Carnegie Mellon University

# DATABASE SYSTEMS

## Multi-Versioning

LECTURE #20 » 15-445/645 FALL 2025 » PROF. ANDY PAVLO

# ADMINISTRIVIA

**Project #3** is due Sunday Nov 16th @ 11:59pm

→ Recitation Video + Slides (see @235)

→ Saturday Office Hours Nov 5th @ 3:00-5:00pm (GHC 5207)

**Homework #5** is due Sunday Nov 23rd @ 11:59pm

**Project #4** is due Sunday Dec 7th @ 11:59pm

# LAST CLASS

Optimistic Concurrency Control (OCC) uses timestamps, assigned during the validation phase, to ensure serializability instead of locks.

→ Txns first write changes into private workspaces and then attempt to install them into the database upon commit.

Phantom Reads occur when a txns re-reads a range of data and finds new rows or missing rows.

# MULTI-VERSION CONCURRENCY CONTROL

The DBMS maintains multiple **physical** versions of a single **logical** object in the database:

→ When a txn writes to an object, the DBMS creates a new version of that object.
→ When a txn reads an object, it reads the newest version that existed when the txn started.
→ Use timestamps to determine visibility.
→ Multi-versioning without garbage collection allows the DBMS to support time-travel queries.

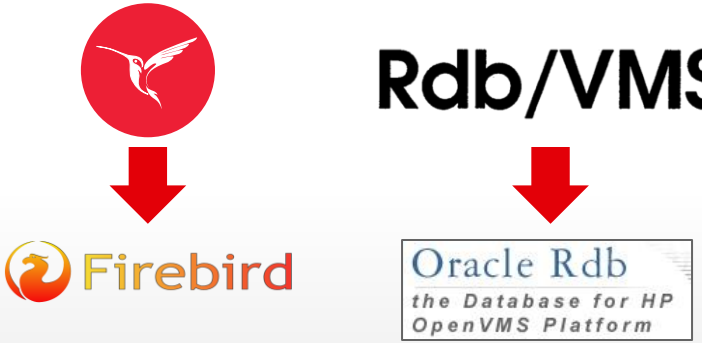
**Writers do not block readers.**
**Readers do not block writers.**

# MVCC HISTORY

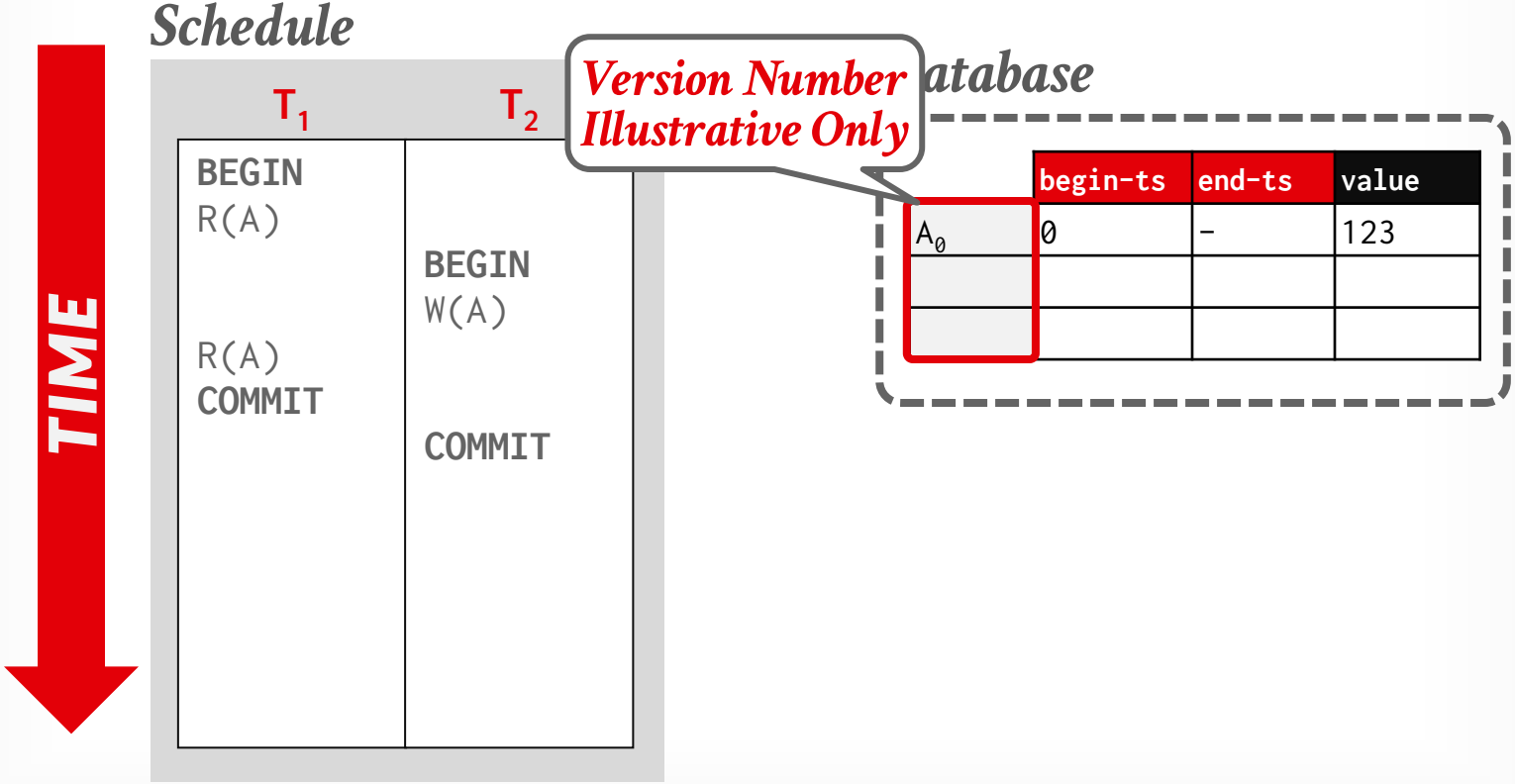
Protocol was first proposed in 1978 MIT PhD dissertation.

First implementations was Rdb/VMS and InterBase at DEC in early 1980s.

→ Both were by Jim Starkey, co-founder of NuoDB.
→ DEC Rdb/VMS is now "Oracle Rdb".
→ InterBase was open-sourced as Firebird.



# MVCC: EXAMPLE #1



# MVCC: EXAMPLE #1

## Schedule

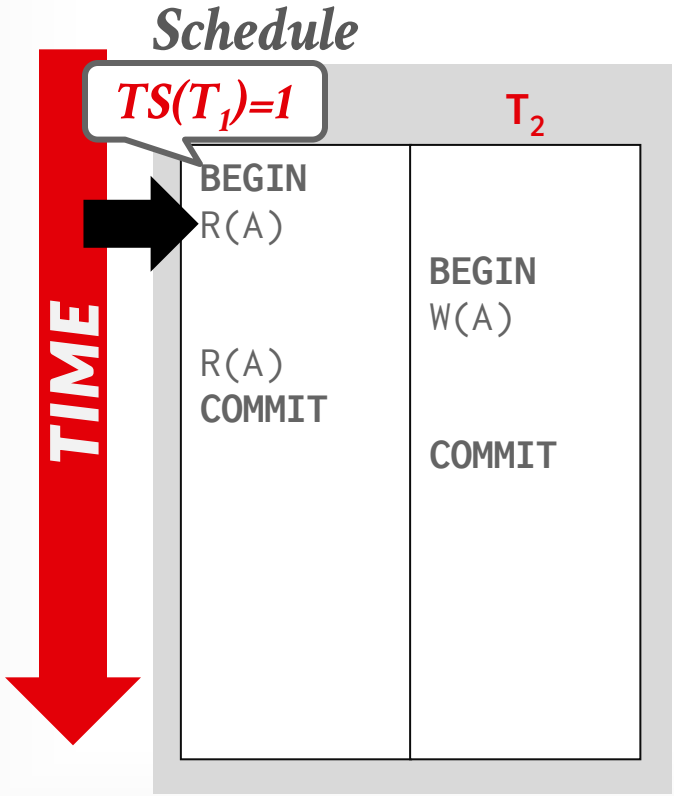
TIME

| $T_1$ | $T_2$ |
|---|---|
| BEGIN | |
| R(A) | |
| | BEGIN |
| | W(A) |
| R(A) | |
| COMMIT | |
| | COMMIT |

## Database

| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_0$ | 0 | – | 123 |
| | | | |
| | | | |

# MVCC: EXAMPLE #1

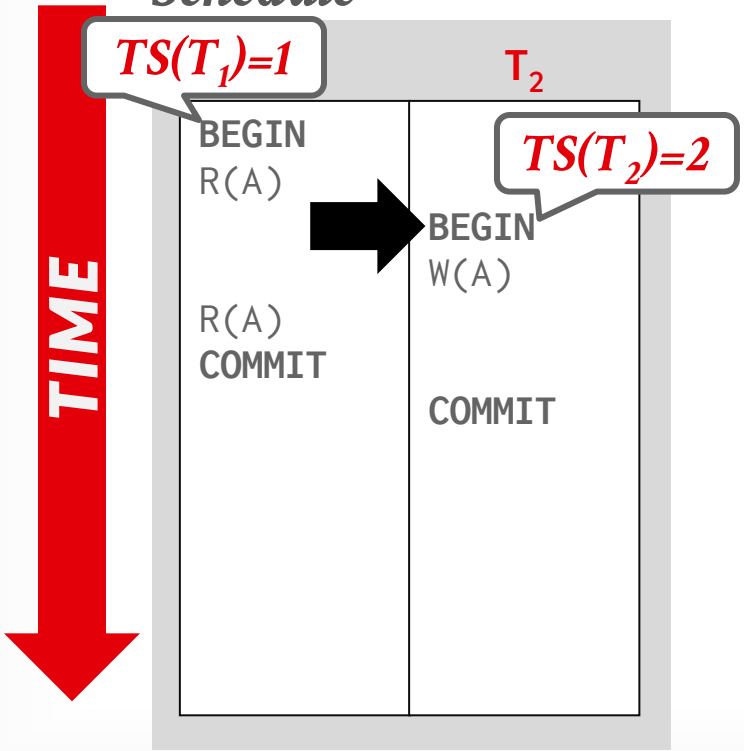



## Database

| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_0$ | 0 | - | 123 |
| | | | |
| | | | |

# MVCC: EXAMPLE #1

## Schedule




## Database

| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_0$ | 0 | - | 123 |
| | | | |
| | | | |

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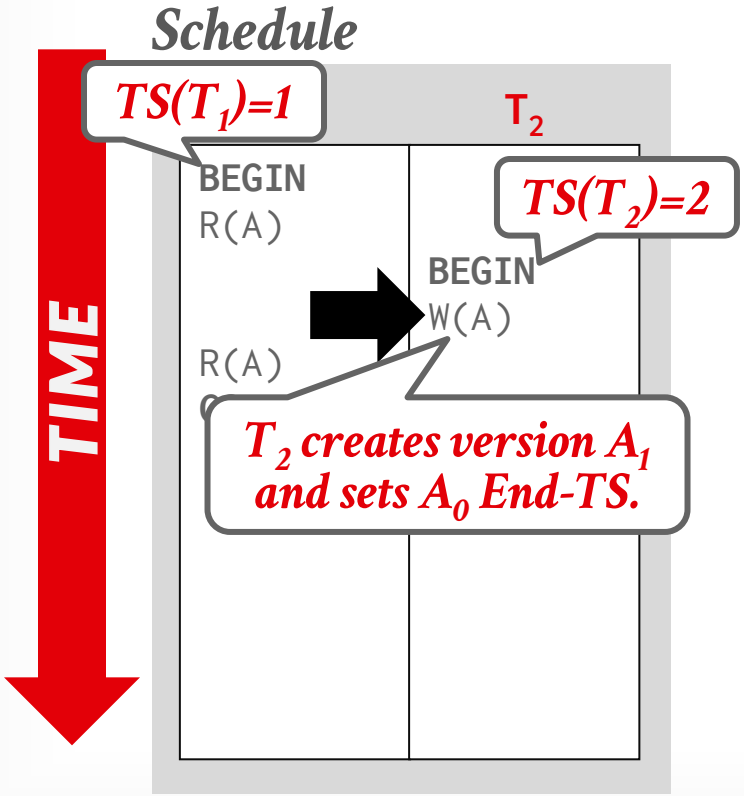
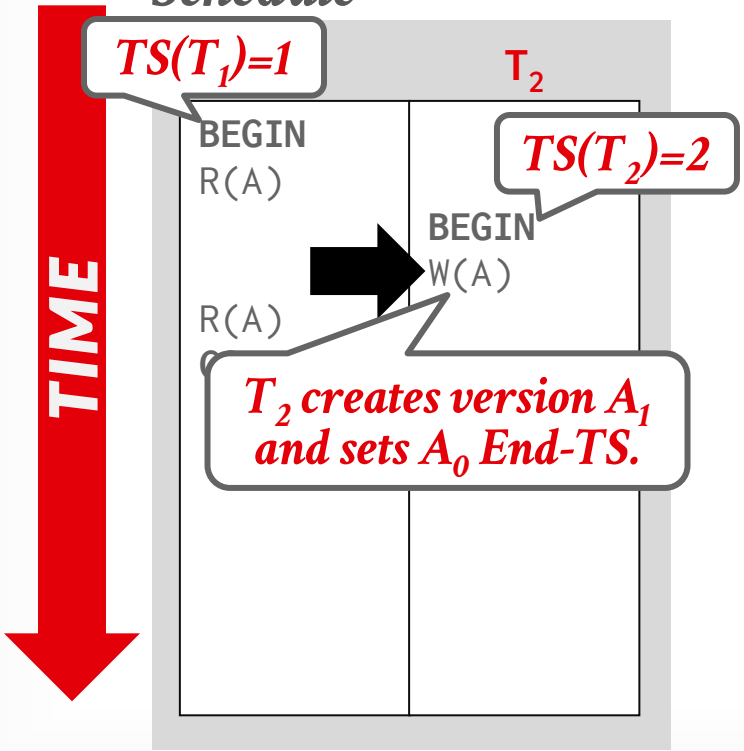



## Database

| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_0$ | 0 | - | 123 |
| $A_1$ | 2 | - | 456 |
| | | | |

# MVCC: EXAMPLE #1

## Schedule




## Database

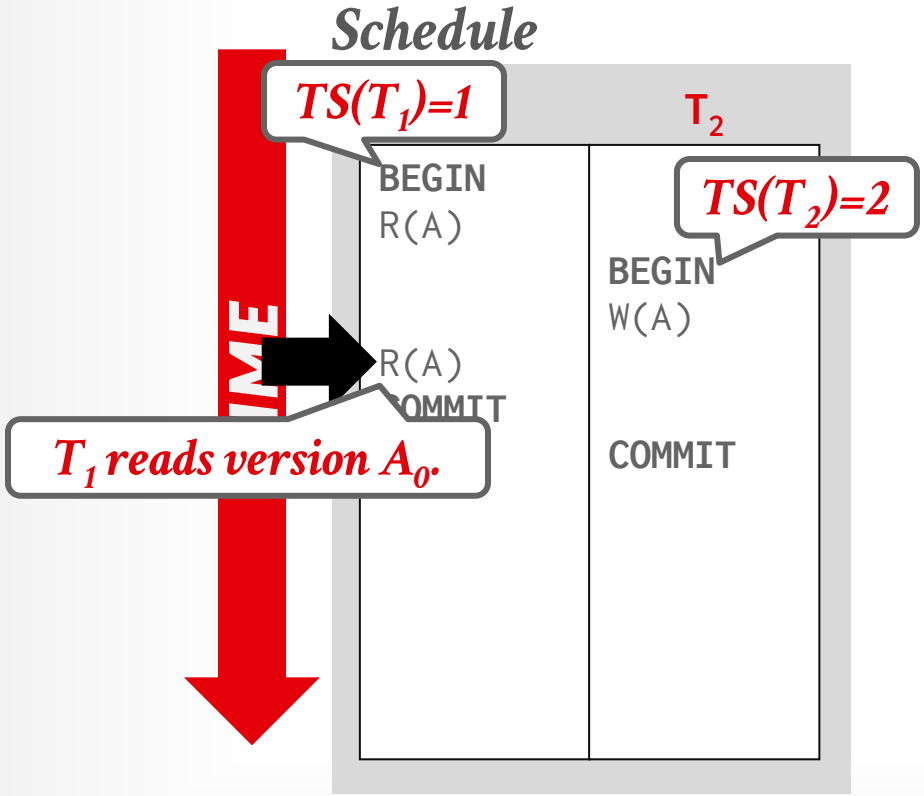
| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_0$ | 0 | 2 | 123 |
| $A_1$ | 2 | - | 456 |
| | | | |

## Txn Status Table

| txnid | timestamp | status |
|---|---|---|
| $T_1$ | 1 | Active |
| $T_2$ | 2 | Active |
| | | |

# MVCC: EXAMPLE #1






## Database

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| txnid | timestamp | status |
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| $T_1$ | 1 | Active |
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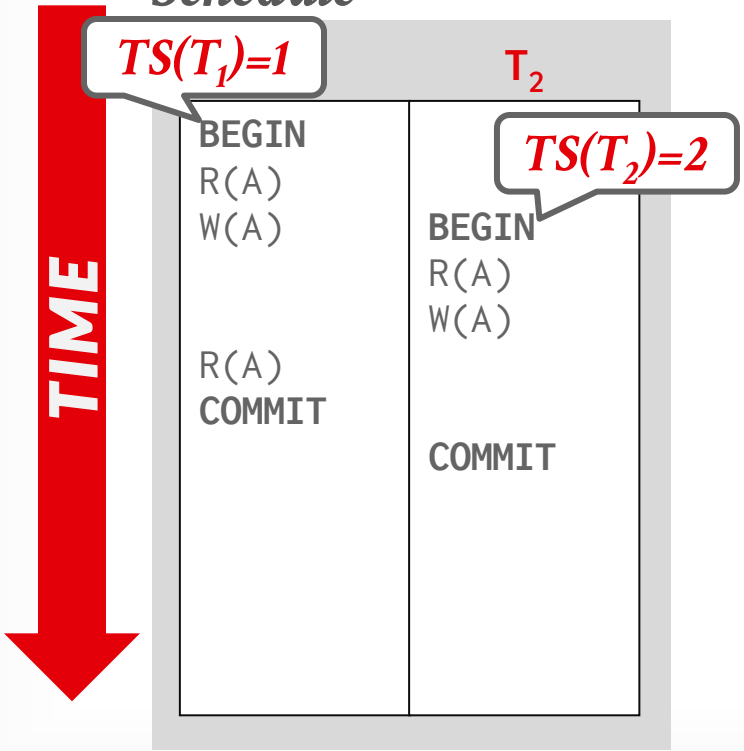
# MVCC: EXAMPLE #2

## Schedule




## Database

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|---|---|---|---|
| $A_0$ | 0 | - | 123 |
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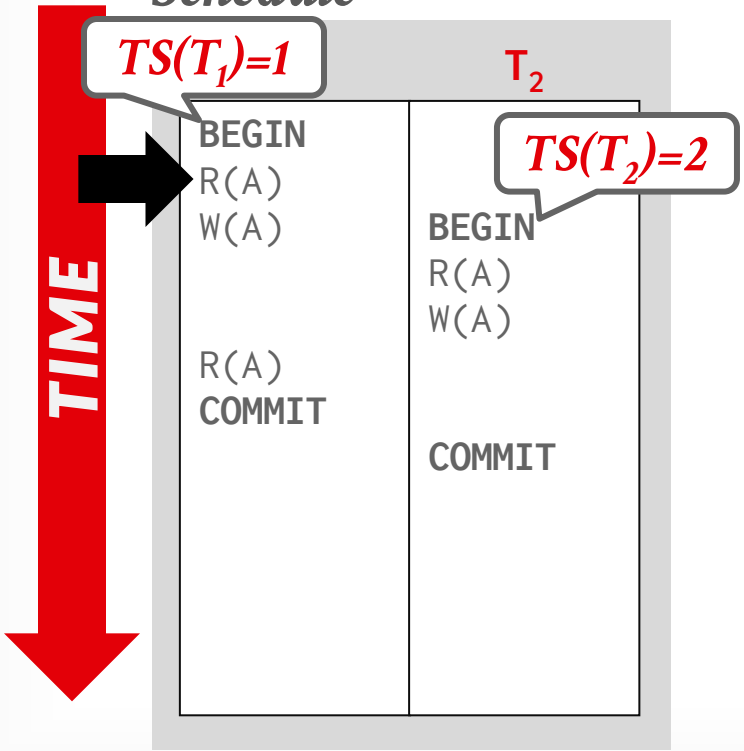


## Database

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| $A_0$ | 0 | - | 123 |
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| txnid | timestamp | status |
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| $T_1$ | 1 | Active |
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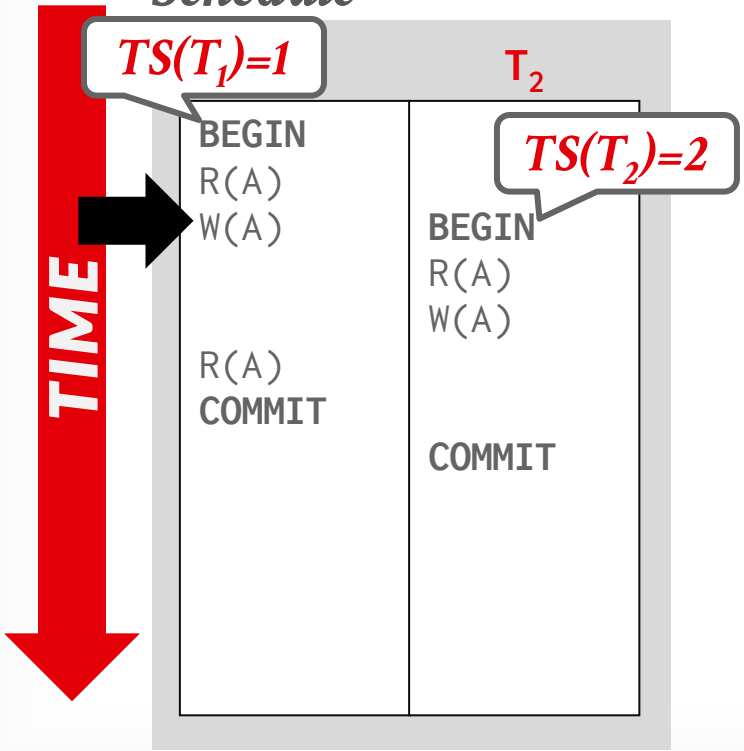


## Database

| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_0$ | 0 | - | 123 |
| $A_1$ | 1 | - | 456 |
| | | | |

## Txn Status Table

| txnid | timestamp | status |
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| $T_1$ | 1 | Active |
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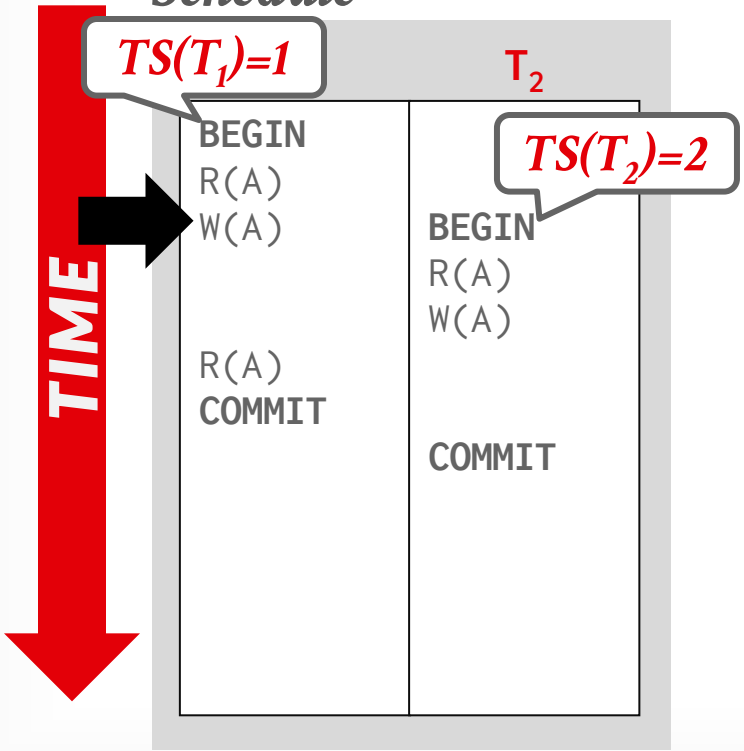
## Schedule




## Database

| | begin-ts | end-ts | value |
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| $A_0$ | 0 | 1 | 123 |
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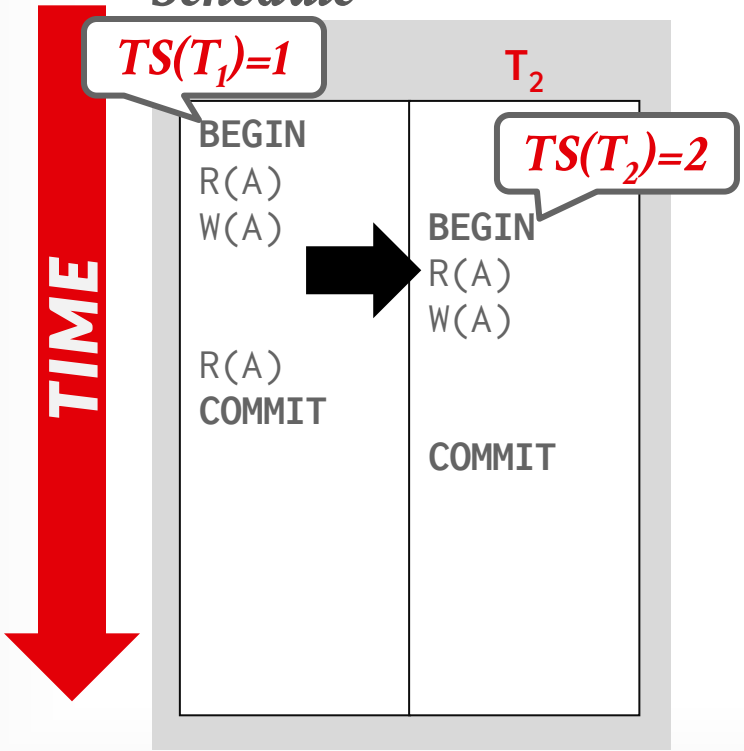


## Database

| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_0$ | 0 | 1 | 123 |
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|---|---|---|
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| | | |

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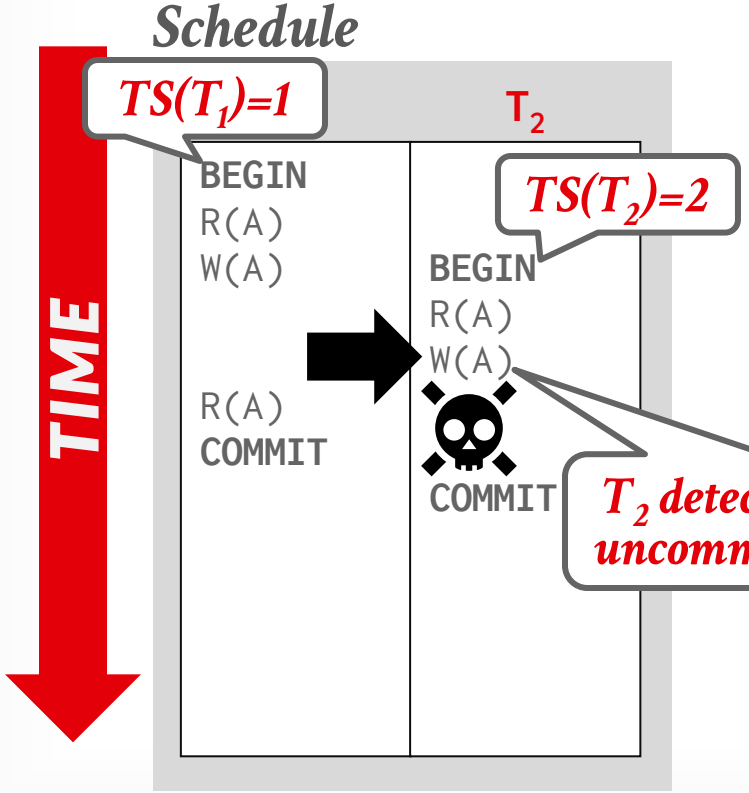



## Database

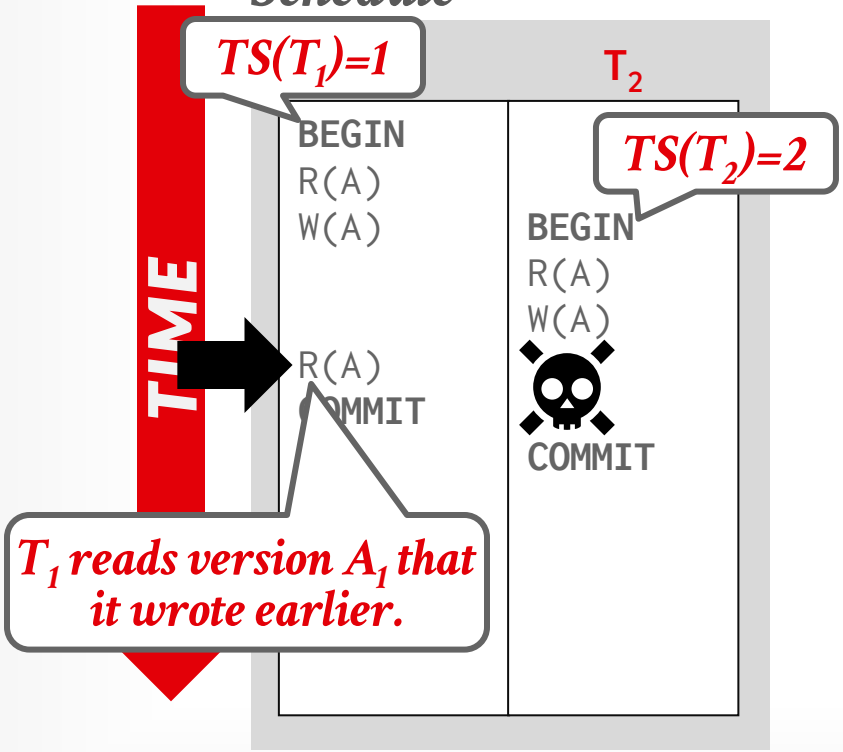
| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_0$ | 0 | 1 | 123 |
| $A_1$ | 1 | - | 456 |
| | | | |

## Status Table

| txnid | timestamp | status |
|---|---|---|
| $T_1$ | 1 | Active |
| $T_2$ | 2 | Aborted |
| | | |

# MVCC: EXAMPLE #2

## Schedule




## Database

| | begin-ts | end-ts | value |
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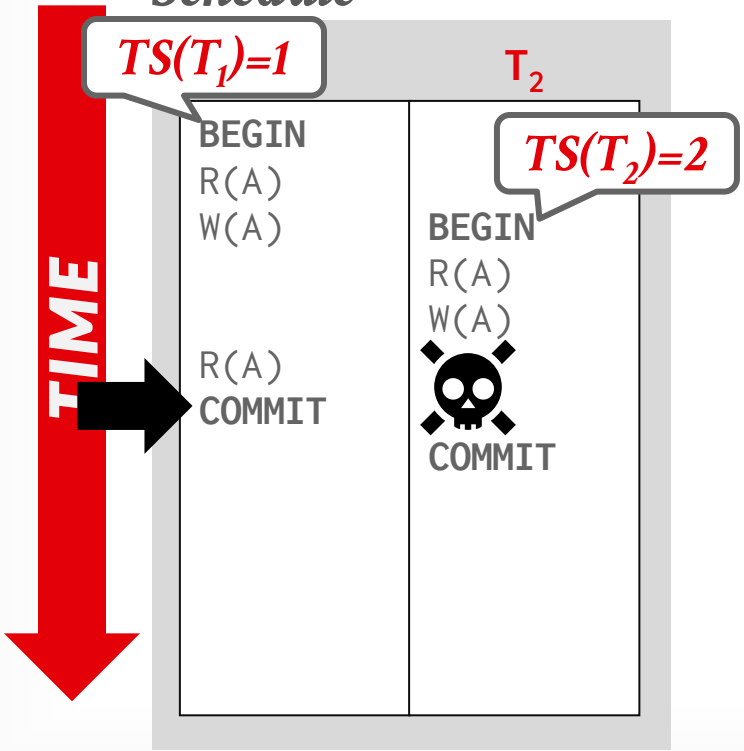


## Database

| | begin-ts | end-ts | value |
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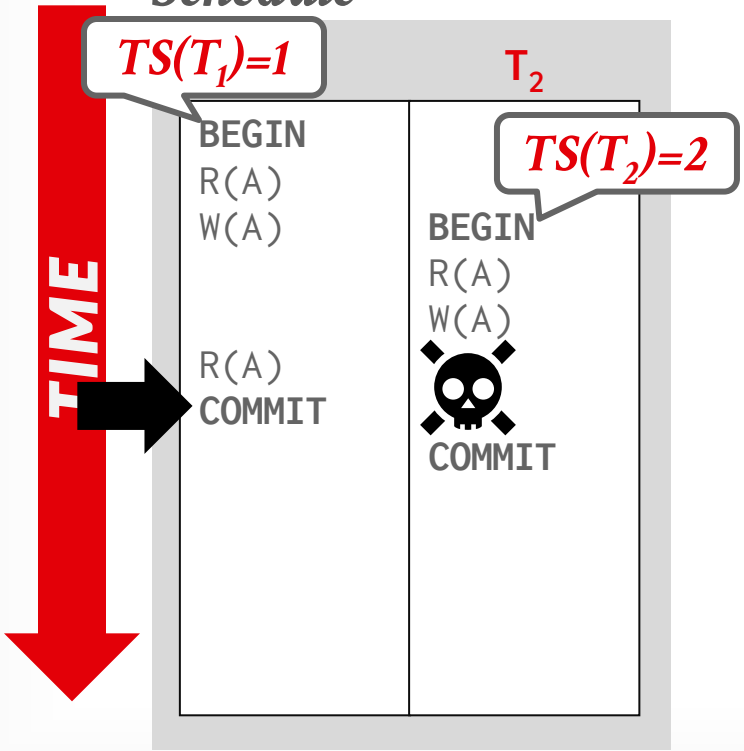


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| | | | |

## Txn Status Table

| txnid | timestamp | status |
|---|---|---|
| $T_1$ | 1 | Committed |
| $T_2$ | 2 | Aborted |
| | | |

# SNAPSHOT ISOLATION (SI)



When a txn starts, it sees a consistent snapshot of the database that existed when that the txn started.

→ No torn writes from active txns.

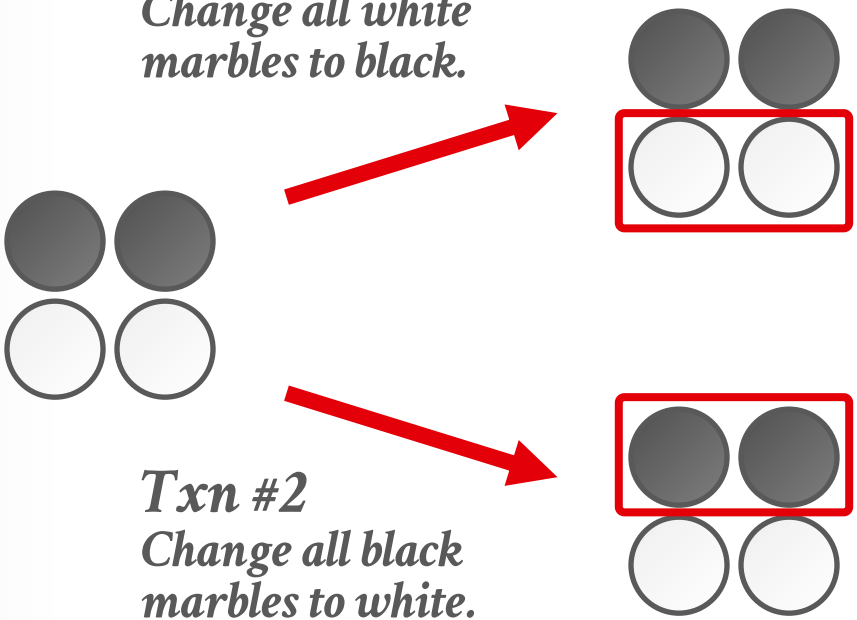
→ If two txns update the same object, then last writer wins.

SI is susceptible to the **Write Skew Anomaly**.

# WRITE SKEW ANOMALY

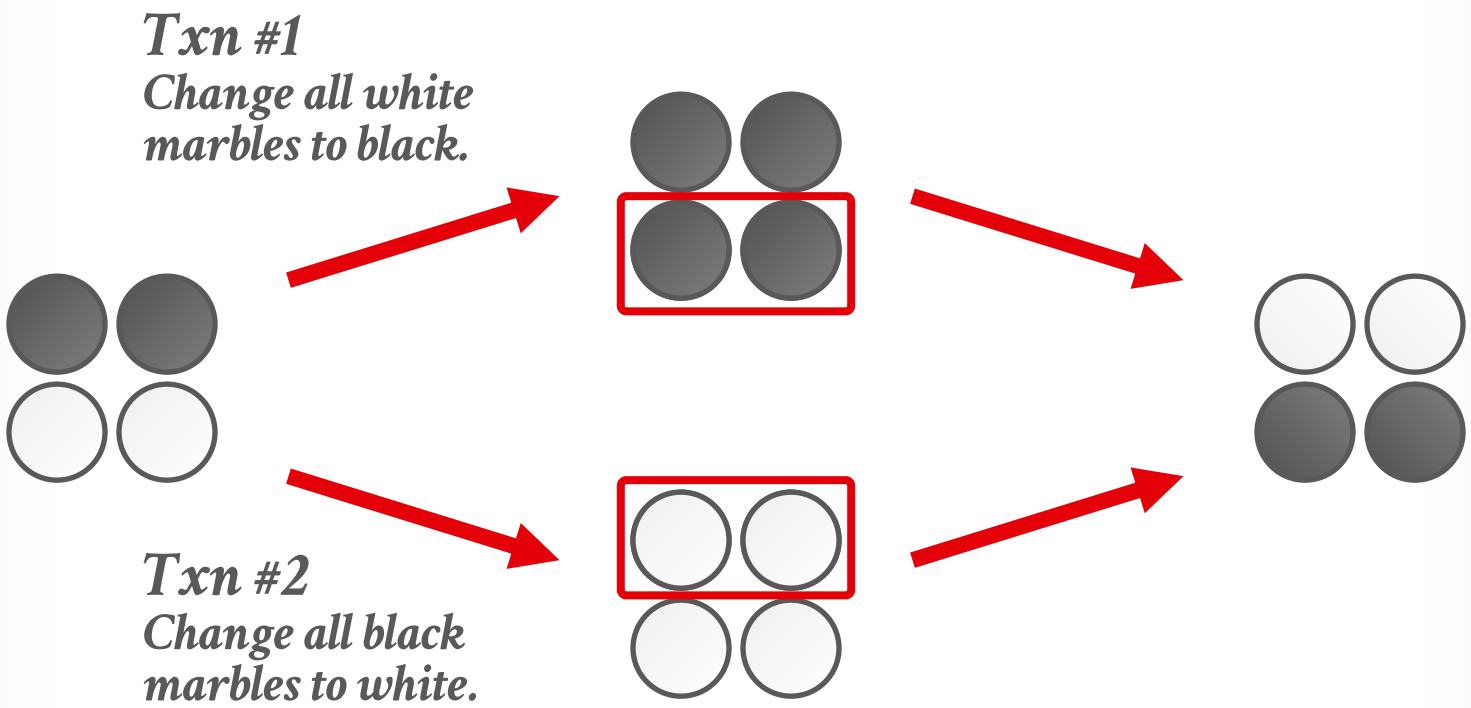


*Txn #1*
*Change all white marbles to black.*



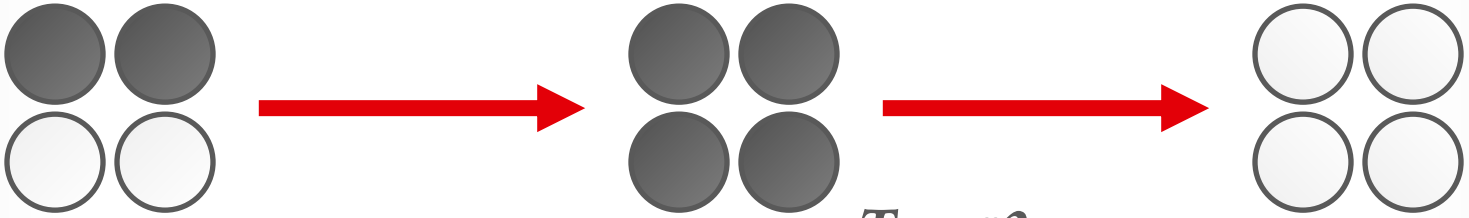
*Txn #2*
*Change all black marbles to white.*

# WRITE SKEW ANOMALY



# WRITE SKEW ANOMALY

*Txn #1*
*Change all white marbles to black.*



*Txn #2*
*Change all black marbles to white.*

# MULTI-VERSION CONCURRENCY CONTROL

MVCC is more than just a concurrency control protocol. It completely affects how the DBMS manages transactions and the database.

# MVCC DESIGN DECISIONS



Concurrency Control Protocol

Version Storage

Garbage Collection

Index Management

Deletes

# CONCURRENCY CONTROL PROTOCOL

## Approach #1: Timestamp Ordering

→ Assign txns timestamps that determine serial order.

## Approach #2: Optimistic Concurrency Control

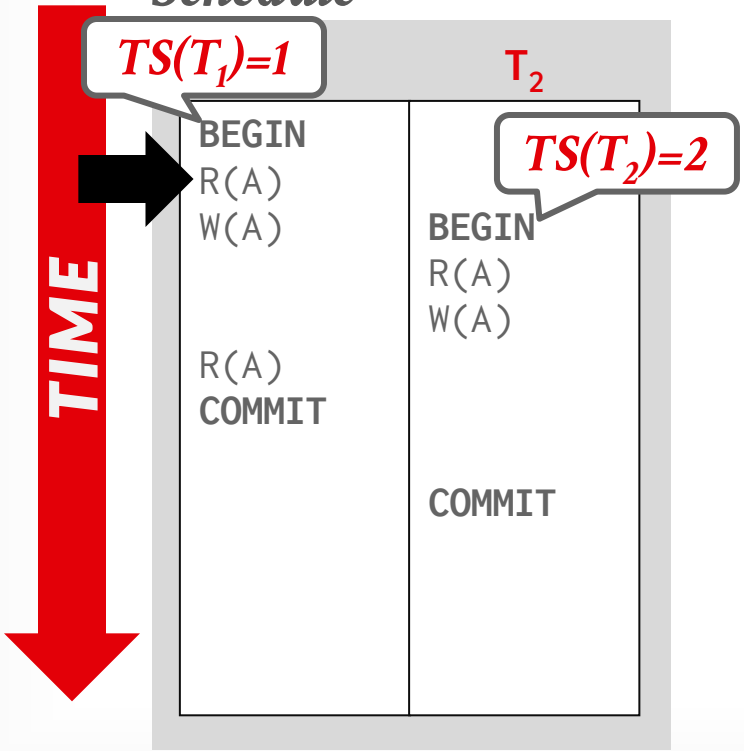
→ Three-phase protocol from last class.
→ Use private workspace for new versions.

## Approach #3: Two-Phase Locking

→ Txns acquire appropriate lock on physical version before they can read/write a logical tuple.

# MVCC WITH 2PL

## Schedule




## Database

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|---|---|---|---|
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| | | | |
| | | | |

## Txn Status Table

| txnid | timestamp | status |
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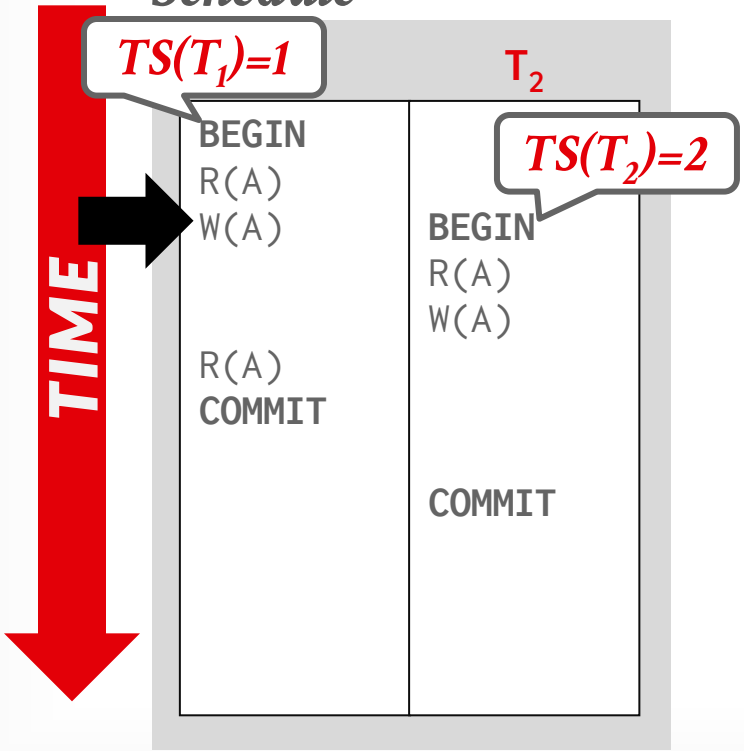


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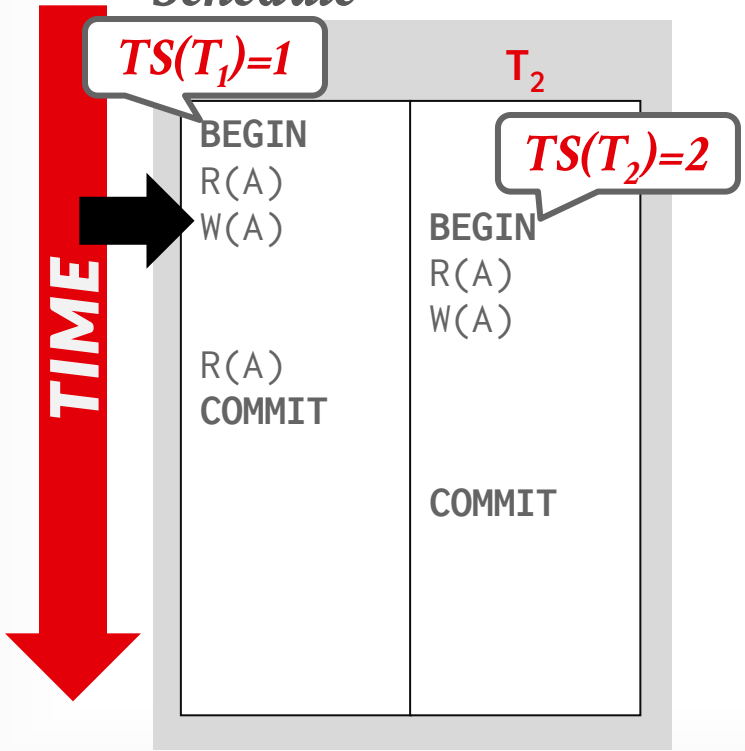


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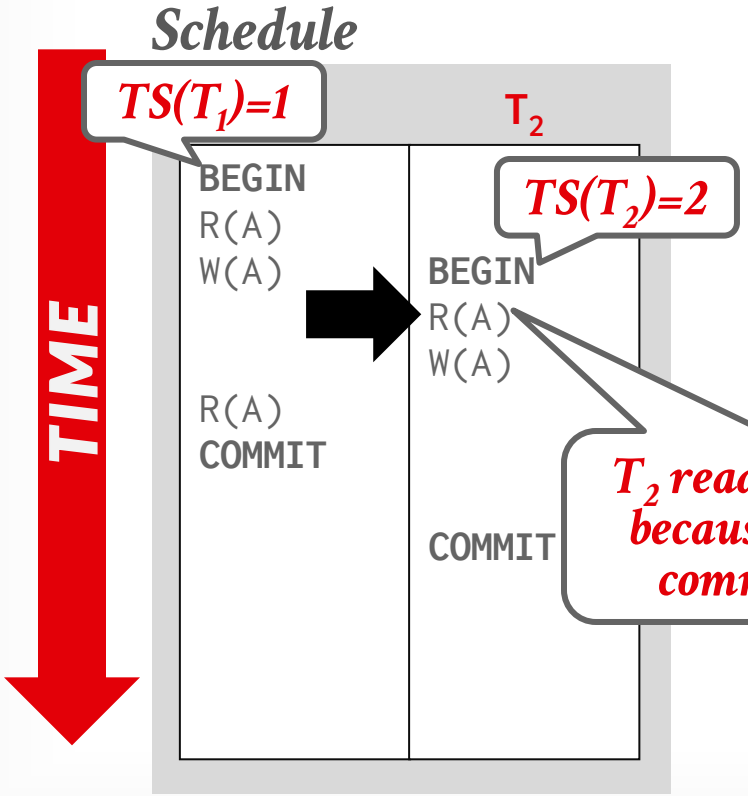


## Database

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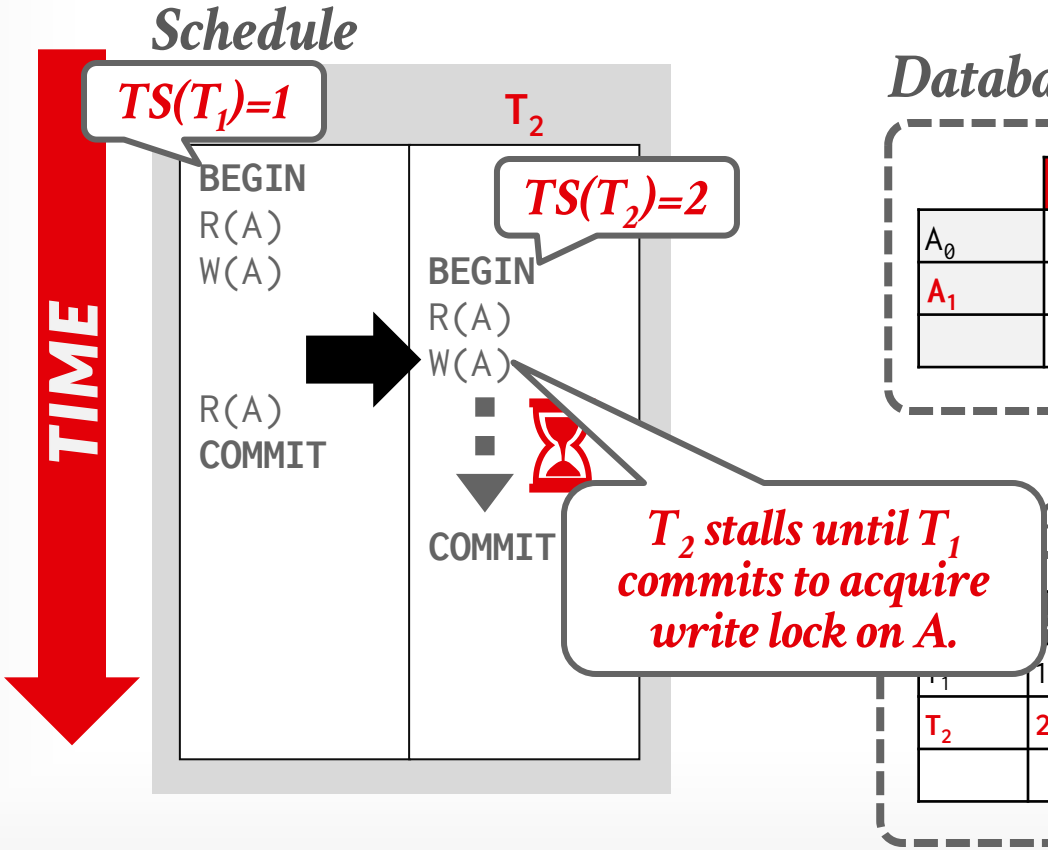
| | | | |

## atus Table

| | timestamp | status |
|---|---|---|
| $T_1$ | 1 | Active |
| $T_2$ | 2 | Active |
| | | |

# MVCC WITH 2PL




## Database

| | begin-ts | end-ts | value |
|---|---|---|---|
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| | | | |

## atus Table

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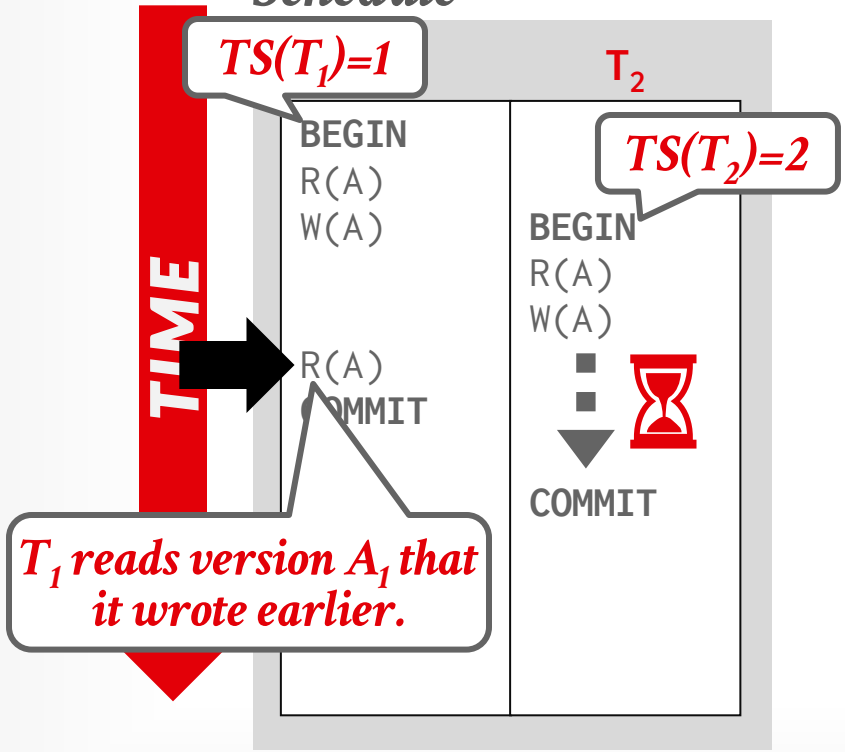
| | | |

# MVCC WITH 2PL

## Schedule




## Database

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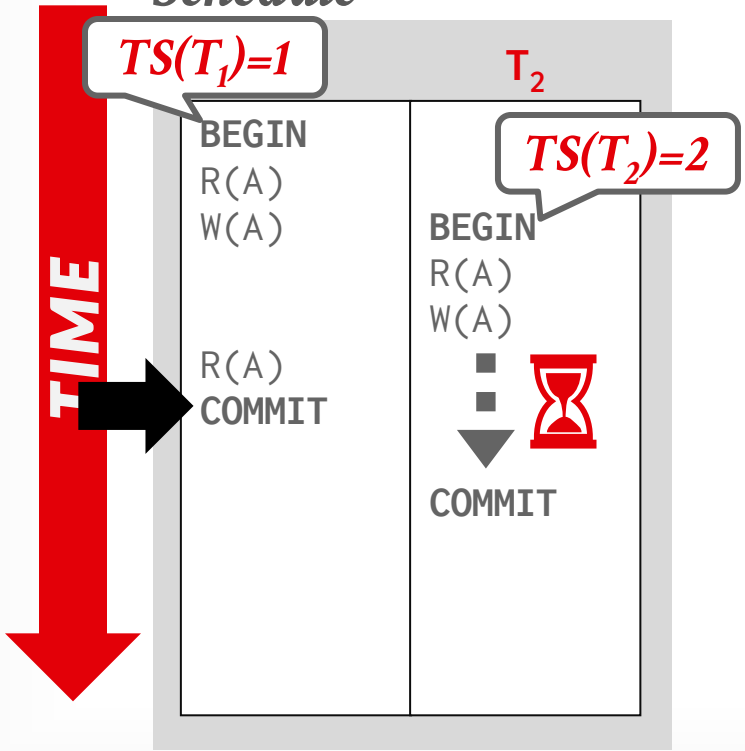


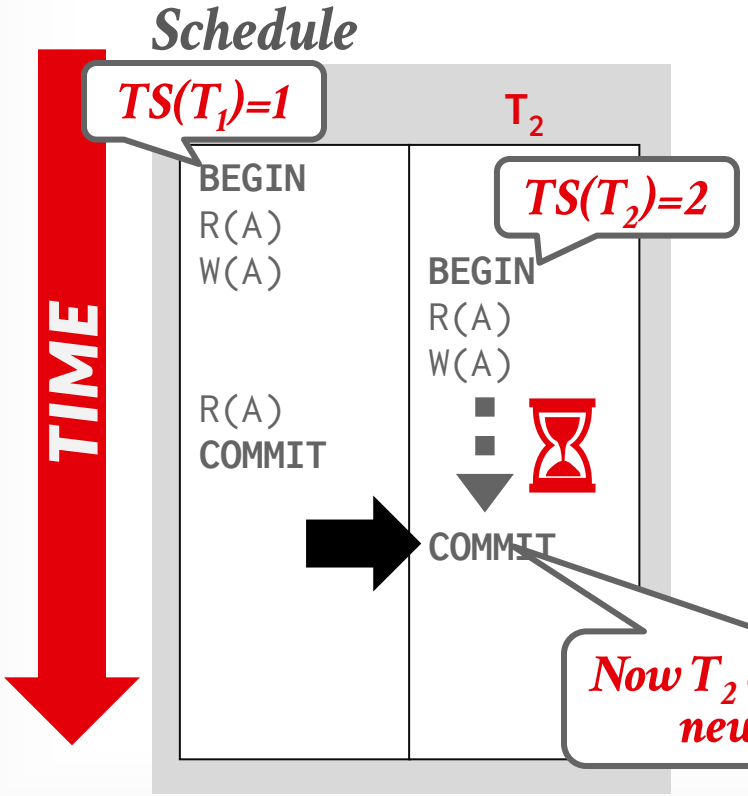

## Database

| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_0$ | 0 | 1 | 123 |
| $A_1$ | 1 | - | 456 |
| | | | |

## Txn Status Table

| txnid | timestamp | status |
|---|---|---|
| $T_1$ | 1 | Committed |
| $T_2$ | 2 | Active |
| | | |

# MVCC WITH 2PL




## Database

| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_0$ | 0 | 1 | 123 |
| $A_1$ | 1 | 2 | 456 |
| $A_2$ | 2 | - | 789 |

## Txn Status Table

| txnid | timestamp | status |
|---|---|---|
| | | Committed |
| | | Active |
| | | |

# VERSION STORAGE

The DBMS uses the tuples' pointer field to create a **version chain** per logical tuple.

→ This allows the DBMS to find the version that is visible to a particular txn at runtime.

→ Indexes always point to the "head" of the chain.

Different storage schemes determine where/what to store for each version.

# VERSION STORAGE

**Approach #1: Append-Only Storage** ← *Less Common*

→ New versions are appended to the same table space.

**Approach #2: Time-Travel Storage** ← *Rare*

→ Old versions are copied to separate table space.

**Approach #3: Delta Storage** ← *Common*

→ The original values of the modified attributes are copied into a separate delta record space.

# VERSION STORAGE

*Don't Do This!*

**Approach #1: Append-Onl**
→ New versions are appended to

**Approach #2: Time-Trave**
→ Old versions are copied to sep

**Approach #3: Delta Storag**
→ The original values of the mo
separate delta record space.

Andy Pavlo

## The Part of PostgreSQL We Hate the Most

Posted on April 26, 2023

*This article was written in collaboration with Bohan Zhang and originally appeared on the OtterTune website.*

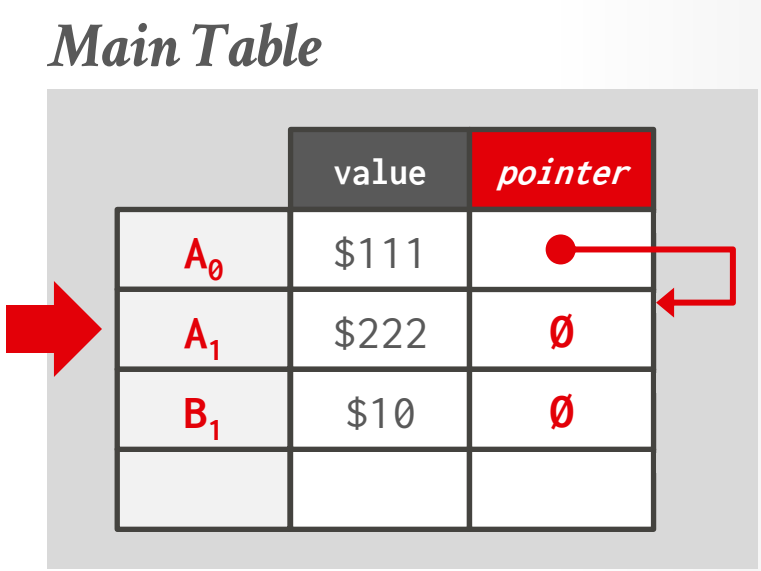
There are a lot of choices in databases (897 as of April 2023). With so many systems, it's hard to know what to pick! But there is an interesting phenomenon where the Internet collectively decides on the default choice for new applications. In the 2000s, the conventional wisdom selected MySQL because rising tech stars like Google and Facebook were using it. Then in the 2010s, it was MongoDB because non-durable writes made it "webscale". In the last five years, PostgreSQL has become the Internet's darling DBMS. And for good reasons! It's dependable, feature-rich, extensible, and well-suited for most operational workloads.

But as much as we love PostgreSQL at OtterTune, certain aspects of it are not great. So instead of writing yet another blog article like everyone else touting the awesomeness of everyone's favorite elephant-themed DBMS, we want to discuss the one major thing that sucks: how PostgreSQL implements multi-version concurrency control (MVCC). Our research at Carnegie Mellon University and experience optimizing PostgreSQL database instances on Amazon RDS have shown that its MVCC implementation is the worst

# APPEND-ONLY STORAGE

All the physical versions of a logical tuple are stored in the same table space. The versions are inter-mixed.

On every update, append a new version of the tuple into an empty space in the table.



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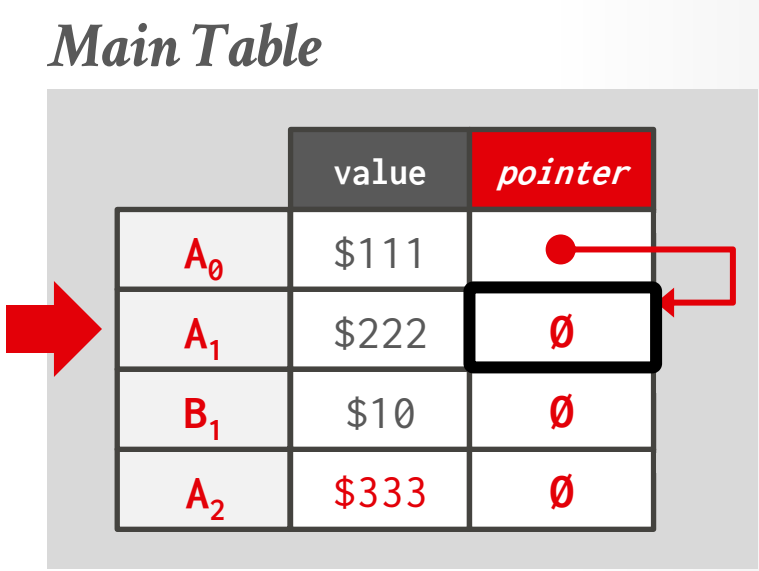

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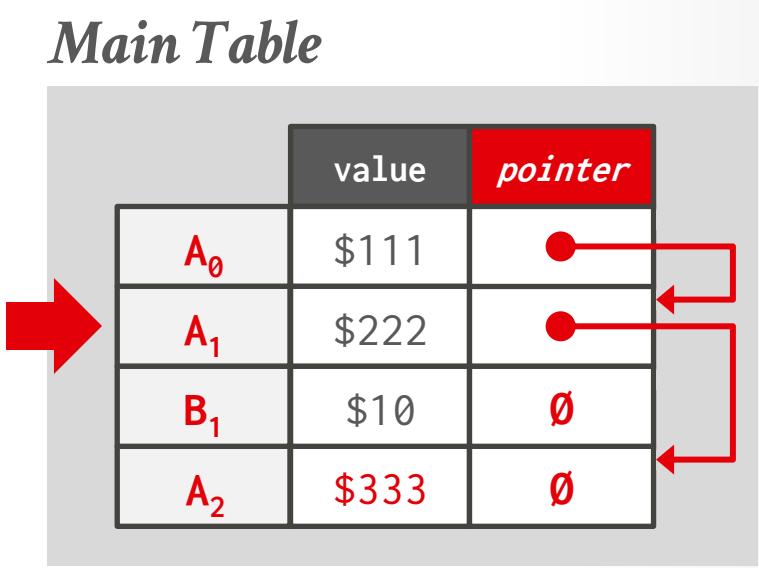
All the physical versions of a logical tuple are stored in the same table space. The versions are inter-mixed.

On every update, append a new version of the tuple into an empty space in the table.

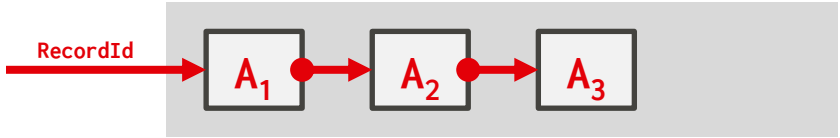


# VERSION CHAIN ORDERING

## Approach #1: Oldest-to-Newest (O2N)

→ Append new version to end of the chain.

→ Must traverse chain on look-ups.



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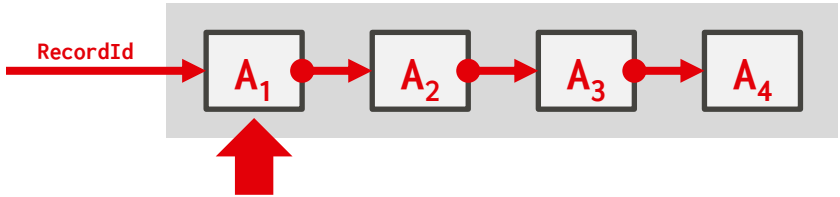

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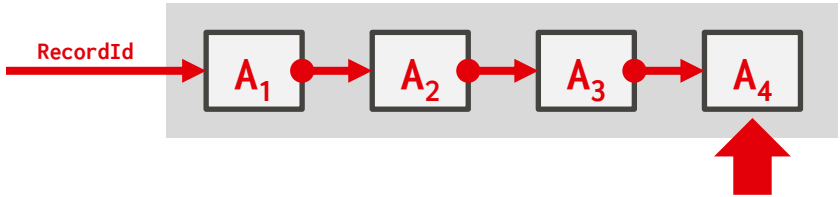

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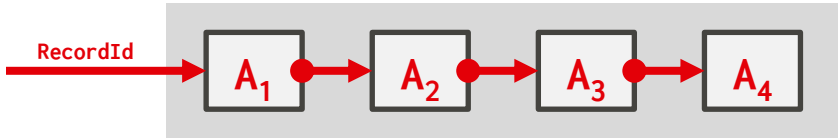
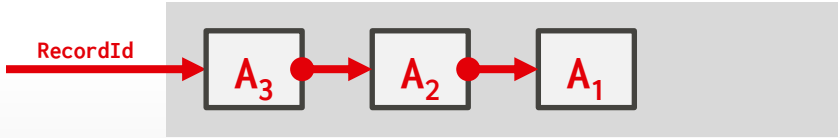



## Approach #2: Newest-to-Oldest (N2O)

→ Must update index pointers for every new version.
→ Do not have to traverse chain on look-ups.
→ Better approach if most txns only want the newest version.



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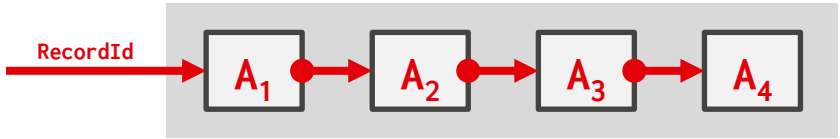


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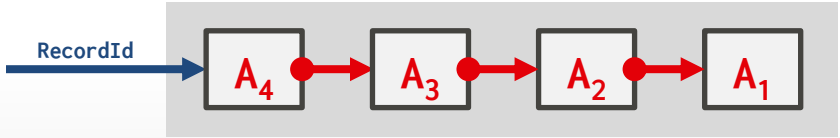

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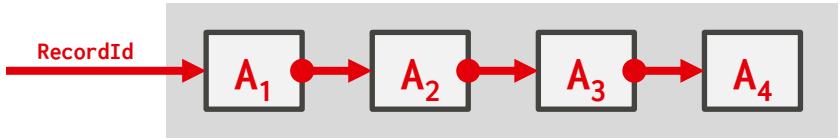


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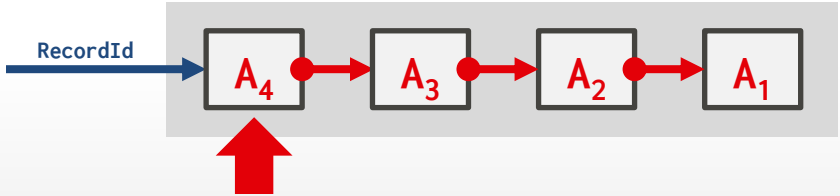
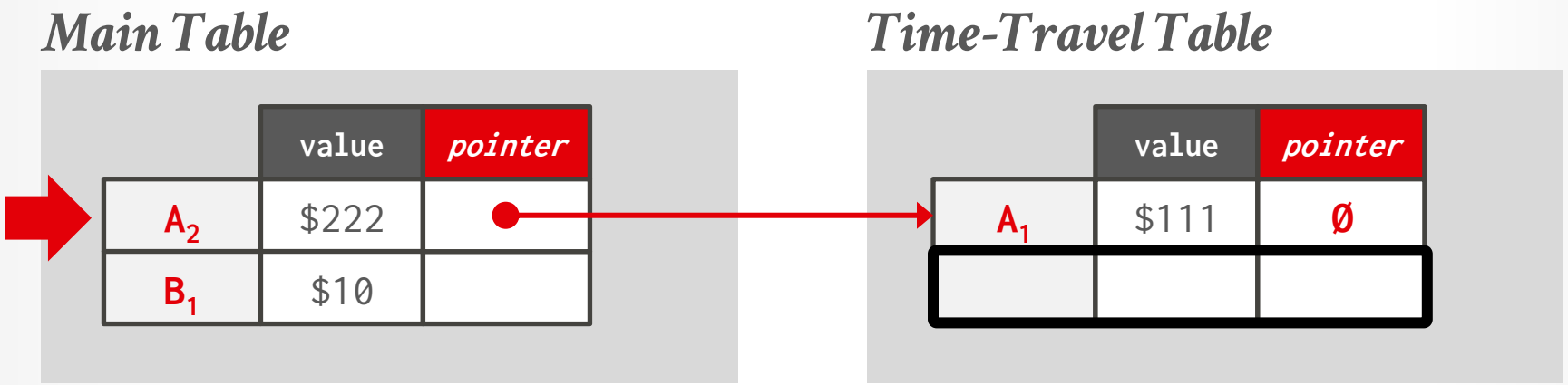
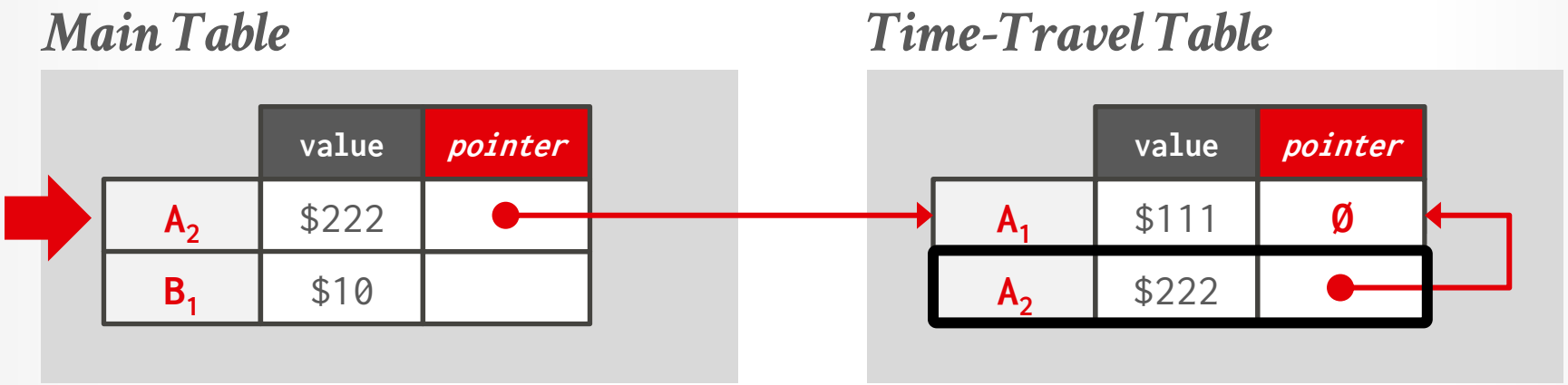


# TIME-TRAVEL STORAGE




On every update, copy the current version to the time-travel table. Update pointers.

# TIME-TRAVEL STORAGE

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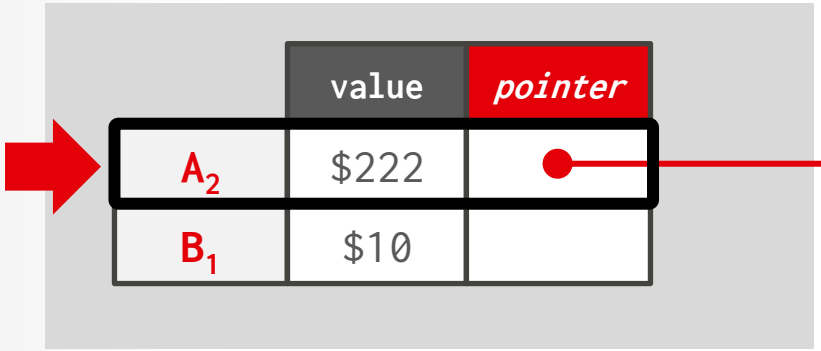
*Main Table*

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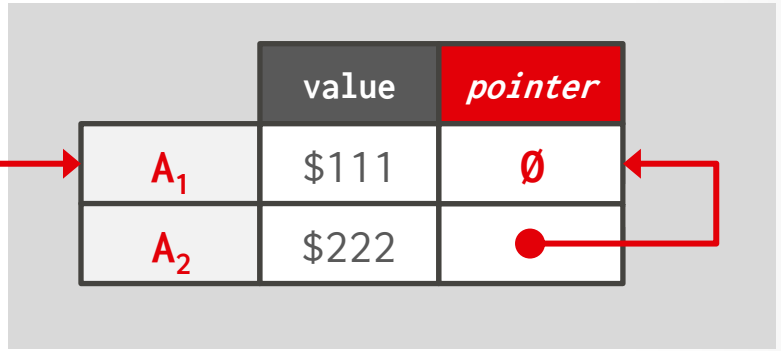


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Overwrite master version in the main table and update pointers.

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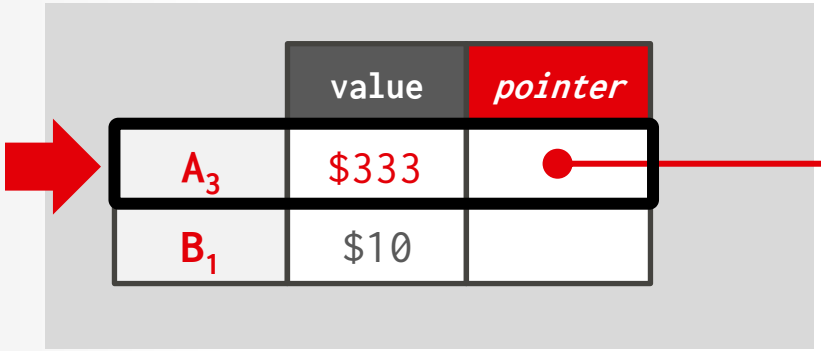


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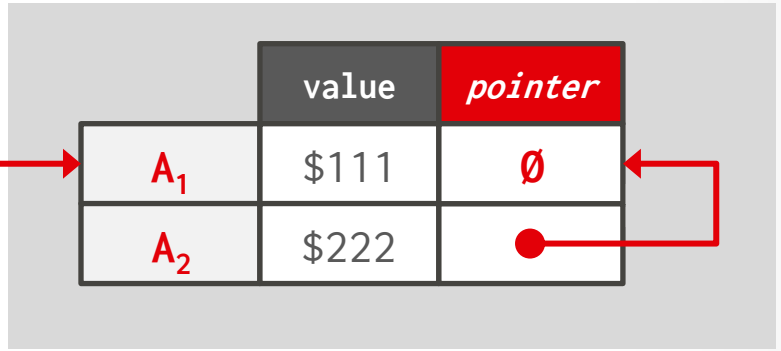


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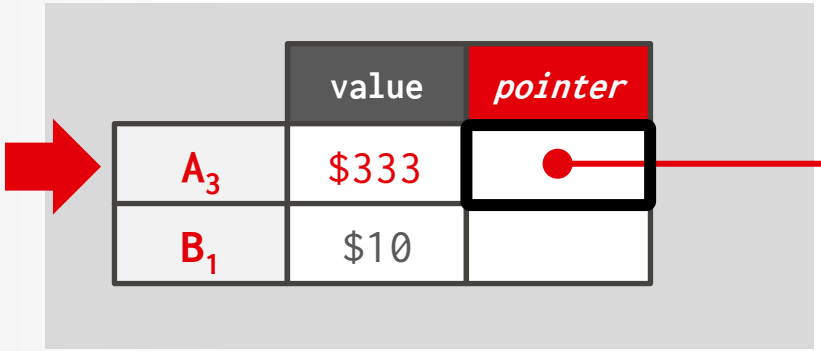


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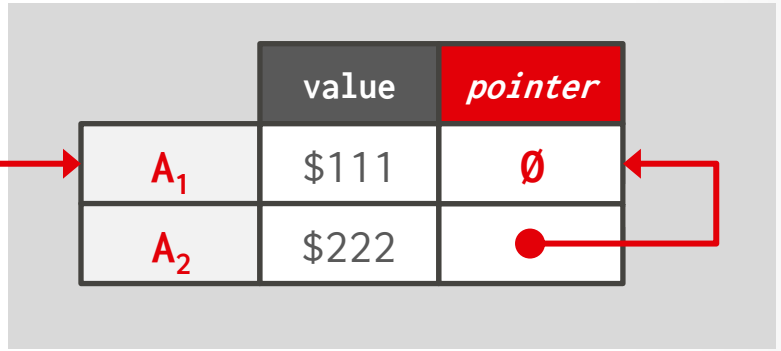


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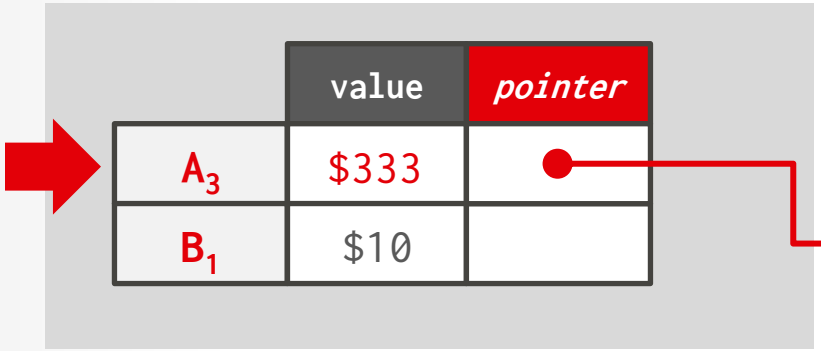


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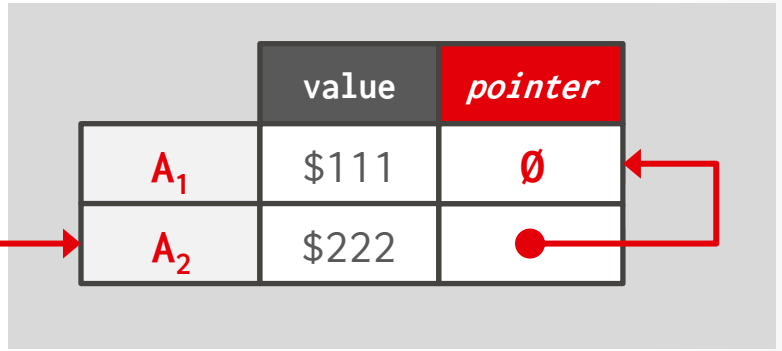


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# DELTA STORAGE

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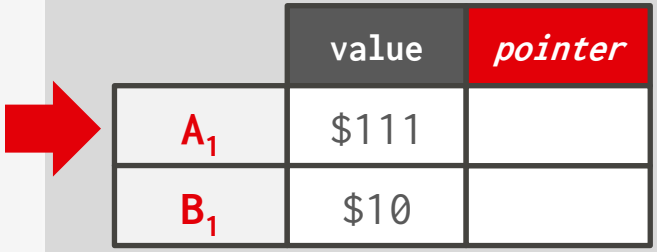


## *Delta Storage Segment*

On every update, copy only the column values that were modified to the delta storage and overwrite the master version.

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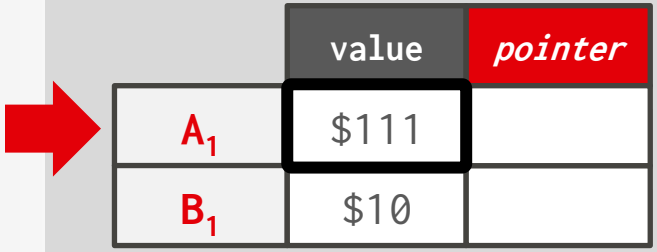


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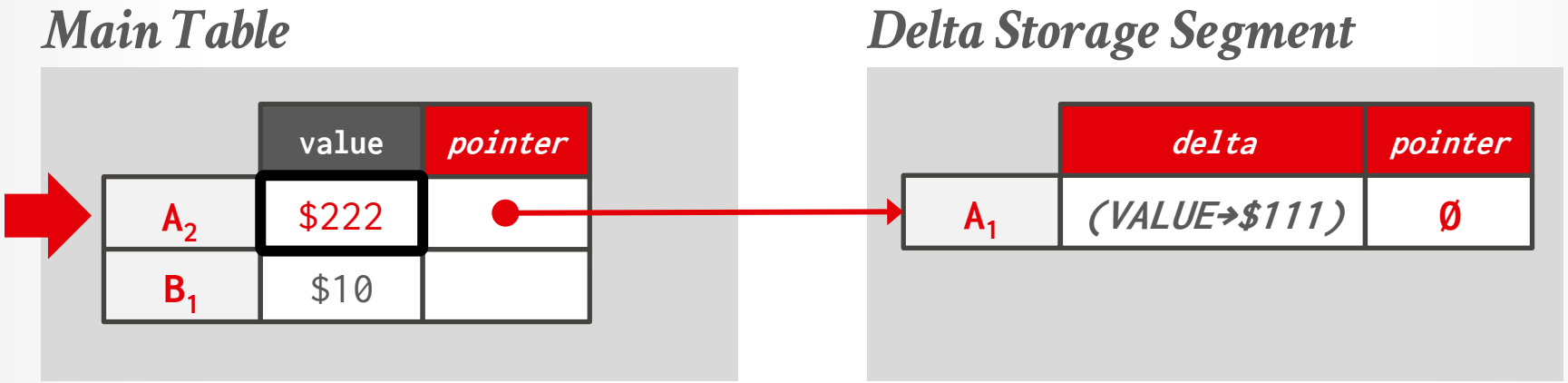


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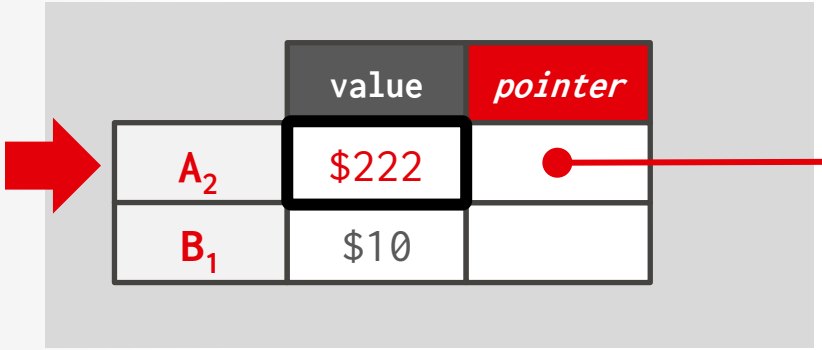


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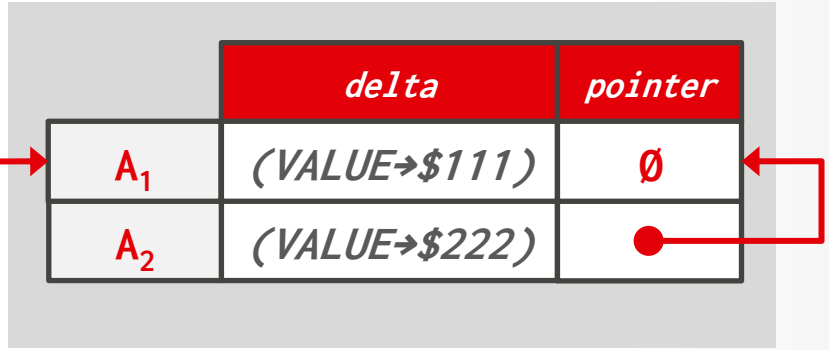


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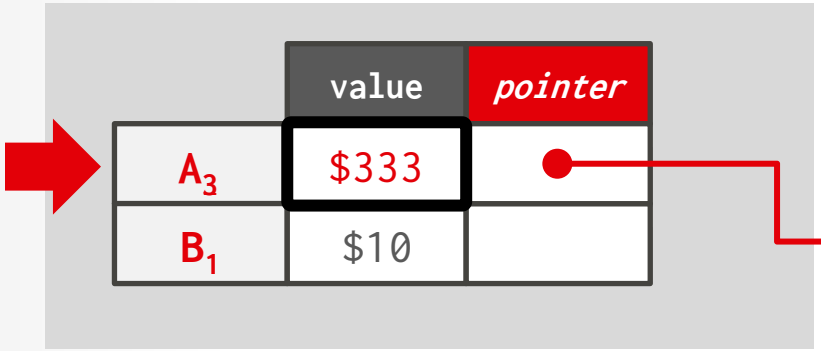


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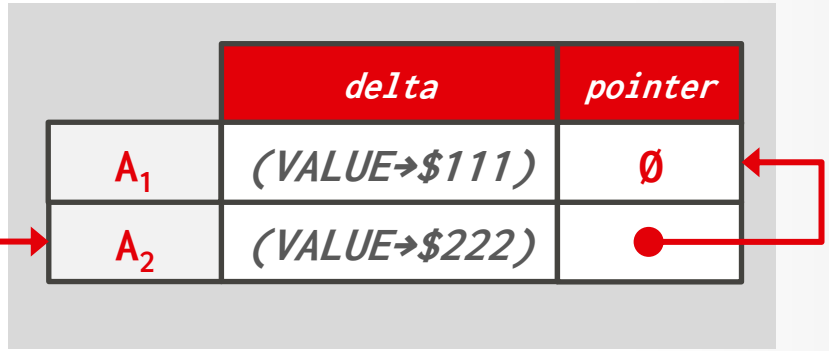



Txns can recreate old versions by applying the delta in reverse order.

# GARBAGE COLLECTION

The DBMS needs to remove **reclaimable** physical versions from the database over time.

→ No active txn in the DBMS can "see" that version (SI).
→ The version was created by an aborted txn.

Two additional design decisions:

→ How to look for expired versions?
→ How to decide when it is safe to reclaim memory?

# GARBAGE COLLECTION

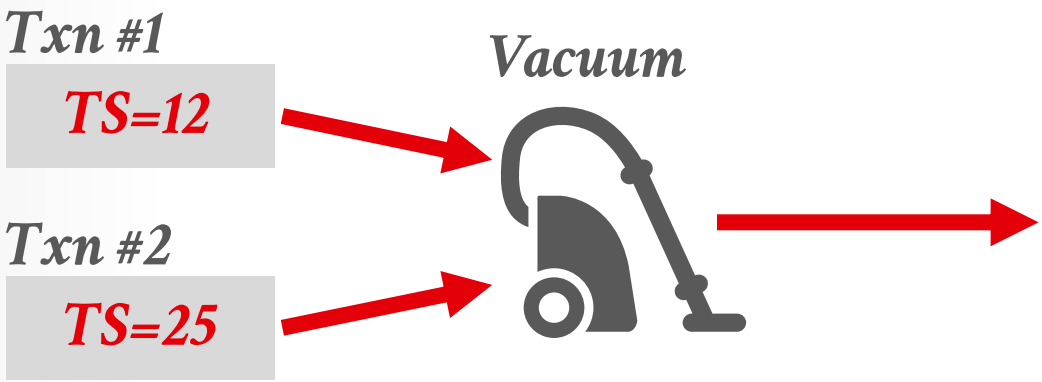
## Approach #1: Tuple-level

→ Find old versions by examining tuples directly.
→ Background Vacuuming vs. Cooperative Cleaning

## Approach #2: Transaction-level

→ Txns keep track of their old versions so the DBMS does not have to scan tuples to determine visibility.

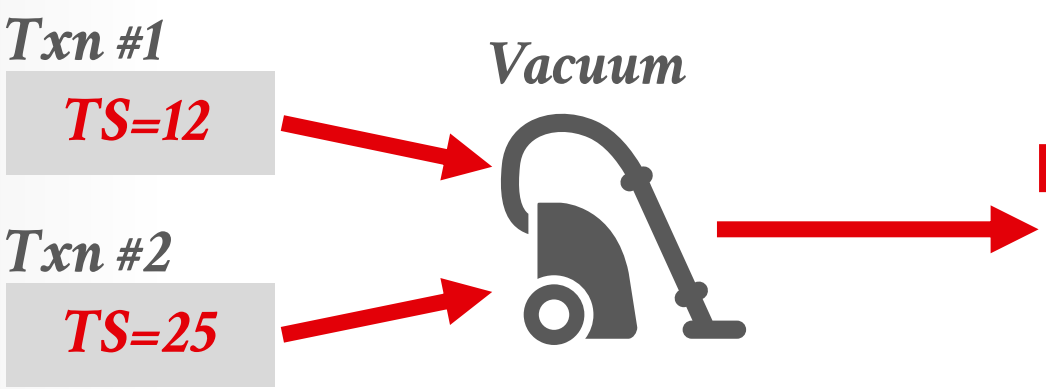
# TUPLE-LEVEL GC




| | begin-ts | end-ts |
|---|---|---|
| $A_{100}$ | 1 | 9 |
| $B_{100}$ | 1 | 9 |
| $B_{101}$ | 10 | 20 |

**Background Vacuuming:**
Separate thread(s) periodically scan the table and look for reclaimable versions. Works with any storage.

# TUPLE-LEVEL GC

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|---|---|---|
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| $B_{101}$ | 10 | 20 |

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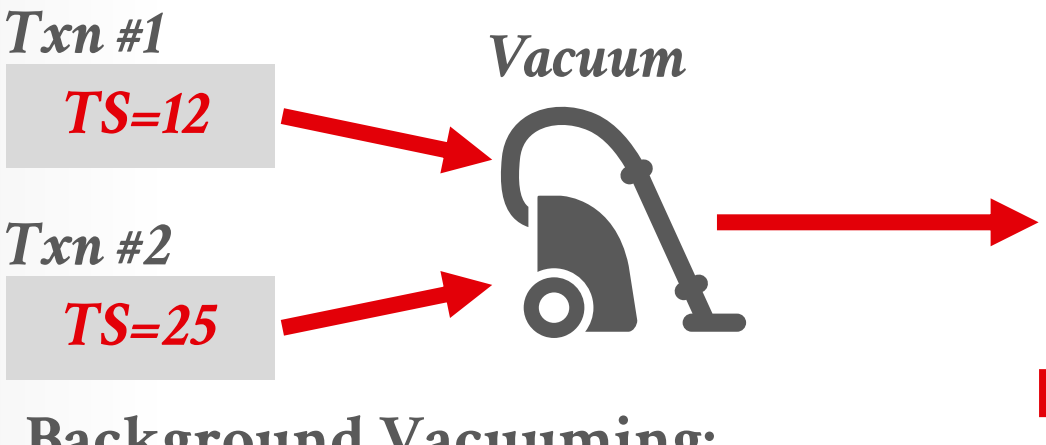


| | begin-ts | end-ts |
|---|---|---|
| $A_{100}$ | 1 | 9 |
| $B_{100}$ | 1 | 9 |
| $B_{101}$ | 10 | 20 |

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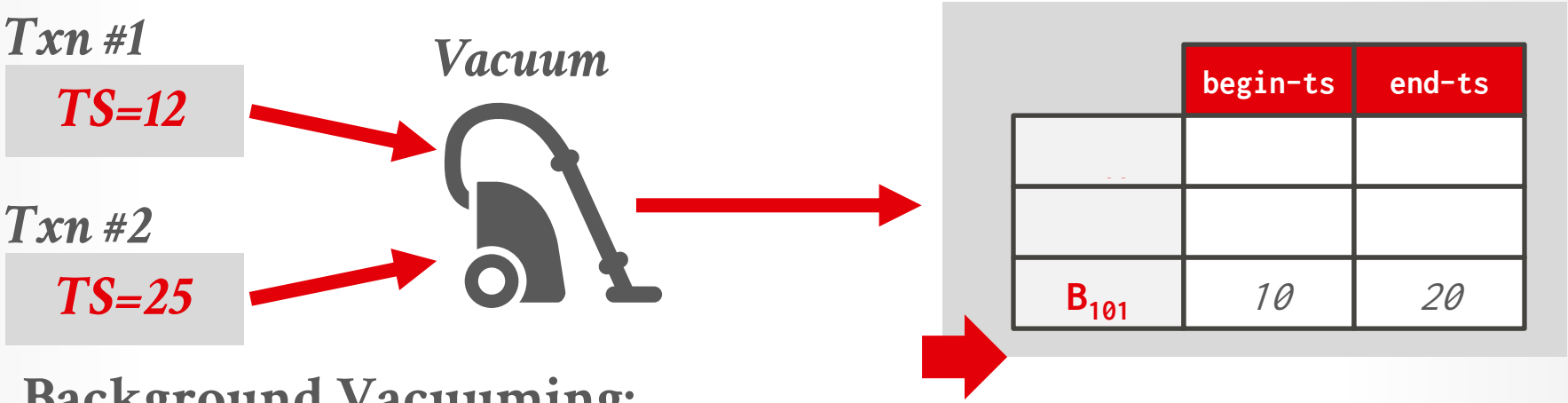


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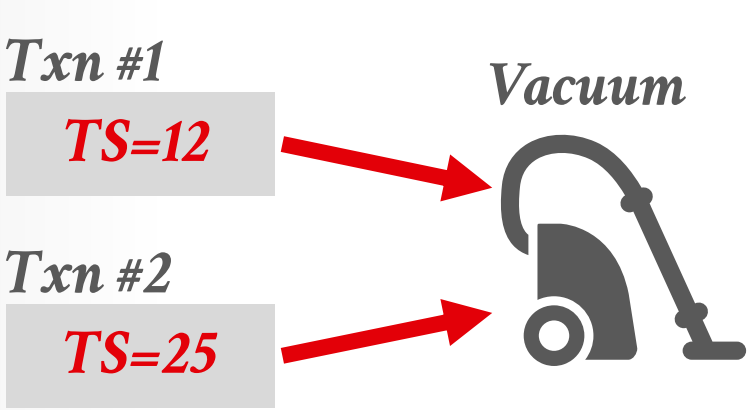


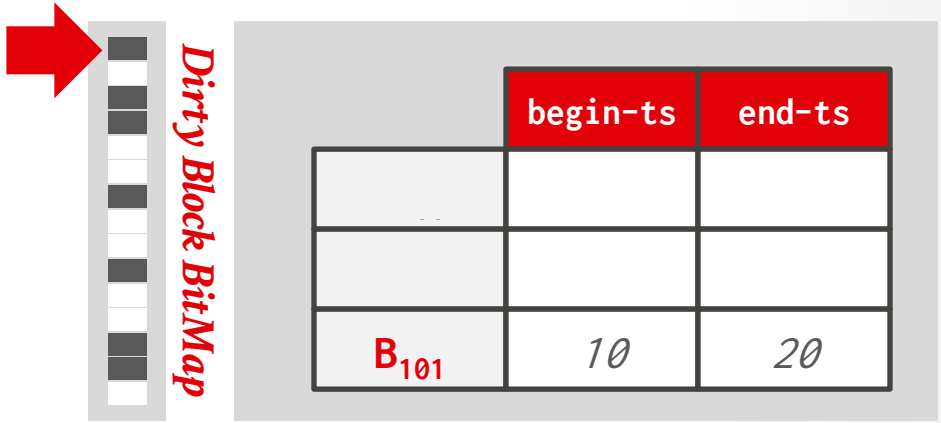


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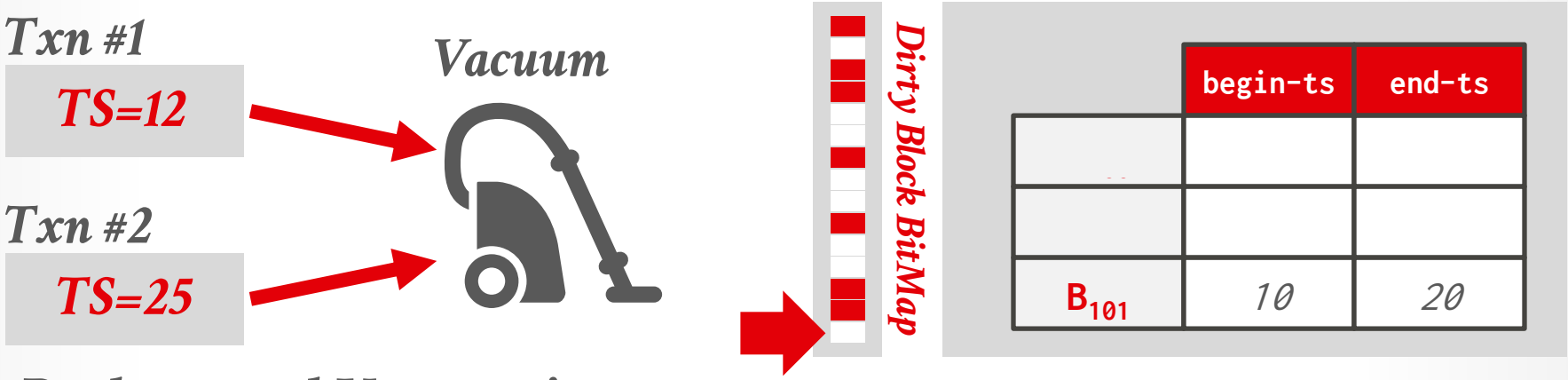



**Background Vacuuming:**
Separate thread(s) periodically scan the table and look for reclaimable versions. Works with any storage.

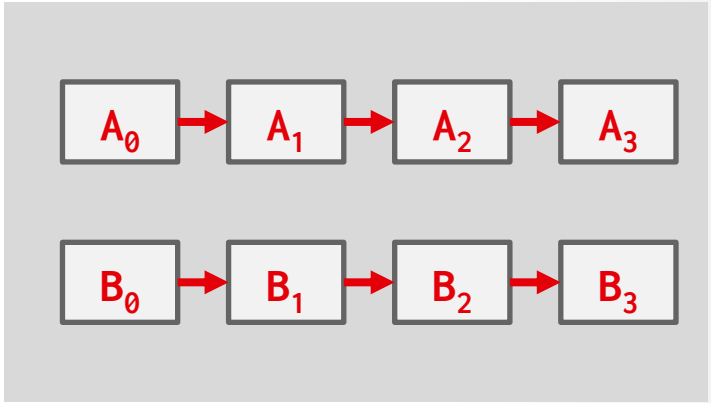
# TUPLE-LEVEL GC

*Txn #1*

*TS=12*

*Txn #2*

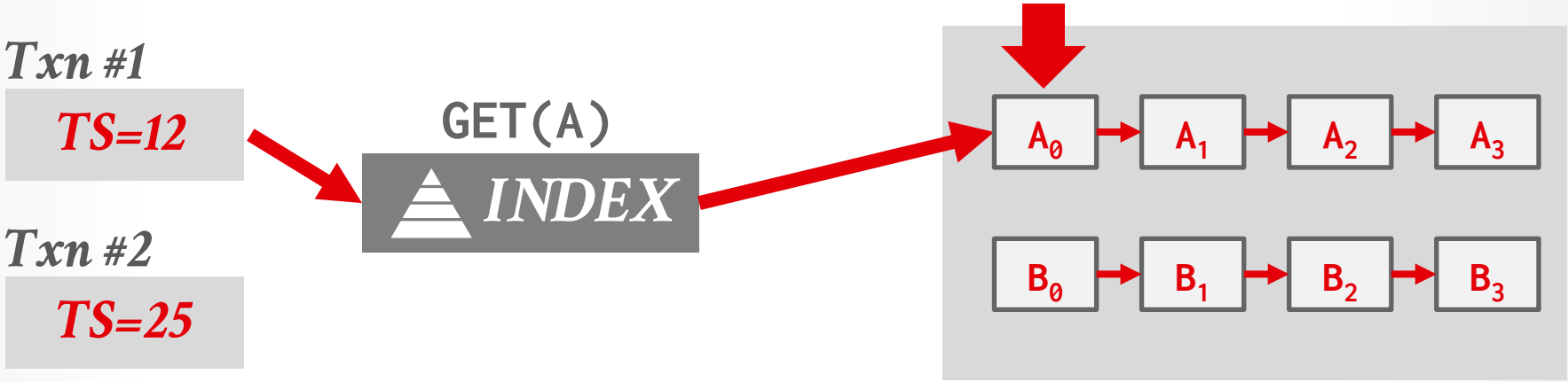
*TS=25*


**Background Vacuuming:**
Separate thread(s) periodically scan the table and look for reclaimable versions. Works with any storage.

**Cooperative Cleaning:**
Worker threads identify reclaimable versions as they traverse version chain. Only works with O2N.

# TUPLE-LEVEL GC

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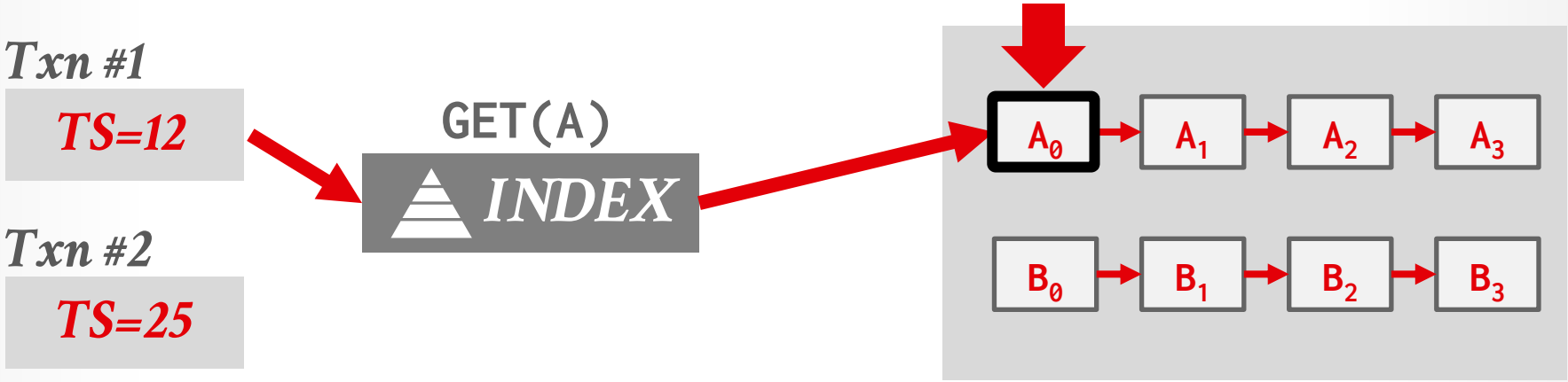


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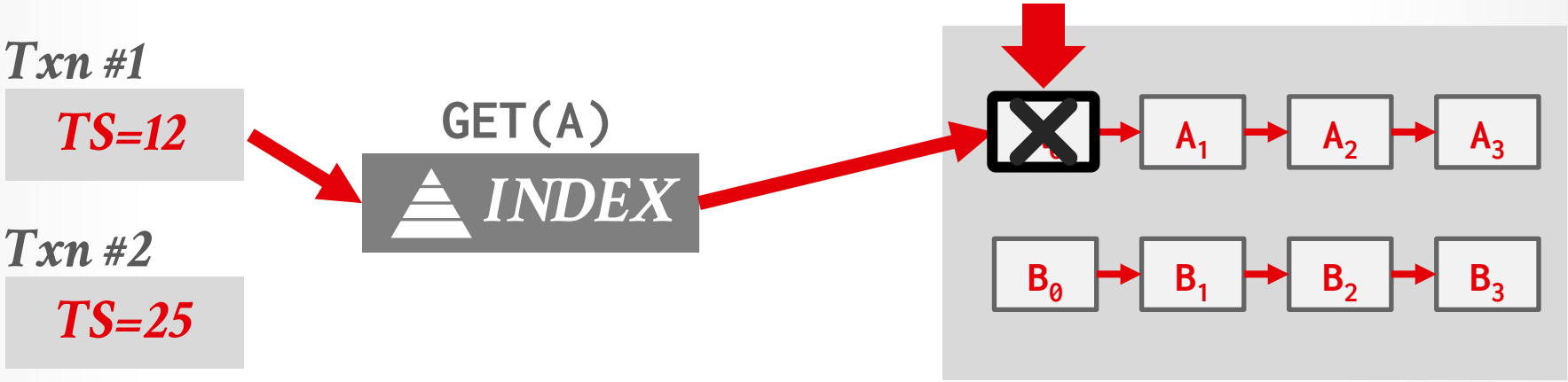


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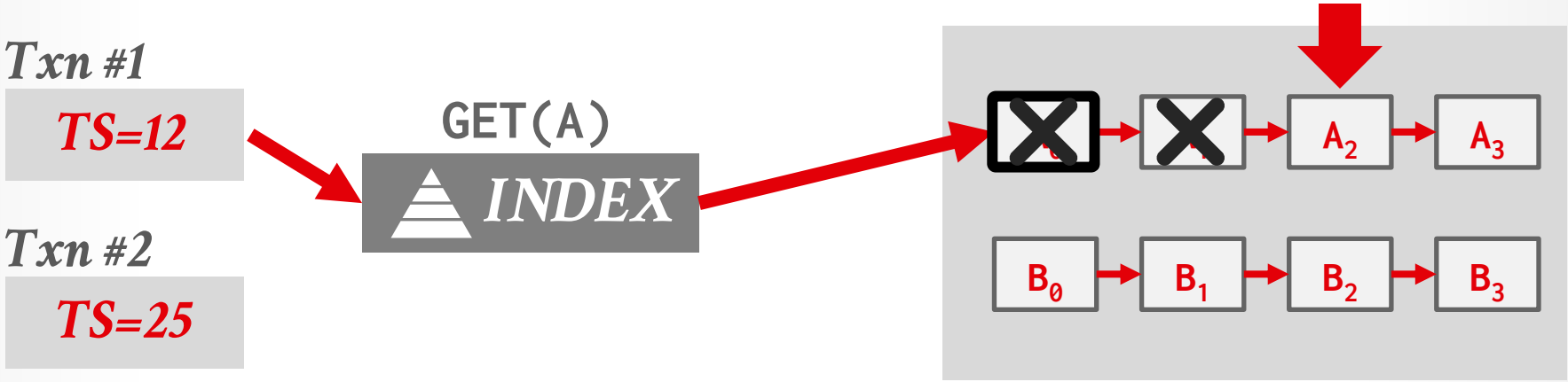


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# TUPLE-LEVEL GC


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Separate thread(s) periodically scan the table and look for reclaimable versions. Works with any storage.

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Worker threads identify reclaimable versions as they traverse version chain. Only works with O2N.

# TRANSACTION-LEVEL GC



Each txn keeps track of its read/write set.

On commit/abort, the txn provides this information to a centralized vacuum worker.

The DBMS periodically determines when all versions created by a finished txn are no longer visible.

# TRANSACTION-LEVEL GC



*Txn #1*

```
BEGIN TS=10
```


| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_2$ | 1 | ∞ | - |
| $B_6$ | 8 | ∞ | - |
| | | | |
| | | | |

# TRANSACTION-LEVEL GC



*Txn #1*

```
BEGIN TS=10
```


| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_2$ | 1 | 10 | - |
| $B_6$ | 8 | ∞ | - |
| $A_3$ | 10 | ∞ | - |
| | | | |

# TRANSACTION-LEVEL GC

*Txn #1*

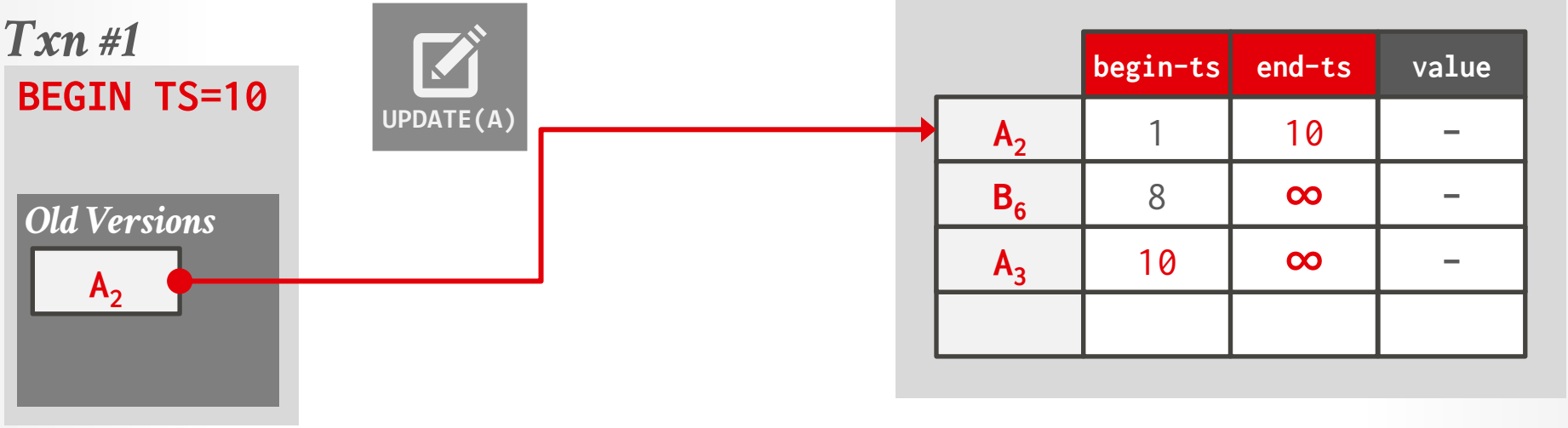
BEGIN TS=10

*Old Versions*

$A_2$


| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_2$ | 1 | 10 | - |
| $B_6$ | 8 | ∞ | - |
| $A_3$ | 10 | ∞ | - |
| | | | |

# TRANSACTION-LEVEL GC



# TRANSACTION-LEVEL GC

*Txn #1*

BEGIN TS=10

*Old Versions*

$A_2$



| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_2$ | 1 | 10 | - |
| $B_6$ | 8 | ∞ | - |
| $A_3$ | 10 | ∞ | - |
| | | | |

# TRANSACTION-LEVEL GC



*Txn #1*

BEGIN TS=10

*Old Versions*

$A_2$



| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_2$ | 1 | 10 | - |
| $B_6$ | 8 | 10 | - |
| $A_3$ | 10 | ∞ | - |
| $B_7$ | 10 | ∞ | - |

# TRANSACTION-LEVEL GC

*Txn #1*

BEGIN TS=10

*Old Versions*

$A_2$

$B_6$

UPDATE(A)

UPDATE(B)

| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_2$ | 1 | 10 | - |
| $B_6$ | 8 | 10 | - |
| $A_3$ | 10 | ∞ | - |
| $B_7$ | 10 | ∞ | - |

# TRANSACTION-LEVEL GC

*Txn #1*

BEGIN TS=10
COMMIT TS=15

*Old Versions*

- $A_2$
- $B_6$



| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_2$ | 1 | 10 | - |
| $B_6$ | 8 | 10 | - |
| $A_3$ | 10 | ∞ | - |
| $B_7$ | 10 | ∞ | - |

# TRANSACTION-LEVEL GC

*Txn #1*

```
BEGIN TS=10
COMMIT TS=15
```

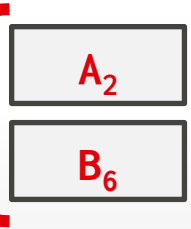
*Old Versions*



| | begin-ts | end-ts | value |
|---|---|---|---|
| $A_2$ | 1 | 10 | - |
| $B_6$ | 8 | 10 | - |
| $A_3$ | 10 | ∞ | - |
| $B_7$ | 10 | ∞ | - |

*Vacuum*

*TS<10*




# INDEX MANAGEMENT



Primary key indexes point to version chain head.

→ How often the DBMS must update the pkey index depends on whether the system creates new versions when a tuple is updated.

→ If a txn updates a tuple's pkey attribute(s), then this is treated as a **DELETE** followed by an **INSERT**.

Secondary indexes are more complicated…

Primary key inde

→ How often the D whether the sys updated.

→ If a txn updates a **DELETE** follo

Secondary inde

UBER Engineering

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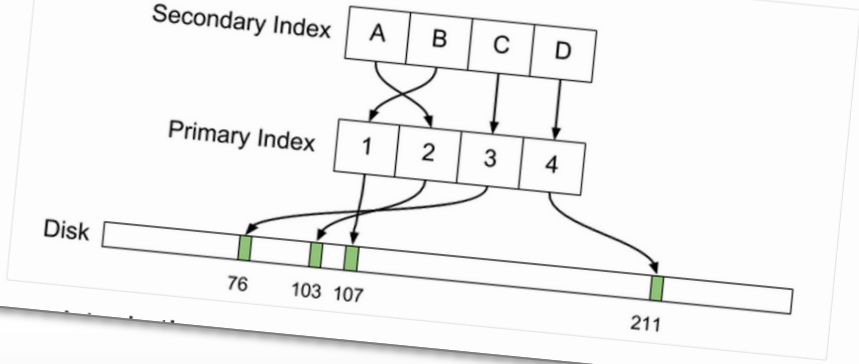
# WHY UBER ENGINEERING SWITCHED FROM POSTGRES TO MYSQL

JULY 26, 2016

BY EVAN KLITZKE



# SECONDARY INDEXES

## Approach #1: Logical Pointers

→ Use a fixed identifier per tuple that does not change.
→ Requires an extra indirection layer.
→ Primary Key vs. Tuple Id

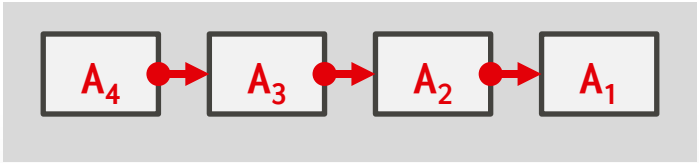
## Approach #2: Physical Pointers

→ Use the physical address to the version chain head.

# INDEX POINTERS: APPEND-ONLY

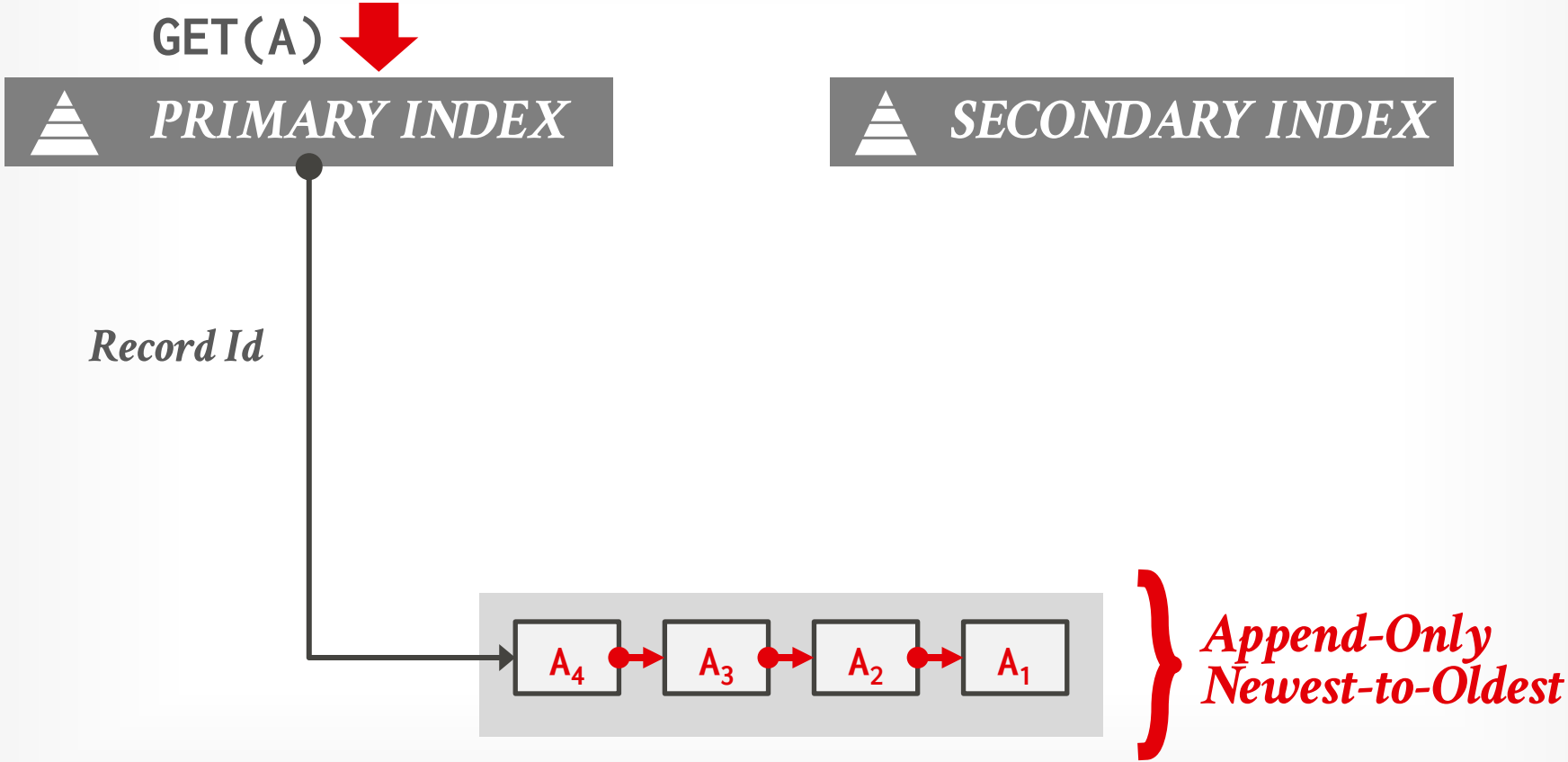
**PRIMARY INDEX**

**SECONDARY INDEX**

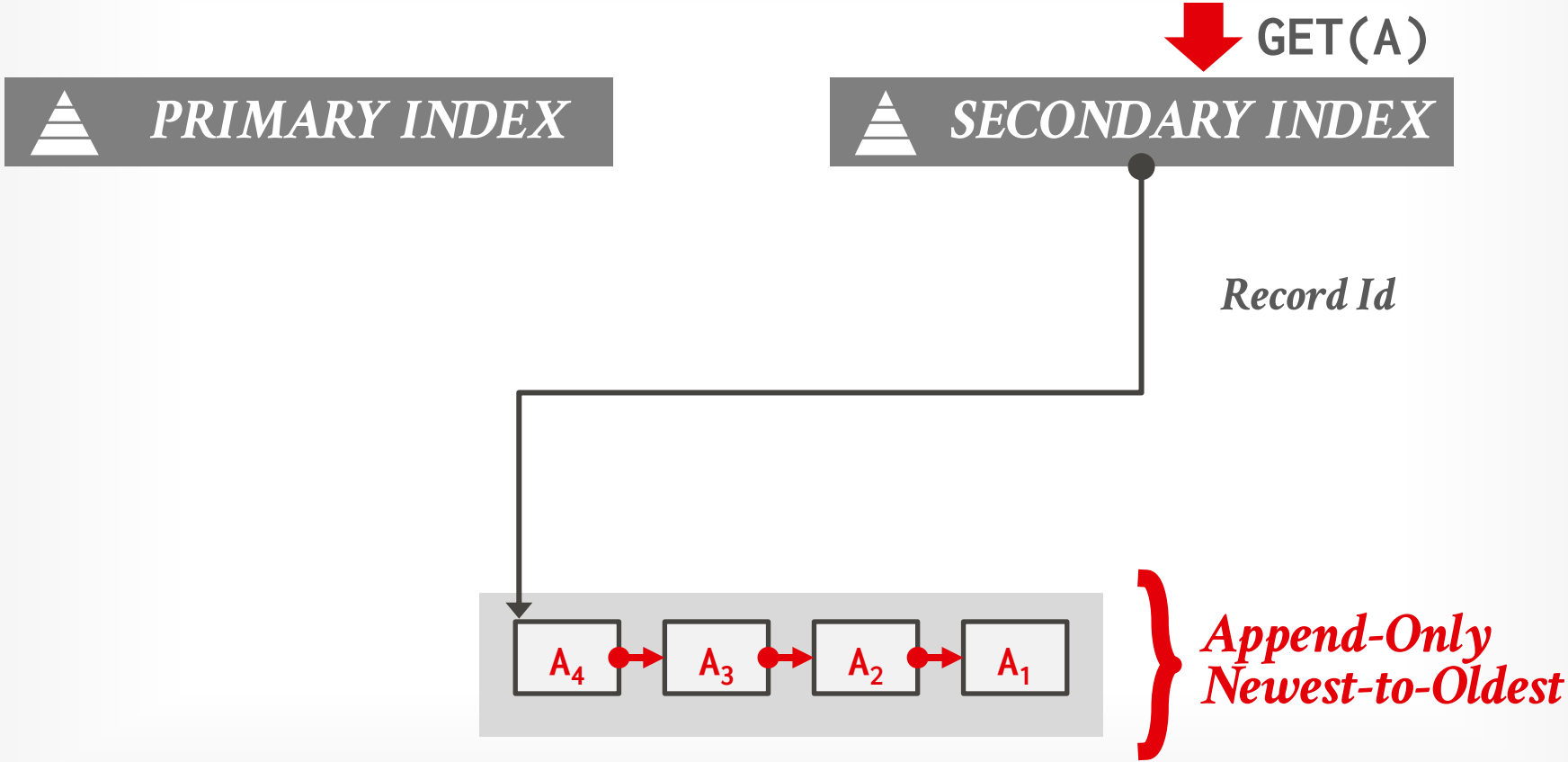



*Append-Only*
*Newest-to-Oldest*

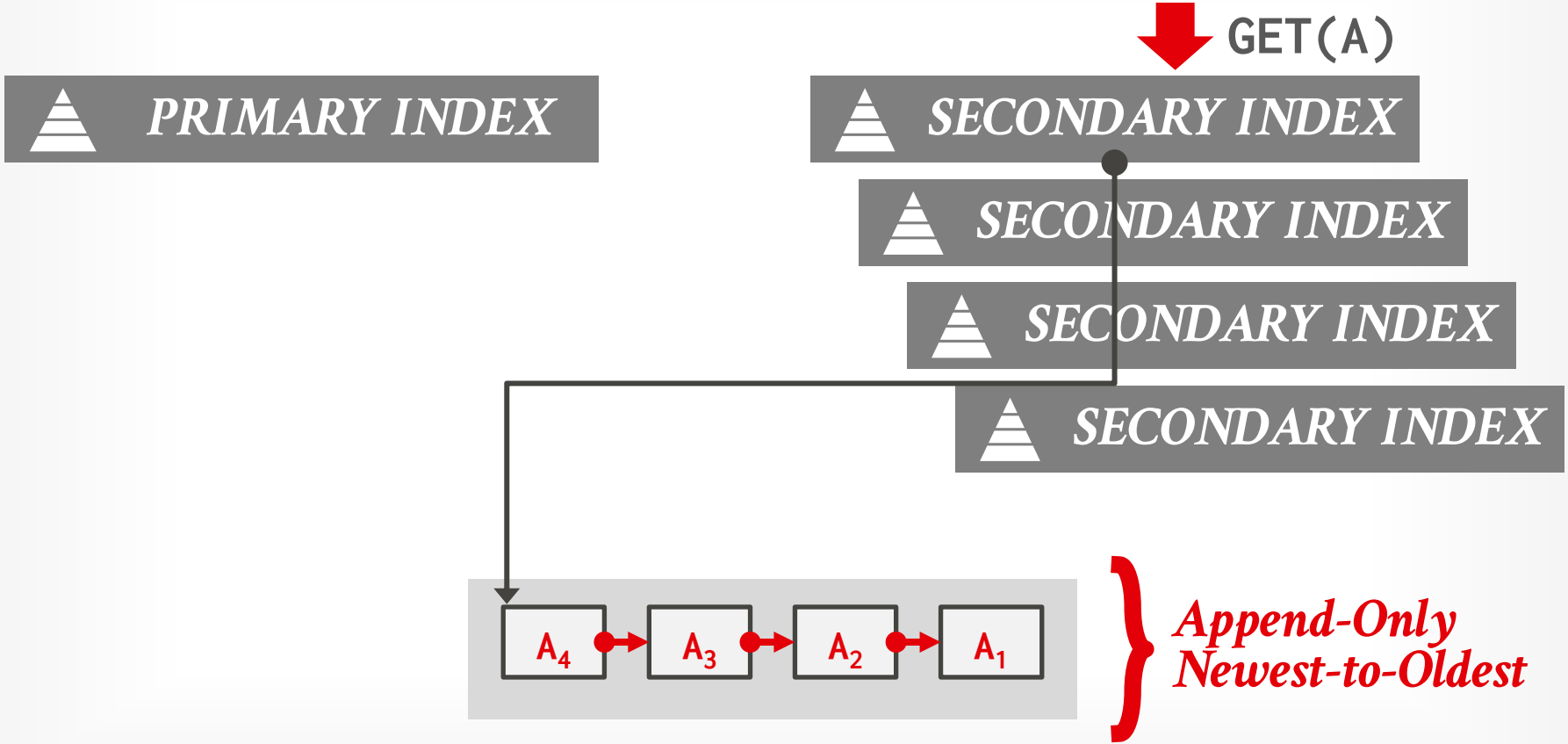
# INDEX POINTERS: APPEND-ONLY



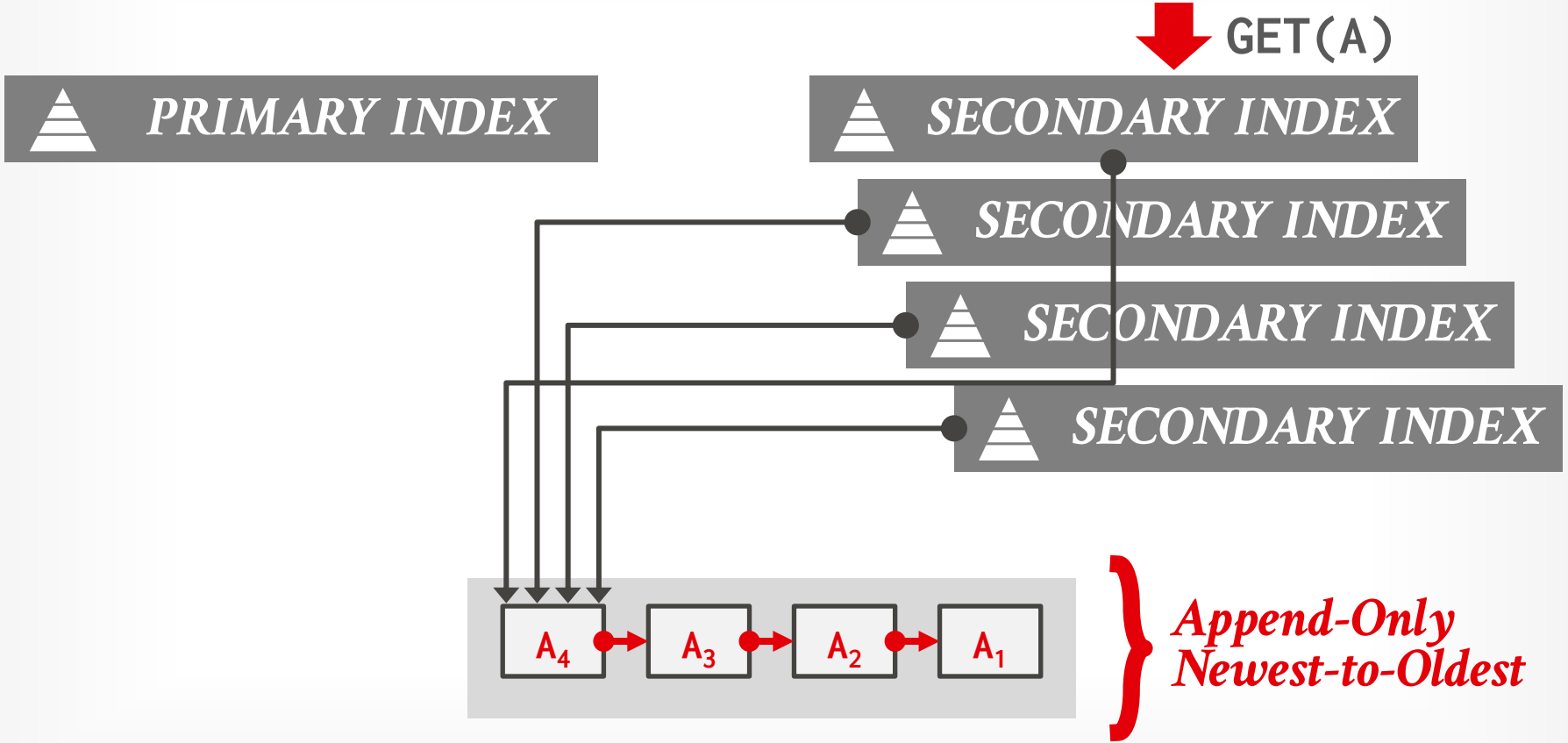
# INDEX POINTERS: APPEND-ONLY



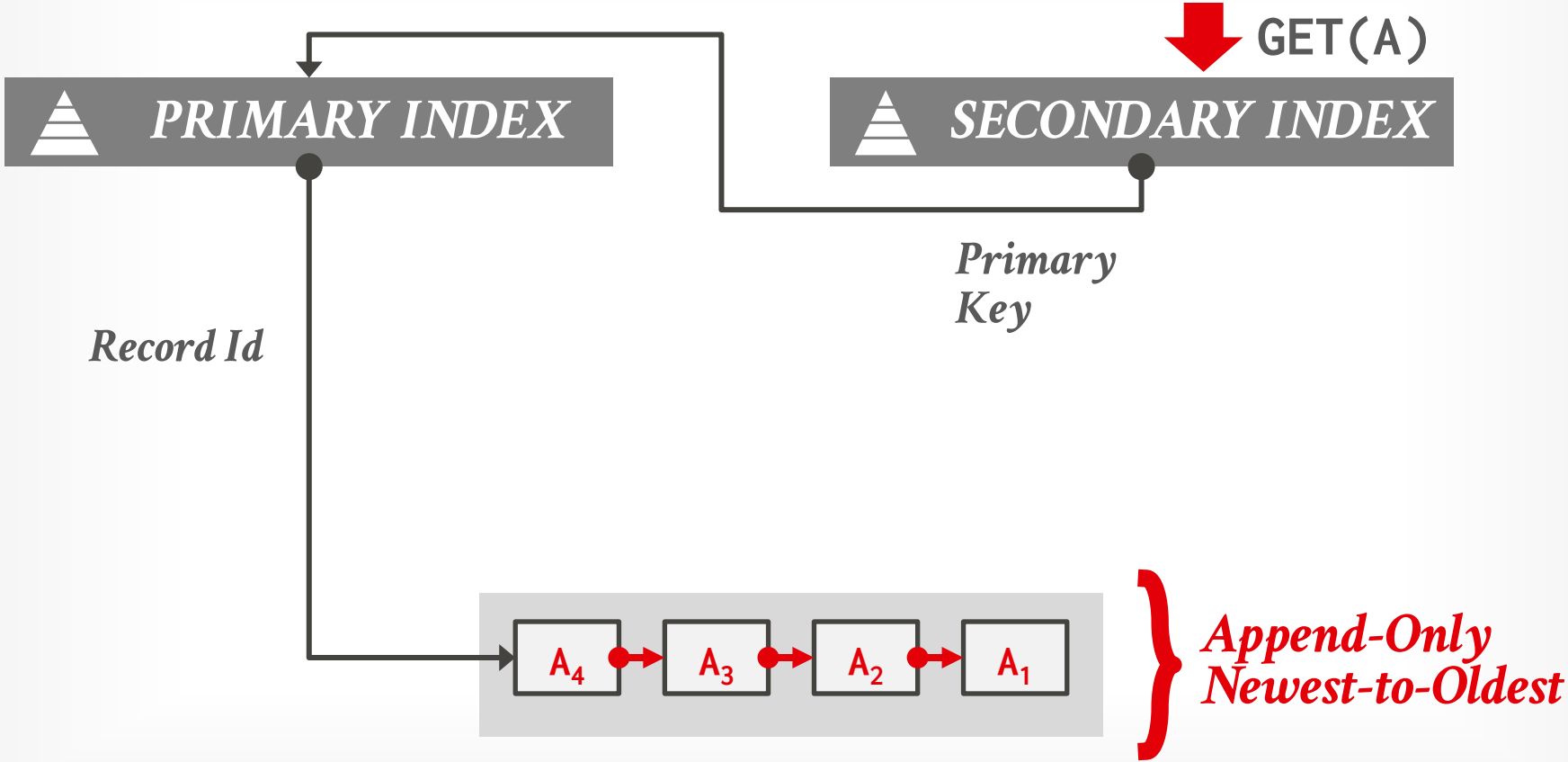
# INDEX POINTERS: APPEND-ONLY



# INDEX POINTERS: APPEND-ONLY



# INDEX POINTERS: APPEND-ONLY



# MVCC INDEXES

MVCC DBMS indexes (usually) do not store version information about tuples with their keys.

→ Exception: Index-organized tables (e.g., MySQL)

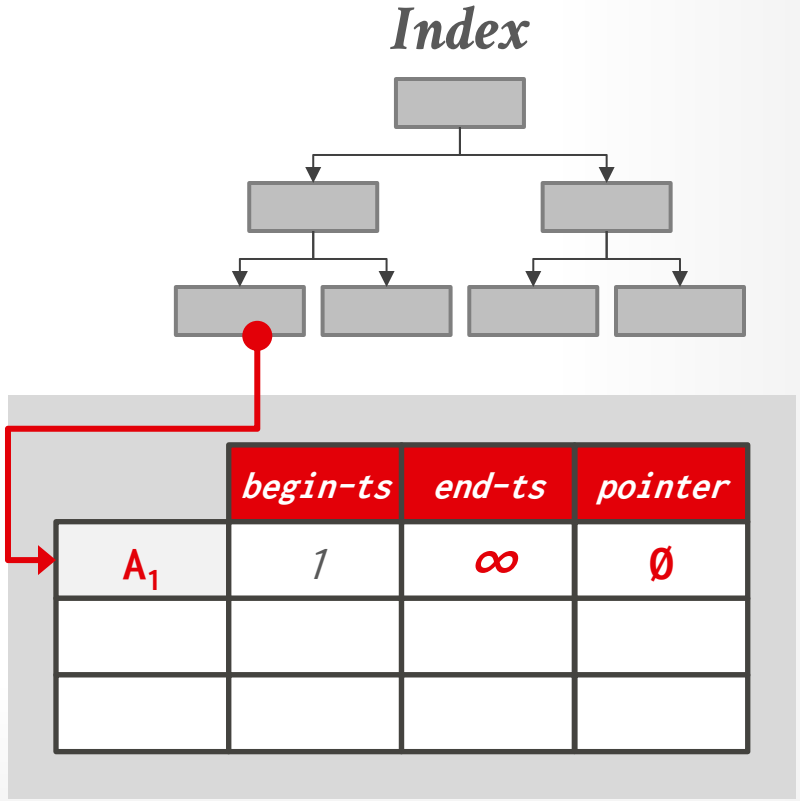
Every index must support duplicate keys from different snapshots:

→ The same key may point to different logical tuples in different snapshots.

# MVCC DUPLICATE KEY PROBLEM

*Txn #1*

```
BEGIN TS=10
```

# MVCC DUPLICATE KEY PROBLEM

*Txn #1*

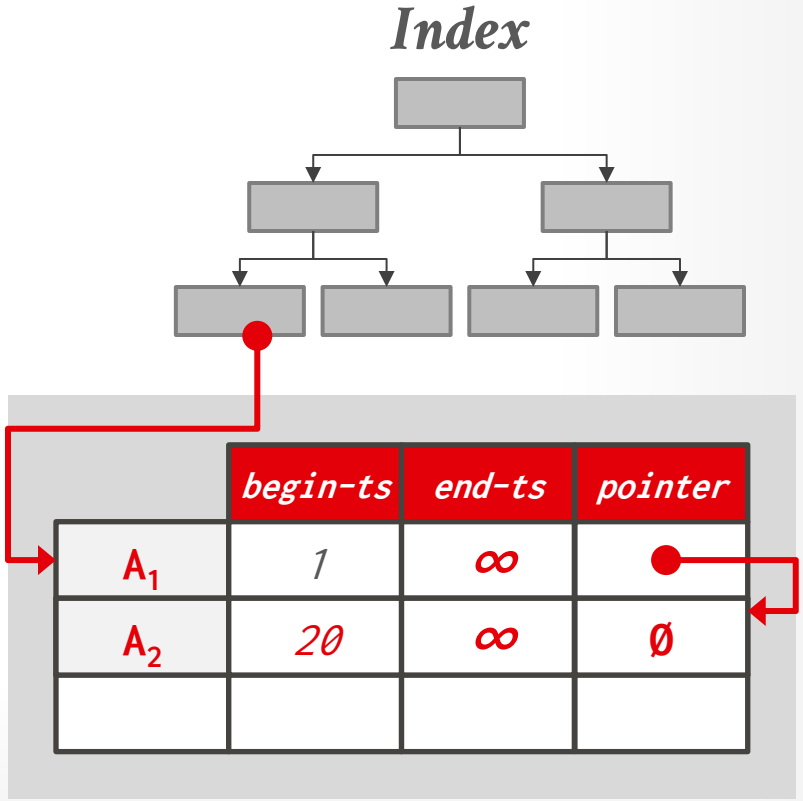
```
BEGIN TS=10
```

READ(A)

*Txn #2*

```
BEGIN TS=20
```

UPDATE(A)



# MVCC DUPLICATE KEY PROBLEM

*Txn #1*

```
BEGIN TS=10
```

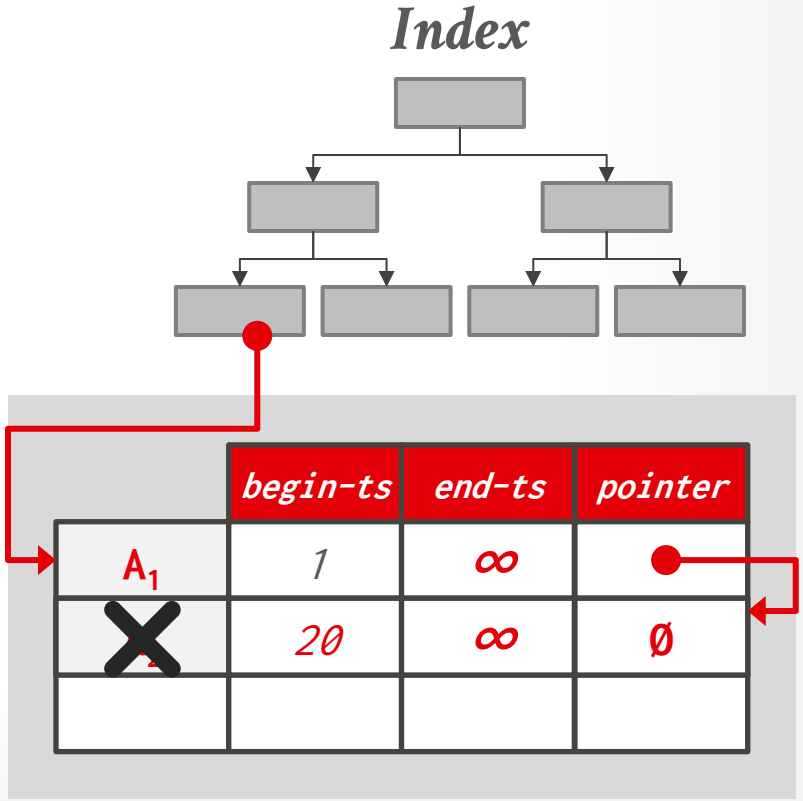
READ(A)

*Txn #2*

```
BEGIN TS=20
```

UPDATE(A)

DELETE(A)



# MVCC DUPLICATE KEY PROBLEM

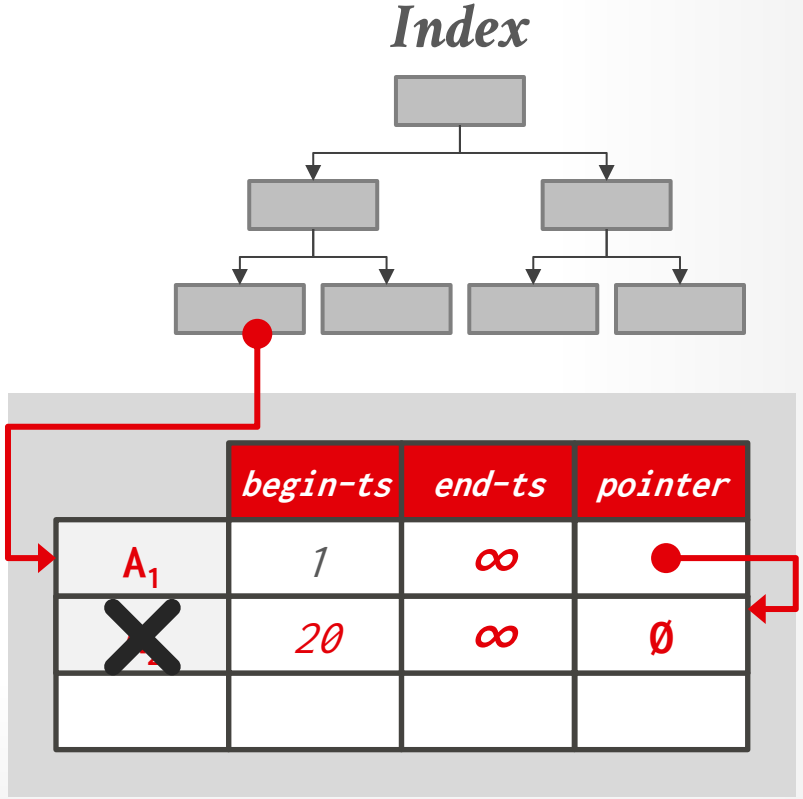
*Txn #1*

```
BEGIN TS=10
```


*Txn #2*

```
BEGIN TS=20
COMMIT TS=25
```





# MVCC DUPLICATE KEY PROBLEM

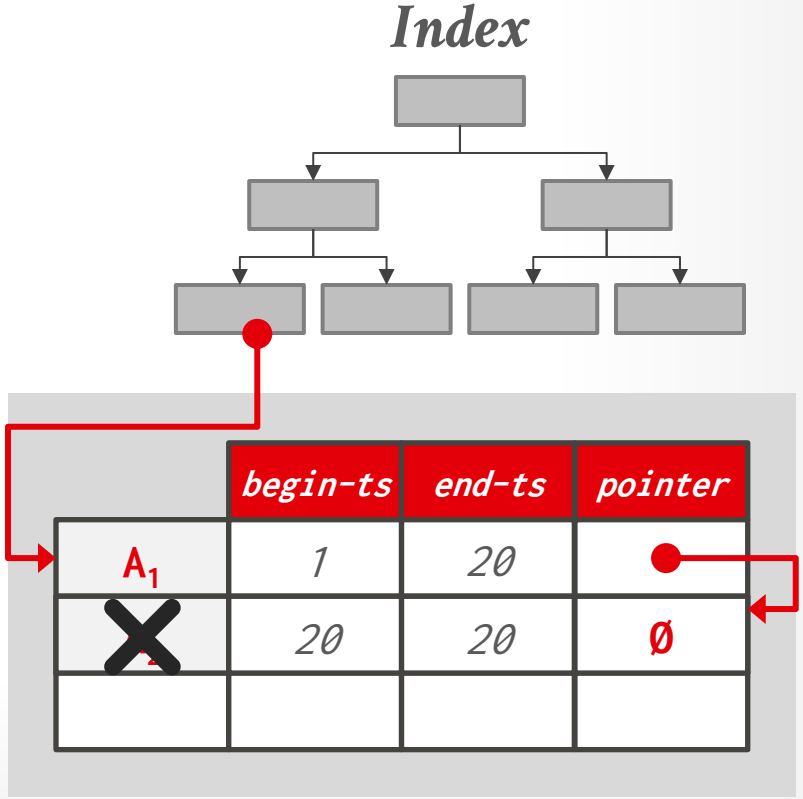
*Txn #1*

```
BEGIN TS=10
```


*Txn #2*

```
BEGIN TS=20
COMMIT TS=25
```





# MVCC DUPLICATE KEY PROBLEM

*Txn #1*

```
BEGIN TS=10
```

READ(A)

*Txn #2*

```
BEGIN TS=20
COMMIT TS=25
```

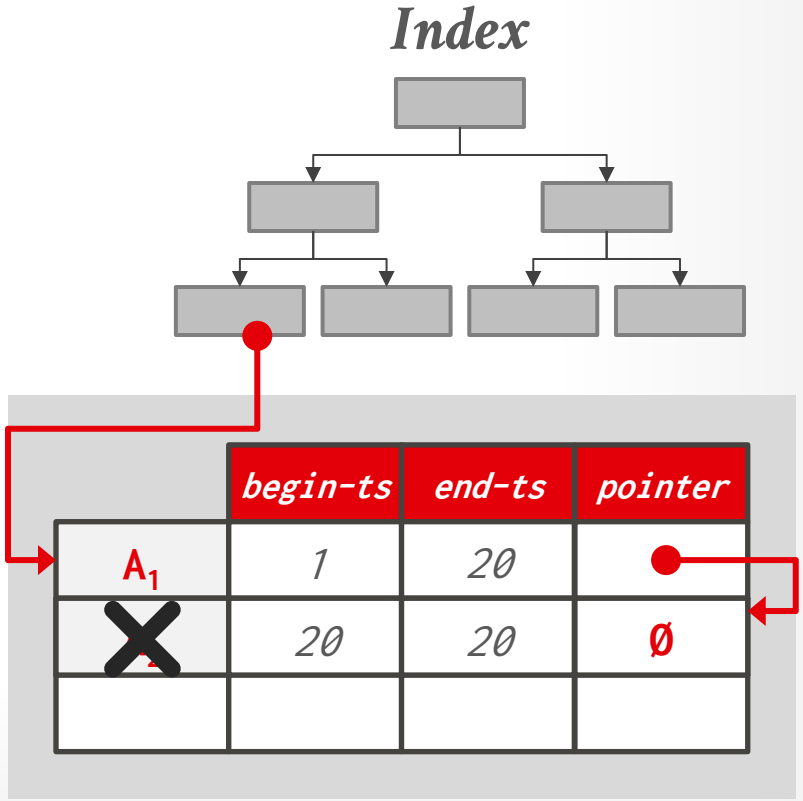
UPDATE(A)

DELETE(A)

*Txn #3*

```
BEGIN TS=30
```

INSERT(A)



# MVCC DUPLICATE KEY PROBLEM

*Txn #1*

```
BEGIN TS=10
```

READ(A)

*Txn #2*

```
BEGIN TS=20
COMMIT TS=25
```

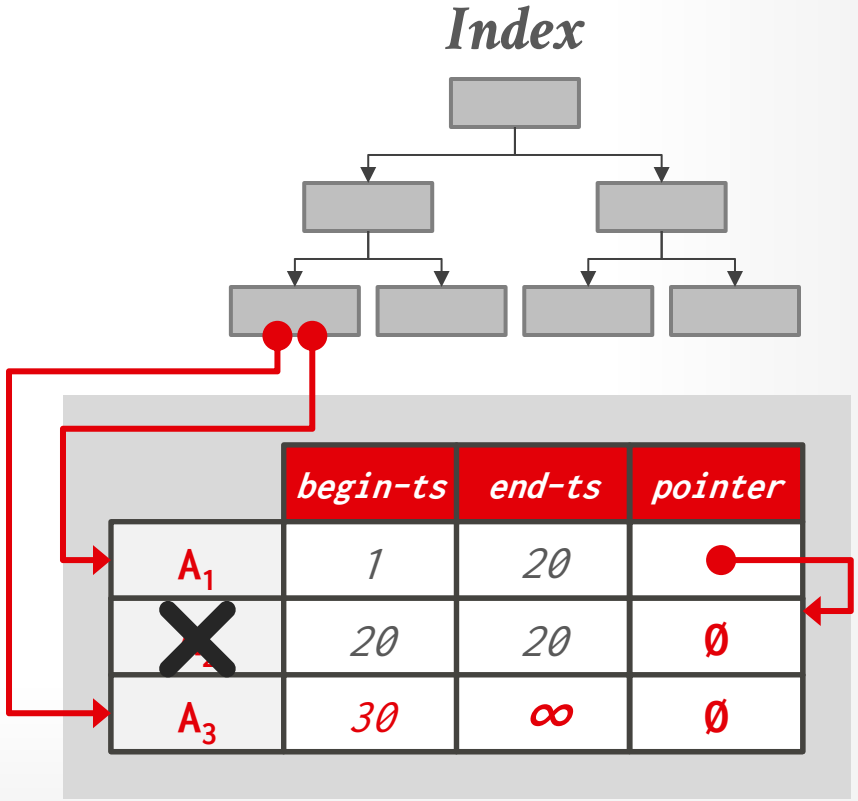
UPDATE(A)

DELETE(A)

*Txn #3*

```
BEGIN TS=30
```

INSERT(A)



# MVCC DUPLICATE KEY PROBLEM

*Txn #1*

BEGIN TS=10

READ(A)

READ(A)

*Txn #2*

BEGIN TS=20

COMMIT TS=25

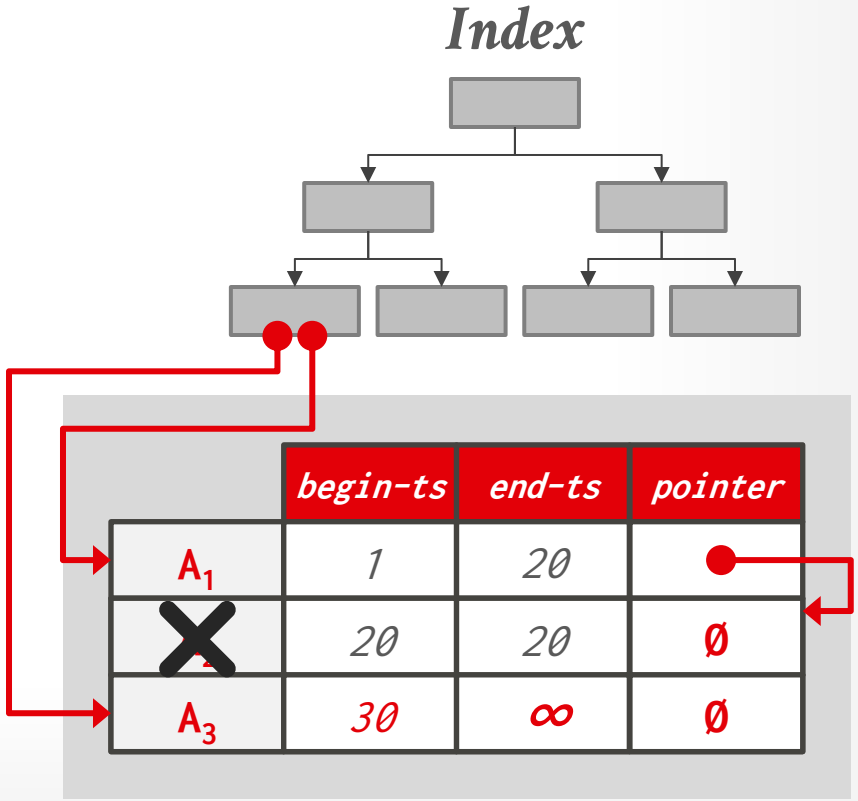
UPDATE(A)

DELETE(A)

*Txn #3*

BEGIN TS=30

INSERT(A)



# MVCC INDEXES

Each index's underlying data structure must support the storage of non-unique keys.

Use additional execution logic to perform conditional inserts for pkey / unique indexes.
→ Atomically check whether the key exists and then insert.

Workers may get back multiple entries for a single fetch. They then must follow the pointers to find the proper physical version.

# MVCC DELETES

The DBMS physically deletes a tuple from the database only when all versions of a logically deleted tuple are not visible.

→ If a tuple is deleted, then there cannot be a new version of that tuple after the newest version.

→ No write-write conflicts / first-writer wins

We need a way to denote that tuple has been logically delete at some point in time.

# MVCC DELETES

## Approach #1: Deleted Flag

→ Maintain a flag to indicate that the logical tuple has been deleted after the newest physical version.
→ Can either be in tuple header or a separate column.

## Approach #2: Tombstone Tuple

→ Create an empty physical version to indicate that a logical tuple is deleted.
→ Use a separate pool for tombstone tuples with only a special bit pattern in version chain pointer to reduce the storage overhead.

# MVCC IMPLEMENTATIONS

| | *Protocol* | *Version Storage* | *Garbage Collection* | *Indexes* |
|---|---|---|---|---|
| Oracle | MV2PL | Delta | Vacuum | Logical |
| Postgres | MV-2PL/MV-TO | Append-Only | Vacuum | Physical |
| MySQL-InnoDB | MV-2PL | Delta | Vacuum | Logical |
| MSSQL Hekaton | MV-OCC | Append-Only | Cooperative | Physical |
| SingleStore | MV-OCC | Delta | Vacuum | Physical |
| SAP HANA | MV-2PL | Time-travel | Hybrid | Logical |
| DuckDB | MV-OCC | Delta | Txn-Level | Logical |
| HyPer | MV-OCC | Delta | Txn-level | Logical |
| CockroachDB | MV-2PL | Delta (LSM) | Compaction | Logical |

# CONCLUSION

MVCC is the widely used scheme in DBMSs.
Even systems that do not support multi-statement txns (e.g., NoSQL) use it.

# NEXT CLASS

Logging and recovery!