CompSci 516
Database Systems

Lecture 15
Transactions
– Concurrency Control

Instructor: Sudeepa Roy

Announcements

- HW2 deadline - Saturday, 10/21, 5 pm
  - submit on time
- Project midterm report deadline - Wednesday, 11/01, 11:55 pm
  - Keep working on your proposed project

Reading Material

- [RG]
  - Chapter 17.5.1, 17.5.3, 17.6
- [GUW]
  - Chapter 18.8, 18.9
  - Today's examples are from GUW (lecture slides will be sufficient for this class and exams)

Acknowledgement:
The following slides have been created adapting the instructor material of the [RG] book provided by the authors Dr. Ramakrishnan and Dr. Gehrke.

Today's topics

- Dynamic databases and Phantom problem (17.5.1)
- Multiple—granularity locking (17.5.3)
- Optimistic concurrency control (17.6.1)
- Timestamp-based concurrency control (17.6.2)
- Multi-version concurrency control (17.6.3)

Dynamic Database and Phantom Problem

Dynamic Databases

- If we relax the assumption that the DB is a fixed collection of objects
- Then even Strict 2PL will not assure serializability
- causes "Phantom Problem" in dynamic databases

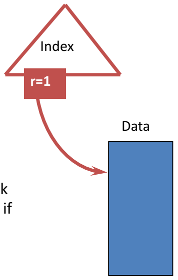
Example: Phantom Problem

- T1 wants to find oldest sailors in rating levels 1 and 2
  - Suppose the oldest at rating 1 has age 71
  - Suppose the oldest at rating 2 has age 80
  - Suppose the second oldest at rating 2 has age 63
- Another transaction T2 intervenes:
  - Step 1: T1 locks all pages containing sailor records with rating = 1, and finds oldest sailor (age = 71)
  - Step 2: Next, T2 inserts a new sailor onto a new page (rating = 1, age = 96)
  - Step 3: T2 locks pages with rating = 2, deletes oldest sailor with rating = 2 (age = 80), commits, releases all locks
  - Step 4: T1 now locks all pages with rating = 2, and finds oldest sailor (age = 63)
- No consistent DB state where T1 is "correct"
  - T1 found oldest sailor with rating = 1 before modification by T2
  - T1 found oldest sailor with rating = 2 after modification by T2

What was the problem?

- Conflict serializability guarantees serializability only if the set of objects is fixed
- Problem:
  - T1 implicitly assumed that it has locked the set of all sailor records with rating = 1
  - Assumption only holds if no sailor records are added while T1 is executing
  - Need some mechanism to enforce this assumption
- Index locking and predicate locking

Index Locking



- If there is a dense index on the rating field using Alt. (2), T1 should lock the index page containing the data entries with rating = 1
  - If there are no records with rating = 1, T1 must lock the index page where such a data entry would be, if it existed
- If there is no suitable index, T1 must lock all pages, and lock the file/table to prevent new pages from being added
  - to ensure that no new records with rating = 1 are added

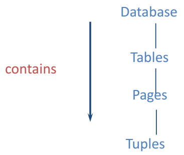
Predicate Locking

- Grant lock on all records that satisfy some logical predicate, e.g. rating = 1 or, age > 2*salary
- Index locking is a special case and an efficient implementation of predicate locking
  - e.g. Lock on the index pages for records satisfying rating = 1
- The general predicate locking has a lot of locking overhead and so not commonly used

Multiple-granularity Locking

DB Objects may contain other objects

- A DB contains several files
- A file is a collection of pages
- A page is a collection of records/tuples



Carefully choose lock granularity

- If a transaction needs most of the pages
  - set a lock on the entire file
  - reduces locking overhead
- If only a few pages are needed
  - lock only those pages
- Need to efficiently ensure no conflicts
  - e.g. a page should not be locked by T1 if T2 already holds the lock on the file

contains

Database
Tables
Pages
Tuples

New Lock Modes & Protocol

- Allow transactions to lock at each level, but with a special protocol using new "intention locks":
- Before locking an item (S or X), transaction must set "intention locks" (IS or IX) on all its ancestors
- For unlock, go from specific to general (i.e., bottom-up)
  - otherwise conflicting lock possible at root

contains

Database
Tables
Pages
Tuples

conflicting locks

	--	IS	IX	S	X
--	√	√	√	√	√
IS	√	√	√	√	🟥
IX	√	√	√	🟥	🟥
S	√	√	🟥	√	🟥
X	√	🟥	🟥	🟥	🟥

other tr. cannot have IX or X

other tr. cannot have any other lock

SIX mode = S + IX

- Common situation: a transaction needs to read an entire file and modify a few records
  - S lock
  - IX lock (to subsequently lock) some containing objects in X mode
- Obtain a SIX lock
  - conflict with either S or IX

conflicting locks

	--	IS	IX	S	X
--	√	√	√	√	√
IS	√	√	√	√	🟥
IX	√	√	√	🟥	🟥
S	√	√	🟥	√	🟥
X	√	🟥	🟥	🟥	🟥

other tr. cannot have IX or X

other tr. cannot have any other lock

Transaction in SQL

- SET TRANSACTION ISOLATION LEVEL READ UNCOMMITTED [;]
- BEGIN TRANSACTION
- <.... SQL STATEMENTS>
- COMMIT or ROLLBACK
- Four isolation levels : performance and serializability

	Dirty Read	Unrepeatable Read	Phantom
READ UNCOMMITTED	Maybe	Maybe	Maybe
READ COMMITTED	No	Maybe	Maybe
REPEATABLE READS	No	No	Maybe
SERIALIZABLE	No	No	No

Approaches to CC other than locking

Approaches to Concurrency Control (CC)

- Lock-based CC
  - (so far)
- Optimistic CC
  - today
- Time-stamp-based CC
  - today
- Multi-version CC
  - today

uses "timestamps" in some way

Timestamp

- Each transaction gets a unique timestamp
- e.g.
  - system's clock value when it is issued by the scheduler (assume one transactions issued on one tick of the clock)
  - or a unique number given by a counter (incremented after each transaction)

Locking is a "pessimistic or conservative" approach to CC

- Locking is a conservative approach in which conflicts are prevented
- Either uses "blocking" (delay) or abort
  - note the several usages of a "block"!
- Disadvantages of locking:
  - Lock management overhead
  - Deadlock detection/resolution
  - Lock contention for heavily used objects
- If only light contention for data objects, still the overhead of following a locking protocol is paid

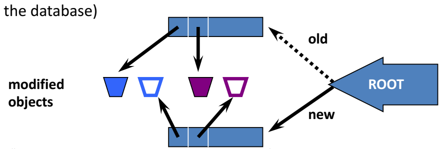
Optimistic CC

A second approach to CC: Optimistic CC (Kung-Robinson)

- If conflicts are rare, we might be able to gain concurrency by not locking, and instead checking for conflicts before transactions commit
- Premise:
  - most transactions do not conflict with other transactions
  - be as permissive as possible in allowing transactions to execute

Kung-Robinson Model

- Transactions have three phases:
  1. **READ:** Read from the database, but make changes to "private copies" of objects (assume private workspace)
  2. **VALIDATE:** When decide to commit, also check for conflicts with concurrently executing transactions
     - if a possible conflict, abort, clear private workspace, restart
  3. **WRITE:** If no conflict, make local copies of changes public (copy them into the database)



Validation

- Test conditions that are sufficient to ensure that no conflict occurred
- Each transaction T_i is assigned a numeric id
  - Use a timestamp $TS(T_i)$
- Transaction ids assigned at end of READ phase, just before validation begins
- Validation checks whether the timestamp ordering has an equivalent serial order

Notation

- TS(T_i): Transaction id or timestamp of T_i BEFORE the validation step starts
- ReadSet(T_i): Set of objects read by transaction T_i
- WriteSet(T_i): Set of objects modified by transaction T_i

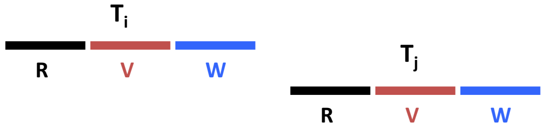
next, three tests used for validation

Validation Tests

- To validate T_j
  - for each committed transactions T_i
  - such that TS(T_i) < TS(T_j)
  - one of the three validation tests (TEST 1, TEST 2, TEST 3) must be satisfied
  - (see the tests next)
- Ensures that T_j-s modifications are not visible to the previous transaction T_i
- Check yourself: No RW, WR, WW conflicts if any of these tests satisfy

Test 1

- For all i and j such that TS(T_i) < TS(T_j), check that T_i completes (all three phases) before T_j begins

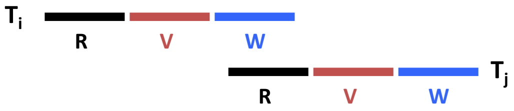


- T_j sees some changes by T_i
- But they execute completely in serial order

Test 2

figure not exactly correct since V and W steps cannot overlap

- For all i and j such that TS(T_i) < TS(T_j), check that:
  - T_i completes before T_j begins its Write phase +
  - WriteSet(T_i) ∩ ReadSet(T_j) is empty



Does T_j read dirty data? Does T_i overwrite T_j's writes?

- Allows T_j to read objects while T_i is still modifying objects
- But no conflict because T_j does not read any object modified by T_i
- T_j can overwrite some writes by T_i (ok since T_j starts later)

Test 3

figure not exactly correct since V and W steps cannot overlap

- For all i and j such that T_i < T_j, check that:
  - T_i completes Read phase before T_j completes its Read +
  - WriteSet(T_i) ∩ ReadSet(T_j) is empty **+**
  - WriteSet(T_i) ∩ WriteSet(T_j) is empty

i.e. T_i does not write any object that T_j reads or writes

Does T_j read dirty data? Does T_i overwrite T_j's writes?

- Allows T_i and T_j write objects at the same time
- More overlap than Test 2
- But the sets of objects written cannot overlap

Comments on Serial Validation

- List of objects written/read by each transaction has to be maintained
- While one transaction is validating, no transaction can commit
  - otherwise some conflicts may be missed
- Assignment of transaction id, validation, and the Write phase are inside a critical section
  - i.e., Nothing else goes on concurrently
  - If Write phase is long, major drawback
- The write phase of a validated transactions must be completed before other tr. s are validated
  - i.e. changes should be reflected to the DB from private workspace
- Optimization for Read-only transactions:
  - Don't need critical section (because there is no Write phase)

Overheads in Optimistic CC

- Must record read/write activity in ReadSet and WriteSet per transaction
  - Must create and destroy these sets as needed
- Must check for conflicts during validation, and must make validated writes ``global''
  - Critical section can reduce concurrency
- Optimistic CC restarts transactions that fail validation
  - Work done so far is wasted; requires clean-up

Optimistic CC vs locking

- If there are few conflicts and validation is efficient
  - optimistic CC is better than locking
- If many conflicts
  - cost of repeatedly restarting transactions hurts performance significantly

Timestamp-based CC

A third approach to CC

So far…

- Lock-based CC
  - conflicting actions of different transactions are ordered by the order in which locks are obtained
  - locking protocols ensure serializability
- Optimistic CC
  - A timestamp ordering is imposed on transactions
  - Validation checks that all conflicting transactions occurred in the same order
- Next: Timestamp-based CC
  - another use of timestamp

Timestamp CC

Main Idea:

- Give each object O
  - a read-timestamp RT(O), and
  - a write-timestamp WT(O)
    - RG uses RTS/WTS, GUW uses RT/WT, either of these is fine
- Give each transaction T
  - a timestamp TS(T) when it begins
- If
  - action ai of Ti conflicts with action aj of Tj,
  - and TS(Ti) < TS(Tj)
- then
  - ai must occur before aj
- Otherwise, abort and restart violating transaction

Request for a read: $R_T(X)$

1. If TS(T) >= WT(X)
   - last written by a previous transaction –- *OK (i.e. "physically realizable")*
   - If C(X) is true –- *check if previous transaction has committed*
     - Grant the read request by T
     - if TS(T) > RT(X)
       - set RT(X) = TS(T)
   - If C(X) is false
     - Delay T until C(X) becomes true, or the transaction that wrote X aborts
2. If TS(T) < WT(X)
   - write is not realizable -- already *written by a later trans.*
   - Abort (or, Rollback) T --*i.e. abort and restart with a larger timestamp*

Request for a write: $W_T(X)$

1. If TS(T) >= RT(X) and TS(T) >= WT(X)
   - last written/read by a previous transaction – *OK*
   - Grant the write request by T
     - write the new value of X
   - Set WT(X) = TS(T)
   - Set C(X) = false   -- *T not committed yet*
2. If TS(T) >= RT(X) but TS(T)< WT(X)
   - write is still realizable –-*but already a later value in X*
   - If C(X) is true
     - previous writer of X has committed
     - simply ignore the write request by T
     - but allow T to proceed without making changes to the database
   - If C(X) is false
     - Delay T until C(X) becomes true, or the transaction that wrote X aborts

- If TS(T) < RT(X)
  - write is not realizable   -- *already read by a later transaction*
  - Abort (or, Rollback) T

Thomas Write Rule

- If TS(T) < WT(O) and a write request comes
  - violates timestamp order of T w.r.t. writer of O

Thomas Write Rule:

- But we can safely ignore such outdated writes
- no need to restart T
- T's write is effectively followed by another write, with no intervening reads
- Allows some serializable, but NOT conflict serializable schedules

Timestamp CC and Recoverability

Without "block or delay", unrecoverable schedules are allowed:

- TS(T1) = 1
- TS(T2) = 2

T1 (1)	T2 (2)
W(A); WT(A)=1	
	R(A): RT(A)=2 **W(B): WT(B)=2** **Commit**

- Timestamp CC with "delays" allows only recoverable schedules:
  - "Block" readers T (where TS(T) > WT(O)) until writer of O commits
  - **a full example from GUW next**
- Similar to writers holding X locks until commit, but still not quite 2PL

Example

- Three transactions T1 (TS = 200), T2 (TS = 150), T3 (TS = 175)
- Three objects A, B, C
  - initially all have RT = WT = 0, C = 1 (i.e. true)
- Sequence of actions
  - $R_1(B)$, $R_2(A)$, $R_3(C)$, $W_1(B)$, $W_1(A)$, $W_2(C)$, $W_3(A)$
- Q. What is the state of the database at the end if the timestamp-based CC protocol is followed
  - i.e. report the RT, WT, C

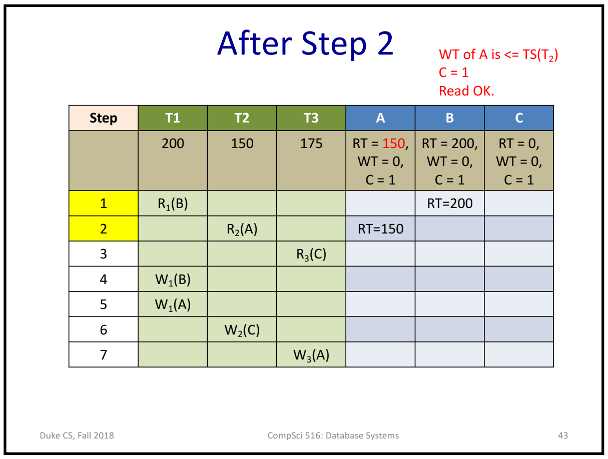
Initial condition and Steps

Step	T1	T2	T3	A	B	C
	200	150	175	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
1	$R_1(B)$					
2		$R_2(A)$				
3			$R_3(C)$			
4	$W_1(B)$					
5	$W_1(A)$					
6		$W_2(C)$				
7			$W_3(A)$			

After Step 1

WT of B is <= $TS(T_1)$
C = 1
Read OK.

Step	T1	T2	T3	A	B	C
	200	150	175	RT = 0, WT = 0, C = 1	RT = 200, WT = 0, C = 1	RT = 0, WT = 0, C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$				
3			$R_3(C)$			
4	$W_1(B)$					
5	$W_1(A)$					
6		$W_2(C)$				
7			$W_3(A)$			

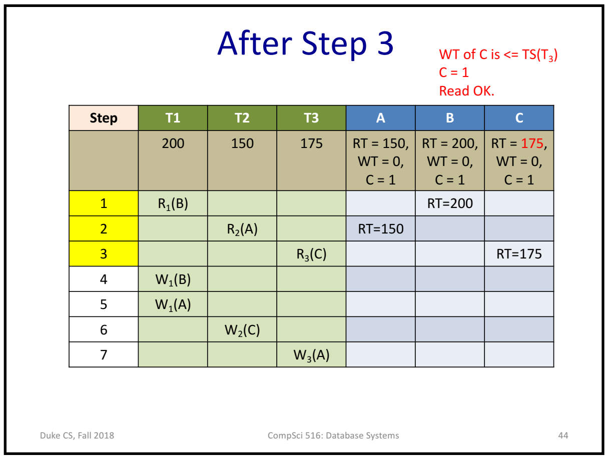


After Step 2

WT of A is <= TS(T_2)
C = 1
Read OK.

Step	T1	T2	T3	A	B	C
	200	150	175	RT = 150, WT = 0, C = 1	RT = 200, WT = 0, C = 1	RT = 0, WT = 0, C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(C)$			
4	$W_1(B)$					
5	$W_1(A)$					
6		$W_2(C)$				
7			$W_3(A)$			

Duke CS, Fall 2018 CompSci 516: Database Systems 43

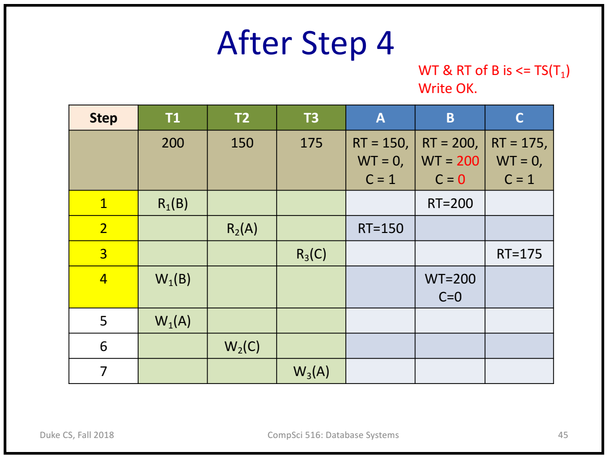


After Step 3

WT of C is <= TS(T_3)
C = 1
Read OK.

Step	T1	T2	T3	A	B	C
	200	150	175	RT = 150, WT = 0, C = 1	RT = 200, WT = 0, C = 1	RT = 175, WT = 0, C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(C)$			RT=175
4	$W_1(B)$					
5	$W_1(A)$					
6		$W_2(C)$				
7			$W_3(A)$			

Duke CS, Fall 2018 CompSci 516: Database Systems 44

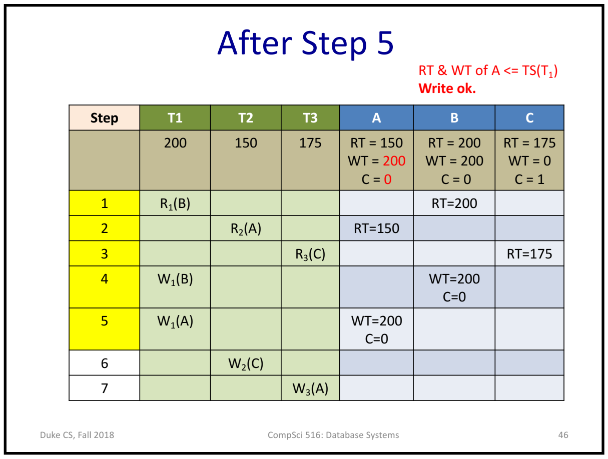


After Step 4

WT & RT of B is <= TS(T_1)
Write OK.

Step	T1	T2	T3	A	B	C
	200	150	175	RT = 150, WT = 0, C = 1	RT = 200, WT = 200 C = 0	RT = 175, WT = 0, C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(C)$			RT=175
4	$W_1(B)$				WT=200 C=0	
5	$W_1(A)$					
6		$W_2(C)$				
7			$W_3(A)$			

Duke CS, Fall 2018 CompSci 516: Database Systems 45

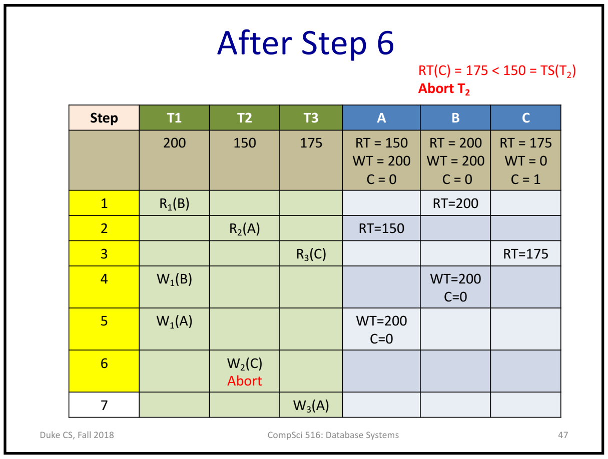


After Step 5

RT & WT of A <= TS(T_1)
Write ok.

Step	T1	T2	T3	A	B	C
	200	150	175	RT = 150 WT = 200 C = 0	RT = 200 WT = 200 C = 0	RT = 175 WT = 0 C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(C)$			RT=175
4	$W_1(B)$				WT=200 C=0	
5	$W_1(A)$			WT=200 C=0		
6		$W_2(C)$				
7			$W_3(A)$			

Duke CS, Fall 2018 CompSci 516: Database Systems 46

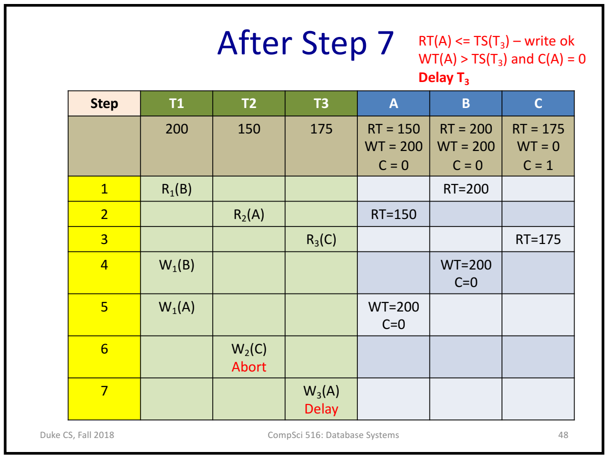


After Step 6

RT(C) = 175 < 150 = TS(T_2)
Abort T_2

Step	T1	T2	T3	A	B	C
	200	150	175	RT = 150 WT = 200 C = 0	RT = 200 WT = 200 C = 0	RT = 175 WT = 0 C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(C)$			RT=175
4	$W_1(B)$				WT=200 C=0	
5	$W_1(A)$			WT=200 C=0		
6		$W_2(C)$ Abort				
7			$W_3(A)$			

Duke CS, Fall 2018 CompSci 516: Database Systems 47



After Step 7

RT(A) <= TS(T_3) – write ok
WT(A) > TS(T_3) and C(A) = 0
Delay T_3

Step	T1	T2	T3	A	B	C
	200	150	175	RT = 150 WT = 200 C = 0	RT = 200 WT = 200 C = 0	RT = 175 WT = 0 C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(C)$			RT=175
4	$W_1(B)$				WT=200 C=0	
5	$W_1(A)$			WT=200 C=0		
6		$W_2(C)$ Abort				
7			$W_3(A)$ Delay			

Duke CS, Fall 2018 CompSci 516: Database Systems 48

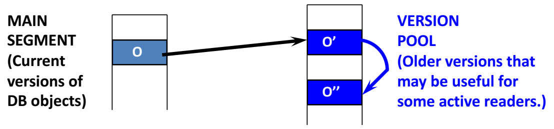
Multiversion CC

A fourth approach to CC

- Multiversion CC
  - another way of using timestamps
  - ensures that a transaction never has to be restarted (aborted) to read an object
    - unlike timestamp-based CC
- The idea is to make several copies of each DB object
  - each copy of each object has a write timestamp
- Ti reads the most recent version whose timestamp precedes TS(Ti)

Multiversion Timestamp CC

- Idea: Let writers make a "new" copy while readers use an appropriate "old" copy:



MAIN SEGMENT (Current versions of DB objects)

VERSION POOL (Older versions that may be useful for some active readers.)

Readers are always allowed to proceed
- But may be "blocked" until writer commits.

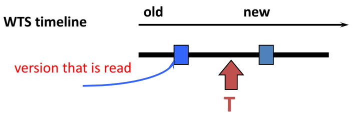
Multiversion CC (Contd.)

- Each version of an object has
  - its writer's TS as its WT, and
  - the timestamp of the transaction that most recently read this version as its RT
- Versions are chained backward
  - we can discard versions that are "too old to be of interest"
- Each transaction is classified as Reader or Writer.
  - Writer may write some object; Reader never will
  - Transaction declares whether it is a Reader when it begins

---

Reader Transaction

- For each object to be read:
  - Finds newest version with WT < TS(T)
  - Starts with current version in the main segment and chains backward through earlier versions
  - Update RT if necessary (i.e. if TS(T) > RT, then RT = TS(T))
- Assuming that some version of every object exists from the beginning of time, Reader transactions are never restarted
  - However, might block until writer of the appropriate version commits



Writer Transaction

- To read an object, follows reader protocol
- To write an object:
  - must make sure that the object has not been read by a "later" transaction
  - Finds newest version V s.t. WT(V) <= TS(T).
- If RT(V) <= TS(T)
  - T makes a copy CV of V, with a pointer to V, with WT(CV) = TS(T), RT(CV) = TS(T)
  - Write is buffered until T commits; other transactions can see TS values but can't read version CV
- Else
  - reject write

Example

- Four transactions T1 (TS = 150), T2 (TS = 200), T3 (TS = 175), T4(TS = 225)
- One object A
  - Initial version is A_0
- Sequence of actions
  - $R_1(A)$, $W_1(A)$, $R_2(A)$, $W_2(A)$, $R_3(A)$, $R_4(A)$
- Q. What is the state of the database at the end if the multiversion CC protocol is followed

Initial condition and Steps

A_0 existed before the transactions started

Step	T1	T2	T3	T4	A_0		
	150	200	175	225	RT=0, WT=0		
1	$R_1(A)$						
2	$W_1(A)$						
3		$R_2(A)$					
4		$W_2(A)$					
5			$R_3(A)$				
6				$R_4(A)$			

After Step 1

A_0 is the newest version with WT <= $TS(T_1)$
Read A_0

Step	T1	T2	T3	T4	A_0		
	150	200	175	225	RT=0, WT=0		
1	$R_1(A)$				Read RT = 150		
2	$W_1(A)$						
3		$R_2(A)$					
4		$W_2(A)$					
5			$R_3(A)$				
6				$R_4(A)$			

After Step 2

- A_0 is the newest version with WT <= $TS(T_1)$
- $RT(A_0)$ <= $TS(T_1)$
- Create a new version A_{150}
- Set its WT, RT to $TS(T_1)$ = 150 (A_{150} named accordingly)

Step	T1	T2	T3	T4	A_0	A_{150}	
	150	200	175	225	RT=150 WT=0	RT=150 WT=150	
1	$R_1(A)$				Read RT = 150		
2	$W_1(A)$					Create RT=150 WT=150	
3		$R_2(A)$					
4		$W_2(A)$					
5			$R_3(A)$				
6				$R_4(A)$			

After Step 3

- A_{150} is the newest version with WT <= $TS(T_2)$
- Read A_{150}
- Update RT

Step	T1	T2	T3	T4	A_0	A_{150}	
	150	200	175	225	RT=150 WT=0	RT=200 WT=150	
1	$R_1(A)$				Read		
2	$W_1(A)$					Create RT=150 WT=150	
3		$R_2(A)$				Read RT=200	
4		$W_2(A)$					
5			$R_3(A)$				
6				$R_4(A)$			

After Step 4

- A_{150} is the newest version with WT <= $TS(T_2)$
- $RT(A_{150})$ <= $TS(T_2)$
- Create a new version A_{200}
- Set its WT, RT to $TS(T_2)$ = 200 (A_{200} named accordingly)

Step	T1	T2	T3	T4	A_0	A_{150}	A_{200}
	150	200	175	225	RT=150 WT=0	RT=200 WT=150	RT=200 WT=200
1	$R_1(A)$				Read		
2	$W_1(A)$					Create RT=150 WT=150	
3		$R_2(A)$				Read RT=200	
4		$W_2(A)$					Create RT=200 WT=200
5			$R_3(A)$				
6				$R_4(A)$			

After Step 5

- A_{150} is the newest version with WT <= $TS(T_3)$
- Read A_{150}
- DO NOT Update RT

Step	T1	T2	T3	T4	A_0	A_{150}	A_{200}
	150	200	175	225	RT=150 WT=0	RT=200 WT=150	RT=200 WT=200
1	$R_1(A)$				Read		
2	$W_1(A)$					Create RT=150 WT=150	
3		$R_2(A)$				Read RT=200	
4		$W_2(A)$					Create RT=200 WT=200
5			$R_3(A)$			Read	
6				$R_4(A)$			

After Step 6

- A_{200} is the newest version with WT <= $TS(T_4)$
- Read A_{200}
- Update RT

Step	T1	T2	T3	T4	A_0	A_{150}	A_{200}
	150	200	175	225	RT=150 WT=0	RT=200 WT=150	RT=225 WT=200
1	$R_1(A)$				Read		
2	$W_1(A)$					Create RT=150 WT=150	
3		$R_2(A)$				Read RT=200	
4		$W_2(A)$					Create RT=200 WT=200
5			$R_3(A)$			Read	
6				$R_4(A)$			Read RT=225

Summary

- "Phantom Problem" and why serializability/2PL fails
- New requirements and mechanisms for multiple-granularity locks
- Note the key ideas for three timestamp-based alternative approaches (to Lock-based approaches) to CC
  - Optimistic: validation tests
  - Timestamp: RT(O) & WT(O) on each object O
  - Multiversion: multiple versions of each object O with different WT and RT
- Note: a new action (block or delay) in addition to commit or abort