CompSci 516
Data Intensive Computing Systems

Lecture 15
Transactions
– Concurrency Control

Instructor: Sudeepa Roy

Announcements

- No class on 3/15 and 3/17 (spring break)
  - there is a class this Thursday 3/10 before the break
- HW3 due after spring break
  - 03/23 (Wed), 11:55 pm
  - Note that the main goal is NOT to solve the problems or to learn a new language..
  - …but to learn a new framework (MapReduce with inbuilt Map and Reduce functions) with some simple tasks
  - it can be useful when you are dealing with "BIG DATA" (e.g. Twitter data), and running complex (even simple) tasks on multiple machines

Reading Material

- [RG]
  - Chapter 17.5.1, 17.5.3, 17.6
- [GUW]
  - Chapter 18.8, 18.9

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

What we learnt in Lectures 12 and 13

- Transaction
  - $R_1(A)$, $W_2(A)$, ….
  - Commit C_1, abort A_1
  - Lock/unlock: $S_1(A)$, $X_1(A)$, $US_1(A)$, $UX_1(A)$
- ACID properties
  - what they mean, whose responsibility to maintain each of them
- Conflicts: RW, WR, WW
- 2PL/Strict 2PL
  - all lock acquires have to precede all lock releases
  - Strict 2PL: release X locks only after commit or abort

What we learnt in Lectures 12 and 13

- Serial schedule
- Serializable schedule (why do we need them?)
- Conflicting actions
- Conflict-equivalent schedules
- Conflict-serializable schedule
- View-serializable schedule (relaxation)
- Conflict Serializability => View Serializability => Serializability
- Recoverable schedules

What we learnt in Lectures 12 and 13

- Dependency (or Precedence) graphs
  - their relation to conflict serializability (by acyclicity)
  - their relation to Strict 2PL
- Lock management basics
- Deadlocks
  - detection
    - waits-for graph has cycle, or timeout
    - what to do if deadlock is detected
  - prevention
    - wait-die and wound-wait

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
- even Strict 2PL will not assure serializability

Dynamic Databases

- If we relax the assumption that the DB is a fixed collection of objects
- Then even Strict 2PL will not assure serializability
- ”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

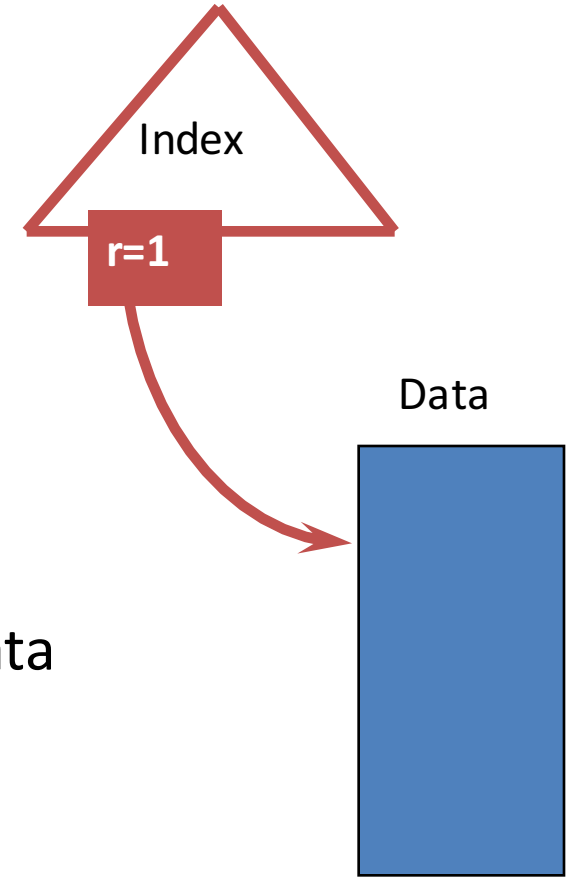
What was the problem?

- 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

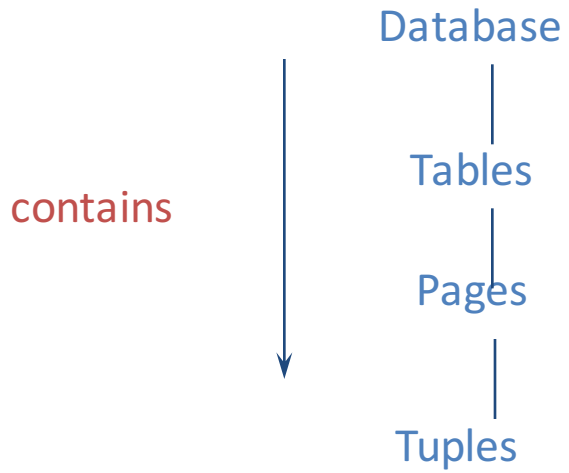
Predicate Locking

- 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

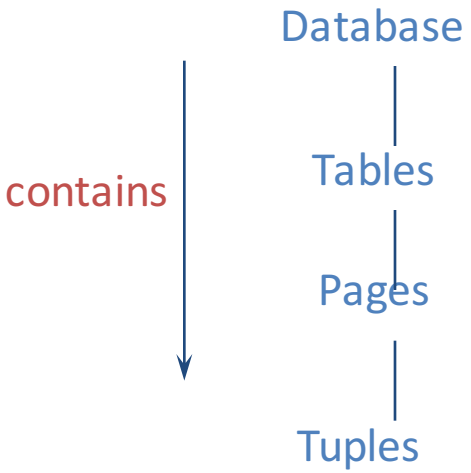
DB Objects may contain other objects

- 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

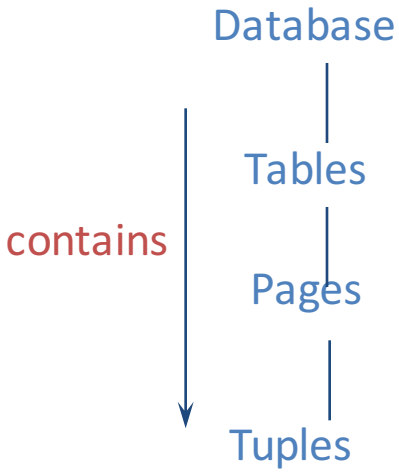
- Need to efficiently ensure no conflicts
  - e.g. a page should not be locked by T1 if T2 already holds the lock on the file

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



other tr. cannot have IX or X

other tr. cannot have any other lock

conflicting locks

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

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

other tr. cannot have IX or X

other tr. cannot have any other lock

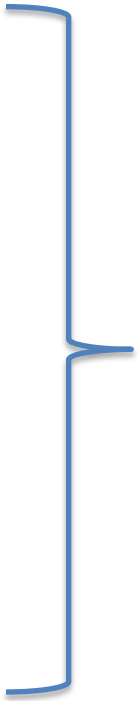
conflicting locks

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

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 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

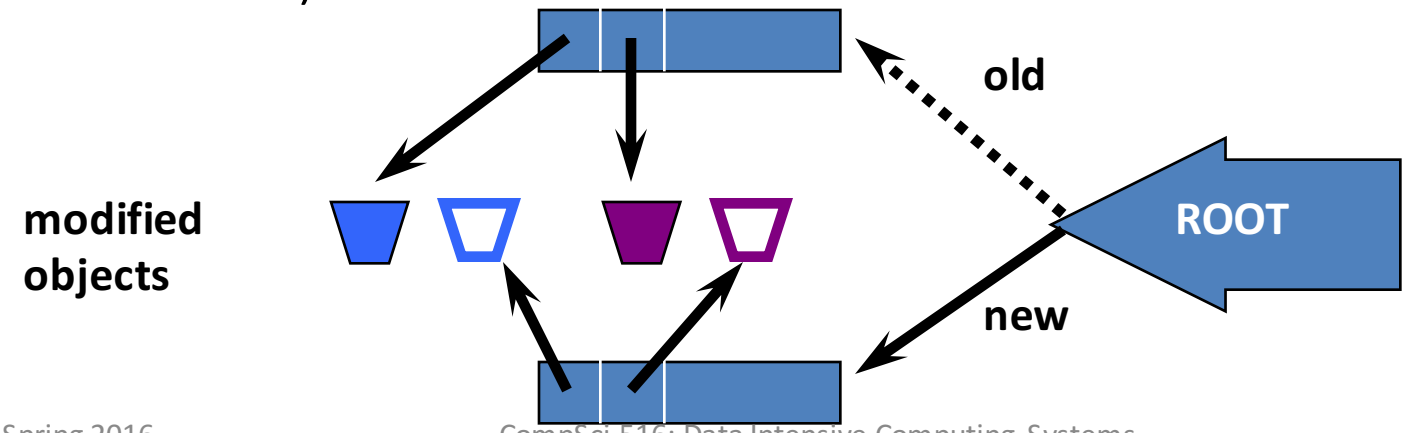
A second approach to CC: Optimistic CC (Kung-Robinson)

- 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 Ti is assigned a numeric id
  - Use a timestamp TS(Ti)
- 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(Ti): Transaction id or timestamp of Ti
  BEFORE the validation step starts

- ReadSet(Ti): Set of objects read by transaction Ti

- WriteSet(Ti): Set of objects modified by transaction Ti

next, three tests used for validation

Validation Tests

- To validate Tj
  - for each committed transactions Ti
  - such that TS(Ti) < TS(Tj)
  - one of the three validation tests (TEST 1, TEST 2, TEST 3) must be satisfied
  - (see the tests next)

- Ensures that Tj-s modifications are not visible to Ti

- Check yourself: No RW, WR, WW conflicts if any of these tests satisfy

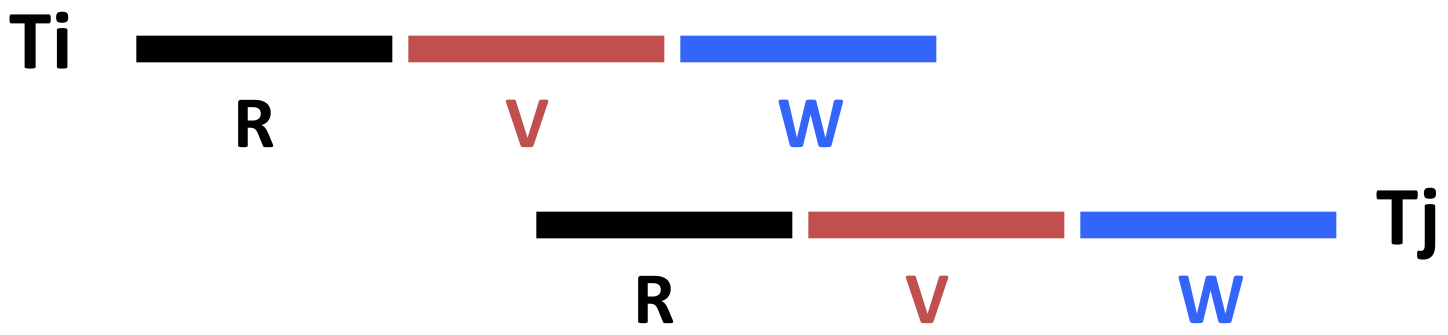
Test 1

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

- Tj sees some changes by Ti
- But they execute completely in serial order

Test 2

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



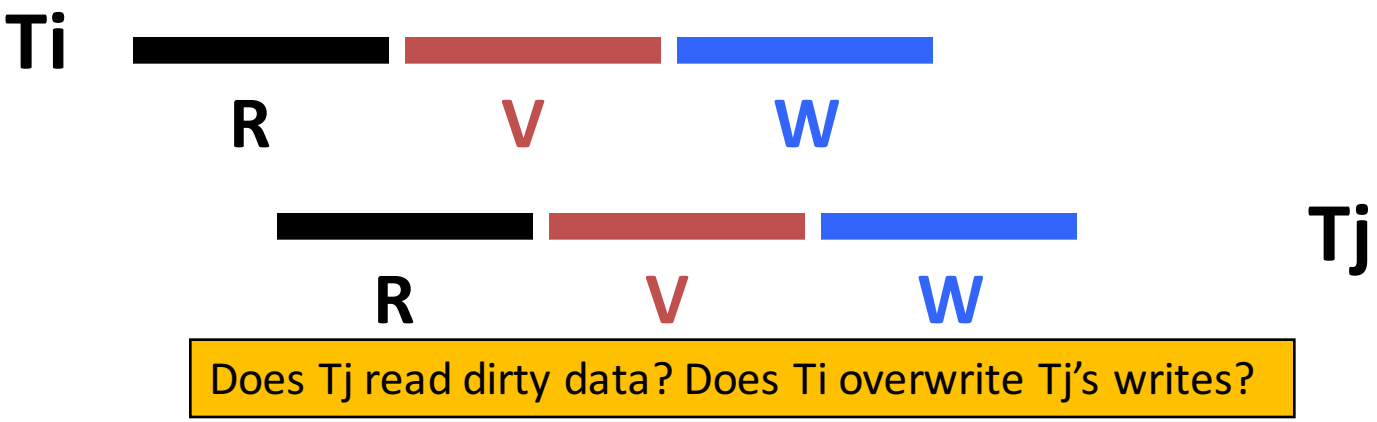
Does Tj read dirty data? Does Ti overwrite Tj's writes?

- Allows Tj to read objects while Ti is still modifying objects
- But no conflict because Tj does not read any object modified by Ti
- Tj can overwrite some writes by Ti

Test 3

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

i.e. Ti does not write any object that Tj reads or writes



- Allows Ti and Tj 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, any 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

When T wants to read Object O

- If TS(T) < WT(O)
  - this violates timestamp order of T w.r.t. writer of O
  - So, abort T and restart it with a new, larger TS
  - Note: If restarted with same TS, T will fail again
    - Revisit: Contrast use of timestamps in 2PL for deadlock prevention (same timestamps were used)
- If TS(T) > WT(O):
  - Allow T to read O
  - Reset RT(O) to max(RT(O), TS(T))
- Change to RT(O) on reads must be written to disk
  - This and restarts represent overheads

When T wants to Write Object O

- If TS(T) < RT(O)
  - this violates timestamp order of T w.r.t. writer of O
  - abort and restart T
- If TS(T) < WT(O)
  - violates timestamp order of T w.r.t. writer of O
  - Naïve approach: abort and restart T
    - (Better approach: use Thomas Write Rule (next))
- Else
  - allow T to write O

Thomas Write Rule

- If TS(T) < WT(O)
  - 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

A Serializable schedule that is not conflict-serializable

S1

```
T1: R(A)        W(A)
T2:      W(A)
T3:                   W(A)
```

S2

```
T1: R(A),W(A)
T2:              W(A)
T3:                   W(A)
```

Timestamp CC and Recoverability

Unfortunately, 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 can be modified to allow only recoverable schedules:
  - Buffer all writes until writer commits (but update WT(O) when the write is allowed.)
  - "Block" readers T (where TS(T) > WT(O)) until writer of O commits
  - **a full example from GUW in the next lecture**
- Similar to writers holding X locks until commit, but still not quite 2PL

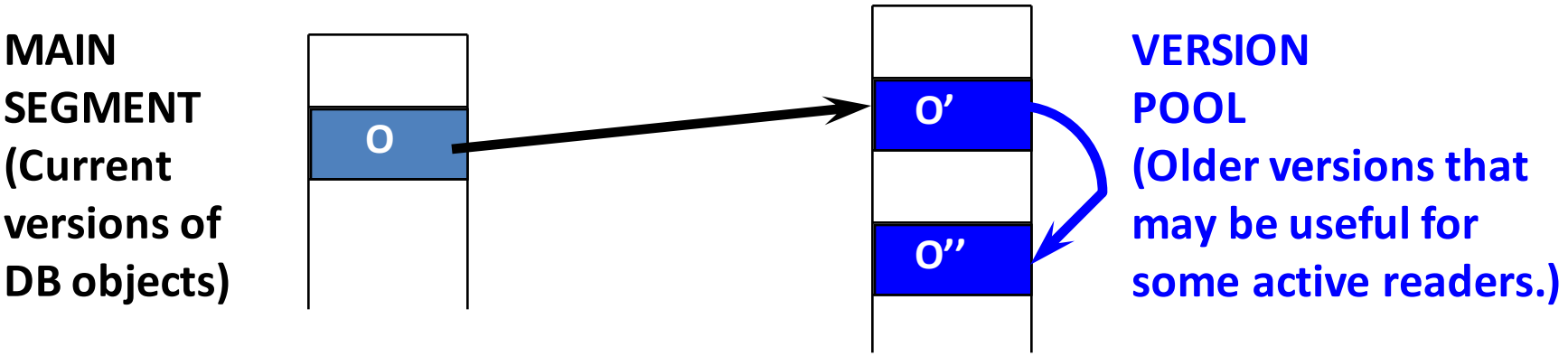
Multiversion CC

A fourth approach to CC

- Multiversion CC
  - another way of using timestamps
  - ensures that a transaction never has to wait to read an object
- 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:



Readers are always allowed to proceed

- But may be "blocked" until writer commits.

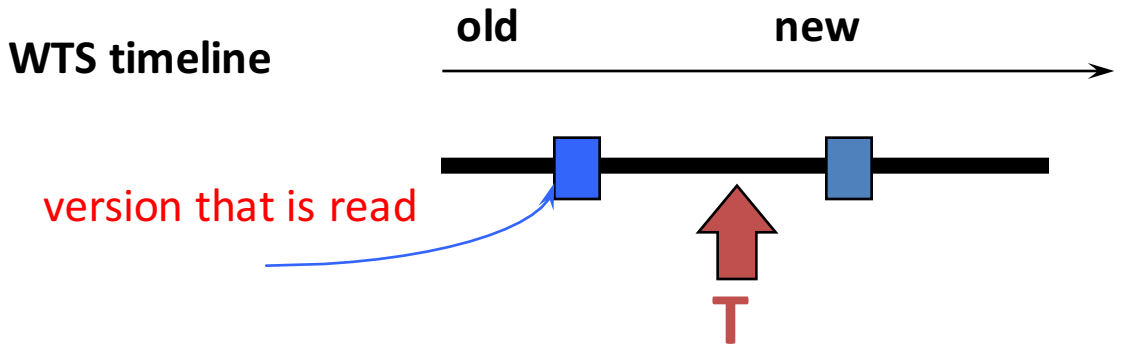
Multiversion CC (Contd.)

- 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

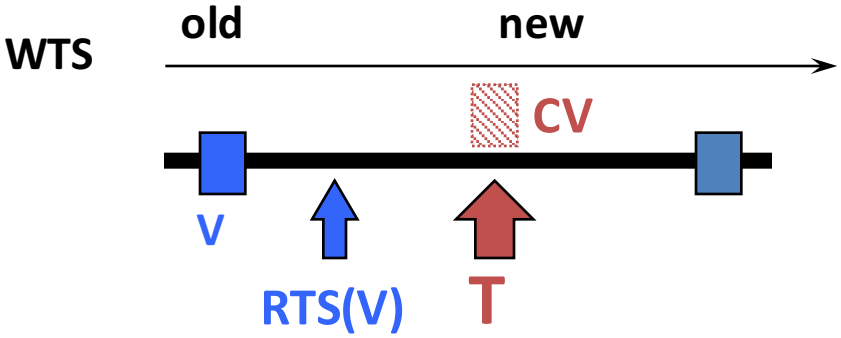
- For each object to be read:
  - Finds newest version with WT < TS(T)
  - Starts with current version in the main segment and chains backward through earlier versions
  - Update RT if necessary (i.e. if TS(T) > RT, then RT = TS(T))

- 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 <= 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



Summary

- Understand the reason for "Phantom Problem" and why serializability/2PL fails
- Understands 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
- Next lecture: full examples on some of these approaches from GUW (lecture slides will be sufficient for the exams and hws)