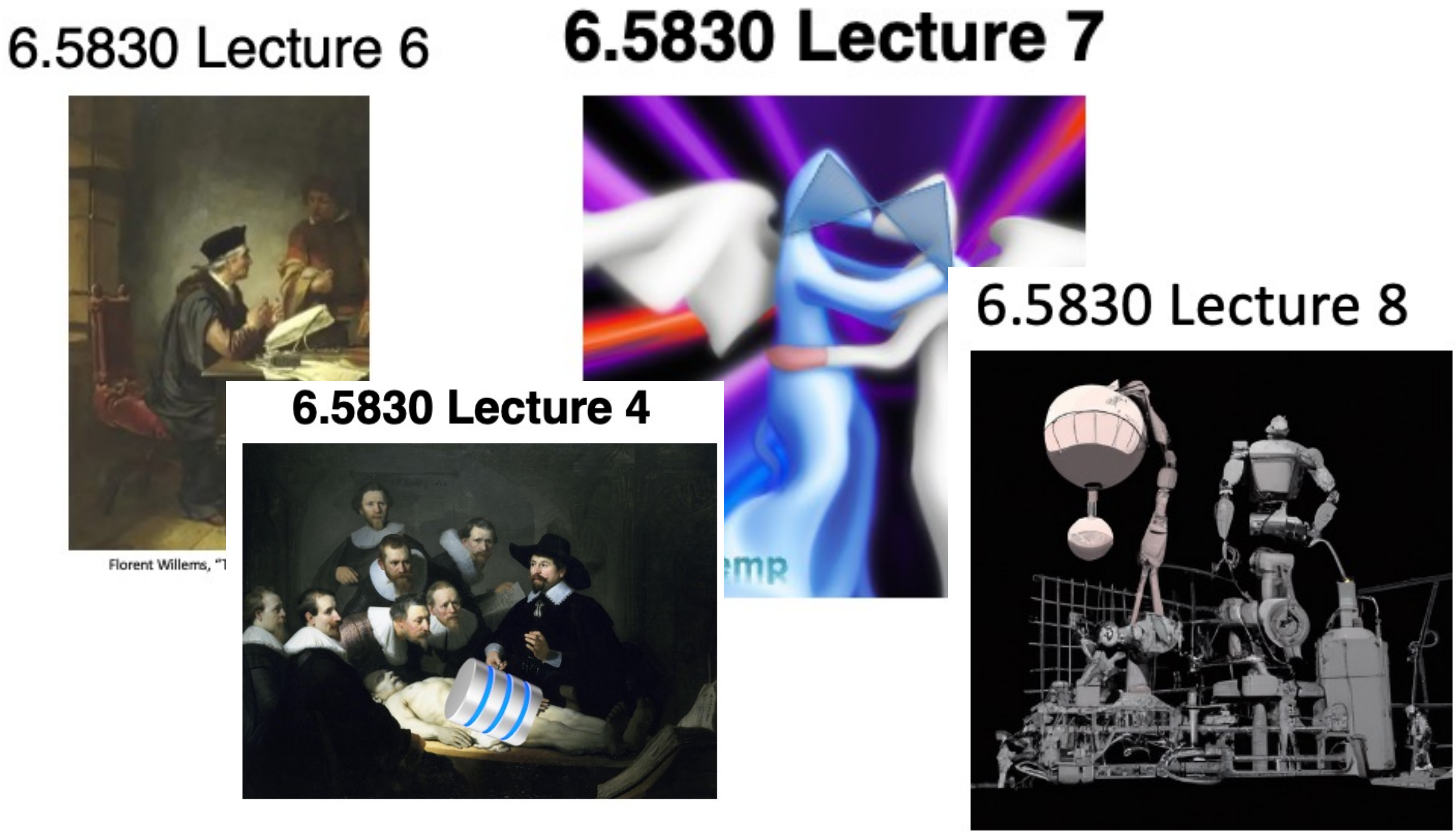
6.5830 Lecture 10
Transactions

10/16/2022

Project proposals are due today

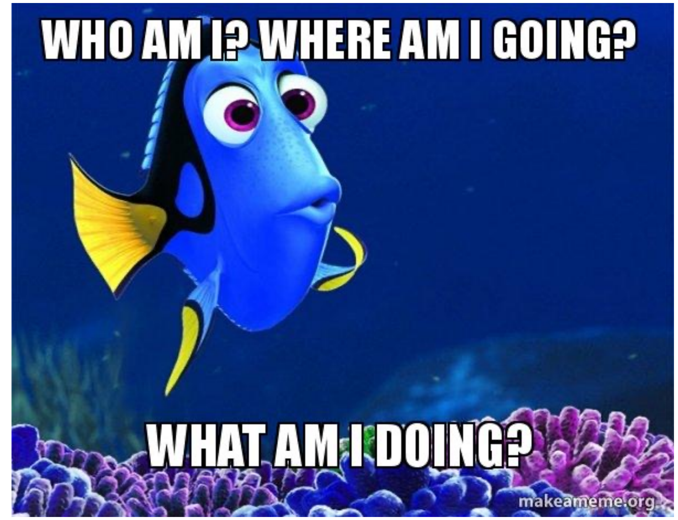
Quiz 1 results (Wednesday)

The Lecture Art Collection So far

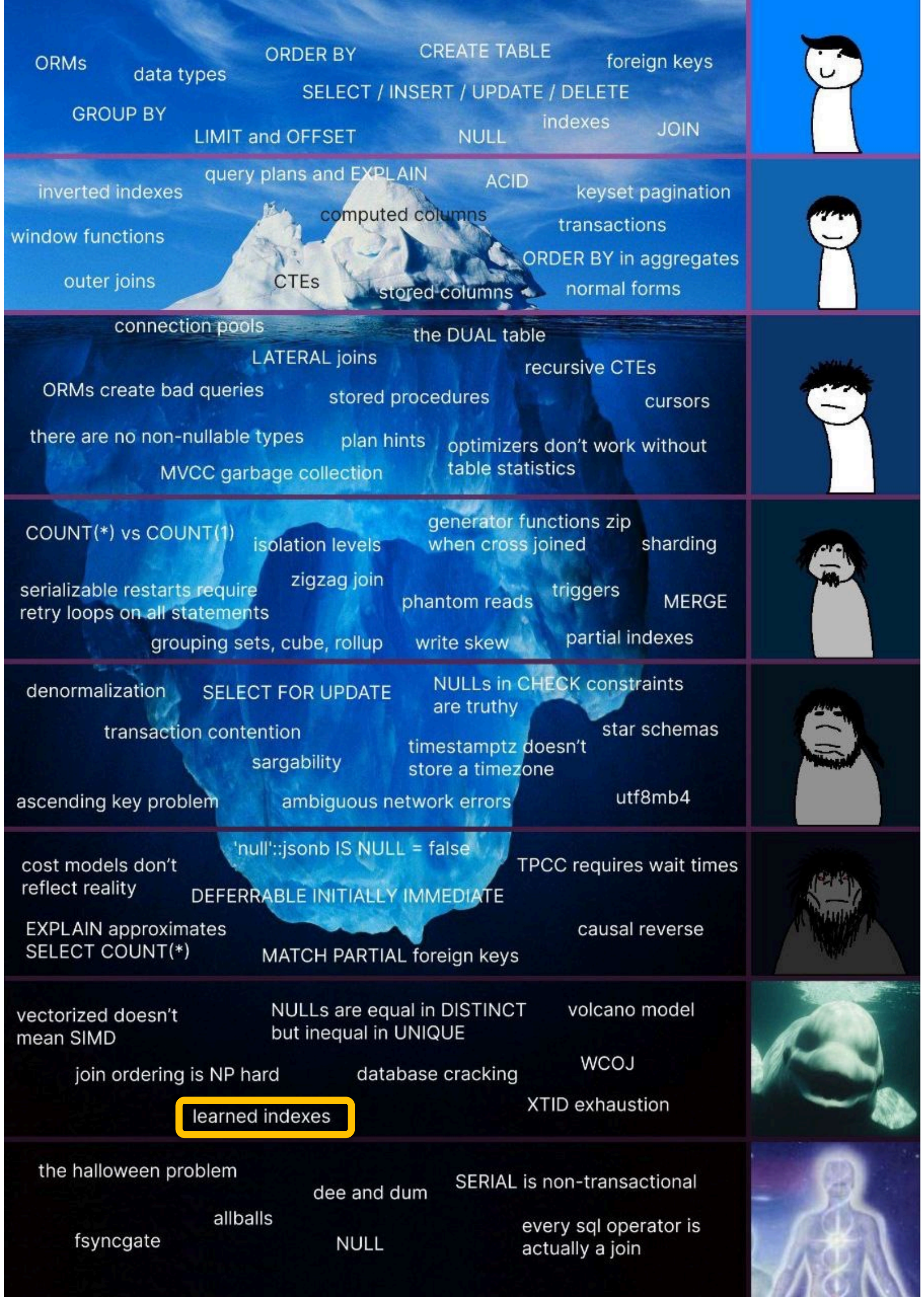


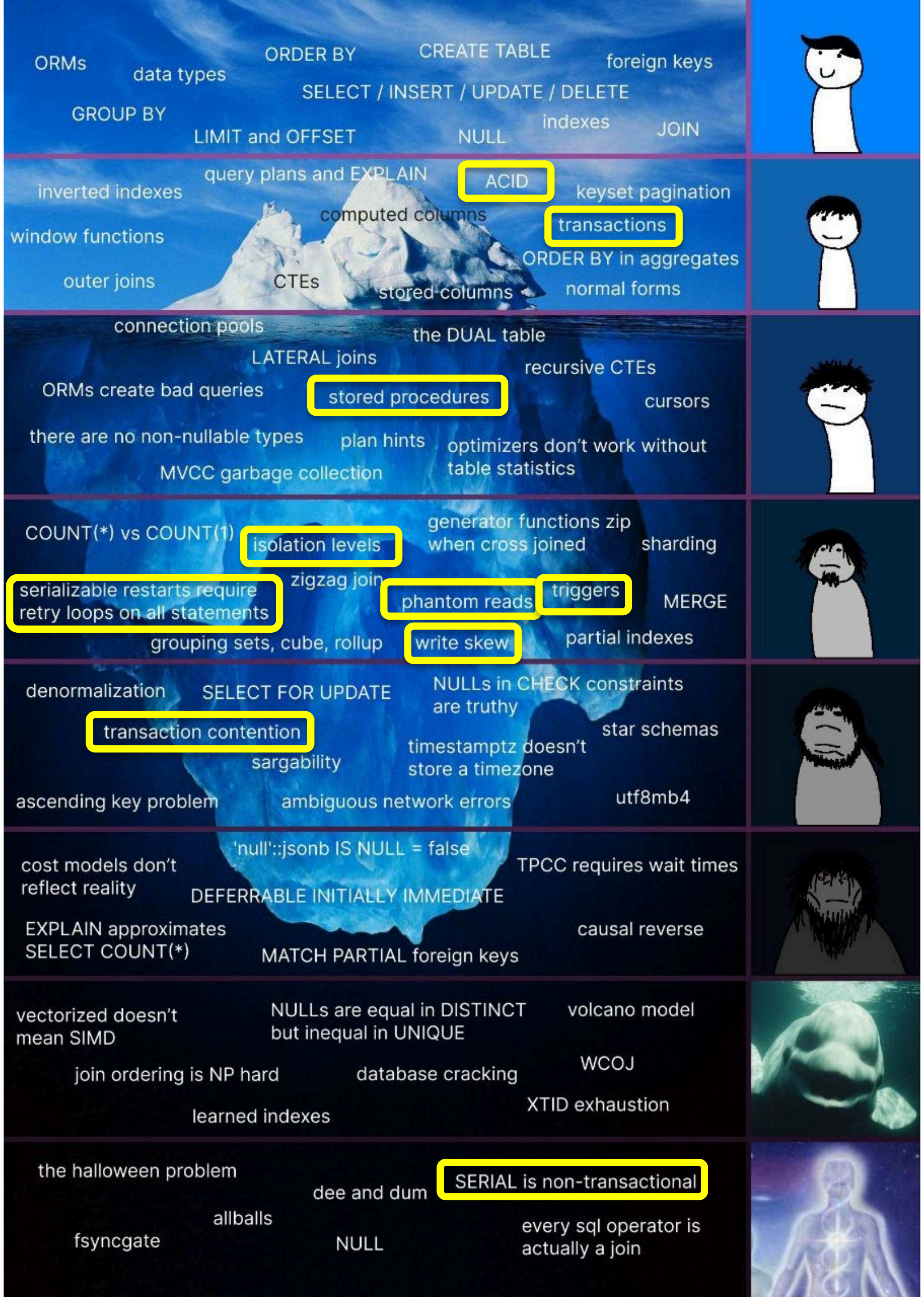
Today's Art

Where Are We?



- So far:
  - Studied relational model & SQL
  - Learned basic architecture of a database system
  - Studied different operator implementations
  - Looked at several data layouts
  - Saw how query optimizer works with statistics to select plans and operators
- What next:
  - *Concurrency Control and Recovery*: How to ensure correctness in the presence of modifications and failures to the database
  - Distributed and parallel query processing
  - “Advanced Topics”


ORMs
data types
ORDER BY
CREATE TABLE
foreign keys
SELECT / INSERT / UPDATE / DELETE
GROUP BY
LIMIT and OFFSET
NULL
indexes
JOIN
query plans and EXPLAIN
ACID
inverted indexes
keyset pagination
computed columns
window functions
transactions
ORDER BY in aggregates
outer joins
CTEs
stored columns
normal forms
connection pools
the DUAL table
LATERAL joins
recursive CTEs
ORMs create bad queries
stored procedures
cursors
there are no non-nullable types
plan hints
optimizers don't work without table statistics
MVCC garbage collection
COUNT(*) vs COUNT(1)
isolation levels
generator functions zip when cross joined
sharding
serializable restarts require retry loops on all statements
zigzag join
phantom reads
triggers
MERGE
grouping sets, cube, rollup
write skew
partial indexes
denormalization
SELECT FOR UPDATE
NULLs in CHECK constraints are truthy
transaction contention
star schemas
sargability
timestamptz doesn't store a timezone
ascending key problem
ambiguous network errors
utf8mb4
'null'::jsonb IS NULL = false
cost models don't reflect reality
TPCC requires wait times
DEFERRABLE INITIALLY IMMEDIATE
EXPLAIN approximates SELECT COUNT(*)
causal reverse
MATCH PARTIAL foreign keys
vectorized doesn't mean SIMD
NULLs are equal in DISTINCT but inequal in UNIQUE
volcano model
join ordering is NP hard
database cracking
WCOJ
learned indexes
XTID exhaustion
the halloween problem
dee and dum
SERIAL is non-transactional
allballs
fsyncgate
NULL
every sql operator is actually a join



Next 4 lectures

Concurrency Control Key Idea: Transactions

- Group related sequence of actions so they are "all or nothing"
  - If the system crashes, partial effects are not seen
  - Other transactions do not see partial effects
- A set of implementation techniques that provides this abstraction with good performance

ACID Properties of Transactions

- **A** tomicity – many actions look like one; “all or nothing”
- **C** onsistency – database preserves invariants
- **I** solation – concurrent actions don’t see each other’s results
- **D** urability – completed actions in effect after crash (“recoverable”)

Concurrent Programming Is Hard

A = ~~0~~ ~~1~~ 1

- Example:

```
T1
t = A
t = t + 1
A = t
```

```
T2
t = A
t = t + 1
A = t
```

- Looks correct!
- But maybe not if other updates to A are interleaved!
- Suppose T1 increment runs just before T2 increment
  – T1 increment will be lost

- Conventional approach: programmer adds locks
  – But must reason about other concurrent programs

Transactions Dramatically Simplify Concurrent Programming

- Concurrent actions are *serially equivalent*
  - I.e., appear to have run one after the other
- Programmer does not have to think about what is running at the same time!
- **One of the big ideas in computer science**

SQL Syntax

- BEGIN TRANSACTION
  - Followed by SQL operations that modify database
- COMMIT: make the effects of the transaction durable
  - After COMMIT returns database guarantees results present even after crash
  - And results are visible to other transactions
- ABORT: undo all effects of the transaction

This Lecture: Atomicity

- **A**tomicity – many actions like one; "all or nothing"
- In reality, actions take time!
  - To get atomicity, to prevent multiple actions from interfering with each other
  - I.e., are **I**solated
- Will return to **D**urability in 2 lectures
  - E.g., how to *recover* a database after a crash into a state where no partial transactions are present

Consistency

- Preservation of invariants
- Usually expressed in terms of constraints
  - E.g., primary keys / foreign keys
  - Triggers
- Example: no employee makes more than their manager
- Requires ugly non-SQL syntax (e.g. PL/pgSQL)
- Often done in the application

Postgres PL/pgSQL Trigger Example

```
CREATE FUNCTION sal_check() RETURNS trigger AS $sal_check$
    DECLARE
        mgr_sal integer;
    BEGIN
        IF NEW.salary IS NOT NULL THEN
            SELECT INTO mgr_sal salary
                FROM emp
                JOIN manages
                    ON NEW.eid = manages.eid
                    AND emp.eid = manages.eid
                LIMIT 1;
            IF (mgr_sal < NEW.salary) THEN
                RAISE EXCEPTION 'employee cannot make more than manager';
            END IF;
        END IF;
        RETURN NEW;
  END;
$sal_check$ LANGUAGE plpgsql;
CREATE TRIGGER eid_sal BEFORE INSERT OR UPDATE ON emp
FOR EACH ROW EXECUTE FUNCTION sal_check();
```

NEW is the record being added

mgr_sal is a local variable
Query finds the salary of one manager

Check salary (if no manager, mgr_sal is NULL)

Declare that we want to call sal_check every time a record changes or is added to emp

How Can We Isolate Actions?

- Serialize execution: one transaction at a time
- Problems with this?
  - No ability to use multiple processors
  - Long running transactions *starve* others

- Goal: allow *concurrent* execution while preserving *serial equivalence*

- *Concurrency control* algorithms do this

Serializability

- An ordering of actions in concurrent transactions that is serially equivalent

T1	T2
RA	
WA	
	RA
	WA
RB	
WB	
	RB
	WB

RA: Read A
WA: Write A, may depend on anything read previously

A/B are "objects" – e.g., records, disk pages, etc

Assume arbitrary application logic between reads and writes

Serially equivalent to T1 then T2

Serializability

- An ordering of actions in concurrent transactions that is serially equivalent

T1	T2
RA	
	RA
	WA
WA	
RB	
WB	
	RB
	WB

RA: Read A
WA: Write A, may depend on anything read previously

A/B are "objects" – e.g., records, disk pages, etc

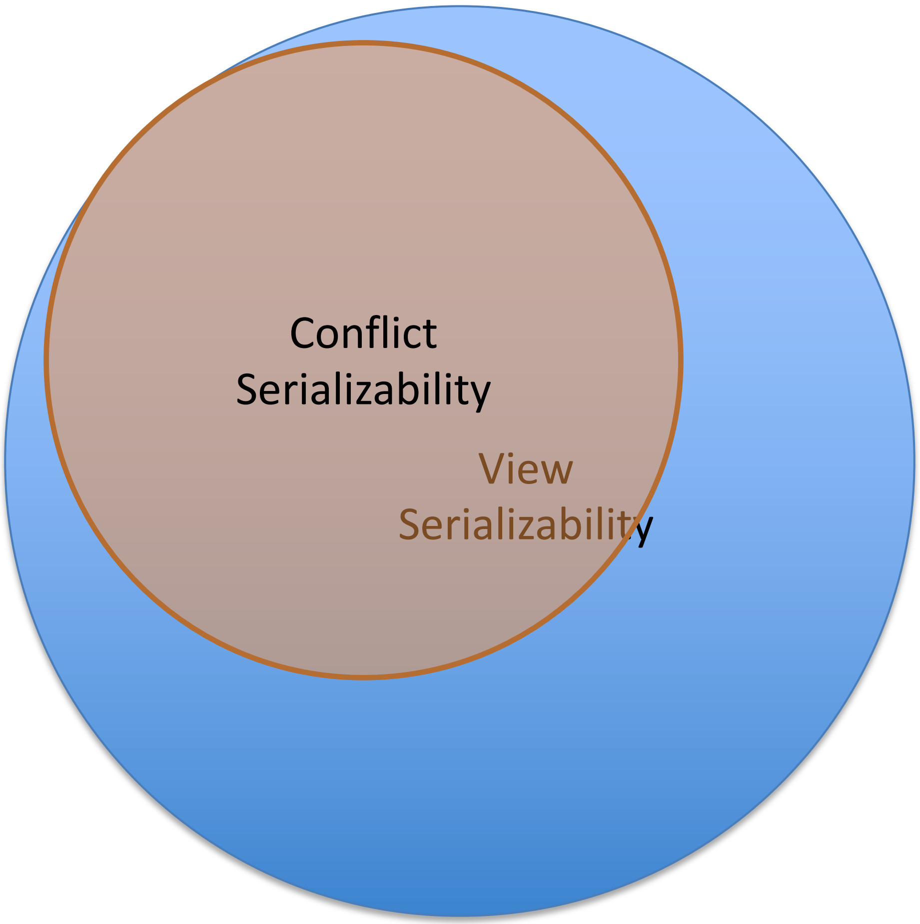
Assume arbitrary application logic between reads and writes

Not serially equivalent – T2's write to A is lost, couldn't occur in a serial schedule

In T1-T2, T2 should see T1's write to A

In T2-T1, T1 should see T2's write to A

Testing for Serializability



Any schedule that is conflict serializable is view serializable, but not vice-versa

View Serializability

A particular ordering of instructions in a schedule S is *view equivalent* to a serial ordering S' iff:

- Every value read in S is the same value that was read by the same read in S'.
- The final write of every object is done by the same transaction T in S and S’
- Less formally, all transactions in S “view” the same values they view in S', and the final state after the transactions run is the same.

View Serializability Example

S

T1	T2
RA=A1	
WA→A2	
	RA = A2
	WA→A3
RB=B1	
WB→B2	
	RB=B2
	WB→B3

Same valu
read in bo
schedules

Every value read in S is the same value that was read by the same read in S'.

The final write of every object is done by the same transaction T in S and S'

https://clicker.mit.edu/6.5830/
Is the following schedule view serializable?

T1	T2
RA=A1	
	RA=A1
	WA->A2
	WB->B2
WB->B3	

A) Yes
B) No

A particular ordering of instructions in a schedule S is *view equivalent* to a serial ordering S' iff:

- Every value read in S is the same value that was read by the same read in S'.
- The final write of every object is done by the same transaction T in S and S’

View Serializability Limitations

- Must test against each possible serial schedule to determine serial equivalence
  - NP-Hard!

(For N concurrent transactions, there are 2^N possible serial schedules)

- No protocol to ensure view serializability as transactions run

- *Conflict serializability* addresses both points

Conflicting Operations

- Two operations are said to conflict if:
  - Both operations are on the same object
  - At least one operation is a write
  - E.g.,
    - $T1_{WA}$ conflicts with $T2_{RA}$, but
    - $T1_{RA}$ does not conflict with $T2_{RA}$

T2 \ T1	R	W
R	✓	✗
W	✗	✗

Conflict Serializability

A schedule is *conflict serializable* if it is possible to swap non-conflicting operations to derive a serial schedule.

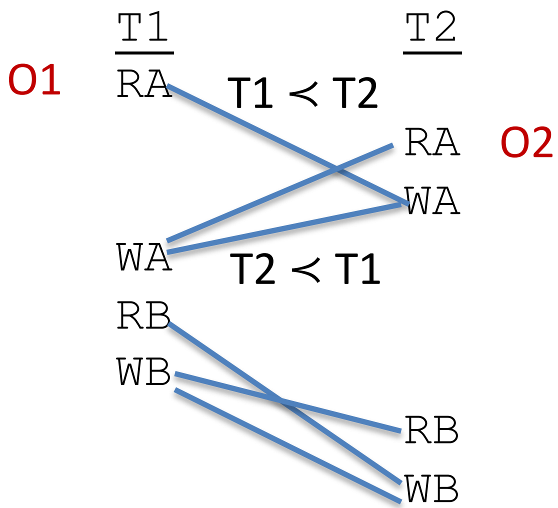
Equivalently

For all pairs of conflicting operations {O1 in T1, O2 in T2} either

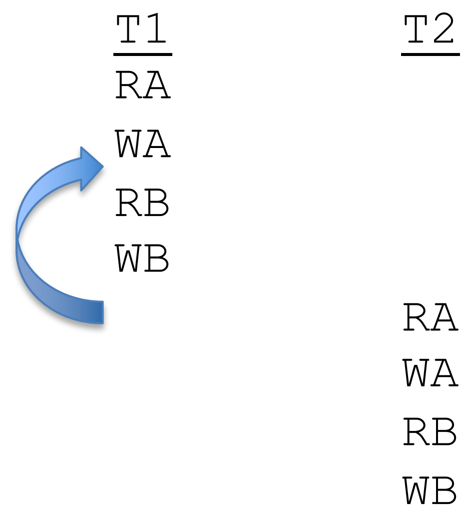
- O1 always precedes O2, or
- O2 always precedes O1.

$T1 \prec T2$: "T1 precedes T2"

Example



Not conflict serializable!



In conflict serializable schedule, can reorder non-conflicting ops to get serial schedule

For all pairs of conflicting operations {O1 in T1, O2 in T2} either
O1 always precedes O2, or
O2 always precedes O1.

Precedence Graph

Given transactions Ti and Tj,
Create an edge from Ti→Tj if:

- Ti reads/writes some A before Tj writes A
  $RA_{Ti} \prec WA_{Tj}$ or $WA_{Ti} \prec WA_{Tj}$

or

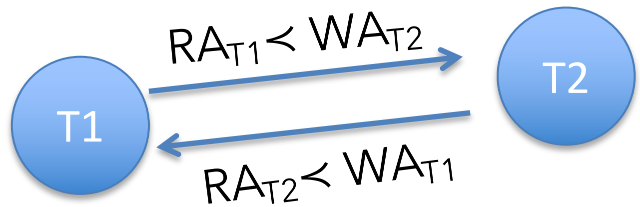
- Ti writes some A before Tj reads A
  $WA_{Ti} \prec RA_{Tj}$

If there are cycles in this graph, schedule is not conflict serializable

Non-Serializable Example

T1	T2
RA	
	RA
	WA
WA	
RB	
WB	
	RB
	WB

Precedence Graph



Cycle!

Create an edge from Ti→Tj if:

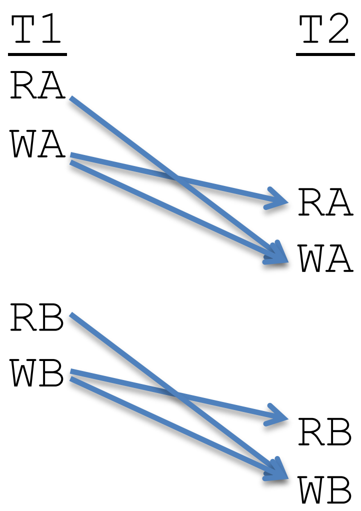
Ti reads/writes some A before Tj writes A, or

$RA_{Ti} \prec WA_{Tj}$ or $WA_{Ti} \prec WA_{Tj}$

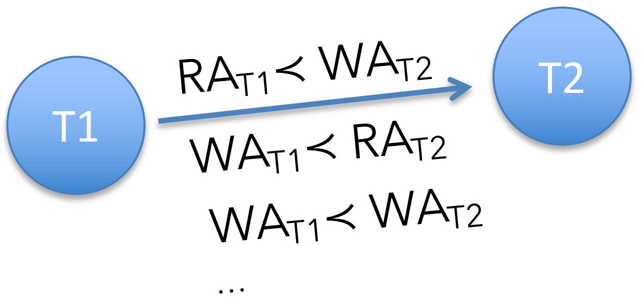
Ti writes some A before Tj reads A

$WA_{Ti} \prec RA_{Tj}$

Serializable Example



Precedence Graph



No Cycles!

Create an edge from Ti→Tj if:

Ti reads/writes some A before Tj writes A, or

$RA_{Ti} \prec WA_{Tj}$ or $WA_{Ti} \prec WA_{Tj}$

Ti writes some A before Tj reads A

$WA_{Ti} \prec RA_{Tj}$

Recap: 3 Ways to Test for Conflict Serializabiliy

1. Check: For all pairs of conflicting operations {O1 in T1, O2 in T2} either
   a. O1 always precedes O2, or
   b. O2 always precedes O1.

2. Swap non-conflicting operations to get serial schedule
3. Build precedence graph, check for cycles

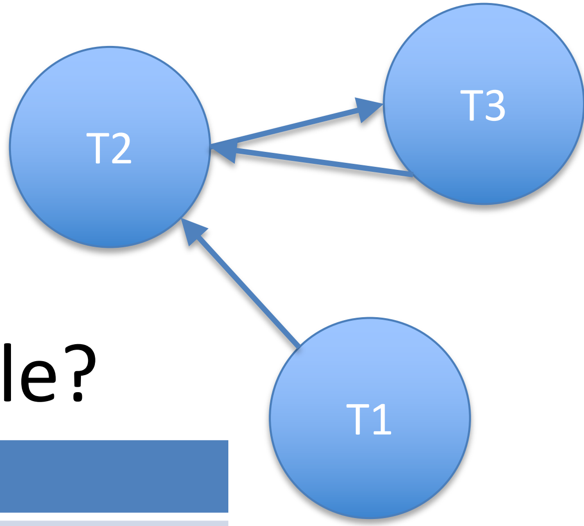
Clicker: https://clicker.mit.edu/6.5830/

- Is this schedule conflict serializable?

A) Yes
B) No

T1	T2	T3
RA		
	RB	
WA		
		RB
	WB	
		WB
	RA	
	WA	
COMMIT	COMMIT	COMMIT

Study Break



- Is this schedule conflict serializable?

T1	T2	T3
RA		
	RB	
WA		
		RB
	WB	
		WB
	RA	
	WA	
COMMIT	COMMIT	COMMIT

No!

https://clicker.mit.edu/6.5830/

T1	T2	T3
RA		
	WA	
WA		
		WA
RB		
WB		

Is this schedule

A) neither view nor conflict serializable

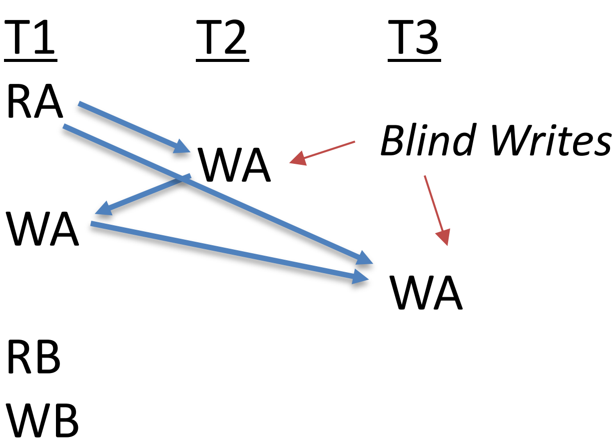
B) conflict serializable but **not** view serializable

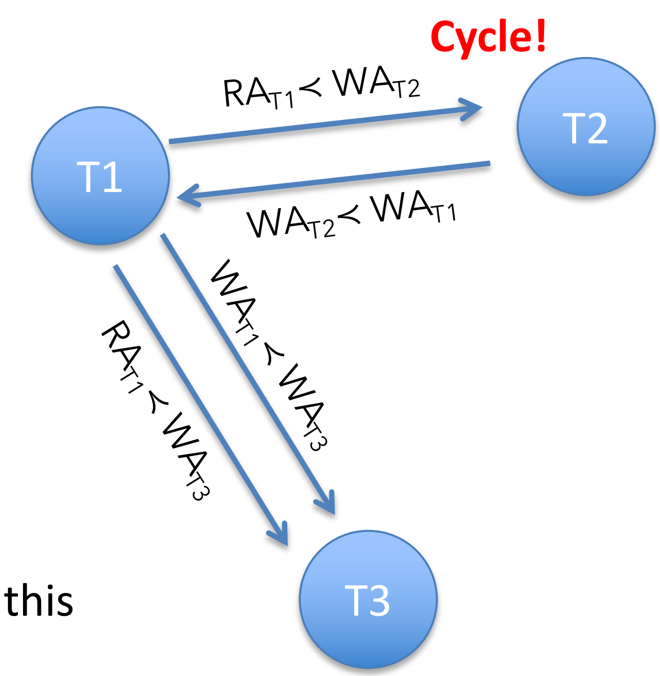
C) view serializable but **not** conflict serializable

D) conflict and view serializable

View vs Conflict Serializable

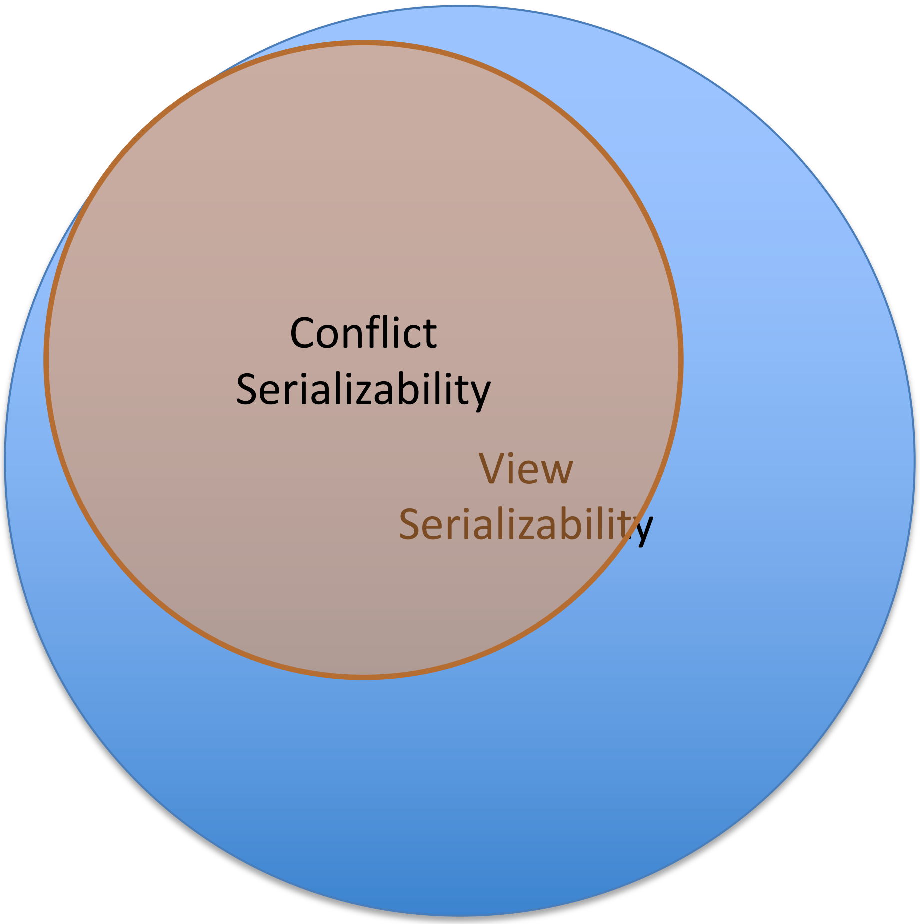
- Testing for view serializability is NP-Hard
  - Have to consider all possible orderings
- Conflict serializability used in practice
  - Not because of NP-Hardness
  - Because we have a way to enforce it as transactions run
- Example of schedule that is view serializable but not conflict serializable:





Equivalent to T1, T2, T3
Conflict serializability does not permit this
Only happens with *blind writes*

View vs Conflict Serializable



Any schedule that is conflict serializable is view serializable, but not vice-versa

Implementing Conflict Serializability

- Several different protocols
- Today: Two Phase Locking (2PL)
- Basic idea:
  - Acquire a shared (S) lock before each read of an object
  - Acquire an exclusive (X) lock before each write of an object
- Several transactions can hold an S lock
- Only one transaction can hold an X lock
- If a transaction cannot acquire a lock it waits ("blocks")

T2 \ T1	R	W
R	✓	✗
W	✗	✗

T2 \ T1	S	X
S	✓	✗
X	✗	✗

Lock Compatibility Table

Conflicting operations (from def. of conflict serializability) are not compatible with each other

When to Release Locks

- After each op completes?
- Or after xaction is done with variable?
- No! Example of problem →
- T2 "sneaks in" and updates A and B before T1 updates B

T1	T2
Xlock A	
RA	
WA	
Rel A	
	Xlock A
	RA
	WA
	Xlock B
	RB
	WB
	Rel A,B
Xlock B	
RB	
WB	
Rel B	

This schedule is not serializable

Solution: Two Phase Locking

- A transaction cannot release any locks until it has acquired all of its locks

Example, Revisited

- Rule: A transaction cannot release any locks until it has acquired all of its locks

	T1	T2
	Xlock A	
	RA	
	WA	
Not allowed →	Rel A	
		Xlock A
		RA
		WA
		Xlock B
		RB
		WB
		Rel A,B
	Xlock B	
	RB	
	WB	
	Rel B	

This schedule is not serializable

Example, Revisited

- Rule: A transaction cannot release any locks until it has acquired all of its locks
- Serial schedule defined by *lock points*
  - Where they acquire last lock

	T1	T2
	Xlock A	
	RA	
	WA	
	Xlock B ← *Lock point*	
Acquired all locks so can release →	Rel A	
		Xlock A
		RA
		WA
	RB	
	WB	
	Rel B	
	Lock point →	Xlock B
		RB
		WB
		Rel A,B

*This schedule *is* serializable*

Correctness Intuition

- Once a transaction T reached its lock point:
  - T’s place in serial order is set
  - Any transactions that haven't acquired all their locks can’t take any conflicting actions until after T releases locks
    - **Ordered later**
  - Any transactions which already have all their locks must have completed their conflicting actions (released their locks) before T can proceed
    - **Ordered earlier**

Two Phase Locking (2PL) Protocol

- Before every read, acquire a shared lock
- Before every write, acquire an exclusive lock (or "upgrade") a shared to an exclusive lock
- Release locks only after last lock has been acquired, and ops on that object are finished

Can you think of any potential problems with 2PL?

Refining 2PL

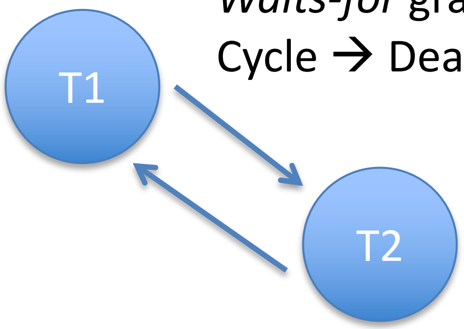
- Problems:
  - Deadlocks
  - Cascading Aborts
  - How do we know when we are done with all operations on an object?

Deadlocks

- Possible for Ti to hold a lock Tj needs, and vice versa

	T1	T2	
	RA		
	WA		
		RB	
		WB	
T1 waits for T2 →	RB		
	WB		
		RA	← *T2 waits for T1*
		WA	

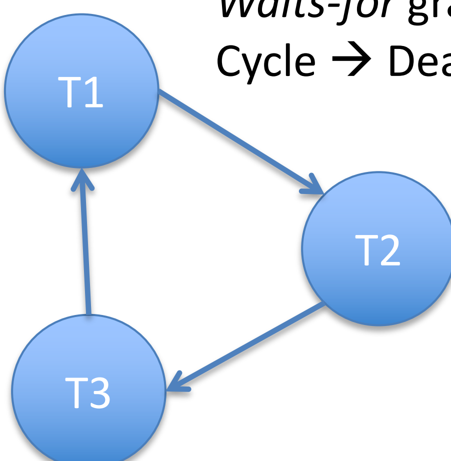
Waits-for graph
Cycle → Deadlock



Complex Deadlocks Are Possible

T1	T2	T3
RA		
WA		
		RC
	RB	
	WB	
		RA ← *T3 waits for T1*
		WA
T1 waits for T2 → RB		
WB		
	RC ← *T2 waits for T3*	
	WC	

Waits-for graph
Cycle → Deadlock



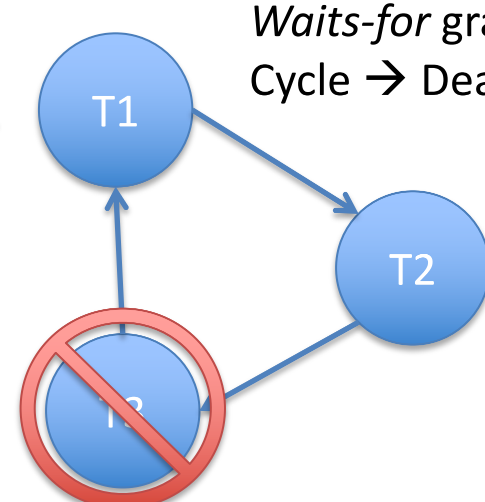
Resolving Deadlock

- Solution: abort one of the transactions
  - Recall: users can abort too

	T1	T2	
	RA		
	WA		
		RB	
		WB	
T1 waits for T2 →	RB		
	WB		
		RC	← ~~*T2 waits for T3*~~
		WC	

Equivalent to T2 - T1

Waits-for graph
Cycle → Deadlock



Cascading Aborts

- Problem: if T1 aborts, and T2 read something T1 wrote, T2 also needs to abort

	T1	T2
	Xlock A	
	RA	
	WA	
	Xlock B	
	Rel A	
		Xlock A
		RA
		WA
If T1 aborts here →	RB	
T2 also needs to abort,	WB	
It reads T1's write of A	Rel B	
		Xlock B
		RB
		WB
		Rel A,B

Can you think of a 2PL variant which neither requires deadlock detection nor has cascading aborts?

Strict Two-Phase Locking

- Can avoid cascading aborts by holding exclusive locks until end of transaction

- Ensures that transactions never read other transaction’s uncommitted data

Strict Two-Phase Locking Protocol

- Before every read, acquire a shared lock
- Before every write, acquire an exclusive lock (or "upgrade") a shared to an exclusive lock
- ~~Release locks only after last lock has been acquired, and ops on that object are finished~~
- Release *shared* locks only after last lock has been acquired, and ops on that object are finished
- Release *exclusive* locks only after the transaction commits
- Ensures cascadeless-ness

Problem: When is it OK to release?

- How does DBMS know a transaction no longer needs a lock?
- Difficult, since transactions can be issued interactively
- In practice, this means that all locks held til end of transaction
- This is called *rigorous two-phase locking*

Rigorous Two-Phase Locking Protocol

- Before every read, acquire a shared lock
- Before every write, acquire an exclusive lock (or "upgrade") a shared to an exclusive lock
- Release (all) locks only after the transaction commits
- Ensures cascadeless-ness, and
- *Commit order = serialization order*

Can you avoid deadlock detection?

Clicker: https://clicker.mit.edu/6.5830/

```
UPDATE  professors
SET status = ‘teaching'
WHERE name = 'Tim'
AND NOT EXISTS
     SELECT 1 FROM employees WHERE
     status = ‘teaching’ AND name= ' Sam'
```

```
UPDATE  professors
SET status = ‘teaching'
WHERE name = ' Sam'
AND NOT EXISTS
     SELECT 1 FROM employees WHERE
     status = ‘teaching’ AND name= ‘Tim'
```

Can you create a serializable interleaved schedule?

Clicker: https://clicker.mit.edu/6.5830/

```
UPDATE  professors
SET status = ‘teaching'
WHERE name = 'Tim'
AND NOT EXISTS
      SELECT 1 FROM employees WHERE
      status = ‘teaching’ AND name= ' Sam'
```

```
UPDATE  professors
SET status = ‘teaching'
WHERE name = ' Sam'
AND NOT EXISTS
      SELECT 1 FROM employees WHERE
      status = ‘teaching’ AND name= ‘Tim'
```

S

T1	T2
Rs=s1	
	Rt=t1
Wt→t1/t2	
	Ws→s1/s2

Clicker: https://clicker.mit.edu/6.5830/

```
UPDATE  professors
SET status = 'teaching'
WHERE name = 'Tim'
AND NOT EXISTS
    SELECT 1 FROM employees WHERE
    status = 'teaching' AND name= ' Sam'
```

```
UPDATE  professors
SET status = 'teaching'
WHERE name = ' Sam'
AND NOT EXISTS
    SELECT 1 FROM employees WHERE
    status = 'teaching' AND name= 'Tim'
```

S

T1	T2
Rs=s1	
	Rt=t1
Wt→t1/t2	
	Ws→s1/s2

Is this schedule

A) neither view nor conflict serializable

B) conflict serializable but **not** view serializable

C) view serializable but **not** conflict serializable

D) conflict and view serializable

Next 1.5 Lectures

- Optimistic concurrency control: Another protocol to achieve conflict serializability
- Nuances that arise with locking granularity