Locking to ensure serializability

- *Concurrent access* to database items is controlled by strategies based on *locking*, *timestamping* or *certification*
- A *lock* is an *access privilege to a single database item*
- *Lock Manager:* manages the locks requested by transactions.
- Locks are
  - *obtained by transactions*
  - stored in a *lock table*
  - Lock is an entry of the form *(item, lock-type, transactionID)*
    - *item* is the item that the transaction locks
    - *lock-type* can be shared or exclusive
    - *transactionID* is the transaction identifier

Locking

- When a transaction holds an *exclusive* lock on a database item, *no other transaction can read or write the item*
  - used for writing
- When a transaction holds a *shared* lock, *other transactions can obtain a shared lock on the same item*
  - used for reading
- ***Assumptions*** *(for now)*
  - there is a *single type of lock* and
  - *every transaction must obtain a lock* on an item before accessing it.
  - *all items locked by a transaction must be unlocked*, *otherwise no other transaction may gain access to them.*
  - a transaction *must wait* until the lock it requests is released by the transaction that holds it.

Transaction Management

1. *Locking* can prevent the *lost update* problem:

   $T_1 = Lock_1(A)\ R_1(A)\ W_1(A)\ Unlock_1(A)\ C_1$

   $T_2 = Lock_2(A)\ R_2(A)\ W_2(A)\ Unlock_2(A)\ C_2$

2. *Locking enforces a serial execution of the transactions*

3. Locking can also prevent the blind write problem:

   $T_1 = Lock_1(A)\ W_1(A)\ Lock_1(B)\ W_1(B)\ Unlock_1(A)\ Unlock_1(B)\ C_1$

   $T_2 = Lock_2(A)\ W_2(A)\ Lock_2(B)\ W_2(B)\ Unlock_2(A)\ Unlock_2(B)\ C_1$

   - ✓Then the following schedule is valid:

$Lock_1(A)\ W_1(A)\ Lock_1(B)\ W_1(B)\ Unlock_1(A)\ Lock_2(A)\ W_2(A)$
$Unlock_1(B)\ Lock_2(B)\ W_2(B)\ Unlock_2(A)\ Unlock_2(B)\ C_1\ C_2$

LiveLock

- Undesirable phenomena if *locks are granted in an arbitrary manner*
- **Example:**
  - while T2 is waiting for T1 to release the lock on A, another transaction T3 that has also requested a lock on A is granted the lock instead of T2. When T3 releases the lock on A the lock is granted to T4 etc.
- *Livelock: The situation where a transaction may wait for ever while other transactions obtain a lock on a database item*
  - Can be avoided by using a first-come-first-served lock granting strategy but, even then a *deadlock* might occur

Deadlock

- Occurs *when a transaction is waiting to lock an item that is currently locked by some other transaction*
- ***Example:*** Consider the transactions:

  T_1 = $Lock_1(A)$ $Lock_1(B)$ …. $Unlock_1(A)$ $Unlock_1(B)$ C_1

  T_2 = $Lock_2(B)$ $Lock_2(A)$ …. $Unlock_2(B)$ $Unlock_1(A)$ C_2

  - Assume T_1 is *granted* a *lock on A* and T_2 is *granted* a *lock on B*
  - Then T_1 *requests* a *lock on B* but is **forced to wait** because T_2 *has* the *lock on B*.
  - Similarly, T_2 *requests a lock on A* but is **forced to wait** because T_1 has the *lock on A.*

Neither transaction can proceed because each one is waiting for the other to release a lock: both processes wait for ever

Different solutions for Deadlocks

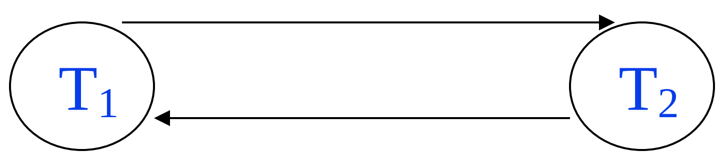
- ***Solution 1:*** Require *each transaction to request all locks at once. Either all locks are granted or none.*
- ***Solution 2:*** Assign *an arbitrary linear order* to the *items* and *require all transactions to request their locks in that order.*
- ***Solution 3:*** *Do nothing to prevent deadlocks: abort* one or more of the deadlocked transactions if a deadlock arises.

Deadlock Discovery

- Deadlocks can be discovered using *wait-for graphs*:
  - Given a set of transactions S, a *wait-for graph* is a *directed graph:*
    - vertices correspond to transactions in the set
    - there exists an edge from T_i to T_j if T_i is waiting to lock an item on which T_j is holding a lock.
- *Theorem*: A set of transactions is deadlocked if and only if there exists a cycle in the *wait-for graph*.
- **Example**: The ***wait-for graph*** for the transactions contains a cycle

  $T_1 = Lock_1(A)\ Lock_1(B)\ ....\ Unlock_1(A)\ Unlock_1(B)\ C_1$

  $T_2 = Lock_2(B)\ Lock_2(A)\ ....\ Unlock_2(B)\ Unlock_2(A)\ C_2$



2-Phase Locking (2PL)

- 2-Phase Locking (2PL): a protocol ensuring *serializability of schedules*
- *Definition:* A schedule is said to obey the *2-phase locking* protocol if the following rules are obeyed by *each transaction* in the schedule
  1. When a transaction attempts to *read (write)* a data item, a read *lock (write lock)* must be acquired first
  2. If a transaction T_1 holds a lock on data item A for operation op_1 and some other transaction T_2 requests the lock to perform a *conflicting operation* op_2 on the same item, the transaction requesting the lock (T_2) is forced to *wait until no conflicting lock on the item exists*
     - ***(only read locks are non-conflicting)***
  3. *A transaction cannot request additional locks once it releases any lock!*

2-Phase Locking (2PL): Conflicts

- two locks by the *same transaction never conflict*
- a transaction with a *read lock on a data item* can acquire a *write lock on the item as long as no other transaction has a lock on the data item;*
- a transaction with *a write lock on a data item need not acquire a read lock* on the same item.
- *2PL permits the early release of locks*
- Notation:
  - RL_i: transaction T_i *obtains* a *read* lock
  - WL_i: transaction T_i *obtains* a *write* lock
  - RU_i: transaction T_i *releases* a *read* lock
  - WU_i: transaction T_i releases a *write* lock

2-Phase Locking (2PL): Example

- Does the following schedule obey the 2PL protocol?

  $S = R_1(A)\ R_2(B)\ W_2(B)\ R_2(A)\ W_2(A)\ R_1(B)\ C_1\ C_2$

Lock/unlock operations must be *added first*. The schedule becomes:

$S' = \boxed{RL_1(A)}\ R_1(A)\ RU_1(A)\ \boxed{RL_2(B)}\ R_2(B)\ \boxed{WL_2(B)}\ W_2(B)\ WU_2(B)\ \boxed{RL_2(A)}$
$R_2(A)\ \boxed{WL_2(A)}\ W_2(A)\ \boxed{RL_1(B)}\ R_1(B)\ C_1\ C_2$

- *Rule 1 :* no item is accessed without a lock being granted to the requested transaction
  - *obeyed*

2-Phase Locking (2PL): Example

- Does the following schedule obey the 2PL protocol?

  $S = R_1(A)\ R_2(B)\ W_2(B)\ R_2(A)\ W_2(A)\ R_1(B)\ C_1\ C_2$

Lock/unlock operations must be *added first*. The schedule becomes:

$S = \boxed{RL_1(A)}\ R_1(A)\ \boxed{RU_1(A)}\ RL_2(B)\ R_2(B)\ WL_2(B)\ W_2(B)\ WU_2(B)\ RL_2(A)$
$R_2(A)\ \boxed{WL_2(A)}\ W_2(A)\ RL_1(B)\ R_1(B)\ C_1\ C_2$

- *Rule 2* : no two conflicting operations have a lock on the same item at the same time
  - *obeyed*

2-Phase Locking (2PL): Example

- Does the following schedule obey the 2PL protocol?

  $S = R_1(A)\ R_2(B)\ W_2(B)\ R_2(A)\ W_2(A)\ R_1(B)\ C_1\ C_2$

- *Lock/unlock operations* must be *added first*. The schedule becomes:

$S = RL_1(A)\ R_1(A)\ \boxed{RU_1(A)}\ RL_2(B)\ R_2(B)\ WL_2(B)\ W_2(B)\ \boxed{WU_2(B)}\ RL_2(A)\ R_2(A)\ \boxed{WL_2(A)}\ W_2(A)\ \boxed{RL_1(B)}\ R_1(B)\ C_1\ C_2$

  - *Rule 3: A transaction cannot request additional locks once it releases any lock!*
    - *Violated!*

2-Phase Locking (2PL): Example

- ✓ Applying the 2PL discipline to the schedule

$$S = R_1(A)\ R_2(B)\ W_2(B)\ R_2(A)\ W_2(A)\ R_1(B)\ C_1\ C_2$$

yields the following interleaved execution (all locks released at commit)

T_1	$RL_1(A)$	$R_1(A)$							
T_2			$RL_2(B)$	$R_2(B)$	$WL_2(B)$	$W_2(B)$	$RL_2(A)$	$R_2(A)$	$WL_2(A)$

T_1		$RL_1(B)$	*wait*	*abort*			*restart*	C_1
T_2	*wait*				$W_2(A)$	C_2		

The deadlock had to be resolved by aborting and restarting one of the transactions.

Under 2PL S is *equivalent* to the *serial schedule* $T_2\ T_1$

2-Phase Locking (2PL): Example

- ***Theorem:*** A schedule that follows 2PL *is always serializable*.
- ***Example:***
  - The schedule $S' = R_1(A)\ R_2(A)\ W_1(A)\ W_2(A)\ C_1\ C_2$ is forced to execute as follows by a transaction scheduler that uses 2PL:

T1	$RL_1(A)$	$R_1(A)$			$WL_1(A)$	wait			abort
T2			$RL_2(A)$	$R_2(A)$			$WL_2(A)$	wait	

T1			restart	C_1
T2	$W_2(A)$	C2		

If no locking were imposed S' would be non-serializable

Transaction Management

- Example: Consider the following transactions
  - T_1: $W_1(U)$ $R_1(Y)$ $W_1(U)$ C_1
  - T_2: $R_2(X)$ $W_2(U)$ $W_2(Y)$ $W_2(W)$ C_2
  - T_3: $W_3(W)$ $R_3(X)$ $W_3(U)$ $W_3(Z)$ C_3
- Is it possible to add lock/unlock steps to these transactions so that every legal schedule is serializable?
- Answer: *yes by adding add lock/unlock steps using 2PL*

Transaction Management

1. T_1: $W_1(U)\ R_1(Y)\ W_1(U)\ C_1$
2. T_2: $R_2(X)\ W_2(U)\ W_2(Y)\ W_2(W)\ C_2$
3. T_3: $W_3(W)\ R_3(X)\ W_3(U)\ W_3(Z)\ C_3$

T_1							
T_2					$RL_2(X)$	$WL_2(U)$	wait
T_3	$WL_3(W)$	$RL_3(X)$	$WL_3(U)$	$WL_3(Z)$			$W_3(W)$

T_1							$WL_1(U)$
T_2	wait	wait	wait	wait	wait	$WL_2(Y)$	
T_3	$WU_3(W)$	$R_3(X)$	$RU_3(X)$	$W_3(U)$	$WU_3(U)$		

Transaction Management

1. T_1: $W_1(U)$ $R_1(Y)$ $W_1(U)$ C_1
2. T_2: $R_2(X)$ $W_2(U)$ $W_2(Y)$ $W_2(W)$ C_2
3. T_3: $W_3(W)$ $R_3(X)$ $W_3(U)$ $W_3(Z)$ C_3

T_1	wait	wait	wait	wait	wait	$RL_1(Y)$	wait
T_2	$WL_2(W)$	$R_2(X)$		$W_2(U)$	$WU_2(U)$		$W_2(Y)$
T_3			$W_3(Z)$				

T_1	$WL_1(U)$	wait	$W_1(U)$					$R_1(Y)$	$W_1(U)$
T_2					$W_2(W)$	$WU_2(W)$	C_2		
T_3		$WU_3(Z)$		C_3					

T_1	$WU_1(U)$	$RU_1(Y)$	C_1
T_2			
T_3			

Transaction Management

Tree Protocols

- In many instances, the set of items accessed by a transaction can be viewed naturally as a tree or forest
- E.g., items are nodes in a B-tree; items have different granularities (relations, tuples, attributes).
- Two different policies may be followed:

1. each node in the tree is locked independently of its descendants
2. a lock on an item implies a lock on all of its descendants

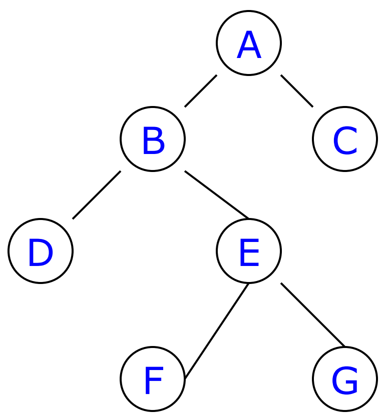
- The latter policy saves time by avoiding locking many items separately
- E.g., when the content of an entire relation needs to be read, the relation can be locked in one step instead of locking each tuple individually

Transaction Management

Tree Protocol #1 (TP1)

- Definition: A transaction obeys the TP1 policy if:
  - except for the first item locked, no item can be locked unless the transaction holds a lock on the item's parent
  - no item is ever locked twice by a transaction
- A schedule obeys the TP1 policy if every transaction in the schedule obeys it.

Example: Consider the following hierarchy of items



Transaction Management

The following schedule obeys TP1

T_1	$L_1(A)$	$L_1(B)$	$L_1(D)$	$U_1(B)$		$L_1(C)$		$U_1(D)$	
T_2					$L_2(B)$				
T_3							$L_3(E)$		$L_3(F)$

T_1	$U_1(A)$		$U_1(C)$						
T_2					$L_2(E)$		$U_2(B)$		$U_2(E)$
T_3		$L_3(G)$		$U_3(E)$		$U_3(F)$		$U_3(G)$	

Does it obey 2PL?

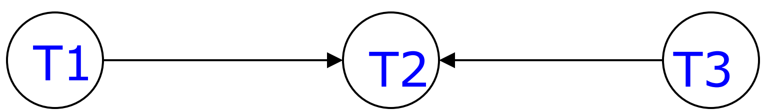
Transaction Management

Note: A transaction that obeys TP1 need not necessarily obey 2PL.

Theorem: Every legal schedule that obeys the protocol TP1 is serializable

Example: The schedule of the previous example is serializable.

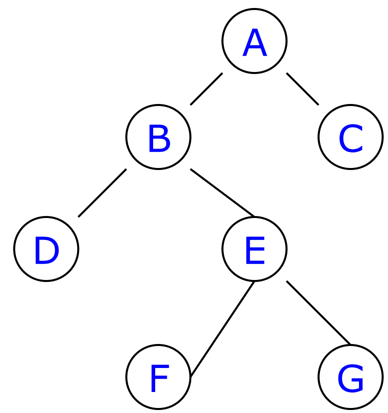
- ✓ its precedence graph is acyclic



Transaction Management

Tree Protocol #2 (TP2)

- Definition: A transaction obeys the TP2 policy if whenever an item is locked, all its descendants are locked
- Indiscriminate locking under TP2 may result in schedules where two transactions hold a lock on the same item at the same time.
- Example: in the hierarchy



transaction T_1 locks E (therefore F,G). Then T_2 locks B, therefore acquires conflicting locks on E,F,G.

Transaction Management

To avoid conflicts of this sort, the warning protocol may be followed:

- a transaction cannot place a lock on an item unless it first places a warning on all its ancestors
- a warning on an item X prevents any other transaction from locking X, but does not prevent them from also placing a warning on X, or from locking some descendant of X that does not have a warning

Definition: A transaction obeys the warning protocol if:

1. It begins by placing a lock or warning at the root
2. It does not place a lock or warning on an item unless it holds a warning on its parent.
3. It does not remove a lock or warning unless it holds no lock or warnings on its children
4. It obeys 2PL in the sense that all unlock operations follow all warnings or lock operations

Transaction Management

- This protocol acts in conjunction with the assumption that a lock can be placed on an item only if no other transaction has a lock or warning on the same item.
- Furthermore, a warning can be placed on an item as long as not other transaction has a lock on the item.
- Theorem: Legal schedules obeying the warning protocol are serializable.