Database Management Systems

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CMPUT 391: Transactions & Concurrency Control

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Chapters 16 and 17 of Textbook

Course Content

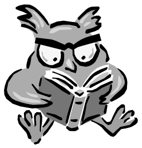
- Introduction
- Database Design Theory
- Query Processing and Optimisation
- **Concurrency Control**
- Data Base Recovery and Security
- Object-Oriented Databases
- Inverted Index for IR
- XML
- Data Warehousing
- Data Mining
- Parallel and Distributed Databases
- Other Advanced Database Topics

Objectives of Lecture 4

Transactions and Concurrency Control

- Introduce some important notions related to DBMSs such as transactions, scheduling, locking mechanisms, committing and aborting transactions, etc.
- Understand the issues related to concurrent execution of transactions on a database.
- Present some typical anomalies with interleaved executions.

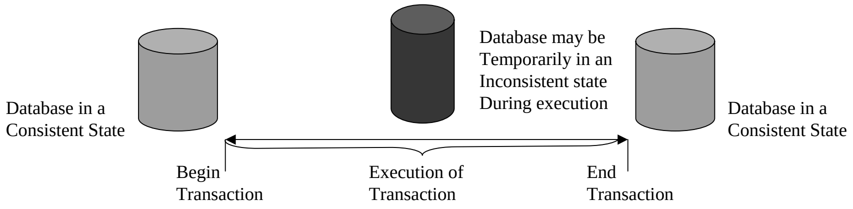
Transactions and Concurrency Control



- Transactions in a Database
- Transaction Processing
- Schedules and Serializability
- Concurrency Control Techniques
- Locking Mechanisms and Timestamps

Transaction

- A transaction is the DBMS's abstract view of a user program: a sequence of reads and writes
- A transaction is a sequence of actions that make consistent transformations of system states while preserving system consistency



Database in a Consistent State

Database may be Temporarily in an Inconsistent state During execution

Database in a Consistent State

Begin Transaction

Execution of Transaction

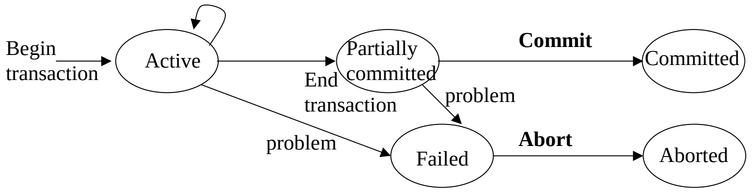
End Transaction

Transaction Operations

- A user's program may carry out many operations on the data retrieved from DB but DBMS is only concerned about Read/Write.
- A database transaction is the execution of a program that include database access operations:
  - Begin-transaction
  - Read
  - Write
  - End-transaction
  - Commit-transaction
  - Abort-transaction
  - Undo
  - Redo
- Concurrent execution of user programs is essential for good DBMS performance.

State of Transactions

- Active: the transaction is executing.
- Partially Committed: the transaction ends after execution of final statement.
- Committed: after successful completion checks.
- Failed: when the normal execution can no longer proceed.
- Aborted: after the transaction has been rolled back.



Begin transaction

Active

End transaction

Partially committed

Commit

Committed

problem

problem

Failed

Abort

Aborted

Concurrency in a DBMS

- Users submit transactions, and can think of each transaction as executing by itself.
  - Concurrency is achieved by the DBMS, which interleaves actions (reads/writes of DB objects) of various transactions.
  - Each transaction must leave the database in a consistent state if the DB is consistent when the transaction begins.
    - DBMS will enforce some ICs, depending on the ICs declared in CREATE TABLE statements.
    - Beyond this, the DBMS does not really understand the semantics of the data. (e.g., it does not understand how the interest on a bank account is computed).
- <u>*Issues:*</u> Effect of *interleaving* transactions, and *crashes*.

Transactions and Concurrency Control

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Transaction Properties

The acronym ACID is often used to refer to the four properties of DB transactions.

- **A**tomicity (all or nothing)
  - A transaction is *atomic*: transaction always executing all its actions in one step, or not executing any actions at all.
- **C**onsistency (no violation of integrity constraints)
  - A transaction must preserve the consistency of a database after execution. (responsibility of the user)
- **I**solation (concurrent changes invisible➔serializable)
  - Transaction is protected from the effects of concurrently scheduling other transactions.
- **D**urability (committed updates persist)
  - The effect of a committed transaction should persist even after a crash.

Atomicity

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

Consistency

- A transaction which executes *alone* against a consistent database leaves it in a *consistent* state.
- Transactions do not violate database integrity constraints.
- Transactions are *correct* programs

Isolation

- If several transactions are executed concurrently, the results must be the same as if they were executed serially in some order (serializability).
- An incomplete transaction cannot reveal its results to other transactions before its commitment.
- Necessary to avoid cascading aborts.

Durability

- Once a transaction commits, the system must guarantee that the result of its operations will never be lost, in spite of subsequent failures.
- Database recovery (will be discussed in the next lecture)

Example

- Consider two transactions:

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

- Intuitively, the first transaction is transferring $100 from B’s account to A’s account. The second is crediting both accounts with a 6% interest payment.
- There is no guarantee that T1 will execute before T2 or vice-versa, if both are submitted together.
- **However, the net effect *must* be equivalent to these two transactions running serially in some order.**

Example (Contd.)

- Consider a possible interleaving (*schedule*):

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

- This is OK. But what about:

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

- The DBMS’s view of the second schedule:

T1:	R(A), W(A),		R(B), W(B)
T2:		R(A), W(A), R(B), W(B)	

T1	T2
Read(A)	
A=A+100	
Write(A)	
	Read(A)
	A=A*1.06
	Write(A)
	Read(B)
	B=B*1.06
	Write(B)
Read(B)	
B=B-100	
Write(B)	

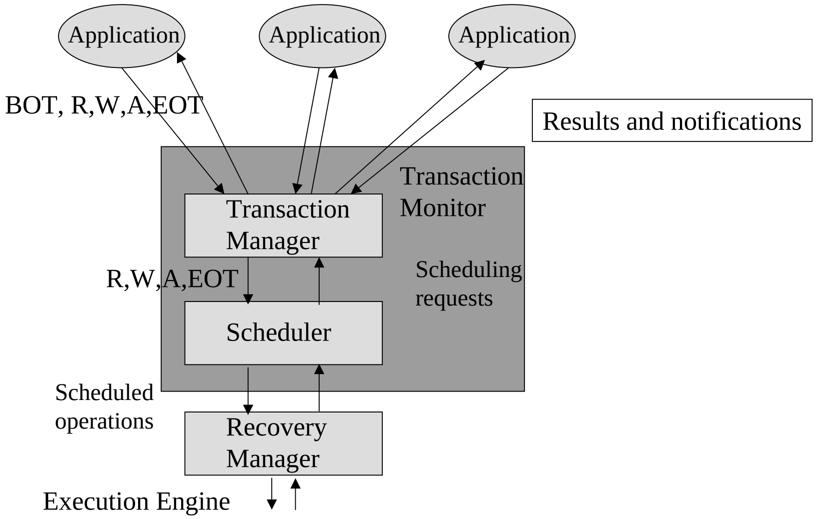
T1	T2
Read(A)	
A=A+100	
Write(A)	
	Read(A)
	A=A*1.06
	Write(A)
Read(B)	
B=B-100	
Write(B)	
	Read(B)
	B=B*1.06
	Write(B)

T1	T2
	Read(A)
	A=A*1.06
	Write(A)
Read(A)	
A=A+100	
Write(A)	
	Read(B)
	B=B*1.06
	Write(B)
Read(B)	
B=B-100	
Write(B)	

T1	T2
	Read(A)
	A=A*1.06
	Write(A)
Read(A)	
A=A+100	
Write(A)	
Read(B)	
B=B-100	
Write(B)	
	Read(B)
	B=B*1.06
	Write(B)

The net effect of an interleaved execution of T1 and T2 must be equivalent to the effect of running T1 and T2 in some serial order!

Transaction Execution


Application
Application
Application
BOT, R,W,A,EOT
Results and notifications
Transaction Monitor
Transaction Manager
Scheduling requests
R,W,A,EOT
Scheduler
Scheduled operations
Recovery Manager
Execution Engine

Transactions and Concurrency Control

- Transactions in a Database
- Transaction Processing
- Schedules and Serializability
- Concurrency Control Techniques
- Locking Mechanisms and Timestamps

Scheduling Transactions

- *A Schedule* is a sequential order of the instructions (R / W / A / C) of *n* transactions such that the ordering of the instructions of each transaction is preserved. (execution sequence preserving the operation order of individual transaction)
- *Serial schedule:* A schedule that does not interleave the actions of different transactions. (transactions executed consecutively)
- *Non-serial schedule*: A schedule where the operations from a set of concurrent transactions are interleaved.

S1

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

S2

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

Scheduling Transactions (continue)

- *Equivalent schedules*: For any database state, the effect (on the set of objects in the database) of executing the first schedule is identical to the effect of executing the second schedule.
- *Serializable schedule*: A non-serial schedule that is equivalent to some serial execution of the transactions.

  (Note: If each transaction preserves consistency, every serializable schedule preserves consistency.)
- Two schedules are conflict equivalent if:
  - Involve the same actions of the same transactions
  - Every pair of conflicting actions is ordered the same way
- Schedule S is conflict serializable if S is conflict equivalent to some serial schedule

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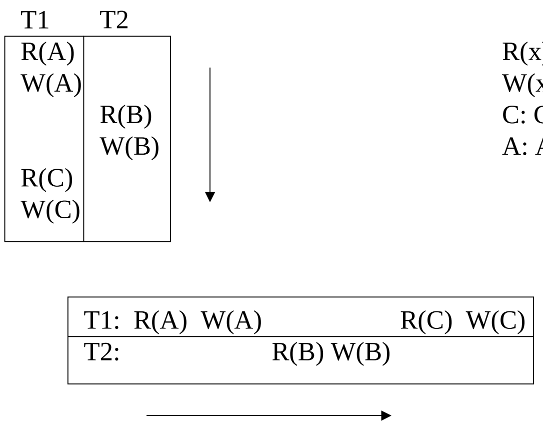
Schedule Conventions



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

R(x): Read x from disk
W(x): Write x to disk
C: Commit
A: Abort

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

Conflicts of Operations

- If two transactions only read a data object, they do not conflict and the order is not important
- If two transactions either read or write completely separate data objects, they do not conflict and the order is not important.
- If one transaction writes a data object and another either reads or writes the same data object, the order of execution is important.

	Read(x)	Write(x)
Read(x)	No	Yes
Write(x)	Yes	Yes

WR conflict: T2 reads a data objects previously written by T1
RW conflict: T2 writes a data object previously read by T1
WW conflict: T2 writes a data object previously written by T1

Anomalies with Interleaved Execution

- Reading Uncommitted Data (WR Conflicts, “dirty reads”: read an object modified by uncommited transaction.):

Aka:
Uncommitted Dependency
Dirty read problem

- T1 transfers $100 from A to B
- T2 adds 6% to A and B
- Avoid cascading aborts

T1:	R(A), W(A),		R(B), W(B), Abort
T2:		R(A), W(A),R(B),W(B), C	

Anomalies (Continued)

- Unrepeatable Reads (RW Conflicts):

  T1 tries to read a data object again after T2 modified it. The data object may have a different value.

T1:	R(A),		R(A), W(A), C
T2:		R(A), W(A), C	

Also,
T1 reads A and add 1. T2 Reads A and subtracts 1. If A initially 5, result should be 5
However: T1: R(A) A+1 W(A)
T2: R(A) A-1 W(A)

Anomalies (Continued)

- Overwriting Uncommitted Data (WW Conflicts) “blind write”:
  - T1 sets salaries to $1000 and T2 sets salaries to $2000
  - Constraint: Salaries must be kept equal.

T1:	W(A),		W(B), C
T2:		W(A), W(B), C	

The Inconsistent Analysis Problem

- Occurs when a transaction reads several values from a database while a second transaction updates some of them.

T1	T2	A	B	C	sum
sum=0		$100	$50	$25	0
R(A)	R(A)	$100	$50	$25	0
sum=sum+A	A=A-10	$100	$50	$25	100
R(B)	W(A)	$90	$50	$25	100
sum=sum+B	R(C)	$90	$50	$25	150
	C=C+10	$90	$50	$25	150
	W(C)	$90	$50	$35	150
R(C)		$90	$50	$35	150
sum=sum+C		$90	$50	$35	185

Should be 175

Serializability

- The objective of *serializability* is to find non-serial schedules that allow transactions to execute concurrently without interfering with one another, and thereby produce a database state that could be produced by a serial execution.
- It is important to guarantee serializability of concurrent transactions in order to prevent inconsistency from transactions interfering with one another.
- In serializability, the ordering of read and write operations is important (see conflict of operations).
- See the following schedules how the order of R/W operations can be changed depending upon the data objects they relate to.

Schedules Example

S1

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

S2

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

S3

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

In S2: change the order of W(A)in T2 with W(B) in T1
In S2: change the order of R(A) in T2 with R(B) in T1
In S2: change the order of ((A) in T2 with W(B) in T1

➔ S3

Dependency Graph

- *<u>Dependency graph</u> (or precedence graph)*:
  - One node per transaction;
  - edge from *Ti* to *Tj* if *Tj* reads/writes an object last written by *Ti*.
- <u>Theorem</u>: Schedule is conflict serializable if and only if its dependency graph is acyclic

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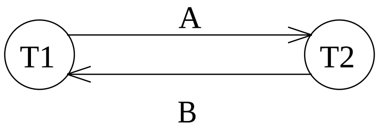
Example

- A schedule that is not conflict serializable:

T1:	R(A), W(A),		R(B), W(B)
T2:		R(A), W(A), R(B), W(B)	



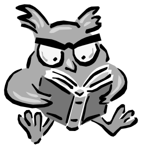
Dependency graph

- The cycle in the graph reveals the problem. The output of T1 depends on T2, and vice-versa.

Algorithm for Testing Serializability of a Schedule S

1. For each transaction T_i in S
   create a node labeled T_i in the precedence graph.
2. For each case in S where T_j executes a Read(x) after a Write(x) executed by T_i
   create an edge (T_i,T_j) in the precedence graph
3. For each case in S where T_j executes a Write(x) after a Read(x) executed by T_i
   create an edge (T_i,T_j) in the precedence graph
4. For each case in S where T_j executes a Write(x) after a Write(x) executed by T_i
   create an edge (T_i,T_j) in the precedence graph
5. S is serializable iff the precedence graph has no cycles

Transactions and Concurrency Control



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Definitions

- **Locking**: A procedure used to control concurrent access to data. When one transaction is accessing the database, a lock may deny access to other transactions to prevent incorrect results.
- **Shared Lock** (or read lock): If a transaction has a shared lock on a data object, it can read the object but not update it.
- **Exclusive Lock** (or write lock): if a transaction has an exclusive lock on a data object, it can both read and update the object.

Serializability in Practice

- In practice, a DBMS does not test for serializability of a given schedule. This would be impractical since the interleaving of operations from concurrent transactions could be dictated by the OS and thus could be difficult to impose.
- The approach taken by the DBMS is to use specific protocols that are known to produce serializable schedules.
- These protocols could reduce the concurrency but eliminate conflicting cases.

Lock-Based Concurrency Control

- *Strict Two-phase Locking (Strict 2PL) Protocol*:
  - Each transaction must obtain a S (*shared*) lock on object before reading, and an X (*exclusive*) lock on object before writing.
  - All locks held by a transaction are released when the transaction completes
  - If a transaction holds an X lock on an object, no other transaction can get a lock (S or X) on that object.
- Strict 2PL allows only serializable schedules.

Aborting a Transaction

- If a transaction T_i is aborted, all its actions have to be undone. Not only that, if T_j reads an object last written by T_i, T_j must be aborted as well!
- Most systems avoid such *cascading aborts* by releasing a transaction's locks only at commit time.
  - If T_i writes an object, T_j can read this only after T_i commits.
- In order to *undo* the actions of an aborted transaction, the DBMS maintains a *log* in which every write is recorded. This mechanism is also used to recover from system crashes: all active transactions at the time of the crash are aborted when the system comes back up.

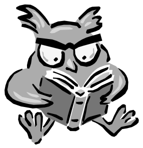
The Log

- The following actions are recorded in the log:
  - T_i *writes an object*: the old value and the new value.
    - Log record must go to disk *before* the changed page!
  - T_i *commits/aborts*: a log record indicating this action.
- Log records are chained together by transaction id, so it's easy to undo a specific transaction.
- Log is often *duplexed* and *archived* on stable storage.
- All log related activities (and in fact, all CC related activities such as lock/unlock, dealing with deadlocks etc.) are handled transparently by the DBMS.

Recovering From a Crash

- There are 3 phases in the *Aries* recovery algorithm:
  - *Analysis*: Scan the log forward (from the most recent *checkpoint*) to identify all transactions that were active, and all dirty pages in the buffer pool at the time of the crash.
  - *Redo*: Redoes all updates to dirty pages in the buffer pool, as needed, to ensure that all logged updates are in fact carried out and written to disk.
  - *Undo*: The writes of all transactions that were active at the crash are undone (by restoring the *before value* of the update, which is in the log record for the update), working backwards in the log. (Some care must be taken to handle the case of a crash occurring during the recovery process!)

Transactions and Concurrency Control



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Concurrency Control Algorithms

- Pessimistic (or Conservative) Approach

  Cause transactions to be delayed in case they conflict with other transactions at some time in the future
  - **Two-Phase Locking (2PL)**
  - **Timestamp Ordering (TO)**
- Optimistic Approach

  Allow transactions to proceed unsynchronized and only check conflicts at the end

  (based on the premise that conflicts are rare)

Pessimistic vs. Optimistic

- Pessimistic Execution

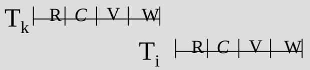
  | Validate | Read | *Compute* | Write |

- Optimistic Execusion

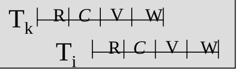
  | Read | *Compute* | Validate | Write |

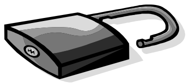
- Optimistic CC Validation Test

Validation succeeds for all transaction T_k and T_i where $ts(T_k)<ts(T_i)$ and T_k start write before T_i start read.



Validation succeeds for all transaction T_k and T_i where $ts(T_k)<ts(T_i)$ and T_k and T_i don't access common data.
$W(T_k) \cap R(T_i) = \emptyset$ and
$W(T_k) \cap W(T_i) = \emptyset$





Locking-Based Algorithms

- Transactions indicate their intensions by requesting locks from the scheduler (lock manager).
- Every transaction that needs to access a data object for reading or writing must first lock the object.
- A transaction holds a lock until it explicitly releases it.
- Locks are either shared or exclusive.
- Shared and exclusive locks conflict

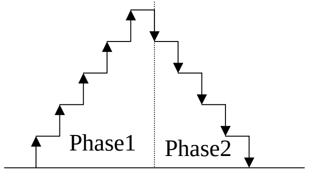
	Shared	Exclusive
Shared	Yes	No
Exclusive	No	No

Compatibility

- Locks allow concurrent processing of transactions.

Two-Phase Locking

- A transaction follows the 2PL protocol if all locking operations precede the first unlock operation in the transaction.

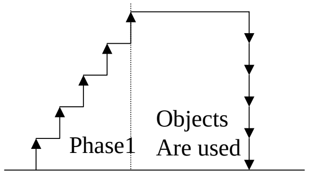


- Phase 1 is the "growing phase" during which all the locks are requested
- Phase 2 is the "shrinking phase" during which all locks are released

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

Strict Two-Phase Locking

- Transaction holds locks until the end of transaction (just before committing)



a.k.a.
Conservative 2PL

Lock Management

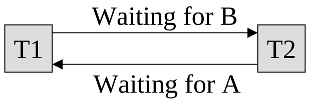
- Lock and unlock requests are handled by the lock manager
- Lock table entry:
  - Number of transactions currently holding a lock
  - Type of lock held (shared or exclusive)
  - Pointer to queue of lock requests
- Locking and unlocking have to be atomic operations
- Lock upgrade: (for some DBMSs) transaction that holds a shared lock can be upgraded to hold an exclusive lock (also downgrade)

Deadlocks

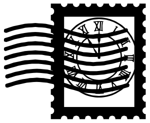
- Deadlock: Cycle of transactions waiting for locks to be released by each other.
- A transaction is deadlocked if it is blocked and will remain blocked until intervention.
- Locking-based Concurrency Control algorithms may cause deadlocks.
- Two ways of dealing with deadlocks:
  - Deadlock prevention (guaranteeing no deadlocks or detecting deadlocks in advance before they occur)
  - Deadlock detection (allowing deadlocks to form and breaking them when they occur)

Deadlock Example

T1	T2
begin-transaction	
Write-lock(A)	begin-transaction
Read(A)	**Write-lock(B)**
A=A-100	Read(B)
Write(A)	B=B*1.06
Write-lock(B)	Write(B)
Wait	**write-lock(A)**
Wait	Wait
…	Wait
	…



Deadlock Prevention



- Assign priorities based on timestamps (i.e. The oldest transaction has higher priority).
- Assume T_i wants a lock that T_j holds. Two policies are possible:
  - Wait-Die: If T_i has higher priority, T_i allowed to wait for T_j; otherwise (T_i younger) T_i aborts
  - Wound-wait: If T_i has higher priority, T_j aborts; otherwise (T_i younger) T_i waits
- If a transaction re-starts, make sure it has its original timestamp

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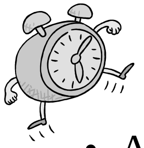


Deadlock and Timeouts

- A simple approach to deadlock prevention (and pseudo detection) is based on lock timeouts
- After requesting a lock on a locked data object, a transaction waits, but if the lock is not granted within a period (timeout), a deadlock is assumed and the waiting transaction is aborted and re-started.
- Very simple practical solution adopted by many DBMSs.

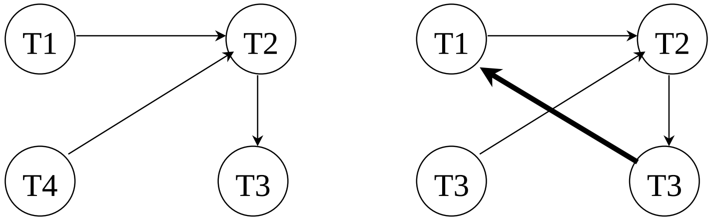
Deadlock Detection

- Create a waits-for graph:
  - Nodes are transactions
  - There is an edge from T_i to T_j if T_i is waiting for T_j to release a lock
- Deadlock exists if there is a cycle in the graph.
- Periodically check for cycles in the waits-for graph.

Deadlock Detection (Continued)

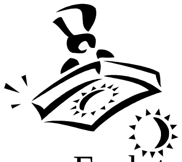
Example:

T1:	S(A), R(A),		S(B)				
T2:		X(B),W(B)			X(C)		
T3:				S(C), R(C)			X(A)
T4:						X(B)	



Recovery from Deadlock

- How to choose a deadlock victim to abort?
  - How long the transaction has been running?
  - How many data objects have been updated?
  - How many data objects the transaction is still to update?
- Do we need to rollback the whole aborted transaction?
- Avoid starvation (when the same transaction is always the victim)



Timestamping

- Each transaction is assigned a globally unique timestamp (starting time using a clock)
- Each data object is assigned
  - a write timestamp wts (largest timestamp on any write on x)
  - a read timestamp rts (largest timestamp on any read on x)
  - a flag that indicates whether the transaction that last wrote x committed.
- Conflict operations are resolved by timestamp ordering.
- A concurrency control protocol that orders transactions in such a way that older transactions get priority in the event of conflict.

Timestamp Ordering

- A Transaction T_i wants to read x: $R_i(x)$
  - if $ts(T_i) < wts(x)$ then reject R_i (x): rollback T_i (abort)
  - else accept $R_i(x)$; $rts(x) \leftarrow max(ts(T_i), rts(x))$

If $ts(T_i) < wts(x)$ => some other transaction T_k that started after T_i wrote a new value to x.
Since the read(x) of T_i should return a value prior to the write operation of T_k T_i is aboted (it is too old)

Timestamp Ordering

- A Transaction T_i wants to write x: W_i (x)
  - if $ts(T_i)<rts(x)$ then reject W_i (x): rollback T_i (abort)
  - if $ts(T_i)<wts(x)$ then ignore after accept $W_i(x)$ [Thomas write rule]
  - else accept $W_i(x)$; $wts(x) \leftarrow ts(T_i)$

If $ts(T_i) < rts(x)$ => some other transaction T_k that started after T_i has read an earlier value of x.
If T_i is allowed to commit, T_k should have read the new value that T_i is attempting to write. Thus T_i is too old to write.

Make sure a transaction has a new larger timestamp if it is re-started
This protocol guarantees serializability and is deadlock-free

Summary

- Concurrency control and recovery are among the most important functions provided by a DBMS.
- Users need not worry about concurrency.
  - System automatically inserts lock/unlock requests and schedules actions of different transactions in such a way as to ensure that the resulting execution is equivalent to executing the transactions one after the other in some order.
- Write-ahead logging (WAL) is used to undo the actions of aborted transactions and to restore the system to a consistent state after a crash.
  - *Consistent state*: Only the effects of commited transactions seen.

Summary (Contd.)

- There are several lock-based concurrency control schemes (Strict 2PL, 2PL). Conflicts between transactions can be detected in the dependency graph
- The lock manager keeps track of the locks issued. Deadlocks can either be prevented or detected.
- Timestamp CC is another alternative to 2PL; allows some serializable schedules that 2PL does not (although converse is also true).
- Ensuring recoverability with Timestamp CC requires ability to block transactions, which is similar to locking (using the commit flag per addressable object).