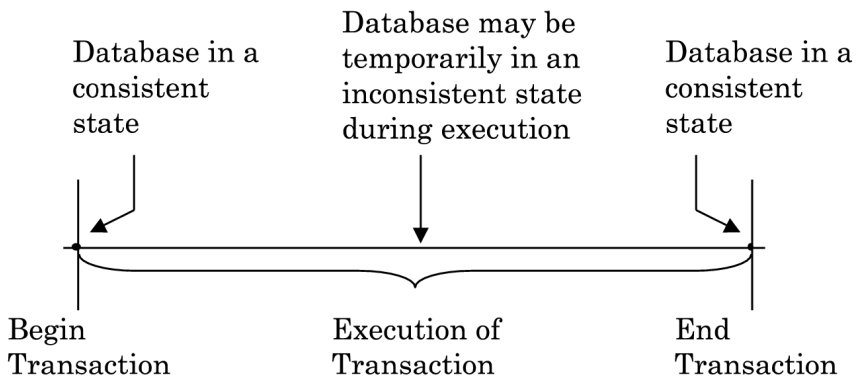
Distributed Database Systems
Fall 2018

Distributed Transactions and Concurrency Control
SL05

- Transactions: Definition, Properties, Classification
- Concurrency, Conflicts, and Schedules
- Locking Based Algorithms
- Timestamp Ordering Algorithms
- Two-Phase Commit Protocol

Transactions/1

- **Transaction:** A collection of actions that transforms the DB from one consistent state into another consistent state; during the execution the DB might be inconsistent.



- **States** of a transaction
  - **Active**: Initial state and during the execution
  - **Partially committed**: After the final statement has been executed
  - **Committed:** After successful completion
  - **Failed:** After discovery that normal execution can no longer proceed
  - **Aborted:** After the transaction has been rolled back and the DB restored to its state prior to the start of the transaction. Restart it again or kill it.

Transaction Example/1

- **Example:** Consider an airline DB with the following relations:

  FLIGHT(FNO, DATE, SRC, DEST, STSOLD, CAP)
  CUST(CNAME, ADDR, BAL)
  FC(FNO, DATE, CNAME, SPECIAL)

- Consider the reservation of a ticket, where a travel agent enters flight number, date and customer name, and then asks for a reservation.

```
Begin_transaction Reservation
begin
    input(flight_no, date, customer_name);
    EXEC SQL UPDATE FLIGHT
        SET    STSOLD = STSOLD + 1
        WHERE FNO = flight_no AND DATE = date;
    ...
```

Transaction Example/2

- (cont'd)

```
    ...
    EXEC SQL INSERT
        INTO    FC(FNO, DATE, CNAME, SPECIAL);
        VALUES (flight_no, date, customer_name, null);
    output("reservation completed")
end.
```

- **Example (contd.):**
  - A transaction always terminates: *commit* (successful completion) or *abort* (does not do the task).
  - The above transaction assumes that there are always free seats.
  - A better solution is to check the availability of free seats and terminate the transaction appropriately.

Transaction Example/3

```
Begin_transaction Reservation
begin
    input(flight_no, date, customer_name);
    EXEC SQL SELECT STSOLD,CAP
        INTO        temp1,temp2
        FROM        FLIGHT
        WHERE       FNO = flight_no  AND DATE = date;
    if temp1 = temp2  then
        output("no free seats");
        Abort
    else
      EXEC SQL UPDATE FLIGHT
        SET    STSOLD = STSOLD + 1
        WHERE FNO = flight_no  AND DATE = date;
      EXEC SQL INSERT
        INTO       FC(FNO, DATE, CNAME, SPECIAL);
        VALUES (flight_no, date, customer_name, null);
      Commit
      output("reservation completed")
   endif
end.
```

Transaction Example/4

- Transactions are mainly characterized by their Read and Write operations:
  - Read set (RS): The data items that a transaction reads
  - Write set (WS): The data items that a transaction writes
  - Base set (BS): the union of the read set and write set

- **Example (contd.):** Read and Write set of the "Reservation" transaction

$$\begin{aligned}
\text{RS[Reservation]} &= \{ \text{FLIGHT.STSOLD, FLIGHT.CAP,} \\
&\quad \text{FLIGHT.FNO, FLIGHT.DATE } \} \\
\text{WS[Reservation]} &= \{ \text{FLIGHT.STSOLD, FC.FNO, FC.DATE,} \\
&\quad \text{FC.CNAME, FC.SPECIAL } \} \\
\text{BS[Reservation]} &= \{ \text{FLIGHT.STSOLD, FLIGHT.CAP,} \\
&\quad \text{FC.FNO, FC.DATE, FC.CNAME,} \\
&\quad \text{FC.SPECIAL } \}
\end{aligned}$$

Definition of a Transaction/1

- We use the following notation:
  - T_i is a transaction; x is a data item (attribute value, tuple, relation)
  - O_{ij} = operation O_j of transaction T_i
  - $O_{ij} \in \{R(x), W(x)\}$: atomic *read*/*write* operation of T_i on item x
  - $OS_i = \bigcup_j O_{ij}$ be the set of all operations of T_i
  - $N_i \in \{A, C\}$ be the termination operation, i.e., *abort*/*commit*
- Two operations $O_{ij}(x)$ and $O_{ik}(x)$ on the same data item are in **conflict** if at least one of them is a *write* operation.
- A **transaction** T_i is a **partial order** over its operations, i.e., $T_i = \{\Sigma_i, \prec_i\}$, where
  1. $\Sigma_i = OS_i \cup N_i$
  2. For $O_{ij} \in \{R(x), W(x)\}$ and $O_{ik} = W(x)$: $O_{ij} \prec_i O_{ik}$ or $O_{ik} \prec_i O_{ij}$
  3. $\forall O_{ij} \in OS_i (O_{ij} \prec_i N_i)$

Definition of a Transaction/2

- Remarks
  - The partial order $\prec$ is given and is actually application dependent
  - It has to specify the **execution order** between the conflicting operations and between all operations and the termination operation
- **Example:** Consider the following transaction T

```
Read(x)
Read(y)
x ← x + y
Write(x)
Commit
```

- The transaction is formally represented as

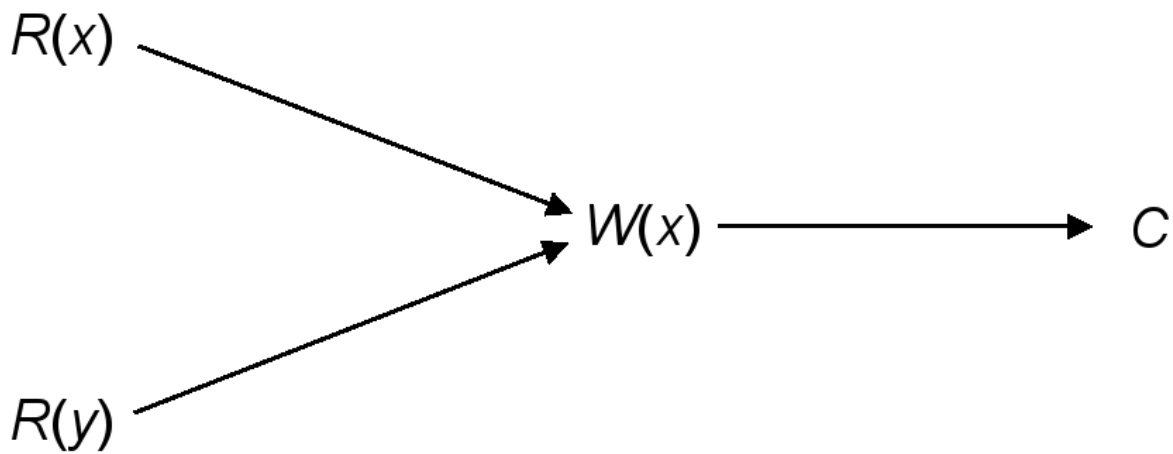
$$\Sigma = \{R(x), R(y), W(x), C\}$$
$$\prec = \{(R(x), W(x)), (R(y), W(x)), (W(x), C), (R(x), C), (R(y), C)\}$$

Definition of a Transaction/3

- **Example (contd.):** A transaction can also be specified/represented as a directed acyclic graph (DAG), where the vertices are the operations and the edges indicate the ordering.
  - Assume

    $$\prec = \{(R(x), W(x)), (R(y), W(x)), (W(x), C), (R(x), C), (R(y), C)\}$$

  - The DAG is



  - Often a total order given by the relative ordering of operations is used to simplify notation, e.g., $T = \{R(x), R(y), W(x), C\}$

Definition of a Transaction/4

- **Example:** The reservation transaction is more complex, as it has two possible termination conditions, but a transaction allows only one
  - BUT, a transaction is the **execution** of a program which has obviously only one termination
  - Thus, it can be represented as two transactions, one that aborts and one that commits

- Transaction T1:

$$\Sigma = \{R(STSOLD), R(CAP), R(FNO), R(DATE), A\}$$
$$\prec = \{(R(STSOLD), A), (R(CAP), A), (R(FNO), A), (R(DATE), A)\}$$

- Transaction T2:

$$\begin{aligned}\Sigma = \{&R(STSOLD), R(CAP), R(FNO), R(DATE),\\ &W(STSOLD), W(FNO), W(DATE),\\ &W(CNAME), W(SPECIAL), C\}\end{aligned}$$
$$\prec = \{(R(STSOLD), W(STSOLD)), \dots\}$$

Transaction Processing Issues

- A **transaction** is a collection of actions that transforms the system from one consistent state into another consistent state.
- Transaction T can be viewed as a **partial order**: $T = \{\Sigma, \prec\}$, where Σ is the set of all operations, and $\prec$ denotes the order of operations. T can also be represented as a **directed acyclic graph** (DAG).
- **Transaction manager** aims to achieve four properties of transactions: atomicity, consistency, isolation, and durability.
- Transactions can be classified according to (i) organization of reads and writes, (ii) time, and (iii) structure.
- Transaction processing involves **concurrency**, **reliability**, and **replication** protocols to ensure the **ACID properties**:
  - Atomicity: execute all operations or no operation
  - Consistency: transform consistent state into new consistent state
  - Isolation: behave as if transactions are executed one after the other
  - Durability: committed changes are permanent

Classification of Transactions

- **Classification** of transactions according to various criteria (cnt'd)
  - **Duration** of transaction
    - On-line (short-life)
    - Batch (long-life)
  - **Structure** of transaction
    - **Flat** transaction: Consists of a sequence of primitive operations between a begin and end marker
    - **Nested** transaction: The operations of a transaction may themselves be transactions.
    - **Workflows:** A collection of tasks organized to accomplish a given business process

Concurrency

- Concurrency deals with operations from multiple transactions.
- **Concurrency control** is the problem of synchronizing concurrent transactions (i.e., order the operations of concurrent transactions) such that the following two properties are achieved:
  - the consistency of the DB is maintained
  - the maximum degree of concurrency of operations is achieved
- Obviously, the serial execution of a set of transaction achieves consistency, if each single transaction is consistent

Conflicts

- **Conflicting operations:** Two operations $O_{ij}(x)$ and $O_{kl}(x)$ of transactions T_i and T_k are in **conflict** iff at least one of the operations is a write, i.e.,
  - $O_{ij} = read(x)$ and $O_{kl} = write(x)$
  - $O_{ij} = write(x)$ and $O_{kl} = read(x)$
  - $O_{ij} = write(x)$ and $O_{kl} = write(x)$
- Intuitively, a conflict between two operations indicates that their order of execution is important.
- Read operations do not conflict with each other, hence the ordering of read operations does not matter.
- The **conflict graph** contains a node for each transaction. It contains an edge from T_i to T_j if there is an operation p in T_i that conflicts with an operation q in T_j and $p \prec q$.

Schedules/1

- Terminology:
  - A **history** includes all operations from all transactions together with an ordering for conflicting operations.
  - A **schedule** is a prefix of a history.
  - A **complete schedule** is a history.

- A **schedule** (history) specifies a possibly interleaved order of execution of all operations O of a set of transactions $T = \{T_1, T_2, \ldots, T_n\}$, where T_i is specified by a partial order $(\Sigma_i, \prec_i)$.

- A schedule can be specified as a partial order over O, where
  1. $\Sigma_T = \bigcup_{i=1}^{n} \Sigma_i$
  2. $\prec_T \supseteq \bigcup_{i=1}^{n} \prec_i$
  3. For conflicting operations $O_{ij}, O_{kl} \in \Sigma_T$: $O_{ij} \prec_T O_{kl}$ or $O_{kl} \prec_T O_{ij}$

Schedules/2

- **Example:** Consider the following two transactions

T_1: $Read(x)$, $x \leftarrow x + 1$, $Write(x)$, $Commit$

T_2: $Read(x)$, $x \leftarrow x + 1$, $Write(x)$, $Commit$

- A possible schedule over $T = \{T_1, T_2\}$ can be written as the partial order $S = \{\Sigma_T, \prec_T\}$, where

$$\begin{aligned}\Sigma_T &= \{R_1(x), W_1(x), C_1, R_2(x), W_2(x), C_2\} \\ \prec_T &= \{(R_1, W_1), (R_1, C_1), (W_1, C_1), \\ &\quad (R_2, W_2), (R_2, C_2), (W_2, C_2), \\ &\quad (R_2, W_1), (W_1, W_2), \dots\}\end{aligned}$$

Schedules/3

- A schedule is **serial** if all transactions in T are executed serially.
- **Example:** Consider the following two transactions

T_1: $Read(x)$, $x \leftarrow x + 1$, $Write(x)$, $Commit$

T_2: $Read(x)$, $x \leftarrow x + 1$, $Write(x)$, $Commit$

  - The two serial schedules are $S_1 = \{\Sigma_1, \prec_1\}$ and $S_2 = \{\Sigma_2, \prec_2\}$, where

$$\Sigma_1 = \Sigma_2 = \{R_1(x), W_1(x), C_1, R_2(x), W_2(x), C_2\}$$
$$\prec_1 = \{(R_1, W_1), (R_1, C_1), (W_1, C_1), (R_2, W_2), (R_2, C_2), (W_2, C_2), (C_1, R_2), \ldots\}$$
$$\prec_2 = \{(R_1, W_1), (R_1, C_1), (W_1, C_1), (R_2, W_2), (R_2, C_2), (W_2, C_2), (C_2, R_1), \ldots\}$$

- Simplified notation with relative ordering:
  - $\{T_1, T_2\} = \{R_1(x), W_1(x), C_1, R_2(x), W_2(x), C_2\}$
  - $\{T_2, T_1\} = \{R_2(x), W_2(x), C_2, R_1(x), W_1(x), C_1\}$

Serializability/1

- Two schedules are **equivalent** if they have the same effect on the DB.
- **Conflict equivalence:** Two schedules S_1 and S_2 defined over the same set of transactions $T = \{T_1, T_2, \ldots, T_n\}$ are said to be **conflict equivalent** if for each pair of conflicting operations O_{ij} and O_{kl}, whenever $O_{ij} <_1 O_{kl}$ then $O_{ij} <_2 O_{kl}$.
  - i.e., conflicting operations must be executed in the same order in both schedules.
- A concurrent schedule is said to be **(conflict-)serializable** iff it is conflict equivalent to a serial schedule

Serializability/2

- A conflict-serializable schedule can be transformed into a serial schedule by swapping non-conflicting operations
- **Example:** Consider the following two schedules

T_1: $Read(x)$
$x \leftarrow x + 1$
$Write(x)$
$Write(z)$
$Commit$

T_2: $Read(x)$
$x \leftarrow x + 1$
$Write(x)$
$Commit$

  - The schedule $\{R_1(x), W_1(x), R_2(x), W_2(x), W_1(z), C_2, C_1\}$ is conflict-equivalent to $\{T_1, T_2\}$ but not to $\{T_2, T_1\}$

Serializability/3

- The **primary function** of a concurrency controller is to generate a serializable schedule for the execution of pending transactions.
- In a DDBMS two schedules must be considered
  - Local schedule
  - Global schedule
- **Serializability** in DDBMS
  - The key concepts of transactions, histories, schedules, and conflicts remain valid.
  - Serializability extends to a DDBMS if local schedules are replaced by global schedules, etc.
  - Without global schedules local schedules can be modified (e.g., by introducing explicit conflicts) to get global guarantees.
  - Requires care if data is *replicated* and transactions are run on all sites with replicated data items:

Serializability/4

- **Example:** Consider two sites and a data item x which is replicated at both sites.

T_1:	$Read(x)$	T_2:	$Read(x)$
	$x \leftarrow x + 5$		$x \leftarrow x * 10$
	$Write(x)$		$Write(x)$

  - Both transactions need to run on both sites
  - The following two schedules might have been produced at both sites:
    - Site1: $S_1 = \{R_1(x), W_1(x), R_2(x), W_2(x)\}$
    - Site2: $S_2 = \{R_2(x), W_2(x), R_1(x), W_1(x)\}$
  - Both schedules are (trivially) serializable, thus are correct in the local context
  - But they produce different results for x and are therefore not correct.
  - Solution: same serialization order of transactions on both sites

Concurrency Control Algorithms

- The most common concurrency control algorithms are
  - locking: ensure mutually exclusive access to data
  - ordering: order execution of transactions according to a protocol
- Two-Phase Locking (2PL)
  - Centralized (primary site) 2PL
  - Primary copy 2PL
  - Distributed 2PL
- Timestamp Ordering (TO)
  - Multiversion TO

Locking Based Algorithms

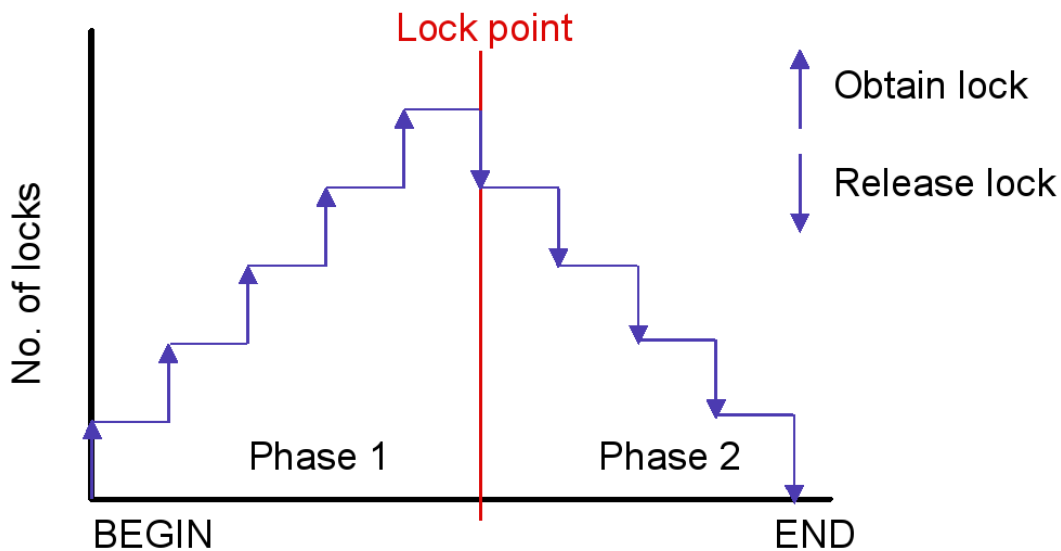
- **Locking-based concurrency algorithms** ensure that data items shared by conflicting operations are accessed in a mutually exclusive way. This is accomplished by associating a "lock" with each such data item.
- Two types of **locks** (lock modes)
  - **read lock** (rl) – also called **shared** lock
  - **write lock** (wl) – also called **exclusive** lock
- **Compatibility matrix** of locks

	$rl_i(x)$	$wl_i(x)$
$rl_j(x)$	compatible	not compatible
$wl_j(x)$	not compatible	not compatible

- General locking algorithm
  1. Before using item x, transaction requests lock for x from lock mngr
  2. If x is already locked and the existing lock is incompatible with the requested lock, the transaction is delayed
  3. Otherwise, the lock is granted

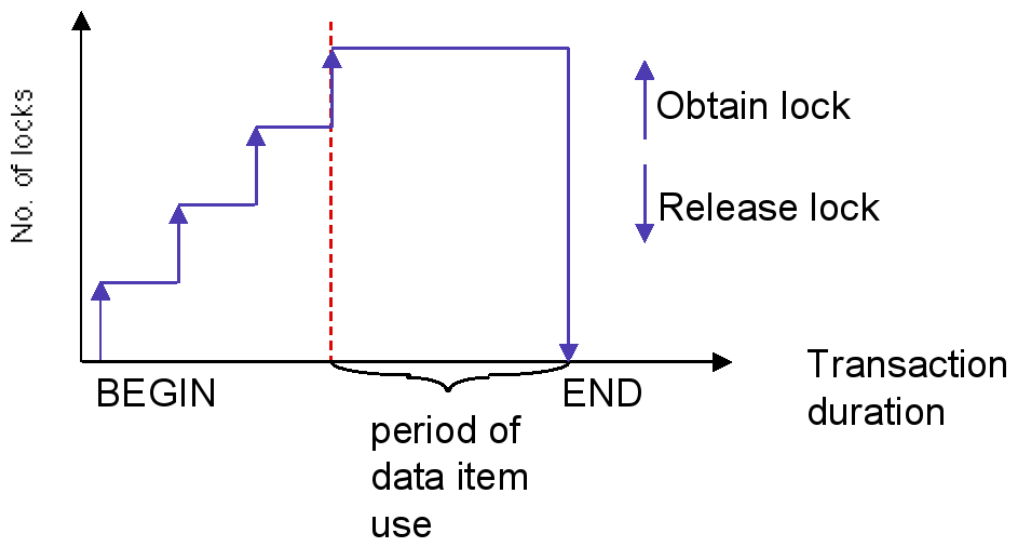
Two-Phase Locking (2PL)/1

- **Two-phase locking** protocol
  - Each transaction is executed in two phases
    - **Growing phase:** the transaction obtains locks
    - **Shrinking phase:** the transaction releases locks
  - The **lock point** is the moment when transitioning from the growing phase to the shrinking phase



Two-Phase Locking (2PL)/2

- **Properties** of the 2PL protocol
  - Generates **conflict-serializable** schedules
  - But schedules may cause **cascading aborts**
    - If a transaction aborts after it releases a lock, it may cause other transactions that have accessed the unlocked data item to abort as well
- **Strict 2PL locking** protocol
  - Holds the locks till the end of the transaction
  - Cascading aborts are avoided



Two-Phase Locking (2PL)/3

- **Example:** The following schedule S is not valid in the 2PL protocol:

$$\begin{aligned} S = \{ & wl_1(x), R_1(x), W_1(x), lr_1(x) \\ & wl_2(x), R_2(x), W_2(x), lr_2(x) \\ & wl_2(y), R_2(y), W_2(y), lr_2(y) \\ & wl_1(y), R_1(y), W_1(y), lr_1(y)\} \end{aligned}$$

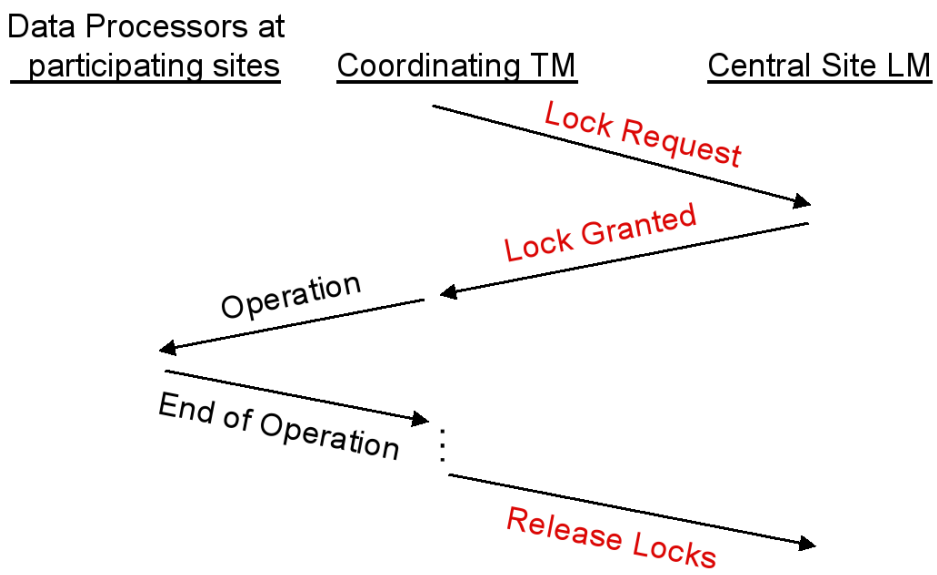
- e.g., after $lr_1(x)$ (in line 1) transaction T_1 cannot request the lock $wl_1(y)$ (in line 4).

- Valid schedule in the 2PL protocol

$$\begin{aligned} S = \{ & wl_1(x), R_1(x), W_1(x), \\ & wl_1(y), R_1(y), W_1(y), lr_1(x), lr_1(y) \\ & wl_2(x), R_2(x), W_2(x), \\ & wl_2(y), R_2(y), W_2(y), lr_2(x), lr_2(y)\} \end{aligned}$$

2PL for DDBMS/1

- Various extensions of the 2PL to DDBMS
- **Centralized 2PL**
  - A single site is responsible for the lock management, i.e., one lock manager for the whole DDBMS
  - Lock requests are sent to the lock manager
  - Coordinating transaction manager (TM at site where the transaction is initiated) makes lock requests on behalf of local transaction managers
- Advantage: Easy to implement
- Disadvantages: Bottlenecks and lower reliability
- Replica control protocol is additionally needed if data are replicated (see also primary copy 2PL)



2PL for DDBMS/2

- **Primary copy 2PL**
  - Several lock managers are distributed to a number of sites
  - Each lock manager is responsible for managing the locks for a set of data items
  - For replicated data items, one copy is chosen as primary copy, others are slave copies
  - Only the primary copy of a data item that is updated needs to be write-locked
  - Once primary copy has been updated, the change is propagated to the slaves
- Advantages
  - Lower communication costs and better performance than the centralized 2PL
- Disadvantages
  - Deadlock handling is more complex

2PL for DDBMS/3

- **Distributed 2PL**
  - Lock managers are distributed to all sites
  - Each lock manager responsible for locks for data at that site
  - If data is not replicated, it is equivalent to primary copy 2PL
  - If data is replicated, the Read-One-Write-All (ROWA) replica control protocol is implemented
    - *Read*(x): Any copy of a replicated item x can be read by obtaining a read lock on the copy
    - *Write*(x): All copies of x must be write-locked before x can be updated
- Disadvantages
  - Deadlock handling more complex
  - Communication costs higher than primary copy 2PL

2PL for DDBMS/4

- Communication structure of the distributed 2PL
  - The coordinating TM sends the lock request to the lock managers of all participating sites
  - The LMs pass the operations to the data processors
  - The end of the operation is signaled to the coordinating TM