Chapter 10 : Concurrency Control

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Chapter 10: Concurrency Control

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

- Transactions have to acquire locks on data items before accessing them.
- If a lock is hold by one transaction on a data item this restricts the ability of other transactions to acquire locks for that data item.
- By locking a data item we want to ensure that no access to that data item is possible that would lead to non-serializable schedules.
- The trick is to design a lock model and protocol that guarantees that.
- Lock-based concurrency protocols are a form of **pessimistic concurrency control mechanism**
  - We avoid ever getting into a state that can lead to a non-serializable schedule.
- Alternative concurrency control mechanism do not avoid conflicts, but determine later on (at commit time) whether committing a transaction would cause a non-serializable schedule to be generated.
  - **Optimistic concurrency control mechanism**
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.

- Transactions do not access data items before having acquired a lock on that data item.
- Transactions release their locks on a data item only after they have accessed a data item.
Lock-Based Protocols (Cont.)

- **Lock-compatibility matrix**

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>X</td>
<td>false</td>
<td>false</td>
</tr>
</tbody>
</table>

- 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 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 (Cont.)

- Example of a transaction performing locking:

  \[ T_2: \text{lock-S}(A); \]
  \[ \quad \text{read} \ (A); \]
  \[ \quad \text{unlock}(A); \]
  \[ \text{lock-S}(B); \]
  \[ \quad \text{read} \ (B); \]
  \[ \quad \text{unlock}(B); \]
  \[ \text{display}(A+B) \]

- 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.
Pitfalls of Lock-Based Protocols

- Consider the partial schedule

<table>
<thead>
<tr>
<th></th>
<th>T₃</th>
<th>T₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>lock-x (B)</td>
<td>read (B)</td>
<td>lock-s (A)</td>
</tr>
<tr>
<td>read (B)</td>
<td>B := B - 50</td>
<td>write (B)</td>
</tr>
<tr>
<td>write (B)</td>
<td></td>
<td>lock-s (B)</td>
</tr>
<tr>
<td>lock-x (A)</td>
<td></td>
<td>lock-x (A)</td>
</tr>
</tbody>
</table>

- Neither T₃ nor T₄ can make progress — executing lock-S(B) causes T₄ to wait for T₃ to release its lock on B, while executing lock-X(A) causes T₃ to wait for T₄ to release its lock on A.

- Such a situation is called a **deadlock**.
  - To handle a deadlock one of T₃ or T₄ must be rolled back and its locks released.
The potential for deadlock exists in most locking protocols. Deadlocks are a necessary evil.

Starvation is also possible 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 managers can be designed to prevent starvation.
The Two-Phase Locking Protocol

- This is 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).
Two-phase locking does not ensure freedom from deadlocks

Cascading roll-back is possible under two-phase locking. To avoid this, follow a modified protocol called strict two-phase locking. Here 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.
The Two-Phase Locking Protocol (Cont.)

- 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 in the following sense:

  Given a transaction $T_i$ that does not follow two-phase locking, we can find a transaction $T_j$ that uses two-phase locking, and a schedule for $T_i$ and $T_j$ that is not conflict serializable.
Lock Conversions

- Two-phase locking with lock conversions:
  - First 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)
  - Second Phase:
    - can release a lock-S
    - can release a lock-X
    - can convert a lock-X to a lock-S (downgrade)

- This protocol assures serializability. But still relies on the programmer to insert the various locking instructions.
Automatic Acquisition of Locks

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

  
  \[
  \text{if } T_i \text{ has a lock on } D \\
  \text{then} \\
  \text{read}(D) \\
  \text{else begin} \\
  \text{if necessary wait until no other transaction has a lock-}X \text{ on } D \\
  \text{grant } T_i \text{ a lock-}S \text{ on } D; \\
  \text{read}(D) \\
  \text{end}
  \]
write\((D)\) is processed as:

\[
\begin{align*}
&\text{if } T_i \text{ has a lock-X on } D \\
&\quad \text{then} \\
&\quad \text{write}(D) \\
&\text{else begin} \\
&\quad \text{if necessary wait until no other trans. has any lock on } D, \\
&\quad \text{if } T_i \text{ has a lock-S on } D \\
&\quad \quad \text{then} \\
&\quad \quad \text{upgrade lock on } D \text{ to lock-X} \\
&\quad \text{else} \\
&\quad \quad \text{grant } T_i \text{ a lock-X on } D \\
&\quad \text{write}(D) \\
&\text{end} \\
\end{align*}
\]

All locks are released after commit or abort
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

- Black rectangles indicate granted locks, white 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 $D = \{d_1, d_2, \ldots, d_h\}$ 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.
1. Only exclusive locks are allowed.
2. 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 $T_i$.
3. Data items may be unlocked at any time.
4. A data item that has been locked and unlocked by $T_i$ cannot subsequently be relocked by $T_i$.
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
- Schedules not possible under two-phase locking are possible under tree protocol, and vice versa.
Deadlock Handling

- Consider the following two transactions:
  \[
  T_1: \text{write}(X) \quad T_2: \text{write}(Y)
  \]
  \[
  \text{write}(Y) \quad \text{write}(X)
  \]
- Schedule with deadlock

<table>
<thead>
<tr>
<th></th>
<th>\text{T}_1</th>
<th>\text{T}_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{lock-X} on A</td>
<td>\text{lock-X} on B</td>
<td></td>
</tr>
<tr>
<td>\text{write (A)}</td>
<td>\text{write (B)}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>wait for \text{lock-X} on A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>wait for \text{lock-X} on B</td>
<td></td>
</tr>
</tbody>
</table>
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.

- **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 (predeclaration).
  - 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).
More Deadlock Prevention Strategies

- Following schemes use transaction timestamps for the sake of deadlock prevention alone.

- **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 needed data item

- **wound-wait** scheme — preemptive
  - older transaction *wounds* (forces rollback) of younger transaction instead of waiting for it. Younger transactions may wait for older ones.
  - may be fewer rollbacks than *wait-die* scheme.
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.

**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.
- thus deadlocks are not possible
- simple to implement; but starvation is possible. Also difficult to determine good value of the timeout interval.
Deadlock Detection

- 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 (Cont.)

Wait-for graph without a cycle

Wait-for graph with a cycle
Deadlock Recovery

When deadlock is detected:

- Some transaction will have to be rolled back (made a victim) to break deadlock. Select that transaction as victim that will incur minimum cost.

- Rollback -- determine how far to roll back transaction
  - **Total rollback**: Abort the transaction and then restart it.
  - More effective to roll back transaction only as far as necessary to break deadlock.

- Starvation happens if same transaction is always chosen as victim. Include the number of rollbacks in the cost factor to avoid starvation.
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 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:
  - **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 descendant nodes.
The compatibility matrix for all lock modes is:

<table>
<thead>
<tr>
<th></th>
<th>IS</th>
<th>IX</th>
<th>S</th>
<th>SIX</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS</td>
<td>true</td>
<td>true</td>
<td>true</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>IX</td>
<td>true</td>
<td>true</td>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>S</td>
<td>true</td>
<td>false</td>
<td>true</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>SIX</td>
<td>true</td>
<td>false</td>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>X</td>
<td>false</td>
<td>false</td>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
</tbody>
</table>
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.
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-timestamp**($Q$) is the largest time-stamp of any transaction that executed $\text{write}(Q)$ successfully.
- **R-timestamp**($Q$) is the largest time-stamp of any transaction that executed $\text{read}(Q)$ successfully.
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 $TS(T_i) \leq W$-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 $TS(T_i) \geq W$-timestamp($Q$), then the read operation is executed, and $R$-timestamp($Q$) is set to $\max(R$-timestamp($Q$), $TS(T_i)$).
Suppose that transaction $T_i$ issues $\text{write}(Q)$.

1. If $\text{TS}(T_i) < \text{R-timestamp}(Q)$, 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 $\text{write}$ operation is rejected, and $T_i$ is rolled back.

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

3. Otherwise, the $\text{write}$ operation is executed, and $\text{W-timestamp}(Q)$ is set to $\text{TS}(T_i)$. 
Example Use of the Protocol

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

<table>
<thead>
<tr>
<th></th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_3$</th>
<th>$T_4$</th>
<th>$T_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>read ($Y$)</td>
<td>write ($Y$)</td>
<td>write ($Z$)</td>
<td>read ($X$)</td>
</tr>
<tr>
<td></td>
<td>read ($Y$)</td>
<td></td>
<td>read ($Z$)</td>
<td>abort</td>
<td></td>
</tr>
<tr>
<td></td>
<td>read ($X$)</td>
<td>abort</td>
<td>write ($W$)</td>
<td>abort</td>
<td>write ($Y$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>read ($W$)</td>
<td>write ($Z$)</td>
</tr>
</tbody>
</table>
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

Problem with timestamp-ordering protocol:

- Suppose $T_i$ aborts, but $T_j$ has read a data item written by $T_i$
- Then $T_j$ must abort; if $T_j$ had been allowed to commit earlier, the schedule is not recoverable.
- Further, any transaction that has read a data item written by $T_j$ must abort
- This can lead to cascading rollback --- that is, a chain of rollbacks

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 $\text{TS}(T_i) < \text{W-timestamp}(Q)$, 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 \text{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.
Validation-Based Protocol

- 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 as **optimistic concurrency control** since transaction executes fully in the hope that all will go well during validation.
Validation-Based Protocol (Cont.)

- Each transaction $T_i$ has 3 timestamps
  - Start($T_i$) : the time when $T_i$ started its execution
  - Validation($T_i$): the time when $T_i$ entered its validation phase
  - Finish($T_i$) : the time when $T_i$ finished its write phase

- Serializability order is determined by timestamp given at validation time, to increase concurrency.
  - Thus $TS(T_i)$ is given the value of Validation($T_i$).

- This protocol is useful and gives greater degree of concurrency if probability of conflicts is low.
  - because the serializability order is not pre-decided, and
  - relatively few transactions will have to be rolled back.
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:
  
  - $\text{finish}(T_i) < \text{start}(T_j)$
  - $\text{start}(T_j) < \text{finish}(T_i) < \text{validation}(T_j)$ 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 overlapped 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

<table>
<thead>
<tr>
<th>$T_{25}$</th>
<th>$T_{26}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>read (B)</td>
<td>read (B)</td>
</tr>
<tr>
<td>read (A)</td>
<td>$B := B \ 50$</td>
</tr>
<tr>
<td>$\langle$ validate $\rangle$</td>
<td>read (A)</td>
</tr>
<tr>
<td>display (A + B)</td>
<td>$A := A + 50$</td>
</tr>
<tr>
<td>$\langle$ validate $\rangle$</td>
<td>write (B)</td>
</tr>
<tr>
<td></td>
<td>write (A)</td>
</tr>
</tbody>
</table>
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

- 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 $TS(T_j) > R$-timestamp($Q_k$).
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-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. 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 $T_i$.

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.
  - 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 (Cont.)

- When an update transaction wants to read a data item:
  - it obtains a shared lock on it, and reads the latest version.
- When it wants to write an item
  - it obtains X lock on; it then creates a new version of the item and sets this version's timestamp to $\infty$.
- When update transaction $T_i$ completes, commit processing occurs:
  - $T_i$ sets timestamp on the versions it has created to $\text{ts-counter} + 1$
  - $T_i$ increments $\text{ts-counter}$ by 1
- Read-only transactions that start after $T_i$ increments $\text{ts-counter}$ will see the values updated by $T_i$.
- Read-only transactions that start before $T_i$ increments the $\text{ts-counter}$ 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
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: 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, updates alone use 2-phase locking to guard against concurrent updates
  - Problem: variety of anomalies such as lost update can result
  - Partial solution: snapshot isolation level (next slide)
    - Proposed by Berenson et al, SIGMOD 1995
    - Variants implemented in many database systems
      - E.g. Oracle, PostgreSQL, SQL Server 2005
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.

<table>
<thead>
<tr>
<th></th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>W(Y := 1)</td>
<td>Commit</td>
<td>Start</td>
<td>W(X:=2) Commit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R(X) → 0</td>
<td>W(Z:=3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R(Y) → 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>W(X:=3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Commit-Req</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Abort</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$T_1$ deposits 50 in $Y$</th>
<th>$T_2$ withdraws 50 from $X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1(X_0, 100)$</td>
<td>$r_2(Y_0, 0)$</td>
</tr>
<tr>
<td>$r_1(Y_0, 0)$</td>
<td>$r_2(X_0, 100)$</td>
</tr>
<tr>
<td>$w_1(Y_1, 50)$</td>
<td>$w_2(X_2, 50)$</td>
</tr>
<tr>
<td>$r_1(X_0, 100)$ (update by $T_2$ not seen)</td>
<td></td>
</tr>
<tr>
<td>$r_1(Y_1, 50)$ (can see its own updates)</td>
<td></td>
</tr>
</tbody>
</table>

$X_0 = 100, Y_0 = 0$

$X_2 = 50, Y_1 = 50$
### Snapshot Write: First Committer Wins

#### 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)
- Differs only in when abort occurs, otherwise equivalent

**Table:**

<table>
<thead>
<tr>
<th>Action</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$ deposits 50 in $X$</td>
<td>$r_1(X_0, 100)$</td>
</tr>
<tr>
<td>$T_2$ withdraws 50 from $X$</td>
<td>$r_2(X_0, 100)$</td>
</tr>
<tr>
<td>$w_1(X_1, 150)$</td>
<td>$w_2(X_2, 50)$</td>
</tr>
<tr>
<td>$commit_1$</td>
<td>$commit_2$ (Serialization Error $T_2$ is rolled back)</td>
</tr>
</tbody>
</table>

**States:**
- $X_0 = 100$
- $X_1 = 150$
Benefits of SI

- Reading is *never* blocked,
  - and also doesn’t block other txns 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 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

- E.g. of problem with SI
  - 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:
    - Find max order number among all orders
    - Create a new order with order number = previous max + 1
Snapshot Isolation Anomalies

- SI breaks serializability when txns 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 too (like a total quantity) so SI will abort one of them
  - But does 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
**Warning**: SI used when isolation level is set to serializable, by Oracle, and PostgreSQL versions prior to 9.1

- PostgreSQL’s implementation of SI (versions prior to 9.1) described in Section 26.4.1.3
- 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
  - Oracle and PostgreSQL < 9.1 do not support true serializable execution
- PostgreSQL 9.1 introduced new protocol called “Serializable Snapshot Isolation” (SSI)
  - Which guarantees true serializability including handling predicate reads (coming up)
SI In Oracle and PostgreSQL

- Can sidestep SI for specific queries by using `select .. for update` in Oracle and PostgreSQL
  - E.g.,
    1. `select max(orderno) from orders for update`
    2. read value into local variable maxorder
    3. insert into orders (maxorder+1, …)
  - Select for update (SFU) treats all data read by the query as if it were also updated, preventing concurrent updates
  - Does not always ensure serializability since phantom phenomena can occur (coming up)
- In PostgreSQL versions < 9.1, SFU locks the data item, but releases locks when the transaction completes, even if other concurrent transactions are active
  - Not quite same as SFU in Oracle, which keeps locks until all concurrent transactions have completed
Insert and Delete Operations

- 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**.
  - A transaction that scans a relation
    - (e.g., find sum of balances of all accounts in Perryridge)
    and a transaction that inserts a tuple in the relation
    - (e.g., insert a new account at Perryridge)
    (conceptually) conflict in spite of not accessing any tuple in common.
  - If only tuple locks are used, non-serializable schedules can result
    - E.g. the scan transaction does not see the new account, but reads some other tuple written by the update transaction.
Insert and Delete Operations (Cont.)

- 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 with the relation, to represent the information about what tuples the relation contains.
  - Transactions scanning the relation acquire a shared lock in the data item,
  - Transactions inserting or deleting a tuple acquire an exclusive lock on the data item. (Note: locks on the data item do not conflict with locks on individual tuples.)

- Above protocol provides very low concurrency for insertions/deletions.

- Index locking protocols provide higher concurrency while preventing the phantom phenomenon, by requiring locks on certain index buckets.
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 a relation $r$.
    - must update all indices to $r$
    - 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 phantom phenomenon won’t occur.
Next-Key Locking

- Index-locking protocol to prevent phantoms required locking entire leaf
  - Can result in poor concurrency if there are many inserts
- Alternative: for an index lookup
  - Lock all values that satisfy index lookup (match lookup value, or fall in lookup range)
  - Also lock next key value in index
  - 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
Concurrence 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.)

- Example of index concurrency protocol:
  - Use **crabbing** instead of two-phase locking on the nodes of the \(B^+\)-tree, as follows. 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

- Better protocols are available; see Section 16.9 for one such protocol, the B-link tree protocol
  - Intuition: release lock on parent before acquiring lock on child
    - And deal with changes that may have happened between lock release and acquire
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 many database systems, read committed is the default consistency level

- has to be explicitly changed to serializable when required
  - `set isolation level serializable`
Transactions across User Interaction

- 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`

- Equivalent to optimistic concurrency control without validating read set

- Used internally in Hibernate ORM system, and manually in many applications

- Version numbering can also be used to support first committer wins check of snapshot isolation
  - Unlike SI, reads are not guaranteed to be from a single snapshot
End of Chapter

Thanks to Alan Fekete and Sudhir Jorwekar for Snapshot Isolation examples

modified from:

Database System Concepts, 6th Ed.
©Silberschatz, Korth and Sudarshan
See www.db-book.com for conditions on re-use
<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>X</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>$T_1$</td>
<td>$T_2$</td>
<td>concurrency-control manager</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>lock-x ($B$)</td>
<td></td>
<td>grant-x ($B$, $T_1$)</td>
</tr>
<tr>
<td>read ($B$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B := B - 50$</td>
<td>lock-s ($A$)</td>
<td>grant-s ($A$, $T_2$)</td>
</tr>
<tr>
<td>write ($B$)</td>
<td>read ($A$)</td>
<td>grant-s ($B$, $T_2$)</td>
</tr>
<tr>
<td>unlock ($B$)</td>
<td>unlock ($A$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lock-s ($B$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>read ($B$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>unlock ($B$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>display ($A + B$)</td>
<td></td>
</tr>
<tr>
<td>lock-x ($A$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>read ($A$)</td>
<td></td>
<td>grant-x ($A$, $T_2$)</td>
</tr>
<tr>
<td>$A := A + 50$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>write ($A$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unlock ($A$)</td>
<td></td>
<td></td>
</tr>
</tbody>
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### Figure 15.07

<table>
<thead>
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<th>$T_3$</th>
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<td>lock-x ($B$)</td>
<td>lock-s ($A$)</td>
</tr>
<tr>
<td>read ($B$)</td>
<td>read ($A$)</td>
</tr>
<tr>
<td>$B := B - 50$</td>
<td>lock-s ($B$)</td>
</tr>
<tr>
<td>write ($B$)</td>
<td></td>
</tr>
<tr>
<td>lock-x ($A$)</td>
<td></td>
</tr>
<tr>
<td>$T_5$</td>
<td>$T_6$</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
</tr>
<tr>
<td>lock-x ($A$)</td>
<td></td>
</tr>
<tr>
<td>read ($A$)</td>
<td></td>
</tr>
<tr>
<td>lock-s ($B$)</td>
<td>read ($B$)</td>
</tr>
<tr>
<td>read ($B$)</td>
<td>write ($A$)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_8$</td>
<td>$T_9$</td>
</tr>
<tr>
<td>------------</td>
<td>------------------</td>
</tr>
<tr>
<td>lock-s ($a_1$)</td>
<td>lock-s ($a_1$)</td>
</tr>
<tr>
<td>lock-s ($a_2$)</td>
<td>lock-s ($a_2$)</td>
</tr>
<tr>
<td>lock-s ($a_3$)</td>
<td>unlock-s ($a_3$)</td>
</tr>
<tr>
<td>lock-s ($a_4$)</td>
<td>unlock-s ($a_4$)</td>
</tr>
<tr>
<td>lock-s ($a_n$)</td>
<td>upgrade ($a_2$)</td>
</tr>
</tbody>
</table>
Figure 15.10

[Diagram showing a sequence of transactions and resource allocation]

- T8
- T1 T23
- T23 14
- T23 T1 T8 T2
- T23
- 123
- 17
- T23
- 1912
- 14
- T1 T23
- T8
- 144
- granted
- waiting
Figure 15.11
<table>
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<tr>
<th></th>
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<th>T\textsubscript{11}</th>
<th>T\textsubscript{12}</th>
<th>T\textsubscript{13}</th>
</tr>
</thead>
<tbody>
<tr>
<td>lock-x (B)</td>
<td></td>
<td>lock-x (D)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lock-x (E)</td>
<td>lock-x (D)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lock-x (D)</td>
<td></td>
<td>lock-x (H)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unlock (B)</td>
<td>unlock (D)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unlock (E)</td>
<td>unlock (H)</td>
<td></td>
<td>lock-x (B)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>unlock (H)</td>
<td>lock-x (E)</td>
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</tr>
<tr>
<td>lock-x (G)</td>
<td>unlock (D)</td>
<td></td>
<td></td>
<td>lock-x (D)</td>
</tr>
<tr>
<td>unlock (D)</td>
<td>unlock (E)</td>
<td></td>
<td></td>
<td>lock-x (H)</td>
</tr>
<tr>
<td>unlock (G)</td>
<td></td>
<td></td>
<td></td>
<td>unlock (H)</td>
</tr>
</tbody>
</table>
Figure 15.13
Figure 15.14
Figure 15.15
### Figure 15.16

<table>
<thead>
<tr>
<th></th>
<th>IS</th>
<th>IX</th>
<th>S</th>
<th>SIX</th>
<th>X</th>
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<tr>
<td>S</td>
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<td>true</td>
<td>false</td>
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<tr>
<td>SIX</td>
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</tr>
<tr>
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<tr>
<td>$T_{25}$</td>
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<td>----------------</td>
<td>--------------------------------</td>
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<tr>
<td>read ($B$)</td>
<td>read ($B$)</td>
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</tr>
<tr>
<td></td>
<td>$B := B - 50$</td>
<td></td>
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<tr>
<td>read ($A$)</td>
<td>write ($B$)</td>
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<tr>
<td>display ($A + B$)</td>
<td>read ($A$)</td>
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<td>$A := A + 50$</td>
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<td>write ($A$)</td>
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</tr>
<tr>
<td></td>
<td>display ($A + B$)</td>
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Figure 15.18

<table>
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<td>read (Q)</td>
<td>write (Q)</td>
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<tr>
<td>write (Q)</td>
<td></td>
</tr>
<tr>
<td>$T_{25}$</td>
<td>$T_{26}$</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>read ($B$)</td>
<td>read ($B$)</td>
</tr>
<tr>
<td></td>
<td>$B := B + 50$</td>
</tr>
<tr>
<td></td>
<td>read ($A$)</td>
</tr>
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<td></td>
<td>$A := A + 50$</td>
</tr>
<tr>
<td>read ($A$)</td>
<td></td>
</tr>
<tr>
<td>$\langle validate \rangle$</td>
<td></td>
</tr>
<tr>
<td>display ($A + B$)</td>
<td>$\langle validate \rangle$</td>
</tr>
<tr>
<td></td>
<td>write ($B$)</td>
</tr>
<tr>
<td></td>
<td>write ($A$)</td>
</tr>
<tr>
<td></td>
<td>$T_{32}$</td>
</tr>
<tr>
<td>------</td>
<td>------------------</td>
</tr>
<tr>
<td>lock-s (Q)</td>
<td>read (Q)</td>
</tr>
<tr>
<td>read (Q)</td>
<td>unlock (Q)</td>
</tr>
<tr>
<td>unlock (Q)</td>
<td></td>
</tr>
<tr>
<td>lock-s (Q)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 15.21
Figure 15.22

The diagram illustrates a hierarchical structure with the following disciplines:

- **History**
  - **Comp. Sci.**
  - **Elec. Eng.**
    - **Music**
    - **History**
      - **Finance**
      - **Physics**
    - **Comp. Sci.**
      - **Chemistry**
      - **Comp. Sci.**
    - **Elec. Eng.**
      - **Music**
    - **History**
      - **Music**
  - **Comp. Sci.**
    - **Biology**
    - **Chemistry**
  - **Elec. Eng.**
    - **Physics**
  - **Comp. Sci.**
    - **History**
  - **Elec. Eng.**
    - **Music**
  - **History**
    - **Physics**
### Figure 15.23

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>X</th>
<th>I</th>
</tr>
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<tbody>
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<td>S</td>
<td>true</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>X</td>
<td>false</td>
<td>false</td>
<td>false</td>
</tr>
<tr>
<td>I</td>
<td>false</td>
<td>false</td>
<td>true</td>
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</tbody>
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### Figure in-15.1

<table>
<thead>
<tr>
<th>$T_{27}$</th>
<th>$T_{28}$</th>
<th>$T_{29}$</th>
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</thead>
<tbody>
<tr>
<td>read $(Q)$</td>
<td>write $(Q)$</td>
<td>write $(Q)$</td>
</tr>
<tr>
<td>write $(Q)$</td>
<td>write $(Q)$</td>
<td></td>
</tr>
</tbody>
</table>