Department of Computer Science

# CS 44800: Introduction To Relational Database Systems

*Advanced Locking*

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## Lock-Based Protocols

- A lock is a mechanism to control concurrent access to a data item
  - Goal: Prevent *conflicting* access

*Read-Read is not a conflicting access!*

- Solution: Multiple Lock Types
  1. **exclusive** *(X) mode*. Data item can be both read as well as written. X-lock is requested using **lock-X** instruction.
  2. **shared** *(S) mode*. Data item can only be read. S-lock is requested using **lock-S** instruction.
- Lock requests are made to concurrency-control manager. Transaction can proceed only after request is granted.

## Lock-Based Protocols (Cont.)

- **Lock-compatibility matrix**

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

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



## Lock Conversions

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

## 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*
  **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.)

- The operation **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**

## Shared locks

So far:

$S = \ldots l_1(A)\ r_1(A)\ u_1(A)\ \ldots\ l_2(A)\ r_2(A)\ u_2(A)\ \ldots$

Do not conflict

Instead:

$S = \ldots\ ls_1(A)\ r_1(A)\ ls_2(A)\ r_2(A)\ \ldots .\ us_1(A)\ us_2(A)$

## Operations

Lock actions

$l\text{-}t_i(A)$: lock A in t mode (t is S or X)

$u\text{-}t_i(A)$: unlock t mode (t is S or X)

Shorthand:

$u_i(A)$: unlock whatever modes $T_i$ has locked A

# What about transactions that read and write same object?

Option 1: Request exclusive lock

$T_i$ = ...l-$X_1$(A) … $r_1$(A) ... $w_1$(A) ... u(A) …

Option 2: Upgrade

$T_i$=... l-$S_1$(A) … $r_1$(A) ... l-$X_1$(A) …$w_1$(A) ...u(A)…

Think of
- Get 2nd lock on A, or
- Drop S, get X lock

# Locking Rules

- Rule #1 Well formed transactions
- $T_i$ =... l-$S_1$(A) … $r_1$(A) … $u_1$ (A) …
- $T_i$ =... l-$X_1$(A) … $w_1$(A) … $u_1$ (A) …
- Rule #2 Legal scheduler
  - S = ....l-$S_i$(A) … … $u_i$(A) …
    no l-$X_j$(A)
  - S = ... l-$X_i$(A) … … $u_i$(A) …
    no l-$X_j$(A)
    no l-$S_j$(A)

## A way to summarize Rule #2

- Compatibility matrix

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

## Rule # 3 2PL transactions

No change except for upgrades:

(I) If upgrade gets more locks

(e.g., S → {S, X}) then no change!

(II) If upgrade releases read (shared) lock (e.g., S → X)

- can be allowed in growing phase

# Why this works

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- Theorem Rules 1,2,3 $\Rightarrow$ Conflict serializable for S/X lock schedules
- Proof: similar to X locks case
  - Detail:
  - l-$t_i$(A), l-$r_j$(A) do not conflict if comp(t,r)
  - l-$t_i$(A), u-$r_j$(A) do not conflict if comp(t,r)

## Implementation of Locking

- A **lock manager** can be implemented as a separate process
- Transactions can send lock and unlock requests as messages
- The lock manager replies to a lock request by sending a lock grant messages (or a message asking the transaction to roll back, in case of a deadlock)
  - The requesting transaction waits until its request is answered
- The lock manager maintains an in-memory data-structure called a **lock table** to record granted locks and pending requests

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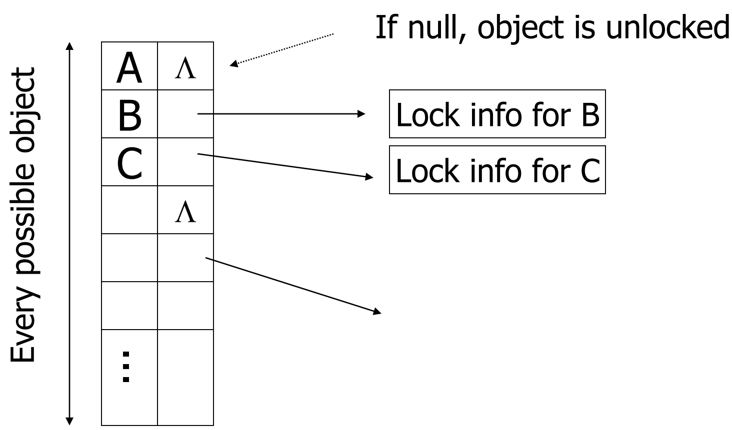
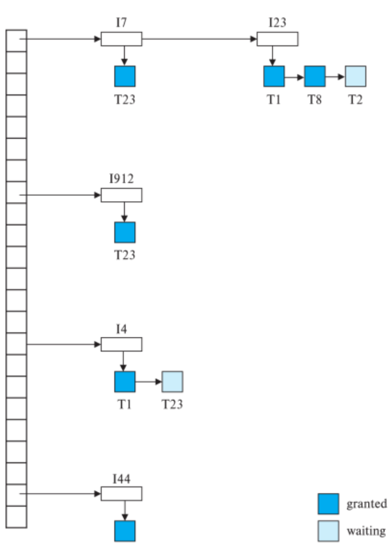
# Lock table: Conceptually




# Lock Table




- Dark rectangles indicate granted locks, light colored ones indicate waiting requests
- Lock table also records the type of lock granted or requested
- New request is added to the end of the queue of requests for the data item, and granted if it is compatible with all earlier locks
- Unlock requests result in the request being deleted, and later requests are checked to see if they can now be granted
- If transaction aborts, all waiting or granted requests of the transaction are deleted
  - lock manager may keep a list of locks held by each transaction, to implement this efficiently

## Deadlock Handling

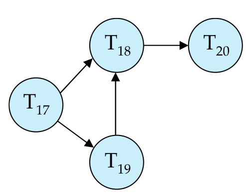
- System is **deadlocked** if there is a set of transactions such that every transaction in the set is waiting for another transaction in the set.

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

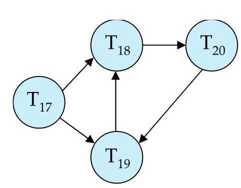


## Deadlock Detection

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




Wait-for graph without a cycle




Wait-for graph with a cycle

## Deadlock Recovery

- When deadlock is detected :
  - Some transaction will have to rolled back (made a **victim**) to break deadlock cycle.
    - Select that transaction as victim that will incur minimum cost
  - Rollback -- determine how far to roll back transaction
    - **Total rollback**: Abort the transaction and then restart it.
    - **Partial rollback**: Roll back victim transaction only as far as necessary to release locks that another transaction in cycle is waiting for
- Starvation can happen (why?)
  - One solution: oldest transaction in the deadlock set is never chosen as victim



## Deadlock Handling

- ***Deadlock prevention*** protocols ensure that the system will *never* enter into a deadlock state. Some prevention strategies:
  - Require that each transaction locks all its data items before it begins execution (pre-declaration).
  - 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

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



## Deadlock prevention (Cont.)

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

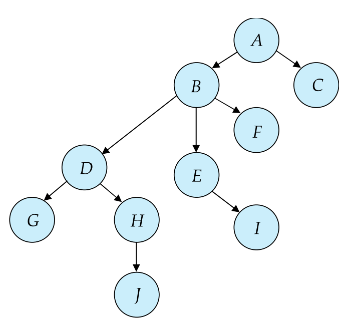
## Graph-Based Protocols

- 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.



## Tree Protocol

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



## 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 the tree protocol, and vice versa.



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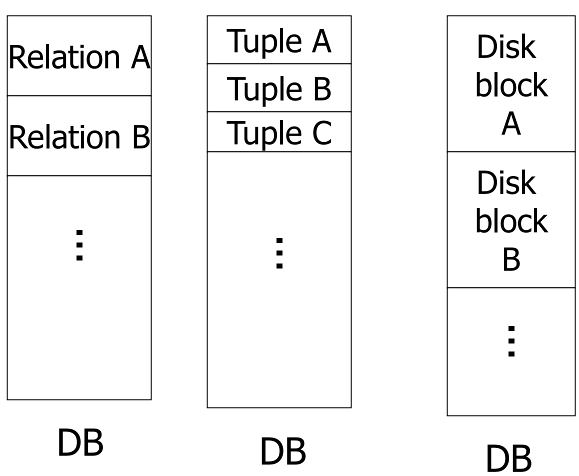
## What are the objects we lock?



## Locking works in any case, but should we choose small or large objects?

- If we lock large objects (e.g., Relations)
  - – Need few locks
  - – Low concurrency
- If we lock small objects (e.g., tuples,fields)
  - – Need more locks
  - – More concurrency

## Multiple Granularity

- Allow data items to be of various sizes and define a hierarchy of data granularities, where the small granularities are nested within larger ones
- Can be represented graphically as a tree (but don't confuse with tree-locking protocol)
- When a transaction locks a node in the tree *explicitly*, it *implicitly* locks all the node's descendants in the same mode.
- Granularity of locking (level in tree where locking is done):
  - **Fine granularity** (lower in tree): high concurrency, high locking overhead
  - **Coarse granularity** (higher in tree): low locking overhead, low concurrency

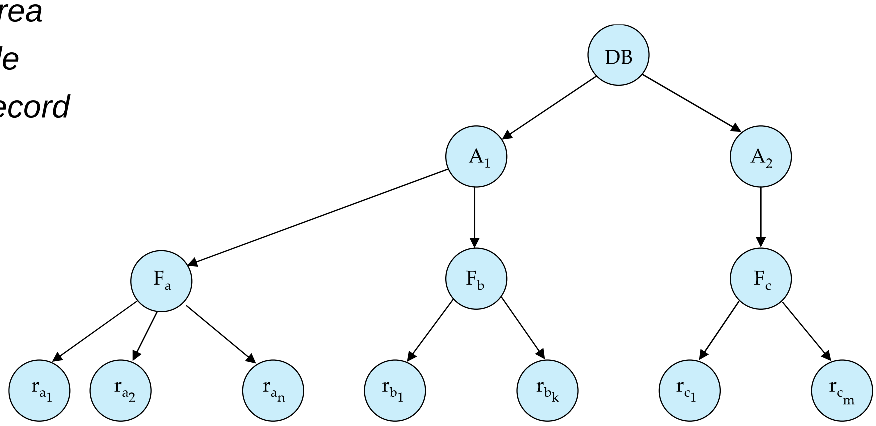


## Example of Granularity Hierarchy

The levels, starting from the coarsest (top) level are

- *database*
- *area*
- *file*
- *record*






## Compatibility Matrix with Intention Lock Modes

- The compatibility matrix for all lock modes is:

| | IS | IX | S | SIX | X |
|---|---|---|---|---|---|
| IS | true | true | true | true | false |
| IX | true | true | false | false | false |
| S | true | false | true | false | false |
| SIX | true | false | false | false | false |
| X | false | false | false | false | false |



## Multiple Granularity Locking Scheme

- Transaction $T_i$ can lock a node $Q$, using the following rules:
  1. The lock compatibility matrix must be observed.
  2. The root of the tree must be locked first, and may be locked in any mode.
  3. A node $Q$ can be locked by $T_i$ in S or IS mode only if the parent of $Q$ is currently locked by $T_i$ in either IX or IS mode.
  4. A node $Q$ can be locked by $T_i$ in X, SIX, or IX mode only if the parent of $Q$ is currently locked by $T_i$ in either IX or SIX mode.
  5. $T_i$ can lock a node only if it has not previously unlocked any node (that is, $T_i$ is two-phase).
  6. $T_i$ can unlock a node $Q$ only if none of the children of $Q$ are currently locked by $T_i$.
- Observe that locks are acquired in root-to-leaf order, whereas they are released in leaf-to-root order.
- **Lock granularity escalation**: in case there are too many locks at a particular level, switch to higher granularity S or X lock



## Insert/Delete Operations and Predicate Reads

- Locking rules for insert/delete operations
  - An exclusive lock must be obtained on an item before it is deleted
  - A transaction that inserts a new tuple into the database I automatically given an X-mode lock on the tuple
- Ensures that
  - reads/writes conflict with deletes
  - Inserted tuple is not accessible by other transactions until the transaction that inserts the tuple commits

## Phantom Phenomenon

- Example of **phantom phenomenon**.
  - A transaction T1 that performs **predicate read** (or scan) of a relation
    - **select count**(*)
      **from** *instructor*
      **where** *dept_name* = 'Physics'
  - and a transaction T2 that inserts a tuple while T1 is active but after predicate read
    - **insert into** *instructor* **values** ('11111', 'Feynman', 'Physics', 94000)

    (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 instructor, but may read some other tuple written by the update transaction
- Can also occur with updates
  - E.g. update Wu's department from Finance to Physics



## Insert/Delete Operations and Predicate Reads

- **Another Example**: T1 and T2 both find maximum instructor ID in parallel, and create new instructors with ID = maximum ID + 1
  - Both instructors get same ID, not possible in serializable schedule
- Schedule

| T1 | T2 |
|---|---|
| Read(instructor where dept_name='Physics') | |
| | Insert Instructor in Physics |
| | Insert Instructor in Comp. Sci. |
| | Commit |
| Read(instructor where dept_name='Comp. Sci.') | |

## Handling Phantoms

- There is a conflict at the data level
  - The transaction performing predicate read or scanning the relation is reading information that indicates what tuples the relation contains
  - The transaction inserting/deleting/updating 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 To Prevent Phantoms

- **Index locking protocol** to prevent phantoms
  - Requires that 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 to Prevent Phantoms

- Index-locking protocol to prevent phantoms locks entire leaf node
  - Can result in poor concurrency if there are many inserts
- **Next-key locking protocol**: provides higher concurrency
  - Lock all values that satisfy index lookup (match lookup value, or fall in lookup range)
  - Also lock next key value in index
    - even for inserts/deletes
  - Lock mode: S for lookups, X for insert/delete/update
- Ensures detection of query conflicts with inserts, deletes and updates

Consider B+-tree leaf nodes as below, with query predicate $7 \leq X \leq 16$.
Check what happens with next-key locking when inserting: (i) 15 and (ii) 7