Isolation Levels in Popular Commercial DBMSs

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In this paper, we summarize the classic mechanisms that implement isolation levels widely used in popular commercial DBMSs. In Sec. 1, we first discuss the definition of isolation levels. Then, we summarize the classic mechanisms of eliminating isolation anomalies in Sec. 2. Finally, in Sec. 3, we analyze that what classic mechanism combination does a DBMS use to implementing isolation levels.

Contents

1 Isolation Level Definitions

The concept of isolation level was first introduced in [1] with the name "degrees of consistency". Isolation level serves as a correctness contract between applications and DBMSs. The strongest isolation level is serializable, but it usually exhibits a relative poor performance. A weak isolation level, on the other hand, offers better performance but sacrificing the guarantees of a perfect isolation. For example, snapshot isolation allows some data corruptions to facilitate a high concurrency [2]. Thus, commercial DBMSs support various isolation levels to provide applications with a trade-off between consistency and performance [3].

Various isolation levels are wildly used in DBMSs, including *read committed* (*RC*), *repeatable read* (*RR*), *snapshot isolation* (*SI*), *serializable* (*SR*), and so on. However, how to precisely define isolation levels is still a challenging and critical problem. The early ANSI standard [4] defines different isolation levels as preventing different phenomena. Due to its inaccuracy, the following work [5] takes the most popular implementation, i.e., *two-phase locking*, to define isolation levels. However, this definition is criticized by work [6] because it does not work for DBMSs that do not use lock implementations. To achieve both precision and generality, Adya et. al. [6] define different isolation levels as preventing different types of cycles in the dependency graph. Several recent work [2, 7, 8] attempt to make such a definition more developer-friendly by defining isolation levels from the external view. Generally speaking, there is no unified definition of isolation levels, and each DBMS has its own definition.

2 Isolation Anomalies Elimination Mechanisms

The data accesses performed by concurrently executing transactions have a potential of suffering from isolation anomalies. In this section, we first define the notations used in our paper. Then, we introduce several isolation anomalies. Next, we discuss how to eliminate isolation anomalies with concurrency control protocols. Finally, we summarize the four classic mechanisms implementing concurrency control protocols in popular commercial DBMSs.

2.1 Notations

A database $\mathbb{D}$ has a set of data items, i.e., $x \in \mathbb{D}$. A transaction t consists of several operations typed read or write, ended with either commit or abort as a terminal operation. A write operation creates a new version for a record while a read operation queries a specific database snapshot. A database snapshot is consistent with versions created at the time of the snapshot creation. A commit installs all versions created by a transaction while an abort discards them. For a transaction t, we denote $r_t(rs)$ as a read in t with its read set rs, and denote $w_t(ws)$ as a write in t with its write set ws. Each element in rs (resp. ws) is an accessed version by the read operation (resp. the write operation). We denote x^i as the i^{th} version of record x, and x^{i+1} as its direct successor version. Table. 1 summarizes the notations used in this paper.

Table 1: Notations

Notations	Description
t	a transaction
x and x^i	a data item and the i^{th}(new) version of x
$r_t(rs)/w_t(ws)$	a read/write in t with read/write set rs/ws
c_t, a_t	a commit or abort in t
$ww/wr/rw$	a direct write-/read-/anti-dependency

Isolation levels define the degree to which a transaction must be isolated from the modifications made by any other transaction. An isolation anomaly can be indicated by a specific transaction dependency pattern [6]. In general, there are three kinds transaction dependencies between any two committed transactions (denoted as t_m and t_n): 1) If t_m installs a version x^i and t_n installs x^i's direct successor x^{i+1}, t_n has a **direct write-dependency** (ww) on t_m. 2) If t_m installs a version x^i and t_n reads x^i, t_n has a **direct read-dependency** (wr) on t_m. 3) If t_m reads a version x^i and t_n installs x^i's direct successor version x^{i+1}, t_n has a **direct anti-dependency** (rw) on t_m.

2.2 Isolation Anomalies

We introduce several isolation anomalies that are usually prohibited by the definition of isolation levels.

Dirty Write: Transaction t_0 modifies a data item. Another transaction t_1 then further modifies that data item before t_0 performs a commit or abort. If t_0 or t_1 then performs a abort, it is unclear what the correct data value should be.

Dirty Read: Transaction t_0 modifies a data item. Another transaction t_1 then reads that data item before t_0 performs a commit or abort. If t_1 then performs a abort, t_1 has read a data item that was never committed and so never really existed.

Non-repeatable Read: Transaction t_0 reads a data item. Another transaction t_1 then modifies or deletes that data item and commits. If t_0 then attempts to reread the data item, it receives a modified value or discovers that the data item has been deleted.

Phantom: Transaction t_0 reads a set of data items satisfying some <search condition>. Transaction t_1 then creates data items that satisfy t_0's <search condition> and commits. If t_0 then repeats its read with the same <search condition>, it gets a set of data items different from the first read.

Read Skew: Suppose there are two data items x_0 and x_1. Transaction t_0 reads x_0, and then a second transaction t_1 updates x_0 and x_1 to new versions and commits. If now t_0 reads the x_1's version created by t_1, it sees an inconsistent state of the database.

Lost Update: The lost update anomaly occurs when transaction t_0 reads a data item and then t_1 updates the data item (possibly based on a previous read), then T1 (based on its earlier read value) updates the data item and commits.

Write Skew: Suppose there are two data items x_0 and x_1. Transaction t_0 reads x_0 and x_1, and then a transaction t_1 reads x_0 and x_1, writes x_0, and commits. Then t_0 writes x_1.

If there were a constraint between x_0 and x_1, it might be violated.

Serialization Anomaly: The conflicts between concurrent transactions is not equivalent to the conflicts between serial transactions.

2.3 Concurrency Control Protocols

We describe how the commonly used concurrency control protocols eliminate the above isolation anomalies.

Two-phase Locking(2PL): In a transaction, 2PL rules that locks are acquired and released in two phases, that is, growing phase and shrinking phase. Growing phase rules that locks are acquired and no locks are released, while shrinking phase rules that locks are released and no locks are acquired. Note that, commercial DBMSs usually takes a variant of two-phase locking, called strict two-phase locking. Specifically, strict two-phase locking rules that all locks that a transaction has acquired are held until the transaction terminates.

Multi-version Concurrency Control (MVCC): MVCC requires that the DBMS maintains multiple physical versions of each logical data item as an ordered version chain. Specifically, in a transaction, write operations append a new version into the version chain of a data item, and read operations sees the newest versions that existed when the transaction started.

Serializable Snapshot Isolation (SSI): SSI provides serializability using snapshot isolation, by detecting potential anomalies at runtime, and aborting transactions as necessary.

Optimistic Concurrency Control (OCC): OCC rules that the DBMS executes a transaction in three phases: *read*, *validation*, and *write*. In the *read* phase, the transaction performs read and write operations to data item without blocking. When the transaction finishes execution, it enters the *validation* phase where the DBMS checks whether the transaction conflicts with any other active transaction. If there are no conflicts, the transaction enters the *write* phase where the DBMS propagates the changes in the transaction's write set to the database and makes them visible to other transactions

Timestamp Ordering (TO): TO uses timestamps to determine the serializability order of transactions. Specifically, each transaction t is assigned a unique fixed timestamp that is monotonically increasing, denoted $ts(t)$. Every data item x is tagged with timestamp of the last transaction that successfully did read/write, denoted as $r - ts(x)/w - ts(x)$. If $ts(t) < r - ts(x)$ or $ts(t) < w - ts(x)$, this violates timestamp order of transaction t with regard to the reader or writer of data item x, then abort t.

2.4 Classic Mechanisms

Although there are various concurrency control protocols (*CCP*) as shown in the above section, we discover that almost all CCPs in commercial DBMSs can be implemented by assembling the following four classic mechanisms: *consistent read* (*CR*), *first updater wins* (*FUW*), *serialization certifier* (*SC*) and *mutual exclusion* (*ME*). In Fig. 2, we summarize the relationship among isolation anomalies, concurrency control protocols and the four

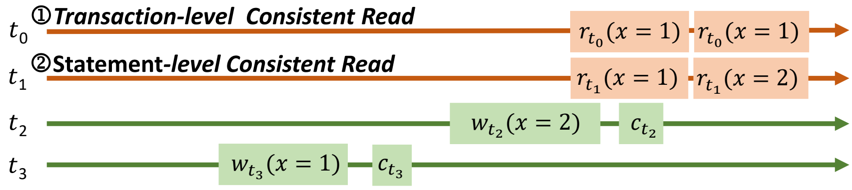

Figure 1: Example for Consistent Read

classic mechanisms. Note that, there still exist some other mechanisms [9, 10, 11, 12, 13, 14], almost all of which stay only in the academic papers instead of in practical products.

Table 2: Four Classic Mechanisms

CCP	Mechanism	Anomaly
MVCC	CR	Read Skew, Dirty Read
2PL	ME	Dirty Write, Dirty Read, Non-repeatable Read, Phantom
OCC	SC	Serialization Anomaly
TO	SC	Serialization Anomaly
SSI	CR+ME+FUW+SC	Read Skew, Dirty Read, Dirty Write, Lost Update, Write Skew

2.4.1 Consistent read

CR provides a consistent view of the database at a specific time point. To provide different isolation levels, there are transaction-level CR and statement-level CR. Transaction-level consistent read provides a consistent view of the database at the beginning of a transaction, while statement-level consistent read at the beginning of an operation. Fig. 1 shows an example of two types of CR. There are four transactions, i.e., t_{0-3}, operating on record x, among which t_{0-1} present two different types of consistent reads. The two reads in t_0 see the same snapshot generated by t_3 for the requirement of transaction-level consistent read; the two reads in t_1 see different values, i.e., $x = 1$ and $x = 2$, constrained by statement-level consistent read.

As described above, *read skew* indicates a kind of anomalies where a transaction sees an inconsistent state of the database. Aiming at eliminating *read skew*, most popular commercial DBMSs take the mechanism of CR to see the committed version of a record as of a specific time point. Specifically, by maintaining multiple physical versions of each logical record, a read operation sees the changes made by other transactions committed before a specific time point and the changes made by earlier operations within the same transaction and the changes. Note that, as described above, *dirty read* indicates a read operation sees a temporary results of a concurrent write operation, which means that there is no *dirty read* when eliminating *read skew*.

2.4.2 Mutual exclusion

ME uses the locking strategy to provide a kind of exclusive access to a shared resource. There are two mode of locking, i.e., shared and exclusive, where the exclusive mode is imcompatible with others and the shared mode is mutually compatible. According to the locking object, there are two granularities of locking, i.e., range-level lock and record lock. We discuss how 2PL takes the mechanism of ME to eliminate *dirty write*, *dirty read*, *non-repeatable read* and *phantom* as follows:

1. As described above, *dirty write* indicates two concurrent operations modify the same record. Aiming at eliminating *dirty write*, most popular commercial DBMSs take ME to exclusively modify a record. Specifically, in a transaction, each write operation should hold a exclusive record-level lock on the modified record until the transaction terminated.

2. As described above, *dirty read* indicates a read operation sees a temporary results of a concurrent write operation. Aiming at eliminating *dirty read*, a part of popular commercial DBMSs take ME to exclusively see a committed result. Specifically, in a transaction, each read operation should hold a shared record-level lock on the access record until the read operation terminated.

3. As described above, *non-repeatable read* indicates there is a concurrent write operation between two read operation in a transaction. Aiming at eliminating *non-repeatable read*, most popular commercial DBMSs take ME to exclusively access a record. Specifically, in a transaction, each read operation should hold a shared record-level lock on the access record until the transaction terminated.

4. As described above, *phantom* indicates there is a write operation inserting a new record that fall into the <search condition> of a concurrent read operation. Aiming at eliminating *phantom*, most popular commercial DBMSs take ME to exclusively access the <search condition> of a read operation. Specifically, in a transaction, each read operation should hold a shared range-level lock on the the <search condition> until the transaction terminated.

2.4.3 First updater wins

FUW prevents transactions which modify the same record from concurrent execution. As described above, *lost update* indicates a transaction does not see the update of another transaction before updating the same record itself. Aiming at eliminating *lost update*, most popular commercial DBMSs take FUW to ensure that all transactions modifying the same record execute in a serial order. Specifically, the target record of an update operation might have already been modified by another concurrent transaction by the time it is found. In this case, the second updater will wait for the first updater to commit or abort (if it is still in progress). If the updater aborts, then its effects are negated and the second updater can proceed with modifying the originally found record. But if the first updater commits, then the second updater will abort.

Table 3: Serialization Certifier

CCP	Certifier
OCC	aborting the transaction conflicting with other active ones
TO	ordering transactions as a monotonically increasing timestamp
SSI	detecting write skew anomalies

2.4.4 Serialization Certifier

SC guarantees transaction execution is conflict serializability [15]. Conflict serializability means that the conflicts between concurrent transactions is equivalent to the conflicts between serial transactions, which eliminates all serialization anomalies. Each concurrency control protocol has its own "certifier" to guarantee conflict serializability. Here, we discuss three concurrency control protocols widely used in commercial DBMSs, and we have summarized them in Table. 3.

Before committing a transaction, OCC takes the mechanism of SC to check whether the transaction conflicting with other active ones. TO takes the mechanism of SC to generate serializable transaction execution by ordering transactions as a monotonically increasing timestamp. SSI is based on snapshot isolation to provide conflict serializability. As the definition of snapshot isolation, all reads within a transaction see a consistent view of the database, concurrent transactions are prohibited from modifying the same record. However, snapshot isolation stills suffers from *write skew*, as discussed in [5]. SSI takes the mechanism of SC to detect *write skew* and abort transactions as necessary.

3 Isolation Level Implementation Mechanisms

A DBMS usually mixes up multiple concurrency control protocols (*CCP*) to eliminate isolation anomalies that should be prevented as the definition of isolation levels. There are various isolation levels widely used in DBMS community, including *read committed* (*RC*), *repeatable read* (*RR*), *snapshot isolation* (*SI*) and *serializable* (*SR*). In this section, we discuss the mechanisms of popular commercial DBMSs implementing isolation levels, including *consistent read* (*CR*), *mutual exclusion* (*ME*), *first updater wins* (*FUW*) and *serialization certifier* (*SC*). We summarize the mechanisms of implementing isolation levels in Table. 4.

3.1 PostgreSQL

In PostgreSQL document [33], *read committed* is defined as:

1. **Eliminating Dirty Read** A read operation sees a snapshot of the database as of the instant the read operation begins to run.
2. **Eliminating Dirty Write** The would-be writer will wait for the previous writing transaction to commit or abort (if it is still in progress). If the previous writer aborts,

Table 4: Isolation Level Implementations in DBMSs

DBMS	CCP	IL	CR	ME	FUW	SC
PostgreSQL [16], yugabyteDB [17], OpenGauss [18]	2PL+MVCC +SSI	SR	✓	✓	✓	✓
		SI	✓	✓	✓	
		RC	✓	✓		
InnoDB [19], Aurora [20], PolarDB [21], SQL server [22]	2PL+MVCC	SR,RR, RC	✓	✓		
TiDB [23]	2PL+MVCC	RR,RC	✓	✓		
	Percolator [24]	SI	✓			✓
RocksDB [25]	2PL+MVCC	SI	✓	✓	✓	
	OCC+MVCC	SI	✓			✓
SQLite [26]	2PL	SR		✓		
FoundationDB [27]	OCC+MVCC	SR	✓			✓
SingleStore [28]	2PL+MVCC	RC	✓	✓		
CockroachDB [29]	TO+MVCC	SR	✓			✓
Spanner [30]	2PL+MVCC	SR	✓	✓		
Oracle [31], NuoDB [32]	2PL+MVCC	SI	✓	✓	✓	
		RC	✓	✓		

then its effects are negated and the would-be writer can proceed with modifying the originally found record. If the previous writer commits, the would-be writer will attempt to apply its operation to the modified version of the record.

Snapshot isolation[1] is defined as:

1. **Eliminating Read Skew** A read operation sees a snapshot as of the start of the first non-transaction-control statement in the transaction.

2. **Eliminating Lost Update&Dirty Write** The would-be writer will wait for the previous writing transaction to commit or abort (if it is still in progress). If the previous writer aborts, then its effects are negated and the would-be writer can proceed with modifying the originally found record. If the previous writer commits, the would-be writer will be aborted[2].

Serializable is defined as:

[1]It is called repeatable read on PostgreSQL official website, but it is essentially a snapshot isolation [16].

[2]The definition is more strict than *read committed*, so it also eliminates *dirty write*.

1. **Eliminating Serialization Anomaly** SR is implemented using a concurrency control protocol known in academic literature as *serializable snapshot isolation*, which builds on snapshot isolation by adding checks for serialization anomalies.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of PostgreSQL as follows:

1. *Read committed* in PostgreSQL takes *consistent read* to eliminate *dirty read*, and takes *mutual exclusion* to eliminating *dirty write*.

2. *Snapshot isolation* in PostgreSQL takes *consistent read* to eliminate *read skew*, takes *mutual exclusion* to eliminating *dirty write*, and takes *first updater wins* to eliminating *lost update*.

3. *Serialzable* in PostgreSQL is based on snapshot isolation except that it takes *serialization certifier* to eliminate *serialization anomalies*.

3.2 YugabyteDB

In YugabyteDB document [34], *read committed* is defined as:

1. **Eliminating Dirty Read** Every statement in the transaction will see all data that has been committed before it is issued

2. **Eliminating Dirty Write** The would-be writer will wait for the previous writing transaction to commit or abort (if it is still in progress). If the previous writer aborts, then its effects are negated and the would-be writer can proceed with modifying the originally found record. If the previous writer commits, the would-be writer will attempt to apply its operation to the modified version of the record.

Snapshot isolation[3] is defined as:

1. **Eliminating Read Skew** The Snapshot isolation level only sees data committed before the transaction began. Transactions running under Snapshot isolation do not see either uncommitted data or changes committed during transaction execution by other concurrently running transactions. Note that the query does see the effects of previous updates executed within its own transaction, even though they are not yet committed.

2. **Eliminating Lost Update&Dirty Write** INSERT, UPDATE, and DELETE commands behave the same as SELECT in terms of searching for target rows. They will only find target rows that were committed as of the transaction start time. If such a target row might have already been updated (or deleted or locked) by another concurrent transaction by the time it is found. This scenario is called a transaction conflict, where the current transaction conflicts with the transaction that made (or is attempting to make) an update. In such cases, one of the two transactions get aborted, depending on priority[4].

[3]It is called repeatable read on PostgreSQL official website, but it is essentially a snapshot isolation [16].

[4]The definition is more strict than *read committed*, so it also eliminates *dirty write*.

Serializable is defined as:

1. **Eliminating Serialization Anomaly** The Serializable isolation level is implemented using a concurrency control protocol known in academic literature as *serializable snapshot isolation*, which builds on snapshot isolation by adding checks for serialization anomalies. The Serializable isolation level provides the strictest transaction isolation. This level emulates serial transaction execution for all committed transactions; as if transactions had been executed one after another, serially, rather than concurrently. Serializable isolation can detect read-write conflicts in addition to write-write conflicts. This is accomplished by writing provisional records for read operations as well.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of YugabyteDB as follows:

1. *Read committed* in PostgreSQL takes *consistent read* to eliminate *read skew*, and takes *mutual exclusion* to eliminating *dirty write*.
2. *Snapshot isolation* in PostgreSQL takes *consistent read* to eliminate *read skew*, takes *mutual exclusion* to eliminating *dirty write*, and takes *first updater wins* to eliminating *lost update*.
3. *Serialzable* in PostgreSQL is based on snapshot isolation except that it takes *serialization certifier* to eliminate *serialization anomalies*.

3.3 OpenGauss

As described OpenGauss document [35], OpenGauss is compatible with PostgreSQL. The definitions of OpenGauss's isolation levels is consistent with PostgreSQL except that *Serializble* is not supported and is equivalent to *repeatable read*.

3.4 MySQL

In MySQL document [19], *read committed* is defined as:

1. **Eliminating Dirty Read** Each read operation (SELECT statement), even within the same transaction, sets and reads its own fresh snapshot.
2. **Eliminating Dirty Write** Each write operation (UPDATE, DELETE, INSERT statement) locks the record accessed in the exclusive mode.

Repeatable read is defined as:

1. **Eliminating Read Skew** The read operations (SELECT statement) within the same transaction read the snapshot established by the first read operation.

2. **Eliminating Dirty Write** Each write operation (UPDATE, DELETE, INSERT statement) locks its <search condition> in the exclusive mode.

Serializable is defined as:

1. **Eliminating Phantom&Non-repeatable Read&Dirty Read** a read operation (SELECT statement) locks its <search condition> in the shared mode
2. **Eliminating Dirty Write** Each write operation (UPDATE, DELETE, INSERT statement) locks its <search condition> in the exclusive mode.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of MySQL as follows:

1. *Read committed* in MySQL takes *consistent read* to eliminate *dirty read*, and takes *mutual exclusion* to eliminating *dirty write*.
2. *Repeatable read* in MySQL takes *consistent read* to eliminate *read skew*, and takes *mutual exclusion* to eliminating *dirty write*.
3. *Serialzable* in MySQL takes *mutual exclusion* to eliminating *dirty write*, *dirty read*, *non-repeatable read* and *phantom*.

3.5 Aurora&PolarDB

Since both Aurora [20] and PolarDB [21] are compatible with MySQL InnoDB, the definitions of their isolation levels is consistent with MySQL InnoDB.

3.6 SQLserver

In SQLserver document [36], *read committed* is defined as:

1. **Dirty Read** The Database Engine uses row versioning to present each statement with a transactionally consistent snapshot of the data as it existed at the start of the statement.
2. **Dirty Write** The Database Engine uses exclusive locks to prevent other transactions from modifying rows while the current transaction is running a write operation.

Repeatable read is defined as:

1. **Non-repeatable Read&Dirty Read** Specifies that statements cannot read data that has been modified but not yet committed by other transactions and that no other transactions can modify data that has been read by the current transaction until the current transaction completes.

2. **Dirty Write** The Database Engine uses exclusive locks to prevent other transactions from modifying rows while the current transaction is running a write operation.

Snapshot[5] is defined as:

1. **Read Skew** Specifies that data read by any statement in a transaction will be the transactionally consistent version of the data that existed at the start of the transaction.

2. **Dirty Write** The Database Engine uses exclusive locks to prevent other transactions from modifying rows while the current transaction is running a write operation.

Serialzable is defined as:

1. **Eliminating Phantom&Non-repeatable Read&Dirty Read** Statements cannot read data that has been modified but not yet committed by other transactions. No other transactions can modify data that has been read by the current transaction until the current transaction completes. Other transactions cannot insert new rows with key values that would fall in the range of keys read by any statements in the current transaction until the current transaction completes.

2. **Dirty Write** The Database Engine uses exclusive locks to prevent other transactions from modifying rows while the current transaction is running a write operation.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of SQLserver as follows:

1. *Read committed* in SQLserver takes *mutual exclusion* to eliminating *dirty write* and *dirty read.*

2. *Repeatable read* in SQLserver takes *mutual exclusion* to eliminating *dirty write*, *dirty read* and *non-repeatable read.*

3. *Snapshot* in SQLserver takes *consistent read* to eliminate *read skew*, and takes *mutual exclusion* to eliminating *dirty write.*

4. *Serialzable* in SQLserver takes *mutual exclusion* to eliminating *dirty write*, *dirty read*, *non-repeatable read* and *phantom.*

3.7 TiDB

In TiDB paper [23], there are two transaction modes, including optimistic mode and pessimistic mode. They are adapted from Percolator [24], which selects one key as the primary key and uses it to stand for the status of a transaction, and base two-phase commit protocol to conduct transaction. With optimistic transactions, conflicting changes

[5] It is the same with *repeatable read* of MySQL. In Table. 4, we call it *repeatable read.*

are detected as part of a transaction commit, while they are detected before operation execution with pessimistic transactions.

In optimistic mode, *snapshot isolation* is defined as:

1. **Eliminating Read Skew** Percolator stores multiple versions of each record. Each transaction reads from a stable snapshot at some timestamp.
2. **Eliminating Lost Update** If transactions A and B, running concurrently, write to the same cell, at most one will commit[6].

In pessimistic mode, *read committed* is defined as:

1. **Eliminating Dirty Read** Each read operation, even within the same transaction, sets and reads its own fresh snapshot.
2. **Eliminating Dirty Write** Each write operation locks the record accessed in the exclusive mode.

In pessimistic mode, *repeatable read* is defined as:

1. **Eliminating Read Skew** The Repeatable Read isolation level only sees data committed before the transaction begins, and it never sees either uncommitted data or changes committed during transaction execution by concurrent transactions.
2. **Eliminating Dirty Write** Each write operation locks the record accessed in the exclusive mode.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of TiDB as follows:

1. *Read committed* in TiDB takes *consistent read* to eliminate *dirty read*, and takes *mutual exclusion* to eliminating *dirty write.*
2. *Repeatable read* in TiDB takes *consistent read* to eliminate *read skew*, and takes *mutual exclusion* to eliminating *dirty write.*
3. *Snapshot Isolation* in TiDB takes *consistent read* to eliminating *read skew*, and takes *serialization certifier* to eliminating *lost update.*

3.8 RocksDB

As described in RocksDB document [37], RocksDB supports two kinds of transactions: pessimistic transaction and optimistic transaction, both of which support *snapshot isolation.*

Under pessimistic transaction, *snapshot isolation* is defined as:

[6] Percolator takes first committer wins to avoid lost update. First committer wins differs from first updater wins in that the time to check *lost update*, as described in [5].

1. **Eliminating Read Skew** A snapshot captures a point-in-time view of the database at the time it's created.

2. **Eliminating Lost Update&Dirty Write** All keys that are written are locked internally by RocksDB to perform conflict detection.

Under optimistic transaction, *snapshot isolation* is defined as:

1. **Eliminating Read Skew** A snapshot captures a point-in-time view of the database at the time it's created.

2. **Eliminating Lost Update** Optimistic transactions do not take any locks when preparing writes. Instead, they rely on doing conflict-detection at commit time to validate that no other writers have modified the keys being written by the current transaction. If there is a conflict with another write (or it cannot be determined), the commit will return an error and no keys will be written.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of MySQL as follows:

1. Under pessimistic transaction, *snapshot isolation* in RocksDB takes *consistent read* to eliminate *read skew*, takes *mutual exclusion* to eliminate *dirty write*, and takes *first updater wins* to eliminate *lost update*.

2. Under optimistic transaction, *snapshot isolation* in RocksDB takes *consistent read* to eliminate *read skew*, takes *mutual exclusion* to eliminate *dirty write*, and takes *first updater wins* to eliminate *lost update*.

3.9 SQLite

In SQLserver document [38], *read committed* is defined as:

1. **Eliminating Phantom&Non-repeatable Read&Dirty Read&Dirty Write** SQLite follows strict two phase locking, and implements a very simple database-level locking protocol which allows multiple readers but only one writer in one database at a time.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of SQLserver as follows:

1. *Serialzable* in MySQL takes *mutual exclusion* to eliminating *dirty write*, *dirty read*, *non-repeatable read* and *phantom*.

3.10 FoundationDB

In FoundationDB paper [36], *serializable* is defined as:

1. **Eliminating Read Skew&Dirty Read&Serialization Anomaly** FoundationDB implements serializable by combining optimistic concurrency control with multi-version concurrency control.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of FoundationDB as follows:

1. *Serialzable* in FoundationDB it takes *consistent read* to eliminate *read skew* and *dirty read*, and takes *serialization certifier* to eliminate *serialization anomalies.*

3.11 SingleStore

In SingleStore document [39], *read committed* is defined as:

1. **Dirty Read** This guarantees that no transaction will read any uncommitted data from another transaction. This does not guarantee that a row will remain the same for every read query in a given transaction.
2. **Dirty Write** This uses exclusive locks to prevent other transactions from modifying rows while the current transaction is running a write operation.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of SingleStore as follows:

1. *Read committed* in SingleStore takes *consistent read* to eliminate *dirty read*, and takes *mutual exclusion* to eliminating *dirty write.*

3.12 CockroachDB

In CockroachDB document [40], *read committed* is defined as:

1. **Eliminating Serialization Anomaly** A transaction behaves as though it has the entire database all to itself for the duration of its execution. This means that no concurrent writers can affect the transaction unless they commit before it starts, and no concurrent readers can be affected by the transaction until it has successfully committed.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of MySQL as follows:

1. *Serialzable* in CockroachDB it takes *serialization certifier* to eliminate *serialization anomalies.*

3.13 Spanner

In Spanner document [41], *serializable* is defined as:

1. **Eliminating Read Skew** Spanner uses multi-versioned concurrency control. Spanner's MVCC implementation is unique in that it uses hardware devices (e.g., GPS, atomic clocks) for high-precision clock synchronization. Spanner uses these clocks to assign timestamps to transactions to enforce consistent views of its multi-version database over wide-area networks.

2. **Eliminating Phantom&Non-repeatable Read&Dirty Read&Dirty Write** Spanner uses a combination of shared locks and exclusive locks to control access to the data. When you perform a read as part of a transaction, Spanner acquires shared read locks, which allows other reads to still access the data until your transaction is ready to commit. When your transaction is committing and writes are being applied, the transaction attempts to upgrade to an exclusive lock. It blocks new shared read locks on the data, waits for existing shared read locks to clear, then places an exclusive lock for exclusive access to the data.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of Spanner as follows:

1. *Serializable* in Spanner takes *consistent read* to eliminate *read skew*, and takes *mutual exclusion* to eliminating *dirty write*, *dirty read*, *non-repeatable read* and *phantom*.

3.14 Oracle

In Oracle document [40], *read committed* is defined as:

1. **Eliminating Dirty Read** Every read operation executed by a transaction sees only data committed before the query—not the transaction—began.

2. **Eliminating Dirty Write** The transaction that prevents the row modification is sometimes called a blocking transaction. The read committed transaction waits for the blocking transaction to end and release its row lock. If the blocking transaction aborts, then the waiting transaction proceeds to change the previously locked record as if the other transaction never existed. If the blocking transaction commits and releases its locks, then the waiting transaction proceeds with its intended update to the newly changed record.

Serializable[7] is defined as:

1. **Eliminating Read Skew** A transaction sees only changes committed at the time the transaction—not the query—began and changes made by the transaction itself.

[7] It is essentially a snapshot isolation as defined in [5].

2. **Eliminating Lost Update&Dirty Write** Oracle Database permits a serializable transaction to modify a row only if changes to the row made by other transactions were already committed when the serializable transaction began[8].

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of MySQL as follows:

1. *Read committed* in Oracle takes *consistent read* to eliminate *dirty read*, and takes *mutual exclusion* to eliminating *dirty write*.
2. *Serialzable* in Oracle takes *consistent read* to eliminate *read skew*, takes *mutual exclusion* to eliminating *dirty write*, and takes *first updater wins* to eliminating *lost update*.

3.15 NuoDB

In NuoDB document [42], *read committed* is defined as:

1. **Eliminating Serialization Anomaly**

Serializable[9] is defined as:

1. **Eliminating Read Skew** A transaction running with this isolation level reads a snapshot of the database at the start of the transaction.
2. **Eliminating Lost Update&Dirty Write** The transaction can perform updates, including deletes, successfully on those rows, providing no other concurrent transaction has updated those same rows. When a transaction running at this isolation level attempts to update or delete a record that has been changed by a concurrent transaction, it waits for the other transaction to complete. When the other transaction completes then the waiting transaction succeeds in its update only if the previous transaction rolled back. Otherwise, the waiting transaction gets an error.

As discussed above, in Fig. 2, we summarize the relationship between isolation anomalies and the four classic mechanisms. According to the above definitions, we conclude that the classic mechanisms of implementing isolation levels of NuoDB as follows:

1. *Read committed* in NuoDB takes *consistent read* to eliminate *dirty read*, and takes *mutual exclusion* to eliminating *dirty write*.
2. *Serialzable* in NuoDB takes *consistent read* to eliminate *read skew*, takes *mutual exclusion* to eliminating *dirty write*, and takes *first updater wins* to eliminating *lost update*.

[8]The definition is more strict than *read committed*, so it also eliminates *dirty write*.

[9]It is essentially a snapshot isolation as defined in [5].

3.16 OceanBase

Since OceanBase [43] is compatible with Oracle, the definitions of their isolation levels is consistent with Oracle.

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