CS 4604: Introduction to Database Management Systems

B. Aditya Prakash

Lecture #16: Transactions 1: Intro. to ACID
Why Transactions?

- Database systems are normally being accessed by many users or processes at the same time.
  - Both queries and modifications.
- Unlike operating systems, which support interaction of processes, a DMBS needs to keep processes from troublesome interactions.
Transactions - dfn

- = unit of work, eg.
  - move $10 from savings to checking
Statement of Problem

- Concurrent execution of independent transactions (why do we want that?)
Statement of Problem

- Concurrent execution of independent transactions
  - utilization/throughput (“hide” waiting for I/Os.)
  - response time
Statement of Problem

- Concurrent execution of independent transactions
  - utilization/throughput ("hide" waiting for I/Os.)
  - response time
- would also like:
  - correctness &
  - fairness
- Example: Book an airplane seat
Definitions

- **database** - a fixed set of named data objects \((A, B, C, \ldots)\)

- **transaction** - a sequence of **read** and **write** operations \((\text{read}(A), \text{write}(B), \ldots)\)
  
  – DBMS’s abstract view of a user program
Example: ‘Lost-update’ problem

<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read(N)</td>
<td>Read(N)</td>
</tr>
<tr>
<td>N = N - 1</td>
<td>N = N - 1</td>
</tr>
<tr>
<td>Write(N)</td>
<td>Write(N)</td>
</tr>
</tbody>
</table>
Arbitrary interleaving can lead to
   – Temporary inconsistency (ok, unavoidable)
   – “Permanent” inconsistency (bad!)

Need formal correctness criteria.
Example: Bad Interaction

- You and friend each take $100 from different ATMs at about the same time.
  - The DBMS better make sure one account deduction doesn’t get lost.

- **Compare**: An OS allows two people to edit a document at the same time. If both write, one’s changes get lost.
ACID Transactions

- **ACID transactions** are:
  - *Atomic*: Whole transaction or none is done.
  - *Consistent*: Database constraints preserved.
  - *Isolated*: It appears to the user as if only one process executes at a time.
  - *Durable*: Effects of a process survive a crash.

- **Optional**: weaker forms of transactions are often supported as well (like Google, Amazon system etc.): Recall NoSQL systems
The SQL statement COMMIT causes a transaction to complete. 

- It’s database modifications are now permanent in the database.
The SQL statement ROLLBACK also causes the transaction to end, but by *aborting*.

– No effects on the database.

Failures like division by 0 or a constraint violation can also cause rollback, even if the programmer does not request it.
Overview

- **ACID transactions** are:
  - **Atomic**: Whole transaction or none is done.
  - **Consistent**: Database constraints preserved.
  - **Isolated**: It appears to the user as if only one process executes at a time.
  - **Durable**: Effects of a process survive a crash.
Atomicity of Transactions

- Two possible outcomes of executing a transaction:
  - Xact might *commit* after completing all its actions
  - or it could *abort* (or be aborted by the DBMS) after executing some actions.

- DBMS guarantees that Xacts are *atomic*.
  - From user’s point of view: Xact always either executes all its actions, or executes no actions at all.
Transaction states

- active
- partially committed
- committed
- failed
- aborted
Mechanisms for Ensuring Atomicity

- What would you do?
Mechanisms for Ensuring Atomicity

- One approach: LOGGING
  - DBMS logs all actions so that it can undo the actions of aborted transactions.
- ~ like black box in airplanes ...
Mechanisms for Ensuring Atomicity

- Logging used by all modern systems.
- Q: why?
Mechanisms for Ensuring Atomicity

- Logging used by all modern systems.
- Q: why?
- A:
  - audit trail &
  - efficiency reasons
- What other mechanism can you think of?
Mechanisms for Ensuring Atomicity

- Another approach: SHADOW PAGES
  - (not as popular)
Overview

- **ACID transactions** are:
  - **Atomic**: Whole transaction or none is done.
  - **Consistent**: Database constraints preserved.
  - **Isolated**: It appears to the user as if only one process executes at a time.
  - **Durable**: Effects of a process survive a crash.
Transaction Consistency

- “Database consistency” - data in DBMS is accurate in modeling real world and follows integrity constraints
Transaction Consistency

- "Transaction Consistency": if DBMS consistent before Xact (running alone), it will be after also
- Transaction consistency: User’s responsibility
  - DBMS just checks IC
Transaction Consistency (cont.)

- Recall: Integrity constraints
  - must be true for DB to be considered consistent

Examples:
1. FOREIGN KEY R.sid REFERENCES S
2. ACCT-BAL >= 0
Transaction Consistency (cont.)

- System checks ICs and if they fail, the transaction rolls back (i.e., is aborted).
  - Beyond this, DBMS does not understand the semantics of the data.
  - e.g., it does not understand how interest on a bank account is computed

- Since it is the user’s responsibility, we don’t discuss it further
Overview

- **ACID transactions** are:
  - *Atomic*: Whole transaction or none is done.
  - *Consistent*: Database constraints preserved.
  - *Isolated*: It appears to the user as if only one process executes at a time.
  - *Durable*: Effects of a process survive a crash.
Isolation of Transactions

- Users submit transactions, and
- Each transaction executes as if it was running by itself.
  - Concurrency is achieved by DBMS, which interleaves actions (reads/writes of DB objects) of various transactions.
- Q: How would you achieve that?
  - Tough problem!
Isolation of Transactions

A: Many methods - two main categories:
- Pessimistic – don’t let problems arise in the first place
- Optimistic – assume conflicts are rare, deal with them after they happen.
Example

Consider two transactions (Xacts):

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

- 1st xact transfers $100 from B’s account to A’s
- 2nd credits both accounts with 6% interest.
- Assume at first A and B each have $1000. What are the legal outcomes of running T1 and T2?
Example

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

- many - but A+B should be: $2000 * 1.06 = $2120
- There is no guarantee that T1 will execute before T2 or vice-versa, if both are submitted together. But, the net effect *must* be equivalent to these two transactions running serially in some order.
Example (Contd.)

- Legal outcomes: \( A=1166, B=954 \) or \( A=1160, B=960 \)
- Consider a possible interleaved *schedule*:

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T1:</strong></td>
<td>( A=A+100, B=B-100 )</td>
</tr>
<tr>
<td><strong>T2:</strong></td>
<td>( A=1.06^*A, B=1.06^*B )</td>
</tr>
</tbody>
</table>

- This is OK (same as T1;T2). But what about:

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T1:</strong></td>
<td>( A=A+100, B=B-100 )</td>
</tr>
<tr>
<td><strong>T2:</strong></td>
<td>( A=1.06^*A, B=1.06^*B )</td>
</tr>
</tbody>
</table>
Example (Contd.)

- Legal outcomes: $A=1166, B=954$ or $A=1160, B=960$
- Consider a possible interleaved schedule:

\[
\begin{array}{ll}
T1: & A = A+100, \quad B = B-100 \\
T2: & A = 1.06\times A, \quad B = 1.06\times B \\
\end{array}
\]

- This is OK (same as $T1;T2$). But what about:

\[
\begin{array}{ll}
T1: & A = A+100, \quad B = B-100 \\
T2: & A = 1.06\times A, \quad B = 1.06\times B \\
\end{array}
\]

- Result: $A=1166, B=960$; $A+B = 2126$, bank loses $6$
- The DBMS’ s view of the second schedule:

\[
\begin{array}{ll}
T1: & R(A), W(A), \quad R(B), W(B) \\
T2: & R(A), W(A), R(B), W(B) \\
\end{array}
\]
‘Correctness’?

- Q: How would you judge that a schedule is ‘correct’?
(‘schedule’ = ‘interleaved execution’)
‘Correctness’?

- Q: How would you judge that a schedule is ‘correct’?
- A: if it is equivalent to some serial execution
Formal Properties of Schedules

- Serial schedule: Schedule that does not interleave the actions of different transactions.
- Equivalent schedules: For any database state, the effect of executing the first schedule is identical to the effect of executing the second schedule. (*)

(*) no matter what the arithmetic etc. operations are!
Formal Properties of Schedules

- Serializable schedule: A schedule that is equivalent to some serial execution of the transactions.

(Note: If each transaction preserves consistency, every serializable schedule preserves consistency. )
Anomalies with interleaved execution:

- R-W conflicts
- W-R conflicts
- W-W conflicts

(why not R-R conflicts?)
Anomalies with Interleaved Execution

- Reading Uncommitted Data (WR Conflicts, “dirty reads”):

| T1: | R(A), W(A), R(B), W(B), Abort |
| T2: | R(A), W(A), C |
Anomalies with Interleaved Execution

- Reading Uncommitted Data (WR Conflicts, “dirty reads”):

  T1: R(A), W(A), R(B), W(B), Abort
  T2: R(A), W(A), C
Anomalies with Interleaved Execution

- Unrepeatable Reads (RW Conflicts):

<table>
<thead>
<tr>
<th></th>
<th>T1: R(A),</th>
<th>R(A), W(A), C</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2:</td>
<td>R(A), W(A), C</td>
<td></td>
</tr>
</tbody>
</table>
Anomalies with Interleaved Execution

- Unrepeatable Reads (RW Conflicts):

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

- Overwriting Uncommitted Data (WW Conflicts):

| T1:  | W(A),                 | W(B), C |
| T2:  | W(A),                 | W(B), C |
Anomalies (Continued)

- Overwriting Uncommitted Data (WW Conflicts):

T1: W(A), W(B), C
T2: W(A), W(B), C
Objective: find non-serial schedules, which allow transactions to execute concurrently without interfering, thereby producing a DB state that could be produced by a serial execution

BUT

– Trying to find schedules equivalent to serial execution is too slow!
Conflict Serializability

- We need a formal notion of equivalence that can be implemented efficiently...
  - Base it on the notion of “conflicting” operations

- Definition: Two operations conflict if:
  - They are by different transactions,
  - they are on the same object,
  - and at least one of them is a write.
Conflict Serializable Schedules

- Definition: Two schedules are conflict equivalent iff:
  - They involve the same actions of the same transactions, and
  - every pair of conflicting actions is ordered the same way

- Definition: Schedule S is conflict serializable if:
  - S is conflict equivalent to some serial schedule.

- Note, some “serializable” schedules are NOT conflict serializable (See Example 4 later)
A schedule $S$ is conflict serializable if:
- You are able to transform $S$ into a serial schedule by swapping consecutive non-conflicting operations of different transactions.

\[
\begin{align*}
R(A) & \quad W(A) \\
R(A) & \quad W(A) \\
R(A) & \quad W(A) \\
R(A) & \quad W(A) \\
R(A) & \quad W(A) \quad R(B) & \quad W(B) \\
R(A) & \quad W(A) \quad R(B) & \quad W(B) \quad R(B) & \quad W(B) \\
R(A) & \quad W(A) \quad R(B) & \quad W(B) \quad R(B) & \quad W(B) \\
R(A) & \quad W(A) \quad R(B) & \quad W(B) \quad R(B) & \quad W(B)
\end{align*}
\]
CS---Intuition

- A schedule $S$ is conflict serializable if:
  - You are able to transform $S$ into a serial schedule by swapping consecutive non-conflicting operations of different transactions

\[
R(A) \quad W(A) \\
R(A) \quad W(A)
\]

$IS \ NOT \ SERIALIZABLE!\$
Serializability

- Q: any faster algorithm? (faster than transposing operations?)
Dependency Graph

- One node per Xact
- Edge from Ti to Tj if:
  - An operation Oi of Ti conflicts with an operation Oj of Tj and
  - Oi appears earlier in the schedule than Oj.
THEOREM: Schedule is conflict serializable iff the dependency graph is acyclic

- Dependency graph is also called the precedence graph
  - different than the waits-for graph we will see later
Example

- **T1:** R(A), W(A)  \( \rightarrow \)  R(B), W(B)
- **T2:**  \( \rightarrow \)  R(A) W(A) R(B) W(B)

- D. Graph:

  ![Graph Diagram]

  - NOT Conflict serializable
    - Cycle is the problem---output of T1 depends on T2 and vice versa
Example #2 (Lost update)

<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read(N)</td>
<td>Read(N)</td>
</tr>
<tr>
<td>N = N - 1</td>
<td>N = N - 1</td>
</tr>
<tr>
<td>Write(N)</td>
<td>Write(N)</td>
</tr>
</tbody>
</table>
Example #2 (Lost update)

T1

Read(N)

N = N - 1

Write(N)

T2

Read(N)

N = N - 1

Write(N)
Example #2 (Lost update)

T1

Read(N)

N = N - 1

Write(N)

T2

Read(N)

N = N - 1

Write(N)

R/W
Example #2 (Lost update)

T1

Read(N)

N = N - 1

Write(N)

T2

Read(N)

N = N - 1

Write(N)

R/W

T1

T2
Example #3

T1 T2 T3

Read(A)

... write(A)

Read(A)

... Write(A)

Read(B)

... Write(B)

Read(B)

... Write(B)
Example #3

T1    T2    T3
Read(A)...
write(A)

Read(B)...
Write(B)

Read(A)...
Write(A)

Read(B)...
Write(B)

T1    T2    T3
A      B

equivalent serial execution?
Example #3

- A: T2, T1, T3
  (Notice that T3 should go after T2 in the equivalent serial order, although it starts before it!)

- Q: algo for generating serial execution from (acyclic) dependency graph?
Example #3

- A: T2, T1, T3

(Notice that T3 should go after T2 in the equivalent serial order, although it starts before it!)

- Q: algo for generating serial execution from (acyclic) dependency graph?

- A: Topological sorting
Example #4 (Inconsistent Analysis)

<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
<th>dependency graph?</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (A)</td>
<td>R(A)</td>
<td></td>
</tr>
<tr>
<td>A = A-10</td>
<td>Sum = A</td>
<td></td>
</tr>
<tr>
<td>W (A)</td>
<td>R (B)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sum += B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R(B)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B = B+10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W(B)</td>
<td></td>
</tr>
</tbody>
</table>
Example #4 (Inconsistent Analysis)

<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (A)</td>
<td>R(A)</td>
</tr>
<tr>
<td>A = A - 10</td>
<td>Sum = A</td>
</tr>
<tr>
<td>W (A)</td>
<td>R (B)</td>
</tr>
<tr>
<td>R(B)</td>
<td>Sum += B</td>
</tr>
<tr>
<td>B = B + 10</td>
<td></td>
</tr>
<tr>
<td>W(B)</td>
<td></td>
</tr>
</tbody>
</table>

dependency graph?

So NOT Conflict Serializable (and not serializable)
### Example #4 (Inconsistent Analysis)

<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (A)</td>
<td>Q: create a ‘correct’ Schedule based on this one that is not conflict-serializable</td>
</tr>
<tr>
<td>A = A-10</td>
<td></td>
</tr>
<tr>
<td>W (A)</td>
<td></td>
</tr>
<tr>
<td>R (A)</td>
<td></td>
</tr>
<tr>
<td>Sum = A</td>
<td></td>
</tr>
<tr>
<td>R (B)</td>
<td></td>
</tr>
<tr>
<td>Sum += B</td>
<td></td>
</tr>
<tr>
<td>R(B)</td>
<td></td>
</tr>
<tr>
<td>B = B+10</td>
<td></td>
</tr>
<tr>
<td>W(B)</td>
<td></td>
</tr>
</tbody>
</table>

Prakash 2016

VT CS 4604
Example #4’ (Inconsistent Analysis)

T1
R (A)
A = A-10
W (A)

T2

R (A)
if (A>0), count=1
R (B)
if (B>0), count++
R(B)

B = B+10
W(B)

A: T2 asks for the count of my active Accounts (assuming A>10, B>0)

NOTES:
1. This schedule is still not CS
2. BUT it is serializable! It is equivalent to either of [T1 T2] or [T2 T1] (both are OK)
Serializability in Practice

- DBMS does not test for conflict serializability of a given schedule
  - Impractical as interleaving of operations from concurrent Xacts could be dictated by the OS

- Approach:
  - Use specific protocols that are known to produce conflict serializable schedules
  - But may reduce concurrency
Solution?

- One solution for “conflict serializable” schedules is Two Phase Locking (2PL)
(Full answer:) use locks; keep them until commit (‘strict 2 phase locking’)
We’ll see the details later (in next class!)
(Review) Goal: ACID Properties

- **ACID transactions** are:
  - *Atomic*: Whole transaction or none is done.
  - *Consistent*: Database constraints preserved.
  - *Isolated*: It appears to the user as if only one process executes at a time.
  - *Durable*: Effects of a process survive a crash.

What happens if system crashes between *commit* and *flushing modified data to disk*?
Durability

- == Recovery
- We’ll see it later (after concurrency control)
Summary

- **Concurrency control** and **recovery** are among the most important functions provided by a DBMS.

- Concurrency control is automatic
  - System automatically inserts lock/unlock requests and schedules actions of different Xacts
  - Property ensured: resulting execution is equivalent to executing the Xacts one after the other in some order.
ACID properties

Atomicity (all or none)
Consistency
Isolation (as if alone)
Durability