Advanced Databases

Concurrency Control

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by Silberschatz, Korth, Sudarshanhttp://codex.cs.yale.edu/avi/db-book/db6/slide-dir/index.html

Outline

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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

	S	X
S	*true*	*false*
X	*false*	*false*

- 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.

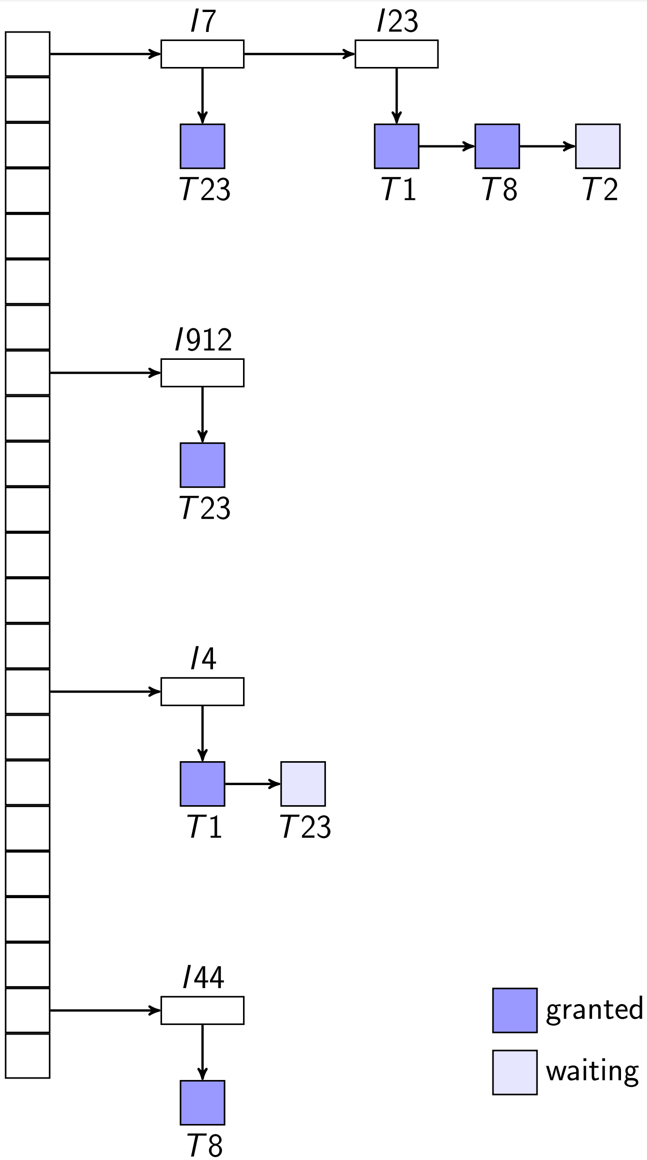
Deadlocks/3

- 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

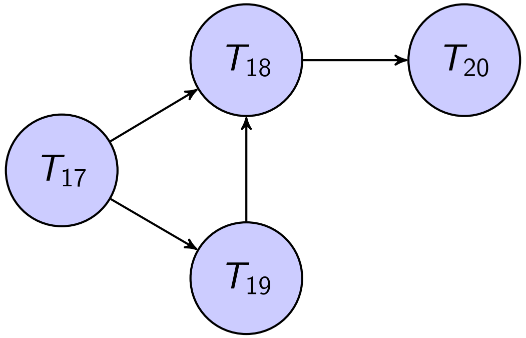
- A system is deadlocked if there is a set of transactions such that every transaction in the set is waiting for another transaction in the set.

- 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.

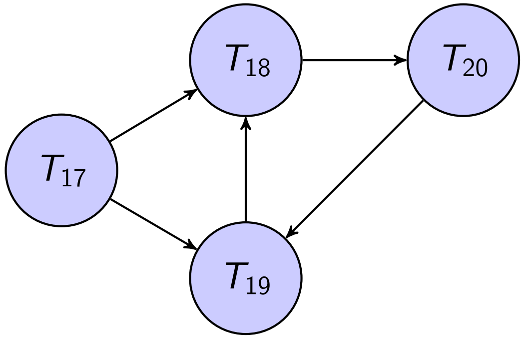
Deadlock Detection/1

- 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.

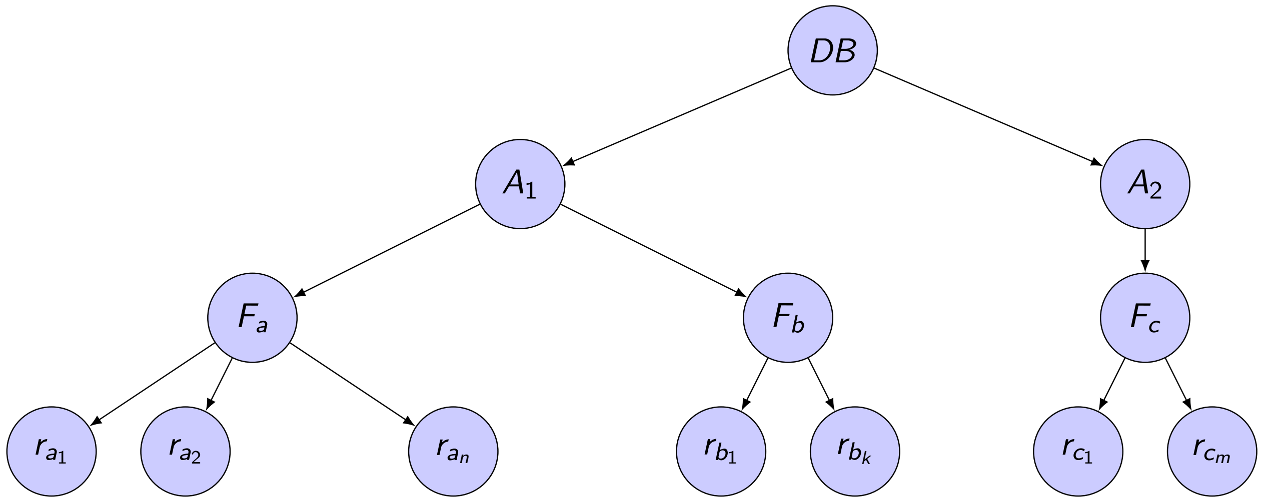
Deadlock Prevention Strategies/4

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 descendents 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:

	IS	*IX*	*S*	*SIX*	*X*
IS	*true*	*true*	*true*	*true*	*false*
IX	*true*	*true*	*false*	*false*	*false*
S	*true*	*false*	*true*	*false*	*false*
SIX	*true*	*false*	*false*	*false*	*false*
X	*false*	*false*	*false*	*false*	*false*

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

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. If $TS(T_i) \geq W\text{-}timestamp(Q)$, then 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 Ti 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 $TS(T_i)$.

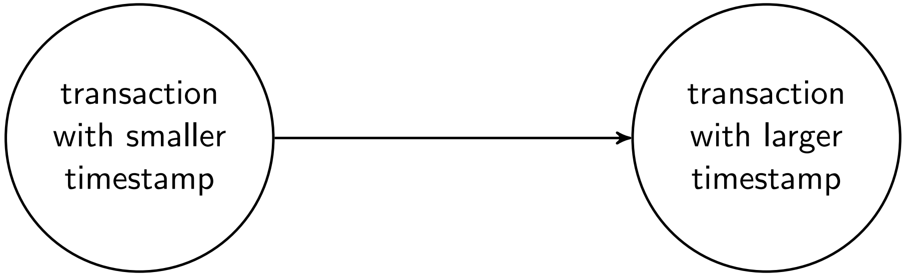
Example Use of the Protocol

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
				$read(X)$
	$read(Y)$			
$read(Y)$				
		$write(Y)$		
		$write(Z)$		
				$read(Z)$
	$read(Z)$			
	$abort$			
$read(X)$				
			$read(W)$	
		$write(W)$		
		$abort$		
				$write(Y)$
				$write(Z)$

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

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.
- The three phases of concurrently executing transactions can be interleaved, but each transaction must go through the three phases in that order.
  - 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

- Timestamp $TS(T_i)$ is the time where validation of T_i starts, i.e., $TS(T_i) = validation(T_i)$.
- If for all T_i with $TS(T_i) < TS(T_j)$ either one of the following condition holds:
  - $finish(T_i) < start(T_j)$
  - $start(T_j) < finish(T_i) < validation(T_j)$ and the set of data items written by T_i does not intersect with the set of data items read by T_j

  then validation succeeds and T_j can be committed.
- Otherwise, validation fails, and 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_i since they occur after T_i has finished its reads
  - the writes of T_i do not affect reads of T_j since T_j does not read any item written by T_i

Schedule Produced by Validation

- Example of schedule produced using validation

T_{25}	T_{26}
$read(B)$	
	$read(B)$
	$B := B - 50$
	$read(A)$
	$A := A + 50$
$read(A)$	
$< validate >$	
$display(A + B)$	
	$< validate >$
	$write(B)$
	$write(A)$

Outline

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 $< Q_1, Q_2, \ldots, Q_m >$. 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 $TS(T_j) > R\text{-}timestamp(Q_k)$.

Multiversion Timestamp Ordering/2

- Suppose that transaction T_i issues a **read(Q)** or **write(Q)** operation. Let Q_k denote the version of Q whose write timestamp is the largest write timestamp less than or equal to $TS(T_i)$.
  1. If transaction T_i issues a **read(Q)**, then the value returned is the content of version Q_k.
  2. If transaction T_i issues a **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.
- Observe that
  - Reads always succeed
  - A write by T_i is rejected if some other transaction T_j that (in the serialization order defined by the timestamp values) 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 transactions and update transactions
- Update transactions:
  - Acquire locks for reads and writes, and hold all locks up to the end of the transaction, i.e., follow rigorous two-phase locking.
  - Each successful write results in the creation of 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 $\textit{ts-counter} + 1$
  - T_i increments $\textit{ts-counter}$ 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

T_1	T_2	T_3	T_4
	— begin —		
	$write(A)$		
— begin —			
$read(A)$			
		— begin —	
		$read(A)$	
		$read(B)$	
	$commit$		
$write(A)$			
		$read(A)$	
			— begin —
			$read(A)$
$commit$			

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, than 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 $R(X) \to 0$ $R(Y) \to 1$	
			$W(X := 2)$ $W(Z := 3)$ Commit
Concurrent updates not visible Own updates are visible Not first-committer of X Serialization error, T_2 is rolled back		$R(Z) \to 0$ $R(Y) \to 1$ $W(X := 3)$ Commit-Req Abort	

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 seen)	
$r_1(Y_1, 50)$ (can see its own updates)	
	$r_2(Y_0, 0)$ (update by T_1 not seen)

- $X_2 = 50,\ Y_1 = 50$

Snapshot Write: First Committer Wins

T_1 deposits 50 in X	T_2 withdraws 50 from X
$r_1(X_0, 100)$	
	$r_2(X_0, 100)$
	$w_2(X_2, 50)$
$w_1(X_1, 150)$	
$commit_1$	
	$commit_2$ (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 serializabilty

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 ($maxorder + 1, \ldots$)

Outline

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

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.