Carnegie Mellon University

Database Systems

Two-Phase Locking

15-445/645 FALL 2024 » PROF. ANDY PAVLO

ADMINISTRIVIA

Project #3 is due Sunday Nov 17th @ 11:59pm
→ **Recitation: Monday Nov 4th @ 8:00pm (Zoom)**

UPCOMING DATABASE TALKS

Synnada (DB Seminar)
→ Monday Nov 4th @ 4:30pm
→ Zoom

InfluxDB (DB Seminar)
→ Monday Nov 11th @ 4:30pm
→ Zoom

GlareDB (DB Seminar)
→ Monday Nov 18th @ 4:30pm
→ Zoom

LAST CLASS

Conflict Serializable

→ Verify using either the "swapping" method or dependency graphs.
→ Any DBMS that says that they support "serializable" isolation does this.

View Serializable

→ No efficient way to verify.
→ No DBMS that supports this.

OBSERVATION

We need a way to guarantee that all execution schedules are correct (i.e., serializable) without knowing the entire schedule ahead of time.

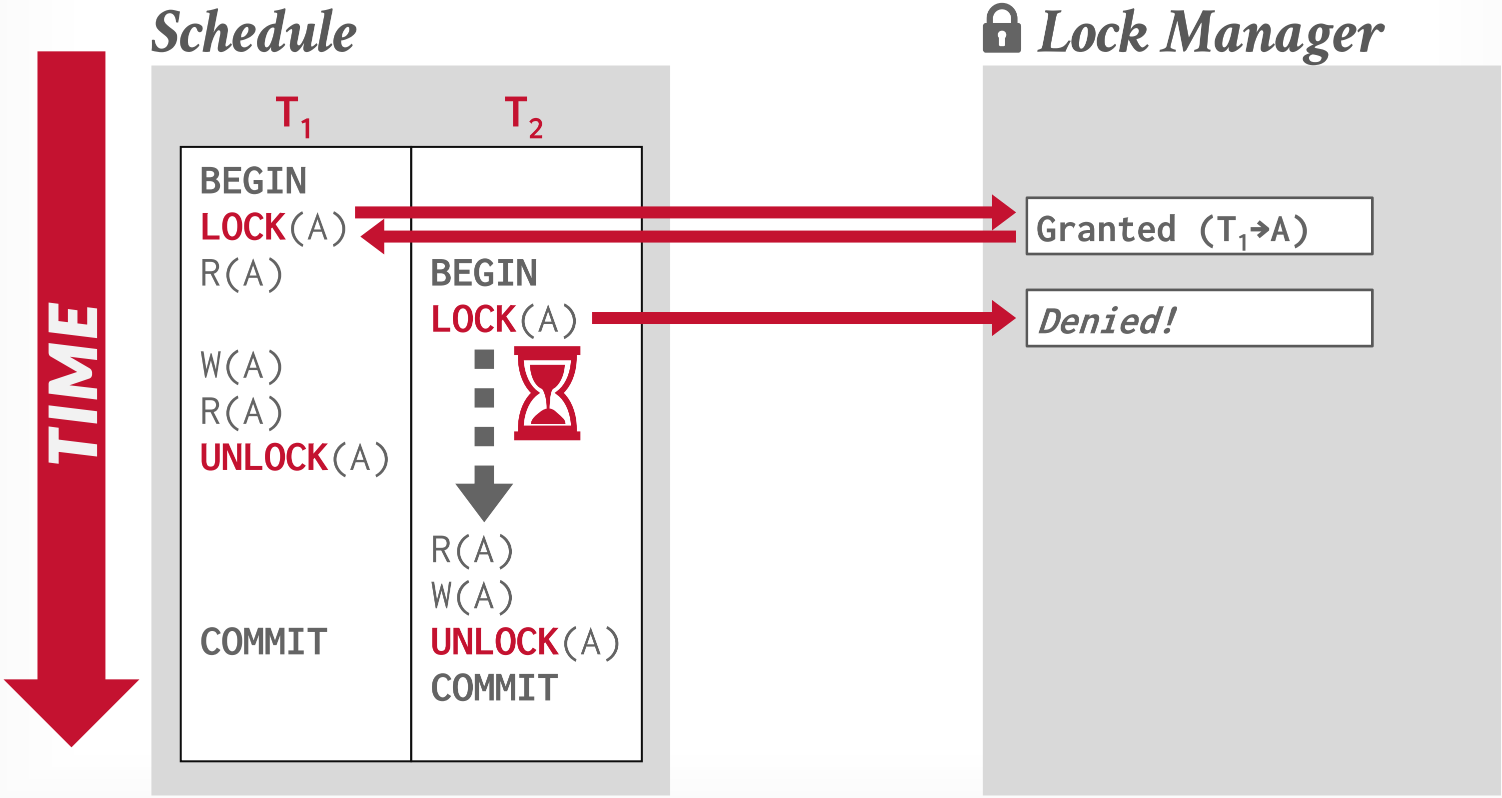
Solution: Use **locks** to protect database objects.

LOCKS VS. LATCHES

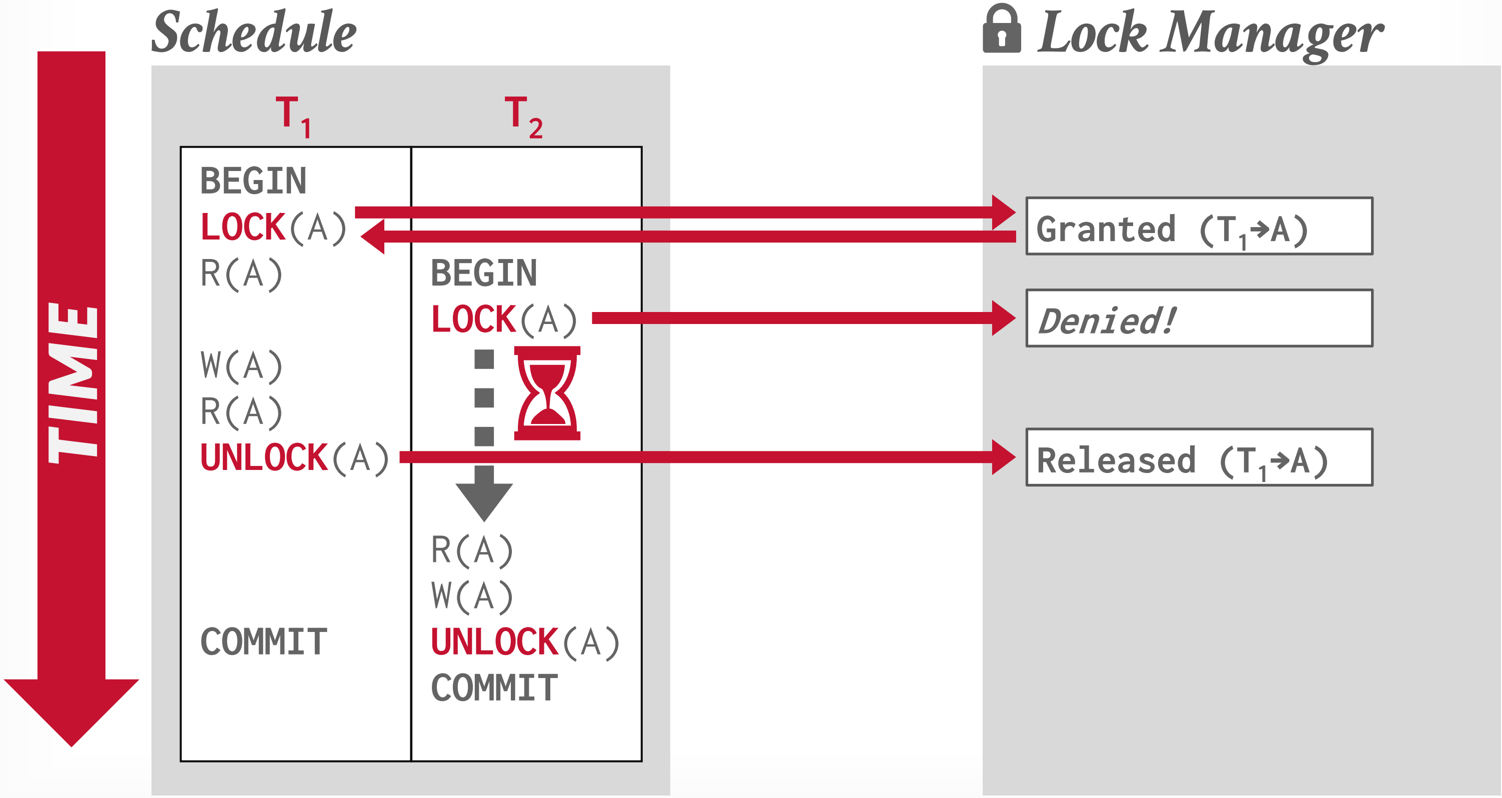
	Locks	*Latches*
Separate…	Transactions	Workers (threads, processes)
Protect…	Database Contents	In-Memory Data Structures
During…	Entire Transactions	Critical Sections
Modes…	Shared, Exclusive, Update, Intention	Read, Write
Deadlock	Detection & Resolution	Avoidance
…by…	Waits-for, Timeout, Aborts	Coding Discipline
Kept in…	Lock Manager	Protected Data Structure

Source: Goetz Graefe

EXECUTING WITH LOCKS



EXECUTING WITH LOCKS



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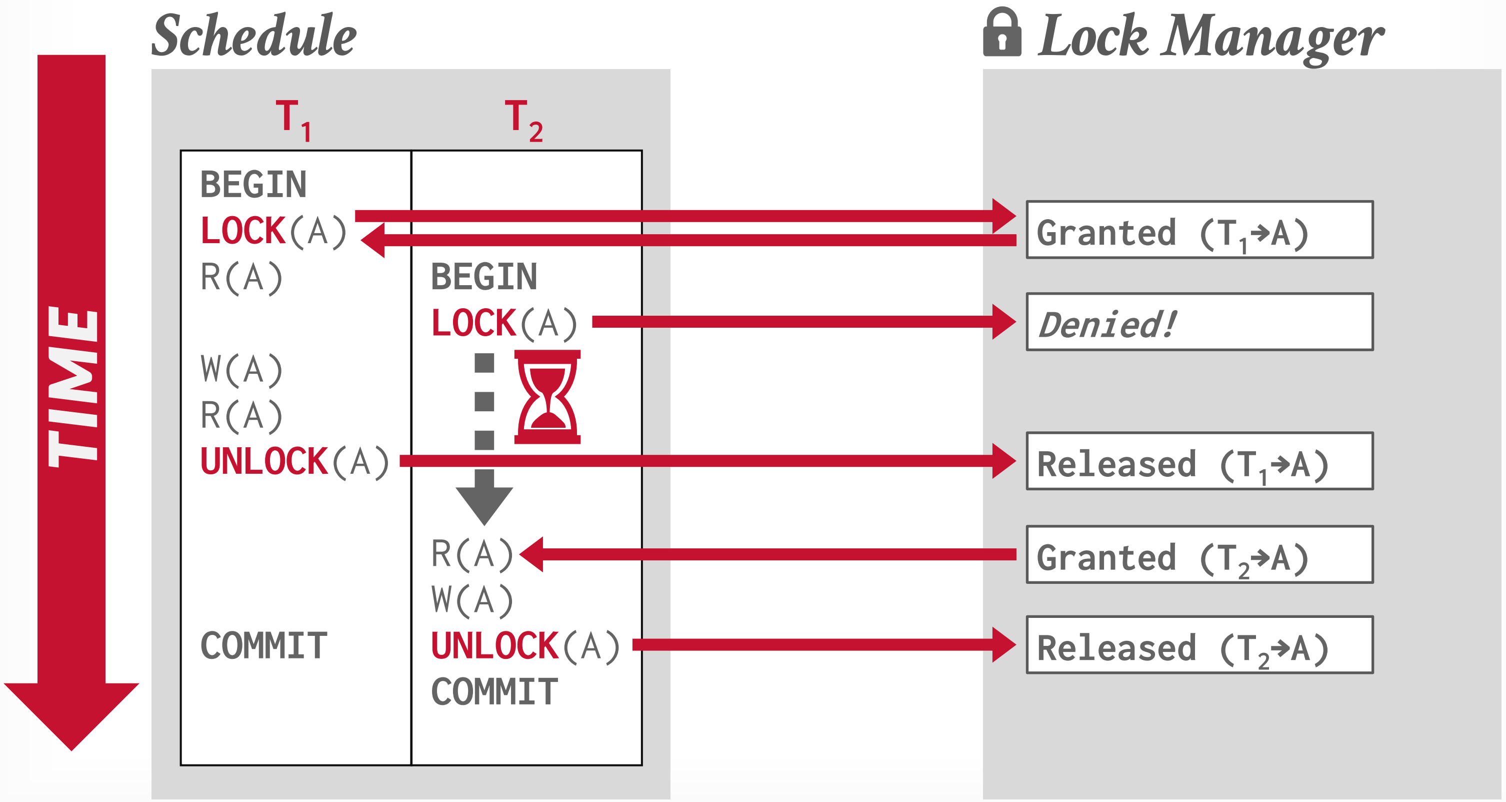


TODAY'S AGENDA

Lock Types

Two-Phase Locking

Deadlock Detection + Prevention

Hierarchical Locking

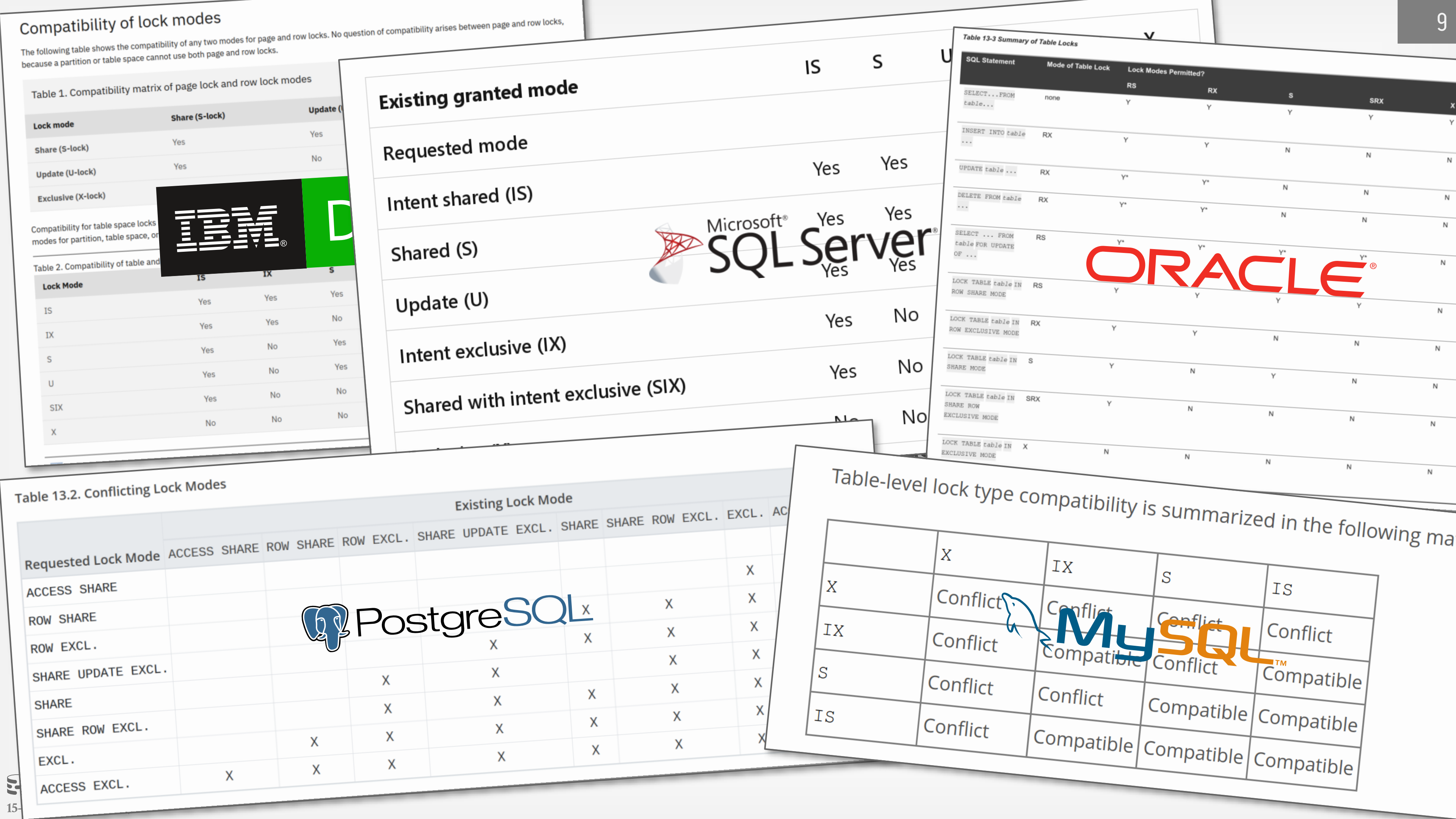
BASIC LOCK TYPES

S-LOCK: Shared locks for reads.

X-LOCK: Exclusive locks for writes.

Compatibility Matrix

	Shared S-LOCK	Exclusive X-LOCK
Shared S-LOCK	✓	×
Exclusive X-LOCK	×	×


Compatibility of lock modes
The following table shows the compatibility of any two modes for page and row locks. No question of compatibility arises between page and row locks, because a partition or table space cannot use both page and row locks.
Table 1. Compatibility matrix of page lock and row lock modes
Lock mode
Share (S-lock)
Update (U-lock)
Exclusive (X-lock)
Table 2. Compatibility of table and
Lock Mode
IBM
Existing granted mode
Requested mode
Intent shared (IS)
Shared (S)
Update (U)
Intent exclusive (IX)
Shared with intent exclusive (SIX)
Microsoft SQL Server
Table 13-3 Summary of Table Locks
SQL Statement
Mode of Table Lock
Lock Modes Permitted?
ORACLE
Table 13.2. Conflicting Lock Modes
Existing Lock Mode
Requested Lock Mode
ACCESS SHARE
ROW SHARE
ROW EXCL.
SHARE UPDATE EXCL.
SHARE
SHARE ROW EXCL.
EXCL.
ACCESS EXCL.
PostgreSQL
Table-level lock type compatibility is summarized in the following ma
Conflict
Compatible
MySQL

EXECUTING WITH LOCKS

Transactions request locks (or upgrades).

Lock manager grants or blocks requests.

Transactions release locks.

Lock manager updates its internal lock-table.

→ It keeps track of what transactions hold what locks and what transactions are waiting to acquire any locks.

EXECUTING WITH LOCKS

Schedule

TIME

T_1	T_2
BEGIN	
X-LOCK(A)	
R(A)	
W(A)	
UNLOCK(A)	
	BEGIN
	X-LOCK(A)
	W(A)
	UNLOCK(A)
S-LOCK(A)	
R(A)	
UNLOCK(A)	
COMMIT	COMMIT

Lock Manager

Granted (T_1→A)

EXECUTING WITH LOCKS

Schedule

TIME

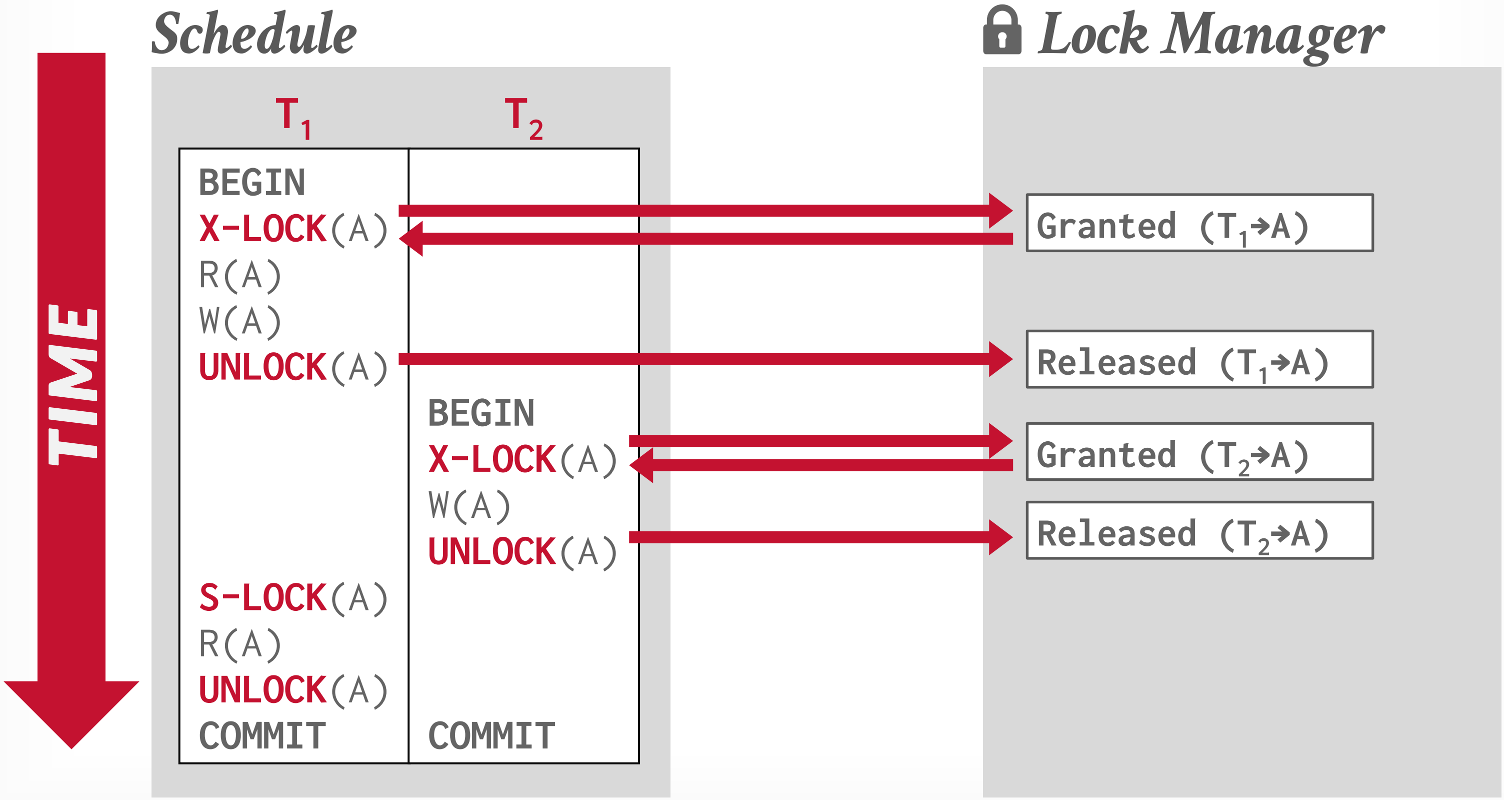
T_1	T_2
BEGIN	
X-LOCK(A)	
R(A)	
W(A)	
UNLOCK(A)	
	BEGIN
	X-LOCK(A)
	W(A)
	UNLOCK(A)
S-LOCK(A)	
R(A)	
UNLOCK(A)	
COMMIT	COMMIT

Lock Manager

Granted (T_1→A)

Released (T_1→A)

EXECUTING WITH LOCKS



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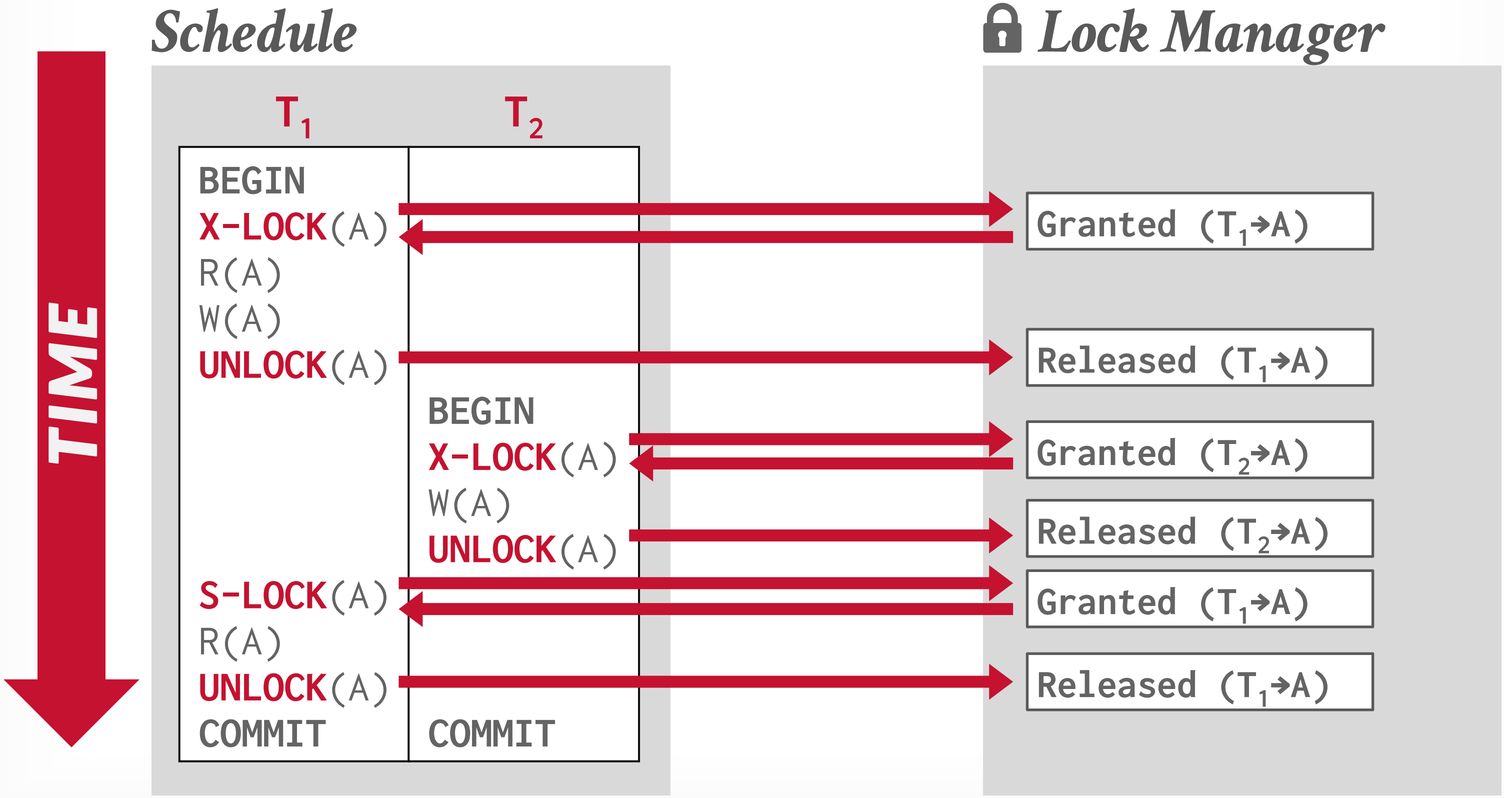


EXECUTING WITH LOCKS

Schedule

TIME

T_1	T_2
BEGIN	
X-LOCK(A)	
R(A)	
W(A)	
UNLOCK(A)	
	BEGIN
	X-LOCK(A)
	W(A)
	UNLOCK(A)
S-LOCK(A)	
R(A)	
UNLOCK(A)	
COMMIT	COMMIT

Lock Manager

- Granted (T_1→A)
- Released (T_1→A)
- Granted (T_2→A)
- Released (T_2→A)
- Granted (T_1→A)
- Released (T_1→A)

CONCURRENCY CONTROL PROTOCOL

Two-phase locking (2PL) is a concurrency control protocol that determines whether a txn can access an object in the database at runtime.

The protocol does not need to know all the queries that a txn will execute ahead of time.

TWO-PHASE LOCKING

Phase #1: Growing

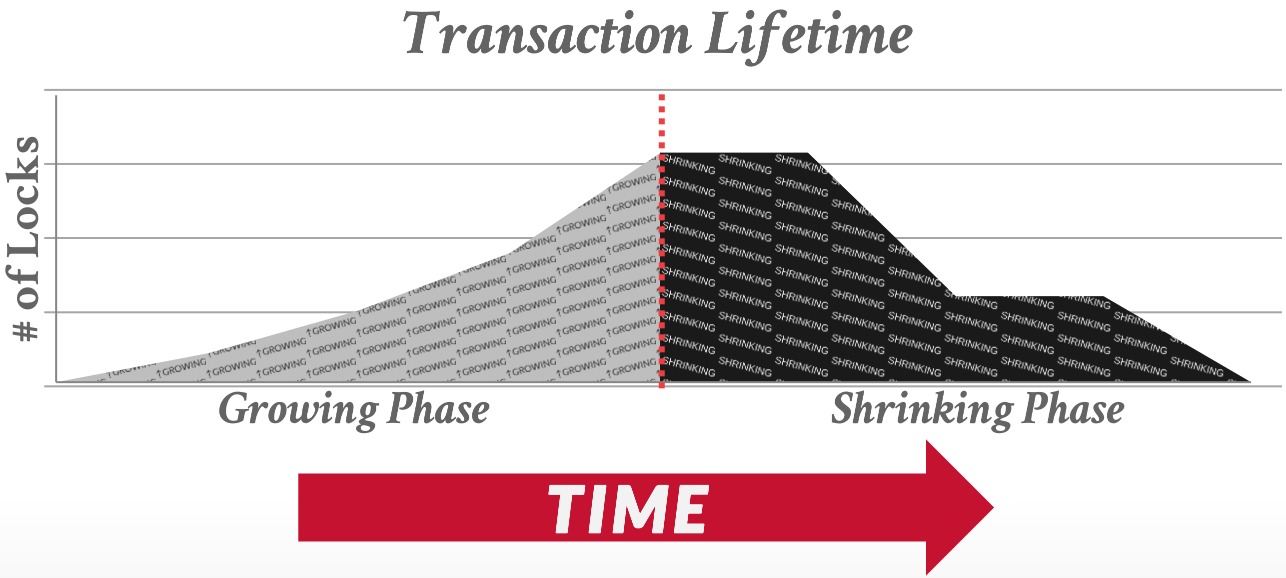
→ Each txn requests the locks that it needs from the DBMS's lock manager.
→ The lock manager grants/denies lock requests.

Phase #2: Shrinking

→ The txn is allowed to only release/downgrade locks that it previously acquired. It cannot acquire new locks.

TWO-PHASE LOCKING

The txn is not allowed to acquire/upgrade locks after the growing phase finishes.



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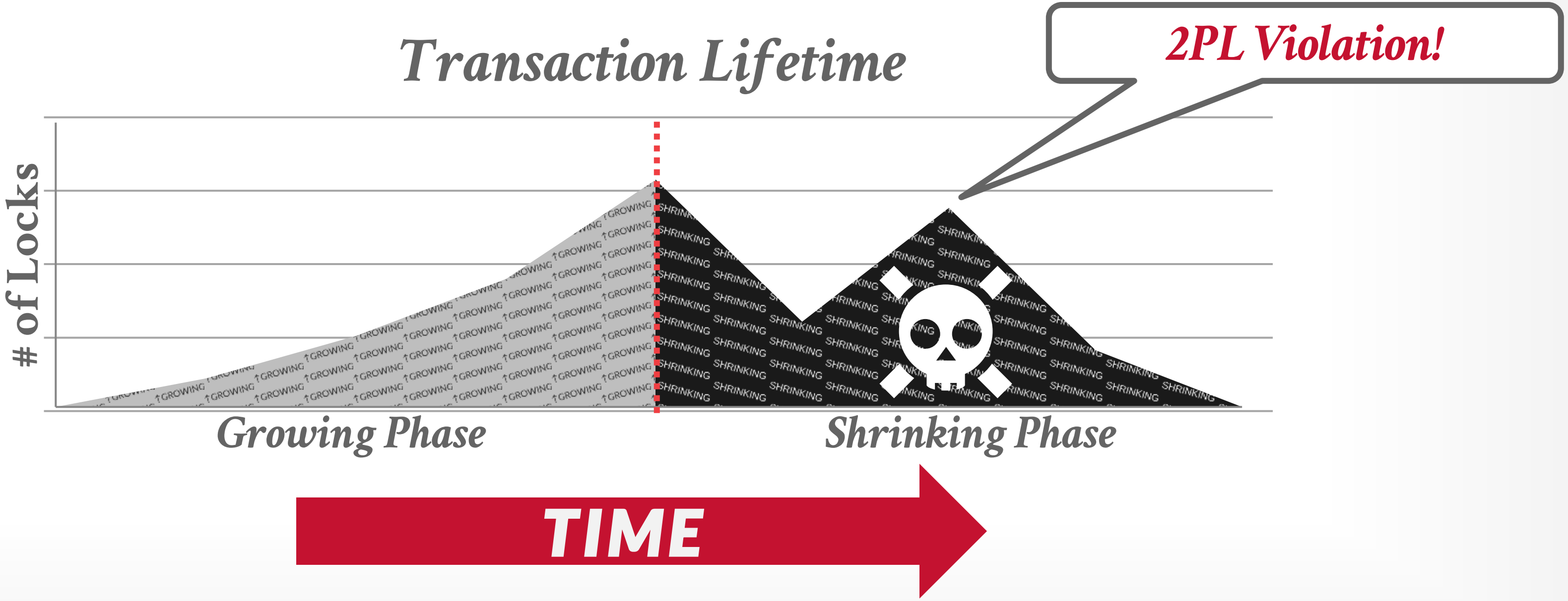


EXECUTING WITH 2PL

Schedule

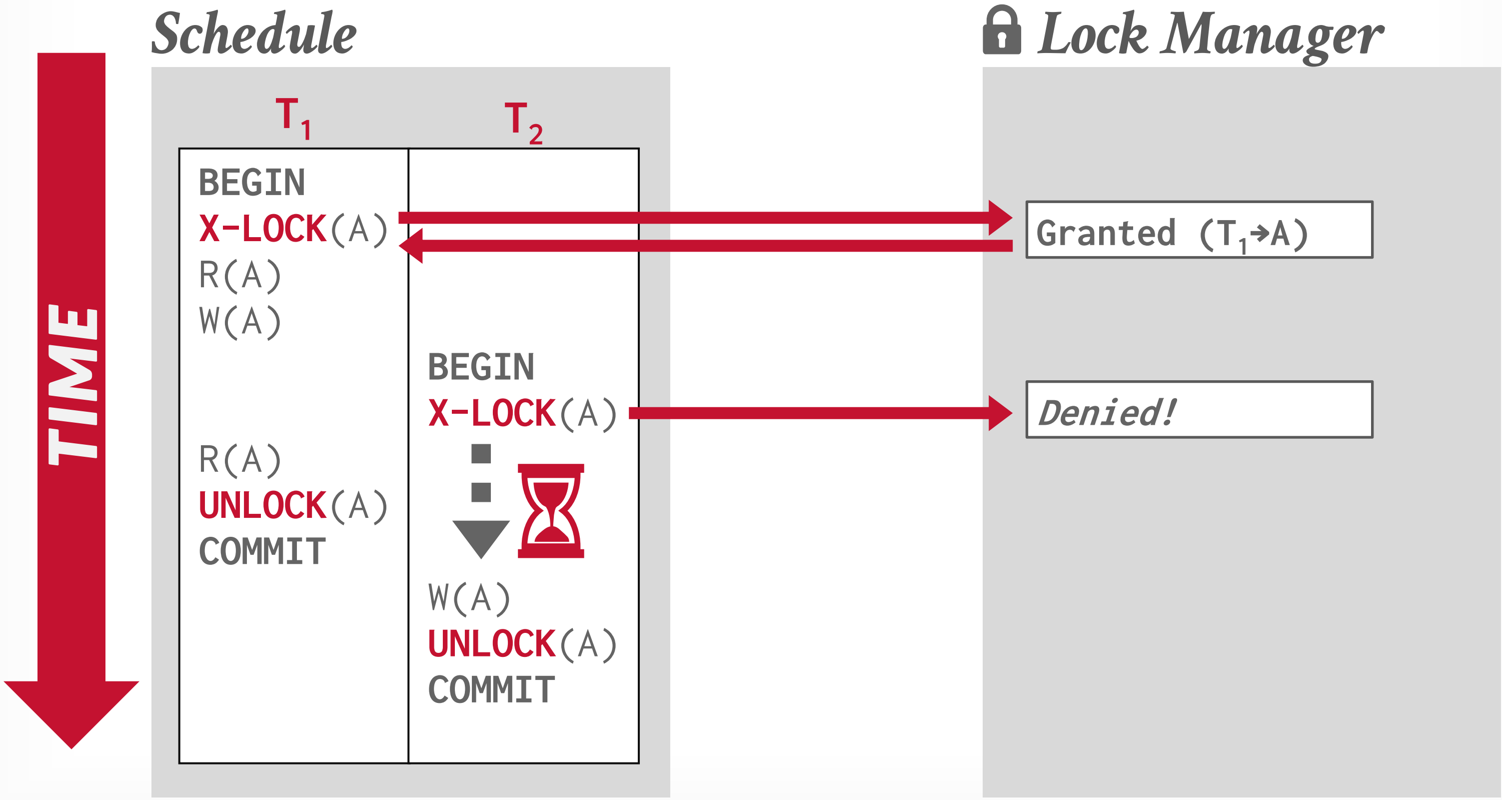
TIME

T_1	T_2
BEGIN	
X-LOCK(A)	
R(A)	
W(A)	
	BEGIN
	X-LOCK(A)
R(A)	
UNLOCK(A)	
COMMIT	
	W(A)
	UNLOCK(A)
	COMMIT

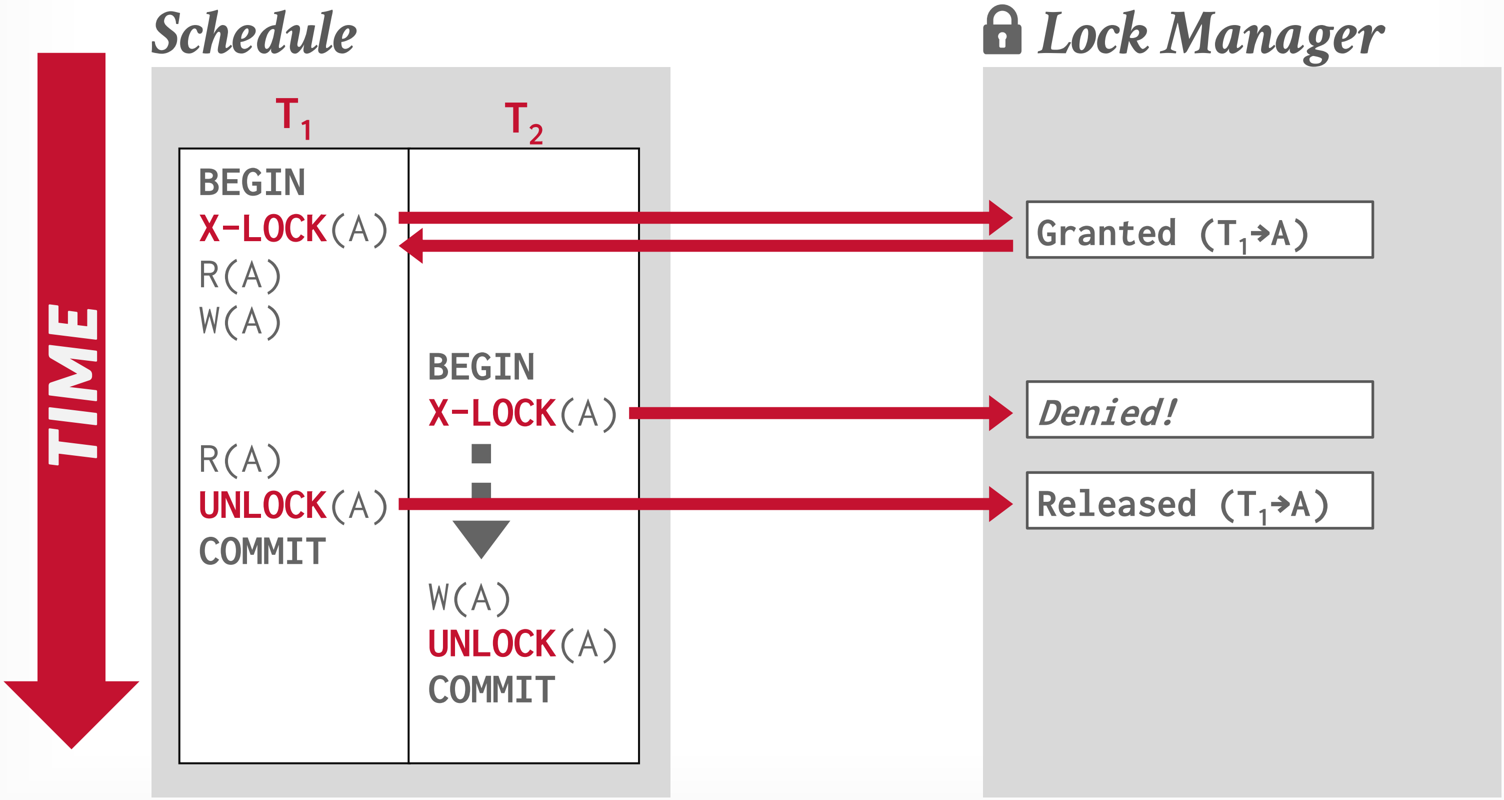
Lock Manager

Granted (T_1→A)

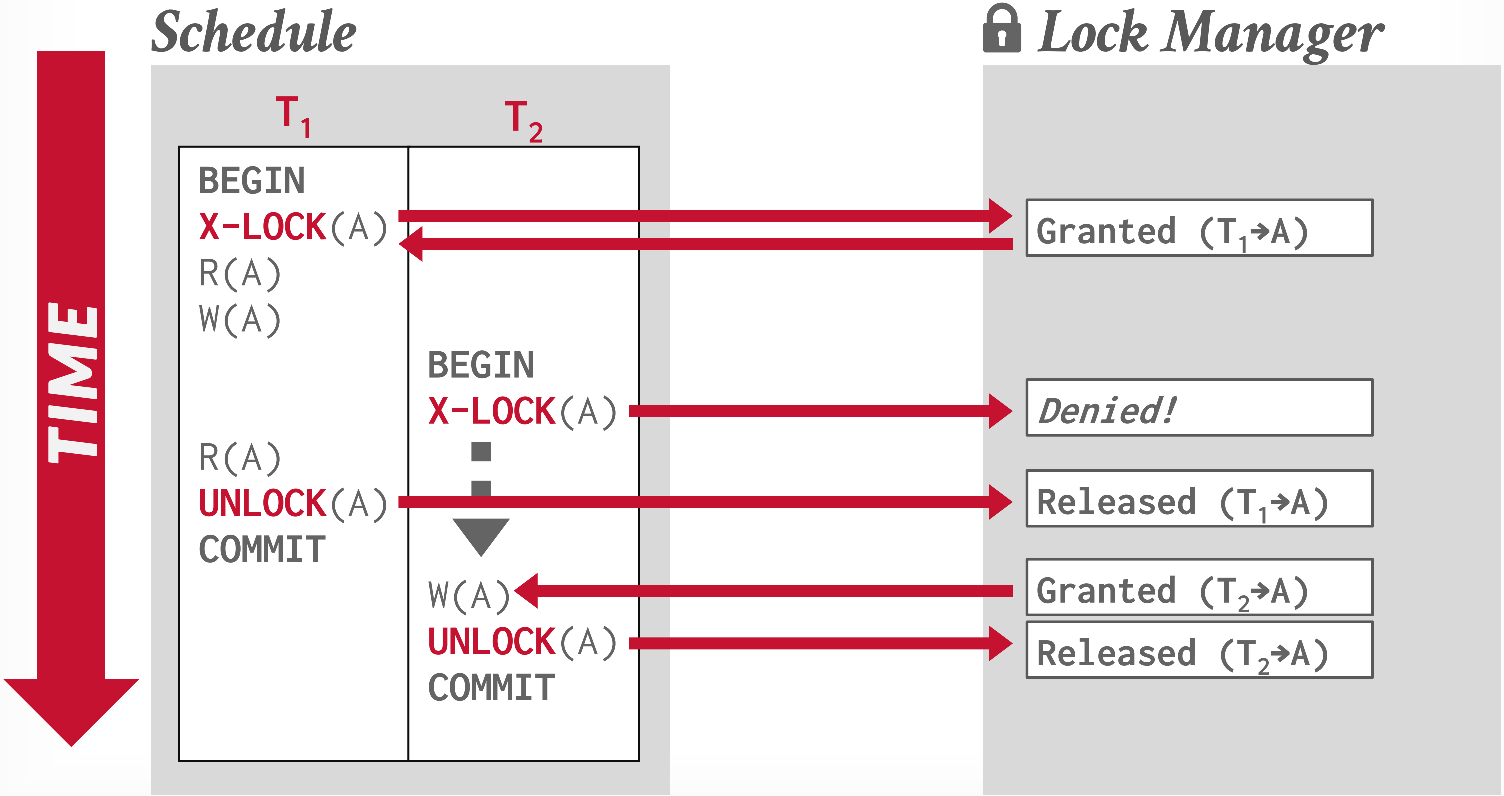
EXECUTING WITH 2PL



EXECUTING WITH 2PL



EXECUTING WITH 2PL



TWO-PHASE LOCKING

2PL on its own is sufficient to guarantee conflict serializability because it generates schedules whose precedence graph is acyclic.

But it is subject to **cascading aborts**.

2PL: CASCADING ABORTS

Schedule

TIME ↓

T_1	T_2
BEGIN	
X-LOCK(A)	
X-LOCK(B)	
R(A)	
W(A)	
UNLOCK(A)	BEGIN
	X-LOCK(A)
	R(A)
	W(A)
	⋮
R(B)	
W(B)	
⋮	
ABORT	

2PL: CASCADING ABORTS

Schedule

TIME

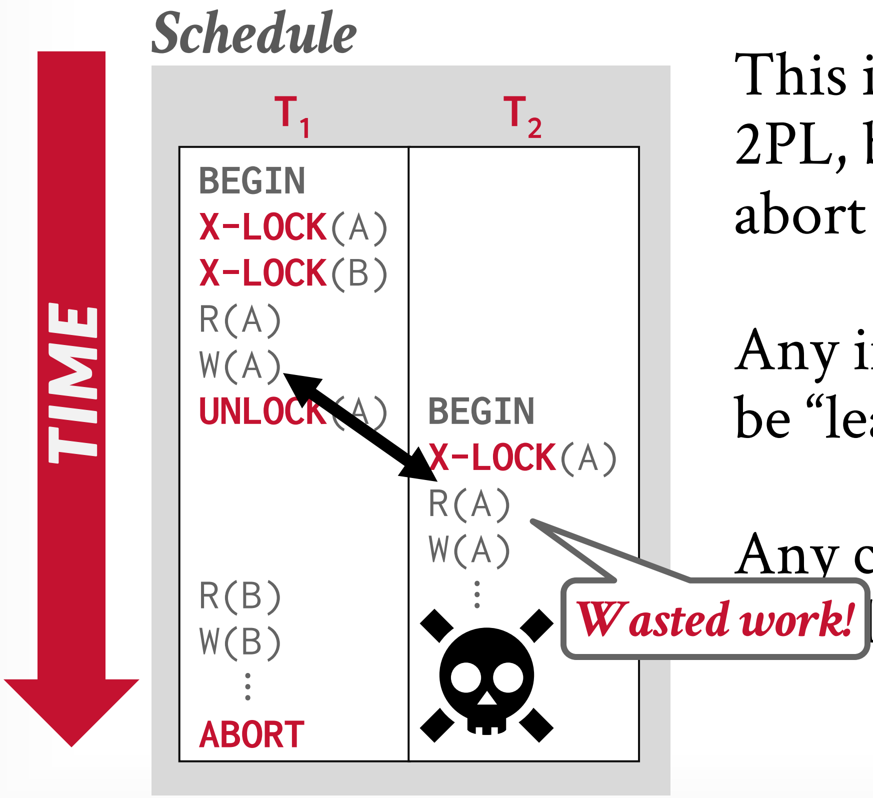
T_1	T_2
BEGIN	
X-LOCK(A)	
X-LOCK(B)	
R(A)	
W(A)	
UNLOCK(A)	BEGIN
	X-LOCK(A)
	R(A)
	W(A)
	⋮
R(B)	
W(B)	
⋮	
ABORT	

This is a permissible schedule in 2PL, but the DBMS has to also abort T_2 when T_1 aborts.

Any information about T_1 cannot be "leaked" to the outside world.

Any computation performed must be rolled back.

2PL: CASCADING ABORTS



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Any computation performed must lled back.

2PL OBSERVATIONS

There are potential schedules that are serializable but would not be allowed by 2PL because locking limits concurrency.

→ Most DBMSs prefer correctness before performance.

May still have "dirty reads".

→ Solution: **Strong Strict 2PL (aka Rigorous 2PL)**

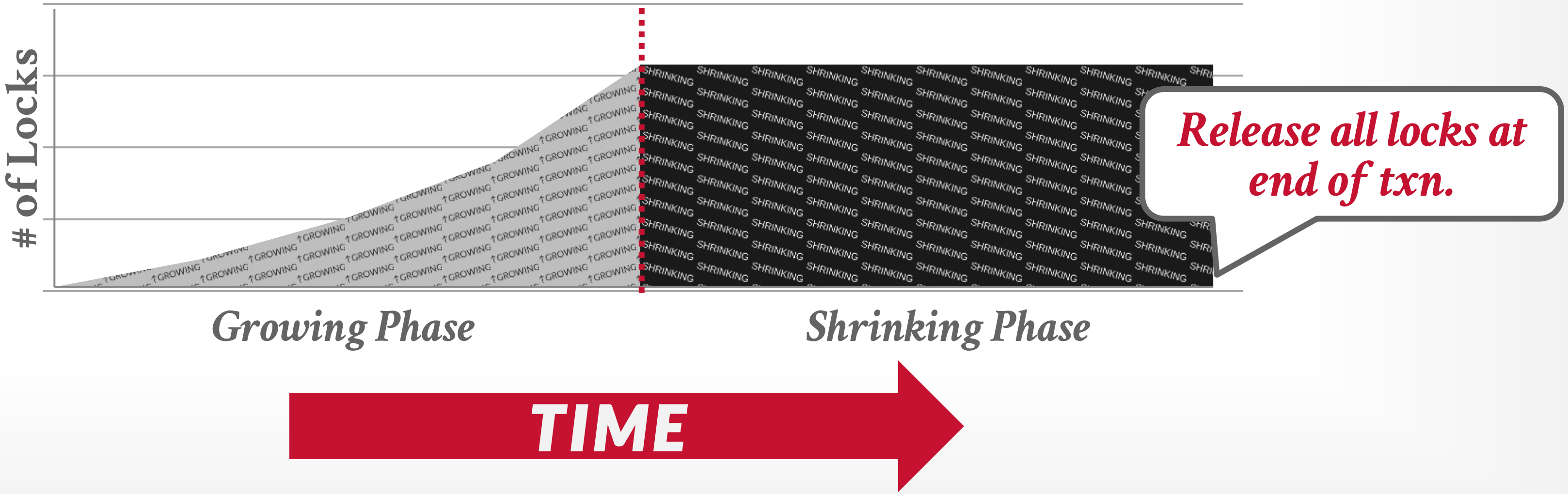
May lead to deadlocks.

→ Solution: **Detection** or **Prevention**

STRONG STRICT TWO-PHASE LOCKING

The txn is only allowed to release locks after it has ended (i.e., committed or aborted).

Allows only conflict serializable schedules, but it is often stronger than needed for some apps.



STRONG STRICT TWO-PHASE LOCKING

A schedule is **strict** if a value written by a txn is not read or overwritten by other txns until that txn finishes.

Advantages:

→ Does not incur cascading aborts.

→ Aborted txns can be undone by just restoring original values of modified tuples.

EXAMPLES

T_1 – Move $100 from Andy's account (**A**) to his bookie's account (**B**).

T_2 – Compute the total amount in all accounts and return it to the application.

T_1

```
BEGIN
A=A-100
B=B+100
COMMIT
```

T_2

```
BEGIN
ECHO A+B
COMMIT
```

NON-2PL EXAMPLE

TIME

Schedule

T_1	T_2
BEGIN	BEGIN
X-LOCK(A)	
R(A)	
	S-LOCK(A)
A=A-100	
W(A)	
UNLOCK(A)	
	R(A)
	UNLOCK(A)
	S-LOCK(B)
X-LOCK(B)	
	R(B)
	UNLOCK(B)
R(B)	ECHO A+B
B=B+100	COMMIT
W(B)	
UNLOCK(B)	
COMMIT	

Initial Database State

A=1000, B=1000

T_2 Output

A+B=1900

2PL EXAMPLE

Schedule

TIME

T_1	T_2
BEGIN	BEGIN
X-LOCK(A)	
R(A)	S-LOCK(A)
A=A-100	
W(A)	
X-LOCK(B)	
UNLOCK(A)	R(A)
	S-LOCK(B)
R(B)	
B=B+100	
W(B)	
UNLOCK(B)	R(B)
COMMIT	UNLOCK(A)
	UNLOCK(B)
	ECHO A+B
	COMMIT

Initial Database State

A=1000, B=1000

T_2 Output

A+B=2000

STRONG STRICT 2PL EXAMPLE

TIME

Schedule

T_1	T_2
BEGIN	BEGIN
X-LOCK(A)	
R(A)	S-LOCK(A)
A=A-100	
W(A)	
X-LOCK(B)	
R(B)	
B=B+100	
W(B)	
UNLOCK(A)	
UNLOCK(B)	R(A)
COMMIT	S-LOCK(B)
	R(B)
	ECHO A+B
	UNLOCK(A)
	UNLOCK(B)
	COMMIT

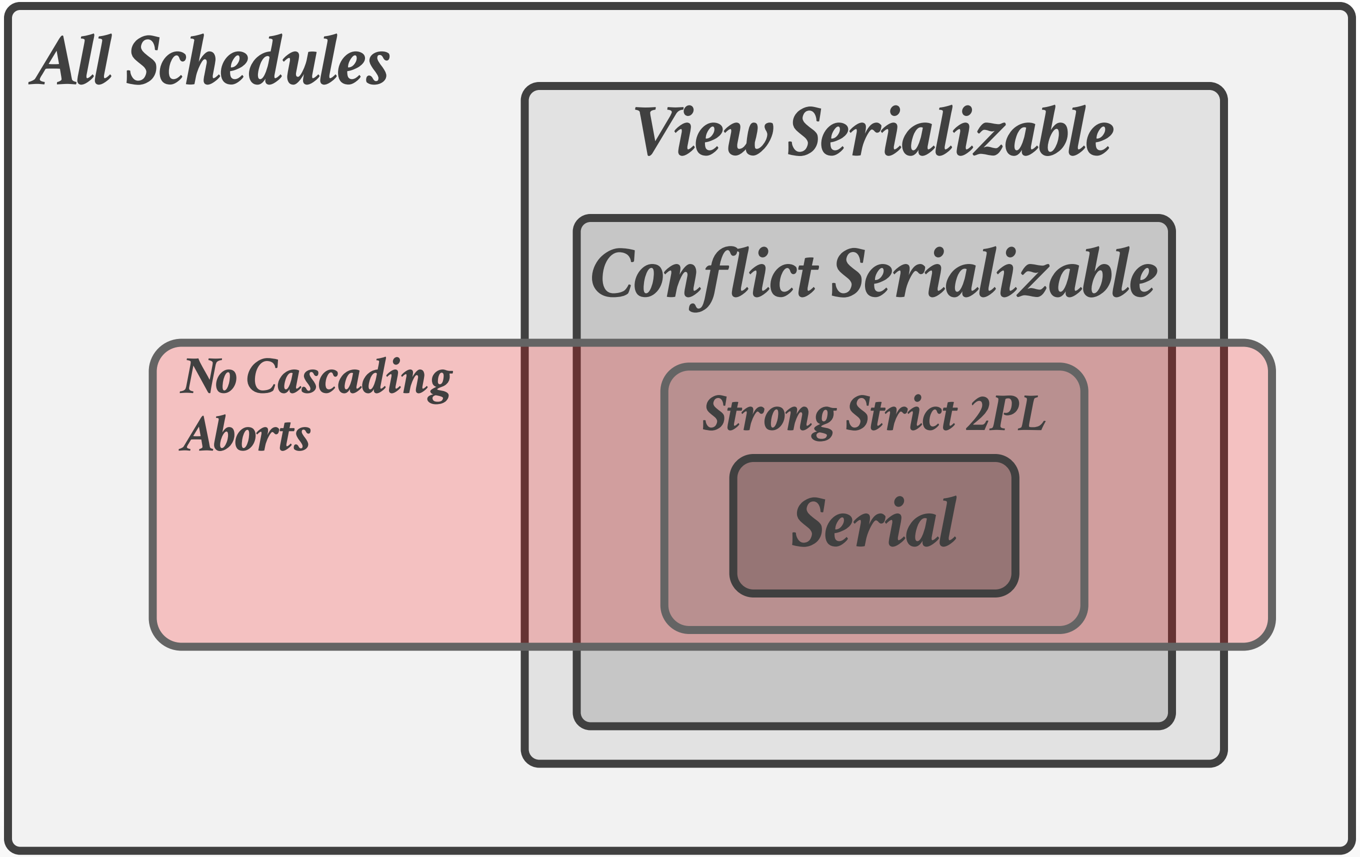
Initial Database State

A=1000, B=1000

T_2 Output

A+B=2000

UNIVERSE OF SCHEDULES



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May still have “dirty reads”.

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May lead to deadlocks.

→ Solution: **Detection** or **Prevention**

IT JUST GOT REAL

TIME

Schedule

T_1	T_2
BEGIN	BEGIN
X-LOCK(A)	
	S-LOCK(B)
	R(B)
	S-LOCK(A)
R(A)	
X-LOCK(B)	

Lock Manager

Granted (T_1→A)

IT JUST GOT REAL

Schedule

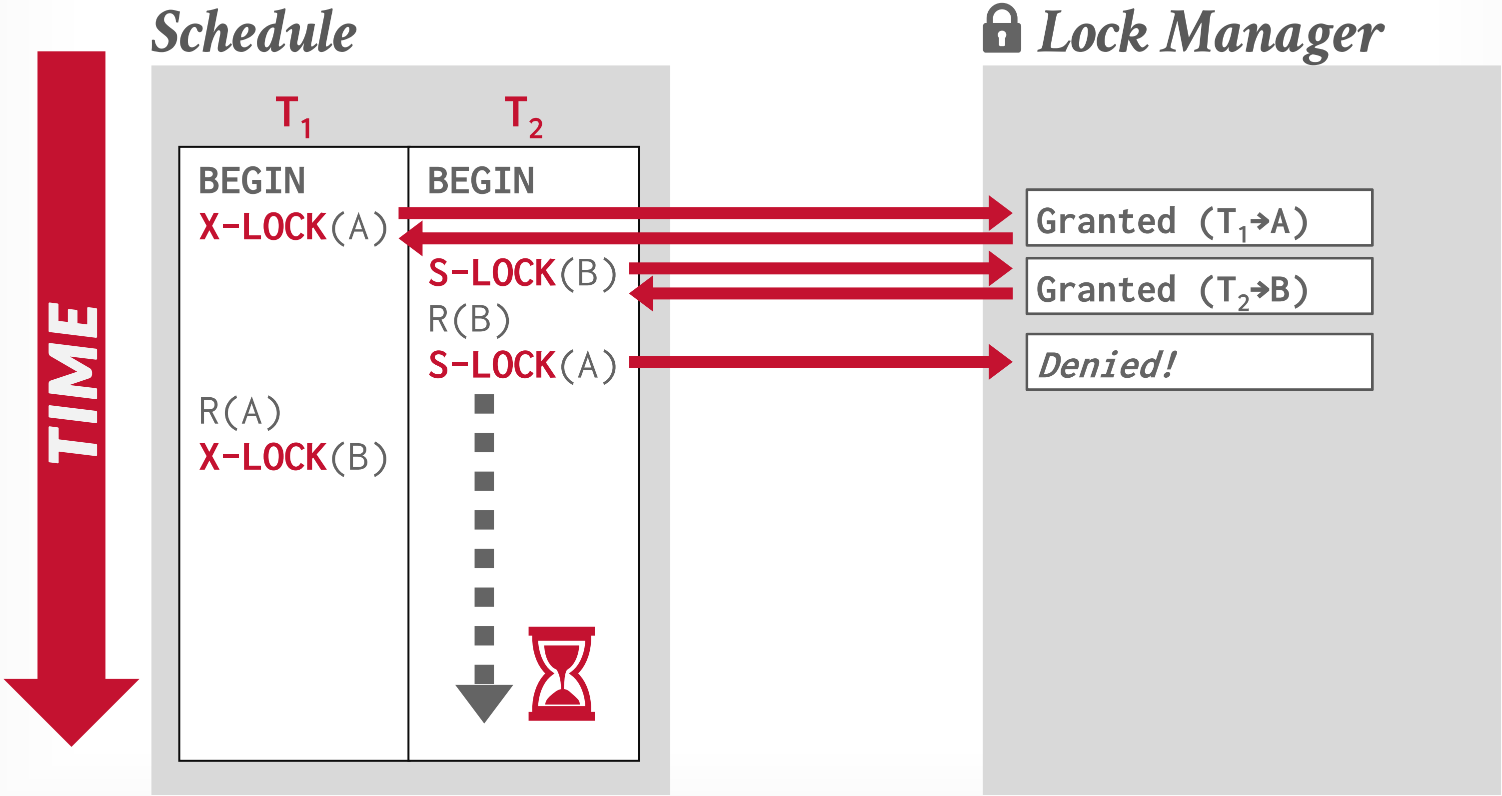
T_1	T_2
BEGIN	BEGIN
X-LOCK(A)	
	S-LOCK(B)
	R(B)
	S-LOCK(A)
R(A)	
X-LOCK(B)	

TIME

Lock Manager

- Granted (T_1→A)
- Granted (T_2→B)

IT JUST GOT REAL



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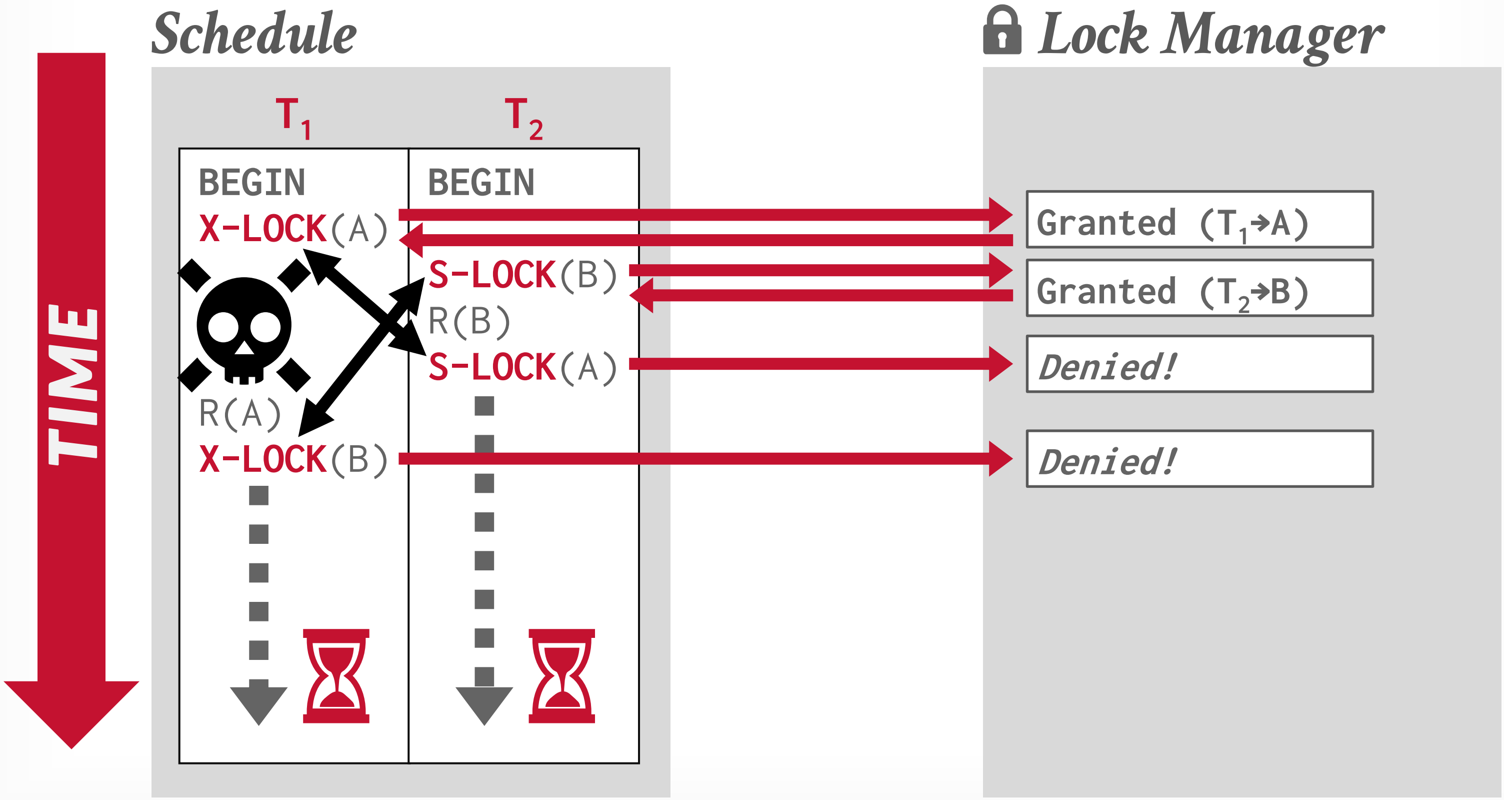


2PL DEADLOCKS

A **deadlock** is a cycle of transactions waiting for locks to be released by each other.

Two ways of dealing with deadlocks:

→ **Approach #1: Deadlock Detection**
→ **Approach #2: Deadlock Prevention**

DEADLOCK DETECTION

The DBMS creates a **waits-for** graph to keep track of what locks each txn is waiting to acquire:

→ Nodes are transactions

→ Edge from T_i to T_j if T_i is waiting for T_j to release a lock.

The system periodically checks for cycles in ***waits-for*** graph and then decides how to break it.

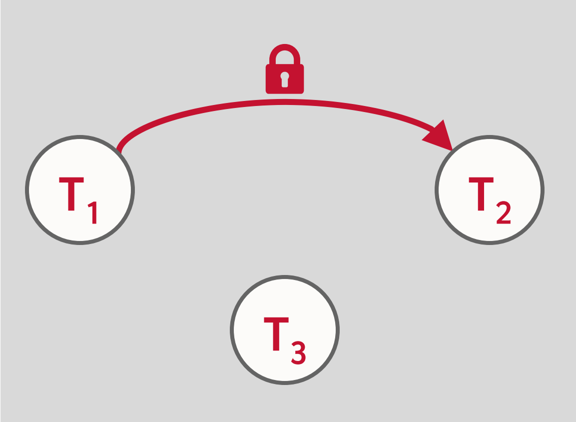
DEADLOCK DETECTION

Schedule

TIME

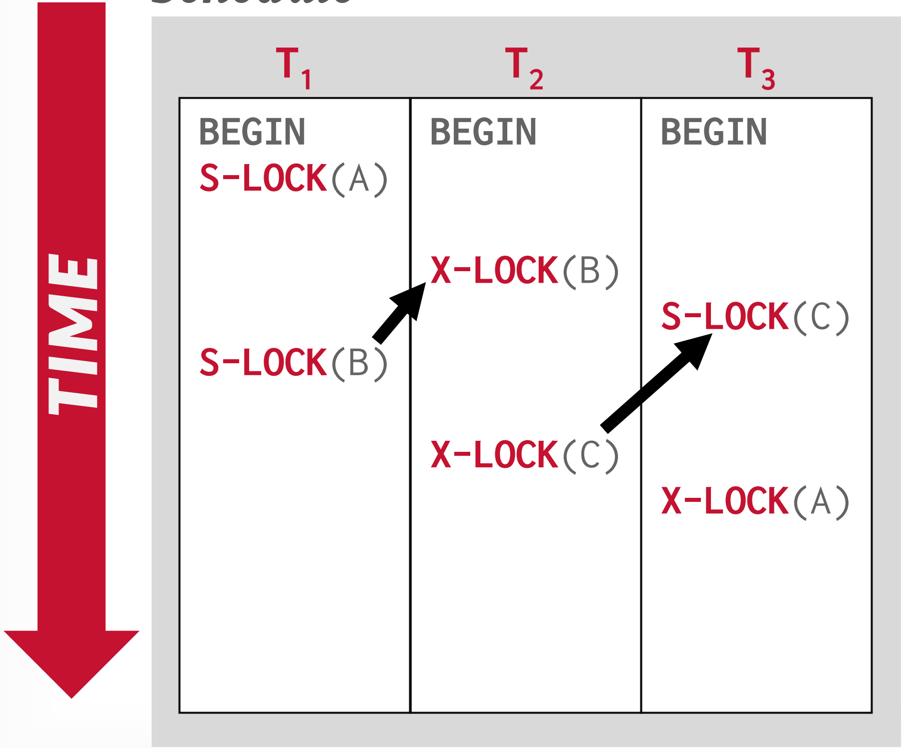
T_1	T_2	T_3
BEGIN	BEGIN	BEGIN
S-LOCK(A)		
	X-LOCK(B)	
		S-LOCK(C)
S-LOCK(B)		
	X-LOCK(C)	
		X-LOCK(A)

Waits-For Graph

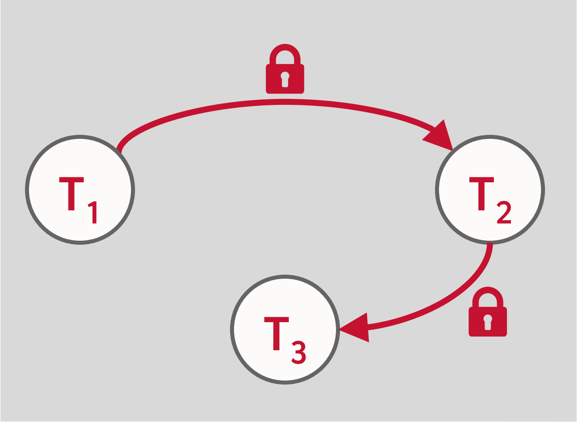


DEADLOCK DETECTION

Schedule



Waits-For Graph



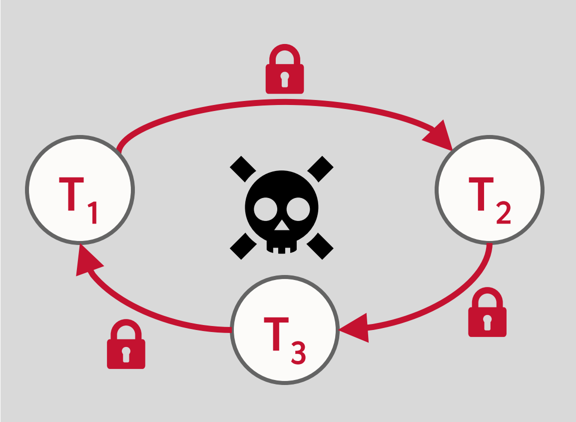
DEADLOCK DETECTION

TIME

Schedule

T_1	T_2	T_3
BEGIN	BEGIN	BEGIN
S-LOCK(A)		
	X-LOCK(B)	
		S-LOCK(C)
S-LOCK(B)		
	X-LOCK(C)	
		X-LOCK(A)

Waits-For Graph



DEADLOCK HANDLING

When the DBMS detects a deadlock, it will select a "victim" txn to rollback to break the cycle.

The victim txn will either restart or abort (more common) depending on how it was invoked.

There is a trade-off between the frequency of checking for deadlocks and how long txns wait before deadlocks are broken.

DEADLOCK HANDLING: VICTIM SELECTION

Selecting the proper victim depends on a lot of different variables….

→ By age (lowest timestamp)
→ By progress (least/most queries executed)
→ By the # of items already locked
→ By the # of txns that we have to rollback with it

We also should consider the # of times a txn has been restarted in the past to prevent starvation.

DEADLOCK HANDLING: ROLLBACK LENGTH

After selecting a victim txn to abort, the DBMS can also decide on how far to rollback the txn's changes.

Approach #1: Completely

→ Rollback entire txn and tell the application it was aborted.

Approach #2: Partial (Savepoints)

→ DBMS rolls back a portion of a txn (to break deadlock) and then attempts to re-execute the undone queries.

DEADLOCK PREVENTION

When a txn tries to acquire a lock that is held by another txn, the DBMS kills one of them to prevent a deadlock.

This approach does not require a ***waits-for*** graph or detection algorithm.

DEADLOCK PREVENTION

Assign priorities based on timestamps:

→ Older Timestamp = Higher Priority (e.g., $T_1 > T_2$)

Wait-Die ("Old Waits for Young")

→ If *requesting txn* has higher priority than *holding txn*, then *requesting txn* waits for *holding txn*.

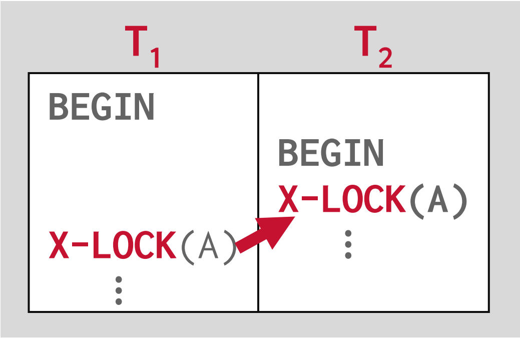
→ Otherwise *requesting txn* aborts.

Wound-Wait ("Young Waits for Old")

→ If *requesting txn* has higher priority than *holding txn*, then *holding txn* aborts and releases lock.

→ Otherwise *requesting txn* waits.

DEADLOCK PREVENTION

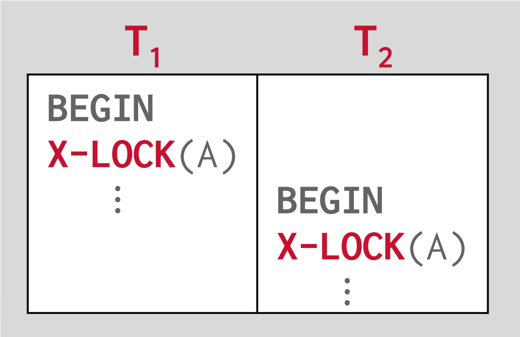


Wait-Die

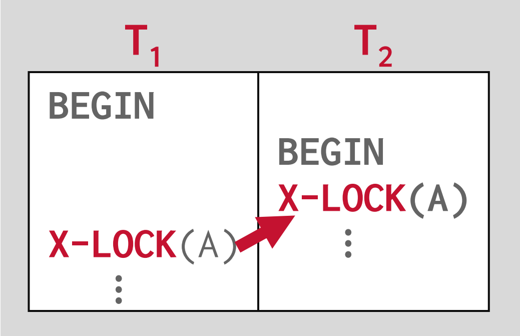
T_1 waits

Wound-Wait

T_2 aborts

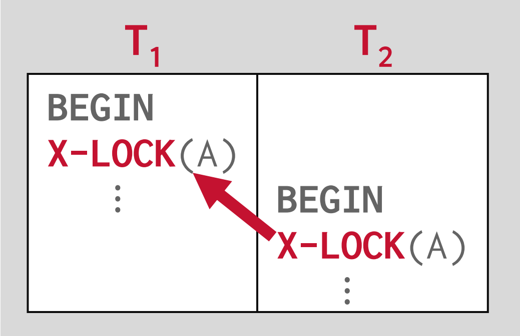


DEADLOCK PREVENTION



Wait-Die: T_1 waits

Wound-Wait: T_2 aborts



Wait-Die: T_2 aborts

Wound-Wait: T_2 waits

DEADLOCK PREVENTION

Why do these schemes guarantee no deadlocks?

Only one "type" of direction allowed when waiting for a lock.

When a txn restarts, what is its (new) priority?

Its original timestamp to prevent it from getting starved for resources like an old man at a corrupt senior center.

OBSERVATION

All these examples have a one-to-one mapping from database objects to locks.

If a txn wants to update one billion tuples, then it must acquire one billion locks.

Acquiring locks is a more expensive operation than acquiring a latch even if that lock is available.

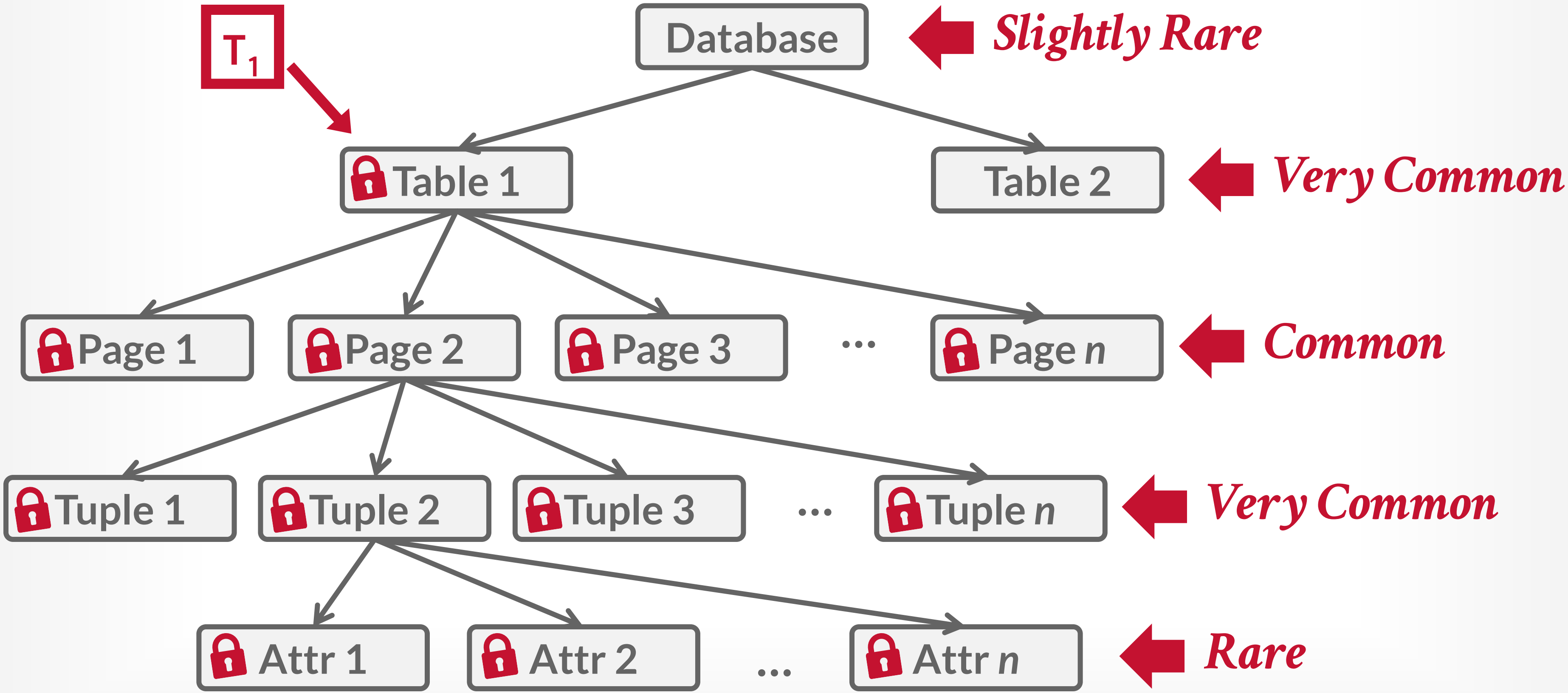
LOCK GRANULARITIES

When a txn wants to acquire a "lock", the DBMS can decide the granularity (i.e., scope) of that lock.
- → Attribute? Tuple? Page? Table?

The DBMS should ideally obtain fewest number of locks that a txn needs.

Trade-off between parallelism versus overhead.
- → Fewer Locks, Larger Granularity vs. More Locks, Smaller Granularity.

DATABASE LOCK HIERARCHY



INTENTION LOCKS

An **intention lock** allows a higher-level node to be locked in **shared** or **exclusive** mode without having to check all descendent nodes.

If a node is locked in an intention mode, then some txn is doing explicit locking at a lower level in the tree.

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	×	×	×	×	×

LOCKING PROTOCOL

Each txn obtains appropriate lock at highest level of the database hierarchy.

To get **S** or **IS** lock on a node, the txn must hold at least **IS** on parent node.

To get **X**, **IX**, or **SIX** on a node, must hold at least **IX** on parent node.

EXAMPLE

T_1 – Get the balance of Andy's off-shore bank account.

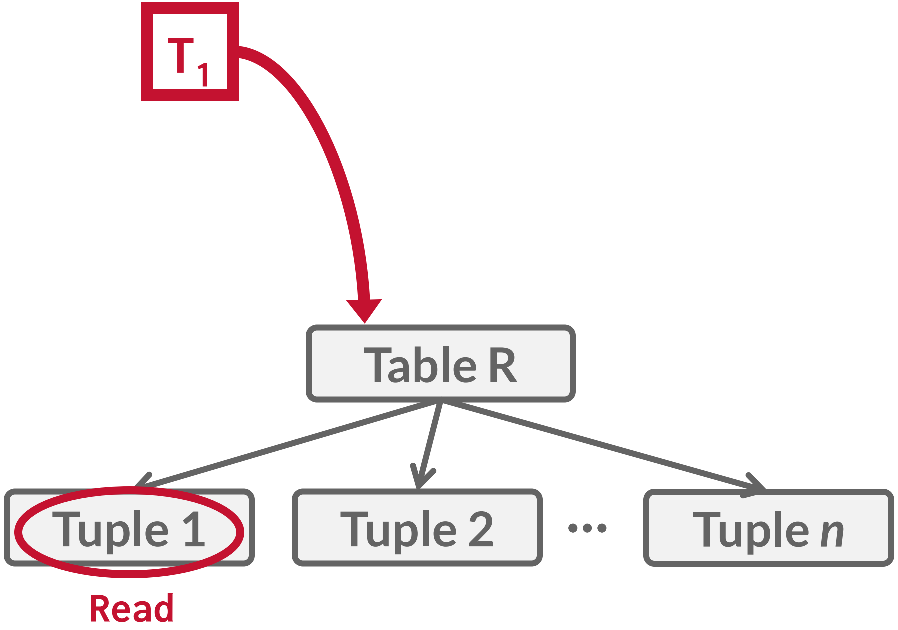
T_2 – Increase bookie's account balance by 1%.

What locks should these txns obtain?

→ **Exclusive** + **Shared** for leaf nodes of lock tree.
→ Special **Intention** locks for higher levels.

EXAMPLE – TWO-LEVEL HIERARCHY

Read Andy's record in **R**.



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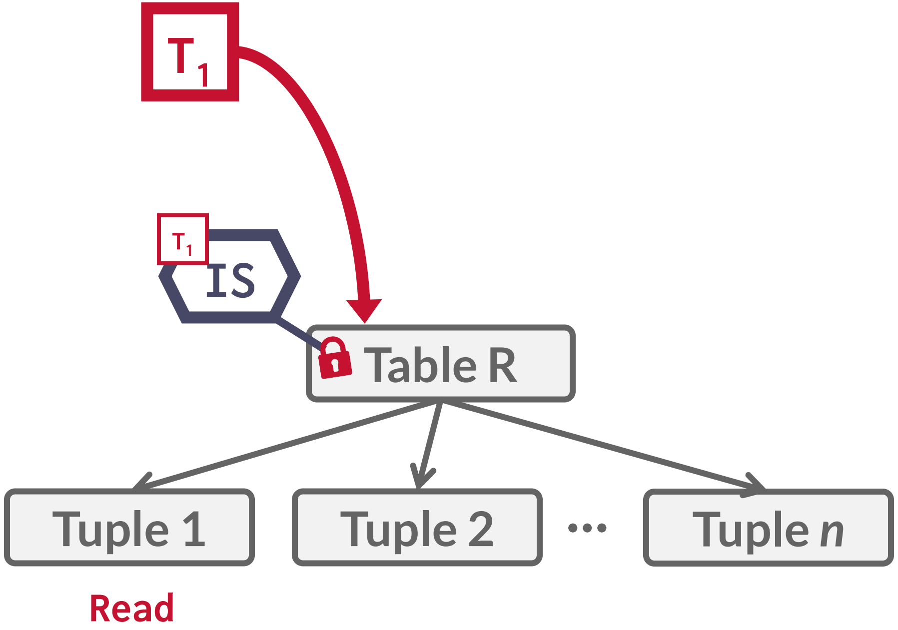

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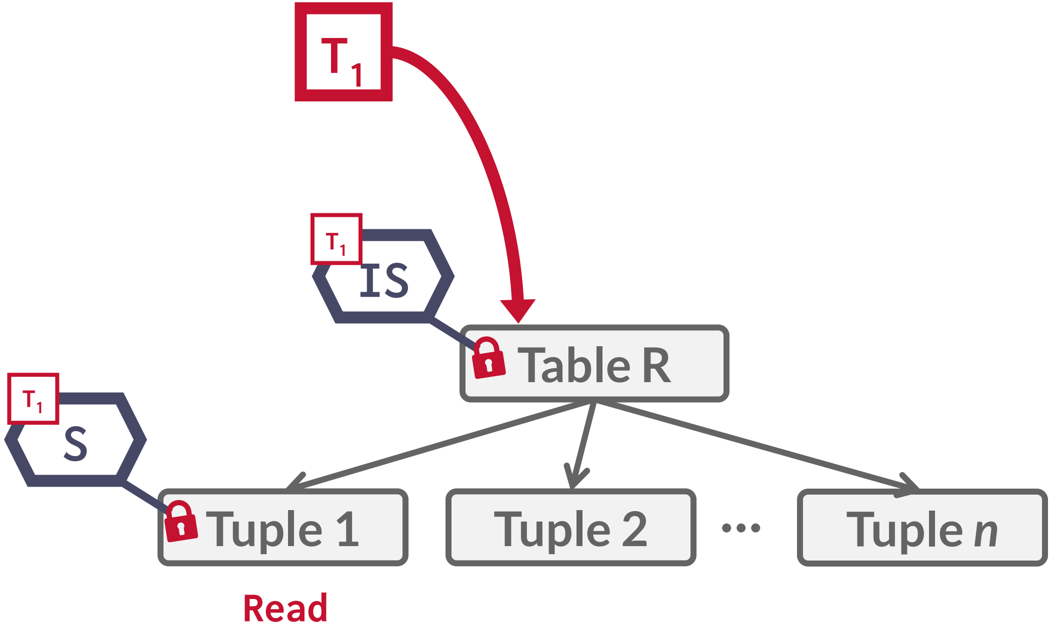
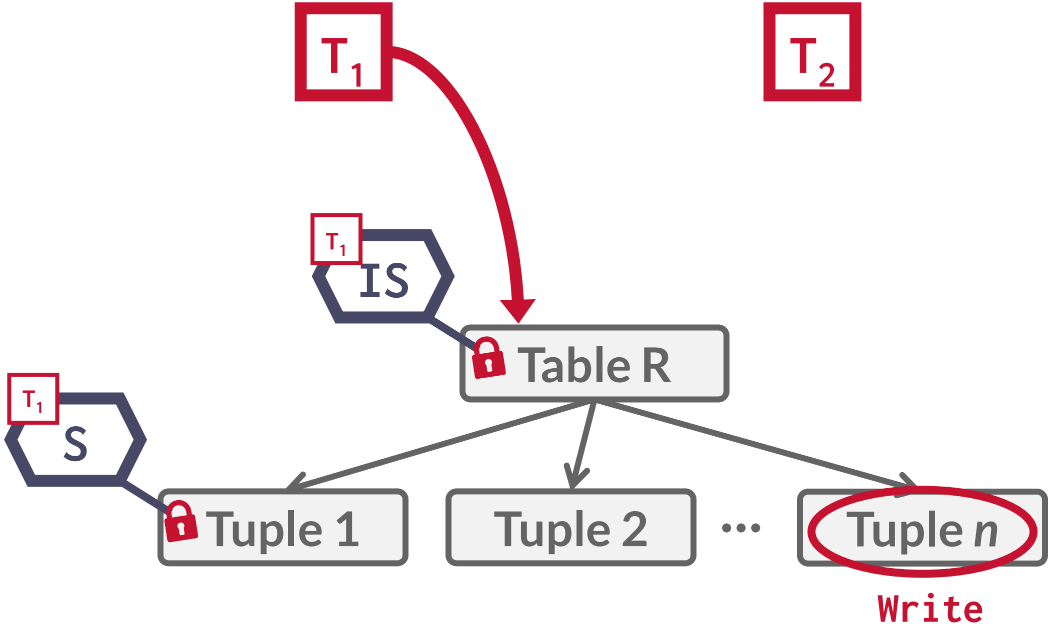


EXAMPLE – TWO-LEVEL HIERARCHY

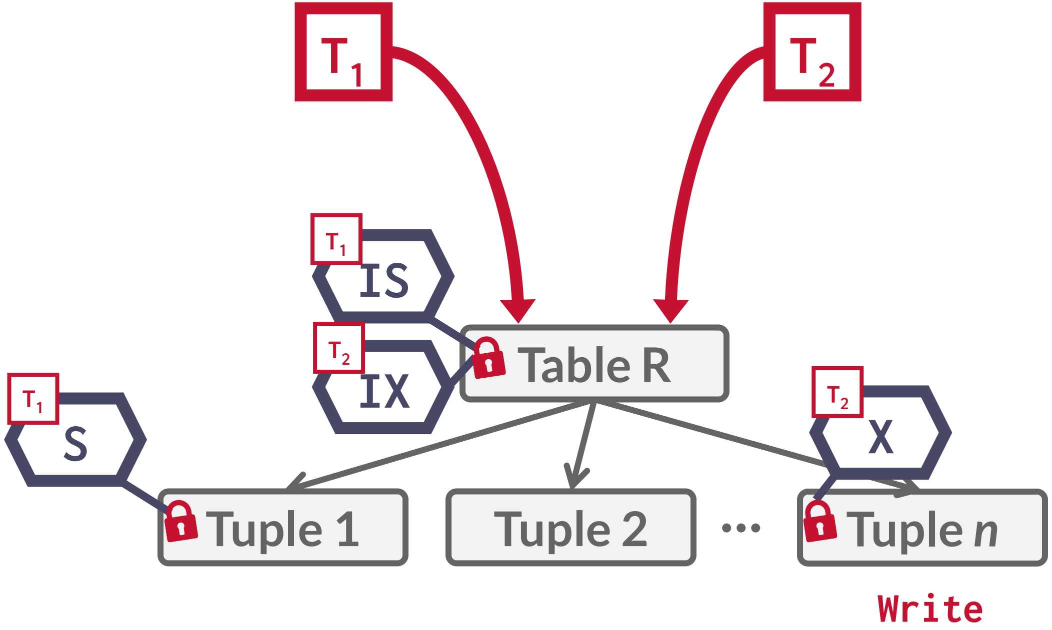
Update bookie's record in **R**.



	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

EXAMPLE – TWO-LEVEL HIERARCHY

Update bookie's record in **R**.

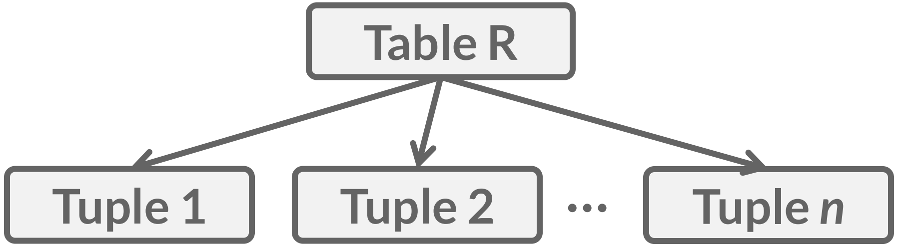


	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

EXAMPLE – THREE TXNS

Assume three txns execute at same time:

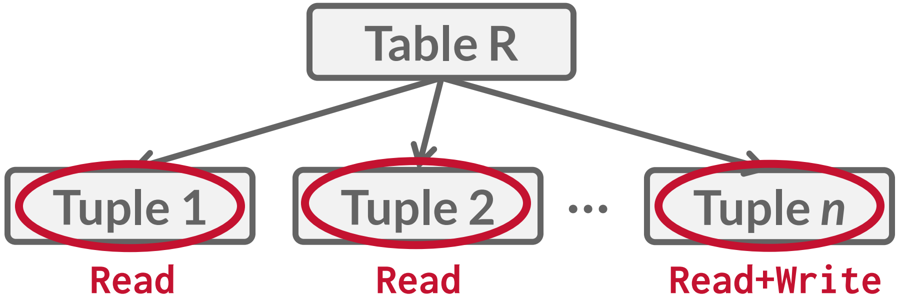
→ T_1 – Scan all tuples in **R** and update one tuple.
→ T_2 – Read a single tuple in **R**.
→ T_3 – Scan all tuples in **R**.



EXAMPLE – THREE TXNS

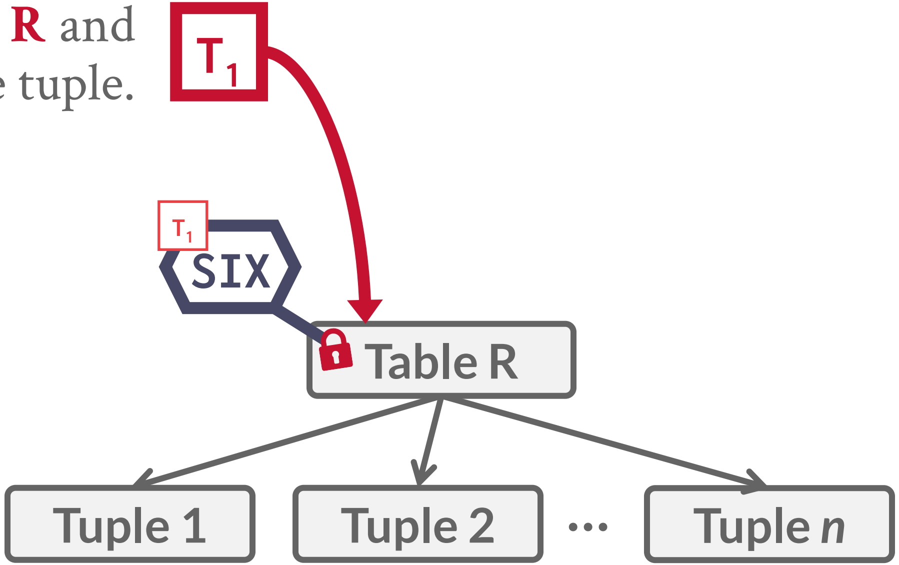
Scan all tuples in **R** and update one tuple.

T_1



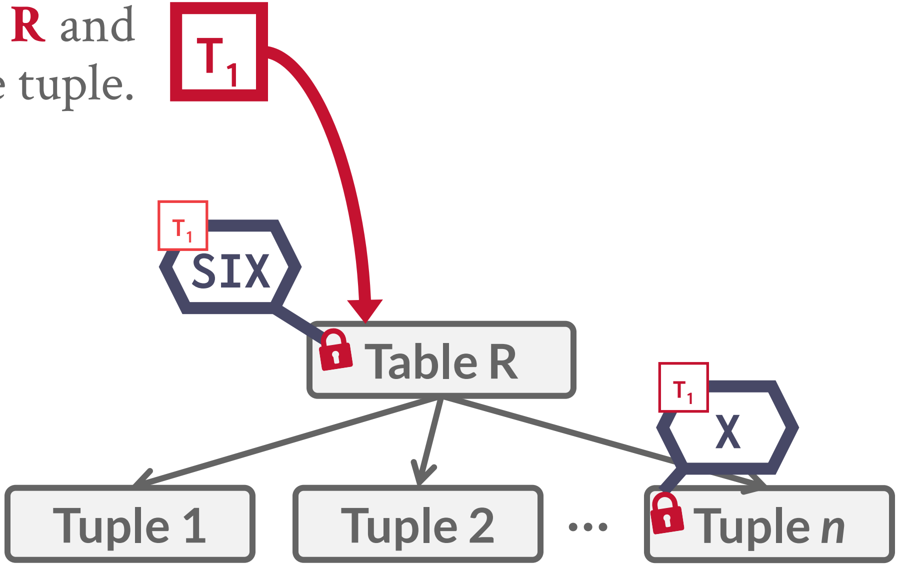
EXAMPLE – THREE TXNS

Scan all tuples in **R** and update one tuple.

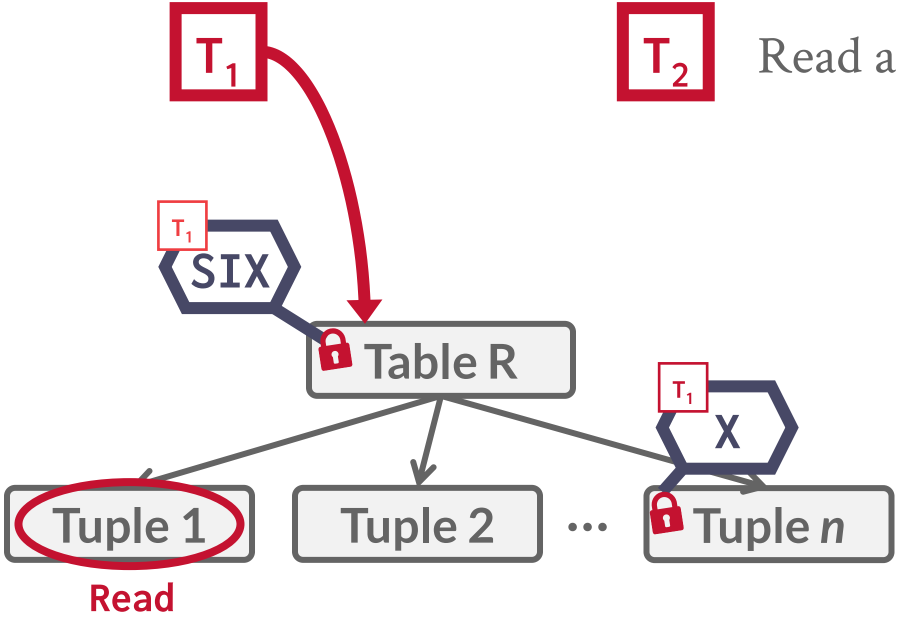


EXAMPLE – THREE TXNS

Scan all tuples in **R** and update one tuple.



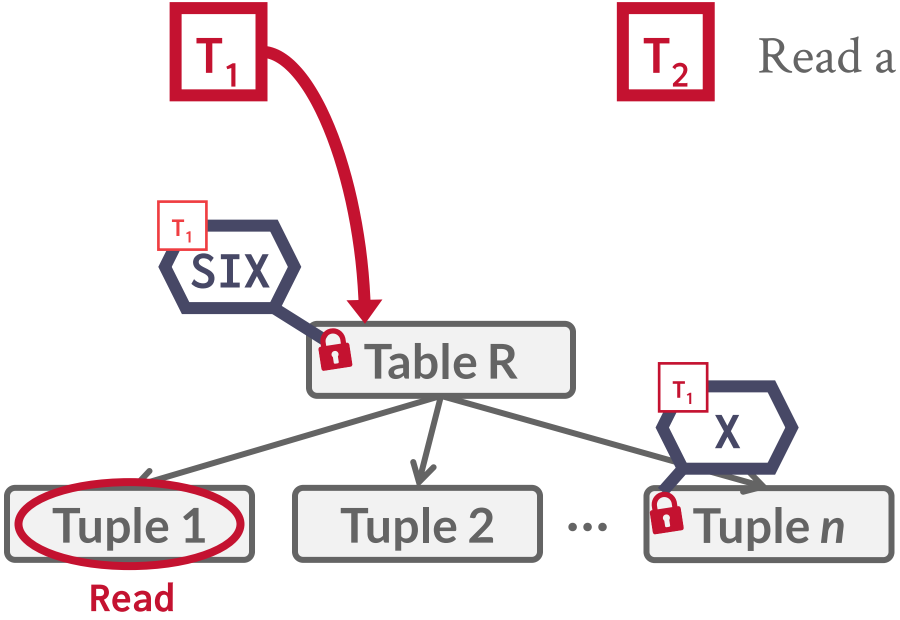
EXAMPLE – THREE TXNS



T_2 Read a single tuple in **R**.

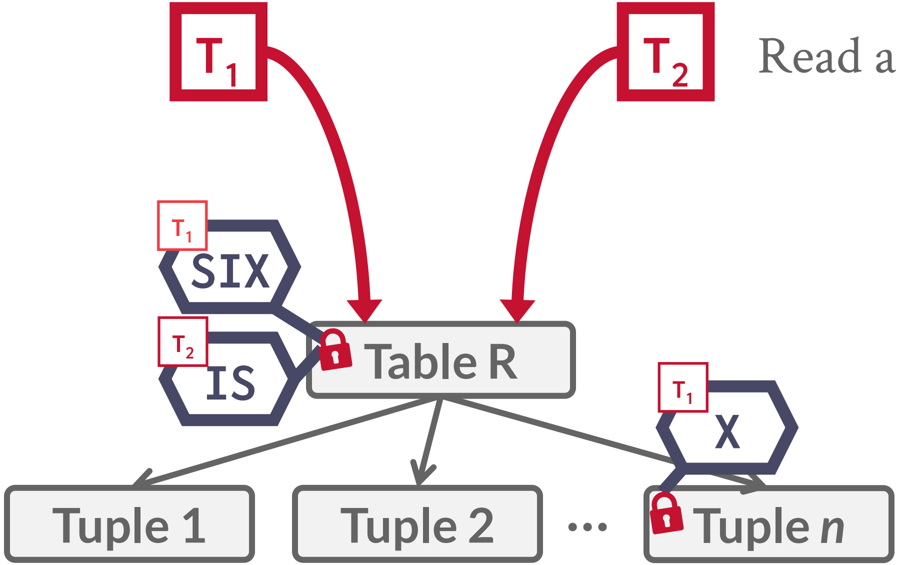
EXAMPLE – THREE TXNS

Read a single tuple in **R**.



	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

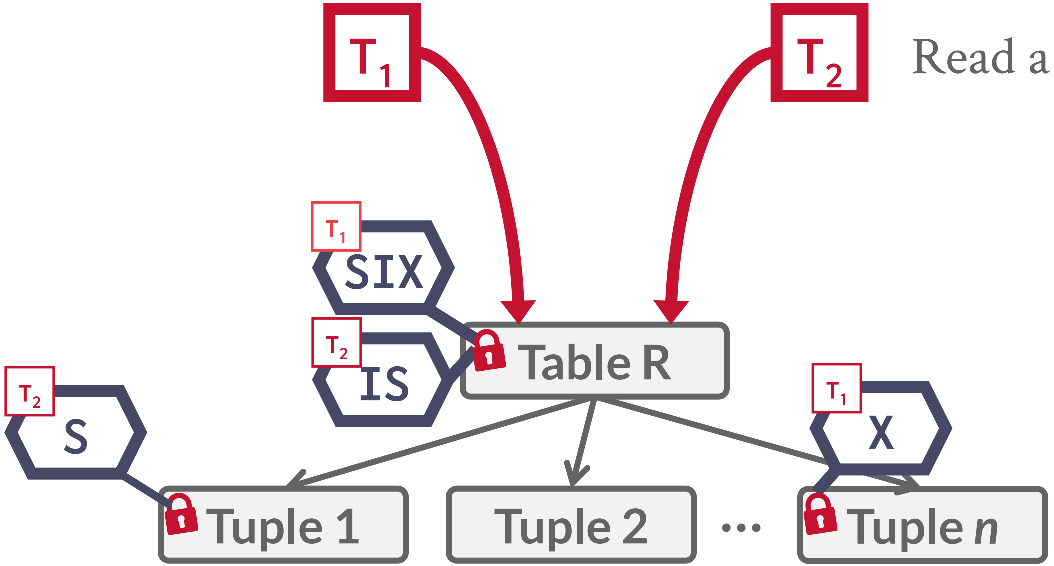
EXAMPLE – THREE TXNS



Read a single tuple in **R**.

	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

EXAMPLE – THREE TXNS

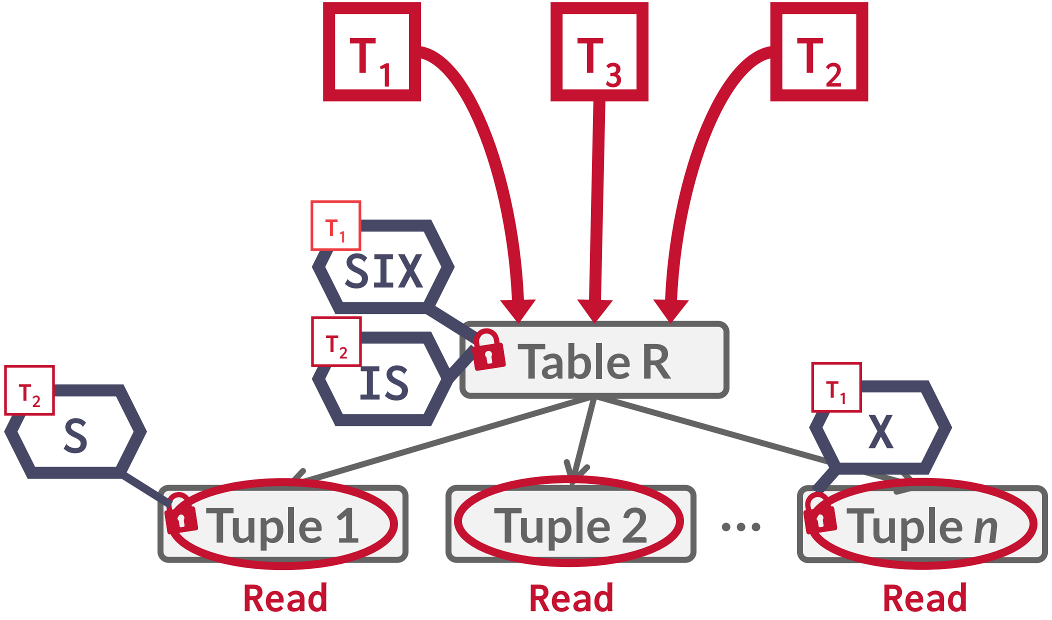


Read a single tuple in **R**.

	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

EXAMPLE – THREE TXNS

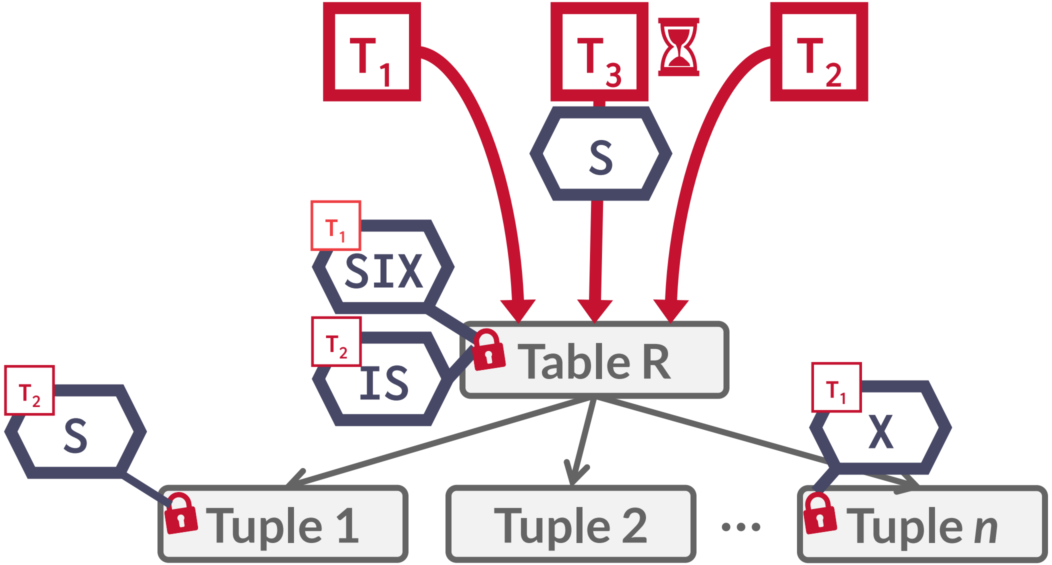
Scan all tuples in **R**.



	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

EXAMPLE – THREE TXNS

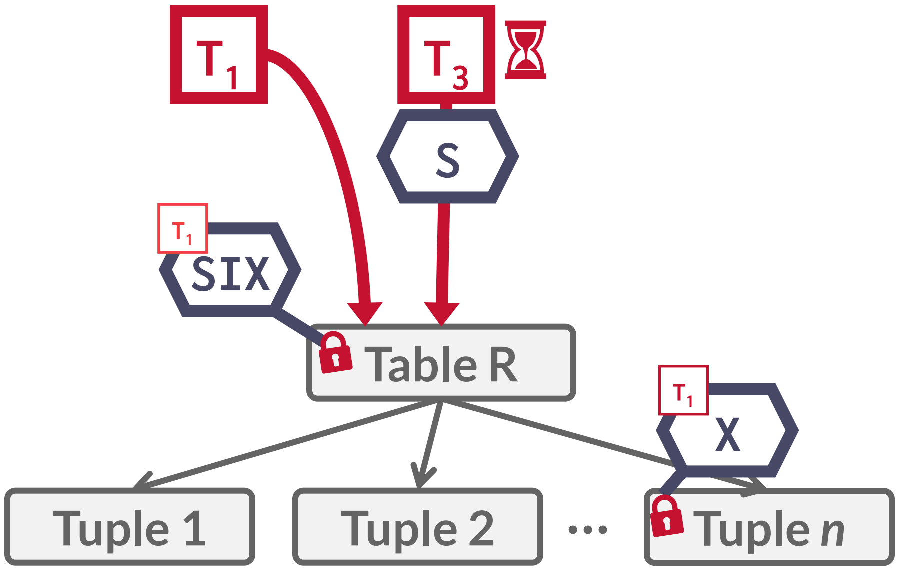
Scan all tuples in **R**.



	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

EXAMPLE – THREE TXNS

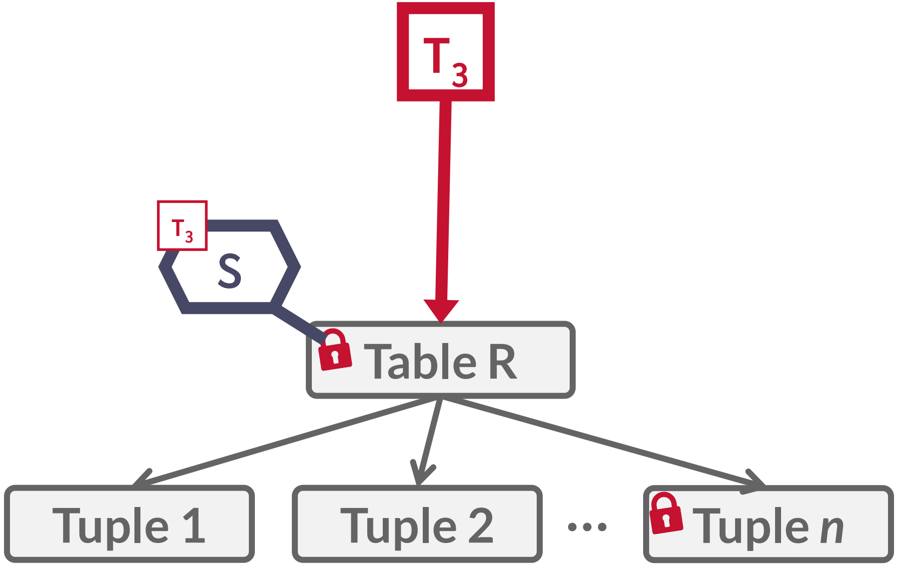
Scan all tuples in **R**.



	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

EXAMPLE – THREE TXNS

Scan all tuples in **R**.



	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

LOCK ESCALATION

The DBMS can automatically switch to coarser-grained locks when a txn acquires too many low-level locks.

This reduces the number of requests that the lock manager must process.

LOCKING IN PRACTICE

Applications typically do not acquire a txn's locks manually (i.e., explicit SQL commands).

Sometimes you need to provide the DBMS with hints to help it to improve concurrency.

→ Update a tuple after reading it.
→ Skip any tuple that is locked.

Explicit locks are also useful when doing major changes to the database.

SELECT...FOR UPDATE

Perform a **SELECT** and then sets an exclusive lock on the matching tuples.

Can also set shared locks:

→ Postgres: **FOR SHARE**

→ MySQL: **LOCK IN SHARE MODE**

Table 13.3. Conflicting Row-Level Locks

	Current Lock Mode			
Requested Lock Mode	FOR KEY SHARE	FOR SHARE	FOR NO KEY UPDATE	FOR UPDATE
FOR KEY SHARE				X
FOR SHARE			X	X
FOR NO KEY UPDATE		X	X	X
FOR UPDATE	X	X	X	X

```
SELECT * FROM <table>
 WHERE <qualification> FOR UPDATE;
```

SELECT...SKIP LOCKED

Perform a **SELECT** and automatically ignore any tuples that are already locked in an incompatible mode.

→ Useful for maintaining queues inside of a DBMS.

```
SELECT * FROM <table>
 WHERE <qualification> SKIP LOCKED;
```

CONCLUSION

2PL is used in almost every DBMS.

Automatically generates correct interleaving:
→ Locks + protocol (2PL, SS2PL ...)
→ Deadlock detection + handling
→ Deadlock prevention

Many more things not discussed…
→ Nested Transactions
→ Savepoints

PROJECT #3 – QUERY EXECUTION

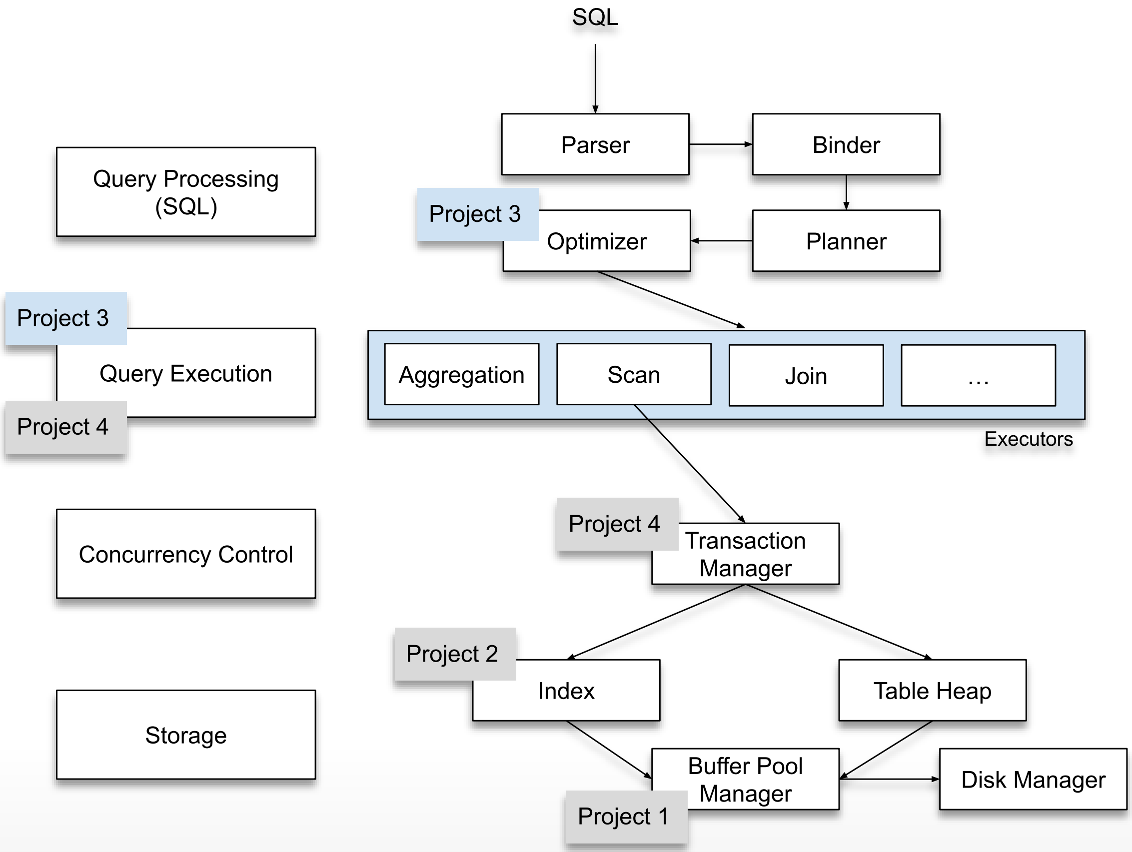
You will add support for optimizing and executing queries in BusTub.

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

Prompt: *Red and white bus driving on a road through mountains. The bus has a bubbly bath as its roof with a showerhead. The bus has crazy eyes and a mouth in the front. There are bold red letters that say "CMU" on the side of the bus*

https://15445.courses.cs.cmu.edu/fall2024/project3

PROJECT #3 – QUERY EXECUTION



PROJECT #3 – TASKS

Plan Node Executors

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

Optimizer Rule:

→ Convert Nested Loops to Hash Join
→ Convert Sequential Scan to Index Scan

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.

Tasks:

→ Column Pruning
→ More Aggressive Predicate Pushdown
→ Bloom Filter for Hash Join

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 hash table does not need to be backed by your buffer pool (i.e., use STL)

Gradescope is for meant for grading, not debugging. 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!

PLAGIARISM WARNING

The homework and projects must be your own original work. They are **not** group assignments.

You may **not** copy source code from other people or the web.

Plagiarism is **not** tolerated. You will get lit up.
→ Please ask me if you are unsure.

See CMU's Policy on Academic Integrity for additional information.

NEXT CLASS

Timestamp Ordering Concurrency Control

Isolation Levels