What are Transactions?

- So far, we looked at individual queries; in practice, a task consists of a sequence of actions

  - E.g., “Transfer $1000 from account A to account B”
    - Subtract $1000 from account A
    - Subtract transfer fee from account A
    - Credit $1000 to account B

- A *transaction* is the DBMS’s view of a user program:
  - Must be interpreted as “unit of work”: either entire transaction executes, or no part of it executes/has any effect on DBMS
  - Two special final actions: COMMIT or ABORT
Concurrent Execution

- DBMS receives large numbers of concurrent requests
  - Concurrent (or parallel) execution improves performance
  - Two transactions are concurrent if they overlap in time.
  - Disk accesses are frequent, and relatively slow; CPU can do a lot of work while waiting for the disk, or even SSD
  - Goal is to increase/maximize system throughput
    - Number of transactions executed per time unit

Concurrence control

- Protocols that ensure things execute correctly in parallel
- Broad and difficult challenge that goes beyond DBMS realm
  - OS, Distributed Programming, hardware scheduling (CPU registers), etc
- Our focus is DBMS, but some principles span beyond DBMS
Major Example: the web app

Concurrent web requests from users

Web layer

Multi-threaded Object layer

JDBC

App server(s)

Database server

Database

Other apps
Web app in execution (CS636)

- To keep transactions executing concurrently, yet isolated from each other, each has own objects related to DB data.

Diagram:
- Transaction Thread using objects
- Database Cache
- Employee objects
- Employee rows
- Database On disk
Web app Transactions

- Each application action turns into a database transaction
- A well-designed app has a “service API” describing those actions
- A request execution calls the service API one or more times.
- Each service call represents an application action and contains a transaction
- Thus transactions are contained in request-response cycles
- This ensures that transactions are short-lived, good for performance
- But they still can run concurrently under high-enough load
The web app service API

Concurrent web requests from users

Web layer

Multi-threaded Object layer

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App server(s)

Database server

Other apps
ACID Properties

Transaction Management must fulfill four requirements:

1. **Atomicity**: either all actions within a transaction are carried out, or none is
   - Only actions of committed transactions must be visible

2. **Consistency**: concurrent execution must leave DBMS in consistent state

3. **Isolation**: each transaction is protected from effects of other concurrent transactions
   - Net effect is that of some sequential execution

4. **Durability**: once a transaction commits, DBMS changes will persist
   - Conversely, if a transaction aborts/is aborted, there are no effects
Roles of Transaction Manager

- **Concurrency Control**
  - Ensuring correct execution in the presence of multiple transactions running in parallel

- **Crash recovery**
  - Ensure that atomicity is preserved if the system crashes while one or more transactions are still incomplete
  - Main idea is to keep a log of operations; every action is logged before execution (Write-Ahead Log or WAL)
Modeling Transactions

- User programs may carry out many operations …
  - Data-related computations
  - Prompting user for input, handling web requests
- … but the DBMS is only concerned about what data is read/written from/to the database
- A transaction is abstracted by a sequence of time-ordered read and write actions
  - e.g., R(X), R(Y), W(X), W(Y)
  - R=read, W=write, data element in parentheses
  - Each individual action is indivisible, or atomic
  - SQL UPDATE = R(X) W(X)
Important dataflow assumptions

- Transactions interact with one another as they run only via database read and write operations.
  - No messages exchanged between transactions
  - No use of shared memory between transactions
  - Oracle, other DBs, enforce this

- Transactions may accept information from the environment when they start and return information to the environment when they finish by committing.
  - The agent that starts a transaction will come to know whether it committed or aborted, and can act on that information.
  - Thus it is possible for data to go from one transaction to the environment and then to another starting transaction, but note that these transactions are not concurrent.
Scheduling Transactions

- **Serial schedule**: no interleaving of transactions
  - Safe, but poor performance!

- **Schedule equivalence**: two schedules are equivalent if they lead to the same state of the DBMS (see footnote on pg. 525 that includes values returned to user in relevant ”state”)

- **Serializable schedule**: schedule that is equivalent to some serial execution of transactions
  - But still allows interleaving/concurrency!
Serializable schedule example

<table>
<thead>
<tr>
<th>T1:</th>
<th>A=A+100,</th>
<th>B=B-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2:</td>
<td>A=1.06*A,</td>
<td>B=1.06*B</td>
</tr>
</tbody>
</table>

- Same effect as executing T1 completely, then T2
If execution is not serializable…

- Non-serializable concurrent executions can show anomalies, i.e., clearly bad behavior
- Let’s look at some examples
Consider two transactions (in a really bad DB) where A = 100

<table>
<thead>
<tr>
<th>T1:</th>
<th>A = A + 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2:</td>
<td>A = A + 100</td>
</tr>
</tbody>
</table>

T1 & T2 are concurrent, running same transaction program
T1 & T2 both read old value, 100, add 100, store 200
One of the updates has been lost!

**Consistency requirement**: after execution, A should reflect all deposits (Money should not be created or destroyed)

No guarantee that T1 will execute before T2 or vice-versa…

… but the net effect must be equivalent to these two transactions running **one-after-the-other in some order**
Consider two transactions running different programs

T1: \[ A = A + 100, \quad B = B - 100 \]
T2: \[ A = 1.06 \times A, \quad B = 1.06 \times B \]

T1 performs an account transfer

T2 performs credit of (6%) interest amount

**Consistency requirement**: after execution, sum of accounts must be 106% the initial sum (before execution)

No guarantee that T1 will execute before T2 or vice-versa…

… but the net effect must be equivalent to these two transactions running one-after-the-other in *some* order
Concurrency: when things go wrong (2/3)

- Assume that initially there are $500 in both accounts
- Consider a possible *interleaving* or *schedule*

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

- After execution, \( A = 636, B = 424, A + B = 1060 \)
Concurrence: when things go wrong (3/3)

- Consider another interleaving or schedule:

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

- After execution, \( A=636, \) \( B=430, \) \( A+B=1066 \)

  **WRONG!!!**

- The DBMS view

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

- Anomalies may occur in concurrent execution

- The notion of conflicts helps understand anomalies

- Is there a conflict when multiple READ operations are posted? No

- What if one of the operations is a WRITE? YES!

- WR, RW and WW conflicts
WR Conflicts

- Reading Uncommitted Data (Dirty Reads)

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

- The earlier example where interest is not properly credited is due to a WR conflict
- Value of A written by T1 is read by T2 before T1 completed all its changes
RW Conflicts

- Unrepeatable Reads

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

- Scenario: Let $A (=1)$ be the number of copies of an item. $T1$ checks the number available. If the number is greater than 0, $T1$ places an order by decrementing the count.
- In the meantime, $T2$ updated the value of the count (say, to zero).
- $T1$ will set the count to a negative value!
WW Conflicts

- **Overwriting Uncommitted Data**

<table>
<thead>
<tr>
<th>T1:</th>
<th>W(A), W(B), Commit</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2:</td>
<td>W(A), W(B), Commit</td>
</tr>
</tbody>
</table>

- Assume two employees must always have same salary
- \( T1 \) sets the salaries to $1000, \( T2 \) to $2000
- There is a “lost update”, and the final salaries are $1000 and $2000
- “Lost” update because the transaction that comes last in serial order should set both values. One got lost.
Scheduling Transactions: recall terminology

- **Serial schedule**: no interleaving of transactions
  - Safe, but poor performance!

- **Schedule equivalence**: two schedules are equivalent if they lead to the same state of the DBMS (see footnote on pg. 525 that includes values returned to user in relevant "state")

- **Serializable schedule**: schedule that is equivalent to some serial execution of transactions
  - But still allows interleaving/concurrency!
Conflict Serializable Schedules

- 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
- A conflict serializable schedule is serializable (to be shown in future classes)
- Some other schedules are also serializable
Why is serializability important?

- If each transaction preserves consistency, every **serializable** schedule preserves consistency
  - For example, transactions that move money around should always preserve the total amount of money.
  - If running with serializable transactions, we only need to check that each transaction program has this property, and we know that the system does.

How to ensure serializable schedules?
- Use **locking** protocols (ensuring conflict serializability)
- DBMS inserts proper locking actions, user is oblivious to locking (except through its effect on performance, and deadlocks)
- There are other ways too, covered later.
Strict Two-Phase Locking (Strict 2PL)

- Protocol steps
  - Each transaction must obtain a **S (shared)** lock on object before reading, and an **X (exclusive)** lock on object before writing.
  - All locks held are released when the transaction completes
    - **(Non-strict) 2PL**: Release locks anytime, but cannot acquire locks after releasing any lock.

- Strict 2PL allows only serializable schedules.
  - It simplifies transaction aborts
  - **(Non-strict) 2PL** also allows only serializable schedules, but involves more complex abort processing
Strict 2PL Example (red op is blocked)

T1: S(A) R(A)  
T2: S(A) R(A) X(B) 

T1: S(A) R(A)  
T2: S(A) R(A) X(B) R(B) 

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

T1: S(A) R(A)  
T2: S(A) R(A) X(B) R(B) W(B) C
Aborting Transactions

- When $Ti$ is aborted, all its actions have to be undone
  - if $Tj$ reads an object last written by $Ti$, $Tj$ must be aborted as well!
  - *cascading aborts* can be avoided with 2PL by releasing locks only at commit (Strict 2PL)
  - If $Ti$ writes an object, $Tj$ can read this only after $Ti$ commits
  - This also means the schedule is “recoverable”: transactions commit only after all transactions whose changes they read commit.
  - In general, recoverable and serializable are separate properties of concurrency protocols, but Strict 2PL has both.

- **Strict 2PL is recoverable, and cascading aborts are prevented**
  - At the cost of decreased concurrency
  - No free lunch!
  - Increased parallelism leads to locking protocol complexity
Deadlocks

- Cycle of transactions waiting for locks to be released by each other

| T1:   | X(A) W(A) | S(B) [R(B) …]| T2:   | X(B) W(B) S(A) [R(A) …] |

- Two ways of dealing with deadlocks:
  - Deadlock prevention
  - Deadlock detection
Locking Performance

- Lock-based schemes rely on two mechanisms
  - Blocking
  - Aborting

- Both blocking and aborting cause performance overhead
  - Transactions may have to wait
  - Transactions may need to be re-executed

- How does blocking affect throughput?
  - First few transactions do not conflict – no blocking
    - Parallel execution, performance increase
  - As more transactions execute, blocking occurs
  - After a point, adding more transactions decreases throughput!
Locking Performance (2)

Throughput vs. Active Transaction Count

Thrashing
Improving Performance

- Locking the smallest-sized objects possible
  - e.g., row set instead of table
- Reduce the time a lock is held for
  - Release locks faster
- Reducing hot spots
  - Careful review of application design
  - Reduce contention
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
Transaction Support in SQL

- A transaction is automatically started when user executes a statement or accesses the catalogs
- Transaction is either committed (COMMIT) or aborted (ROLLBACK)
- New in SQL-99: SAVEPOINT feature
  - SAVEPOINT <savepoint name>
  - Actions …
  - ROLLBACK TO SAVEPOINT <savepoint name>
- SAVEPOINT advantage vs. sequence of transactions
  - Can roll back over multiple savepoints
  - Lower overhead: no new transaction initiated (book, pg. 536)
  - But transaction initiation is not an expensive action. Locks are still held on changes done before savepoint, when rollback to savepoint done. Locks would be released if a real commit is done.
  - Conceivably of use for “what-if” calculations, but hard to find examples.
Setting Transaction Properties in SQL

- **Access Mode**
  - **READ ONLY vs READ WRITE**

- **Isolation Level (decreasing level of concurrency)**

<table>
<thead>
<tr>
<th>Level</th>
<th>Dirty Read</th>
<th>Unrepeatable Read</th>
<th>Phantom</th>
</tr>
</thead>
<tbody>
<tr>
<td>READ UNCOMMITTED</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td>READ COMMITTED</td>
<td>No</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td>REPEATABLE READ</td>
<td>No</td>
<td>No</td>
<td>Possible</td>
</tr>
<tr>
<td>SERIALIZABLE</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

- We haven’t yet seen an example of a phantom—next time.
Isolation Levels in Practice

- Databases default to RC, read-committed, so many apps run that way, can have their read data changed, and phantoms
- Web apps (JEE, anyway) have a hard time overriding RC, so most are running at RC
- The 2PL locking scheme we studied was for RR, repeatable read: transaction takes long term read and write locks
- Long term = until commit of that transaction
Read Committed (RC) Isolation

- 2PL can be modified for RC: take long-term write locks but not long term read locks.
- Reads are atomic as operations, but that’s it.
- Lost updates can happen in RC: system takes 2PC locks only for the write operations:
  
  \[ R1(A)R2(A)W2(B)C2W1(B)C1 \]
  
  \[ R1(A)R2(A)X2(B)W2(B)C2X1(B)W1(B)C1 \] (RC isolation)

- Update statements are atomic, so that case of read-then-write is safe even at RC.
- Update $T$ set $A = A + 100$ (safe at RC isolation).
- Remember to use update when possible!
Syntax for SQL

SET TRANSACTION ISOLATION LEVEL
   SERIALIZABLE READ WRITE

SET TRANSACTION ISOLATION LEVEL
   REPEATABLE READ READ ONLY

Note:
   READ UNCOMMITTED cannot be READ WRITE