol

- Also called as optimistic concurrency control since transaction executes fully in the hope that all will go well during validation
- In case of few conflicts, validation can be done efficiently and leads to better performance than locking
- If there are many conflicts, cost of repeatedly restarting transactions hurts performance
- No checking is done while transaction is executing
- Updates by the transaction are not directly applied to the database items until transaction reaches end
- intermediate changes are made to the local copies and at validation it is checked for possible conflicts (serializability violation)

# Kung-Robinson Model

- Transactions have three phases:
  - **READ:** Transaction read from the database, but make changes to private copies of objects
  - **VALIDATE:** Check for conflicts
  - **WRITE:** Make local copies of changes public

## Validation-Based Protocol (Cont.)

- Each transaction  $T_i$  has 3 timestamps:
  - $\text{Start}(T_i)$  : the time when  $T_i$  started its execution
  - $\text{Validation}(T_i)$ : the time when  $T_i$  entered its validation phase
  - $\text{Finish}(T_i)$  : the time when  $T_i$  finished its write phase
- **Serializability order is determined by timestamp given at validation time, to increase concurrency.**
  - **Thus  $TS(T_i)$  is given the value of  $\text{Validation}(T_i)$ .**
- This protocol is useful and gives greater degree of concurrency if probability of conflicts is low.
  - because the serializability order is not pre-decided, and
  - relatively few transactions will have to be rolled back.

# Validation

- Test conditions that are sufficient to ensure that no conflict occurred.
- Each transaction is assigned a numeric id.
  - use a **timestamp**.
- transaction ids assigned at the beginning of validation phase
- $\text{ReadSet}(T_i)$ : Set of objects read by transaction  $T_i$ .
- $\text{WriteSet}(T_i)$ : Set of objects modified by  $T_i$ .

## Validation contd...

- Validation criterion checks whether the timestamp ordering of transactions is an equivalent serial order
- To validate  $T_j$ , one of the validation conditions must hold with respect to each committed transaction  $T_i$  such that  $TS(T_i) < TS(T_j)$
- Validation conditions :
  - Each condition ensures that  $T_j$ 's modifications are not visible to  $T_i$
  - To validate  $T_j$  we must check to see that one of the validation conditions holds with respect to each committed transaction  $T_i$  such that  $TS(T_i) < TS(T_j)$
  - At most one transaction is in validation/write phases at any time

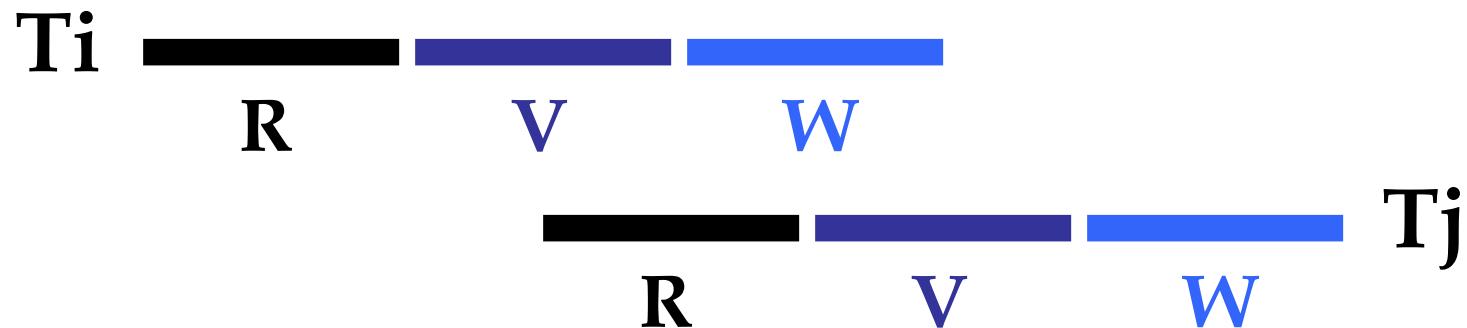
## Test 1

- For all  $i$  and  $j$  such that  $T_i < T_j$ , check that  $T_i$  completes before  $T_j$  begins.



## Test 2

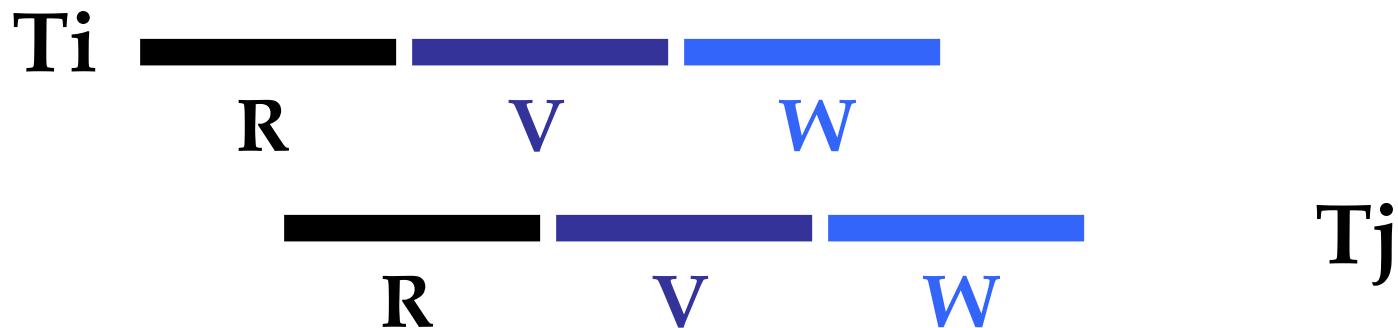
- For all  $i$  and  $j$  such that  $T_i < T_j$ , check that:
  - $T_i$  completes before  $T_j$  begins its Write phase **+**
  - $\text{WriteSet}(T_i)$  **intersection**  $\text{ReadSet}(T_j)$  is empty.



Does  $T_j$  read dirty data? Does  $T_i$  overwrite  $T_j$ 's writes?

## Test 3

- For all  $i$  and  $j$  such that  $T_i < T_j$ , check that:
  - $T_i$  completes Read phase before  $T_j$  does +
  - $\text{WriteSet}(T_i) \cap \text{ReadSet}(T_j)$  is empty +
  - $\text{WriteSet}(T_i) \cap \text{WriteSet}(T_j)$  is empty.



Does  $T_j$  read dirty data? Does  $T_i$  overwrite  $T_j$ 's writes?

# Overheads in Optimistic CC

- Must record read/write activity in ReadSet and WriteSet per transaction.
  - Must create and destroy these sets as needed.
- Must check for conflicts during validation, and must make validated writes ``global''.
  - Critical section can reduce concurrency.
- Optimistic CC restarts transactions that fail validation.
  - Work done so far is wasted; requires clean-up.

# Optimistic 2PL

- If desired, we can do the following:
  - Set S locks as usual.
  - Make changes to private copies of objects.
  - Obtain all X locks at end of transaction, make writes global, then release all locks.
- In contrast to Optimistic CC as in Kung-Robinson, this scheme results in transactions being blocked, waiting for locks.
  - However, no validation phase, no restarts

# Timestamp CC

- In lock based CC , conflicting actions of different transactions are ordered by the order in which locks are obtained, this is extended to actions (using lock protocols) and hence serializability is achieved
- In optimistic CC timestamp ordering checks are done for the stamps for conflicting actions of transactions
- **Timestamp based CC** : Give each object a read-timestamp (RTS) and a write-timestamp (WTS), give each transaction a timestamp (TS) when it begins:
- If action  $a_i$  of transaction  $T_i$  conflicts with action  $a_j$  of transaction  $T_j$ , and  $TS(T_i) < TS(T_j)$ , then  $a_i$  must occur before  $a_j$ . Otherwise, restart violating transaction

# Timestamp-Based Protocols

- Each transaction is issued a timestamp when it enters the system. If an old transaction  $T_i$  has time-stamp  $\text{TS}(T_i)$ , a new transaction  $T_j$  is assigned time-stamp  $\text{TS}(T_j)$  such that  $\text{TS}(T_i) < \text{TS}(T_j)$ .
- 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.

## Contd..

- Every database object is given:
- Read timestamp RTS(O)
- Write timestamp WTS (O)

## When transaction T wants to read Object O

- If  $TS(T) < WTS(O)$ , the order of this read with respect to the most recent write on O would violate the TS order between this transaction and the writer
  - So, abort T and restart it with a new, larger TS. (If restarted with same TS, T will fail again! Contrast use of timestamps in 2PL for ddk prevention)
- If  $TS(T) > WTS(O)$ :
  - Allow T to read O.
  - Reset RTS(O) to  $\max(CTS(O), TS(T))$
- Change to RTS(O) on reads must be written to disk and recorded in the log.
- Log entry and restarts represent overheads.

## Timestamp-Based Protocols (Cont.)

- 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):
  1. If  $TS(T_i) \leq W\text{-timestamp}(Q)$ , 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.
  2. If  $TS(T_i) \geq W\text{-timestamp}(Q)$ , then the **read** operation is executed, and  $R\text{-timestamp}(Q)$  is set to **max**( $R\text{-timestamp}(Q)$ ,  $TS(T_i)$ ).

## Timestamp-Based Protocols (Cont.)

- Suppose that transaction  $T_i$  issues **write** (Q).
  1. If  $TS(T_i) < R\text{-timestamp } (Q)$ , 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.
  2. If  $TS(T_i) < W\text{-timestamp } (Q)$ , then  $T_i$  is attempting to write an obsolete value of Q.
    - Hence, this **write** operation is rejected, and  $T_i$  is rolled back.
  3. Otherwise, the **write** operation is executed, and  $W\text{-timestamp}(Q)$  is set to  $TS(T_i)$ .

## When transaction T wants to Write Object O

- If  $TS(T) < RTS(O)$ , the write action conflicts with the most recent read action of O, and T is aborted and restarted.
- If  $TS(T) < WTS(O)$ , the write of T conflicts with the most recent write of O and is out of timestamp order
- Thomas Write Rule: We can safely ignore such outdated writes; need not restart T! (T's write is effectively followed by another write, with no intervening reads.) Allows some serializable but nonconflict serializable schedules:
- Else, allow T to write O and  $WTS(O)$  is set to  $TS(T)$

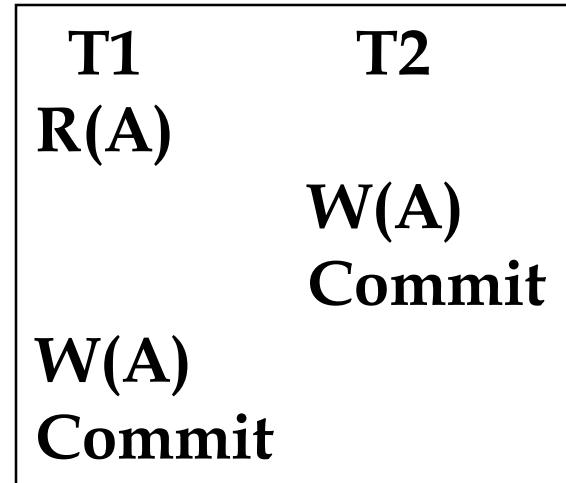
<b>T1</b>	<b>T2</b>
<b>R(A)</b>	
	<b>W(A)</b>
	<b>Commit</b>
<b>W(A)</b>	
	<b>Commit</b>

# Thomas Write Rule

- Ignoring outdated writes
- it states that, if a more recent transaction has already written the value of an object, then a less recent transaction does not need perform its own write since it will eventually be overwritten by the more recent one.
- If  $TS(T) < WTS(O)$ , the current write action has been made obsolete by the most recent write of  $O$ , which follows the current write according to the timestamp ordering
- It is as if  $T$ 's write action had occurred immediately before the most recent write of  $O$  and hence was never read by anyone
- If TRL is not used and  $T$  is aborted (when  $TS(T) < WTS(O)$ ), the protocol like 2PL will allow only conflict serializable schedules
- Use of TRL will allow some schedules which are not conflict serializable

## TRL (2)

- Serializable schedule
- Not conflict serializable
- T2's write follows T1's read and precedes T1's write of the same object (non conflict serializable because writes of T1 and T2 ordering is different)



## TRL (3)

- TRL relies on the observation that T2's write is never seen by any transaction and therefore the write action of T2 can be deleted to make the schedule serializable
- A conflict serializable schedule

T1	T2
R(A)	
	Commit

T1	T2
R(A)	
	Commit

# Timestamp CC and Recoverability

- ❖ Unfortunately, unrecoverable schedules are allowed:

T1	T2
W(A)	R(A) W(B) <b>Commit</b>

- Timestamp CC can be modified to allow only recoverable schedules:
  - Buffer all writes until writer commits (but update WTS(O) when the write is allowed.)
  - Block readers T (where  $TS(T) > WTS(O)$ ) until writer of O commits.
- Similar to writers holding X locks until commit, but still not quite 2PL.

# Recoverability

- If  $TS(T1) = 1$  and  $TS(T2) = 2$  the schedule is permitted by timestamp protocol (TSP) with or without TRL
- The TSP can be modified to disallow such schedules by buffering all write actions until the transaction commits
- When  $T1$  wants to write to  $A$ ,  $WTS(A)$  is updated to reflect this action, but the change to  $A$  is not carried out immediately instead it is recorded in a private workspace (buffer)
- When  $T2$  wants to read  $A$ , its timestamp is compared with  $WTS(A)$ , and the read is seen to be permissible
- $T2$  is blocked till  $T1$  completes
- If  $T1$  commits, the change to  $A$  is copied from the buffer, otherwise the changes in the buffer are discarded
- $T2$  is then allowed to read  $A$

## Multiversion Timestamp Protocol

- Multiversion schemes keep old versions of data item to increase concurrency.
- Each successful **write** results in the creation of a new version of the data item written.
- Use timestamps to label versions.
- When a **read(Q)** operation is issued, select an appropriate version of Q based on the timestamp of the transaction, and return the value of the selected version.
- **reads** never have to wait as an appropriate version is returned immediately.

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- Each data item  $Q$  has a sequence of versions  $\langle Q_1, Q_2, \dots, Q_m \rangle$ . Each version  $Q_k$  contains three data fields:
  - **Content** -- the value of version  $Q_k$ .
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# Multiversion Timestamp Ordering (Cont)

- Suppose that transaction  $T_i$  issues a **read(Q)** or **write(Q)** operation. Let  $Q_k$  denote the version of Q whose write timestamp is the largest write timestamp less than or equal to  $TS(T_i)$ .
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  2. If transaction  $T_i$  issues a **write(Q)**
    1. if  $TS(T_i) < R\text{-timestamp}(Q_k)$ , then transaction  $T_i$  is rolled back.
    2. if  $TS(T_i) = W\text{-timestamp}(Q_k)$ , the contents of  $Q_k$  are overwritten
    3.  $TS(T_i) > R\text{-timestamp}(Q_k)$ , a new version of Q is created.
- Observe that
  - Reads always succeed.
  - A write by  $T_i$  is rejected if some other transaction  $T_j$  that (in the serialization order defined by the timestamp values) should read  $T_i$ 's write, has already read a version created by a transaction older than  $T_i$ .
- Protocol guarantees serializability.

# MVCC: Implementation Issues

- Reading of data items also requires the updating of R-timestamp field (2 disk accesses)
- Conflicts are resolved through rollbacks rather than through waits (expensive)
- Creation of multiple versions increases storage overhead
  - Extra tuples
  - Extra space in each tuple for storing version information
- Versions can, however, be garbage collected
  - E.g., if Q has two versions  $Q_k$  and  $Q_j$ , and both versions have W-timestamp less than the timestamp of the oldest transaction in the system. Then the older of the 2 versions ( $Q_k, Q_j$ ) will not be used again and can be deleted
  - the oldest active transaction has timestamp  $> 9$ , then  $Q_5$  will never be required again

# Multiversion CC

- The goal is to ensure that a transaction never has to wait to read
- Maintain several versions of each database object, each with a write timestamp, and let transaction  $T_i$  read the most recent version whose timestamp precedes  $TS(T_i)$
- If transaction  $T_i$  wants to write to object, ensure that the object has not already been read by some other transaction  $T_j$  such that  $TS(T_i) < TS(T_j)$ , if we allow  $T_i$  to write to such an object, its change should be seen by  $T_j$  for serializability, but  $T_j$  which read the object at some time in the past, will not see  $T_i$ 's change

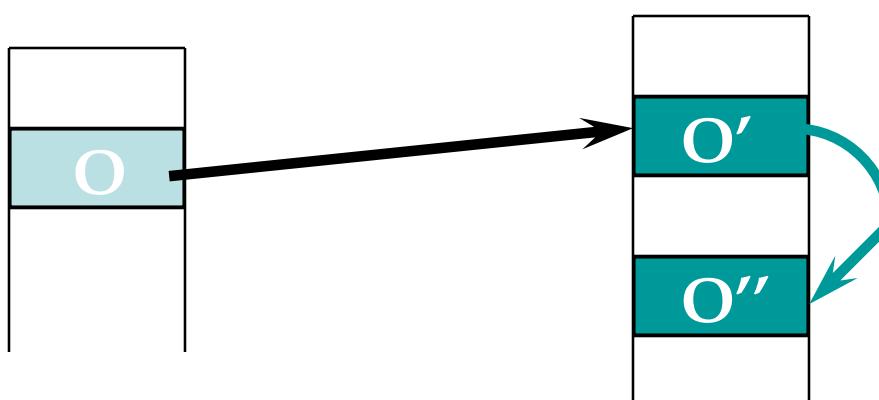
# MVCC

- Every object has a read timestamp
- Whenever a transaction reads the object, the read timestamp is set to the maximum of the current read timestamp and the reader's timestamp
- If  $T_i$  wants to write an object  $O$  and  $TS(T_i) < RTS(O)$ ,  $T_i$  is aborted and restarted with a new larger timestamp
- Otherwise  $T_i$  creates a version of  $O$  and sets the read and write timestamps of the new version to  $TS(T_i)$
- Reads are never blocked but there is overhead of maintaining the versions

# Multiversion Timestamp CC

- **Idea:** Let writers make a “new” copy while readers use an appropriate “old” copy:

**MAIN  
SEGMENT  
(Current  
versions of  
DB objects)**



**VERSION  
POOL  
(Older versions that  
may be useful for  
some active readers.)**

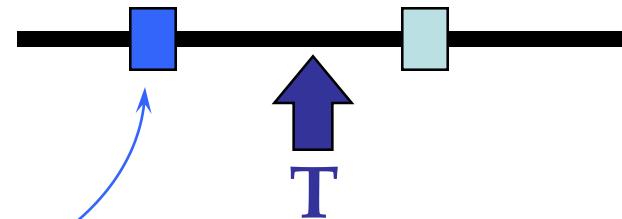
- ❖ Readers are always allowed to proceed.
  - But may be blocked until writer commits.

## Multiversion CC ....

- Each version of an object has its writer's TS as its **WTS**, and the TS of the Xact that most recently read this version as its **RTS**.
- Versions are chained backward; we can discard versions that are “too old to be of interest”.
- Each Xact is classified as **Reader** or **Writer**.
  - Writer *may* write some object; Reader never will.
  - Xact declares whether it is a Reader when it begins.

## WTS timeline $\xrightarrow{\text{old} \quad \text{new}}$

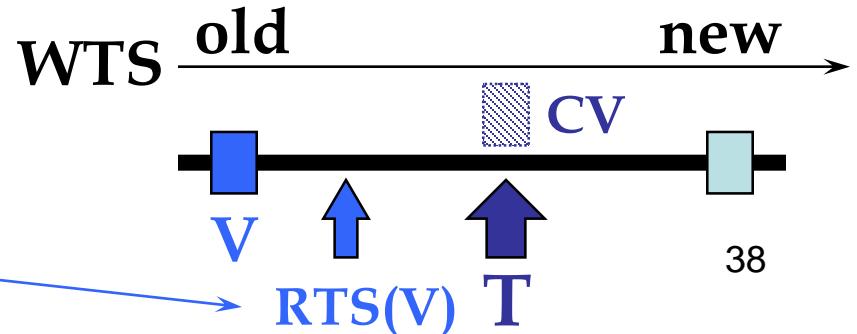
### Reader Xact



- For each object to be read:
  - Finds **newest version** with  $\text{WTS} < \text{TS}(T)$ . (Starts with current version in the main segment and chains backward through earlier versions.)
- Assuming that some version of every object exists from the beginning of time, Reader Xacts are never restarted.
  - However, might block until writer of the appropriate version commits.

# Writer Xact

- To read an object, follows reader protocol.
- To write an object:
  - Finds **newest version V** s.t.  $WTS < TS(T)$ .
  - If  $RTS(V) < TS(T)$ , T makes a copy **CV** of V, with a pointer to V, with  $WTS(CV) = TS(T)$ ,  $RTS(CV) = TS(T)$ . (Write is buffered until T commits; other Xacts can see TS values but can't read version **CV**.)
  - Else, reject write.



# Transaction Support in SQL-92

- Each transaction has an access mode, a diagnostics size, and an isolation level.

Isolation Level	Dirty Read	Unrepeatable Read	Phantom Problem
Read Uncommitted	Maybe	Maybe	Maybe
Read Committed	No	Maybe	Maybe
Repeatable Reads	No	No	Maybe
Serializable	No	No	No

# Summary

- There are several lock-based concurrency control schemes (Strict 2PL, 2PL). Conflicts between transactions can be detected in the dependency graph
- The lock manager keeps track of the locks issued. Deadlocks can either be prevented or detected.
- Naïve locking strategies may have the phantom problem

# Summary (Contd.)

- Index locking is common, and affects performance significantly.
  - Needed when accessing records via index.
  - Needed for **locking logical sets of records** (index locking/predicate locking).
- Tree-structured indexes:
  - Straightforward use of 2PL very inefficient.
  - Bayer-Schkolnick illustrates potential for improvement.
- In practice, better techniques now known; do record-level, rather than page-level locking.

## Summary (Contd.)

- Multiple granularity locking reduces the overhead involved in setting locks for nested collections of objects (e.g., a file of pages); should not be confused with tree index locking!
- Optimistic CC aims to minimize CC overheads in an ``optimistic'' environment where reads are common and writes are rare.
- Optimistic CC has its own overheads however; most real systems use locking.
- SQL-92 provides different isolation levels that control the degree of concurrency

## Summary (Contd.)

- Timestamp CC is another alternative to 2PL; allows some serializable schedules that 2PL does not (although converse is also true).
- Ensuring recoverability with Timestamp CC requires ability to block Xacts, which is similar to locking.
- Multiversion Timestamp CC is a variant which ensures that read-only Xacts are never restarted; they can always read a suitable older version. Additional overhead of version maintenance.