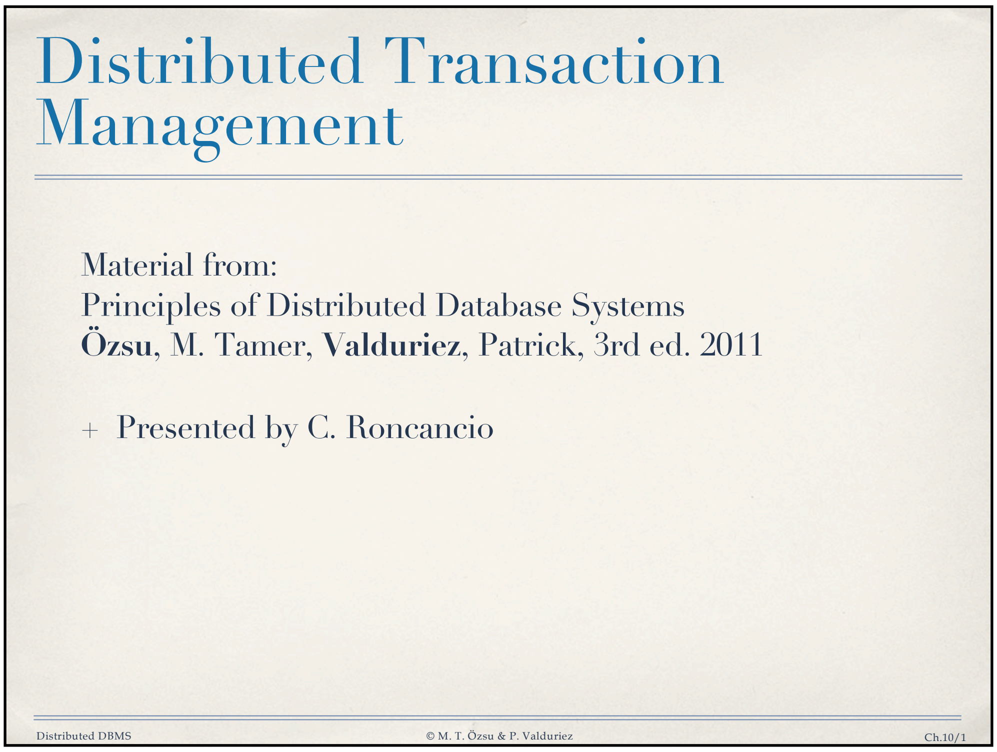
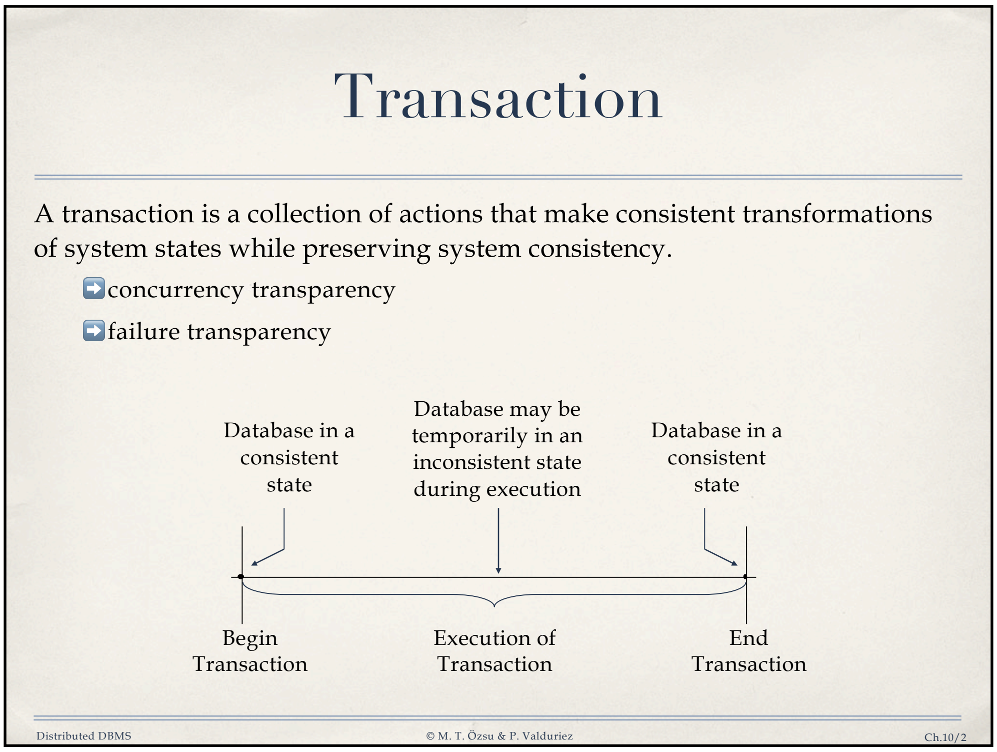


# Distributed Transaction Management

Material from:
Principles of Distributed Database Systems
**Özsu**, M. Tamer, **Valduriez**, Patrick, 3rd ed. 2011

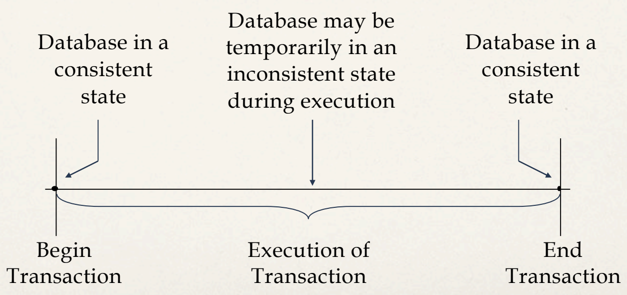
+ Presented by C. Roncancio

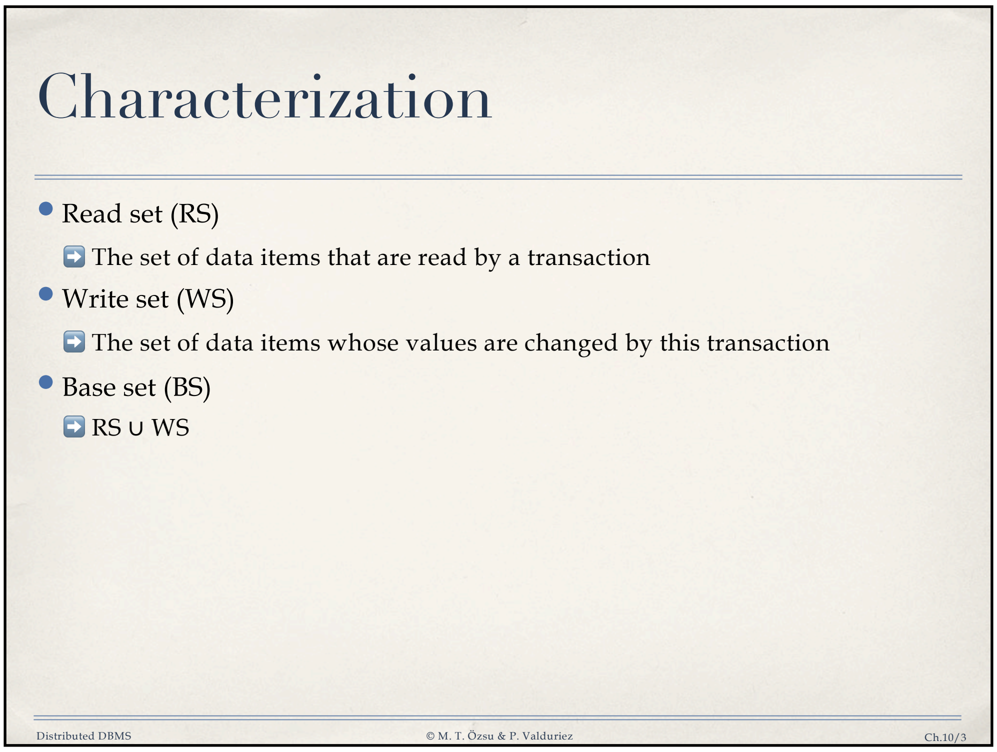


## Transaction

A transaction is a collection of actions that make consistent transformations of system states while preserving system consistency.

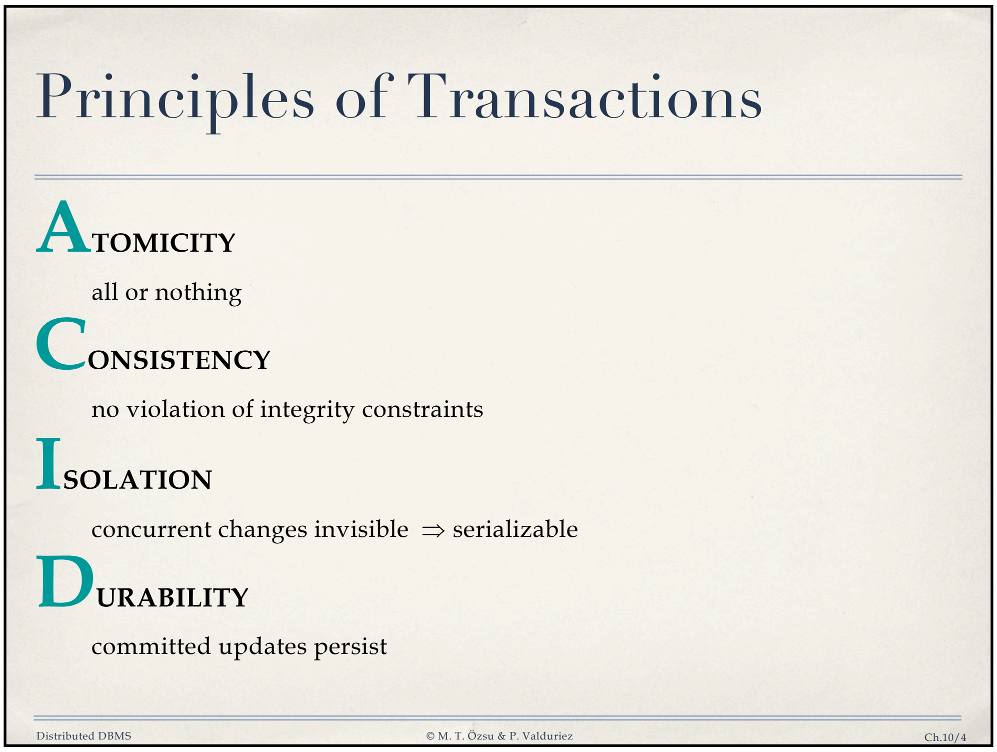
- ➡️concurrency transparency
- ➡️failure transparency


Database in a consistent state
Database may be temporarily in an inconsistent state during execution
Database in a consistent state
Begin Transaction
Execution of Transaction
End Transaction



## Characterization

- Read set (RS)
  - ➡️ The set of data items that are read by a transaction
- Write set (WS)
  - ➡️ The set of data items whose values are changed by this transaction
- Base set (BS)
  - ➡️ RS ∪ WS



## Principles of Transactions

**ATOMICITY**

all or nothing

**CONSISTENCY**

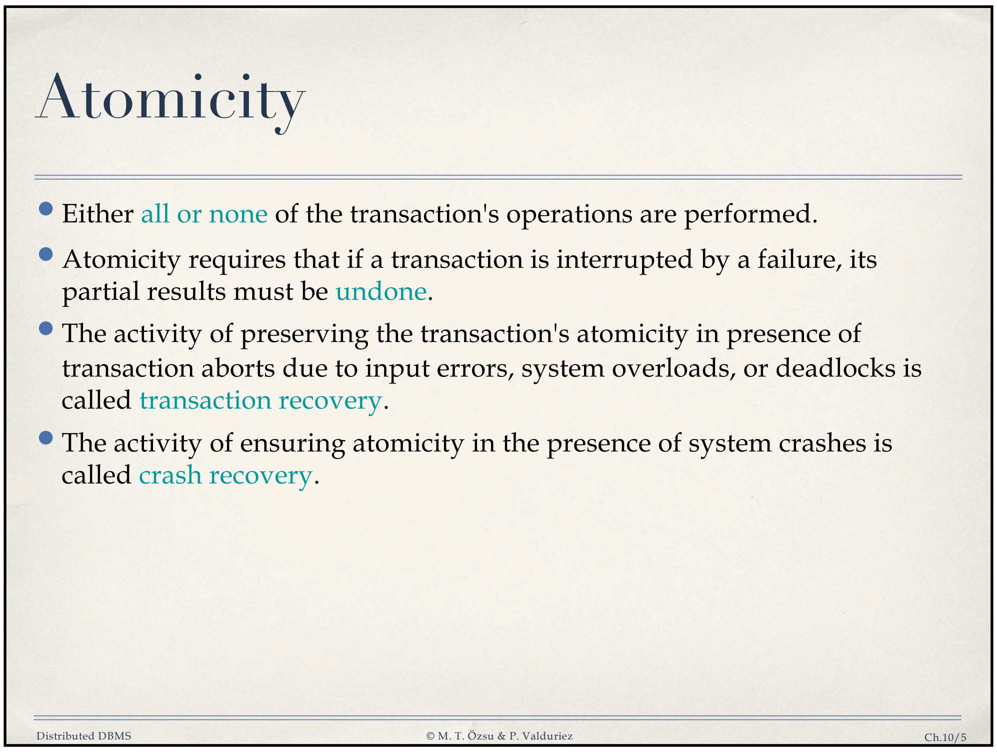
no violation of integrity constraints

**ISOLATION**

concurrent changes invisible $\Rightarrow$ serializable

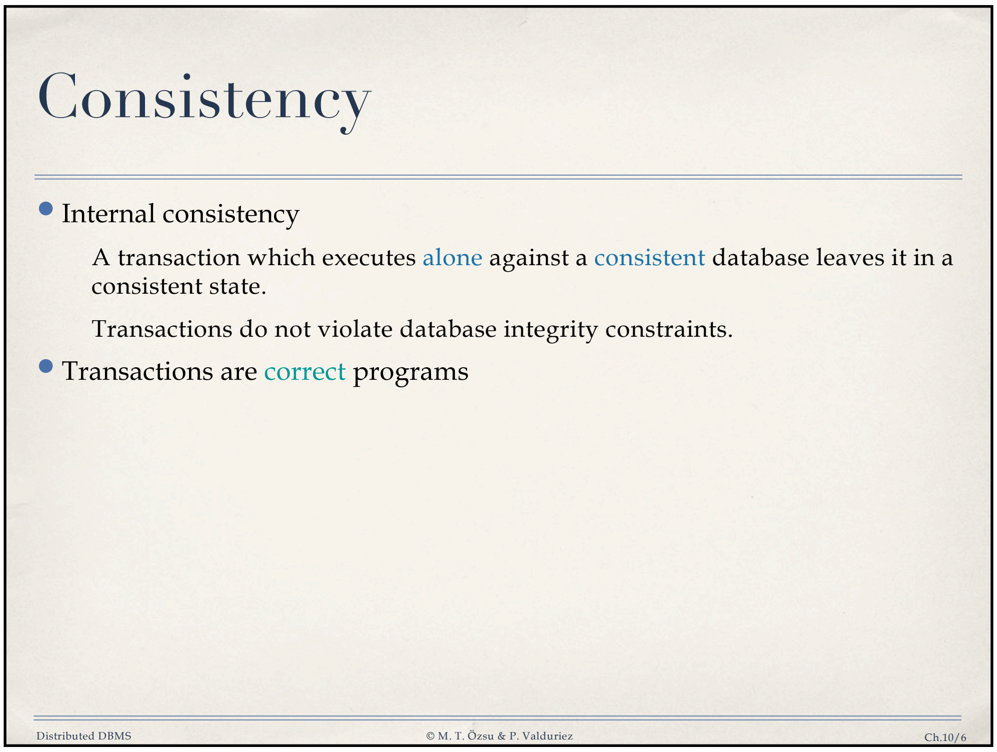
**DURABILITY**

committed updates persist



## Atomicity

- Either all or none of the transaction's operations are performed.
- Atomicity requires that if a transaction is interrupted by a failure, its partial results must be undone.
- The activity of preserving the transaction's atomicity in presence of transaction aborts due to input errors, system overloads, or deadlocks is called transaction recovery.
- The activity of ensuring atomicity in the presence of system crashes is called crash recovery.

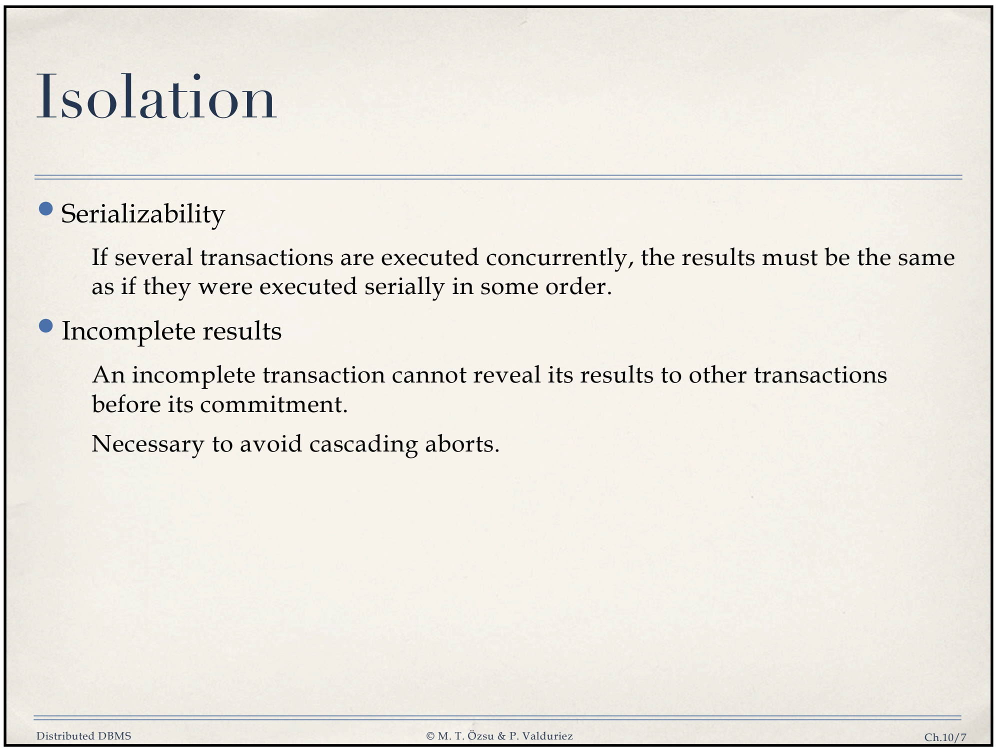


## Consistency

- Internal consistency

  A transaction which executes alone against a consistent database leaves it in a consistent state.

  Transactions do not violate database integrity constraints.
- Transactions are correct programs



## Isolation

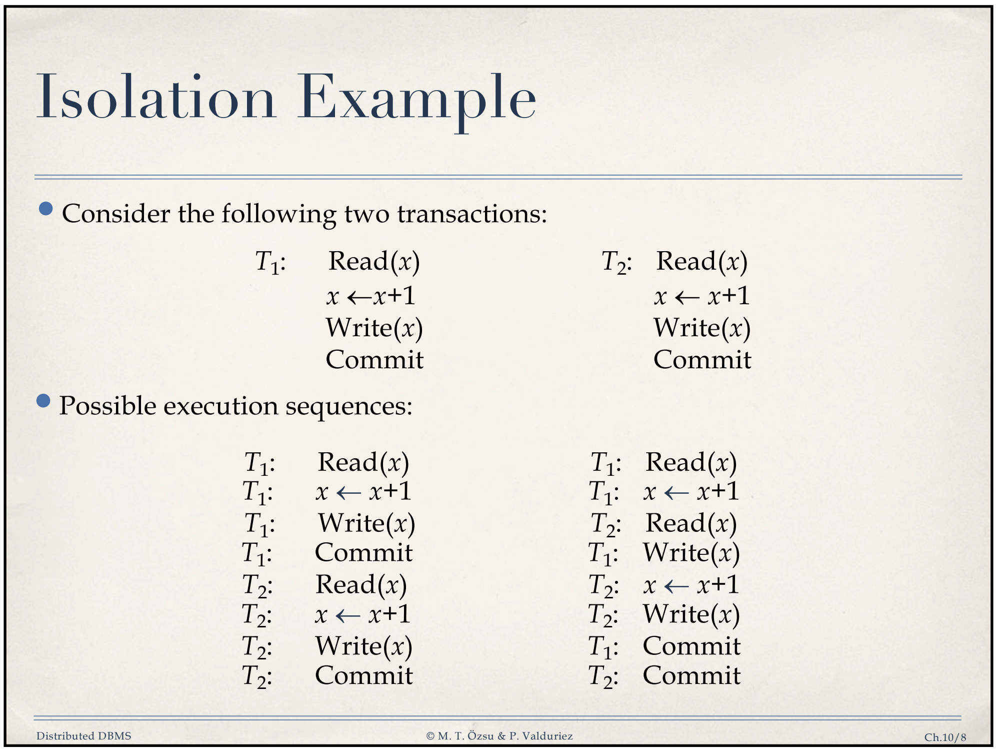
- Serializability

  If several transactions are executed concurrently, the results must be the same as if they were executed serially in some order.

- Incomplete results

  An incomplete transaction cannot reveal its results to other transactions before its commitment.

  Necessary to avoid cascading aborts.



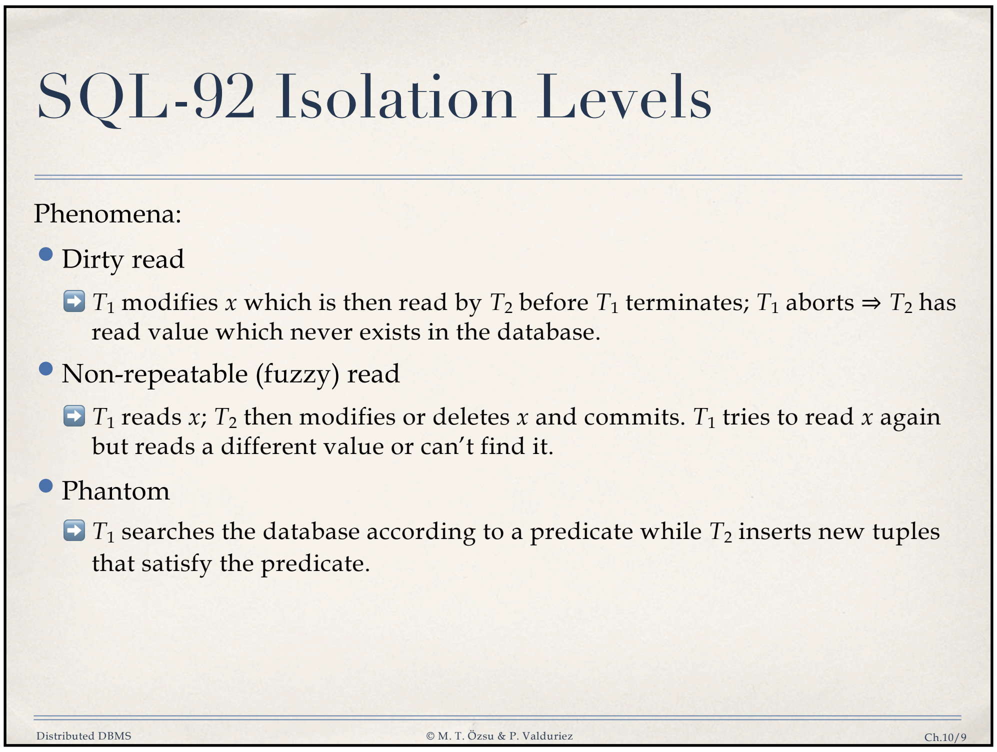
## Isolation Example

- Consider the following two transactions:

| | | | |
|---|---|---|---|
| $T_1$: | Read($x$) | $T_2$: | Read($x$) |
| | $x \leftarrow x+1$ | | $x \leftarrow x+1$ |
| | Write($x$) | | Write($x$) |
| | Commit | | Commit |

- Possible execution sequences:

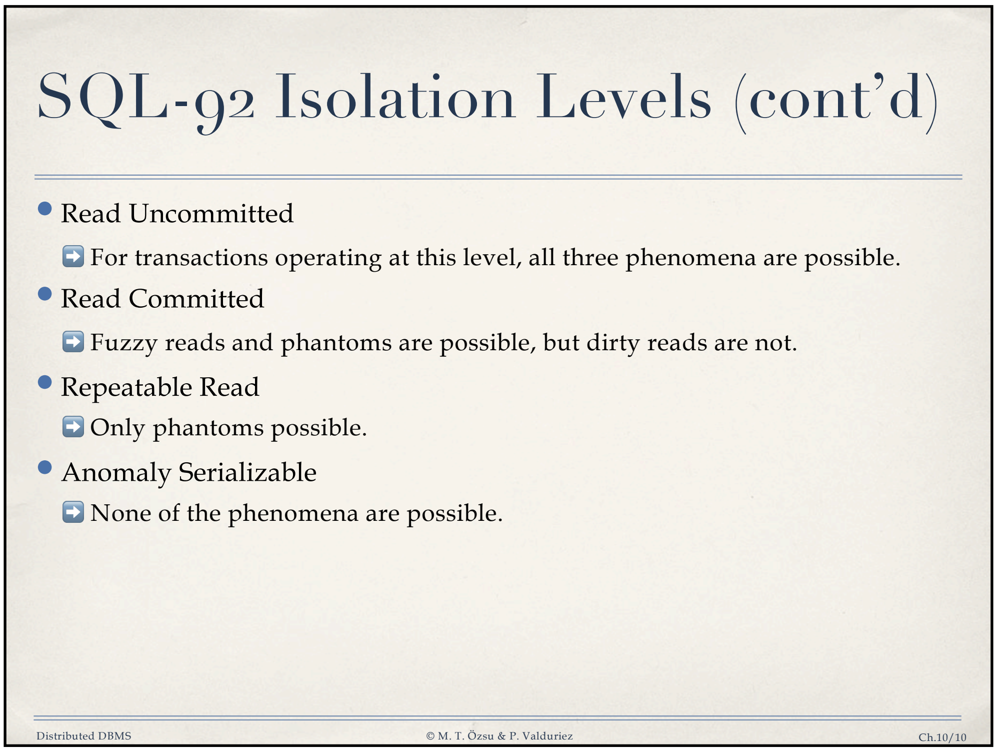
| | | | |
|---|---|---|---|
| $T_1$: | Read($x$) | $T_1$: | Read($x$) |
| $T_1$: | $x \leftarrow x+1$ | $T_1$: | $x \leftarrow x+1$ |
| $T_1$: | Write($x$) | $T_2$: | Read($x$) |
| $T_1$: | Commit | $T_1$: | Write($x$) |
| $T_2$: | Read($x$) | $T_2$: | $x \leftarrow x+1$ |
| $T_2$: | $x \leftarrow x+1$ | $T_2$: | Write($x$) |
| $T_2$: | Write($x$) | $T_1$: | Commit |
| $T_2$: | Commit | $T_2$: | Commit |



## SQL-92 Isolation Levels

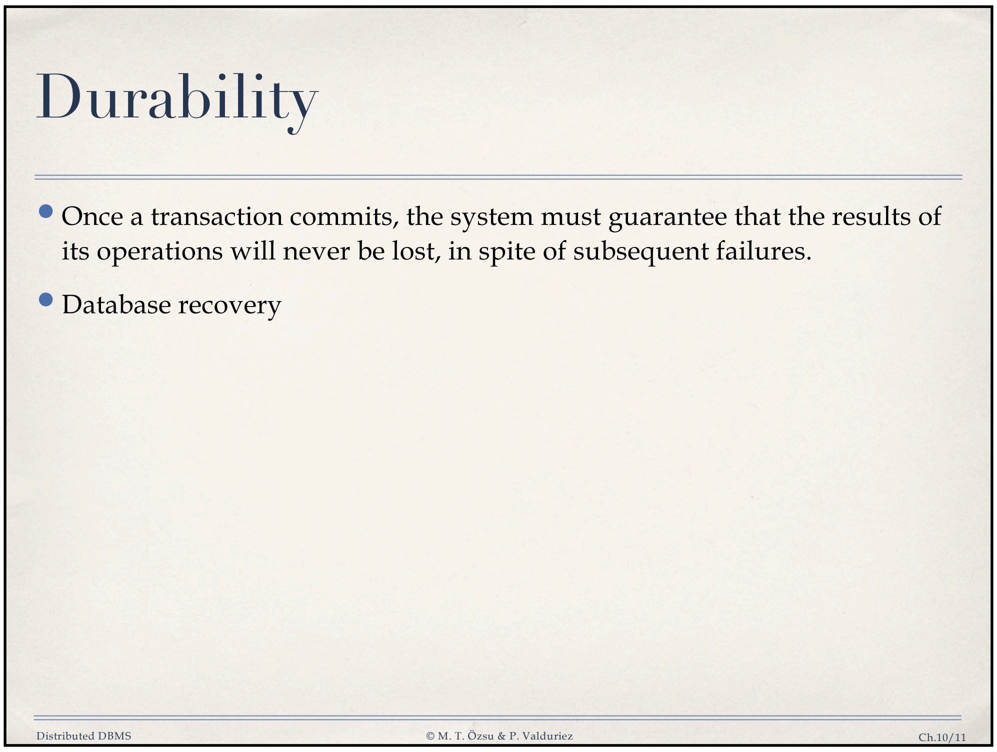
Phenomena:

- Dirty read
  - ➡ $T_1$ modifies $x$ which is then read by $T_2$ before $T_1$ terminates; $T_1$ aborts $\Rightarrow T_2$ has read value which never exists in the database.
- Non-repeatable (fuzzy) read
  - ➡ $T_1$ reads $x$; $T_2$ then modifies or deletes $x$ and commits. $T_1$ tries to read $x$ again but reads a different value or can't find it.
- Phantom
  - ➡ $T_1$ searches the database according to a predicate while $T_2$ inserts new tuples that satisfy the predicate.



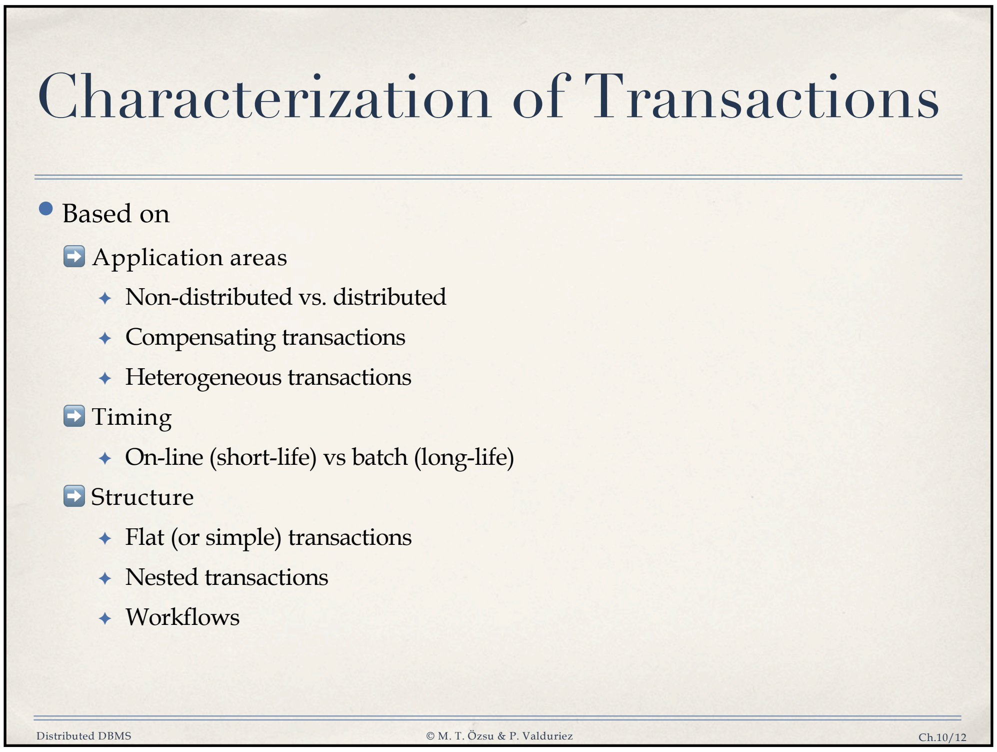
## SQL-92 Isolation Levels (cont'd)

- Read Uncommitted
  - ➡ For transactions operating at this level, all three phenomena are possible.
- Read Committed
  - ➡ Fuzzy reads and phantoms are possible, but dirty reads are not.
- Repeatable Read
  - ➡ Only phantoms possible.
- Anomaly Serializable
  - ➡ None of the phenomena are possible.



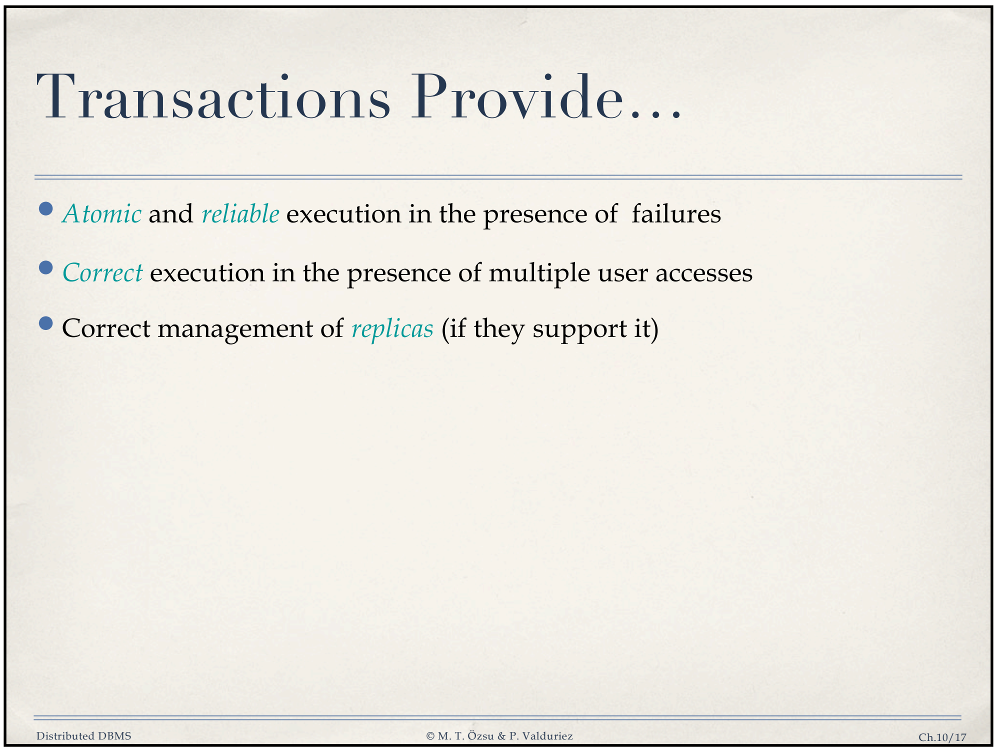
## Durability

- Once a transaction commits, the system must guarantee that the results of its operations will never be lost, in spite of subsequent failures.
- Database recovery



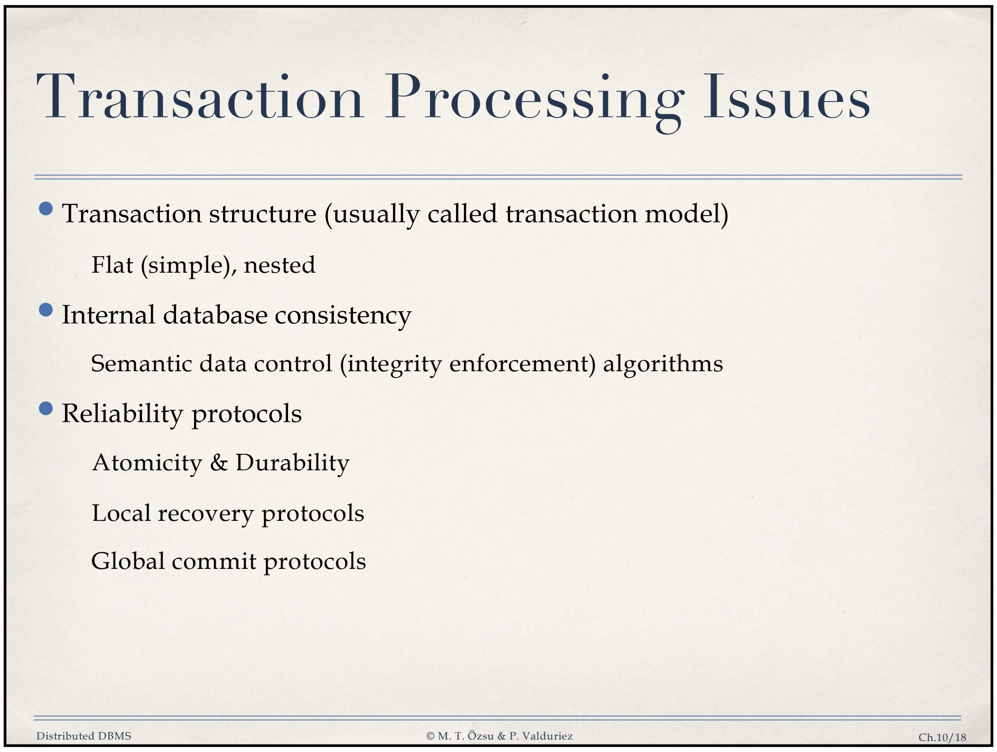
## Characterization of Transactions

- Based on
  - Application areas
    - Non-distributed vs. distributed
    - Compensating transactions
    - Heterogeneous transactions
  - Timing
    - On-line (short-life) vs batch (long-life)
  - Structure
    - Flat (or simple) transactions
    - Nested transactions
    - Workflows



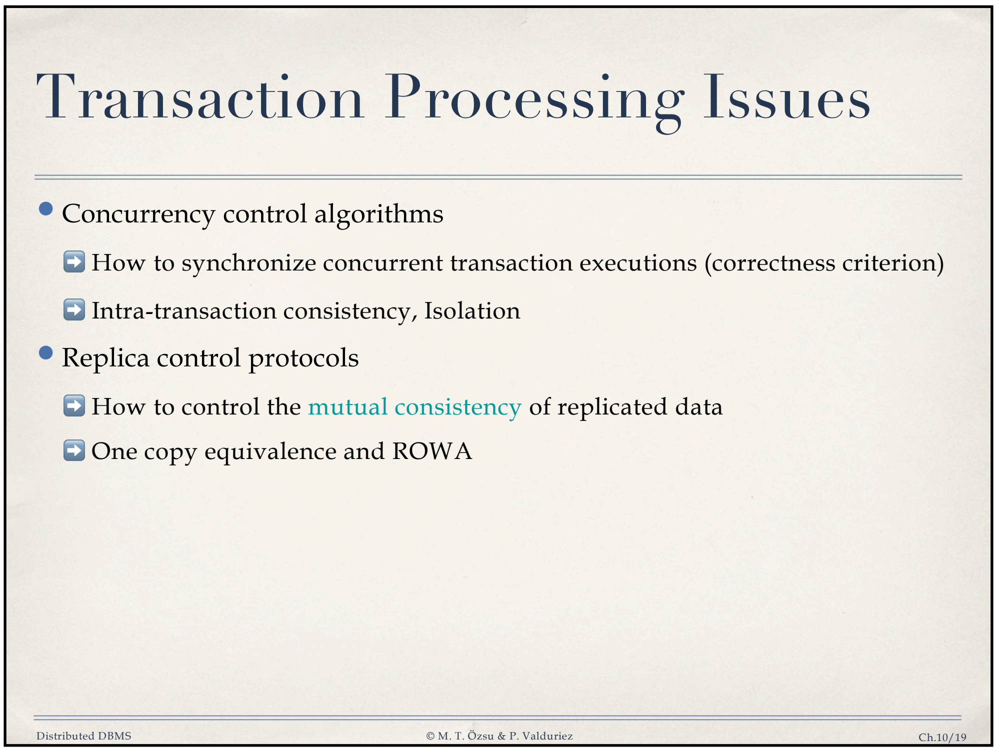
## Transactions Provide…

- *Atomic* and *reliable* execution in the presence of failures
- *Correct* execution in the presence of multiple user accesses
- Correct management of *replicas* (if they support it)



## Transaction Processing Issues

- Transaction structure (usually called transaction model)
  - Flat (simple), nested
- Internal database consistency
  - Semantic data control (integrity enforcement) algorithms
- Reliability protocols
  - Atomicity & Durability
  - Local recovery protocols
  - Global commit protocols



## Transaction Processing Issues

- Concurrency control algorithms
  - ➡ How to synchronize concurrent transaction executions (correctness criterion)
  - ➡ Intra-transaction consistency, Isolation
- Replica control protocols
  - ➡ How to control the mutual consistency of replicated data
  - ➡ One copy equivalence and ROWA

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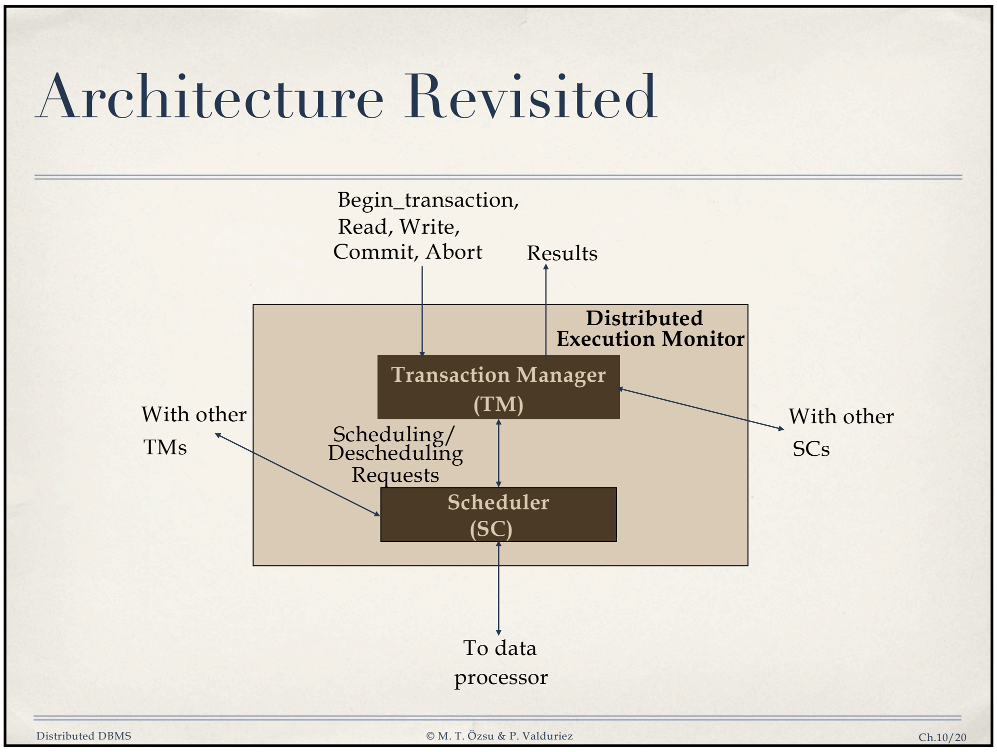
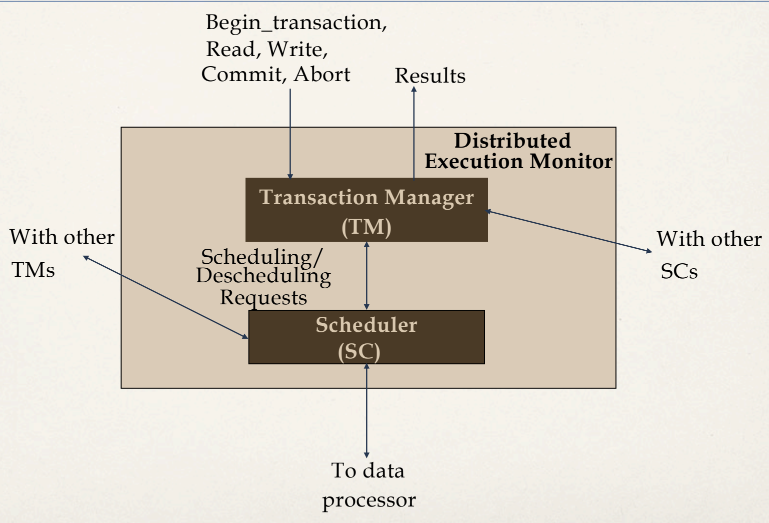


## Architecture Revisited


Begin_transaction, Read, Write, Commit, Abort
Results
Distributed Execution Monitor
Transaction Manager (TM)
With other TMs
Scheduling/ Descheduling Requests
With other SCs
Scheduler (SC)
To data processor

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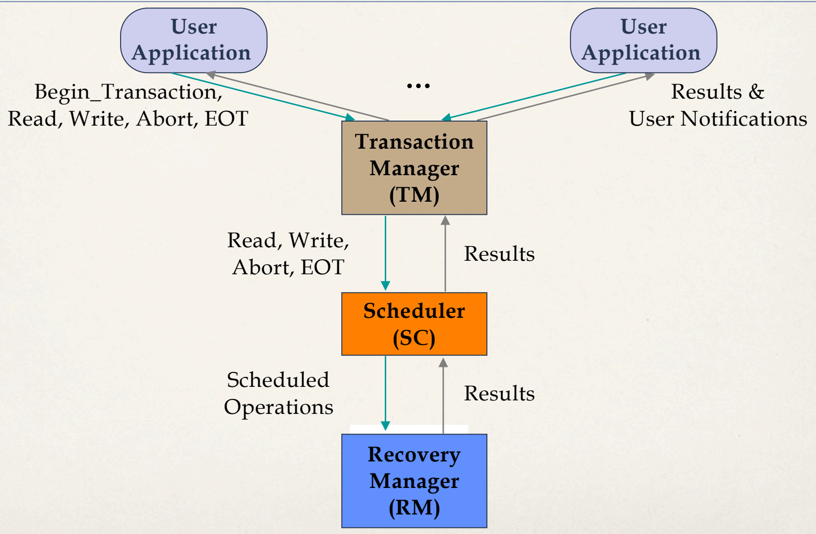
## Centralized Transaction Execution



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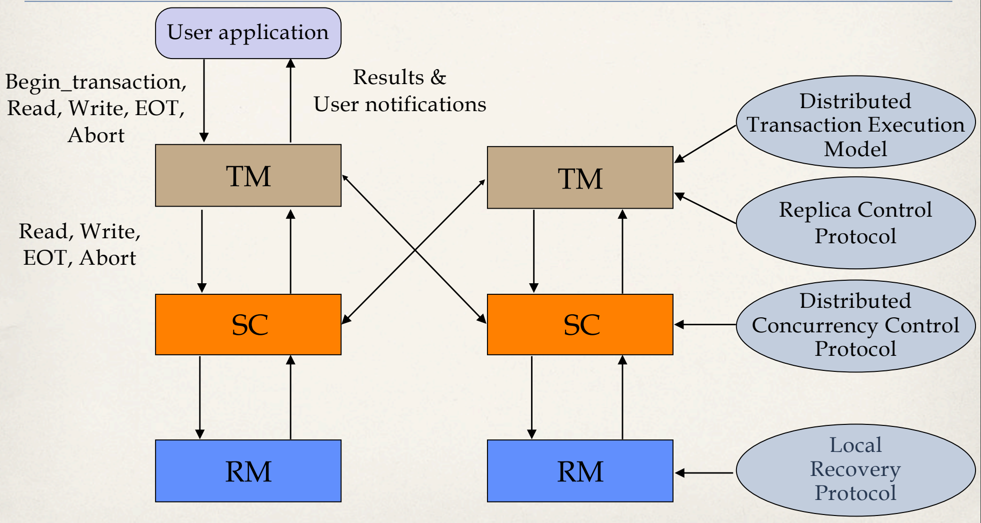
## Distributed Transaction Execution


User application
Begin_transaction, Read, Write, EOT, Abort
Results & User notifications
TM
TM
Read, Write, EOT, Abort
SC
SC
RM
RM
Distributed Transaction Execution Model
Replica Control Protocol
Distributed Concurrency Control Protocol
Local Recovery Protocol

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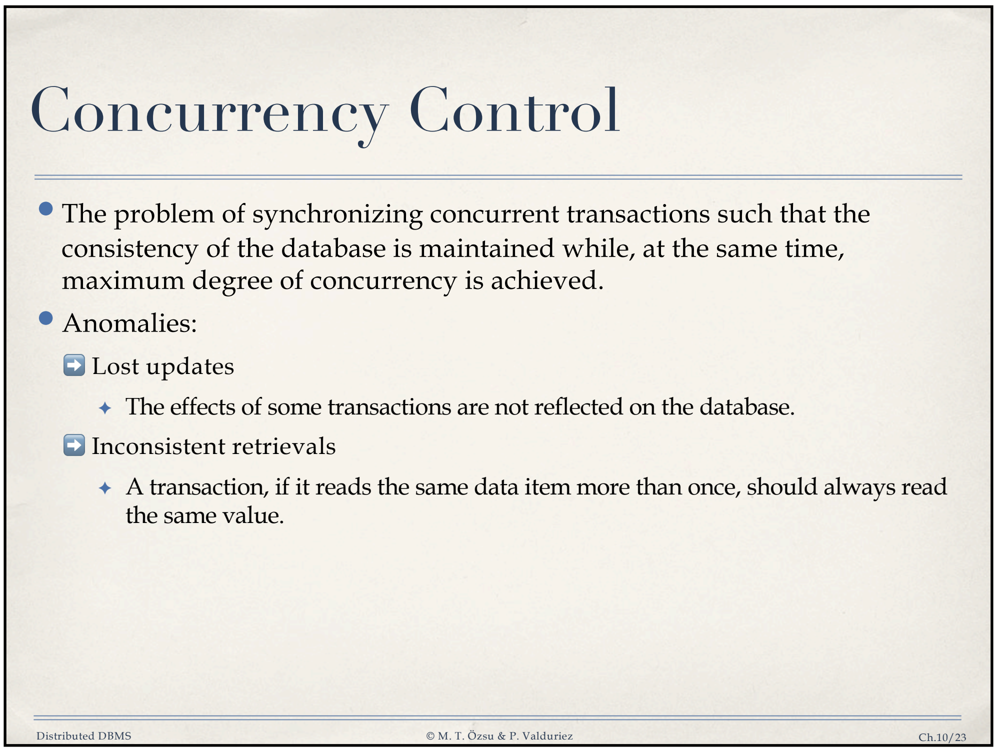

## Concurrency Control

- The problem of synchronizing concurrent transactions such that the consistency of the database is maintained while, at the same time, maximum degree of concurrency is achieved.
- Anomalies:
  - ➡ Lost updates
    - ✦ The effects of some transactions are not reflected on the database.
  - ➡ Inconsistent retrievals
    - ✦ A transaction, if it reads the same data item more than once, should always read the same value.

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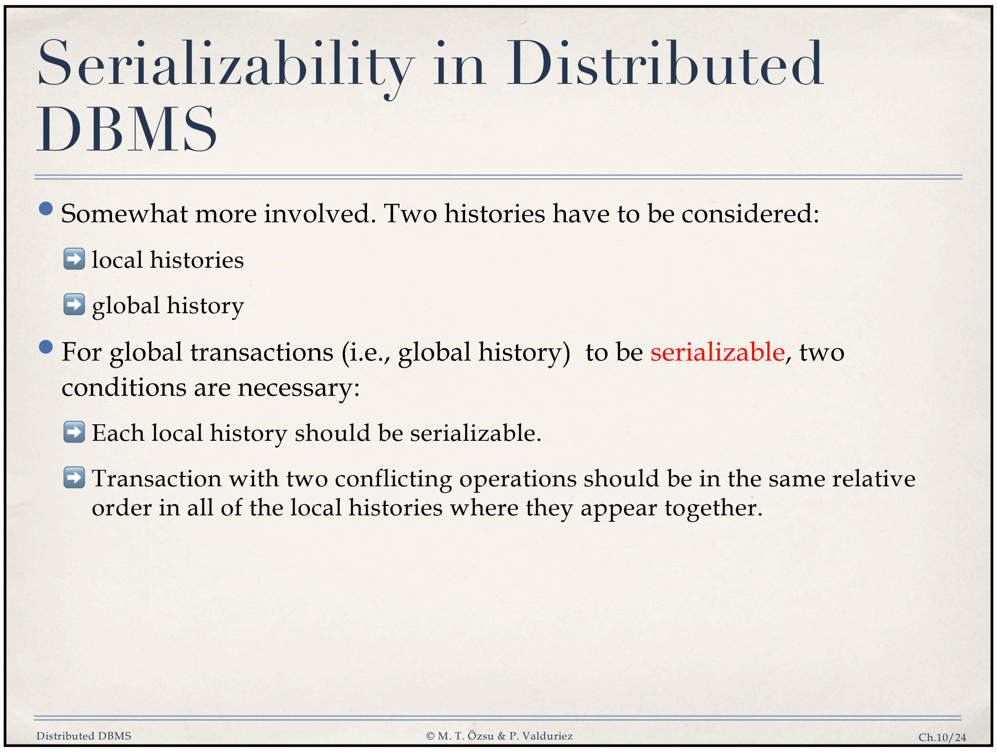

## Serializability in Distributed DBMS

- Somewhat more involved. Two histories have to be considered:
  - ➡ local histories
  - ➡ global history
- For global transactions (i.e., global history) to be serializable, two conditions are necessary:
  - ➡ Each local history should be serializable.
  - ➡ Transaction with two conflicting operations should be in the same relative order in all of the local histories where they appear together.

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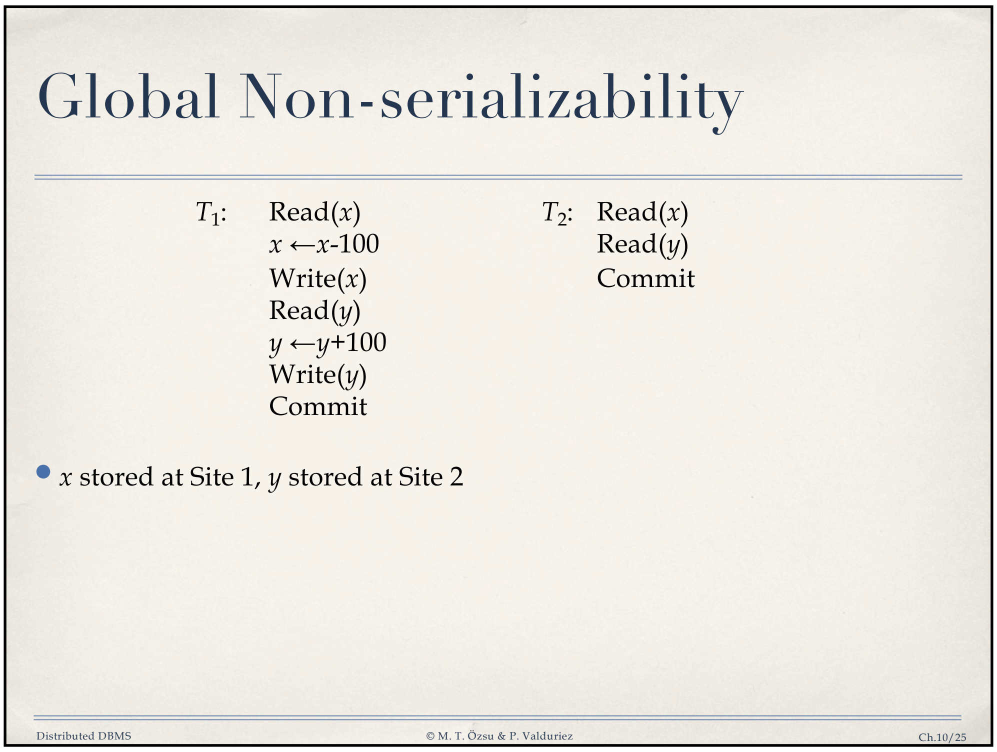
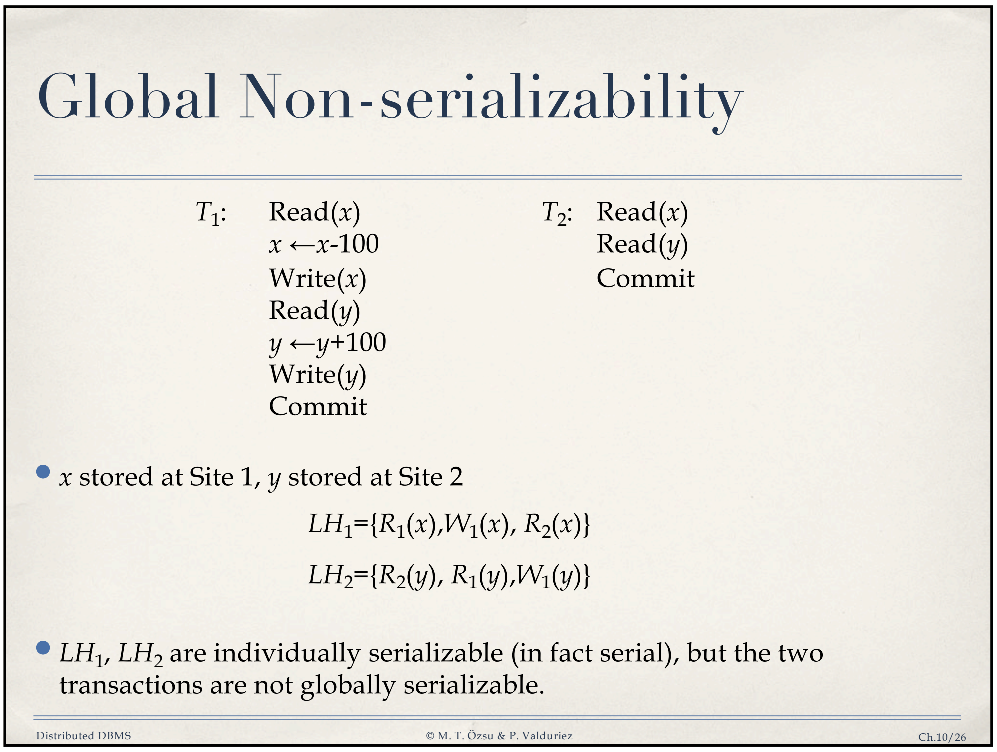


## Global Non-serializability

| | | | |
|---|---|---|---|
| $T_1$: | Read($x$) | $T_2$: | Read($x$) |
| | $x \leftarrow x$-100 | | Read($y$) |
| | Write($x$) | | Commit |
| | Read($y$) | | |
| | $y \leftarrow y$+100 | | |
| | Write($y$) | | |
| | Commit | | |

- $x$ stored at Site 1, $y$ stored at Site 2



## Global Non-serializability

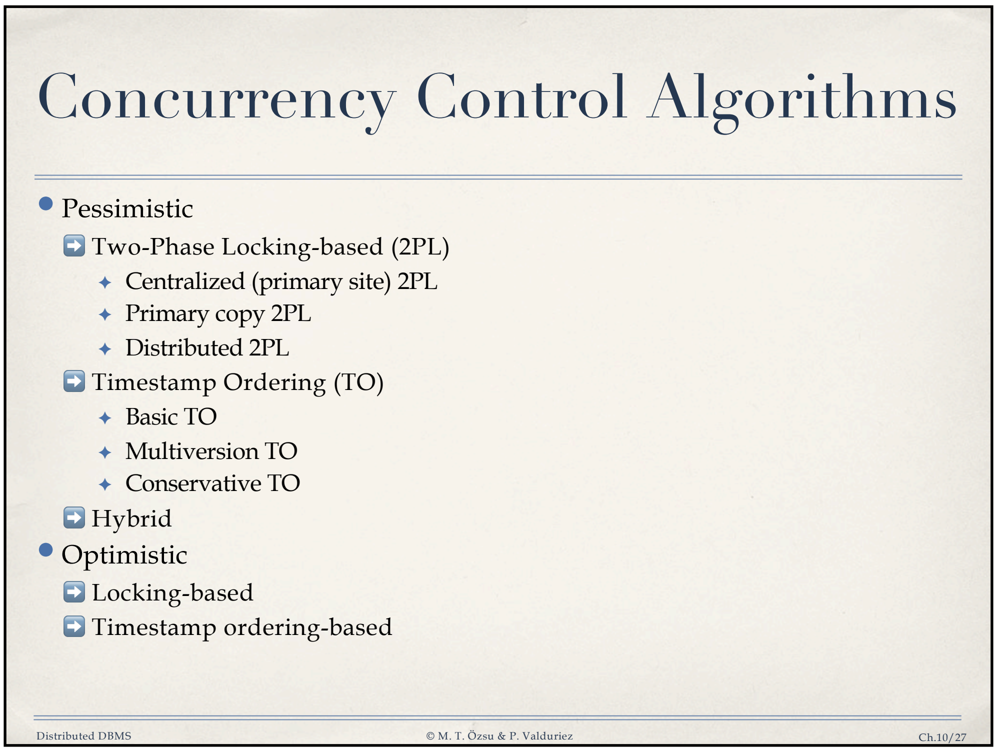
| | | | |
|---|---|---|---|
| $T_1$: | Read($x$) | $T_2$: | Read($x$) |
| | $x \leftarrow x$-100 | | Read($y$) |
| | Write($x$) | | Commit |
| | Read($y$) | | |
| | $y \leftarrow y$+100 | | |
| | Write($y$) | | |
| | Commit | | |

- $x$ stored at Site 1, $y$ stored at Site 2

$$LH_1=\{R_1(x),W_1(x), R_2(x)\}$$

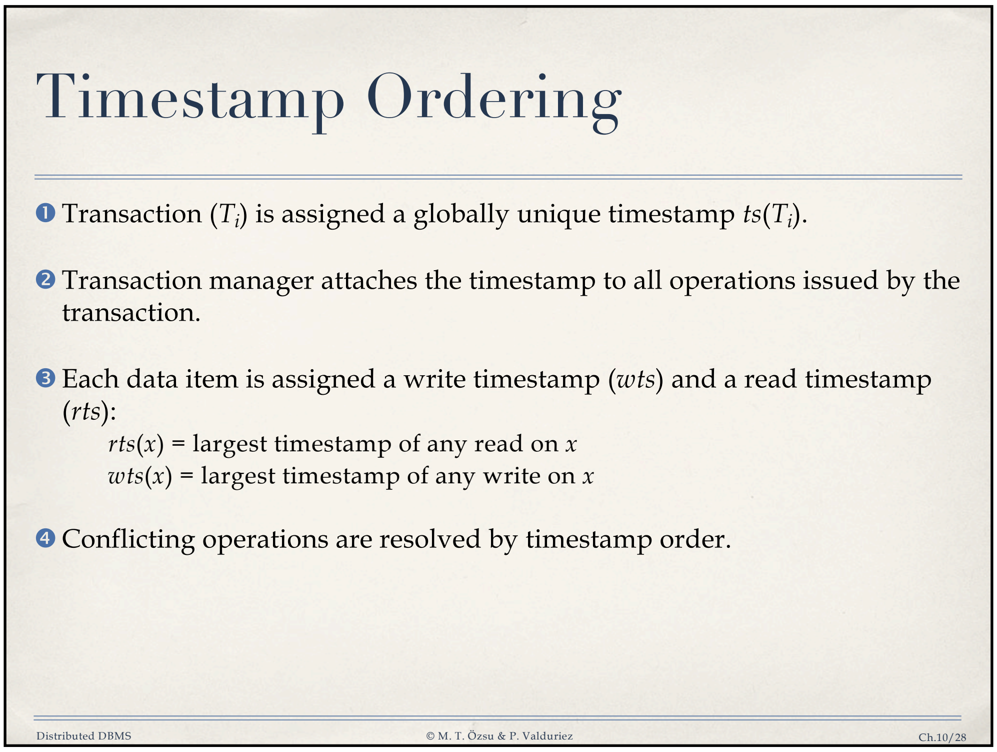
$$LH_2=\{R_2(y), R_1(y),W_1(y)\}$$

- $LH_1$, $LH_2$ are individually serializable (in fact serial), but the two transactions are not globally serializable.



## Concurrency Control Algorithms

- Pessimistic
  - Two-Phase Locking-based (2PL)
    - Centralized (primary site) 2PL
    - Primary copy 2PL
    - Distributed 2PL
  - Timestamp Ordering (TO)
    - Basic TO
    - Multiversion TO
    - Conservative TO
  - Hybrid
- Optimistic
  - Locking-based
  - Timestamp ordering-based



## Timestamp Ordering

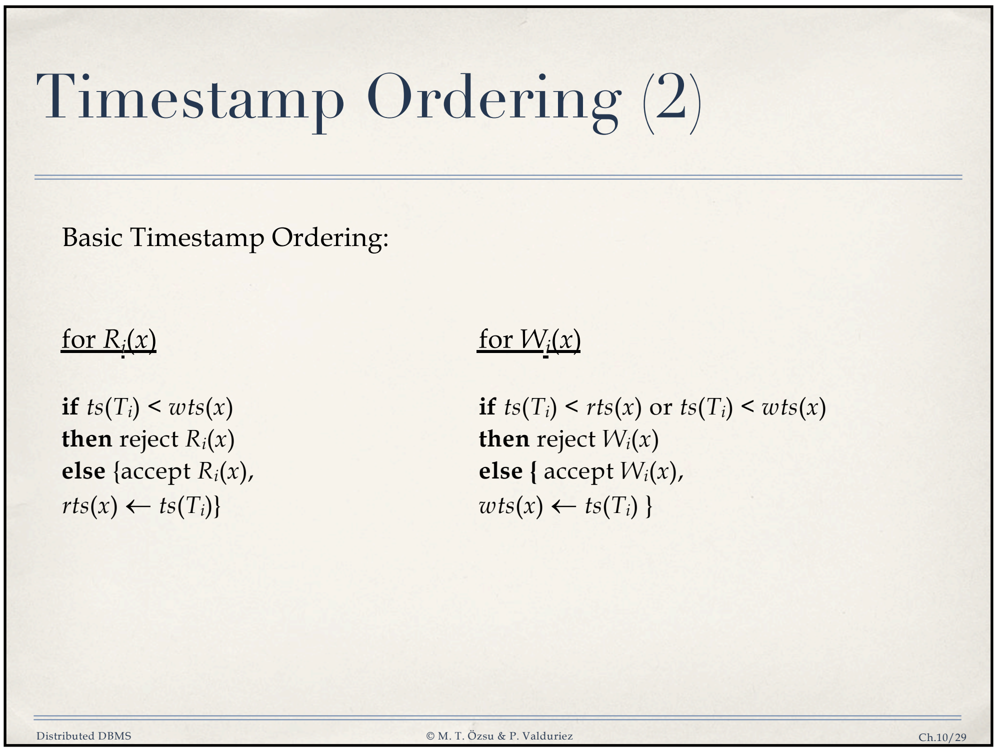
❶ Transaction ($T_i$) is assigned a globally unique timestamp $ts(T_i)$.

❷ Transaction manager attaches the timestamp to all operations issued by the transaction.

❸ Each data item is assigned a write timestamp (*wts*) and a read timestamp (*rts*):

$rts(x)$ = largest timestamp of any read on $x$
$wts(x)$ = largest timestamp of any write on $x$

❹ Conflicting operations are resolved by timestamp order.



## Timestamp Ordering (2)

Basic Timestamp Ordering:

<u>for $R_i(x)$</u>

```
**if** $ts(T_i) < wts(x)$
**then** reject $R_i(x)$
**else** {accept $R_i(x)$,
$rts(x) \leftarrow ts(T_i)$}
```

<u>for $W_i(x)$</u>

```
**if** $ts(T_i) < rts(x)$ or $ts(T_i) < wts(x)$
**then** reject $W_i(x)$
**else** { accept $W_i(x)$,
$wts(x) \leftarrow ts(T_i)$ }
```

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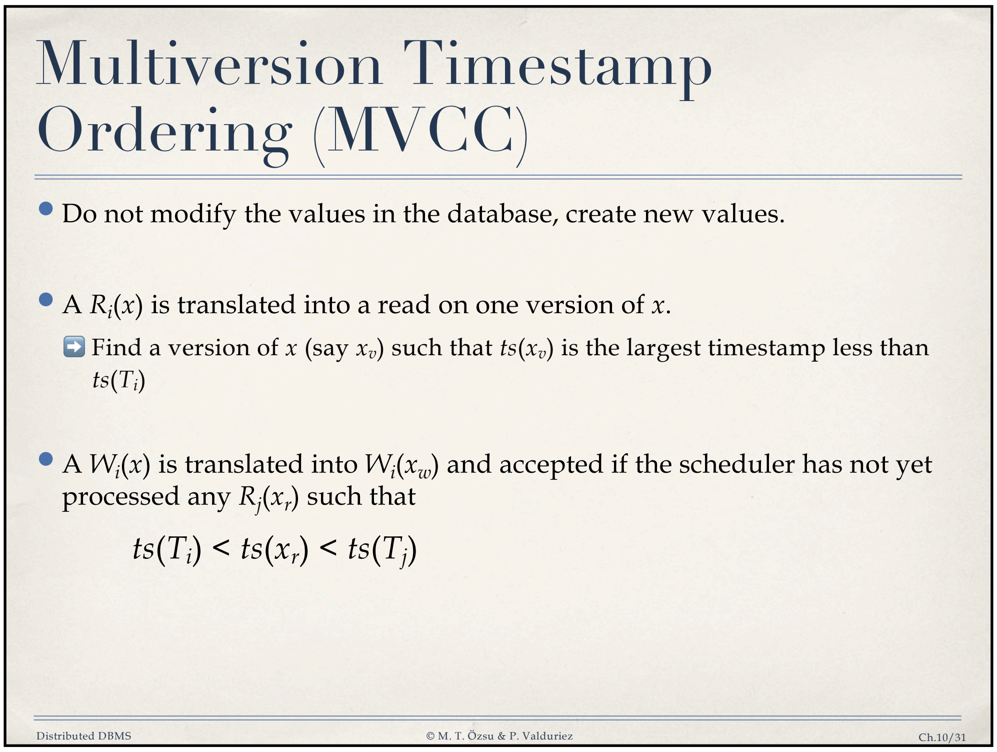

## Multiversion Timestamp Ordering (MVCC)

- Do not modify the values in the database, create new values.
- A $R_i(x)$ is translated into a read on one version of $x$.
  - ➡️ Find a version of $x$ (say $x_v$) such that $ts(x_v)$ is the largest timestamp less than $ts(T_i)$
- A $W_i(x)$ is translated into $W_i(x_w)$ and accepted if the scheduler has not yet processed any $R_j(x_r)$ such that

$$ts(T_i) < ts(x_r) < ts(T_j)$$

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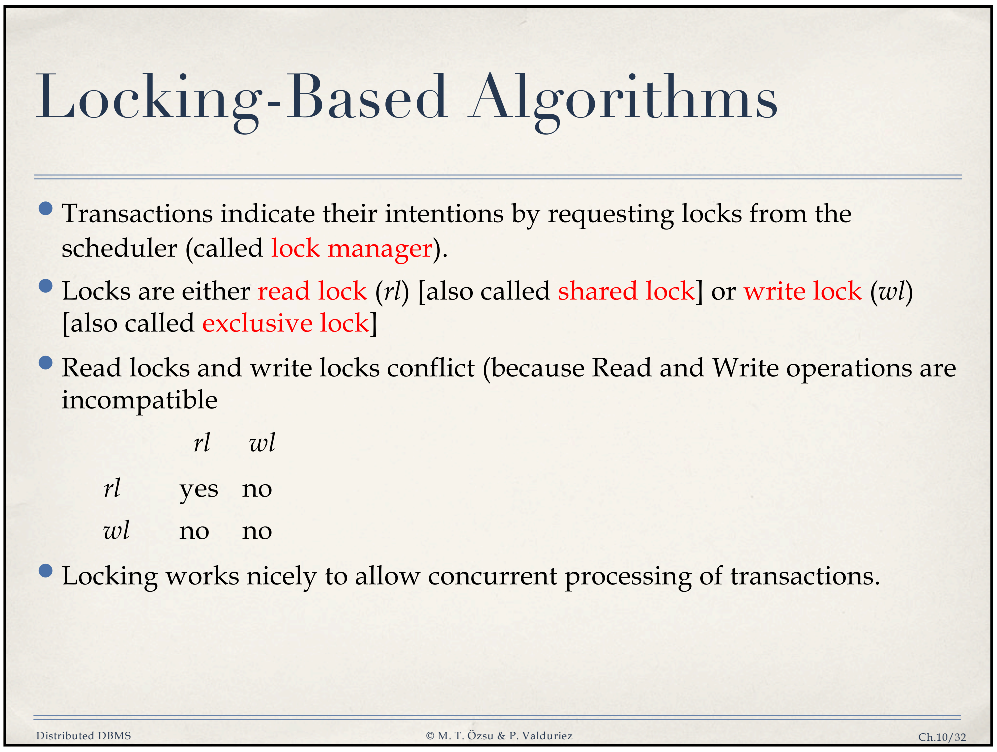
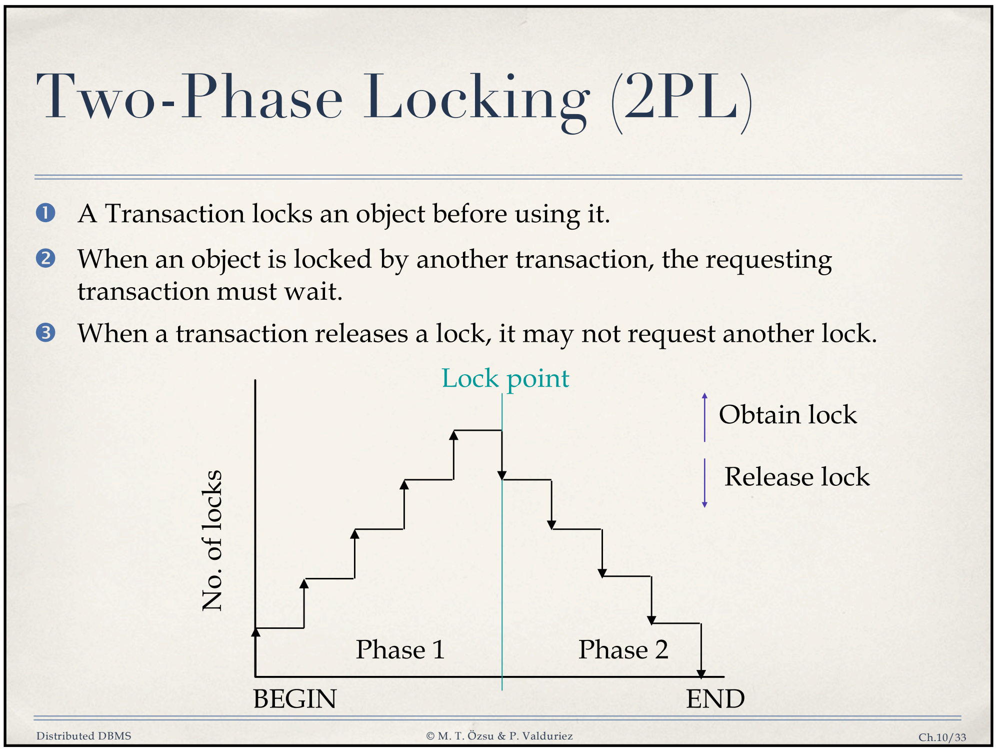


## Locking-Based Algorithms

- Transactions indicate their intentions by requesting locks from the scheduler (called lock manager).
- Locks are either read lock (*rl*) [also called shared lock] or write lock (*wl*) [also called exclusive lock]
- Read locks and write locks conflict (because Read and Write operations are incompatible

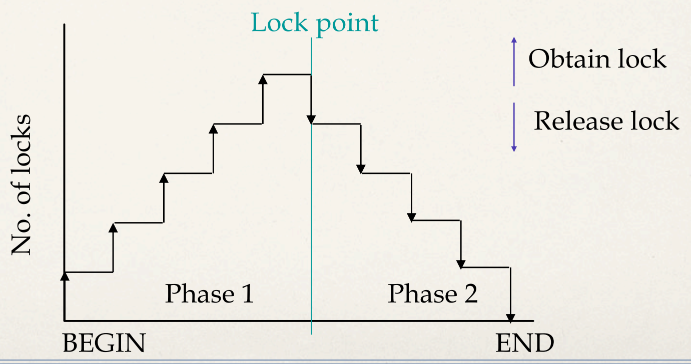
| | *rl* | *wl* |
|---|---|---|
| *rl* | yes | no |
| *wl* | no | no |

- Locking works nicely to allow concurrent processing of transactions.



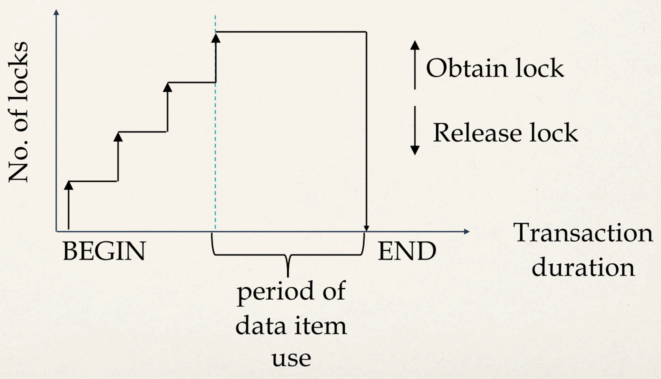
## Two-Phase Locking (2PL)

1. A Transaction locks an object before using it.
2. When an object is locked by another transaction, the requesting transaction must wait.
3. When a transaction releases a lock, it may not request another lock.



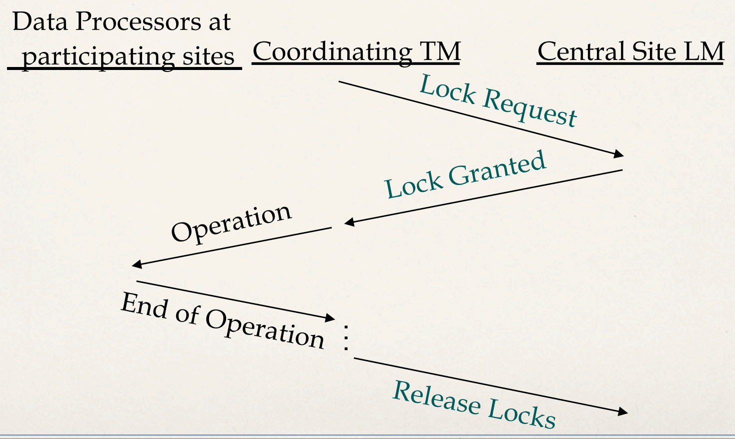
## Strict 2PL

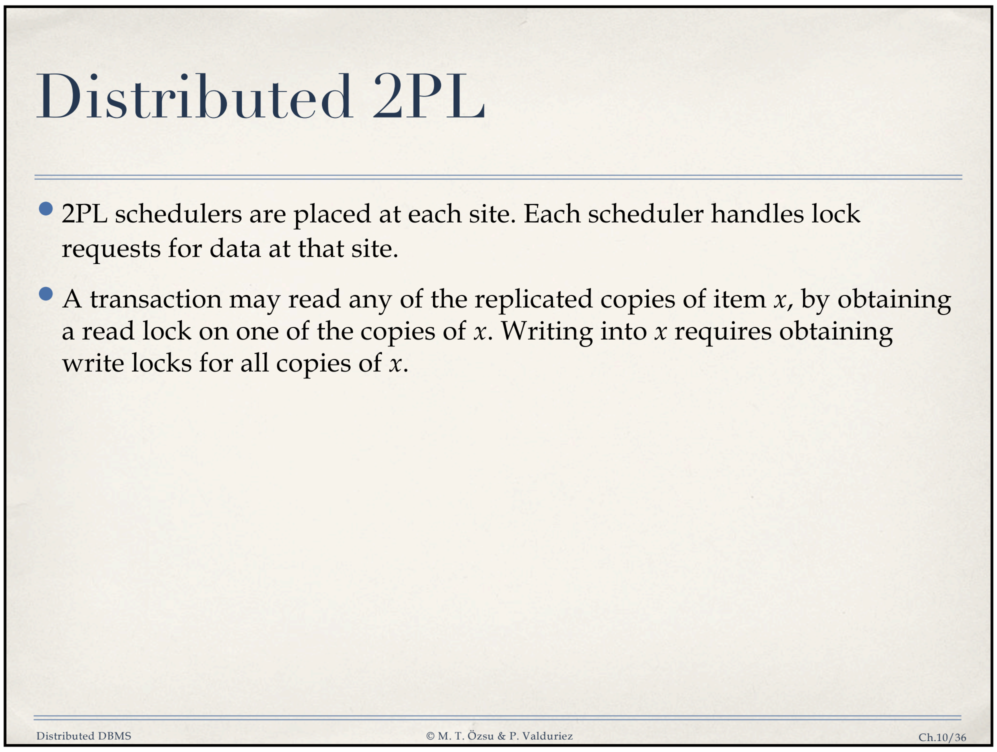
Hold locks until the end.



## Centralized 2PL

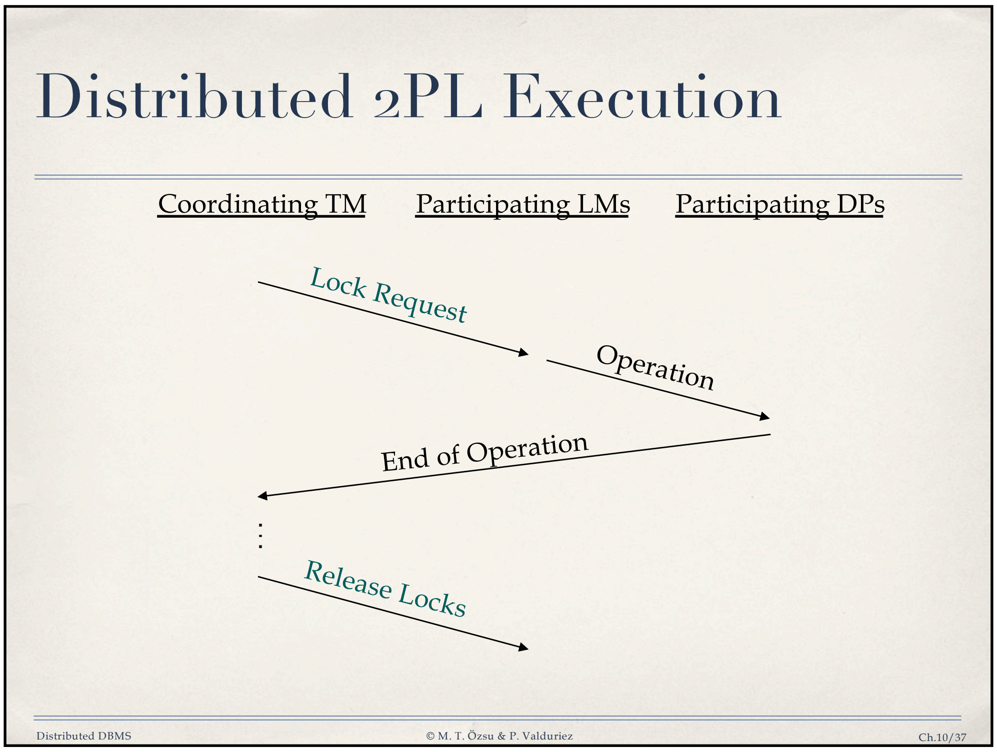
- There is only one 2PL scheduler in the distributed system.
- Lock requests are issued to the central scheduler.



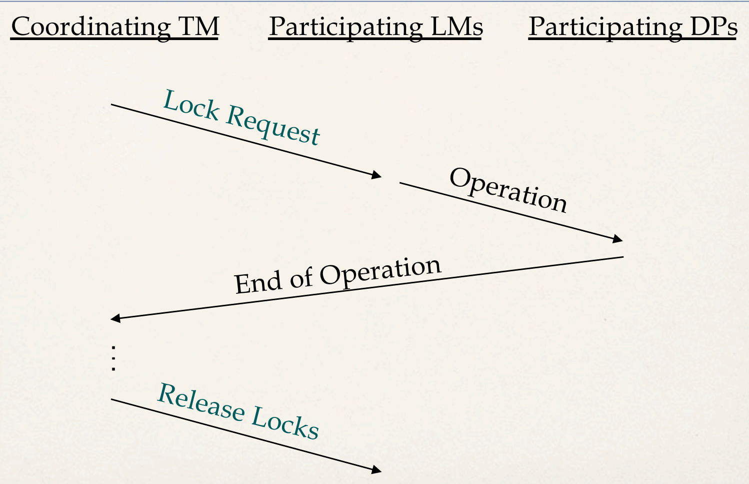


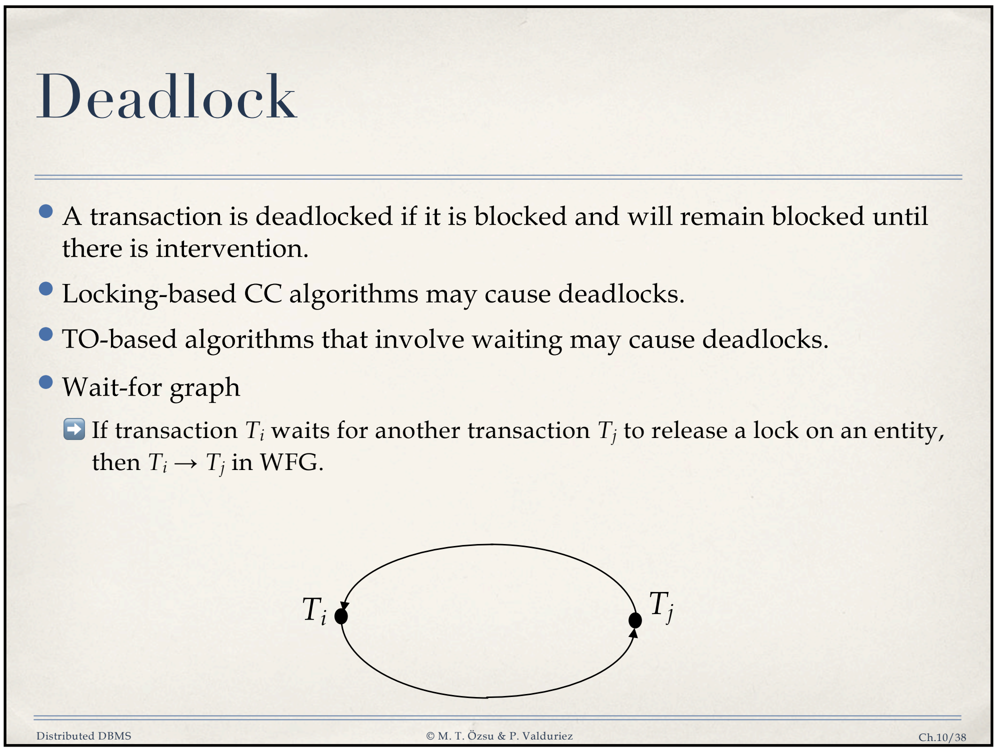
## Distributed 2PL

- 2PL schedulers are placed at each site. Each scheduler handles lock requests for data at that site.
- A transaction may read any of the replicated copies of item *x*, by obtaining a read lock on one of the copies of *x*. Writing into *x* requires obtaining write locks for all copies of *x*.



## Distributed 2PL Execution

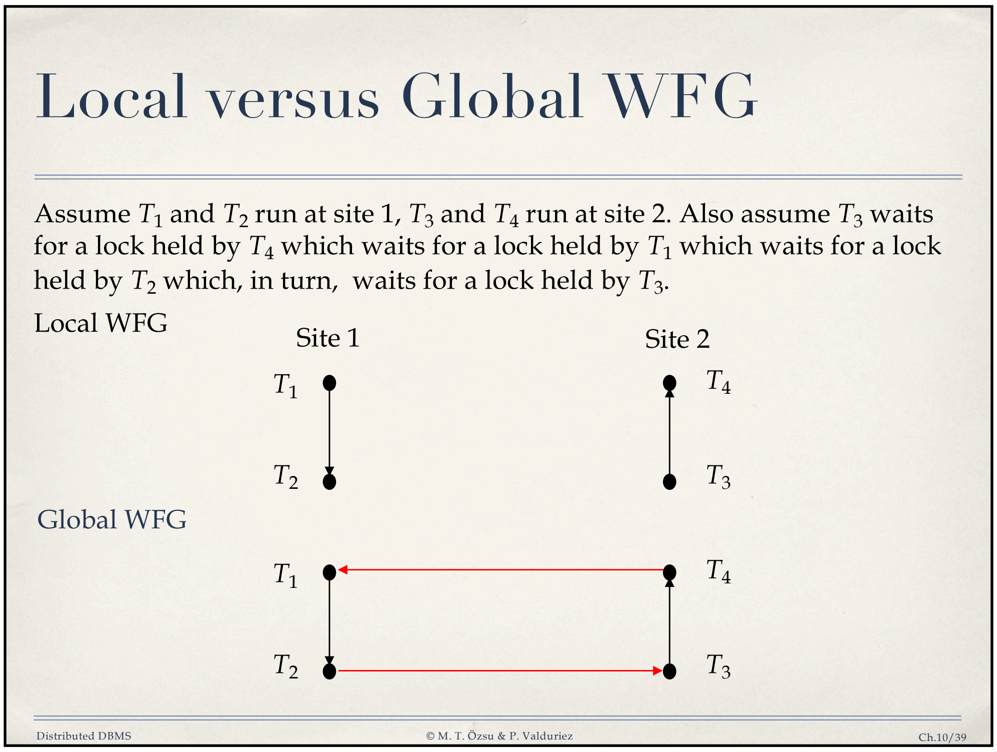




## Deadlock

- A transaction is deadlocked if it is blocked and will remain blocked until there is intervention.
- Locking-based CC algorithms may cause deadlocks.
- TO-based algorithms that involve waiting may cause deadlocks.
- Wait-for graph
  - ➡️ If transaction $T_i$ waits for another transaction $T_j$ to release a lock on an entity, then $T_i \rightarrow T_j$ in WFG.

$$\begin{tikzcd} T_i \arrow[r, bend right] & T_j \arrow[l, bend right] \end{tikzcd}$$



## Local versus Global WFG

Assume $T_1$ and $T_2$ run at site 1, $T_3$ and $T_4$ run at site 2. Also assume $T_3$ waits for a lock held by $T_4$ which waits for a lock held by $T_1$ which waits for a lock held by $T_2$ which, in turn, waits for a lock held by $T_3$.

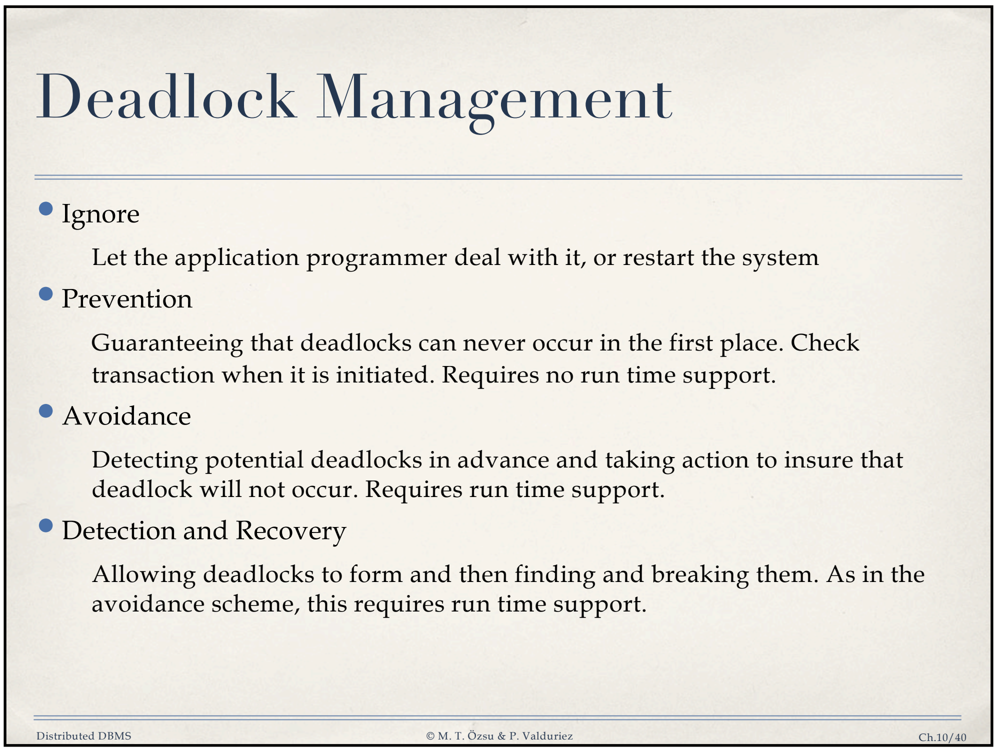
Local WFG

Site 1 Site 2

$$\begin{tikzcd} T_1 \arrow[d] & & T_4 \\ T_2 & & T_3 \arrow[u] \end{tikzcd}$$

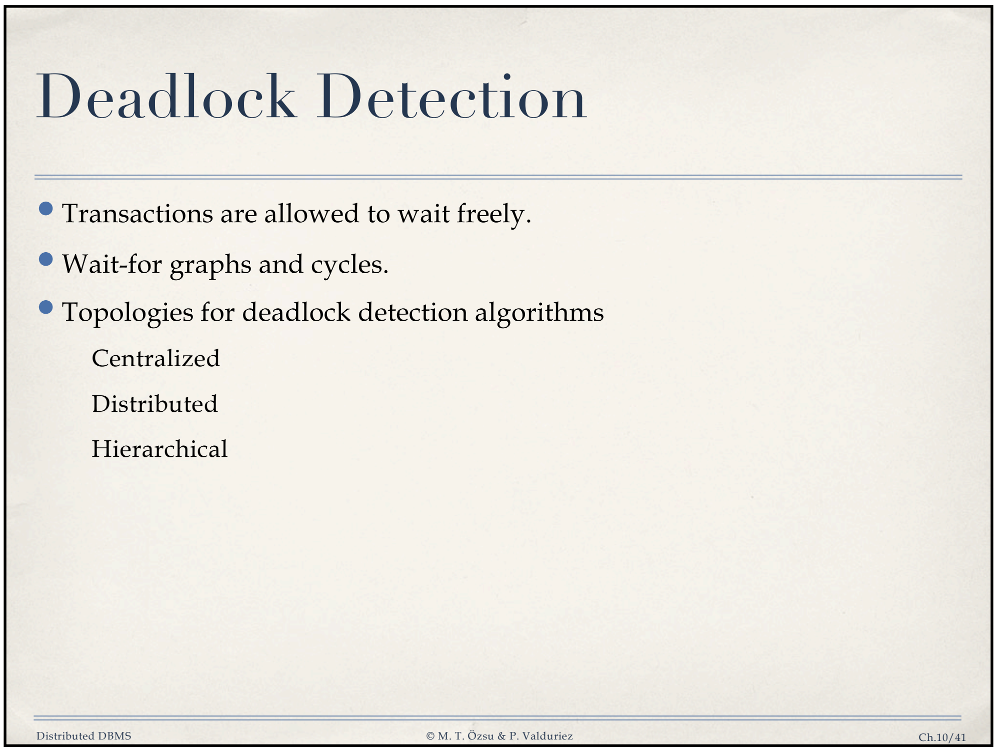
Global WFG

$$\begin{tikzcd} T_1 \arrow[d] & & T_4 \arrow[ll] \\ T_2 \arrow[rr] & & T_3 \arrow[u] \end{tikzcd}$$



## Deadlock Management

- Ignore
  - Let the application programmer deal with it, or restart the system
- Prevention
  - Guaranteeing that deadlocks can never occur in the first place. Check transaction when it is initiated. Requires no run time support.
- Avoidance
  - Detecting potential deadlocks in advance and taking action to insure that deadlock will not occur. Requires run time support.
- Detection and Recovery
  - Allowing deadlocks to form and then finding and breaking them. As in the avoidance scheme, this requires run time support.



## Deadlock Detection

- Transactions are allowed to wait freely.
- Wait-for graphs and cycles.
- Topologies for deadlock detection algorithms
  - Centralized
  - Distributed
  - Hierarchical

## Centralized Deadlock Detection

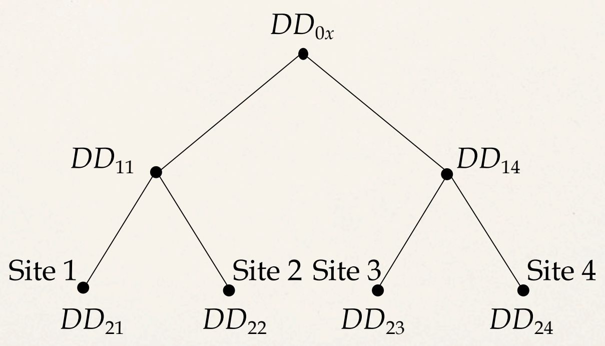
- One site is designated as the deadlock detector for the system. Each scheduler periodically sends its local WFG to the central site which merges them to a global WFG to determine cycles.
- How often to transmit?

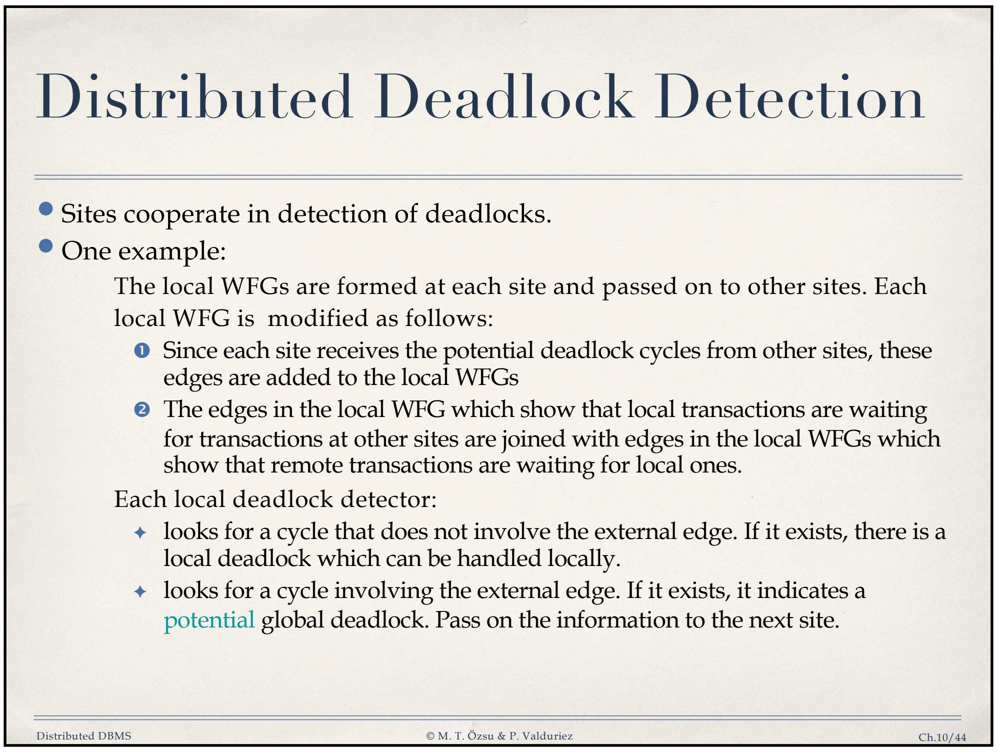
  Too often ⇒ higher communication cost but lower delays due to undetected deadlocks

  Too late ⇒ higher delays due to deadlocks, but lower communication cost
- Would be a reasonable choice if the concurrency control algorithm is also centralized.

## Hierarchical Deadlock Detection

Build a hierarchy of detectors





## Distributed Deadlock Detection

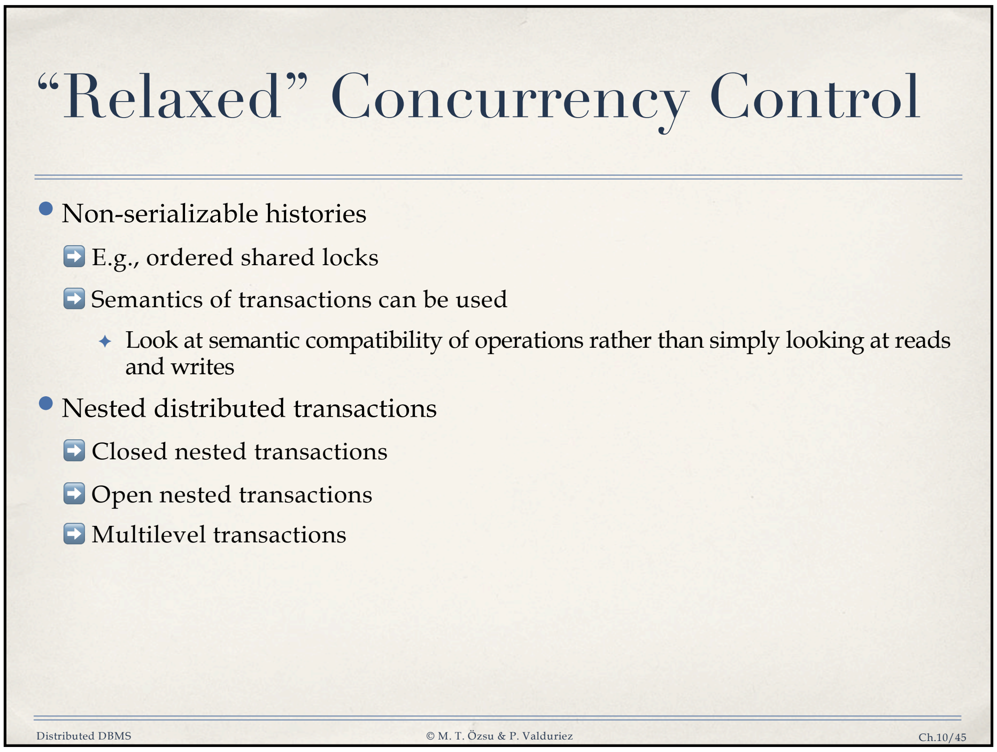
- Sites cooperate in detection of deadlocks.
- One example:

  The local WFGs are formed at each site and passed on to other sites. Each local WFG is modified as follows:

  1. Since each site receives the potential deadlock cycles from other sites, these edges are added to the local WFGs
  2. The edges in the local WFG which show that local transactions are waiting for transactions at other sites are joined with edges in the local WFGs which show that remote transactions are waiting for local ones.

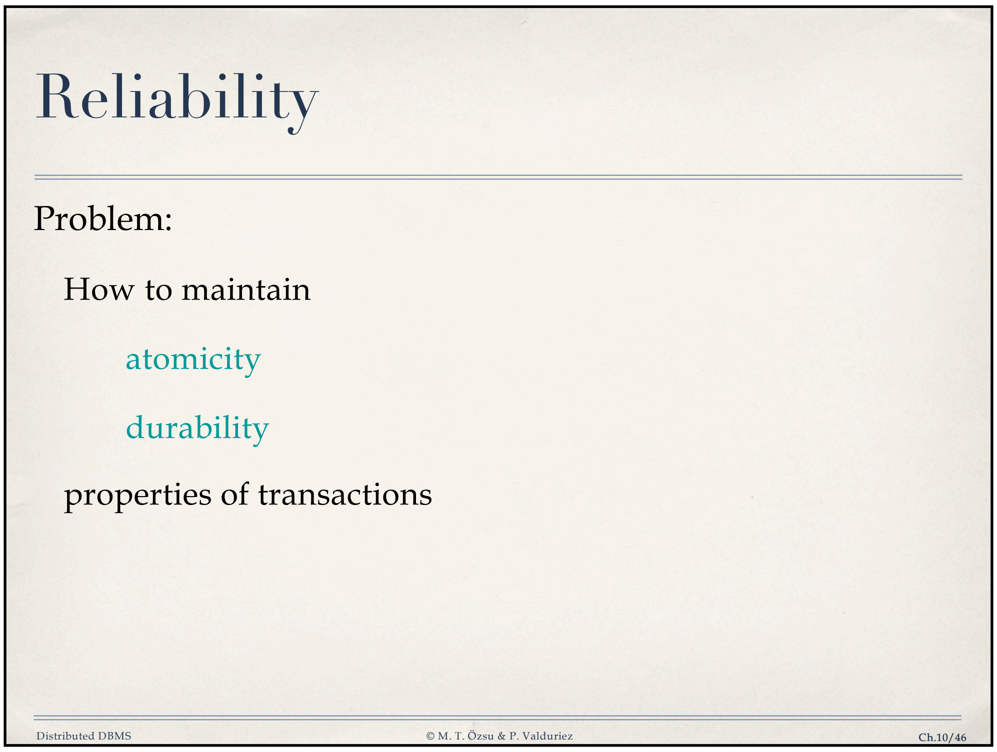
  Each local deadlock detector:

  - looks for a cycle that does not involve the external edge. If it exists, there is a local deadlock which can be handled locally.
  - looks for a cycle involving the external edge. If it exists, it indicates a potential global deadlock. Pass on the information to the next site.



## "Relaxed" Concurrency Control

- Non-serializable histories
  - E.g., ordered shared locks
  - Semantics of transactions can be used
    - Look at semantic compatibility of operations rather than simply looking at reads and writes
- Nested distributed transactions
  - Closed nested transactions
  - Open nested transactions
  - Multilevel transactions



## Reliability

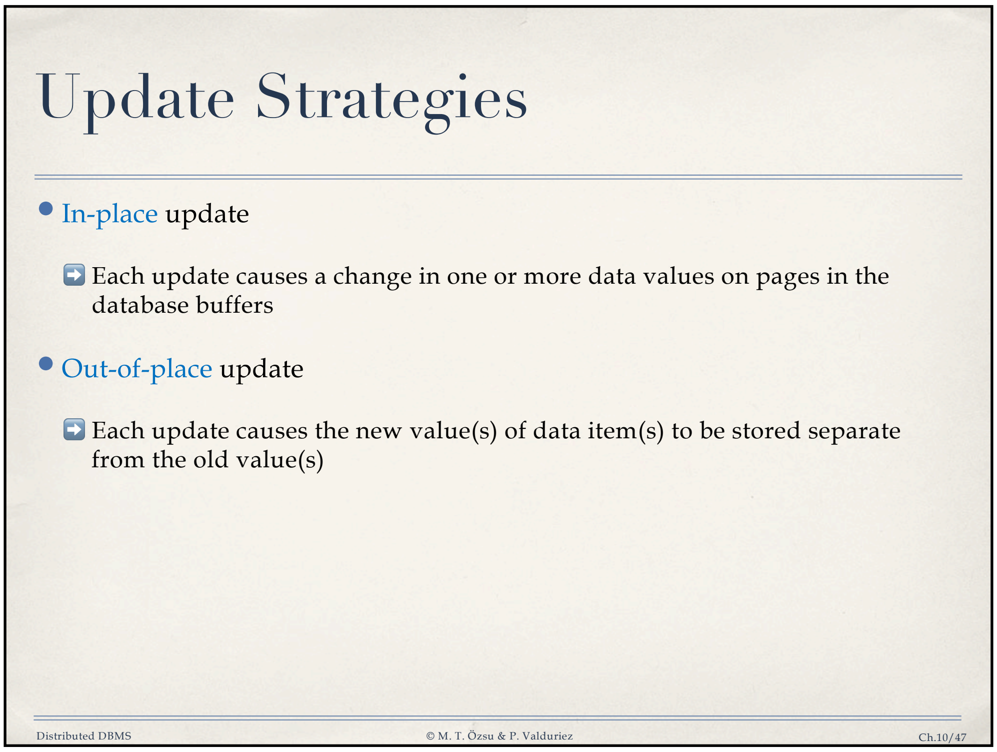
Problem:

How to maintain

atomicity

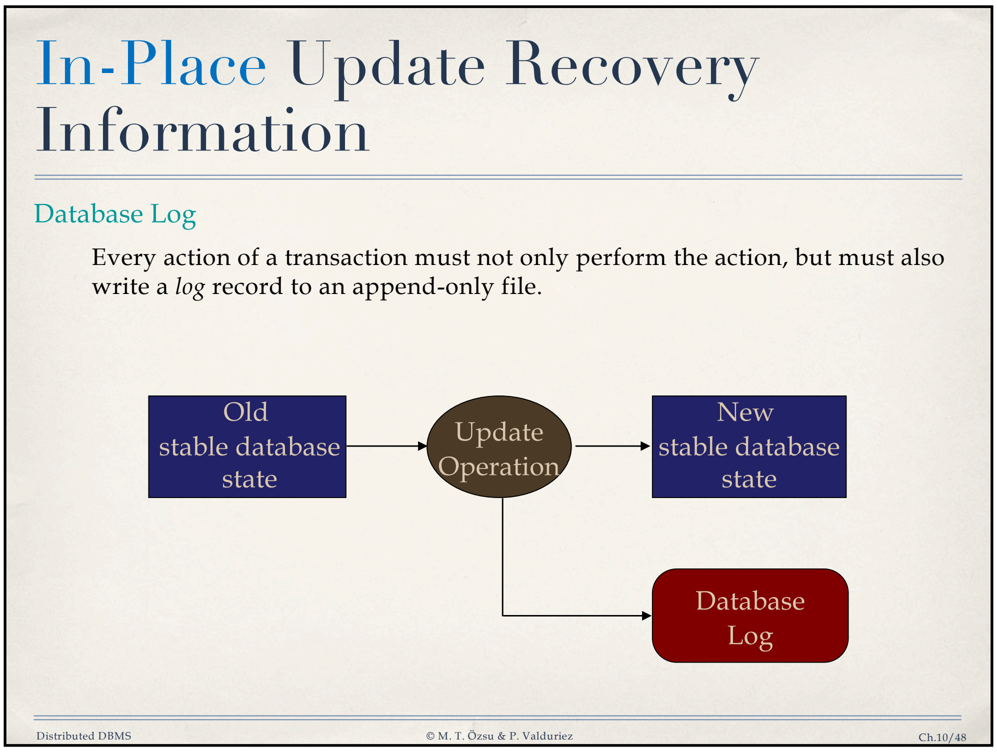
durability

properties of transactions



## Update Strategies

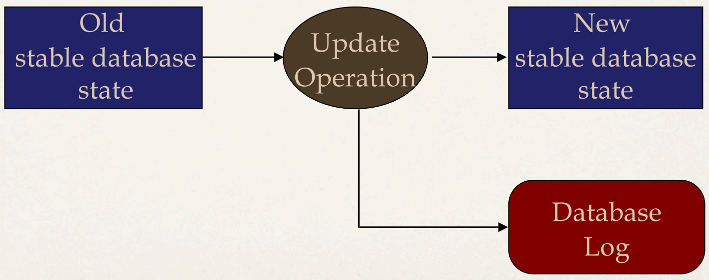
- In-place update
  - ➡️ Each update causes a change in one or more data values on pages in the database buffers
- Out-of-place update
  - ➡️ Each update causes the new value(s) of data item(s) to be stored separate from the old value(s)

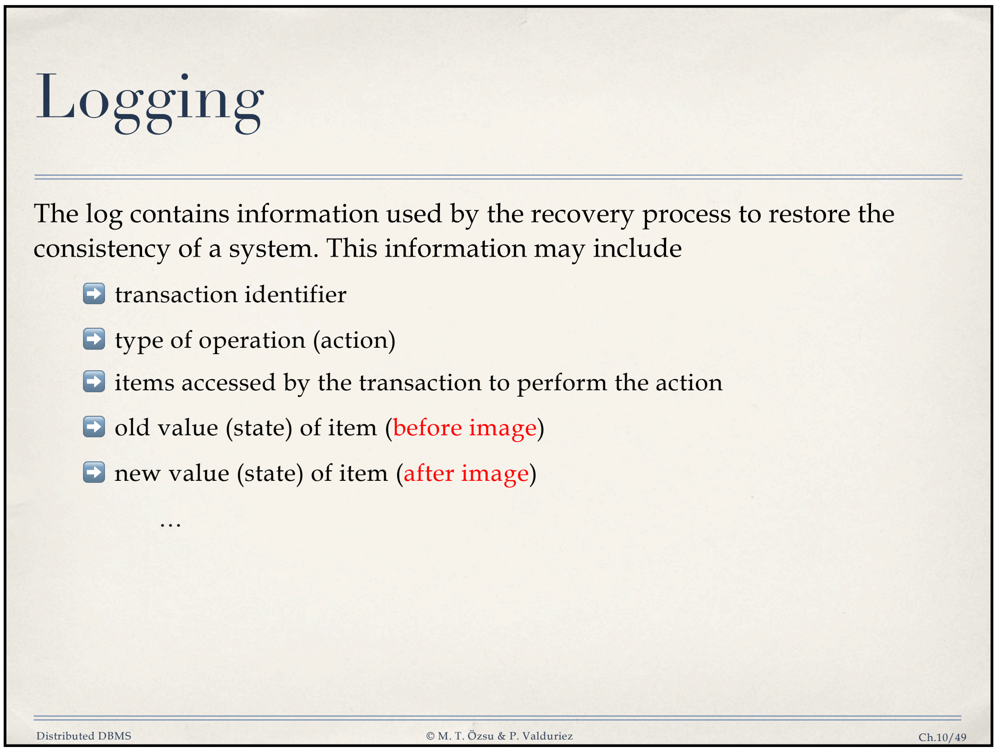


## In-Place Update Recovery Information

Database Log

Every action of a transaction must not only perform the action, but must also write a *log* record to an append-only file.



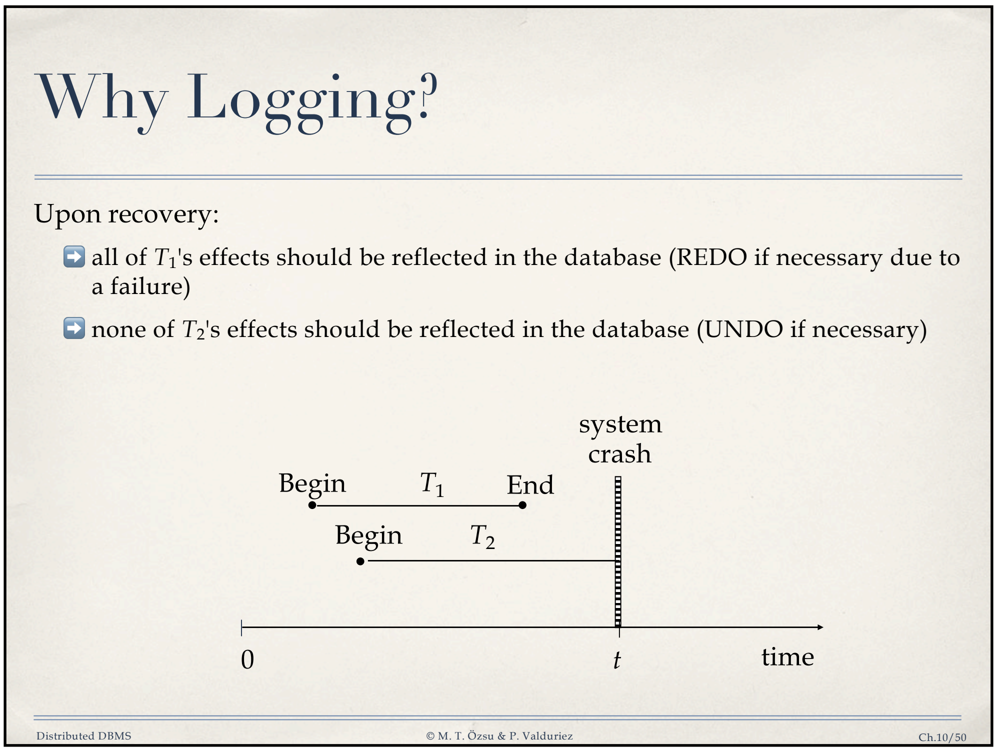


## Logging

The log contains information used by the recovery process to restore the consistency of a system. This information may include

- transaction identifier
- type of operation (action)
- items accessed by the transaction to perform the action
- old value (state) of item (before image)
- new value (state) of item (after image)

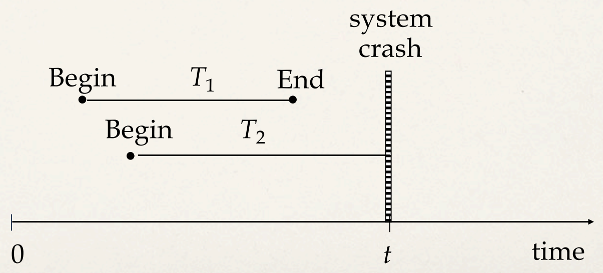
…

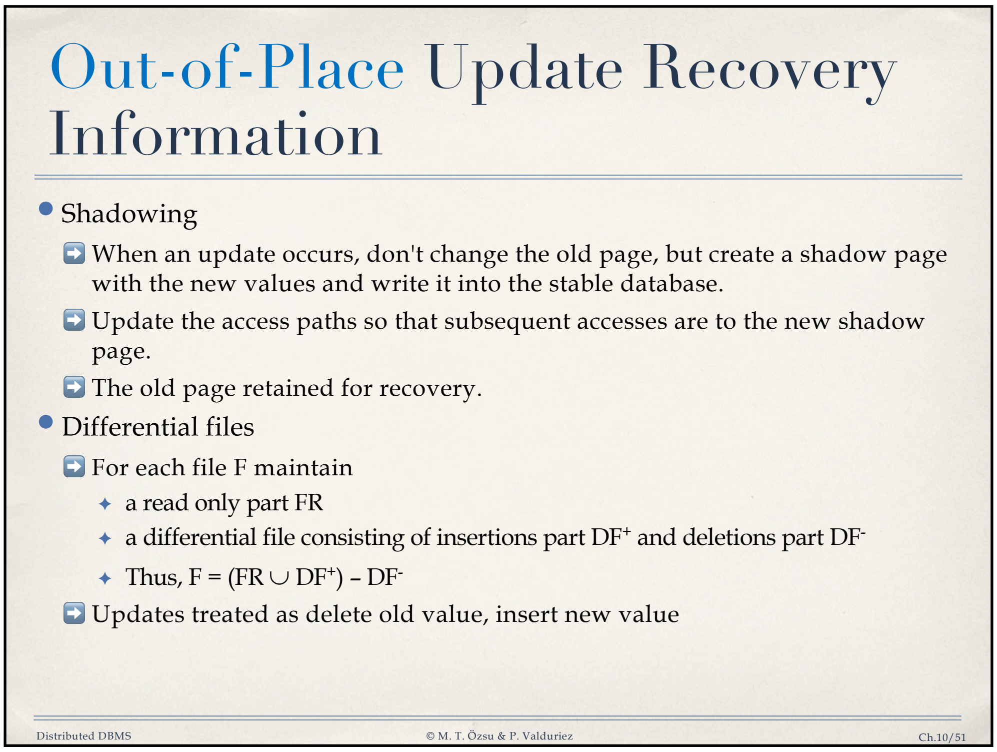


## Why Logging?

Upon recovery:

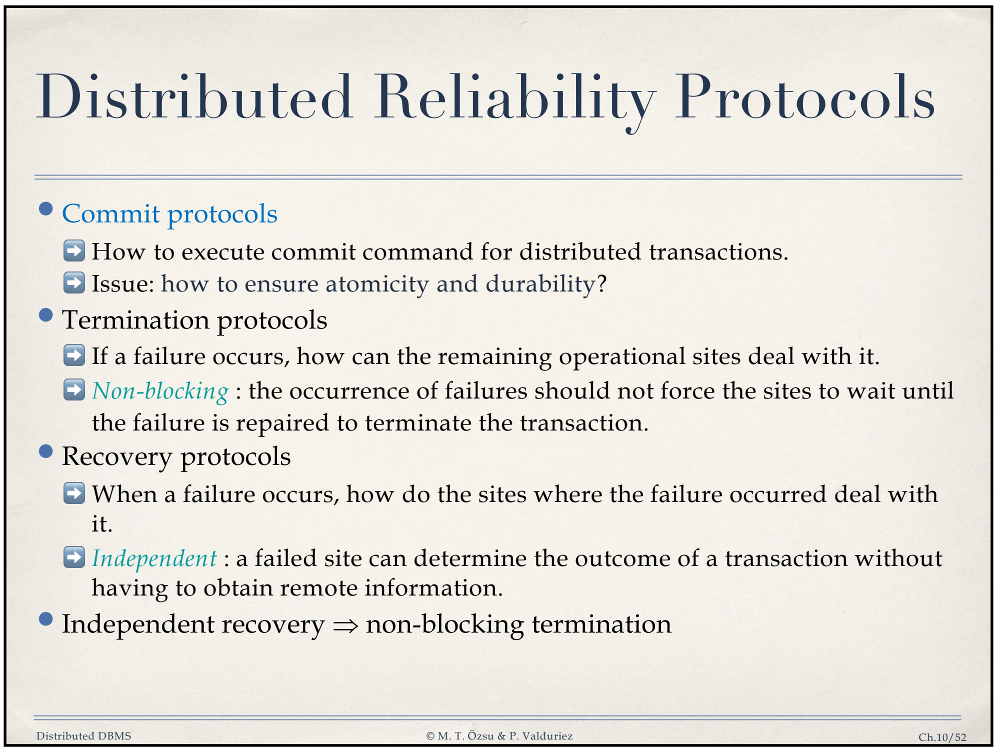
- all of $T_1$'s effects should be reflected in the database (REDO if necessary due to a failure)
- none of $T_2$'s effects should be reflected in the database (UNDO if necessary)





## Out-of-Place Update Recovery Information

- Shadowing
  - When an update occurs, don't change the old page, but create a shadow page with the new values and write it into the stable database.
  - Update the access paths so that subsequent accesses are to the new shadow page.
  - The old page retained for recovery.
- Differential files
  - For each file F maintain
    - a read only part FR
    - a differential file consisting of insertions part $DF^+$ and deletions part $DF^-$
    - Thus, $F = (FR \cup DF^+) - DF^-$
  - Updates treated as delete old value, insert new value



## Distributed Reliability Protocols

- Commit protocols
  - ➡ How to execute commit command for distributed transactions.
  - ➡ Issue: how to ensure atomicity and durability?
- Termination protocols
  - ➡ If a failure occurs, how can the remaining operational sites deal with it.
  - ➡ *Non-blocking* : the occurrence of failures should not force the sites to wait until the failure is repaired to terminate the transaction.
- Recovery protocols
  - ➡ When a failure occurs, how do the sites where the failure occurred deal with it.
  - ➡ *Independent* : a failed site can determine the outcome of a transaction without having to obtain remote information.
- Independent recovery $\Rightarrow$ non-blocking termination

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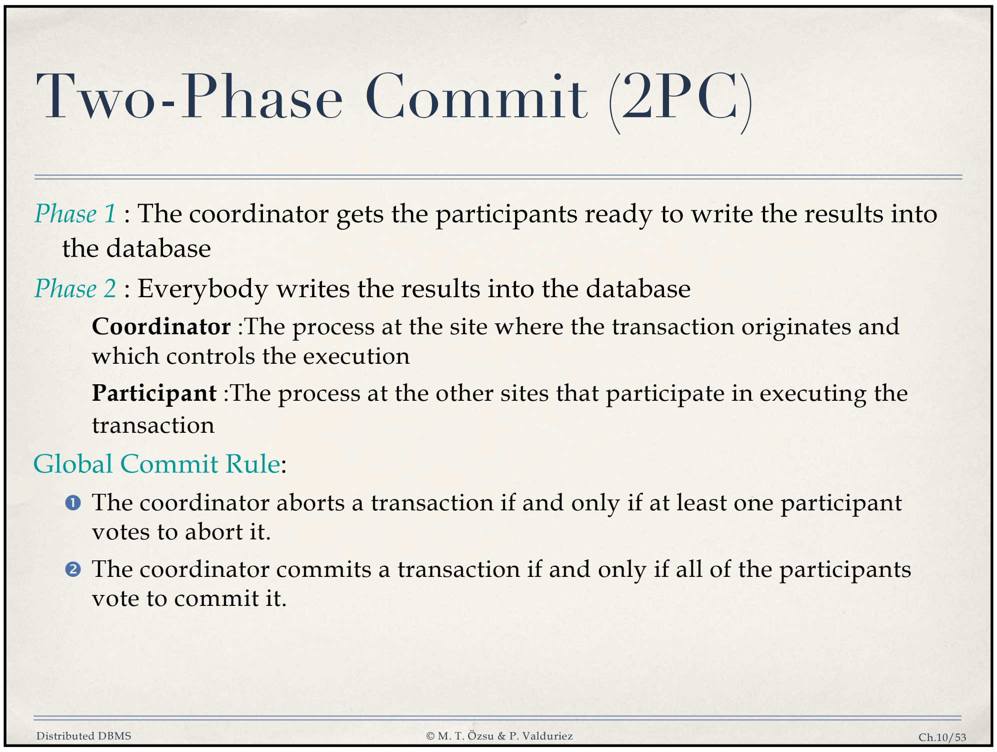

## Two-Phase Commit (2PC)

*Phase 1* : The coordinator gets the participants ready to write the results into the database

*Phase 2* : Everybody writes the results into the database

**Coordinator** :The process at the site where the transaction originates and which controls the execution

**Participant** :The process at the other sites that participate in executing the transaction

Global Commit Rule:

1. The coordinator aborts a transaction if and only if at least one participant votes to abort it.
2. The coordinator commits a transaction if and only if all of the participants vote to commit it.

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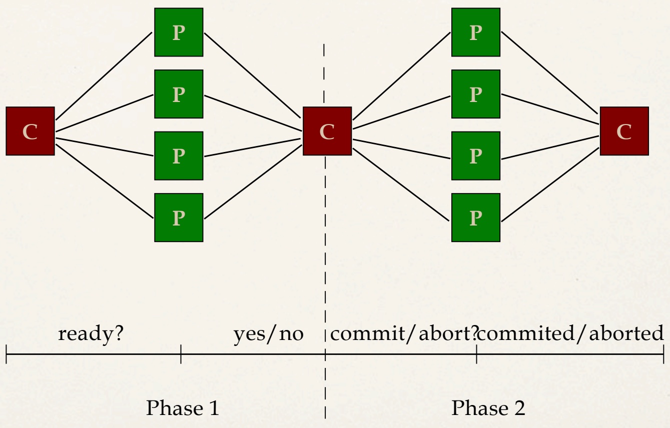
## Centralized 2PC



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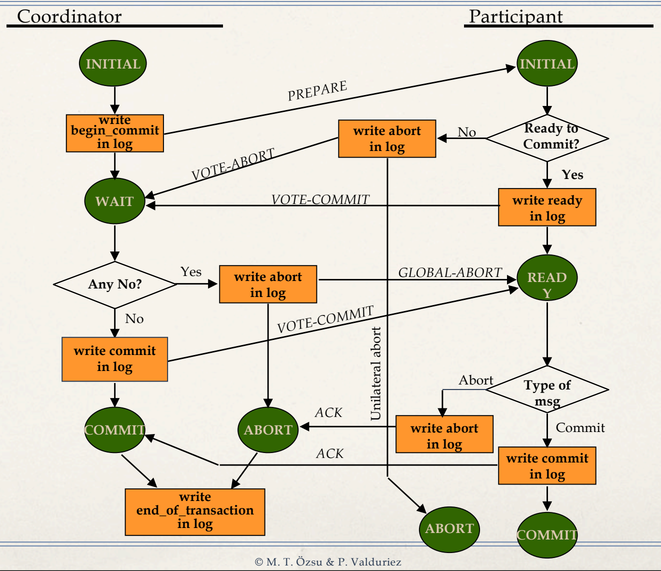
## 2PC Protocol Actions



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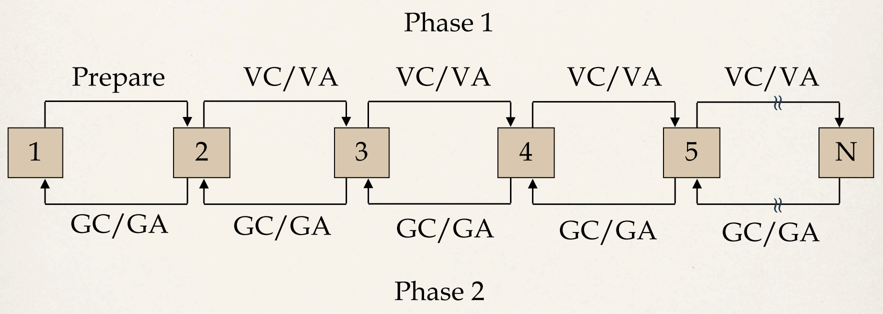
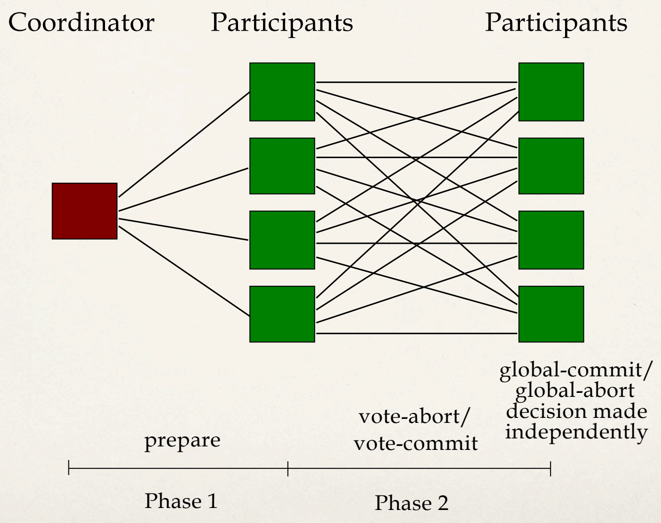
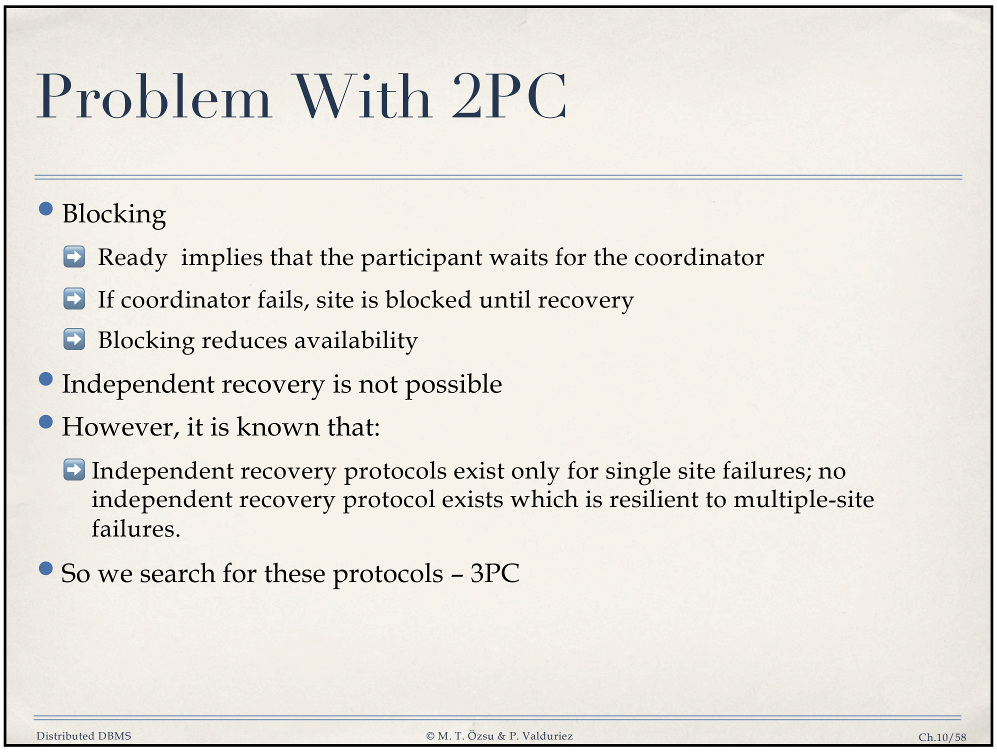
## Linear 2PC



VC: Vote-Commit, VA: Vote-Abort, GC: Global-commit, GA: Global-abort

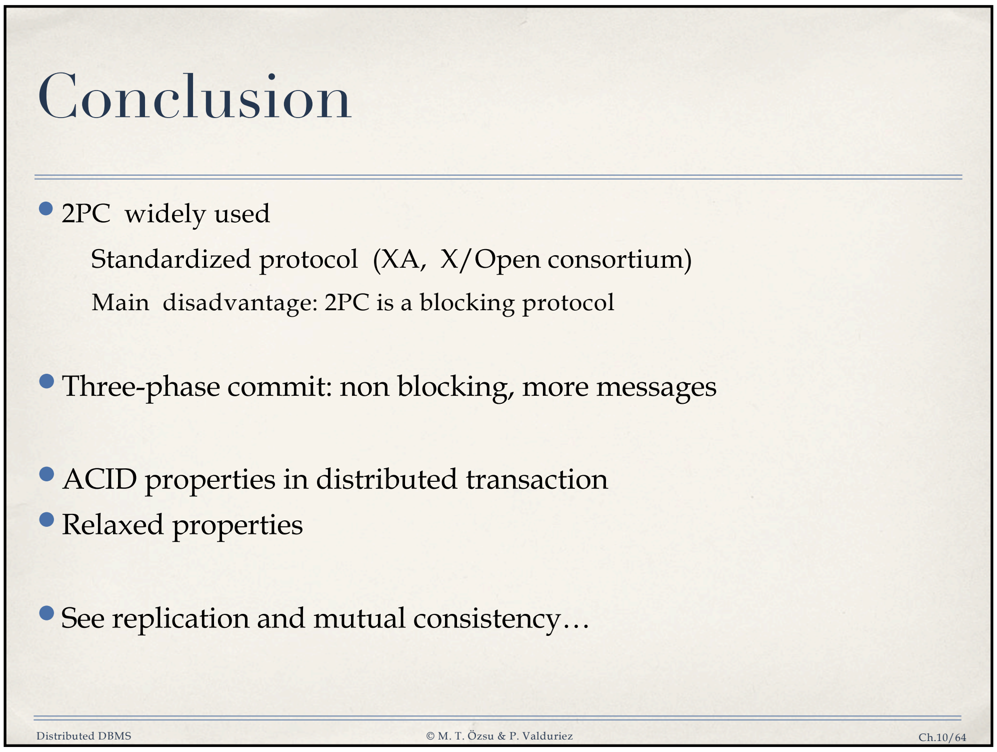
## Distributed 2PC





## Problem With 2PC

- Blocking
  - Ready implies that the participant waits for the coordinator
  - If coordinator fails, site is blocked until recovery
  - Blocking reduces availability
- Independent recovery is not possible
- However, it is known that:
  - Independent recovery protocols exist only for single site failures; no independent recovery protocol exists which is resilient to multiple-site failures.
- So we search for these protocols – 3PC



## Conclusion

- 2PC widely used

  Standardized protocol (XA, X/Open consortium)

  Main disadvantage: 2PC is a blocking protocol
- Three-phase commit: non blocking, more messages
- ACID properties in distributed transaction
- Relaxed properties
- See replication and mutual consistency…