Information Systems

Computer Science Department
ETH Zurich
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Lecture VI: Transaction Management (Concurrency Control)

An Example

- My bank issued a debit card for me to access my account.
- Every once in a while, I use it at an ATM to withdraw some money from my account, causing the ATM to perform a **"transaction"** in the bank's database.
- My account is properly updated to reflect the new balance.

```
1 bal ← read_bal (acct_no) ;
2 bal ← bal – 100 CHF ;
3 write_bal (acct_no, bal) ;
```

Concurrent Access

- Problem: My husband has a card for the same account, too.
  - We might end up using our cards at different ATMs at the **same time**.

me	my husband	DB state
$bal \leftarrow$ read $(acct)$;		1200
	$bal \leftarrow$ read $(acct)$;	1200
$bal \leftarrow bal - 100$;		1200
	$bal \leftarrow bal - 200$;	1200
write $(acct, bal)$;		1100
	write $(acct, bal)$;	1000

  - The first update was **lost** during this execution. Lucky me! ☺

Failures

- This time, I want to **transfer** money over to another account.

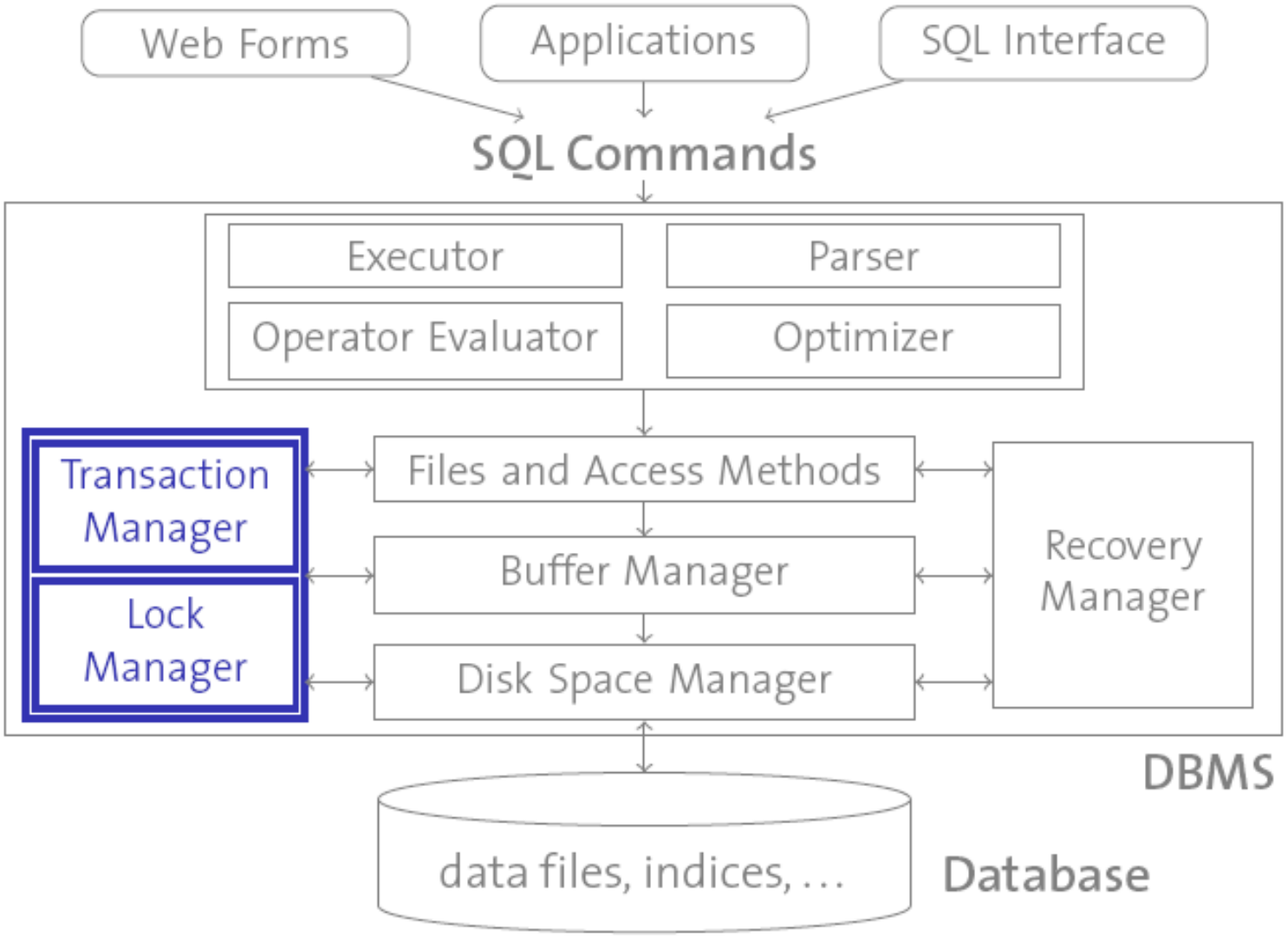
```
   // Subtract money from source (checking) account
1  chk_bal ← read_bal (chk_acct_no) ;
2  chk_bal ← chk_bal – 500 CHF ;
3  write_bal (chk_acct_no, chk_bal) ;
   // Credit money to the target (saving) account
4  sav_bal ← read_bal (sav_acct_no) ;
5  sav_bal ← sav_bal + 500 CHF ;
6  write_bal (sav_acct_no, sav_bal) ;
```

- Before the transaction gets to step 6, its execution is **interrupted/cancelled** (power outage, disk failure, software bug, etc.). My money is **lost** ☹ .

ACID Properties

- To prevent these (and many other) effects from happening, a DBMS must guarantee the following transactional properties:
  - **A**tomicity : Either all or none of the updates in a database transaction are applied.
  - **C**onsistency : Every transaction brings the database from one consistent state to another.
  - **I**solation : A transaction must not see any effect from other transactions that run in parallel.
  - **D**urability : The effects of a successful transaction are made persistent and cannot be undone for system reasons.

Concurrency Control



Anomalies: Lost Update

- The effects of one transaction are lost because of an uncontrolled overwriting by another transaction.

- We saw an example of this anomaly in slide #4 (the effect of my money withdrawal transaction was overwritten by my husband's).

Anomalies: Inconsistent Read

- Consider the money transfer example in slide #5, expressed in SQL syntax:

Transaction 1	Transaction 2

`UPDATE Accounts`
`  SET balance = balance - 500`
`  WHERE customer = 4711`
`  AND account_type = 'C';`	

	`SELECT SUM(balance)`
	`  FROM Accounts`
	`  WHERE customer = 4711;`

`UPDATE Accounts`
`  SET balance = balance + 500`
`  WHERE customer = 4711`
`  AND account_type = 'S';`	

- Transaction 2 sees an **inconsistent** database state.

Anomalies: Dirty Read

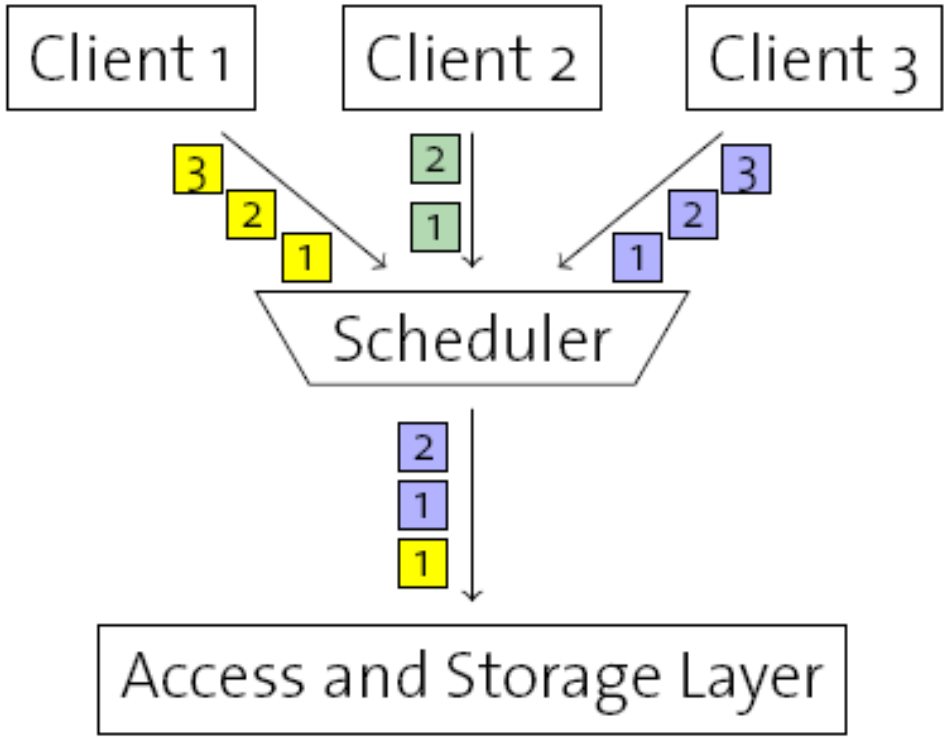
- At a different day, my husband and me again end up in front of two different ATMs at roughly the same time:

me	my husband	DB state
bal ← read (*acct*) ;		1200
bal ← *bal* − 100 ;		1200
write (*acct*, *bal*) ;		1100
	bal ← read (*acct*) ;	1100
	bal ← *bal* − 200 ;	1100
abort ;		1200
	write (*acct*, *bal*) ;	900

- My husband's transaction has already read the modified account balance before my transaction was rolled back.

Concurrent Execution

- The **scheduler** decides the execution order of concurrent database accesses.



Database Objects and Accesses

- We now assume a slightly simplified model of database access:
  1. A database consists of a number of named **objects**. In a given database state, each object has a **value**.
  2. Transactions access an object *o* using the two operations: *read(o)* and *write(o)*.

- In a relational DBMS, we typically have that:

$$\text{object} \equiv \text{attribute}$$

Transactions

- A **database transaction** *T* is a (strictly ordered) sequence of **steps**. Each **step** (s_i) is a pair of an **access operation** (a_i) applied to an **object** (e_i).
  - Transaction $T = \langle s_1, \ldots, s_n \rangle$
  - Step $s_i = (a_i, e_i)$
  - Access operation $a_i \in \{r(ead), w(rite)\}$
- The **length** of a transaction *T* is its number of steps $|T| = n$.
- We could write the money transfer transaction as:

$$T = \langle (\texttt{read}, \mathit{Checking}), (\texttt{write}, \mathit{Checking}), (\texttt{read}, \mathit{Saving}), (\texttt{write}, \mathit{Saving}) \rangle$$

- More concisely:

$$T = \langle r(C), w(C), r(S), w(S) \rangle$$

Schedules

- A schedule S for a given set of transactions $T = \{T_1, \ldots, T_n\}$ is an arbitrary sequence of execution steps

$$S(k) = (T_j, a_i, e_i) \qquad k = 1 \ldots m \ ,$$

such that

1. S contains all steps of all transactions and nothing else, and
2. the order among steps in each transaction T_j is preserved:

$$(a_p, e_p) < (a_q, e_q) \text{ in } T_j \Rightarrow (T_j, a_p, e_p) < (T_j, a_q, e_q) \text{ in } S$$

- We sometimes write:

$$S = \langle r_1(B), r_2(B), w_1(B), w_2(B) \rangle$$

to mean:

$$S(1) = (T_1, \texttt{read}, B) \quad S(3) = (T_1, \texttt{write}, B)$$
$$S(2) = (T_2, \texttt{read}, B) \quad S(4) = (T_2, \texttt{write}, B)$$

Serial Execution

- One particular schedule is for the serial execution.
  - A schedule S is serial, iff for each contained transaction T_j, all its steps follow each other (i.e., no interleaving of transactions).
- Consider again the ATM example from slide #4.

$$S = \langle r_1(B), r_2(B), w_1(B), w_2(B) \rangle$$

This schedule is **not serial**.

- If my husband had gone to the bank one hour later, "our" schedule probably would have been serial.

$$S = \langle r_1(B), w_1(B), r_2(B), w_2(B) \rangle$$

Correctness of Serial Execution

- Anomalies such as the “lost update” problem on slide #4 can only occur in multi-user mode.
- If all transactions were fully executed one after another (no concurrency), no anomalies would occur.
- **Any serial execution is correct**.

- Disallowing concurrent access, however, is not practical.
- Therefore, **allow concurrent executions if they are “equivalent” to a serial execution**.

Conflict Equivalence

- What does it mean for a schedule *S* to be **equivalent** to another schedule *S'*?
- Sometimes, we may be able to **reorder** steps in a schedule.
  - We must not change the order among steps of any transaction T_j.
  - Rearranging operations must not lead to a different result.
- Two operations (*a*, *e*) and (*a'*, *e'*) are said to be **in conflict** (*a*, *e*) $\not\leftrightarrow$ (*a'*, *e'*), if their order of execution matters.
  - When reordering a schedule, we must not change the relative order of such operations.
- Any schedule *S'* that can be obtained this way from *S* is said to be **conflict equivalent** to *S*.

Conflicts

- Based on our read/write model, we can come up with a more machine-friendly definition of a conflict.
  - Two operations (T_i, a, e) and (T_j, a', e') are **in conflict** in S, if
    1. they belong to two **different transactions** ($T_i \neq T_j$),
    2. they access the **same database object**, i.e., $e = e'$, and
    3. at least one of them is a **write operation**.
  - This inspires the following conflict matrix:

	read	write
read		×
write	×	×

  - **Conflict relation**:

$$(T_i, a, e) \prec_S (T_j, a', e') := (a, e) \nleftrightarrow (a', e') \wedge (T_i, a, e) \text{ occurs before } (T_j, a', e') \text{ in } S \wedge T_i \neq T_j$$

Conflict Serializability

- A schedule *S* is **conflict serializable**, iff it is conflict equivalent to **some** serial schedule *S'*.
- **The execution of a conflict serializable schedule *S* is correct**.
  - *S* does not have to be a serial schedule.
- This allows us to prove the correctness of a schedule *S* based on its **conflict graph** *G(S)* (a.k.a., **serialization graph**).
  - Nodes are all transactions T_i in *S*.
  - There is an edge $T_i \rightarrow T_j$, iff *S* contains operations (T_i, *a*, *e*) and (T_j, *a'*, *e'*) such that:

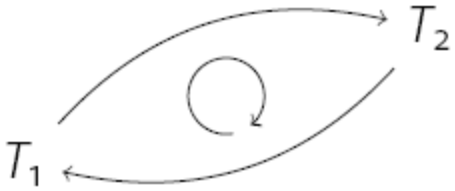
$$(T_i, a, e) \prec_S (T_j, a', e')$$

- *S* is conflict serializable if *G(S)* is **acyclic** (i.e., a serial execution of *S* could be obtained by sorting *G(S)* topologically.)

Serialization Graph

- Example: ATM transactions (slide #4)
  - $S = \langle r_1(A), r_2(A), w_1(A), w_2(A) \rangle$
  - Conflict relation:

$$(T_1, \mathtt{r}, A) \prec_S (T_2, \mathtt{w}, A)$$
$$(T_2, \mathtt{r}, A) \prec_S (T_1, \mathtt{w}, A)$$
$$(T_1, \mathtt{w}, A) \prec_S (T_2, \mathtt{w}, A)$$



$\rightarrow$ **not** serializable

- Example: Money transfers
  - $S = \langle r_1(C), w_1(C), r_2(C), w_2(C), r_1(S), w_1(S), r_2(S), w_2(S) \rangle$
  - Conflict relation:

$$(T_1, \mathtt{r}, C) \prec_S (T_2, \mathtt{w}, C)$$
$$(T_1, \mathtt{w}, C) \prec_S (T_2, \mathtt{r}, C)$$
$$(T_1, \mathtt{w}, C) \prec_S (T_2, \mathtt{w}, C)$$
$$\vdots$$

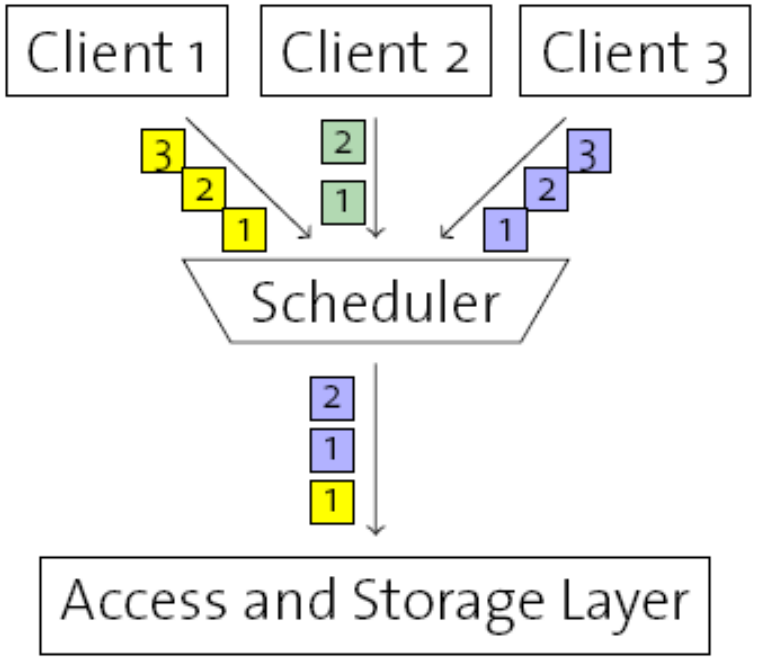
$\rightarrow$ serializable

Query Scheduling

- Can we build a scheduler that **always** emits a **serializable schedule**?
- Idea:
  - Require each transaction to obtain a **lock** before it accesses a data object *o:*

```
1 lock o;
2 ...access o...;
3 unlock o;
```

  - This prevents **concurrent** access to *o*.



Locking

- If a lock cannot be granted to the requesting transaction *T* (e.g., because another transaction *T'* already holds a **conflicting lock**), then *T* gets **blocked**.
- The scheduler **suspends** the execution of the blocked transaction *T*.
- Once *T'* **releases** the lock, it can be granted to *T*, whose execution is then **resumed**.
- Since other transactions can continue execution while *T* is blocked, **locks can be used to control the relative order of operations**.

ATM Transaction Example with Locking

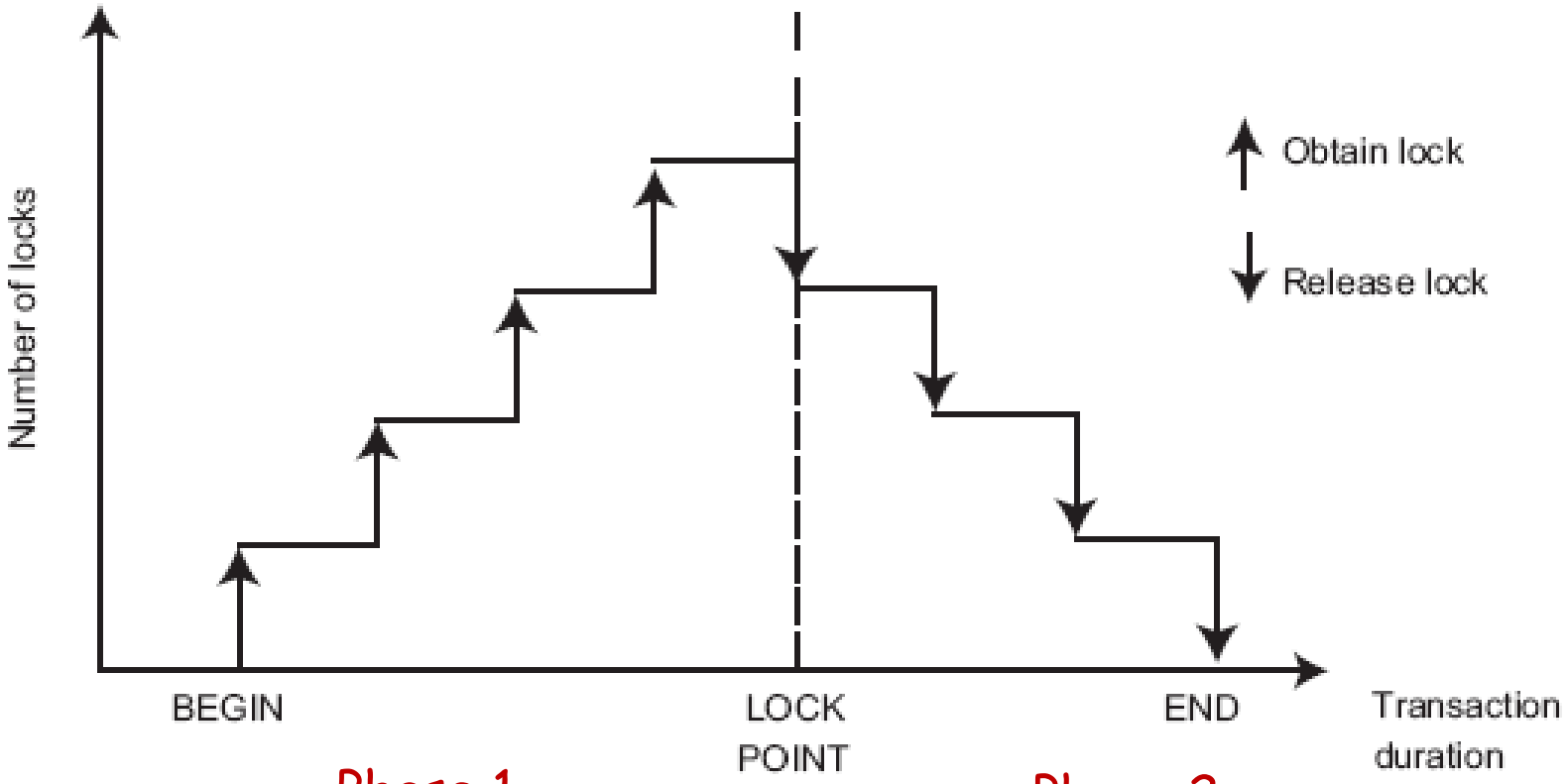
Transaction 1	Transaction 2	DB state
`lock (acct) ;`		1200
`read (acct) ;`		
`unlock (acct) ;`		
	`lock (acct) ;`	
	`read (acct) ;`	
	`unlock (acct) ;`	
`lock (acct) ;`		
`write (acct) ;`		1100
`unlock (acct) ;`		
	`lock (acct) ;`	
	`write (acct) ;`	1000
	`unlock (acct) ;`	

- Is locking by itself enough to guarantee serializable schedules?

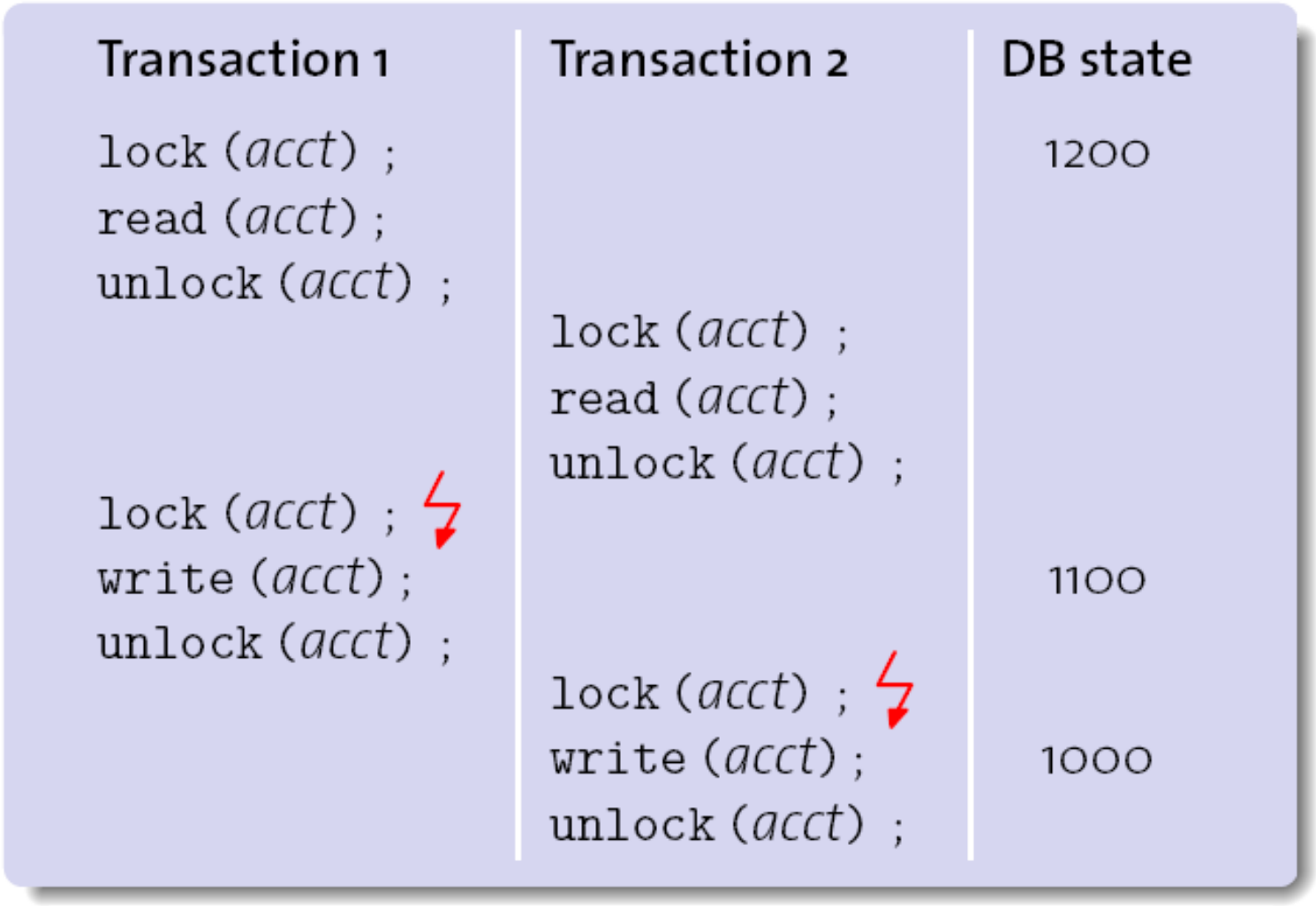
Two-Phase Locking (2PL)

- To generate serializable histories, the locking and releasing operations of transactions must be coordinated.
- 2PL achieves the coordination as follows:
  - A transaction must lock an object before using it.
  - When an object is locked by another transaction, the requesting transaction must wait.
  - Once a transaction releases any lock, it cannot request additional locks.
- Any history generated by a concurrency algorithm that obeys the 2PL rule is serializable.

Two-Phase Locking (2PL)



ATM Transaction Example violates 2PL



Making the ATM Transaction 2PL-Compliant

- To comply with the two-phase locking protocol, the ATM transaction must not acquire any new locks after the first lock has been released.

```
1 lock (acct) ;                          } lock phase
2 bal ← read_bal (acct) ;
3 bal ← bal – 100 CHF ;
4 write_bal (acct, bal) ;
5 unlock (acct) ;                        } unlock phase
```

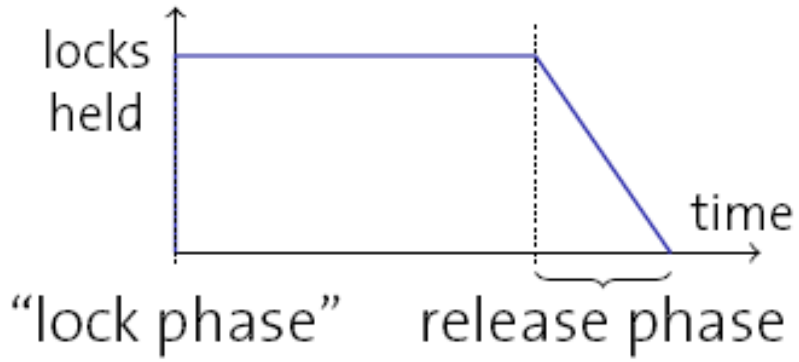
Resulting ATM Transaction Schedule

Transaction 1	Transaction 2	DB state
`lock (acct) ;`		1200
`read (acct) ;`		
	`lock (acct) ;`	
`write (acct) ;`	Transaction	1100
`unlock (acct) ;`	blocked	
	`read (acct) ;`	
	`write (acct) ;`	900
	`unlock (acct) ;`	

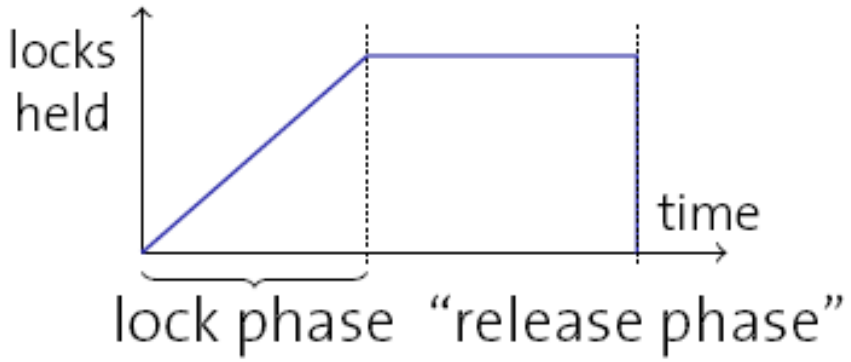
- Use of locking with 2PL leads to a correct (and serializable) schedule.

Variants of 2PL

- The two-phase locking protocol does not prescribe exactly when locks have to be acquired and released.
- Variants are possible. Examples:



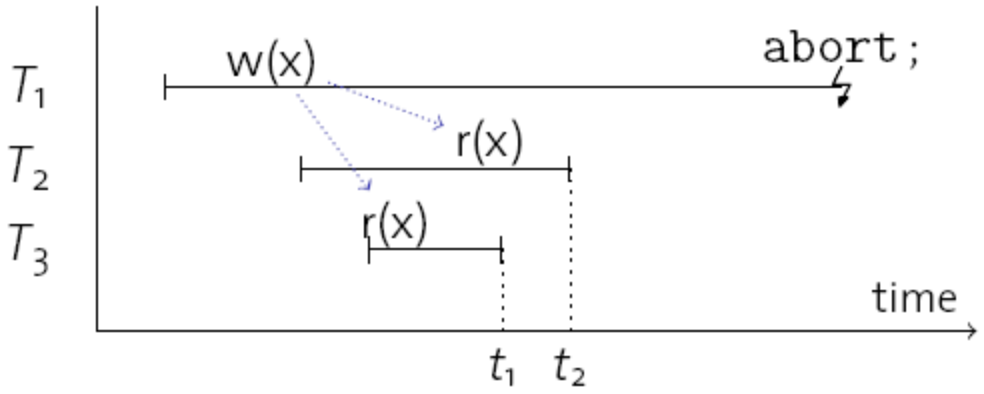
preclaiming 2PL



strict 2PL

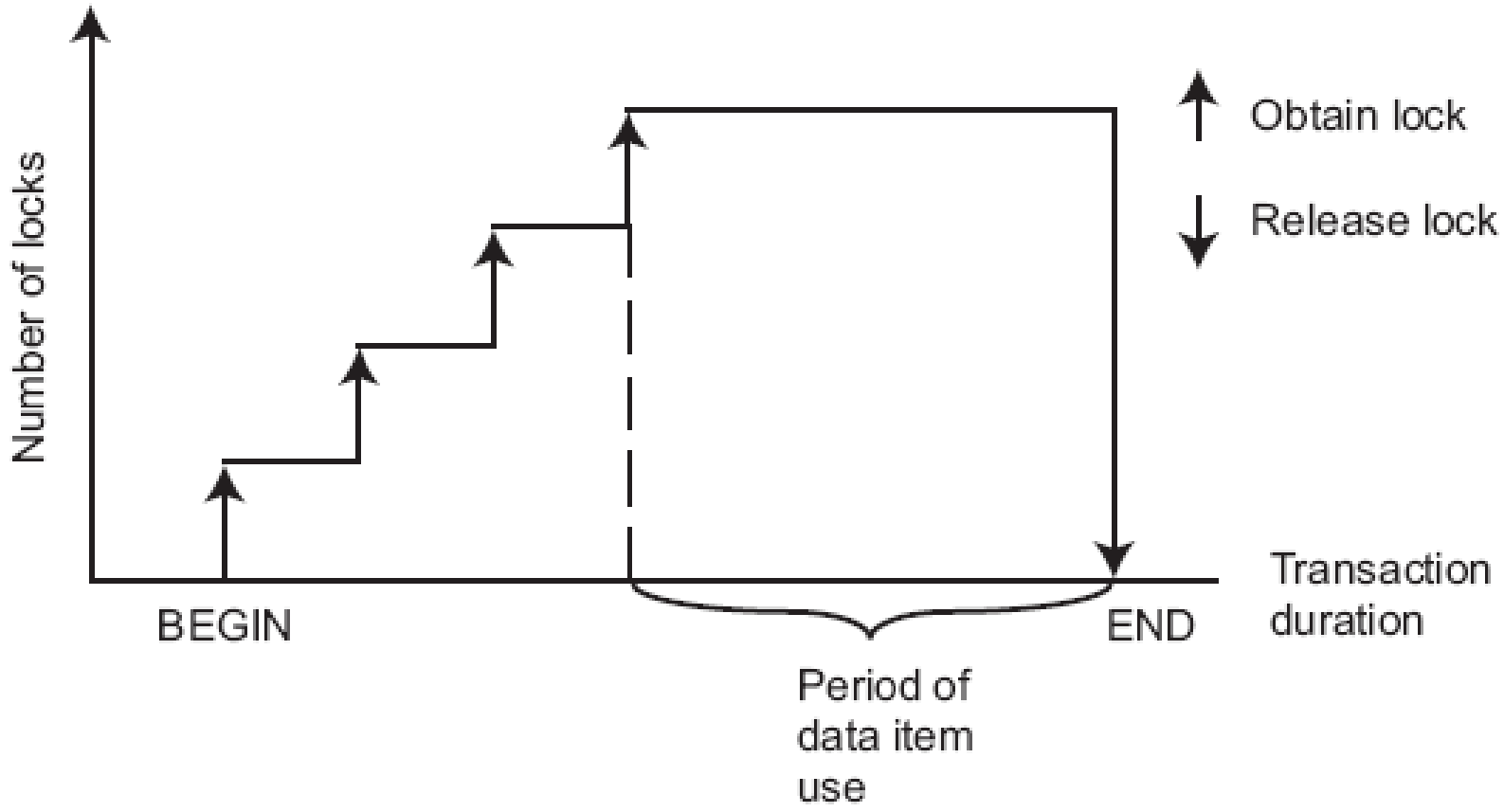
Cascading Rollbacks

- Consider three transactions:



- When transaction T_1 aborts, transactions T_2 and T_3 have already read data written by T_1 (dirty read).
- T_2 and T_3 need to be **rolled back**, too.
- T_2 and T_3 **cannot** commit until the fate of T_1 is known.
- **Strict two-phase locking avoids this problem.**

Strict Two-Phase Locking



- Facilitates lock management
- Avoids cascading aborts

Lock Modes

- We saw earlier that two read operations do not conflict with each other.
- Systems typically use different types of locks ("lock modes") to allow read operations to run concurrently.
  - **read locks** or **shared locks**: mode S
  - **write locks** or **exclusive locks**: mode X
- Locks are only in conflict if at least one of them is an X lock:

	shared (S)	exclusive (X)
shared (S)		×
exclusive (X)	×	×

- It is a safe operation in two-phase locking to convert a shared lock into an exclusive lock during the lock phase.

Deadlocks

- Like many lock-based protocols, two-phase locking has the risk of **deadlock** situations:

Transaction 1	Transaction 2
`lock` (A) ;	
⋮	`lock` (B)
do something	⋮
⋮	do something
`lock` (B)	⋮
[wait for T_2 to release lock]	`lock` (A)
	[wait for T_1 to release lock]

- Both transactions would **wait** for each other **indefinitely**.

Deadlock Handling

- A typical approach to deal with deadlocks is **deadlock detection**:
  - The system maintains a **waits-for graph**, where an edge $T_1 \rightarrow T_2$ indicates that T_1 is blocked by a lock held by T_2.
  - Periodically, the system tests for **cycles** in the graph.
  - If a cycle is detected, the deadlock is **resolved by aborting** one or more transactions.
  - Selecting the **victim** is a challenge:
    - Aborting **young** transactions may lead to **starvation**: the same transaction is cancelled again and again.
    - Aborting an **old** transaction may cause a lot of investment to be thrown away.

Deadlock Handling

- Other common techniques:
  - **Deadlock prevention:** e.g., by handling lock requests in an asymmetric way:
    - **Wait-Die:** A transaction is never blocked by an older transaction.
    - **Wound-Wait:** A transaction is never blocked by a younger transaction.
  - **Timeout:** Only wait for a lock until a timeout expires. Otherwise, assume that a deadlock has occurred and abort.
- Example: IBM DB2:

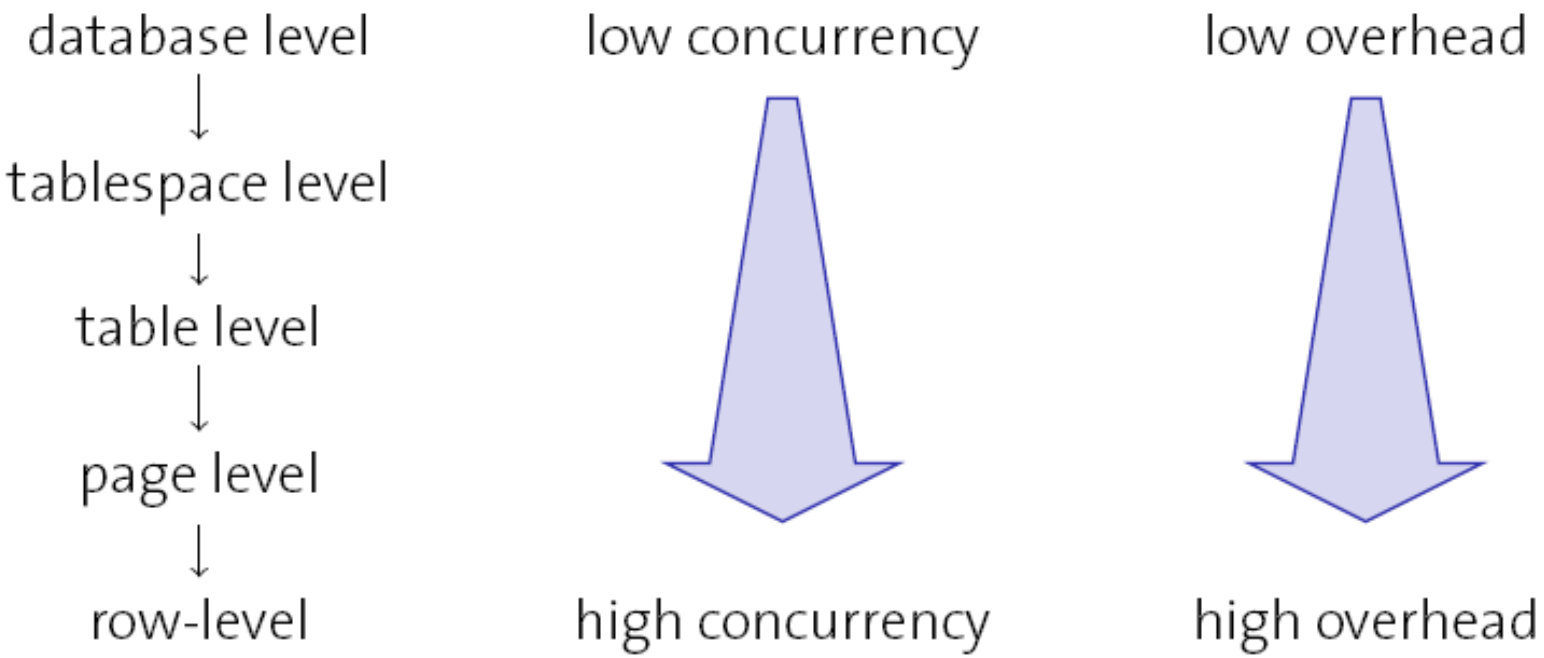
```
db2 => GET DATABASE CONFIGURATION;
   :
Interval for checking deadlock (ms)      (DLCHKTIME) = 10000
Lock timeout (sec)                      (LOCKTIMEOUT) = -1
```

Implementing a Lock Manager

- We'd like the lock manager to perform the following three tasks very efficiently:
  1. Check which locks are currently held for a given resource (in order to decide whether another lock request can be granted).
  2. When a lock is released, transactions that requested locks on the same resource have to be identified and granted the lock.
  3. When a transaction terminates, all held locks must be released.

Granularity of Locking

- The **granularity** of locking is a trade-off:



➢ Idea: **multi-granularity** locking

Multi-Granularity Locking

- Decide on the granularity of locks held **for each transaction** (depending on the characteristics of the transaction).
  - A row lock, e.g., for

```
SELECT * FROM CUSTOMERS                    Q1
 WHERE C_CUSTKEY = 42
```

  - and a table lock for

```
SELECT * FROM CUSTOMERS                    Q2
```

- How do such transactions know about each others' locks?
  - Note that locking is performance-critical. Q_2 doesn't want to do an extensive search for row-level conflicts.
  - Idea: Exploit the hierarchical nature of granularities.

Intention Locks

- Databases use an additional type of locks: intention locks
  - Lock mode intention share: IS
  - Lock mode intention exclusive: IX
  - Conflict matrix:

	S	X	IS	IX
S		×		×
X	×	×	×	×
IS		×		
IX	×	×		

- A lock I* on a coarser level means that there's some lock * on a lower level.

Intention Locks

- Protocol for multi-granularity locking:
  1. A transaction can lock any granule *g* in * ϵ {S, X} mode.
  2. Before a granule *g* can be locked in * mode, it has to obtain an I* lock on all coarser granularities that contain *g*.
- Query Q_1 would, e.g.,
  - obtain an IS lock on table CUSTOMERS (also on tablespace and database levels), and
  - obtain an S lock on the row with C_CUSTKEY = 42.
- Query Q_2 would place an
  - S lock on table CUSTOMERS (and an IS lock on tablespace and database).

Detecting Conflicts

- Now suppose a write query comes in:

```
UPDATE CUSTOMERS                                    Q3
  SET NAME = 'John Doe'
  WHERE C_CUSTKEY = 17
```

- It'll want to place
  - an IX lock on table CUSTOMER (and tablespace and database), and
  - an X lock on the row holding customer 17.
- As such it is
  - compatible with Q_1 (there's no conflict between IX and IS on the table level),
  - but incompatible with Q_2 (the S lock held by Q_2 is in conflict with Q_3's IX lock).

Consistency Guarantees and SQL 92

- Sometimes, some degree of inconsistency may be acceptable for specific applications:
  - "Mistakes" in few data sets, e.g., will not considerably affect the outcome of an aggregate over a huge table.
  - SQL 92 specifies different isolation levels.
  - E.g.,

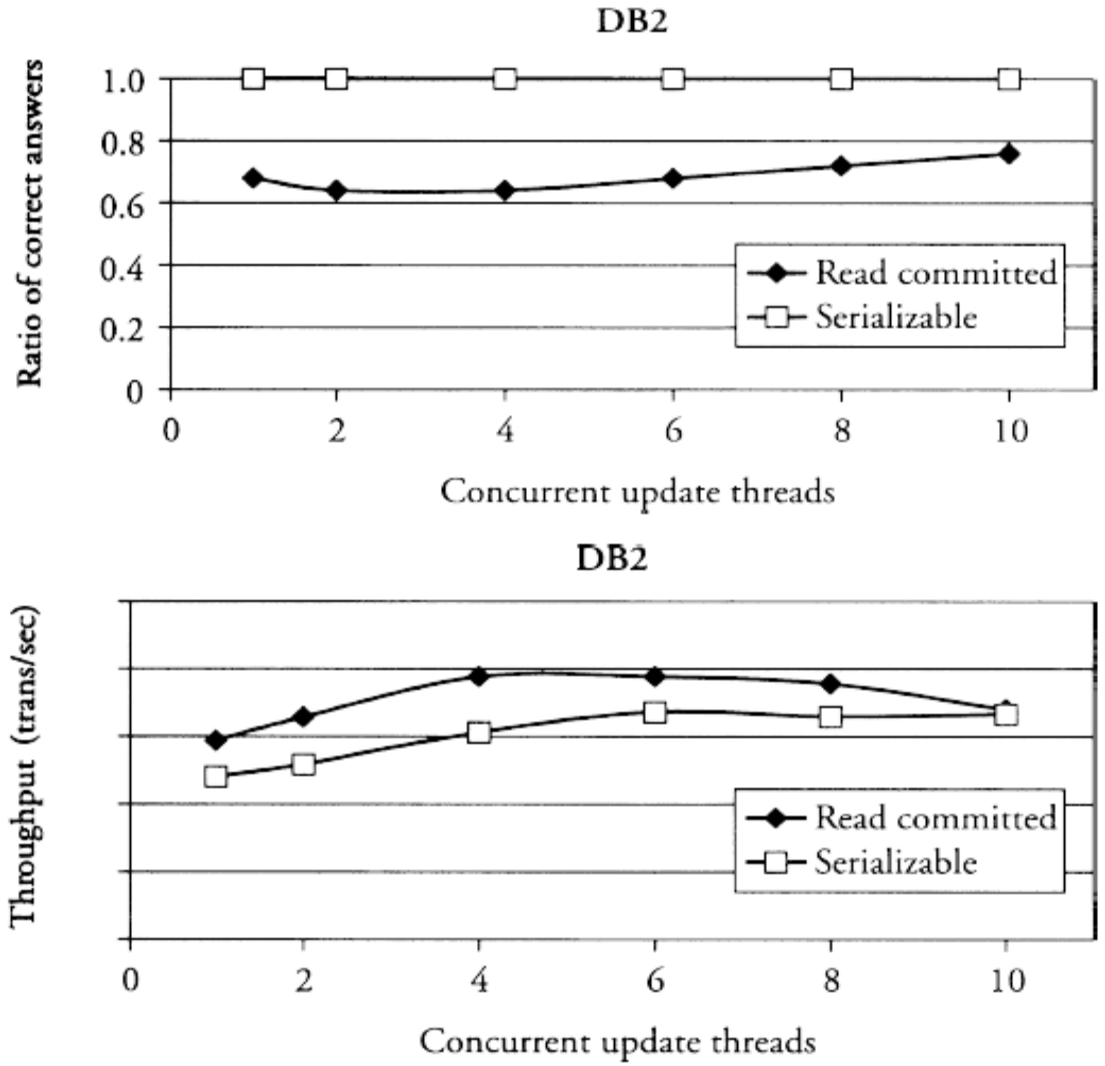
```
SET ISOLATION SERIALIZABLE;
```

  - Obviously, less strict consistency guarantees should lead to increased throughput.

SQL 92 Isolation Levels

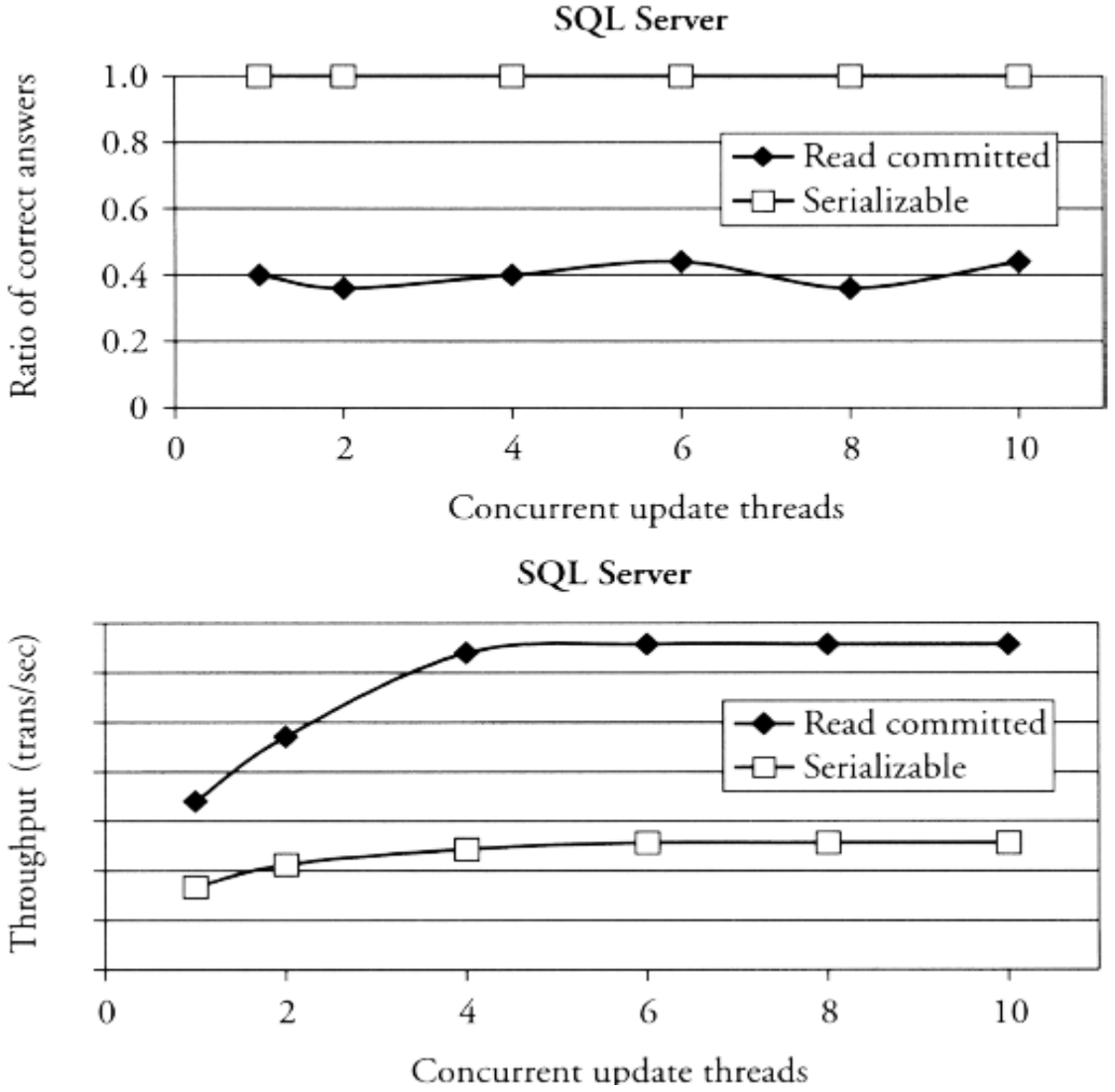
- **read uncommitted (also: ‘dirty read’ or ‘browse’)**
  - Only write locks are acquired according to strict 2PL.
- **read committed (also: ‘cursor stability’)**
  - Read locks are only held for as long as a cursor sits on the particular row. Write locks acquired according to strict 2PL.
- **repeatable read (also: ‘read stability’)**
  - Acquires read and write locks according to strict 2PL.
- **serializable**
  - Additionally, obtains locks to avoid **phantom reads**.

Performance Comparison



Dennis Shasha nad Philippe Bonnet. Database Tuning. Morgan Kaufmann, 2003.

Performance Comparison



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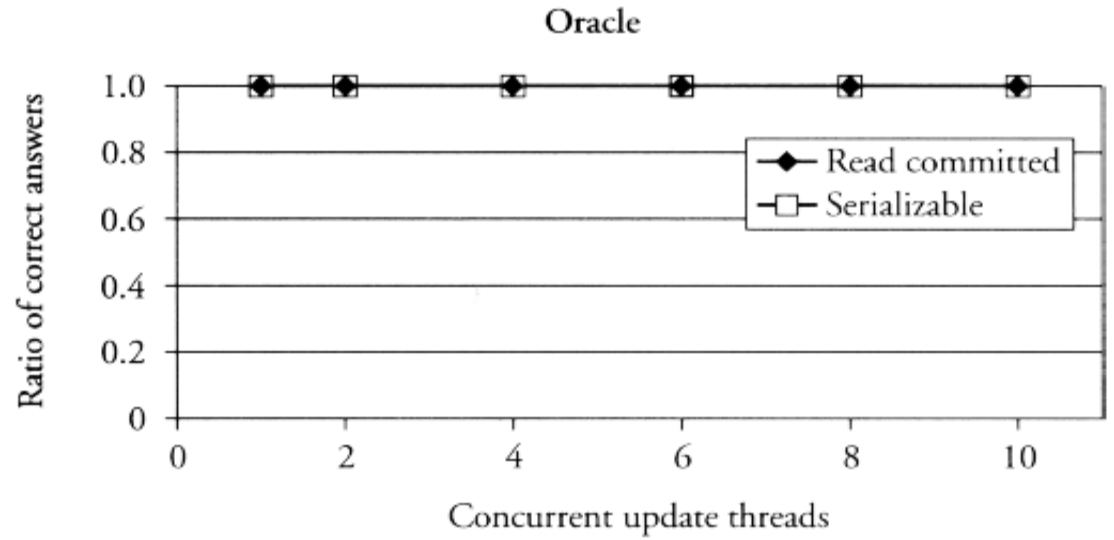
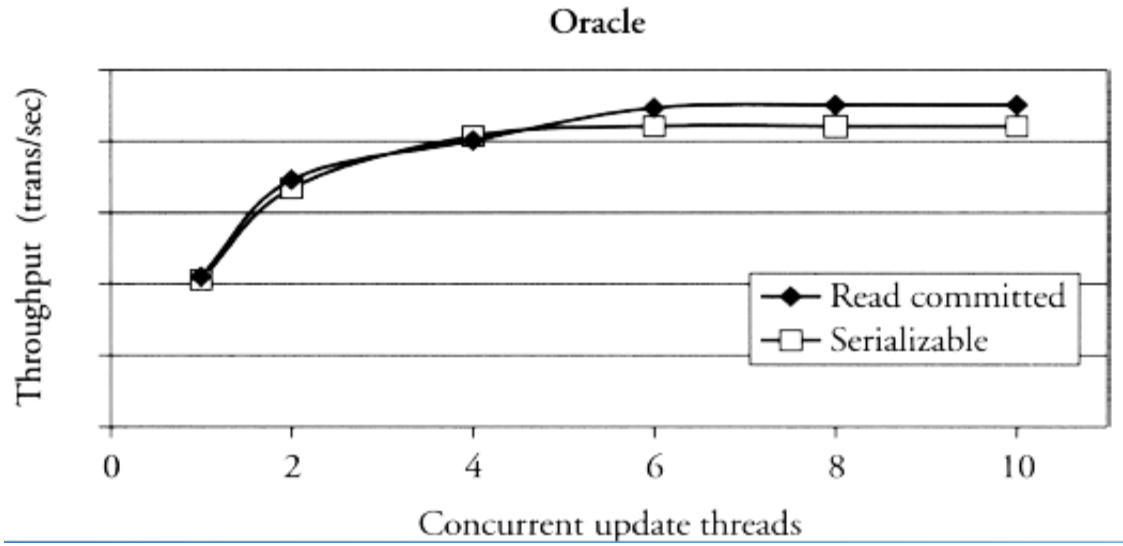
Performance Comparison





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Resulting Consistency Guarantees

isolation level	dirty read	non-repeat. rd	phantom rd
read uncommitted	possible	possible	possible
read committed	not possible	possible	possible
repeatable read	not possible	not possible	possible
serializable	not possible	not possible	not possible

- Some implementations support more, less, or different levels of isolation.
- Few applications really need serializability.

Phantom Problem

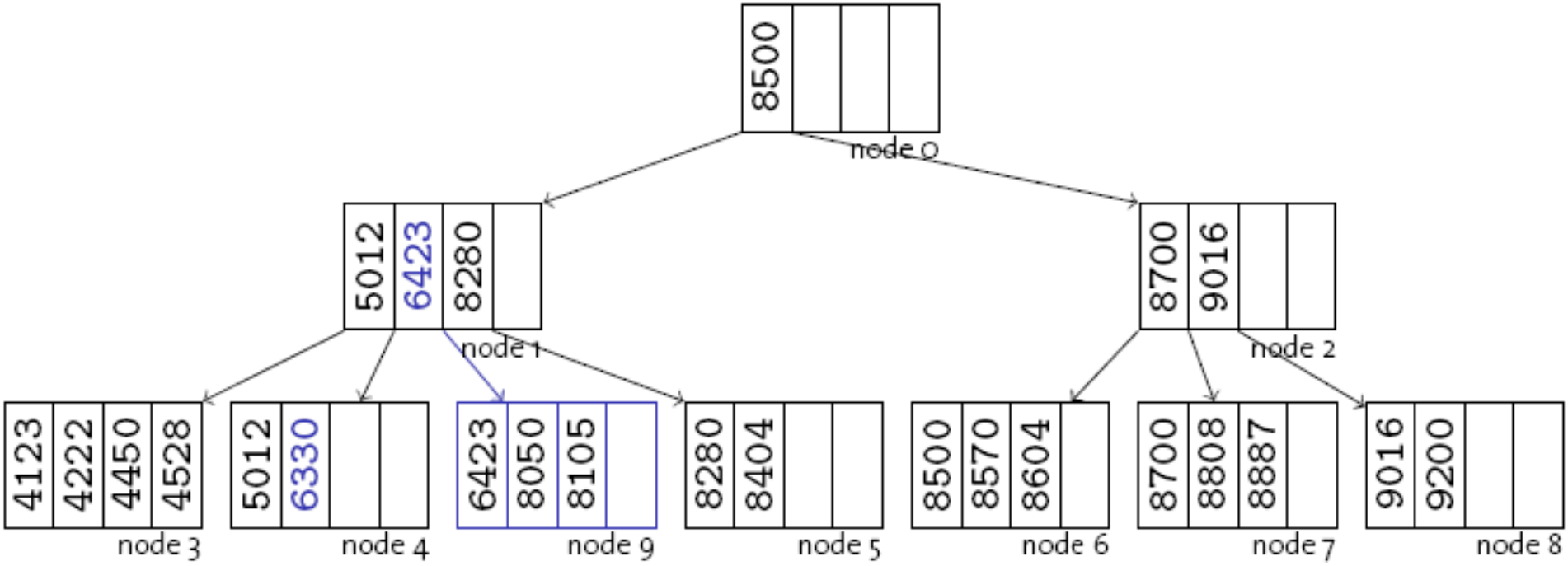
Transaction 1	Transaction 2	Effect
scan relation R ;		T_1 locks all rows
	insert new row into R ;	T_2 locks new row
	commit ;	T_2's lock released
scan relation R ;		reads **new** row, too!

- Although both transactions properly followed the 2PL protocol, T_1 observed an effect caused by T_2.
- Cause of the problem: T_1 can only lock existing rows.
- Possible solutions:
  - Key range locking, typically in B-trees
  - Predicate locking

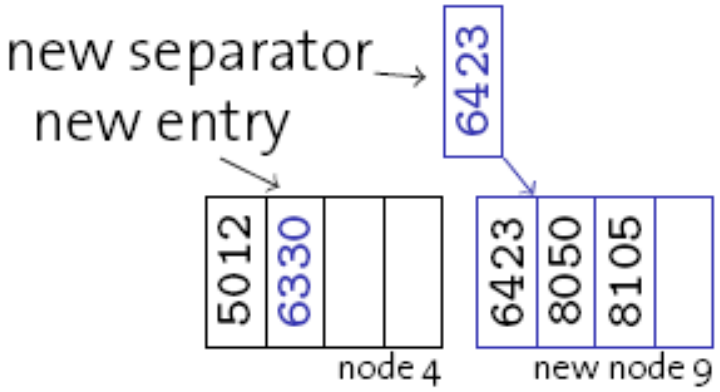
Concurrency in B-Tree Indices

- Consider an insert transaction T_w into a B$^+$-tree that resulted in a leaf node split.
  - Assume node 4 has just been split, but the new separator has not yet been inserted into node 1.
  - Now a concurrent read transaction T_r tries to find 8050.
  - The (old) node 1 guides T_r to node 4.
  - Node 4 no longer contains entry 8050, T_r believes there is no data item with zip code 8050.
  - This calls for concurrency control in B-trees.

Insertion to a B$^+$-tree: Example



- Insert key 6330.
  - Must **split** node 4.
  - **New separator** goes into node 1 (including pointer to new page).



Locking and B-Tree Indices

- Remember how we performed operations on B$^+$-trees:
  - To search a B$^+$-tree, we descended the tree top-down. Based on the content of a node *n*, we decided in which child *n'* to continue the search.
  - To update a B$^+$-tree, we
    - first did a search,
    - then inserted new data into the right leaf.
    - depending on the fullness levels of nodes, we had to split tree nodes and propagate splits bottom-up.
- According to the two-phase locking protocol, we'd have to
  - obtain $\mathbb{S}/\mathbb{X}$ locks when we walk down the tree and
  - keep all locks until we're finished.

Locking and B-Tree Indices

- This strategy would seriously reduce **concurrency**.
- All transactions would have to lock the tree root, which becomes a locking **bottleneck**.
- Root node locks, effectively, **serialize** all (write) transactions.
- Two-phase locking is **not practical** for B-trees.

Lock Coupling

- Let us consider the **write-only** case first (i.e., all locks conflict).
- The **write-only tree locking (WTL) protocol** is sufficient to guarantee serializability:
  1. For all tree nodes *n* other than the root, a transaction may only acquire a lock on *n* if it already holds a lock on *n*'s parent.
  2. Once a node *n* has been unlocked, the same *n* may not be locked again by the same transaction.
- Effectively,
  - All transactions have to follow a **top-down access pattern.**
  - No transaction can "bypass" any other transaction along the same path. Conflicting transactions are thus **serializable.**
  - The WTL protocol is **deadlock free.**

Lock Coupling with Split Safety

- We still have to keep as many write locks as nodes might be affected by node splits.
- It is easy to check for a node *n* whether an update might affect *n*'s ancestors:
  - if *n* contains less than 2*d* entries, no split will propagate above *n*.
- If *n* satisfies this condition, it is said to be **(split) safe**.
- We can use this definition to release write locks early:
  - if, while searching top-down for an insert location, we encounter a safe node *n*, we can release locks on all of *n*'s ancestors.
- Effectively, locks near the root are held for a shorter time.

The Optimistic Lock Coupling Variant

- Even with lock coupling there's a considerable amount of locks on inner tree nodes (reducing concurrency).
- Chances that inner nodes are actually affected by updates are very small.
  - Back-of-the-envelope calculation:

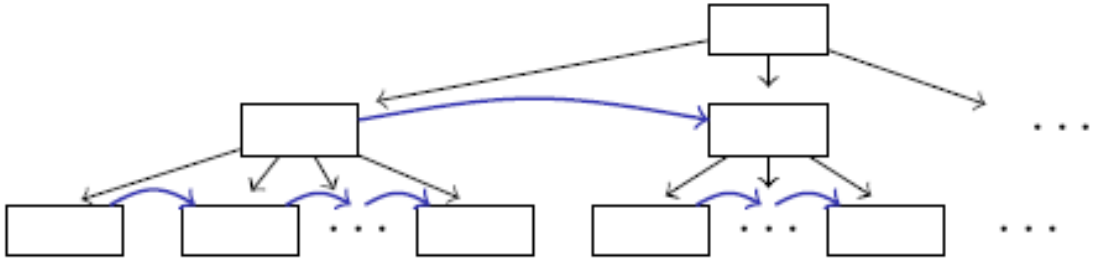
    d = 50 => every 50th insert causes a split (2% chance).
- An insert transaction could thus optimistically assume that no leaf split is going to happen.
  - On inner nodes, only read locks acquired during tree navigation (plus a write lock on the affected leaf).
  - If assumption is wrong, re-traverse the tree and obtain write locks.

Discussion

- If a leaf split happens, the writer bails out without having done any changes to the tree, then starts a whole new attempt from scratch.
- The resulting executions are **correct**, even though this looks like re-locking some nodes (which is disallowed by WTL).
- The **drawback** of the optimistic variant is that, in case of a leaf node split, it throws away all the work it invested in the first attempt.
- A number of other protocol variations try to improve on that.

B$^+$-Trees without Read Locks

- Lehman and Yao [TODS vol. 6(4), 1981] proposed a protocol that does not need any read locks on B-tree nodes.
- Requirement: a `next` pointer, pointing to the right sibling.



- Linked list along the leaf level.
- Pointers provide a second path to find each node.
- This way, mis-guided (by concurrent splits) read operations can still find the node that they need.

Optimistic Concurrency Control

- So far, we've been rather **pessimistic**:
  - We've assumed the worst and prevented that from happening.
- In practice, conflict situations are not that frequent.
- **Optimistic concurrency control:** Hope for the best and only act in case of conflicts.

Optimistic Concurrency Control

- Handle transactions in three phases:
  1. **Read Phase:** Execute transaction, but do not write data back to disk immediately. Instead, collect updates in a private workspace.
  2. **Validation Phase:** When the transaction wants to commit, test whether its execution was correct. If it is not, abort the transaction.
  3. **Write Phase:** Transfer data from private workspace into database.

Validating Transactions

- Validation is typically implemented by looking at transactions'
  - **Read Sets** $RS(T_i)$: attributes read by transaction T_i
  - **Write Sets** $WS(T_i)$: attributes written by transaction T_i
- Backward-Oriented Optimistic Concurrency Control (BOCC):
  - Compare T against all committed transactions T_c.
  - Check succeeds if T_c committed before T started, or

$$RS(T) \cap WS(T_c) = \emptyset$$

- Forward-Oriented Optimistic Concurrency Control (FOCC):
  - Compare T against all running transactions T_r.
  - Check succeeds if

$$WS(T) \cap RS(T_r) = \emptyset$$

Multi-version Concurrency Control

- Consider the schedule

$$r_1(x), w_1(x), r_2(x), w_2(y), r_1(y), w_1(z)$$

(t ↓ between $r_2(x)$ and $w_2(y)$)

- Now suppose that when T_1 wants to read y, we still had the "old" value of y (valid at time t) around.
- We could then create a history equivalent to

$$r_1(x), w_1(x), r_2(x), r_1(y), w_2(y), w_1(z)$$

which is serializable.

Multi-version Concurrency Control

- With old object versions still around, read transactions need no longer be blocked.
- They might see outdated, but consistent versions of data.
- Problem: Versioning requires space and management overhead (garbage collection).

Multi-version Concurrency Control

- Maintain multiple versions of each database object o, each with a write timestamp (WTS(o)) and a read timestamp (RTS(o)).
- Transaction T_i can read the most recent version whose timestamp precedes $TS(T_i)$.
- If T_i wants to write an object o, we must ensure that o has not been read by another transaction T_j such that $TS(T_i) < TS(T_j)$. Otherwise, T_i's change should have been seen by T_j for serializability, but it's too late for that. To handle this:
  - Whenever a transaction T_j reads an object o, the RTS(o) is set to max(current RTS(o), $TS(T_j)$).
  - If T_i wants to write an object o and $TS(T_i) < RTS(o)$, T_i is aborted and restarted with a new larger timestamp.
  - Otherwise, T_i creates a new version of o (say o'), and sets RTS(o') = $TS(T_i)$ and WTS(o') = $TS(T_i)$.

Summary

- **ACID and Serializability**
  - To prevent from different types of anomalies, DBMSs guarantee ACID properties. Serializability is a sufficient criterion to guarantee isolation.
- **Two-Phase Locking**
  - Two-phase locking is a practical technique to guarantee serializability. Most systems implement strict 2PL. SQL 92 allows explicit relaxation of the ACID isolation constraints in the interest of performance.
- **Other Concurrency Control Issues**
  - B-trees: Specialized protocols exist for concurrency control in B-trees (the root would be a locking bottleneck otherwise).
  - Optimistic concurrency control
  - Multi-version concurrency control