CSE 544
Principles of Database Management Systems

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Lecture 12 –
Transactions: Concurrency Control
(Part 2 aka the Interesting Stuff)

Announcements

- Project milestone report due **next Wednesday**
  - See project page for details
- HW3 due **next Thursday**
- No lecture and OH next Tuesday
- Today: finish discussion on concurrency control

References

- **Concurrency control and recovery.**

  Michael J. Franklin. The handbook of computer science and engineering. A. Tucker ed. 1997

- **Database management systems.**

  Ramakrishnan and Gehrke.

  Third Ed. **Chapters 16 and 17.**

Outline

- Transactions motivation, definition, properties
- Concurrency control and locking
- Optimistic concurrency control

Motivating Example

```
UPDATE Budget
SET money=money-100
WHERE pid = 1

UPDATE Budget
SET money=money+60
WHERE pid = 2

UPDATE Budget
SET money=money+40
WHERE pid = 3
```

```
SELECT sum(money)
FROM Budget
```

Would like to treat each group of instructions as a unit

Definition

- **A transaction** = one or more operations, (seemingly) single real-world transition

- Examples
  - Transfer money between accounts
  - Purchase a group of products
  - Register for a class (either waitlist or allocated)
  - What else?

ACID Properties

- Atomicity: Either all changes performed by transaction occur or none occurs
- Consistency: A transaction as a whole does not violate integrity constraints
- Isolation: Transactions appear to execute one after the other in sequence
- Durability: If a transaction commits, its changes will survive failures

Types of Problems: Summary

- Concurrent execution problems
  - Write-read conflict: dirty read (includes inconsistent read)
    - A transaction reads a value written by another transaction that has not yet committed
  - Read-write conflict: unrepeatable read
    - A transaction reads the value of the same object twice. Another transaction modifies that value in between the two reads
  - Write-write conflict: lost update
    - Two transactions update the value of the same object. The second one to write the value overwrite the first change
- Failure problems
  - DBMS can crash in the middle of a series of updates
  - Can leave the database in an inconsistent state

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A Serial Schedule

Time ↓

T1	T2
READ(A, t)	
t := t+100	
WRITE(A, t)	
READ(B, t)	
t := t+100	
WRITE(B,t)	
	READ(A,s)
	s := s*2
	WRITE(A,s)
	READ(B,s)
	s := s*2
	WRITE(B,s)

Serializable Schedule

- A schedule is ***serializable*** if it is equivalent to a serial schedule

A Serializable Schedule

T1	T2
READ(A, t)	
t := t+100	
WRITE(A, t)	
	READ(A,s)
	s := s*2
	WRITE(A,s)
READ(B, t)	
t := t+100	
WRITE(B,t)	
	READ(B,s)
	s := s*2
	WRITE(B,s)

Notice:
This is NOT a serial schedule

Notation

T_1: $r_1(A)$; $w_1(A)$; $r_1(B)$; $w_1(B)$
T_2: $r_2(A)$; $w_2(A)$; $r_2(B)$; $w_2(B)$

Serializable Execution

- **Serializability**: interleaved execution has same effect as some serial execution

- Schedule of two transactions (Figure 1)

  $r_0[A] \rightarrow w_0[A] \rightarrow r_1[A] \rightarrow r_1[B] \rightarrow c_1 \rightarrow$
  $\rightarrow r_0[B] \rightarrow w_0[B] \rightarrow c_0$

- Serializable schedule: equiv. to serial schedule

  $r_0[A] \rightarrow w_0[A] \rightarrow r_1[A] \rightarrow r_0[B] \rightarrow$
  $\rightarrow w_0[B] \rightarrow c_0 \rightarrow r_1[B] \rightarrow c_1$

Conflict Serializability

Conflicts: (aka bad things happen if swapped)

Two actions by same transaction T_i: $r_i(X); w_i(Y)$

Two writes by T_i, T_j to same element $w_i(X); w_j(X)$

Read/write by T_i, T_j to same element

$w_i(X); r_j(X)$

$r_i(X); w_j(X)$

Conflict Serializability

- A schedule is *conflict serializable* if it can be transformed into a serial schedule by a series of swappings of adjacent non-conflicting actions

Example:

$r_1(A); w_1(A); r_2(A); w_2(A); r_1(B); w_1(B); r_2(B); w_2(B)$

⇓

$r_1(A); w_1(A); r_1(B); w_1(B); r_2(A); w_2(A); r_2(B); w_2(B)$

The Precedence Graph Test

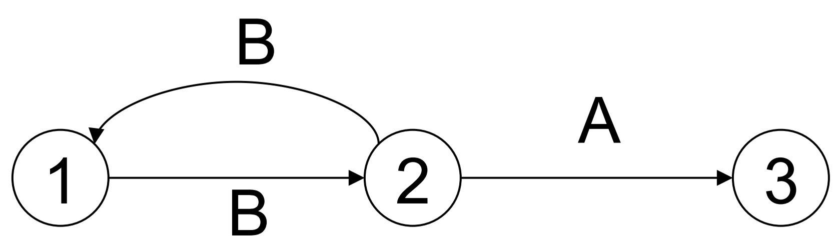
Is a schedule conflict-serializable ?

Simple test:

- Build a graph of all transactions T_i
- Edge from T_i to T_j if T_i makes an action that conflicts with one of T_j and comes first
- Fact: if the graph has no cycles, then it is conflict serializable !

Example 2

$r_2(A); r_1(B); w_2(A); r_2(B); r_3(A); w_1(B); w_3(A); w_2(B)$



This schedule is NOT conflict-serializable

Conflict Serializability

- A serializable schedule need not be conflict serializable, even under the "worst case update" assumption

Lost write

$w_1(Y); w_2(Y); w_2(X); w_1(X); w_3(X);$

$w_1(Y); w_1(X); w_2(Y); w_2(X); w_3(X);$

Equivalent, but can't swap

Scheduler

- The scheduler is the module that schedules the transaction's actions, ensuring serializability
- How? We discuss three techniques in class:
  - Locks
  - Timestamps
  - Validation

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Locking Scheduler

Simple idea:

- Each element has a unique lock
- Each transaction must first acquire the lock before reading/writing that element
- If lock is taken by another transaction, then wait
- The transaction must release the lock(s)

Notation

$l_i(A)$ = transaction T_i acquires lock for element A

$u_i(A)$ = transaction T_i releases lock for element A

Example

T1	T2
$L_1(A)$; READ(A, t)	
t := t+100	
WRITE(A, t); $U_1(A)$; $L_1(B)$	
	$L_2(A)$; READ(A,s)
	s := s*2
	WRITE(A,s); $U_2(A)$;
	$L_2(B)$; **DENIED…**
READ(B, t)	
t := t+100	
WRITE(B,t); $U_1(B)$;	
	…**GRANTED;** READ(B,s)
	s := s*2
	WRITE(B,s); $U_2(B)$;

Scheduler has ensured a conflict-serializable schedule

Is this enough?

T1	T2
$L_1(A)$; READ(A, t)	
t := t+100	
WRITE(A, t); $U_1(A)$;	
	$L_2(A)$; READ(A,s)
	s := s*2
	WRITE(A,s); $U_2(A)$;
	$L_2(B)$; READ(B,s)
	s := s*2
	WRITE(B,s); $U_2(B)$;
$L_1(B)$; READ(B, t)	
t := t+100	
WRITE(B,t); $U_1(B)$;	

Locks did not enforce conflict-serializability !!!

Two Phase Locking (2PL)

The 2PL rule:

- In every transaction, all lock requests must preceed all unlock requests

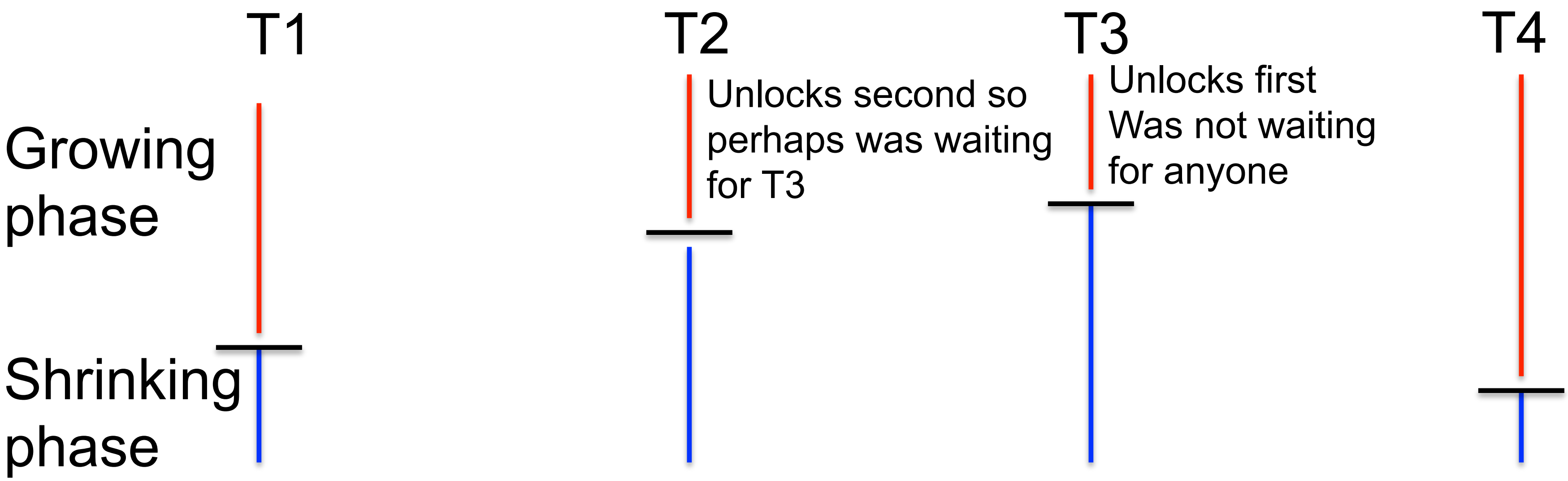
- This ensures conflict serializability ! (why?)

Example: 2PL transactions

T1	T2
$L_1(A)$; $L_1(B)$; READ(A, t)	
t := t+100	
WRITE(A, t); $U_1(A)$	
	$L_2(A)$; READ(A,s)
	s := s*2
	WRITE(A,s);
	$L_2(B)$; **DENIED…**
READ(B, t)	
t := t+100	
WRITE(B,t); $U_1(B)$;	
	…**GRANTED;** READ(B,s)
	s := s*2
	WRITE(B,s); $U_2(A)$; $U_2(B)$;

Now it is conflict-serializable

Example with Multiple Transactions



Equivalent to each transaction executing entirely the moment it enters shrinking phase

What about Aborts?

- 2PL enforces conflict-serializable schedules
- But what if a transaction releases its locks and then aborts?

Example with Abort

T1	T2
L_1(A); L_1(B); READ(A, t)	
t := t+100	
WRITE(A, t); U_1(A)	
	L_2(A); READ(A,s)
	s := s*2
	WRITE(A,s);
	L_2(B); **DENIED…**
READ(B, t)	
t := t+100	
WRITE(B,t); U_1(B);	
	…**GRANTED;** READ(B,s)
	s := s*2
	WRITE(B,s); U_2(A); U_2(B);
Abort	Commit

Strict 2PL

- Strict 2PL: All locks held by a transaction are released when the transaction is completed
  - Also called "long-duration locks"
- Ensures that schedules are recoverable
  - Transactions commit only after all transactions whose changes they read also commit
- Avoids cascading rollbacks

Deadlock

- Transaction T_1 waits for a lock held by T_2;
- But T_2 waits for a lock held by T_3;
- While T_3 waits for . . . .
- . . .
- . . .and T_{73} waits for a lock held by T_1 !!

- A deadlock is when two or more transactions are waiting for each other to complete

Handling Deadlock

- **Deadlock avoidance**
  - Acquire locks in pre-defined order
  - Acquire all locks at once before starting
- **Deadlock detection**
  - Timeouts (but hard to pick the right threshold)
  - Wait-for graph
    - What commercial systems use (they check graph periodically)

Lock Modes

- S = shared lock (for READ)
- X = exclusive lock (for WRITE)

- U = update lock
  - Initially like S
  - Later may be upgraded to X
- I = increment lock (for A := A + something)
  - Increment operations commute

Lock Granularity

- Fine granularity locking (e.g., tuples)
  - High concurrency
  - High overhead in managing locks
- Coarse grain locking (e.g., tables)
  - Many false conflicts
  - Less overhead in managing locks
- Alternative techniques
  - Hierarchical locking (and intentional locks) [commercial DBMSs]
  - Lock escalation

Phantom Problem

- A “phantom” is a tuple that is invisible during part of a transaction execution but not all of it.

- Example:
  - T0: reads list of books in catalog
  - T1: inserts a new book into the catalog
  - T2: reads list of books in catalog
    - New book will appear!

- How can this occur?
- Depends on locking details (eg, granularity of locks)
- Can’t lock a tuple that doesn’t exist yet

Dealing with Phantoms: Predicate Locks

- Lock predicates rather than actual database elements
  - "lock all books that have createTime > T"
  - Two predicates p and p' are *compatible* iff no tuple can satisfy both at the same time

- Issue: very expensive to implement
  - NP-hard to determine if predicates are compatible with each other
  - What if DB has hidden predicates (e.g., functional dependencies) that make p and p' incompatible?

Dealing with Phantoms: Granular Locks

- Implement multi-level locking
  - Tuple
  - Table
  - Entire database
- Allow transactions to lock at any granularity
  - Lock tuples if reading
  - Lock the entire table if inserting new records
  - Need a hierarchy of locks: table lock > tuple lock

- Issue: can cause many deadlocks among transactions

Dealing with Phantoms: Intent Locks

- Reduce possibility of deadlocks with three lock modes:
  - Shared
  - Exclusive
  - Intent
- Intent: transaction will be locking at finer granularity
- Lock compatibilities:

Request \ Current mode	None	Intent	Shared	Exclusive
None	✓	✓		
Intent	✓	✓		
Shared	✓		✓	
Exclusive	✓			

Degrees of Isolation

- Isolation level “serializable” (i.e. ACID)
  - Gold standard
  - Requires strict 2PL and predicate locking
  - But often too inefficient
  - Imagine there are only a few update operations and many long read operations
- Weaker isolation levels
  - Sacrifice correctness for efficiency
  - Often used in practice (often **default**)
  - Sometimes are hard to understand

Degrees of Isolation

- **Four levels of isolation**
  - All levels use **long-duration exclusive locks**
  - READ UNCOMMITTED: no read locks
  - READ COMMITTED: short duration read locks
  - REPEATABLE READ:
    - Long duration read locks on individual items
  - SERIALIZABLE:
    - All locks long duration and lock predicates

- **Trade-off: consistency vs concurrency**
- Commercial systems give **choice** of level + **others**

The Tree Protocol

- An alternative to 2PL, for tree structures
- E.g. B+ trees (the indexes of choice in databases)

- Because
  - Indexes are hot spots!
  - 2PL would lead to great lock contention

  - Also, unlike data, the index is not directly visible to transactions
  - So only need to guarantee that index returns correct values

The Tree Protocol

Rules:

- A lock on a node A may only be acquired if the transaction holds a lock on its parent B
- Nodes can be unlocked in any order (no 2PL necessary)
- Cannot relock a node for which already released a lock
- "Crabbing"
  - First lock parent then lock child
  - Keep parent locked only if may need to update it
  - Release lock on parent if child is not full

- The tree protocol is NOT 2PL, yet ensures conflict-serializability !
- (More in the R&G)

Outline

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Locking vs Optimistic

- Locking prevents unserializable behavior from occurring: it causes transactions to wait for locks

- Optimistic methods assume no unserializable behavior will occur: they abort transactions if it does

- Locking typically better in case of high levels of contention; optimistic better otherwise

Optimistic Concurrency Control

Timestamp-based technique

- Each object, O, has read and write timestamps: RTS(O) and WTS(O)
- Each transaction, T, has a timestamp TS(T)
- **INVARIANT**: **Timestamp order defines serialization order**

Transaction wants to read object O

- If TS(T) < WTS(O) abort
- Else read and update RTS(O) to larger of TS(T) or RTS(O)

Transaction wants to write object O

- If TS(T) < RTS(O) abort
- If TS(T) < WTS(O) ignore my write and continue (Thomas Write Rule)
- Otherwise, write O and update WTS(O) to TS(T)

Optimistic Concurrency Control

Timestamp-based technique

- What about aborts? Need to add a commit bit C to each element
- Read dirty data:
  - T wants to read X, and WT(X) < TS(T)
  - If C(X)= false, T needs to wait for it to become true in case previous writer aborts
- Write dirty data:
  - T wants to write X, and WT(X) > TS(T)
  - If C(X)= false, T needs to wait for it to become true in case of abort

- Bottom line: When T requests r(X) or w(X), scheduler examines RT(X), WT(X), C(X), and decides one of:
  - To grant the request, or
  - To rollback T (and restart with later timestamp)
  - To delay T until C(X) = true

Optimistic Concurrency Control

Multiversion-based technique

- Object timestamps: RTS(O) & WTS(O); transaction timestamps TS(T)
- Transaction can read most recent version that precedes TS(T)
  - When reading object, update RTS(O) to larger of TS(T) or RTS(O)
- Transaction wants to write object O
  - If TS(T) < RTS(O) abort
  - Otherwise, create a new version of O with WTS(O) = TS(T)
- Common variant (used in commercial systems)
  - To write object O only check for conflicting writes not reads
  - Use locks for writes to avoid aborting in case conflicting transaction aborts

Optimistic Concurrency Control

Validation-based technique

- Phase 1: Read
  - Transaction reads from database and writes to a private workspace
  - Each transaction keeps track of its read set RS(T) and write set WS(T)

- Phase 2: Validate
  - At commit time, system performs validation using read/write sets
  - Validation checks if transaction could have conflicted with others
    - Each transaction gets a timestamp
    - Check if timestamp order is equivalent to a serial order
  - If there is a potential conflict: abort

- Phase 3: Write
  - If no conflict, transaction changes are copied into database

Snapshot Isolation

- A type of multiversion concurrency control algorithm
- Provides yet another level of isolation

- Very efficient, and very popular
  - Oracle, PostgreSQL, SQL Server 2005

- Prevents many classical anomalies BUT…
- Not serializable (!), yet ORACLE and PostgreSQL use it even for SERIALIZABLE transactions!
  - But "serializable snapshot isolation" now in PostgreSQL

Snapshot Isolation Rules

- Each transactions receives a timestamp TS(T)
- Transaction T sees snapshot at time TS(T) of the database
- When T commits, updated pages are written to disk
- Write/write conflicts resolved by “first committer wins” rule
  - Loser gets aborted
- Read/write conflicts are ignored

Snapshot Isolation (Details)

- Multiversion concurrency control:
  - Versions of X: X_{t1}, X_{t2}, X_{t3}, . . .
- When T reads X, return $X_{TS(T)}$.
- When T writes X: if other transaction updated X, abort
  - Not faithful to "first committer" rule, because the other transaction U might have committed after T. But once we abort T, U becomes the first committer ☺

What Works and What Not

- No dirty reads (Why ?)
- No inconsistent reads (Why ?)
  - A: Each transaction reads a consistent snapshot
- No lost updates ("first committer wins")
- Moreover: no reads are ever delayed
- However: read-write conflicts not caught !

Write Skew

T1:	T2:
READ(X);	READ(Y);
if X >= 50	if Y >= 50
then Y = -50; WRITE(Y)	then X = -50; WRITE(X)
COMMIT	COMMIT

In our notation:

$R_1(X), R_2(Y), W_1(Y), W_2(X), C_1, C_2$

Starting with X=50,Y=50, we end with X=-50, Y=-50.
Non-serializable !!!

Questions/Discussions

- How does snapshot isolation (SI) compare to repeatable reads and serializable?
  - A: SI avoids most but not all phantoms (e.g., write skew)
- Note: Oracle & PostgreSQL implement it even for isolation level SERIALIZABLE
  - But most recently: “serializable snapshot isolation”
- How can we enforce serializability at the app level ?
  - Recall that all read / write conflicts are ignored.
  - A: Use dummy writes for all reads to create write-write conflicts… but that is confusing for developers!!!

Commercial Systems

Always check documentation as DBMSs keep evolving and thus changing! Just to get an idea:

- DB2: Strict 2PL
- SQL Server:
  - Strict 2PL for standard 4 levels of isolation
  - Multiversion concurrency control for snapshot isolation
- PostgreSQL: Multiversion concurrency control
- Oracle: Multiversion concurrency control

Important Lesson

- ACID transactions/serializability make it easy to develop applications
- BUT they add overhead and slow things down

- Lower levels of isolation reduce overhead
- BUT they are hard to reason about for developers!