# Module 11: Transaction and Recovery Management

## Winter 2026

Cheriton School of Computer Science

CS 348: Intro to Database Management

# Reading Assignments and References

## To be read during the Week of March 30–April 3:

- Sections 17.1 through 17.9 of Chapter 17 of course textbook.[1]
- Sections 19.1 through 19.4 of Chapter 19 of course textbook.

[1] Silberschatz, Korth and Sudarshan, *Database Systems Concepts*, $7^{th}$ edition

# Outline

# Basics of Transaction Processing

DML processing converts interaction with *sets of tuples* to a sequence of operations that read and write *physical objects* in the database.

Database objects can correspond to:

- individual record fields,
- records,
- physical pages,
- entire files (typically for concurrency control purposes), and
- predicates qualifying one or more records, parts of records, etc.

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- entire files (typically for concurrency control purposes), and
- predicates qualifying one or more records, parts of records, etc.

Transaction and recovery management entails:

- ensuring correct and concurrent execution of operations for reading and writing physical objects originating from DML commands of client transactions; and
- guaranteeing that *acknowledged client transaction commits* are reliably recorded, and that *acknowledged client transaction aborts* are reliably undone.

# Transactions (from Module 1)

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## ACID Properties of a Transaction

| | |
|---|---|
| Atomicity | A transaction occurs entirely, or not at all. |
| Consistency | Each transaction preserves the consistency of the database. |
| Isolation | Concurrent transactions do not interfere with each other. |
| Durability | Once completed, a transaction's changes are permanent. |

# Transactions (cont'd)

Transaction and recovery management is implemented in a DBMS with two subsystems:

## Concurrency Control Management

Responsible for scheduling the execution of reads and writes on physical objects in a way that ensures transaction isolation.

## Recovery Management

Responsible for ensuring transaction atomicity and durability.

NOTE: DML processing is responsible for ensuring the part of transaction consistency defined by integrity constraints.

# Concurrency Control: Assumptions

- We consider a database to be a finite set of independent physical objects $x_j$ that are read and written by transactions $T_i$, and write:
  1. $r_i[x_j]$ to say that transaction $T_i$ reads object $x_j$, and
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- A transaction $T_i$ is a sequence of read and write operations on a database

$$T_i = r_i[x_1], r_i[x_2], w_i[x_1], \ldots, r_i[x_4], w_i[x_2], c_i$$

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- For a *set of transactions* $\{T_1, \ldots, T_k\}$, we want to produce an execution order of operations $S$, called a *schedule*, such that
  1. every operation $o_i \in T_i$ appears also in $S$, and
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Goal: Produce a *correct schedule* with maximal parallelism.

# Transactions and Schedules

If $T_i$ and $T_j$ are concurrent transactions, then it is always correct to schedule the operations in such a way that:

- $T_i$ will appear to precede $T_j$ meaning that $T_j$ will "see" all updates made by $T_i$, and $T_i$ will not see any updates made by $T_j$, or
- $T_i$ will appear to follow $T_j$, meaning that $T_i$ will see $T_j$'s updates and $T_j$ will not see $T_i$'s.

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## Idea

Define a schedule $S$ to be *correct* if it appears to clients that the transactions are executed sequentially, that is, in some strictly serial order.

## Serializable Schedule

A schedule $S$ is said to be serializable if it is equivalent to some serial execution of the same transactions.

# Serializable Schedules

Examples:

- An interleaved execution of two transactions:

$$S_a = w_1[x], r_2[x], w_1[y], c_1, r_2[y], c_2$$

- An equivalent serial execution ($T_1$ , $T_2$):

$$S_b = w_1[x], w_1[y], c_1, r_2[x], r_2[y], c_2$$

- An interleaved execution with no equivalent serial execution:

$$S_c = w_1[x], r_2[x], r_2[y], c_2, w_1[y], c_1$$

# Serializable Schedules (cont'd)

How do we determine if two schedules are *equivalent*?

$\Rightarrow$ *cannot be based on any particular database instance*

## Conflict Equivalence

Two operations conflict if they

1. belong to different transactions
2. access the same data item $x$, and
3. at least one of them is a write operation $w[x]$.

Two schedules $S_1$ and $S_2$ are conflict equivalent when all *conflicting operations* are ordered the same way.

A schedule $S_1$ is a conflict serializable schedule if it is conflict equivalent to some serial schedule $S_2$.

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View Equivalence: Preserves initial reads and final writes; allows more schedules, but is harder (NP-hard) to diagnose.

# Serializable Schedules (cont'd)

How does one diagnose if a schedule $S$ is a conflict serializable schedule?

## Serialization Graph

A *serialization graph* $SG(N, E)$ *for a schedule* $S$ is a directed graph with

1. nodes $T_i \in N$, corresponding to the transactions of $S$, and
2. edges $T_i \rightarrow T_j \in E$ whenever an operation $o_i[x]$ for transaction $T_i$ occurrs prior to an operation $o_j[x]$ for transaction $T_j$ in $S$, where $o_i[x]$ and $o_j[x]$ are conflicting operations.

## Theorem

A schedule $S$ is serializable if and only if the serialization graph $SG$ for $S$ is acyclic.

# Other Properties of Schedules

Serializability guarantees correctness. However, we'd like to avoid other *undesirable* situations.

## Recoverable Schedules (RC)

*The situation*: Transaction $T_j$ *reads* a value $T_i$ has written, then $T_j$ commits, then $T_i$ attempts to abort.

$\Rightarrow$ *aborting* $T_i$ *makes it necessary to undo effects of a committed transaction* $T_j$

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## Cascadeless Schedules (ACA)

*The situation*: Transaction $T_j$ *reads* a value $T_i$ has written, then $T_i$ attempts to abort .

$\Rightarrow$ *aborting $T_i$ makes it necessary to abort $T_j$, which may lead to a cascade of further aborts of other transactions*

*The repair*: Do not allow transactions to read uncommitted objects.

# Outline

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How does a DBMS admit ultimate schedules for execution of the operations of transactions that are conflict serializable and cascade free?

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The DBMS scheduler is responsible for this.

1. It receives requests to execute operations from the query processor(s), and
2. for each operation it chooses one of the following actions:
   - execute it (by sending to a lower module),
   - delay it (by inserting in some queue),
   - reject it (thereby causing abort of the transaction), or
   - ignore it (since it has no effect).

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There are two kinds of schedulers:

1. conservative schedules favour delaying operations, and
2. aggressive schedulers favour rejecting operations.

# Two Phase Locking

Conservative schedulers are lock based.

A simple lock based scheduler requires transactions to have a lock on objects before access:

- a *shared lock* is required to read an object, and
- an *exclusive lock* is required to write an object,

where an exclusive lock on an object $x$ by a transaction disallows any other lock at all to be held on $x$ by any other transaction.

It is insufficient for a scheduler just to acquire a lock, access the data item, and then release it immediately.

Exercise: *Show why this is the case.*

# Two Phase Locking (cont'd)

## Two Phase Locking

A scheduler follows the *two phase locking protocol* (2PL) if it allows no lock to be acquired by a transaction $T$ on some object after the first lock by $T$ on some other (not necessarily distinct) object is released by $T$.

## Theorem

Any execution order of operations admitted by a scheduler following the two phase locking protocol will be a prefix of an ultimate schedule that is a conflict serializable schedule.

# Strict Two Phase Locking (cont'd)

The 2PL locking protocol can still allow operations to proceed that lead to:

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A refinement of 2PL addresses the first of these problems.

## Strict Two Phase Locking

A scheduler follows the *strict two phase locking protocol* (strict 2PL) if it allows no lock for a transaction $T$ to be released until $T$ requests either a commit or abort operation.

## Theorem

Any execution order of operations admitted by a scheduler following the strict two phase locking protocol will be a prefix of an ultimate schedule that is a conflict serializable schedule and will also have the ACA property ensuring there are no cascading aborts.

# Deadlocks

Either 2PL or strict 2PL may lead to a *deadlock* involving a sequence of transactions $(T_1, \ldots, T_n)$ where $T_i$ must wait for $T_{i+1}$ to release locks, $1 \leq i < n$, and where $T_n$ must wait for $T_1$ to release locks.

Example: *Consider where a strict 2PL scheduler has received the following sequence of operations leading to deadlock with the transaction sequence* $(T_2, T_1)$:

$$r_1[x], r_2[y], w_2[x] \text{ (blocked by } T_1), w_1[y] \text{ (blocked by } T_2)$$

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There are two general ways to resolve deadlocking:

deadlock prevention

$\Rightarrow$ *locks granted only if they can't lead to a deadlock*

$\Rightarrow$ *all objects are ordered, and locks granted in this order*

deadlock detection

$\Rightarrow$ *use wait for graphs and cycle detection*

$\Rightarrow$ *resolution: the system aborts one of the offending transactions; called an involuntary abort*

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In practice, some schedulers detect a lock request timeout instead of a deadlock and resolve by aborting.

# Variations on Locking

- Multi-granularity Locking

  $\Rightarrow$ *not all locked objects have the same size*
  $\Rightarrow$ *advantageous in presence of bulk versus tiny updates*

- Predicate Locking

  $\Rightarrow$ *locks based on selection predicate rather than on a value*

- Tree Locking

  $\Rightarrow$ *can be used to avoid congestion in roots of Btrees*
  $\Rightarrow$ *allows relaxation of 2PL due to tree structure of data*

- Lock Upgrade protocols

- ...

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Neither 2PL nor strict 2PL correctly handles such cases.

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1. *Based on a sufficient fixed budget, transaction $T_1$ gives each employee a bonus.*
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This situation is called the phantom tuple problem.

Resolution: DML requests that modify the database according to the results of a query need larger scale locks, such as

- locks on entire indices, or
- predicate locks on tables

together with appropriate *lock compatibility* rules.

# Isolation Levels in SQL

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The SQL standard addresses by allowing four isolation levels for a transaction that can be set by a client SQL command:

Level 3: (*serializability*) Realized by strict 2PL with table level locks.

Level 2: (*repeatable read*) Realized by strict 2PL with tuple level locks only; phantom tuples may occur.

Level 1: (*cursor stability*) Realized by strict 2PL with tuple level exclusive locks only.

$\Rightarrow$ *the same query executed twice in a transaction can produce different answers*

Level 0: Realized by simply not requiring any locking.

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$\Rightarrow$ *transaction queries may read uncommitted updates*

Exercise: *Consider cases where each of these isolations levels might suffice.*

# Outline

Unit 1: Concurrency Control

Unit 2: Two Phase Locking

Unit 3: **Failure Recovery**

# Failure Recovery

The DBMS module responsible for recovery management must satisfy two requirements:

1. (regarding atomicity) enable a transaction to be
   - committed (with a guarantee database changes are permanent), or
   - aborted (with a guarantee that there are no database changes)

2. (regarding reliability) enable a database to be recovered to a consistent state in case of hardware or software failure.

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Interaction with recovery management:

Input: a 2PL and ACA schedule of operations produced by the transaction manager, and

Output: a schedule of object reads, object writes, and object forced writes.

# Approaches to Recovery

Two essential approaches:

1. Shadowing
   - ⇒ *copy-on-write and merge-on-commit approaches*
   - ⇒ *poor clustering*
   - ⇒ *used in system R, but not in modern systems*

2. Logging
   - ⇒ *uses log files on (separate) stable media*
   - ⇒ *good utilization of buffers*
   - ⇒ *preserves original clusters*

# Logging Approaches to Recovery

A log is a read/append only data structure on stable media.

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Log records record several types of information:

- UNDO information: old versions of objects that have been modified by a transaction. UNDO information can be used to undo database changes made by a transaction that aborts.
- REDO information: new versions of objects that have been modified by a transaction. REDO records can be used to redo the work done by a transaction that commits.
- BEGIN/COMMIT/ABORT information: record when transactions begin, commit, or abort.

# Example of a LOG

Five transactions: $\{T_0, T_1, T_2, T_3, T_4\}$

Transaction status:

$\{T_1, T_3\}$ committed,

$\{T_2\}$ aborted, and

$\{T_0, T_4\}$ active.

Exercises:

1. *Explain how to abort a translation using a log.*

2. *Explain how to recover from a failure using a log, assuming active transactions should be aborted.*

| | | |
|---|---|---|
| log head | → | $T_0$, BEGIN |
| (oldest part) | | $T_0$, UNDO, $x_1$, 99 |
| | | $T_0$, REDO, $x_1$, 100 |
| | | $T_1$, BEGIN |
| | | $T_1$, UNDO, $x_2$, 199 |
| | | $T_1$, REDO, $x_2$, 200 |
| | | $T_2$, BEGIN |
| | | $T_2$, UNDO, $x_3$, 51 |
| | | $T_2$, REDO, $x_3$, 50 |
| | | $T_1$, UNDO, $x_4$, 1000 |
| | | $T_1$, REDO, $x_4$, 10 |
| | | $T_1$, COMMIT |
| | | $T_3$, BEGIN |
| | | $T_2$, ABORT |
| | | $T_3$, UNDO, $x_2$, 200 |
| | | $T_3$, REDO, $x_2$, 50 |
| | | $T_4$, BEGIN |
| | | $T_4$, UNDO, $x_4$, 10 |
| (newest part) | | $T_4$, REDO, $x_4$, 100 |
| log tail | → | $T_3$, COMMIT |

# Write-Ahead Logging

Allowing indices on stable store to be updated prior to a LOG can lead to inconsistency.

A *write-ahead logging* (WAL) protocol avoids this by following:

1. an undo rule: a log record for an update is appended to the LOG file *before* the corresponding data page is written to stable store.

   $\Rightarrow$ *guarantees atomicity*

2. a redo rule: all log records for a transaction are appended to the LOG file *before* acknowledging a commit.

   $\Rightarrow$ *guarantees durability*

# Summary

ACID properties of transactions guarantee correctness of concurrent access to the database and of data storage.

- Consistency and isolation based on serializability
  1. leads to definition of correct schedulers, and
  2. is the responsibility of the transaction manager.
- Durability and atomicity are the responsibility of the recovery manager.
- Synchronous writing is too inefficient, and replaced by synchronous writes to a LOG file according to WAL.