

Advanced Databases

Concurrency Control

Nikolaus Augsten

nikolaus.augsten@plus.ac.at
Department of Computer Science
University of Salzburg



WS 2023/24

Version 21. November 2023

Adapted from slides for textbook “Database System Concepts”
by Silberschatz, Korth, Sudarshan <http://codex.cs.yale.edu/avi/db-book/db6/slide-dir/index.html>

Outline

- 1 Lock-Based Protocols
- 2 Timestamp-Based Protocols
- 3 Validation-Based Protocols
- 4 Multiversion Schemes
- 5 Insert, Delete, and Concurrency in Indexes
- 6 Weak Levels of Consistency

Outline

- 1 Lock-Based Protocols
- 2 Timestamp-Based Protocols
- 3 Validation-Based Protocols
- 4 Multiversion Schemes
- 5 Insert, Delete, and Concurrency in Indexes
- 6 Weak Levels of Consistency

Lock-Based Protocols/1

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

Lock-Based Protocols/2

- Lock-compatibility matrix

	<i>S</i>	<i>X</i>
<i>S</i>	<i>true</i>	<i>false</i>
<i>X</i>	<i>false</i>	<i>false</i>

- A transaction may be granted a lock on an item if the requested lock is **compatible with locks already held** on the item by other transactions.
- **Any number** of transactions **can hold shared locks** on an item,
- **If any transaction holds an exclusive lock** on the item **no other transaction may hold** any lock on the item.
- **If a lock cannot be granted**, the requesting transaction is made to **wait** till all incompatible locks held by other transactions have been released. The lock is then granted.

Lock-Based Protocols/3

- Example of a transaction performing locking:

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

- Locking as above is **not sufficient to guarantee serializability** — if A and B get updated in-between the read of A and B , the displayed sum would be wrong.
- A **locking protocol** is a set of rules followed by all transactions while requesting and releasing locks. Locking protocols restrict the set of possible schedules.

The Two-Phase Locking Protocol/1

- This protocol ensures **conflict-serializable schedules**.
- Phase 1: **Growing Phase**
 - Transaction may obtain locks
 - Transaction may not release locks
- Phase 2: **Shrinking Phase**
 - Transaction may release locks
 - Transaction may not obtain locks
- The protocol **assures serializability**. It can be shown that the transactions can be serialized in the **order of their lock points** (i.e., the point where a transaction acquired its final lock).

The Two-Phase Locking Protocol/2

- There can be **conflict serializable schedules** that cannot be obtained if two-phase locking is used.
- However, in the absence of extra information (e.g., ordering of access to data), two-phase locking is **needed for conflict serializability**.

Lock Conversions

- Two-phase locking with **lock conversions**:
 - First Phase:
 - can acquire **lock-S** on item
 - can acquire **lock-X** on item
 - can convert **lock-S** to **lock-X** (upgrade)
 - Second Phase:
 - can release **lock-S** on item
 - can release **lock-X** on item
 - can convert **lock-X** to **lock-S** (downgrade)
- This protocol **assures serializability**. But still relies on the programmer to insert the various locking instructions.

Automatic Acquisition of Locks/1

- A transaction T_i issues the standard read/write instruction, **without explicit locking calls**.
- The operation $read(D)$ is processed as:
 - if** T_i has a lock on D **then**
 - $read(D)$
 - else begin**
 - if necessary wait until no other transaction has a **lock-X** on D
 - grant T_i a **lock-S** on D
 - $read(D)$
 - end**
- end if**

Automatic Acquisition of Locks/2

- $write(D)$ is processed as:
 - if** T_i has a **lock-X** on D **then**
 - $write(D)$
 - else begin**
 - if necessary wait until no other transaction has any lock on D
 - if** T_i has a **lock-S** on D **then**
 - upgrade** lock on D to **lock-X**
 - else**
 - grant T_i a **lock-X** on D
 - end if**
 - $write(D)$
 - end**
 - end if**
- All locks are released after commit or abort

Deadlocks/1

- Consider the partial schedule

T_3	T_4
$lock-x(B)$	
$read(B)$	
$B := B - 50$	
$write(B)$	
	$lock-s(A)$
	$read(A)$
	$lock-s(B)$
$lock-x(A)$	

- Neither T_3 nor T_4 can make progress — executing **lock-S**(B) causes T_4 to wait for T_3 to release its lock on B , while executing **lock-X**(A) causes T_3 to wait for T_4 to release its lock on A .
- Such a situation is called a **deadlock**.
- To handle deadlock, one of T_3 or T_4 must be **aborted** and its **locks released**.

Deadlocks/2

- Two-phase locking **does not ensure freedom from deadlocks.**
- In addition to deadlocks, there is a possibility of starvation.
- **Starvation** occurs if the concurrency control manager is badly designed. For example:
 - A transaction may be **waiting for an X-lock** on an item, while a sequence of other transactions request and are **granted an S-lock** on the same item.
 - The same transaction is **repeatedly rolled back** due to deadlocks.
- Concurrency control manager **can be designed to prevent starvation.**

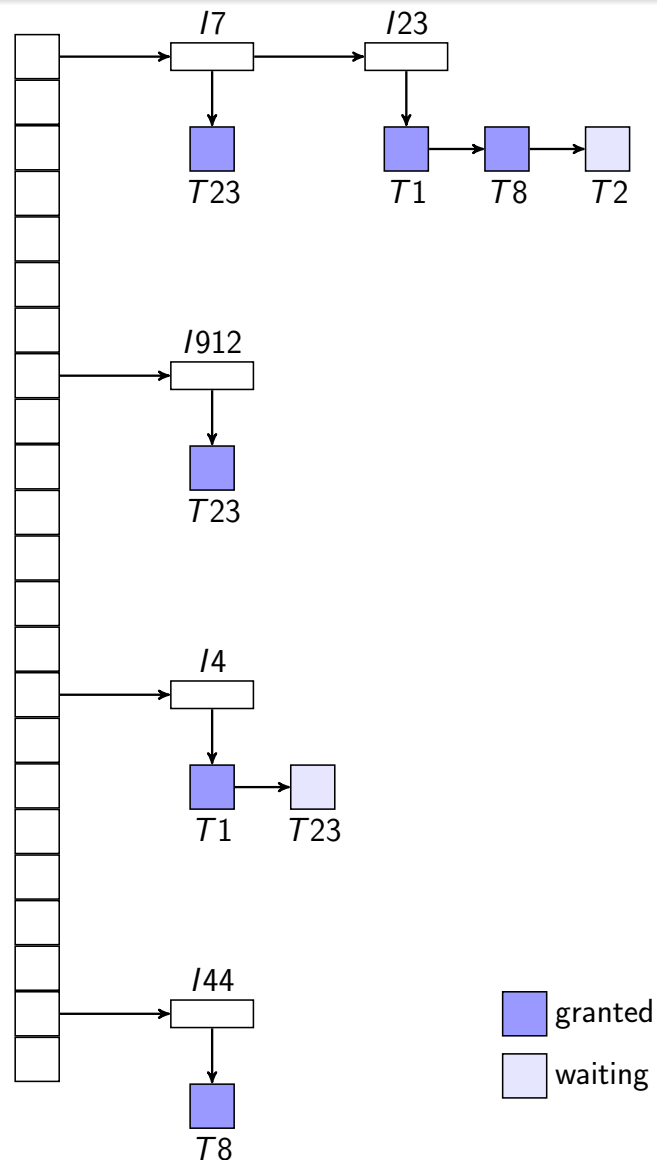
Deadlocks/3

- The **potential for deadlock exists in most** locking protocols. Deadlocks are a necessary evil.
- When a deadlock occurs there is a possibility of **cascading rollbacks**.
- Cascading roll-back is possible under two-phase locking. To avoid this, follow a modified protocol called **strict two-phase locking** — a transaction must hold all its exclusive locks till it commits/aborts.
- **Rigorous two-phase locking** is even stricter. Here, all locks are held till commit/abort. In this protocol transactions can be serialized in the order in which they commit.

Implementation of Locking

- A **lock manager** can be implemented as a separate process to which transactions send lock and unlock requests
- The lock manager replies to a lock request by sending a **lock grant messages** (or a message asking the transaction to roll back, in case of a deadlock)
- The **requesting transaction waits** until its request is answered
- The lock manager maintains a data-structure called a **lock table** to record granted locks and pending requests
- The lock table is usually implemented as an **in-memory hash table** indexed on the name of the data item being locked

Lock Table



- Dark blue rectangles indicate **granted locks**; light blue indicate **waiting requests**
- Lock table also records the **type of lock** granted or requested
- **New request is added to the end** of the queue of requests for the data item, and granted if it is compatible with all earlier locks
- **Unlock requests** result in the **request being deleted**, and later requests are checked to see if they can now be granted
- If **transaction aborts**, **all waiting or granted requests** of the transaction are **deleted**
 - lock manager may **keep a list of locks** held by each transaction, to implement this efficiently

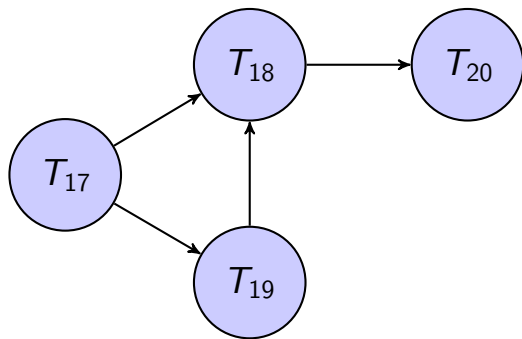
Deadlock Handling

- A system is **deadlocked** if there is a set of transactions such that every transaction in the set is **waiting for another** transaction in the set.
- How to deal with deadlocks?
 1. **Detection and Recovery**: Allow deadlocks to happen and recover from them.
 2. **Prevention**: Ensure that the system will never enter into a deadlock state.

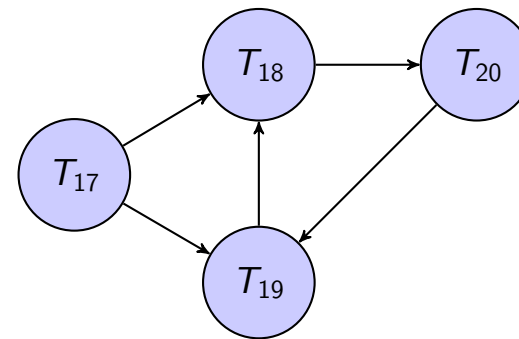
Deadlock Detection/1

- Deadlocks can be described as a **wait-for graph**, which consists of a pair $G = (V, E)$,
 - V is a set of **vertices** (all the **transactions** in the system)
 - E is a set of **edges**; each element is an **ordered pair** $T_i \rightarrow T_j$.
- If $T_i \rightarrow T_j$ is in E , then there is a **directed edge** from T_i to T_j , implying that T_i is **waiting for** T_j to release a data item.
- When T_i **requests** a data item currently being held by T_j , then the edge $T_i \rightarrow T_j$ is **inserted** in the wait-for graph. This edge is **removed** only when T_j is **no longer holding** a data item needed by T_i .
- The system is in a **deadlock state** if and only if the **wait-for graph has a cycle**. Must invoke a deadlock-detection algorithm periodically to look for cycles.

Deadlock Detection/2



Wait-for graph without a cycle



Wait-for graph with a cycle

Deadlock Recovery

- When deadlock is detected:
 - **Pick a victim:** Some transaction will have to be rolled back (made a victim) to break deadlock.
 - select that transaction as victim that will **incur minimum cost**
 - **starvation** happens if same transaction is always chosen as victim
 - include the **number of rollbacks** in the cost factor to avoid starvation
 - **How far to roll back** victim transaction?
 - **total rollback:** abort the transaction and then restart it
 - more efficient to roll back transaction only **as far as necessary** to break deadlock

Deadlock Prevention Strategies/1

1. **Predeclaration:** Require that each transaction **locks all its data items** before it begins execution.

2. **Lock Order:**

- Impose a (partial) order on all data items. Transaction can **lock only in the specified order**.
- Works also with **2PL** if data items are always locked in ascending order.
 - easy to implement on top of existing 2PL implementation
 - problem: need to know data items to be locked upfront

Deadlock Prevention Strategies/2

3. Preemptive and non-preemptive based on timestamps:

- Use **transaction timestamps** for the sake of deadlock prevention alone.
- **Preemption**: steal lock from a transaction that currently holds the lock by aborting it.
- **Two schemes**:
 - **wait-die** scheme – non-preemptive
 - **wound-wait** scheme – preemptive

Deadlock Prevention Strategies/3

- **Wait-Die:** non-preemptive
 - older transaction may wait for younger one to release data item (older means smaller timestamp).
 - Younger transactions never wait for older ones; they are rolled back instead.
- **Wound-Wait:** preemptive
 - older transaction wounds (forces rollback) younger transaction instead of waiting for it.
 - Younger transactions may wait for older ones.
- Both in wait-die and in wound-wait schemes, a rolled back transactions is restarted with its original timestamp.
- Older transactions thus have precedence over newer ones, and starvation is hence avoided.

Deadlock Prevention Strategies/4

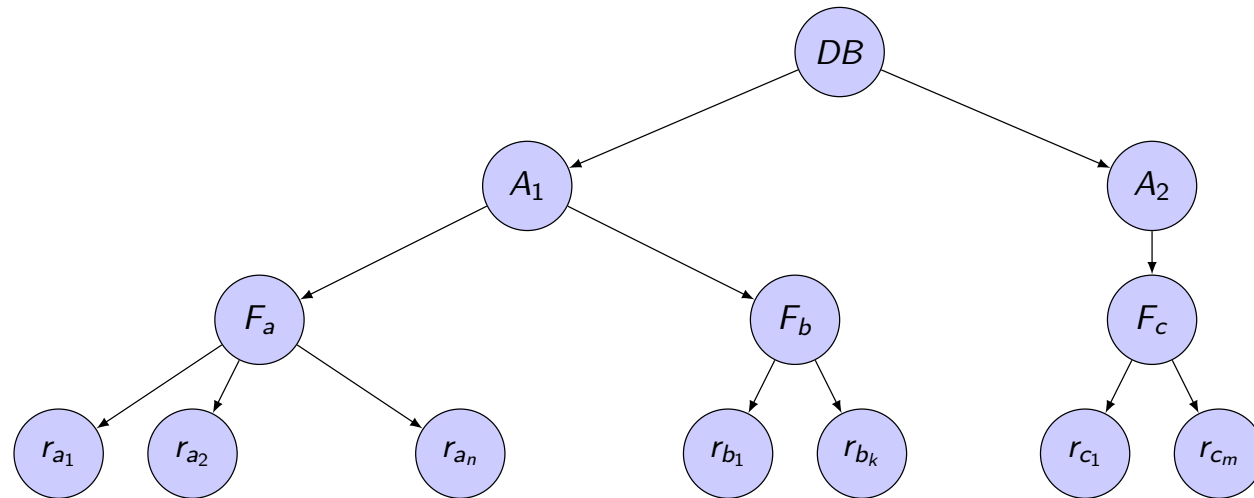
4. Timeout-Based schemes:

- A transaction **waits** for a lock only for a **specified amount of time**.
- If the lock has not been granted within that time, the transaction is rolled back and restarted.
- Thus, **deadlocks are not possible**.
- Easy to implement, but **starvation is possible**.
- Also difficult to determine good value of the timeout interval.

Multiple Granularity

- Define a **hierarchy of data item granularities**, where the small granularities are nested within larger ones.
- Can be represented graphically as a **tree**.
- When a transaction locks a node in the tree explicitly, it **implicitly locks all** the node's **descendants** in the same mode.
- Granularity of locking (level in tree where locking is done):
 - **fine granularity** (lower in tree): high concurrency, high locking overhead
 - **coarse granularity** (higher in tree): low locking overhead, low concurrency

Example of Granularity Hierarchy



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

- database
- area
- file
- record

Intention Lock Modes

- In addition to S and X lock modes, there are **three additional lock modes** with multiple granularity.
- If a node n is locked in mode
 - **intention-shared (IS)**, then at least one lower-level subtree of n is locked in shared mode;
 - **intention-exclusive (IX)**, then at least one lower-level subtree of n is locked in exclusive mode;
 - **shared and intention-exclusive (SIX)**: then n is locked in shared mode and a at least one lower-level subtree of n is locked in exclusive mode.
- **Intention locks** (or their absence) allow a higher level node to be locked in S or X mode **without** having to **check all descendent nodes**.

Compatibility Matrix with Intention Lock Modes

- The **compatibility matrix** for all lock modes is:

	<i>IS</i>	<i>IX</i>	<i>S</i>	<i>SIX</i>	<i>X</i>
<i>IS</i>	<i>true</i>	<i>true</i>	<i>true</i>	<i>true</i>	<i>false</i>
<i>IX</i>	<i>true</i>	<i>true</i>	<i>false</i>	<i>false</i>	<i>false</i>
<i>S</i>	<i>true</i>	<i>false</i>	<i>true</i>	<i>false</i>	<i>false</i>
<i>SIX</i>	<i>true</i>	<i>false</i>	<i>false</i>	<i>false</i>	<i>false</i>
<i>X</i>	<i>false</i>	<i>false</i>	<i>false</i>	<i>false</i>	<i>false</i>

Multiple Granularity Locking Scheme

- Transaction T_i can lock a node Q , using the following rules:
 1. The lock compatibility matrix must be observed.
 2. The root of the tree must be locked first, and may be locked in any mode.
 3. A node Q can be locked by T_i in S or IS mode only if the parent of Q is currently locked by T_i in either IX or IS mode.
 4. A node Q can be locked by T_i in X , SIX , or IX mode only if the parent of Q is currently locked by T_i in either IX or SIX mode.
 5. T_i can lock a node only if it has not previously unlocked any node (that is, T_i is two-phase).
 6. T_i can unlock a node Q only if none of the children of Q are currently locked by T_i .
- Observe that locks are acquired in root-to-leaf order, whereas they are released in leaf-to-root order.
- Lock granularity escalation: in case there are too many locks at a particular level, switch to higher granularity S or X lock

Outline

- 1 Lock-Based Protocols
- 2 Timestamp-Based Protocols**
- 3 Validation-Based Protocols
- 4 Multiversion Schemes
- 5 Insert, Delete, and Concurrency in Indexes
- 6 Weak Levels of Consistency

Timestamp-Based Protocols/1

- Each transaction is issued a timestamp when it enters the system. If an old transaction T_i has time-stamp $TS(T_i)$, a new transaction T_j is assigned time-stamp $TS(T_j)$ such that $TS(T_i) < TS(T_j)$.
- The protocol manages concurrent execution such that the time-stamps determine the serializability order.
- In order to assure such behavior, the protocol maintains for each data Q two timestamp values:
 - $W\text{-timestamp}(Q)$ is the largest time-stamp of any transaction that executed **write(Q)** successfully.
 - $R\text{-timestamp}(Q)$ is the largest time-stamp of any transaction that executed **read(Q)** successfully.

Timestamp-Based Protocols/2

- The timestamp ordering protocol ensures that any conflicting **read** and **write** operations are **executed in timestamp order**.
- Suppose a transaction T_i issues a **read(Q)**
 1. If $TS(T_i) < W\text{-timestamp}(Q)$, then T_i needs to read a value of Q that was **already overwritten**.
 - Hence, the **read** operation is rejected, and T_i is **rolled back**.
 2. Otherwise, the **read operation is executed**, and $R\text{-timestamp}(Q)$ is set to $\max(R\text{-timestamp}(Q), TS(T_i))$.

Timestamp-Based Protocols/3

- Suppose that transaction T_i issues **write(Q)**.
 1. If $TS(T_i) < R\text{-timestamp}(Q)$, then the **value of Q** that T_i is producing **was needed previously**, and the system assumed that that value would never be produced.
 - Hence, the **write(Q)** operation is **rejected**, and T_i is rolled back.
 2. If $TS(T_i) < W\text{-timestamp}(Q)$, then T_i is attempting to **write an obsolete value of Q**.
 - Hence, this **write(Q)** operation is **rejected**, and T_i is rolled back.
 3. Otherwise, the **write(Q)** operation is **executed**, and $W\text{-timestamp}(Q)$ is set to $TS(T_i)$.

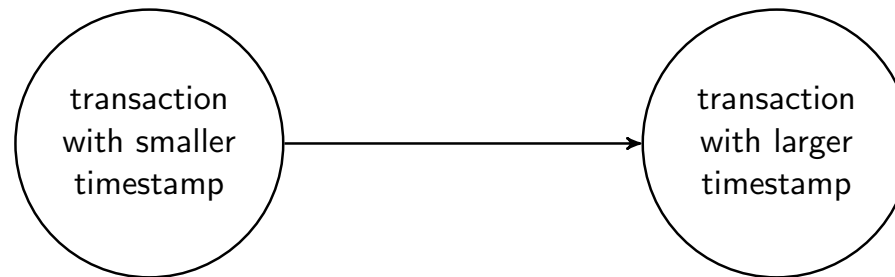
Example Use of the Protocol

A partial schedule for several data items for transactions with timestamps 1, 2, 3, 4, 5

T_1	T_2	T_3	T_4	T_5
	<i>read(Y)</i>			<i>read(X)</i>
<i>read(Y)</i>		<i>write(Y)</i> <i>write(Z)</i>		
	<i>read(Z)</i> <i>abort</i>			<i>read(Z)</i>
<i>read(X)</i>		<i>write(W)</i> <i>abort</i>	<i>read(W)</i>	
				<i>write(Y)</i> <i>write(Z)</i>

Correctness of Timestamp-Ordering Protocol

- The timestamp-ordering protocol **guarantees serializability** since all the arcs in the precedence graph are of the form:



- Timestamp protocol ensures **freedom from deadlock** as no transaction ever waits.
- But the schedule may **not be cascade-free**, and may **not even be recoverable**.

Timestamp-Ordering: Recoverability and Cascadeless

- **Read rule:** If $j > i$, then T_j is allowed to read a value written by T_i .
- Therefore, timestamp-ordering protocol allows:
 - **non-recoverable** schedules: T_j reads value of uncommitted T_i ; T_j commits before T_i
 - **cascading rollbacks:** T_j reads value of uncommitted T_i ; when T_i aborts then also T_j must abort
- **Solution 1:**
 - writes are all performed at the end of the transaction
 - the writes form an **atomic action**: no transaction can read any of the written values during write
 - a transaction that aborts is **restarted with a new timestamp**
- **Solution 2:** Limited form of locking: **wait for data** to be committed before reading it
- **Solution 3:** Use **commit dependencies** to ensure recoverability

Thomas' Write Rule

- Modified version of the timestamp-ordering protocol in which **obsolete write** operations **may be ignored** under certain circumstances.
- T_i attempts to write data item Q :
 - if $TS(T_i) < W\text{-timestamp}(Q)$, then T_i is attempting to write an obsolete value of Q
 - rather than rolling back T_i (as the timestamp ordering protocol would do), this **write** operation can be **ignored**
- Otherwise this protocol is the **same as the timestamp ordering protocol**.
- **Thomas' Write Rule** allows greater potential concurrency.
 - Allows **view-serializable schedules** that are not conflict serializable.
 - Any view-serializable schedule that is not conflict serializable has so-called **blind writes** (**write**(Q) without preceding **read**(Q))

Outline

- 1 Lock-Based Protocols
- 2 Timestamp-Based Protocols
- 3 Validation-Based Protocols**
- 4 Multiversion Schemes
- 5 Insert, Delete, and Concurrency in Indexes
- 6 Weak Levels of Consistency

Validation-Based Protocol/1

- Execution of transaction T_i is done in **three phases**:
 1. **Read and execution phase**: Transaction T_i writes only to temporary local variables.
 2. **Validation phase**: Transaction T_i performs a **validation test** to determine if local variables can be written without violating serializability.
 3. **Write phase**: If T_i is validated, the updates are applied to the database; otherwise, T_i is rolled back.

Validation-Based Protocol/2

- Each transaction must go through the three phases in that order.
- The three phases of concurrently executing transactions can be **interleaved**.
- Assume for simplicity that the validation and write phase occur together, atomically and serially, i.e., **only one transaction** executes validation/write at a time.
- Also called **optimistic concurrency control** since transaction executes fully in the hope that all will go well during validation

Validation Test for Transaction T_j

- **Validation test:** If for all T_k with $validation(T_k) < validation(T_j)$ one of the following holds:
 - $finish(T_k) < start(T_j)$
 - $start(T_j) < finish(T_k) < validation(T_j)$ and the set of data items written by T_k **does not intersect** with the set of data items read by T_j
- then validation succeeds and T_j can be committed.
- If validation fails, T_j is aborted.
 - **Justification:** Either the first condition is satisfied, and there is no overlapping execution, or the second condition is satisfied and
 - the writes of T_j do not affect reads of T_k since they occur after T_k has finished its reads
 - the writes of T_k do not affect reads of T_j since T_j does not read any item written by T_k

Schedule Produced by Validation

- Example of schedule produced using validation

T_{25}	T_{26}
$read(B)$	$read(B)$
	$B := B - 50$
	$read(A)$
	$A := A + 50$
$read(A)$	
$\langle validate \rangle$	
$display(A + B)$	
	$\langle validate \rangle$
	$write(B)$
	$write(A)$

Outline

- 1 Lock-Based Protocols
- 2 Timestamp-Based Protocols
- 3 Validation-Based Protocols
- 4 Multiversion Schemes**
- 5 Insert, Delete, and Concurrency in Indexes
- 6 Weak Levels of Consistency

Multiversion Schemes

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

Multiversion Timestamp Ordering/1

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

Multiversion Timestamp Ordering/2

- For a transaction T_i , Q_k is the **version of Q** with the largest write timestamp less than or equal to $TS(T_i)$.
- T_i .**read(Q)** returns the content of version Q_k .
- T_i .**write(Q)**:
 1. if $TS(T_i) < R\text{-timestamp}(Q_k)$, then transaction T_i is **rolled back**.
 2. if $TS(T_i) = W\text{-timestamp}(Q_k)$, the contents of Q_k are **overwritten**
 3. else a **new version** of Q is created.

Multiversion Timestamp Ordering/3

- Reads always succeed \Rightarrow fewer aborts than TSO without versions.
- A write by T_i is **rejected** if some other transaction T_j that (in the serialization order defined by the timestamps) should read T_i 's write, has already read a version created by a transaction older than T_i .
- Multiversion Timestamp Ordering schedules are
 - **serializable**
 - **not recoverable** (extension to recoverable and cascadeless schedules like for timestamp-based protocol)

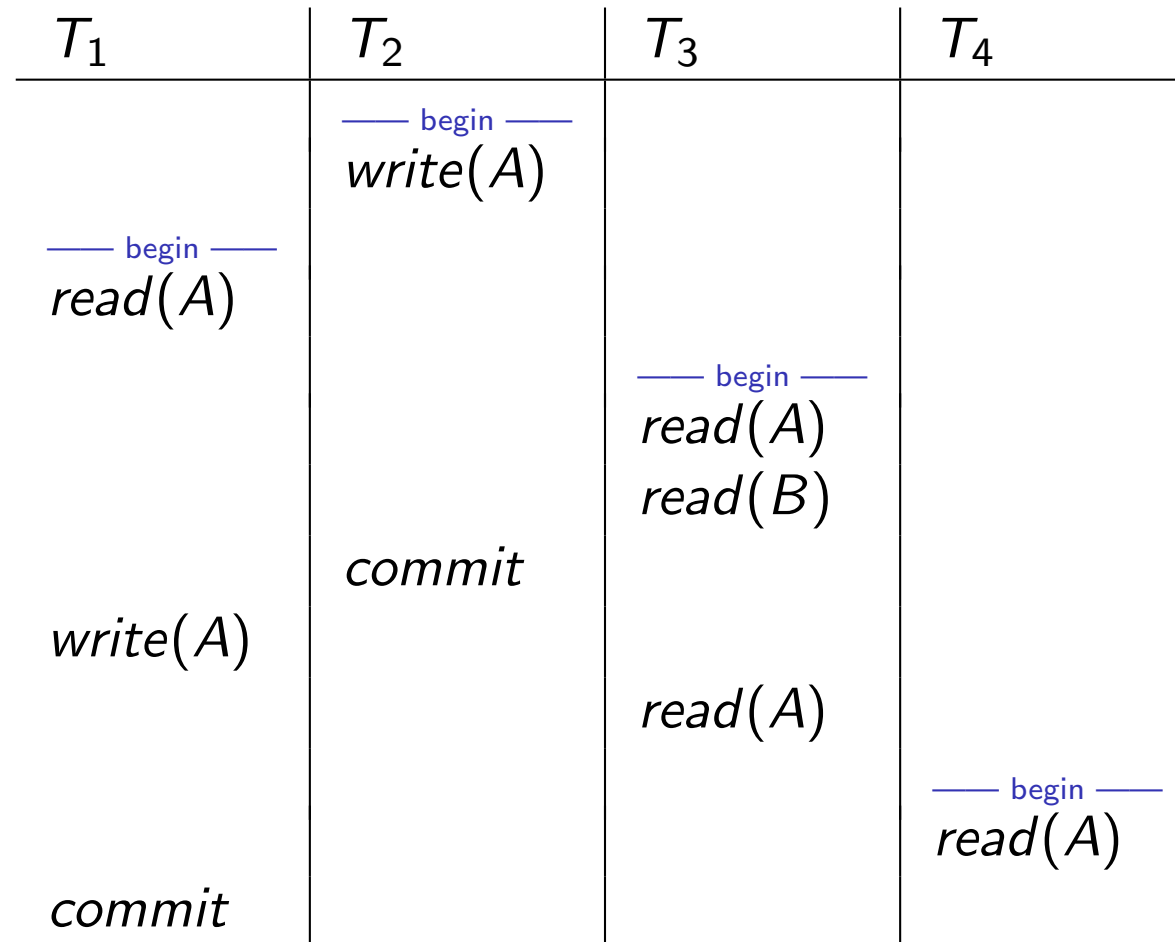
Multiversion Two-Phase Locking/1

- Differentiates between **read-only** and **update** transactions.
- **Update transactions:**
 - Follow **rigorous two-phase locking**: Acquire locks for reads and writes, and hold all locks up to the end of the transaction.
 - Each successful **write** creates a **new version** of the data item written.
 - Each **version** of a data item has a **single timestamp** whose value is obtained from a counter **ts-counter** that is incremented during commit processing.
- **Read-only transactions** are assigned a timestamp by reading the current value of ts-counter before they start execution; they **follow the multiversion timestamp-ordering protocol** for performing reads.

Multiversion Two-Phase Locking/2

- When an update transaction wants to **read a data item**:
 - it obtains a **shared lock** on it, and **reads the latest version**.
- When an update transaction wants to **write an item**
 - it obtains **X-lock** on the item, then creates a **new version** of the item, finally sets this version's **timestamp to ∞** .
- When update transaction T_i completes, **commit processing** occurs:
 - T_i sets timestamp on the versions it has created to **$ts-counter + 1$**
 - T_i increments **$ts-counter$** by 1
- Read-only transactions that **start after T_i increments $ts-counter$** will see the values **updated by T_i** .
- Read-only transactions that **start before T_i increments the $ts-counter$** will see the value **before the updates by T_i** .
- Only **serializable schedules** are produced.

Multiversion Two-Phase Locking Example



MVCC: Implementation Issues

- Creation of multiple versions **increases storage overhead**
 - Extra tuples.
 - Extra space in each tuple for storing version information
- Versions can, however, be **garbage collected**,
 - e.g. if Q has two versions Q_5 and Q_9 , and the oldest active transaction has *timestamp* > 9 , then Q_5 will never be required again.

Snapshot Isolation/1

- **Motivation:** Concurrent OLAP and OLTP queries.
 - OLAP (online analytic processing) queries read large amounts of data.
 - OLTP (online transaction processing) transactions update a few rows.
 - Combination results in many **concurrency conflicts** and **poor performance**.
- **Solution 1:** Give logical “snapshot” of database **state to read only transactions**, read-write transactions use normal locking.
 - **multiversion 2-phase locking**
 - works well, but how does system know a transaction is read only?
- **Solution 2:** Give **snapshot** of database state **to every transaction**, only updates use 2-phase locking.
 - **problem:** variety of anomalies such as lost update can result
- **Solution 3: Snapshot isolation** (next slide).
 - proposed by Berenson et al. (SIGMOD 1995)
 - variants implemented in many database systems (e.g. Oracle, PostgreSQL, SQL Server 2005)

Snapshot Isolation/2

- A transaction T_1 executing with Snapshot Isolation
 - takes snapshot of committed data at start
 - always reads/modifies data in its own snapshot
 - updates of concurrent transactions are not visible to T_1
 - writes of T_1 complete when it commits
 - First-committer-wins rule:
 - Commits only if no other concurrent transaction has already written data that T_1 intends to write.

Initial values: $X = 0, Y = 0, Z = 0$		
T_1	T_2	T_3
$W(Y := 1)$ Commit		
	Start $R(Y) \rightarrow 1$ $W(Y := 2)$	
		$W(X := 2)$ $W(Z := 3)$ Commit
	$R(Z) \rightarrow 0$ $R(Y) \rightarrow 2$ $W(X := 3)$ Commit-Req Abort	

Concurrent updates not visible
Own updates are visible
Not first-committer of X

Serialization error, T_2 is rolled back

Snapshot Read

- Concurrent updates invisible to snapshot read
- $X_0 = 100, Y_0 = 0$

T_1 deposits 50 in Y	T_2 withdraws 50 from X
$r_1(X_0, 100)$ $r_1(Y_0, 0)$	$r_2(Y_0, 0)$ $r_2(X_0, 100)$ $w_2(X_2, 50)$
$w_1(Y_1, 50)$ $r_1(X_0, 100)$ (update by T_2 not visible) $r_1(Y_1, 50)$ (can see its own updates)	$r_2(Y_0, 0)$ (update by T_1 not visible)

- $X_2 = 50, Y_1 = 50$

Snapshot Write: First Committer Wins

T_1 deposits 50 in X	T_2 withdraws 50 from X
$r_1(X_0, 100)$	$r_2(X_0, 100)$
$w_1(X_1, 150)$	$w_2(X_2, 50)$
$commit_1$	$commit_2$ (Serialization Error T_2 is rolled back)

- Variant: "First-updater-wins"
 - Check for concurrent updates when write occurs by locking item
 - but lock should be held till all concurrent transactions have finished
 - Differs only in when abort occurs, otherwise equivalent

Benefits of Snapshot Isolation

- Reading is **never blocked**,
 - and also **doesn't block** other transactions' activities
- Performance similar to **Read Committed**
- **Avoids the usual anomalies**
 - No dirty read
 - No lost update
 - No non-repeatable read
 - Predicate based selects are repeatable (no phantoms)
- **Problems with snapshot isolation**
 - Snapshot isolation does not always give serializable executions
 - Serializable: among two concurrent transactions, one sees the effects of the other
 - In snapshot isolation: neither sees the effects of the other
 - Result: **Integrity constraints can be violated**

Snapshot Isolation/3

- Example of problem with snapshot isolation
 - $T1 : x := y$
 - $T2 : y := x$
 - Initially $x = 3$ and $y = 17$
 - Serial execution: $x = ??, y = ??$
 - if both transactions start at the same time, with snapshot isolation:
 $x = ??, y = ??$
- Called *skew write*
- Skew also occurs with *inserts*, e.g., a query that creates order numbers as follows:
 - Find max order number among all orders
 - Create a new order with $ordernumber = previousmax + 1$

Snapshot Isolation Anomalies

- Snapshot isolation **breaks serializability** when transactions modify different items, each based on a previous state of the item the other modified
 - not very common in practice
 - for example, the TPC-C benchmark runs correctly under snapshot isolation
 - when transactions conflict due to modifying different data, there is usually also a shared item they both modify too (like a total quantity) so SI will abort one of them
 - but does occur
 - application developers should be careful about write skew
- Using **snapshots** to verify primary/foreign key integrity **can lead to inconsistency**
 - integrity constraint checking usually done outside of snapshot

Snapshot Isolation in Oracle and PostgreSQL/1

- **Warning:** Snapshot isolation is used when isolation level is set to serializable in Oracle and PostgreSQL (versions prior to 9.1)
- Oracle implements "first updater wins" rule
 - concurrent writer check is done at time of write, not at commit time
 - allows transactions to be rolled back earlier
 - Oracle and PostgreSQL < 9.1 do not support true serializable execution
- PostgreSQL 9.1 introduced "Serializable Snapshot Isolation" (SSI)
 - guarantees true serializability

Snapshot Isolation in Oracle and PostgreSQL/2

- Can sidestep snapshot isolation for specific queries by using **select .. for update** in Oracle and PostgreSQL
- Select for update (SFU) **treats all data read** by the query **as if** it were also **updated**, preventing concurrent updates.
- Example transaction:
 1. **select max (orderno) from orders for update**
 2. read value into local variable *maxorder*
 3. insert into orders (*maxorder* + 1, ...)

Outline

- 1 Lock-Based Protocols
- 2 Timestamp-Based Protocols
- 3 Validation-Based Protocols
- 4 Multiversion Schemes
- 5 Insert, Delete, and Concurrency in Indexes**
- 6 Weak Levels of Consistency

Insert and Delete Operations/1

- If **two-phase locking** is used:
 - A **delete operation** may be performed only if the transaction deleting the tuple has an **exclusive lock on the tuple** to be deleted.
 - A transaction that **inserts a new tuple** into the database is given an **X-mode lock on the tuple**
- Insertions and deletions can lead to the **phantom phenomenon**:
 - T_1 **scans a relation r** (e.g., find sum of balances of all accounts in Perryridge).
 - T_2 **inserts a tuple** into relation r (e.g., insert a new account at Perryridge).
 - T_1 and T_2 **(conceptually) conflict** in spite of not accessing any tuple in common.
- If **only tuple locks** are used, **non-serializable schedules** can result
 - for example, the scan transaction T_1 does not see the new account, but reads some other tuple updated by transaction T_2

Insert and Delete Operations/2

- The **transaction scanning** the relation is **reading information** that indicates what tuples the relation contains, while a **transaction inserting** a tuple **updates the same information**.
 - The conflict should be detected, e.g. by **locking the information**.
- **One solution:**
 - Associate a **data item X** with the relation, to represent the information about what tuples the relation contains.
 - Transactions scanning the relation acquire a **shared lock** on X .
 - Transactions inserting or deleting a tuple acquire an **exclusive lock** on data item X .
 - **Note:** locks on X do not conflict with locks on individual tuples.
- Above protocol provides **very low concurrency** for insertions/deletions.
- **Index locking protocol**
 - prevents the phantom phenomenon
 - provide higher concurrency

Index Locking Protocol

- Index locking protocol:
 - Every relation must have at least one index.
 - A transaction can access tuples only after finding them through one or more indices on the relation.
 - A transaction T_i that performs a lookup must lock all the index leaf nodes that it accesses, in S-mode
 - even if the leaf node does not contain any tuple satisfying the index lookup (e.g. for a range query, no tuple in a leaf is in the range)
 - A transaction T_i that inserts, updates, or deletes a tuple t_i in relation r
 - must update all indices of r
 - must obtain exclusive locks on all index leaf nodes affected by the insert/update/delete
 - The rules of the two-phase locking protocol must be observed
- Guarantees that the phantom phenomenon won't occur

Next-Key Locking

- **Problem** with index-locking protocol:
 - to prevent phantom reads the entire index leaf must be locked
 - results in **poor concurrency** if there are many inserts
- **Alternative:** for an index lookup
 - **Lock all key values** that satisfy index lookup (i.e., match lookup value or fall into lookup range).
 - **Lock next key value** in index (after lookup value or range) as well.
 - **Lock mode:** S for lookups, X for insert/delete/update.
- Ensures that **range queries will conflict** with inserts/deletes/updates
 - regardless of which happens first, as long as both are concurrent

Concurrency in Index Structures/1

- Indices are unlike other database items in that their only job is to **help in accessing data**.
- Index-structures are typically **accessed very often**, much more than other database items.
 - Treating index-structures like other database items, e.g. by 2-phase locking of index nodes can **lead to low concurrency**.
- There are several index concurrency protocols where **locks** on internal nodes are **released early**, and not in a two-phase fashion.
 - It is acceptable to have **nonserializable concurrent access** to an index as long as the **accuracy** of the index **is maintained**.
 - In particular, the exact values read in an internal node of a B^+ -tree are irrelevant so long as we land up in the **correct leaf node**.

Concurrency in Index Structures/2

- **Crabbing protocol** for $B+$ -trees. During search/insertion/deletion:
 - first **lock the root** node in shared mode.
 - after **locking all required children** of a node in shared mode, **release** the lock on the **node**.
 - during insertion/deletion, **upgrade leaf node locks** to exclusive mode.
 - when splitting or coalescing requires changes to a parent, **lock the parent** in exclusive mode.
- The crabbing protocol can cause **deadlocks**
 - searches coming down the tree deadlock with updates going up the tree
 - can abort and restart search, without affecting transaction
- **B -link tree protocol:**
 - Intuition: release lock on parent before acquiring lock on child
 - Deal with changes that may have happened between lock release and acquire.
 - Requires forward links between sibling nodes in $B+$ -tree (in addition to the forward links between leaves that exist anyways).

Outline

- 1 Lock-Based Protocols
- 2 Timestamp-Based Protocols
- 3 Validation-Based Protocols
- 4 Multiversion Schemes
- 5 Insert, Delete, and Concurrency in Indexes
- 6 Weak Levels of Consistency

Weak Levels of Consistency

- **Degree-two consistency:** differs from two-phase locking in that *S*-locks may be released at any time, and locks may be acquired at any time
 - X-locks must be **held till end** of transaction
 - **Serializability is not guaranteed**, programmer must ensure that no erroneous database state will occur
- **Cursor stability:**
 - For reads, each tuple is locked, read, and **lock is immediately released**
 - X-locks are **held till end** of transaction
 - Special case of **degree-two consistency**

Weak Levels of Consistency in SQL

- SQL allows **non-serializable executions**
 - **Repeatable read**: allows only committed records to be read, and **repeating** a read should return the same value (so read locks should be retained)
 - however, the **phantom phenomenon need not be prevented**
 - T_1 may see some records inserted by T_2 , but may not see others inserted by T_2 .
 - **Read committed**: same as **degree two consistency**, but most systems implement it as cursor-stability.
 - **Read uncommitted**: allows even uncommitted data to be read
- In many database systems, read committed is the default consistency level.
- The isolation level can be changed when required:
SET TRANSACTION ISOLATION LEVEL SERIALIZABLE

Transactions across User Interaction/1

- Many applications need transaction support across user interactions
 - Can't use locking
 - Don't want to reserve database connection per user
- Application level concurrency control
 - Each tuple has a **version number**
 - Transaction notes version number when reading tuple
 - **select** *r.balance, r.version* **into** *:A, :version*
from *r* **where** *acctId = 23*
 - When writing tuple, **check that current version number** is same as the version when tuple was read
 - **update** *r* **set** *r.balance = r.balance + :deposit*
where *acctId = 23 and r.version = :version*

Transactions across User Interaction/2

- Equivalent to optimistic concurrency control without validating read set
- Used internally in Hibernate ORM system, and manually in many applications
- Unlike snapshot isolation, reads are not guaranteed to be from a single snapshot.