Transaction Management: Concurrency Control

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Slides Courtesy of R. Ramakrishnan and J. Gehrke
DBMS Architecture

- Query Parser
- Query Rewriter
- Query Optimizer
- Query Executor
- Lock Manager
- Access Methods
- Buffer Manager
- Log Manager
- Recovery
- Disk Space Manager

Concurrency Control
Online Transaction Processing (OLTP)

- Banking: Multiple programs can touch the same data
- Ticketing: Have you tried to get popular concert tickets online?
- E-commerce: Have you experienced online shopping during sales?
- Voting
- Telecommunications
- Online gaming

A lot of (small) reads and writes on the same data
Outline

- Transaction management overview
- Serializability & recoverability
- Lock-based concurrency control
- Efficient B+tree locking
- Optimistic concurrency control
Concurrent User Programs

- **Concurrent execution of user programs**: good for performance.
  - When task 1 is doing I/O, run task 2 to utilize the CPU.
  - Improve *average response time* (average delay that a user task experiences)
  - Improve *system throughput* (number of user tasks processed in each time unit)
Transactions

- User programs may do many things on the data retrieved.
  - E.g., operations on Bob’s bank account.
  - E.g. transfer of money from account A to account B.
  - E.g., search for a ticket, think about it…, and buy it.

- But the DBMS is only concerned about what data is read from/written to the database.

- A transaction is DBMS’s abstract view of a user program, simply, *a sequence of reads and writes of DB objects.*
ACID Properties for Concurrency

- Many users submit xacts, but each user thinks of his as executing by itself.
  - DMBS *interleaves* reads and writes of xacts for concurrency.

- **Consistency**: each xact starts and ends with a consistent state (i.e., satisfying all integrity constraints).
  - E.g., if an IC states that all accounts must have a positive balance, no transaction can violate this rule.

- **Isolation**: execution of one xact appears isolated from others.
  - Nobody else can see the data in its intermediate state, e.g., account A being debited but B not being credited.
ACID Properties for Recovery

- A transaction might *commit* after completing all its actions, or it could be *aborted* after executing some actions.

- **Atomicity**: either all actions of a xact are performed or none of them is *(all-or-none).*
  - DBMS logs all actions so that it can *undo* the actions of aborted xacts.

- **Durability**: once a user program has been notified of success, its effect will persist despite system failure.
  - DBMS logs all actions so that it can *redo* the actions of committed xacts.
Outline

- Transaction management overview
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- Lock-based concurrency control
- Efficient B+tree locking
- Other locking issues
- Optimistic concurrency control
Consider two transactions:

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

- 1st xact transfers $100 from B’s account to A’s.
- 2nd xact credits both accounts with a 6% interest payment.
- 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) |
Scheduling Transactions

- **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.

- **Serializable schedule**: A schedule that is equivalent to some serial execution of the transactions.
  - If each transaction preserves consistency, every serializable schedule preserves consistency.
Serializability

- Serializability theory concerns the schedules of transactions that are not (explicitly) aborted.

- Given a set of such xacts, ideally want to allow any serializable schedule.
  - Recognizing any serializable schedule is highly complex, if possible.

- Instead, allow only a subset of serializable schedules that are easy to detect.
Conflict Serializability

- 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.

- Given a set of xacts, conflict serializable schedules are a *subset* of serializable schedules.
  - There are serializable schedules that can’t be detected using conflict serializability.
Dependency Graph

- **Precedence graph:**
  - One node per Xact;
  - Edge from Xact $T_i$ to Xact $T_j$ if an action of $T_i$ *precedes* and (potentially) *conflicts with* one of $T_j$’s actions (*RW, WR, WW operations on the same object*).

- **Theorem:** Schedule is conflict serializable *if and only if* its precedence graph is acyclic.
Example

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

The schedule is not conflict serializable:
- The cycle in the graph reveals the problem. The output of T1 depends on T2, and vice-versa.
Weaker Condition on Serializability

- Conflict serializability is \textit{sufficient but not necessary} for serializability.

\begin{itemize}
  \item S1: interleaved schedule
  \begin{array}{l}
  \text{T1: R(A), W(A)} \\
  \text{T2: W(A)} \\
  \text{T3: W(A)}
  \end{array}

  \item S2: serial schedule
  \begin{array}{l}
  \text{T1: R(A), W(A)} \\
  \text{T2: W(A)} \\
  \text{T3: W(A)}
  \end{array}
\end{itemize}
Recoverability

- **Recoverability theory** concerns schedules that involve aborted transactions.

  T1: R(A), W(A)                Abort
  T2: R(A), W(A) Commit

  Unrecoverable!

- A schedule S is **recoverable** if each xact commits only after all xacts from which it read have committed.
Recoverability (Contd.)

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

Recoverable, but with cascading aborts.

- S avoids cascading rollback if each xact may read only those values written by committed xacts.
Recoverability (Contd.)

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

Recoverable, no cascading aborts, but update by T2 may be overwritten when aborting T1. So need to consider other xacts during abort!

- S is *strict* if each xact may *read and write* only objects *previously* written by committed xacts.
  - No cascading aborts.
  - Actions of aborted xacts can be simply undone by restoring the original values of modified objects.
Venn Diagram for Schedules

- All schedules
  - Recoverable
    - Avoid cascading aborts
  - Strict
  - Serial
  - Conflict serializable

- Commit Xacts
- Also Aborted Xacts
Outline

- Transaction management overview
- Serializability & recoverability
  - Lock-based concurrency control
- Efficient B+tree locking
- Other locking issues
- Optimistic concurrency control
(1) Locking Protocol: Strict 2PL

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

<table>
<thead>
<tr>
<th>Compatibility</th>
<th>Shared</th>
<th>Exclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shared</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Exclusive</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>
\section*{Strict 2PL (contd.)}

\begin{itemize}
  \item **Theorem**: Strict 2PL allows only schedules whose precedence graph is acyclic.
    \begin{itemize}
      \item Strict 2PL only allows \textit{conflict serializable schedules}!
    \end{itemize}
  \item Strict 2PL is strict with respect to recoverability.
    \begin{itemize}
      \item Strict 2PL is \textit{recoverable without anomalies related to aborted transactions}.
      \item Hence, it simplifies transaction aborts.
    \end{itemize}
\end{itemize}
Nonstrict 2PL

- Nonstrict Two-Phase Locking Protocol
  1. Each Xact must obtain a S (shared) lock on object before reading, an X (exclusive) lock on object before writing.
  2. If an Xact holds an X lock on an object, no other Xact can get a lock (S or X) on that object.
  3. Duration of locks: A transaction cannot request additional locks once it releases any locks.
Nonstrict 2PL (contd.)

- **Theorem**: Nonstrict 2PL ensures acyclicity of precedence graph.
  - Nonstrict 2PL only allows *conflict serializable* schedules.
  - An equivalent serial schedule is given by the order of xacts entering their *shrinking phase*.

- Nonstrict 2PL is recoverable but *not strict*!
  - Involves complex abort processing.
  - But allows xacts to go through more quickly.

![Graph](image-url)
(2) **Deadlocks**

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

- Two ways of dealing with deadlocks:
  - Deadlock *detection*
  - Deadlock *prevention*
Deadlock Detection

- Create a \textit{waits-for graph}:
  - Nodes are Xacts.
  - There is an edge from Xact Ti to Xact Tj if Ti is \textit{waiting for} Tj to release a lock.
  - Cycles indicate deadlocks!

- Periodically check for cycles in the \textit{waits-for graph}.
  - Resolve a deadlock by aborting a transaction on the cycle and releasing all its locks.
Deadlock Detection (Contd.)

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

Now T1, T2, T3 are all blocked, waiting infinitely… Abort one!
Waits-for vs. Precedence Graphs

- Precedence graph is a theoretical tool to detect conflict serializable schedules.

- Real implementation: (strict) 2PL + deadlock handling
  - 2PL prevents conflicting actions from being materialized in the DB by blocking xact’s.
  - Waits-for graph fixes infinite blocking when xact’s are waiting for each other to release locks.
Deadlock Prevention

- Assign priorities based on timestamps.
  - The older the timestamp, the higher the xact’s priority.
- **Wait-Die**: Ti wants a lock that Tj holds. If Ti has higher priority, Ti waits for Tj; otherwise Ti aborts.
  - Lower priority xacts can never wait.
- **Wound-wait**: Ti wants a lock that Tj holds. If Ti has higher priority, Tj aborts; otherwise Ti waits.
  - Higher priority xacts never wait.

- If a transaction re-starts, make sure it has its original timestamp so its priority increases.
(3) The Phantom Problem

- If we consider *insertion and update* of records in a DB, even *Strict 2PL* won’t assure serializability:
  - T1 locks *all* pages containing sailor records with *rating* = 1, and finds oldest sailor, say, *age* = 71.
  - T2 next *inserts* a new sailor: *rating* = 1, *age* = 96.
  - T1 now reads the oldest sailor again; now, *age* = 96 appears as a *phantom*!

- What is broken in our xact model/protocol?
- Propose a solution to fix it!
BEGIN TRANSACTION

SELECT max(age) FROM Sailors WHERE rating = 1;

... 

SELECT max(age) FROM Sailors WHERE rating = 1;

END TRANSACTION

BEGIN TRANSACTION

INSERT INTO Sailors(sid, sname, rating, age) VALUES (123, 'Fred', 1, 96);

END TRANSACTION

BEGIN TRANSACTION

UPDATE Sailors S SET rating = S.rating - 1 WHERE NOT EXISTS
(SELECT * FROM Reserves R WHERE R.date >= 01/01/2016 and R.sid = S.sid);

END TRANSACTION
The Phantom Problem (Contd.)

- **Problem:** T1 assumes that it has locked all sailor records with \textit{rating} = 1.
  - This is only true if nobody adds/updates records while T1 is running!
  - Phantoms can occur with both inserts and updates.
  - E.g., update a sailor’s \textit{rating} from 3 to 1.

- Need to enforce the assumption that T1 indeed holds locks on \textit{all} records satisfying a condition, e.g., rating=1.
Fundamental Reason (cont’d)

- Fundamental reason for the phantom problem:
  - The old transaction model consists of reads and writes to \textit{individual} data items.
  - In practice, transactions include queries that \textit{dynamically} define sets of items based on \textit{predicates}.
  - When the query is executing, all the records satisfying this predicate at a particular time can be locked.
  - Locking individual items, however, cannot prevent later addition of a record satisfying this predicate.

- Solution: extend lockable objects to \textit{index pages} and further to \textit{arbitrary predicates}!
  - \textbf{Index locking}: used in practice
  - \textbf{Predicate locking}: not very practical
Index Locking

- If there is an index on the `rating` field, T1 should lock the `index page` containing data entries with `rating = 1`.
  - If there are no data entries with `rating = 1`, T1 must lock the index page where such a data entry *would* be, if it existed!

- If there is no suitable index, T1 must lock the entire file/table to prevent new pages from being added.
  - so that no new records with `rating = 1` can be added.
Predicate Locking

- Grant locks on some logical predicate
  - e.g. $age > 2*sal$, or $(age > 50 \text{ or } age < 30) \text{ and } sal > 10K$
- Index locking is a special case of predicate locking
  - An existing index matches the predicate.
  - It supports efficient implementation of the predicate lock.
- In general, predicate locking has a lot of overhead.
  - For each record, we need to check if it satisfies a complex predicate.
  - Therefore, it is not commonly used.