Transactions & Concurrency

CS460 Databases for Data Scientists

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Flashback to First Lecture

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- We already stumbled upon transactions

```
Delete from file: active lecturers

Add to file: retired lecturers
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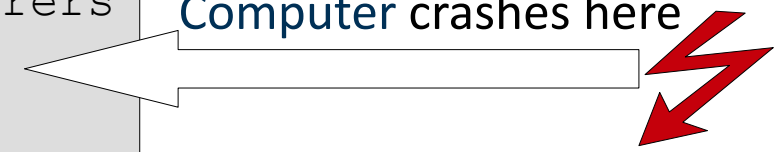

File: **active** lecturers

Prof. Smith
Dr. Stevens
Prof. Miller

File: **retired** lecturers

Dr. Hawkins
Prof. Brown
Prof. Wilson

Flashback to First Lecture

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- ... and we already stumbled upon concurrency


```
Read num_participants from file

If num_participants < limit:
    add participant to file
```

User 1

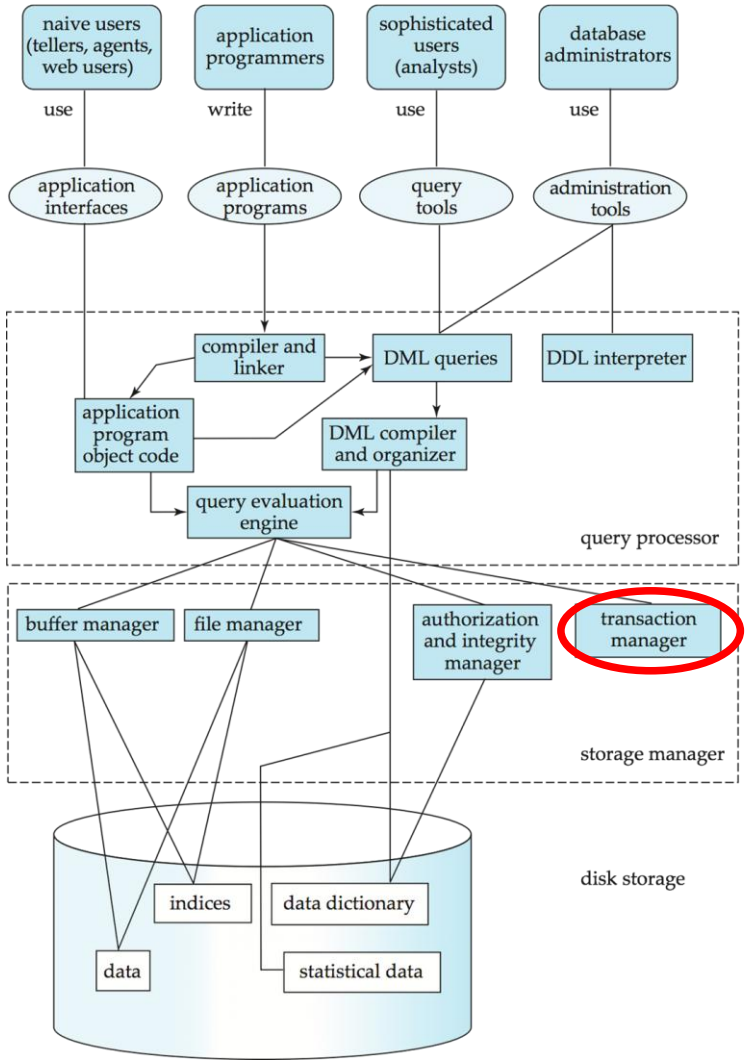
```
Read num_participants from file

If num_participants < limit:
    add participant to file
```

User 2

Flashback to First Lecture

- One of the tasks of a DBMS:
  - handle transactions
  - take care of concurrency



Today's Lecture

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- Transactions
- Schedules
  - Serializability
  - Recoverability
- Protocols for Concurrent Execution
  - Lock-based protocols
    - Two-Phase Locking Protocol
    - Deadlocks
  - Timestamp-Based Protocols
  - Validation-Based Protocols

Concept of a Transaction

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- A **transaction** is a **unit** of program execution that accesses and possibly updates various data items
- E.g., transaction to transfer $50 from account A to account B:

T_1
read(A) A := A – 50 **write** (A) **read** (B) B := B + 50 **write** (B)

- Two main issues to deal with:
  - Failures of various kinds, such as hardware failures and system crashes
    - Lecture next week
  - Concurrent (=parallel) execution of multiple transactions (today)

Requirements for Transactions

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- **Atomicity requirement**
  - If the transaction fails after writing to account A and before writing to account B, money will be “lost” leading to an inconsistent database state
  - Failure could be due to software or hardware
  - DBMS should ensure that updates of a partially executed transaction are not reflected in the database

Requirements for Transactions

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- **Consistency requirement**
  - The sum of A and B is unchanged by the execution of the transaction
  - In general, consistency requirements include
    - Explicitly specified integrity constraints, e.g., primary keys and foreign keys
    - Implicit integrity constraints
      - e.g., sum of balances of all accounts, minus sum of loan amounts must equal value of cash-in-hand
  - A transaction, when starting to execute, must see a consistent database
  - During transaction execution, the database may be temporarily inconsistent
  - When the transaction completes successfully the database must be consistent
    - Erroneous transaction logic can lead to inconsistency

Requirements for Transactions

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- **Isolation requirement**
  - if between steps 3 and 9, another transaction T2 is allowed to access the partially updated database, it will see an inconsistent database

Step	T_1	T_2
1	**read**(A)	
2	A = A – 50	
3	**write**(A)	
4		**read**(A)
5		**read**(B)
6		print(A+B)
7	**read**(B)	
8	B = B + 50	
9	**write**(B)	

- Isolation can be ensured trivially by running transactions serially
  - i.e., one after the other
  - however, parallel execution is often desired due to performance benefits

Requirements for Transactions

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- **Durability requirement**
  - once the user has been notified that the transaction has completed,
    - i.e., the transfer of the $50 has taken place,
  - the updates to the database by the transaction must persist
    - even if there are software or hardware failures

ACID Properties

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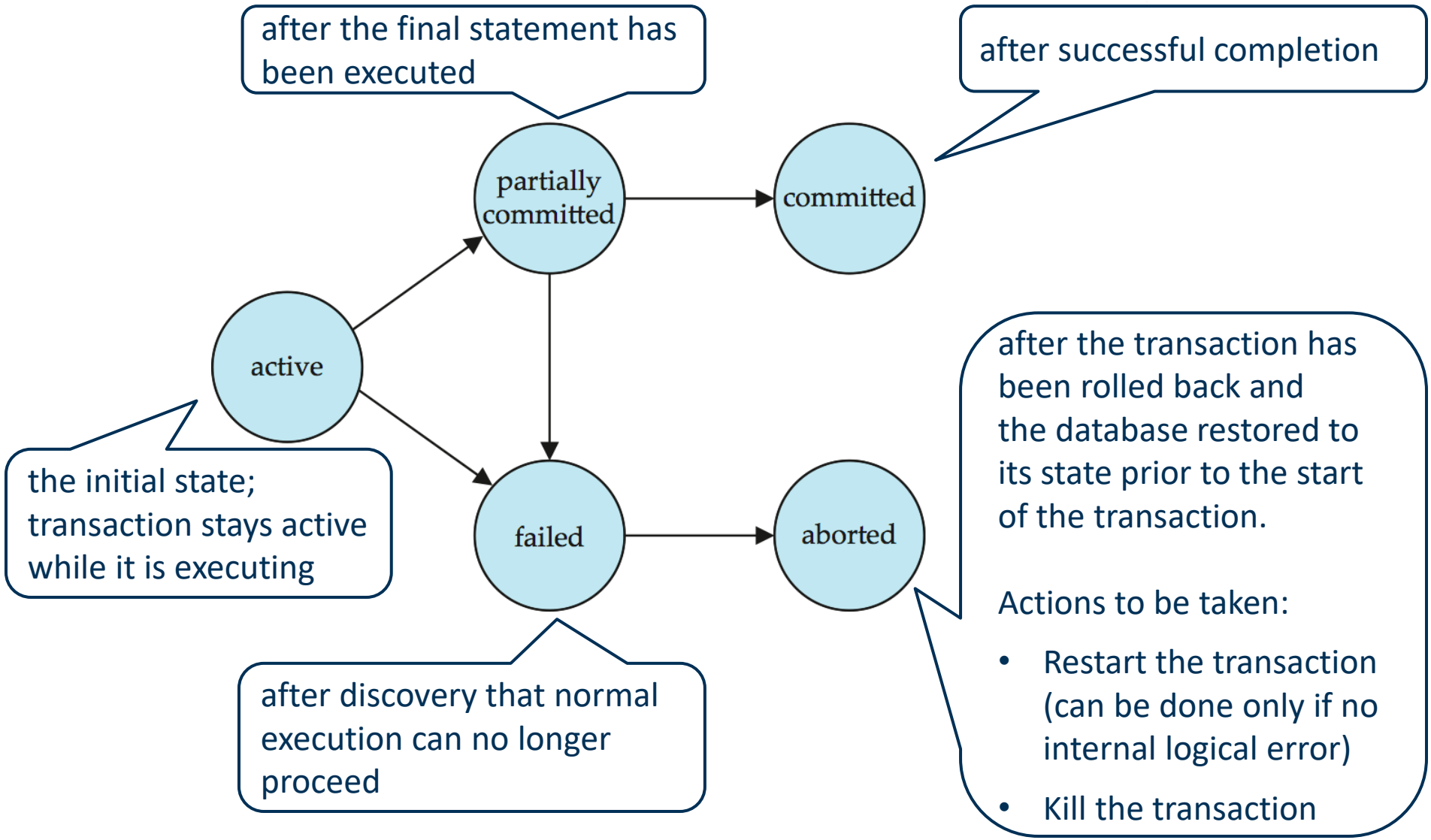
- **Atomicity:** Either all operations of the transaction are properly reflected in the database, or none
- **Consistency:** Execution of a full transaction preserves the consistency of the database
- **Isolation:** Although multiple transactions may execute concurrently, each transaction must be unaware of other concurrently executing transactions
- **Durability:** After a transaction completes successfully, the changes it has made to the database persist, even if there are system failures

Transaction States



Concurrent Execution of Transactions

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- Multiple transactions are allowed to run concurrently in the system
  - **Increased processor and disk utilization**, leading to better transaction throughput
    - e.g., one transaction can be using the CPU while another is reading from or writing to the disk
  - **Reduced average response** time for transactions
    - e.g., short transactions need not wait behind long ones
- **Concurrency control schemes**
  - mechanisms to achieve isolation
  - control the interaction among the concurrent transactions
  - prevent them from destroying the consistency of the database

Schedules

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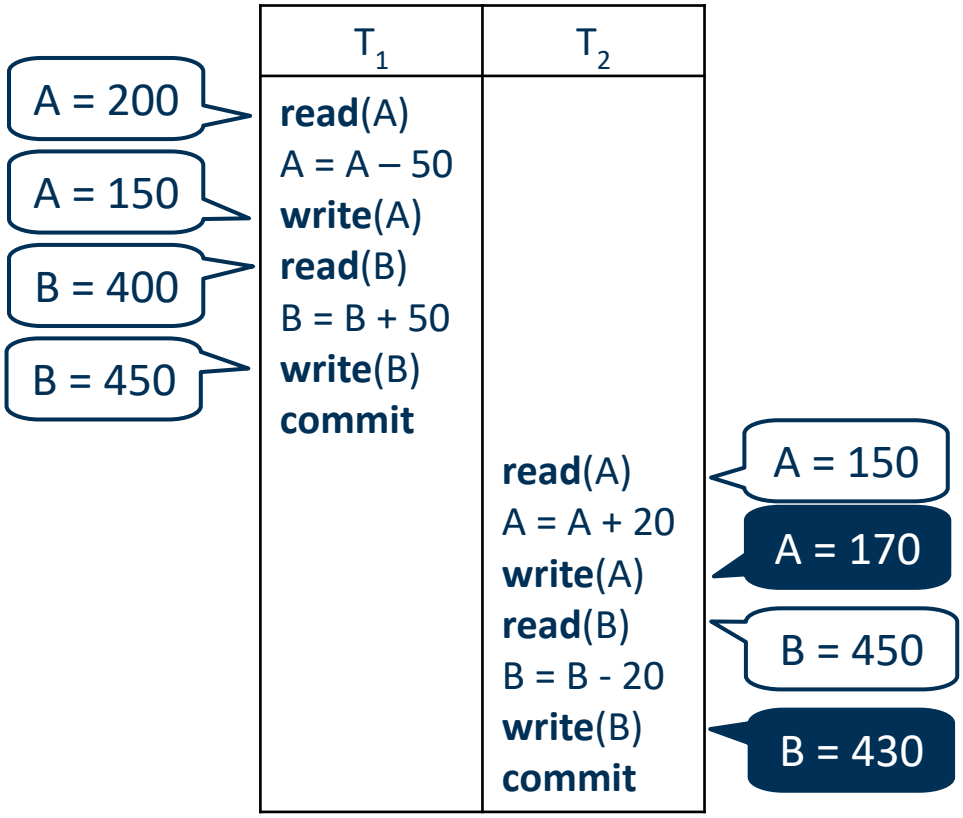
- **Schedule**
  - A sequence of instructions that specifies the chronological order in which instructions of concurrent transactions are executed
  - A schedule for a set of transactions must consist of all instructions of those transactions
  - Must preserve the order in which the instructions appear in each individual transaction
- A transaction that successfully completes its execution will have a **commit** instruction as the last statement
  - By default, a transaction is assumed to execute a COMMIT instruction as its last step
- A transaction that fails to successfully complete its execution will have an **abort** instruction as the last statement

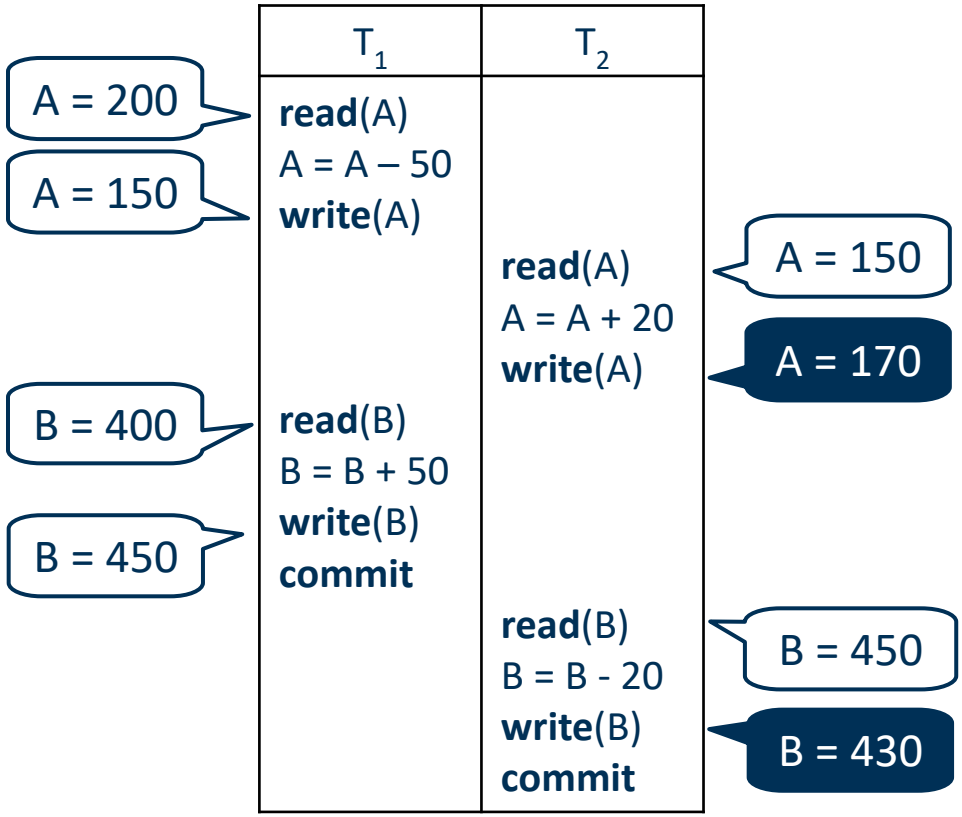
Schedule Example: Serial Schedule

- Let T_1 transfer \$ 50 from *A* to *B*, and T_2 transfer \$ 20 of the balance from *B* to *A*
- Start with e.g.
  - A: \$ 200
  - B: \$ 400
- **Serial** schedule: T_1 is executed as a whole, followed by T_2 :



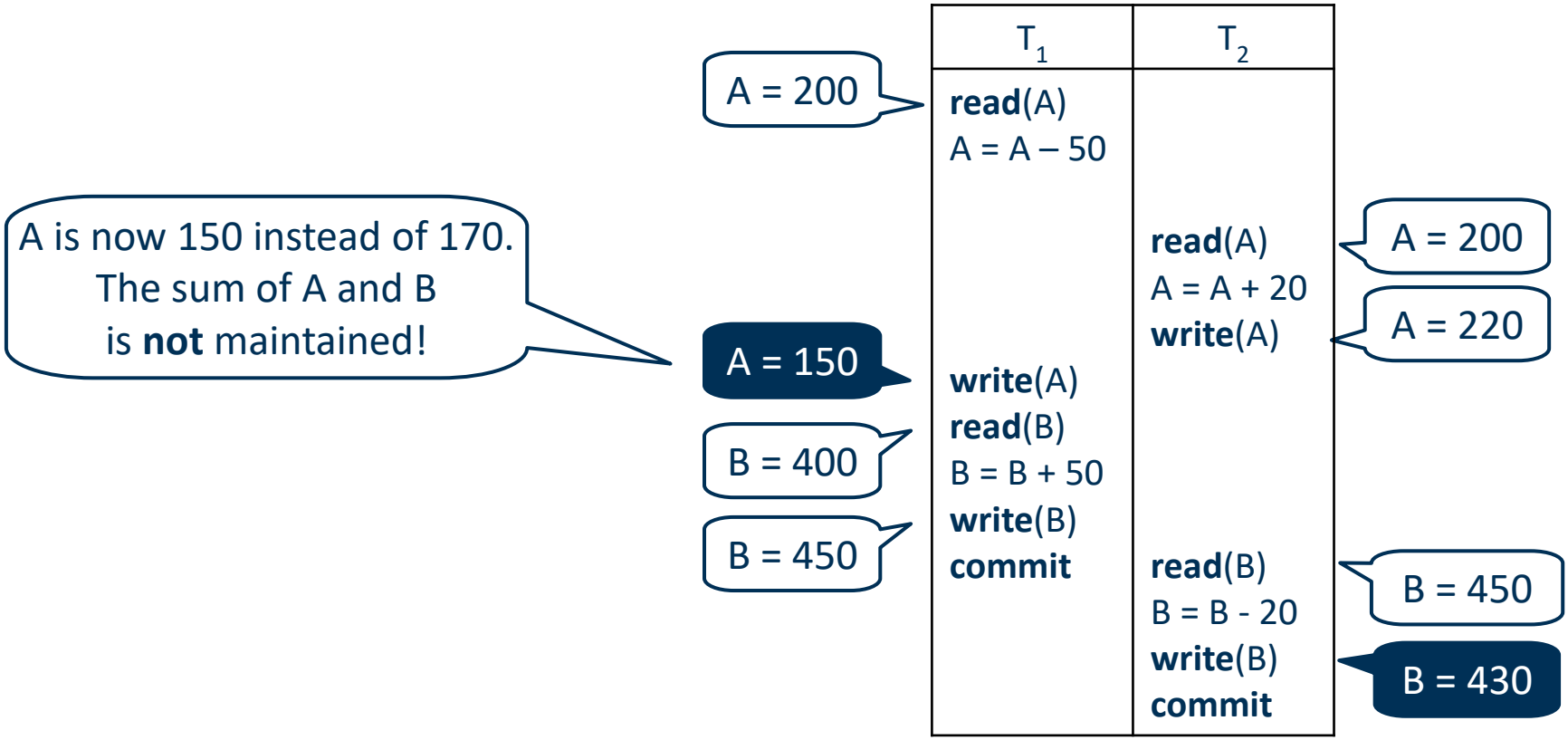
Schedule Example: Intertwined Schedule

- Let T_1 transfer \$ 50 from *A* to *B*, and T_2 transfer \$ 20 of the balance from *B* to *A*
- **Intertwined** schedule: parts of T_1 are executed, interrupted by parts of T_2
  - the sum A+B is maintained



Schedule Examples:
Wrong Schedule

- Let T_1 transfer \$ 50 from *A* to *B*,
  and T_2 transfer \$ 20 of the balance from *B* to *A*



Serializability

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- Basic assumption: transactions preserve database consistency
  - i.e., serial execution of a set of transactions
    also preserves database consistency
- A (possibly concurrent) schedule is **serializable**
  if its outcome is equivalent to a serial schedule
  - We ignore operations other than read and write instructions
  - Transactions may perform arbitrary computations on data in between
  - Our simplified schedules consist of only read and write instructions

Conflicting Transactions

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- When can we swap instructions of transactions?

T_1	T_2
read(A) **write**(A)	 **read**(B) **write**(B)

T_1	T_2
read(A) **write**(A)	 **read**(B) **write**(B)

T_1	T_2
read(A) **write**(A)	 **read**(B) **write**(B)

  - We can swap all statements if transactions work on completely different sets of data items
    - In the example T_1 work on data item A and T_2 work on data item B
    - Result will always be the same
  - Conflicts can only occur if the same data item is accessed

Conflicting Transactions

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- When can we swap instructions of transactions? (four cases)

1.

T_1	T_2
read(A)	
	read(A)

The order of T_1 or T_2 doesn't matter
Same value of A is read

2.

T_1	T_2
read(A)	
	write(A)

If swapped, T_1 reads a different value.
Order of $T_1$and T_2 matters -> conflict

3.

T_1	T_2
write(A)	
	read(A)

If swapped, T_2 reads a different value.
Order of $T_1$and T_2 matters -> conflict

4.

T_1	T_2
write(A)	
	write(A)

Only value written by T_2 is preserved in the DB.
If swapped, only value of T_1 is preserved.
Order of $T_1$and T_2 matters -> conflict

Conflicting Transactions

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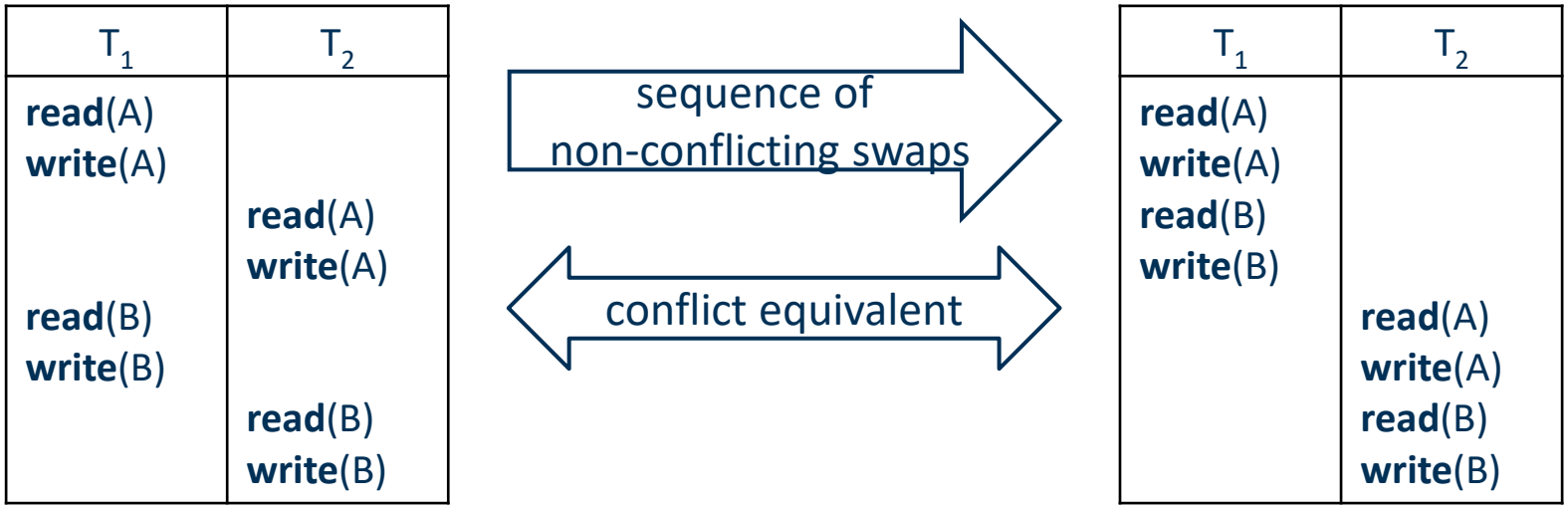
- When can we swap instructions of transactions?
- Let I_i and I_j be two instructions of transactions T_i and T_j
  - Instructions I_i and I_j **conflict**
    - if and only if there exists some data item Q accessed by both I_i and I_j, and at least one of these instructions wrote Q
- Implications on serializability:
  - Non-conflicting instructions can be executed in **any** order
  - A conflict between I_i and I_j forces a **temporal order** between them

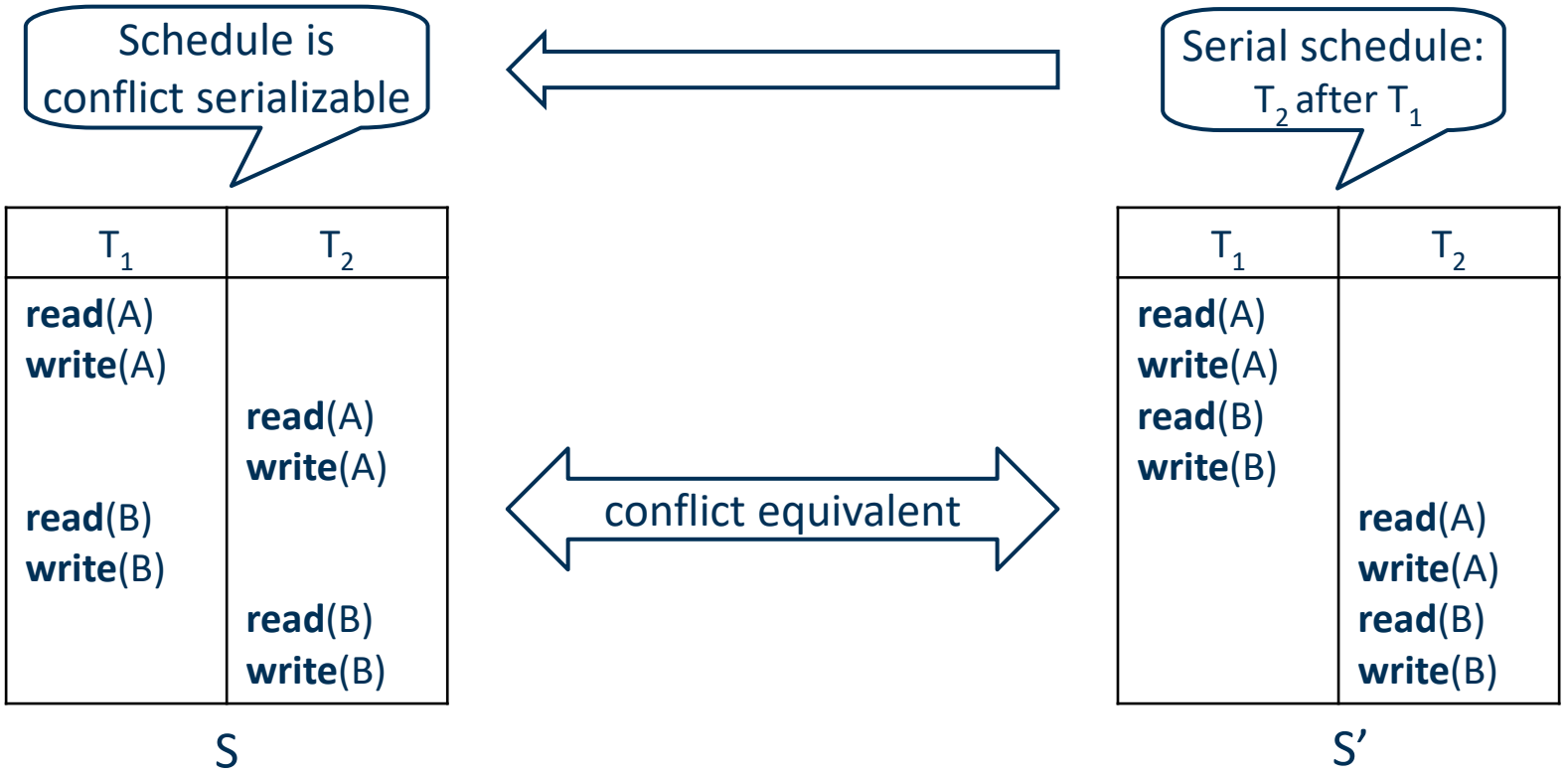
Conflict Equivalence

- If a schedule *S* can be transformed into a schedule *S'* by a series of swaps of non-conflicting instructions, we say that *S* and *S´* are **conflict equivalent**.



Conflict Serializability

- We say that a schedule *S* is **conflict serializable** if it is conflict equivalent to a serial schedule



Conflict Equivalence and Serializability

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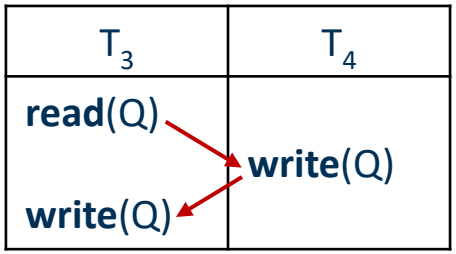
- Example of a schedule that is not conflict serializable:

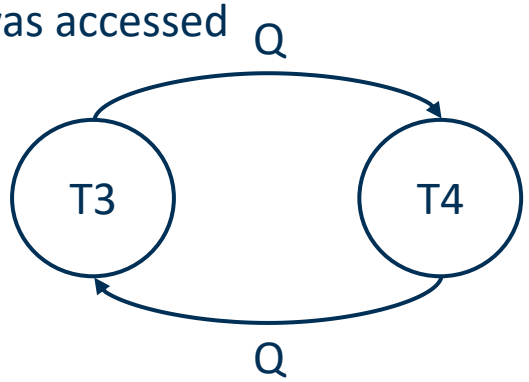


- **write**(Q) in T_3 conflicts with **write**(Q) in T_4 and **write**(Q) in T_4 conflicts with **read**(Q) in T_3
  - i.e., we are unable to swap instructions in the above schedule to obtain either the **serial** schedule < T_3, T_4 >, or the **serial** schedule < T_4, T_3 >

Precedence Graph

- Consider some schedule of a set of transactions T_1, T_2, ..., T_n
- **Precedence graph:** a directed graph where
  - Transactions are the vertices
  - Conflicts between statements of these transactions are edges
    - draw an edge from T_i to T_j if one of the conditions hold
      - T_i executes **write**(Q) before T_j executes **read**(Q)
      - T_i executes **read**(Q) before T_j executes **write**(Q)
      - T_i executes **write**(Q) before T_j executes **write**(Q)
    - We may label the edge by the item that was accessed

T_3	T_4
read(Q)	
	write(Q)
write(Q)	



Testing for Conflict Serializability

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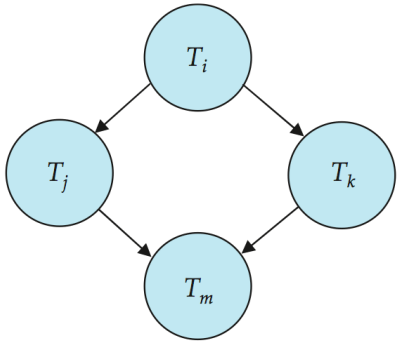
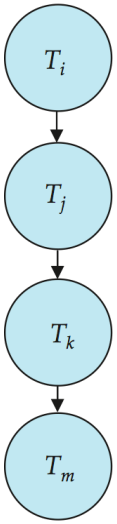
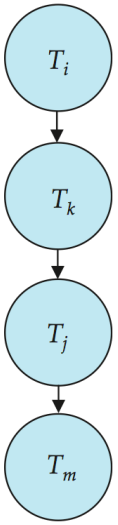
- A schedule is conflict serializable
  - if and only if its precedence graph is acyclic
  - serializability order can be obtained by a topological sorting of the graph
    - i.e., a linear order consistent with the partial order of the graph
    - Example: both (b) and (c) are possible partial orders of (a)
- Cycle-detection algorithms in $O(n^2)$ exist
  - where n is the number of vertices in the graph
  - better algorithms are in O(n+e) where e is the number of edges



(a)



(b)



(c)

Recoverable Schedules

- Consider the following schedule:

T_8	T_9
read(A)	
write(A)	
	read(A)
	commit
read(B)	

T_8 aborts here

- What happens if T_8 aborts after T_9 commits?
  - T_9 would have read an inconsistent database state and possibly shown the value of A to the user (because T_9 is commited) -> this should be avoided
- A schedule is ***recoverable*** if the following holds:
  - if a transaction T_j (T_9 in the example) reads a data item previously written by a transaction T_i
  - then the **commit** operation of T_i **must** appear before the **commit** operation of T_j

T_{8a}	T_{9a}
read(A)	
write(A)	
	read(A)
read(B)	
commit	
	commit

Cascading Rollbacks

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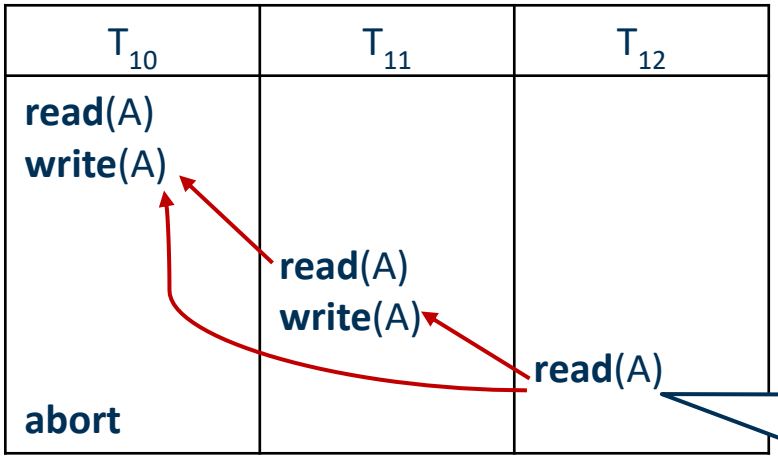
- Consider the following schedule:



Recoverable schedule means: If T_{11} or T_{12} wants to commit, they need to wait for T_{10} to commit

- On the abort of T_{10}
  - all three transactions need to abort and be rolled back
  - can mean undoing a significant amount of work

Still cascading rollbacks will happen

Cascadeless Schedules

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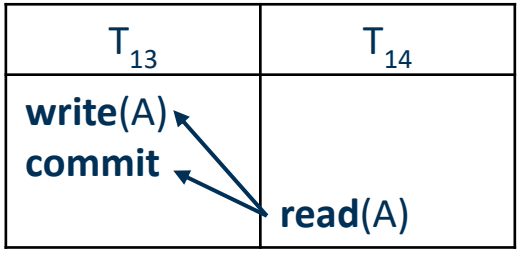
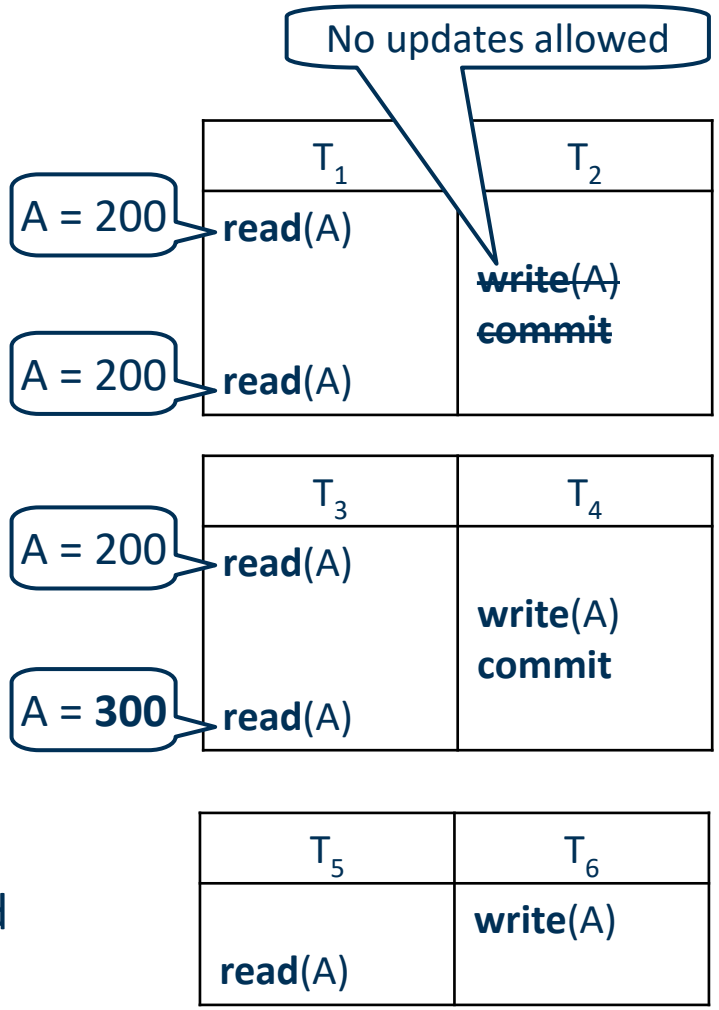
- To prevent cascading rollbacks, a stronger version exists
  - A schedule is **cascadeless** if and only if
    - for each pair of transactions T_i and T_j such that T_j reads a data item previously written by T_i,
    - the **commit** operation of T_i appears before the **read** operation of T_j
  - It is desirable to restrict the schedules to those that are cascadeless
  - Every cascadeless schedule is also recoverable
    - the reverse need not hold



Cascadeless (commit before read)

Levels of Consistency

- **Serializable:** default
- **Repeatable read:**
  - only committed records to be read
  - successive reads of same record must return the same value
- **Read committed:**
  - only committed records can be read,
  - successive reads of record may return different (but committed) values
- **Read uncommitted:**
  - even uncommitted records may be read



Levels of Consistency

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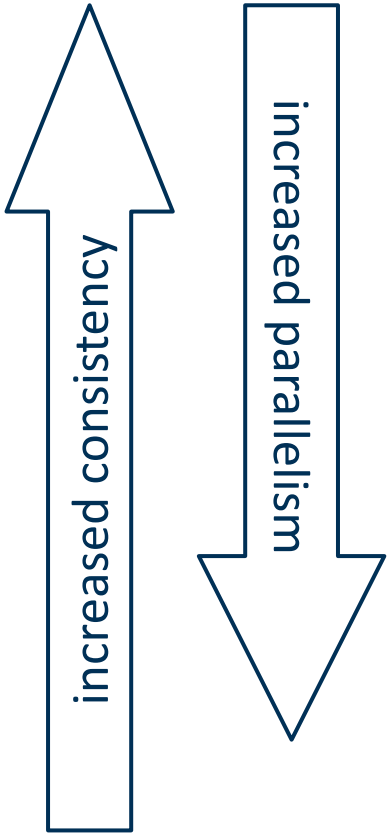

Transaction Definition in SQL

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- Data manipulation language must include a construct for specifying the set of actions that comprise a transaction
- In SQL
  - A transaction begins implicitly
  - A transaction ends by:
    - **Commit work** commits current transaction and begins a new one
    - **Rollback work** causes current transaction to abort
- In almost all database systems, by default, every SQL statement also commits implicitly if it executes successfully
  - implicit commit can be turned off by a database directive
  - e.g., in JDBC, `connection.setAutoCommit(false);`

Concurrency Control in DBMS

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- A database must provide a mechanism that will ensure that all possible schedules are both:
  - Conflict serializable
  - Recoverable and preferably cascadeless
- A policy in which only one transaction can execute at a time generates serial schedules
  - but provides a poor degree of parallelism
- Concurrency control protocols have to trade off
  - degree of parallelism they achieve
  - amount of overhead they incur

Lock-based Protocols

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- A lock is a mechanism to control concurrent access to a data item
- Data items can be locked in two modes :
  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 the concurrency-control manager
  - by the application accessing the database
  - transaction can proceed only after request is granted

Requesting and Granting Locks

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- Transactions request locks
  - can be granted if the requested lock is compatible
- Compatibility:
  - Any number of transactions can hold shared locks on an item
  - If any transaction holds an exclusive on the item, no other transaction may hold any lock on the item
- If a lock cannot be granted
  - the requesting transaction has to wait until all incompatible locks are released

requested \ already granted	S	X
S	true	false
X	false	false

Lock-based Protocols

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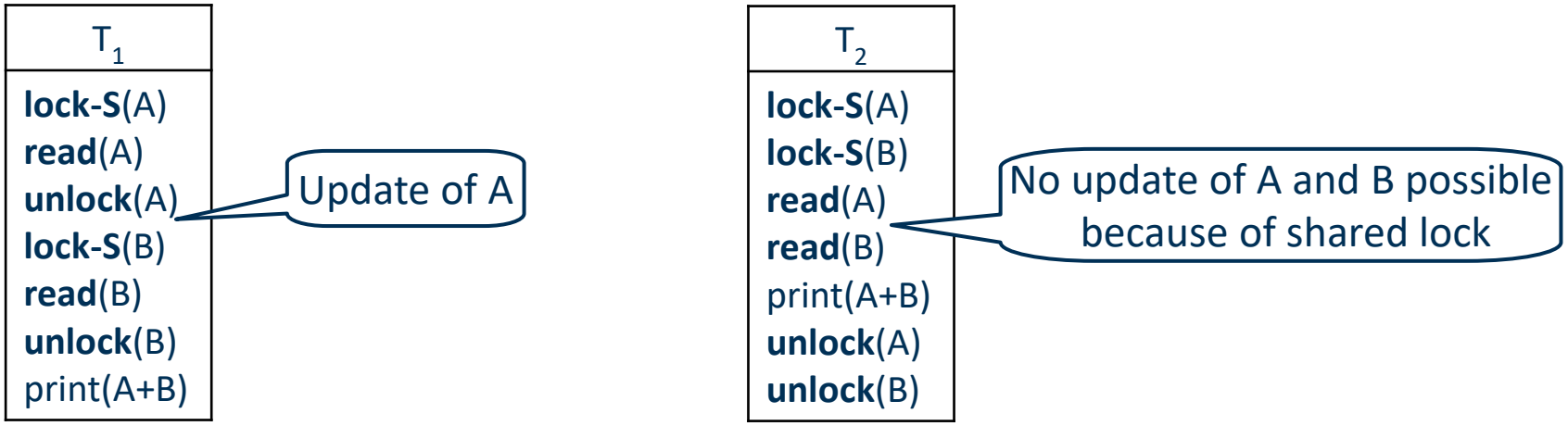
- Example of two transactions performing locking:



- Only T_2 is serializable
  - in T_1, if *A* and *B* get updated in-between the read of *A* and *B*, the displayed sum would be inconsistent
- A **locking protocol** is a set of rules followed by all transactions
  - Locking protocols restrict the set of possible schedules

The Two-Phase Locking Protocol

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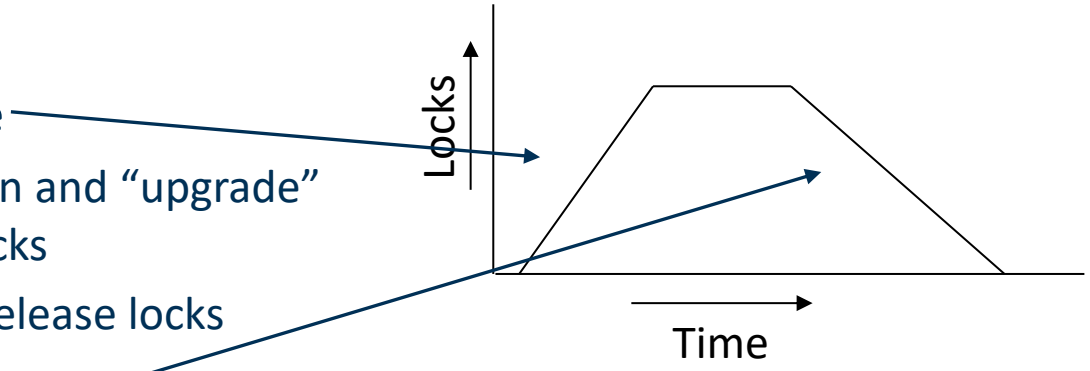
- Protocol that ensures conflict serializable schedules
- Runs in two phases
  - Phase 1: Growing Phase
    - Transaction may obtain and “upgrade” shared to exclusive locks
    - Transaction may not release locks
  - Phase 2: Shrinking Phase
    - Transaction may release and “downgrade” exclusive to shared locks
    - Transaction may not obtain locks



- The protocol assures serializability
  - It can be proved that the transactions can be serialized in the order of their **lock points**,
  - i.e., the point where a transaction acquired its final lock

Automatic Acquisition of Locks

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- A transaction T_i issues the standard read/write instruction, without explicit locking calls
- The operation **read**(D) is processed by the DBMS as:

```
if T_i has a lock on D
    read(D)
else
    if necessary wait until no other transaction has a lock-X on D
    grant T_i a  lock-S on D
    read(D)
```

Automatic Acquisition of Locks

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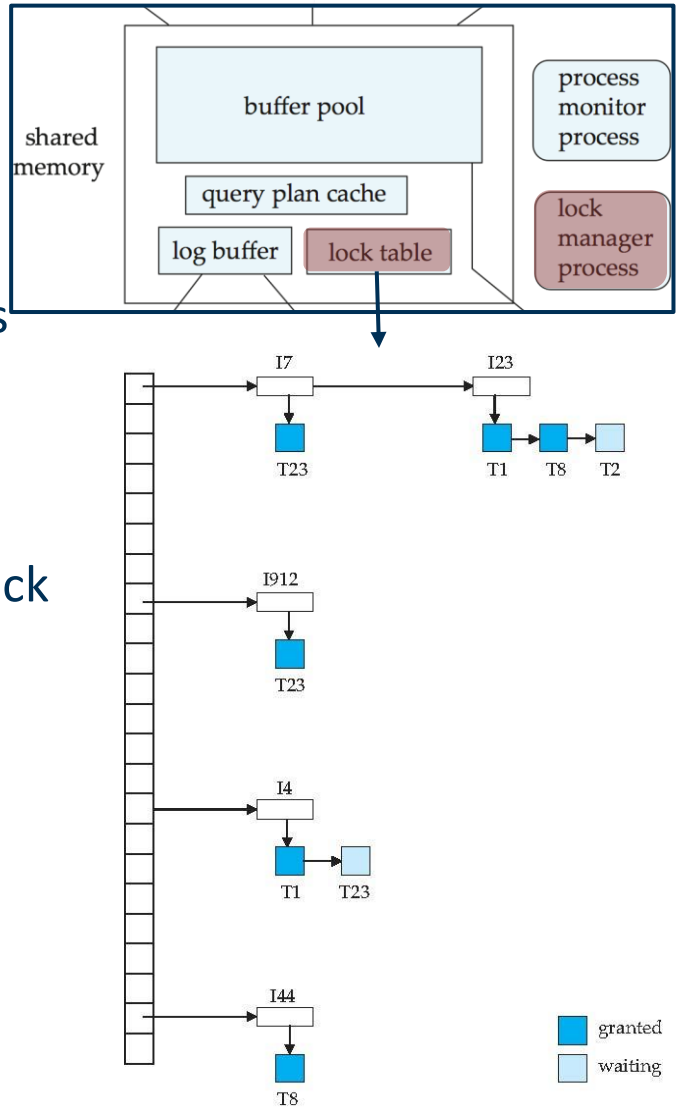
- A transaction T_i issues the standard read/write instruction, without explicit locking calls
- The operation **write*(D)*** is processed by the DBMS as:

```
if T_i has a lock-X on D
    write(D)
else
    if necessary wait until no other transaction has any lock on D
    if T_i has a lock-S on D
        upgrade lock on D to lock-X
    else
        grant T_i a lock-X on D
    write(D)
```

- All locks are released after commit or abort

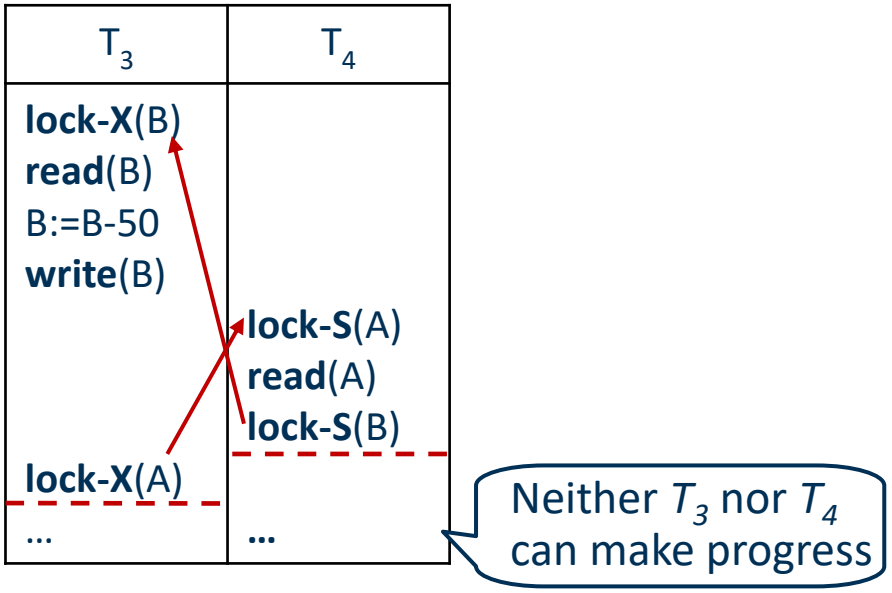
Implementation of Locking – Lock Table

- A **lock manager** can be implemented as a separate process
  - transactions send lock and unlock requests to the lock manager
  - lock manager replies to a lock request by sending a lock grant message or a message asking the transaction to roll back in case of a deadlock
- The lock manager maintains **lock table** to record granted locks and pending requests
  - implemented as an in-memory hash table indexed on the name of the data item



Deadlocks

- Consider the partial schedule



- Situation:
  - executing **lock-S***(B)* causes T_4 to wait for T_3 to release its lock on B,
  - executing **lock-X***(A)* causes T_3 to wait for T_4 to release its lock on *A*
- Such a situation is called a **deadlock**
  - to handle the problem,
    one of T_3 or T_4 must be rolled back and its locks released

Deadlocks

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- Two-phase locking protocol
  - guarantees **serializability** but does **not** ensure freedom from deadlocks
- The potential for deadlock exists in most locking protocols
  - but there are prevention mechanisms (see later)
- When a deadlock occurs
  - rollbacks are necessary
  - there is a possibility of cascading roll-backs
    (also under two-phase locking protocol)
    - but cascading rollbacks can be expensive
    - Modified protocol called **strict two-phase locking**
      - a transaction must hold all its exclusive locks until it commits/aborts
      - avoids cascading rollbacks

Starvation

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- In addition to deadlocks, there is a possibility of **starvation:**
  - A transaction may be waiting for an X-lock on an item
  - while a sequence of other transactions request and are granted an S-lock on the same item

- **Starvation** occurs if the concurrency control manager is badly designed
  - Unfair Prioritization etc
  - Concurrency control manager can be designed to prevent starvation

Might wait forever

T_1	T_2	T_3	T_4
lock-X(B)	**lock-S**(B) …. **unlock**(B)		
		lock-S(B) … **unlock**(B)	
			lock-S(B) … **unlock**(B)

Deadlock Detection

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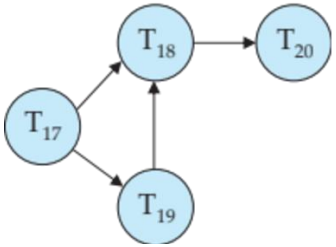
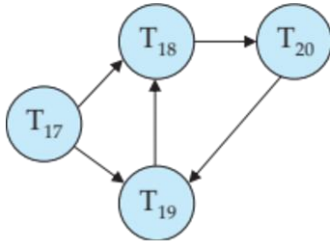
- Deadlocks can be detected using a **wait-for graph**
  - Vertices are the transactions
  - Edges:
    - T_i requests a lock on a data item currently being locked by T_j, the edge $T_i \rightarrow T_j$ is inserted (T_i is waiting for T_j)
    - T_j releases lock on a data item needed by T_i (or T_i is rolled back), the edge $T_i \rightarrow T_j$ is removed from the wait-for graph
  - System is in a deadlock state $\leftrightarrow$ the wait-for graph has a cycle
    - invoke a deadlock-detection algorithm to look for cycles



Wait-for graph without a cycle



Wait-for graph with a cycle

Deadlock Recovery

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- When deadlock is detected :
  - some transaction will have to rolled back (made a victim)
  - select a transaction as a victim that will incur minimum cost
- Rollback – determine how far to roll back transaction
  - Total rollback: Abort the transaction and then restart it
  - More effective: roll back transaction only as far as necessary to break deadlock
- Starvation happens if same transaction is always chosen as victim
  - Solution: include the number of rollbacks in the cost factor to avoid starvation

Deadlock Prevention Protocols

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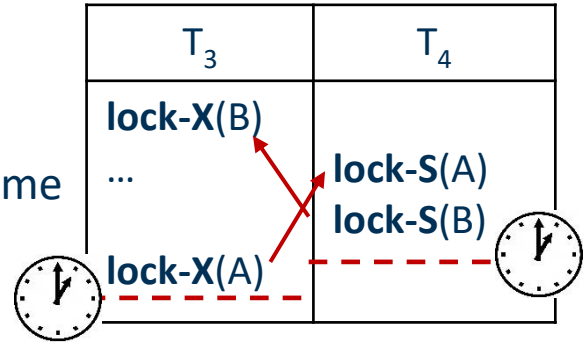
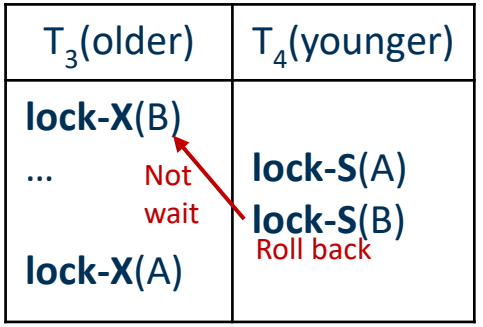
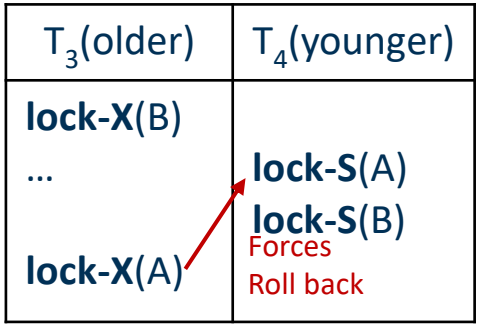
- **Timeout-Based** Scheme
  - transactions wait for a lock for specified amount of time
  - if the lock has not been granted within that time → roll back
- **Wait-Die** Scheme
  - older transaction may wait for younger one to release data item
  - younger transactions never wait for older ones (they are rolled back instead)
  - a transaction may die several times
- **Wound-Wait** Scheme
  - older transaction *wounds* (forces rollback) of younger transaction (instead of waiting for it)
  - younger transactions may wait for older ones
  - may cause fewer rollbacks than *wait-die* scheme







Timestamp-based Protocols

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- Locking protocol (before) determine order by first lock
- Timestamp-based protocol determine order in advance
  - Each transaction T_i is issued a timestamp **TS(T_i)** when it enters the system
    - timestamps must be free of duplicates
  - The protocol manages concurrent execution such that the time-stamps determine the serializability order
  - In order to assure such behavior, the protocol maintains two timestamp values for each data *Q*:
    - **W-TS**(*Q*) is the largest time-stamp **of any transaction** that executed **write**(*Q*) successfully
    - **R-TS**(*Q*) is the largest time-stamp **of any transaction** that executed **read**(*Q*) successfully

Timestamp-based Scheduling

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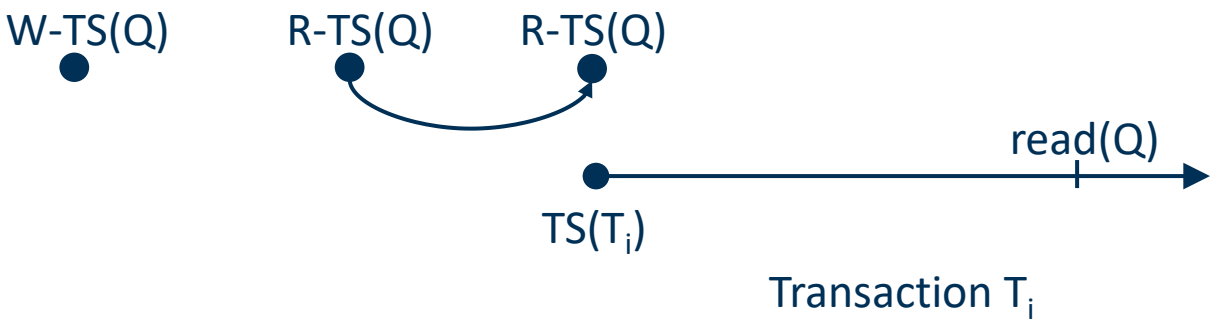
- Transaction T_i issues a **read**(Q)
  - if **TS**(T_i) > **W-TS**(Q)
    - execute **read** operation,
      set **R-TS**(Q) to **max**(**R-TS**(Q),**TS**(T_i))



Timestamp-based Scheduling

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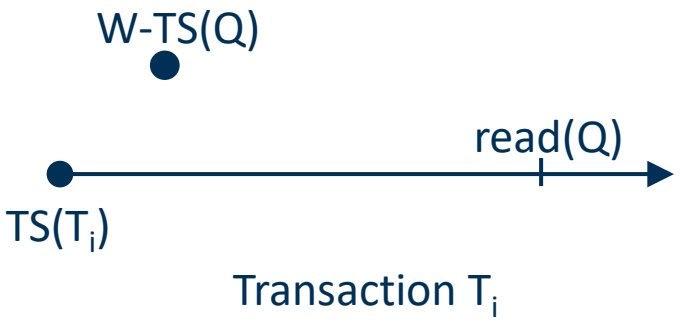
- Transaction T_i issues a **read**(Q)
  - if **TS**(T_i) $\leq$ **W-TS**(Q),
    then T_i needs to read a value of Q that was already overwritten
    → reject **read**, rollback T_i



Timestamp-based Scheduling

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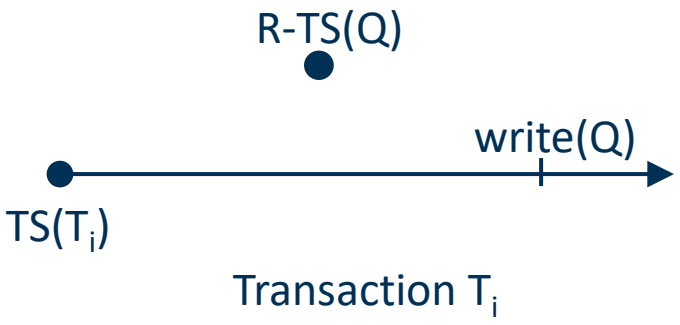
- Transaction T_i issues **write**(Q)
  - if **TS**(T_i) < **R-TS**(Q),
    then the value of Q that T_i is producing was read previously
    → reject **write**, rollback T_i



Timestamp-based Scheduling

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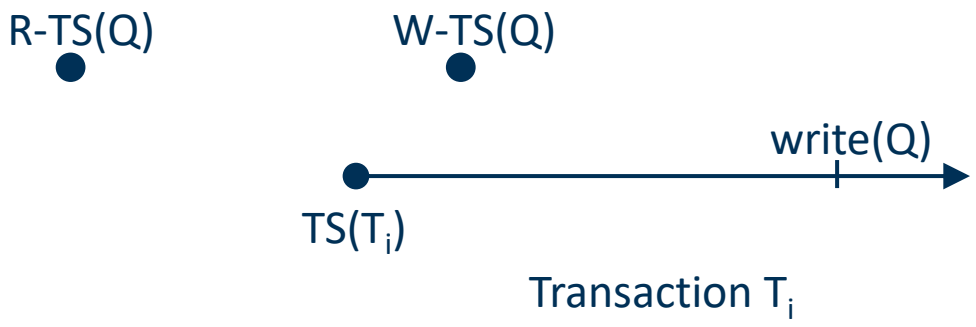
- Transaction T_i issues **write**(Q)
  - if **TS**(T_i) < **W-TS**(Q),
    then T_i is attempting to write an obsolete value of Q
    → reject **write**, rollback T_i



Timestamp-based Scheduling

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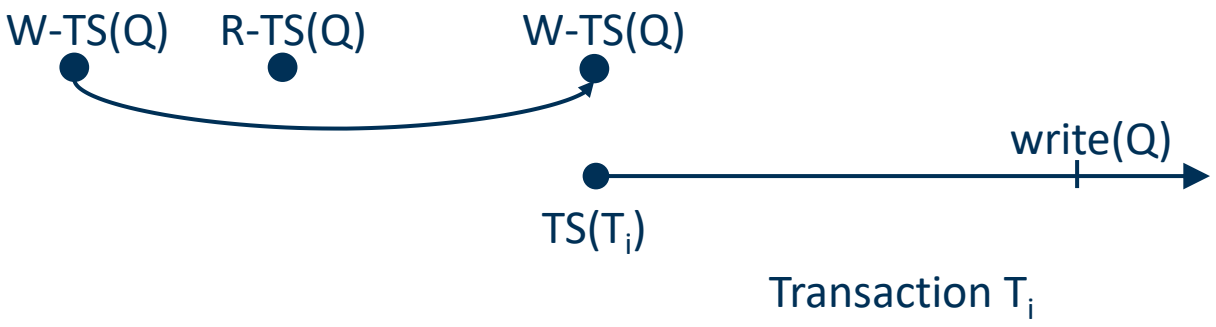
- Transaction T_i issues **write**(Q)
  - **TS**(T_i) ≥ **R-TS**(Q) and **TS**(T_i) ≥ **W-TS**(Q)
    - execute **write** and set **W-TS**(Q) to **TS**(T_i)



Timestamp-based Scheduling

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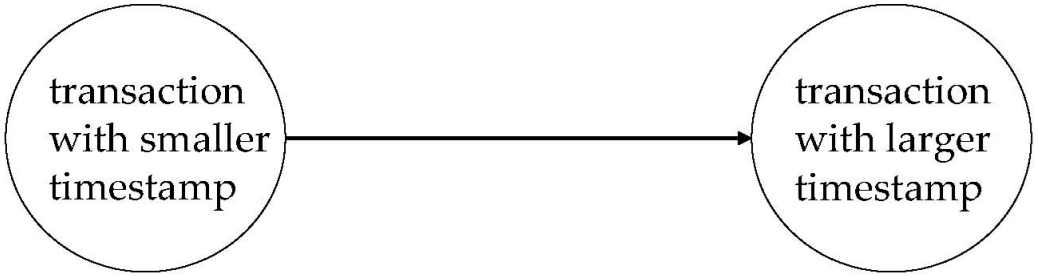
- The timestamp-ordering protocol guarantees serializability since all the arcs in the precedence graph are of the form



Thus, there will be no cycles in the precedence graph

- Timestamp protocol ensures freedom from deadlock
  - no transaction ever waits, there are only rollbacks
- But the schedule may not be cascade-free
  - and may not even be recoverable

Validation Based Protocol

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- Execution of transaction T_i is done in three phases
  1. **Read and execution phase**: Transaction T_i writes only to temporary local variables
  2. **Validation phase**: Transaction T_i performs a ''validation test'' to determine if local variables can be written without violating serializability
  3. **Write phase**: If T_i is validated, the updates are applied to the database; otherwise, T_i is rolled back
- The three phases of concurrently executing transactions can be interleaved
  - but each transaction must go through the three phases in that order
- Assume for simplicity that the validation and write phase occur together, atomically and serially
  - i.e., only one transaction executes validation/write at a time.
- Also called as **optimistic concurrency control** since transaction executes fully in the hope that all will go well during validation

Validation Based Protocol

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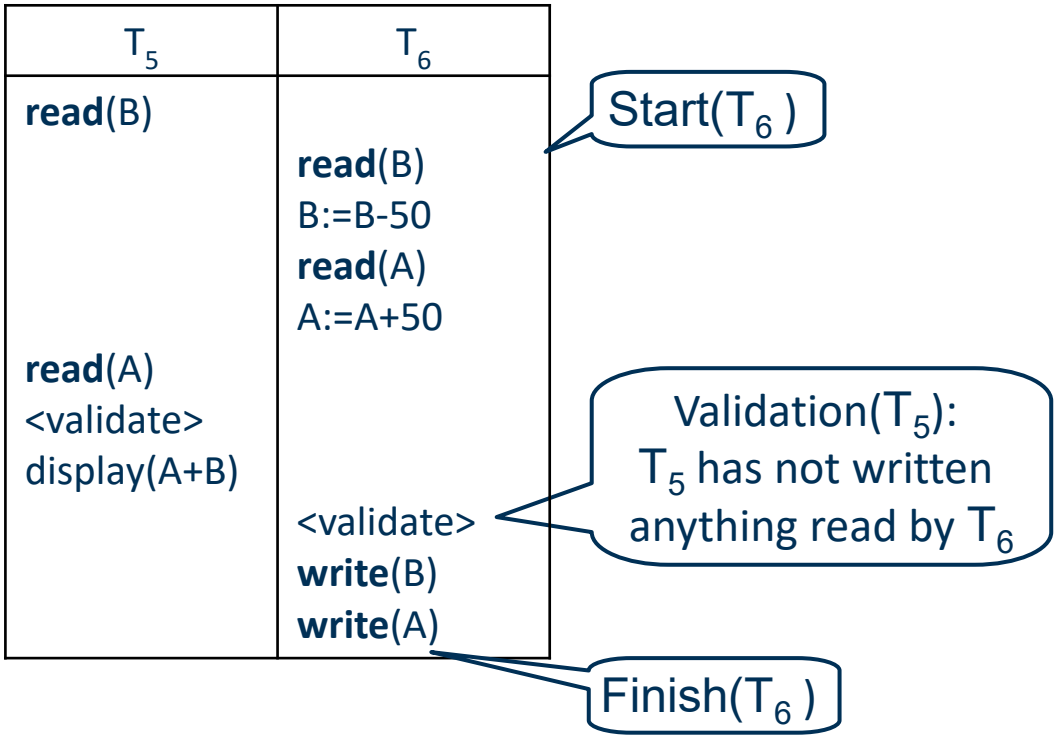
- Each transaction T_i has 3 timestamps
  - Start(T_i) : the time when T_i started its execution
  - Validation(T_i): the time when T_i entered its validation phase
  - Finish(T_i) : the time when T_i finished its write phase
- Serializability order is determined by timestamp given at validation time; this is done to increase concurrency.
  - Thus, TS(T_i) is given the value of Validation(T_i)
- This protocol is useful and gives greater degree of concurrency
  - if probability of conflicts is low
  - serializability order is not pre-decided
  - relatively few transactions will have to be rolled back

Validation Test for Transaction T_j

- Example schedule using validation



Validation Test for Transaction T_j

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- If for all T_i with TS (T_i) < TS (T_j) either one of the following condition holds:
  - **finish**(T_i) < **start**(T_j)
  - **start**(T_j) < **finish**(T_i) < **validation**(T_j) and the set of data items written by T_i does not intersect with the set of data items read by T_j
- then validation succeeds and T_j can be committed
  - otherwise, validation fails and T_j is aborted
- *Explanation*: Either the first condition is satisfied, i.e., there is no overlapped execution, or the second condition is satisfied, i.e.,
  - the writes of T_j do not affect reads of T_i since they occur after T_i has finished its reads
  - the writes of T_i do not affect reads of T_j since T_j does not read any item written by T_i

Summary

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- Parallel access to databases brings challenges
  - easy solution: process one transaction after the other
  - higher performance solution: support parallelism
- Transactions & Serializability
  - Methods for generating serializations
- Locks & Deadlocks
- Protocols

Questions?

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