# Lecture 9
# Concurrency Control

Chapter 16

(Sections 16.1.1, 16.1.2, 16.1.3, 16.1.5, 16.2--16.7)

## Concurrency Control

- Lock-Based Protocols
- Timestamp-Based Protocols
- Validation-Based Protocols
- Multiple Granularity
- Multiversion Schemes
- Deadlock Handling
- Insert and Delete Operations



## Lock-Based Protocols

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



## Lock-Based Protocols (Cont.)

Lock-compatibility matrix

| | S | X |
|---|---|---|
| S | true | false |
| X | false | false |

- A transaction may be granted a lock on an item if the requested lock *is compatible* with locks already held on the item by other transactions
- Any number of transactions can hold shared locks on an item, but if any transaction holds an exclusive on the item no other transaction may hold any lock on the item.
- 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:

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

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



## Pitfalls of Lock-Based Protocols

Consider the partial schedule

| $T_3$ | $T_4$ |
|---|---|
| lock-X($B$) | |
| read($B$) | |
| $B := B - 50$ | |
| write($B$) | |
| | lock-S($A$) |
| | read($A$) |
| | lock-S($B$) |
| lock-X($A$) | |

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

## Pitfalls of Lock-Based Protocols (Cont.)

- The potential for deadlock exists in most locking protocols. Deadlocks are a necessary evil.
- **Starvation** is also possible if concurrency control manager is badly designed. For example:
  - ★ A transaction may starve 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.



## Automatic Acquisition of Locks

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

if $T_i$ has a lock on $D$<br>
**then**<br>
read($D$)<br>
**else**<br>
**begin**<br>
if necessary wait until no other transaction has a **lock-X** on $D$<br>
grant $T_i$ a **lock-S** on $D$;<br>
read($D$)<br>
**end**

## Automatic Acquisition of Locks (Cont.)

- **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**

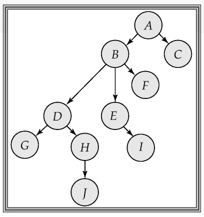


## Graph-Based Protocols

- Graph-based protocols are an alternative to two-phase locking.
- Impose a partial ordering $\rightarrow$ on the set **D** = $\{d_1, d_2, ..., d_h\}$ of all *data* items.
  - ★ If $d_i \rightarrow d_j$ then any transaction accessing both $d_i$ and $d_j$ must access $d_i$ before accessing $d_j$.
  - ★ Implies that the set **D** may now be viewed as a directed acyclic graph, called a *database graph*.
- The *tree-protocol* is a simple kind of graph protocol.



## Tree Protocol




- Only exclusive locks are allowed.
- The first lock by $T_i$ may be on any data item. Subsequently, a data *Q* can be locked by $T_i$ only if the parent of *Q* is currently locked by $T_i$.
- Data items may be unlocked at any time.
- A data item that has been locked and unlocked by $T_i$ cannot subsequently be re-locked 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
  - ★ the abort of a transaction can still lead to cascading rollbacks.
- However, in the tree-locking protocol, a transaction may have to lock data items that it does 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.



## 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 timestamps 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.



## Timestamp-Based Protocols (Cont.)

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

## Timestamp-Based Protocols (Cont.)

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



## Example Use of the Protocol

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

| $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | |
|---|---|---|---|---|---|
| | | | | **read**($X$) | **RTS**($X$) := 5 |
| | **read**($Y$) | | | | **RTS**($Y$) := 2 |
| **read**($Y$) | | | | | |
| | | **write**($Y$) | | | **WTS**($Y$) := 3 |
| | | **write**($Z$) | | | **WTS**($Z$) := 3 |
| | | | | **read**($Z$) | **RTS**($Z$) := 5 |
| | **read**($X$) **abort** | | | | |
| **read**($X$) | | | | | |
| | | **write**($Z$) **abort** | | | |
| | | | | **write**($Y$) | **WTS**($Y$) := 5 |
| | | | | **write**($Z$) | **WTS**($Z$) := 5 |



## 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:

- ★ 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



## 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 {$Q$}. Hence, 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. Unlike previous protocols, it 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.

- Also known as **optimistic concurrency control** protocols since transactions execute fully in the hope that all will go well during their validation phase.

## 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.
  That is because the serializability order is not pre-decided and relatively less 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:
  - ★ **finish**($T_i$) < **start**($T_j$)
  - ★ **start**($T_j$) < **finish**($T_i$) < **validation**($T_j$) **and** the set of data items written by $T_i$ does not intersect with the set of data items read by $T_j$.

  then validation succeeds and $T_j$ can be committed. Otherwise, validation fails and $T_j$ is aborted.

*Justification*: Either first condition is satisfied, and there is no overlapped execution, or second condition is satisfied and

1. the writes of $T_j$ do not affect reads of $T_i$ since they occur after $T_i$ has finished its reads.
2. the writes of $T_i$ do not affect reads of $T_j$ since $T_j$ does not read any item written by $T_i$.



## Schedule Produced by Validation

Example of schedule produced using validation

| $T_{14}$ | $T_{15}$ |
|---|---|
| **read**(*B*) | |
| | **read**(*B*)<br>*B* := *B-50*<br>**read**(*A*)<br>*A* := *A+50* |
| **read**(*A*)<br>(*validate*)<br>**display** (*A+B*) | |
| | (*validate*)<br>**write** (*B*)<br>**write** (*A*) |

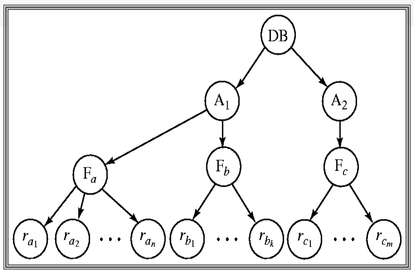


## Multiple Granularity

- 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 highest level in the example hierarchy is the entire database.

The levels below are of type *area*, *file* and *record* in that order.



## Intention Lock Modes

- In addition to **S** and **X** lock modes, there are three additional lock modes with multiple granularity:
  - ★ ***intention-shared*** (**IS**): indicates explicit locking at a lower level of the tree but only with shared locks.
  - ★ ***intention-exclusive*** (**IX**): indicates explicit locking at a lower level with exclusive or shared locks
  - ★ ***shared and intention-exclusive*** (**SIX**): the subtree rooted by that node is locked explicitly in shared mode and explicit locking is being done at a lower level with exclusive-mode locks.
- Intention locks allow a higher level node to be locked in **S** or **X** mode without having to check all descendent nodes.

## Compatibility Matrix with Intention Lock Modes

The compatibility matrix for all lock modes is:

| | IS | IX | S | S IX | X |
|---|---|---|---|---|---|
| **IS** | ✓ | ✓ | ✓ | ✓ | × |
| **IX** | ✓ | ✓ | × | × | × |
| **S** | ✓ | × | ✓ | × | × |
| **S IX** | ✓ | × | × | × | × |
| **X** | × | × | × | × | × |



## 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.



## 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.
- **read**s never have to wait as an appropriate version is returned immediately.



## Multiversion Timestamp Ordering

- Each data item $Q$ has a sequence of versions $<Q_1, Q_2,....,Q_m>$. 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**($Q_k$).



## 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**($Q$), and if TS($T_i$) < **R-timestamp**($Q_k$), then transaction $T_i$ is rolled back. Otherwise, if TS($T_i$) = **W-timestamp**($Q_k$), the contents of $Q_k$ are overwritten, otherwise a new version of $Q$ is created.
- **Read**s always succeed; a **write** by $T_i$ is rejected if some other transaction $T_j$ that (in the serialization order defined by the timestamp values) should **read** $T_i$'s **write**, has already read a version created by a transaction older than $T_i$.



## Multiversion Two-Phase Locking

Differentiates between read-only 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 **read**s.

## Multiversion Two-Phase Locking (Cont.)

- When an update transaction wants to read a data item, it obtains a **S** 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 ∞.
- When update transaction $T_i$ completes, commit processing occurs:
  - ★ $T_i$ sets timestamp on the versions it has created to **ts-counter** + 1
  - ★ $T_i$ increments **ts-counter** by 1
- Read-only transactions that start after $T_i$ increments **ts-counter** will see the values updated by $T_i$.
- Read-only transactions that start before $T_i$ increments the **ts-counter** will see the value before the updates by $T_i$.

Therefore, only serializable schedules are produced.



## Deadlock Handling

- Consider the following two transactions:

$T_1$: **write**(*X*) **write**(*Y*)    $T_2$: **write**(*Y*) **write**(*X*)

- Schedule with deadlock

| $T_1$ | $T_2$ |
|---|---|
| **lock-X** on *X*<br>**write** (*X*) | |
| | **lock-X** on *Y*<br>**write** (*X*)<br>wait for **lock-X** on *X* |
| wait for **lock-X** on *Y* | |



## Deadlock Handling

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

***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

The following schemes use transaction timestamps for the sake of deadlock prevention only.

- **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.)

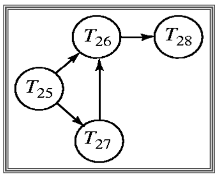
- Both in *wait-die* and in *wound-wait* schemes, a rolled back transactions is restarted with its original timestamp. Older transactions thus have precedence over newer ones, and starvation is hence avoided.
- Timeout-Based Schemes :
  - ★ A transaction waits for a lock only for a specified amount of 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.



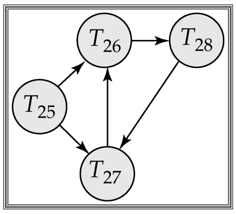
## Deadlock Detection

- 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 a deadlock is detected :

- ★ Some transaction will have to rolled back 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



## 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 **insert**s 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 all accounts in Perryridge) and a transaction that inserts a tuple in the relation (e.g., insert a new account at Perryridge) may conflict in spite of not accessing any tuple in common.
- ★ If only tuple locks are used, non-serializable schedules can result: the scan transaction may not see the new account, yet may be serialized before the insert transaction.



## Insert and Delete Operations (Cont.)

- Actually, 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.)

The above protocol provides very low concurrency for insertions/deletions.