CSE 444: Database Internals

Section 6:
Transactions

Today

- Serializability and Conflict Serializability
  - Precedence graph
- Two-Phase Locking
  - Strict two phase locking
- Lab 3 Intro

Problem 1: Serializability and Locking

- Is this schedule conflict serializab

What is
- Serializability
- Conflict Serializability?

T_0	T_1
$R_0(A)$	
$W_0(A)$	
	$R_1(A)$
	$R_1(B)$
	C_1
$R_0(B)$	
$W_0(B)$	
C_0	

Review: (Conflict) Serializable Schedule

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

Example:

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

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

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

....

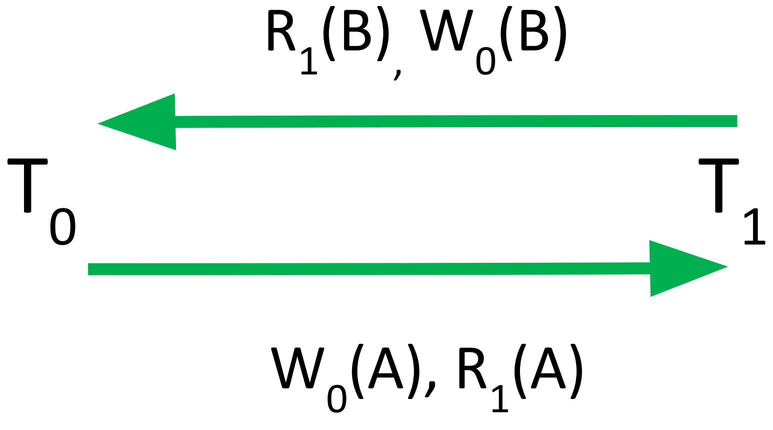
$r_1(A); w_1(A); r_1(B); w_1(B); r_2(A); w_2(A); r_2(B); w_2(B)$

Problem 1: Serializability and Locking

- Is this schedule conflict serializable?

T_0	T_1
$R_0(A)$	
$W_0(A)$	
	$R_1(A)$
	$R_1(B)$
	C_1
$R_0(B)$	
$W_0(B)$	
C_0	

- No.
- The **precedence graph** contains a cycle



- So, use 2PL ...
  - Original schedule below

T_0	T_1
$R_0(A)$	
$W_0(A)$	
	$R_1(A)$
	$R_1(B)$
	C_1
$R_0(B)$	
$W_0(B)$	
C_0	

- So, use 2PL ...
  - Original schedule below

What is
- Two Phase Locking
- Strict Two Phase Locking?

T_0	T_1
$R_0(A)$	
$W_0(A)$	
	$R_1(A)$
	$R_1(B)$
	C_1
$R_0(B)$	
$W_0(B)$	
C_0	

Review: (Strict) Two Phase Locking (2PL)

The 2PL rule:

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

Strict 2PL:

All locks held by a transaction are released when the transaction is completed

- Ensures that schedules are <u>recoverable</u>
  - Transactions commit only after all transactions whose changes they read also commit
- Avoids <u>cascading rollbacks</u>

- How can 2PL can ensure a conflict-serializable schedule?
  - Original schedule below

T_0	T_1
$R_0(A)$	
$W_0(A)$	
	$R_1(A)$
	$R_1(B)$
	C_1
$R_0(B)$	
$W_0(B)$	
C_0	

T_0	T_1
$L_0(A)$	
$R_0(A)$	
$W_0(A)$	

T_0	T_1
$L_0(A)$	
$R_0(A)$	
$W_0(A)$	
	$L_1(A)$: Block

T_0	T_1
L_0(A)	
R_0(A)	
W_0(A)	
	L_1(A) : Block
L_0(B)	
R_0(B)	
W_0(B)	
U_0(A)	
U_0(B)	
C_0	

T_0	T_1
$L_0(A)$	
$R_0(A)$	
$W_0(A)$	
	$L_1(A)$: Block
$L_0(B)$	
$R_0(B)$	
$W_0(B)$	
$U_0(A)$	
$U_0(B)$	
C_0	
	$L_1(A)$: Granted
	$R_1(A)$
	$L_1(B)$
	$R_1(B)$
	$U_1(A)$
	$U_1(B)$
	C_1

T_0	T_1
$L_0(A)$	
$R_0(A)$	
$W_0(A)$	
	$L_1(A)$: Block
$L_0(B)$	
$R_0(B)$	
$W_0(B)$	
$U_0(A)$	
$U_0(B)$	
C_0	
	$L_1(A)$: Granted
	$R_1(A)$
	$L_1(B)$
	$R_1(B)$
	$U_1(A)$
	$U_1(B)$
	C_1

Is this strict 2PL?

No, release locks after commit

- That example ended in a serial schedule, 2PL doesn't necessarily require that
  - Here's an example that doesn't become serial

T_0	T_1
$R_0(A)$	
$W_0(A)$	
	$R_1(A)$
	$R_1(B)$
	C_1
$R_0(B)$	
$W_0(B)$	
C_0	

T_0	T_1
$L_0(A)$	
$R_0(A)$	
$W_0(A)$	
$L_0(B)$	
$U_0(A)$	

If we get the lock on B first, we have completed the locking phase, and can start unlocking

T_0	T_1
$L_0(A)$	
$R_0(A)$	
$W_0(A)$	
$L_0(B)$	
$U_0(A)$	
	$L_1(A)$
	$R_1(A)$
	$L_1(B)$: Block

Allowing for interleaving can help performance

T_0	T_1
$L_0(A)$	
$R_0(A)$	
$W_0(A)$	
$L_0(B)$	
$U_0(A)$	
	$L_1(A)$
	$R_1(A)$
	$L_1(B)$: Block
$R_0(B)$	
$W_0(B)$	
$U_0(B)$	
C_0	

T_0	T_1
L_0(A)	
R_0(A)	
W_0(A)	
L_0(B)	
U_0(A)	
	R_1(A)
	L_1(B): Block
R_0(B)	
W_0(B)	
U_0(B)	
C_0	
	L_1(B): Granted
	R_1(B)
	U_1(A)
	U_1(B)
	C_1

We have unlocks in a transaction before committing, so this isn't strict 2 PL

Common 2PL Misconceptions

- Remember, only one transaction can hold a lock for an element at once
- In 2PL, within each transaction there must be a growing (lock acquiring phase) followed by a shrinking (unlocking) phase
  - Before unlocking, all locks must be be <u>granted</u>, not just requested
- Both 2PL and Strict 2PL ensure conflict serializability, neither guarantee a serial schedule or prevent deadlocks

Lab 3 - Transactions

- NO STEAL / FORCE buffer management policy
  - you shouldn't evict dirty (updated) pages from the buffer pool if they are locked by an uncommitted transaction. (this is **NO STEAL**)
  - on transaction commit, you should force dirty pages to disk (e.g., write the pages out) (this is **FORCE**)
- Recommend - locking at page level
  - you can acquire and release locks in BufferPool.getPage(), instead of adding calls to each of your operators
  - Might have to change previous implementations to access pages using BufferPool.getPage()

Lab 3 - Transactions (contd.)

- You need to implement **shared** and **exclusive** locks
  - Before read, it must have a shared lock or exclusive lock
  - Before write, it must have an exclusive lock
  - Multiple transactions can have a shared lock
  - Only one transaction may have an exclusive lock on an object
  - If transaction t is the only transaction holding a shared lock on an object o, t may upgrade its lock on o to an exclusive lock

- You need to implement **strict two-phase locking**
  - transactions should acquire the appropriate type of lock on any object before accessing that object
  - transaction shouldn't release any locks until after the transaction commits.

Lab 3 - Transactions (contd.)

- You will need to implement a [LockManager class](#) that will hold data structures to keep track of which locks each transaction holds and that check to see if a lock should be granted to a transaction when it is requested.
- Read about [Synchronization](#) in Java, and use the [synchronized](#) keyword in appropriate places in [LockManager](#)
- You will have to also throw appropriate exceptions like [TransactionAbortedException](#)

Lab 3 - Transactions (contd.)

Synchronized method:

Only one thread executing that method per instance

```
public synchronized void releaseLock()
```

```
public void acquireLock() {
    // wait for lock
    synchronized (this) {
        // update state
    }
}
```

Synchronized block:

Only one thread executing that block of code at one time

Usually used to update that object's state synchronously

Lab 3 - Transactions (contd.)

- Handling deadlocks
  - implement a simple timeout policy that aborts a transaction if it has not completed after a given period of time
  - implement a cycle-detection in a dependency graph data structure, if cycle exists when granting a new lock abort something.

- Design Choices:
  - Locking Granularity: page-level vs tuple-level (our tests assume page-level)
  - Deadlock Detection: timeout vs dependency graphs
  - Deadlock Resolution: aborting yourself vs aborting others

- Read the spec carefully for more details about various methods and edge cases.

Problem 2: Timestamp-based Concurrency Control

Timestamp-based Concurrency Control

- Some transaction, T.
- Some element (tuple/page), X.

- **TS**(T) - timestamp for transaction T
  - Stays constant for all of T's operations

- **WT**(X) – latest write timestamp for X
  - Set WT(X) = TS(T)

- **RT**(X) – latest read timestamp for X
  - Set RT(X) = TS(T)

- **C**(X) – X's value has been committed
  - 1 if true, 0 if not

Timestamp-based Concurrency Control

- **Actions for transaction T**
  - **Grant** a read/write request for a transaction
  - **Abort** (in case T violates physical reality – late actions)
  - **Delay** (make the Grant or Abort decision later)
    - When writing, the change is always tentative until we decide to commit. For this, we use a commit bit C to keep track if the transaction that last wrote X has committed
  - **Ignore** ***Thomas Write Rule*** – ignore outdated writes

Timestamp-based Concurrency Control - Four Rules

- **Rule 1**: **Read** request on X by T

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

  – TS(T) < WT(X), **abort**, (read too late)

  – TS(T) >= WT(X), physically realizable
    - If C = 1, **grant**, update RT(X)
    - If C = 0, **delay** T

Timestamp-based Concurrency Control - Four Rules

- **Rule 2**: **Write** request on X by T

START(T) … START(U) … $r_U(X)$ . . . $w_T(X)$

  – TS(T) < RT(X) (write too late)
    - **Abort**

– TS(T) >= RT(X), physically realizable

- TS(T) >= WT(X)
  – then **grant**, update WT(X), set C = 0 (as it's not committed yet)

START(T) … START(V) … $w_V(X)$ . . . $w_T(X)$

- TS(T) < WT(X)
  – If C = 1, **don't write X at all!** (***Thomas Write Rule*** – ignore outdated writes)
  – If C = 0, **delay**

Timestamp-based Concurrency Control - Four Rules

- **Rule 3**: **Commit** request by T
  - Set C = 1 for all X written by T
  - Allow waiting transactions to proceed
- **Rule 4**: **Abort** transaction T
  - Check if the waiting transactions can proceed now.

Summary

Transaction wants to READ element X

If $WT(X) > TS(T)$ then ROLLBACK
Else If $C(X)$ = false, then WAIT
Else READ and update $RT(X)$ to larger of $TS(T)$ or $RT(X)$

Transaction wants to WRITE element X

If $RT(X) > TS(T)$ then ROLLBACK
Else if $WT(X) > TS(T)$
Then If $C(X)$ = false then WAIT
else IGNORE write (Thomas Write Rule)
Otherwise, WRITE, and update $WT(X)=TS(T)$, $C(X)$=false

Timestamp-based Concurrency Control

Two transactions get started.

- Start(T_1) -> Start(T_2)

Timestamp-based Concurrency Control

What will happen at the last request?

- $S_{tart}(T_1)$ -> $S_{tart}(T_2)$ -> $R_{T1}(A)$ -> $R_{T2}(A)$ -> $W_{T1}(B)$ -> **$W_{T2}(B)$**

Timestamp-based Concurrency Control

What will happen at the last request?

- $S_{tart}(T_1)$ -> $S_{tart}(T_2)$ -> $R_{T1}(A)$ -> $R_{T2}(A)$ -> $W_{T1}(B)$ -> $\mathbf{W_{T2}(B)}$
  - **ACCEPTED**

Timestamp-based Concurrency Control

What will happen at the last request?

- $S_{tart}(T_1)$ -> $S_{tart}(T_2)$ -> $R_{T1}(A)$ -> $R_{T2}(A)$ -> $W_{T1}(B)$ -> $\mathbf{W_{T2}(B)}$
  - **ACCEPTED**

- $S_{tart}(T_1)$ -> $S_{tart}(T_2)$ -> $R_{T2}(A)$ -> $C_{ommit_{T2}}$ -> $R_{T1}(A)$ -> $\mathbf{W_{T1}(A)}$

Timestamp-based Concurrency Control

What will happen at the last request?

- $S_{tart}(T_1)$ -> $S_{tart}(T_2)$ -> $R_{T1}(A)$ -> $R_{T2}(A)$ -> $W_{T1}(B)$ -> $\mathbf{W_{T2}(B)}$
  - **ACCEPTED**

- $S_{tart}(T_1)$ -> $S_{tart}(T_2)$ -> $R_{T2}(A)$ -> $C_{ommit_{T2}}$ -> R_{T1} (A) -> $\mathbf{W_{T1}(A)}$
  - **ABORT** T_1 because $R_{T2}(A)$ precedes

Problem 2: Timestamp-based Concurrency Control

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$						

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$					

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$					

1. Physically realizable:
$TS(T_1) >= WT(X)$

2. C = 1: grant request

3. Update RT : $TS(T_1) > RT(X)$

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$					

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$					

1. Physically realizable: $TS(T_2) >= WT(X)$

2. C = 1: grant request

3. Update WT

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$						

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						

1. **NOT** Physically realizable:
$TS(T_1) < RT(X)$

Abort/rollback

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						
		$W_3(Y)$				

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						
		$W_3(Y)$			WT=3, C=0	

1. Physically realizable:
$TS(T_3) >= RT(Y)$ and $TS(T_3) >= WT(Y)$

2. Update WT and C (not committed yet)

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						
		$W_3(Y)$			WT=3, C=0	
	$W_2(Y)$					

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						
		$W_3(Y)$			WT=3, C=0	
	$W_2(Y)$: **delay**					

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						
		$W_3(Y)$			WT=3, C=0	
	$W_2(Y)$: **delay**					

1. Physically realizable:
$TS(T_2) >= RT(Y)$ although $TS(T_2) < WT(Y)$
2. We could not apply Thomas' write rule **(ignore $W_2(Y)$)** since C=0

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						
		$W_3(Y)$			WT=3, C=0	
	$W_2(Y)$: **delay**					
		C_3				

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						
		$W_3(Y)$			WT=3, C=0	
	$W_2(Y)$: **delay**					
		C_3			C=1	

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						
		$W_3(Y)$			WT=3, C=0	
	$W_2(Y)$: **delay**					
		C_3			C=1	

A later write by T_3 has been committed!

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
$R_1(X)$				RT=1		
	$R_2(X)$			RT=2		
	$W_2(X)$			WT=2, C=0		
$W_1(X)$: **abort**						
		$W_3(Y)$			WT=3, C=0	
	$W_2(Y)$: **delay**					
		C_3			C=1	
	Ignore $W_2(Y)$ and proceed					

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
	Ignore $W_2(Y)$ and **proceed**					
			$W_4(Z)$			

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
	Ignore $W_2(Y)$ and **proceed**					
			$W_4(Z)$			WT=4, C = 0

1. Physically realizable:
$TS(T_4)$ >= $RT(Z)$ and $TS(T_4)$ >= $WT(Z)$

2. Update WT and C (not committed yet)

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
	Ignore $W_2(Y)$ and **proceed**					
			$W_4(Z)$			WT=4, C = 0
			C_4			C=1

T1	T2	T3	T4	X	Y	Z
1	2	3	4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
	Ignore $W_2(Y)$ and **proceed**					
			$W_4(Z)$			WT=4, C = 0
			C_4			C=1
	$R_2(Z)$					

1. **NOT** Physically realizable: $TS(T_2) < WT(Z)$

Abort/rollback

			T4	X	Y	Z
			4	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
	d **proceed**					
			$W_4(Z)$			WT=4, C = 0
			C_4			C=1
	$R_2(Z)$: **abort**					

Timestamp-based Concurrency Control

Questions?

Multiversion Concurrency Control

- Maintains **old** versions of database elements in addition the current version in the database itself.
- The idea is to allow reads that would otherwise result in an abort (as the current version was written by future transaction)

Problem with Timestamp-Based Scheduling

T1	T2	T3	T4	A
150	200	175	225	RT = 0 WT = 0
$R_1(A)$				RT = 150
$W_1(A)$				WT = 150
	$R_2(A)$			RT = 200
	$W_2(A)$			WT = 200
		$R_3(A)$		
		Abort		
			$R_4(A)$	RT = 225

Had to abort because WT(A) is greater than my own timestamp

Would have been useful if I had access to an old version of A (from 150)…

Multiversion Timestamps

T1	T2	T3	T4	A_0	A_{150}	A_{225}
150	200	175	225	RT = 0 WT = 0		
$R_1(A)$				RT = 150		
$W_1(A)$					Create	
	$R_2(A)$				RT=200	
	$W_2(A)$					Create
		$R_3(A)$			RT=175	
			$R_4(A)$			RT=225

Don't have to abort

Just read a previous value of A