Lecture 19: Transaction

CS348 Spring 2025:
Introduction to Database Management

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Sections: 001, 002, 003

Outline

- Transactions
  - Motivations
  - ACID properties

- Isolation
  - Different isolation levels
  - The lowest isolation level to set
  - Serializability

Why we need transactions

- A database is a shared resource accessed by many users and processes concurrently.
  - Both queries and modifications
- Not managing this concurrent access to a shared resource will cause problems (not unlike in operating systems)
  - Problems due to concurrency
  - Problems due to failures

Problems caused by concurrency

- Inconsistent reads
  - If the applications run concurrently, the total balance returned may be inaccurate

```
UPDATE Accounts
SET Balance = Balance +100
WHERE AccountNum = 9999
```

```
SELECT SUM(Balance)
FROM Account
```

Another concurrency problem

- Lost Updates
  - If the applications run concurrently, one of the updates may be “lost”, and the database may be inconsistent.

```
UPDATE Accounts
SET Balance = Balance +100
WHERE AccountNum = 9999
```

```
UPDATE Accounts
SET Balance = Balance – 50
WHERE AccountNum = 9999
```

Yet another concurrency problem

- Non-Repeatable Reads
  - If there are employees in D11 with surnames that begin with "A", Application 2's queries may see them with different salaries.

```
UPDATE Employee
SET Salary = Salary +1000
WHERE WorkDept = 'D11'
```

```
SELECT * FROM Employee
WHERE WorkDept = 'D11'

SELECT * FROM Employee
WHERE Lastname like 'A%'
```

Problems caused by failures

- Update all account balances at a bank branch.

```
UPDATE Accounts
SET Balance = Balance * 1.05
WHERE BranchID = 12345
```

- What happens if the system crashes while processing this update?
- What if the system crashes after this update is processed but before all changes are made permanent?

Another failure-related problem

- Transfer money between accounts:

```
UPDATE Accounts
SET Balance = Balance – 100
WHERE AccountNum = 8888
```

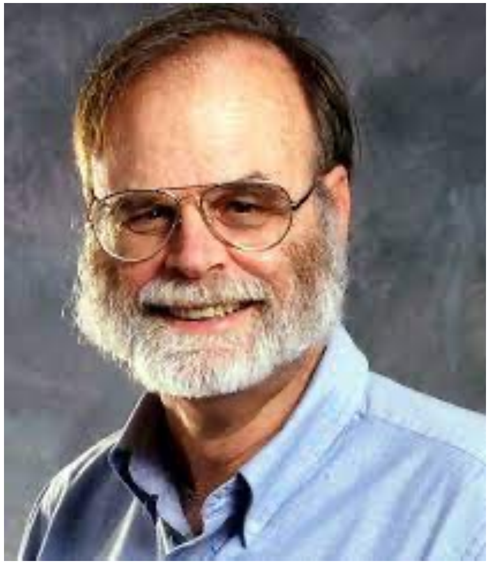
```
UPDATE Accounts
SET Balance = Balance + 100
WHERE AccountNum = 9999
```

- Problem: If the system fails between these updates, money may be withdrawn but not redeposited.

Transactions

```
-- Begins implicitly
SELECT … ;
UPDATE … ;
ROLLBACK | COMMIT
```

- A transaction is a sequence of database operations (read or write)
- ACID properties of transactions (TXs)
  - Atomicity: TXs are either completely done or not done at all (next lecture)
  - Consistency: TXs should leave the database in a consistent state
  - Isolation: TXs must behave as if they execute in isolation (this-next lecture)
  - Durability: Effects of committed TXs are resilient against failures (next lecture)



Jim Gray, Turing Award 1998, who coined this term (as well as data cube and many other things)

Outline

- Overview of Transactions
  - Motivations
  - ACID properties
- Isolation
  - Different isolation levels
  - The lowest isolation level to set
  - Serializability

Different Isolation Levels

Stronger Consistency

Higher Overheads

Less Concurrency

[Isolation Levels in SQL Standard]()
Read Uncommitted
Read Committed
Repeatable Read
Serializable

Weaker Consistency

Lower Overheads

More Concurrency

```
SET TRANSACTION ISOLATION LEVEL REPEATABLE READ;
BEGIN TRANSACTION;
SELECT * FROM Order;
...
COMMIT TRANSACTION
```

READ UNCOMMITTED

- Can read "dirty" data
  - A data item is dirty if it is written by an uncommitted transaction
- Problem: What if the transaction that wrote the dirty data eventually aborts?
- Example: wrong average
  -
```
-- T1:                      -- T2:
UPDATE User
SET pop = 0.99
WHERE uid = 142;            SELECT AVG(pop)
                            FROM User;
ROLLBACK;
                            COMMIT;
```

READ COMMITTED

- No dirty reads, but non-repeatable reads possible
  - Reading the same data item twice sees different values
- Example: different averages
  - -- T1: / -- T2:

```
-- T1:                          -- T2:
                                SELECT AVG(pop)
                                FROM User;
UPDATE User
SET pop = 0.99
WHERE uid = 142;
COMMIT;
                                SELECT AVG(pop)
                                FROM User;
                                COMMIT;
```

REPEATABLE READ

- Reads are repeatable, but may see phantoms
  - Reading the same data item twice still see the same value
  - But some new data item may appear
- Example: different average (still!)
  - -- T1:

```
-- T1:                                   -- T2:
                                         SELECT AVG(pop)
                                         FROM User;
INSERT INTO User
VALUES(789, 'Nelson',10, 0.1);
COMMIT;
                                         SELECT AVG(pop)
                                         FROM User;
                                         COMMIT;
```

SQL: set isolation levels

Isolation level/anomaly	Dirty reads	Non-repeatable reads	Phantoms
READ UNCOMMITTED	Possible	Possible	Possible
READ COMMITTED	Impossible	Possible	Possible
REPEATABLE READ	Impossible	Impossible	Possible
SERIALIZABLE	Impossible	Impossible	Impossible

- Syntax: At the beginning of a transaction,
  SET TRANSACTION ISOLATION LEVEL *isolation_level*
  [READ ONLY | READ WRITE];
  - READ UNCOMMITTED can only be READ ONLY
  - Update/Insertion/deletion query cannot have READ UNCOMMITED
- PostgreSQL defaults to READ COMMITTED

The lowest isolation level to set?

```
INSERT INTO Order
VALUES (03,10)
COMMIT;
```

Isolation level	Possible anomalies
READ UNCOMMITTED	No Dirty reads
READ COMMITTED	No unrepeatable reads
REPEATABLE READ	No phantoms
SERIALIZABLE	No

- Consider other possible concurrent transactions
  - Does not do any reads
  - No read concern
  - Lowest isolation level: read uncommitted

The lowest isolation level to set?

```
UPDATE User
SET pop = 0.99
WHERE uid = 142;
COMMIT;
```

Isolation level	Possible anomalies
READ UNCOMMITTED	Dirty reads
READ COMMITTED	No unrepeatable reads
REPEATABLE READ	No phantoms
SERIALIZABLE	No

- Consider other possible concurrent transactions
  - Assume each table is an object
  - It reads User only once, i.e. read(User), write(User)
  - For example, another transaction is updating uid
  - Lowest isolation level: read committed

The lowest isolation level to set?

```
SELECT AVG(pop)
FROM User;
COMMIT;
```

Isolation level	Possible anomalies
READ UNCOMMITTED	Dirty reads
READ COMMITTED	No unrepeatable reads
REPEATABLE READ	No phantoms
SERIALIZABLE	No

- Consider other possible concurrent transactions
  - Assume each table is an object
  - It reads User only once, i.e., Read(User)
  - For example, another transaction is updating pop
  - Lowest isolation level: read committed

The lowest isolation level to set?

```
SELECT AVG(pop)
FROM User;

SELECT MAX(pop)
FROM User;
COMMIT;
```

Isolation level	Possible anomalies
READ UNCOMMITTED	Dirty reads
READ COMMITTED	Unrepeatable reads
REPEATABLE READ	Phantoms
SERIALIZABLE	No

- Consider other possible concurrent transactions
  - Assume each table is an object
  - It reads User twice: READ(User), READ(User)
  - For example, another transaction is inserting/deleting a row to User
  - Lowest isolation level: serializable

Outline

- Transactions
  - Motivations
  - Properties: ACID

- Isolation
  - Different isolation levels
  - The lowest isolation level to set
  - Serializability:
    - Serial executions of T1 and T2 definitely prevent all anomalies. Can we run T1 and T2 concurrently and achieve the same serial effect?

Execution histories of Transactions

- A transaction is an ordered sequence of read or write operations on the database, followed by abort or commit.
  - Database is *a set* of independent data items x, y, z etc.
  - T = {read(x), write(y), read(z), write(z), write(x), commit}

- An execution history over a set of transactions $T_1 \ldots T_n$ is an interleaving of the operations of $T_1 \ldots T_n$ in which the operation ordering imposed by each transaction is preserved.
  - Transactions interact with each other only via reads and writes of the same date item

Examples for valid execution history

- $T_1 = \{w_1[x], w_1[y], c_1\}, T_2 = \{r_2[x], r_2[y], c_2\}$
  - $H_a = w_1[x]r_2[x]w_1[y]r_2[y]c_1c_2$
  - $H_b = w_1[x]w_1[y]c_1r_2[x]r_2[y]c_2$
  - $H_c = w_1[x]r_2[x]r_2[y]w_1[y]c_1c_2$
  - $H_d = r_2[x]r_2[y]c_2\ w_1[x]w_1[y]c_1$

Examples for valid execution history

- $T_1 = \{w_1[x], w_1[y], c_1\}, T_2 = \{\, r_2[x], r_2[y], c_2\,\}$

T_1	T_2
w1(x)	
	r2(x)
w1(y)	
	r2(y)
c1	
	c2

H_a

T_1	T_2
w1(x)	
w1(y)	
c1	
	r2(x)
	r2(y)
	c2

H_b

T_1	T_2
w1(x)	
	r2(x)
	r2(y)
w1(y)	
c1	
	c2

H_c

T_1	T_2
	r2(x)
	r2(y)
	c2
w1(x)	
w1(y)	
c1	

H_d

Serial execution histories

no interleaving operations from different transactions

- $T_1 = \{w_1[x], w_1[y], c_1\}, T_2 = \{\, r_2[x], r_2[y], c_2 \,\}$

H_a

T_1	T_2
w1(x)	
	r2(x)
w1(y)	
	r2(y)
c1	
	c2

H_b

T_1	T_2
w1(x)	
w1(y)	
c1	
	r2(x)
	r2(y)
	c2

H_c

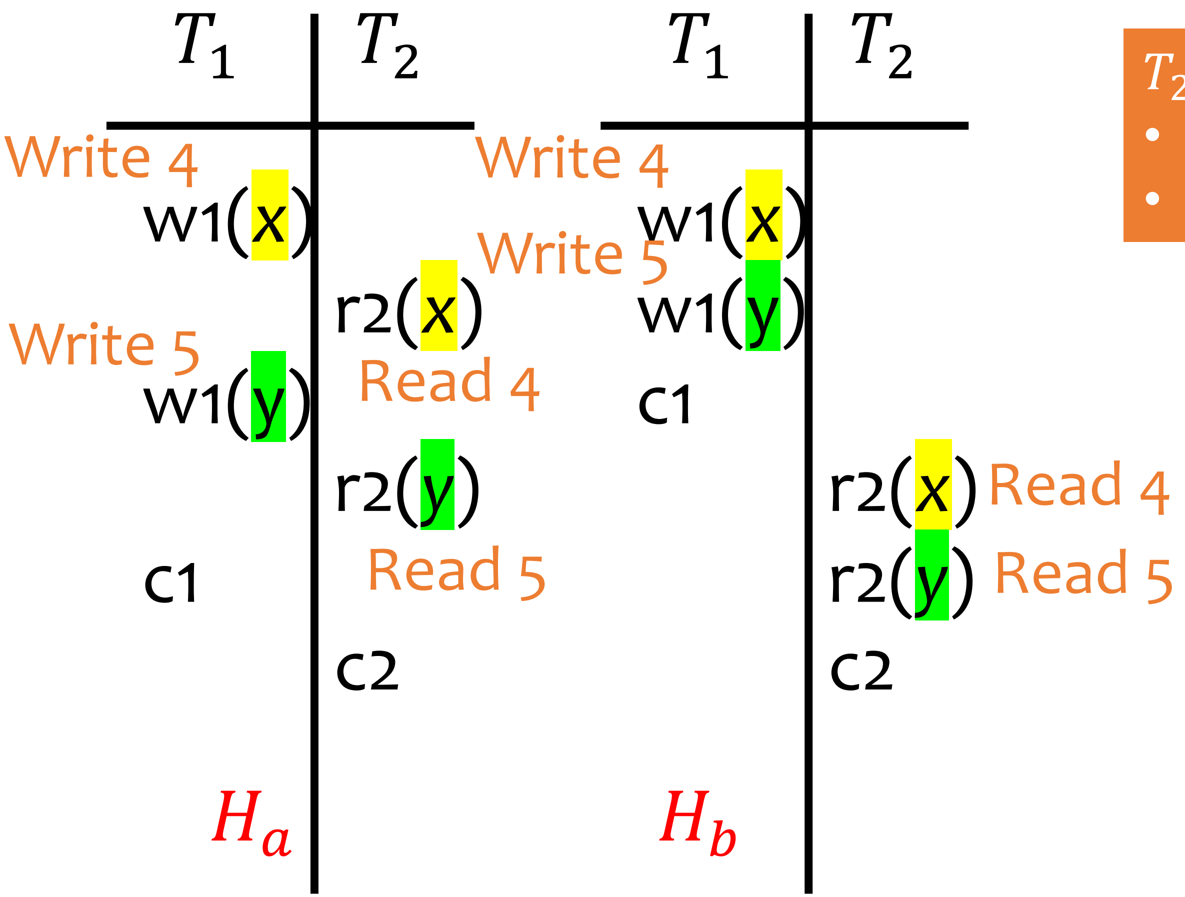
T_1	T_2
w1(x)	
	r2(x)
	r2(y)
w1(y)	
c1	
	c2

H_d

T_1	T_2
	r2(x)
	r2(y)
	c2
w1(x)	
w1(y)	
c1	

Equivalent execution histories

- H_a is “equivalent” to H_b (a serial execution)
- x=3, y=1 before T1 and T2



T_2 sees all the updates by T_1
- T_2 reads x written by T_1
- T_2 reads y written by T_1

Equivalent execution histories

- H_c is not "equivalent" to H_b (a serial execution)
- x=3, y=1 before T1 and T2

T_1	T_2
Write 4 w1(x)	
Write 5 w1(y)	
c1	
	r2(x) Read 4
	r2(y) Read 5
	c2

H_b

T_1	T_2
Write 4 w1(x)	
	r2(x) Read 4
	r2(y) Read 1
Write 5 w1(y)	
c1	
	c2

H_c

T_2 reads different y in H_b as in H_c

Equivalence of execution histories

- Two operations conflict if
  - they belong to different transactions,
  - they operate on the same data item, and
  - at least one of the operations is write
    - two types of conflicts: read-write and write-write

- Two execution histories are (conflict) equivalent if
  - they are over the same set of transactions
  - the ordering of each pair of conflicting operations is the same in each history

Example

- Are these execution histories conflict equivalent?
  - $H_a = w_1[x]r_2[x]w_1[y]r_2[y]c_1c_2$
  - $H_b = w_1[x]w_1[y]r_2[x]r_2[y]c_1c_2$
- Check if they are over the same set of transactions
  - $T_1 = \{w_1[x], w_1[y], c_1\}, T_2 = \{r_2[x], r_2[y], c_2\}$
- Check if all conflicting pairs have the same order

Conflicting pairs	H_a	H_b
$w_1[x], r_2[x]$	$<$	$<$
$w_1[y], r_2[y]$	$<$	$<$

In class exercise

Are these execution histories conflict equivalent?

- H_A: $r_1[x]r_3[x]w_4[y]r_2[u]w_4[z]r_1[y]r_3[u]r_2[z]w_2[z]r_3[z]r_1[z]w_3[y]$
- H_B: $r_1[x]w_4[y]r_3[x]r_2[u]r_1[y]r_3[u]r_2[z]w_2[z]w_4[z]r_1[z]r_3[z]w_3[y]$

- Check if they are over the same set of transactions

  $\{r_1[x]\ r_1[y]\ r_1[z]\ \}$,

  $\{r_2[u]\ r_2[z]w_2[z]\}$,

  $\{r_3[x]\ r_3[u]\ r_3[z]w_3[y]\}$,

  $\{w_4[y]\ w_4[z]\}$

- Check if all conflicting pairs have the same order

In class exercise

What are the conflicting pairs in H_A?

- H_A: $r_1[x]r_3[x]w_4[y]r_2[u]w_4[z]r_1[y]r_3[u]r_2[z]w_2[z]r_3[z]r_1[z]w_3[y]$

For x: no conflicts

For y: w4[y], r1[y], w3[y]

- $w_4[y] < r_1[y]$
- $w_4[y] < \mathrm{w}_3[y]$
- $r_1[y] < \mathrm{w}_3[y]$

For z: w4[z], r2[z], w2[z], r3[z], r1[z]

- $w_4[z] < r_2[z]$
- $w_4[z] < w_2[z]$
- $w_4[z] < r_3[z]$
- $w_4[z] < r_1[z]$
- $r_2[z]$, $w_2[z]$ are not, as they are from the same transactions
- $\mathrm{w}_2[z] < r_3[z]$
- $\mathrm{w}_2[z] < r_1[z]$

In class exercise

Are these execution histories conflict equivalent?

- H_A: $r_1[x]r_3[x]w_4[y]r_2[u]w_4[z]r_1[y]r_3[u]r_2[z]w_2[z]r_3[z]r_1[z]w_3[y]$
- H_B: $r_1[x]w_4[y]r_3[x]r_2[u]r_1[y]r_3[u]r_2[z]w_2[z]w_4[z]r_1[z]r_3[z]w_3[y]$

- Check if they are over the same set of transactions

  $\{r_1[x]\ r_1[y]\ r_1[z]\ \}$,

  $\{r_2[u]\ r_2[z]w_2[z]\}$,

  $\{r_3[x]\ r_3[u]\ r_3[z]w_3[y]\}$,

  $\{w_4[y]\ w_4[z]\}$

- Check if all conflicting pairs have the same order

Conflicting pairs	H_A	H_B
$w_4[y], r_1[y]$	$<$	$<$
$w_4[y], w_3[y]$	$<$	$<$
…	$<$	$<$
$w_4[z], w_2[z]$	$<$	$>$

Serializable

- A history H is said to be (conflict) serializable if there is some serial history H' (conflict) equivalent to H.

T_1	T_2
w1(x)	
	r2(x)
w1(y)	
	r2(y)
c1	
	c2

$H_a = H_b$

T_1	T_2
w1(x)	
	r2(x)
	r2(y)
w1(y)	
c1	
	c2

H_c ?

Serializable

- Serialization graph (V, E) for history H:
  - $V = \{T\colon\ T$ is a committed transaction in $H\}$
  - $E = \{T_i \to T_j\colon \exists\ o_i \in T_i$ and $o_j \in T_j$ conflict; and $o_i < o_j\}$

Two operations conflict if
- they belong to different transactions;
- they operate on the same data item;
- at least one of the operations is write

- A history is serializable if and only if its serialization graph is acyclic (i.e., no cycles)

Example

- Example: $H_a = w_1[x] r_2[x] w_1[y] r_2[y] c_1 c_2$

T_1	T_2
w1(x)	
	r2(x)
w1(y)	
	r2(y)
c1	
	c2

H_a

$w_1[x]$ and $r_2[x]$ conflict, and $w_1[x] < r_2[x]$
$w_1[y]$ and $r_2[y]$ conflict, and $w_1[y] < r_2[y]$

$$T_1 \rightarrow T_2$$

no cycles,
so serializable

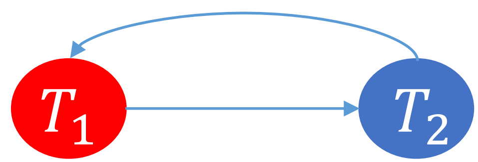
Example

- Example: $H_c = w_1[x]r_2[x]r_2[y]w_1[y]c_1c_2$

T_1	T_2
w1(x)	
	r2(x)
	r2(y)
w1(y)	
c1	
	c2

H_c

$w_1[x]$ and $r_2[x]$ conflict, and $w_1[x] < r_2[x]$;
$w_1[y]$ and $r_2[y]$ conflict, and $r_2[y] < w_1[y]$



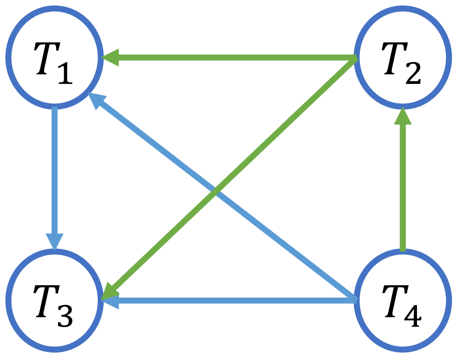
Not serializable

In class exercise

Is the following execution history serializable?

- $r_1[x]r_3[x]w_4[y]r_2[u]w_4[z]r_1[y]r_3[u]r_2[z]w_2[z]r_3[z]r_1[z]w_3[y]$

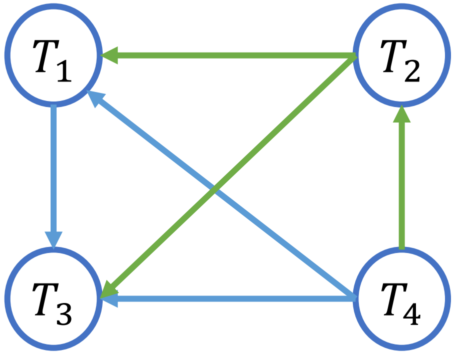
- Conflicting pairs:
  - Related to x: no conflicting pairs, as all are reads
  - Related to y: w4[y], r1[y], w3[y]
    - $w_4[y] < r_1[y]$ T4 → T1
    - $w_4[y] < w_3[y]$ T4 → T3
    - $r_1[y] < w_3[y]$ T1 → T3
  - Related to z: w4[z], r2[z], w2[z], r3[z], r1[z]
    - $w_4[z] < r_2[z]$ T4 → T2
    - $w_4[z] < w_2[z]$ T4 → T2
    - $w_4[z] < r_3[z]$ T4 → T3
    - $w_4[z] < r_1[z]$ T4 → T1
    - $r_2[z]$, $w_2[z]$ are not, as they are from the same transactions
    - $w_2[z] < r_3[z]$ T2 → T3
    - $w_2[z] < r_1[z]$ T2 → T1



In class exercise

Is the following execution history serializable?
$r_1[x]r_3[x]w_4[y]r_2[u]w_4[z]r_1[y]r_3[u]r_2[z]w_2[z]r_3[z]r_1[z]w_3[y]$

- No cycles in this serialization graph
    - Topological sort: T4 -> T2 -> T1->T3



- The history above is (conflict) equivalent to
  $w_4[y]w_4[z]r_2[u]r_2[z]w_2[z]r_1[x]r_1[y]r_1[z]r_3[x]r_3[u]r_3[z]w_3[y]$

Summary

- Transactions
  - Properties: ACID
- Isolation
  - Different isolation levels
  - The lowest isolation level to set
  - Serializability

Isolation level/anomaly	Dirty reads	Non-repeatable reads	Phantoms
READ UNCOMMITTED	Possible	Possible	Possible
READ COMMITTED	Impossible	Possible	Possible
REPEATABLE READ	Impossible	Impossible	Possible
SERIALIZABLE	Impossible	Impossible	Impossible