CS422
Database systems

Today: Transactions & concurrency control

Data-Intensive Applications and Systems (DIAS) Laboratory
École Polytechnique Fédérale de Lausanne

Slides adapted from material of
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Overview

- Transactions and ACID
- Schedules
- Locking protocols
  - 2PL, strict 2PL

Definition of transactions

A transaction (txn, or Xact) is a sequence of actions that are executed on a shared database to perform some higher-level function.

Transactions are the basic unit of change in the DBMS. No partial txns are allowed.

A quick reminder of ACID

- **A**tomicity: Either all actions in the txn happen, or none happen.
- **C**onsistency: If each txn is consistent, and the DB starts consistent, it ends up consistent.
- **I**solation: Execution of one txn is isolated from that of other txns.
- **D**urability: If a txn commits, its effects persist.

Atomicity and Durability

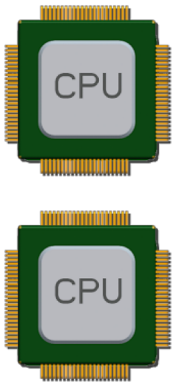
- A transaction might *commit* after completing all its actions, or it could *abort* (or be aborted by the DBMS) after executing some actions.
- All transactions are *atomic*.
  - A user can think of a txn as always executing all its actions in one step, or not executing any actions at all.
  - DBMS logs all actions so that it can undo the actions of aborted transactions.
- Durability also relies on logs

Consistency and Isolation

- Each transaction must leave the database in a consistent state.
  - DBMS will enforce some integrity constraints.
  - Clearly, no semantic consistency.
- Users submit transactions, and expect isolation -- each transaction executed by itself.
  - **Concurrency** very important for performance: interleaving actions from different transactions.
  - Net effect identical to executing all transactions one after the other in some serial order.

A note on concurrency

- Several transactions arrive at (almost) the same time
- Need to execute in parallel to fully utilize hardware



T1: R(A) R(B) compute-something W(C) COMMIT

T2: R(E) R(A) R(D) compute-something …

T3: R(D) compute-something R(E) …

User writes SQL queries.
Translated to actions!

Schedules

- The DBMS gets as input a set of transactions and executes a schedule.

- Schedule: a list of actions (reading, writing, aborting, or committing) from a set of txns
  - All actions appear in the schedule
  - The order in which two actions of a transaction T appear in a schedule must be the same as the order in which they appear in T.

Example

- **T1:** transfer $100 from B's account to A's account.
  T2: credit both accounts with a 6% interest payment.

```
T1:    BEGIN  A=A+100,   B=B-100   END
T2:    BEGIN  A=1.06*A,  B=1.06*B  END
```

- There is no guarantee that T1 will execute before T2 or vice-versa, if both are submitted together.
- Actions of two transactions can interleave!
- However, the net effect **must be equivalent** to these two transactions running serially in some order.

Example (Contd.)

- Consider a possible interleaving schedule:

```
T1:     A=A+100,                    B=B-100
T2:                 A=1.06*A,                   B=1.06*B
```

- This is OK. But what about:

```
T1:     A=A+100,                                B=B-100
T2:                 A=1.06*A, B=1.06*B
```

- The system's view of the second schedule:

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

There can be more than one serializable schedules and more than one final states

- *Serial schedule:* Schedule that does not interleave the actions of different transactions.
- *Equivalent schedules*: For any database state, the effect (on the set of objects in the database) of executing the first schedule is identical to the effect of executing the second schedule.
- *Serializable schedule*: A schedule that is equivalent to some serial execution of the transactions.

If each transaction preserves consistency, every serializable schedule preserves consistency.

Anomalies created when we have at least one write!

- Reading Uncommitted Data (WR Conflicts, “dirty reads”):

```
T1:   R(A), W(A),                    R(B), W(B), Abort
T2:                          R(A), W(A), C
```

- Unrepeatable Reads (RW Conflicts):

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

- Overwriting Uncommitted Data (WW Conflicts):

```
T1:   W(A),                                  W(B), C
T2:              W(A), W(B), C
```

Think of concrete scenarios where cascading aborts are very costly!

- If T_i is aborted, all its actions have to be undone.
- Cascading aborts: If T_j reads an object last written by T_i, T_j must be aborted as well!
  - Alternative to avoid cascading aborts: If T_i writes an object, T_j can read this only after T_i commits.
- DBMS maintains a write log, in order to be able to *undo* the actions of aborted txns.
  - Also used to recover from system crashes: all active txns at the time of the crash are aborted when the system comes back up.

Conflict Serializable Schedules

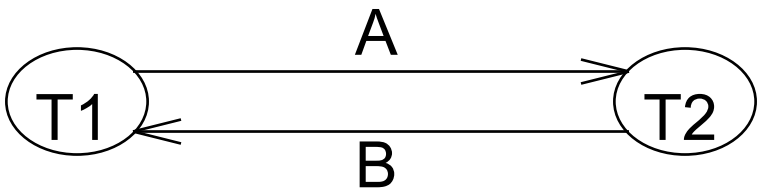
- Two schedules are conflict equivalent if:
  - They involve the same actions of the same transactions
  - Every pair of conflicting actions is ordered the same way
  - i.e., we can turn the one into the other by swapping non-conflicting adjacent actions

- Schedule S is conflict serializable if S is conflict equivalent to some serial schedule.

Example

- A schedule that is not conflict serializable:

T1:	R(A), W(A),	R(B), W(B)
T2:	R(A), W(A), R(B), W(B)	



Dependency graph
a.k.a. precedence graph

- *Dependency graph*: One node per txn; edge from T_i to T_j if T_j reads/writes an object last written by T_i.
- The cycle in the graph reveals the problem. The output of T1 depends on T2, and vice-versa.

Dependency Graph

- *Dependency graph*: One node per txn; edge from T_i to T_j if T_j reads/writes an object last written by T_i.

- Theorem: A schedule is conflict serializable if and only if its dependency graph is acyclic

Concurrency protocols

- Two-phase locking (2PL)
  - Pessimistic approach
  - Assume txns will conflict!
  - Acquire locks on all items before accessing them!

Lock-Based Concurrency Control

- Transactions acquire locks before reading and writing
- Locking protocol guarantees that schedule will be conflict serializable (*correct)* if it completes
  - Deadlocks are possible
- Locking granularity can be anything
  - Tables, indexes, pages, records

Lock-Based Concurrency Control

Two-Phase Locking (2PL) Protocol

- Rule 1: Each txn obtains
  - S (shared) lock before reading
  - X (exclusive) lock before writing
  - Sometimes also called read/write locks
- Rule 2: A txn cannot request additional locks once it releases any locks.
- 2PL allows only schedules whose precedence graph is acyclic => serializable.

Example schedule with locks:

T1: S(A) R(A) S(B) R(B)

T2: X(C) R(C) W(C) S(D) R(D)

Lock-Based Concurrency Control

Two-Phase Locking (2PL) Protocol

- Rule 1: Each txn obtains
  - S (shared) lock before reading
  - X (exclusive) lock before writing
  - Sometimes also called read/write locks
- Rule 2: A txn cannot request additional locks once it releases any locks.
- 2PL allows only schedules whose precedence graph is acyclic => serializable.

***Strict** Two-phase Locking (Strict 2PL) Protocol*

- Rule 3: All locks released when the txn completes.
- Strict 2PL additionally simplifies transaction aborts
  - (Non-strict) 2PL involves more complex abort processing.

Deadlocks

- Deadlock: Cycle of transactions waiting for locks to be released by each other.

- Two ways of dealing with deadlocks
  - Deadlock detection: detect and resolve deadlocks when they are created.
  - Deadlock prevention: never let deadlocks happen.

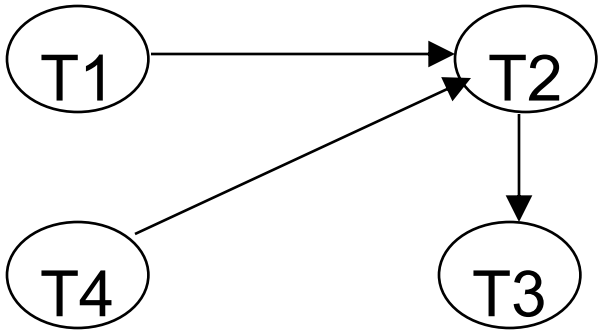
Deadlock Detection

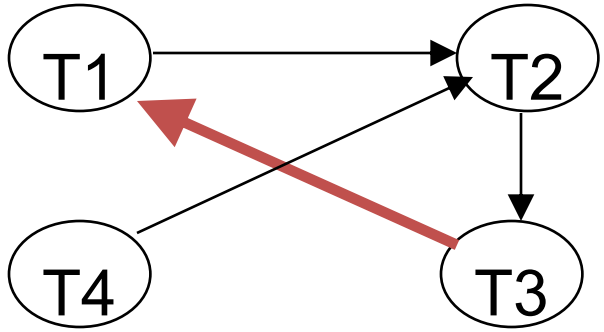
- If a lock request cannot be satisfied, the transaction is suspended and must wait until the resource becomes available.
- Create a waits-for graph:
  - Nodes are transactions
  - Edge from T_i to T_j if T_i is waiting for T_j to release a lock
- Periodically check for cycles in the waits-for graph

Deadlock Detection (Continued)

Example:

```
T1: S(A)  R(A)              S(B)
T2:             X(B)  W(B)                  X(C)
T3:                                 S(C)  R(C)            X(A)
T4:                                                 X(B)
```





Deadlock Prevention

- Assign priorities based on timestamps.
  - Earlier timestamp → higher priority
- Assume T_i wants a lock that T_j holds.
  Two policies:
  - Wait-Die: It T_i has higher priority, T_i waits for T_j. Otherwise T_i aborts
  - Wound-wait: If T_i has higher priority, T_j aborts. Otherwise T_i waits
- If a transaction re-starts, make sure it has its original timestamp

Fixed vs dynamic databases

- Fixed tuples
  - Set of tuples is fixed
  - Can update, but no inserts/deletes
  - Can lock all related tuples

```
UPDATE employees
      SET salary=salary*1.2 WHERE age>60
```

- Dynamic databases
  - Can insert/delete tuples
  - Cannot lock all related tuples
  -
```
INSERT INTO employees(name,age,salary)
      VALUES("Superman", 62, 10000)
```

Dynamic Databases

- If insertions/deletions are allowed, then even Strict 2PL **cannot** assure serializability
  - T1: Print the oldest sailors with rating=1 and rating=2
  - T2: Insert a sailor with (rating=1,age=96), and delete the oldest sailor with rating=2
  - The results **may not** correspond to a serial execution → not conflict-serializable!

Dynamic Databases

- If insertions/deletions are allowed (not only updates), then even Strict 2PL **cannot** assure serializability
  - T1 **locks all pages** containing sailor records with rating = 1, and finds oldest sailor (age = 71).
  - Next, T2 **inserts a new sailor**; rating = 1, age = 96.
  - T2 also **deletes** oldest sailor with rating = 2 (age = 80), and commits.
  - T1 now locks all pages containing sailor records with rating = 2, and finds oldest (age = 63).
- Not conflict serializable!!!

T1:	S(A*) R(A*)		S(B*) R(B*) W(C)
T2:		X(A') I(A') X(B) D(B)	

How did serializability break aka "The phantom menace"

- T1 implicitly assumes 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!

- Conflict serializability guarantees serializability only if the set of objects is fixed!
- Need some mechanism to enforce this assumption.
  - (Index locking and predicate locking).

Predicate Locking

- Implicitly lock all records (also new) that satisfy a logical predicate
  - I.e., rating=1 or rating=2.

- How would you implement predicate locking?
  - Very expensive

Index Locking

- T1 locks the index pages containing the data entries with *rating* = 1 and *rating* = 2.
  - Index needs to be updated after the insert → will fail if locked
  - If there are no records with rating = 1, T1 must lock the index page where such a data entry would be, if it existed!

- Special case of predicate locking – more efficient implementation.

Are 2PL protocols always good?

- Locking: Conservative approach in which conflicts are prevented.
- Disadvantages
  - Lock management overhead.
  - Deadlock detection/resolution.
  - Lock contention for heavily used objects.
- If conflicts are rare, gain concurrency by not locking, and instead checking for conflicts before txns commit
  - *more on the other side part of the lesson*

Describing transactions

Different transaction models

- Flat txns
- Flat txns with savepoints
- Chained txns
- Nested txns
- Saga txns
- Compensating txns

Commercial DBMS do not support all models!

Flat Transactions

- The standard txn model
  - Starts with BEGIN
  - One or more actions
  - Completes with COMMIT or ROLLBACK

Limitations of flat txns

- It's all or nothing – coarse-grained granularity!
  - Commit all, or rollback all
  - No partial rollbacks!
- If DBMS fails, all work is lost
  - Think of updating millions of tuples!
  - Still, will not lose old data – the D in ACID!
- Each txn takes place at a single point in time
  - Actions need to be predefined when transaction starts!
  - Cannot interrupt, ask the user, and then continue the tnx

Limitations of flat txns

Applications limited by flat txns

- Multi-stage planning
  - Not all applications know a priori all actions
  - E.g., book a trip (flight, train, hotel, …)
- Bulk updates
  - How to update 1 billion records
    - In the presence of failures
      - And without locking the entire database

Sometimes, bulk updates have a huge impact!

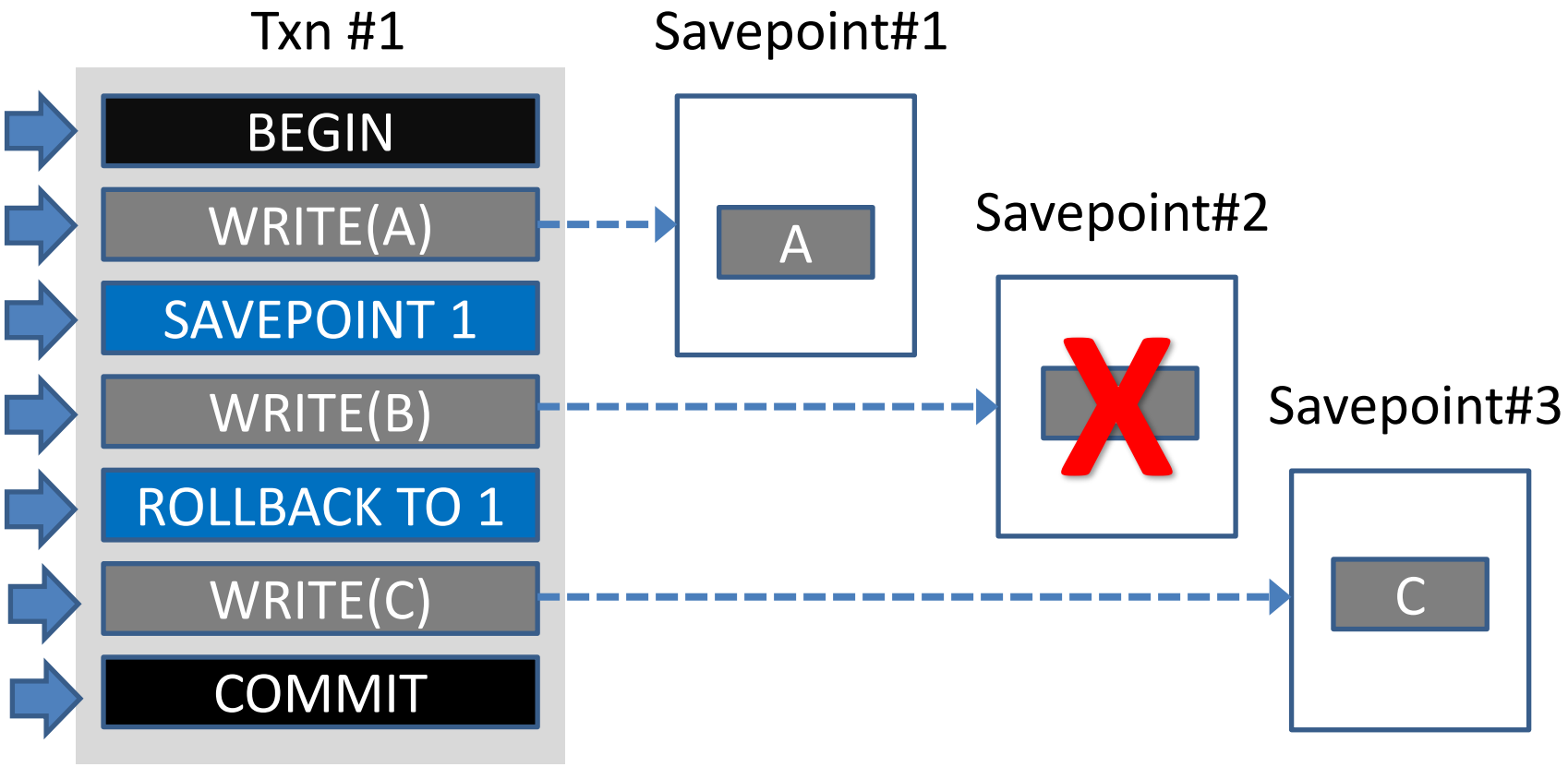
Please note that online banking will be unavailable next Sunday, between 03:00 and 05:00 for maintenance. We apologize for any inconvenience.

Transaction savepoints

- Savepoint: Save the current state of processing for the txn and provide a handle for the application to refer to that savepoint

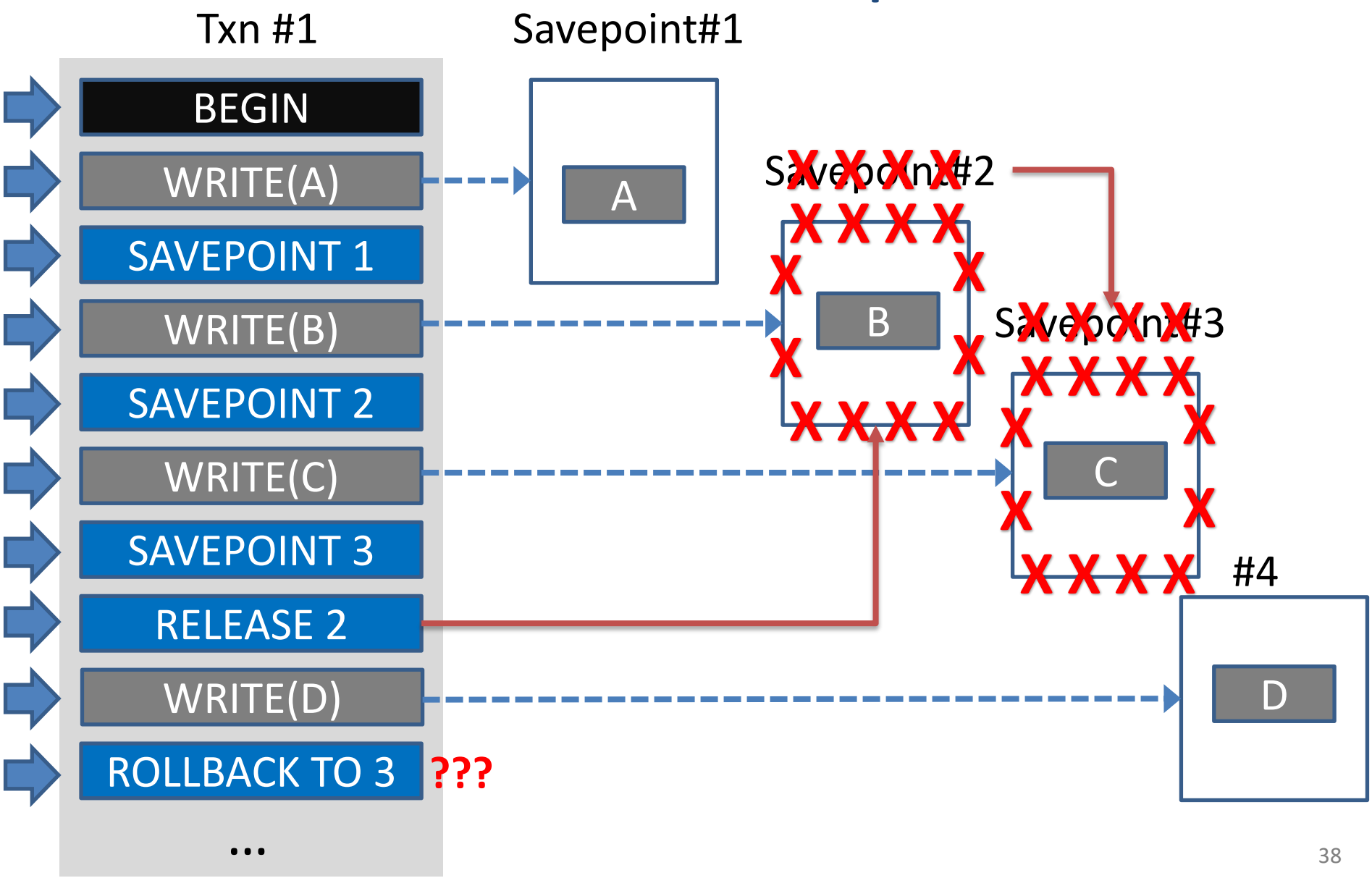
- ROLLBACK
  - Revert all changes back to the state of the savepoint
- RELEASE
  - Destroy a previously-defined savepoint

Transaction savepoints



What will commit write?

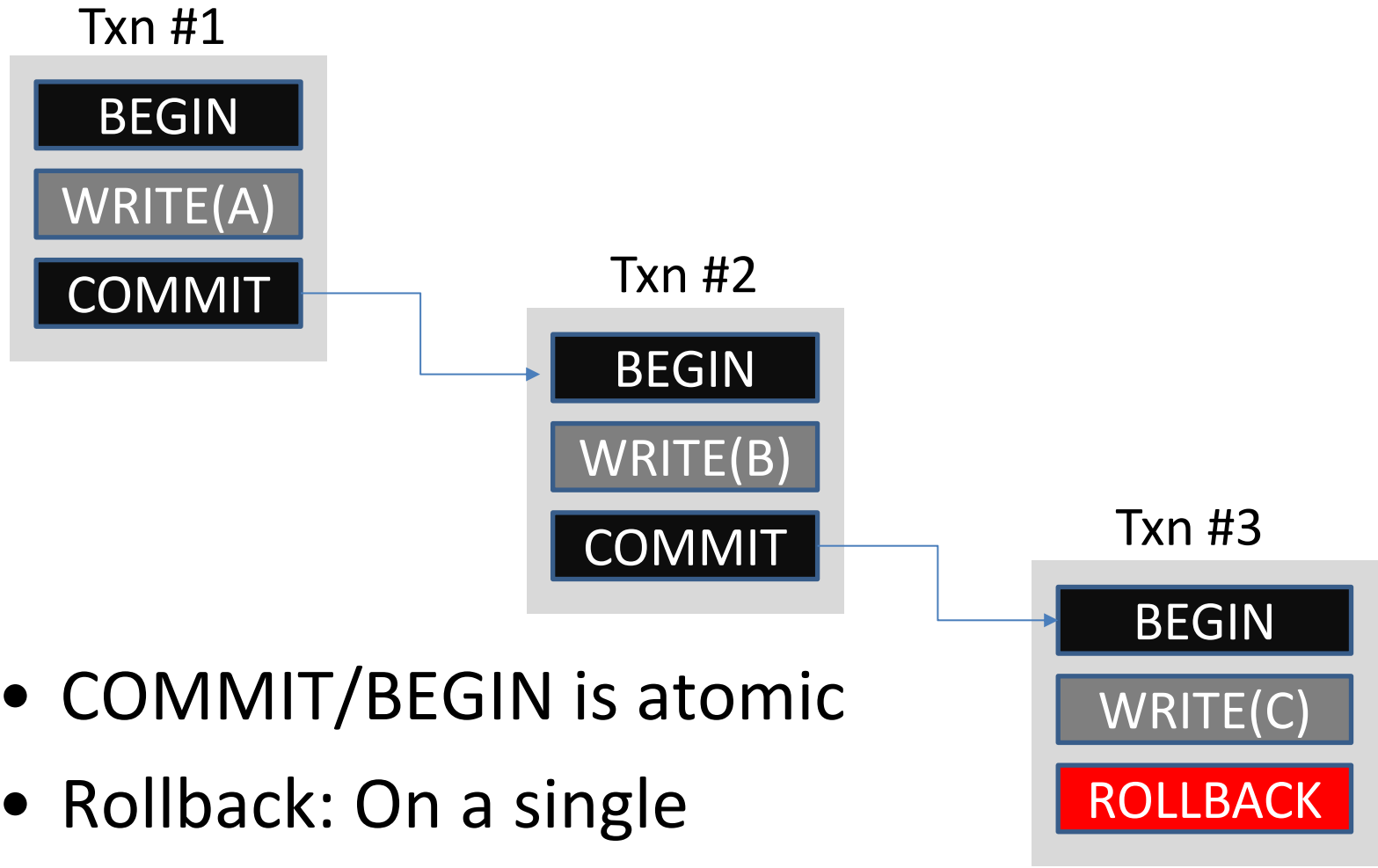
Transaction savepoints



Transaction chains

- Multiple txns executed one after another.
- Combined COMMIT/BEGIN operation is atomic.
  - No other txn can change the state of the database as seen by the second txn from the time that the first txn commits and the second txn begins.
- Differences with savepoints
  - Commit allows the DBMS to free locks
  - Cannot rollback previous txns in chain.

Transaction chains

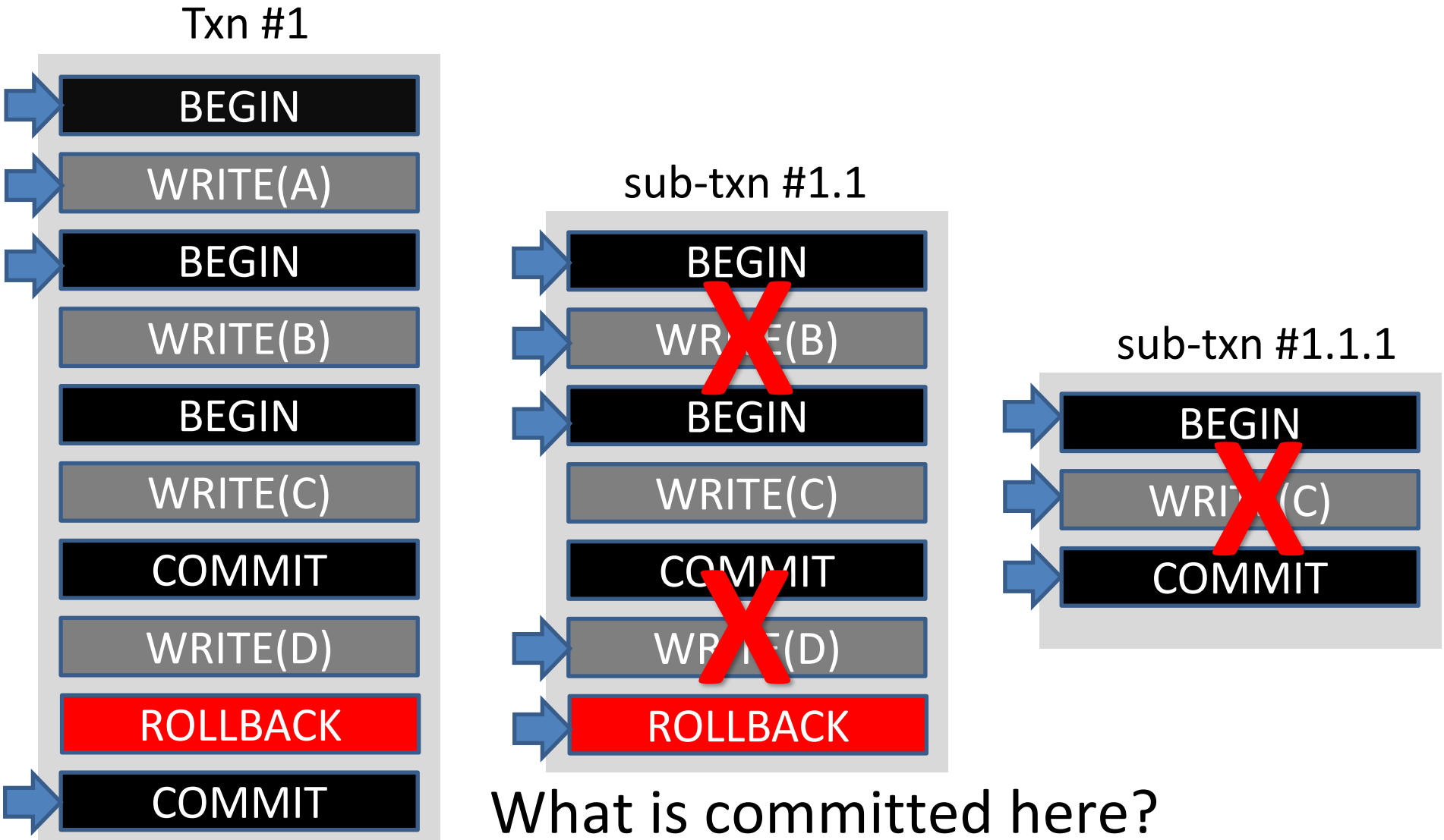


- COMMIT/BEGIN is atomic
- Rollback: On a single transaction

Nested transactions

- Savepoints organize a transaction as a sequence of actions that can be rolled back individually
- Nested txns form a hierarchy of work
  - The outcome of a child txn depends on the outcome of its parent txn

Nested transactions



What is committed here?

Why do we need compensating transactions? Why not just restore the old value?

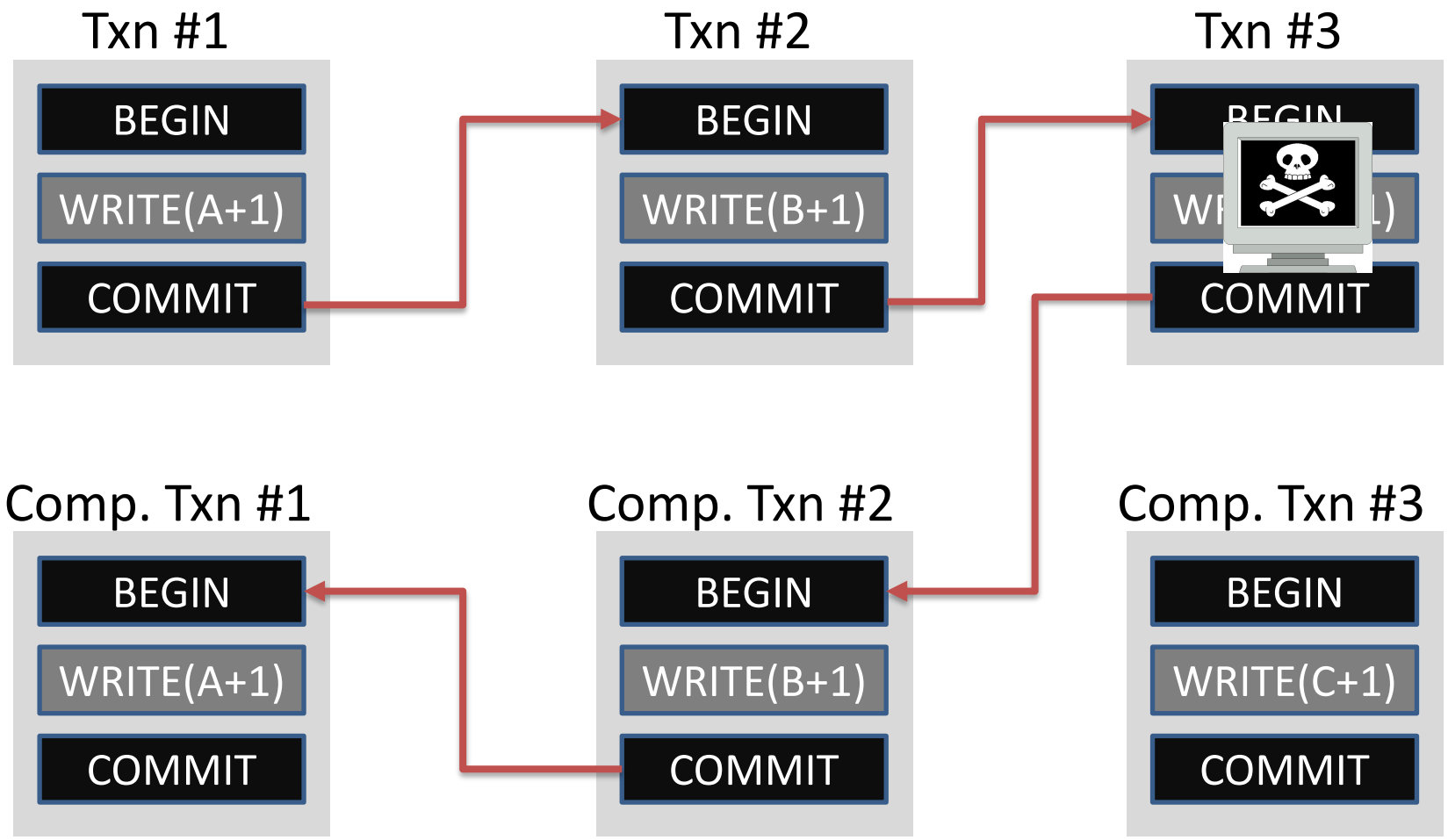
- A special type of txn designed to semantically reverse the effects of another already committed txn

- Reversal has to be logical instead of physical.
  - Example: decrement a counter by one instead of reverting to the original value!

SAGA transactions

- A sequence of chained txns $T_1, T_2, \ldots T_n$ and compensating txns $C_1, C_2, \ldots C_n$ where one of the following is guaranteed:
  - The txns will commit in the order $T_1, T_2, \ldots T_n$
  - The txns will commit in the order $T_1, T_2, \ldots T_j, C_j, C_{j-1}, \ldots C_1$ where j<n

SAGA transactions



OTHERSIDE

RED HOT CHILI PEPPERS

Concurrency protocols

- Two-phase locking (2PL)
  - Pessimistic approach
  - Assume txns will conflict!
  - Acquire locks on all items before accessing them!

- Timestamp ordering (T/O)
  - Optimistic approach
  - Assume that conflicts are rare!
  - Do not acquire locks, check for conflicts at commit!

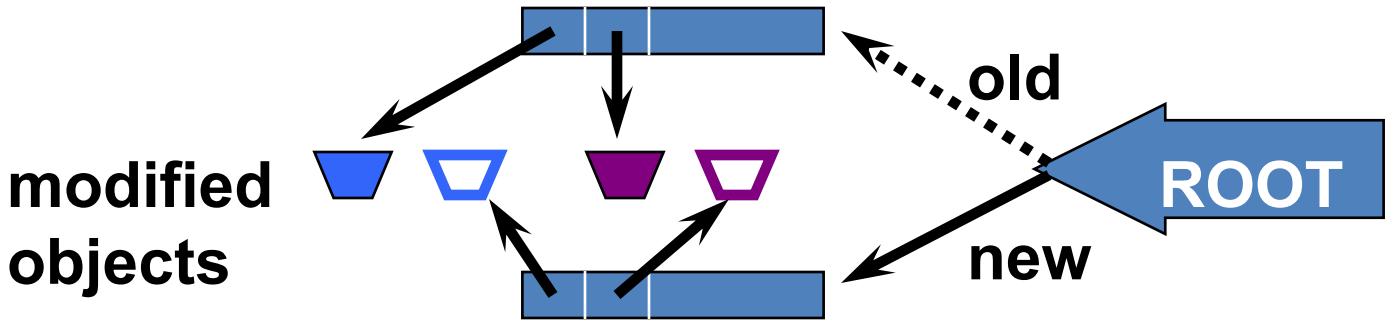
Optimistic Concurrency Control

The Kung-Robinson Model

- Key idea: Timestamp ordering is imposed on transactions, and validation phase checks that all conflicting actions occurred in the same order.
- If this is not the case, abort the transaction that started later!

Kung-Robinson Model

- Txns have three phases:
  - READ: txns read from the database, but make changes to **private copies** of objects.
  - VALIDATE: Check for conflicts.
  - WRITE: Make local copies of changes public.

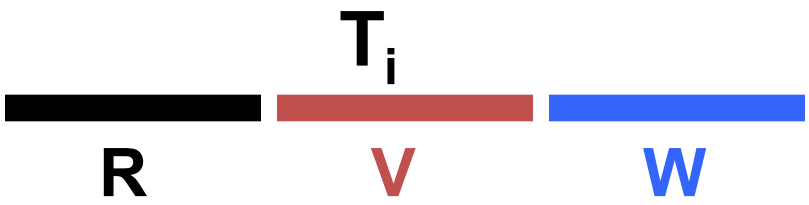


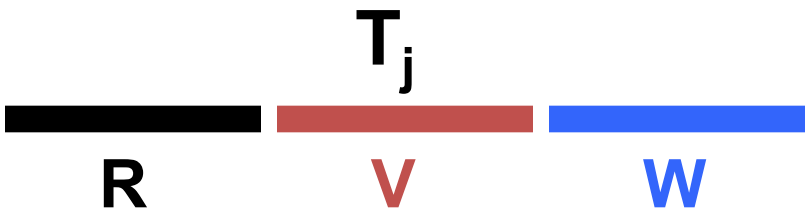
Validation

- Test conditions that are sufficient to ensure that no conflict occurred.
- Each txn assigned a numeric id.
  - Just use a **timestamp**.
  - Txn ids assigned at end of READ phase, just before validation begins.
- ReadSet(T_i): Set of objects read by txn T_i.
- WriteSet(T_i): Set of objects modified by T_i.

Test 1

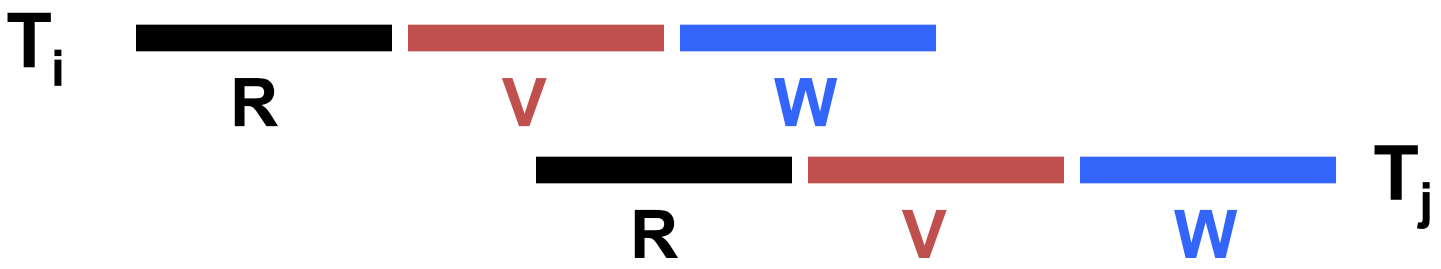
- For all i and j such that $T_i < T_j$, check that T_i completes before T_j begins.





Test 2

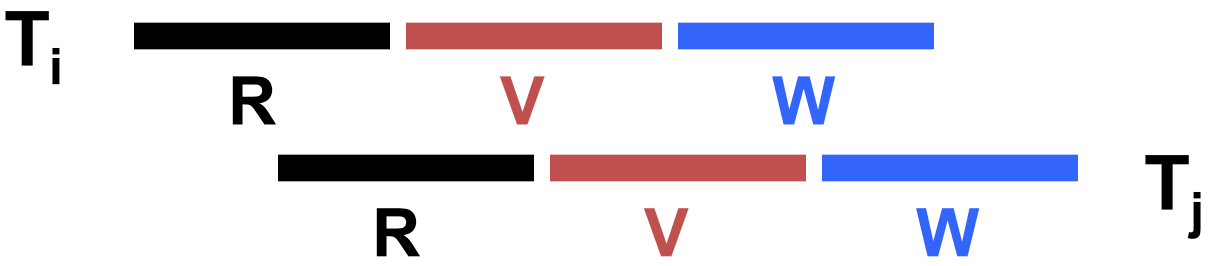
- For all i and j such that $T_i < T_j$, check that:
  - T_i completes before T_j begins its Write phase
  - WriteSet(T_i) ⋂ ReadSet(T_j) is empty.



✓ **"Does T_j read dirty data?"**

Test 3

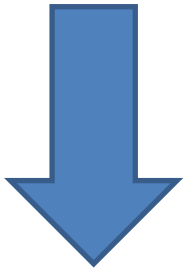
- For all i and j such that $T_i < T_j$, check that:
  - T_i completes Read phase before T_j does **+**
  - WriteSet(T_i) ⋂ ReadSet(T_j) is empty **+**
  - WriteSet(T_i) ⋂ WriteSet(T_j) is empty.

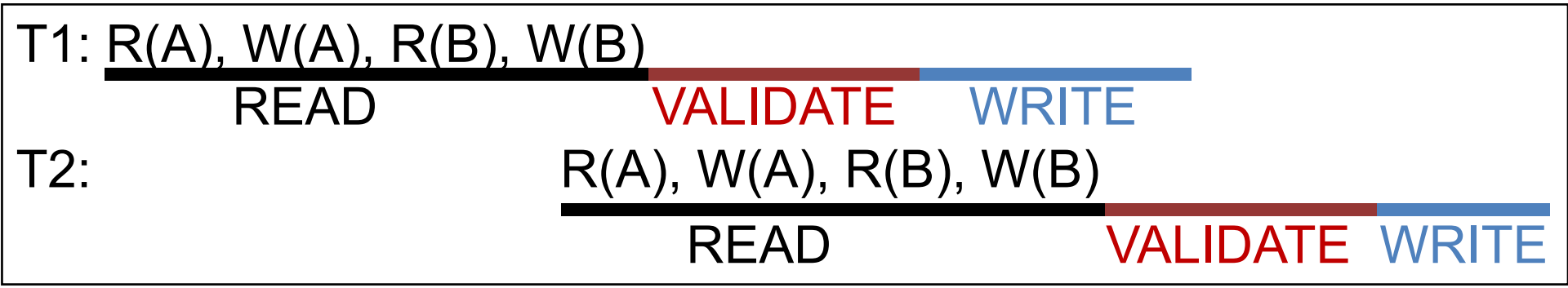


✓ "Does T_j read dirty data?"
✓ "Does T_i overwrite T_j's writes?"

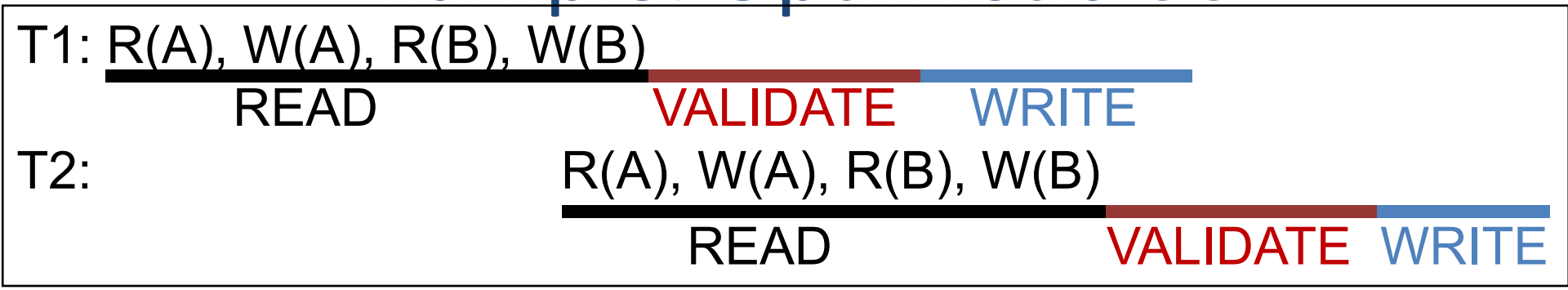
Example: Optimistic CC

T1: R(A), W(A), R(B), W(B) C
T2: R(A), W(A), R(B), W(B) C





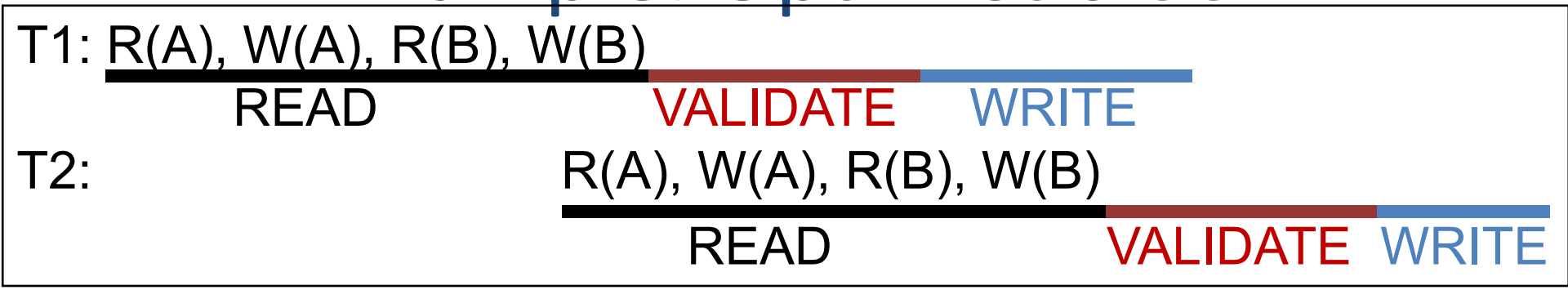
Example: Optimistic CC



- Validation of T2:
  - Test 1: ???

- For all i and j such that $T_i < T_j$, check that T_i completes before T_j begins.

Example: Optimistic CC

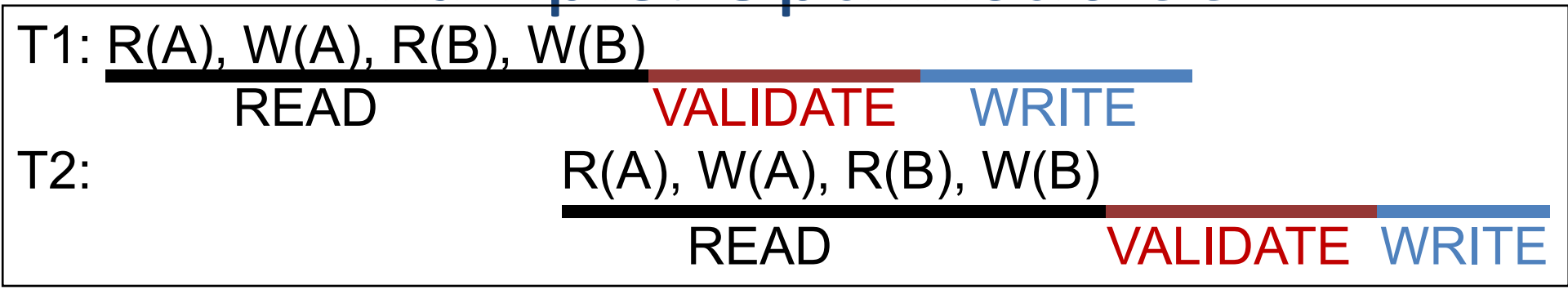


- Validation of T2:
  - Test 1: fails Test 2: ???

For all i and j such that $T_i < T_j$, check that:

- T_i completes before T_j begins its Write phase
- WriteSet(T_i) ⋂ ReadSet(T_j) is empty.

Example: Optimistic CC

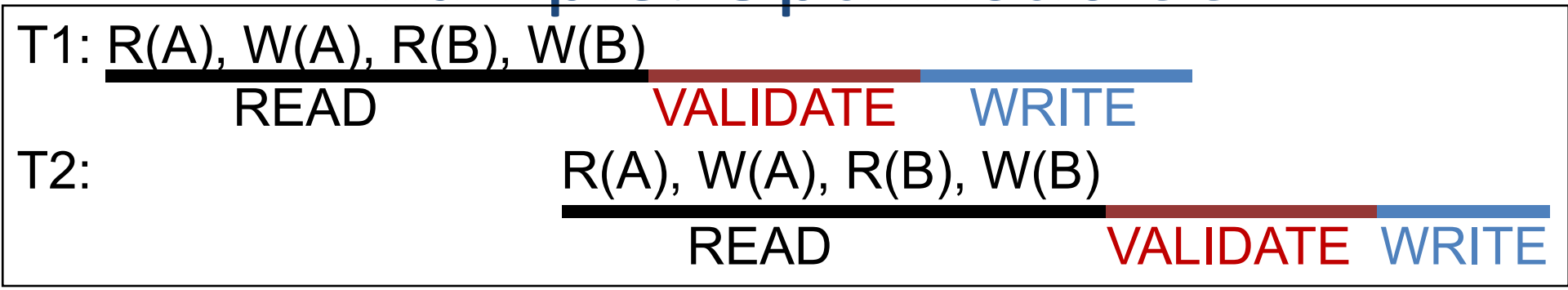


- Validation of T2:
  - Test 1: fails Test 2: fails Test 3: ???

For all i and j such that $T_i < T_j$, check that:

- T_i completes Read phase before T_j does **+**
- WriteSet(T_i) ⋂ ReadSet(T_j) is empty **+**
- WriteSet(T_i) ⋂ WriteSet(T_j) is empty.

Example: Optimistic CC



- Validation of T2:
  - Test 1: fails Test 2: fails Test 3: fails

T2 gets restarted once T1 is completely finished

Comments on Validation

- Assignment of txn id, validation, and the Write phase are inside a **critical section**!
  - Nothing else goes on concurrently.
  - If validation/write phase is long, major drawback!

- Optimization for Read-only txns:
  - Shorter critical section
    (because there is no Write phase).

Overheads in Optimistic CC

- Record read/write activity in ReadSet and WriteSet per txn.
  - Must create and destroy these sets as needed.
- Check for conflicts during validation, and make validated writes "global".
  - Critical section can reduce concurrency.
- **Optimistic CC restarts txns that fail validation**.
  - Work done so far is wasted.
  - Requires clean-up.

Timestamp-based CC

- Optimistic CC: Timestamp ordering is imposed on transactions, and **validation** checks that all conflicting actions occurred in the same order.
- Timestamp-based CC
  - **Continuous validation – not a distinct phase**
  - Keep read and write timestamps **per object**, and starting timestamp of each txn
  - Compare txn timestamp with read/write timestamps of the objects in order to decide between:
    - Continue, Abort, Commit, Skip write

Continuous, per-object validation

Timestamp-based CC

Idea:

- Txn timestamp TS ← begin time
- Object: read-timestamp (RTS) and a write-timestamp (WTS)
  - If action a_i of txn T_i conflicts with action a_j of txn T_j, and $TS(T_i) < TS(T_j)$, then a_i must occur before a_j. Otherwise, restart violating txn.
  - Use RTS, WTS to detect conflicts.

Object	Read-timestamp	Write-Timestamp
A	10	4
B	15	13
…	…	…

When txn T wants to READ Object O

- TS(T) < WTS(O): violates timestamp order of T w.r.t. writer of O.
  - Abort T and restart it with a new, larger TS.
- TS(T) >= WTS(O):
  - Allow T to read O.
  - Reset RTS(O) to max(RTS(O), TS(T))
- Change to RTS(O) on reads must be written in some persistent fashion → overhead.

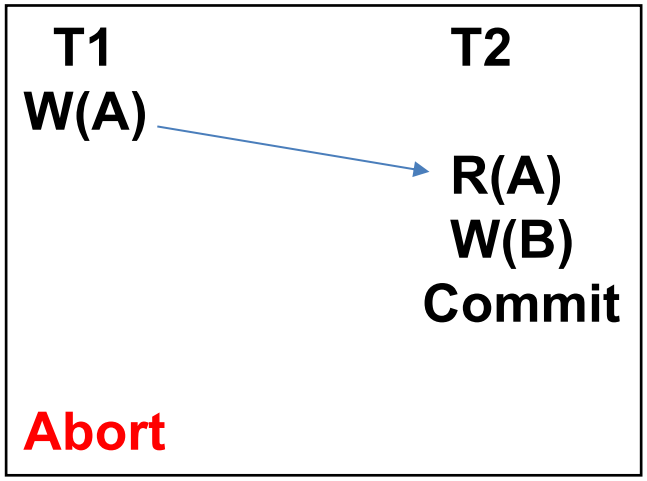
When txn T wants to write Object O

- TS(T) < RTS(O): violates timestamp order of T w.r.t. writer of O → abort and restart T.
- TS(T) < WTS(O) → violates timestamp order of T w.r.t. writer of O. → ???
  - Thomas Write Rule: Outdated write → Safely ignore; need not restart T!
    Allows some **serializable schedules (correct) that are not conflict serializable**.

- Else, allow T to write O (and update WTS(O)).

Timestamp-based CC and Recoverability

- Unrecoverable schedules are possible



- Solution
  - Make changes of T1 in a memory buffer and block T2 from committing
  - Write changes to disk ONLY at commit

Multiversion Concurrency Control

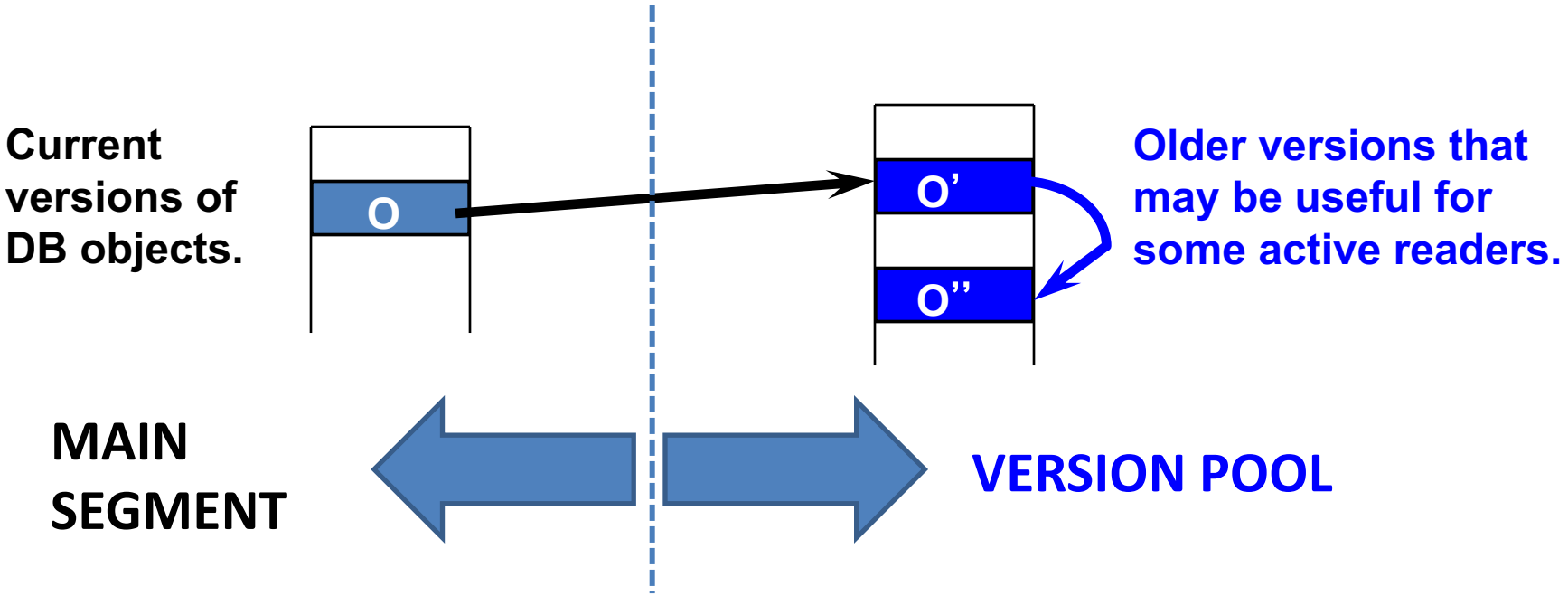
- **Goal: A transaction never waits on read!**
- **Idea**
  - Maintain **several versions** of each database object (multi-version), each with a read and a write timestamp.
  - Transaction T_i reads the most recent version whose write timestamp precedes $TS(T_i)$, i.e., $WTS(O)<TS(T_i)$.

Multiversioning is a storage mgmt concept!

Combine with CC => MVTO, MVOCC, MV2PL

Multiversion Concurrency Control

MVCC lets writers make a “new” copy while readers use an appropriate “old” copy:



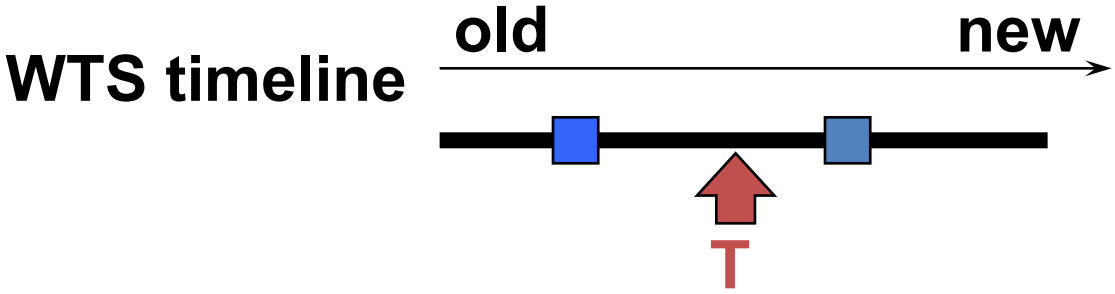
MV + Timestamp Ordering (MVTO)

For each version

- WTS: the timestamp of the txn that created it
- RTS: the timestamp of the txn that last read it
- Versions are (usually) chained backward; we can discard versions that are "too old to be of interest" (i.e., garbage collection).
- Each txn is classified as Reader or Writer.
  - Writer may write some object; Reader never will.
  - Txn declares whether it is a Reader when it begins.
- Readers are always allowed to proceed.

Reader txn

- For each object to be read:
  - Finds **newest version** with WTS < TS(T): Starts with current version in the main segment and chains backward through earlier versions.
  - Updates RTS to MAX(RTS, TS(T)).
- Reader txns are never restarted.



Readers always proceed

Writer txn

- To read an object, follow reader protocol.
- To write an object:
  - Finds **newest version V**
  - RTS(V) > TS(T): Reject write
  - RTS(V) ≤ TS(T): T makes a copy CV of V, with a pointer to V, with WTS(CV) = TS(T), RTS(CV) = TS(T).
    - Write is buffered / locked until T commits; other txns cannot read version CV. WHY????

Writers create new copy
(…if no younger transaction has read the data)
(…and if no active xaction holds V's lock)

Bottlenecks

- Lock thrashing
  - 2PL, Strict 2PL
- Timestamp allocation
  - All T/O algorithms + deadlock prevention
- Memory allocation
  - MVCC, OCC

Improving performance of txn

Goal is to

- reduce conflicts
- reduce time spent on each transaction

Three key approaches

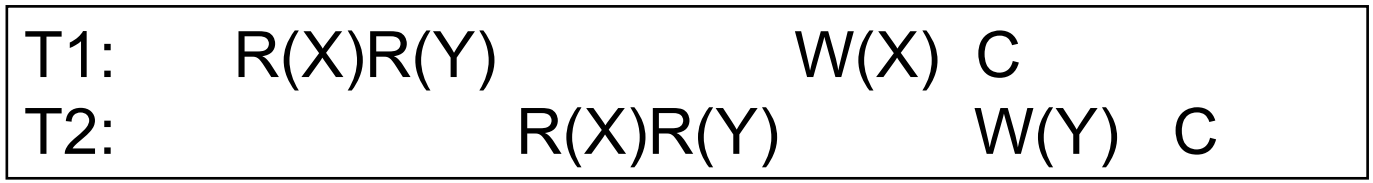
- Stored procedures --> faster
- Prepared statements --> precompiled
- Query batches --> batch locking

Snapshot isolation

- Snapshot isolation (SI) is the most popular **isolation guarantee** in real DBMS.
  - all txn reads will see a consistent snapshot of the database
  - the txn successfully commits only if no updates it has made conflict with any concurrent updates made since that snapshot.
- SI does not guarantee serializability!
  - SerializableSI: Stronger, more conservative protocol
- Implemented in Oracle, MS SQL Server, Postgres.

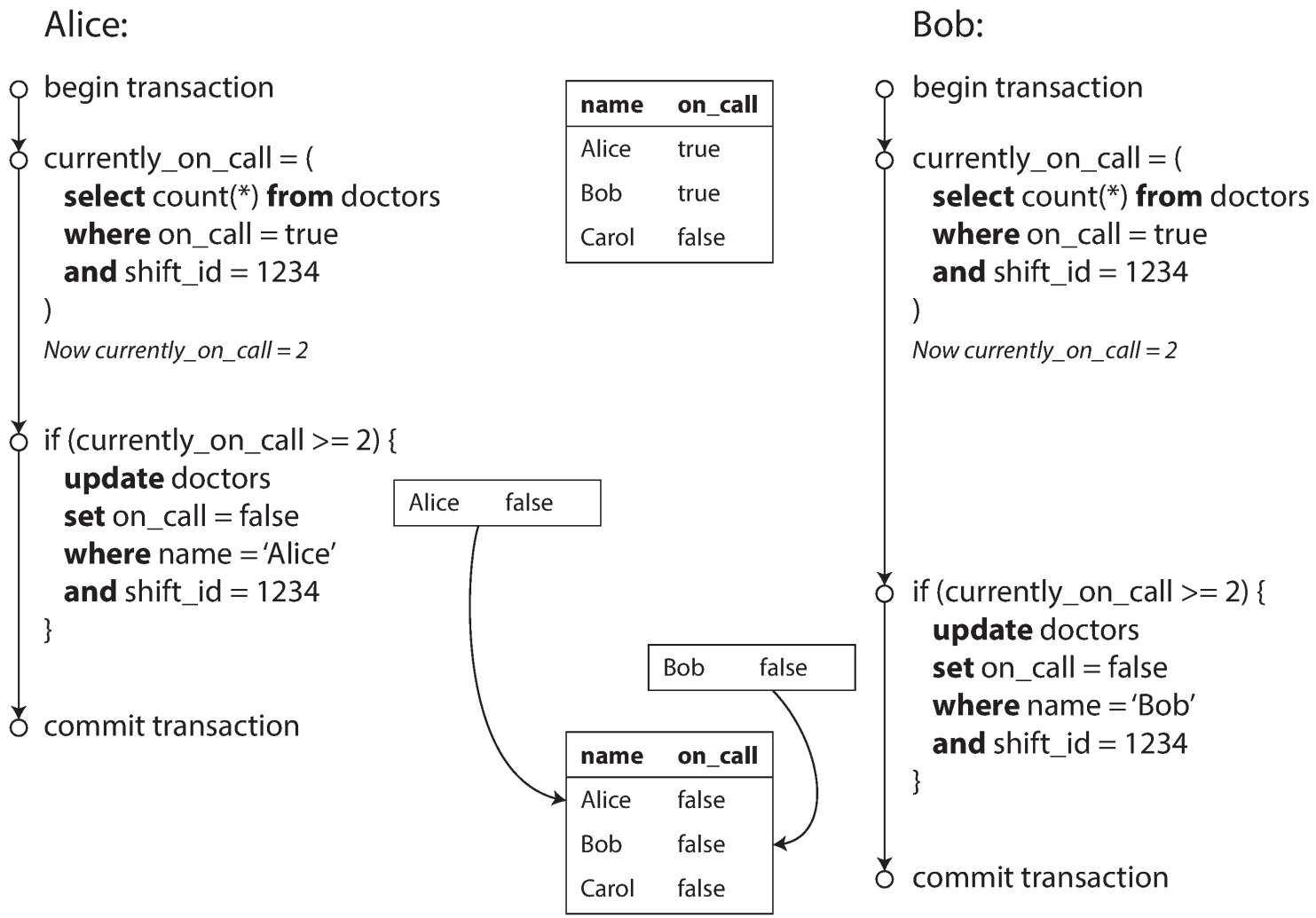
Snapshot isolation

- Conceptually, txn works on a copy of the db made at txn start time.
  - Very expensive → not implemented that way but still expensive.
  - Guarantees that reads in the txn see a consistent version of the db.
- At commit time, verify that the values changed by the transaction have not been changed by other transactions since the snapshot was taken.
- *Write skew* anomaly
  - Not serializable, but permitted by snapshot isolation!



Write skew – (more concrete) example

[Source: Martin Kleppmann]



Discussion

- SI is related to optimistic CC, in that
  - Conceptually, snapshots are created at txn start.
  - There is an analysis phase at the end to decide whether a transaction may commit (do writesets overlap?).

- Multiversion CC is a way to implement (a stronger) snapshot isolation.

Transaction Support in SQL-92

- Transaction characteristics:
  - Access mode: Read-only, Read-write
  - Isolation level: How isolated is each txn compared to other concurrent txns

Isolation Level	Dirty Read	Unrepeatable Read	Phantom Problem
Read Uncommitted	Maybe	Maybe	Maybe
Read Committed	No	Maybe	Maybe
Repeatable Reads	No	No	Maybe
Serializable	No	No	No

- Let the developer/user choose isolation level based on the importance of the task!

Example

T1:	R(A)			W(B)			C	
T2:			R(B)			W(A)		C

	RTS	WTS	V0
A:	0	0	15
B:	0	0	6

Readings

- COW Book (3rd edition), chapters 16, 17

or

- COW Book (2nd edition), chapters 18, 19

(This material is partially covered at CS-322)