Courses B0B36DBS, A4B33DS, A7B36DBS: **Database Systems**

Lecture 11:

Database Transactions

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Today’s lecture outline

- motivation and the ACID properties
- schedules („interleaved“ transaction execution)
  - serializability
  - conflicts
  - (non)recoverable schedule
- locking protocols
  - 2PL, strict 2PL, conservative 2PL
  - deadlock and prevention
  - phantom
- alternative protocols

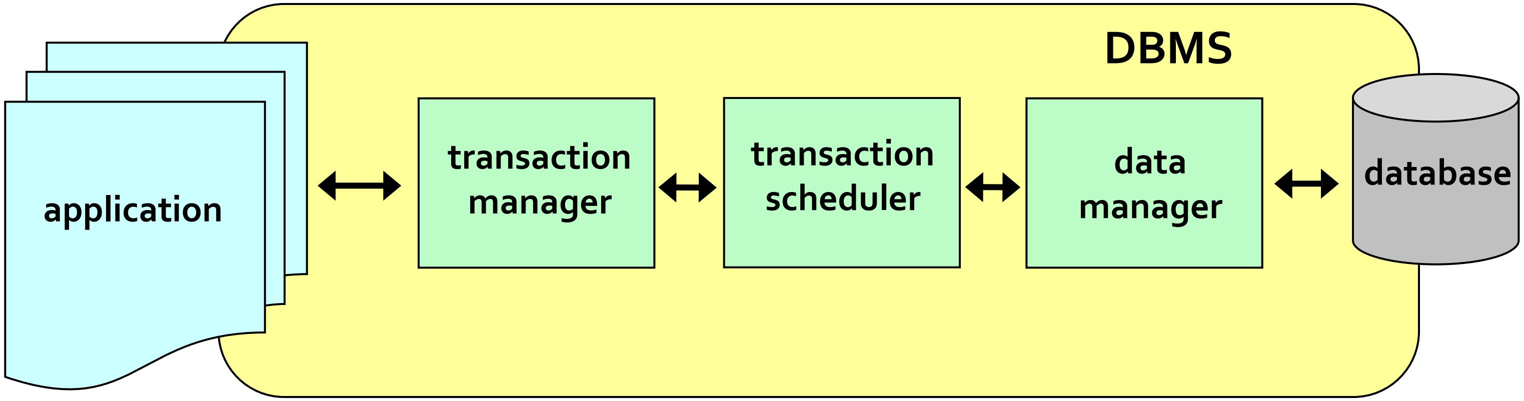
Motivation

- problem: we need to execute complex database operations
  - e.g., stored procedures, triggers, etc.
  - in a multi-user and parallel environment
- database transaction
  - **<u>sequence of actions</u>** on database objects (+ others like arithmetic, etc.)
- example:
  - Let us have a bank database with table ***Accounts*** and the following transaction to transfer the money (pseudocode):

```
transaction PaymentOrder(amount, fromAcc, toAcc)
      {
       SELECT Balance INTO X FROM Accounts WHERE accNr = fromAcc;
       if (X < amount) AbortTransaction("Not enough money!");
       UPDATE Accounts SET Balance = Balance – amount WHERE accNr = fromAcc;
       UPDATE Accounts SET Balance = Balance + amount WHERE accNr = toAcc;
       CommitTransaction;
      }
```

Transaction management in DBMS

- application launches transactions
- transaction manager executes transactions
- scheduler dynamically schedules the parallel transaction execution, producing a **schedule** (history)
- data manager executes partial operation of transactions



Transaction management in DBMS

- transaction termination
  - **successful** – terminated by **COMMIT** command in the transaction code
    - the performed actions are confirmed
  - **unsuccessful** – transaction is cancelled
    1. termination by the transaction code **– ABORT** (or **ROLLBACK**) command
       - user can be notified
    2. system abort – DBMS aborts the transaction
       - some integrity constraint is violated – user is notified
       - by transaction scheduler (e.g., a deadlock occurs) – user is not notified
    3. system failure – HW failure, power loss – transaction must be restarted
- main objectives of transaction management
  - enforcement of **ACID properties**
  - maximal performance (throughput)
    - parallel/concurrent execution of transactions

ACID – desired properties of transaction management

- **A**tomicity – partial execution is not allowed (all or nothing)
  - prevents from incorrect transaction termination (or failure)

  = consistency at the DBMS level
- **C**onsistency
  - any transaction will bring the database from one **consistent** (valid) state to another

  = consistency at application level
- **I**solation
  - transactions executed in parallel do not “see” effects of each other unless committed
  - parallel/concurrent execution is necessary to achieve high throughput
- **D**urability
  - once a transaction has been committed, it will remain so, even in the event of power loss, crashes, or errors
  - logging necessary (log/journal maintained)

Transaction

- an executed transaction is a sequence of actions

  T = <A_T^1, A_T^2, ... , COMMIT or ABORT>
- basic database actions (operations)
- for now consider a **static database** (no inserts/deletes, just updates), let **A** be a database object (table, row, attribute in row)
  - we omit other actions such as control construct (if, for), etc.
- **READ**(A) – reads A from database
- **WRITE**(A) – writes A to database
- **COMMIT** – confirms executed actions as valid, terminates transaction
- **ABORT** – cancels executed actions, terminates transaction (with error)
- SQL commands **SELECT**, **INSERT**, **UPDATE**, could be viewed as transactions implemented using the basic actions (in SQL command **ROLLBACK** is used instead of abort)

Example:

Subtract 5 from A (some attribute), such that A>0.

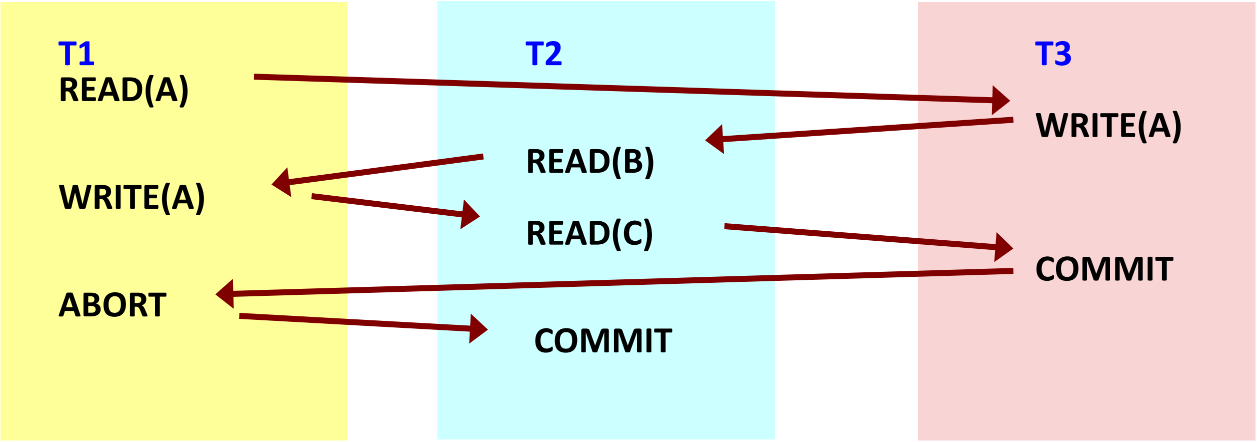
T = <READ(A), **// action 1**
if $(A \leq 5)$ ***then ABORT***
else **WRITE(A – 5),** **// action 2**
COMMIT> **// action 3**

or

T = <READ(A), **// action 1**
if $(A \leq 5)$ ***then*** **ABORT** **// action 2**
else ... **>**

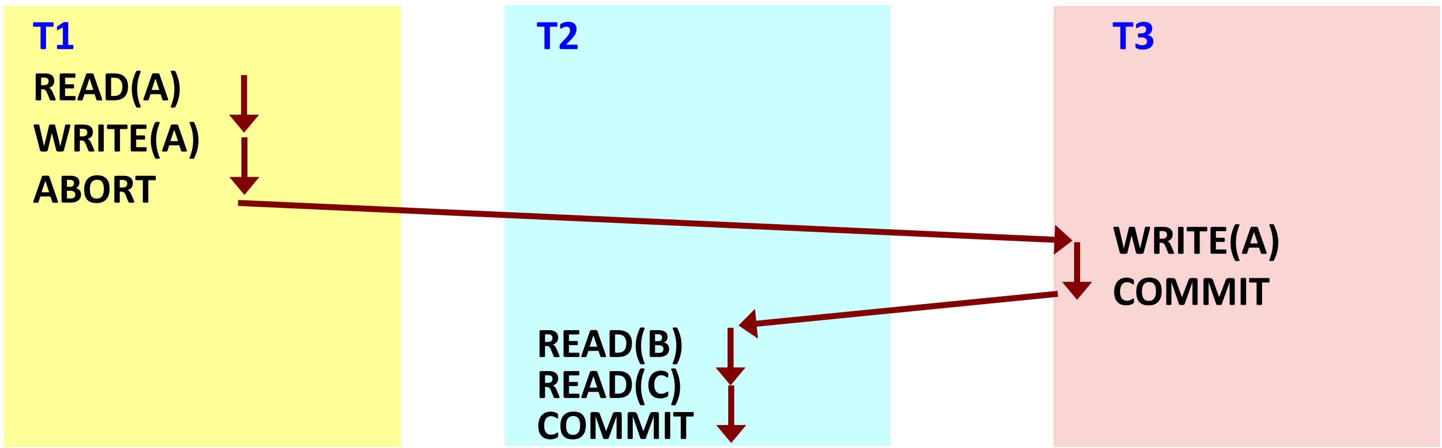
Transaction programs vs. schedules

- **database program**
  - "design-time" (not running) piece of code (that will be executed as a transaction)
  - i.e., nonlinear – branching, loops, jumps
- **schedule** (history) is a sorted list of actions coming from several transactions (i.e., transactions as interleaved)
  - „runtime" history **of already concurrently executed** actions of **several** transactions
  - i.e., linear – sequence of primitive operations, w/o control constructs



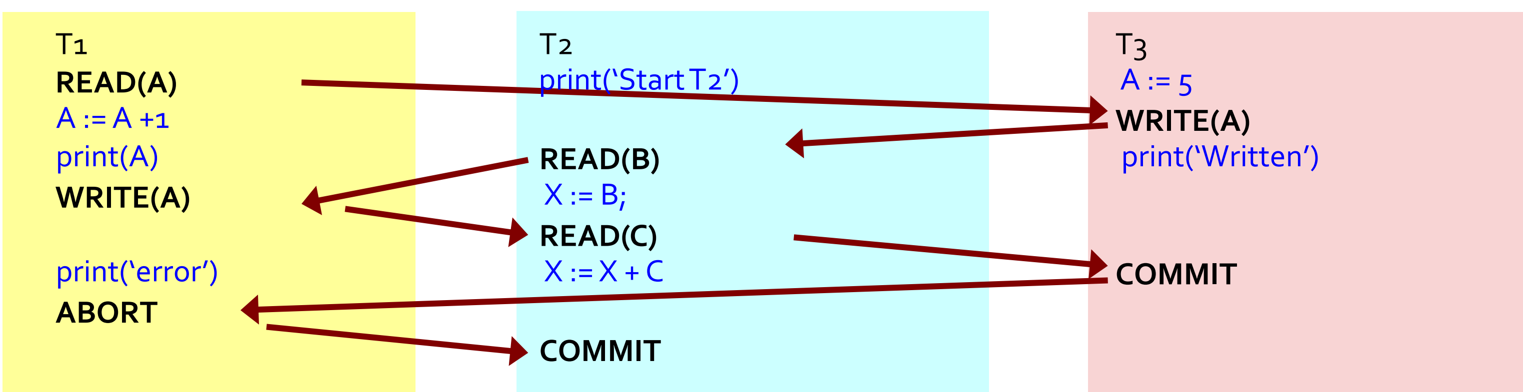
Serial schedules

- specific schedule, where all actions of a transaction are coupled together
  - no action interleaving
- given a set *S* of transactions, we can obtain |S|! serial schedules
  - from the definition of ACID properties, all the schedules are equivalent – it does not matter if one transaction is executed before or after another one
    - if it matters, they are not independent and so they should be merged into single transactions
- example:



Why to interleave transactions?

- every schedule leads to interleaved **sequential** execution of transactions (there is <u>no parallel execution</u> of database operations)
  - simplified model justified by single storage device
- <u>Question:</u> So why to interleave transactions when the number of steps is the same as in a serial schedule?
- two reasons
  - parallel execution of non-database operations with database operations
  - response proportional to transaction complexity (e.g., OldestEmployee vs. ComputeTaxes)
- example

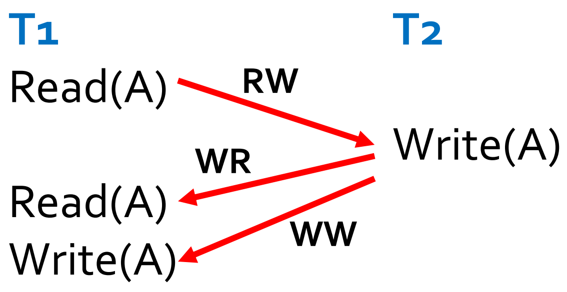


Serializability

- a schedule is **serializable** if its execution leads to consistent database state, i.e., if the schedule is **equivalent to any serial schedule**
  - for now we consider only committed transactions and a static database
  - note that non-database operations are not considered so that consistency cannot be provided for non-database state (e.g., print on console)
  - it does not matter which serial schedule is equivalent (independent transactions)
- strong property
  - secures the Isolation and Consistency in ACID
- **view serializability** extends serializability by including aborted transactions and dynamic database
  - however, testing is NP-complete, so it is not used in practice
  - instead, **conflict serializability** + other techniques are used

“Dangers” caused by interleaving

- to achieve serializability (i.e., consistency and isolation), the action of interleaving cannot be arbitrary
- there exist 3 types of local dependencies in the schedule, so-called <u>conflict pairs</u>
- four possibilities of reading/writing the same resource in schedule
  - read-read – ok, by reading the transactions do not affect each other
  - write-read (WR) – T1 writes, then T2 reads – reading uncommitted data
  - read-write (RW) – T1 reads, then T2 writes – unrepeatable reading
  - write-write (WW) – T1 writes, then T2 writes – overwrite of uncommitted data



Conflicts (WR)

- reading uncommitted data (**write-read conflict**)
  - transaction T2 reads A that was earlier updated by transaction T1, but T1 did not commit so far, i.e., T2 reads potentially inconsistent data
    - so-called **dirty read**

Example: T1 transfers 1000 USD from account A to account B (A = 12000, B = 10000)
T2 adds 1% per account

T1	T2
R(A) // A = 12000	
A := A – 1000	
W(A) // database is now inconsistent – account B still contains the old balance	
	R(A) // uncommitted data is read
	R(B)
	A := 1.01*A
	B := 1.01*B
	W(A)
	W(B)
	COMMIT
R(B) // B = 10100	
B := B + 1000	
W(B)	
COMMIT // inconsistent database, A = 11110, B = 11100	

Conflicts (RW)

- unrepeatable read (**read-write conflict**)
  - transaction T2 writes A that was read earlier by T1 that didn't finish yet
  - T1 cannot repeat the reading of A (A now contains another value)
    - so-called **unrepeatable read**

Example: T1 transfers 1000 USD from account A to account B (A = 12000, B = 10000)
T2 adds 1% per account

T1		T2	
R(A)	// A = 12000		
		R(A)	
		R(B)	
		A := 1.01*A	
		B := 1.01*B	
		W(A)	// update of A
		W(B)	
		COMMIT	
// database now contains A = 12120			
R(B)			
A := A – 1000			
W(A)			
B := B + 1000			
W(B)			
COMMIT		// inconsistent database, A = 11000, B = 11100	

Conflicts (WW)

- overwrite of uncommitted data (**write-write conflict**)
  - transaction T2 overwrites A that was earlier written by T1 that still runs
  - loss of update (original value of A is lost)
    - so-called **blind write** (update of unread data)

Example: Set the same price to all DVDs.
(let's have two instances of this transaction, one setting price to 10 USD, second 15 USD)

T1	T2	
	DVD1 := 15	
	W(DVD1)	
DVD2 := 10		
W(DVD2)		
	DVD2 := 15	
	W(DVD2)	// overwrite of uncommitted data
	COMMIT	
DVD1 := 10		
W(DVD1)		
COMMIT	// inconsistent database, DVD1 = 10, DVD2 = 15	

Conflict serializability

- two schedules are **conflict equivalent** if they share the set of conflict pairs
- a schedule is **conflict serializable** if it is conflict-equivalent to some serial schedule, i.e., there are no “real” conflicts
  - more restrictive than serializability (defined only by consistency preservation)
- conflict serializability alone does not consider:
  - cancelled transactions
    – ABORT/ROLLBACK, so the schedule could be **unrecoverable**
  - dynamic database (inserting / deleting database objects)
    – so-called **phantom** may occur
  - hence, conflict serializability is not sufficient condition to provide ACID (**view serializability** is ultimate condition)

<u>Example</u>: schedule, that is **serializable** (serial schedule <T1, T2, T3>), but **is not conflict serializable** (writes in T1 and T2 are in wrong order)

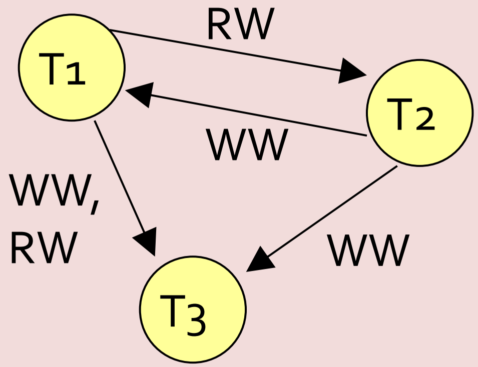
T1	T2	T3
R(A)		
	W(A)	
	COMMIT	
W(A)		
COMMIT		
		W(A)
		COMMIT

Detection of conflict serializability

- **precedence graph** (also serializability graph) on a schedule
  - nodes T_i are **committed** transactions
  - edges represent RW, WR, WW conflicts in the schedule
- schedule is conflict serializable
  if its precedence graph is **acyclic**

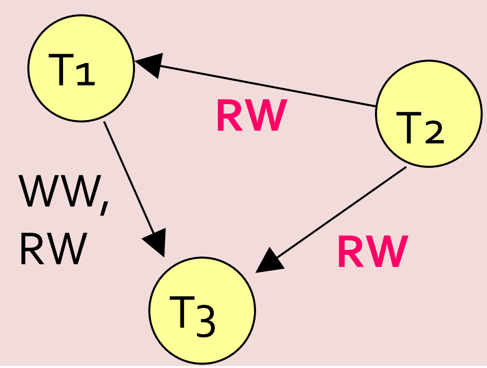
Example: not conflict serializable

T1	T2	T3
R(A)		
	W(A)	
	COMMIT	
W(A)		
COMMIT		
		W(A)
		COMMIT



Example: conflict serializable

T1	T2	T3
R(A)		
	R(A)	
	COMMIT	
W(A)		
COMMIT		
		W(A)
		COMMIT



Unrecoverable schedule

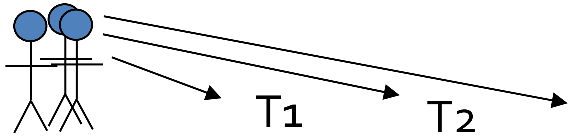
- at this moment we extend the transaction model by ABORT which brings another "danger" – **unrecoverable schedule**
  - one transaction aborts so that undos of every write must be done, however, this cannot be done for already committed transactions that read changes caused by the aborted transaction
    - durability property of ACID
- in **recoverable schedule** a transaction T is committed after all other transactions that affected T commit (i.e., they changed data later read by T)
- if reading changed data is allowed only for committed transactions, we also avoid **cascade aborts of transactions**

Example: T1 transfers 1000 USD from A to B, T2 adds annual interests

T1		T2
R(A)		
A := A - 1000		
W(A)		
		R(A)
	commited, cannot be undone! →	A := A *1.01
		W(A)
		R(B)
		B := B *1.01
	cascade aborts	**W(B)**
		COMMIT
ABORT		

Protocols for concurrent transaction scheduling

- transaction scheduler works under some **protocol** that allows to guarantee the ACID properties and maximal throughput
- **pessimistic control** (highly concurrent workloads)
  - locking protocols
  - time stamps
- **optimistic control** (not very concurrent workloads)
- why protocol?
  - the scheduler cannot create the entire schedule beforehand
  - scheduling is performed in local time context – dynamic transaction execution, branching parts in code



DB client(s)

T1	T2	T3
R(A)	R(C)	R(A)
W(B)	W(C)	R(B)
W(A)		R(C)

Schedule

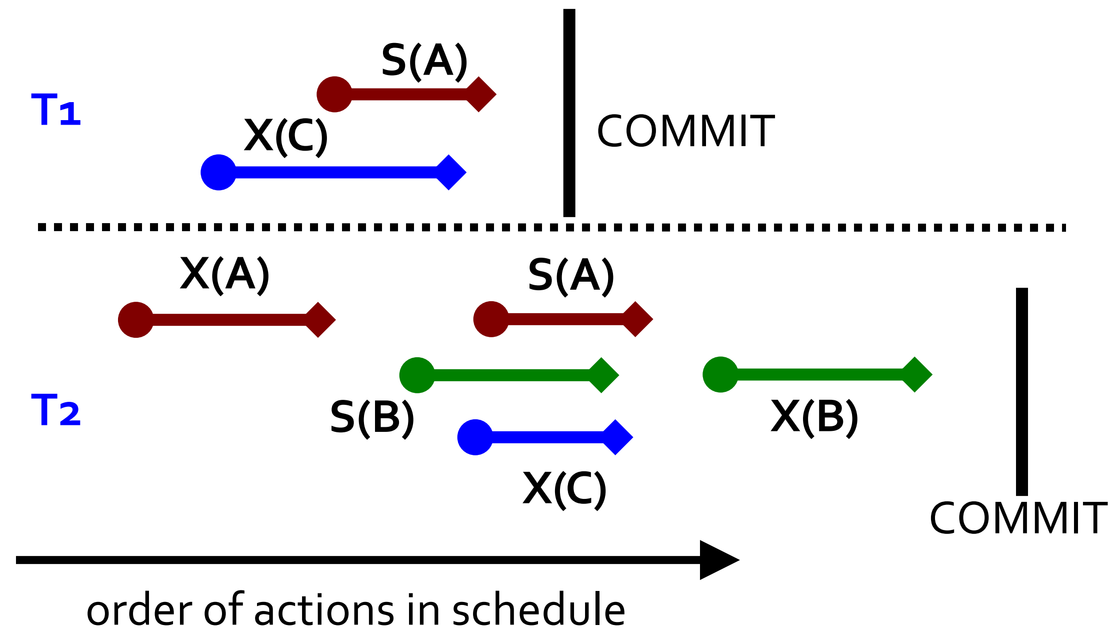
T1	T2	T3
R(A)		
	R(C)	
		R(A)
	W(C)	
		R(B)
W(B)		
W(A)		
		R(C)

Locking protocols

- locking of database entities can be used to control the order of reads and writes and so to secure the <u>conflict serializability</u>
- **exclusive locks**
  - **X(A)** locks A so that reads and writes of A are allowed only to the lock owner/creator
  - can be granted to just one transaction
- **shared locks**
  - **S(A)** – only reads of A are allowed
  - can be granted to (shared by) multiple transactions
- **unlocking** by **U(A)**
- if a lock that is not available is required for a transaction, the transaction execution is suspended and waits for releasing the lock
  - in the schedule, the lock request is denoted, followed by empty rows of waiting
- the un/locking code is added by the transaction scheduler
  - i.e., operation on locks appear just in the schedules, not in the original transaction code

Example: schedule with locking

T1	T2
	X(A)
X(C)	
	W(A)
R(C)	
W(C)	
	U(A)
S(A)	
	S(B)
R(A)	
	R(B)
U(C)	
	X(C)
U(A)	
	S(A)
COMMIT	
	W(C)
	R(A)
	U(B)
	U(C)
	U(A)
	X(B)
	W(B)
	U(B)
	COMMIT



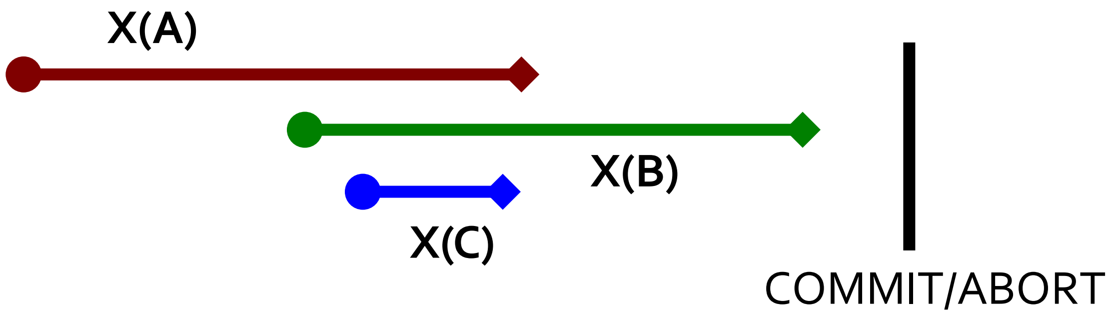
Two-phase locking protocol (2PL)

2PL protocol applies two rules for building the schedule:

1) if a transaction wants to read (write) an entity A, it must first acquire a shared (exclusive) lock on A
2) transaction **cannot requests a lock**, if it already released one (regardless of the locked entity)

Two obvious phases – locking and unlocking

Example: 2PL adjustment of the second transaction in the previous schedule

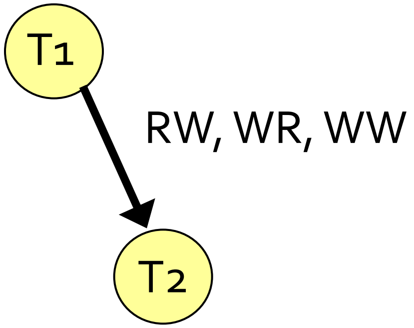


Properties of 2PL

- the 2PL restriction of schedule ensures that the precedence graph is acyclic, i.e., the schedule is **conflict serializable**
- 2PL does **not guarantee recoverable schedules**

<u>Example:</u> 2PL-compliant schedule, but not recoverable, if T1 aborts

T1	T2
X(A)	
R(A)	
W(A)	
U(A)	
	X(A)
	R(A)
	A := A *1.01
	W(A)
	X(B)
	U(A)
	R(B)
	B := B *1.01
	W(B)
	U(B)
	COMMIT
ABORT / COMMIT	

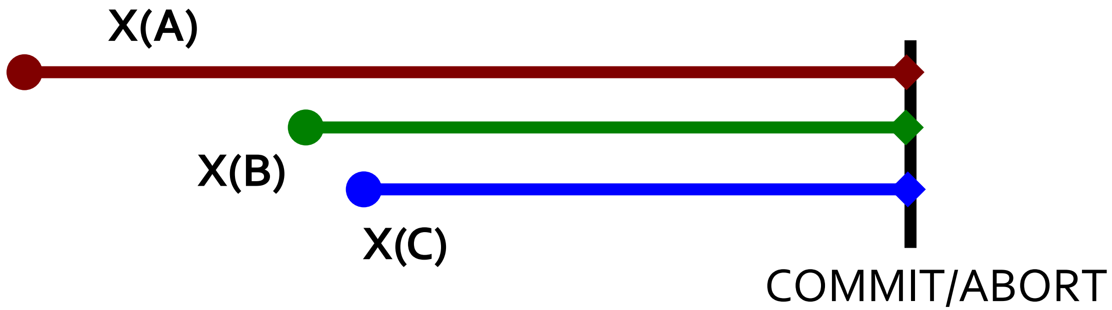


Strict 2PL

Strict 2PL protocol makes the second rule of 2PL stronger, so that both rules become:

1) if a transaction wants to read (write) an entity A, it must first acquire a shared (exclusive) lock on A
2) **all locks are released at the transaction termination**

Example: strict 2PL adjustment of second transaction in the previous example



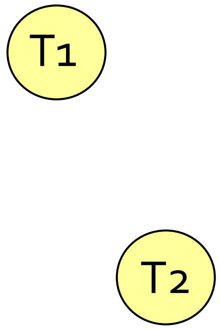
Insertions of U(A) are not needed (implicit at the time of COMMIT/ABORT).

Properties of strict 2PL

- the 2PL restriction of schedule ensures that the precedence graph is acyclic, i.e., the schedule is **conflict serializable**
- moreover, strict 2PL ensures
  - schedule **recoverability**
  - avoids **cascade aborts**

<u>Example:</u> schedule built using strict 2PL

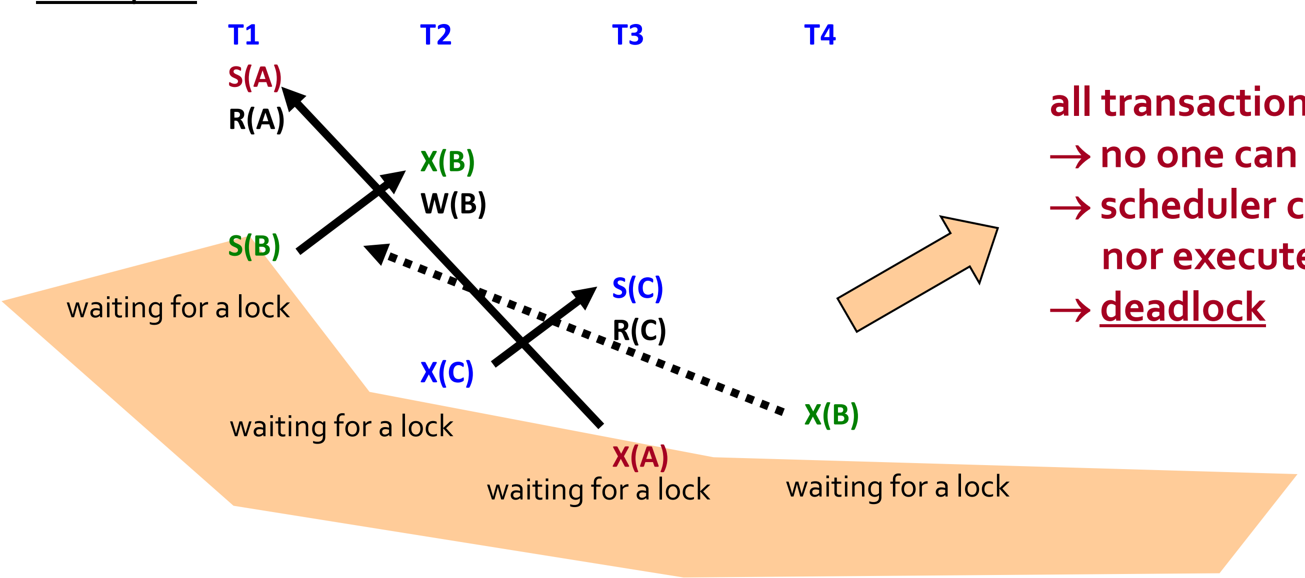
T1	T2
S(A)	
R(A)	
	S(A)
	R(A)
	X(B)
X(C)	
R(C)	
	R(B)
	W(B)
	COMMIT
W(C)	
ABORT / COMMIT	



Deadlock

- during transaction execution it may happen that transaction T_1 requests a lock that was already granted to T_2, but T_2 cannot release it because it waits for another lock kept by T_1
  - could be generalized to multiple transactions, T1 waits for T_2, T_2 waits for T_3, ..., T_n waits for T_1
- strict 2PL cannot prevent from deadlock (not speaking about the weaker protocols)

Example:



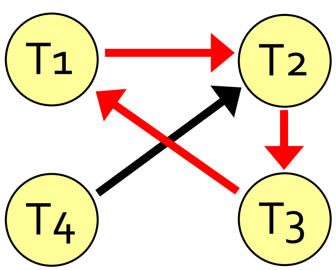
all transactions wait for a lock
→ no one can release a lock
→ scheduler cannot schedule nor execute transactions
→ <u>deadlock</u>

Deadlock detection

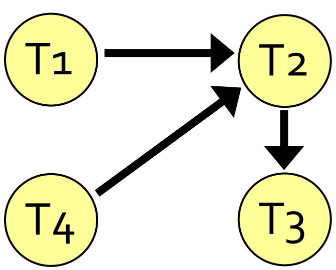
- deadlock can be detected by repeated checking the waits-for graph
- **waits-for graph** is a dynamic graph that captures the waiting of transactions for locks
  - nodes are active transactions
  - an edge denotes waiting of transaction for lock kept by another transaction
  - a cycle in the graph = **deadlock**

Example: waits-for graph for the previous example

(a) T3 requests X(A)



(b) T3 does not request X(A)



Deadlock resolution and prevention

- deadlocks are usually not very frequent, so the **resolution** could be simple
  - abort of the waiting transaction and its restart (user will not notice)
  - testing waits-for graph – if a deadlock occurs, abort and restart a transaction in the cycle
    - such transaction is aborted, that
      - holds the smallest number of locks
      - performed the least amount of work
      - is far from completion
    - an aborted transaction is not aborted again (if another deadlock occurs)
- deadlocks could be **prevented**
  - prioritizing
    - each transaction has a priority (e.g., time stamp); if T1 requests a lock kept by T2, the lock manager chooses between two strategies
      - **wait-die** – if T1 has higher priority, it can wait, if not, it is aborted and restarted
      - **wound-wait** – if T1 has higher priority, T2 is aborted, otherwise T1 waits

Coffman Conditions

- Deadlocks can arise if all of the following conditions hold simultaneously in a system
  - **Mutual exclusion** – resources can be held in a non-shareable mode
  - **Resource holding** (hold and wait) – additional resources may be requested even when already some resources are held
  - **No preemption** – resources can be released only voluntarily
  - **Circular wait** – transactions can request and wait for resources in cycles

- Unfulfillment of any of these conditions is enough to prevent deadlocks from occurring

Phantom

- now <u>consider dynamic database</u>
  - allowing inserts and deletes
- if one transaction works with some *set* of data entities, while another transaction changes this set (inserts or deletes), it could lead to inconsistent database (inserializable schedule)
  - Why? T1 locks all entities that at the given moment are relevant
    - e.g., fulfill some WHERE condition of a SELECT command
  - during execution of T1 a new transaction T2 could logically extend the set of entities
    - i.e., at that moment the number of locks defined by WHERE would be larger
    - so that some entities are locked and some are not
- applied also to strict 2PL

Example – phantom

T1: find the oldest male and female employees
(**SELECT * FROM** Employees ...) + **INSERT INTO** Statistics ...
T2: insert new employee Phill and delete employee Eve (employee replacement)
(**INSERT INTO** Employees ..., **DELETE FROM** Employees ...)

Initial state of the database: **{[Peter, 52, m], [John, 46, m], [Eve, 55, f], [Dana, 30, f]}**

T1	T2
lock men, i.e.,	
S(Peter)	
S(John)	
M = max{R(Peter), R(John)}	
	Insert(Phill, 72, m)
	X(Eve)
	Delete(Eve)
	COMMIT
lock women, i.e.,	
S(Dana)	
F = max{R(Dana)}	
Insert(M, F) // result is inserted into table Statistics	
COMMIT	

phantom

a new male employee can be inserted, although **all men** should be locked

Although the schedule is **strict 2PL** compliant, the result **[Peter, Dana]** is not correct as it does not follow the serial schedule T1, T2, resulting in **[Peter, Eve]**, nor T2, T1, resulting in **[Phill, Dana]**.

Phantom – prevention

- if there do not exist indexes, everything relevant must be locked
  - e.g., entire table or even multiple tables must be locked
- if there exist indexes (e.g., B$^+$-trees) on the entities defined by the „lock condition“, it is possible to “watch for phantom“ at the index level – **index locking**
  - external attempt for the set modification is identified by the index locks updated
  - as an index usually maintains just one attribute, its applicability is limited
- generalization of index locking is **predicate locking**, when the locks are requested for the logical sets, not particular data instances
  - however, this is hard to implement and so not used much in practice

Optimistic (not locking) protocols

- if concurrently executed transactions are not often in conflict (not competing for resources), the locking overhead is unnecessarily large
- 3-phase optimistic protocol
  1. **Read**: transaction reads data from database but writes into its private local data space
  2. **Validation**: if the transaction wants to commit, it forwards the private data space to the transaction manager (i.e., request on database update)
     - the transaction manager decides if the update is in conflict with another transaction
       - if there is a conflict, the transaction is aborted and restarted
       - if not, the last phase takes place:
  3. **Write**: the private data space is copied into the database