ICCS240 Database Management

Transactions, ACID
& Concurrency Controls

Transaction Concept

- A transaction is a unit of program execution that accesses and possibly updates various data items.

  E.g. transaction to transfer $50 from account A to account B:

  ```
  1. READ(A)
  2. A := A-50
  3. WRITE(A)
  4. READ(B)
  5. B := B+50
  6. WRITE(B)
  ```

- Two main issues to deal with
  - Failures of various kinds, such as hardware failures and system crashes
  - Concurrent execution of multiple transactions

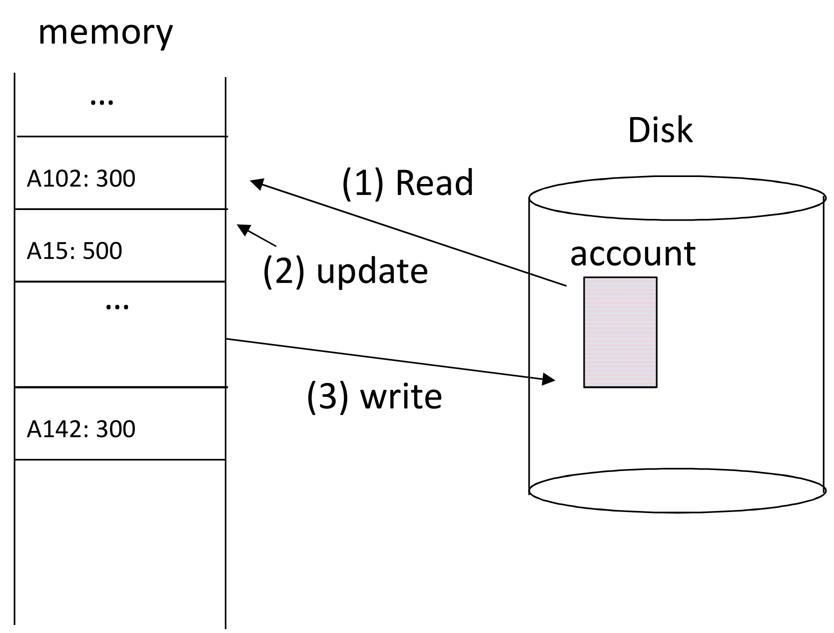
Example of UPDATE in SQL

```
UPDATE account
SET balance = balance - 50
WHERE acct_no = A102
```

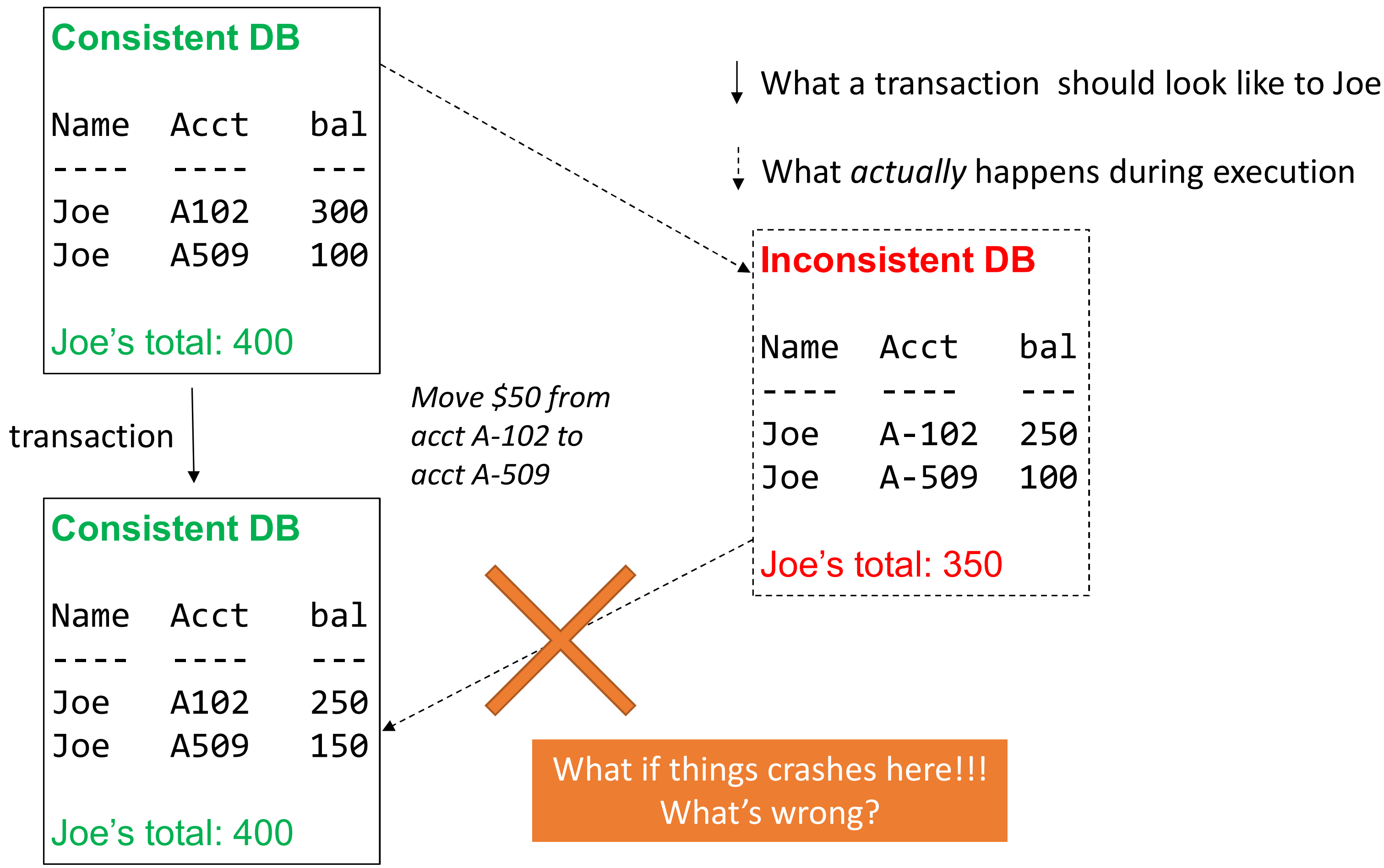
Transaction:

1. Read(A)
2. A <- A -50
3. Write(A)

What takes place:



The Threat to Data Integrity: Crashes



3 Famous Anomalies

- Lost Updates
  - Two task T_1 and T_2 modify the same data and both commit
  - Final state shows effects of only T_1 or T_2, but not both.
- Dirty Reads
  - T reads data written by T' while T' has not yet committed.
- Inconsistent Read
  - One task T sees some but not all changes made by T'

1st: Lost Updates

Client 1:

```
UPDATE Customer
SET rentals= rentals + 1
WHERE cname= ‘Fred’
```

Client 2:

```
UPDATE Customer
SET rentals= rentals + 1
WHERE cname= ‘Fred’
```

Two people attempt to rent two movies for Fred, from two different terminals.

What happens ?

2nd: Dirty Reads

Client 1: transfer \$100 acc1→acc2

```
X = Account1.balance
Account2.balance += 100

If (X>=100) Account1.balance -=100
else { /* rollback ! */
       account2.balance -= 100
       println("Denied !")
```

Client 2: transfer \$100 acc2→acc3

```
Y = Account2.balance
Account3.balance += 100

If (Y>=100) Account2.balance -=100
else { /* rollback ! */
         account3.balance -= 100
         println("Denied !")
```

What's wrong?

3rd: Inconsistent Reads

Client 1: move from gizmo→gadget

```
UPDATE Products
SET quantity = quantity + 5
WHERE product = ‘gizmo’
```

```
UPDATE Products
SET quantity = quantity - 5
WHERE product = ‘gadget’
```

Client 2: inventory….

```
SELECT sum(quantity)
FROM Product
```

Transactions

What?

- One or more operations, which reflect a single real-world transition.
  A unit of work!
- Can be executed concurrently

Why?

1. Updates can require multiple reads, writes on a DB.
   e.g., transfer $50 from A102 to A509
   = `READ(A); A ← A-50; WRITE(A); READ(B); B ← B+50; WRITE(B);`
2. For performance reasons, DBs permit updates to be executed concurrently.

Concern: concurrent access/updates of data can compromise data integrity

ACID

Properties that transactions need to have:

✓ **Atomicity**: either all operations in a transaction take effect, or none

✓ **Consistency**: operations, taken together preserve DB consistency

✓ **Isolation**: intermediate, inconsistent states must be concealed from other transactions

✓ **Durability**: If a transaction successfully completes ("commits"), changes made to DB must persist, even if system crashes

Demonstration of ACID

transaction to transfer $50 from account A to account B:

```
1. READ(A)
2. A := A-50
3. WRITE(A)
4. READ(B)
5. B := B+50
6. WRITE(B)
```

FAILURE

Consistency: total value A+B unchanged by transaction

Atomicity: if transaction fails after 3. and before 6., then 3. should not affect DB

Durability: once user notified of transaction commit, updates to A,B should not be undone by system failure

Isolation: other transactions should not be able to see A, B between steps 3-6

Threat to ACID

- Programmer Error
  e.g.: $50 subtracted from A, $30 added to B
  → threatens **consistency**

- System Failures
  e.g.: crash after write(A) and before write(B)
  → threatens **atomicity**
  e.g.: crash after write(B)
  → threatens **durability**

- Concurrency
  e.g.: concurrent transaction reads A, B between steps 3-6
  → threatens **isolation**

Isolation …

Simplest way to guarantee: *forbid concurrent transactions!?*

But, concurrency is ***desirable***:

- Achieves better throughput (TPS: transactions per second)
  one transaction can use CPU while another is waiting for disk to service request
- Achieves better average response time
  short transactions don't need to get stuck behind long ones

Prohibiting concurrency is *not* an option!

So we need a **concurrency control**

Concurrency Control

- Multiple concurrent transactions: $T_1, T_2, \ldots$
- Read/Write common elements: $A_1, A_2, \ldots$
- How to prevent unwanted interference?

The SCHEDULER is responsible for that

Schedules

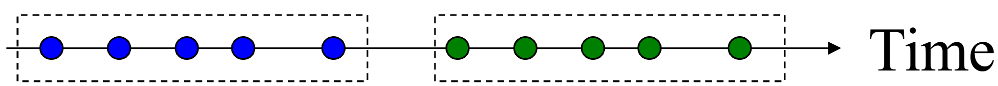
A schedule is a **sequence** of interleaved actions from all transactions.

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)

A Serial Schedule

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)

If any action of transaction T_1 precedes any action of T_2, then all action of T_1 precede all action of T_2.



A Schedule is serializable if it is equivalent to a serial 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 NOT a *serial* schedule, but is *serializable*

A schedule is serializable if it is guaranteed to give the same final result as some serial schedule.

Exercise: Which of these are serializable?

Assume WRITE(x) may change values of x

```
READ(A)
        READ(A)
        WRITE(A)
WRITE(A)
READ(B)
WRITE(B)
        READ(B)
        WRITE(B)
```

```
READ(A)
        READ(A)
WRITE(A)
        WRITE(A)
READ(B)
WRITE(B)
        READ(B)
        WRITE(B)
```

```
READ(A)
WRITE(A)
        READ(A)
        WRITE(A)
        READ(B)
        WRITE(B)
READ(B)
WRITE(B)
```

Notation for Transaction and Schedules

We do not consider the details of local computation steps such as $t \coloneqq t + 100$
Assume *worst case* updates: so only the READs and WRITEs matter

- Actions: $r_i(X)$ or $w_i(X)$
- Transaction T_i: a sequence of actions
- Schedule S: a sequence of actions from a set of transaction $\mathcal{T}$.

```
T1: r1(A); w1(A); r1(B); w1(B);
T2: r2(A); w2(A); r2(B); w2(B);
S:  r1(A); w1(A); r2(A); w2(A); r1(B); w1(B); r2(B); w2(B);
```

Conflicts

WRITE-READ : WR

READ-WRITE : RW

WRITE-WRITE : WW

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

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

Read/write by T_i, T_j to same element: $w_i(X); r_j(X)$ or $r_i(X); w_j(Y)$

A **conflict** means: you cannot *swap* the two operations

Conflict Serializability

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

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

$\Downarrow$

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

The Precedence Graph Test
– Is a schedule S conflict-serializable?

Build a graph of all transaction T_i in S such that

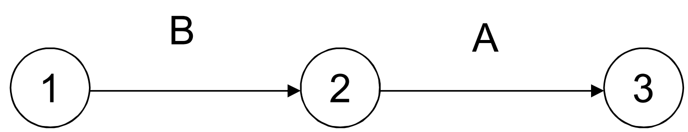
- Vertices are denoted by transaction T_i
- Edges from T_i to T_j if T_i makes an action that conflicts with one of T_j and that T_i's action comes first.

Then,

If the graph has <u>no cycles</u>, then S is conflict serializable.

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

Exercise

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

View Equivalence

A serializable schedule need not be conflict serializable, even under the “worst case update” assumption

$$\boxed{w_1(X);\ w_2(X);\ w_2(Y);\ w_1(Y);\ w_3(Y);}$$

$$\not\Downarrow$$

$$\boxed{w_1(X);\ w_1(Y);\ w_2(X);\ w_2(Y);\ w_3(Y);}$$

Equivalent, but not conflict-equivalent

View Equivalence

Two schedules $S$and S' are **view equivalent** if:

- If T reads an initial value of A in S,
  then T also reads the initial value of A in S'.
- If T reads a value of A written by T' in S,
  then T also reads a value of A written by T' in S'.
- If T writes the final value of A in S,
  then it writes the final value of A in S'.

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

If a schedule is **conflict serializable**, then it is also **view serializable**. But not vice versa

Schedule with Aborted Transactions

When a transaction aborts, the recovery manager undoes its updates

But some of its updates may have affected other transactions !

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

Cannot abort T1 because cannot undo T2

Recoverable Schedules

A schedule S is recoverable if:

- It is *conflict-serializable*, and
- Whenever a transaction T commits, *all* transactions who have written elements read by T have already committed

Examples

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

Non-recoverable

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

Recoverable

Cascading Aborts

If a transaction T aborts, then we need to abort any other transaction T' that has read an element written by T.

A schedule is said to avoid cascading aborts if whenever a transaction read an element, the transaction that has last written it has already committed.

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

Without cascading aborts

“Schedule” Summary

Serializability

Serial

Serializable

Conflict Serializable

View Serialzable

Recovererability

Recoverable

(Avoid) Cascade Aborts

Scheduler ensures serializability

The scheduler is the module that schedules the transaction's actions, ensuring serializability.

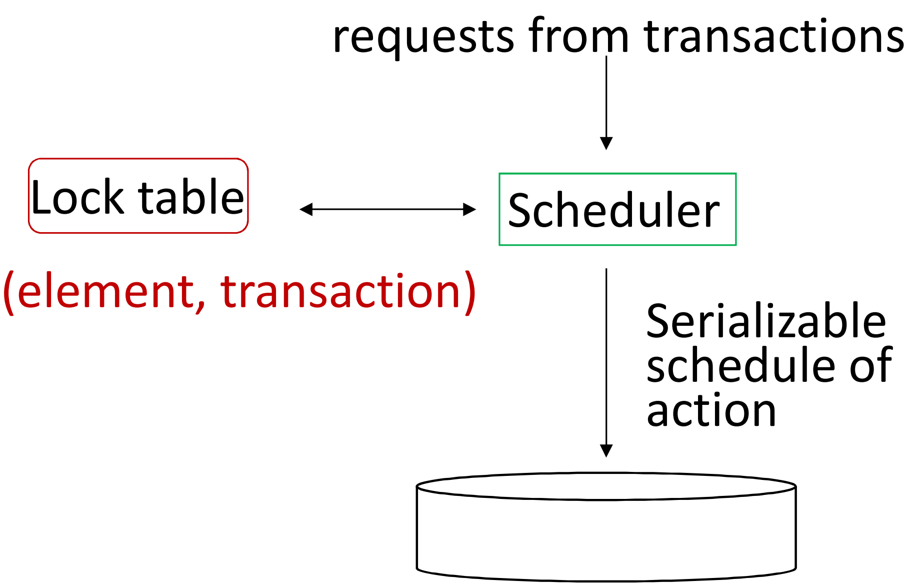
Two main approaches

- *Pessimistic* scheduler: uses **LOCK**s
- *Optimistic* scheduler: **time stamps**, **validation**

Not covered!

Locks

A scheduler uses a lock table to guide decisions



Notion: $l_i(X)$ = T_i requests lock on element X
$u_i(X)$ = T_i releases lock on element X

Consistency of transactions:

1. A transaction can only read or write an element if it previously requested a lock on that element and hasn't yet released the lock
2. If a transaction locks an element, it must later unlock that element

Legality: No two transactions may have locked the same element without one having first released the lock

Example: A legal but not serializable schedule

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);	

2-Phase Locking (2PL)
– no new locks once you've given up

- In every transaction, all lock requests must preceed all unlock requests.
- This ensures conflict serializability!

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

Now, it is non-recoverable ☹

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/Rollback	**Commit**

We should never have let T2 commit.

2PL does not guarantee recoverable, so …

Commit transaction T only after all transactions that wrote data that T read have committed

Or only let a transaction read an item after the transaction that last wrote this item has committed

Strict 2PL:

2PL + a transaction releases its locks *only after* it has committed.

Deadlocks

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_{100} waits for a lock held by T_1!! ---- **Cycle**!

Deadlock avoidance

- Acquire locks in pre-defined order
- Acquire all locks at once before starting

Deadlock detection

Timeouts

Wait-for graph *(this is what commercial systems use)*

In general, the Locking Scheduler looks like …

Task 1:
Add lock/unlock requests to transactions

- Examine all `READ(A)` or `WRITE(A)` actions
- Add appropriate lock requests
- Ensure Strict 2PL !

Task 2:
Execute the locks accordingly

- When a lock is requested, check the lock table
- When a lock is released, re-activate a transaction from its wait list
- When a transaction aborts, release all its locks
- Check for deadlocks occasionally

Concurrency Control by Timestamps

Main variant:

The timestamp order defines
the serialization order of the transaction

Will generate a schedule that is view-equivalent to a serial schedule, and recoverable

Timestamp

$TS(T)$ is a timestamp of transaction T.

With each element X, associate:

- $RT(X) =$ the highest timestamp of any transaction T that read X.
- $WT(X) =$ the highest timestamp of any transaction T that wrote X.
- $C(X) =$ the commit bit:
  - true when transaction with highest timestamp that wrote X committed.

Example

For any two *conflicting actions*, ensure that their order is the serialized order:

In each of these cases:

- $w_U(X) \ldots r_T(X)$ Read too late ?
- $r_U(X) \ \ldots w_T(X)$
- $w_U(X) \ldots w_T(X)$

When T requests $r_T(X)$, need to check $TS(U) \leq TS(T)$

Timestamp to ensure recoverable

Recall the definition:

if a transaction reads an element,
then the transaction that wrote it must have already committed

Use the commit bit $C(X)$ to keep track if the transaction that last wrote X has committed

Some consideration:

- T wants to read X, and $TS(T) < WT(X)$

$$\boxed{\text{START}(T) \ldots \text{START}(U) \ldots w_U(X) \ldots r_T(X)}$$

- T wants to write X, and $TS(T) < RT(X)$

$$\boxed{\text{START}(T) \ldots \text{START}(U) \ldots r_U(X) \ldots w_T(X)}$$

- T wants to write X, and $TS(T) \geq RT(X)$ but $WT(X) > TS(T)$

$$\boxed{\text{START}(T) \ldots \text{START}(V) \ldots w_V(X) \ldots w_T(X)}$$

So need to ROLLBACK T

Ensuring Recoverability (1)

- T wants to read X, and WT(X) < TS(T)
- Seems OK, but…

START(U) … START(T) … w_U(X). . . r_T(X)… ABORT(U)

If C(X)=false, T needs to wait for it to become true

Ensuring Recoverability (2)

- T wants to read X, and WT(X) > TS(T)
- Seems OK not to write at all, but…

START(T) … START(U)… w_U(X). . . w_T(X)… ABORT(U)

If C(X)=false, T needs to wait for it to become true

Simplified Timestamp-based Scheduling

Only for transactions that do not abort

Transaction T wants to read element X

If $\boldsymbol{TS(T) < WT(X)}$, then ROLLBACK

Elseif $\boldsymbol{C(X) = \mathrm{false}}$, then WAIT until $C(X) = \mathrm{true}$ or ABORT

Else READ and update $RT(X)$ to larger of $TS(T)$ or $RT(X)$

Transaction T wants to write element X

If $\boldsymbol{TS(T) < RT(X)}$, then ROLLBACK

Else if $\boldsymbol{TS(T) < WT(X)}$,

If $\boldsymbol{C(X) = \mathrm{false}}$, then WAIT

Else IGNORE WRITE & continue --- *(Thomas WRITE rule)*

Otherwise, WRITE and update $WT(X) = TS(T)$ and set $C(X) = \mathrm{false}$

Example

T1	T2	T3	A	B	C
200	150	175	RT=0	RT=0	RT=0
			WT=0	WT=0	WT=0
r1(B)					
	r2(A)				
		r3(C)			
w1(B)					
w1(A)					
	w2(C)				
		w3(A)			

TS(T2)>=RT(C) & WT(C)<TS(T2)
Writing too late! Check C(C);

Timestamp vs. Lock

Timestamp

- Optimistic
  - Poor when there are many conflicts (rollbacks)
  - Great when there are few conflicts
- Storage: Read and write times for recently accessed database elements

Lock

- *Lock delay transactions by avoid rollback!*
- Pessimistic
  - Great when there are many conflicts
  - Poor when there are few conflict (lock delays)
- Storage: space in the lock table $\propto$ # elements locked

Compromise

READ ONLY transactions $\rightarrow$ timestamps

READ/WRITE transactions $\rightarrow$ locks

Multi-version Concurrency Control

- When update data element, database will not overwrite original item with new data, but creates a new version of the element.
- Thus, there are multiple versions stored.
- The version that each transaction sees depends on isolation level implemented, e.g., snapshot isolation – a transaction observes a state of data as when the transaction started.
- Issues to consider is how/when to remove version that become obsolete and will no longer be read.

Not cover in this class,
but you may read more from the textbook.

Transaction in MySQL

Example from https://www.w3resource.com/mysql/mysql-transaction.php

Transaction in MySQL

```
START TRANSACTION
{ command1 }
{ command2 }
…
COMMIT (or ROLLBACK)
```

```
SET autocommit = {0 | 1}
```

By default, MySQL runs with **autocommit mode enabled**.

This means that as soon as you execute a statement that updates (modifies) a table, MySQL stores the update on disk to make it permanent.

The change cannot be rolled back.

```
mysql> /* CASE STUDY 1: */

mysql> select * from student;
+------------+------------------+-----------+
| STUDENT_ID | NAME             | REG_CLASS |
+------------+------------------+-----------+
| 2          | Neena Kochhar    |         9 |
| 3          | Lex De Haan      |         9 |
| 4          | Alexander Hunold |        11 |
+------------+------------------+-----------+

mysql> update STUDENT set ST_CLASS=8 where STUDENT_ID=2;

mysql> select * from STUDENT;
+------------+------------------+-----------+
| STUDENT_ID | NAME             | REG_CLASS |
+------------+------------------+-----------+
| 2          | Neena Kochhar    |         8 |
| 3          | Lex De Haan      |         9 |
| 4          | Alexander Hunold |        11 |
+------------+------------------+-----------+
```

```
mysql> ROLLBACK;

mysql> select * from student;
+------------+------------------+-----------+
| STUDENT_ID | NAME             | REG_CLASS |
+------------+------------------+-----------+
| 2          | Neena Kochhar    |         8 |
| 3          | Lex De Haan      |         9 |
| 4          | Alexander Hunold |        11 |
+------------+------------------+-----------+

mysql> /* There is no rollback as MySQL runs with autocommit
mode enabled!!! */
```

```
mysql> /* CASE STUDY 2: */
```

SET autocommit=0;

```
mysql> START TRANSACTION;
mysql> update STUDENT set ST_CLASS=10 where STUDENT_ID=2;
mysql> select * from STUDENT;
+------------+------------------+-----------+
| STUDENT_ID | NAME             | REG_CLASS |
+------------+------------------+-----------+
| 2          | Neena Kochhar    |        10 |
| 3          | Lex De Haan      |         9 |
| 4          | Alexander Hunold |        11 |
+------------+------------------+-----------+
mysql> ROLLBACK;
mysql> select * from STUDENT;
+------------+------------------+-----------+
| STUDENT_ID | NAME             | REG_CLASS |
+------------+------------------+-----------+
| 2          | Neena Kochhar    |         8 |
| 3          | Lex De Haan      |         9 |
| 4          | Alexander Hunold |        11 |
+------------+------------------+-----------+
```

SAVEPOINT

- A SAVEPOINT is a point in a transaction when you can roll the transaction back to a certain point without rolling back the entire transaction.

```
SAVEPOINT SAVEPOINT_NAME;
```

```
SQL> SAVEPOINT SP1;
Savepoint created.

SQL> DELETE FROM CUSTOMERS WHERE ID=1;
1 row deleted.

SQL> SAVEPOINT SP2;
Savepoint created.

SQL> DELETE FROM CUSTOMERS WHERE ID=2;
1 row deleted.
```

```
SQL> SAVEPOINT SP3;
Savepoint created.

SQL> DELETE FROM CUSTOMERS WHERE ID=3;
1 row deleted.

SQL> ROLLBACK TO SP2;
Rollback complete.

SQL> RELEASE SAVEPOINT SP_3;
Savepoint removed.
```

The `SET` Transaction Command

- You can specify a transaction to be read only or read write.

```
SET TRANSACTION [ READ WRITE | READ ONLY ];
```

Unused slides

Not covered in this class

Concurrency Control by Validation

- Another type of **optimistic** concurrency control
- Maintains a record of what active transactions are doing
- Just before a transaction starts to write,
  it goes through a “validation phase”
- If a there is a risk of physically unrealizable behavior, the transaction is rolled back

Validation-based Scheduler

- Keep track of each transaction T's
  - Read set RS(T): the set of elements T read
  - Write set WS(T): the set of elements T write
- Execute transactions in three phases:
  1. **Read.** T reads all the elements in RS(T)
  2. **Validate.** Validate T by comparing its RS(T) an WS(T) with those in other transactions. If the validation fails, T is rolled back
  3. **Write.** T writes its values for the elements in WS(T)

Validation Rules

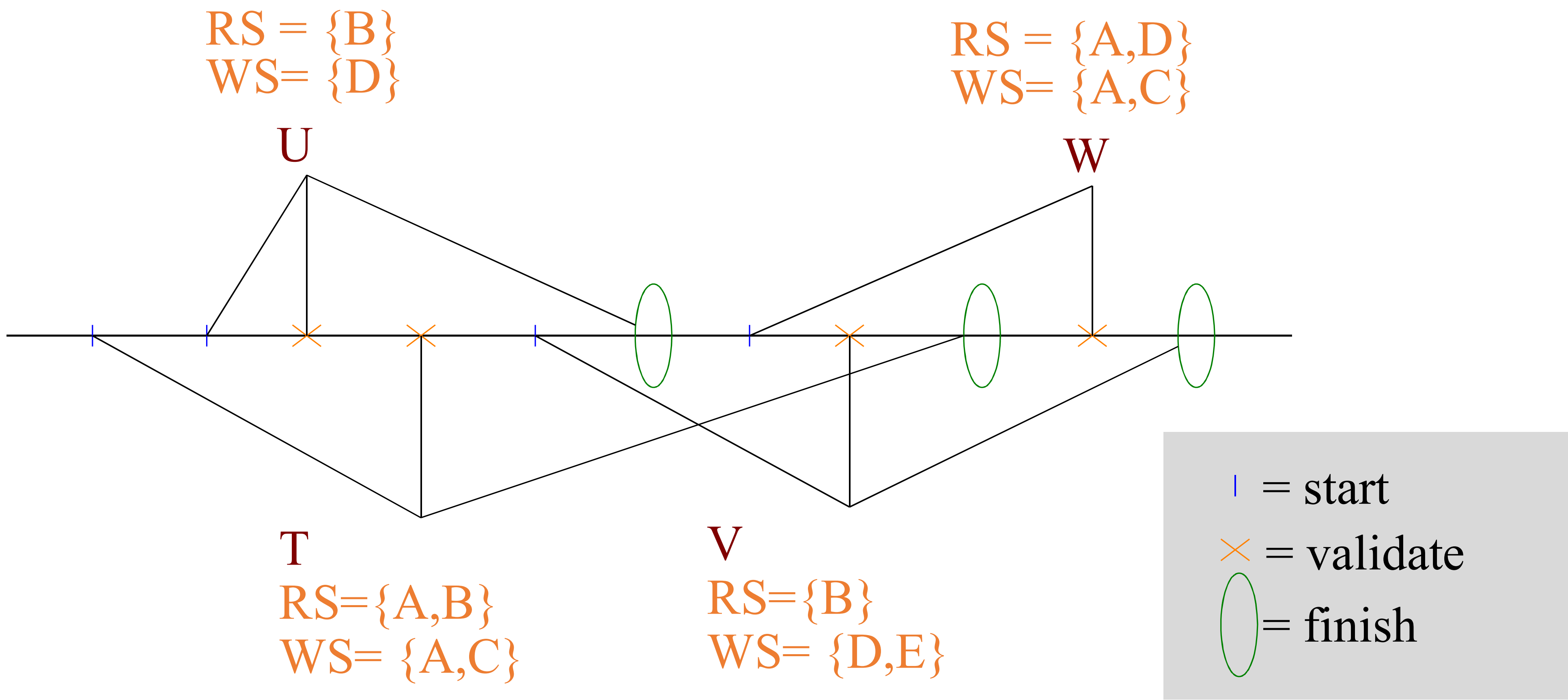
For each T,

- maintain $\langle T, START(T)\rangle$: set of transactions that have started but not yet completed validation.
- maintain $\langle T, START(T), VAL(T)\rangle$: set of transactions that have been validated, but not yet finished.
- maintain $\langle T, START(T), VAL(T), FIN(T)\rangle$: set of transactions that have completed.

To validate a transaction T,

1. Check that $RS(T) \cap WS(U) = \emptyset$ for any *validated* U and $START(T) < FIN(U)$.
2. Check that $WS(T) \cap WS(U) = \emptyset$ for any *validated* U that did not finish before T validated, i.e., if $VAL(T) < FIN(U)$.

Example



RS = {B}
WS= {D}
U
RS = {A,D}
WS= {A,C}
W
T
RS={A,B}
WS= {A,C}
V
RS={B}
WS= {D,E}
= start
= validate
= finish

Technique Choices in Commercial Systems

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