Chapter 15 : Concurrency Control
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- Lock-Based Protocols
- Timestamp-Based Protocols
- Validation-Based Protocols
- Multiple Granularity
- Multiversion Schemes
- Insert and Delete Operations
- Concurrency in Index Structures
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**

<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 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.
Example of a transaction performing locking:

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

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>$T_3$</th>
<th>$T_4$</th>
</tr>
</thead>
<tbody>
<tr>
<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>
</tbody>
</table>

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.
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

- 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).
The Two-Phase Locking Protocol (Cont.)

- 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.
A transaction $T_i$ issues the standard read/write instruction, without explicit locking calls.

The operation $\text{read}(D)$ is processed as:

if $T_i$ has a lock on $D$
    then
        read($D$)
    else begin
        if necessary wait until no other transaction has a lock-$X$ on $D$
        grant $T_i$ a lock-$S$ on $D$
        read($D$)
    end
Automatic Acquisition of Locks (Cont.)

- $$\textbf{write}(D)$$ is processed as:
  
  if $$T_i$$ has a **lock-X** on $$D$$
  
  then
  
  write($$D$$)
  
  else begin
  
  if necessary wait until no other trans. has any lock on $$D$$,
  
  if $$T_i$$ has a **lock-S** on $$D$$
  
  then
  
  upgrade lock on $$D$$ to **lock-X**
  
  else
  
  grant $$T_i$$ a **lock-X** on $$D$$
  
  write($$D$$)
  
  end;

- 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 $D = \{d_1, d_2, ..., d_n\}$ 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 item $Q$ 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 $T_i$. 
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>( T_1 )</th>
<th>( T_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>lock-X</td>
<td>on A</td>
<td>lock-X on B</td>
</tr>
<tr>
<td></td>
<td>write (A)</td>
<td>write (B)</td>
</tr>
<tr>
<td></td>
<td>wait for lock-X on B</td>
<td>wait for lock-X on A</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
Deadlock prevention (Cont.)

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 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 descendent nodes.
Compatibility Matrix with Intention Lock Modes

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.
Timestamp-Based Protocols

- 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 **write**($Q$) successfully.
  - **R-timestamp**($Q$) is the largest time-stamp of any transaction that executed **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 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 write operation is rejected, and $T_i$ is rolled back.

3. Otherwise, the 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>read (Y)</td>
<td></td>
<td>write (Y)</td>
<td></td>
<td>read (X)</td>
</tr>
<tr>
<td></td>
<td>read (X)</td>
<td>abort</td>
<td>write (Y)</td>
<td>write (Z)</td>
<td>read (Z)</td>
</tr>
<tr>
<td></td>
<td>read (X)</td>
<td>abort</td>
<td></td>
<td>read (W)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>write (W)</td>
<td>abort</td>
<td>write (Y)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></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:

  ![Diagram](transaction_with_smaller_timestamp -> transaction_with_larger_timestamp)

  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 $TS(T_i) < W$-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.
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 \texttt{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 \texttt{write}(Q) operation of transaction \( T_j \).
3. The transaction (if any) that performs the final \texttt{write}(Q) operation in schedule \( S \) must also perform the final \texttt{write}(Q) operation in schedule \( S' \).

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

<table>
<thead>
<tr>
<th></th>
<th>$T_3$</th>
<th>$T_4$</th>
<th>$T_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>read($Q$)</td>
<td>write($Q$)</td>
<td>write($Q$)</td>
</tr>
<tr>
<td></td>
<td>write($Q$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

What serial schedule is above equivalent to?

Every view serializable schedule that is not conflict serializable has **blind writes**.
Other Notions of Serializability

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

<table>
<thead>
<tr>
<th></th>
<th>(T_1)</th>
<th>(T_5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>read((A))</td>
<td>read((B))</td>
</tr>
<tr>
<td></td>
<td>(A := A - 50)</td>
<td>(B := B - 10)</td>
</tr>
<tr>
<td></td>
<td>write((A))</td>
<td>write((B))</td>
</tr>
<tr>
<td></td>
<td>read((B))</td>
<td>write((B))</td>
</tr>
<tr>
<td></td>
<td>(B := B + 50)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>write((B))</td>
<td>read((A))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(A := A + 10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>write((A))</td>
</tr>
</tbody>
</table>

- Determining such equivalence requires analysis of operations other than read and write.
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, the existence of an efficient algorithm is extremely unlikely.
- However, practical algorithms that just check some sufficient conditions for view serializability can still be used.
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.
Each transaction $T_i$ has 3 timestamps:
- $\text{Start}(T_i)$: the time when $T_i$ started its execution
- $\text{Validation}(T_i)$: the time when $T_i$ entered its validation phase
- $\text{Finish}(T_i)$: 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 $\text{Validation}(T_i)$.

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></td>
<td>$B := B \ 50$</td>
</tr>
<tr>
<td>read ($A$)</td>
<td>read ($A$)</td>
</tr>
<tr>
<td>$\langle \text{validate} \rangle$</td>
<td>$A := A + 50$</td>
</tr>
<tr>
<td>display ($A + B$)</td>
<td>$\langle \text{validate} \rangle$</td>
</tr>
<tr>
<td></td>
<td></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 $\langle Q_1, Q_2, \ldots, Q_m \rangle$. Each version $Q_k$ contains three data fields:
  - **Content** -- the value of version $Q_k$.
  - **W-timestamp**($Q_k$) -- timestamp of the transaction that created (wrote) version $Q_k$.
  - **R-timestamp**($Q_k$) -- largest timestamp of a transaction that successfully read version $Q_k$.

- When a transaction $T_i$ creates a new version $Q_k$ of $Q$, $Q_k$'s W-timestamp and R-timestamp are initialized to $TS(T_i)$.

- R-timestamp of $Q_k$ is updated whenever a transaction $T_j$ reads $Q_k$, and $TS(T_j) > R$-timestamp($Q_k$).
Multiversion Timestamp Ordering (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 $Q_k$.
  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
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.

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

Concurrent updates not visible
Own updates are visible
Not first-committer of X
Serialization error, T2 is rolled back
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
SI In Oracle and PostgreSQL

- **Warning**: SI used when isolation level is set to serializable, by Oracle and PostgreSQL
  - PostgreSQL’s implementation of SI 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
  - Neither supports true serializable execution
- Can sidestep for specific queries by using `select .. for update` in Oracle and PostgreSQL
  - Locks the data which is read, preventing concurrent updates
  - E.g.,
    1. `select max(orderno) from orders for update`
    2. read value into local variable maxorder
    3. insert into orders (maxorder+1, ...)

- Can sidestep for specific queries by using `select .. for update` in Oracle and PostgreSQL
  - Locks the data which is read, preventing concurrent updates
  - E.g.,
    1. `select max(orderno) from orders for update`
    2. read value into local variable maxorder
    3. insert into orders (maxorder+1, ...)
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 information should be locked.
- 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.
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`
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.
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 $\text{B}^+$-tree are irrelevant so long as we land up in the correct leaf node.
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
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
End of Chapter

Thanks to Alan Fekete and Sudhir Jorwekar for Snapshot Isolation examples
Snapshot Read

- Concurrent updates invisible to snapshot read

<table>
<thead>
<tr>
<th></th>
<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></td>
<td>$r_2(Y_0,0)$</td>
</tr>
<tr>
<td>$r_1(Y_0,0)$</td>
<td></td>
<td>$r_2(X_0,100)$</td>
</tr>
<tr>
<td>$w_1(Y_1,50)$</td>
<td>(update by $T_2$ not seen)</td>
<td>$w_2(X_2,50)$</td>
</tr>
<tr>
<td>$r_1(X_0,100)$</td>
<td>(can see its own updates)</td>
<td>$r_2(Y_0,0)$</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
  - (Oracle uses this plus some extra features)
  - Differs only in when abort occurs, otherwise equivalent

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

$X_0 = 100$

$X_1 = 150$
<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>
## Figure 15.04

<table>
<thead>
<tr>
<th>$T_1$</th>
<th>$T_2$</th>
<th>concurrency-control manager</th>
</tr>
</thead>
<tbody>
<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></td>
<td></td>
</tr>
<tr>
<td>write ($B$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unlock ($B$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>lock-s ($A$)</td>
<td>grant-s ($A$, $T_2$)</td>
</tr>
<tr>
<td></td>
<td>read ($A$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>unlock ($A$)</td>
<td>grant-s ($A$, $T_2$)</td>
</tr>
<tr>
<td></td>
<td>lock-s ($B$)</td>
<td>grant-s ($B$, $T_2$)</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>grant-x ($A$, $T_2$)</td>
</tr>
<tr>
<td>read ($A$)</td>
<td></td>
<td></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>
<tr>
<td>$T_3$</td>
<td>$T_4$</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>lock-x ($B$)</td>
<td>lock-s ($A$)</td>
<td></td>
</tr>
<tr>
<td>read ($B$)</td>
<td>read ($A$)</td>
<td></td>
</tr>
<tr>
<td>$B := B - 50$</td>
<td>lock-s ($B$)</td>
<td></td>
</tr>
<tr>
<td>write ($B$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lock-x ($A$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_5$</td>
<td>$T_6$</td>
</tr>
<tr>
<td>-----</td>
<td>-------------</td>
<td>-----------</td>
</tr>
<tr>
<td></td>
<td>lock-x ($A$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>read ($A$)</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>write ($A$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>unlock ($A$)</td>
<td></td>
</tr>
<tr>
<td>$T_8$</td>
<td>$T_9$</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>lock-$s$ ($a_1$)</td>
<td>lock-$s$ ($a_2$)</td>
<td></td>
</tr>
<tr>
<td>lock-$s$ ($a_2$)</td>
<td>lock-$s$ ($a_2$)</td>
<td></td>
</tr>
<tr>
<td>lock-$s$ ($a_3$)</td>
<td>unlock-$s$ ($a_3$)</td>
<td></td>
</tr>
<tr>
<td>lock-$s$ ($a_4$)</td>
<td>unlock-$s$ ($a_4$)</td>
<td></td>
</tr>
<tr>
<td>lock-$s$ ($a_n$)</td>
<td>upgrade ($a_3$)</td>
<td></td>
</tr>
</tbody>
</table>
### Figure 15.12

<table>
<thead>
<tr>
<th></th>
<th>( T_{10} )</th>
<th>( T_{11} )</th>
<th>( T_{12} )</th>
<th>( T_{13} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lock-( x ) (( B ))</td>
<td>lock-( x ) (( D ))</td>
<td>lock-( x ) (( B ))</td>
<td>lock-( x ) (( D ))</td>
</tr>
<tr>
<td></td>
<td>lock-( x ) (( E ))</td>
<td>lock-( x ) (( H ))</td>
<td>lock-( x ) (( E ))</td>
<td>lock-( x ) (( H ))</td>
</tr>
<tr>
<td></td>
<td>lock-( x ) (( D ))</td>
<td>unlock (( D ))</td>
<td>lock-( x ) (( H ))</td>
<td>unlock (( D ))</td>
</tr>
<tr>
<td></td>
<td>unlock (( B ))</td>
<td>unlock (( D ))</td>
<td>unlock (( E ))</td>
<td>unlock (( H ))</td>
</tr>
<tr>
<td></td>
<td>unlock (( E ))</td>
<td>unlock (( H ))</td>
<td>unlock (( B ))</td>
<td>unlock (( H ))</td>
</tr>
<tr>
<td></td>
<td>unlock (( G ))</td>
<td>unlock (( B ))</td>
<td>unlock (( E ))</td>
<td>unlock (( H ))</td>
</tr>
</tbody>
</table>
Figure 15.13
### Figure 15.16

<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>
<tr>
<td>$T_{25}$</td>
<td>$T_{26}$</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>---------------</td>
<td>---------------------</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>read ($B$)</td>
<td>read ($B$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$B := B - 50$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>write ($B$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>read ($A$)</td>
<td>read ($A$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>display ($A + B$)</td>
<td>$A := A + 50$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>write ($A$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>display ($A + B$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{27}$</td>
<td>$T_{28}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>read $(Q)$</td>
<td>write $(Q)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Figure 15.19

<table>
<thead>
<tr>
<th>$T_{25}$</th>
<th>$T_{26}$</th>
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</thead>
<tbody>
<tr>
<td>read ($B$)</td>
<td>read ($B$)</td>
</tr>
<tr>
<td></td>
<td>$B := B \ 50$</td>
</tr>
<tr>
<td>read ($A$)</td>
<td>read ($A$)</td>
</tr>
<tr>
<td>$\langle validate \rangle$</td>
<td>$A := A + 50$</td>
</tr>
<tr>
<td>display ($A + B$)</td>
<td>$\langle validate \rangle$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{32}$</td>
<td>$T_{33}$</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>lock-s ($Q$)</td>
<td>lock-x ($Q$)</td>
</tr>
<tr>
<td>read ($Q$)</td>
<td>read ($Q$)</td>
</tr>
<tr>
<td>unlock ($Q$)</td>
<td>write ($Q$)</td>
</tr>
<tr>
<td></td>
<td>unlock ($Q$)</td>
</tr>
</tbody>
</table>
Figure 15.21

The diagram shows a tree structure with the following nodes:

- History
- Elec. Eng.
- Elec. Eng.
- Finance
- History
- Music
- Comp. Sci.
- Biology
- Music
- Physics
Figure 15.22

A diagram illustrating a tree structure with the following nodes:
- Biology
- Chemistry
- Comp. Sci.
- Elec. Eng.
- Finance
- History
- Music
- Physics

The tree structure shows a hierarchical relationship among these nodes.
### Figure 15.23

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