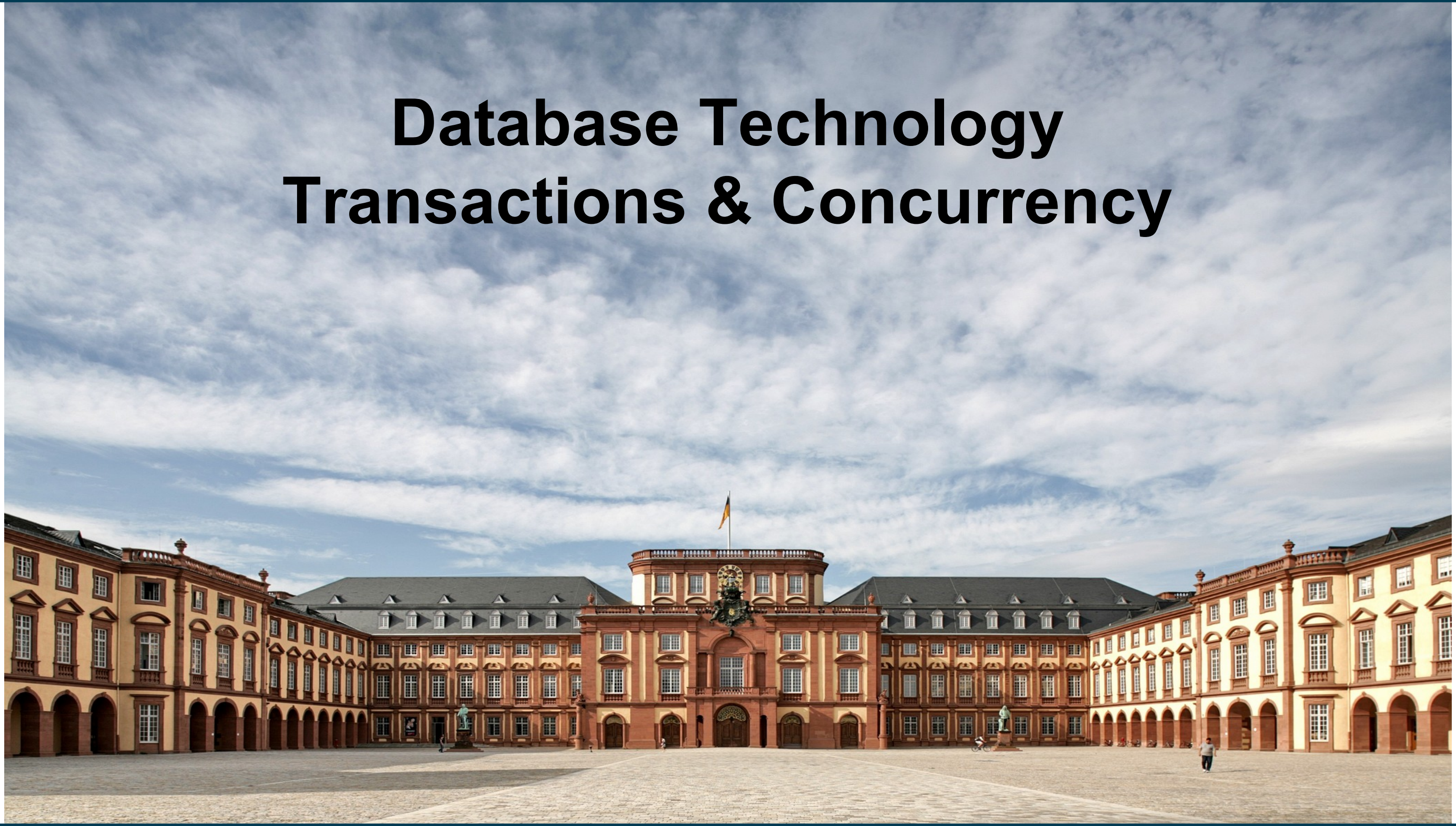
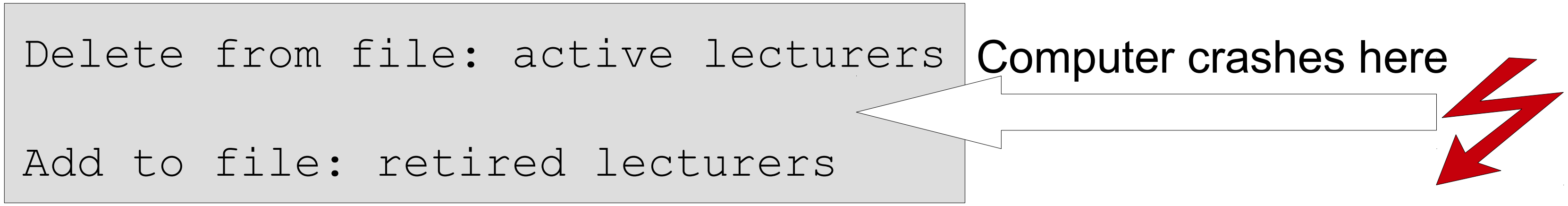


Database Technology
Transactions & Concurrency

Heiko Paulheim

Flashback to First Lecture

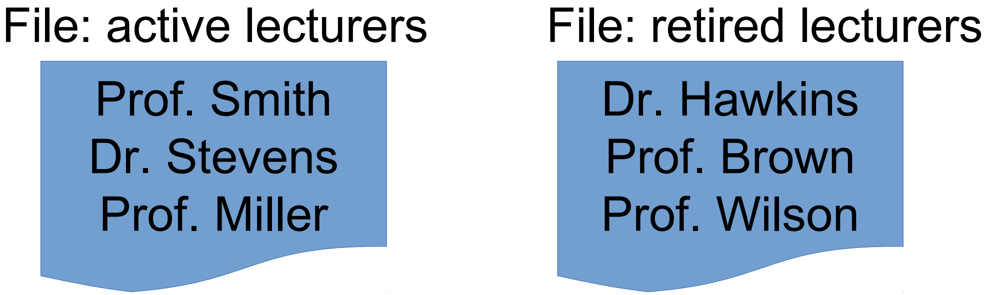
- We already stumbled upon transactions



```
Delete from file: active lecturers

Add to file: retired lecturers
```

Computer crashes here



File: active lecturers

Prof. Smith
Dr. Stevens
Prof. Miller

File: retired lecturers

Dr. Hawkins
Prof. Brown
Prof. Wilson

Flashback to First Lecture

- ...and we already stumbled upon concurrency

```
Read num_current_participants
       from file

If num_current_participants
       < limit
Then
       add participant to fi
```

User 1

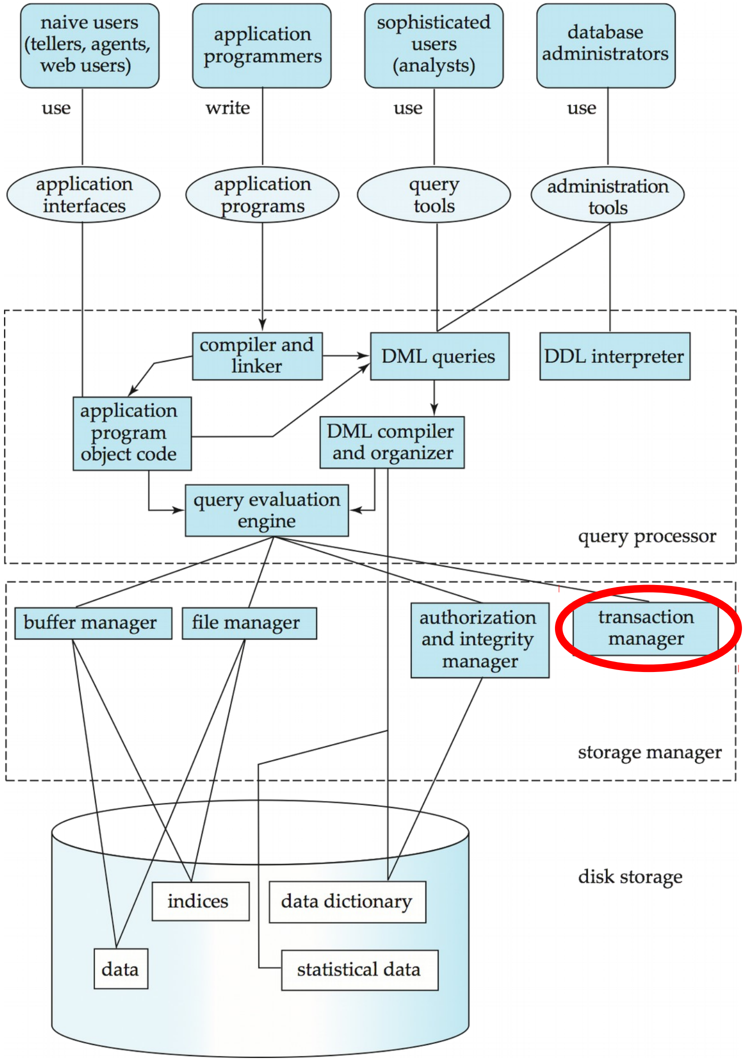
```
Read num_current_participants
       from file

If num_current_participants
       < limit
Then
       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

- Transactions
  - Concurrent Executions
  - Serializability
  - Recoverability
  - Testing for Serializability
  - Transaction Definition in SQL
- Protocols for Concurrent Execution
  - Lock-Based Protocols
  - Timestamp-Based Protocols
  - Validation-Based Protocols
  - Handling Insert and Delete Operations
  - Concurrency in Index Structures

Concept of a Transaction

- 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:

```
1.   read(A)
2.   A := A – 50
3.   write(A)
4.   read(B)
5.   B := B + 50
6.   write(B)
```

- Two main issues to deal with:
  - Failures of various kinds, such as hardware failures and system crashes
  - Concurrent execution of multiple transactions

Requirements for Transactions

- **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
- **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

Requirements for Transactions

- **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

- **Isolation requirement**
  - if between steps 3 and 6, another transaction **T2** is allowed to access the partially updated database, it will see an inconsistent database

T1	**T2**
1. **read**(*A*)	
2. *A* := *A* – 50	
3. **write**(*A*)	
	read(A), read(B), print(A+B)
4. **read**(*B*)	
5. *B* := *B* + 50	
6. **write**(*B*)	

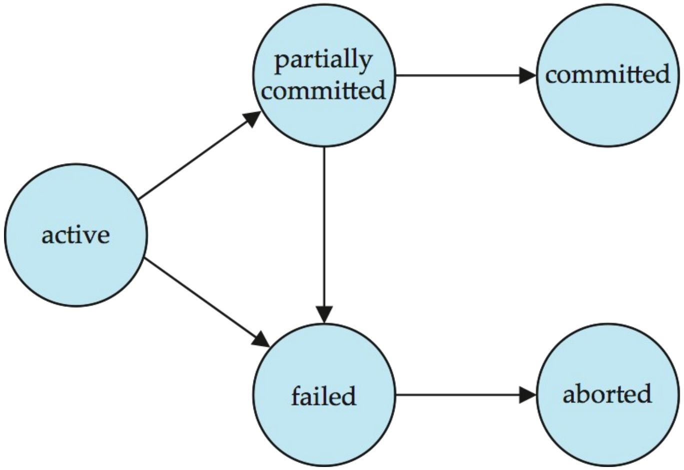
- Isolation can be ensured trivially by running transactions **serially**
  - i.e., one after the other
  - however, parallel execution is often desired due to performance benefits

ACID Properties

- **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
  - Intermediate transaction results must be hidden from other concurrently executed transactions
  - i.e., for every pair of transactions T_i and T_j, it appears to T_i that either T_j, finished execution before T_i started, or T_j started execution after T_i finished
- **Durability:** After a transaction completes successfully, the changes it has made to the database persist, even if there are system failures

Transaction States

- **Active:** the initial state; transaction stays active while it is executing
- **Partially committed:** after the final statement has been executed
- **Failed:** after discovery that normal execution can no longer proceed
- **Aborted:** after the transaction has been rolled back and the database restored to its state prior to the start of the transaction. Actions to be taken:
  - Restart the transaction (can be done only if no internal logical error)
  - Kill the transaction
- **Committed:** after successful completion



Concurrent Execution of Transactions

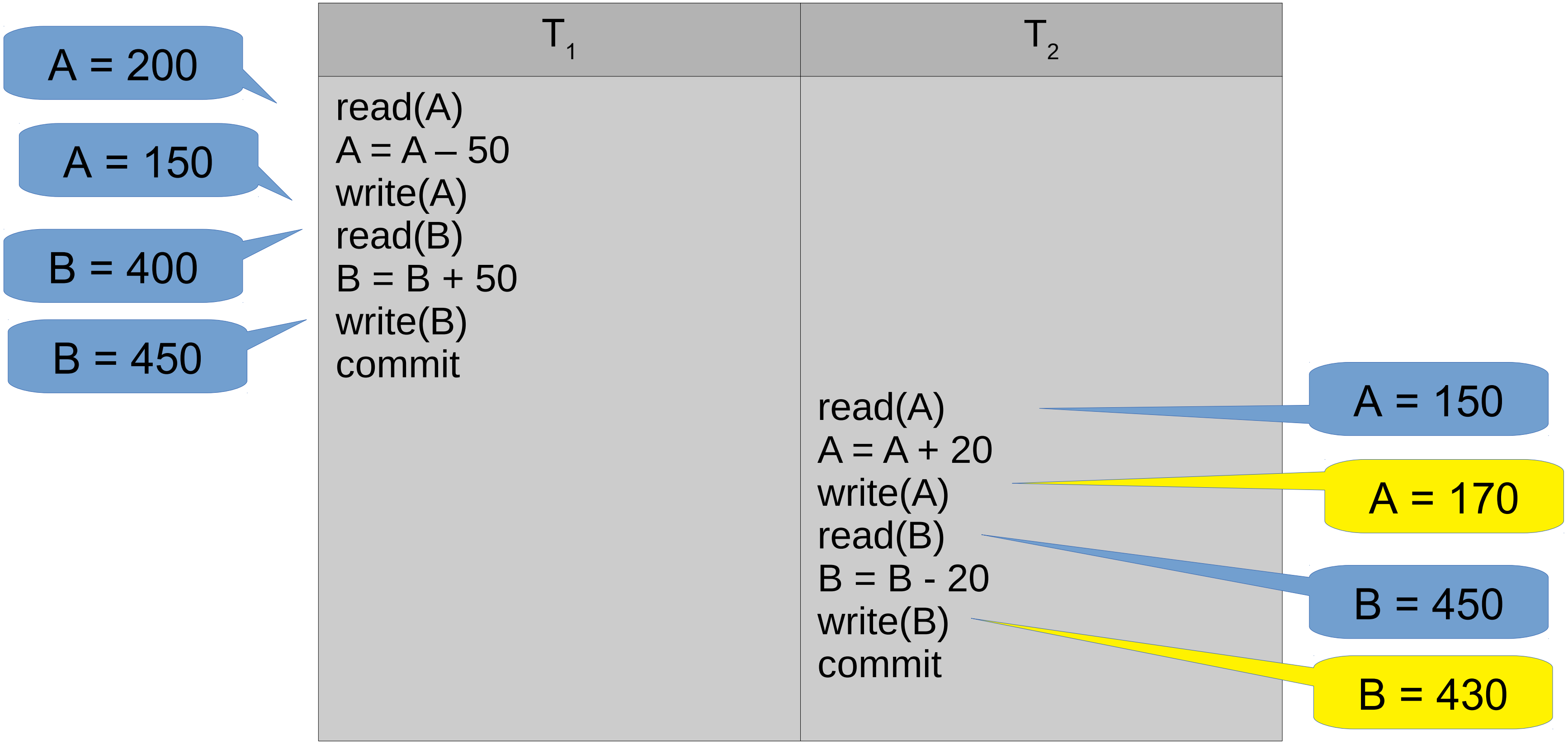
- Multiple transactions are allowed to run concurrently in the system
  - **Increased processor and disk utilization**, leading to better transaction *throughput*
    - e.g., one transaction can be using the CPU while another is reading from or writing to the disk
  - **Reduced average response time** 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

- **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** instructions as the last statement
  - By default, a transaction is assumed to execute 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

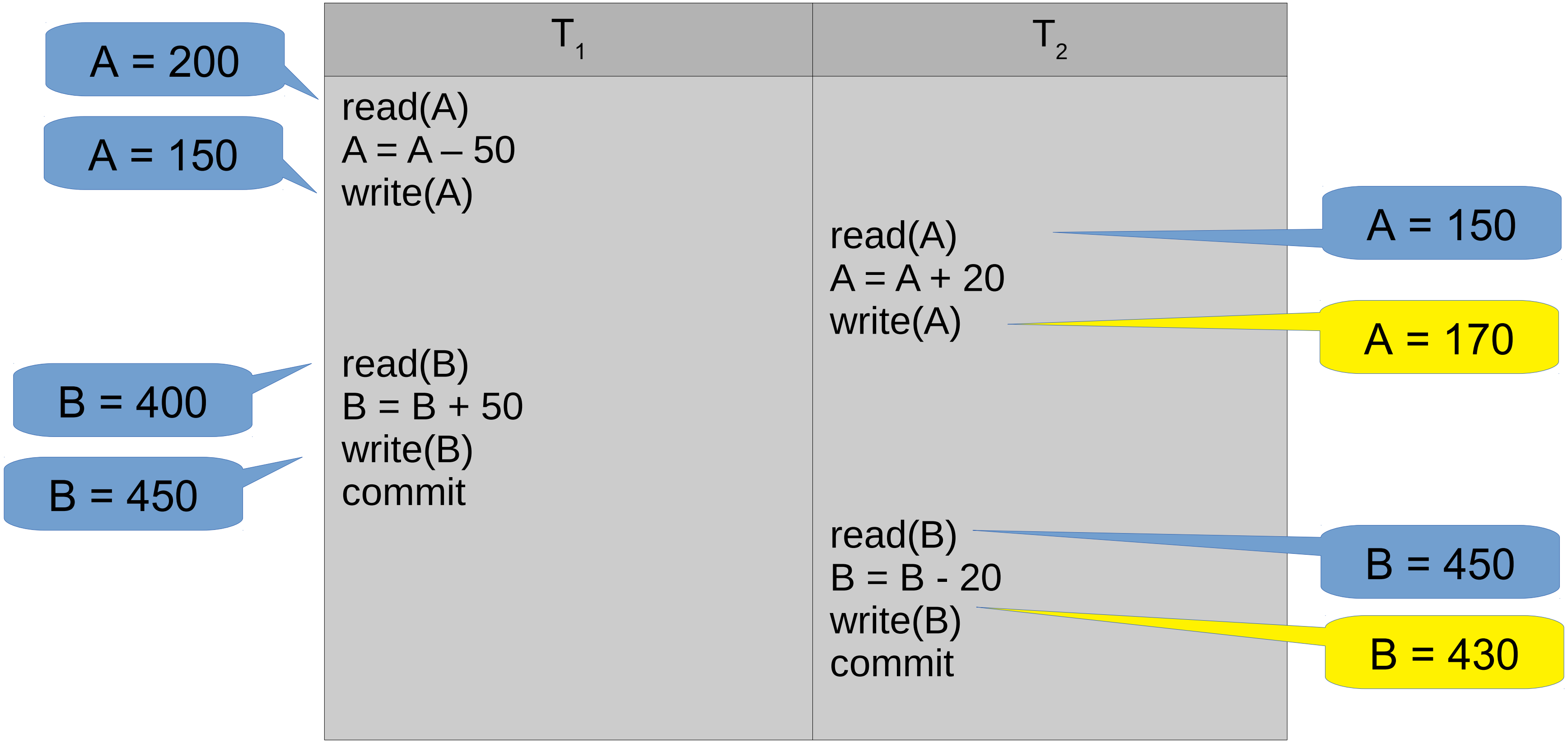
- Let T_1 transfer \$50 from *A* to *B*, and T_2 transfer \$20 of the balance from *B* to *A*
- Serial schedule: T_1 is executed as a whole, followed by T_2 :



T_1	T_2
read(A)	
A = A – 50	
write(A)	
read(B)	
B = B + 50	
write(B)	
commit	
	read(A)
	A = A + 20
	write(A)
	read(B)
	B = B - 20
	write(B)
	commit

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



T_1	T_2

read(A)
A = A – 50
write(A)	

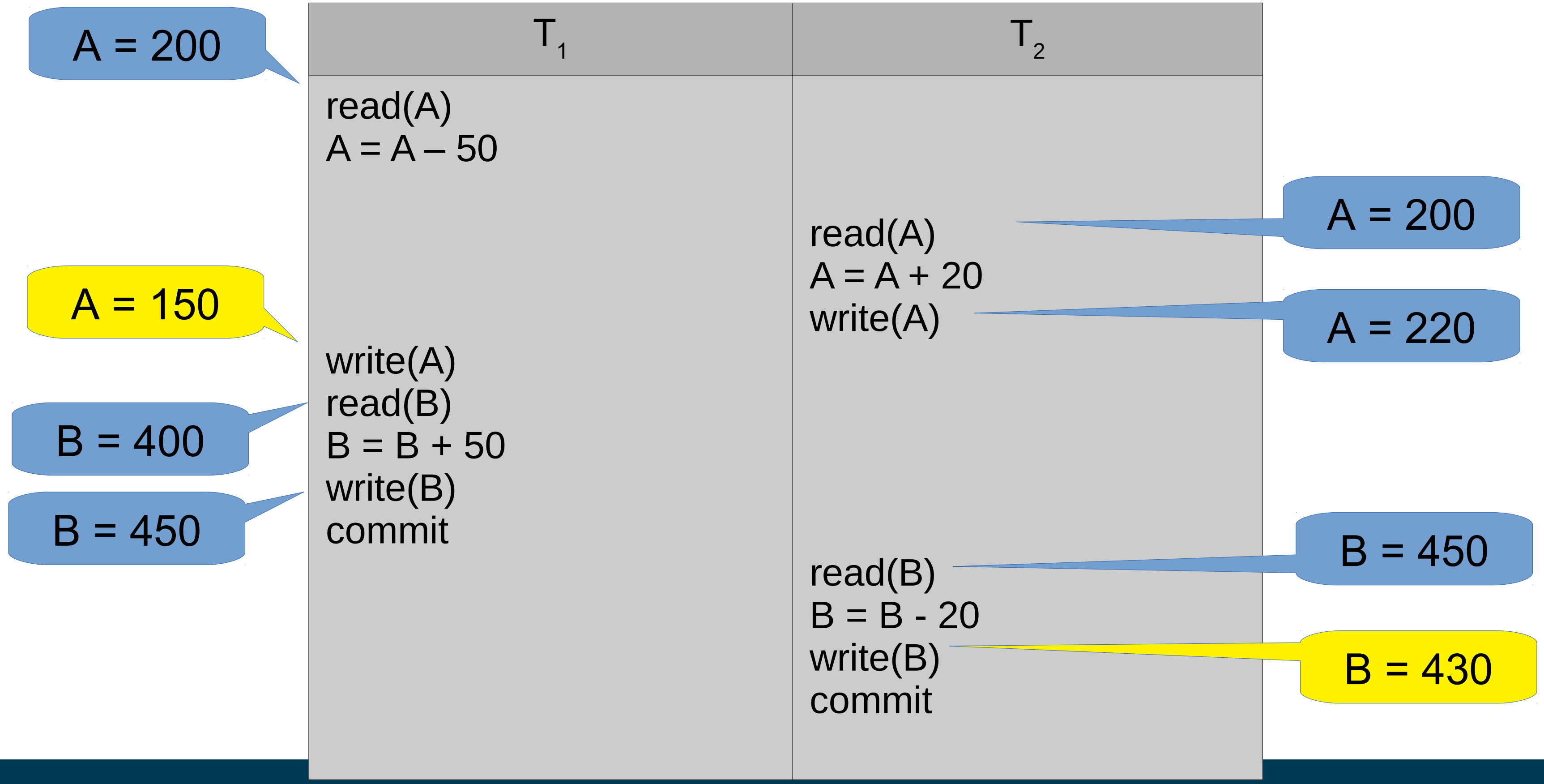
	read(A)
	A = A + 20
	write(A)

read(B)
B = B + 50
write(B)
commit	

	read(B)
	B = B - 20
	write(B)
	commit

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*
- The sum of A and B is not maintained!



T_1	T_2

read(A)
A = A – 50	

	read(A)
	A = A + 20
	write(A)

write(A)
read(B)
B = B + 50
write(B)
commit	

	read(B)
	B = B - 20
	write(B)
	commit

Serializability

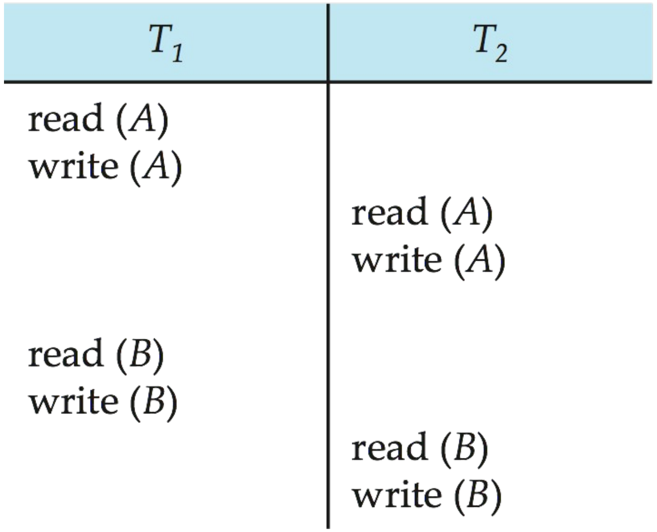
- Basic assumption: transactions preserve database consistency
  - i.e., serial execution of a set of transactions also preserves database consistency
- A (possibly concurrent) schedule is serializable if it is equivalent to a serial schedule
  - We ignore operations other than read and write instructions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

Conflicting Transactions

- Let I_i and I_j be two Instructions of transactions T_i and T_j respectively
- 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
  - 1. I_i = **read**(Q), I_j = **read**(Q). → No conflict
    2. I_i = **read**(Q), I_j = **write**(Q). → Conflict
    3. I_i = **write**(Q), I_j = **read**(Q). → Conflict
    4. I_i = **write**(Q), I_j = **write**(Q). → Conflict
    5. I_i = **write**(Q), I_j = **write**(R). → No conflict
    6. I_i = **read**(Q), I_j = ***write***(R). → No conflict
- 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

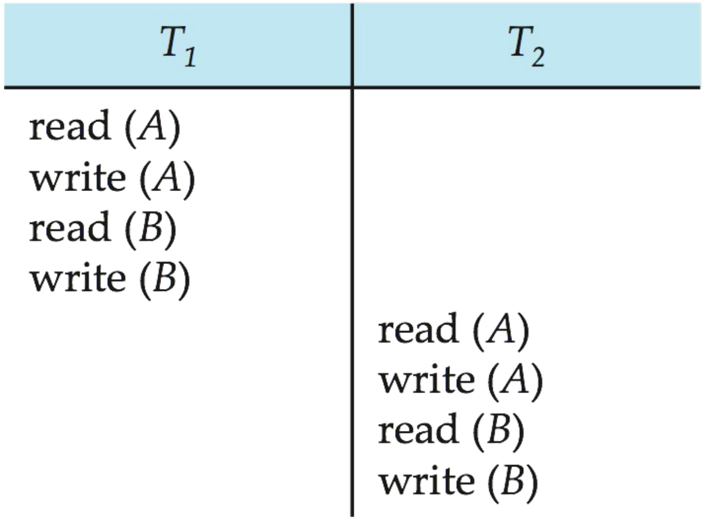
Conflict Equivalence and Serializability

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



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

S

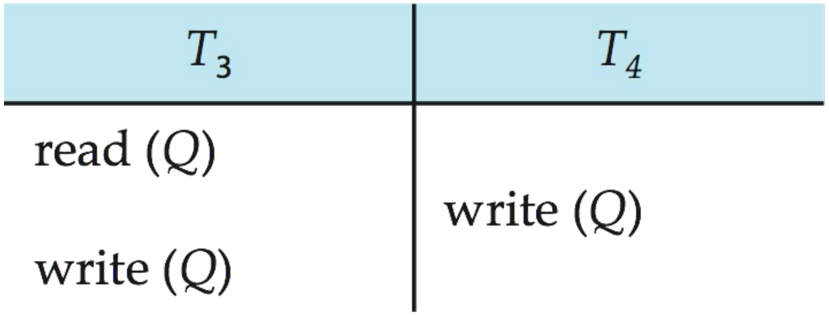


T_1	T_2
read (*A*)	
write (*A*)	
read (*B*)	
write (*B*)	
	read (*A*)
	write (*A*)
	read (*B*)
	write (*B*)

S’

Conflict Equivalence and Serializability

- Example of a schedule that is not conflict serializable:

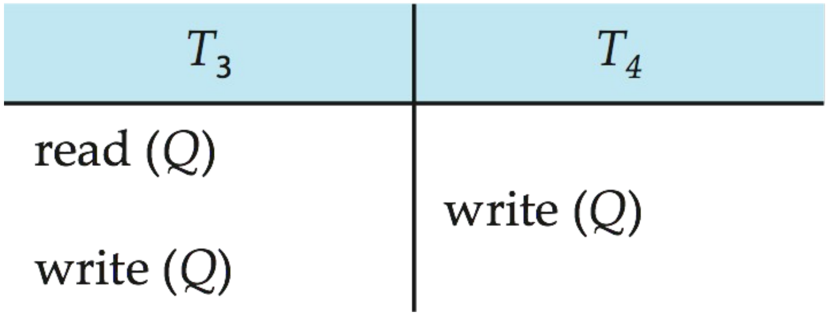


T_3	T_4
read (Q)	
	write (Q)
write (Q)	

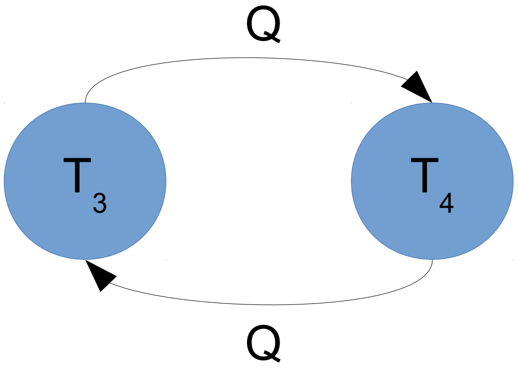
- write(Q) in T_4 conflicts both with read(Q) and with write(Q) in T_3
  - i.e., we are unable to swap instructions in the above schedule to obtain either the serial schedule < T_3, T_4 >, or the serial schedule < T_4, T_3 >

Precedence Graph

- Consider some schedule of a set of transactions T_1, T_2, ..., T_n
- **Precedence graph:** a directed graph where the vertices are the transactions (names)
  - We draw an arc from T_i to T_j if the two transaction conflict, and T_i accessed the data item on which the conflict arose earlier
  - We may label the arc by the item that was accessed
- Example:

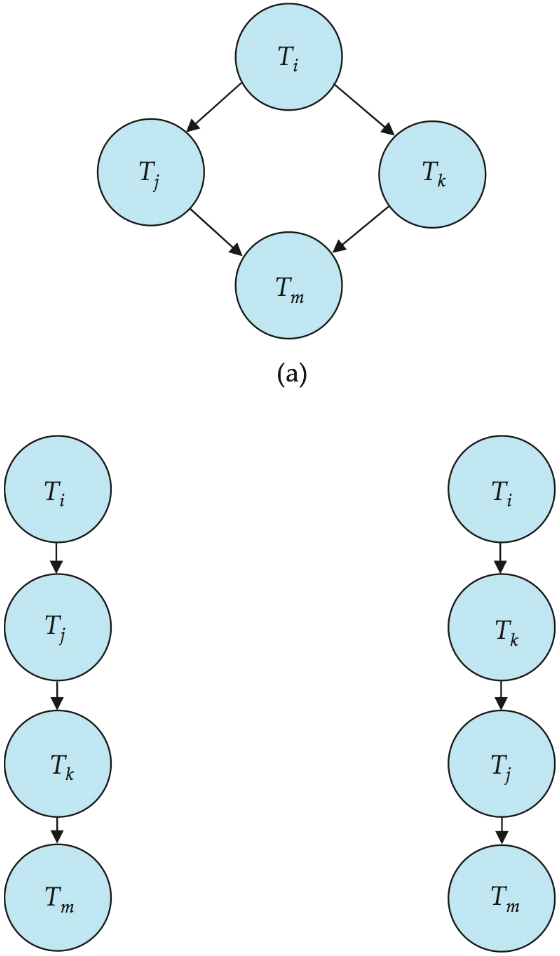


T_3	T_4
read (Q)	
	write (Q)
write (Q)	



Testing for Conflict Serializability

- 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 exist which take order n^2 time
  - where n is the number of vertices in the graph
  - better algorithms take order n + e where e is the number of edges



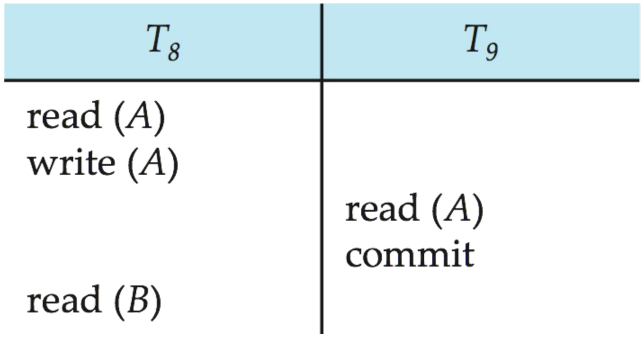
(a)

(b)

(c)

Recoverable Schedules

- Consider the following schedule:

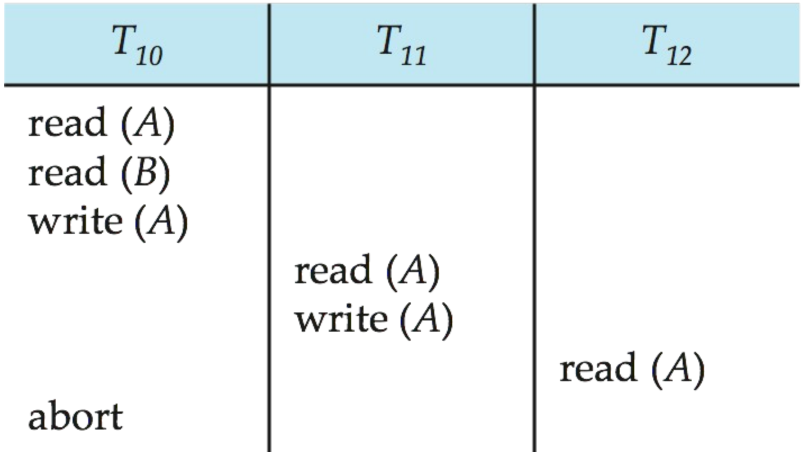


T_8	T_9
read (A)	
write (A)	
	read (A)
	commit
read (B)	

- What happens if T_8 should abort after T_9 commits?
  - T_9 would have read (and possibly shown to the user) an inconsistent database state
  - The DBMS should avoid those cases
- A schedule is *recoverable* if the following holds:
  - if a transaction T_j 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

Cascading Rollbacks

- Consider the following schedule:



T_{10}	T_{11}	T_{12}
read (A)		
read (B)		
write (A)		
	read (A)	
	write (A)	
		read (A)
abort		

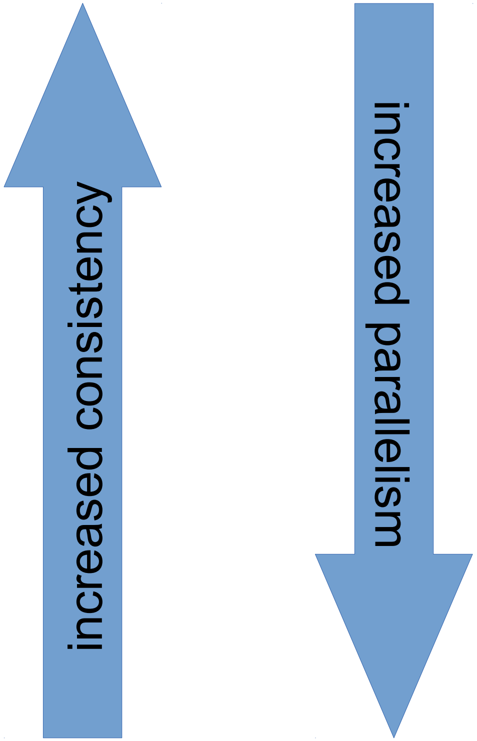
- On the abort of T_{10}
  - all three transactions need to be rolled back
  - can mean undoing a significant amount of work

Cascadeless Schedules

- 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
- Every cascadeless schedule is also recoverable
  - the reverse need not hold
- It is desirable to restrict the schedules to those that are cascadeless

Levels of Consistency

- **Serializable:** default
- **Repeatable read:**
  - only committed records to be read
  - successive reads of same record must return the same value
  - transactions may not be serializable
- **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



increased consistency

increased parallelism

Transaction Definition in SQL

- 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

- 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

Locks

- 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

- 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

already granted

requested

	S	X
S	true	false
X	false	false

- If a lock cannot be granted
  - the requesting transaction has to wait until all incompatible locks are released

Lock-based Protocols

- Example of two transactions performing locking:

T_1:	T_2:
lock-S(*A*);	**lock-S**(*A*);
read(*A*);	**lock-S**(*B*);
unlock(*A*);	**read**(*A*);
lock-S(*B*);	**read**(*B*);
read(*B*);	**display**(*A+B*);
unlock(*B*);	**unlock**(*A*);
display(*A+B*);	**unlock**(*B*);

- 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

- 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

- 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

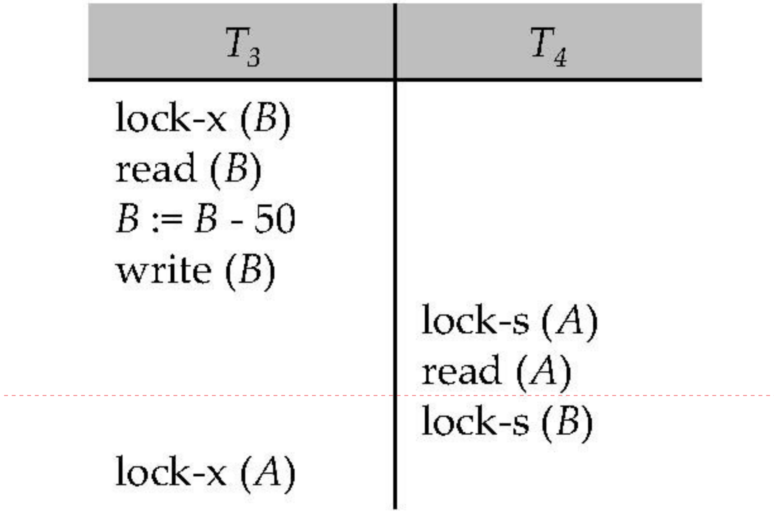
- A transaction T_i issues the standard read/write instruction, without explicit locking calls
- The operation **write*(D)*** is processed by the DBMS as:

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

- All locks are released after commit or abort

Deadlocks

- Consider the partial schedule



T_3	T_4
lock-x (B)	
read (B)	
B := B - 50	
write (B)	
	lock-s (A)
	read (A)
	lock-s (B)
lock-x (A)	

- Neither T_3 nor T_4 can make progress
  - executing **lock-S**(*B*) causes T_4 to wait for T_3 to release its lock on ,
  - 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 & Starvation

- Two-phase locking protocol
  - guarantees *serializability*
  - does *not* ensure freedom from deadlocks
- 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
  - The same transaction is repeatedly rolled back due to deadlocks
  - Concurrency control manager can be designed to prevent starvation

Deadlocks

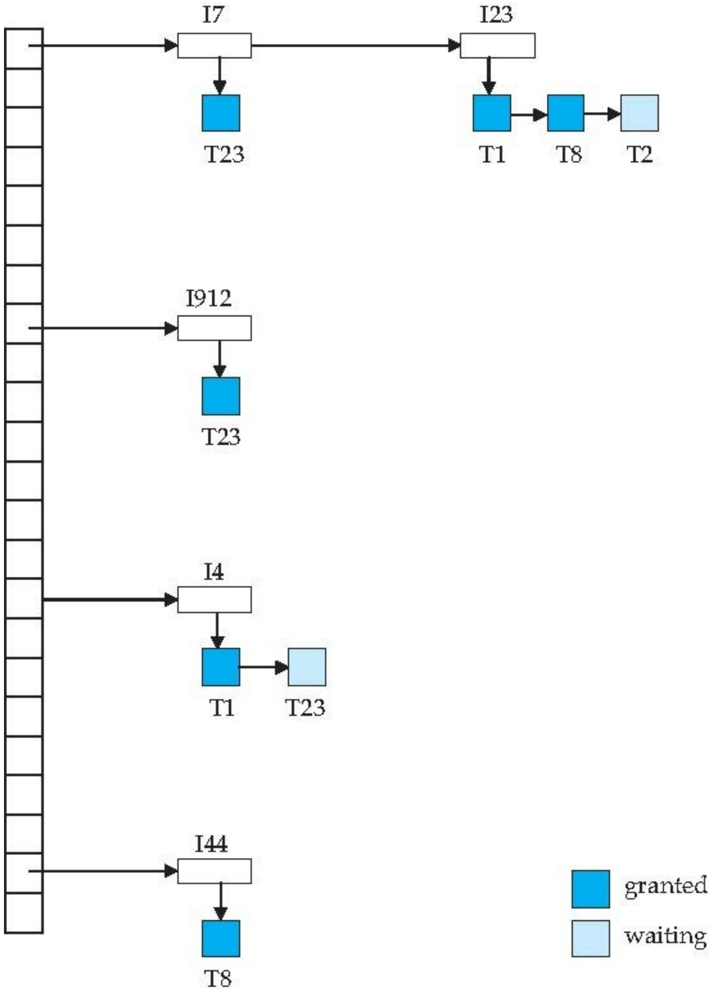
- The potential for deadlock exists in most locking protocols
  - but there are prevention mechanisms (see later)
- When a deadlock occurs
  - rollbacks are necessary
  - there is a possibility of cascading roll-backs
    - but cascading rollbacks can be expensive
- Cascading roll-back is possible under two-phase locking
- Modified protocol called **strict two-phase locking**
  - a transaction must hold all its exclusive locks until it commits/aborts
  - avoids cascading rollbacks

Implementation of Locking

- 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 requesting transaction waits until its request is answered
- The lock manager maintains a data-structure called a **lock table** to record granted locks and pending requests
  - The lock table is usually implemented as an in-memory hash table indexed on the name of the data item being locked

Lock Table

- Dark blue rectangles indicate granted locks; light blue indicate waiting requests
  - Lock table also records the type of lock granted or requested
- New request is added to the end of the queue of requests for the data item
  - granted if it is compatible with all earlier locks
- Unlock requests result in the request being deleted
  - later requests are checked to see if they can now be granted
- If transaction aborts, all waiting or granted requests of the transaction are deleted
  - lock manager may keep an index of locks held by each transaction, to implement this efficiently



Deadlock Prevention

- System is deadlocked:
  - there is a set of transactions such that every transaction in the set is waiting for another transaction in the set
- ***Deadlock prevention*** protocols
  - ensure that the system will *never* enter into a deadlock state
- Some prevention strategies :
  - Require that each transaction locks all its data items before it begins execution (predeclaration)
  - Impose partial ordering of all data items and require that a transaction can lock data items only in the order specified by the partial order

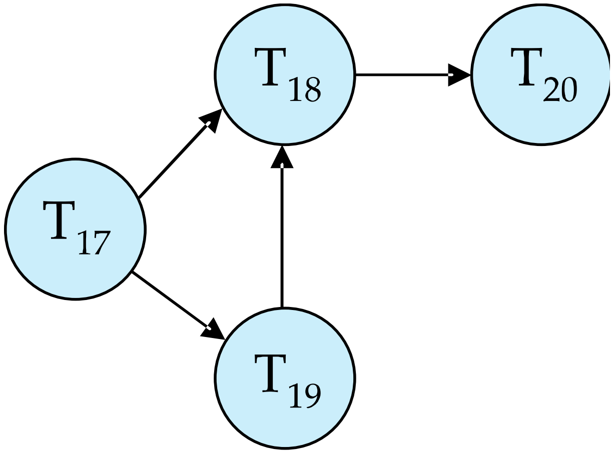
Deadlock Prevention

- **timeout-based schemes**
  - transactions wait for a lock only for a specified amount of time
    - if the lock has not been granted within that time → roll back
  - simple to implement; but starvation is possible
  - also difficult to determine good value of the timeout interval
- **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 before acquiring needed data item
- **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

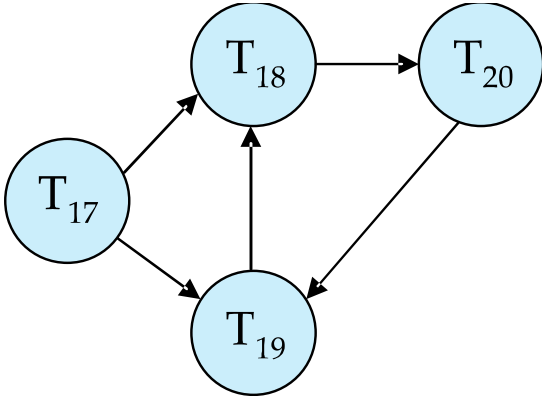
Deadlock Detection

- Deadlocks can be detected using a *wait-for graph*, which consists of a pair $G = (V,E)$
  - V is a set of vertices (all the transactions in the system)
  - E is a set of edges; each element is an ordered pair $T_i \rightarrow T_j$.
  - Edge from T_i to T_j implies that T_i is waiting for T_j to release a data item
- T_i requests a lock on a data item currently being locked by T_j,
  - the edge $T_i \rightarrow T_j$ is inserted in the wait-for graph
- 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 ↔ the wait-for graph has a cycle
  - invoke a deadlock-detection algorithm periodically to look for cycles

Deadlock Detection



Wait-for graph without a cycle



Wait-for graph with a cycle

Deadlock Recovery

- When deadlock is detected :
  - some transaction will have to rolled back (made a victim)
  - select that transaction as 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

Timestamp-based Scheduling

- Each transaction is issued a timestamp 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-timestamp**(*Q*) is the largest time-stamp of any transaction that executed **write**(*Q*) successfully
  - **R-timestamp**(*Q*) is the largest time-stamp of any transaction that executed **read**(*Q*) successfully

Timestamp-based Scheduling

- Transaction T_i issues a **read**(Q)
  - if TS(T_i) > **W**-timestamp(Q)
    - execute **read** operation, set R-timestamp(Q) to **max**(R-timestamp(Q),TS(T_i))
  - if TS(T_i) ≤ **W**-timestamp(Q),
    then T_i needs to read a value of Q that was already overwritten

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

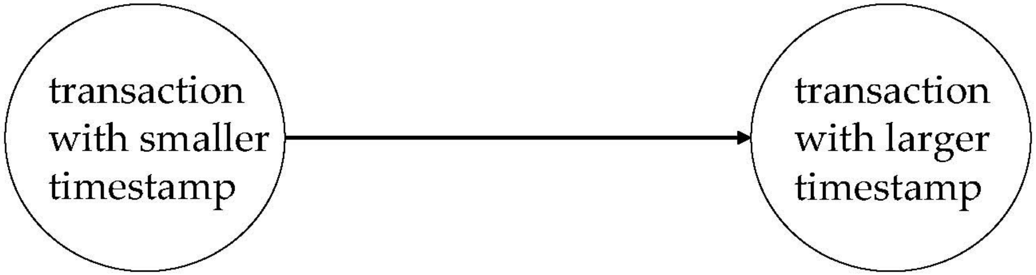
    → reject **write**, rollback T_i
  - if TS(T_i) < W-timestamp(Q), then T_i is attempting to write an obsolete value of Q

    → reject **write**, rollback T_i
  - Otherwise, execute **write** and set W-timestamp(Q) to TS(T_i)

Thomas Write Rule: we can also simply ignore this **write**

Timestamp-based Scheduling

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


transaction with smaller timestamp
transaction with larger timestamp

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

- 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

- 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

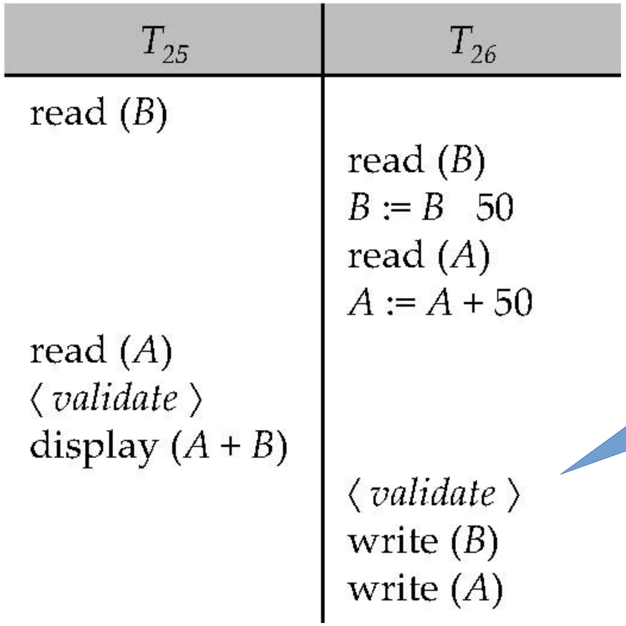
Validation Test for Transaction T_j

- 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

Validation Test for Transaction T_j

- Example schedule using validation:



T_{25}	T_{26}
read (B)	
	read (B)
	$B := B \quad 50$
	read (A)
	$A := A + 50$
read (A)	
⟨ *validate* ⟩	
display ($A + B$)	
	⟨ *validate* ⟩
	write (B)
	write (A)

T_{25} has not written anything read by T_{26}

Insert and Delete Operations

- If two-phase locking is used :
  - A **delete** operation may be performed only if the transaction deleting the tuple has an exclusive lock on the tuple to be deleted
  - A transaction that **insert**s a new tuple into the database is given an exclusive lock on the tuple
- Insertions and deletions can lead to the **phantom phenomenon**
- A transaction that scans a relation

  (e.g., read number of all accounts in Perryridge)

  and a transaction that inserts a tuple in the relation

  (e.g., insert a new account at Perryridge)

  (conceptually) conflict in spite of not accessing any tuple in common

Insert and Delete Operations

- The transaction scanning the relation is reading information that indicates what tuples the relation contains
  - while a transaction inserting a tuple updates the same information
- The conflict should be detected, e.g., by locking the information
- One solution:
  - Associate a data item with the relation, to represent the information about what tuples the relation contains
  - Transactions scanning the relation acquire a shared lock in the data item
  - Transactions inserting or deleting a tuple acquire an exclusive lock on the data item.
    (Note: locks on the data item do not conflict with locks on individual tuples.)
- Above protocol provides very low concurrency for insertions/deletions
  - Index locking protocols provide higher concurrency while preventing the phantom phenomenon
  - requiring locks on certain index buckets

Index Locking Protocol

- Index locking protocol
  - Every relation must have at least one index
  - A transaction can access tuples only after finding them through one or more indices on the relation
- A transaction T_i that performs a lookup must lock all the index leaf nodes that it accesses, in S-mode
  - Even if the leaf node does not contain any tuple satisfying the index lookup (e.g. for a range query, no tuple in a leaf is in the range)
- A transaction T_i that inserts, updates or deletes a tuple t_i in a relation r
  - must update all indices to r
  - must obtain exclusive locks on all index leaf nodes affected by the insert/update/delete
- The rules of the two-phase locking protocol must be observed
  - Guarantees that phantom phenomenon does not occur

Concurrency in Index Structures

- Indices are unlike other database items
  - their only job is to help in accessing the actual data
- Index structures are typically accessed very often
  - much more than other database items
  - Treating index-structures like other database items,
    e.g. by 2-phase locking of index nodes can lead to low concurrency
- Special protocols for index structures
  - e.g., locks on internal nodes are released early, instead of two-phase fashion
  - it is acceptable to have nonserializable concurrent access to an index as long as the accuracy of the index is maintained
  - in particular, the exact values read in an internal node of a
    B^+-tree are irrelevant so long as we end up in the correct leaf node

Concurrency in Index Structures

- Example of index concurrency protocol:Use **crabbing** instead of two-phase locking on the nodes of the B$^+$-tree, as follows
- During search/insertion/deletion:
  - First lock the root node in shared mode
  - After locking all required children of a node in shared mode, release the lock on the parent node
- During insertion/deletion
  - upgrade leaf node locks to exclusive mode
- When splitting or coalescing requires changes to a parent
  - lock the parent in exclusive mode
- Above protocol can cause excessive deadlocks
  - Searches coming down the tree deadlock with updates going up the tree
  - Can abort and restart search, without affecting transaction
  - Better protocols are available; e.g., the B-link tree protocol
    - Intuition: release lock on parent before acquiring lock on child

Summary

- 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
  - for “normal” data
  - for indices

Questions?