Introduction to Data Management
CSE 344

Unit 7: Transactions

Schedules

Implementation

Two-phase Locking

(3-4 lectures)

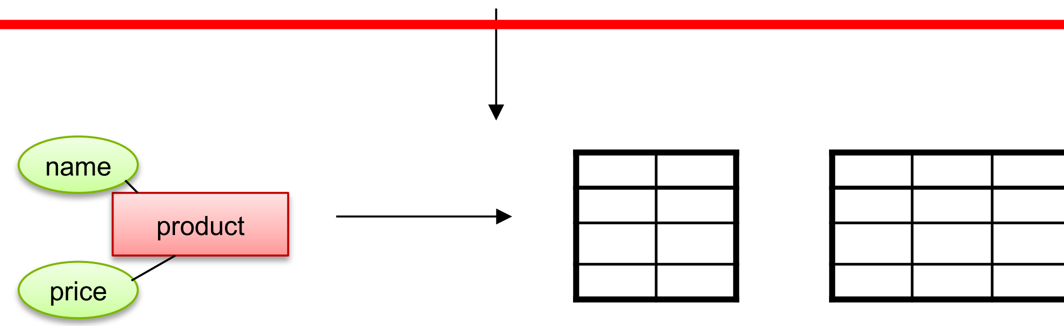
Class Overview

- Unit 1: Intro
- Unit 2: Relational Data Models and Query Languages
- Unit 3: Non-relational data
- Unit 4: RDMBS internals and query optimization
- Unit 5: Parallel query processing
- Unit 6: DBMS usability, conceptual design
- Unit 7: Transactions
  - Writing DB applications
  - Locking and schedules

Data Management Pipeline

Transactions

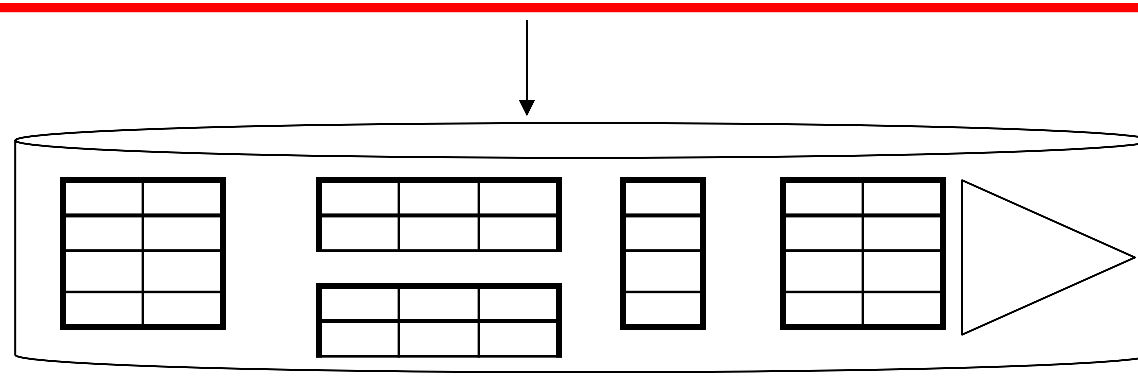
Application programmer



Schema designer

Conceptual Schema

Transactions



Database administrator

Physical Schema

Transactions

- We use database transactions everyday
  - Bank $$$ transfers
  - Online shopping
  - Signing up for classes
- Applications that talk to a DB ***must*** use transactions in order to keep the database consistent.

What’s the big deal?

Challenges

- Suppose we only serve one app at a time
  - No problem…
- Suppose we execute apps concurrently
  - What's the problem?
- Want: multiple operations to be executed *atomically* over the same DBMS

What can go wrong?

- Manager: balance budgets among projects
  - Remove $10k from project A
  - Add $7k to project B
  - Add $3k to project C

- CEO: check company's total balance
  - `SELECT SUM(money) FROM budget;`

- This is called a dirty / inconsistent read
  aka a WRITE-READ conflict

What can go wrong?

- App 1: `SELECT inventory FROM products WHERE pid = 1`

```
SELECT inventory FROM products
WHERE pid = 1
```

- App 2:

```
UPDATE products SET inventory = 0
WHERE pid = 1
```

- App 1:

```
SELECT inventory * price FROM products
WHERE pid = 1
```

- This is known as an unrepeatable read
  aka READ-WRITE conflict

What can go wrong?

Account 1 = $100
Account 2 = $100
Total = $200

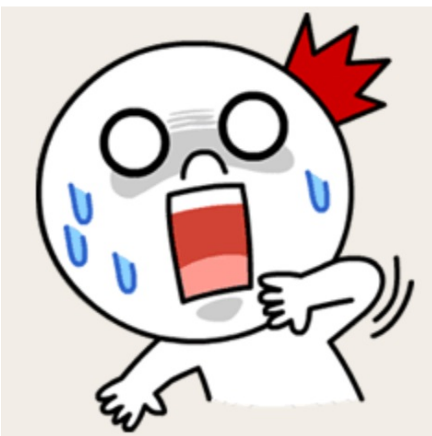
- App 1:
  - Set Account 1 = $200
  - Set Account 2 = $0
- App 2:
  - Set Account 2 = $200
  - Set Account 1 = $0
- At the end:
  - Total = $200

- App 1: Set Account 1 = $200
- App 2: Set Account 2 = $200
- App 1: Set Account 2 = $0
- App 2: Set Account 1 = $0
- At the end:
  - Total = $0

This is called the lost update aka WRITE-WRITE conflict

What can go wrong?

- Buying tickets to the next Bieber concert:
  – Fill up form with your mailing address
  – Put in debit card number
  – Click submit
  – Screen shows money deducted from your account
  – [Your browser crashes]



Lesson:

Changes to the database should be ALL or NOTHING

Transactions

- Collection of statements that are executed atomically (logically speaking)

```
BEGIN TRANSACTION
  [SQL statements]
COMMIT    or
ROLLBACK (=ABORT)
```

```
[single SQL statement]
```

If `BEGIN`… missing, then TXN consists of a single instruction

Know your ~~chemistry~~ transactions: ACID

- Atomic
  - State shows either all the effects of txn, or none of them
- Consistent
  - Txn moves from a DBMS state where integrity holds, to another where integrity holds
    - remember integrity constraints?
- Isolated
  - Effect of txns is the same as txns running one after another (i.e., looks like batch mode)
- Durable
  - Once a txn has committed, its effects remain in the database

Atomic

- **Definition**: A transaction is ATOMIC if all its updates must happen or not at all.

```
-- Example: move $100 from A to B:
BEGIN TRANSACTION;
  UPDATE accounts SET bal = bal – 100 WHERE acct = A;
  UPDATE accounts SET bal = bal + 100 WHERE acct = B;
COMMIT;
```

Isolated

- **Definition** An execution ensures that txns are isolated, if the effect of each txn is as if it were the only txn running on the system.

```
-- App 1:
BEGIN TRANSACTION;

  SELECT inventory
  FROM products
  WHERE pid = 1;

  SELECT inventory * price
  FROM products
  WHERE pid = 1;

COMMIT
```

```
-- App 2:
BEGIN TRANSACTION;
  UPDATE products
  SET inventory = 0
  WHERE pid = 1;
COMMIT;
```

Consistent

- Recall: integrity constraints govern how values in tables are related to each other
  - Can be enforced by the DBMS, or ensured by the app
- How consistency is achieved by the app:
  - App programmer ensures that txns only takes a consistent DB state to another consistent state
  - DB makes sure that txns are atomic and isolated
- Can defer checking the validity of constraints until the end of a transaction

Durable

- A transaction is durable if its effects continue to exist after the transaction and even after the program has terminated

- How?
  – By writing to disk!
  – More in 444

Rollback transactions

- If the app gets to a state where it cannot complete the transaction successfully, execute ROLLBACK
- The DB returns to the state prior to the transaction
- What are examples of such program states?

ACID

- Atomic
- Consistent
- Isolated
- Durable

- Enjoy this in HW8!

- Again: by default each statement is its own txn
  - Unless auto-commit is off then each statement starts a new txn

Implementing Transactions

Need to address two problems:

- ”I” – Isolation:
  - Means concurrency control
  - We will discuss this
- “A” – Atomicity:
  - Means recover from crash
  - We will not discuss this (see 444)

Transactions Demo

Transaction Schedules

Modeling a Transaction

- Database = a collection of *elements*
  - An element can be a record (logical elements)
  - Or can be a disc block (physical element)

Database: | A | B | C | D | …

- Transaction = sequence of read/writes of elements

Schedules

A schedule is a sequence of interleaved actions from all transactions

Serial Schedule

- A *serial schedule* is one in which transactions are executed one after the other, in some sequential order
- **Fact:** nothing can go wrong if the system executes transactions serially
- But DBMS don't do that because we want better overall system performance

Example

A and B are elements in the database
t and s are variables in txn source code

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

Example of 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)

Another Serial Schedule

Time

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

Review: 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)

This is a serializable schedule.
This is NOT a serial schedule

A Non-Serializable Schedule

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

How do We Know if a Schedule is Serializable?

Notation:

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

Key Idea: Focus on *conflicting* operations

Conflicts

- Write-Read – WR
- Read-Write – RW
- Write-Write – WW

Conflict Serializability

Conflicts: (i.e., swapping will change program behavior)

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

- Every conflict-serializable schedule is serializable
- The converse is not true (why?)

Conflict Serializability

Example:

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

Conflict Serializability

Example:

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

⇩

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

Conflict Serializability

Example:

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

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

Conflict Serializability

Example:

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Conflict Serializability

Example:

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

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

….

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

Serializable, Not Conflict-Serializable

T1	T2
READ(A, t)	
t := t+100	
WRITE(A, t)	
	READ(A,s)
	s := s + 200
	WRITE(A,s)
	READ(B,s)
	s := s + 200
	WRITE(B,s)
READ(B, t)	
t := t+100	
WRITE(B,t)	

Testing for Conflict-Serializability

Precedence graph:

- A node for each transaction T_i,
- An edge from T_i to T_j whenever an action in T_i conflicts with, and comes before an action in T_j

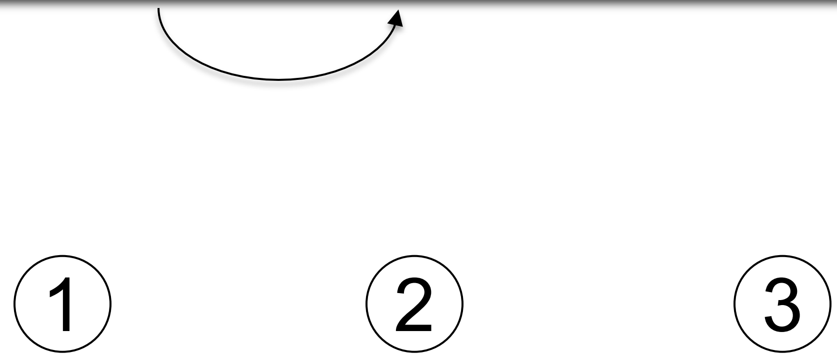
- The schedule is conflict-serializable iff the precedence graph is acyclic

Example 1

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

Example 1

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



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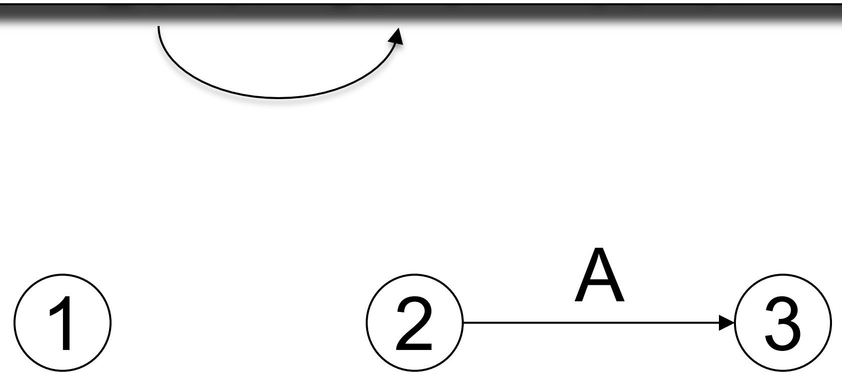
$r_2(A); r_1(B); w_2(A); r_3(A); w_1(B); w_3(A); r_2(B); w_2(B)$



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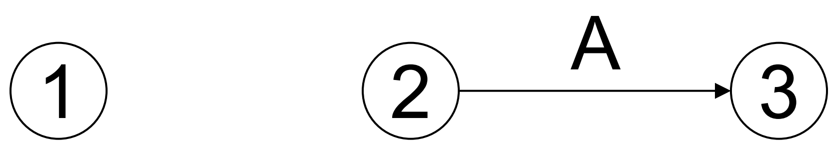

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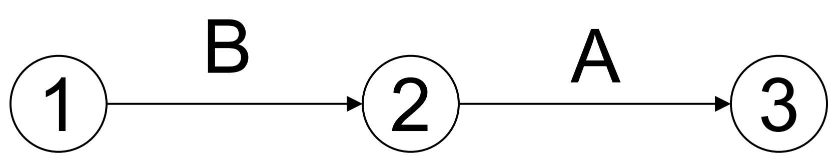

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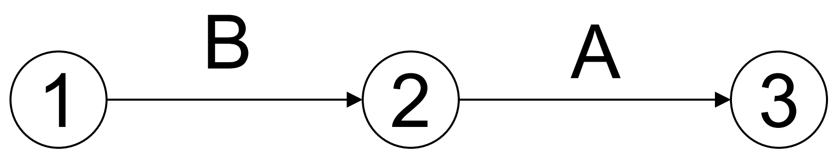
$r_2(A); r_1(B); w_2(A); r_3(A); w_1(B); w_3(A); r_2(B); w_2(B)$



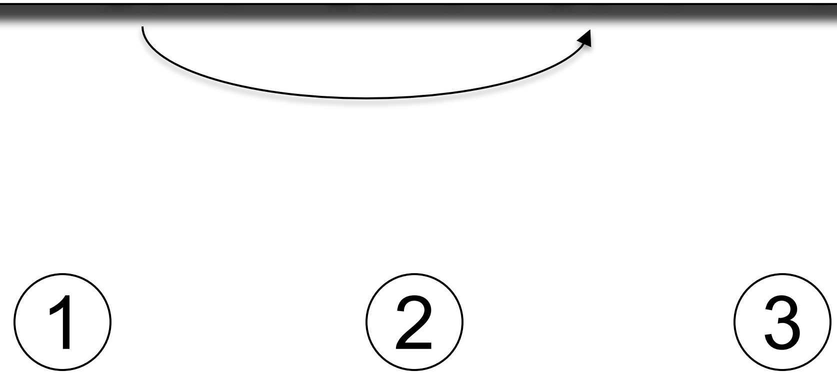
This schedule is conflict-serializable

Example 2

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

Example 2

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



Example 2

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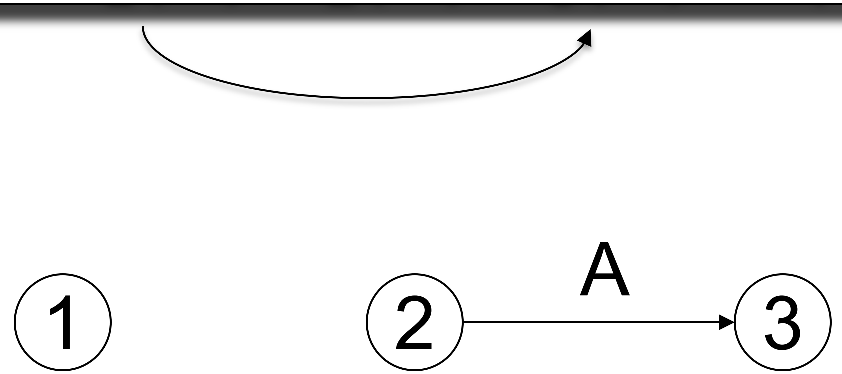

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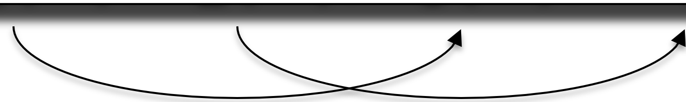

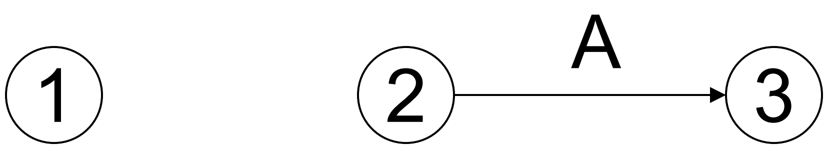

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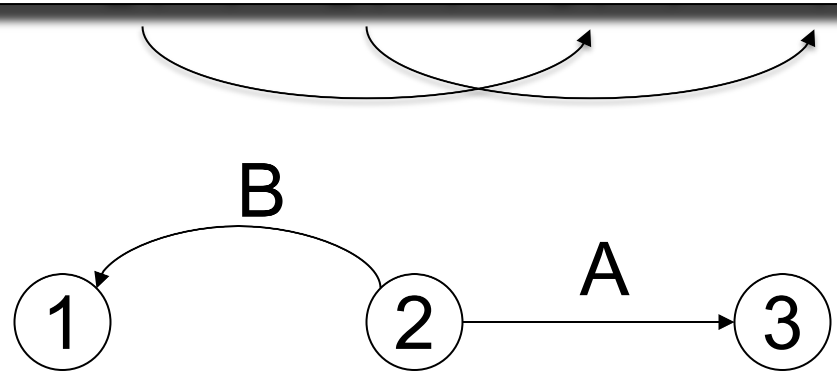

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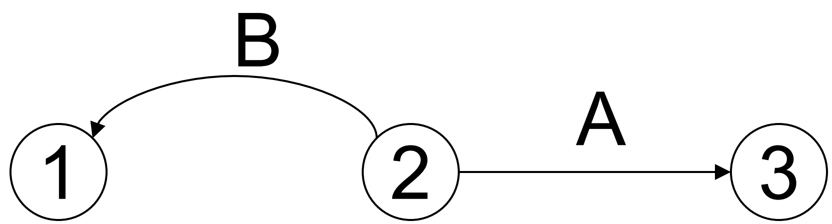

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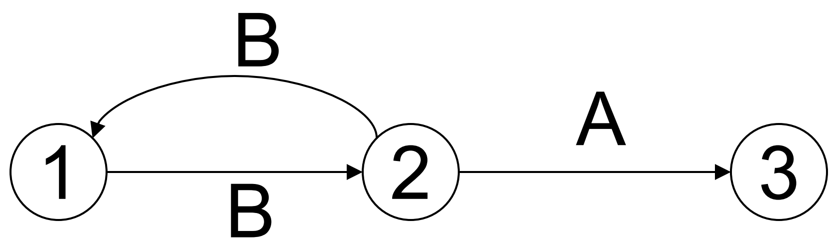

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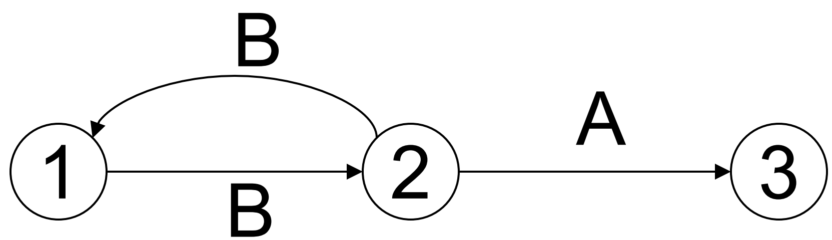


This schedule is NOT conflict-serializable

Implementing Transactions

Scheduler

- Scheduler a.k.a. Concurrency Control Manager
  – The module that schedules the transaction's actions
  – Goal: ensure the schedule is serializable

- We discuss next how a scheduler may be implemented

Implementing a Scheduler

Two major approaches:

- Locking Scheduler
  - Aka "pessimistic concurrency control"
  - SQLite, SQL Server, DB2
- Multiversion Concurrency Control (MVCC)
  - Aka "optimistic concurrency control"
  - Postgres, Oracle: Snapshot Isolation (SI)

We discuss only locking schedulers in this class

Lock-based Implementation of Transactions

Locking Scheduler

Simple idea:

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

By using locks scheduler ensures conflict-serializability

What Data Elements are Locked?

Major differences between vendors:

- Lock on the entire database
  - SQLite
- Lock on individual records ("elements")
  - SQL Server, DB2, etc

Actions on Locks

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

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

Let's see this in action…

A Non-Serializable Schedule

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

Example

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

Scheduler has ensured a conflict-serializable schedule

But…

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

Locks did not enforce conflict-serializability !!! What's wrong ?

Two Phase Locking (2PL)

The 2PL rule:

In every transaction, all lock requests must precede all unlock requests

Example: 2PL transactions

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

Now it is conflict-serializable

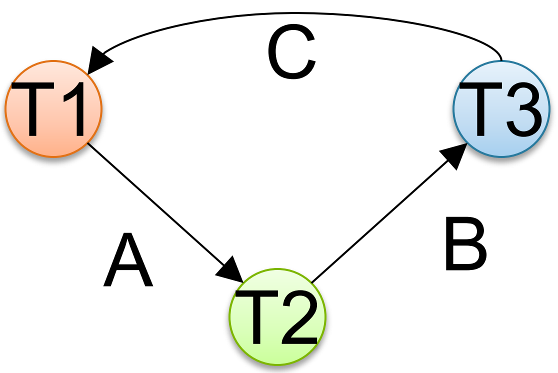
Two Phase Locking (2PL)

Theorem: 2PL ensures conflict serializability

Two Phase Locking (2PL)

Theorem: 2PL ensures conflict serializability

Proof. Suppose not: then there exists a cycle in the precedence graph.



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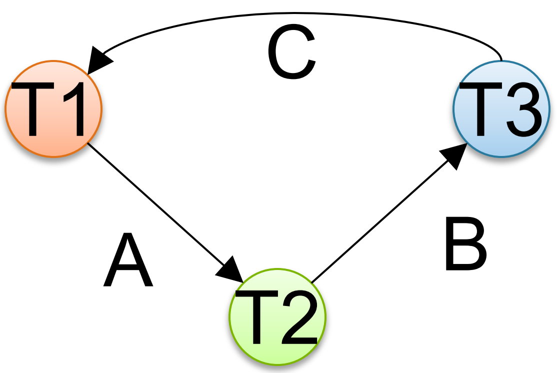

Then there is the following **temporal** cycle in the schedule:

Two Phase Locking (2PL)

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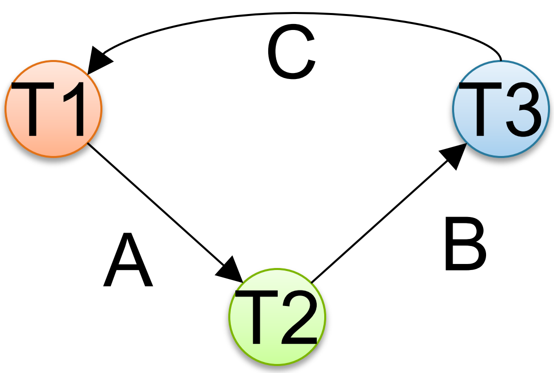

Then there is the following **temporal** cycle in the schedule:

$U_1(A) \rightarrow L_2(A)$ why?

$U_1(A)$ happened strictly *before* $L_2(A)$

Two Phase Locking (2PL)

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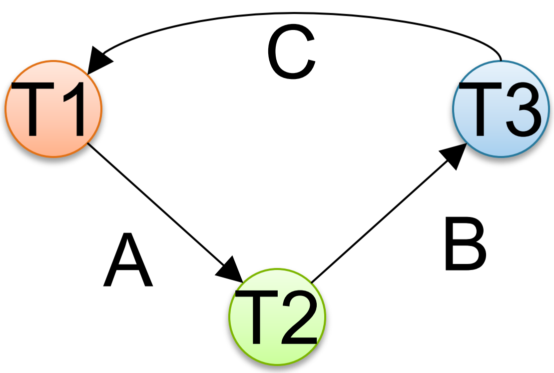

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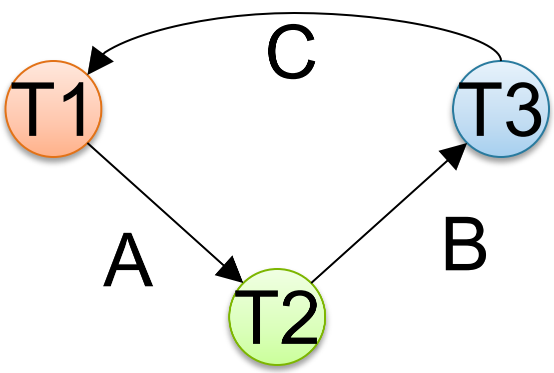


Then there is the following **temporal** cycle in the schedule:

$U_1(A) \rightarrow L_2(A)$

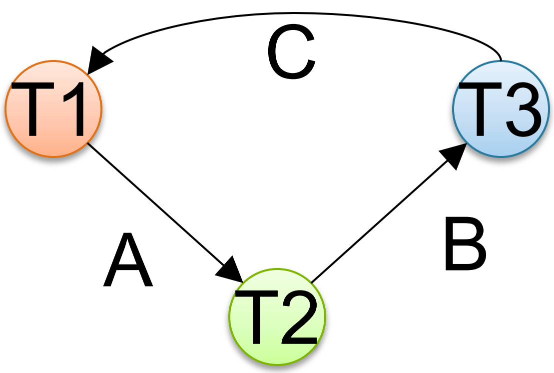
$L_2(A) \rightarrow U_2(B)$ why?

$L_2(A)$ happened strictly *before* $U_1(A)$

Two Phase Locking (2PL)

Theorem: 2PL ensures conflict serializability

Proof. Suppose not: then there exists a cycle in the precedence graph.



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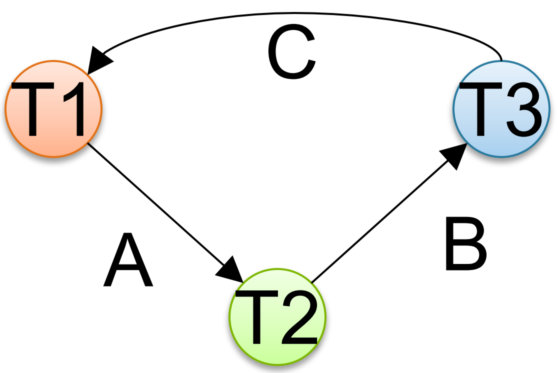
Theorem: 2PL ensures conflict serializability

Proof. Suppose not: then there exists a cycle in the precedence graph.



Then there is the following **temporal** cycle in the schedule:

$U_1(A) \rightarrow L_2(A)$
$L_2(A) \rightarrow U_2(B)$
$U_2(B) \rightarrow L_3(B)$ why?

Two Phase Locking (2PL)

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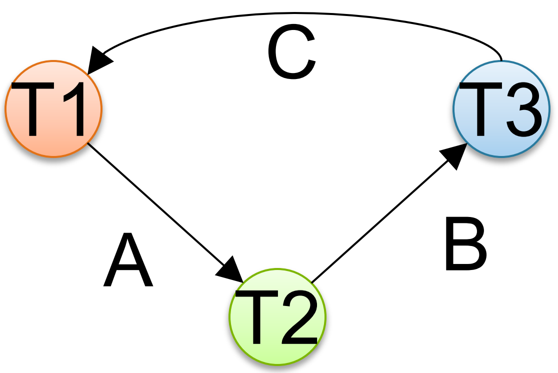

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$L_2(A) \rightarrow U_2(B)$

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......etc.....

Two Phase Locking (2PL)

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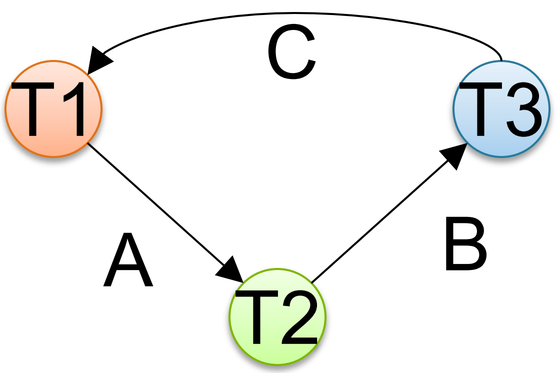

Then there is the following **temporal** cycle in the schedule:

$U_1(A) \rightarrow L_2(A)$
$L_2(A) \rightarrow U_2(B)$
$U_2(B) \rightarrow L_3(B)$
$L_3(B) \rightarrow U_3(C)$
$U_3(C) \rightarrow L_1(C)$
$L_1(C) \rightarrow U_1(A)$

Cycle in time: Contradiction

A New Problem: Non-recoverable Schedule

T1	T2
L_1(A); L_1(B); READ(A)	
A :=A+100	
WRITE(A); U_1(A)	
	L_2(A); READ(A)
	A := A*2
	WRITE(A);
	L_2(B); BLOCKED…
READ(B)	
B :=B+100	
WRITE(B); U_1(B);	
	…GRANTED; READ(B)
	B := B*2
	WRITE(B); U_2(A); U_2(B);
	Commit
Rollback	

A New Problem: Non-recoverable Schedule

T1	T2
$L_1(A)$; $L_1(B)$; READ(A)	
A :=A+100	
WRITE(A); $U_1(A)$	
	$L_2(A)$; READ(A)
	A := A*2
	WRITE(A);
	$L_2(B)$; BLOCKED…
READ(B)	
B :=B+100	
WRITE(B); $U_1(B)$;	
	…GRANTED; READ(B)
	B := B*2
	WRITE(B); $U_2(A)$; $U_2(B)$;
	Commit
Rollback	

Elements A, B written by T1 are restored to their original value.

A New Problem: Non-recoverable Schedule

T1	T2
$L_1(A)$; $L_1(B)$; READ(A)	
A :=A+100	
WRITE(A); $U_1(A)$	
	$L_2(A)$; READ(A)
	A := A*2
	WRITE(A);
	$L_2(B)$; BLOCKED…
READ(B)	
B :=B+100	
WRITE(B); $U_1(B)$;	
	…GRANTED; READ(B)
	B := B*2
	WRITE(B); $U_2(A)$; $U_2(B)$;
	Commit
Rollback	

Dirty reads of A, B lead to incorrect writes.

Elements A, B written by T1 are restored to their original value.

A New Problem: Non-recoverable Schedule

T1	T2
$L_1(A)$; $L_1(B)$; READ(A)	
A :=A+100	
WRITE(A); $U_1(A)$	
	$L_2(A)$; READ(A)
	A := A*2
	WRITE(A);
	$L_2(B)$; BLOCKED…
READ(B)	
B :=B+100	
WRITE(B); $U_1(B)$;	
	…GRANTED; READ(B)
	B := B*2
	WRITE(B); $U_2(A)$; $U_2(B)$;
	Commit
Rollback	

Dirty reads of A, B lead to incorrect writes.

Elements A, B written by T1 are restored to their original value.

Can no longer undo!

Strict 2PL

The Strict 2PL rule:

All locks are held until commit/abort:
All unlocks are done together with commit/abort.

With strict 2PL, we will get schedules that are both conflict-serializable and recoverable

Strict 2PL

T1	T2
$L_1(A)$; READ(A)	
A :=A+100	
WRITE(A);	
	$L_2(A)$; BLOCKED…
$L_1(B)$; READ(B)	
B :=B+100	
WRITE(B);	
Rollback & $U_1(A)$;$U_1(B)$;	
	…GRANTED; READ(A)
	A := A*2
	WRITE(A);
	$L_2(B)$; READ(B)
	B := B*2
	WRITE(B);
	Commit & $U_2(A)$; $U_2(B)$;

Strict 2PL

- Lock-based systems always use strict 2PL
- Easy to implement:
  - Before a transaction reads or writes an element A, insert an L(A)
  - When the transaction commits/aborts, then release all locks
- Ensures both conflict serializability and recoverability

Another problem: Deadlocks

- T_1: R(A), W(B)
- T_2: R(B), W(A)

- T_1 holds the lock on A, waits for B
- T_2 holds the lock on B, waits for A

This is a deadlock!

Another problem: Deadlocks

To detect a deadlocks, search for a cycle in the waits-for graph:

- T_1 waits for a lock held by T_2;
- T_2 waits for a lock held by T_3;
- . . .
- T_n waits for a lock held by T_1

Relatively expensive: check periodically, if deadlock is found, then abort one TXN;
re-check for deadlock more often (why?)

Lock Modes

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

Lock compatibility matrix:

	None	S	X
None			
S			
X			

Lock Modes

- S = shared lock (for READ)
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Lock compatibility matrix:

	None	S	X
None			
S			
X			

Lock Granularity

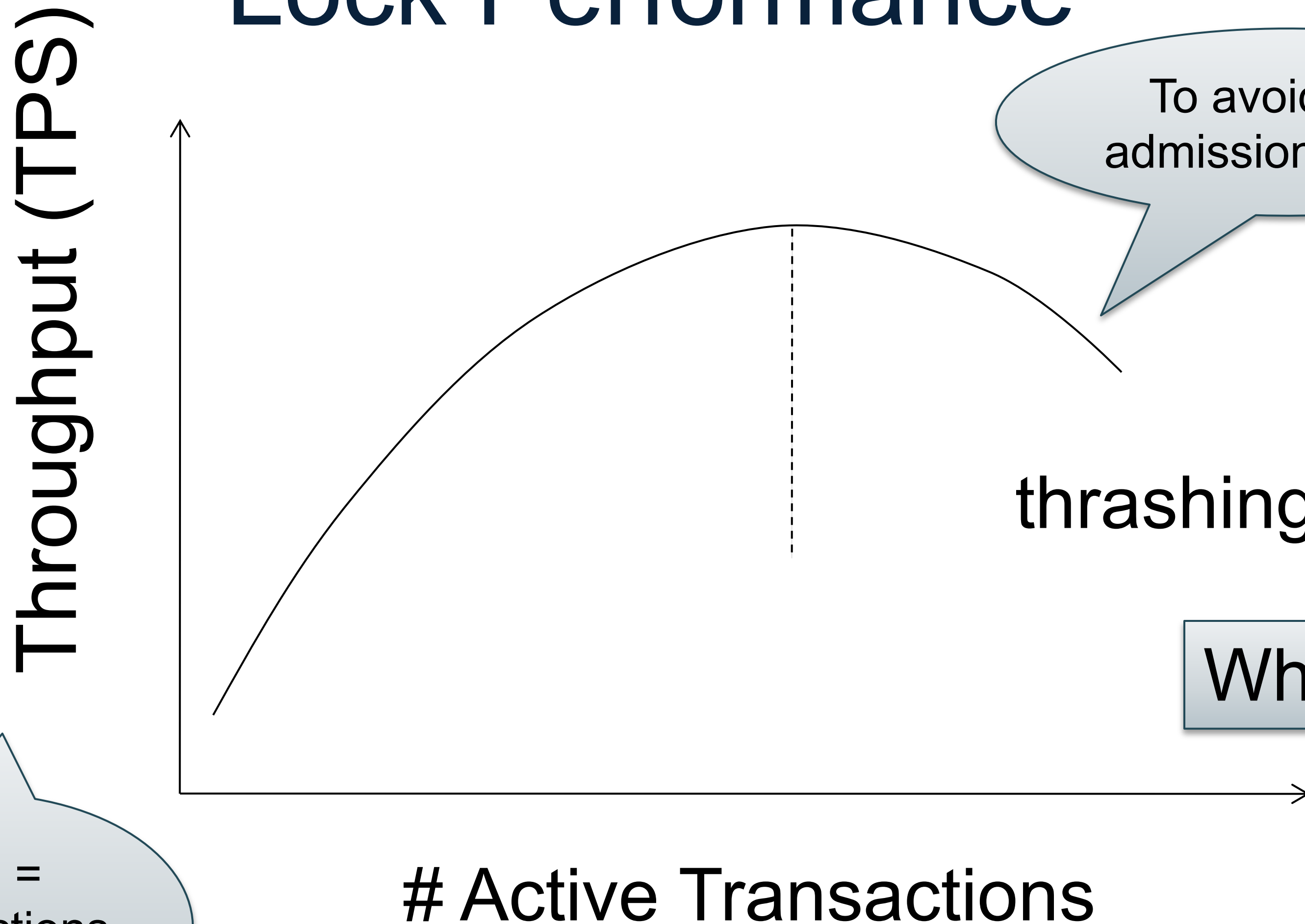
- Fine granularity locking (e.g., tuples)
  - High concurrency
  - High overhead in managing locks
  - E.g., SQL Server

- Coarse grain locking (e.g., tables, entire database)
  - Many false conflicts
  - Less overhead in managing locks
  - E.g., SQL Lite

- Solution: lock escalation changes granularity as needed

Lock Performance

To avoid, use admission control



Why ?

TPS = Transactions per second

Announcement

Final review

- Saturday, 2pm,
- GWN 301

Phantom Problem

- So far we have assumed the database to be a *static* collection of elements (=tuples)
- If tuples are inserted/deleted then the *phantom problem* appears

Suppose there are two blue products, A1, A2:

Phantom Problem

T1	T2
SELECT * FROM Product WHERE color=‘blue’	
	INSERT INTO Product(name, color) VALUES (‘A3’,’blue’)
SELECT * FROM Product WHERE color=‘blue’	

Is this schedule serializable ?

Suppose there are two blue products, A1, A2:

Phantom Problem

T1	T2
SELECT * FROM Product WHERE color='blue'	
	INSERT INTO Product(name, color) VALUES ('A3','blue')
SELECT * FROM Product WHERE color='blue'	

Is this schedule serializable ?

No: T1 sees a "phantom" product A3

Suppose there are two blue products, A1, A2:

Phantom Problem

T1	T2
SELECT * FROM Product WHERE color=‘blue’	
	INSERT INTO Product(name, color) VALUES (‘A3’,’blue’)
SELECT * FROM Product WHERE color=‘blue’	

$R_1(A1);R_1(A2);W_2(A3);R_1(A1);R_1(A2);R_1(A3)$

Suppose there are two blue products, A1, A2:

Phantom Problem

T1	T2
SELECT * FROM Product WHERE color='blue'	
	INSERT INTO Product(name, color) VALUES ('A3','blue')
SELECT * FROM Product WHERE color='blue'	

$R_1(A1);R_1(A2);W_2(A3);R_1(A1);R_1(A2);R_1(A3)$

$W_2(A3);R_1(A1);R_1(A2);R_1(A1);R_1(A2);R_1(A3)$

Suppose there are two blue products, A1, A2:

Phantom Problem

T1	T2
SELECT * FROM Product WHERE color='blue'	
	INSERT INTO Product(name, color) VALUES ('A3','blue')
SELECT * FROM Product WHERE color='blue'	

But this is conflict-serializable!

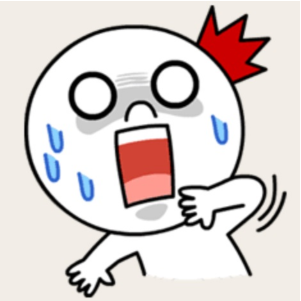
$R_1(A1);R_1(A2);W_2(A3);R_1(A1);R_1(A2);R_1(A3)$

$W_2(A3);R_1(A1);R_1(A2);R_1(A1);R_1(A2);R_1(A3)$

Phantom Problem

- A "phantom" is a tuple that is invisible during part of a transaction execution but not invisible during the entire execution

- In our example:
  - T1: reads list of products
  - T2: inserts a new product
  - T1: re-reads: a new product appears !



- Conflict-serializability assumes DB is *static*
- When DB is *dynamic* then c-s is not serializable.

Dealing With Phantoms

- Lock the entire table
- Lock the index entry for ‘blue’
  – If index is available
- Or use predicate locks
  – A lock on an arbitrary predicate

Dealing with phantoms is expensive !

Summary of Serializability

- Serializable schedule = equivalent to a serial schedule
- (strict) 2PL guarantees *conflict serializability*
  – What is the difference?
- **Static database**:
  – *Conflict serializability* implies serializability
- **Dynamic database**:
  – *Conflict serializability* plus *phantom management* implies serializability

Weaker Isolation Levels

- Serializable are expensive to implement

- SQL allows the application to choose a more efficient implementation, which is not always serializable: *weak isolation levels*

Isolation Levels in SQL

1. "Dirty reads"
   SET TRANSACTION ISOLATION LEVEL READ UNCOMMITTED

2. "Committed reads"
   SET TRANSACTION ISOLATION LEVEL READ COMMITTED

3. "Repeatable reads"
   SET TRANSACTION ISOLATION LEVEL REPEATABLE READ

4. Serializable transactions
   SET TRANSACTION ISOLATION LEVEL SERIALIZABLE

ACID

Lost Update

Write-Write Conflict

T_1: READ(A)

T_1: A := A+5

T_1: WRITE(A)

T_2: READ(A);

T_2: A := A*1.3

T_2: WRITE(A);

Never allowed at any level

1. Isolation Level: Dirty Reads

- "Long duration" WRITE locks
  - Strict 2PL
- No READ locks
  - Read-only transactions are never delayed

Possible problems: dirty and inconsistent reads

1. Isolation Level: Dirty Reads

Write-Read Conflict

T_1: WRITE(A)

T_1: ABORT

T_2: READ(A)

1. Isolation Level: Dirty Reads

Write-Read Conflict

T_1: A := 20; B := 20; T_1: WRITE(A) T_1: WRITE(B)	 T_2: READ(A); T_2: READ(B);

Inconsistent read

2. Isolation Level: Read Committed

- "Long duration" WRITE locks
  - Strict 2PL
- "Short duration" READ locks
  - Only acquire lock while reading (not 2PL)

Unrepeatable reads:
When reading same element twice, may get two different values

2. Isolation Level: Read Committed

Read-Write Conflict

T_1: WRITE(A)

T_2: READ(A);

T_2: READ(A);

Unrepeatable read

3. Isolation Level: Repeatable Read

- "Long duration" WRITE locks
  - Strict 2PL
- "Long duration" READ locks
  - Strict 2PL

Why ?

This is not serializable yet !!!

4. Isolation Level Serializable

- "Long duration" WRITE locks
  - Strict 2PL
- "Long duration" READ locks
  - Strict 2PL
- Predicate locking
  - To deal with phantoms

Beware!

In commercial DBMSs:

- Default level may not be serializable
- Default level differs between DBMSs
- Some engines support subset of levels!
- Also, some DBMSs do NOT use locking and different isolation levels can lead to different pbs

Bottom line: Read the doc for your DBMS!

Case Study: SQLite

- SQLite is very simple
- More info: http://www.sqlite.org/atomiccommit.html

- Lock types
  - READ LOCK (to read)
  - RESERVED LOCK (to write)
  - PENDING LOCK (wants to commit)
  - EXCLUSIVE LOCK (to commit)

SQLite

Step 1: when a transaction begins

- Acquire a READ LOCK (aka "SHARED" lock)
- All these transactions may read happily
- They all read data from the database file
- If the transaction commits without writing anything, then it simply releases the lock

SQLite

Step 2: when one transaction wants to write

- Acquire a RESERVED LOCK
- May coexists with many READ LOCKs
- Writer TXN may write; these updates are only in main memory; others don't see the updates
- Reader TXN continue to read from the file
- New readers accepted
- No other TXN is allowed a RESERVED LOCK

SQLite

Step 3: when writer transaction wants to commit, it needs *exclusive lock*, which can't coexists with *read locks*

- Acquire a PENDING LOCK
- May coexists with old READ LOCKs
- No new READ LOCKS are accepted
- Wait for all read locks to be released

Why not write to disk right now?

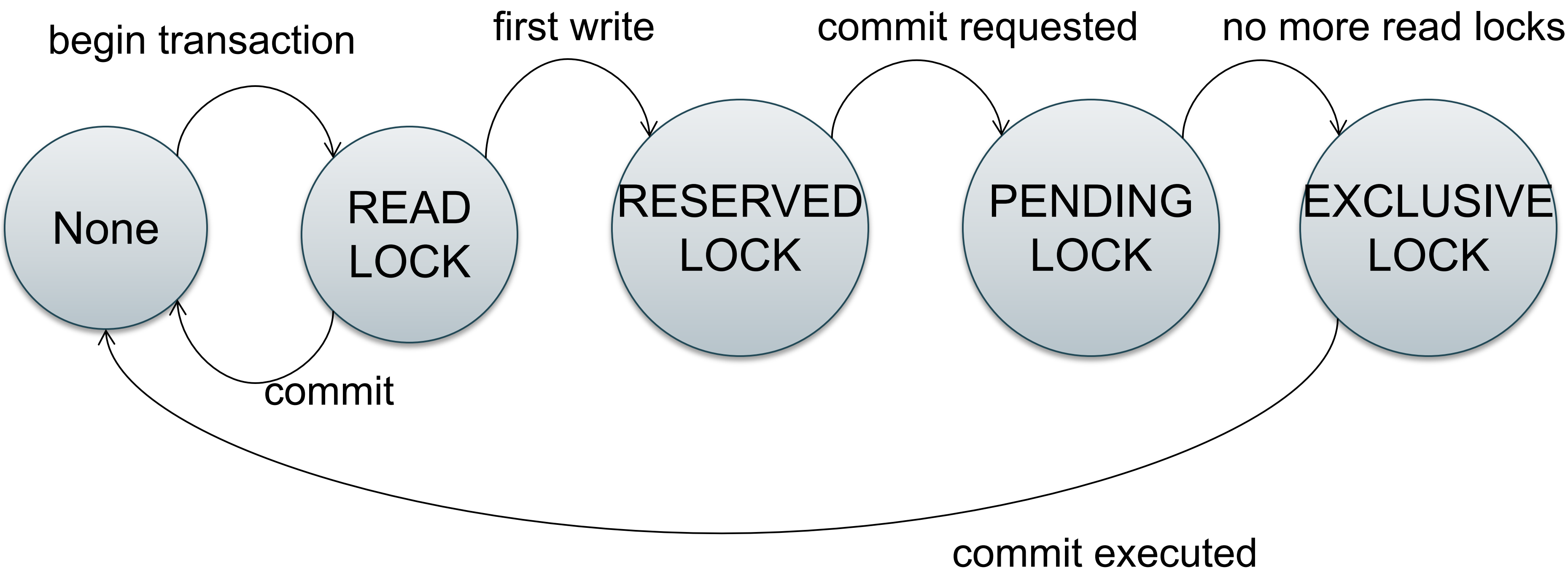
SQLite

Step 4: when all read locks have been released

- Acquire the EXCLUSIVE LOCK
- Nobody can touch the database now
- All updates are written permanently to the database file

- Release the lock and COMMIT

SQLite


begin transaction
first write
commit requested
no more read locks
None
READ LOCK
RESERVED LOCK
PENDING LOCK
EXCLUSIVE LOCK
commit
commit executed

SQLite Demo

```
create table r(a int, b int);
insert into r values (1,10);
insert into r values (2,20);
insert into r values (3,30);
```

Demonstrating Locking in SQLite

T1:

```
begin transaction;
select * from r;
-- T1 has a READ LOCK
```

T2:

```
begin transaction;
select * from r;
-- T2 has a READ LOCK
```

Demonstrating Locking in SQLite

T1:

update r set b=11 where a=1;

-- T1 has a RESERVED LOCK

T2:

update r set b=21 where a=2;

-- T2 asked for a RESERVED LOCK: DENIED

Demonstrating Locking in SQLite

T3:

```
begin transaction;
select * from r;
commit;
-- everything works fine, could obtain READ LOCK
```

Demonstrating Locking in SQLite

T1:

commit;

-- SQL error: database is locked

-- T1 asked for PENDING LOCK -- GRANTED

-- T1 asked for EXCLUSIVE LOCK -- DENIED

Demonstrating Locking in SQLite

T3':

begin transaction;

select * from r;

-- T3 asked for READ LOCK-- DENIED (due to T1)

T2:

commit;

-- releases the last READ LOCK; T1 can commit

How do anomalies show up in schedules?

- What could go wrong if we didn't have concurrency control:
  - Dirty reads (including inconsistent reads)
  - Unrepeatable reads
  - Lost updates

Many other things can go wrong too

Demonstration with SQL Server

Application 1:
create table R(a int);
insert into R values(1);
set transaction isolation level serializable;
begin transaction;
select * from R; -- get a shared lock

Application 2:
set transaction isolation level serializable;
begin transaction;
select * from R; -- get a shared lock
insert into R values(2); -- blocked waiting on exclusive lock
-- App 2 unblocks and executes insert after app 1 commits/aborts

Demonstration with SQL Server

Application 1:

create table R(a int);

insert into R values(1);

set transaction isolation level repeatable read;

begin transaction;

select * from R; -- get a shared lock

Application 2:

set transaction isolation level repeatable read;

begin transaction;

select * from R; -- get a shared lock

insert into R values(3); -- gets an exclusive lock on new tuple

-- If app 1 reads now, it blocks because read dirty

-- If app 1 reads after app 2 commits, app 1 sees new value

Final Exam

1. Relational data model (SQL)
2. Semistructured data model (SQL++)
3. Datalog
4. RDBMS Internals (execution, optimization)
5. Parallel Query Processing
6. Conceptual Design
7. Transactions