Intro to Database Systems (15-445/645)

17 Timestamp Ordering

Carnegie Mellon University

SPRING 2023

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ADMINISTRIVIA

Project 3 ongoing
→ Due Sunday, April 9th at 11:59 p.m.

Homework 4 released today
→ Due Friday, April 7th at 11:59 p.m.

Final exam Monday, May 1st, 8:30 – 11:30 a.m.

PROJECT #3 – QUERY EXECUTION

You will add support for executing queries in BusTub.

BusTub supports (basic) SQL with a rule-based optimizer for converting AST into physical plans.

***Prompt**: A realistic photo of a bath tub with wheels and cartoon eyes driving down a city street.*

https://15445.courses.cs.cmu.edu/spring2023/project3/

PROJECT #3 – TASKS

Plan Node Executors

→ Access Methods: Sequential Scan, Index Scan
→ Modifications: Insert, Update, Delete
→ Joins: Nested Loop Join, Hash Join
→ Miscellaneous: Aggregation, Limit, Sort, Top-N

Optimizer Rules:

→ Convert Nested Loop Join into a Hash Join
→ Convert `ORDER BY` + `LIMIT` into a Top-N

PROJECT #3 - LEADERBOARD

The leaderboard requires you to add additional rules to the optimizer to generate query plans.

→ It will be impossible to get a top ranking by just having the fastest implementations in Project #1 + Project #2.

DEVELOPMENT HINTS

Implement the **Insert** and **Sequential Scan** executors first so that you can populate tables and read from it.

You do **not** need to worry about transactions.

The aggregation and hash join hash tables do not need to be backed by the buffer pool (i.e., use STL)

Gradescope is meant for grading, not debugging. Please write your own local tests.

THINGS TO NOTE

Do **not** change any file other than the ones that you submit to Gradescope.

Make sure you pull in the latest changes from the BusTub main branch.

Post your questions on Piazza or come to TA office hours.

Compare against our solution in your browser!

LAST TIME: TWO-PHASE LOCKING

Two-phase locking (2PL)
→ Regular 2PL
→ Strong strict 2PL

Deadlocks
→ Detection
→ Prevention

Hierarchical intention locks

INTENTION LOCKS

Intention-Shared (IS)

→ Indicates explicit locking at lower level with S locks.

→ Intent to get S lock(s) at finer granularity.

Intention-Exclusive (IX)

→ Indicates explicit locking at lower level with X locks.

→ Intent to get X lock(s) at finer granularity.

Shared+Intention-Exclusive (SIX)

→ The subtree rooted by that node is locked explicitly in S mode and explicit locking is being done at a lower level with X locks.

COMPATIBILITY MATRIX

T_2 Wants

T_1 Holds	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

CONCURRENCY CONTROL APPROACHES

Two-Phase Locking (2PL)
→ Determine serializability order of conflicting operations at runtime while txns execute.

Pessimistic

Timestamp Ordering (T/O)
→ Determine serializability order of txns before they execute.

Optimistic

T/O CONCURRENCY CONTROL

Use timestamps to determine the serializability order of txns.

If $TS(T_i) < TS(T_j)$, then the DBMS must ensure that the execution schedule is equivalent to a serial schedule where T_i appears before T_j.

TIMESTAMP ALLOCATION

Each txn T_i is assigned a unique fixed timestamp that is monotonically increasing

- → Let $TS(T_i)$ be the timestamp allocated to txn T_i
- → Different schemes assign timestamps at different times during the txn

Multiple implementation strategies:

- → System/Wall Clock
- → Logical Counter
- → Hybrid

TODAY'S AGENDA

Basic Timestamp Ordering (T/O) Protocol
Optimistic Concurrency Control
The Phantom Problem (maybe)

BASIC TIMESTAMP ORDERING (T/O)

Txns read and write objects without locks.

Every object X is tagged with timestamp of the last txn that successfully did read/write:
→ W-TS(X) – Write timestamp on X
→ R-TS(X) – Read timestamp on X

Check timestamps for every operation:
→ If txn tries to access an object written with a higher (future) timestamp, it aborts and restarts

BASIC T/O – READS

If $TS(T_i) < W\text{-}TS(X)$, this violates timestamp order of T_i with regard to the writer of X.

→ Abort T_i and restart it with a new TS.

Else:

→ Allow T_i to read X.

→ Update $R\text{-}TS(X)$ to $\max(R\text{-}TS(X), TS(T_i))$

→ Make a local copy of X to ensure repeatable reads for T_i.

BASIC T/O – WRITES

If $TS(T_i) < R\text{-}TS(X)$ or $TS(T_i) < W\text{-}TS(X)$

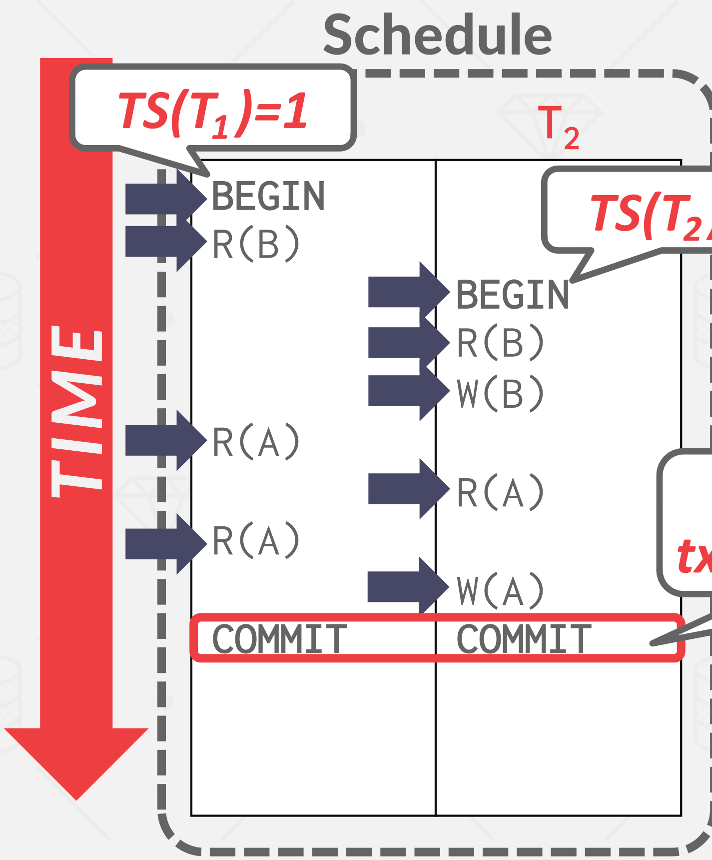
→ Abort and restart T_i.

Else:

→ Allow T_i to write X and update W-TS(X)

→ Also make a local copy of X to ensure repeatable reads.

BASIC T/O – EXAMPLE #1



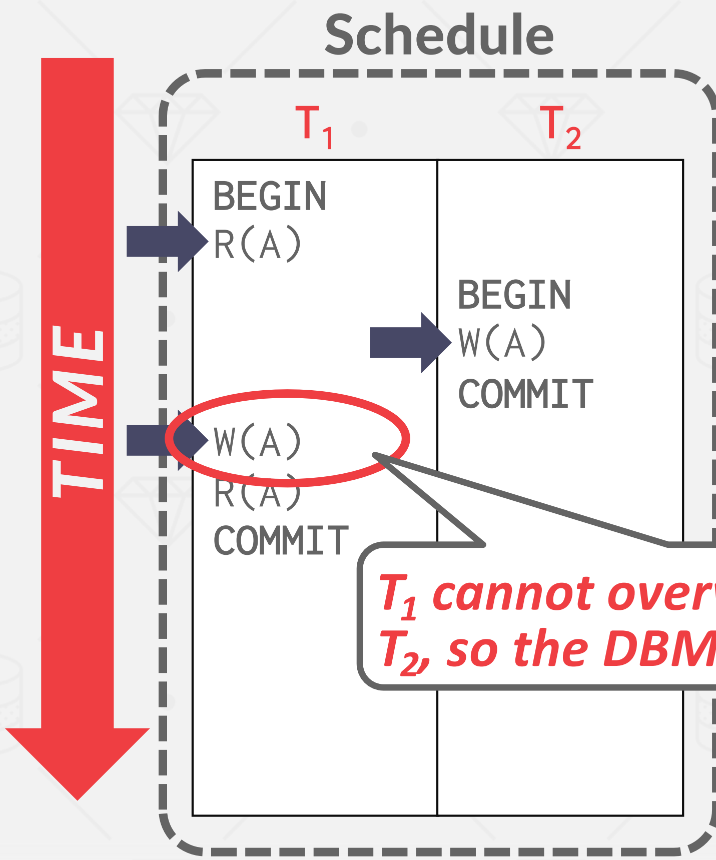
Database

$TS(T_1) < TS(T_2)$

Object	R-TS	W-TS
A	2	2
B	2	2

No violations so both txns are safe to commit.

BASIC T/O – EXAMPLE #2



T_1 cannot overwrite update by T_2, so the DBMS must abort it!

Database

Object	R-TS	W-TS
A	1	2
B	0	0

Violation: $TS(T_1) < W\text{-}TS(A)$

If T

→ A

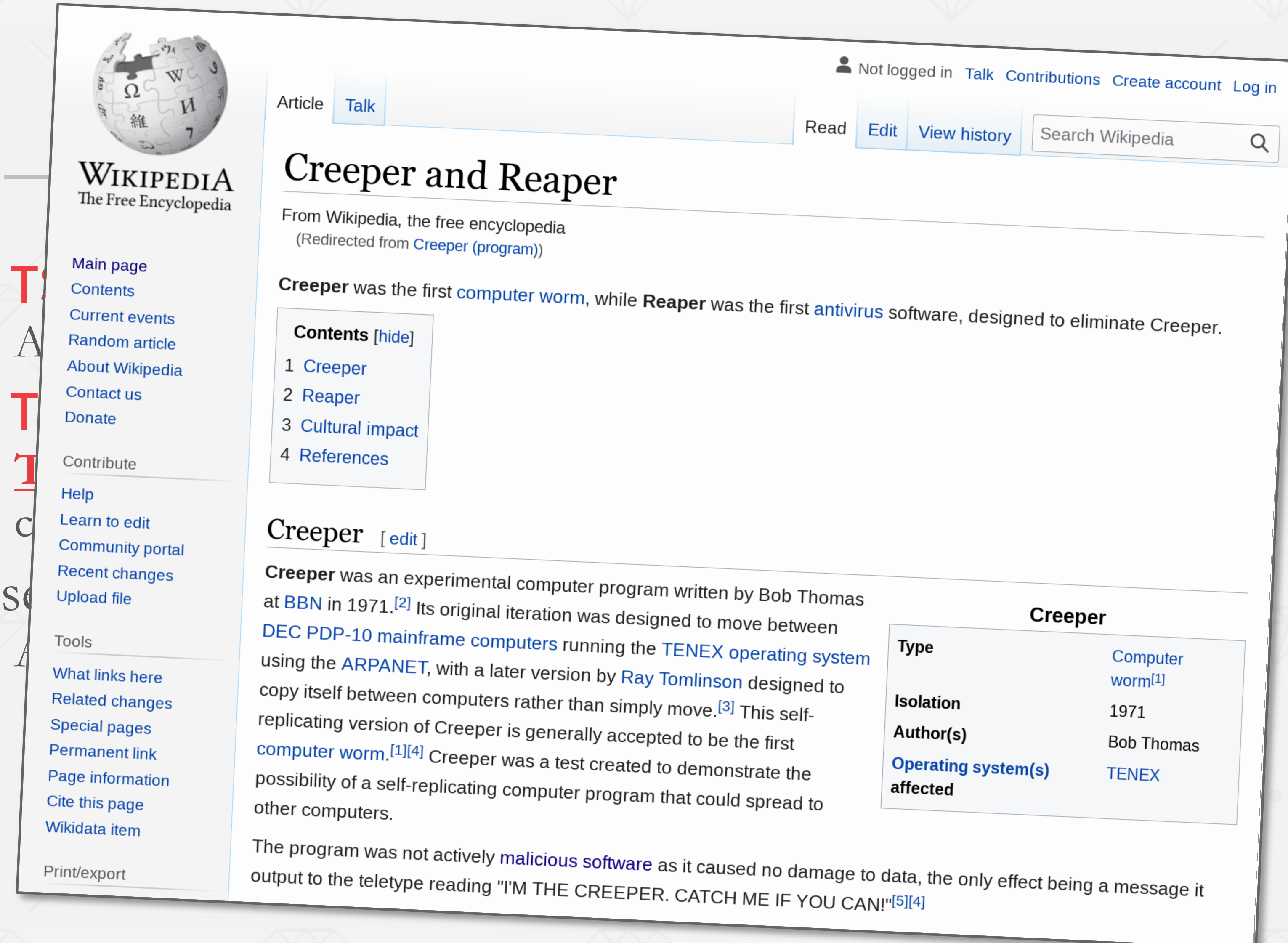
If T

→ T

c

Else

→ A



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Creeper and Reaper

From Wikipedia, the free encyclopedia
(Redirected from Creeper (program))

Creeper was the first computer worm, while **Reaper** was the first antivirus software, designed to eliminate Creeper.

Contents [hide]

Creeper [edit]

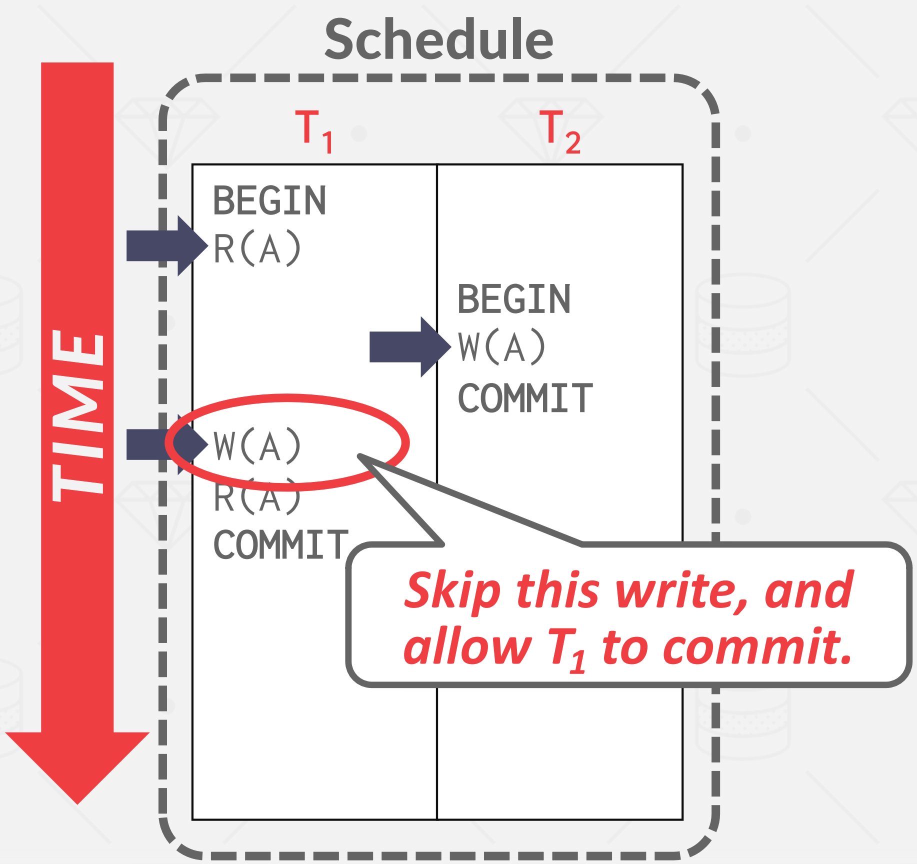
Creeper was an experimental computer program written by Bob Thomas at BBN in 1971.[2] Its original iteration was designed to move between DEC PDP-10 mainframe computers running the TENEX operating system using the ARPANET, with a later version by Ray Tomlinson designed to copy itself between computers rather than simply move.[3] This self-replicating version of Creeper is generally accepted to be the first computer worm.[1][4] Creeper was a test created to demonstrate the possibility of a self-replicating computer program that could spread to other computers.

Creeper

Type	Computer worm[1]
Isolation	1971
Author(s)	Bob Thomas
Operating system(s) affected	TENEX

The program was not actively malicious software as it caused no damage to data, the only effect being a message it output to the teletype reading "I'M THE CREEPER. CATCH ME IF YOU CAN!"[5][4]

BASIC T/O – EXAMPLE #2



Database

Object	R-TS	W-TS
A	1	2
B	0	0

We do not update W-TS(A)

BASIC T/O

Generates a schedule that is conflict serializable if you do **not** use the Thomas Write Rule.

→ No deadlocks because no txn ever waits.

→ Possibility of starvation for long txns if short txns keep causing conflicts.

We're not aware of any DBMS that uses the basic T/O protocol described here.

→ It provides the building blocks for OCC / MVCC.

PARTICIPATION EXERCISE

Why does no real database system use the basic timestamp ordering protocol?

https://bit.ly/cmu-db-quiz

OBSERVATION

If you assume that conflicts between txns are **rare** and that most txns are **short-lived**, then forcing txns to acquire locks or update timestamps adds unnecessary overhead.

A better approach is to optimize for the no-conflict case.

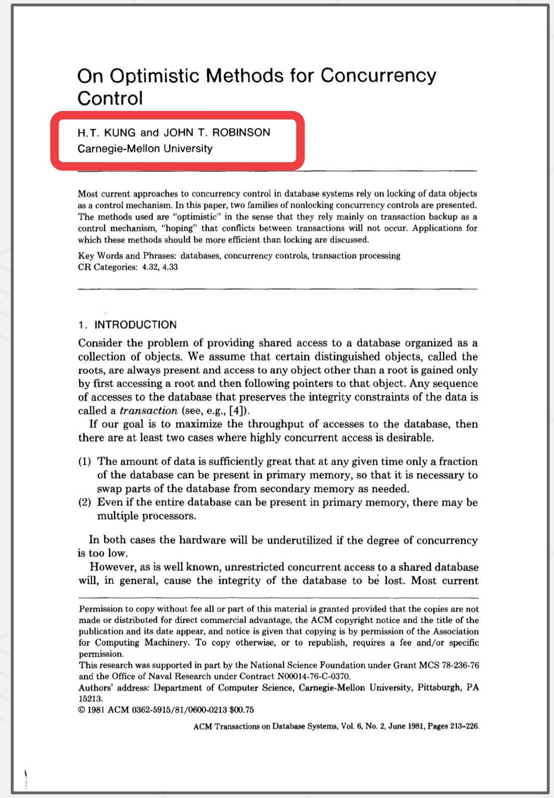
OPTIMISTIC CONCURRENCY CONTROL

The DBMS creates a private workspace for each txn.

→ Any object read is copied into workspace.
→ Modifications are applied to workspace.

When a txn commits, the DBMS compares workspace write set to see whether it conflicts with other txns.

If there are no conflicts, the write set is installed into the "global" database.



On Optimistic Methods for Concurrency Control

H.T. KUNG and JOHN T. ROBINSON
Carnegie-Mellon University

Most current approaches to concurrency control in database systems rely on locking of data objects as a control mechanism. In this paper, two families of nonlocking concurrency controls are presented. The methods used are "optimistic" in the sense that they rely mainly on transaction backup as a control mechanism, "hoping" that conflicts between transactions will not occur. Applications for which these methods should be more efficient than locking are discussed.

Key Words and Phrases: databases, concurrency controls, transaction processing
CR Categories: 4.32, 4.33

1. INTRODUCTION

Consider the problem of providing shared access to a database organized as a collection of objects. We assume that certain distinguished objects, called the roots, are always present and access to any object other than a root is gained only by first accessing a root and then following pointers to that object. Any sequence of accesses to the database that preserves the integrity constraints of the data is called a *transaction* (see, e.g., [4]).

If our goal is to maximize the throughput of accesses to the database, then there are at least two cases where highly concurrent access is desirable.

(1) The amount of data is sufficiently great that at any given time only a fraction of the database can be present in primary memory, so that it is necessary to swap parts of the database from secondary memory as needed.
(2) Even if the entire database can be present in primary memory, there may be multiple processors.

In both cases the hardware will be underutilized if the degree of concurrency is too low.

However, as is well known, unrestricted concurrent access to a shared database will, in general, cause the integrity of the database to be lost. Most current

This research was supported in part by the National Science Foundation under Grant MCS 78-236-76 and the Office of Naval Research under Contract N00014-76-C-0370.
Authors' address: Department of Computer Science, Carnegie-Mellon University, Pittsburgh, PA 15213.

ACM Transactions on Database Systems, Vol. 6, No. 2, June 1981, Pages 213–226.

OCC PHASES

#1 – Read Phase:

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

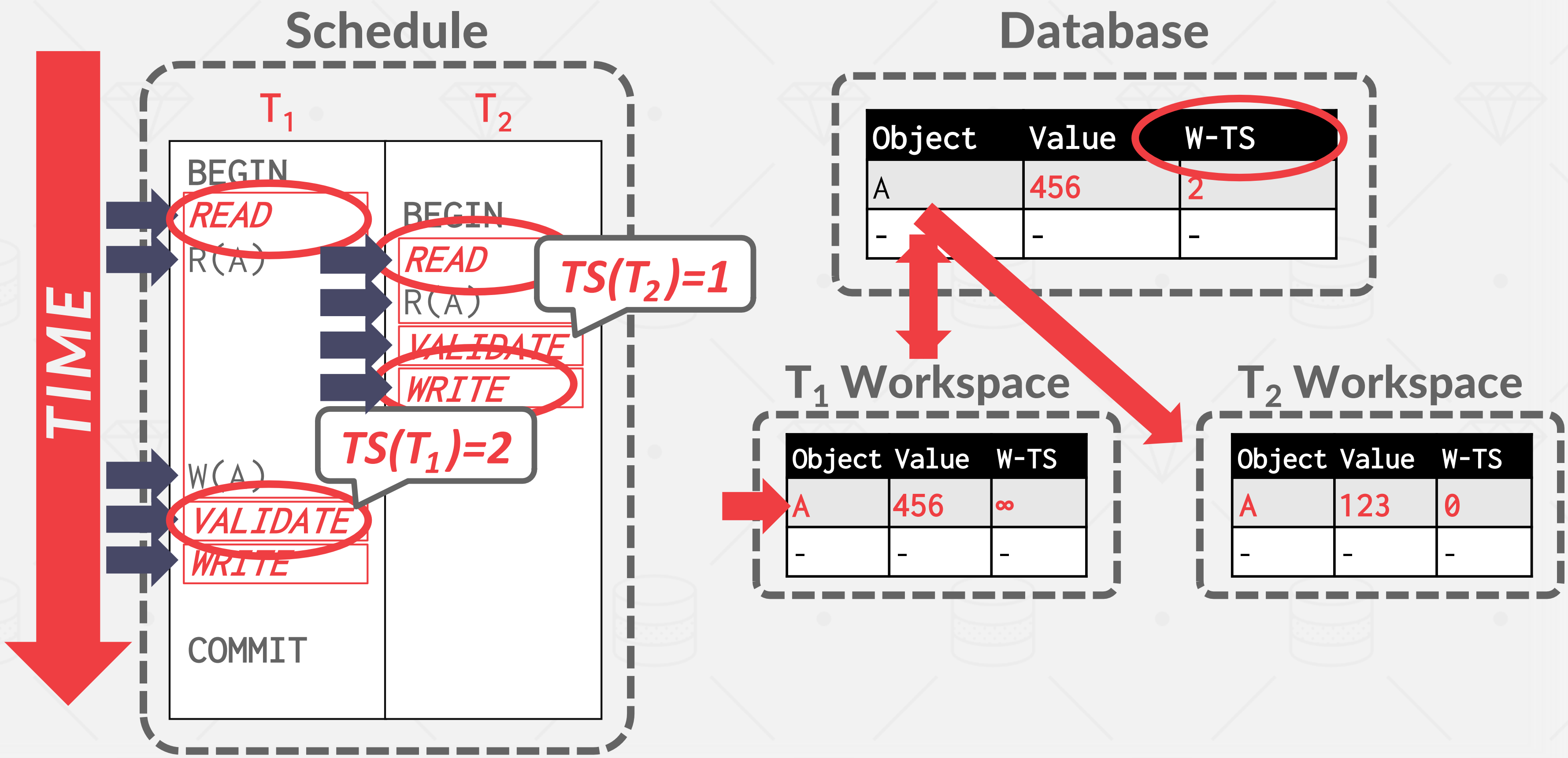
#2 – Validation Phase:

→ When a txn commits, check whether it conflicts with other txns.

#3 – Write Phase:

→ If validation succeeds, apply private changes to database. Otherwise abort and restart the txn.

OCC – EXAMPLE


Schedule
Database
TIME
T_1
T_2
BEGIN
READ
R(A)
W(A)
VALIDATE
WRITE
COMMIT
BEGIN
READ
R(A)
VALIDATE
WRITE
TS(T2)=1
TS(T1)=2
Object Value W-TS
A 456 2
- - -
T1 Workspace
Object Value W-TS
A 456 ∞
- - -
T2 Workspace
Object Value W-TS
A 123 0
- - -

OCC – READ PHASE

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

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

→ We can ignore for now what happens if a txn reads/writes tuples via indexes.

OCC – VALIDATION PHASE

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

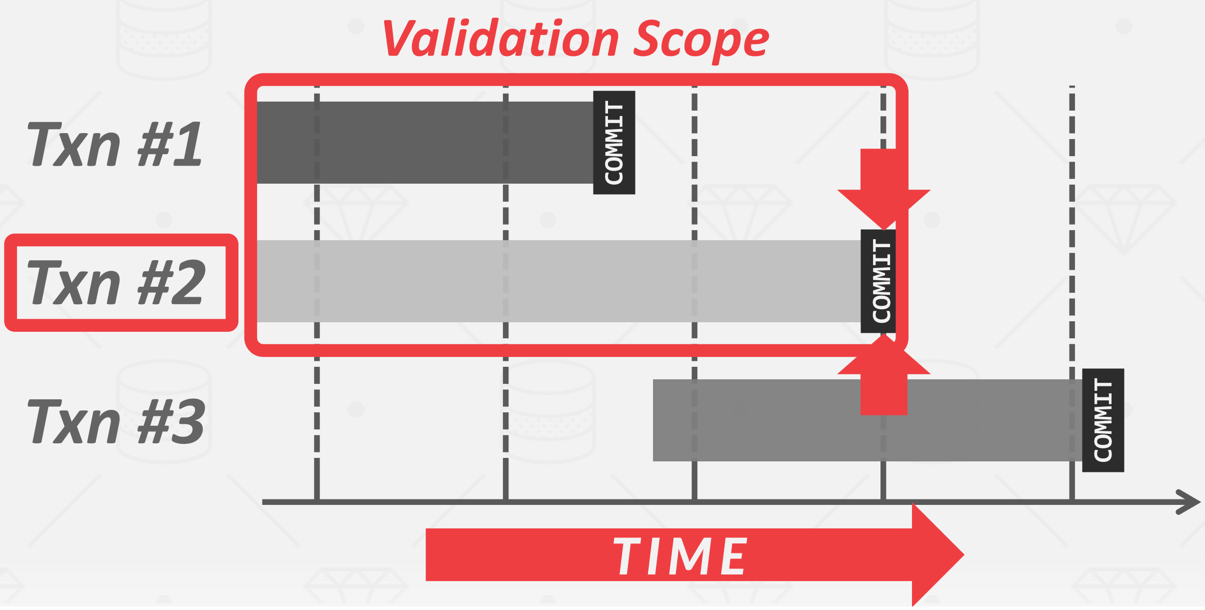
→ The DBMS needs to guarantee only serializable schedules are permitted.
→ Checks other txns for RW and WW conflicts and ensure that conflicts are in one direction (e.g., older→younger).

Approach #1: Backward Validation

Approach #2: Forward Validation

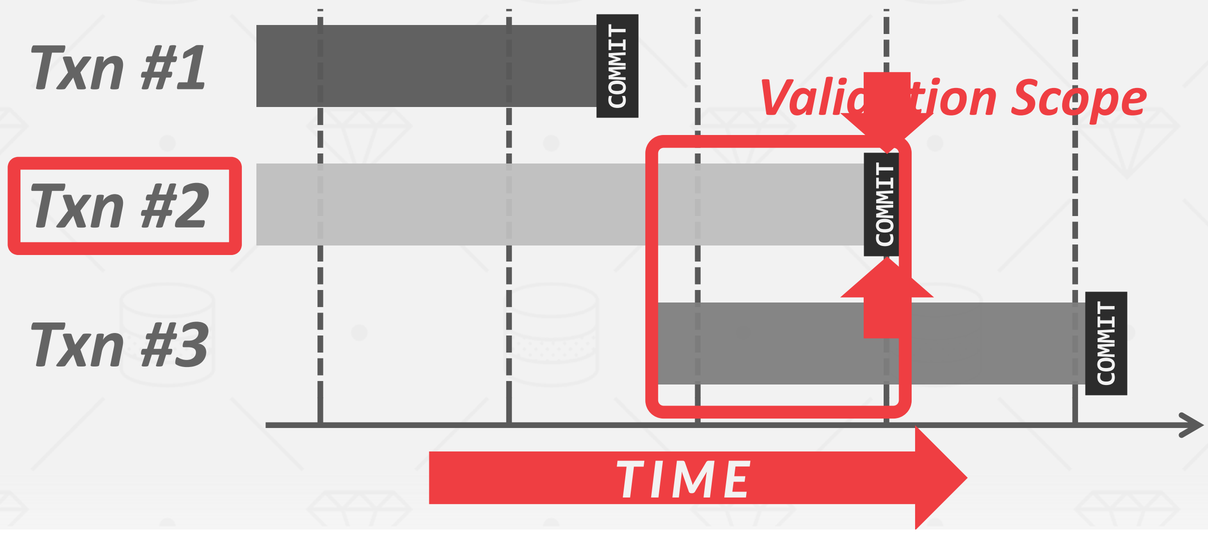
OCC – BACKWARD VALIDATION

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



OCC – FORWARD VALIDATION

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



OCC – FORWARD VALIDATION

Each txn's timestamp is assigned at the beginning of the validation phase.

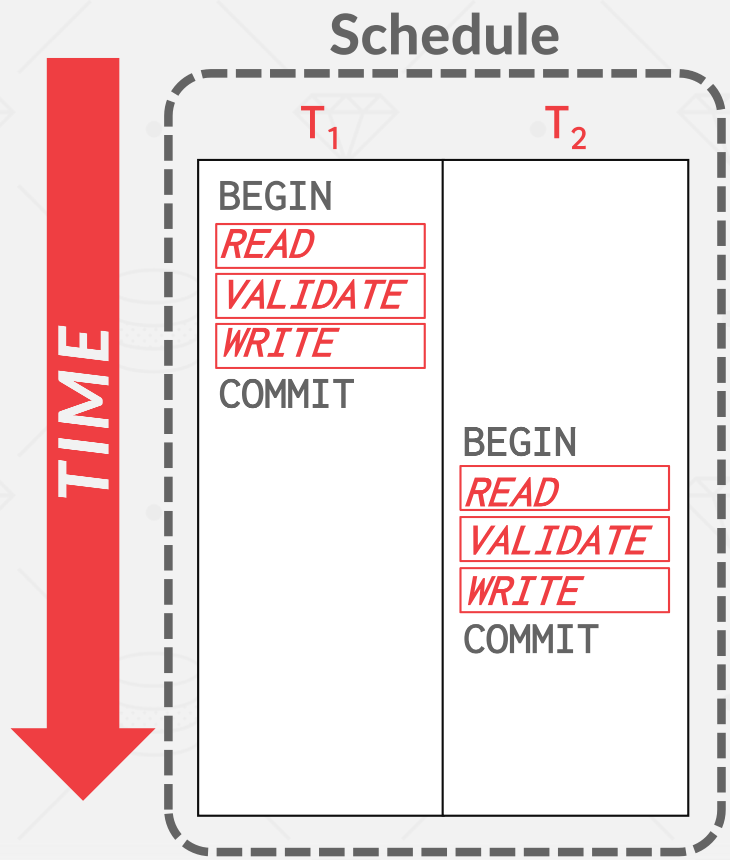
Check the timestamp ordering of the committing txn with all other running txns.

If $TS(T_i) < TS(T_j)$, then one of three cases:

OCC – FORWARD VALIDATION CASE #1

T_i completes all three phases before T_j begins its execution.

This is a serial ordering, so there is no conflict.



OCC – FORWARD VALIDATION CASE #2

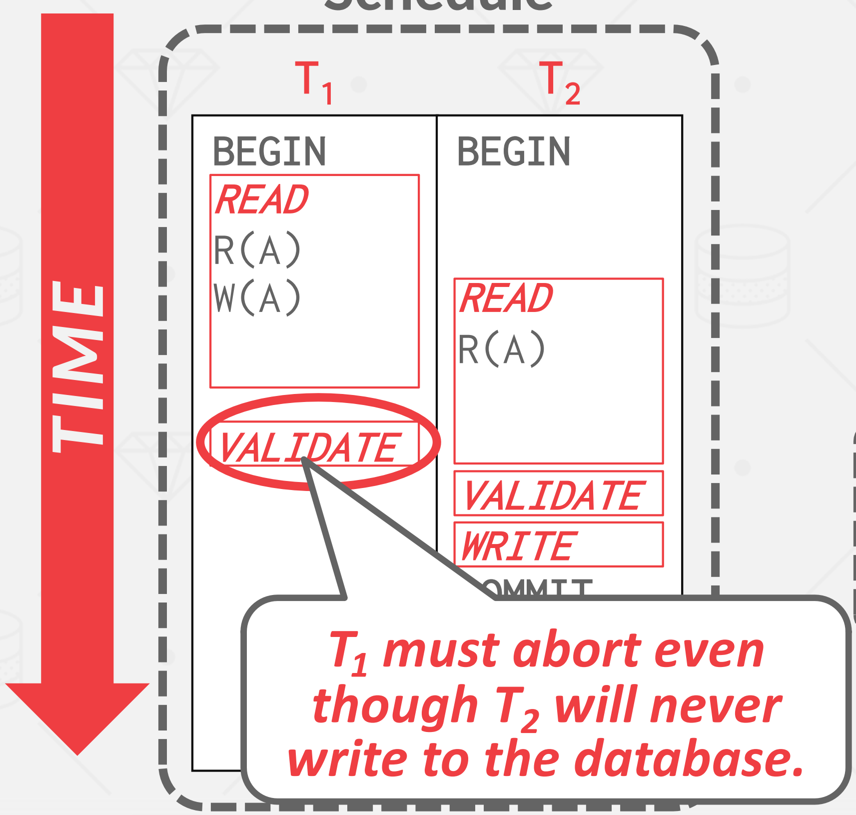
T_i completes before T_j starts its **Write** phase.

If T_i does not write to any object read by T_j, then there is no conflict.

Abort T_i if $\texttt{WriteSet}(T_i) \cap \texttt{ReadSet}(T_j) \neq \emptyset$

OCC – FORWARD VALIDATION CASE #2

Schedule



Database

Object	Value	W-TS
A	123	0
-	-	-

T_1 Workspace

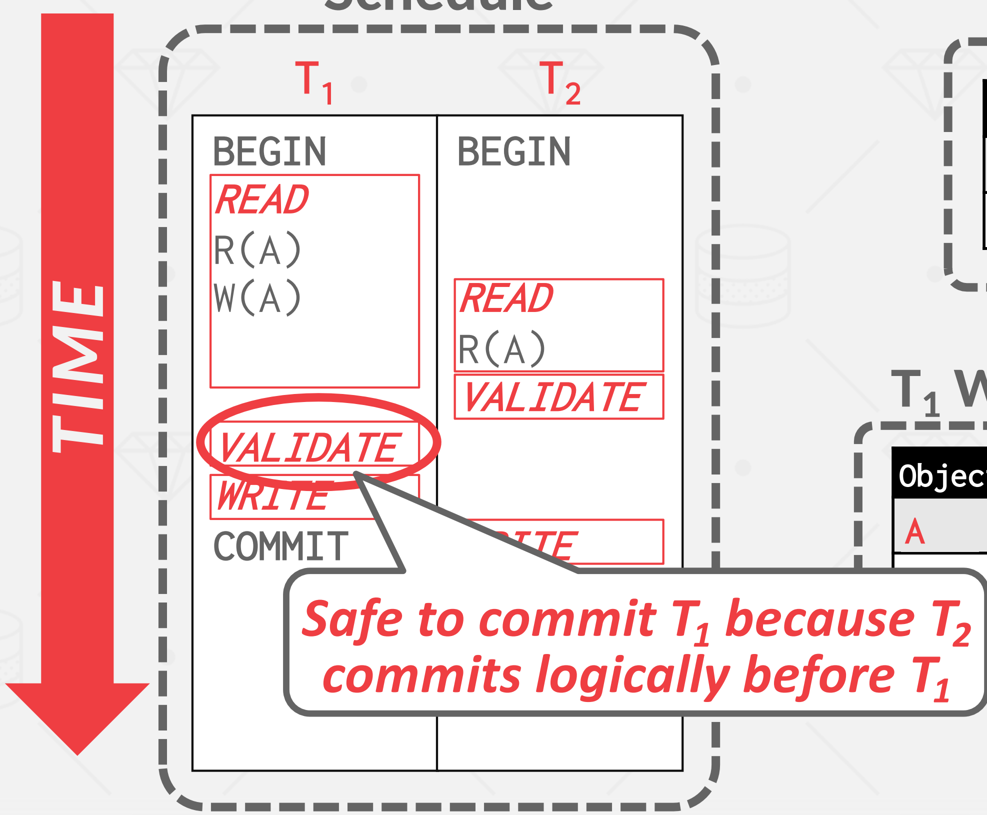
Object	Value	W-TS
A	456	∞
-	-	-

T_2 Workspace

Object	Value	W-TS
A	123	0
-	-	-

OCC – FORWARD VALIDATION CASE #2

Schedule



Database

Object	Value	W-TS
A	123	0
-	-	-

T_1 Workspace

Object	Value	W-TS
A	456	∞
	-	-

T_2 Workspace

Object	Value	W-TS
A	123	0
-	-	-

OCC – FORWARD VALIDATION CASE #3

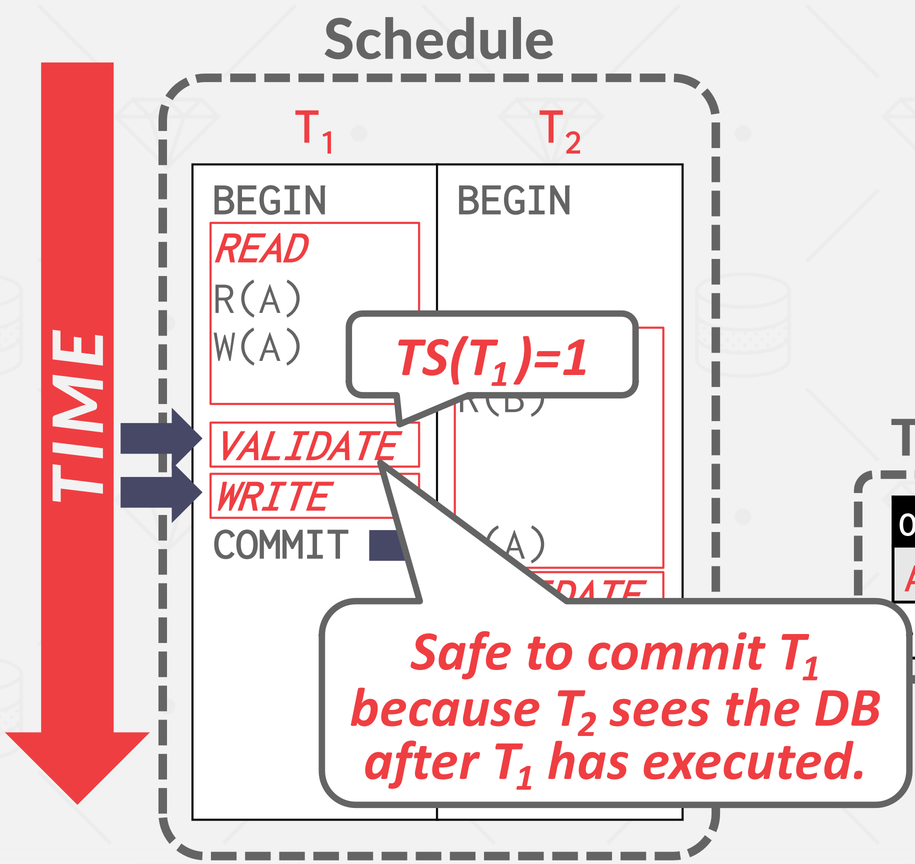
T_i completes its **Read** phase before T_j completes its **Read** phase.

If T_i does not write to any object that is either read or written by T_j, then there is no conflict.

Abort T_i if $\texttt{WriteSet}(T_i) \cap \texttt{ReadSet}(T_j) \neq \emptyset$ or if $\texttt{WriteSet}(T_i) \cap \texttt{WriteSet}(T_j) \neq \emptyset$

OCC – FORWARD VALIDATION CASE #3

Schedule



Database

Object	Value	W-TS
A	456	1
B	XYZ	0

T_1 Workspace

Object	Value	W-TS
A	456	∞
	-	-

T_2 Workspace

Object	Value	W-TS
B	XYZ	0
A	456	1

OCC – WRITE PHASE

Propagate changes in the txn's write set to database to make them visible to other txns.

Serial Commits:

→ Use a global latch to limit a single txn to be in the **Validation/Write** phases at a time.

Parallel Commits:

→ Use fine-grained write latches to support parallel **Validation/Write** phases.

→ Txns acquire latches in primary key order to avoid deadlocks.

OCC – OBSERVATIONS

OCC works well when the # of conflicts is low:
→ All txns are read-only (ideal).
→ Txns access disjoint subsets of data.

If the database is large and the workload is not skewed, then there is a low probability of conflict, then locking is wasteful.

OCC – PERFORMANCE ISSUES

High overhead for copying data locally.

Validation/Write phase bottlenecks.

Aborts are more wasteful than in 2PL because they only occur after a txn has already executed.

DYNAMIC DATABASES

Recall that so far, we have only dealt with transactions that read and update existing objects in the database.

But now if txns perform insertions, updates, and deletions, we have new problems…

THE PHANTOM PROBLEM

Schedule

TIME ↓

T_1	T_2
BEGIN	BEGIN
`SELECT COUNT(age) FROM people WHERE status='lit'`	→ 99
	`INSERT INTO people (age=30, status='lit')`
	COMMIT
`SELECT COUNT(age) FROM people WHERE status='lit'`	→ 100 ☠
COMMIT	

```
CREATE TABLE people (
  id SERIAL,
  name VARCHAR,
  age INT,
  status VARCHAR
);
```

HOW DID THIS HAPPEN?

Because T_1 locked only existing records and not ones under way!

Conflict serializability on reads and writes of individual items guarantees serializability **only** if the set of objects is fixed.

THE PHANTOM PROBLEM

Approach #1: Re-Execute Scans

→ Run queries again at commit to see whether they produce a different result to identify missed changes.

Approach #2: Predicate Locking

→ Logically determine the overlap of predicates before queries start running.

Approach #3: Index Locking

→ Use keys in indexes to protect ranges.

RE-EXECUTE SCANS

The DBMS tracks the WHERE clause for all queries that the txn executes.

→ Retain the scan set for every range query in a txn.

Upon commit, re-execute just the scan portion of each query and check whether it generates the same result.

→ Example: Run the scan for an UPDATE query but do not modify matching tuples.

PREDICATE LOCKING

Proposed locking scheme from System R.

→ Shared lock on the predicate in a **WHERE** clause of a **SELECT** query.

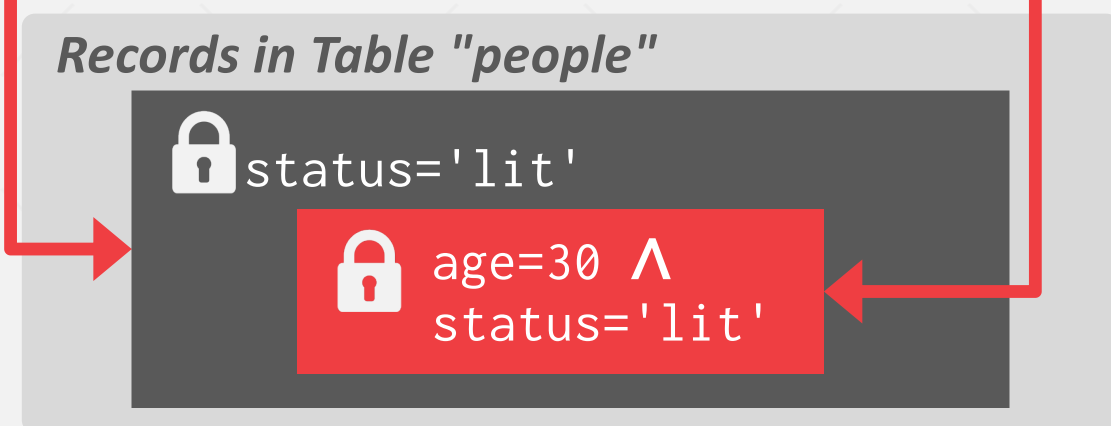
→ Exclusive lock on the predicate in a **WHERE** clause of any **UPDATE**, **INSERT**, or **DELETE** query.

Never implemented in any system except for HyPer (precision locking).

PREDICATE LOCKING

```
SELECT COUNT(age)
  FROM people
WHERE status='lit'
```

```
INSERT INTO people VALUES
(age=30, status='lit')
```



INDEX LOCKING SCHEMES

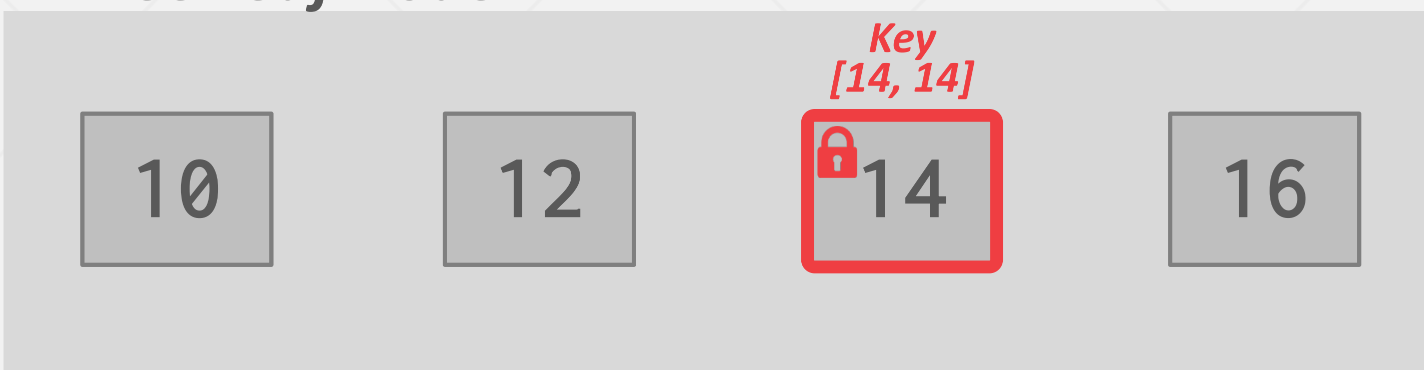
Key-Value Locks
Gap Locks
Key-Range Locks
Hierarchical Locking

KEY-VALUE LOCKS

Locks that cover a single key-value in an index.

Need "virtual keys" for non-existent values.

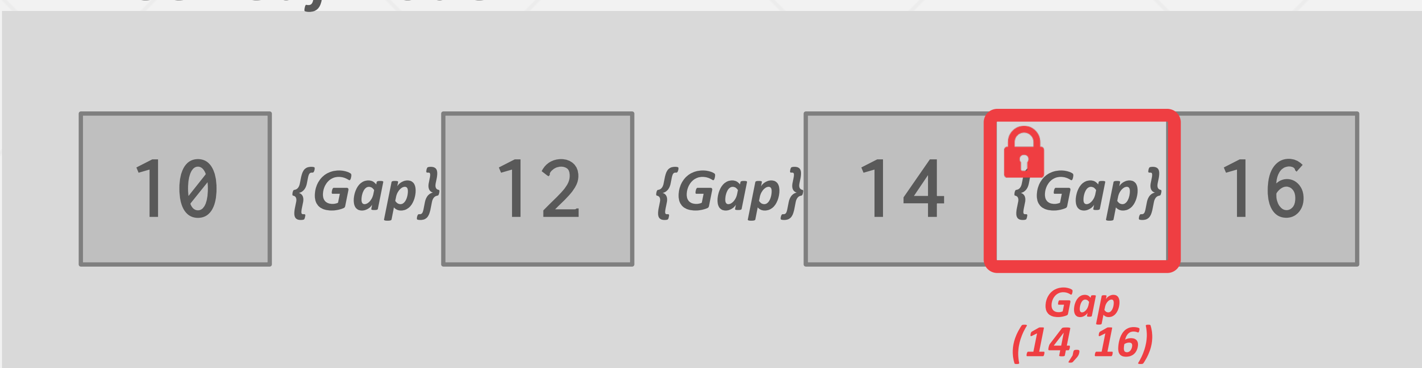
B+Tree Leaf Node



GAP LOCKS

Each txn acquires a key-value lock on the single key that it wants to access. Then get a gap lock on the next key gap.

B+Tree Leaf Node



KEY-RANGE LOCKS

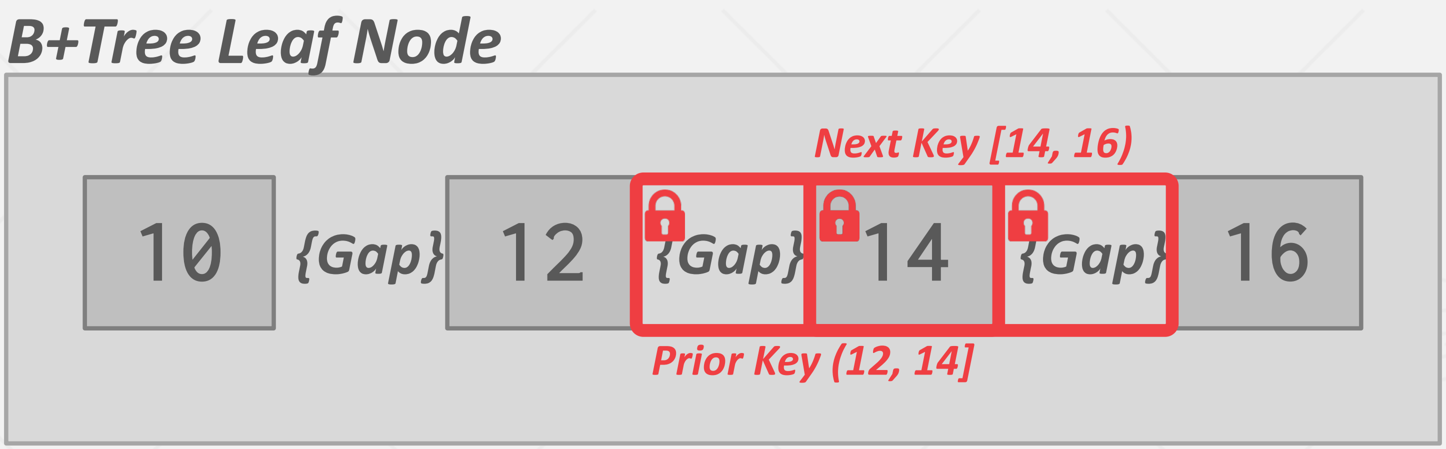
A txn takes locks on ranges in the key space.

→ Each range is from one key that appears in the relation, to the next that appears.

→ Define lock modes so conflict table will capture commutativity of the operations available.

KEY-RANGE LOCKS

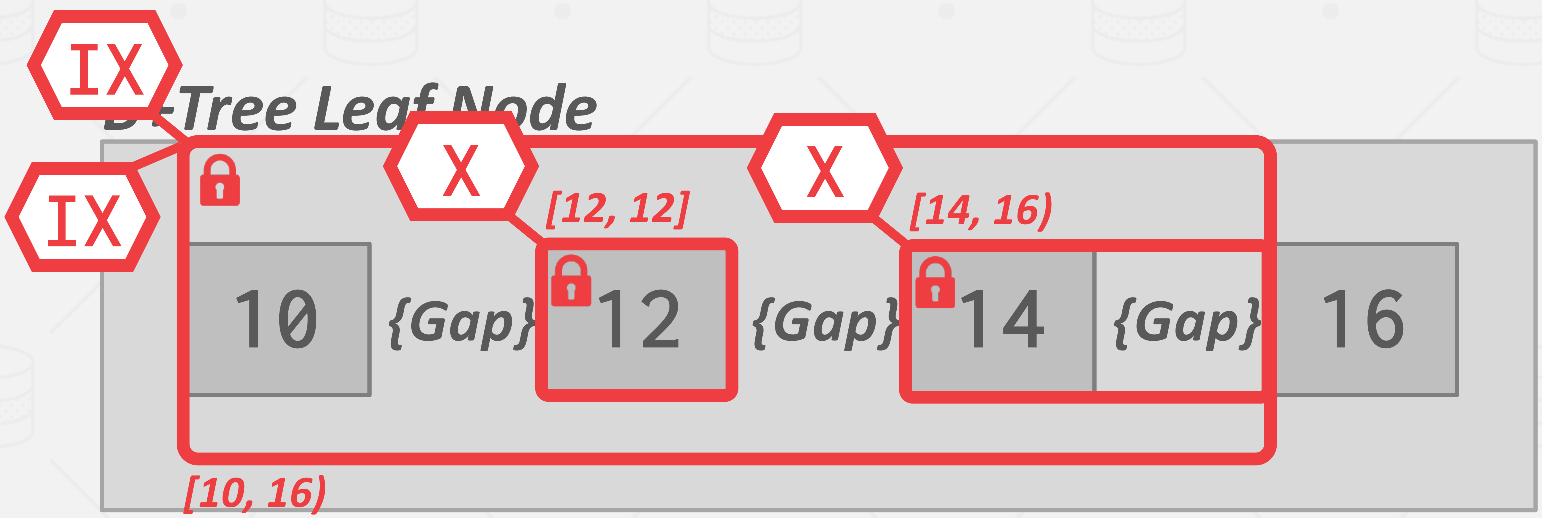
Locks that cover a key value and the gap to the next key value in a single index.
→ Need "virtual keys" for artificial values (infinity)



HIERARCHICAL LOCKING

Allow for a txn to hold wider key-range locks with different locking modes.

→ Reduces the number of visits to lock manager.



LOCKING WITHOUT AN INDEX

If there is no suitable index, then to avoid phantoms the txn must obtain:

→ A lock on every page in the table to prevent a record's `status='lit'` from being changed to `lit`.

→ The lock for the table itself to prevent records with `status='lit'` from being added or deleted.

CONCLUSION

Every concurrency control can be broken down into the basic concepts that I've described in the last two lectures.

Every protocol has pros and cons.

NEXT CLASS

Multi-Version Concurrency Control