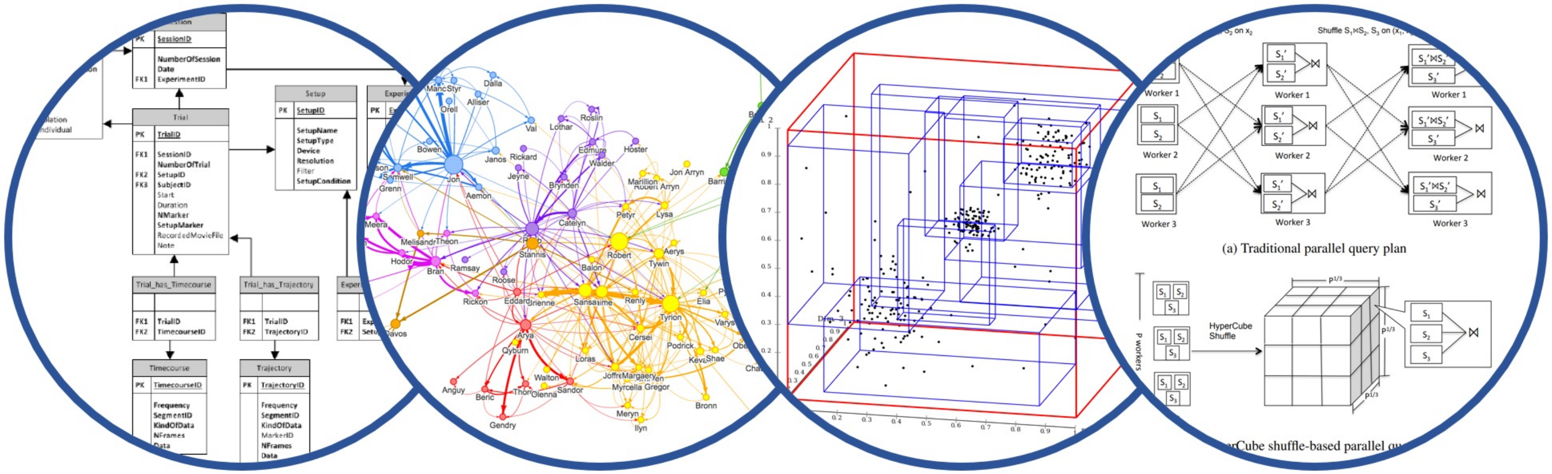

Introduction to Data Management

Transactions: Serializability

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Announcements

- Midterm is graded and released
- HW3 is almost graded
- HW4 is due on Friday

Recap: Applications and Databases

Almost every app uses some database

- General purpose language (Java, Python)
- App issues SQL commands to RDBMS
- Usually, multiple apps (users) access same DB

Recap: SQL in a Programming Language

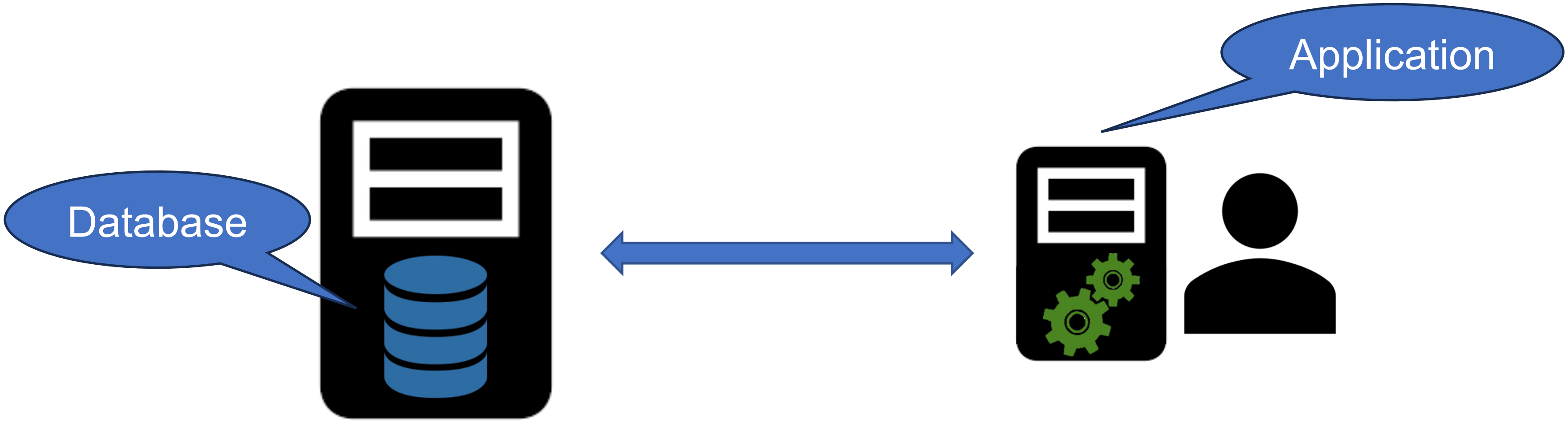
Acc

Usr	Balance
Alice	300
Bob	600
Carol	400

```
...
b1 = b+a                  # the new balance
cur.execute("UPDATE acc
             SET balance = ?
             WHERE usr=?",
             [b1,usr])
```

Recap: Single User

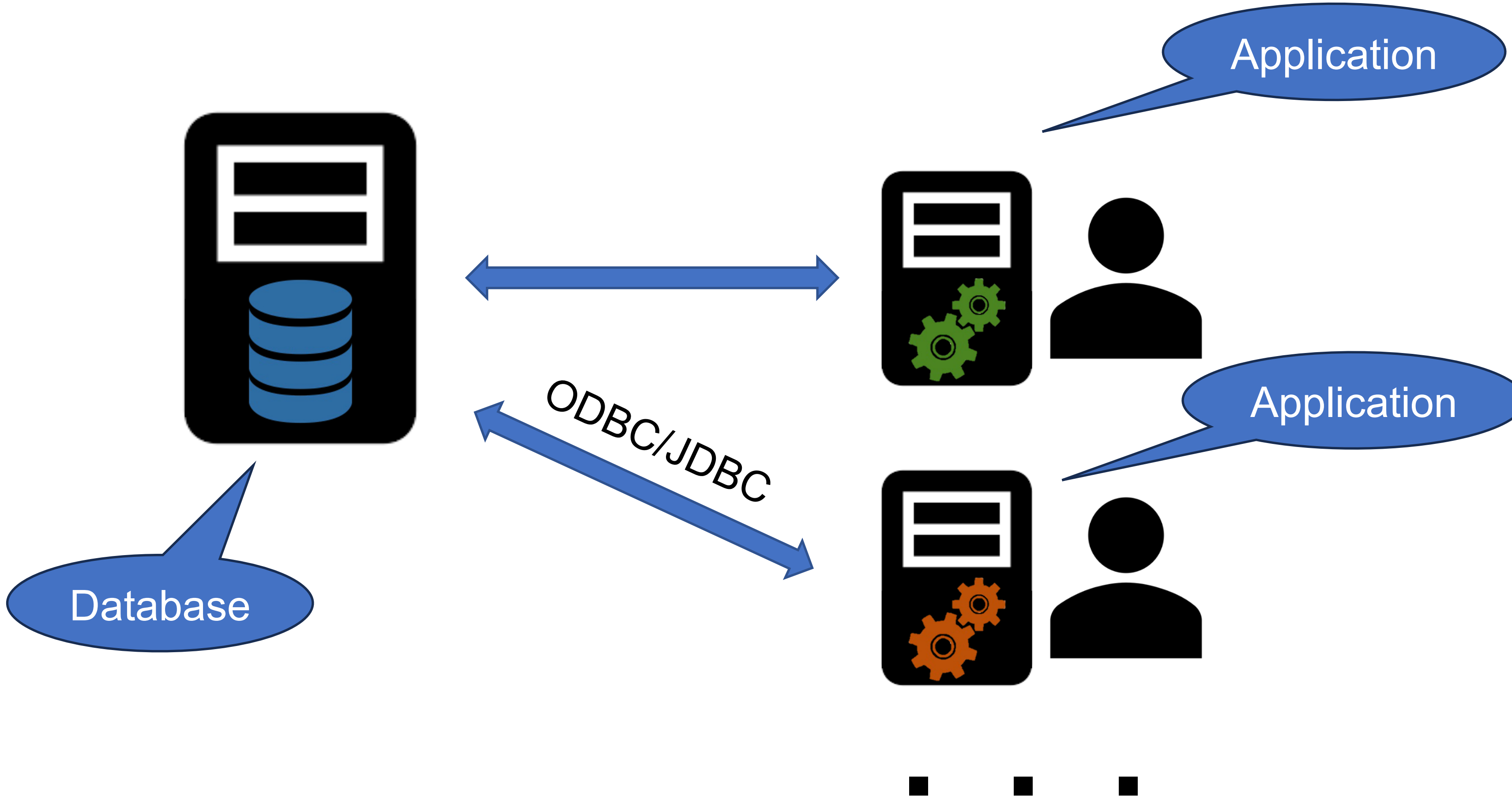
- The database is accessed by a single user:



- RDBMS on same laptop, or a server, or the cloud

Recap: Client-Server

- Multiple users access the database concurrently



Transactions

Transactions

- A transaction is a set of read and writes to the database that execute all or nothing

```
BEGIN TRANSACTION
   ...SQL Statements
COMMIT
```

```
BEGIN TRANSACTION
   ...SQL Statements
ROLLBACK
```

Entire txn is executed

No part of txn is executed

Transactions

- Prevent all concurrency control conflicts
- Easy to use in app: group statements in txns
- What property does a TXN satisfy?
  - Informally: “TXNs have ACID properties”
  - Formally: “execution of TXNs must be serializable”

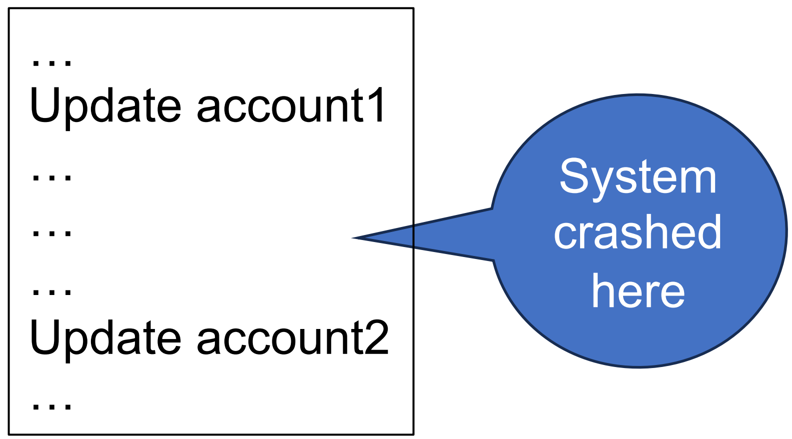
ACID

Transactions are ACID

- Atomic
- Consistent
- Isolated
- Durable

Atomic

- A set of operations is atomic if either all its operations happen, or none happens



Recovery manager (not discussed in this class)

Consistent

Assume TXN is “correct” (this is app specific)

- If TXN starts with the DB in a consistent state,
  it must end leaving the DB in a consistent state

It is a consequence of Atomicity and Isolation

Isolated

- The effect of the transaction on the database is as if it were running alone on the database

TXN1:
…
Update account1
…
…
…
Update account2
…

TXN2:
…
Update account1
…
…
…
Update account2
…

Interleaved actions should not interfere

Concurrency Control Manager

Durable

- Data should be stored persistently on disk, always in a consistent state

Discussion

- ACID properties: popular job interview question

- "A" and "I" matter
  - Atomicity: recover from crashes
  - Isolation: concurrency control

- ACID is informal.

Will discuss the formal property next

Serializability

Problem Definition

- The RDBMs runs several TXNs: T1, T2, T3, …
- It could run T1 to completion before starting T2,
  then run T2 to completion before starting T3,
  then run T3…
  …

Problem Definition

- The RDBMs runs several TXNs: T1, T2, T3, …

- It could run T1 to completion before starting T2,
  then run T2 to completion before starting T3,
  then run T3…
  …
  But this has poor performance

Why?
(in class)

Problem Definition

- The RDBMs runs several TXNs: T1, T2, T3, …

- It could run T1 to completion before starting T2,
  then run T2 to completion before starting T3,
  then run T3…
  …
  But this has poor performance

  Why?
  (in class)

- Instead: interleave commands from multiple TXNs

When is the interleaving ”safe”?

Transaction Modeling

For describing TXNs, we use a simple data model:

- Database = a set of “elements”
- TXN = a sequence of Reads/Writes of elements

- An element could be:
  - A record, or
  - A disk block, or
  - …

Example

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

Example

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

A,B are elements in the DB

Example

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

A,B are elements in the DB

t is a local variable in the app

Example

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

A,B are elements in the DB

t is a local variable in the app

T2
READ(A, s)
s := s*2
WRITE(A,s)
READ(B,s)
s := s*2
WRITE(B,s)

Definitions

- An interleaving of READ/WRITEs from different TXNs is called a schedule
- **Definition**: a serial schedule is a schedule where all operations of transactions come before those of the next transaction
- **Definition**: a serializable schedule is a schedule that is equivalent to a serial schedule

A Schedule

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

time ↓

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)

A Serial Schedule

A = 2
B = 2

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)

A Serial Schedule

	T1	T2
A = 2 B = 2	**READ**(A, t)	
	t := t+100	
	WRITE(A, t)	
	READ(B, t)	
	t := t+100	
	WRITE(B,t)	
A = 102 B = 102		**READ**(A, s)
		s := s*2
		WRITE(A,s)
		READ(B,s)
		s := s*2
		WRITE(B,s)

time

A Serial Schedule

time

State	T1	T2
A = 2 B = 2	**READ**(A, t)	
	t := t+100	
	WRITE(A, t)	
	READ(B, t)	
	t := t+100	
	WRITE(B,t)	
A = 102 B = 102		**READ**(A, s)
		s := s*2
		WRITE(A,s)
		READ(B,s)
		s := s*2
A = 204 B = 204		**WRITE**(B,s)

The Other **Serial** Schedule

time

	T1	T2
A = 2 B = 2		**READ**(A, s)
		s := s*2
		WRITE(A,s)
		READ(B,s)
A = 4 B = 4		s := s*2
		WRITE(B,s)
	READ(A, t)	
	t := t+100	
	WRITE(A, t)	
	READ(B, t)	
	t := t+100	
A = 104 B = 104	**WRITE**(B,t)	

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)

A = 2
B = 2

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)

A = 2
B = 2

A = 102
B = 2

A Serializable Schedule

T1	T2	
		A = 2 B = 2
READ(A, t)		
t := t+100		
WRITE(A, t)		A = 102 B = 2
	READ(A, s)	
	s := s*2	
	WRITE(A,s)	A = 204 B = 2
READ(B, t)		
t := t+100		
WRITE(B,t)		
	READ(B,s)	
	s := s*2	
	WRITE(B,s)	

A Serializable Schedule

T1	T2	
		A = 2 B = 2
READ(A, t)		
t := t+100		
WRITE(A, t)		A = 102 B = 2
	READ(A, s)	
	s := s*2	
	WRITE(A,s)	A = 204 B = 2
READ(B, t)		
t := t+100		
WRITE(B,t)		A = 204 B = 102
	READ(B,s)	
	s := s*2	
	WRITE(B,s)	A = 204 B = 204

A Serializable Schedule

T1	T2	
		A = 2 B = 2
READ(A, t)		
t := t+100		
WRITE(A, t)		A = 102 B = 2
	READ(A, s)	
	s := s*2	
	WRITE(A,s)	A = 204 B = 2
READ(B, t)		
t := t+100		
WRITE(B,t)		A = 204 B = 102
	READ(B,s)	
	s := s*2	
	WRITE(B,s)	A = 204 B = 204

This is NOT a serial schedule
It is a serializable 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)	

A = 2
B = 2

A = 102
B = 2

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)	

A = 2
B = 2

A = 102
B = 2

A = 204
B = 2

A Non-Serializable Schedule

T1	T2	
READ(A, t)		A = 2 B = 2
t := t+100		
WRITE(A, t)		A = 102 B = 2
	READ(A, s)	
	s := s*2	
	WRITE(A,s)	A = 204 B = 2
	READ(B,s)	
	s := s*2	
	WRITE(B,s)	A = 204 B = 4
READ(B, t)		
t := t+100		
WRITE(B,t)		

A Non-Serializable Schedule

T1	T2	
		A = 2 B = 2
READ(A, t)		
t := t+100		
WRITE(A, t)		A = 102 B = 2
	READ(A, s)	
	s := s*2	
	WRITE(A,s)	A = 204 B = 2
	READ(B,s)	
	s := s*2	
	WRITE(B,s)	A = 204 B = 4
READ(B, t)		
t := t+100		
WRITE(B,t)		A = 204 B = 104

A Non-Serializable Schedule

T1	T2	
		A = 2 B = 2
READ(A, t)		
t := t+100		
WRITE(A, t)		A = 102 B = 2
	READ(A, s)	
	s := s*2	
	WRITE(A,s)	A = 204 B = 2
	READ(B,s)	
	s := s*2	
	WRITE(B,s)	A = 204 B = 4
READ(B, t)		
t := t+100		
WRITE(B,t)		A = 204 B = 104

Should be impossible!

Discussion

- If the schedule is serial, then nothing can go wrong
- Same for a serializable schedule
- Concurrency Control Manager of the RDBMs must ensure that the schedule is serializable

How do we check that a schedule is serializable?

Conflict Serializability

Outline

We further simplify the model:

- A transaction is a sequence of reads and writes
- We ignore operations between reads and writes

Example

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

→

T1
R(A)
W(A)
R(B)
W(B)

Also: $R_1(A), W_1(A), R_1(B), W_1(B)$

Example

- T1 then T2

$R_1(A), W_1(A), R_1(B), W_1(B), R_2(A), W_2(A), R_2(B), W_2(B)$

time ↓

T1	T2
R(A)	
W(A)	
R(B)	
W(B)	
	R(A)
	W(A)
	R(B)
	W(B)

Example

- T2 then T1

$R_2(A), W_2(A), R_2(B), W_2(B), R_1(A), W_1(A), R_1(B), W_1(B)$

T1	T2
	R(A)
	W(A)
	R(B)
	W(B)
R(A)	
W(A)	
R(B)	
W(B)	

Example

- Serializable to T1 then T2

$R_1(A), W_1(A), R_2(A), W_2(A), R_1(B), W_1(B), R_2(B), W_2(B)$

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
R(B)	
W(B)	
	R(B)
	W(B)

Example

- Not serializable

$R_1(A), W_1(A), R_2(A), W_2(A), R_2(B), W_2(B), R_1(B), W_1(B)$

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
R(B)	
W(B)	

Main Idea

- To check if a schedule is serializable, try swapping operations until it becomes serial:

… $R_i(A)$, $W_j(B)$, … → … $W_j(B)$, $R_i(A)$, …

- But we only swap if the new schedule is equivalent

- A pair is in conflict if it cannot be swapped

Conflicts

1. Any pair of ops of the same TXN are in conflict
2. $R_i(X)$, $W_j(X)$ forms a read-write conflict
3. $W_i(X)$, $R_j(X)$ forms a write-read conflict
4. $W_i(X)$, $W_j(X)$ forms a write-write conflict

Conflict Serializable Schedule

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

Conflict Serializable Schedule Example

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
R(B)	
W(B)	
	R(B)
	W(B)

Conflict Serializable Schedule Example

T1	T2
R(A)	
W(A)	
	R(A)
R(B)	
	W(A)
W(B)	
	R(B)
	W(B)

Conflict Serializable Schedule Example

T1	T2
R(A)	
W(A)	
R(B)	
	R(A)
	W(A)
W(B)	
	R(B)
	W(B)

Conflict Serializable Schedule Example

T1	T2
R(A)	
W(A)	
R(B)	
	R(A)
W(B)	
	W(A)
	R(B)
	W(B)

Conflict Serializable Schedule Example

T1	T2
R(A)	
W(A)	
R(B)	
W(B)	
	R(A)
	W(A)
	R(B)
	W(B)

Non Conflict Serializable Schedule Example

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
	W(B)
R(B)	
W(B)	

Non Conflict Serializable Schedule Example

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
	R(B)
R(B)	
	W(B)
W(B)	

Conflict rule broken!

Serializable vs Conflict Serializable

Conflict serializability ignores what TXN does between the R’s and the W’s.
It assumes the worst / most complicated updates to the data

Serializable vs Conflict Serializable

Conflict serializability ignores what TXN does between the R's and the W's.
It assumes the worst / most complicated updates to the data

Not serializable nor conflict serializable

	T1	T2	
A←A+100	R(A)		
	W(A)		
		R(A)	A←A*2
		W(A)	
		R(B)	B←B*2
		W(B)	
B←B+100	R(B)		
	W(B)		

Serializable vs Conflict Serializable

Conflict serializability ignores what TXN does between the R's and the W's.
It assumes the worst / most complicated updates to the data

Serializable (because 100+2 = 2+100)
But not conflict serializable, because it assumes the worst

	T1	T2	
A←A+100	R(A)		
	W(A)		
		R(A)	A←A+2
		W(A)	
		R(B)	B←B+2
		W(B)	
B←B+100	R(B)		
	W(B)		

Discussion

- Most RDBMs enforce conflict-serializability
- Next: how to test for conflict-serializability

The Precedence Graph

Testing for Conflict Serializability

Fix a schedule

- **Definition**. The precedence graph has one node for every TXN in the schedule, and one edge for every pair of conflicting ops

- **Theorem**. The schedule is conflict-serializable iff the precedence graph has no cycles

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

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

Nodes: 1 2 3

Example 1

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

Edges:

1 2 3

$r_2(A)$ $r_1(B)$

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

Edges: 1 2 3

$r_2(A)$ $r_1(B)$

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

Edges: ① ② ③

$r_2(A)$ $r_1(B)$

No edge because
no conflict (A != B)

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

Edges: ① ② ③

$r_2(A)$ $w_2(A)$

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

Edges: ① ② ③

$r_2(A)$ $w_2(A)$

No edge because same txn (2)

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

Edges: 1 2 3

$r_2(A)$ $r_3(A)$?

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

Edges: (1) (2) (3)

$r_2(A)$ $w_1(B)$?

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

Edges: 1 2 3

$r_2(A)$ $w_3(A)$?

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

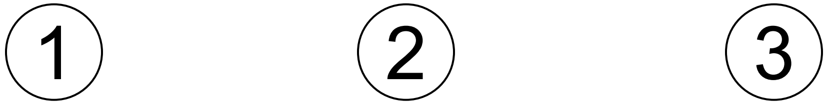
Edges: 1 2 3

$r_2(A)$ $w_3(A)$

Edge! Conflict from T2 to T3

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

Edges:

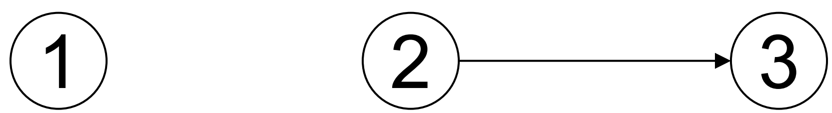


$r_2(A)$ $w_3(A)$

Edge! Conflict from T2 to T3

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

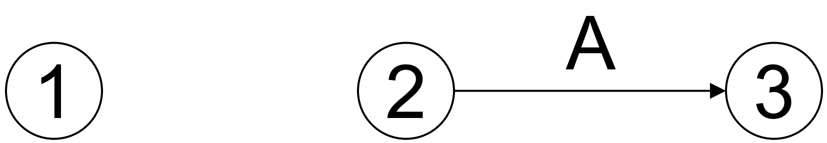
Edges:



$r_2(A)$ $r_2(B)$?

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

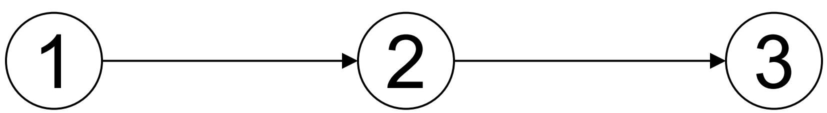
Edges:



And so on until compared every pair of actions…

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

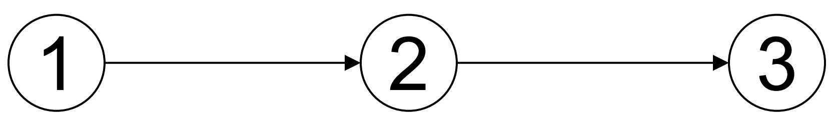
Edges:



Repeating the same directed edge not necessary

Example 1

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



This schedule is conflict-serializable

Example 2

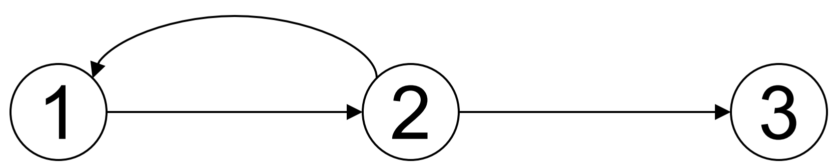
$r_2(A); r_1(B); w_2(A); r_2(B); r_3(A); w_1(B); w_3(A); w_2(B)$

Example 2

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

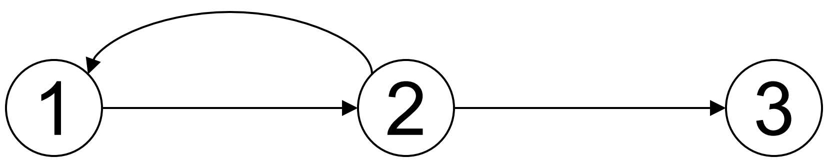
Example 2

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



Example 2

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



This schedule is NOT conflict-serializable