Concurrency Control

Database System Concepts, 7th Ed.

Outline

- Lock-Based Protocols
- Timestamp-Based Protocols
- Validation-Based Protocols
- Multiple Granularity
- Multiversion Schemes
- Insert and Delete Operations
- Concurrency in Index Structures

Lock-Based Protocols

- 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 concurrency-control manager. Transaction can proceed only after request is granted.

Lock-Based Protocols (Cont.)

- **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,
- But, if any transaction holds an exclusive on the item no other transaction may hold any lock on the item.

Lock-Based Protocols (Cont.)

- Example of a transaction performing locking:

T_1:
lock-X(B);
read(B);
$B := B - 50$;
write(B);
unlock(B);
lock-X(A);
read(A);
$A := A + 50$;
write(A);
unlock(A).

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*

Scheduling of Transactions with Lock-Based Protocols

T_1: lock-X(B);
read(B);
$B := B - 50$;
write(B);
unlock(B);
lock-X(A);
read(A);
$A := A + 50$;
write(A);
unlock(A).

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

T_1	T_2	concurrency-control manager
lock-X(B)		
		grant-X(B, T_1)
read(B)		
$B := B - 50$		
write(B)		
unlock(B)		
	lock-S(A)	
		grant-S(A, T_2)
	read(A)	
	unlock(A)	
	lock-S(B)	
		grant-S(B, T_2)
	read(B)	
	unlock(B)	
	display($A + B$)	
lock-X(A)		
		grant-X(A, T_1)
read(A)		
$A := A + 50$		
write(A)		
unlock(A)		

Figure 18.4 Schedule 1.

- This schedule is not serializable (why?)

Transactions with unlocking delayed

T_3: lock-X(B);
read(B);
$B := B - 50$;
write(B);
lock-X(A);
read(A);
$A := A + 50$;
write(A);
unlock(B);
unlock(A).

T_4: lock-S(A);
read(A);
lock-S(B);
read(B);
display($A + B$);
unlock(A);
unlock(B).

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)	

Deadlock

- 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)	

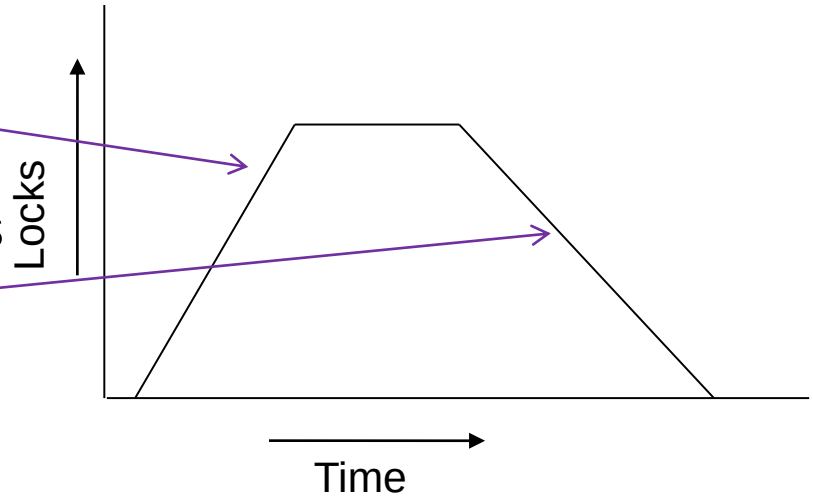
- Neither T_3 nor T_4 can make progress — executing **lock-S**(*B*) causes T_4 to wait for T_3 to release its lock on *B*, while executing **lock-X**(*A*) causes T_3 to wait for T_4 to release its lock on *A*.
- Such a situation is called a **deadlock**.
  - To handle a deadlock one of T_3 or T_4 must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

Deadlock (Cont.)

- The potential for deadlock exists in most locking protocols. Deadlocks are a necessary evil.
- **Starvation** is also possible if 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.

The Two-Phase Locking Protocol

- A protocol which 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 proved that the transactions can be serialized in the order of their **lock points** (i.e., the point where a transaction acquired its final lock).



Partial Schedule under Two-Phase Locking Protocol

T_5	T_6	T_7
lock-X(A)		
read(A)		
lock-S(B)		
read(B)		
write(A)		
unlock(A)		
	lock-X(A)	
	read(A)	
	write(A)	
	unlock(A)	
		lock-S(A)
		read(A)

The Two-Phase Locking Protocol (Cont.)

- Two-phase locking *does not* ensure freedom from deadlocks
- Extensions to basic two-phase locking needed to ensure recoverability and freedom from cascading roll-back
  - **Strict two-phase locking:** a transaction must hold all its exclusive locks till it commits/aborts.
    - Ensures recoverability and avoids cascading roll-backs
  - **Rigorous two-phase locking**: a transaction must hold *all* locks till commit/abort.
    - Transactions can be serialized in the order in which they commit.
- Most databases implement rigorous two-phase locking, *but refer to it as simply two-phase locking*

Lock Conversions

- Two-phase locking protocol with lock conversions:
  - Growing Phase:
    - can acquire a lock-S on item
    - can acquire a lock-X on item
    - can **convert** a lock-S to a lock-X (**upgrade**)
  - Shrinking Phase:
    - can release a lock-S
    - can release a lock-X
    - can convert a lock-X to a lock-S (**downgrade**)
- This protocol ensures serializability

The Two-Phase Locking Protocol with lock conversion

T_8: read(a_1);
read(a_2);
...
read(a_n);
write(a_1).

T_9: read(a_1);
read(a_2);
display($a_1 + a_2$).

T_8	T_9
lock-S(a_1)	
	lock-S(a_1)
lock-S(a_2)	
	lock-S(a_2)
lock-S(a_3)	
lock-S(a_4)	
	unlock(a_1)
	unlock(a_2)
lock-S(a_n)	
upgrade(a_1)	

Locking Protocols

- Given a locking protocol (such as 2PL)
  - A schedule S is **legal** under a locking protocol if it can be generated by a set of transactions that follow the protocol
  - A protocol **ensures** serializability if all legal schedules under that protocol are serializable

Automatic Acquisition of Locks

- A transaction T_i issues the standard read/write instruction, without explicit locking calls.
- The operation **read**(*D*) is processed as:

```
if Ti has a lock on D
  then
      read(D)
  else begin
      if necessary wait until no other
          transaction has a lock-X on D
      grant Ti a  lock-S on D;
      read(D)
  end
```

Automatic Acquisition of Locks (Cont.)

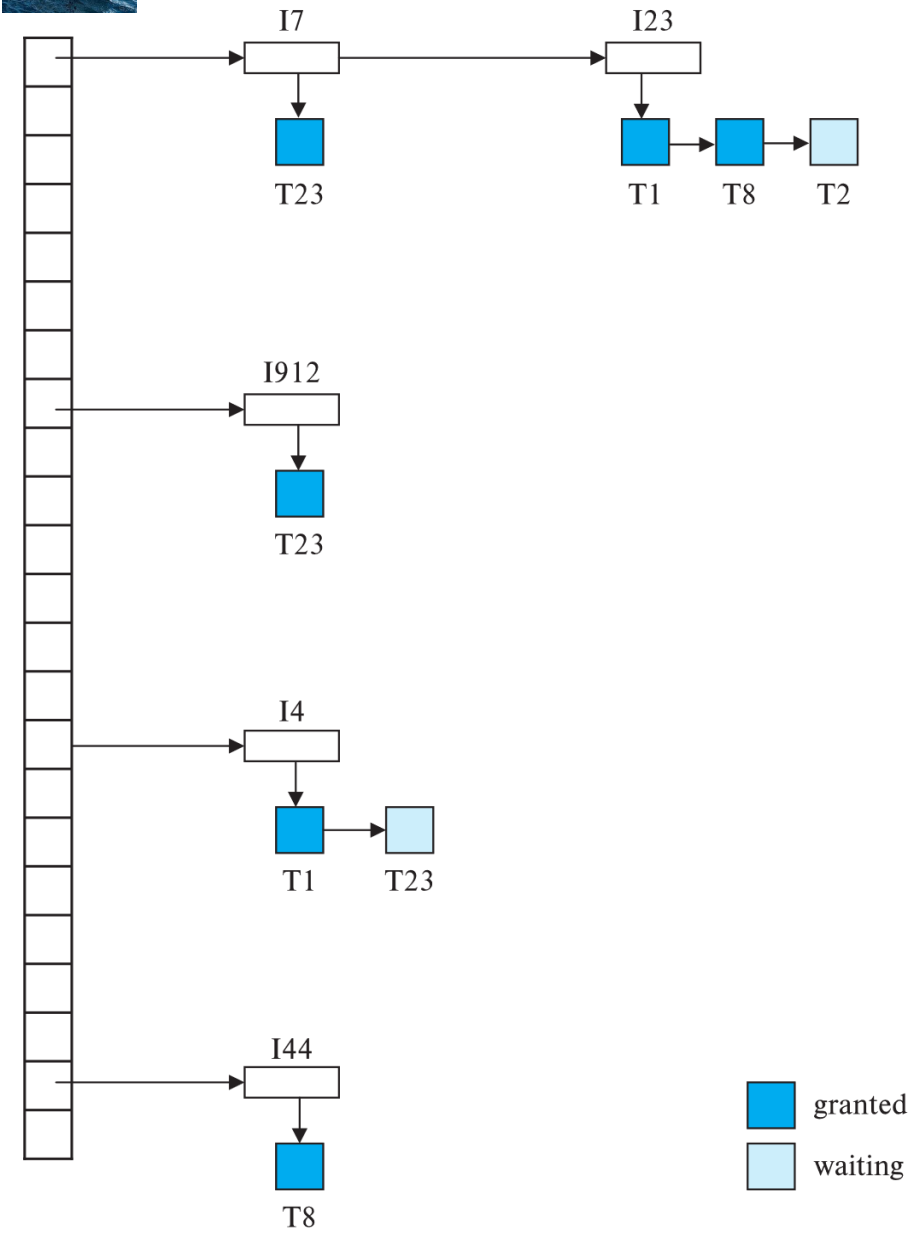
- The operation **write**(*D*) is processed as:

```
if Ti has a lock-X on D
   then
     write(D)
  else begin
       if necessary wait until no other trans. has any lock on D,
       if Ti has a lock-S on D
            then
                upgrade lock on D to lock-X
           else
                grant Ti a lock-X on D
           write(D)
  end;
```

Implementation of Locking

- A **lock manager** can be implemented as a separate process
- Transactions can send lock and unlock requests as messages
- 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 an in-memory data-structure called a **lock table** to record granted locks and pending requests

Lock Table



- Dark rectangles indicate granted locks, light colored ones 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

Graph-Based Protocols

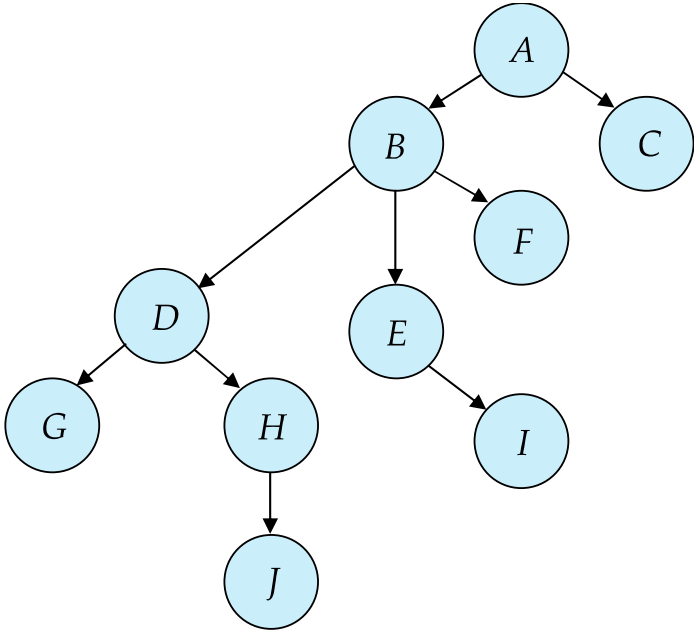
- Graph-based protocols are an alternative to two-phase locking

- Impose a partial ordering $\rightarrow$ on the set **D** = {d_1, d_2 ,..., d_h} of all data items.
  - If $d_i \rightarrow d_j$ then any transaction accessing both d_i and d_j must access d_i before accessing d_j.
  - Implies that the set **D** may now be viewed as a directed acyclic graph, called a *database graph*.

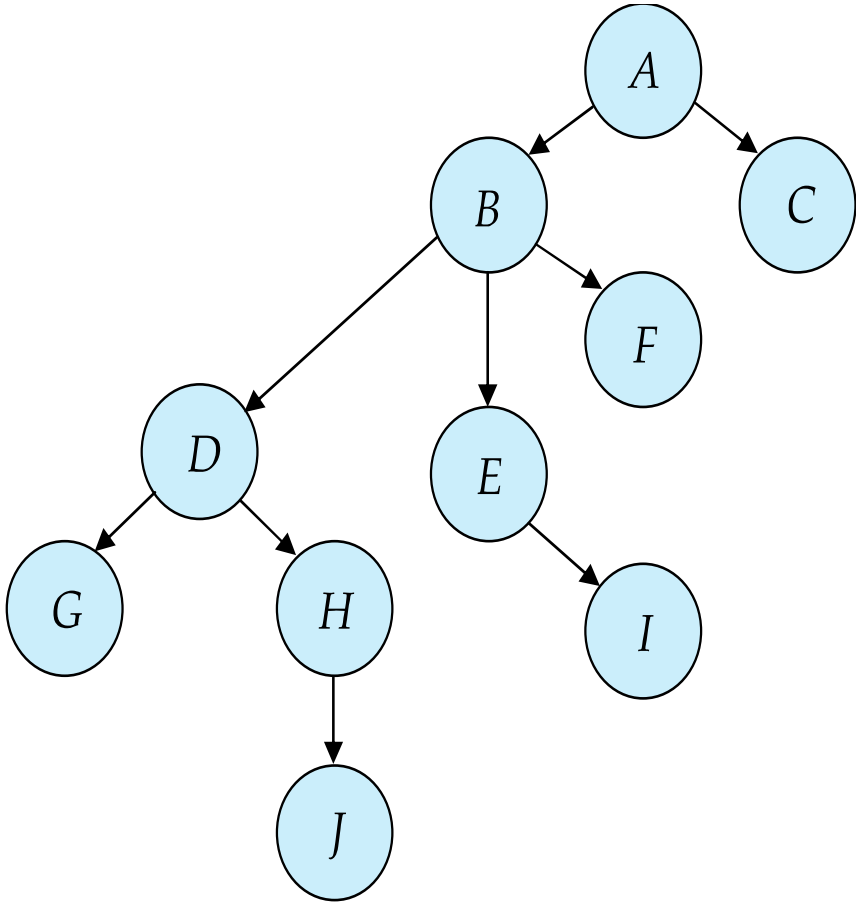
- The *tree-protocol* is a simple kind of graph protocol.

Tree Protocol

- Only exclusive locks are allowed.
- The first lock by T_i may be on any data item. Subsequently, a data Q can be locked by T_i only if the parent of Q is currently locked by T_i.
- Data items may be unlocked at any time.
- A data item that has been locked and unlocked by T_i cannot subsequently be relocked by T_i



Serialized Schedule under Tree Protocol



T_{10}: lock-X(B); lock-X(E); lock-X(D); unlock(B); unlock(E); lock-X(G); unlock(D); unlock(G).
T_{11}: lock-X(D); lock-X(H); unlock(D); unlock(H).
T_{12}: lock-X(B); lock-X(E); unlock(E); unlock(B).
T_{13}: lock-X(D); lock-X(H); unlock(D); unlock(H).

T_{10}	T_{11}	T_{12}	T_{13}
lock-X(B)			
	lock-X(D)		
	lock-X(H)		
	unlock(D)		
lock-X(E)			
lock-X(D)			
unlock(B)			
unlock(E)			
		lock-X(B)	
		lock-X(E)	
	unlock(H)		
lock-X(G)			
unlock(D)			
			lock-X(D)
			lock-X(H)
			unlock(D)
			unlock(H)
		unlock(E)	
		unlock(B)	
unlock(G)			

Graph-Based Protocols (Cont.)

- The tree protocol ensures conflict serializability as well as freedom from deadlock.
- Unlocking may occur earlier in the tree-locking protocol than in the two-phase locking protocol.
  - Shorter waiting times, and increase in concurrency
  - Protocol is deadlock-free, no rollbacks are required
- Drawbacks
  - Protocol does not guarantee recoverability or cascade freedom
    - Need to introduce commit dependencies to ensure recoverability
  - Transactions may have to lock data items that they do not access.
    - increased locking overhead, and additional waiting time
    - potential decrease in concurrency

Deadlock Handling

- 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.

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)	

Deadlock Handling

- ***Deadlock Prevention***
- ***Deadlock Detection & Deadlock Recovery***
- ***Deadlock prevention*** protocols ensure that the system will *never* enter into a deadlock state. Some prevention strategies:
  - Require that each transaction locks all its data items before it begins execution (pre-declaration).
    - Hard to predict what data items need to be locked
    - Poor data-item utilization (most of the time data items are idle)
  - No circular waits in ordering the requests for locks.
  - Transaction roll-back whenever the waiting for the lock is required.
  - Impose partial ordering of all data items and require that a transaction can lock data items only in the order specified by the partial order (graph-based protocol).

Deadlock Prevention Strategies

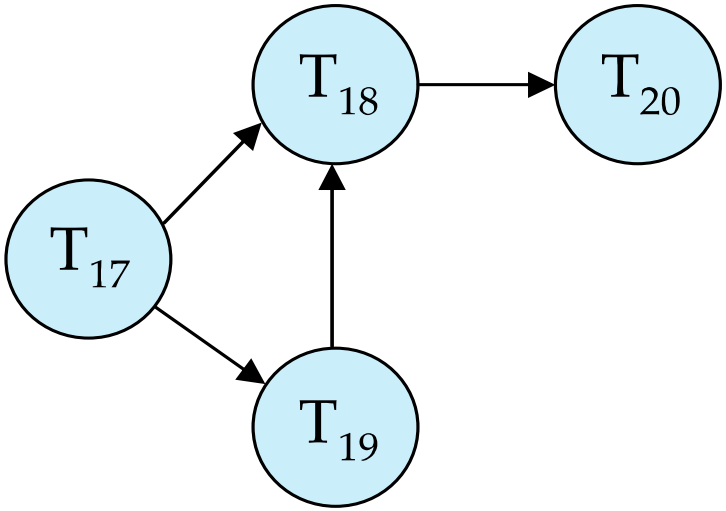
- **wait-die** scheme — non-preemptive
  - Older transaction may wait for younger one to release data item.
  - Younger transactions never wait for older ones; they are rolled back instead.
  - A transaction may die several times before acquiring a lock
- **wound-wait** scheme — preemptive
  - Older transaction *wounds* (forces rollback) of younger transaction instead of waiting for it.
  - Younger transactions may wait for older ones.
  - Fewer rollbacks than *wait-die* scheme.
- In both schemes, a rolled back transactions is restarted with its original timestamp.
  - Ensures that older transactions have precedence over newer ones, and starvation is thus avoided.

Deadlock prevention (Cont.)

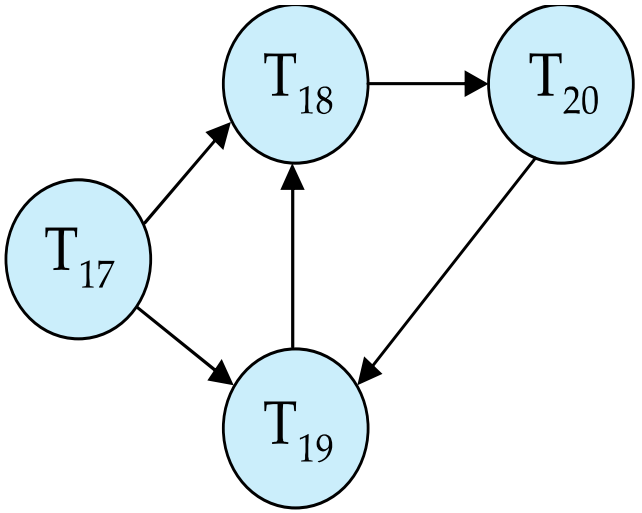
- **Timeout-Based Schemes**:
  - A transaction waits for a lock only for a specified amount of time. After that, the wait times out and the transaction is rolled back.
  - Ensures that deadlocks get resolved by timeout if they occur
  - Simple to implement
  - But may roll back transaction unnecessarily in absence of deadlock
    - Difficult to determine good value of the timeout interval.
  - Starvation is also possible

Deadlock Detection

- **Wait-for graph**
  - *Vertices:* transactions
  - *Edge from* $T_i \rightarrow T_j$. : if T_i is waiting for a lock held in conflicting mode by T_j
- The system is in a deadlock state if and only if the wait-for graph has a cycle.
- Invoke a deadlock-detection algorithm periodically to look for cycles.



Wait-for graph without a cycle



Wait-for graph with a cycle

Deadlock Recovery

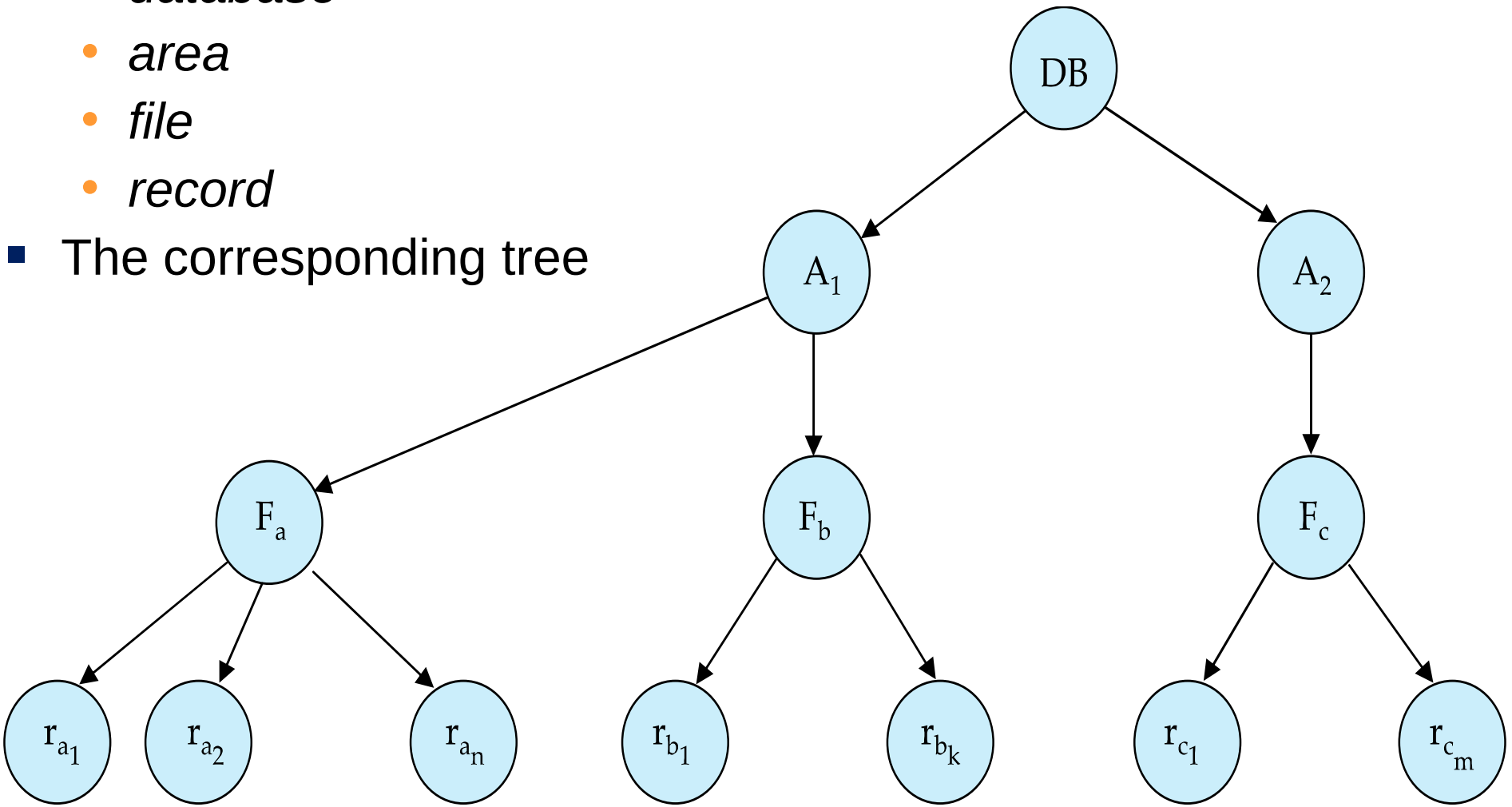
- When deadlock is detected :
  - Some transaction will have to rolled back (made a **victim**) to break deadlock cycle.
    - Select that transaction as victim that will incur minimum cost
    - How long the transaction is completed & left-over
    - How many data items the transaction has used and how many required for completion?
    - How many transactions are involved in deadlock
  - Rollback -- determine how far to roll back transaction
    - **Total rollback**: Abort the transaction and then restart it.
    - **Partial rollback**: Roll back victim transaction only as far as necessary to release locks that another transaction in cycle is waiting for
- Starvation can happen (why?)
  - One solution: oldest transaction in the deadlock set is never chosen as victim

Multiple Granularity

- Allow data items to be of various sizes and define a hierarchy of data granularities, where the small granularities are nested within larger ones
- Can be represented graphically as a tree (but don't confuse with tree-locking protocol)
- 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*
- The corresponding tree



Intention Lock Modes

- In addition to S and X lock modes, there are three additional lock modes with multiple granularity:
  - ***intention-shared*** (IS): indicates explicit locking at a lower level of the tree but only with shared locks.
  - ***intention-exclusive*** (IX): indicates explicit locking at a lower level with exclusive or shared locks
  - ***shared and intention-exclusive*** (SIX): the subtree rooted by that node is locked explicitly in shared mode and explicit locking is being done at a lower level with exclusive-mode locks.
- Intention locks 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

Multiple Granularity Locking Scheme

- Illustration of a Protocol :
  1. Suppose that transaction T1 reads record ra2 in file Fa. Then, T1 needs to lock the database, area A1, and Fa in IS mode (and in that order), and finally to lock ra2 in S mode.
  2. Suppose that transaction *T2* modifies record *ra9* in file *Fa*. Then, *T2* needs to lock the database, area *A1*, and file Fa (and in that order) in IX mode, and finally to lock ra9 in X mode.
  3. Suppose T3 reads all records in file Fa. Then T3 needs to lock the database and area A1 (and in that order) in IS mode, and finally to lock Fa in S mode.
  4. Suppose that transaction T4 reads the entire database. It can do so after locking the database in S mode.

- T1, T3 and T4 can access the database concurrently
- T1 and T2 can execute concurrently
- T2 cannot execute concurrently with either T3 or T4.

Timestamp Based Concurrency Control

Timestamp-Based Protocols

- Each transaction T_i is issued a timestamp TS(T_i) when it enters the system.
  - Each transaction has a *unique* timestamp
  - Newer transactions have timestamps strictly greater than earlier ones
  - Timestamp could be based on a logical counter

- Timestamp-based protocols manage concurrent execution such that **time-stamp order = serializability order**

- Several alternative protocols based on timestamps

Timestamp-Ordering Protocol

The **timestamp ordering (TSO) protocol**

- Maintains for each data *Q* two timestamp values:
  - **W-timestamp**(*Q*) is the largest time-stamp of any transaction that executed **write**(*Q*) successfully.
  - **R-timestamp**(*Q*) is the largest time-stamp of any transaction that executed **read**(*Q*) successfully.
- Imposes rules on read and write operations to ensure that
  - Any conflicting operations are executed in timestamp order
  - Out of order operations cause transaction rollback

Timestamp-Based Protocols (Cont.)

- Suppose a transaction T_i issues a **read**(Q)

  1. If TS(T_i) < **W**-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) ≥ **W**-timestamp(Q), then the **read** operation is executed, and R-timestamp(Q) is set to **max**(R-timestamp(Q), TS(T_i)).

Timestamp-Based Protocols (Cont.)

- Suppose that transaction T_i issues **write**(Q).

1. If TS(T_i) < R-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** operation is rejected, and T_i is rolled back.

2. If TS(T_i) < W-timestamp(Q), then T_i is attempting to write an obsolete value of Q.
   - Hence, this **write** operation is rejected, and T_i is rolled back.

3. Otherwise, the **write** operation is executed, and W-timestamp(Q) is set to TS(T_i).

Example of Schedule Under TSO

- Is this schedule valid under TSO?

  Assume that initially:

  R-TS(A) = W-TS(A) = 0

  R-TS(B) = W-TS(B) = 0

  Assume TS(T_{25}) = 25 and TS(T_{26}) = 26

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

- How about this one, where initially

  R-TS(Q)=W-TS(Q)=0

T_{27}	T_{28}
read(Q)	
	write(Q)
write(Q)	

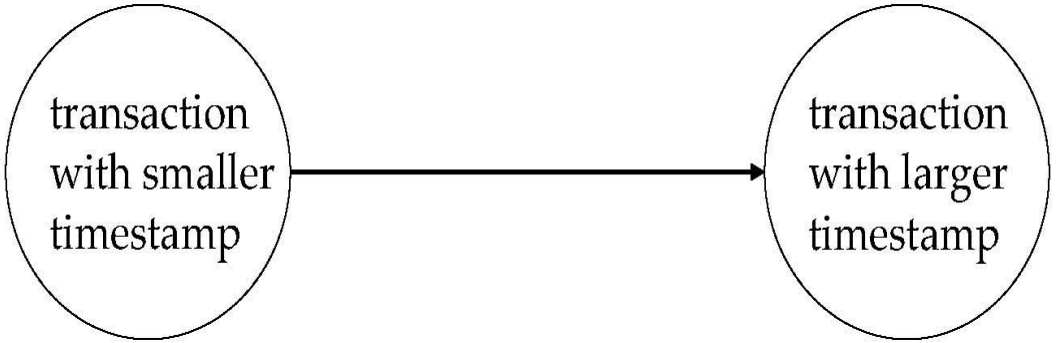
Another Example Under TSO

A partial schedule for several data items for transactions with timestamps 1, 2, 3, 4, 5, with all R-TS and W-TS = 0 initially

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:



Thus, there will be no cycles in the precedence graph

- 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.

Recoverability and Cascade Freedom

- Solution 1:
  - A transaction is structured such that its writes are all performed at the end of its processing
  - All writes of a transaction form an atomic action; no transaction may execute while a transaction is being written
  - 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.
- When T_i attempts to write data item Q, if TS(T_i) < W-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 have done, 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 some view-serializable schedules that are not conflict-serializable.

Concurrency Control under Insertion & Deletion Operations

Insert & Delete Operations

- Delete: Ii = delete(Q)
  - Ij = read(Q). Ii and Ij conflict. If Ii comes before Ij, Tj will have a logical error. If Ij comes before Ii, Tj can execute the read operation successfully.
  - Ij = write(Q). Ii and Ij conflict. If Ii comes before Ij, Tj will have a logical error. If Ij comes before Ii, Tj can execute the write operation successfully.
  - Ij = delete(Q). Ii and Ij conflict. If Ii comes before Ij, Tj will have a logical error. If Ij comes before Ii, Ti will have a logical error.
  - Ij = insert(Q). Ii and Ij conflict. Suppose that data item Q did not exist prior to the execution of Ii and Ij. Then, if Ii comes before Ij, a logical error results for Ti. If Ij comes before Ii, then no logical error results. Likewise, if Q existed prior to the execution of Ii and Ij, then a logical error results if Ij comes before Ii, but not otherwise.

Two-phase locking and TSO protocols for Insert/Delete Operations

- Delete Operation
- Under the two-phase locking protocol, an exclusive lock is required on a data item before that item can be deleted.
- Under the timestamp-ordering protocol, a test similar to that for a write must be performed. Suppose that transaction Ti issues delete(Q).
  - If TS(Ti) < R-timestamp(Q), then the value of Q that Ti was to delete has already been read by a transaction Tj with TS(Tj) > TS(Ti). Hence, the delete operation is rejected, and Ti is rolled back.
  - If TS(Ti) < W-timestamp(Q), then a transaction Tj with TS(Tj) > TS(Ti) has written Q. Hence, this delete operation is rejected, and Ti is rolled back.
  - Otherwise, the delete is executed.
- Insertion Operation
  - Conflicts with delete, read and write operations
  - Under the two-phase locking protocol, if Ti performs an insert(Q) operation, Ti is given an exclusive lock on the newly created data item Q.
  - Under the timestamp-ordering protocol, if Ti performs an insert(Q) operation, the values R-timestamp(Q) andW-timestamp(Q) are set to TS(Ti).

Validation-Based Protocol

Validation-Based Protocol

- Idea: can we use commit time as serialization order?
- To do so:
  - Postpone writes to end of transaction
  - Keep track of data items read/written by transaction
  - **Validation** performed at commit time, detect any out-of-serialization order reads/writes
- Also called as **optimistic concurrency control** since transaction executes fully in the hope that all will go well during validation

Validation-Based Protocol

- Execution of transaction T_i is done in three phases.

1. **Read and execution phase**: During this phase, the system executes transaction T_i. It reads the values of the various data items and stores them in variables local to T_i. It performs all write operations on temporary local variables, without updates of the actual database.

- 2. **Validation phase**: The validation test (described below) is applied to transaction *Ti*. This determines whether *Ti* is allowed to proceed to the write phase without causing a violation of serializability. If a transaction fails the validation test, the system aborts the transaction.

- 3. **Write phase**: If the validation test succeeds for transaction *Ti*, the temporary local variables that hold the results of any write operations performed by *Ti* are copied to the database. Read-only transactions omit this phase.

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

Validation-Based Protocol (Cont.)

- Each transaction T_i has 3 timestamps
  - **StartTS**(T_i) : the time when T_i started its execution
  - **ValidationTS**(T_i): the time when T_i entered its validation phase
  - **FinishTS**(T_i) : the time when T_i finished its write phase
- Validation tests use above timestamps and read/write sets to ensure that serializability order is determined by validation time
  - Thus, TS(T_i) = ValidationTS(T_i)
- Validation-based protocol has been found to give greater degree of concurrency than locking/TSO if probability of conflicts is low.

Validation Test for Transaction T_j

- If for all T_i with TS (T_i) < TS (T_j) either one of the following condition holds:
  - **finishTS**(T_i) < **startTS**(T_j)
  - **startTS**(T_j) < **finishTS**(T_i) < **validationTS**(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:
  - First condition applies when execution is not concurrent
    - The writes of T_j do not affect reads of T_i since they occur after T_i has finished its reads.
  - If the second condition holds, execution is concurrent, 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)

Multiversion Concurrency Control

Multiversion Schemes

- Multiversion schemes keep old versions of data item to increase concurrency. Several variants:
  - **Multiversion Timestamp Ordering**
  - **Multiversion Two-Phase Locking**
  - **Snapshot isolation**
- Key ideas:
  - 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 issuing the read request, and return the value of the selected version.
- **read**s never have to wait as an appropriate version is returned immediately.

Multiversion Timestamp Ordering

- 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

Multiversion Timestamp Ordering (Cont)

- 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
     - If R-timestamp(Q_k) < TS(T_i), set R-timestamp(Q_k) = TS(T_i),
  2. If transaction T_i issues a **write**(Q)
     1. if TS(T_i) < R-timestamp(Q_k), then transaction T_i is rolled back.
     2. if TS(T_i) = W-timestamp(Q_k), the contents of Q_k are overwritten
     3. Otherwise, a new version Q_i of Q is created
        - W-timestamp(Q_i) and R-timestamp(Q_i) are initialized to TS(T_i).

Multiversion Timestamp Ordering (Cont)

- Observations
  - 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.
- Protocol guarantees serializability

Multiversion Two-Phase Locking

- Differentiates between read-only transactions and update transactions
- **Update transactions** acquire read and write locks, and hold all locks up to the end of the transaction. That is, update transactions follow rigorous two-phase locking.
  - Read of a data item returns the latest version of the item
  - The first **write** of Q by T_i results in the creation of a new version Q_i of the data item Q written
    - W-timestamp(Q_i) set to ∞ initially
  - When update transaction T_i completes, commit processing occurs:
    - Value **ts-counter** stored in the database is used to assign timestamps
      - **ts-counter** is locked in two-phase manner
    - Set TS(T_i) = **ts-counter** + 1
    - Set W-timestamp(Q_i) = TS(T_i) for all versions Q_i that it creates
    - **ts-counter** = **ts-counter +** 1

Multiversion Two-Phase Locking (Cont.)

- **Read-only transactions**
  - are assigned a timestamp = **ts-counter** when they start execution
  - follow the multiversion timestamp-ordering protocol for performing reads
    - Do not obtain any locks
- 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.

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 Q5 and Q9, and the oldest active transaction has timestamp > 9, than Q5 will never be required again
- Issues with
  - primary key and foreign key constraint checking
  - Indexing of records with multiple versions

  See textbook for details

Snapshot Isolation

- Motivation: Decision support queries that read large amounts of data have concurrency conflicts with OLTP transactions that update a few rows
  - Poor performance results
- Solution 1: Use multiversion 2-phase locking
  - Give logical “snapshot” of database state to read only transaction
    - Reads performed on snapshot
  - Update (read-write) transactions use normal locking
  - Works well, but how does system know a transaction is read only?
- Solution 2 (partial): Give snapshot of database state to every transaction
  - Reads performed on snapshot
  - Use 2-phase locking on updated data items
  - Problem: variety of anomalies such as lost update can result
  -

Snapshot Isolation

- A transaction T1 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 T1
  - Writes of T1 complete when it commits
  - **First-committer-wins rule**:
    - Commits only if no other concurrent transaction has already written data that T1 intends to write.

T1	T2	T3
W(Y := 1) Commit		
	Start R(X) → 0 R(Y)→ 1	
		W(X:=2) W(Z:=3) Commit
	R(Z) → 0 R(Y) → 1 W(X:=3) Commit-Req Abort	

Concurrent updates not visible
Own updates are visible
Not first-committer of X
Serialization error, T2 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 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

$X_0 = 100$

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)

$X_1 = 150$

- 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
  - (Oracle uses this plus some extra features)
  -

Benefits of SI

- Reads are *never* blocked,
  - and also don't block other txns activities
- Performance similar to Read Committed
- Avoids several anomalies
  - No dirty read, i.e. no read of uncommitted data
  - No lost update
    - I.e., update made by a transaction is overwritten by another transaction that did not see the update)
  - No non-repeatable read
    - I.e., if read is executed again, it will see the same value
- Problems with SI
  - SI does not always give serializable executions
    - Serializable: among two concurrent txns, one sees the effects of the other
    - In SI: neither sees the effects of the other
  - Result: Integrity constraints can be violated

Snapshot Isolation

- Example of problem with SI
  - Initially A = 3 and B = 17
    - Serial execution: A = ??, B = ??
    - if both transactions start at the same time, with snapshot isolation: A = ?? , B = ??
- Called **skew write**
- Skew also occurs with inserts
  - E.g:
    - Find max order number among all orders
    - Create a new order with order number = previous max + 1
    - Two transaction can both create order with same number
      - Is an example of phantom phenomenon

T_i	T_j
read(A)	
read(B)	
	read(A)
	read(B)
A=B	
	B=A
write(A)	
	write(B)

Snapshot Isolation Anomalies

- SI breaks serializability when transactions modify *different* items, each based on a previous state of the item the other modified
  - Not very common in practice
    - E.g., the TPC-C benchmark runs correctly under SI
    - when txns conflict due to modifying different data, there is usually also a shared item they both modify, so SI will abort one of them
  - But problems do occur
    - Application developers should be careful about write skew
- SI can also cause a read-only transaction anomaly, where read-only transaction may see an inconsistent state even if updaters are serializable
  - We omit details
- Using snapshots to verify primary/foreign key integrity can lead to inconsistency
  - Integrity constraint checking usually done outside of snapshot

Serializable Snapshot Isolation

- **Serializable snapshot isolation (SSI)**: extension of snapshot isolation that ensures serializability
- Snapshot isolation tracks write-write conflicts, but does not track read-write conflicts
  - Where T_i writes a data a data item Q, T_j reads an earlier version of Q, but T_j is serialized after T_i
- Idea: track read-write dependencies separately, and roll-back transactions where cycles can occur
  - Ensures serializability
  - Details in book
- Implemented in PostgreSQL from version 9.1 onwards
  - PostgreSQL implementation of SSI also uses index locking to detect phantom conflicts, thus ensuring true serializability

SI Implementations

- Snapshot isolation supported by many databases
  - Including Oracle, PostgreSQL, SQL Server, IBM DB2, etc
  - Isolation level can be set to snapshot isolation
- Oracle implements “first updater wins” rule (variant of “first committer wins”)
  - Concurrent writer check is done at time of write, not at commit time
  - Allows transactions to be rolled back earlier
- **Warning**: *even if isolation level is set to serializable, Oracle actually uses snapshot isolation*
  - Old versions of PostgreSQL prior to 9.1 did this too
  - Oracle and PostgreSQL < 9.1 do not support true serializable execution

Working Around SI Anomalies

- Can work around SI anomalies for specific queries by using **select .. for update** (supported e.g. in Oracle)
  - Example
    - **select max**(orderno) **from** orders **for update**
    - read value into local variable maxorder
    - insert into orders (maxorder+1, …)
- **select for update (SFU) clause** treats all data read by the query as if it were also updated, preventing concurrent updates
- Can be added to queries to ensure serializability in many applications
  - Does not handle phantom phenomenon/predicate reads though

Weak Levels of Concurrency

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
  - **Serializable**: is the default
  - **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
      - T1 may see some records inserted by T2, but may not see others inserted by T2
  - **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 most database systems, read committed is the default consistency level
  - Can be changed as database configuration parameter, or per transaction
    - **set isolation level serializable**

Concurrency Control across User Interactions

- Many applications need transaction support across user interactions
  - Can’t use locking for long durations
- 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, r.version = r.version+1
      where acctId = 23 **and** r.version = :version

Concurrency Control across User Interactions

- Equivalent to **optimistic concurrency control without validating read set**
  - Unlike SI, reads are not guaranteed to be from a single snapshot.
  - Does not guarantee serializability
  - But avoids some anomalies such as “lost update anomaly”
- Used internally in Hibernate ORM system
- Implemented manually in many applications
- Version numbers stored in tuples can also be used to support first committer wins check of snapshot isolation

Advanced topics in Concurrency Control

Online Index Creation

- Problem: how to create an index on a large relation without affecting concurrent updates
  - Index construction may take a long time
  - Two-phase locking will block all concurrent updates
- Key ideas:
  - Build index on a snapshot of the relation, but keep track of all updates that occur after snapshot
    - Updates are not applied on the index at this point
  - Then apply subsequent updates to catch up
  - Acquire relation lock towards end of catchup phase to block concurrent updates
  - Catch up with remaining updates, and add index to system catalog
  - Subsequent transactions will find the index in catalog and update it

Concurrency in Index Structures

- 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 (Cont.)

- **Crabbing protocol** used instead of two-phase locking on the nodes of the B^+-tree 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.
- Above protocol can cause excessive deadlocks
  - Searches coming down the tree deadlock with updates going up the tree
  - Can abort and restart search, without affecting transaction
- The **B-link tree locking protocol** improves concurrency
  - Intuition: release lock on parent before acquiring lock on child
    -

Concurrency Control in Main-Memory Databases

- Index locking protocols can be simplified with main-memory databases
  - Short term lock can be obtained on entire index for duration of an operation, serializing updates on the index
    - Avoids overheads of multiple lock acquire/release
    - No major penalty since operations finish fast, since there is no disk wait
- Latch-free techniques for data-structure update can speed up operations further

Latch-Free Data-structure Updates

- This code is not safe without latches if executed concurrently:

```
insert(value, head) {
    node = new node
    node->value = value
    node->next = head
    head = node
}
```

- This code is safe

```
insert latchfree(head, value) {
    node = new node
    node->value = value
    repeat
        oldhead = head
        node->next = oldhead
        result = CAS(head, oldhead, node)
    until (result == success)
}
```

Latch-Free Data-structure Updates

- This code is not safe without latches if executed concurrently:

```
insert(value, head) {
    node = new node
    node->value = value
    node->next = head
    head = node
}
```

- This code is safe

```
insert latchfree(head, value) {
    node = new node
    node->value = value
    repeat
        oldhead = head
        node->next = oldhead
        result = CAS(head, oldhead, node)
    until (result == success)
}
```

Latch-Free Data-structures (Cont.)

- *Consider:*

```
delete latchfree(head) {
    /* This function is not quite safe; see explanation in text. */
    repeat
        oldhead = head
        newhead = oldhead->next
        result = CAS(head, oldhead, newhead)
    until (result == success)
}
```

- Above code is almost correct, but has a concurrency bug
  - P1 initiates delete with N1 as head; concurrently P2 deletes N1 and next node N2, and then reinserts N1 as head, with N3 as next
  - P1 may set head as N2 instead of N3.
- Known as ABA problem
- See book for details of how to avoid this problem

Concurrency Control with Operations

- Consider this non-two phase schedule, which preserves database integrity constraints
- Can be understood as transaction performing increment operation
  - E.g., increment(A, -50), increment (B, 50)
  - As long as increment operation does not return actual value, increments can be reordered
    - ***Increments commute***
  - New increment-mode lock to support reordering
  - Conflict matrix with increment lock mode
    - *Two increment operations do not conflict with each other*

T_1	T_2
read(A)	
$A := A - 50$	
write(A)	
	read(B)
	$B := B - 10$
	write(B)
read(B)	
$B := B + 50$	
write(B)	
	read(A)
	$A := A + 10$
	write(A)

	S	X	I
S	true	false	false
X	false	false	false
I	false	false	true

Concurrency Control with Operations (Cont.)

- Undo of increment(v, n) is performed by increment (v, -n)
- Increment_conditional(v, n):
  - Updates v by adding n to it, as long as final v > 0, fails otherwise
  - Can be used to model, e.g. number of available tickets, *avail_tickets,* for a concert
  - Increment_conditional is NOT commutative
    - E.g., last few tickets for a concert
  - But reordering may still be acceptable

Real-Time Transaction Systems

- Transactions in a system may have deadlines within which they must be completed.
  - Hard deadline: missing deadline is an error
  - Firm deadline: value of transaction is 0 in case deadline is missed
  - Soft deadline: transaction still has some value if done after deadline
- Locking can cause blocking
- Optimistic concurrency control (validation protocol) has been shown to do will in a real-time setting

End of Chapter 18

View Serializability

- Let *S* and *S´* be two schedules with the same set of transactions. *S* and *S´* are **view equivalent** if the following three conditions are met, for each data item *Q,*

  1. If in schedule S, transaction T_i reads the initial value of *Q*, then in schedule *S'* also transaction T_i must read the initial value of *Q.*

  2. If in schedule S transaction T_i executes **read**(*Q*), and that value was produced by transaction T_j (if any), then in schedule *S'* also transaction T_i must read the value of *Q* that was produced by the same **write**(Q) operation of transaction T_j .

  3. The transaction (if any) that performs the final **write**(*Q*) operation in schedule *S* must also perform the final **write**(*Q*) operation in schedule *S'.*

- As can be seen, view equivalence is also based purely on **reads** and **writes** alone.

View Serializability (Cont.)

- A schedule S is **view serializable** if it is view equivalent to a serial schedule.
- Every conflict serializable schedule is also view serializable.
- Below is a schedule which is view-serializable but *not* conflict serializable.

T_3	T_4	T_6
read(Q)		
	write(Q)	
write(Q)		
		write(Q)

- What serial schedule is above equivalent to?
- Every view serializable schedule that is not conflict serializable has **blind writes**.

Test for View Serializability

- The precedence graph test for conflict serializability cannot be used directly to test for view serializability.
  - Extension to test for view serializability has cost exponential in the size of the precedence graph.
- The problem of checking if a schedule is view serializable falls in the class of *NP*-complete problems.
  - Thus, existence of an efficient algorithm is *extremely* unlikely.
- However practical algorithms that just check some **sufficient conditions** for view serializability can still be used.

Other Notions of Serializability

- The schedule below produces same outcome as the serial schedule < T_1, T_5 >, yet is not conflict equivalent or view equivalent to it.

T_1	T_5
read(A)	
$A := A - 50$	
write(A)	
	read(B)
	$B := B - 10$
	write(B)
read(B)	
$B := B + 50$	
write(B)	
	read(A)
	$A := A + 10$
	write(A)

- Determining such equivalence requires analysis of operations other than read and write.
  - Operation-conflicts, operation locks