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BCA Honours | Semester IV | BCA4CJ205

Database Management System

Module 4 Comprehensive Notes

Module 4: Transaction Processing, Concurrency Control, and Recovery

Enterprise database systems manage concurrent data access across thousands of distributed clients while preserving data integrity in the face of sudden hardware crashes, software faults, and network partitions.

4.1 Transaction Concepts and ACID Properties

A transaction is a logical unit of database processing that includes one or more database access operations (read, write, update). Every transaction must satisfy the four classical **ACID Properties**:

- **Atomicity:** The all-or-nothing guarantee. Either all operations of a transaction are executed and committed to durable storage, or none are; if a failure occurs mid-transaction, all partial modifications are rolled back. Handled by the Recovery Manager.
- **Consistency:** Preservation of database correctness. Execution of a transaction in isolation preserves all declared database integrity constraints, transforming the database from one valid state to another.
- **Isolation:** The execution of a transaction is isolated from the concurrent executions of other transactions. Intermediate uncommitted modifications are invisible to other transactions. Handled by the Concurrency Control Manager.
- **Durability:** Once a transaction successfully commits, its state modifications persist permanently on non-volatile storage, surviving subsequent power outages or system crashes. Handled by Recovery and Logging Subsystems.

4.2 Transaction States and Concurrency Anomalies

A transaction transitions through explicit execution states: **Active** (executing initial read/write steps), **Partially Committed** (final operation completed, but memory buffers not yet flushed to disk), **Failed** (normal execution cannot proceed), **Aborted** (transaction rolled back and database restored), and **Committed** (successful completion).

Concurrency Anomalies in Uncontrolled Concurrent Execution

- **Lost Update Problem:** Occurs when two transactions concurrently access and update the same data item, and the second transaction's write overwrites the first transaction's update without incorporating it.
- **Temporary Update (Dirty Read) Problem:** Occurs when transaction T_1 modifies a data item and subsequently fails, while transaction T_2 reads the uncommitted value before T_1 rolls back.
- **Incorrect Summary / Inconsistent Analysis Problem:** Occurs when transaction T_1 calculates aggregate summaries while transaction T_2 concurrently modifies individual items, yielding inconsistent arithmetic totals.

4.3 Serializability Theory

A concurrent execution schedule is serializable if its outcome is functionally equivalent to some purely serial execution of the identical transactions. Serializability serves as the benchmark of concurrent execution correctness.

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Conflict Serializability: Two operations in a schedule are in conflict if they belong to different transactions, access the exact same data item, and at least one operation is a write operation (W). A schedule is conflict serializable if it can be transformed into a serial schedule via a sequence of non-conflicting adjacent operation swaps.

Testing Conflict Serializability: Construct a directed **Precedence Graph** (Serialization Graph) $G = (V, E)$, where vertices represent active transactions. A directed edge $T_i \rightarrow T_j$ exists if an operation of T_i conflicts with and executes before an operation of T_j. *A schedule is conflict serializable if and only if its precedence graph contains no directed cycles.*

4.4 Concurrency Control Techniques: Locking Protocols

Lock-based protocols regulate concurrent read and write access to shared data items:

- **Shared Lock (S):** Read-only access. Multiple transactions can concurrently hold shared locks on the same data item (S locks are mutually compatible).
- **Exclusive Lock (X):** Exclusive read and write access. No other transaction can hold any lock (S or X) on the item (X locks are conflicting and mutually exclusive).

The Two-Phase Locking (2PL) Protocol

The 2PL protocol guarantees conflict serializability by requiring transactions to acquire and release locks in two distinct phases:

1. **Growing Phase:** The transaction may acquire locks as needed, but cannot release any lock.
2. **Shrinking Phase:** The transaction may release locks, but cannot acquire any new locks. The point at which the transaction obtains its final lock is the *Lock Point*.

Strict 2PL: Enforces that all exclusive (X) locks acquired by a transaction must be held until the transaction explicitly commits or aborts, eliminating cascading rollbacks.

4.5 Deadlocks and Recovery Systems

Deadlocks occur when two or more transactions wait indefinitely for locks held by each other. Managed via prevention (Wait-Die and Wound-Wait schemes based on timestamps) or detection (identifying directed cycles in a Wait-For Graph WFG and selecting a victim transaction to abort and roll back).

Write-Ahead Logging (WAL): Under WAL, the log record describing a database modification must be flushed to non-volatile disk storage *before* the actual data page is written to disk. During recovery, active transactions are rolled back (UNDO) and committed transactions missing from disk are reapplied (REDO) using the log.

Advanced Theoretical Foundations & Industrial Systems Synthesis

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1. Architectural Trade-offs and Computational Complexity

Software architects and systems engineers designing scalable computational pipelines centered on Database Management System must methodically navigate core trade-offs:

- **Time Complexity Optimization versus Spatial Footprint:** In high-throughput algorithmic pipelines handling Module 4 Core Concepts and Methods, pre-computing intermediate lookup tables, spatial indices, and hashing structures achieves near-instantaneous $O(1)$ query latency, but inflates the physical memory footprint. Conversely, in-place algorithms minimize RAM utilization at the cost of higher CPU cycle counts. Modern architectures dynamically calibrate memory allocations using memory-mapped files and cache-aware structures.
- **Concurrency Scalability versus Thread Contention:** While multi-core hardware allows horizontal execution, concurrent modifications to shared state structures create severe lock contention, thread synchronization bottlenecks, and cache line invalidation storms. High-performance frameworks deploy lock-free algorithms, optimistic concurrency control, and atomic compare-and-swap (CAS) primitives.
- **Algorithmic Determinism versus Heuristic Scalability:** Exact mathematical algorithms frequently encounter NP-hard combinatorial barriers as problem dimensions scale. Contemporary systems bridge this gap by deploying bounded approximation algorithms and meta-heuristics that produce near-optimal solutions within guaranteed execution time windows.

2. Empirical Comparative Framework

A structured comparative assessment clarifies operational distinctions across conventional paradigms and modern production implementations in Database Management System:

Evaluation Dimension	Conventional Traditional Approach	Contemporary Integrated Paradigm	Strategic Impact Metric
Architecture Paradigm	Monolithic single-threaded architectures with tightly coupled state.	Distributed microservices with asynchronous event queues and thread-safe data structures.	Linear scalability and resilient fault isolation under peak transactional loads.
Data Processing Pipeline	Synchronous batch processing characterized by high latency and scheduled processing windows.	Real-time streaming pipelines with sub-second event ingestion and processing.	Zero-latency decision intelligence and immediate anomaly response.
Resilience & Failover	Manual failover mechanisms requiring operator intervention and scheduled downtime.	Automated self-healing clusters with dynamic health checking and zero-downtime rolling deployments.	Continuous availability meeting strict 99.999% Service Level Agreements (SLAs).
System Telemetry & Auditing	Passive log file aggregation with retrospective forensic analysis.	Distributed tracing, structured metrics collection, and real-time observability telemetry.	Proactive bottleneck resolution and sub-second mean time to detection (MTTD).

3. Production Implementation Patterns and Resilience Engineering

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- **State Immutability and Event Sourcing:** Maintaining an append-only log of immutable state changes guarantees verifiable auditability, eliminates data race hazards, and facilitates seamless system recovery.
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