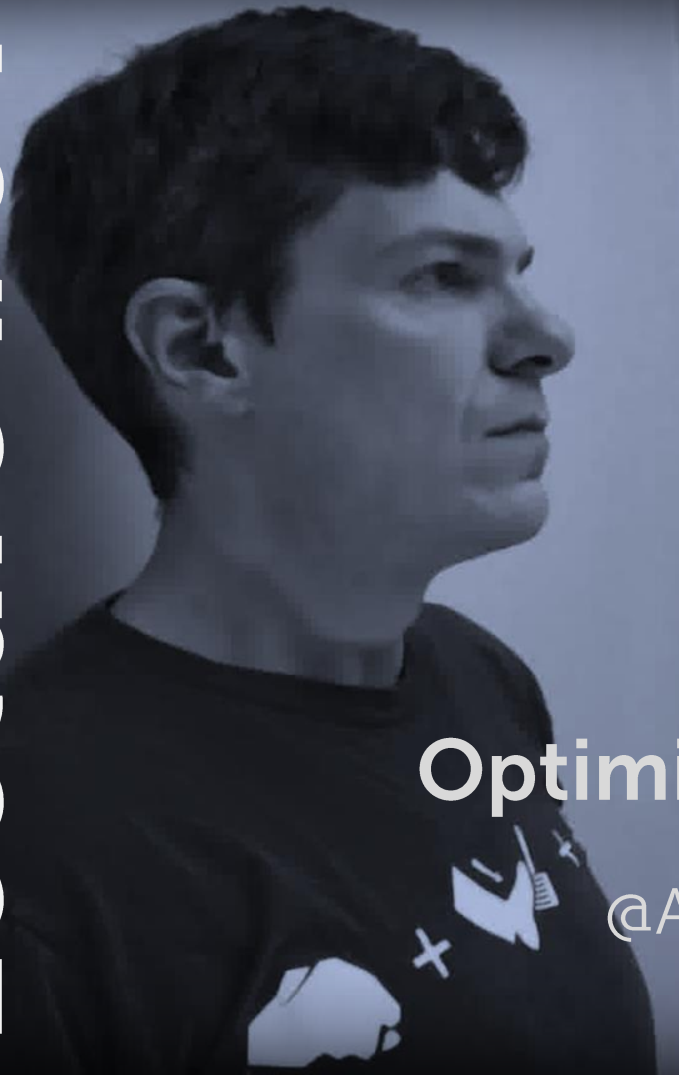
Carnegie Mellon University

ADVANCED DATABASE SYSTEMS

Lecture #04



Optimistic Concurrency Control

@Andy_Pavlo // 15-721 // Spring 2018

ADMINISTRATIVE

Project #1 is due Monday Jan 29th @ 11:59pm

Project #2 will be released on Wednesday.
→ You need a group of three people.
→ I will send out a sign-up sheet.

ADMINISTRATIVE

CMU Database Group Meetings

→ Mondays @ 4:30pm in GHC 8102
→ http://db.cs.cmu.edu/events

Peloton Developer Team Meetings

→ Tuesdays @ 12:00pm in GHC 7501
→ There will be food. Everyone loves food.

TODAY'S AGENDA

Stored Procedures
Optimistic Concurrency Control
Modern OCC Implementations

OBSERVATION

Disk stalls are (almost) gone when executing txns in an in-memory DBMS.

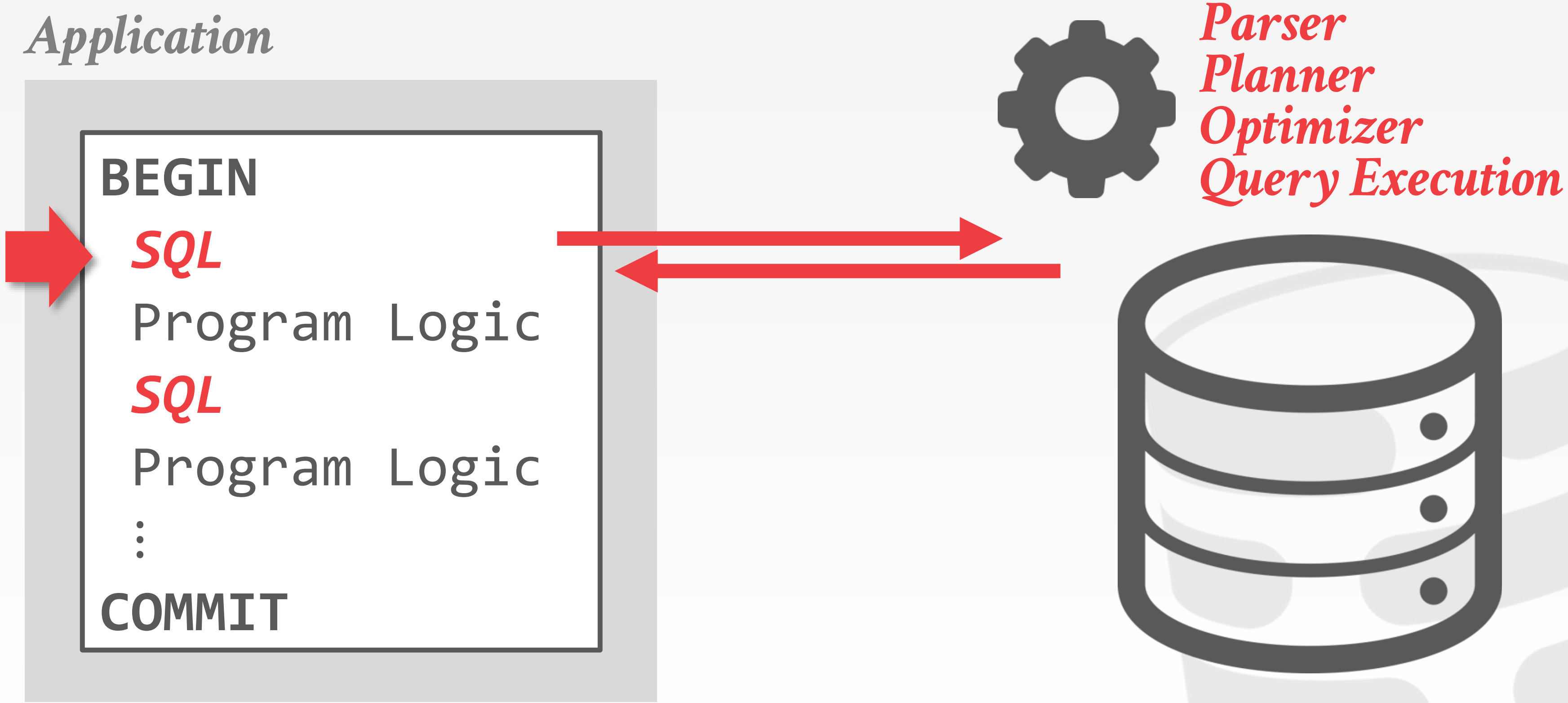
There are still other stalls when an app uses **conversational** API to execute queries on DBMS
→ ODBC/JDBC
→ DBMS-specific wire protocols

CONVERSATIONAL DATABASE API

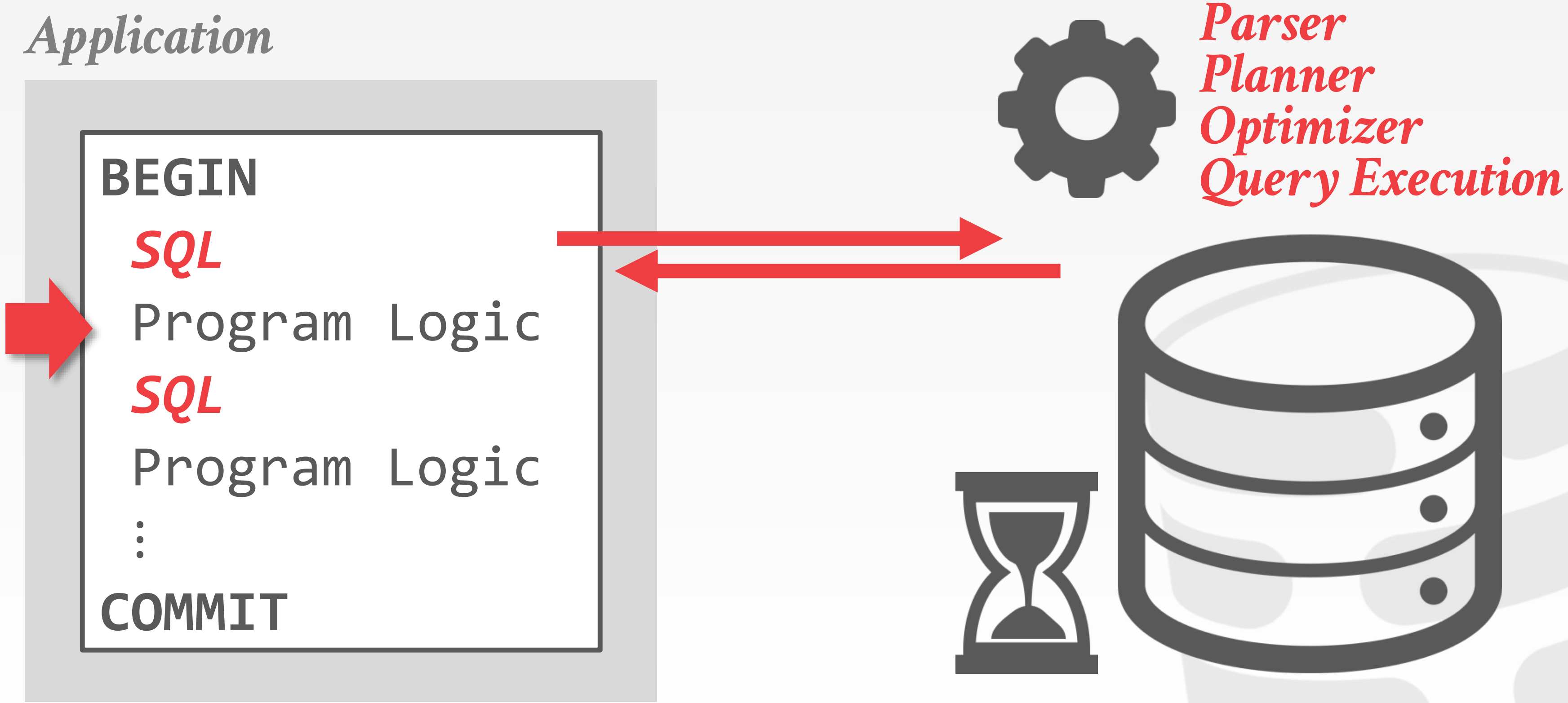
Application

```
BEGIN
  SQL
  Program Logic
  SQL
  Program Logic
  ⋮
COMMIT
```

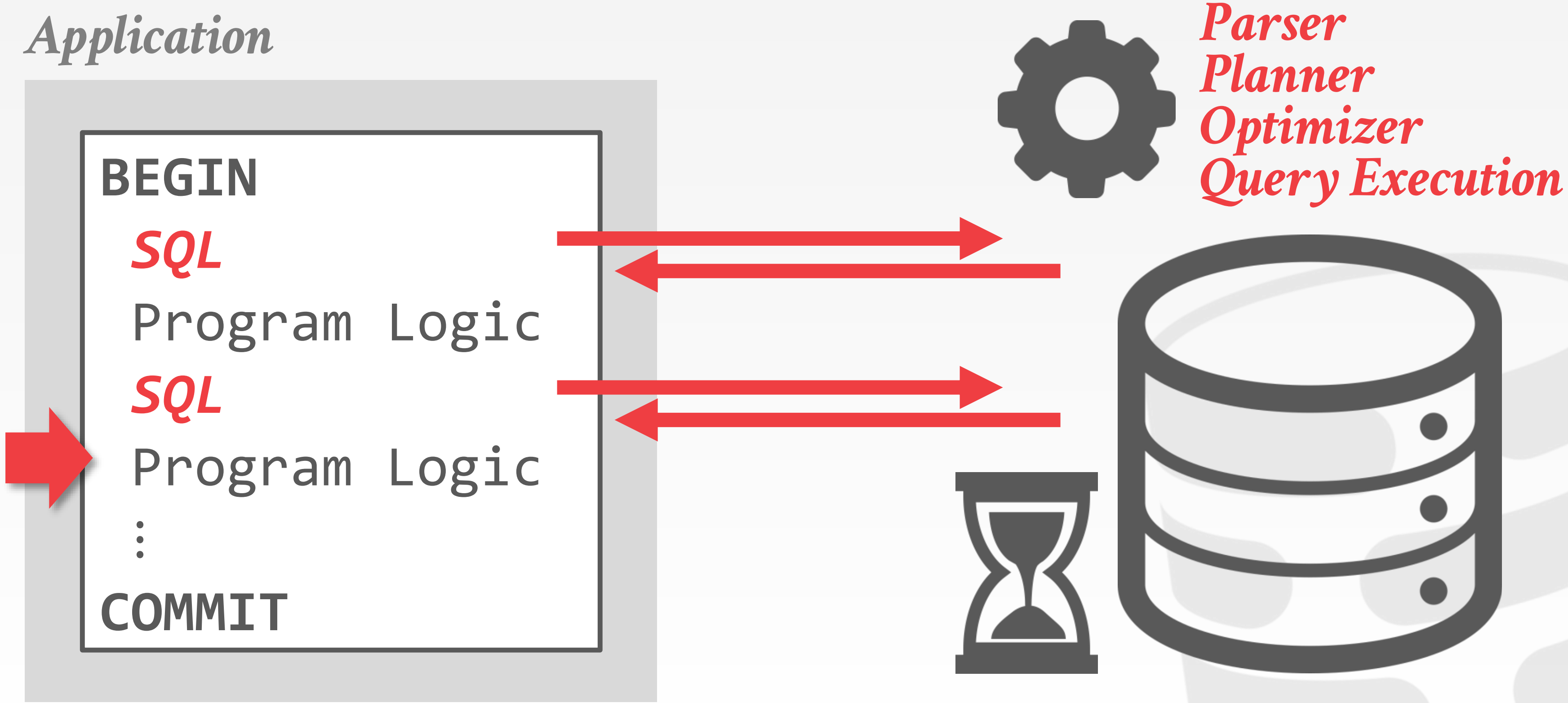
CONVERSATIONAL DATABASE API



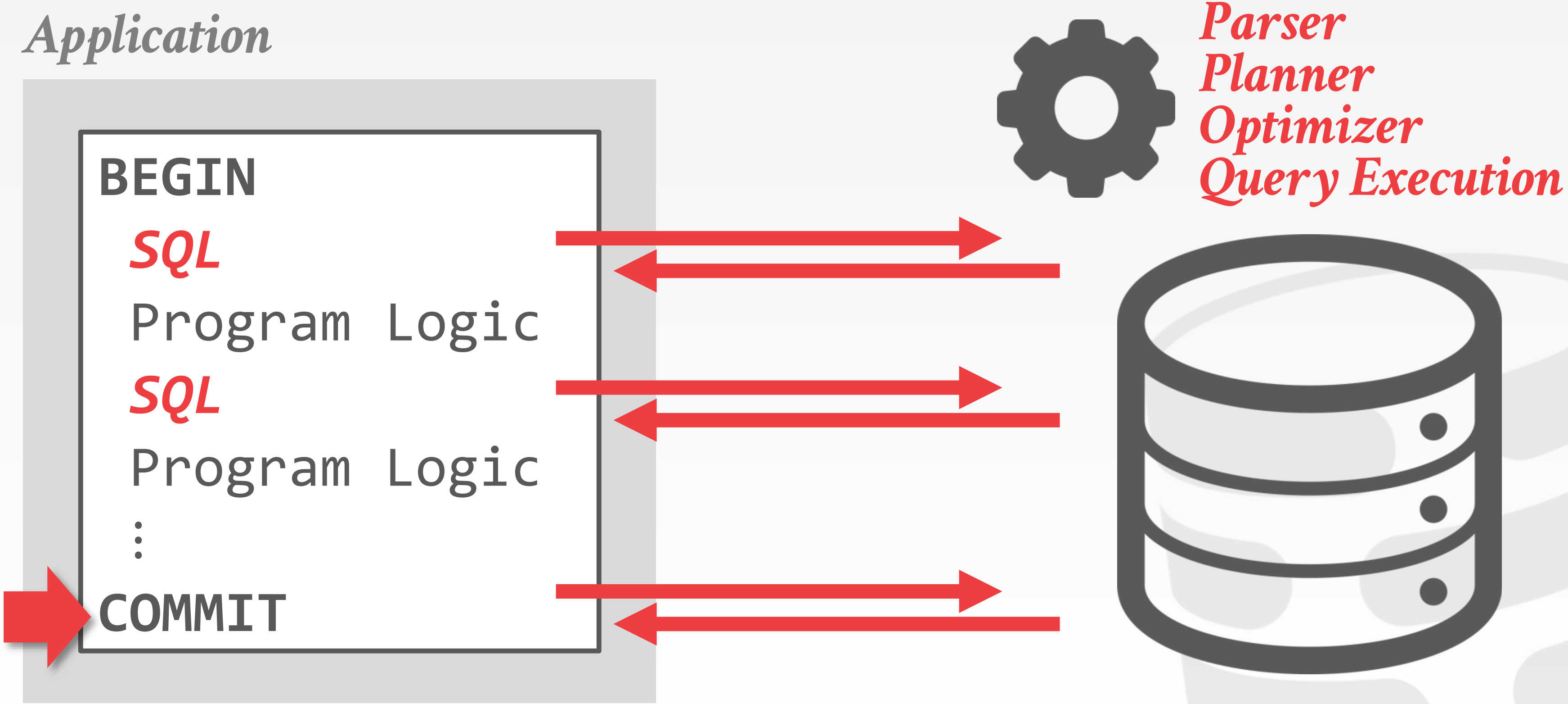
CONVERSATIONAL DATABASE API



CONVERSATIONAL DATABASE API



CONVERSATIONAL DATABASE API



SOLUTIONS

Prepared Statements
→ Removes query preparation overhead.

Query Batches
→ Reduces the number of network roundtrips.

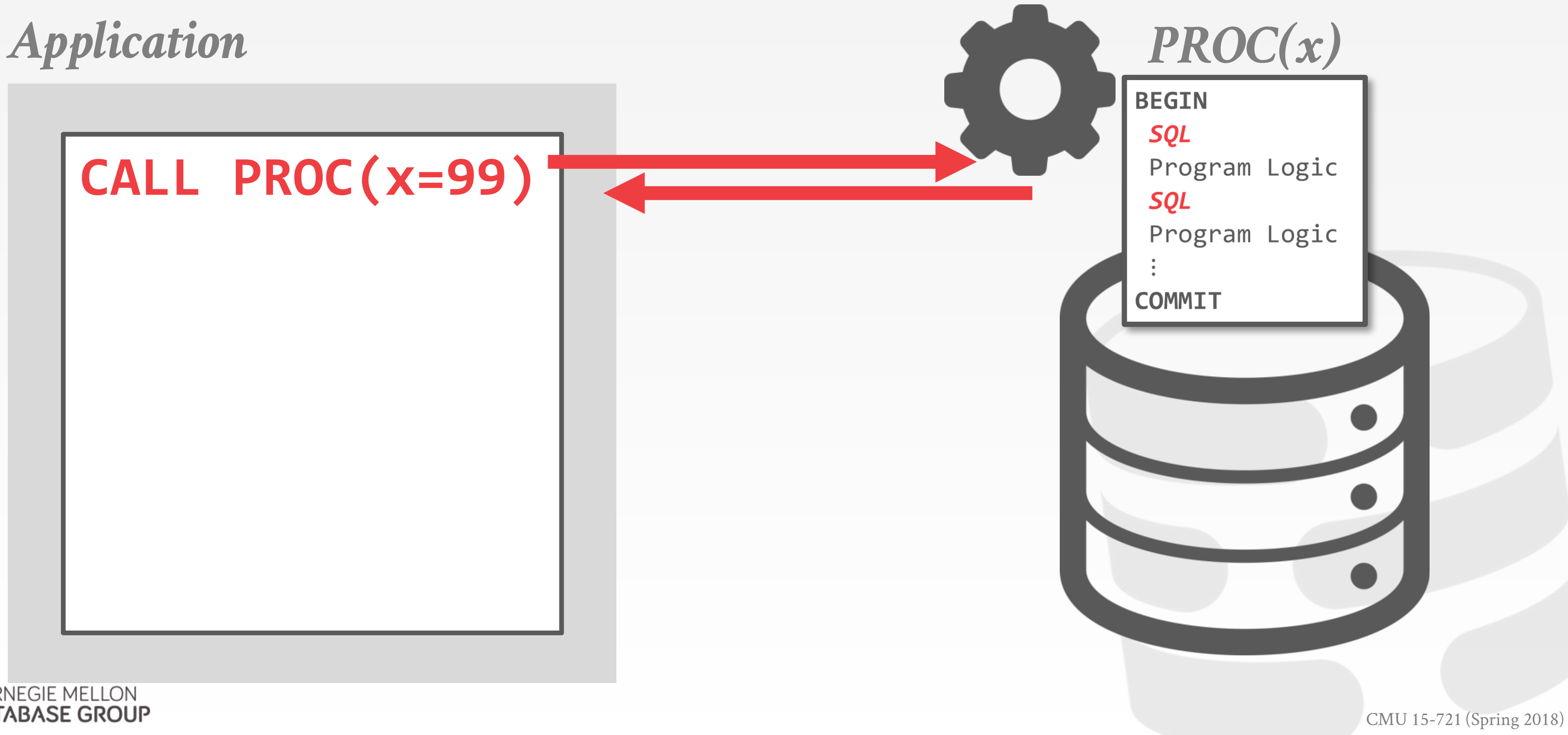
Stored Procedures
→ Removes both preparation and network stalls.

STORED PROCEDURES

A **stored procedure** is a group of queries that form a logical unit and perform a particular task on behalf of an application directly inside of the DBMS.

Programming languages:
→ **SQL/PSM** (standard)
→ **PL/SQL** (Oracle / IBM / MySQL)
→ **PL/pgSQL** (Postgres)
→ **Transact-SQL** (Microsoft / Sybase)

STORED PROCEDURES



STORED PROCEDURE EXAMPLE

```
CREATE PROCEDURE testProc
  (num INT, name VARCHAR) RETURNS INT
  BEGIN
    DECLARE cnt INT DEFAULT 0;
    LOOP
      INSERT INTO student VALUES (cnt, name);
      SET cnt := cnt + 1;
      IF (cnt > num) THEN
        RETURN cnt;
      END IF;
    END LOOP;
  END;
```

ADVANTAGES

Reduce the number of round trips between application and database servers.

Increased performance because queris are pre-compiled and stored in DBMS.

Procedure reuse across applications.

Server-side txn restarts on conflicts.

DISADVANTAGES

Not as many developers know how to write SQL/PSM code.
→ Safe Languages vs. Sandbox Languages

Outside the scope of the application so it is difficult to manage versions and hard to debug.

Probably not be portable to other DBMSs.

DBAs usually don't give permissions out freely…

CONCURRENCY CONTROL

The protocol to allow txns to access a database in a multi-programmed fashion while preserving the illusion that each of them is executing alone on a dedicated system.

→ The goal is to have the effect of a group of txns on the database's state is equivalent to any serial execution of all txns.

Provides **A**tomicity + **I**solation in ACID

CONCURRENCY CONTROL SCHEMES

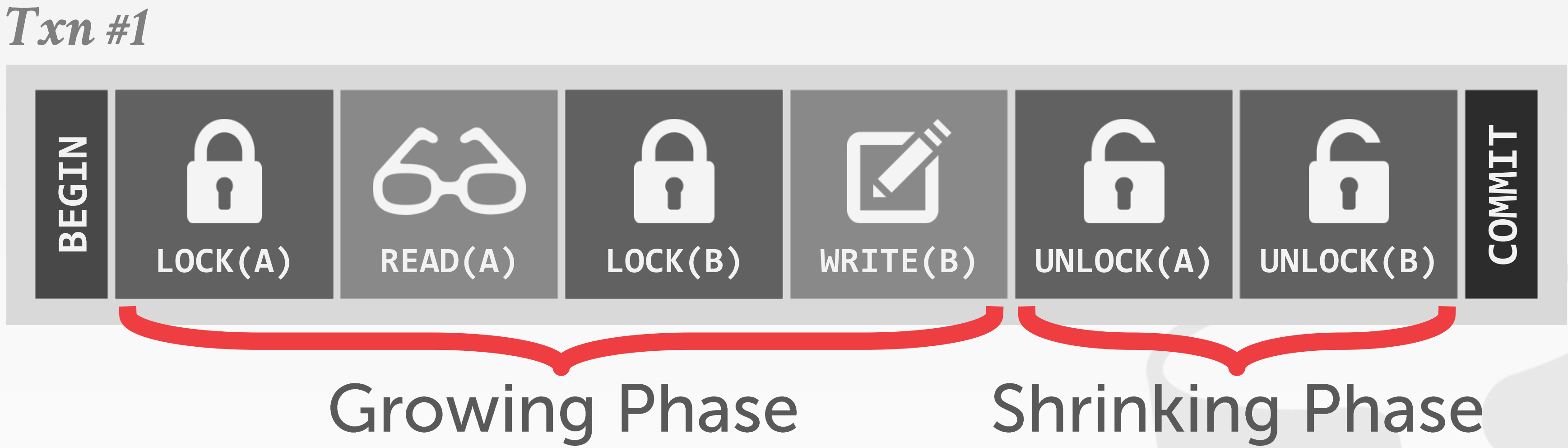
Two-Phase Locking (2PL)

→ Assume txns will conflict so they must acquire locks on database objects before they are allowed to access them.

Timestamp Ordering (T/O)

→ Assume that conflicts are rare so txns do not need to first acquire locks on database objects and instead check for conflicts at commit time.

TWO-PHASE LOCKING



TWO-PHASE LOCKING

Txn #1

Txn #2

TWO-PHASE LOCKING

Txn #1

BEGIN → LOCK(A) → READ(A) → LOCK(B) → WRITE(B) → UNLOCK(A) → UNLOCK(B) → COMMIT

Txn #2

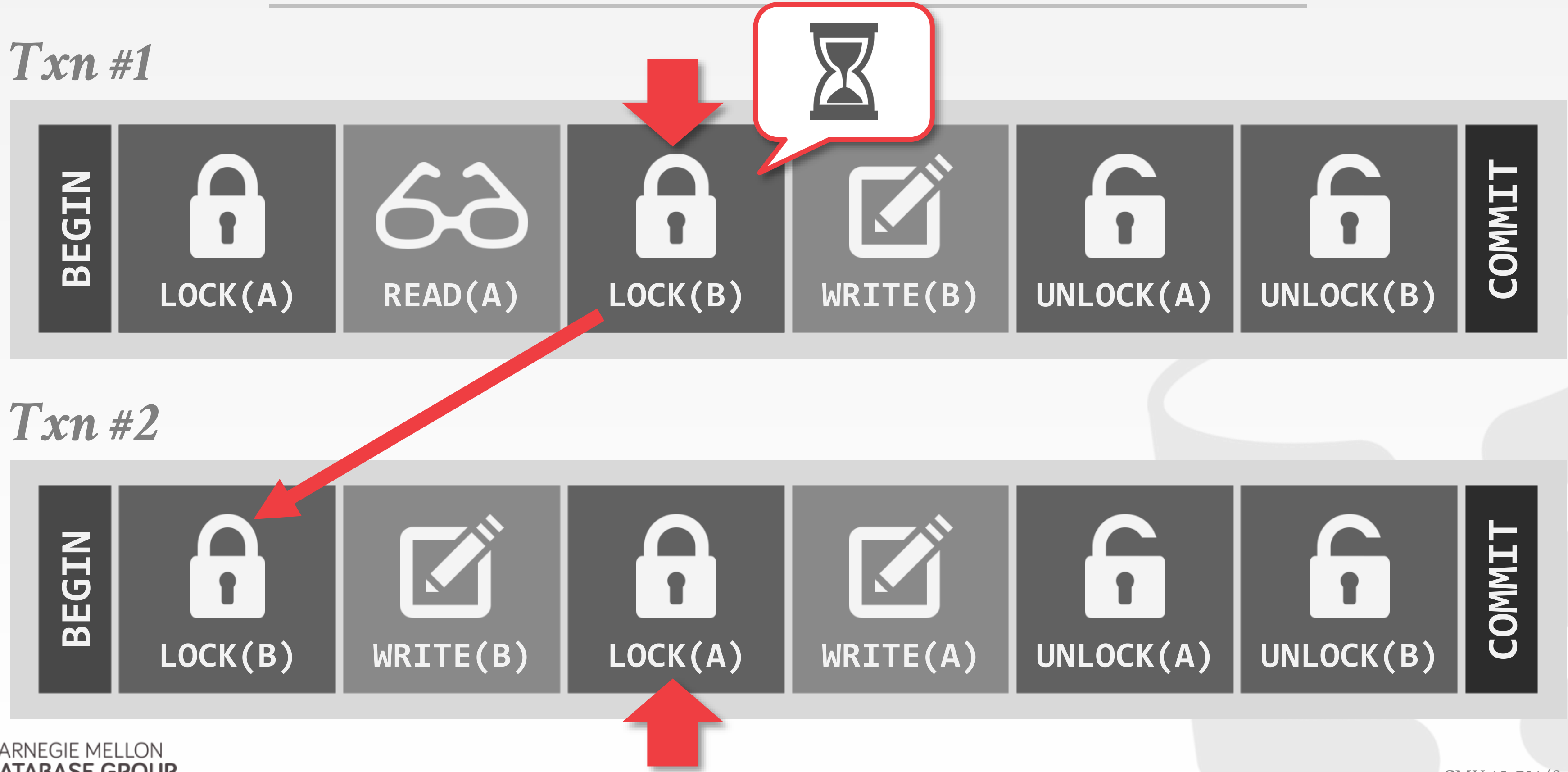
BEGIN → LOCK(B) → WRITE(B) → LOCK(A) → WRITE(A) → UNLOCK(A) → UNLOCK(B) → COMMIT

TWO-PHASE LOCKING

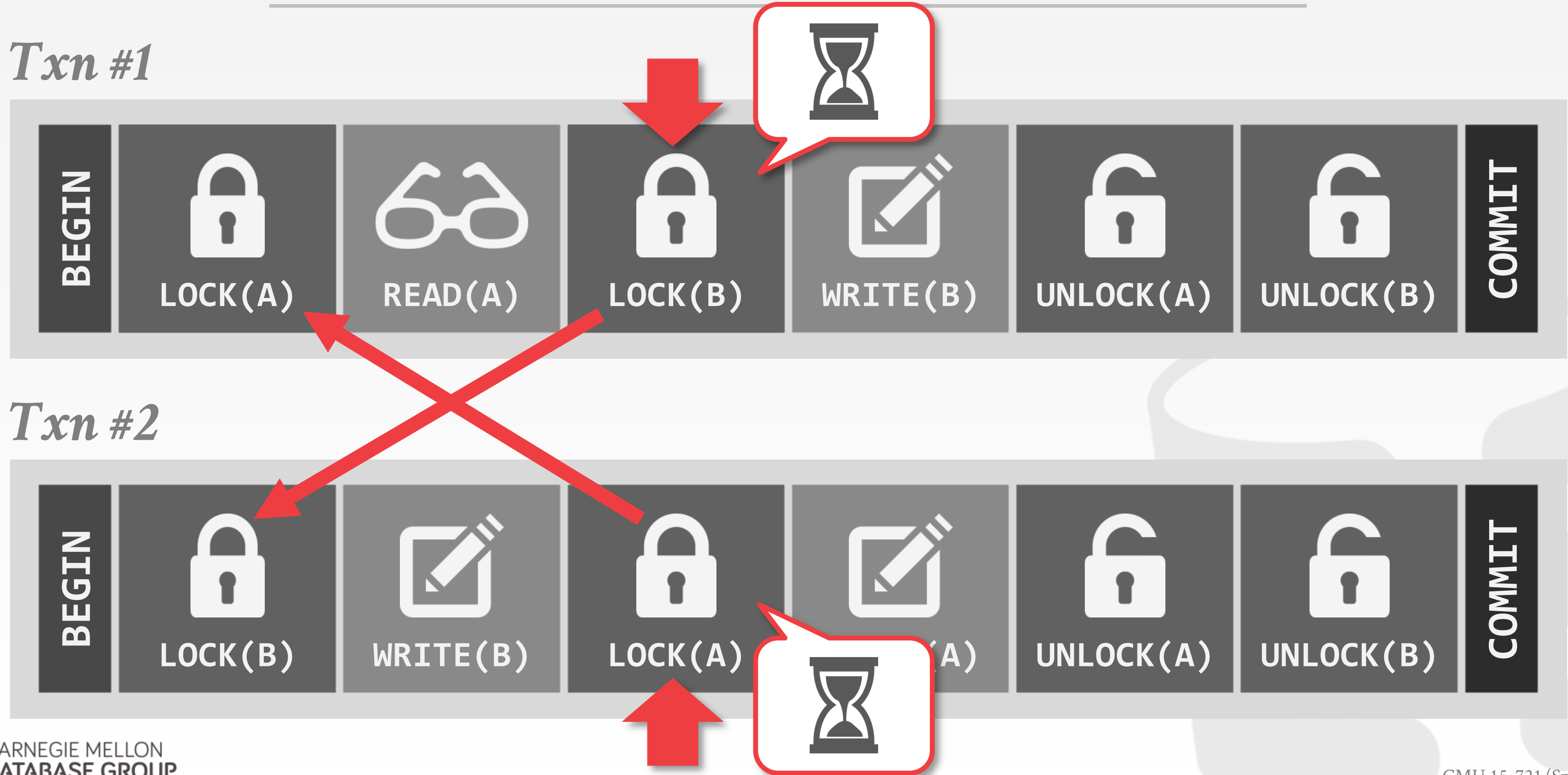
Txn #1

Txn #2

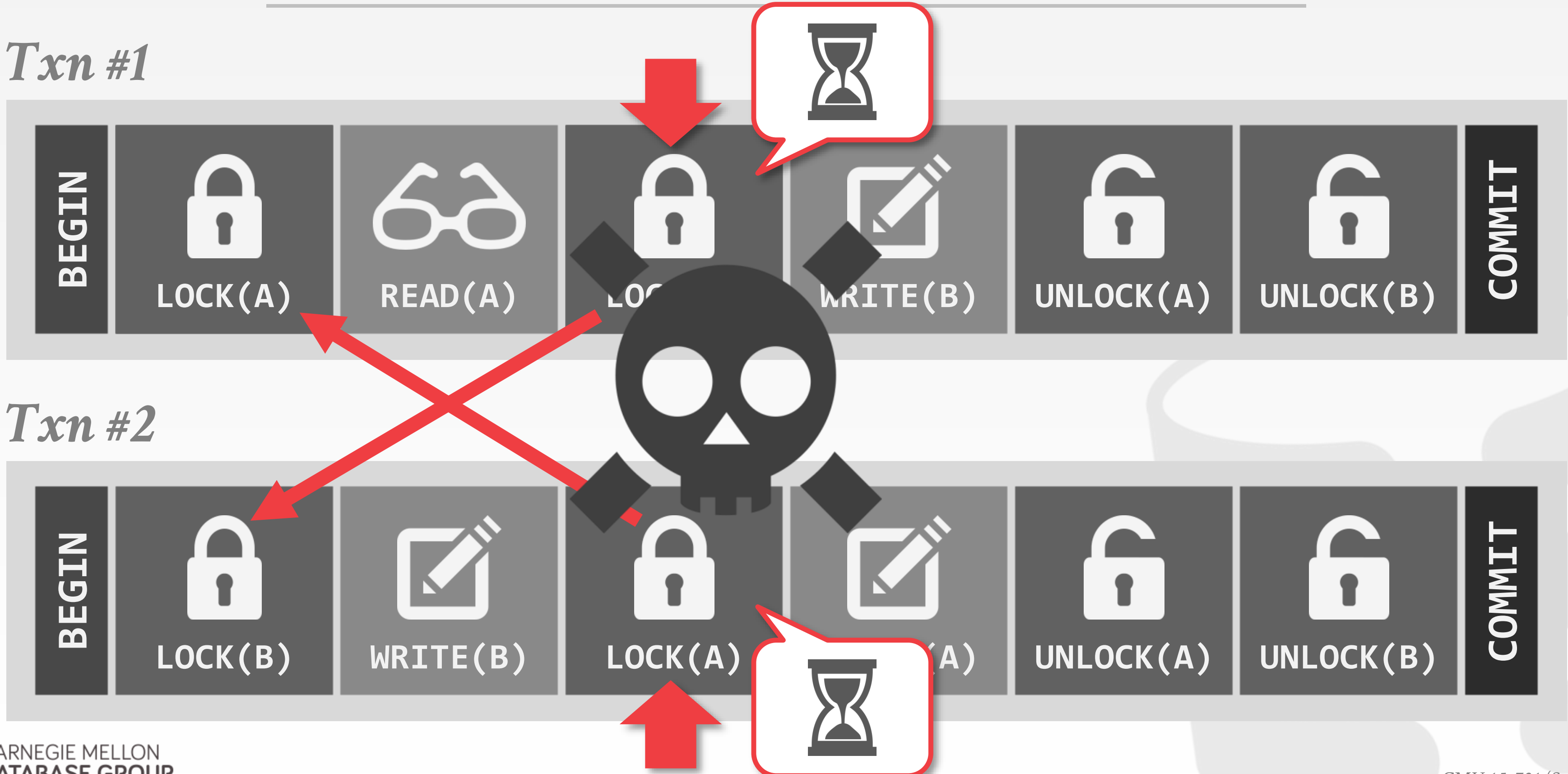
TWO-PHASE LOCKING



TWO-PHASE LOCKING



TWO-PHASE LOCKING



TWO-PHASE LOCKING

Deadlock Detection

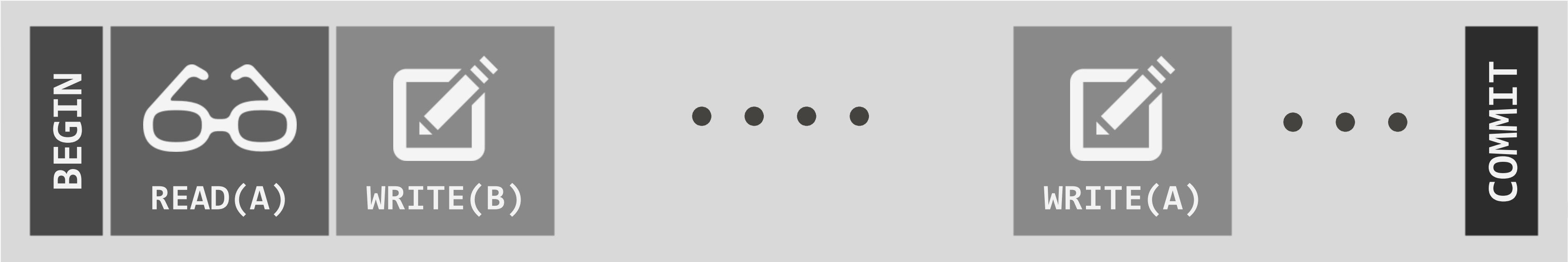
→ Each txn maintains a queue of the txns that hold the locks that it waiting for.
→ A separate thread checks these queues for deadlocks.
→ If deadlock found, use a heuristic to decide what txn to kill in order to break deadlock.

Deadlock Prevention

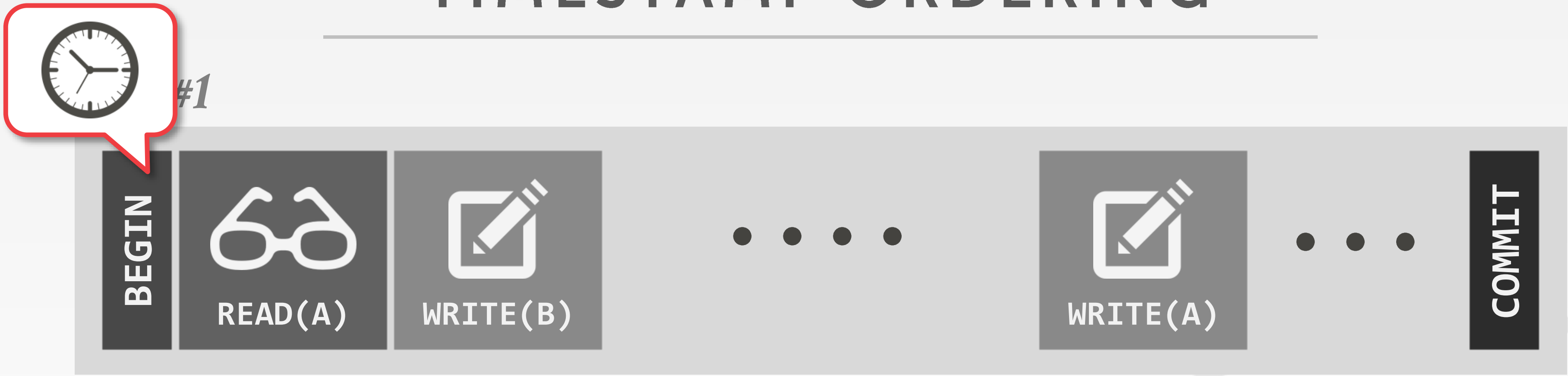
→ Check whether another txn already holds a lock when another txn requests it.
→ If lock is not available, the txn will either (1) wait, (2) commit suicide, or (3) kill the other txn.

TIMESTAMP ORDERING

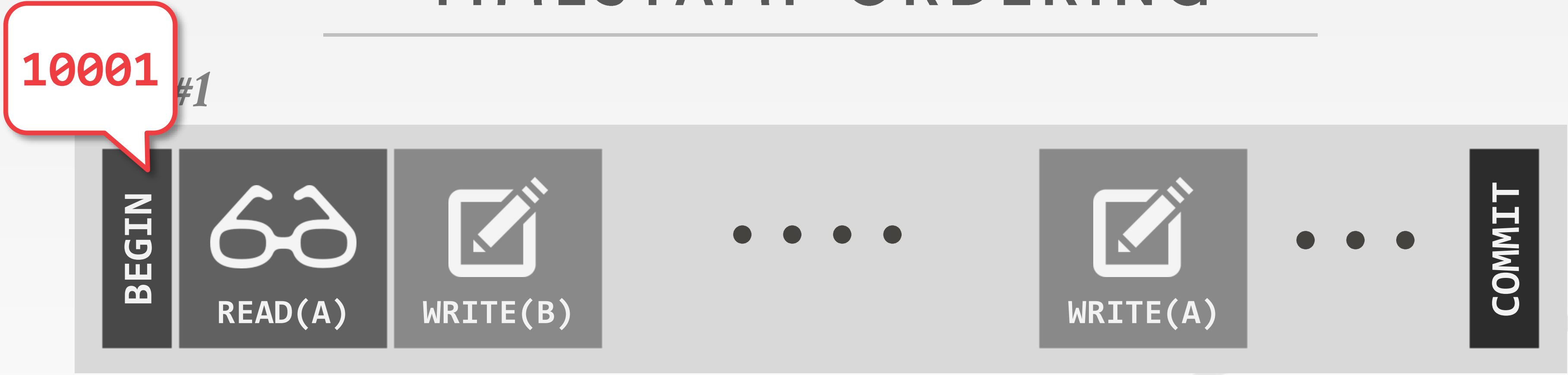
Txn #1



TIMESTAMP ORDERING

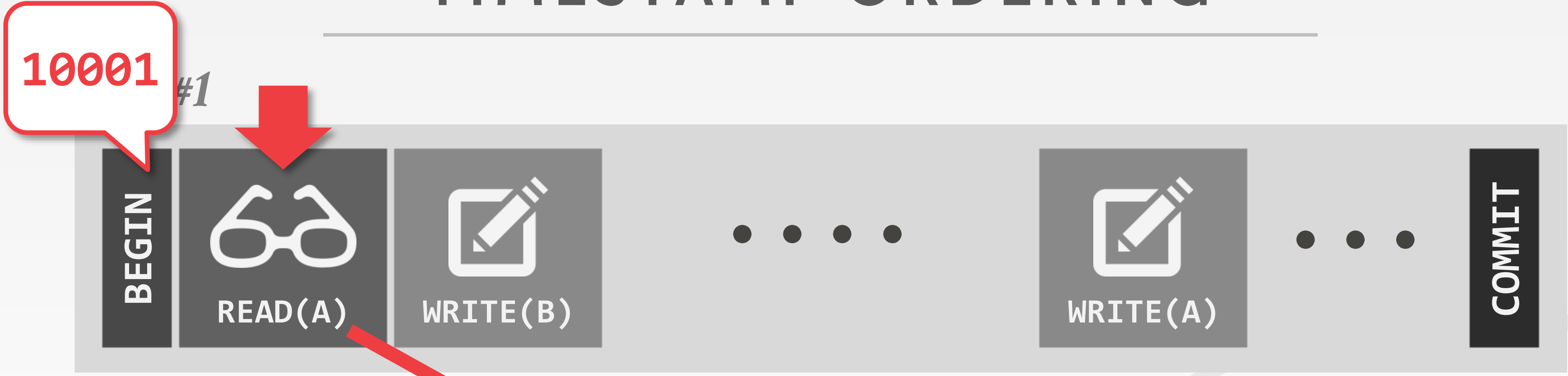


TIMESTAMP ORDERING



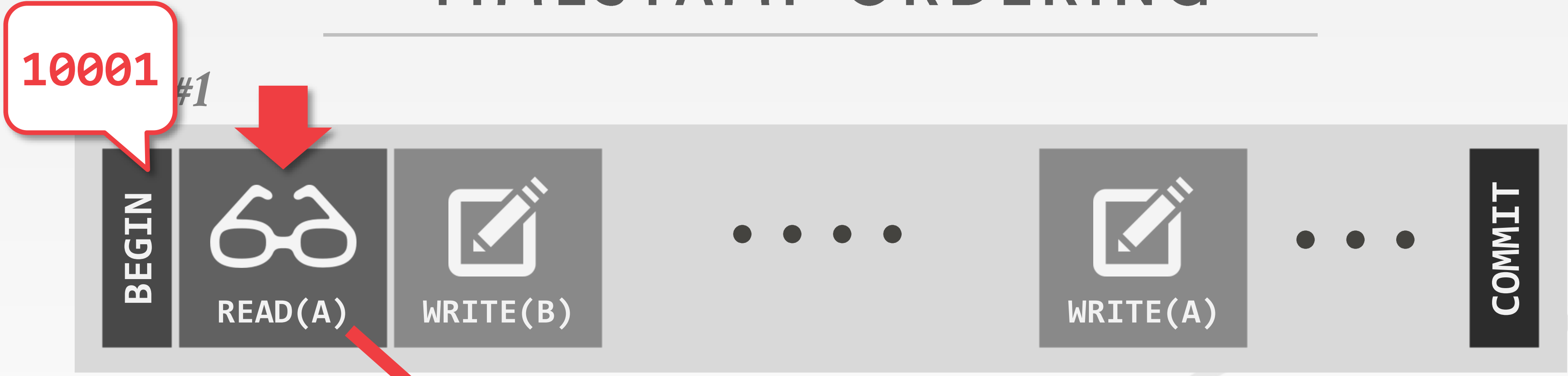
Record	Read Timestamp	Write Timestamp
A	10000	10000
B	10000	10000

TIMESTAMP ORDERING



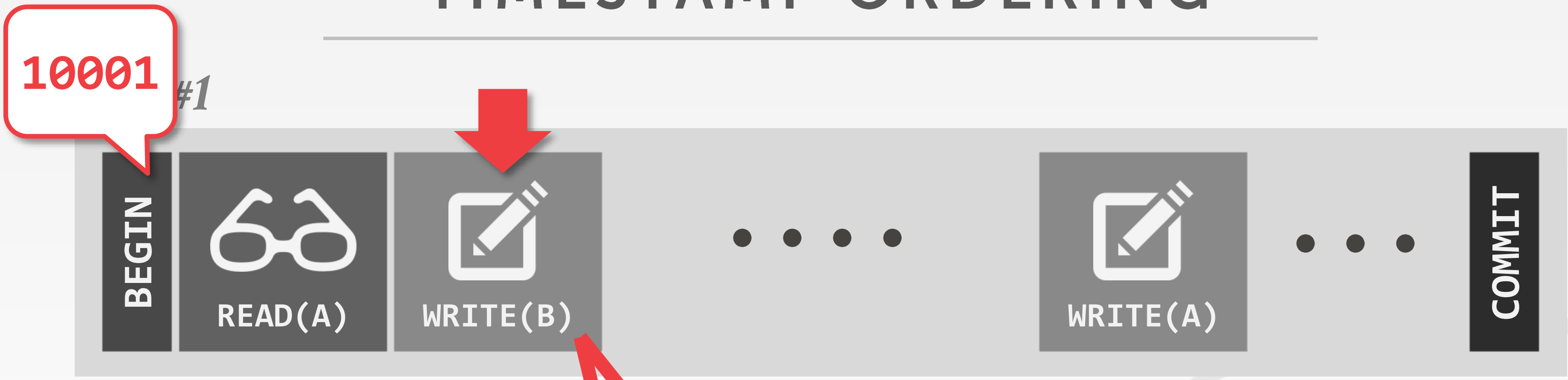
Record	Read Timestamp	Write Timestamp
A	10000	10000
B	10000	10000

TIMESTAMP ORDERING



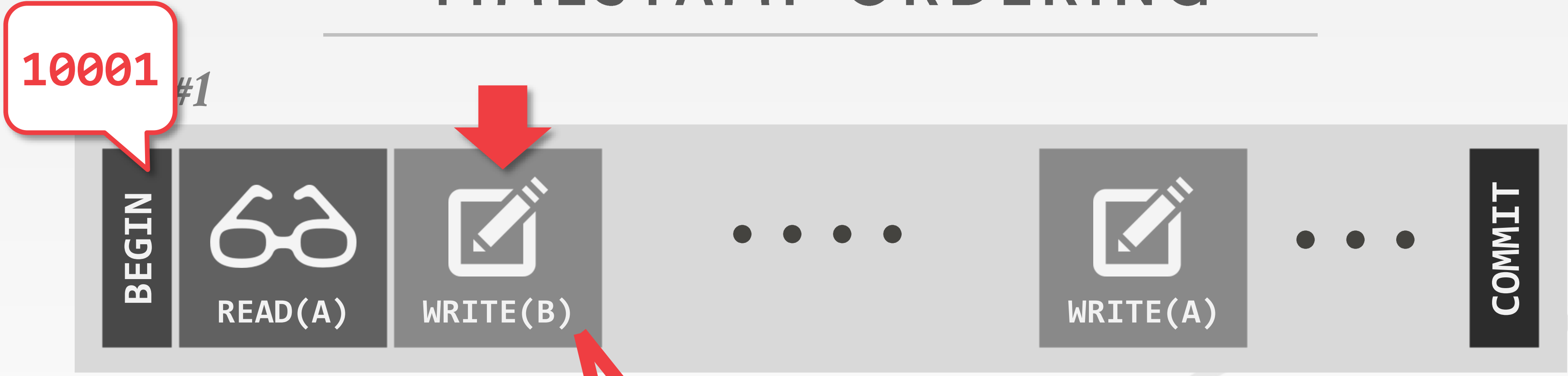
Record	Read Timestamp	Write Timestamp
A	10001	10000
B	10000	10000

TIMESTAMP ORDERING



Record	Read Timestamp	Write Timestamp
A	10001	10000
B	10000	10000

TIMESTAMP ORDERING

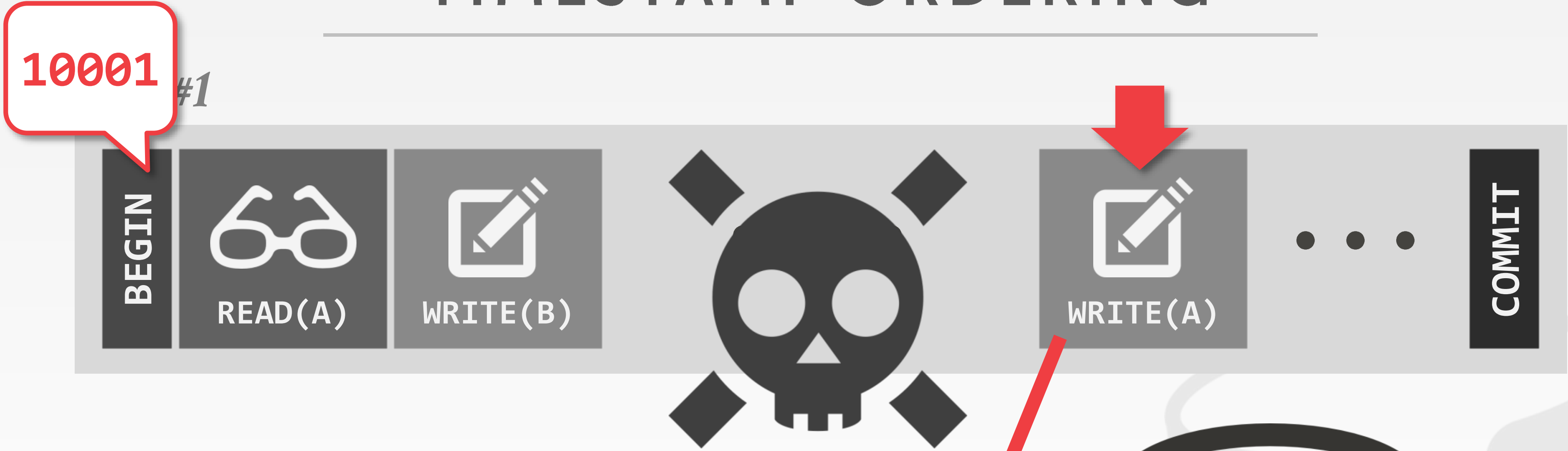


Record	Read Timestamp	Write Timestamp
A	10001	10000
B	10000	10001

TIMESTAMP ORDERING

Record	Read Timestamp	Write Timestamp
A	10001	10005
B	10000	10001

TIMESTAMP ORDERING



Record	Read Timestamp	Write Timestamp
A	10001	10005
B	10000	10001

TIMESTAMP ORDERING

Basic T/O

→ Check for conflicts on each read/write.
→ Copy tuples on each access to ensure repeatable reads.

Optimistic Currency Control (OCC)

→ Store all changes in private workspace.
→ Check for conflicts at commit time and then merge.

OPTIMISTIC CONCURRENCY CONTROL

Timestamp-ordering scheme where txns copy data read/write into a private workspace that is not visible to other active txns.

When a txn commits, the DBMS verifies that there are no conflicts.

First proposed in 1981 at CMU by H.T. Kung.

ON OPTIMISTIC METHODS FOR CONCURRENCY CONTROL
ACM Transactions on Database Systems 1981

OPTIMISTIC CONCURRENCY CONTROL

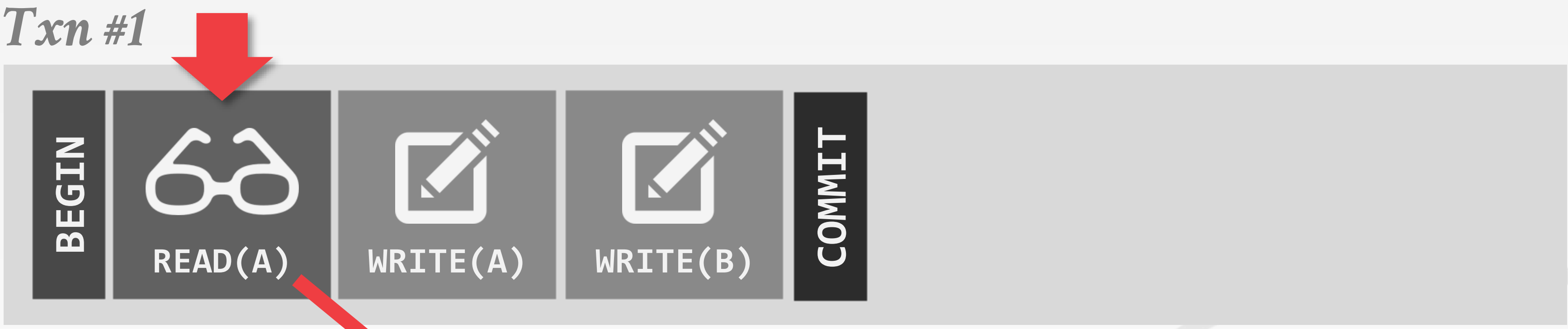
Txn #1

Record	Value	Write Timestamp
A	123	10000
B	456	10000

OPTIMISTIC CONCURRENCY CONTROL

Record	Value	Write Timestamp
A	123	10000
B	456	10000

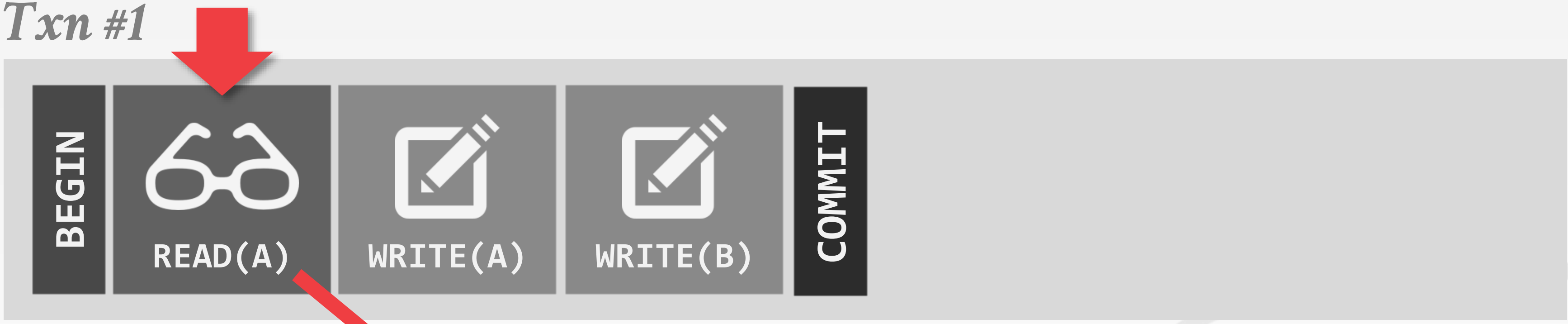
OPTIMISTIC CONCURRENCY CONTROL



Record	Value	Write Timestamp
A	123	10000
B	456	10000

OPTIMISTIC CONCURRENCY CONTROL

Txn #1



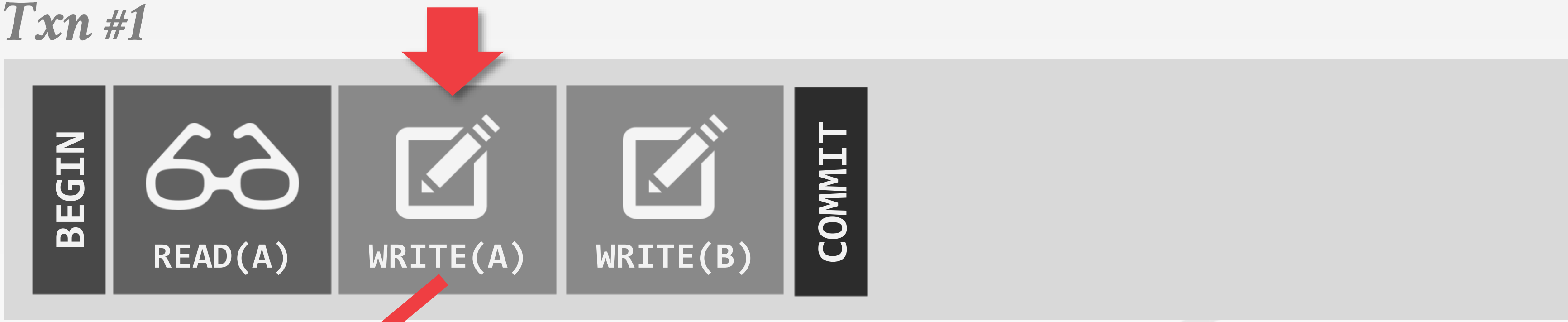
Workspace

Record	Value	Write Timestamp
A	123	10000

Record	Value	Write Timestamp
A	123	10000
B	456	10000

OPTIMISTIC CONCURRENCY CONTROL

Txn #1



Workspace

Record	Value	Write Timestamp
A	123	10000

Record	Value	Write Timestamp
A	123	10000
B	456	10000

OPTIMISTIC CONCURRENCY CONTROL

Txn #1

BEGIN | READ(A) | WRITE(A) | WRITE(B) | COMMIT

Workspace

Record	Value	Write Timestamp
A	888	∞

Record	Value	Write Timestamp
A	123	10000
B	456	10000

OPTIMISTIC CONCURRENCY CONTROL

Txn #1

BEGIN | READ(A) | WRITE(A) | WRITE(B) | COMMIT

Workspace

Record	Value	Write Timestamp
A	888	∞
B	456	10000

Record	Value	Write Timestamp
A	123	10000
B	456	10000

OPTIMISTIC CONCURRENCY CONTROL

Txn #1

BEGIN | READ(A) | WRITE(A) | WRITE(B) | COMMIT

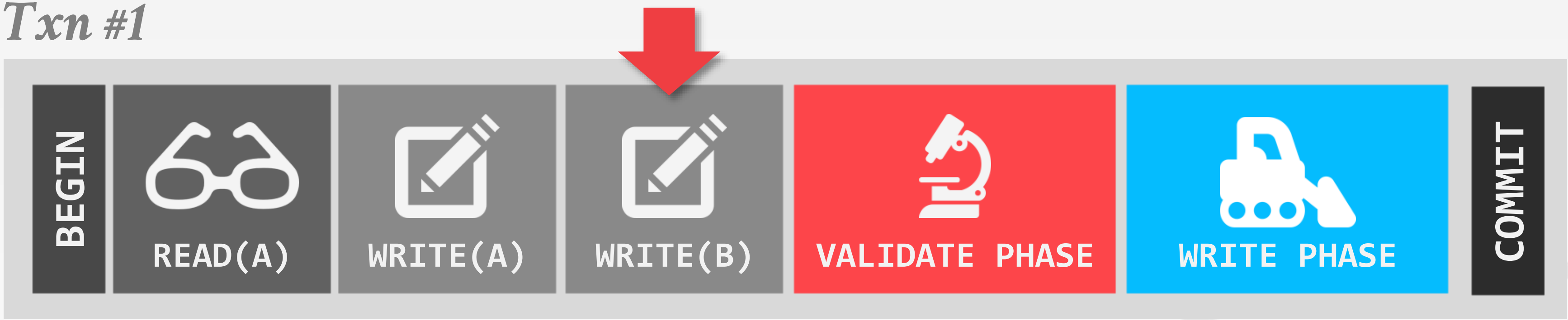
Workspace

Record	Value	Write Timestamp
A	888	∞
B	999	∞

Record	Value	Write Timestamp
A	123	10000
B	456	10000

OPTIMISTIC CONCURRENCY CONTROL

Txn #1



Workspace

Record	Value	Write Timestamp
A	888	∞
B	999	∞

Record	Value	Write Timestamp
A	123	10000
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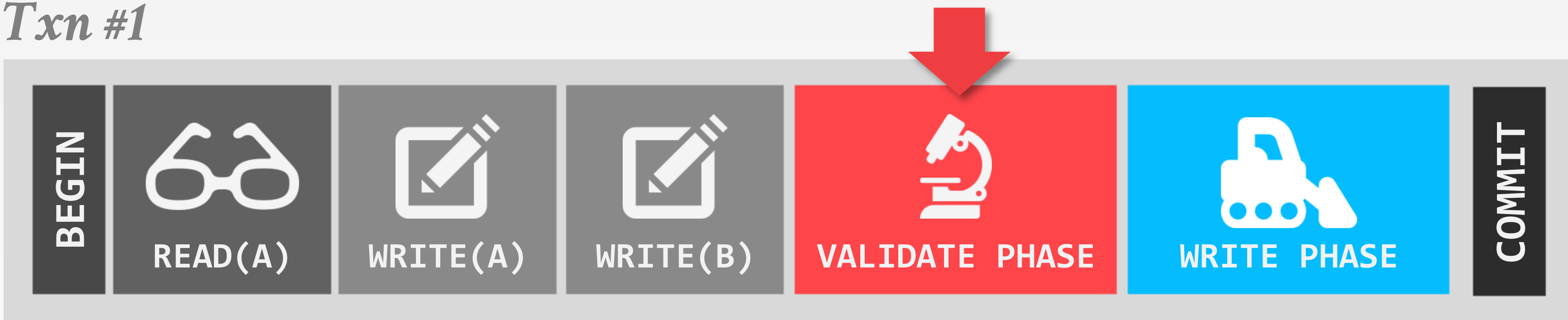
OPTIMISTIC CONCURRENCY CONTROL

Txn #1



Workspace

Record	Value	Write Timestamp
A	888	∞
B	999	∞

Record	Value	Write Timestamp
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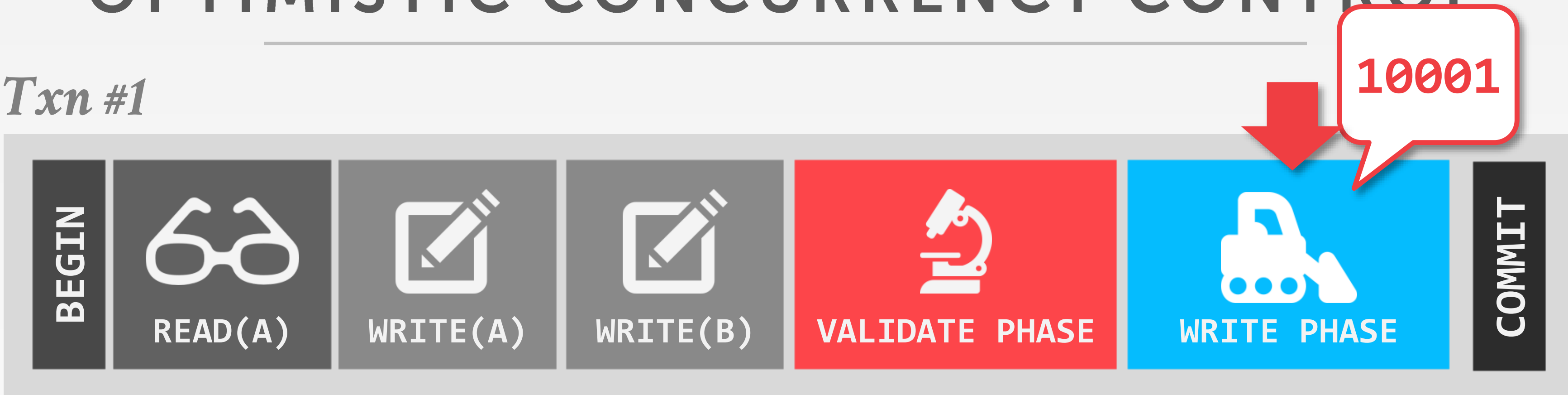
B	456	10000

OPTIMISTIC CONCURRENCY CONTROL

Txn #1



Workspace

Record	Value	Write Timestamp
A	888	∞
B	999	∞

Record	Value	Write Timestamp
A	123	10000
B	456	10000

OPTIMISTIC CONCURRENCY CONTROL

Txn #1

BEGIN | READ(A) | WRITE(A) | WRITE(B) | VALIDATE PHASE | WRITE PHASE | COMMIT

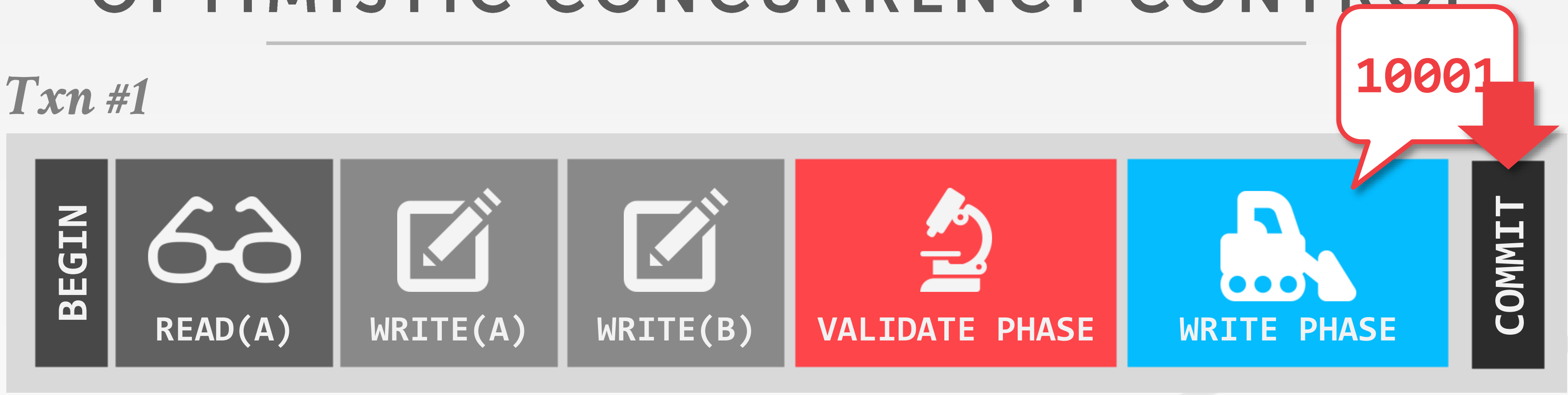
10001

Workspace

Record	Value	Write Timestamp
A	888	∞
B	999	∞

Record	Value	Write Timestamp
A	888	10001
B	999	10001

OPTIMISTIC CONCURRENCY CONTROL



Record	Value	Write Timestamp
A	888	10001
B	999	10001

READ PHASE

Track the read/write sets of txns and store their writes in a private workspace.

The DBMS copies every tuple that the txn accesses from the shared database to its workspace ensure repeatable reads.

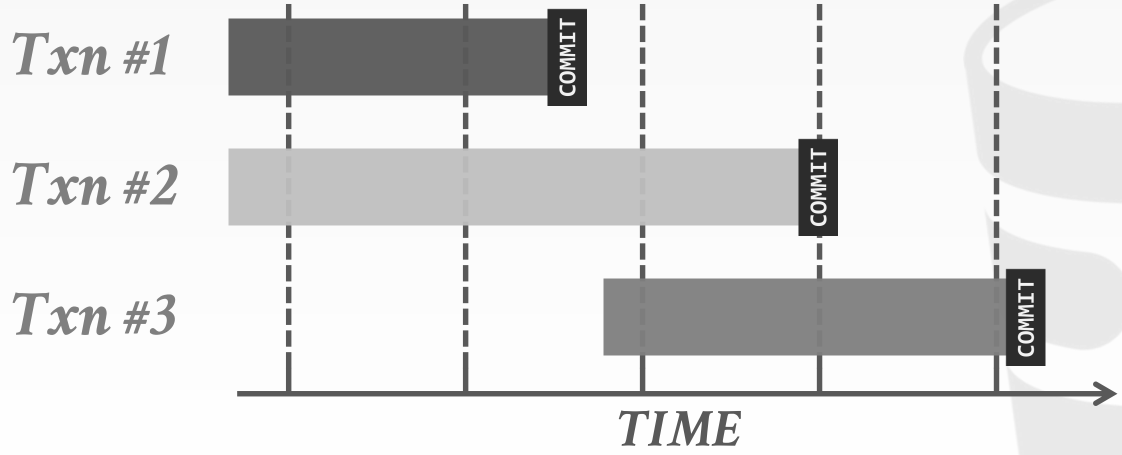
VALIDATION PHASE

When the txn invokes **COMMIT**, the DBMS checks if it conflicts with other txns.

Two methods for this phase:
→ Backward Validation
→ Forward Validation

BACKWARD VALIDATION

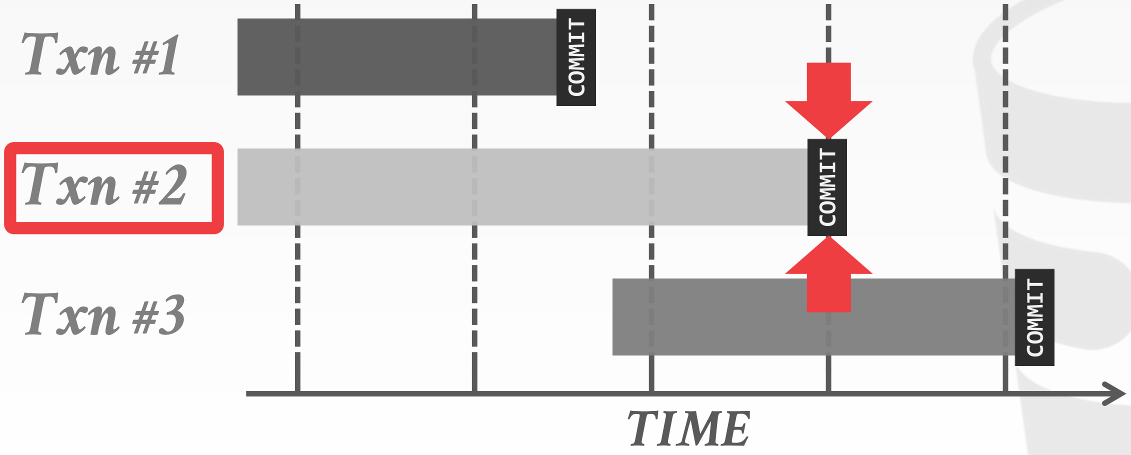
Check whether the committing txn intersects its read/write sets with those of any txns that have **already** committed.



CARNEGIE MELLON
DATABASE GROUP

BACKWARD VALIDATION

Check whether the committing txn intersects its read/write sets with those of any txns that have **already** committed.



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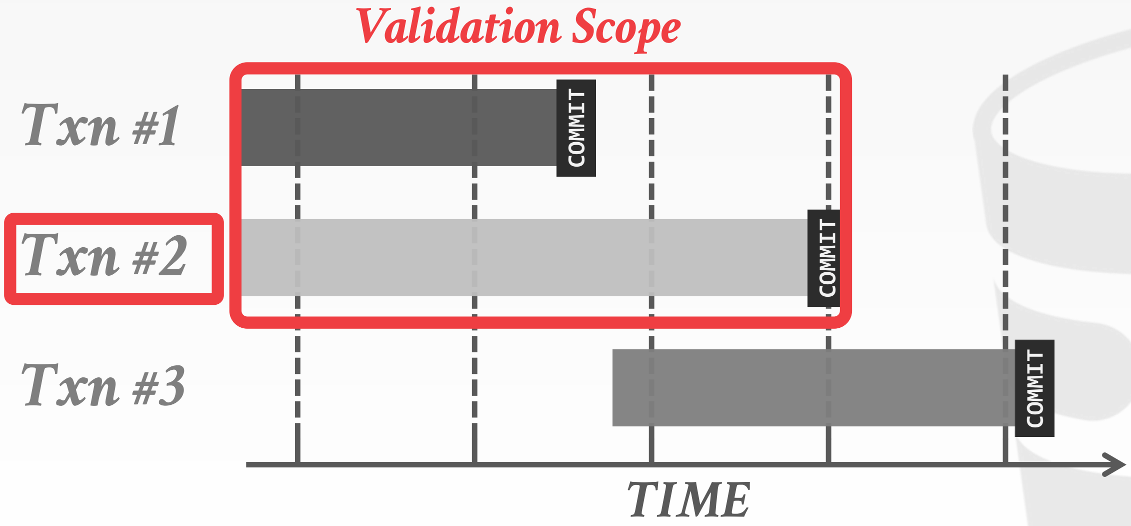
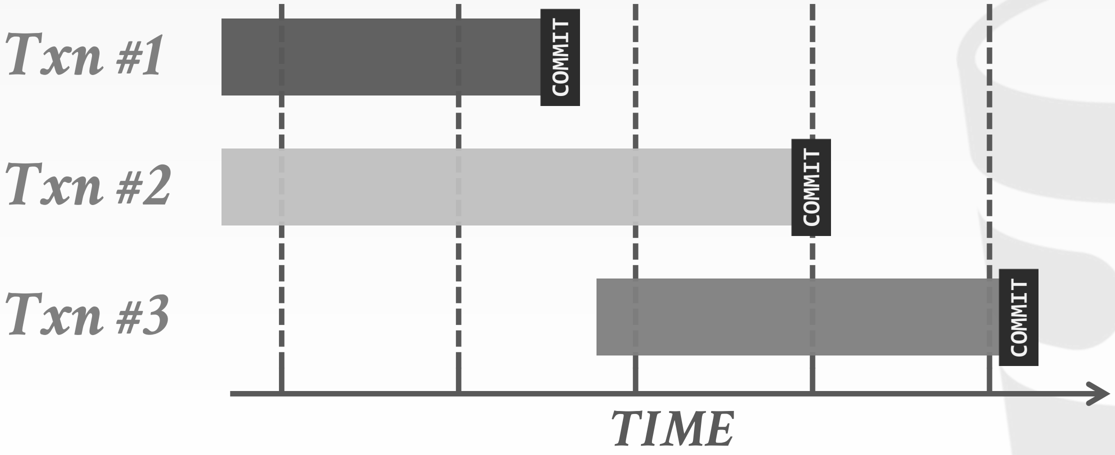


FORWARD VALIDATION

Check whether the committing txn intersects its read/write sets with any active txns that have **not** yet committed.



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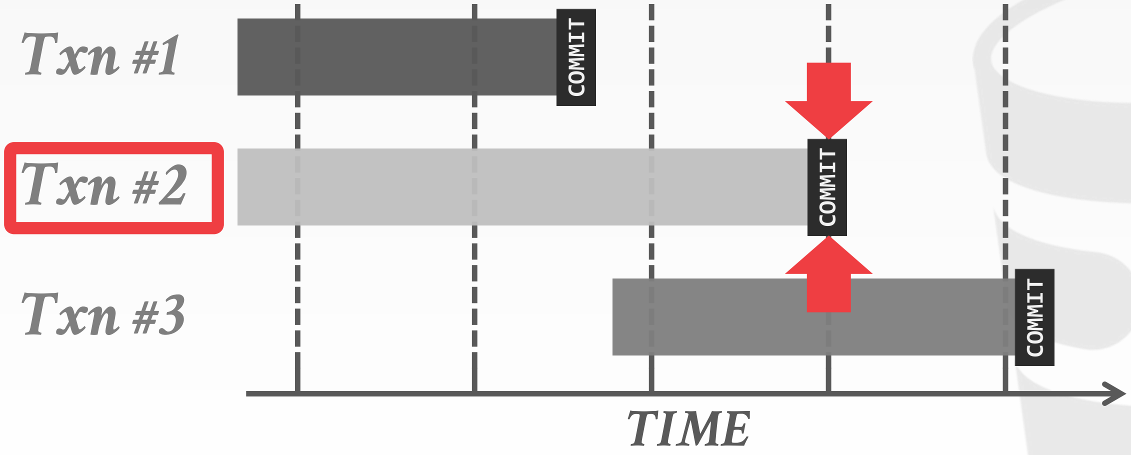

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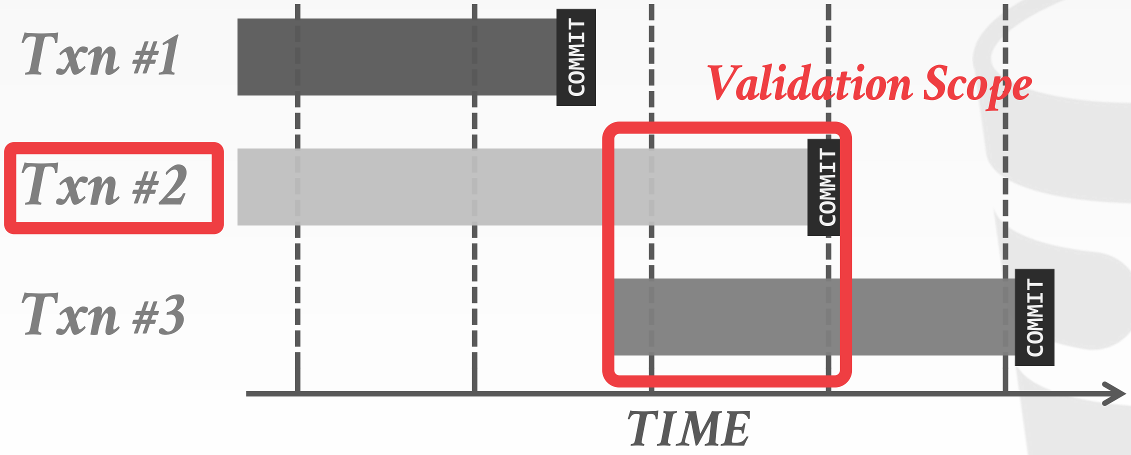
Check whether the committing txn intersects its read/write sets with any active txns that have **not** yet committed.



VALIDATION PHASE

Original OCC uses serial validation.

Parallel validation means that each txn must check the read/write sets of other txns that are trying to validate at the same time.

- → Each txn has to acquire locks for its write set records in some **global order**.
- → The txn does not need locks for read set records.

WRITE PHASE

The DBMS propagates the changes in the txn's write set to the database and makes them visible to other txns.

As each record is updated, the txn releases the lock acquired during the Validation Phase.

TIMESTAMP ALLOCATION

Mutex
→ Worst option. Mutexes are the "Hitler of Concurrency".

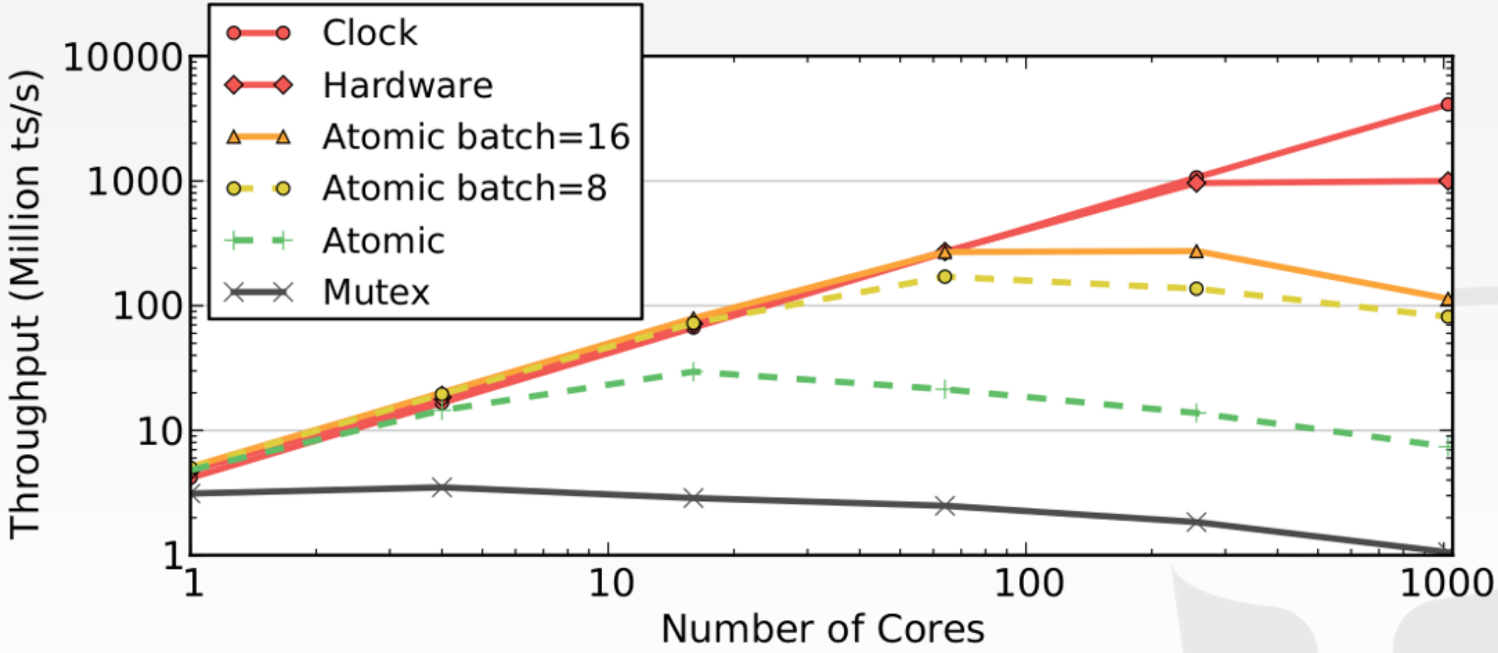
Atomic Addition
→ Requires cache invalidation on write.

Batched Atomic Addition
→ Needs a back-off mechanism to prevent fast burn.

Hardware Clock
→ Not sure if it will exist in future CPUs.

Hardware Counter
→ Not implemented in existing CPUs.

TIMESTAMP ALLOCATION



STARING INTO THE ABYSS: AN EVALUATION OF CONCURRENCY CONTROL WITH ONE THOUSAND CORES
VLDB 2014

MODERN OCC

Harvard/MIT Silo

MIT/CMU TicToc

SILO

Single-node, in-memory OLTP DBMS.
→ Serializable OCC with parallel backward validation.
→ Stored procedure-only API.

No writes to shared-memory for read txns.

Batched timestamp allocation using **epochs**.

Pure awesomeness from Eddie Kohler.

SPEEDY TRANSACTIONS IN MULTICORE IN-MEMORY DATABASES
SOSP 2013

Single

→ Seri

→ Stor

No wr

Batch

Pure a

Session 18: Transactions and Consistency

Thursday 1:30-3:00

Grand Ballroom A

Session Chair: Andy Pavlo (CMU)

- **TARDiS: A Branch-and-Merge Approach To Weak Consistency**
  Natacha Crooks; Youer Pu; Nancy Estrada; Trinabh Gupta; Lorenzo Alvisi; Allen Clement
- **TicToc: Time Traveling Optimistic Concurrency Control**
  Xiangyao Yu; Andy Pavlo; Daniel Sanchez; Srinivas Devadas
- **Scaling Multicore Databases via Constrained Parallel Execution**
  Zhaoguo Wang; Yang Cui; Han Yi; Shuai Mu; haibo Chen; Jinyang Li
- **Towards a Non-2PC Transaction Management in Distributed Database Systems**
  Qian Lin; Pengfei Chang; Gang Chen; Beng Chin Ooi; Kian-Lee Tan; Zhengkui Wang
- **ERMIA: Fast memory-optimized database system for heterogeneous workloads**
  Kangnyeon Kim; Tianzheng Wang; Ryan Johnson; Ippokratis Pandis
- **Transaction Healing: Scaling Optimistic Concurrency Control on Multicores**
  Yingjun Wu; Chee Yong Chan; Kian-Lee Tan

SPEEDY TRANSACTIONS IN
IN-MEMORY DATABASES
SOSP 2013

SILO: EPOCHS

Time is sliced into fixed-length epochs (40ms).

All txns that start in the same epoch will be committed together at the end of the epoch.

→ Txns that span an epoch have to refresh themselves to be carried over into the next epoch.

Worker threads only need to synchronize at the beginning of each epoch.

SILO: TRANSACTION IDS

Each worker thread generates a unique txn id based on the current epoch number and the next value in its assigned batch.

SILO: TRANSACTION IDS

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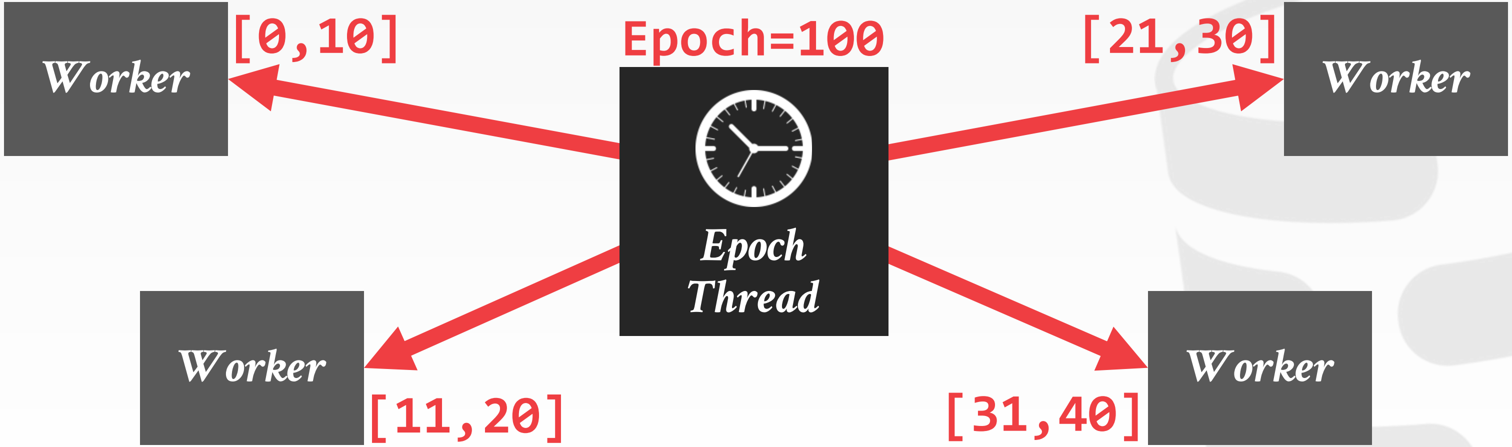

SILO: TRANSACTION IDS

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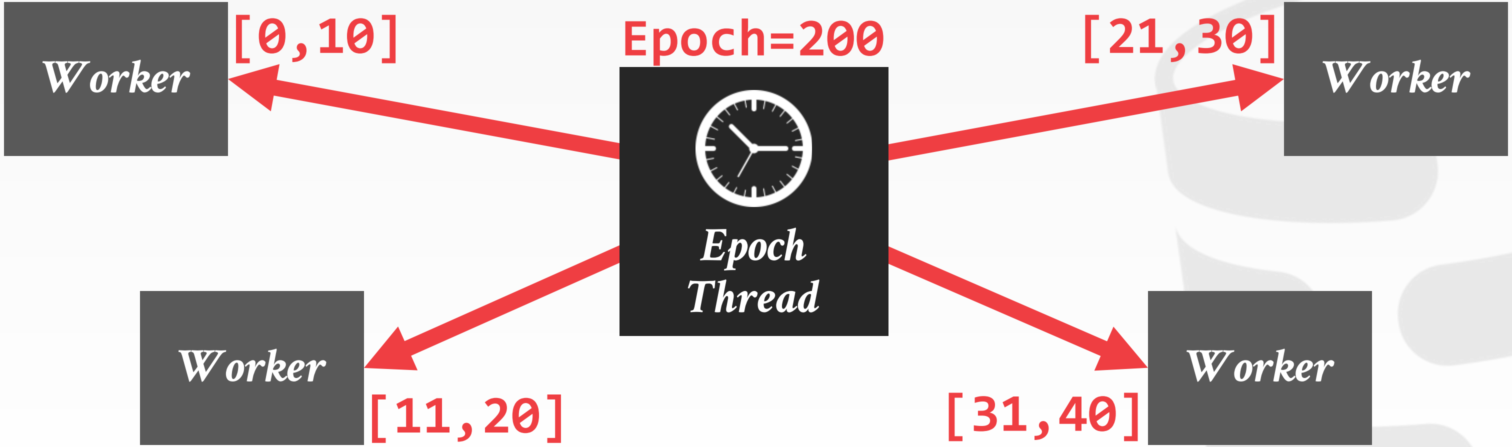

SILO: COMMIT PROTOCOL

TID Word	ATTR1	ATTR2
#-###-#	John	$100
#-###-#	Tupac	$999
#-###-#	Wiz	$67
#-###-#	O.D.B.	$13

Write Lock Bit
Latest Version Bit
Absent Bit

SILO: COMMIT PROTOCOL

Workspace

Read Set

#-###-#	O.D.B.	$13
#-###-#	Tupac	$999

Write Set

Tupac	$777

TID Word	ATTR1	ATTR2
#-###-#	John	$100
#-###-#	Tupac	$999
#-###-#	Wiz	$67
#-###-#	O.D.B.	$13

SILO: COMMIT PROTOCOL

Workspace

Read Set

#-###-#	O.D.B.	$13
#-###-#	Tupac	$999

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TID Word	ATTR1	ATTR2
#-###-#	John	$100
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#-###-#	Wiz	$67
#-###-#	O.D.B.	$13

Step #1: Lock Write Set

SILO: COMMIT PROTOCOL

Workspace

Read Set

#-###-#	O.D.B.	$13
#-###-#	Tupac	$999

Write Set

Tupac	$777

TID Word	ATTR1	ATTR2
#-###-#	John	$100
#-###-#	Tupac	$999
#-###-#	Wiz	$67
#-###-#	O.D.B.	$13

Step #1: Lock Write Set

Step #2: Examine Read Set

SILO: COMMIT PROTOCOL

Workspace

Read Set

#-###-#	O.D.B.	$13
#-###-#	Tupac	$999

Write Set

Tupac	$777

TID Word	ATTR1	ATTR2
#-###-#	John	$100
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Step #1: Lock Write Set

Step #2: Examine Read Set

SILO: COMMIT PROTOCOL

Workspace

Read Set

#-###-#	O.D.B.	$13
#-###-#	Tupac	$999

Write Set

Tupac	$777

???

TID Word	ATTR1	ATTR2
#-###-#	John	$100
#-###-#	Tupac	$999
#-###-#	Wiz	$67
#-###-#	O.D.B.	$13

Step #1: Lock Write Set

Step #2: Examine Read Set

SILO: COMMIT PROTOCOL

Workspace

Read Set

#-###-#	O.D.B.	$13
#-###-#	Tupac	$999

Write Set

Tupac	$777

TID Word	ATTR1	ATTR2
#-###-#	John	$100
#-###-#	Tupac	$999
#-###-#	Wiz	$67
#-###-#	O.D.B.	$13

Step #1: Lock Write Set

Step #2: Examine Read Set

SILO: COMMIT PROTOCOL

Workspace

Read Set

#-###-#	O.D.B.	$13
#-###-#	Tupac	$999

Write Set

Tupac	$777

TID Word	ATTR1	ATTR2
#-###-#	John	$100
#-###-#	Tupac	$777
#-###-#	Wiz	$67
#-###-#	O.D.B.	$13

Step #1: Lock Write Set

Step #2: Examine Read Set

Step #3: Install Write Set

SILO: GARBAGE COLLECTION

Cooperative threads GC.

Each worker thread marks a deleted object with a **reclamation epoch**.

→ This is the epoch after which no thread could access the object again, and thus can be safely removed.
→ Object references are maintained in thread-local storage to avoid unnecessary data movement.

SILO: RANGE QUERIES

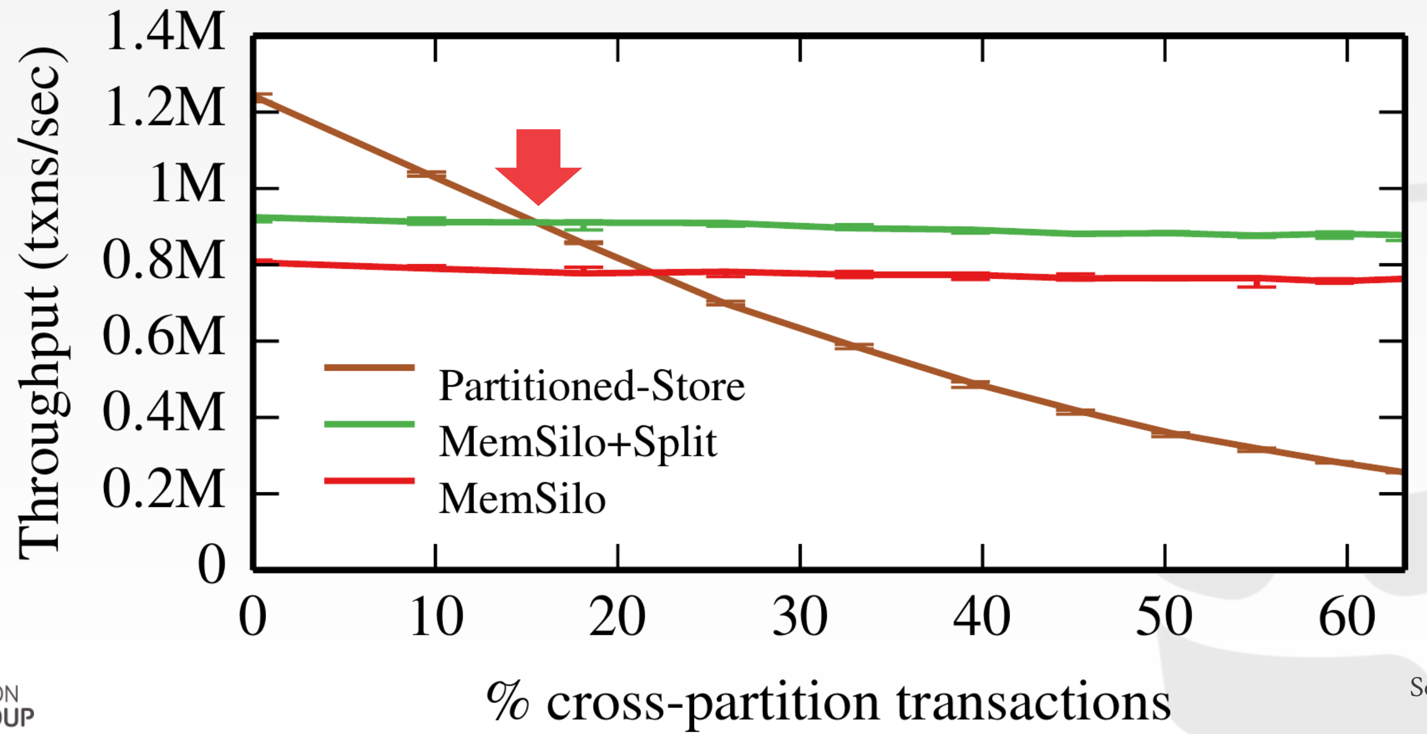
DBMS handles phantoms by tracking the txn's scan set (node set) on indexes.

→ Re-execute scans in the validation phase to see whether the index has changed.
→ Have to include "virtual" entries for keys that do not exist in the index.

We will discuss **key-range** and **index gap** locking next week…

SILO: PERFORMANCE

Database: TPC-C with 28 Warehouses
Processor: 4 sockets, 8 cores per socket



Source: Eddie Kohler

TICTOC

Serializable OCC implemented in DBx1000.

→ Parallel backward validation

→ Stored procedure-only API

No global timestamp allocation.
Txn timestamps are derived from records.

TICTOC: TIME-TRAVELING OPTIMISTIC CONCURRENCY CONTROL
SIGMOD 2016

TICTOC: RECORD TIMESTAMPS

Write Timestamp (W-TS):

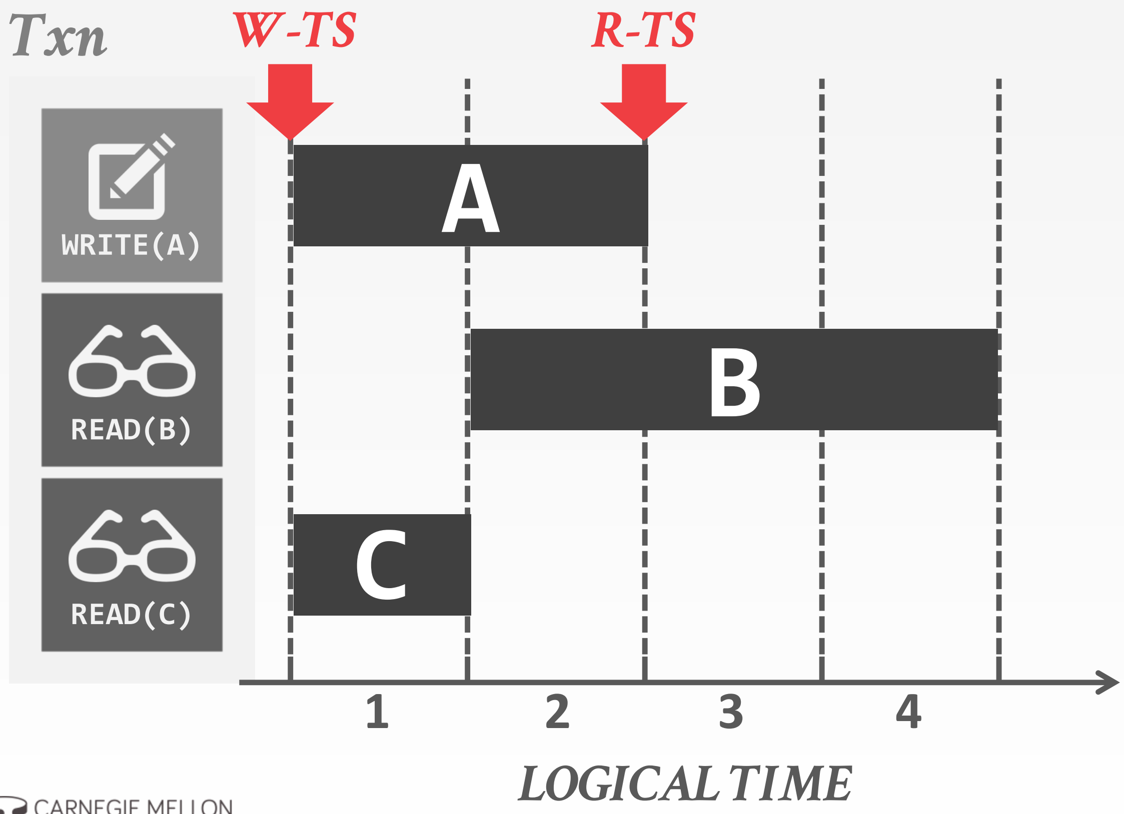
→ The logical timestamp of the last committed txn that wrote to the record.

Read Timestamp (R-TS):

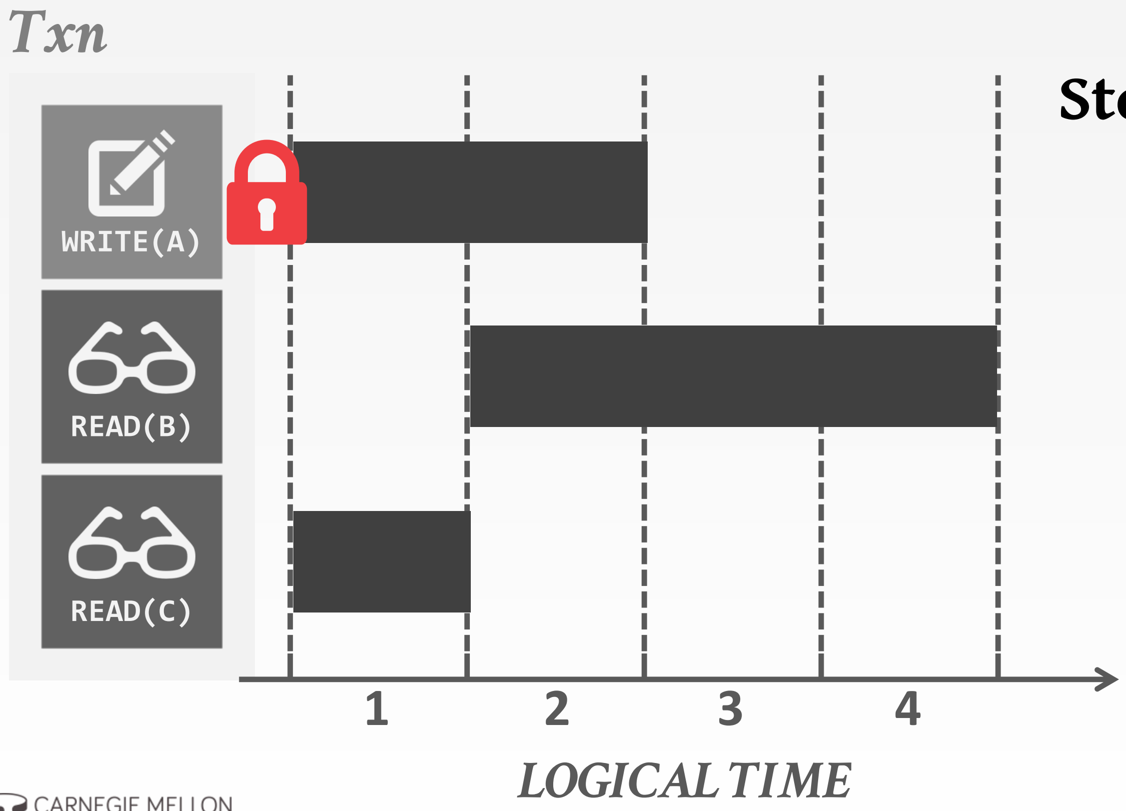
→ The logical timestamp of the last txn that read the record.

A record is considered valid from W-TS to R-TS

TICTOC: VALIDATION PHASE



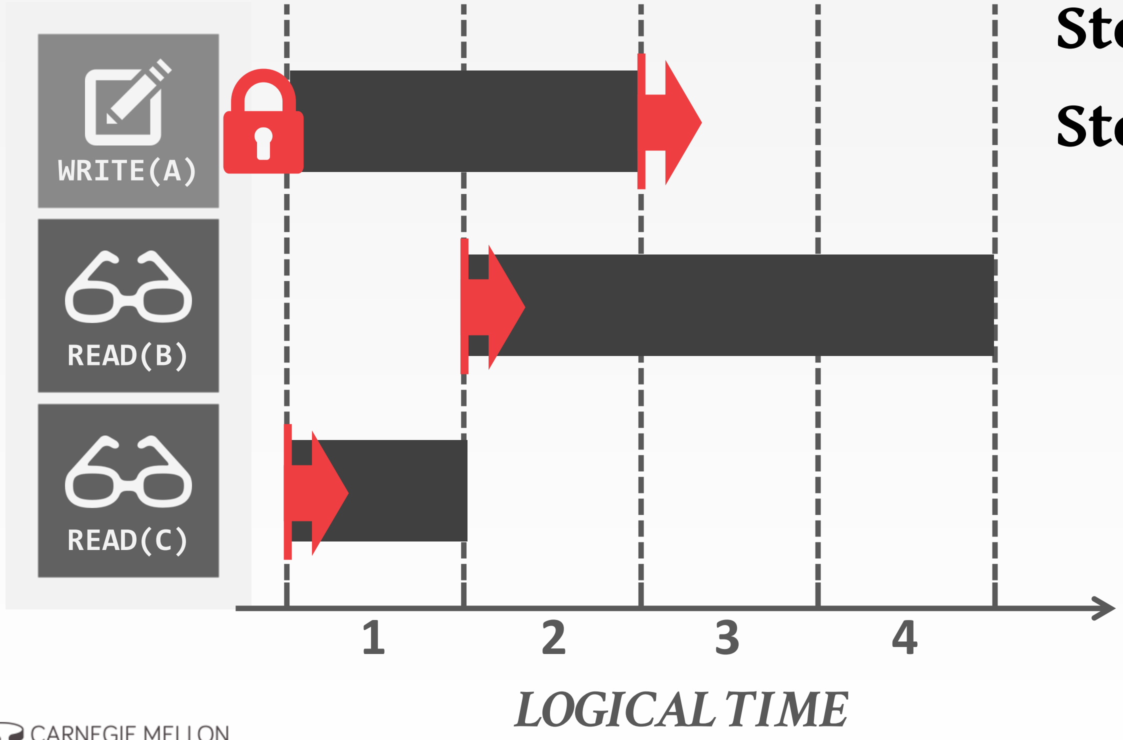
TICTOC: VALIDATION PHASE



Step #1: Lock Write Set

TICTOC: VALIDATION PHASE

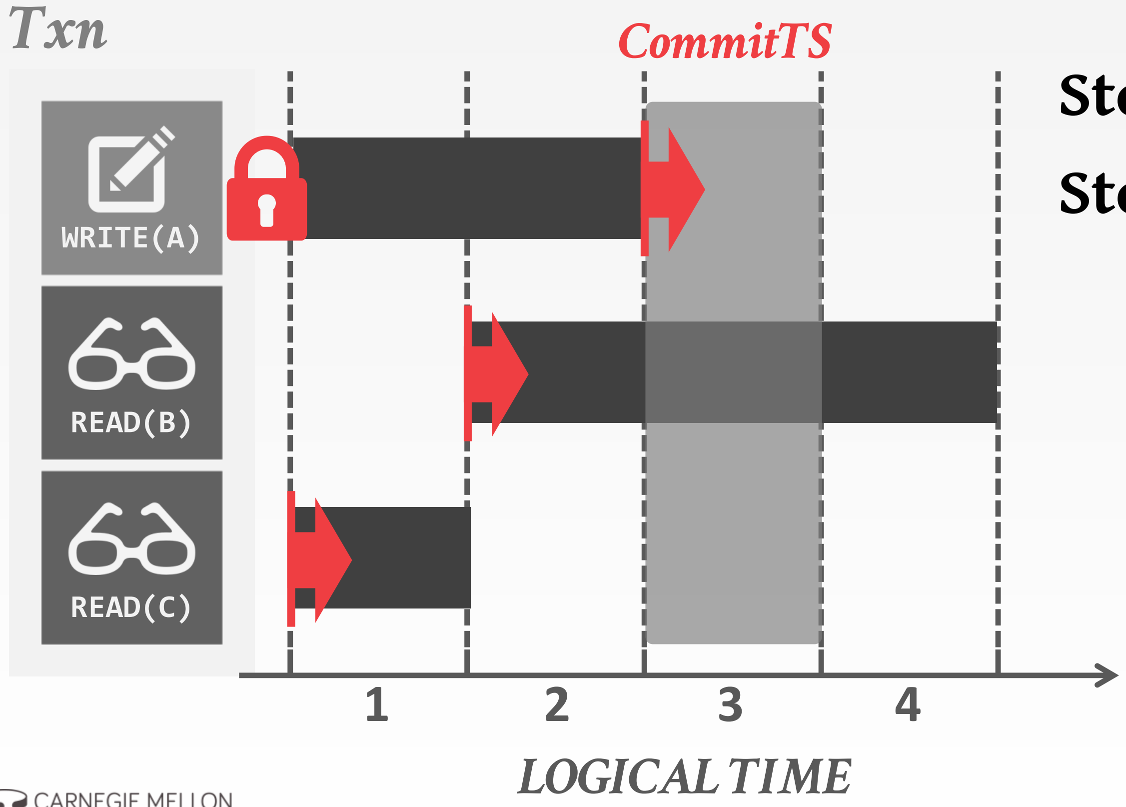
Txn



Step #1: Lock Write Set

Step #2: Compute CommitTS

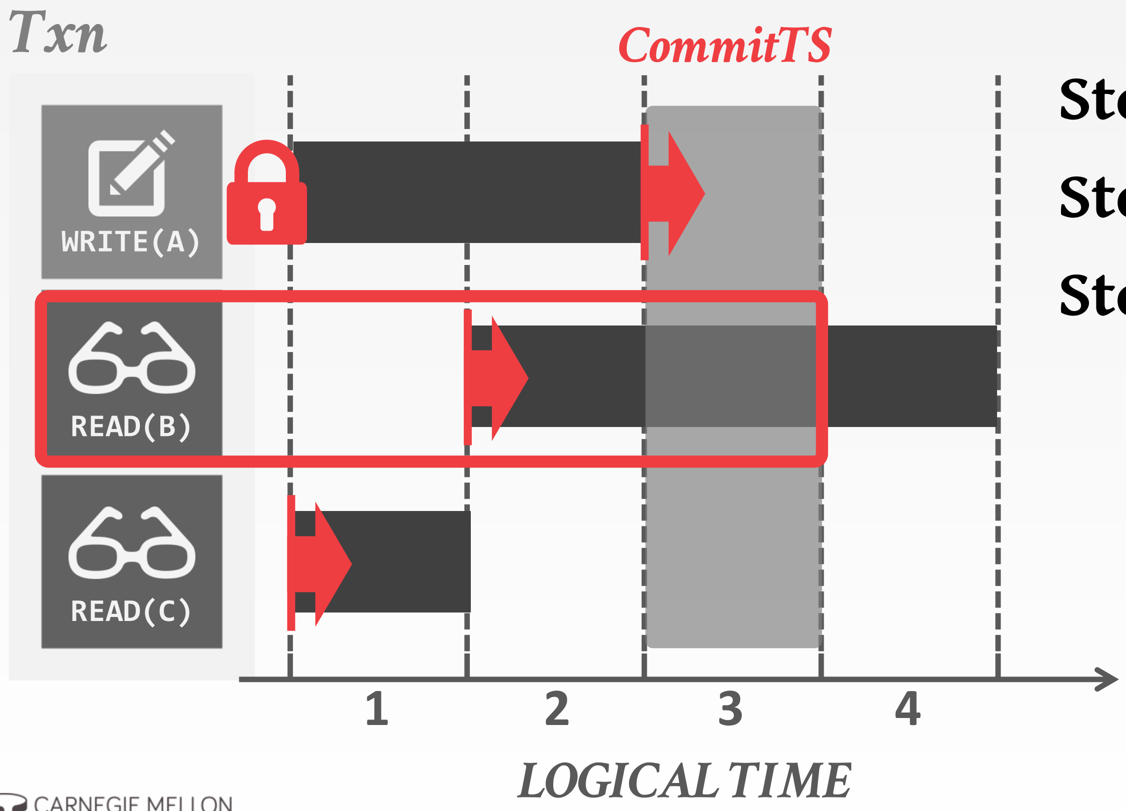
TICTOC: VALIDATION PHASE



Step #1: Lock Write Set

Step #2: Compute CommitTS

TICTOC: VALIDATION PHASE

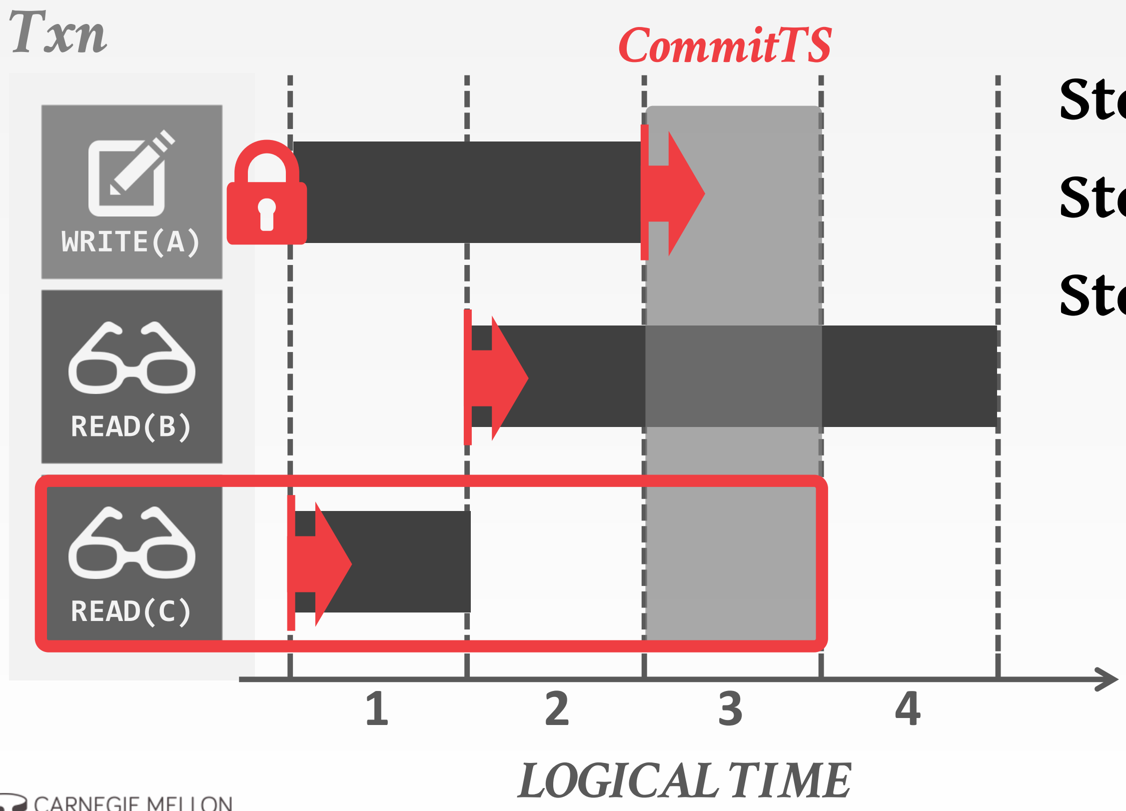


Step #1: Lock Write Set

Step #2: Compute CommitTS

Step #3: Validate Read Set

TICTOC: VALIDATION PHASE

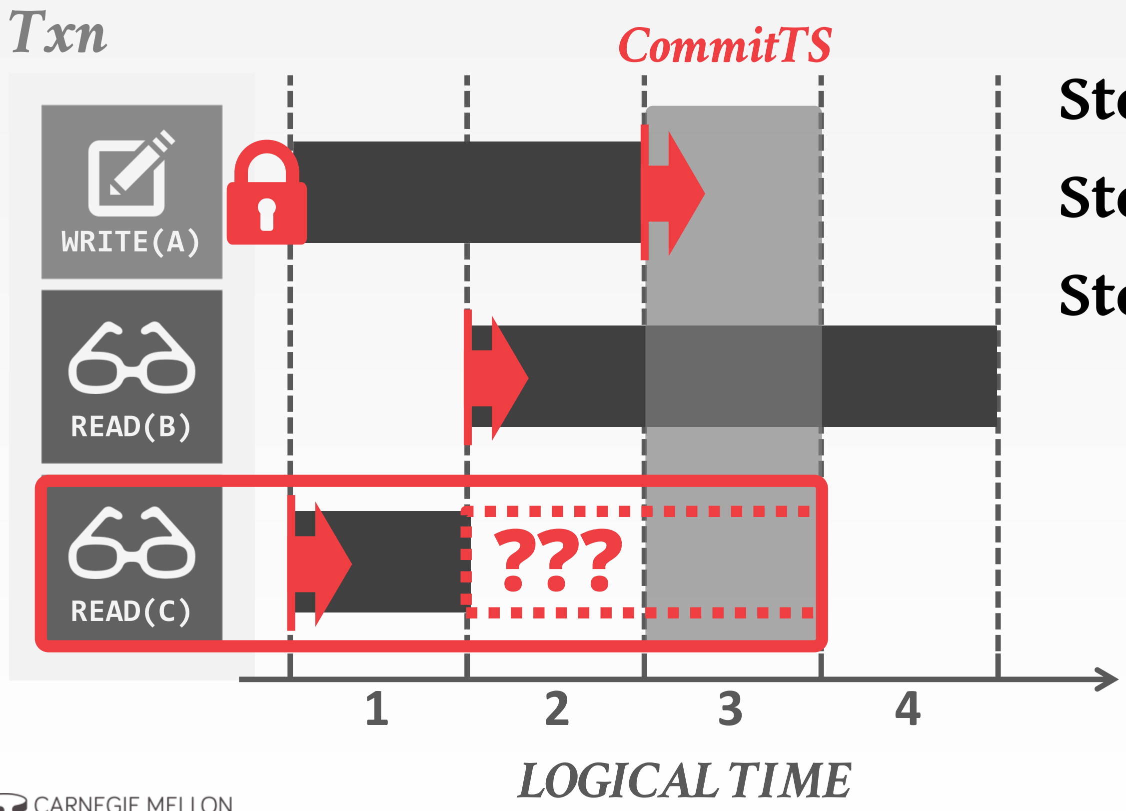


Step #1: Lock Write Set

Step #2: Compute CommitTS

Step #3: Validate Read Set

TICTOC: VALIDATION PHASE

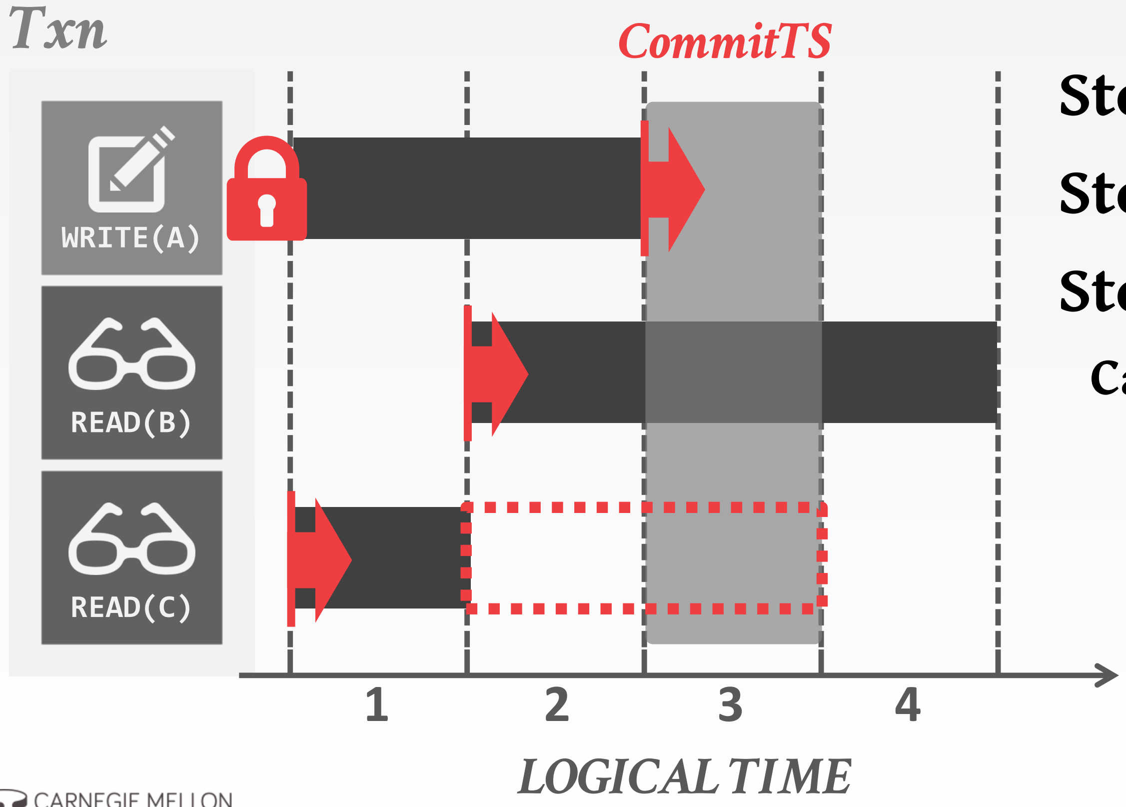


Step #1: Lock Write Set

Step #2: Compute CommitTS

Step #3: Validate Read Set

TICTOC: VALIDATION PHASE



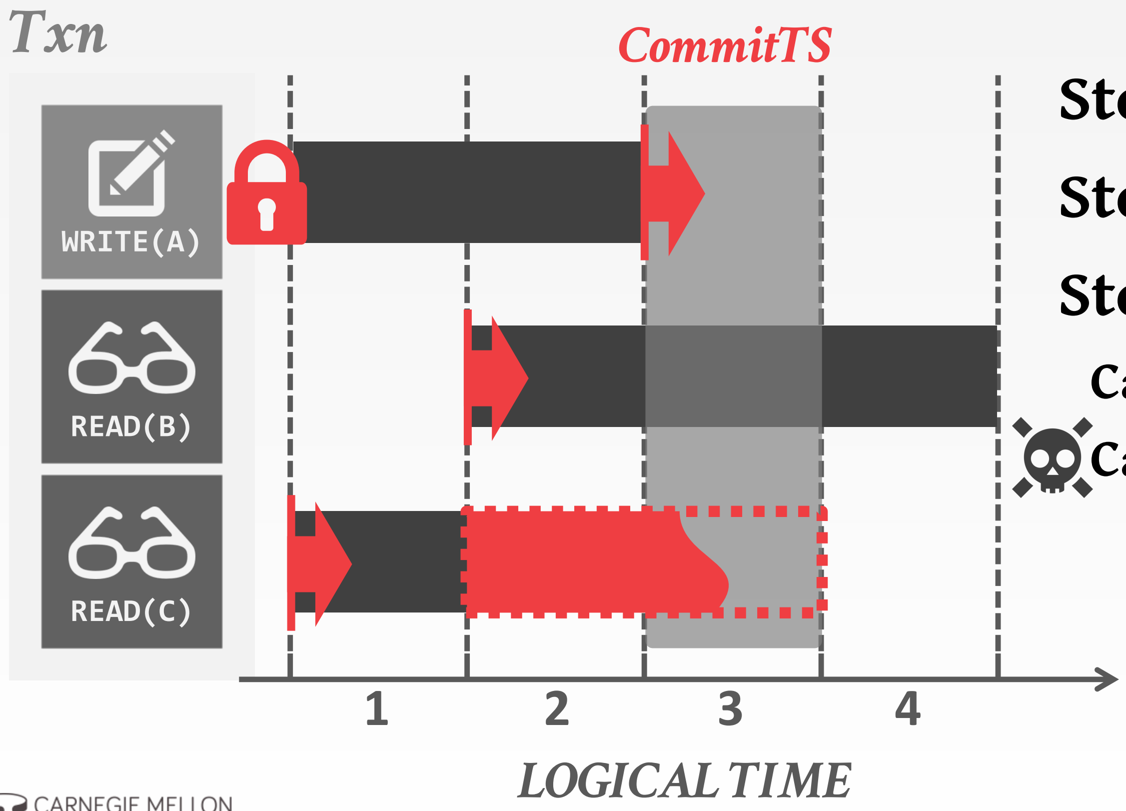
Step #1: Lock Write Set

Step #2: Compute CommitTS

Step #3: Validate Read Set

Case 1: Latest Version

TICTOC: VALIDATION PHASE



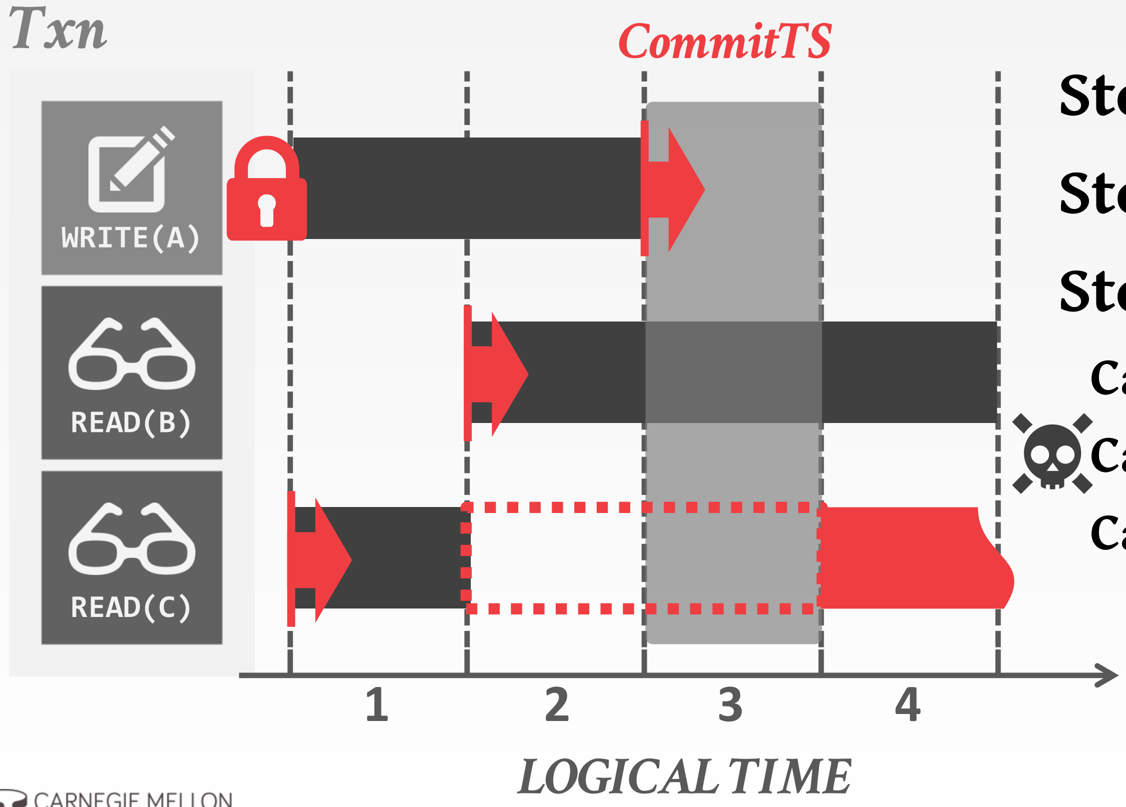
Step #1: Lock Write Set

Step #2: Compute CommitTS

Step #3: Validate Read Set

- **Case 1:** Latest Version
- **Case 2:** Updated Before CommitTS

TICTOC: VALIDATION PHASE



Step #1: Lock Write Set

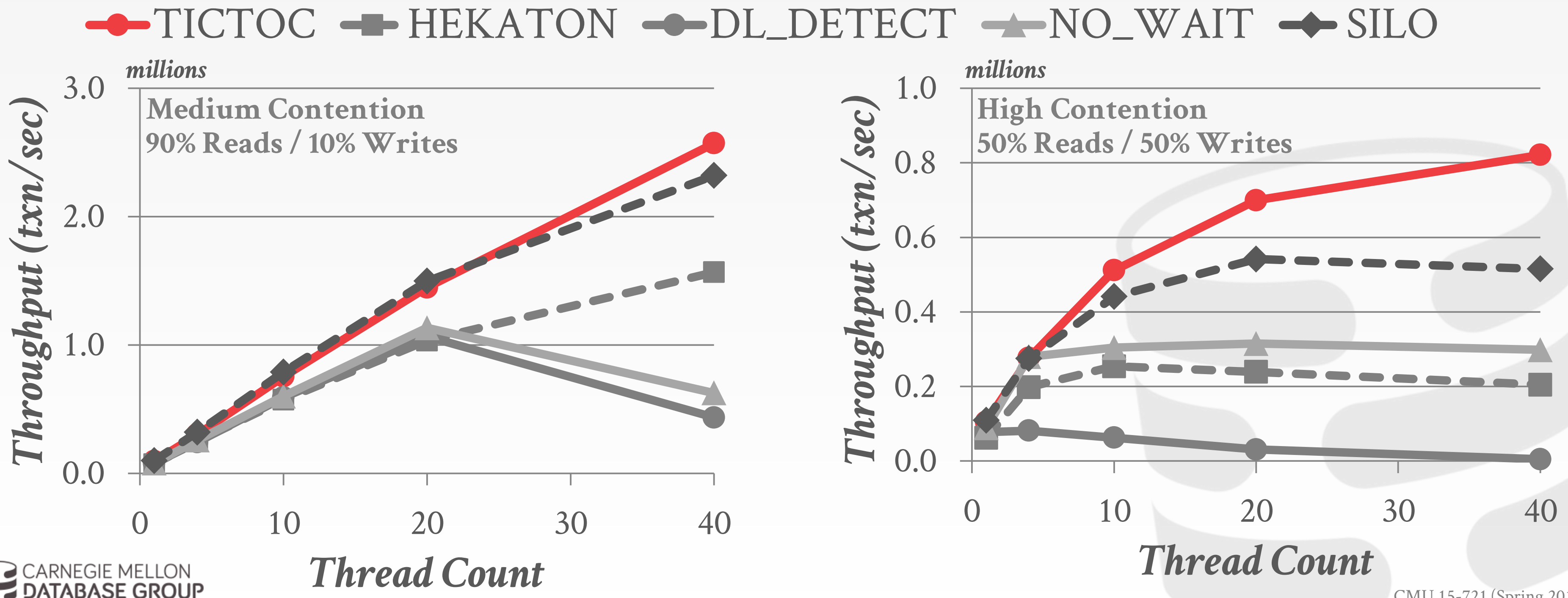
Step #2: Compute CommitTS

Step #3: Validate Read Set

- **Case 1:** Latest Version
- **Case 2:** Updated Before CommitTS
- **Case 3:** Updated After CommitTS

TICTOC: PERFORMANCE

Database: 10GB YCSB
Processor: 4 sockets, 10 cores per socket



PARTING THOUGHTS

Trade-off between aborting txns early or later.

→ **Early**: Avoid wasted work for txns that will eventually abort, but has checking overhead.

→ **Later**: No runtime overhead but lots of wasted work under high contention.

Silo is a very influential system.

NEXT CLASS

Multi-Version Concurrency Control

Paper ID	366
Title	This is the Best Paper Ever on In-Memory Multi-Version Concurrency Control

Masked Meta-Reviewer ID: Meta_Reviewer_1

Meta-Reviews:

Question	
Overall Rating	Revise
Summary Comments	Dear Authors, Thank you for your submission to PVLDB Vol 10. We have now received the reviews for your manuscript as an "Experiments and Analyses Papers" paper from the Review Board. While the reviewers appreciate your research results, they have given a substantial amount of comments for your revision (enclosed). We encourage you to revise your paper taking into consideration of the reviewer comments, and submit an improved version of the manuscript in due course. Regards, Associate Editor
	- Remove "This is the Best Paper Ever" from the title and revise it to be scientific and reflect the experimental nature of the work. from design issues in the classification to make the taxonomy more general.