CompSci 516
Database Systems

Lecture 16
Intro to Transactions

Instructor: Sudeepa Roy
Where are we now?

We learnt

✓ Relational Model and Query Languages
  ✓ SQL, RA, RC
  ✓ Postgres (DBMS)
    ▪ HW1
✓ Database Normalization
✓ DBMS Internals
  ✓ Storage
  ✓ Indexing
  ✓ Query Evaluation
  ✓ Operator Algorithms
  ✓ External sort
  ✓ Query Optimization
✓ Map-reduce and spark
  ▪ HW2

Next

• Transactions
  – Basic concepts
  – Concurrency control
  – Recovery
  – (for the next 4-5 lectures)
Reading Material

- [RG]
  - Chapter 16.1-16.3, 16.4.1
  - 17.1-17.4
  - 17.5.1, 17.5.3

Acknowledgement:
The following slides have been created adapting the instructor material of the [RG] book provided by the authors Dr. Ramakrishnan and Dr. Gehrke.
Motivation: Concurrent Execution

• Concurrent execution of user programs is essential for good DBMS performance.
  – Disk accesses are frequent, and relatively slow
  – it is important to keep the CPU busy by working on several user programs concurrently
  – short transactions may finish early if interleaved with long ones
  – may increase system throughput (avg. #transactions per unit time) and decrease response time (avg. time to complete a transaction)

• A user’s program may carry out many operations on the data retrieved from the database
  – but the DBMS is only concerned about what data is read/written from/to the database
Transactions

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

- A transaction is the DBMS’s abstract view of a user program
  - a sequence of reads and write
  - the same program executed multiple times would be considered as different transactions
  - 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)
Example

- Consider two transactions:

  \[
  \begin{align*}
  T1: & \quad \text{BEGIN } A=A+100, \quad B=B-100 \quad \text{END} \\
  T2: & \quad \text{BEGIN } A=1.06*A, \quad B=1.06*B \quad \text{END}
  \end{align*}
  \]

- 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.
Consider a possible interleaving (schedule):

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

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)
Commit and Abort

- A transaction might commit after completing all its actions
- or it could abort (or be aborted by the DBMS) after executing some actions

T1: BEGIN A=A+100, B=B-100 END
T2: BEGIN A=1.06*A, B=1.06*B END
Concurrency Control and Recovery

- Concurrency Control
  - (Multiple) users submit (multiple) transactions
  - Concurrency is achieved by the DBMS, which interleaves actions (reads/writes of DB objects) of various transactions
  - User should think of each transaction as executing by itself one-at-a-time
  - The DBMS needs to handle concurrent executions

- Recovery
  - Due to crashes, there can be partial transactions
  - DBMS needs to ensure that they are not visible to other transactions

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

• Atomicity
• Consistency
• Isolation
• Durability
Atomicity

- A user can think of a transaction as always executing all its actions in one step, or not executing any actions at all
  - Users do not have to worry about the effect of incomplete transactions

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

- Each transaction, when run by itself with no concurrent execution of other actions, must preserve the consistency of the database
  - e.g. if you transfer money from the savings account to the checking account, the total amount still remains the same

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

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

• A user should be able to understand a transaction without considering the effect of any other concurrently running transaction
  – even if the DBMS interleaves their actions
  – transaction are “isolated or protected” from other transactions
Durability

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

• Once the DBMS informs the user that a transaction has been successfully completed, its effect should persist
  – even if the system crashes before all its changes are reflected on disk

Next, how we maintain all these four properties
But, in detail later
Ensuring Consistency

- e.g. Money debit and credit between accounts
- User’s responsibility to maintain the integrity constraints
- DBMS may not be able to catch such errors in user program’s logic
  - e.g. if the credit is (debit – 1)
- However, the DBMS may be in inconsistent state “during a transaction” between actions
  - which is ok, but it should leave the database at a consistent state when it commits or aborts
- Database consistency follows from transaction consistency, isolation, and atomicity
Ensuring Isolation

• DBMS guarantees isolation (later, how)
• If T1 and T2 are executed concurrently, either the effect would be T1->T2 or T2->T1 (and from a consistent state to a consistent state)
• But DBMS provides no guarantee on which of these order is chosen
• Often ensured by “locks” but there are other methods too
Ensuring Atomicity

• Transactions can be incomplete due to several reasons
  – Aborted (terminated) by the DBMS because of some anomalies during execution
    • in that case automatically restarted and executed anew
  – The system may crash (say no power supply)
  – A transaction may decide to abort itself encountering an unexpected situation
    • e.g. read an unexpected data value or unable to access disks
Ensuring Atomicity

- A transaction interrupted in the middle can leave the database in an inconsistent state
- DBMS has to remove the effects of partial transactions from the database
- DBMS ensures atomicity by “undoing” the actions of incomplete transactions
- DBMS maintains a “log” of all changes to do so
Ensuring Durability

• The log also ensures durability
• If the system crashes before the changes made by a completed transactions are written to the disk, the log is used to remember and restore these changes when the system restarts
• “recovery manager” will be discussed later
  – takes care of atomicity and durability
Notations

- **Transaction is a list of “actions” to the DBMS**
  - includes “reads” and “writes”
  - $R_T(O)$: Reading an object $O$ by transaction $T$
  - $W_T(O)$: Writing an object $O$ by transaction $T$
  - also should specify $\text{Commit}_T (C_T)$ and $\text{Abort}_T (A_T)$
  - $T$ is omitted if the transaction is clear from the context

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

• Transactions communicate only through READ and WRITE
  – i.e. no exchange of message among them

• A database is a fixed collection of independent objects
  – i.e. objects are not added to or deleted from the database
  – this assumption can be relaxed
    • (dynamic db/phantom problem later)
Schedule

• An actual or potential sequence for executing actions as seen by the DBMS

• A list of actions from a set of transactions
  – includes READ, WRITE, ABORT, COMMIT

• Two actions from the same transaction T MUST appear in the schedule in the same order that they appear in T
  – cannot reorder actions from a given transaction
Serial Schedule

If the actions of different transactions are not interleaved
– transactions are executed from start to finish one by one

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Problems with a serial schedule

• The same motivation for concurrent executions, e.g.
  – while one transaction is waiting for page I/O from disk, another transaction could use the CPU
  – reduces the time disks and processors are idle

• Decreases system throughput
  – average #transactions computed in a given time

• Also affects response time
  – average time taken to complete a transaction
  – if we relax it, short transactions can be completed with long ones and do not have to wait for them to finish
Scheduling Transactions

• **Serial schedule:** Schedule that does not interleave the actions of different transactions

• **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 schedule that is equivalent to some serial execution of the committed transactions
  – **Note:** If each transaction preserves consistency, every serializable schedule preserves consistency
Serializable Schedule

- If the effect on any consistent database instance is guaranteed to be identical to that of “some” complete serial schedule for a set of “committed transactions”
- However, no guarantee on T1 -> T2 or T2 -> T1

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serial schedule serializable schedules

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Anomalies with Interleaved Execution

• If two consistency-preserving transactions when run interleaved on a consistent database might leave it in inconsistent state

• Write-Read (WR)
• Read-Write (RW)
• Write-Write (WW)

• No conflict with RR if no write is involved
WR Conflict

- **Reading Uncommitted Data (WR Conflicts, “dirty reads”):**
  - transaction T2 reads an object that has been modified by T1 but not yet committed
  - or T2 reads an object from an inconsistent database state (like fund is being transferred between two accounts by T1 while T2 adds interests to both)
RW Conflict

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<tr>
<th>T1:</th>
<th>R(A), R(A), W(A), C</th>
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<tbody>
<tr>
<td>T2:</td>
<td>R(A), W(A), C</td>
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</table>

• Unrepeatable Reads (RW Conflicts):
  – T2 changes the value of an object A that has been read by transaction T1, which is still in progress
  – If T1 tries to read A again, it will get a different result
  – Suppose two customers are trying to buy the last copy of a book simultaneously
Overwriting Uncommitted Data (WW Conflicts, “lost update”):

- T2 overwrites the value of A, which has been modified by T1, still in progress
- Suppose we need the salaries of two employees (A and B) to be the same
  - T1 sets them to $1000
  - T2 sets them to $2000
Schedules with Aborts

- Actions of aborted transactions have to be undone completely
  - may be impossible in some situations
    - say T2 reads the fund from an account and adds interest
    - T1 aims to deposit money but aborts
  - if T2 has not committed, we can “cascade aborts” by aborting T2 as well
  - if T2 has committed, we have an “unrecoverable schedule”

\[
\begin{array}{l}
\text{T1: } \text{R(A), W(A), } \text{Abort} \\
\text{T2: } \text{R(A), W(A) Commit}
\end{array}
\]
Recoverable Schedule

- Transaction commits if and only after all transactions they read have committed
  - avoids cascading aborts

Example of Unrecoverable schedule

| T1: | R(A), W(A), | Abort |
| T2: | R(A), W(A), R(B), W(B), Commit |
Conflict Equivalent Schedules

• Two schedules are conflict equivalent if:
  – Involve the same actions of the same transactions
  – Every pair of conflicting actions of two committed transactions is ordered the same way

• Conflicting actions:
  – both by the same transaction $T_i$
    • $R_i(X), W_i(Y)$
  – both on the same object by two transactions $T_i$ and $T_j$, at least one action is a write
    • $R_i(X), W_j(X)$
    • $W_i(X), R_j(X)$
    • $W_i(X), W_j(X)$
Conflict Equivalent Schedules

• Two conflict equivalent schedules have the same effect on a database
  – all pairs of conflicting actions are in same order
  – one schedule can be obtained from the other by swapping “non-conflicting” actions
    • either on two different objects
    • or both are read on the same object
Conflict Serializable Schedules

• Schedule S is conflict serializable if S is conflict equivalent to some serial schedule

• In class:
  • \( r_1(A); w_1(A); r_2(A); w_2(A); r_1(B); w_1(B); r_2(B); w_2(B) \)
  • to
  • \( r_1(A); w_1(A); r_1(B); w_1(B); r_2(A); w_2(A); r_2(B); w_2(B) \)
Example

- **A schedule that is not conflict serializable:**

  \[
  \begin{align*}
  \text{T1:} & \quad R(A), W(A), \quad R(B), W(B) \\
  \text{T2:} & \quad R(A), W(A), R(B), W(B)
  \end{align*}
  \]

  can write it in this equivalent way as well:

  \[
  \begin{align*}
  & R_1(A), W_1(A), R_2(A), W_2(A), R_2(B), W_2(B), R_1(B), W_1(B)
  \end{align*}
  \]

  \[
  \begin{tikzpicture}
    \node[circle, draw] (T1) at (0,0) {T1};
    \node[circle, draw] (T2) at (2,0) {T2};
    \draw[->] (T1) -- (T2) node[midway, above] {A};
    \draw[->] (T2) -- (T1) node[midway, below] {B};
  \end{tikzpicture}
  \]

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

• Also called dependency graph, conflict graph, or serializability graph

• One node per committed transaction

• Edge from $T_i$ to $T_j$ if an action of $T_i$ precedes and conflicts with one of $T_j$’s actions
  
  – $W_i(A) \longrightarrow R_j(A)$, or
  
  – $R_i(A) \longrightarrow W_j(A)$, or
  
  – $W_i(A) \longrightarrow W_j(A)$

• $T_i$ must precede $T_j$ in any serial schedule
Conflict Serializability

• Theorem: Schedule is conflict serializable if and only if its precedence graph is acyclic

\[
R_1(A), W_1(A), R_2(A), W_2(A), R_2(B), W_2(B), R_1(B), W_1(B)
\]

\[
T_1 \rightarrow A \rightarrow T_2
\]

\[
T_1 \rightarrow B \rightarrow T_2
\]

\[
r_1(A); w_1(A); r_2(A); w_2(A); r_1(B); w_1(B); r_2(B); w_2(B)
\]
Lock-Based Concurrency Control

• DBMS should ensure that only serializable and recoverable schedules are allowed
  – No actions of committed transactions are lost while undoing aborted transactions

• Uses a locking protocol

• Lock: a bookkeeping object associated with each “object”
  – different granularity

• Locking protocol:
  – a set of rules to be followed by each transaction
Strict two-phase locking (Strict 2PL)

Two rules

1. Each transaction must obtain
   - a *S (shared)* lock on object before reading
   - and an *X (exclusive)* lock on object before writing
   - exclusive locks also allow reading an object, additional shared lock is not required
   - If a transaction holds an X lock on an object, no other transaction can get a lock (S or X) on that object
   - transaction is suspended until it acquires the required lock

2. All locks held by a transaction are released when the transaction completes
Example: Strict 2PL

- **WR conflict (dirty read)**
- **Strict 2PL does not allow this**

<table>
<thead>
<tr>
<th>T1: X(A), R(A), W(A),</th>
<th>T2: HAS TO WAIT FOR LOCK ON A</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1: X(A), R(A), W(A), X(B), R(B), W(B), C</td>
<td>T2: X(A), R(A), W(A), X(B), R(B), W(B), C</td>
</tr>
</tbody>
</table>

All locks released here
Can use UX(A), UX(B) – for shared lock unlocking, US(A), US(B)
Example: Strict 2PL

<table>
<thead>
<tr>
<th>T1:</th>
<th>S(A), R(A), X(C), R(C), W(C), C</th>
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</thead>
<tbody>
<tr>
<td>T2:</td>
<td>S(A), R(A), X(B), R(B), W(B), C</td>
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- Strict 2PL allows interleaving
More on Strict 2PL

• Every transaction has
  – a growing phase of acquiring locks, and
  – a shrinking phase of releasing locks

• Strict 2PL allows only serializable schedules
  – precedence graphs will be acyclic (check yourself)
  – Additionally, allows recoverable schedules and simplifies transaction aborts
  – two transactions can acquire locks on different objects independently
2PL vs. strict 2PL

• **2PL:**
  – first, acquire all locks, release none
  – second, release locks, cannot acquire any other lock

• **Strict 2PL:**
  – release write (X) lock, only after it has ended (committed or aborted)

• **(Non-strict) 2PL also allows only serializable schedules like strict 2PL, but involves more complex abort processing**
Strict 2PL and Conflict Serializability

- Strict 2PL allows only schedules whose precedence graph is acyclic
- Can never allow cycles as the X locks are being held by one transaction
- However, it is sufficient but not necessary for serializability
- Relaxed solution: View serializability
View Serializability

• Schedules S1 and S2 are view equivalent if:
  – If $T_i$ reads initial value of A in $S_1$, then $T_i$ also reads initial value of A in $S_2$
  – If $T_i$ reads value of A written by $T_j$ in $S_1$, then $T_i$ also reads value of A written by $T_j$ in $S_2$
  – For all data object A, if $T_i$ writes final value of A in $S_1$, then $T_i$ also writes final value of A in $S_2$

• S is view serializable, if it is view equivalent to some serial schedule

<table>
<thead>
<tr>
<th>T1: R(A)</th>
<th>W(A)</th>
<th>C</th>
<th>T1: R(A), W(A)</th>
<th>C</th>
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<tr>
<td>T2:</td>
<td>W(A)</td>
<td>C</td>
<td>T2:</td>
<td>W(A)</td>
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<td>T3:</td>
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<td>T3:</td>
<td>W(A)</td>
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S1 (view serializable, not conflict serializable) | S2 (serial)
More on View Serializability

• Every conflict serializable schedule is view serializable (check it yourself)
• But the converse may not be true
• If VS but not CS, would contain a “blind write” (see below)
• Verifying and enforcing VS is more expensive than CS, so less popular than CS

<table>
<thead>
<tr>
<th>S1 (view serializable, not conflict serializable)</th>
<th>S2 (serial)</th>
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</thead>
<tbody>
<tr>
<td>T1: R(A) W(A) C</td>
<td>T1: R(A),W(A) C</td>
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<td>T2: W(A) C</td>
<td>T2: W(A) C</td>
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<tr>
<td>T3: W(A) C</td>
<td>T3: W(A) C</td>
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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 (if the shared or exclusive lock cannot be granted immediately)
• Locking and unlocking have to be atomic operations
• Lock upgrade: transaction that holds a shared lock can be upgraded to hold an exclusive lock
• Transaction commits or aborts
  – all locks released
Deadlocks

• Deadlock: Cycle of transactions waiting for locks to be released by each other
  – database systems periodically check for deadlocks

• Two ways of dealing with deadlocks:
  – Deadlock detection
  – Deadlock prevention
Deadlock Detection

1. Create a waits-for graph: (example on next slide)
   - 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
• Periodically check for cycles in the waits-for graph
• Abort a transaction on a cycle and release its locks, proceed with the other transactions
   - several choices
   - one with the fewest locks
   - one has done the least work/farthest from completion
   - if being repeatedly restarted, should be favored at some point

2. Use timeout, if long delay, assume (pessimistically) a deadlock
Deadlock Detection

Example:

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

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Deadlock Prevention

• Assign priorities based on timestamps
• Assume $T_i$ wants a lock that $T_j$ holds. Two policies are possible:
  – Wait-Die: It $T_i$ has higher priority, $T_i$ waits for $T_j$; otherwise $T_i$ aborts
  – Wound-wait: If $T_i$ has higher priority, $T_j$ aborts; otherwise $T_i$ waits
• Convince yourself that no cycle is possible
• If a transaction re-starts, make sure it has its original timestamp
  – each transaction will be the oldest one and have the highest priority at some point

• A variant of strict 2PL, conservative 2PL, works too
  – acquire all locks it ever needs before a transaction starts
  – no deadlock but high overhead and poor performance, so not used in practice
Summary

• Transaction
  – $R_1(A)$, $W_2(A)$, ...
  – Commit $C_1$, abort $A_1$
  – Lock/unlock: $S_1(A)$, $X_1(A)$, $US_1(A)$, $UX_1(A)$

• ACID properties
  – what they mean, whose responsibility to maintain each of them

• Conflicts: RW, WR, WW

• 2PL/Strict 2PL
  – all lock acquires have to precede all lock releases
  – Strict 2PL: release X locks only after commit or abort
Summary

• Schedule
  – Serial schedule
  – Serializable schedule (why do we need them?)
  – Conflicting actions
  – Conflict-equivalent schedules
  – Conflict-serializable schedule
  – View-serializable schedule (relaxation)
  – Conflict Serializability => View Serializability => Serializability
  – Recoverable schedules

• Dependency (or Precedence) graphs
  – their relation to conflict serializability (by acyclicity)
  – their relation to Strict 2PL
Summary

• Lock management basics

• Deadlocks
  – detection
    • waits-for graph has cycle, or timeout
    • what to do if deadlock is detected
  – prevention
    • wait-die and wound-wait