Chapter 14: Transactions

Database System Concepts, 6th Ed.

Chapter 14: Transactions

- Transaction Concept
- A Simple Transaction Model
- Storage Structure
- Transaction Atomicity and Durability
- Transaction Isolation
- Serializability
- Transaction Isolation and Atomicity
- Transaction Isolation Level
- Implementation of Isolation Levels
- Transaction Definition in SQL

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

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

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A Simple Transaction Model [1/3]

- 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
- 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*)

- **ACID Properties**
  - **Atomicity requirement**
  - **Consistency requirement**
  - **Isolation requirement**
  - **Durability requirement**

A Simple Transaction Model [2/3]

- 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*)

- **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 SW or HW)
  - The system should ensure that updates of a partially executed transaction are not reflected in the database

- **Consistency requirement** in above example:
  - A transaction must see a consistent database
    - Explicitly specified integrity constraints such as primary keys and foreign keys
    - Implicit integrity constraints
      - The sum of A and B is unchanged by the execution of the transactions
  - 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

A Simple Transaction Model [3/3]

- **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	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, as we will see later

- **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

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Storage Structure

- **Volatile storage**:
  - does not survive system crashes
  - examples: main memory, cache memory
- **Nonvolatile storage**:
  - survives system crashes
  - examples: disk, tape, flash memory, non-volatile (battery backed up) RAM
  - but may still fail, losing data
- **Stable storage**:
  - a mythical form of storage that survives all failures
  - approximated by maintaining multiple copies on distinct nonvolatile media
  - See book for more details on how to implement stable storage

- For a transaction to be durable, data changes need to be written to stable storage
- For a transaction to be atomic, log records need to be written to stable storage before any changes are made to the database on disk

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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

Maintaining a log is critical!

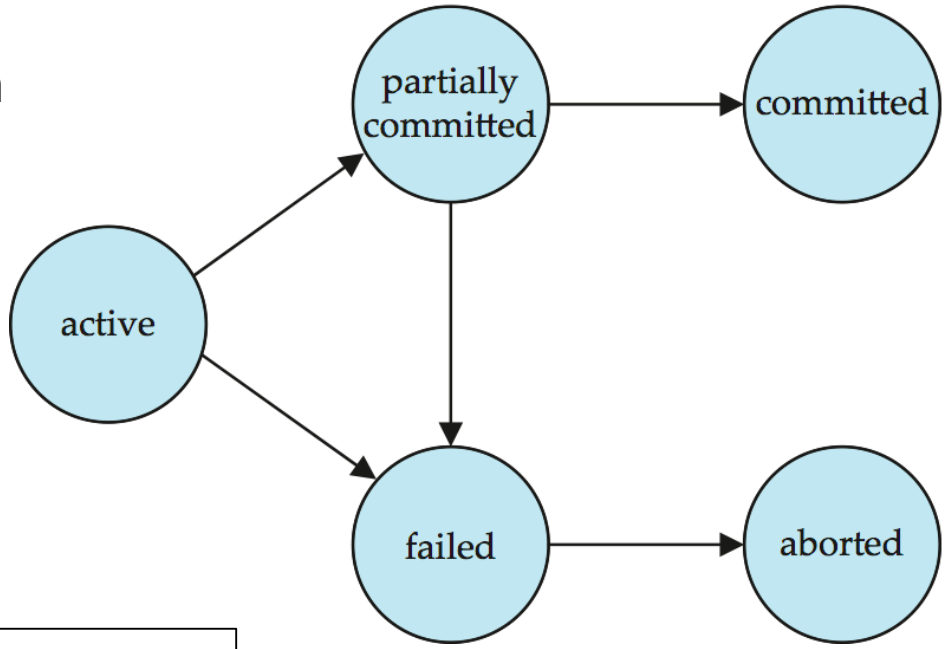

Fig 14.01

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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
    - Will study various CC schemes in Chapter 16, after studying notion of correctness of concurrent executions

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
  - A schedule must preserve the order in which the instructions appear in each individual transaction

- Definition: Serial schedule is instruction sequences from one by one transactions

- 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 and Schedule 2

- Let T_1 transfer \$50 from *A* to *B*, and T_2 transfer 10% of the balance from *A* to *B*.
- Serial schedules: { T_1 ; T_2 } { T_2 ; T_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

Fig 14.02

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	

Fig 14.03

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
- We call it a serializable schedule

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

Fig 13.04

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*)
- The following schedule is not serializable

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

Fig 14.05

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Serializability

- **Basic Assumption** – Each transaction preserves database consistency
- Thus serial execution of a set of transactions preserves database consistency

- Definition: 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**

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 = **read**(Q), I_j = **read**(Q) : I_i and I_j don't conflict
  2. I_i = **read**(Q), I_j = **write**(Q) : They conflict
  3. I_i = **write**(Q), I_j = **read**(Q) : They conflict
  4. 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
  - Intuition
    - 같은 data item을 access하는 instruction 2개는 read-read 경우만 순서를 바꿀수 된다
    - 서로 다른 data item을 access하는 instruction 2개는 순서를 언제든 바꿀수 된다

Conflict Serializability [1/2]

- 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**
- Definition: A schedule S is **conflict serializable** if it is conflict equivalent to a serial schedule
- 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 >

T_3	T_4
read(Q)	
write(Q)	
	write(Q)

T_3	T_4
	write(Q)
read(Q)	
write(Q)	

Conflict Serializability [2/2]

- 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
  - Therefore Schedule 3 is conflict serializable

Schedule3

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

Schedule 5 –
After Swapping a Pair of non conflicting Instructions in schedule 3

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

Schedule 6 –
A Serial Schedule That is Equivalent to Schedule 3

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

View Serializability [1/4]

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- 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,*
  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 [2/4]

G

Schedule A

T_3	T_4
read (Q)	
	write (Q)
write (Q)	

Schedule B

T_3	T_4
read(Q)	
write(Q)	
	write(Q)

Schedule C

T_3	T_4
	write(Q)
read(Q)	
write(Q)	

- 스케줄 A는 Conflict serializable schedule이 아님, View serializable schedule도 아님

View Serializability [3/4]

- 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

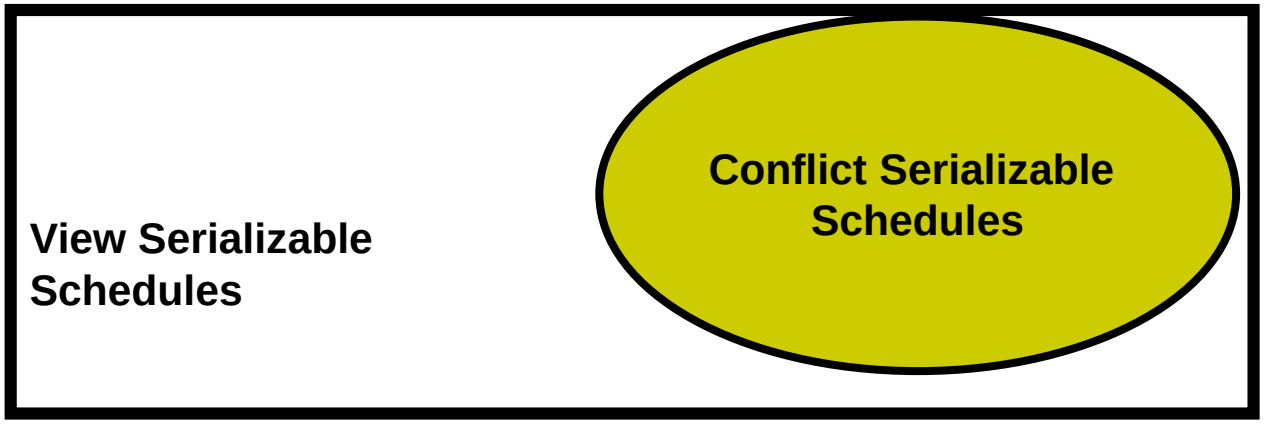
T_{27}	T_{28}	T_{29}
read (Q)		
	write (Q)	
write (Q)		
		write (Q)

- Non-conflicting operations를 swap할 여지가 없다
- T_{27} T_{28} T_{29} 의 어떤 combination도 만들수가 없다
- Conflcit serializable schedule이 될수 없다

- 그러나 왼쪽의 schedule은 <T_{27} T_{28} T_{29}> 와 View-seriablility의 3가지 조건을 만족하므로 View serializable schedule이다

View Serializability [4/4]

- Every view serializable schedule that is not conflict serializable has **blind writes**
- **Intution: 두개 schedule에서 read들이 같은값을 읽었고, final write가 같다면 Database에 반영되는 결과가 serial execution중의 한가지와 같게되는 view serializable schedule이다 ➔ we can have more potential concurrency**



이 예제에서 view equivalent가 result equivalent로 보일수 있다.
많은 경우에 같기도 하지만 꼭 같은것은 아니다
(다음 slide)

Other Notions of Serializability [1/2]

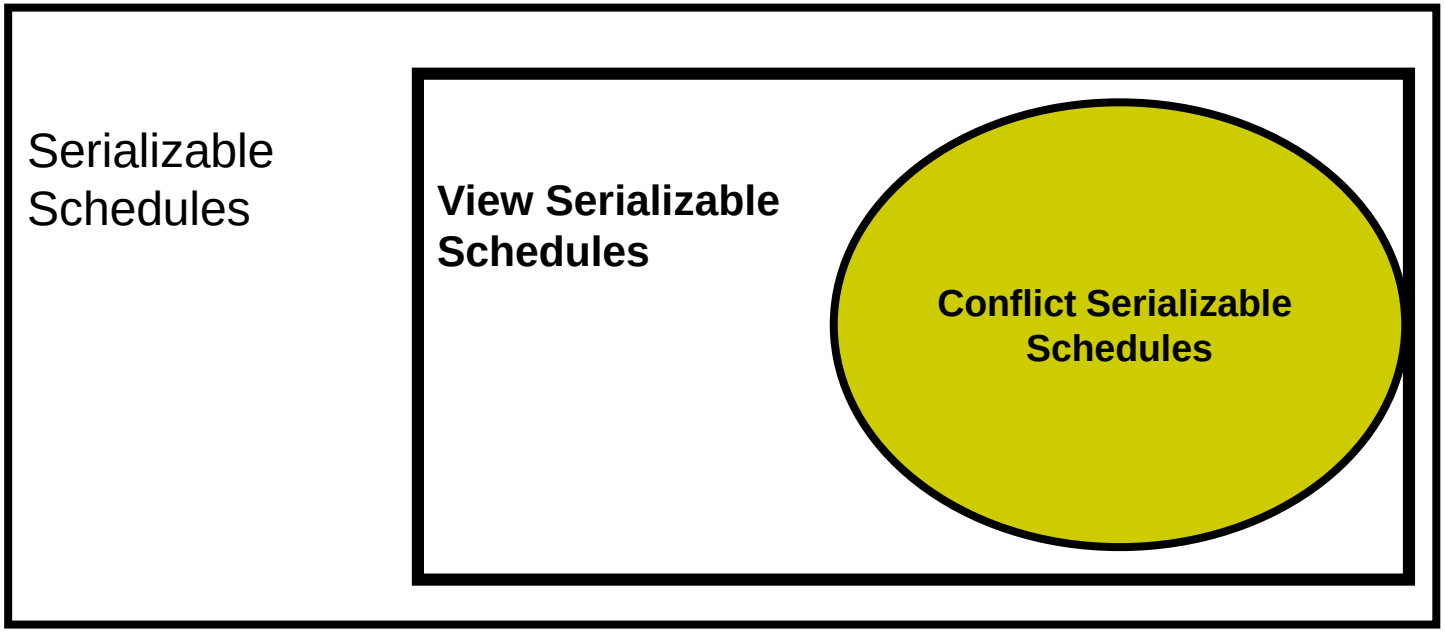
- The schedule below produces same outcome as the serial schedule < T_1, T_5 >, yet is not conflict equivalent or view equivalent to it

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)

- Result Equivalent Schedule
  - 우연에 의한 경우
  - 실제사용은 부적합

Other Notions of Serializability [2/2]

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



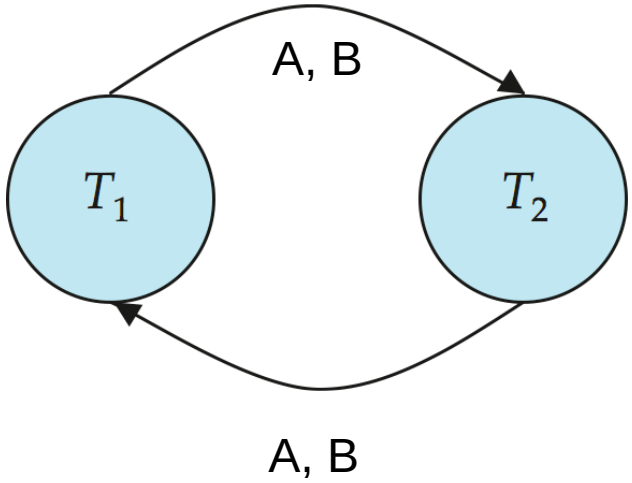
- Still we can pursue potential concurrency!

Testing for Serializability

- 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 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 1**

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)	
	$B := B + temp$
	write(B)

Fig 14.11

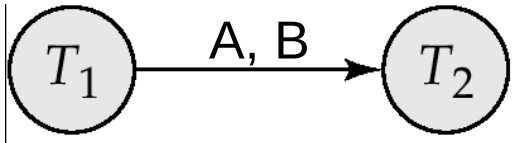


- A schedule is conflict serializable if and only if its precedence graph is acyclic

Precedence Graph

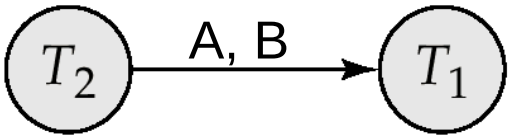
for (a) Serial Schedule 1 and (b) Serial Schedule 2

Fig 14.10



(a)

T_1	T_2
read(A)	
$A := A - 50$	
write (A)	
read(B)	
$B := B + 50$	
write(B)	
	read(A)
	$temp := A * 0.1$
	$A := A - temp$
	write(A)
	read(B)
	$B := B + temp$
	write(B)

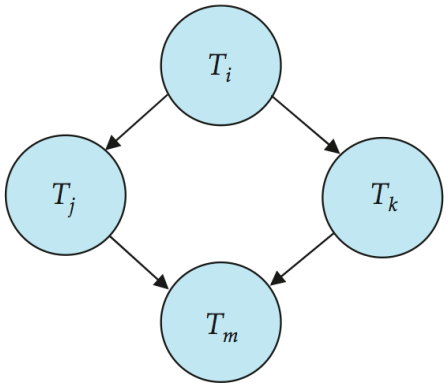


(b)

T_1	T_2
	read(A)
	$temp := A * 0.1$
	$A := A - temp$
	write(A)
	read(B)
	$B := B + temp$
	write(B)
read(A)	
$A := A - 50$	
write(A)	
read(B)	
$B := B + 50$	
write(B)	

Test for Conflict Serializability [1/2]

- 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.)



(a)

Fig 14.12

Serializability를 transaction들이 들어오는 run time에 check하고 concurrent execution 을 허락하는 방법은 현실적이지 못하다!

Serializability를 보장하는 concurrency control scheme들을 이용하는것이 정답!

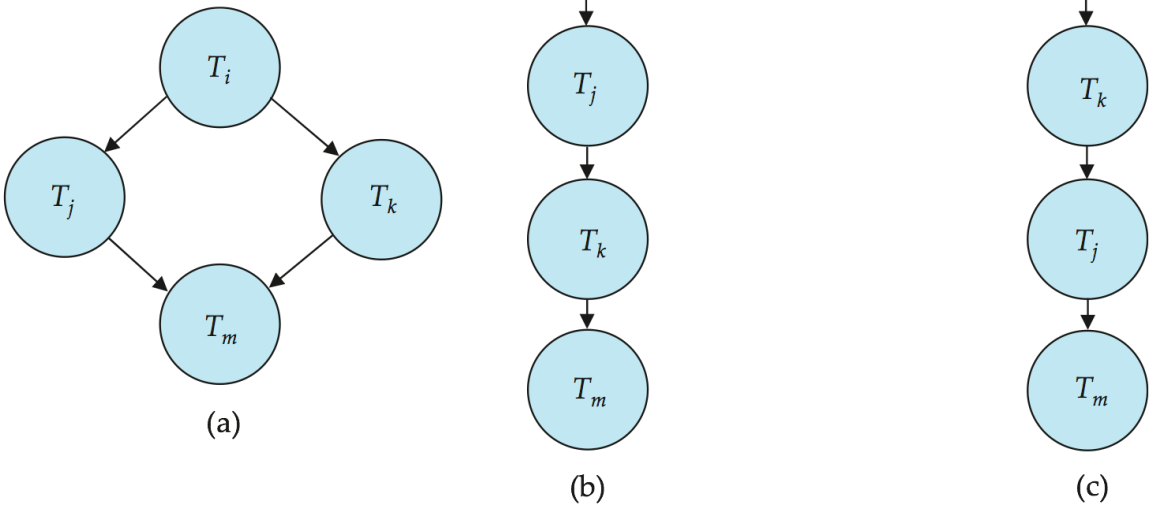
(참고) Cycle detection in DAG
- Depth-First Search 기반 알고리즘: O(n^2)
- Kahn's 알고리즘 : O(n+e)
- Shortest path 방식: O(n+e) (단, 노드에 weight 필요)

Test for Conflict Serializability [2/2]

- 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?

만약 여러 개의 Topological Sorting Order 가 존재한다면 그만큼의 serial 스케줄과 동등하다는 것을 나타냄

Fig 14.12



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

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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 if T_9 commits immediately after the read

Fig 14.14: Schedule 11

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

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

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

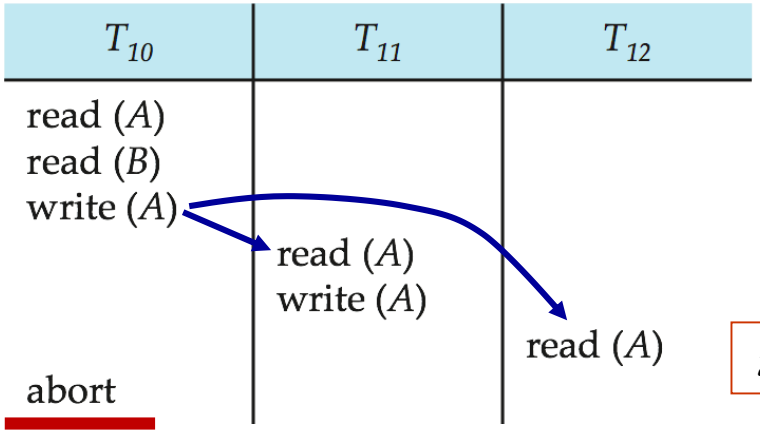

Fig 14.15

불행의 씨앗: T_{10} 이 commit하기전에 unlock을 했기에

- ** Suppose the lock of A is released without executing the commit instruction in $T_{10,}$ If T_{10} fails, T_{10} is supposed to be rolled back, then T_{11} and T_{12} must also be rolled back
- **Cascading rollback** 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
- Idea: hold locks until executing the commit instruction!

T_{10}	T_{11}	T_{12}
read (A)		
read (B)		
write (A)		
	read (A)	
	write (A)	
		read (A)

A가 아닌 다른 아이템에 대해서는 트랜잭션들이 여전히 Interleaved 하게 수행될 수 있음

Commit을 여기에서 하고, A에 대한 lock을 release하면 Cascading rollback은 없다

- Trade Off
  - More concurrency ➔ More cascading rollback // early lock-release
  - Less concurrency ➔ Less cascading rollback // late lock-release

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Weak Levels of DB Consistency

- Serializability is rather strong

- Some applications are willing to live with weak levels of consistency, allowing schedules that are not serializable
  - Read-only transactions need not be serializable with respect to other transactions
    - A read-only transaction that wants to get an approximate total balance of all accounts
    - Database statistics computed for query optimization can be approximate

- Tradeoff accuracy for CC performance
  - Weak consistency ➔ More serializable schedules ➔ High performance
  - Strong consistency ➔ Less serializable schedules ➔ Low performance

Transaction Isolation Level == DB Consistency Level

Transaction Isolation Levels in SQL-92

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- **Serializable: used to be** default (conflict serializable) before 1992
- **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, but successive reads of record may return different (but committed) values
- **Read uncommitted:** even uncommitted records may be read

- Lower degrees of consistency are useful for gathering approximate information about the database
- Warning: some database systems do not ensure serializable schedules by default
  - MSSQL server는 default로 read committed 지원
  - Oracle and PostgreSQL by default support a level of consistency called snapshot isolation (not part of the SQL standard)
  - DBA may change (or reset) the transaction isolation level

Chapter 14: Transactions

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- Storage Structure
- Transaction Atomicity and Durability
- Transaction Isolation
- Serializability
- Transaction Isolation and Atomicity
- Transaction Isolation Level
- Implementation of Isolation Levels
- Transaction Definition in SQL

Implementation of Isolation Levels by Concurrency Control Schemes

- A database must provide a CC scheme ensuring all possible schedules are
  - either conflict or view serializable, and
  - are recoverable and preferably cascadeless
  - We study such protocols in Chapter 16
    - Locking based CC Schemes
    - Timestamps based CC Schemes
    - Multiple Version CC Schemes
    - Snapshot Isolation
- Contradictory Goal of CC Schemes: High Concurrency and High Isolation Level
- Concurrency-control schemes tradeoff between the amount of concurrency they allow and the amount of overhead that they incur
  - A policy in which only one transaction can execute at a time generates serial schedules in a simple way, but provides a poor degree of concurrency
  - 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 generally do not examine the precedence graph as it is being created
  - Testing a schedule for serializability *after* it has executed is a little too late!
  - Instead a protocol imposes a discipline that avoids nonseralizable schedules
  - Tests for serializability help us understand why a concurrency control protocol is correct

- Serializable schedule만을 만들어내는 CC Scheme이 없이 그냥 concurrent하게 transaction들을 수행하고 precedence graph로 serializability를 판단한다면 어떨까?
  - Precedence Graph로 Serializability을 판단하는 것은 run-time에 어떤 트랜잭션들이 들어올지 모두 알고 있어야 하므로 비현실적
  - 만약 동시에 들어오는 트랜잭션들을 실시간으로 precedence 그래프를 그려서 serializabiliy판단한다고 해도 unserializable schedule들은 다 abort시켜야 하므로 비용이나 성능측면에서 비현실적임

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Transaction Definition in SQL

- Data manipulation language (DML) must include a construct for specifying the set of actions that comprise a transaction
- In SQL, a transaction begins implicitly and 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
  - In DBMS Schell, setAutoCommit(false), 개발자가 원하는 시점에 commit() 가능
  - In JDBC, connection.setAutoCommit(false); connection.commit()

```
select name
from instructor
where salary < 90000
```

```
Transaction_begin
S-Lock(name)
Read(name)
……..
Commit-work
```

```
update instructor
   set salary = salary * 1.03
   where salary > 100000;
```

```
Transaction_begin
S-lock (salary)
Read(salary)
Salary = salary * 1.03
W-Lock(salary)
Write(salary)
Abort-work
```

Transaction as SQL Statements [1/2]

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- The current transaction model is based on read(Q) and write(Q) operations, not on SQL statements
- Concurrent execution of SQL statements may cause some strange situation
  - T1: select count(ID) as num, name, sum(salary) as sum
    from instructor where salary > 90000;

    avg_salary = sum/num;
  - T2: insert into instructor values ('11111', 'James', 'Marketing', 100000)
  - T3: update instructor set salary = salary * 0.9 where name = 'Wu'

- Clearly there is a conflict in T1 and T2, but our current transaction model cannot capture the conflict
  - { T1; T2} 혹은 { T2; T1} 처럼 serial schedule의 결과를 가져야 하지만 our simple transaction model이 T2가 T1의 두단계 중간에 실행하는것을 허락하게 된다
  - 그러면 avg_salary의 값은 이상한 값을 return하게 된다
  - 새로 입력이 되는 tuple에 lock을 걸수 있는 방법이 없다!
  - Phantom Phenomenon: A conflict exists on phantom data

Transaction as SQL Statements [2/2]

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- T1과 T3도 interleaving하면 안되는데, simple CC scheme들은 interleaving 을 허락하여 strange 결과를 발생시킨다

- 결론: our simple transaction model은 read(Q), write(Q) 수준에서 serializability를 준수하는것을 기본으로 하지만, 실제 SQL 수준의 transaction에서는 고려해야 추가적인 issue들이 있고, serializability보다 weak한 기준으로 concurrency control을 해야 상황도 있다 (Ch15에 소개)

Semantic Gap between the read-write level transaction and the SQL level transaction!

- Phantom Phenomenon을 극복하는 방법 Index Locking Protocol: relation에 update 를 할때에 해당 record 들에 관련된 index bucket 에 locking
  - Predicate Locking Protocol: query의 predicate (where clause)와 conflict 이 나는 update 들에 locking
- Serializability보다 약한 기준으로 concurrency control 을 하는 방법
  - Snapshot Isolation
- Data record 들간에 concurrency control 을 하면서 Index 구조에도 동시에 concurrency control 를 해야 하는 상황을 위한 방법
  - Crabbing locking protocol