Database Applications (15-415)

DBMS Internals- Part XI
Lecture 22, April 12, 2015

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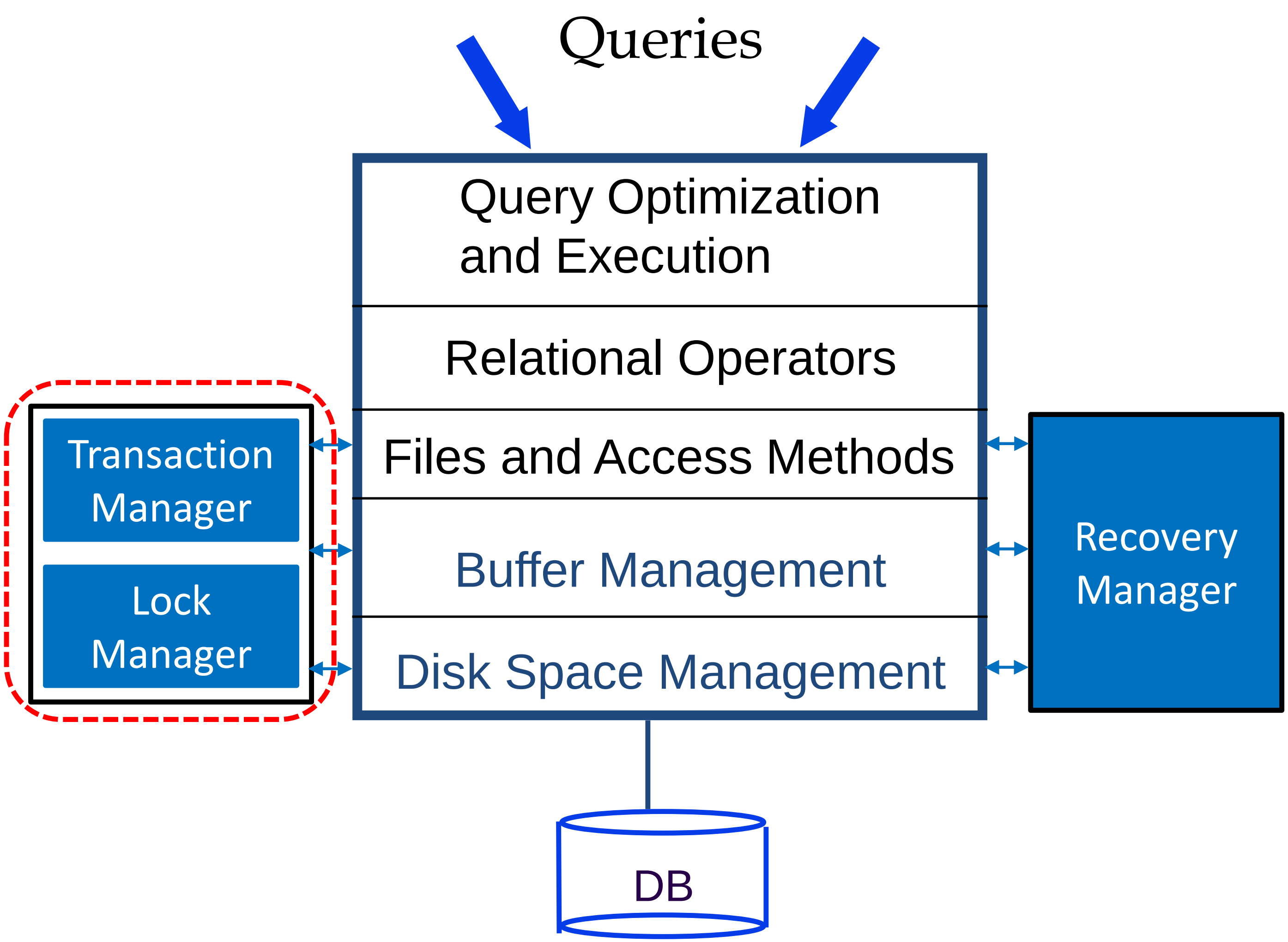
Today…

- Last Session:
  - DBMS Internals- Part X
    - Query Optimization (*Cont'd*)

- Today's Session:
  - DBMS Internals- Part XI
    - Transaction Management

- Announcements:
  - The grades of Quiz II are out
  - PS4 is due today by midnight
  - PS5 will be posted on Tuesday. It is due on Thursday, April 23rd

DBMS Layers



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Outline

- A Brief Primer on Transaction Management ✓
- Anomalies Due to Concurrency
- 2PL and Strict 2PL Locking Protocols
- Schedules with Aborted Transactions

Concurrent Execution of Programs

- A database is typically *shared* by a large number of users

- DBMSs *schedule* users' programs *concurrently*
  - While one user program is waiting for an I/O access to be satisfied, the CPU can process another program
    - Better system throughput

  - Interleaved execution of a short program with a long program allows the short program to complete quickly
    - Better response time
    - Better for fairness reasons

Transactions

- *Any <u>one</u> execution* of a user program in a DBMS is denoted as a transaction
  - Executing the same program several times will generate several transactions

- A transaction is the basic unit of change as seen by a DBMS
  - E.g., Transfer $100 from account A to account B

- A transaction may carry out many operations on data, but DBMSs are only concerned about *reads* and *writes*

- Thus, in essence a transaction becomes *a sequence of reads and writes*

Transactions (*Cont'd*)

- In addition to reading and writing, a transaction must specify as its final action:
  - Either *Commit* (i.e., complete successfully)
  - Or *Abort* (i.e., terminate and *undo* actions)

- We make two assumptions:
  - Transactions interact only via database reads and writes (i.e., no *message passing*)
  - A database is a fixed collection of *independent* objects (A, B, C, etc.)

Schedules

- A schedule is a list of actions (i.e., read, write, abort, and/or commit) from a *set* of transactions

- The *order* in which two actions of a transaction ***T*** appear in a schedule must be the same as they appear in ***T*** itself

- Assume **T1** = [R(A), W(A)] and **T2** = [R(B), W(B), R(C), W(C)]

T1	**T2**
R(A)	R(B)
W(A)	W(B)
	R(C)
	W(C)

✓

T1	**T2**
R(A)	
W(A)	
	R(B)
	W(B)
	R(C)
	W(C)

✓

T1	**T2**
R(A)	R(C)
W(A)	W(C)
	R(B)
	W(B)

✗

Serial Schedules

- A complete schedule must contain all the actions of every transaction that appears on it

- If the actions of different transactions are ***not interleaved***, the schedule is called a serial schedule

T1	T2
R(A)	
W(A)	
Commit	
	R(A)
	W(A)
	R(C)
	W(C)
	Commit

A Serial Schedule

T1	T2
	R(B)
	W(B)
R(A)	
W(A)	
Commit	
	R(C)
	W(C)
	Commit

A Non-Serial Schedule

Serializable Schedules

- Two schedules are said to be *equivalent* if for any database state, the effect of executing the 1st schedule is identical to the effect of executing the 2nd schedule

- A serializable schedule is a schedule that is equivalent to a serial schedule

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
R(B)	
W(B)	
	R(B)
	W(B)
	Commit
Commit	

A *Serializable* Schedule

Equivalent →

T1	T2
R(A)	
W(A)	
R(B)	
W(B)	
Commit	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit

A *Serial* Schedule

← Equivalent

T1	T2
	R(A)
	W(A)
R(A)	
	R(B)
	W(B)
W(A)	
R(B)	
W(B)	
	Commit
Commit	

Another *Serializable* Schedule

Examples

- Assume transactions T1 and T2 as follows:

T1:	BEGIN	A=A-100,	B=B +100	END
T2:	BEGIN	A=1.06*A,	B=1.06*B	END

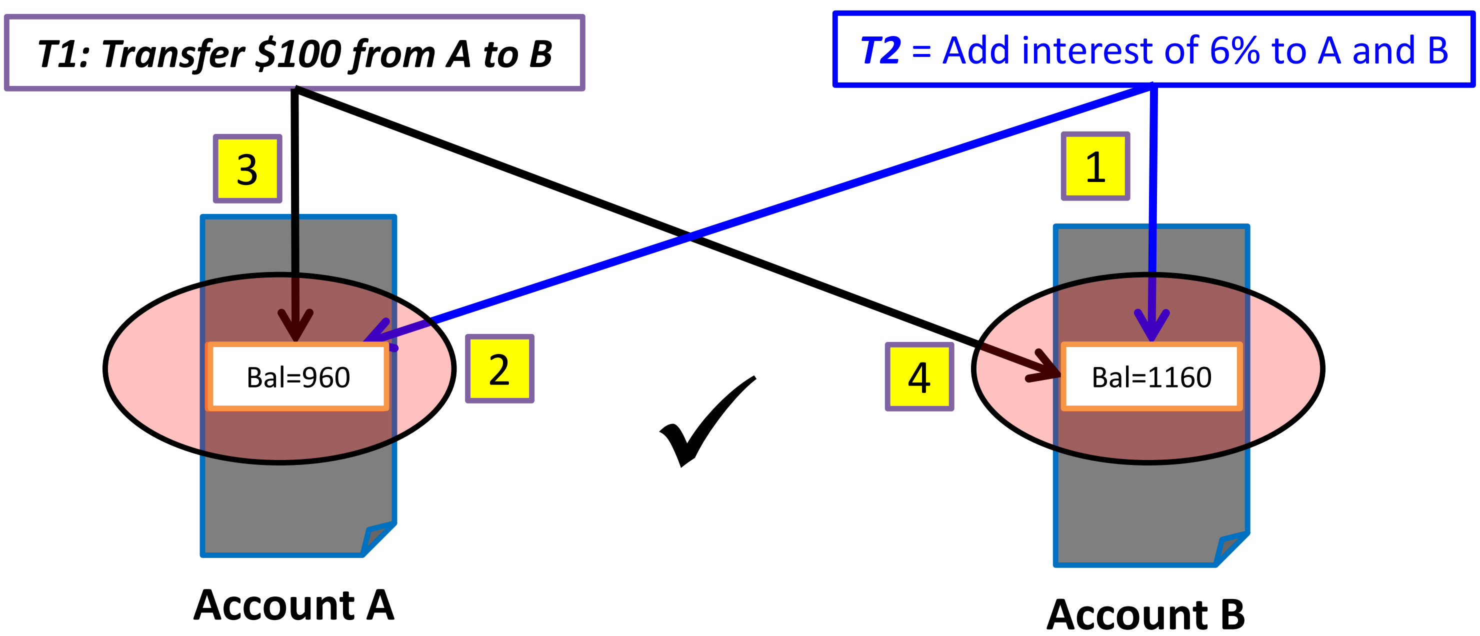
- T1 can be thought of as transferring $100 from A's account to B's account

- T2 can be thought of as crediting accounts A and B with a 6% interest payment

Examples: A *Serial* Schedule

- Assume transactions T1 and T2 as follows:

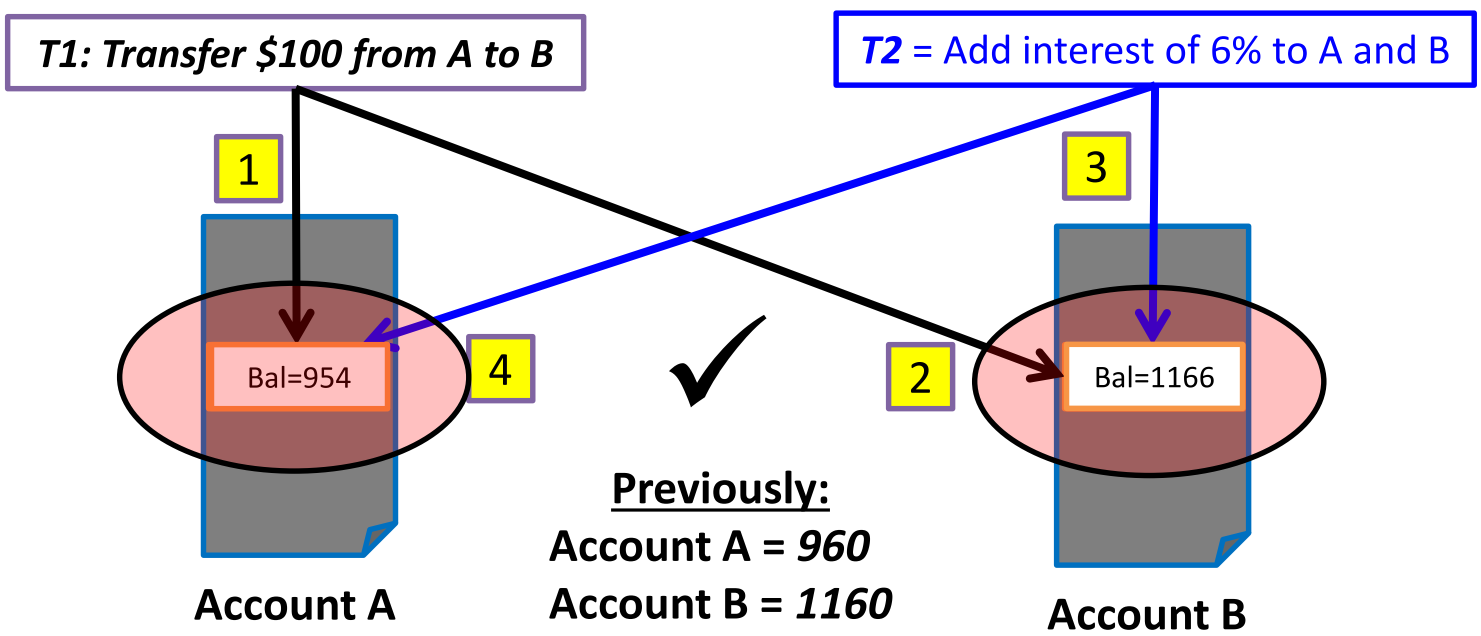
T1:	BEGIN	A=A-100,	B=B +100	END
T2:	BEGIN	A=1.06*A,	B=1.06*B	END



Examples: Another *Serial* Schedule

- Assume transactions T1 and T2 as follows:

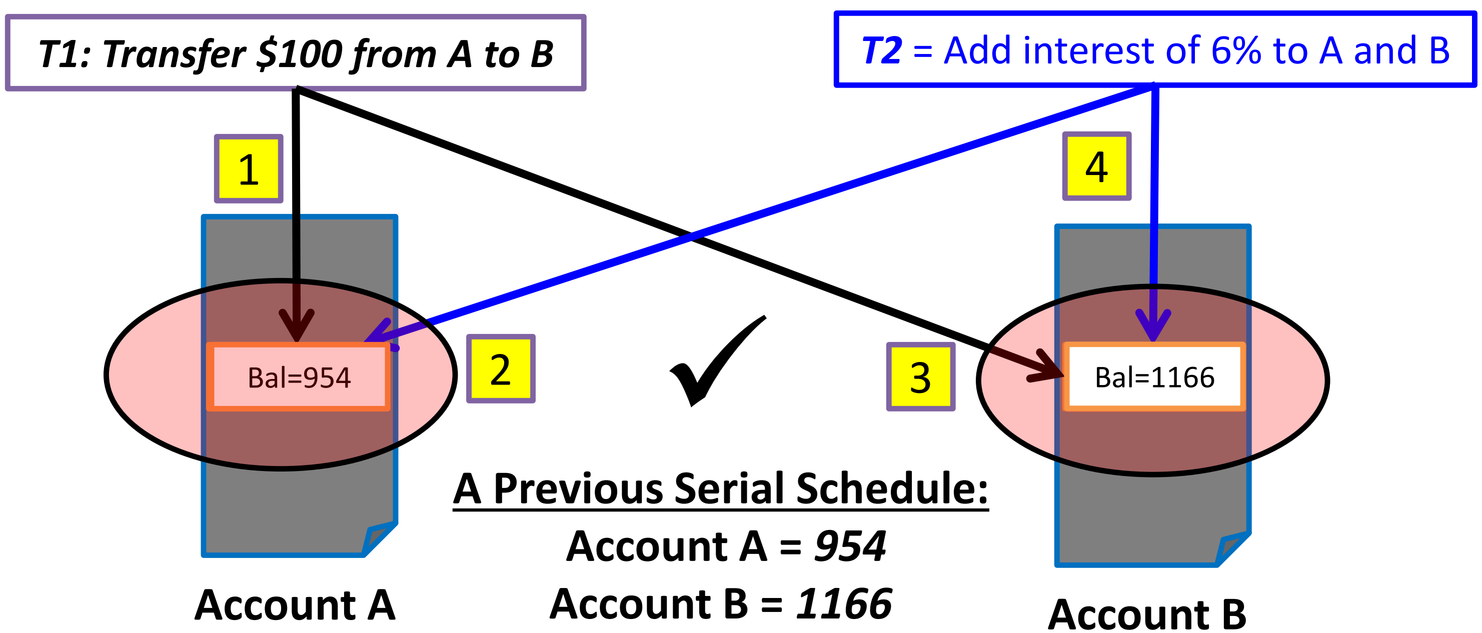
T1:	BEGIN	A=A-100,	B=B +100	END
T2:	BEGIN	A=1.06*A,	B=1.06*B	END



Examples: A *Serializable* Schedule

- Assume transactions T1 and T2 as follows:

T1:	BEGIN	A=A-100,	B=B +100	END
T2:	BEGIN	A=1.06*A,	B=1.06*B	END



Comments

- There is no guarantee that T1 will execute before T2 or vice-versa, if both are submitted together
- However, the net effect *must* be equivalent to these two transactions running *serially* in some order
- Executing transactions serially in different orders may produce different results, but they are all acceptable!
- The DBMS makes no guarantees about which result will be the outcome of an interleaved execution

Outline

- A Brief Primer on Transaction Management
- Anomalies Due to Concurrency ✓
- 2PL and Strict 2PL Locking Protocols
- Schedules with Aborted Transactions

Anomalies

- Interleaving actions of different transactions can leave the database in an inconsistent state

- Two actions on the same data object are said to ***conflict*** if at least one of them is a write

- There are 3 anomalies that can arise upon interleaving actions of different transactions (say, T1 and T2):
  - Write-Read (WR) Conflict: T2 reads a data object previously written by T1
  - Read-Write (RW) Conflict: T2 writes a data object previously read by T1
  - Write-Write (WW) Conflict: T2 writes a data object previously written by T1

Reading Uncommitted Data: WR Conflicts

- WR conflicts arise when transaction T2 reads a data object A that has been modified by another transaction T1, *which has not yet committed*
  - Such a read is called a dirty read

- Assume T1 and T2 such that:
  - T1 transfers $100 from A's account to B's account
  - T2 credits accounts A and B with a 6% interest payment

T1:	BEGIN	A=A-100,	B=B +100	END
T2:	BEGIN	A=1.06*A,	B=1.06*B	END

Reading Uncommitted Data: WR Conflicts

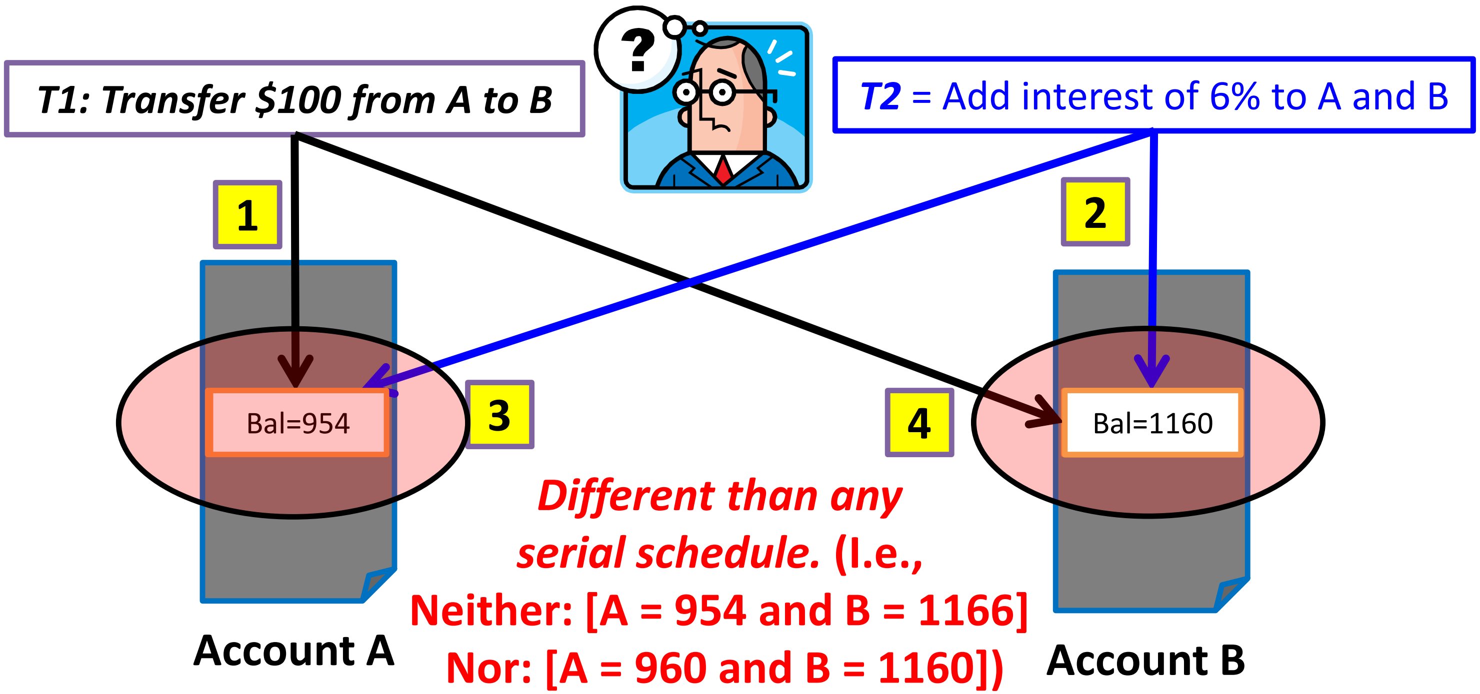
- Suppose that T1 and T2 actions are *interleaved* as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B
  - T1 credits $100 to account B

T1: Transfer $100 from A to B

T2 = Add interest of 6% to A and B

Reading Uncommitted Data: WR Conflicts

- Suppose that T1 and T2 actions are *interleaved* as follows:
  - T1 deducts $100 from account A **1**
  - T2 adds 6% interest to accounts A and B **2 and 3**
  - T1 credits $100 to account B **4**



Reading Uncommitted Data: WR Conflicts

- T1 and T2 can be represented by the following schedule:

T1	**T2**
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
R(B)	
W(B)	
Commit	

The value of A written by T1 is read by T2 before T1 has completed all its changes!

Why is this a problem?

Reading Uncommitted Data: WR Conflicts

- T1 and T2 can be represented by the following schedule:

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
R(B)	
W(B)	
Commit	

The value of A written by T1 is read by T2 before T1 has completed all its changes!

Why is this a problem?

- T1 may write some value into A that makes the database inconsistent
- As long as T1 overwrites this value with a 'correct' value of A before committing, no harm is done if T1 and T2 are run in some serial order (this is because T2 would then not see the <u>temporary</u> inconsistency)

Reading Uncommitted Data: WR Conflicts

- T1 and T2 can be represented by the following schedule:

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
R(B)	
W(B)	
Commit	

The value of A written by T1 is read by T2 before T1 has completed all its changes!

Why is this a problem?

Note that although a transaction must leave a database in a consistent state *after* it completes, it is not required to keep the database consistent while it is still in progress!

Unrepeatable Reads: RW Conflicts

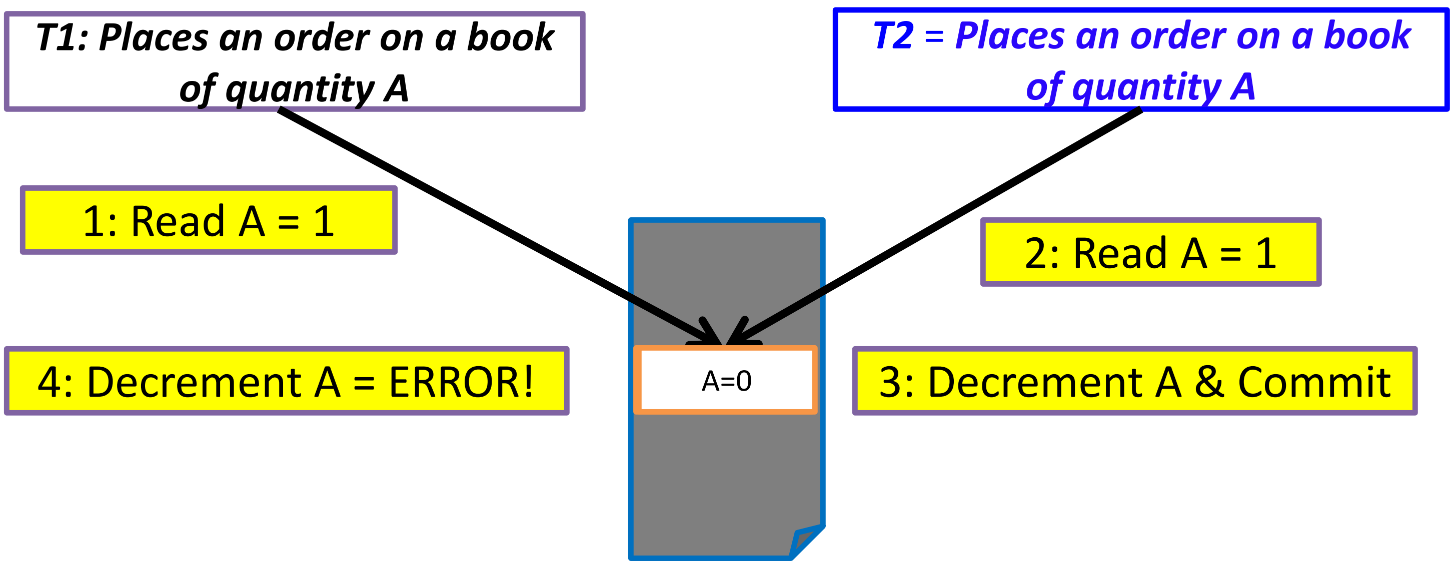
- RW conflicts arise when transaction T2 writes a data object A that has been read by another transaction T1, *while T1 is still in progress*

- If T1 tries to read A again, it will get a different result!
  - Such a read is called an unrepeatable read

- Assume A is the number of available copies for a book
  - A transaction that places an order on the book reads A, checks that A > 0 and decrements A
  - Assume two transactions, T1 and T2

Unrepeatable Reads: RW Conflicts

- Suppose that T1 and T2 actions are interleaved as follows:
  - T1 reads A
  - T2 reads A, decrements A and commit
  - T1 tries to decrement A



This situation will never arise in a serial execution of T1 and T2; T2 would read A and see 0 and therefore not proceed with placing an order!

Overwriting Uncommitted Data: WW Conflicts

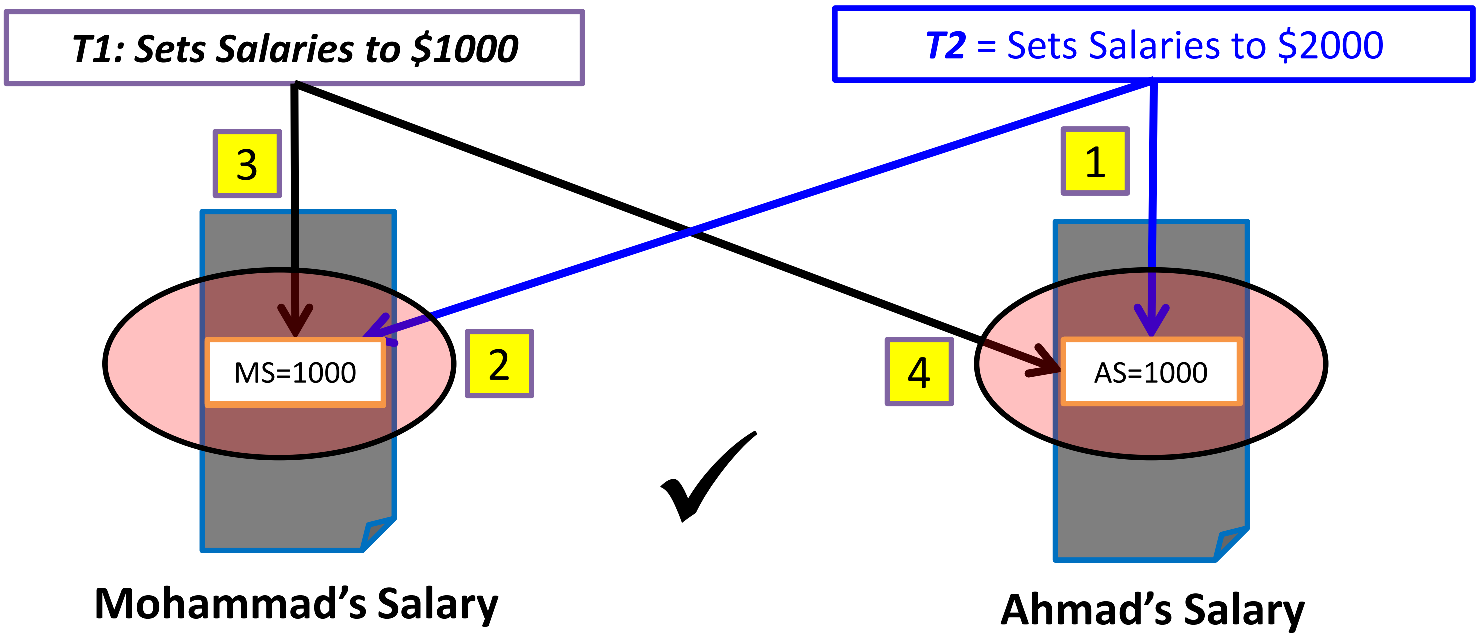
- WW conflicts arise when transaction T2 writes a data object A that has been written by another transaction T1, *while T1 is still in progress*

- Suppose that Mohammad and Ahmad are two employees and their salaries <u>*must be kept equal*</u>

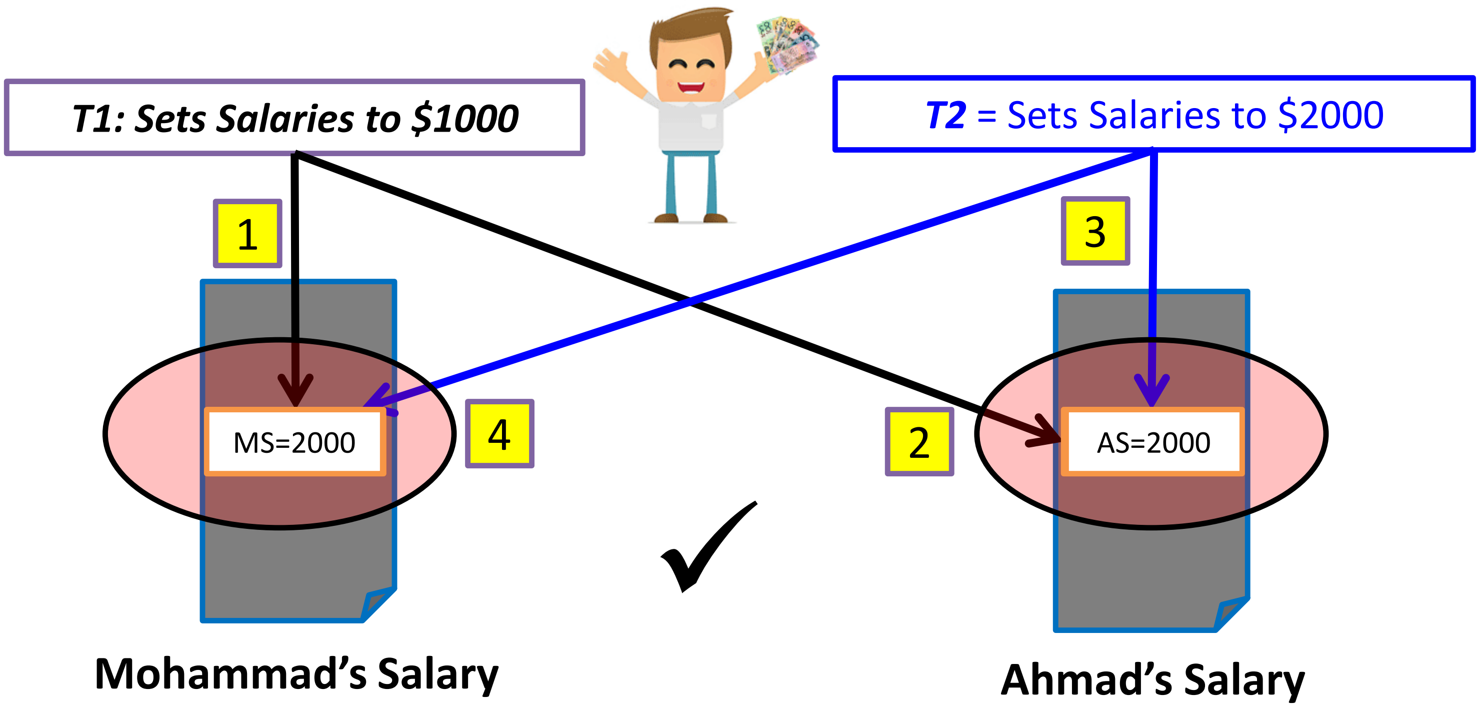
- Assume T1 sets Mohammad's and Ahmad's salaries to $1000

- Assume T2 sets Mohammad's and Ahmad's salaries to $2000

Overwriting Uncommitted Data: WW Conflicts



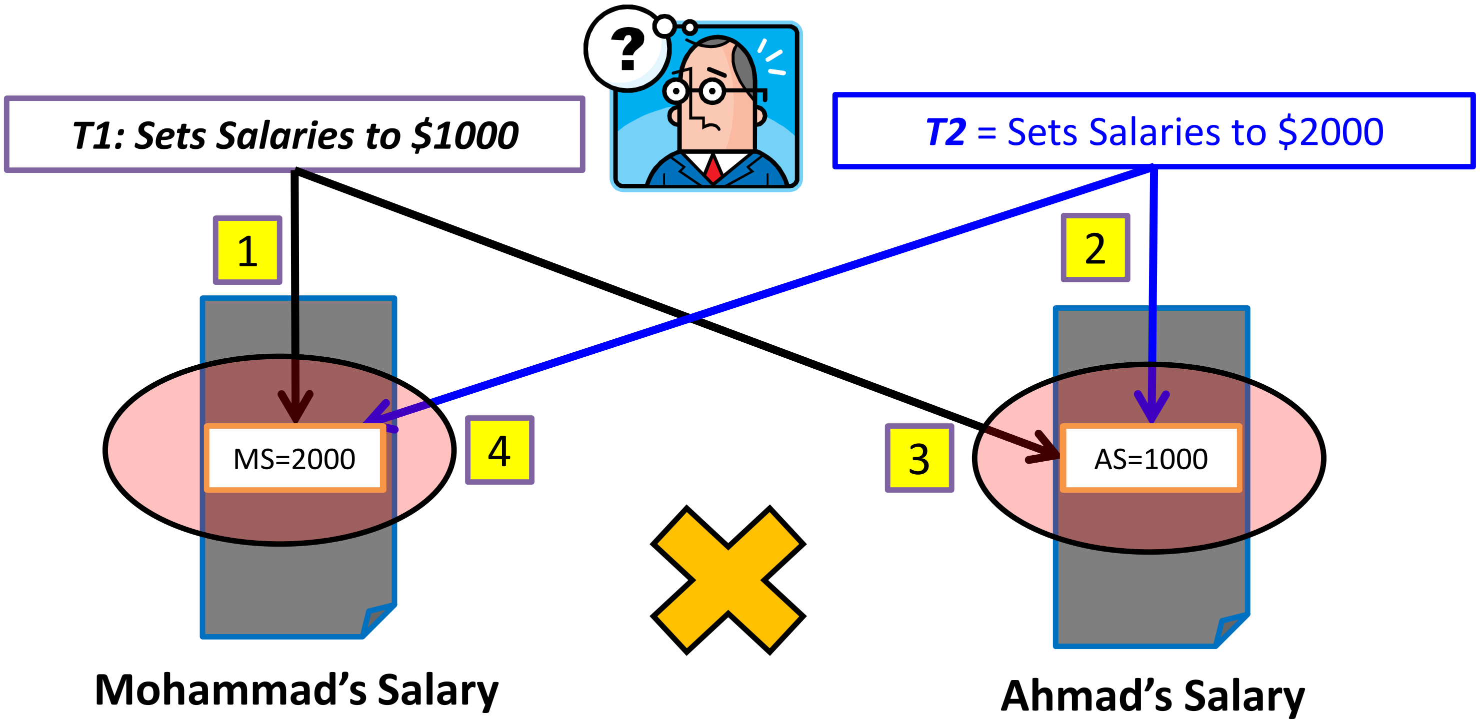
Overwriting Uncommitted Data: WW Conflicts



Either serial schedule is <u>acceptable</u> from a *consistency standpoint* (although Mohammad and Ahmad may prefer a higher salary!)

Neither T1 nor T2 reads a salary value before writing it- such a write is called a ***blind write!***

Overwriting Uncommitted Data: WW Conflicts



The problem is that we have a ***lost update***. In particular, T2 overwrote Mohammad's Salary as set by T1 (this will never happen with a serializable schedule!)

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Locking Protocols

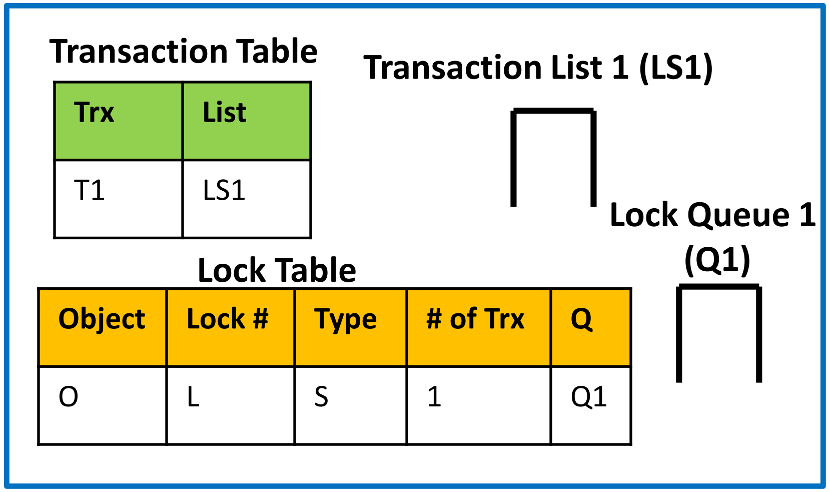
- WR, RW and WW anomalies can be avoided using a *locking protocol*

- A locking protocol:
  - Is *a set of rules* to be followed by each transaction to ensure that only serializable schedules are allowed (*extended later*)
  - Associates a *lock* with each database object, which could be of different types (e.g., *shared* or *exclusive*)
  - *Grants and denies locks* to transactions according to the specified rules

- The part of the DBMS that keeps track of locks is called the *lock manager*

Lock Managers

- Usually, a lock manager in a DBMS maintains three types of data structures:
  - A queue, ***Q***, for each lock, ***L***, to hold its pending requests
  - A lock table, which keeps for each ***L*** associated with each object, ***O***, a record ***R*** that contains:
    - The type of ***L*** (e.g., shared or exclusive)
    - The number of transactions currently holding ***L*** on ***O***
    - A pointer to ***Q***
  - A transaction table, which maintains for each transaction, ***T***, a pointer to a list of locks held by ***T***



Transaction Table

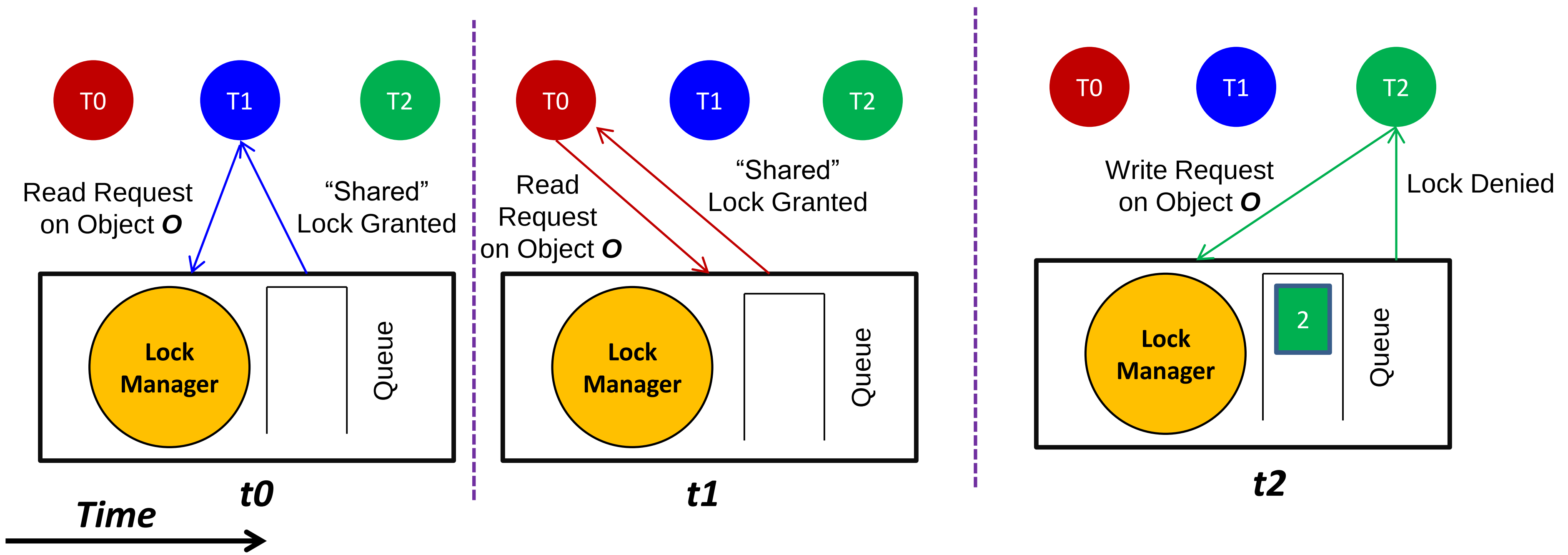
Trx	List
T1	LS1

Lock Table

Object	Lock #	Type	# of Trx	Q
O	L	S	1	Q1

Two-Phase Locking

- A widely used locking protocol, called *Two-Phase Locking* (*2PL*), has two rules:
  - Rule 1: if a transaction ***T*** wants to read (or write) an object ***O***, it first requests the lock manager for a shared (or exclusive) lock on ***O***



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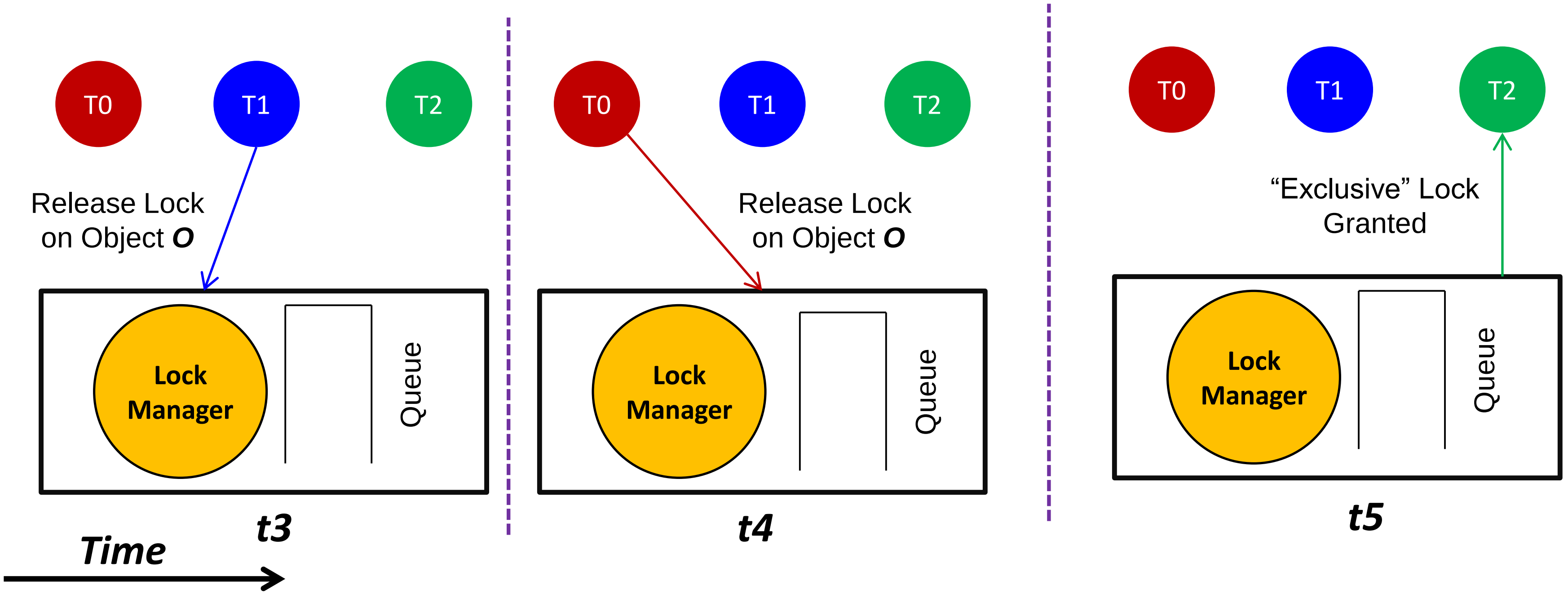

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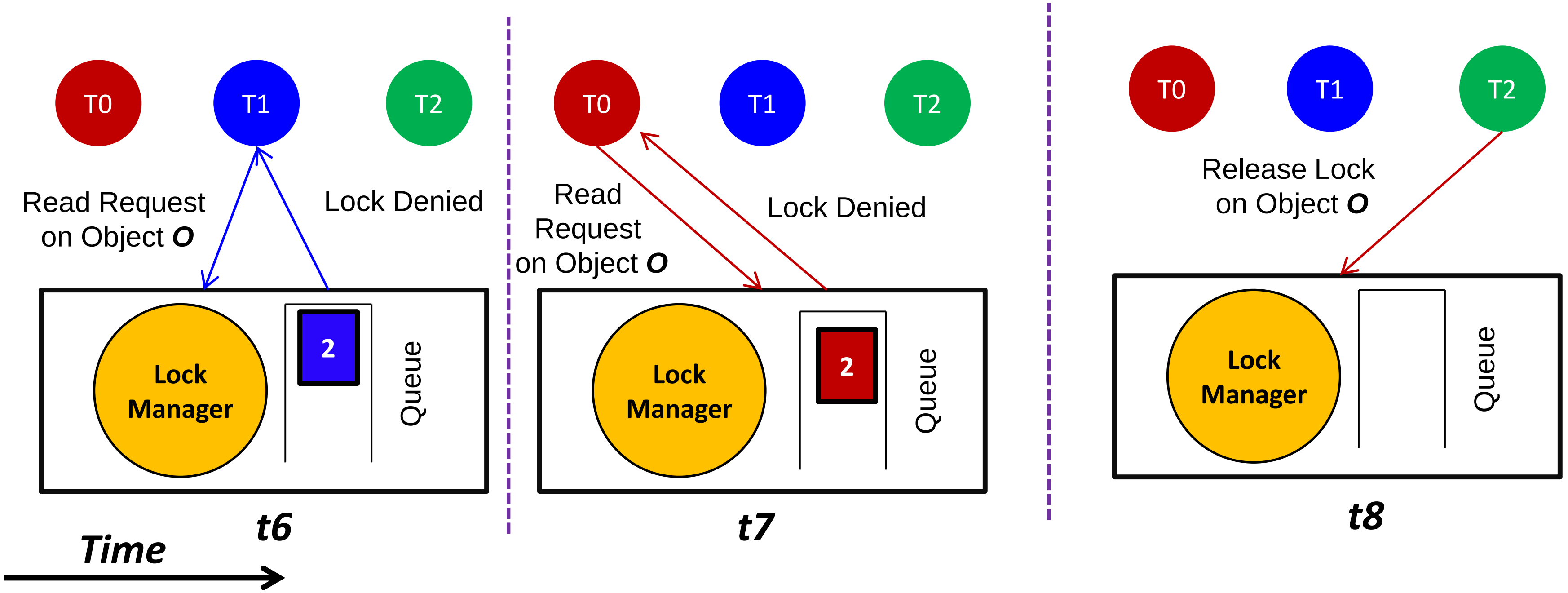

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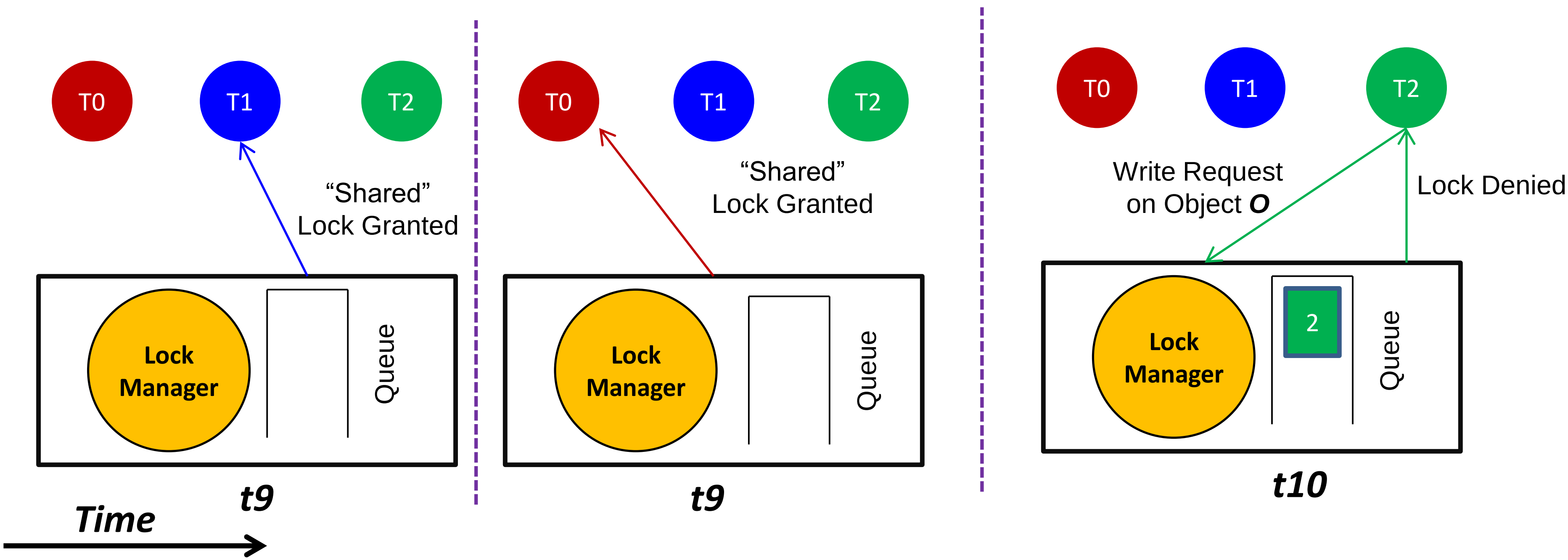
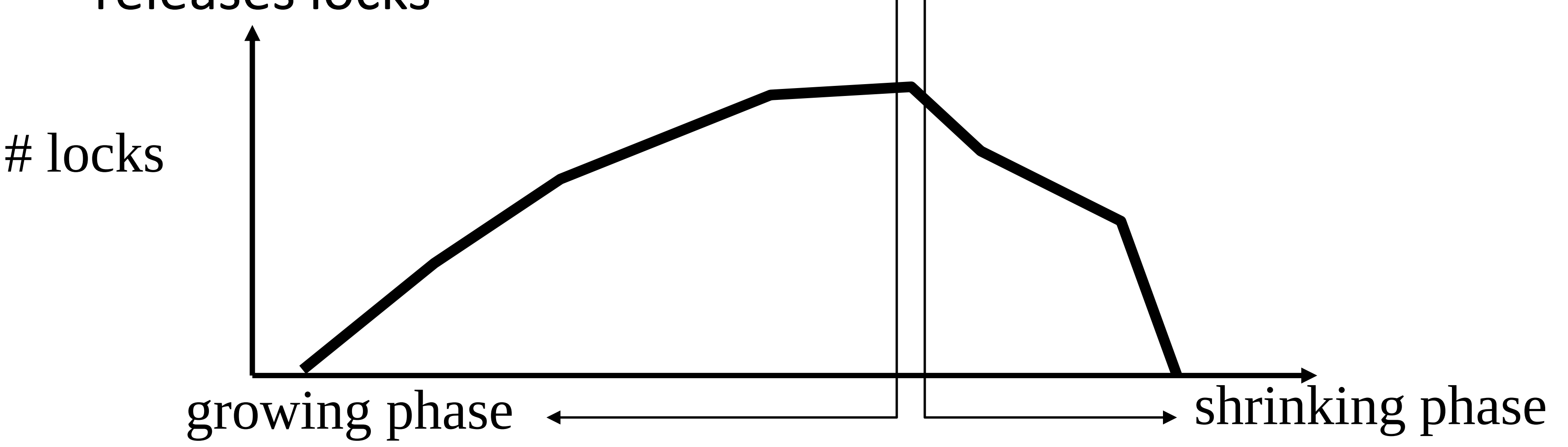


Two-Phase Locking

- A widely used locking protocol, called *Two-Phase Locking* (*2PL*), has two rules:
  - Rule 2: ***T*** can release locks before it *commits* or *aborts*, and cannot request additional locks once it releases <u>*any*</u> lock

- Thus, every transaction has a "growing" phase in which it acquires locks, followed by a "shrinking" phase in which it releases locks



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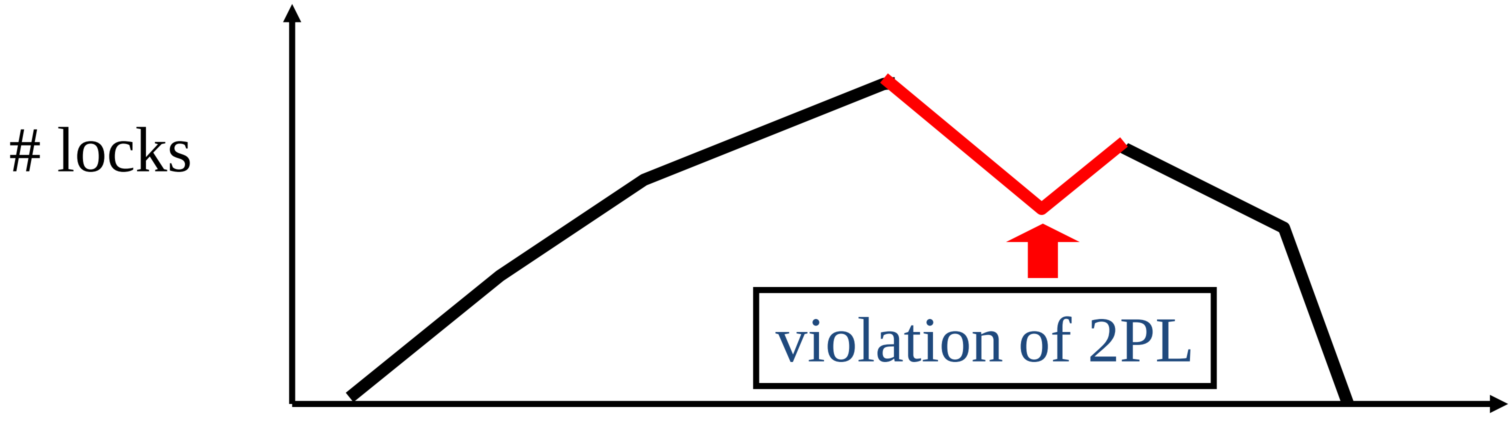

Resolving RW Conflicts Using 2PL

- Suppose that T1 and T2 actions are interleaved as follows:
  - T1 reads A
  - T2 reads A, decrements A and commit
  - T1 tries to decrement A
- T1 and T2 can be represented by the following schedule:

T1	T2
R(A)	
	R(A)
	W(A)
	Commit
W(A)	
Commit	

Exposes RW Anomaly

T1	T2
EXCLUSIVE(A)	
R(A)	
	Lock(A)
	↑ **Wait** ↓
W(A)	
Commit	
	EXCLUSIVE(A)
	R(A)
	W(A)
	Commit

RW Conflict Resolved!

Resolving RW Conflicts Using 2PL

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R(A)	
	R(A)
	W(A)
	Commit
W(A)	
Commit	

Exposes RW Anomaly

T1	T2
EXCLUSIVE(A)	
R(A)	
	Lock(A)
W(A)	↑ **Wait** ↓
Commit	
	EXCLUSIVE(A)
	R(A)
	W(A)
	Commit

But, it can limit parallelism!

Resolving WW Conflicts Using 2PL

- Suppose that T1 and T2 actions are interleaved as follows:
  - T1 sets Mohammad’s Salary to $1000
  - T2 sets Ahmad’s Salary to $2000
  - T1 sets Ahmad’s Salary to $1000
  - T2 sets Mohammad’s Salary to $2000
- T1 and T2 can be represented by the following schedule:

T1	**T2**
W(MS)	
	W(AS)
W(AS)	
Commit	W(MS)
	Commit

Exposes WW Anomaly
(*assuming, MS & AS must be kept equal*)

T1	**T2**
EXCLUSIVE(MS)	
EXCLUSIVE(AS)	
W(MS)	**Lock**(AS)
W(AS)	↑
Commit	**Wait**
	↓
	EXCLUSIVE(AS)
	EXCLUSIVE(MS)
	W(AS)
	W(MS)
	Commit

WW Conflict Resolved!

Resolving WW Conflicts Using 2PL

- Suppose that T1 and T2 actions are interleaved as follows:
  - T1 sets Mohammad's Salary to $1000
  - T2 sets Ahmad's Salary to $2000
  - T1 sets Ahmad's Salary to $1000
  - T2 sets Mohammad's Salary to $2000
- T1 and T2 can be represented by the following schedule:

T1	T2
W(MS)	
	W(AS)
W(AS)	
Commit	W(MS)
	Commit

Exposes WW Anomaly
(*assuming, MS & AS must be kept equal*)

T1	T2
EXCLUSIVE(MS)	
W(MS)	
	EXCLUSIVE(AS)
Lock(AS)	
	W(AS)
↑ **Wait**	**Lock**(MS)
	↑ **Wait**

Deadlock!

Resolving WR Conflicts

- Suppose that T1 and T2 actions are *interleaved* as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B
  - T1 credits $100 to account B

- T1 and T2 can be represented by the following schedule:

T1	**T2**
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
R(B)	
W(B)	
Commit	

Exposes WR Anomaly

T1	**T2**
EXCLUSIVE(A)	
EXCLUSIVE(B)	**Lock**(A)
R(A)	**Lock**(B)
W(A)	
R(B)	**Wait**
W(B)	
Commit	
	EXCLUSIVE(A)
	EXCLUSIVE(B)
	R(A)
	W(A)
	R(B)
	W(B)
	Commit

WR Conflict Resolved!

Resolving WR Conflicts

- Suppose that T1 and T2 actions are *interleaved* as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B
  - T1 credits $100 to account B

- T1 and T2 can be represented by the following schedule:

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
R(B)	
W(B)	
Commit	

Exposes WR Anomaly

T1	T2
EXCLUSIVE(A)	
EXCLUSIVE(B)	**Lock**(A)
R(A)	**Lock**(B)
W(A)	**Wait**
RELEASE(A)	↓
R(B)	**EXCLUSIVE**(A)
W(B)	R(A)
Commit	W(A)
	EXCLUSIVE(B)
	R(B)
	W(B)
	Commit

WR Conflict is ***NOT*** Resolved!

How can we solve this?

Strict Two-Phase Locking

- WR conflicts (as well as RW & WW) can be solved by making 2PL *stricter*
- In particular, *Rule 2* in 2PL can be modified as follows:
  - Rule 2: locks of a transaction ***T*** can only be released after ***T*** completes (i.e., commits or aborts)
- This version of 2PL is called *Strict* Two-Phase Locking

Resolving WR Conflicts: *Revisit*

- Suppose that T1 and T2 actions are *interleaved* as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B
  - T1 credits $100 to account B

- T1 and T2 can be represented by the following schedule:

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
R(B)	
W(B)	
Commit	

Exposes WR Anomaly

T1	T2
EXCLUSIVE(A)	
EXCLUSIVE(B)	**Lock**(A)
R(A)	**Lock**(B)
W(A)	**Wait**
RELEASE(A)	↓
R(B)	**EXCLUSIVE**(A)
W(B)	R(A)
Commit	W(A)
	EXCLUSIVE(B)
	R(B)
	W(B)
	Commit

Not allowed with *strict* 2PL

Resolving WR Conflicts: *Revisit*

- Suppose that T1 and T2 actions are *interleaved* as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B
  - T1 credits $100 to account B

- T1 and T2 can be represented by the following schedule:

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
R(B)	
W(B)	
Commit	

Exposes WR Anomaly

T1	T2
EXCLUSIVE(A)	
EXCLUSIVE(B)	
R(A)	Lock(A)
W(A)	Lock(B)
R(B)	↑ Wait ↓
W(B)	
Commit	
	EXCLUSIVE(A)
	EXCLUSIVE(B)
	R(A)
	W(A)
	R(B)
	W(B)
	Commit

WR Conflict is Resolved!

But, parallelism is limited more!

2PL vs. Strict 2PL

- Two-Phase Locking (2PL):
  - Limits concurrency
  - May lead to deadlocks
  - May have ‘dirty reads’
- Strict 2PL:
  - Limits concurrency more (*but*, actions of different transactions can still be interleaved)
  - May still lead to deadlocks
  - Avoids ‘dirty reads’

T1	T2
SHARED(A)	
R(A)	
	SHARED(A)
	R(A)
	EXECLUSIVE(B)
	R(B)
EXCLUSIVE(C)	W(B)
R(C)	Commit
W(C)	
Commit	

A Schedule with *Strict 2PL* and *Interleaved Actions*

Performance of Locking

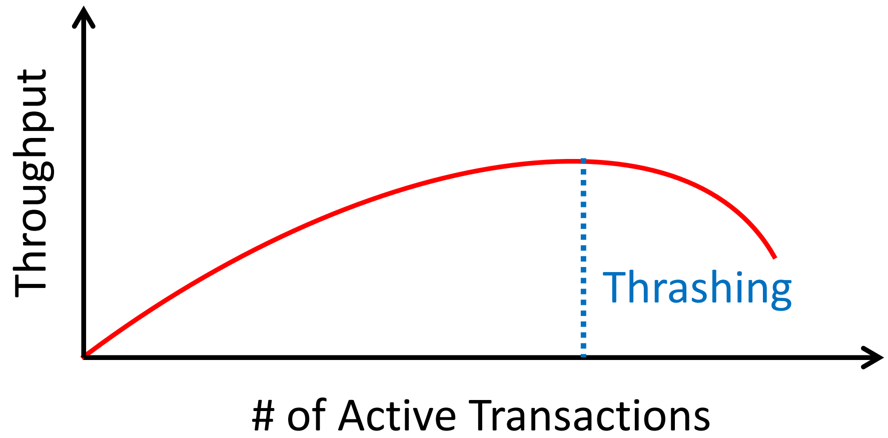
- Locking comes with delays mainly from *blocking*

- Usually, the first few transactions are unlikely to conflict
  - Throughput can rise in proportion to the number of active transactions

- As more transactions are executed concurrently, the likelihood of blocking increases
  - Throughput will increase more slowly with the number of active transactions

- There comes a point when adding another active transaction will actually decrease throughput
  - When the system *thrashes*!

Performance of Locking (*Cont'd*)



- If a database begins to *thrash*, the DBA should reduce the number of active transactions

- Empirically, thrashing is seen to occur when 30% of active transactions are blocked!

Outline

- A Brief Primer on Transaction Management
- Anomalies Due to Concurrency
- 2PL and Strict 2PL Locking Protocols
- Schedules with Aborted Transactions ✓

Schedules with *Aborted* Transactions

- Suppose that T1 and T2 actions are interleaved as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B, and commits
  - T1 is aborted

- T1 and T2 can be represented by the following schedule:

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
Abort	

T2 read a value for A that should have never been there!

How can we deal with the situation, assuming T2 *had not yet committed*?

Schedules with *Aborted* Transactions

- Suppose that T1 and T2 actions are interleaved as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B, and commits
  - T1 is aborted

- T1 and T2 can be represented by the following schedule:

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
Abort	

T2 read a value for A that should have never been there!

We can ***cascade*** the abort of T1 by aborting T2 as well!

This "cascading process" can be *recursively* applied to any transaction that read A written by T1

Schedules with *Aborted* Transactions

- Suppose that T1 and T2 actions are interleaved as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B, and commits
  - T1 is aborted

- T1 and T2 can be represented by the following schedule:

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
Abort	

T2 read a value for A that should have never been there!

How can we deal with the situation, assuming T2 *had actually committed*?

The schedule is indeed *unrecoverable*!

Schedules with *Aborted* Transactions

- Suppose that T1 and T2 actions are interleaved as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B, and commits
  - T1 is aborted

- T1 and T2 can be represented by the following schedule:

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
Abort	

T2 read a value for A that should have never been there!

For a schedule to be *recoverable*, transactions should commit only after all transactions whose changes they read commit!

"Recoverable schedules" avoid *cascading aborts*!

Schedules with *Aborted* Transactions

- Suppose that T1 and T2 actions are interleaved as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B, and commits
  - T1 is aborted

- T1 and T2 can be represented by the following schedule:

T1	**T2**
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
Abort	

T2 read a value for A that should have never been there!

How can we ensure "recoverable schedules"?

By using Strict 2PL!

Schedules with *Aborted* Transactions

- Suppose that T1 and T2 actions are interleaved as follows:
  - T1 deducts $100 from account A
  - T2 adds 6% interest to accounts A and B, and commits
  - T1 is aborted

- T1 and T2 can be represented by the following schedule:

T1	**T2**
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
	Commit
Abort	

T1	**T2**
EXCLUSIVE(A)	
R(A)	
W(A)	**Lock**(A)
	Wait ↓
Abort	
UNDO(T1)	
	EXCLUSIVE(A)
	R(A)
	W(A)
	EXCLUSIVE(B)
	R(B)
	W(B)
	Commit

Cascaded aborts are avoided!

Serializable Schedules: *Redefined*

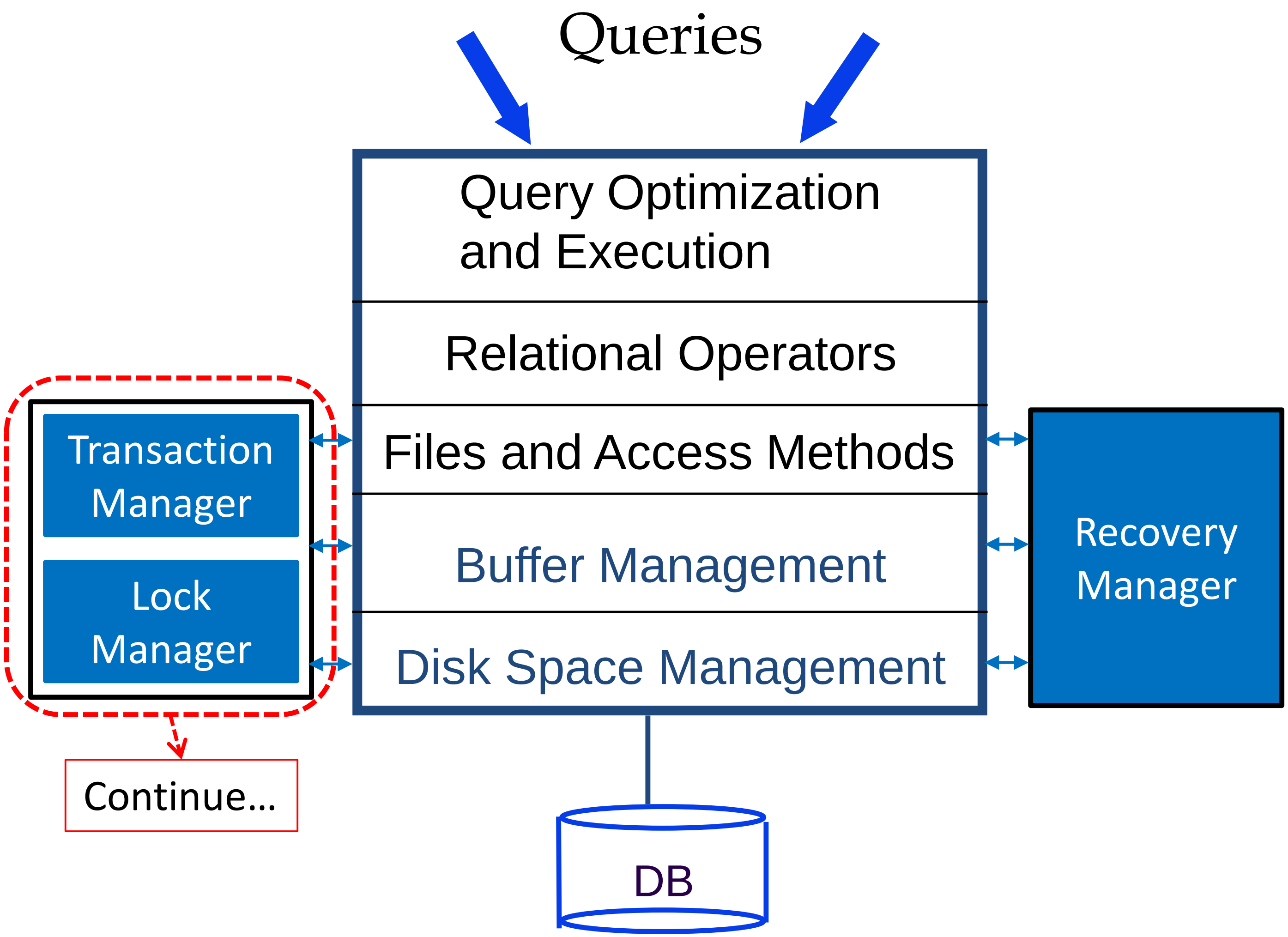
- Two schedules are said to be *equivalent* if for any database state, the effect of executing the 1st schedule is identical to the effect of executing the 2nd schedule

- Previously: a *serializable schedule* is a schedule that is equivalent to a serial schedule

- Now: a *serializable schedule* is a schedule that is equivalent to a serial schedule *over a set of committed transactions*

- This definition captures *serializability* as well as *recoverability*

Next Class



Queries
Query Optimization
and Execution
Relational Operators
Files and Access Methods
Buffer Management
Disk Space Management
Transaction Manager
Lock Manager
Recovery Manager
Continue…
DB