Database System Concepts, 7^{th} Edition
Chapter 17: Transactions

Silberschatz, Korth and Sudarshan

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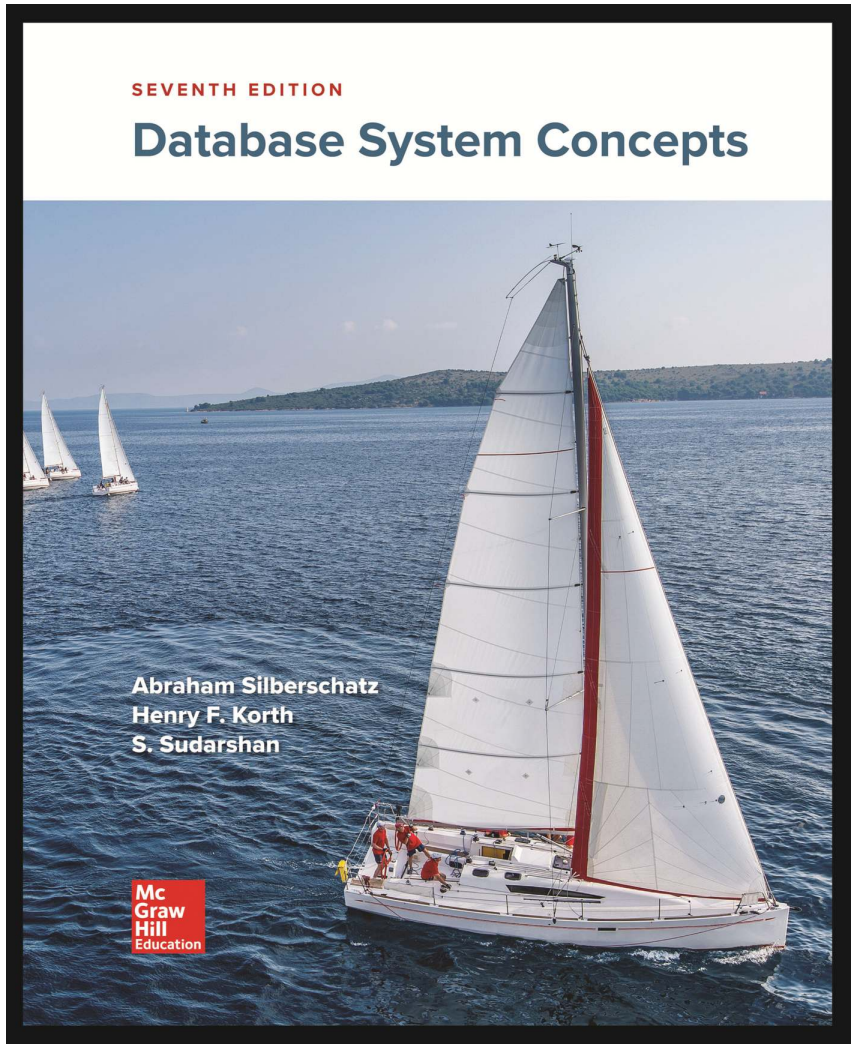
Database System Concepts



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Plan

Transaction Concept

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

- Example of a simple 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:

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

Atomicity Requirement

- Transactions must be atomic - either all operations are executed or none are.
- Example:
  1. If a failure occurs after writing A but before writing B, the system must roll back to a consistent state.
  2. Ensures no partial transactions are committed.

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

- The database must remain in a consistent state before and after a transaction.
- The sum of A and B is unchanged by the execution of the transaction.
- Example:
  - If a transaction debits one account and credits another, the total balance must remain the same.
- In general, consistency requirements include
  - Explicitly specified integrity constraints such as primary keys and foreign keys
  - Implicit integrity constraints.
  - 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	**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.
- Each transaction should appear as if it executes in isolation.
- Intermediate states must not be visible to other transactions.

ACID Properties

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.

Plan

Transaction States

Transactions progress through several states:

- **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. Rolled back, possibly restarted.
- **Committed** - after successful completion.

Transaction States (Cont.)

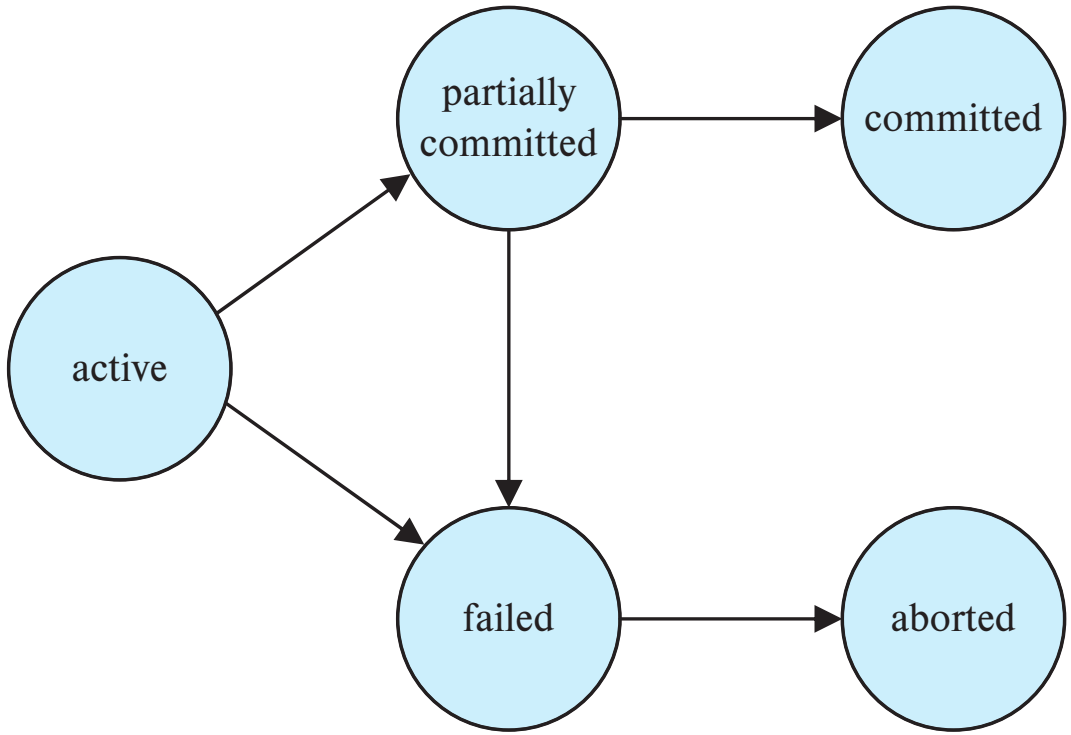

Figure 17.1 State diagram of a transaction.

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.

Concurrent Executions (Cont.)

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.
- They are studied in Chapter 15, after studying notion of correctness of concurrent executions.

Plan

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.

Schedules 1

Let T_1 transfer \$50 from A to B, and T_2 transfer 10% of the balance from A to B. 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

Figure 17.2 Schedule 1—a serial schedule in which T_1 is followed by T_2.

Schedules 2

A serial schedule where T_2 is followed by T_1:

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

Figure 17.3 Schedule 2—a serial schedule in which T_2 is followed by T_1.

Schedules 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

Figure 17.4 Schedule 3—a concurrent schedule equivalent to schedule 1.

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

Schedules 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

Figure 17.5 Schedule 4—a concurrent schedule resulting in an inconsistent state.

Plan

Serializability

- If it is equivalent to a serial execution and ensures the database remains consistent.
- 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.

Conflicting Instructions

- Instructions l_i and l_j of transactions T_i and T_j respectively, conflict if and only if there exists some item Q accessed by both l_i and l_j, and at least one of these instructions wrote Q.
  1. $l_i =$ `read(Q)`, $l_j =$ `read(Q)`. l_i and l_j don't conflict.
  2. $l_i =$ `write(Q)`, $l_j =$ `read(Q)`. They conflict.
  3. $l_i =$ `read(Q)`, $l_j =$ `write(Q)`. They conflict.
  4. $l_i =$ `write(Q)`, $l_j =$ `write(Q)`. They conflict.
- Intuitively, a conflict between l_i and l_j forces a (logical) temporal order between them.
  - If l_i and l_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

- Based on detecting conflicts in transaction operations.
- Conflicts arise when two transactions access the same data item and at least one is a write operation.

Conflict Serializability (Cont.)

- 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 (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 $< T_3, T_4 >$, or the serial schedule $< T_4, T_3 >$.

View Serializability

- Considers the final outcome of transactions, not just conflicts.
- More general but harder to test than conflict serializability.

View Serializability (Cont.)

- 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,

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  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.

View Serializability (Cont.)

- 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.

View Serializability (Cont.)

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  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'.

View Serializability (Cont.)

- 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,
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  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.

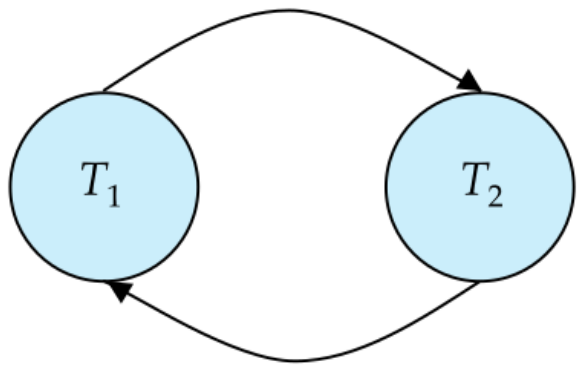
Plan

Testing for Serializability

- Consider some schedule of a set of transactions $T_1, T_2, \ldots, T_n$
- **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.

Precedence Graphs

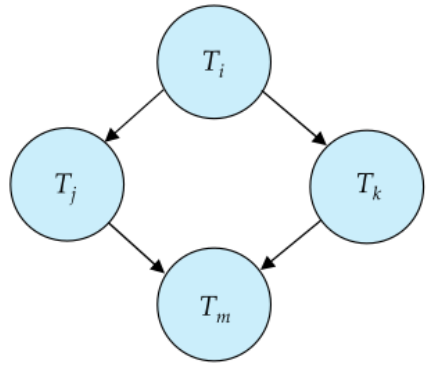
- Used to test for conflict serializability.
- Graph cycles indicate non-serializable schedules.
- Example 1



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.
- If precedence graph is acyclic, the serializability order can be obtained by a *topological sorting* of the graph.

Test for Conflict Serializability (Cont.)



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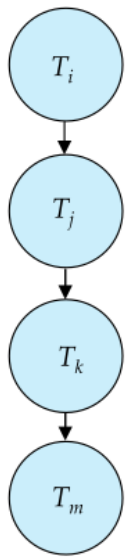

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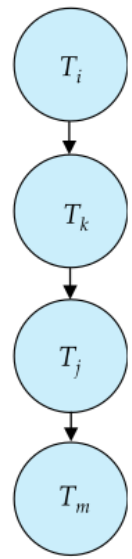


(c)

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 (A)
	commit
read (B)	

- If T_8 should abort, T_9 would have read (and possibly shown to the user) an inconsistent database state. Hence, database must ensure that schedules are recoverable.

Cascading Rollbacks

- **Cascading rollback** – a single transaction failure leads to a series of transaction rollbacks. Consider the following schedule where none of the transactions has yet committed (so the schedule is recoverable)

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

  If T_{10} fails, T_{11} and T_{12} must also be rolled back.

- Can lead to the undoing of a significant amount of work.

Cascadeless Schedules

- **Cascadeless schedules** — 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.

Plan

Concurrency Control

- A database must provide a mechanism that will ensure that all possible schedules are:
  - either conflict or view 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 in SQL-92

Isolation Level	**Dirty Reads**	**Non-Repeatable Reads**	**Phantom Reads**
Serializable	No	No	No
Repeatable Read	No	No	Yes
Read Committed	No	Yes	Yes
Read Uncommitted	Yes	Yes	Yes

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).

Plan

Transaction Definition in SQL

- Transactions begin implicitly.
- End with COMMIT or ROLLBACK.
- Example in SQL:

```
BEGIN TRANSACTION;
UPDATE accounts SET balance = balance - 50 WHERE id = 'A';
UPDATE accounts SET balance = balance + 50 WHERE id = 'B';
COMMIT;
```

Transaction Definition in SQL

- 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

Overview

- 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

Transaction 1:

```
SELECT ID, name FROM instructor WHERE salary > 90000;
```

Transaction 2:

```
INSERT INTO instructor VALUES ('11111', 'James', 'Marketing', 100000);
```

Suppose:

- T_1 starts, finds tuples *salary* > 90000 using index and locks them
- And then T_2 executes.
- Do T_1 and T_2 conflict? Does tuple level locking detect the conflict?
- Instance of the *phantom phenomenon*.

Also consider T_3 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*".

Plan

General Conclusion

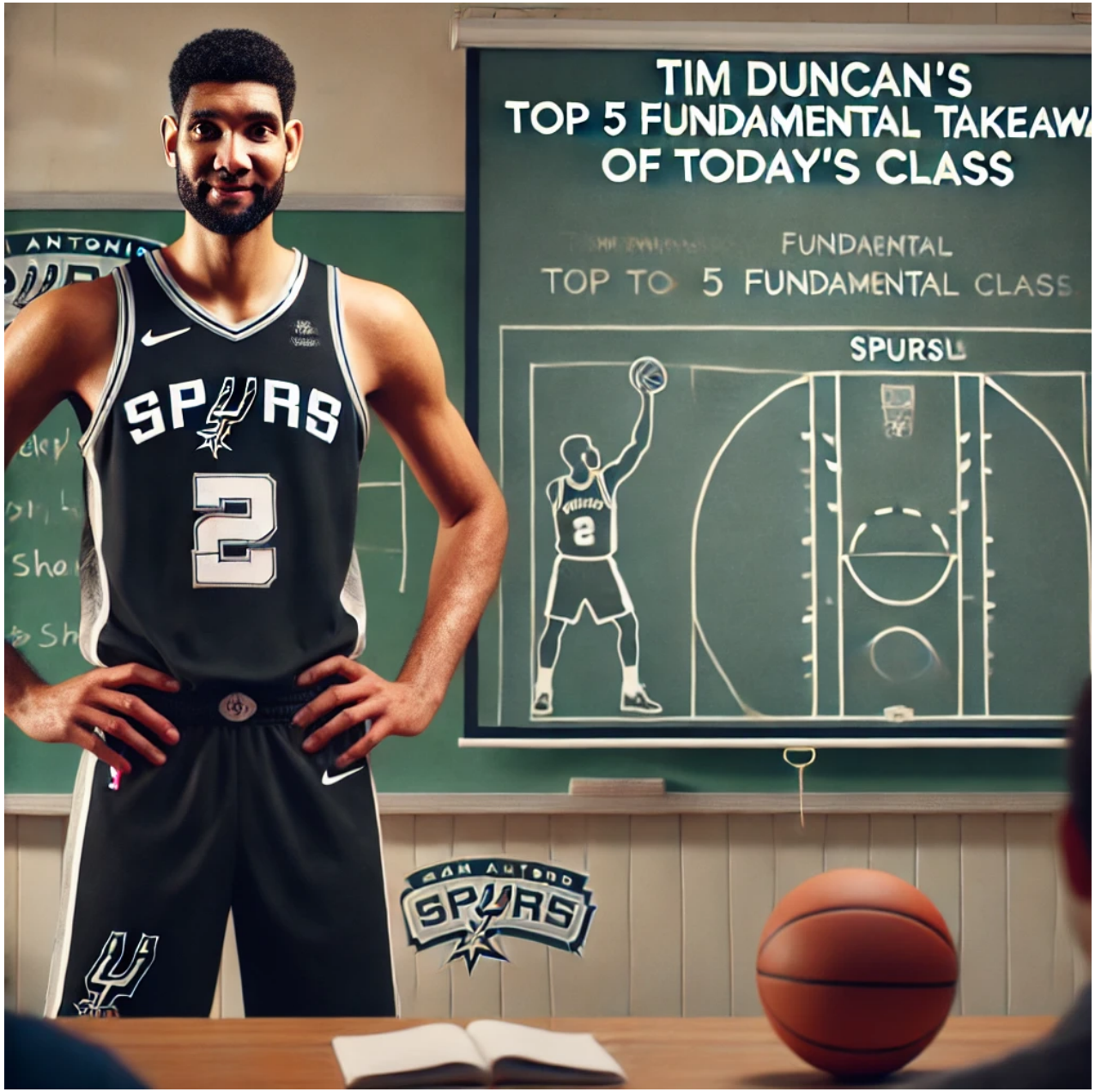
- Transactions are essential for database consistency.
- Proper isolation and concurrency control are critical.
- Advanced techniques like serializability testing ensure reliable performance.

Spacific Conclusion

- **Transactions** are units of execution that access and update data, requiring careful management to prevent data inconsistency.
- **ACID Properties:**
  - **Atomicity:** All or nothing execution.
  - **Consistency:** Leaves the database in a consistent state.
  - **Isolation:** Independent concurrent execution.
  - **Durability:** Committed changes are permanent.
- **Concurrency:** Improves throughput but requires control to prevent conflicts.
- **Scheduling:** Controls transaction order to maintain consistency.
  - **Serializability:** Equivalent to a serial schedule.
  - **Conflict Serializability:** Based on precedence graphs.
  - **View Serializability:** Focuses on the view of data.
- **Concurrency Control:** Prevents conflicts and cascading aborts.
  - Techniques: Locking, timestamp ordering, snapshot isolation.
  - Weaker isolation levels may improve performance but risk inconsistency.

End of Chapter 17.

TDT5FTOTC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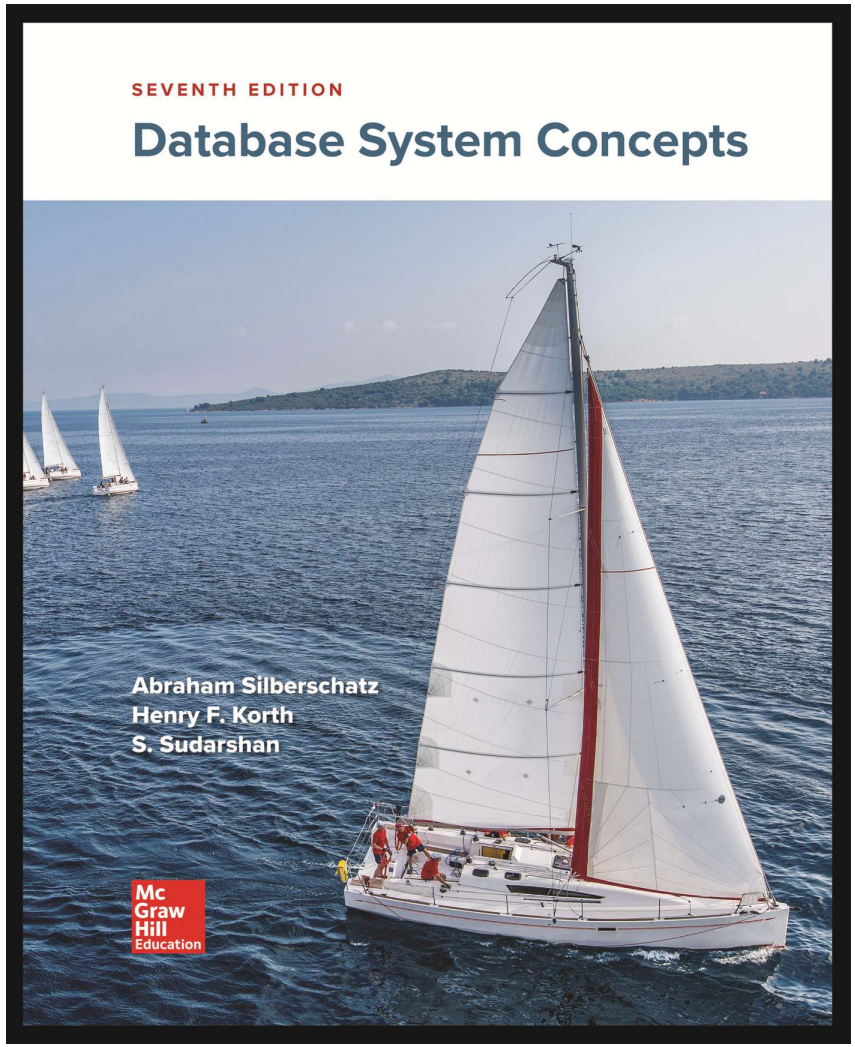
2 Concurrency Control - Effective concurrency control mechanisms, such as locking, timestamp ordering, and snapshot isolation, are essential to prevent conflicts and ensure database consistency during concurrent transaction execution.

1 Consistency Levels - Database systems offer different isolation levels (e.g., serializable, repeatable read, read committed, read uncommitted) that provide varying degrees of consistency and performance trade-offs.

Database System Concepts



Content has been extracted from *Database System Concepts*, Seventh Edition, by Silberschatz, Korth and Sudarshan. Mc Graw Hill Education. 2019.
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