Carnegie Mellon University

Database Systems

15-445/645 FALL 2026

JIGNESH PATEL



Lecture #18

Concurrency Control: Two-Phase Locking

ADMINISTRIVIA

Project #3 is due Sunday Nov 15th @ 11:59pm

Homework #5 is now due Sunday Nov 22nd @ 11:59pm

UPCOMING DATABASE TALKS

daft	Nov 9	Jay Chia, Rohit Kulshreshtha	Database for Visual Data and Robot Sensors: Beyond Vector Search, RAG and Timeseries
TURSO	Nov 16	Mikaël Francoeur	Turso: An SQLite-compatible, Open-Contribution RDBMS
DB9	Nov 23	Ed Huang	DB9: A Database for Agents, Built by Agents
TERADATA	Nov 30	Artur Borycki	Building Distributed Database Engine

LAST CLASS

A DBMS's concurrency control and recovery protocols provide **ACID** guarantees for txns.

Conflict Serializable

→ Verify using 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.

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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

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EXECUTING WITH LOCKS

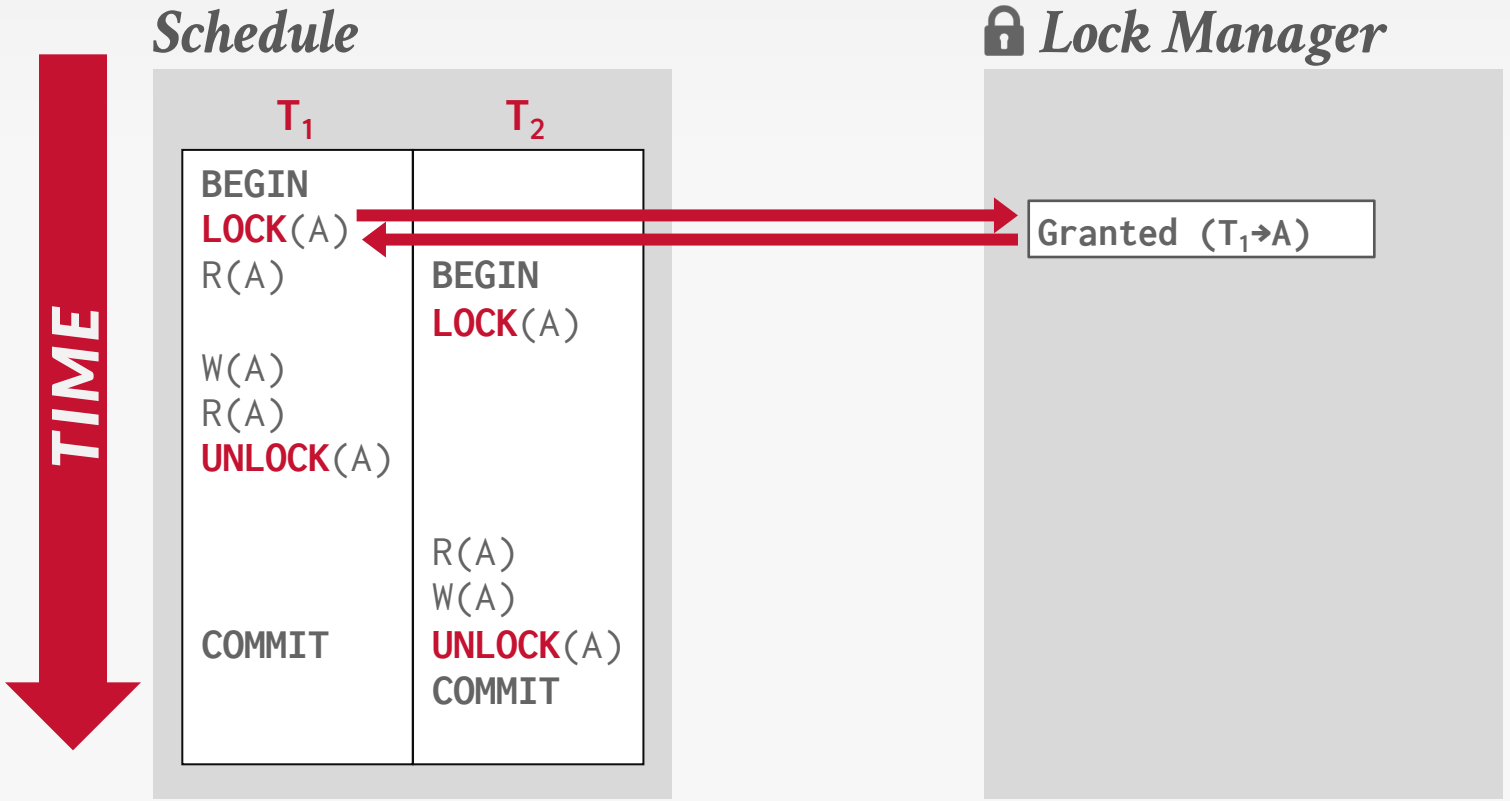


Schedule

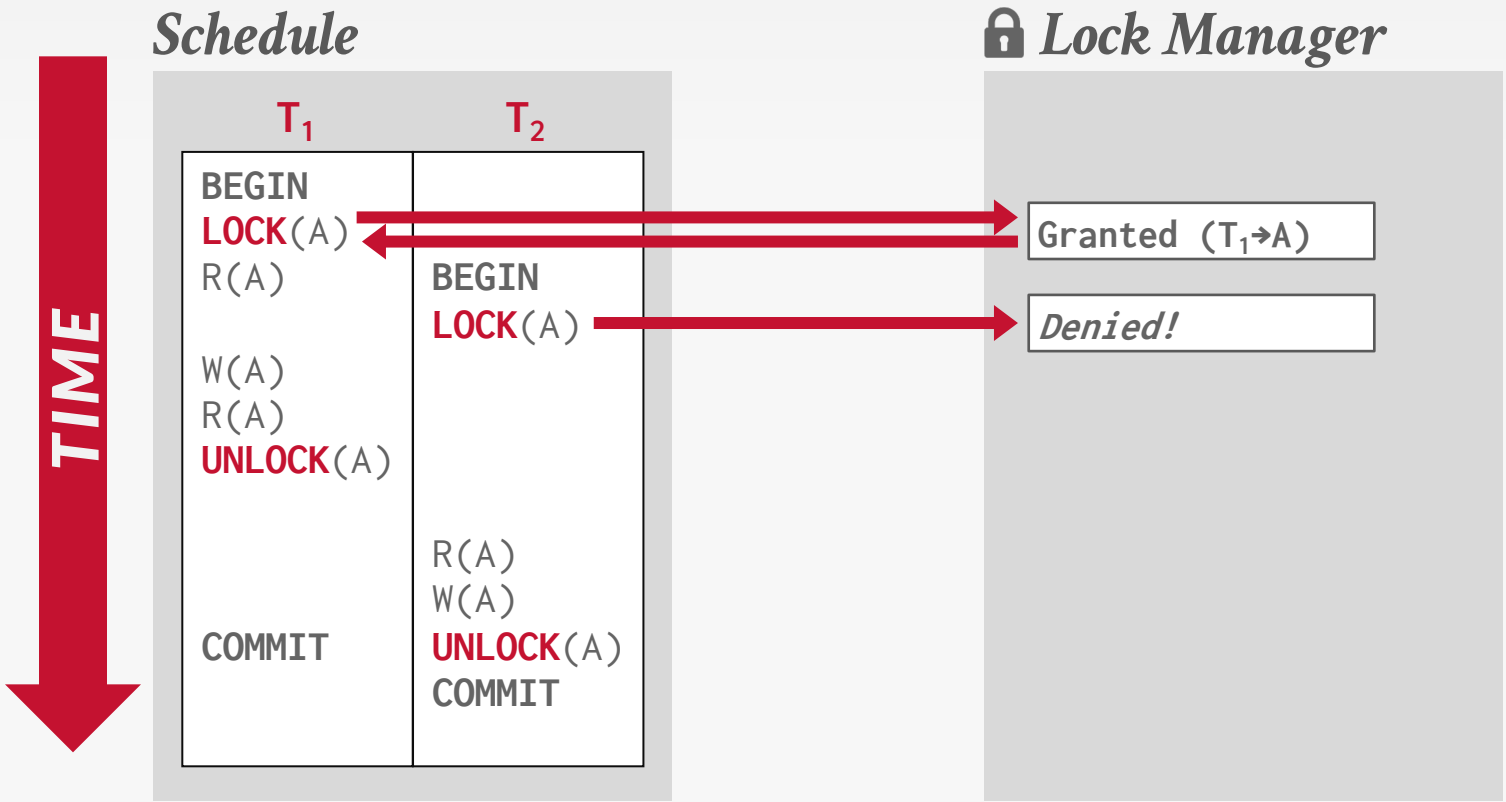
T_1	T_2
BEGIN	
LOCK(A)	
R(A)	BEGIN
	LOCK(A)
W(A)	
R(A)	
UNLOCK(A)	
	R(A)
	W(A)
COMMIT	UNLOCK(A)
	COMMIT

Lock Manager

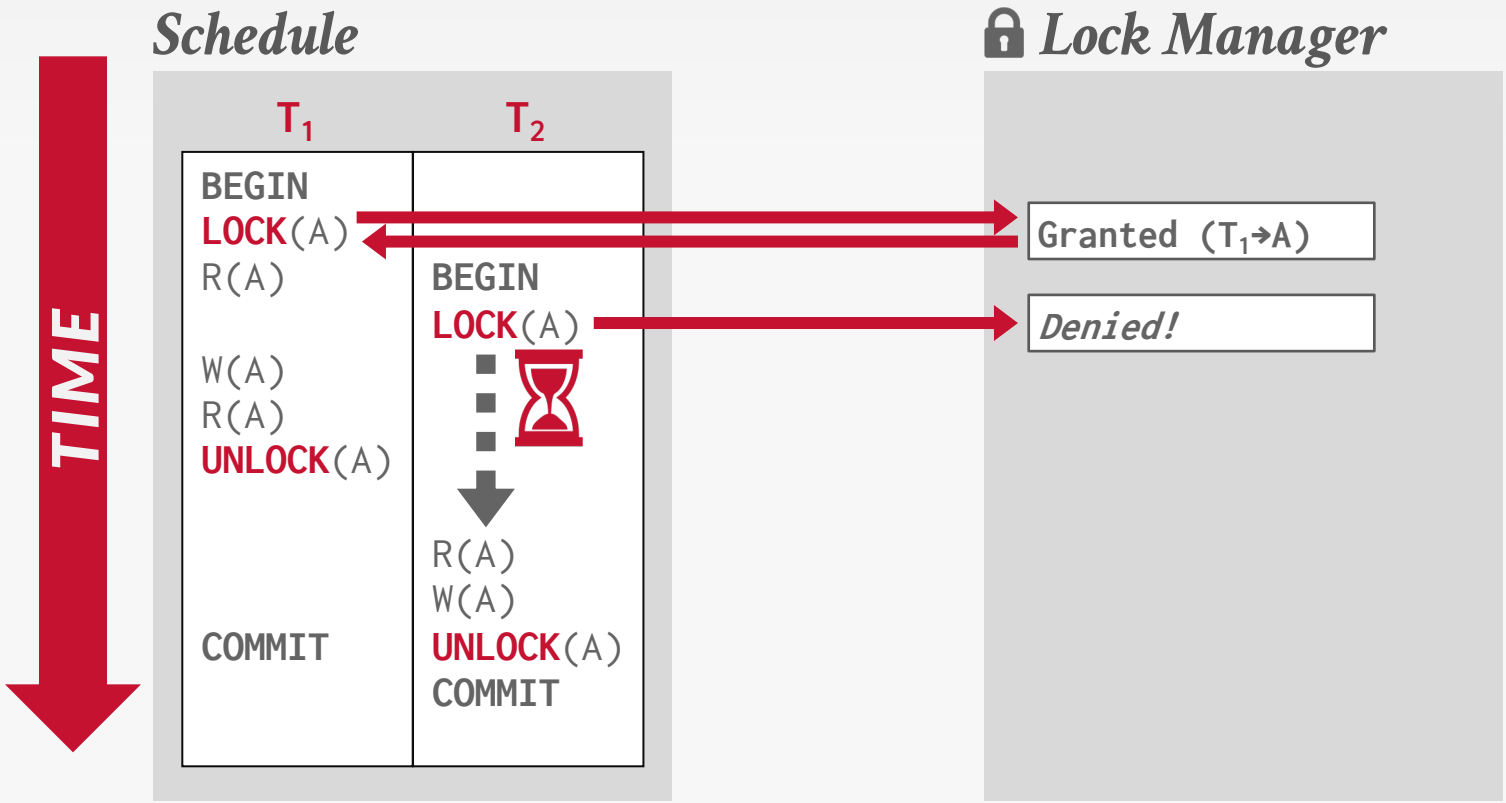
EXECUTING WITH LOCKS



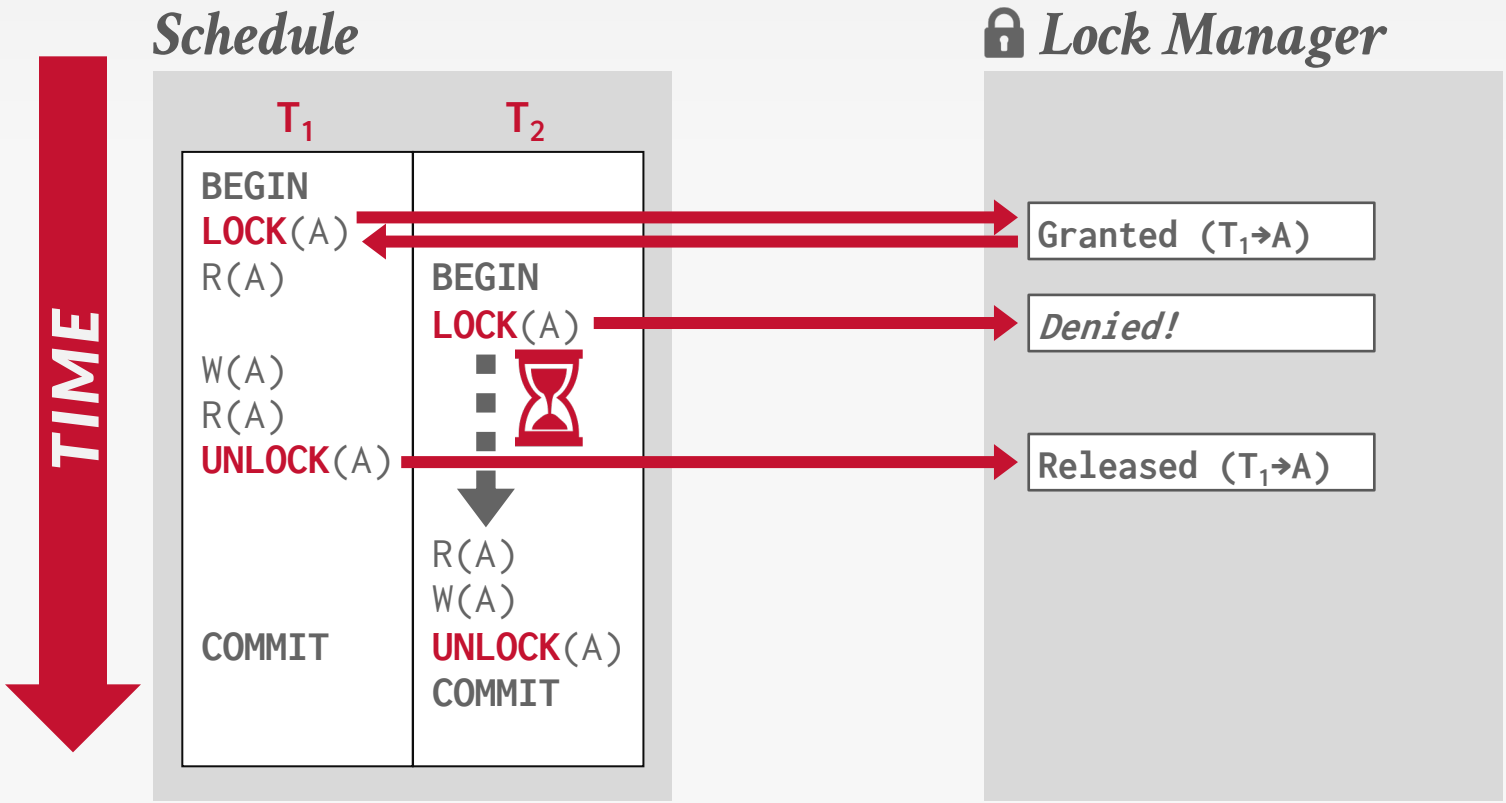
EXECUTING WITH LOCKS



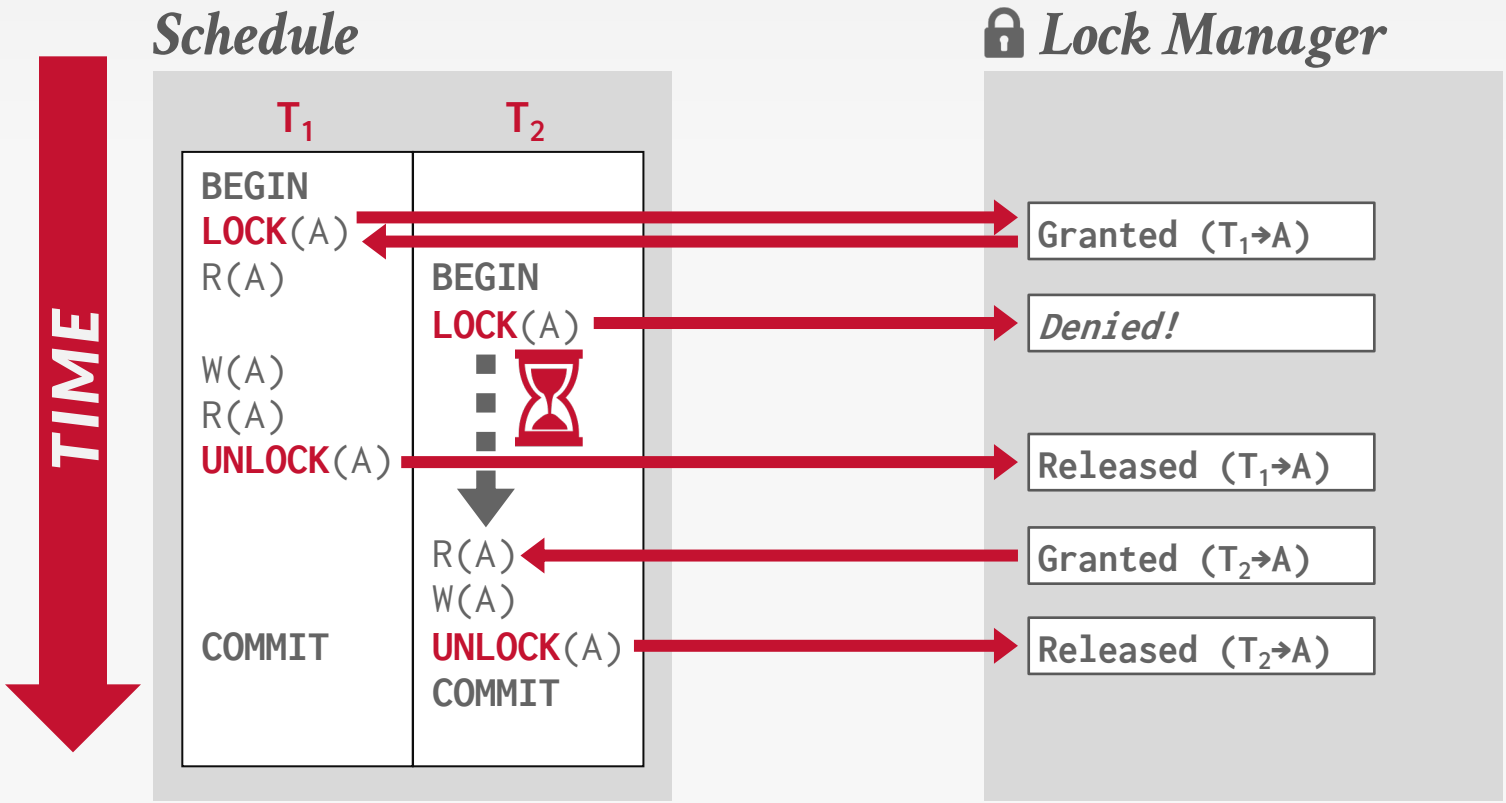
EXECUTING WITH LOCKS



EXECUTING WITH LOCKS



EXECUTING WITH LOCKS



TODAY'S AGENDA

Lock Types

Two-Phase Locking

Deadlock Detection + Prevention

Hierarchical Locking

⚡**DB Flash Talk: RelationalAI**

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 (
Share (S-lock)	Yes	Yes
Update (U-lock)	Yes	No
Exclusive (X-lock)		

Compatibility for table space locks
modes for partition, table space, or

Table 2. Compatibility of table and

Lock Mode	IS	IX	S
IS	Yes	Yes	Yes
IX	Yes	Yes	No
S	Yes	No	Yes
U	Yes	No	Yes
SIX	Yes	No	No
X	No	No	No

IBM

Existing granted mode / Requested mode	IS	S	U
Intent shared (IS)	Yes	Yes	
Shared (S)	Yes	Yes	
Update (U)	Yes	No	
Intent exclusive (IX)	Yes	No	
Shared with intent exclusive (SIX)		No	

Microsoft® SQL Server®

Table 13-3 Summary of Table Locks

SQL Statement	Mode of Table Lock	Lock Modes Permitted? RS	RX	S	SRX	X
SELECT...FROM table...	none	Y	Y	Y	Y	Y
INSERT INTO table ...	RX	Y	Y	N	N	N
UPDATE table ...	RX	Y*	Y*	N	N	N
DELETE FROM table ...	RX	Y*	Y*	N	N	N
SELECT ... FROM table FOR UPDATE OF ...	RS	Y*	Y*	Y*	Y*	N
LOCK TABLE table IN ROW SHARE MODE	RS	Y	Y	Y	Y	N
LOCK TABLE table IN ROW EXCLUSIVE MODE	RX	Y	Y	N	N	N
LOCK TABLE table IN SHARE MODE	S	Y	N	Y	N	N
LOCK TABLE table IN SHARE ROW EXCLUSIVE MODE	SRX	Y	N	N	N	N
LOCK TABLE table IN EXCLUSIVE MODE	X	N	N	N	N	N

ORACLE®

Table 13.2. Conflicting Lock Modes

Requested Lock Mode / Existing Lock Mode	ACCESS SHARE	ROW SHARE	ROW EXCL.	SHARE UPDATE EXCL.	SHARE	SHARE ROW EXCL.	EXCL.	AC
ACCESS SHARE							X	
ROW SHARE						X	X	
ROW EXCL.				X	X	X	X	
SHARE UPDATE EXCL.			X	X		X	X	
SHARE			X	X	X	X	X	
SHARE ROW EXCL.			X	X	X	X	X	
EXCL.		X	X	X	X	X	X	
ACCESS EXCL.	X	X	X	X	X	X	X	

PostgreSQL

Table-level lock type compatibility is summarized in the following ma

	X	IX	S	IS
X	Conflict	Conflict	Conflict	Conflict
IX	Conflict	Compatible	Conflict	Compatible
S	Conflict	Conflict	Compatible	Compatible
IS	Conflict	Compatible	Compatible	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

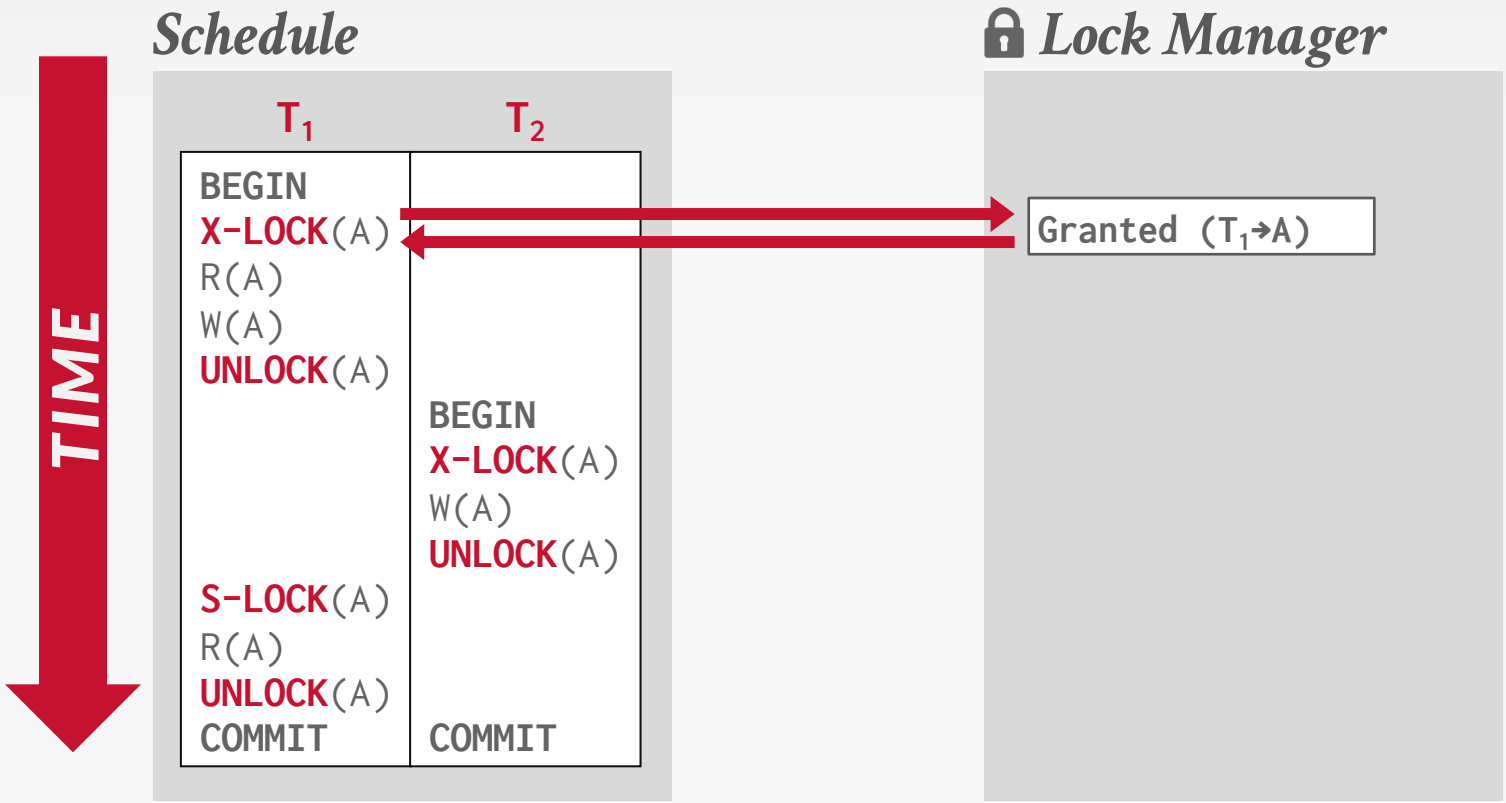
TIME

Schedule

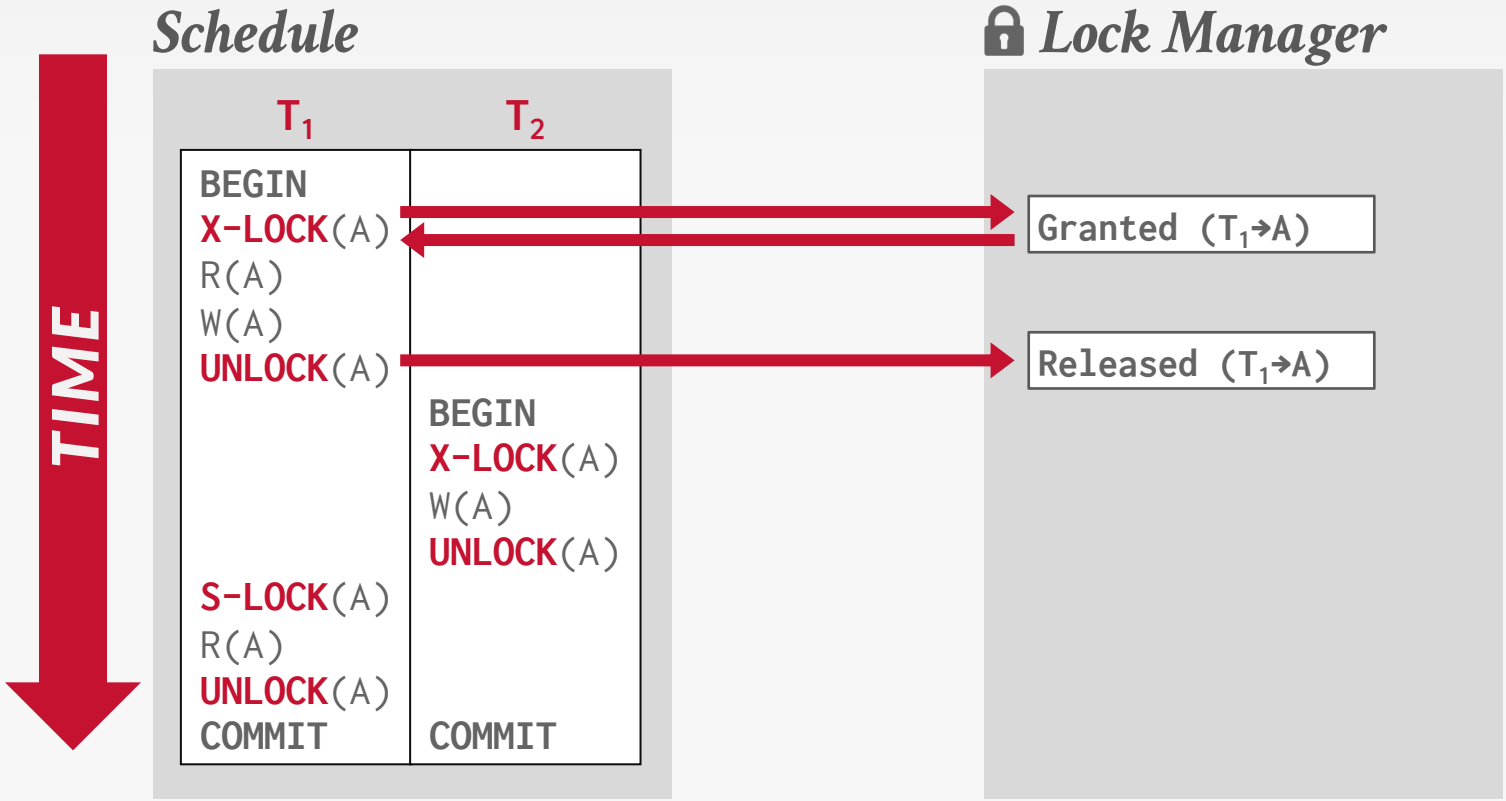
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X-LOCK(A)	
R(A)	
W(A)	
UNLOCK(A)	
	BEGIN
	X-LOCK(A)
	W(A)
	UNLOCK(A)
S-LOCK(A)	
R(A)	
UNLOCK(A)	
COMMIT	COMMIT

Lock Manager

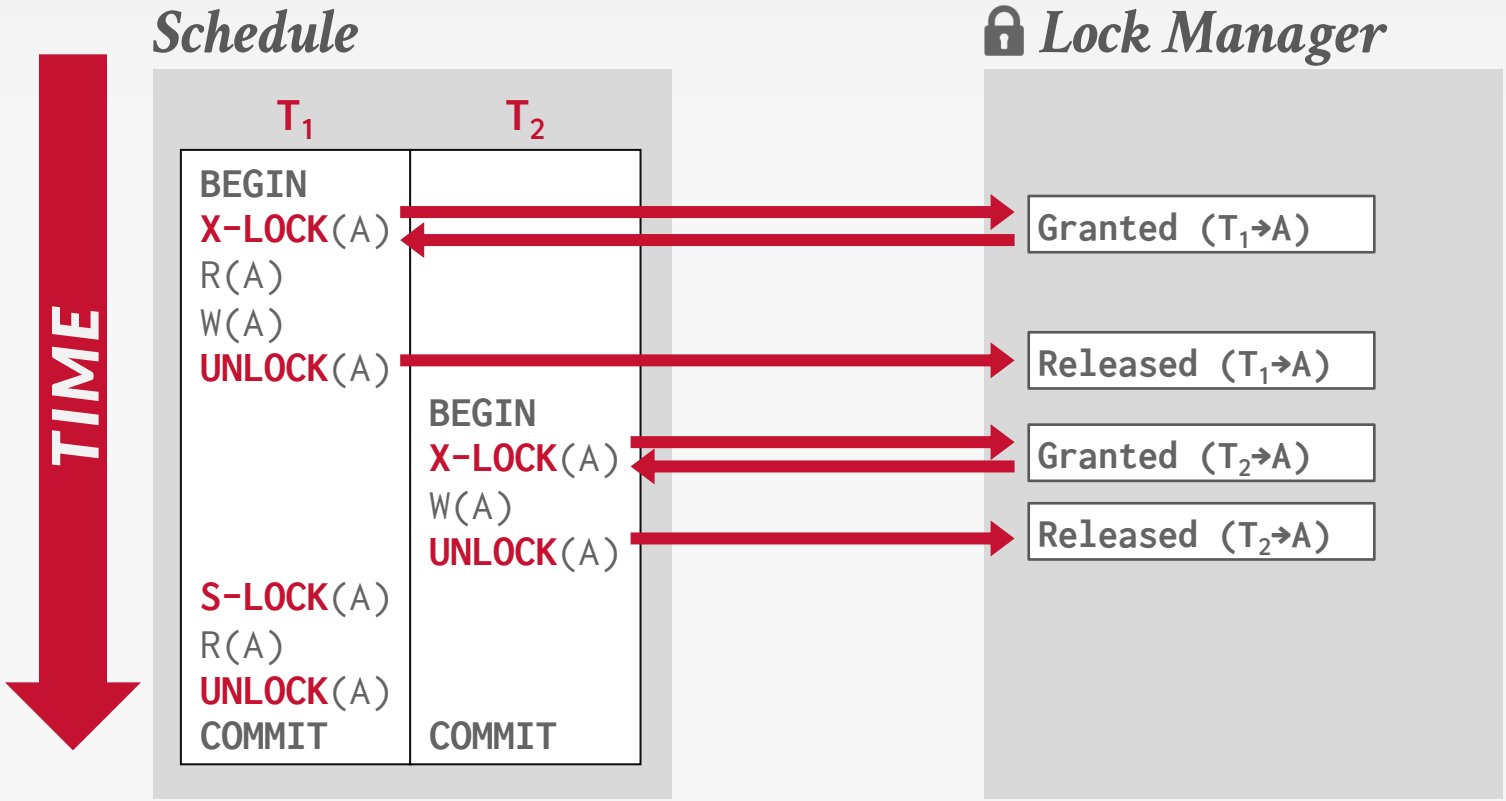
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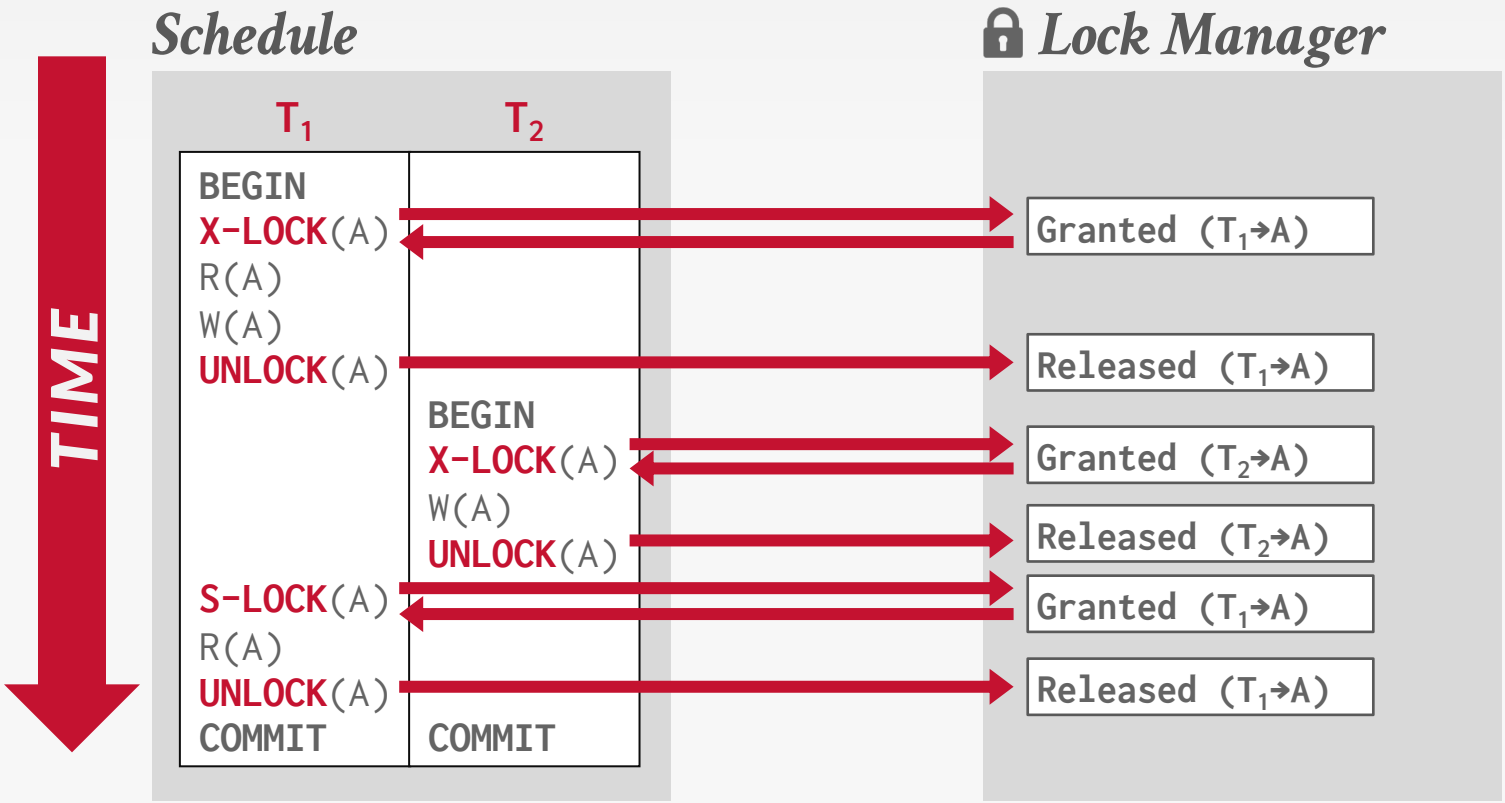
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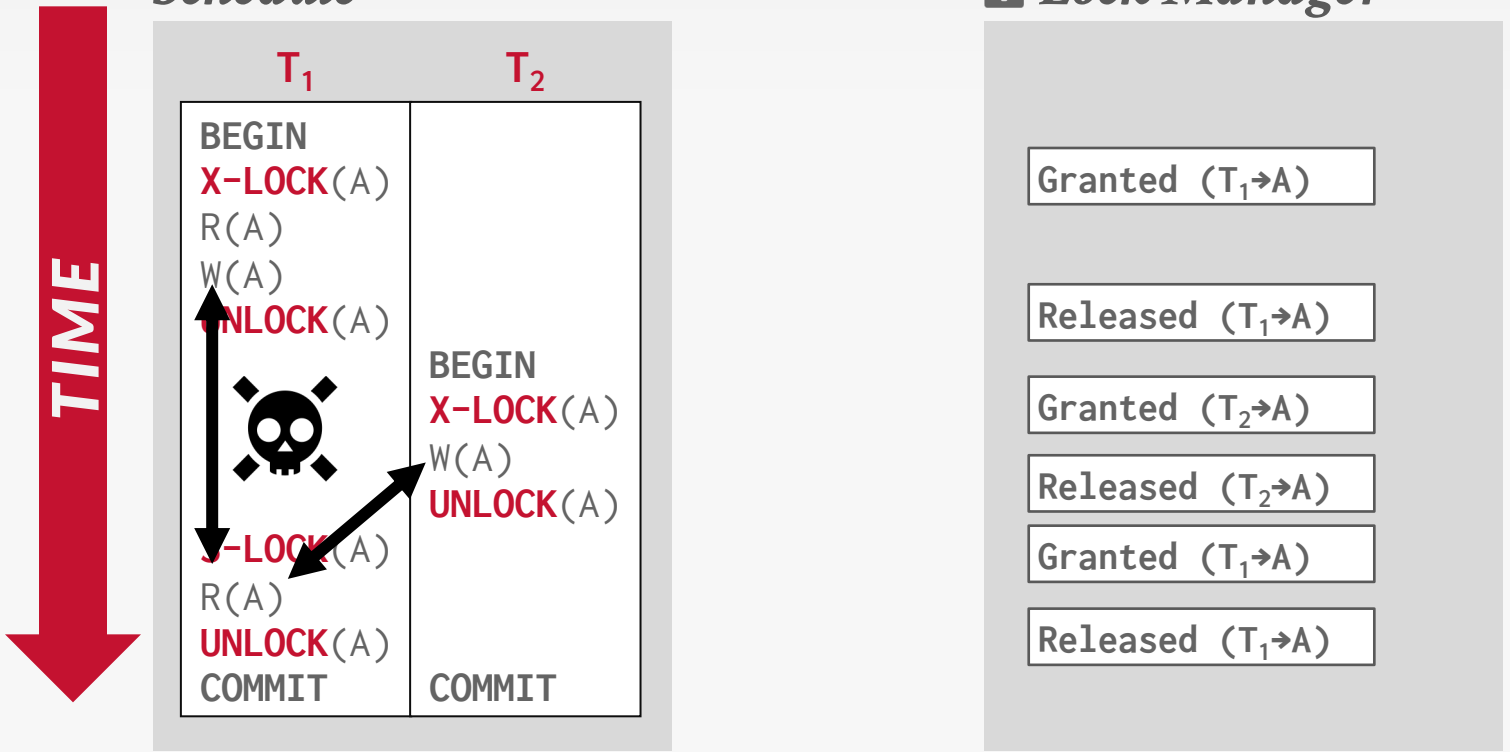
EXECUTING WITH LOCKS



EXECUTING WITH LOCKS



EXECUTING WITH LOCKS



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

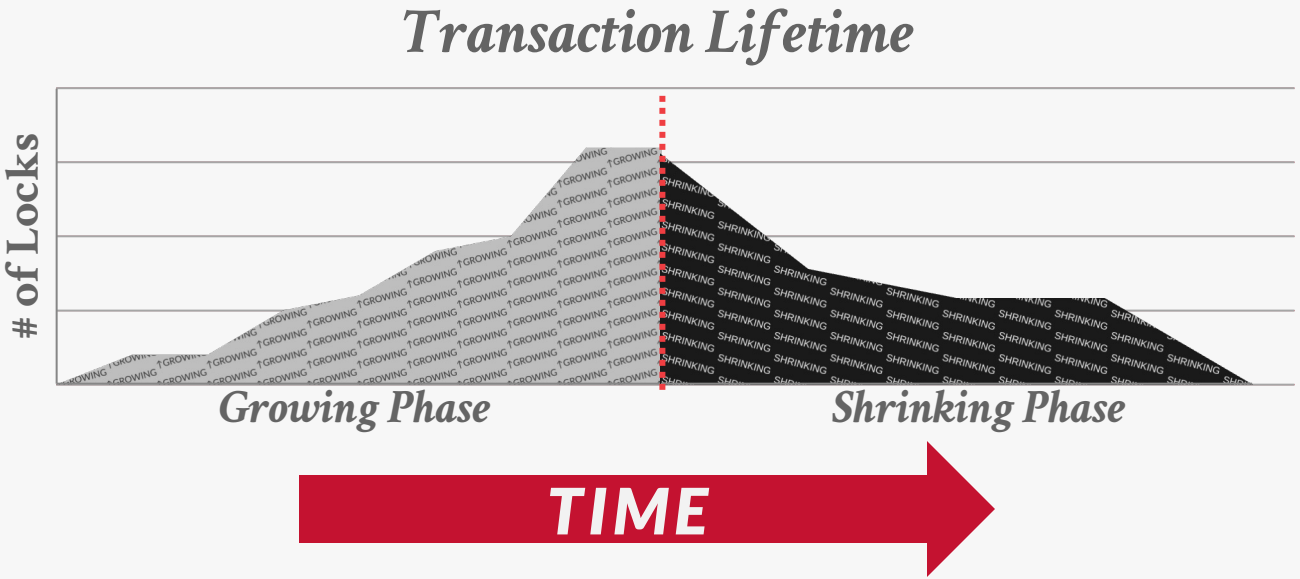
→ Each txn requests the locks that it needs from the DBMS's lock manager.
→ The lock manager grants/denies lock requests.

Phase #2: Shrinking

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

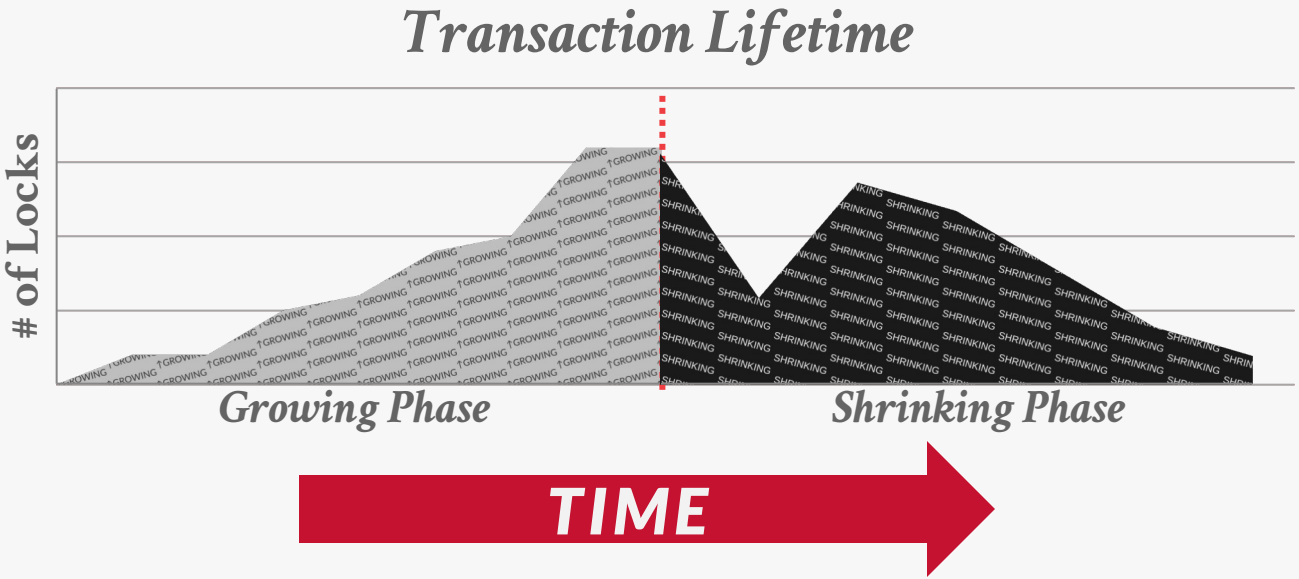
TWO-PHASE LOCKING

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



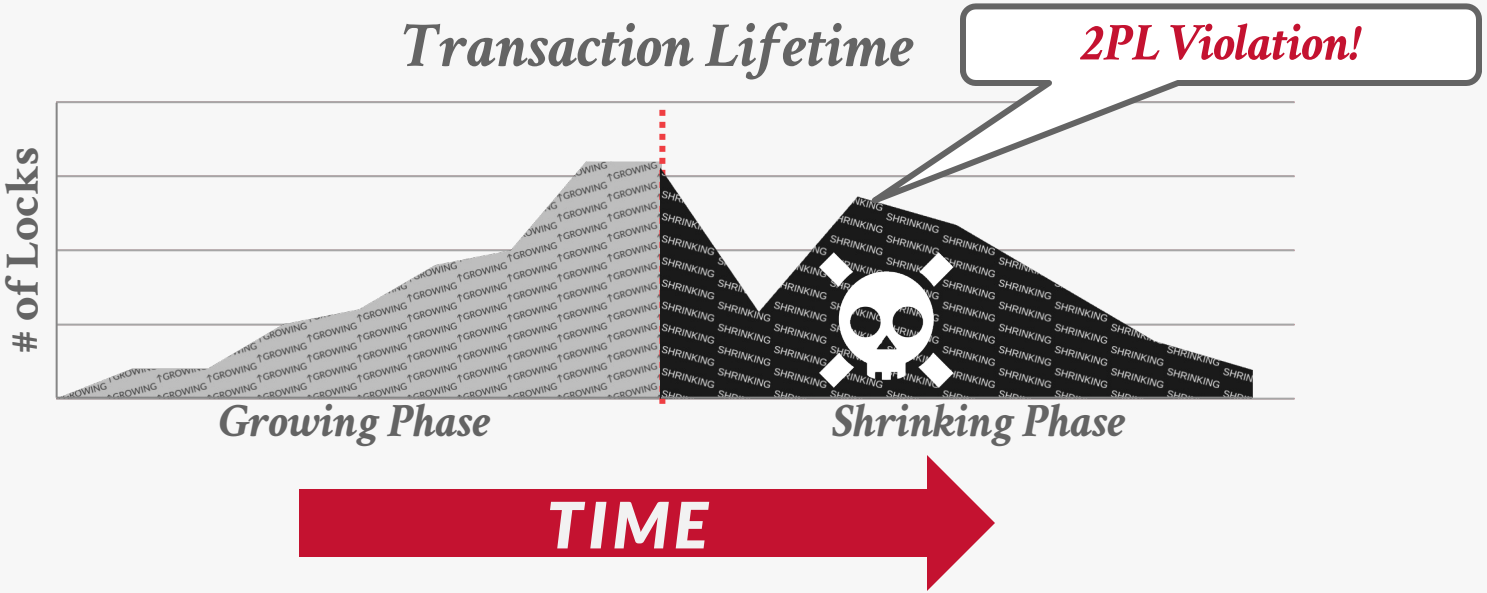
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EXECUTING WITH 2PL

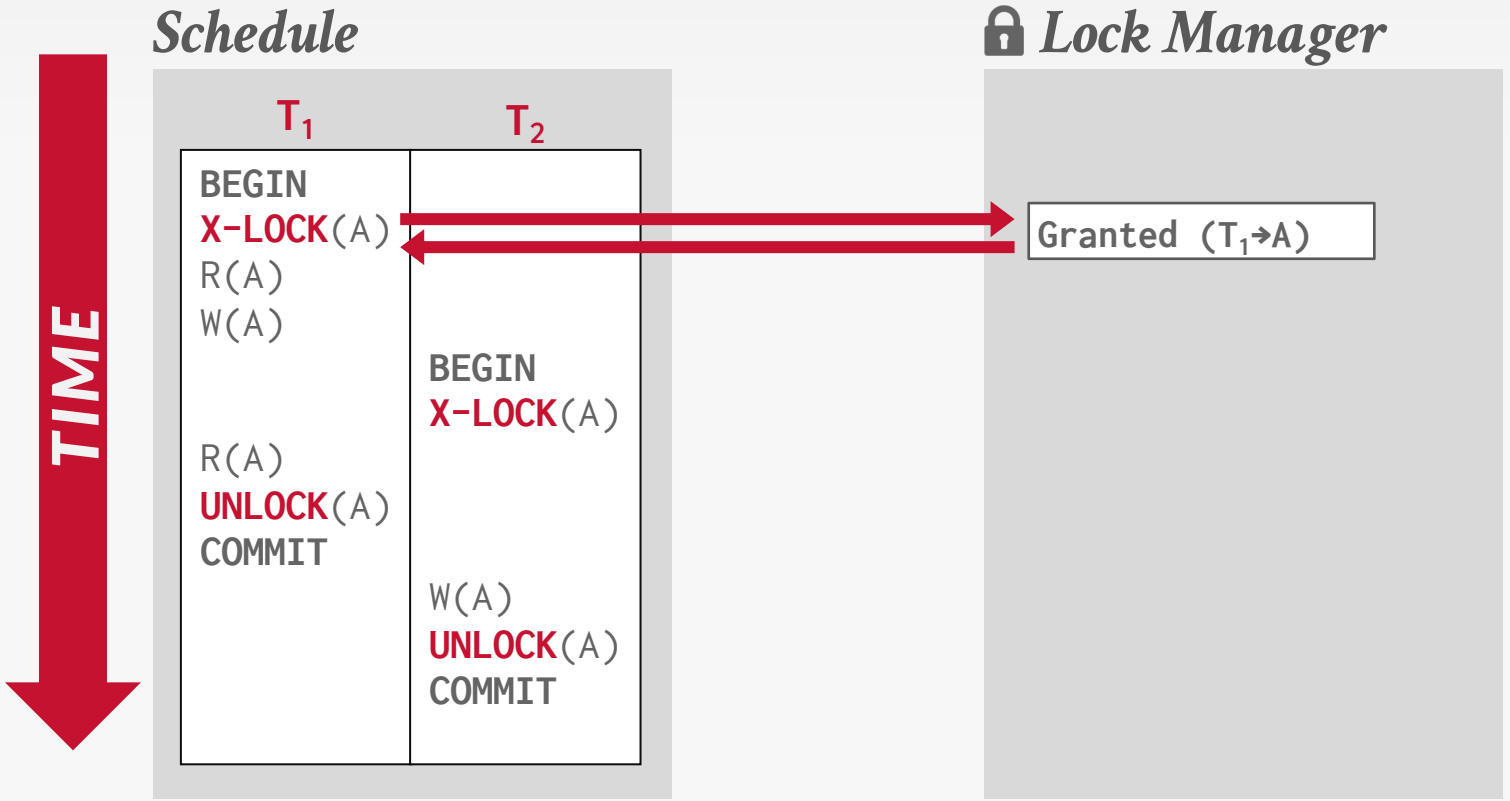
Schedule

TIME

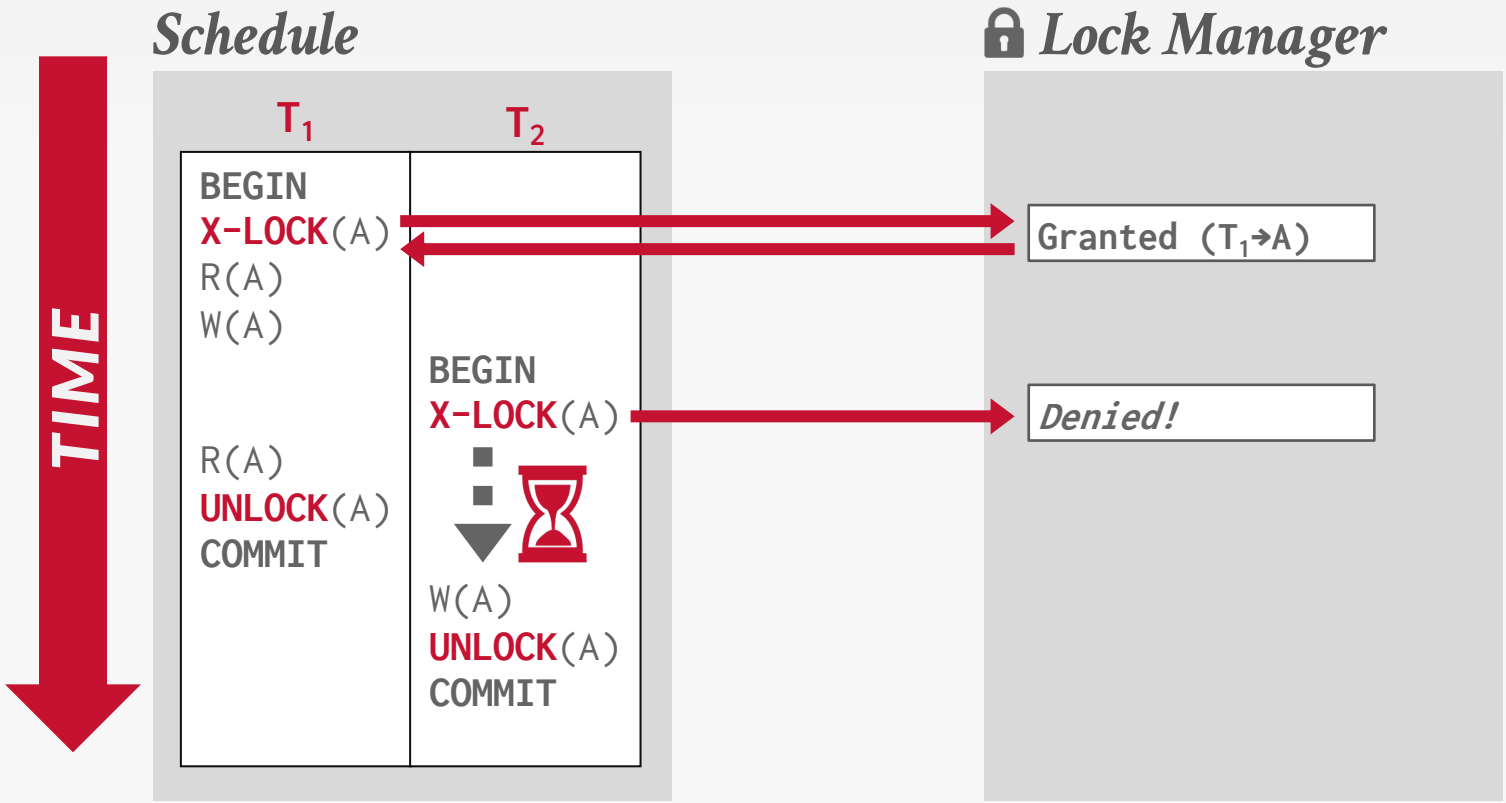
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	COMMIT

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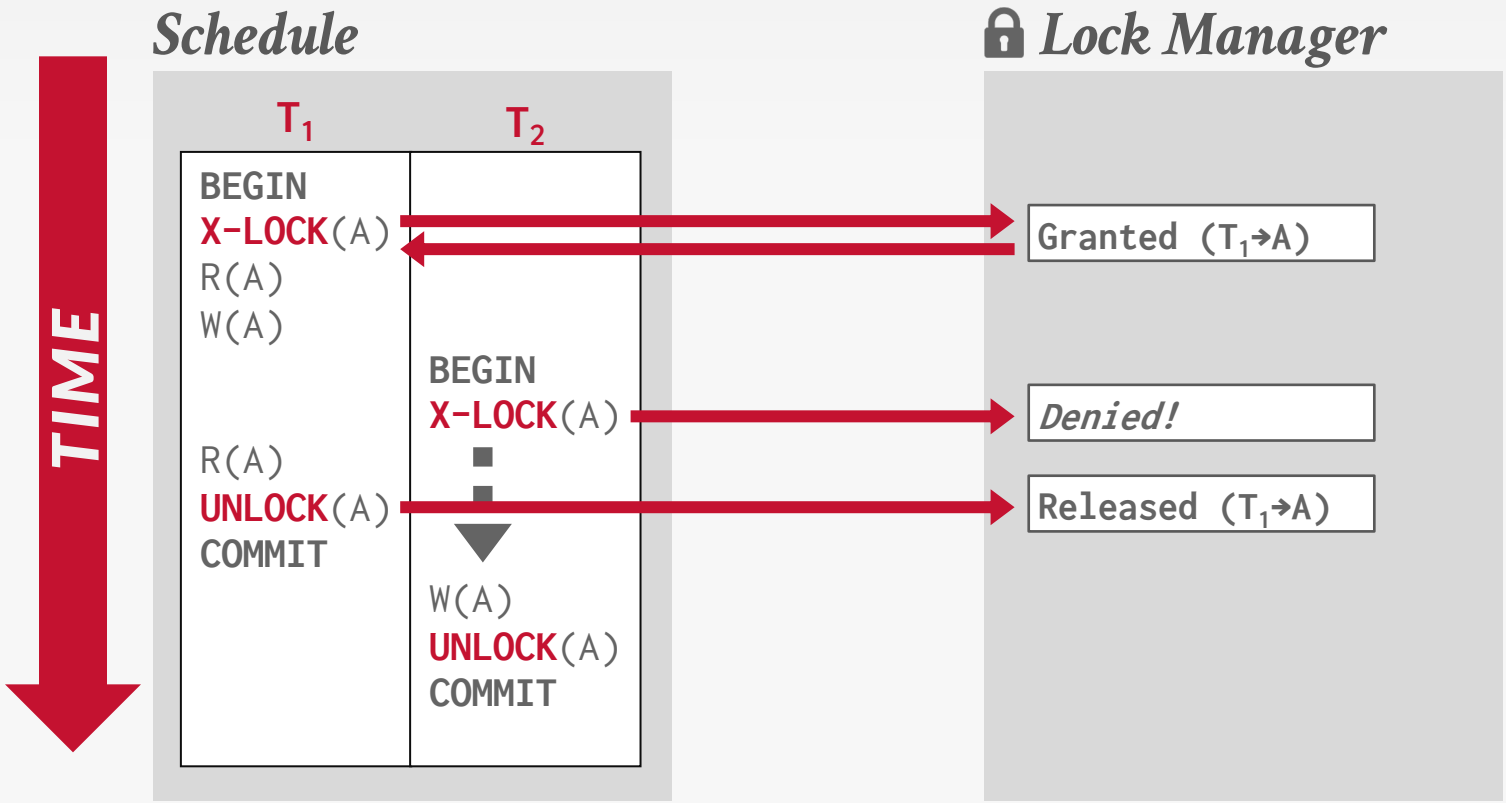
EXECUTING WITH 2PL



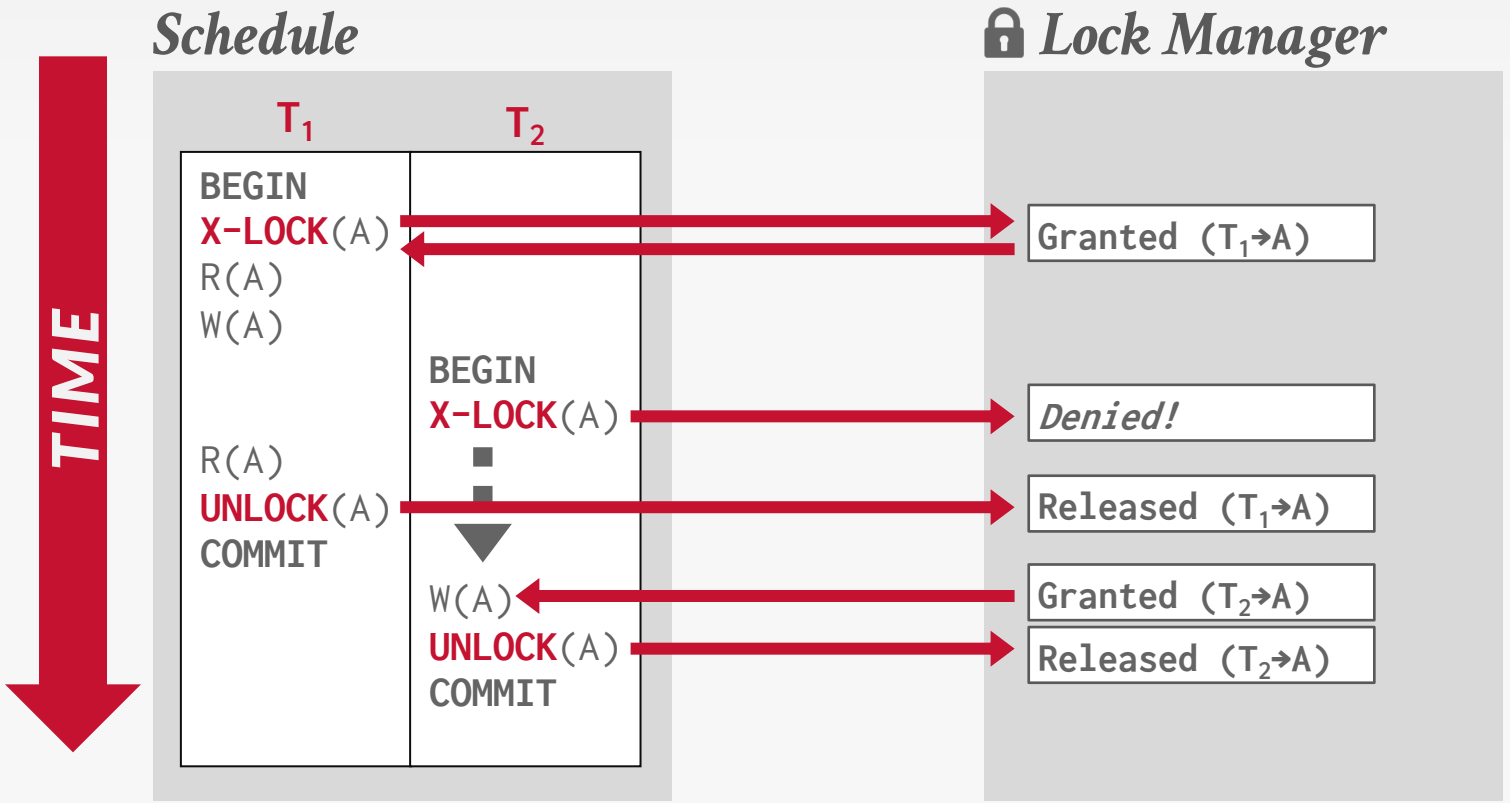
EXECUTING WITH 2PL



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EXECUTING WITH 2PL



OBSERVATION

2PL guarantees conflict serializability because it generates schedules with acyclic precedence graphs.

→ There are schedules that are serializable but 2PL does not allow because its locking limits concurrency.

2PL schedules can have "dirty reads".

→ Solution: **2PL Variants**

2PL schedules can have deadlocks.

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

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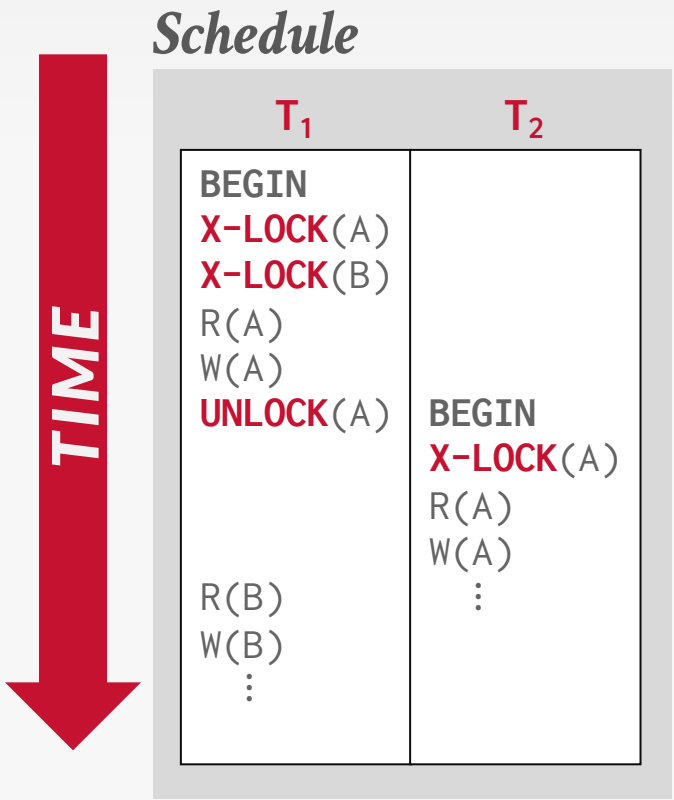
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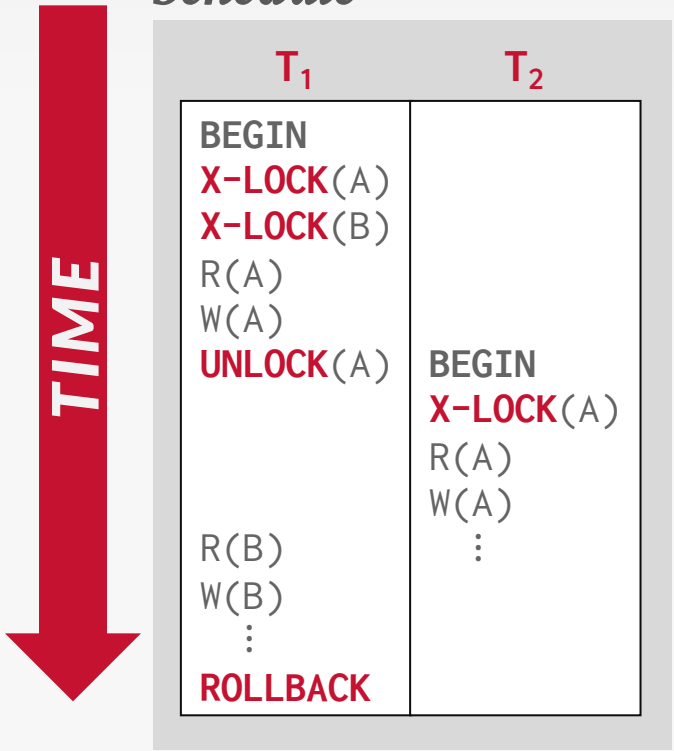
→ Solution: **Detection** or **Prevention**

2PL: CASCADING ABORTS

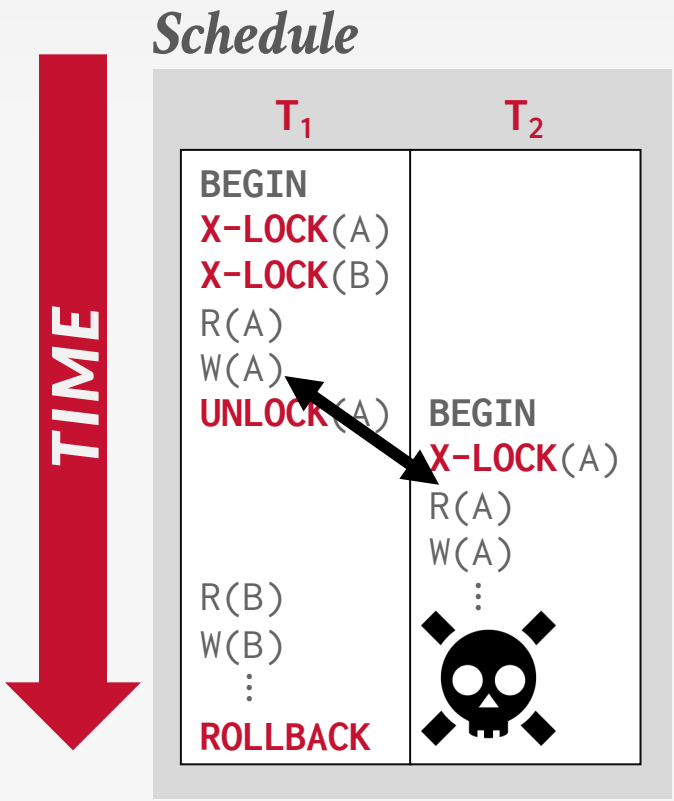


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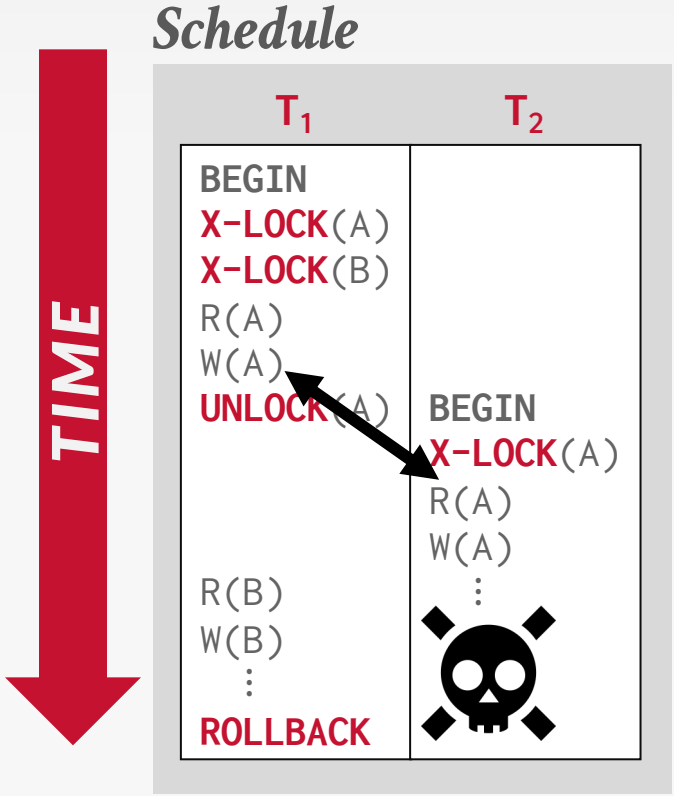
Schedule



2PL: CASCADING ABORTS

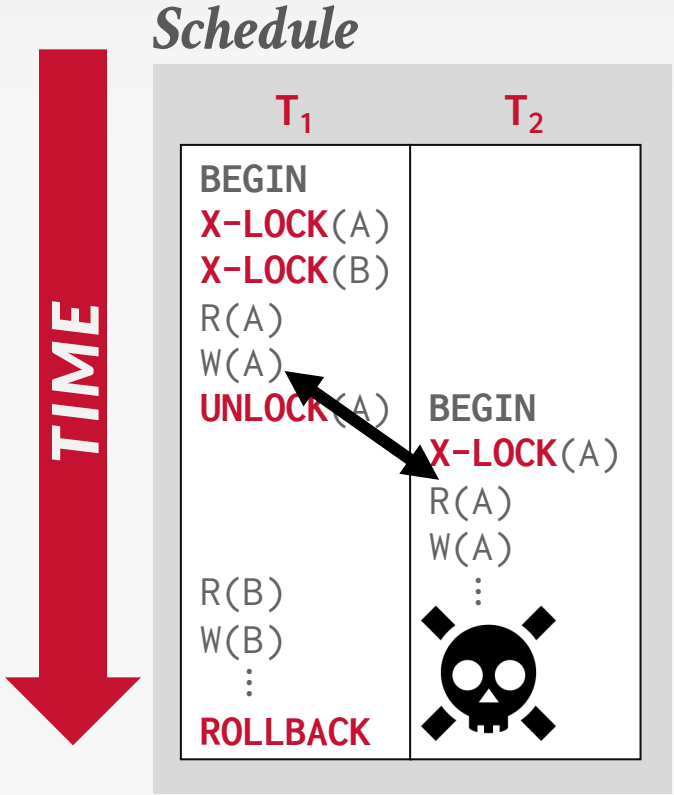


2PL: CASCADING ABORTS



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

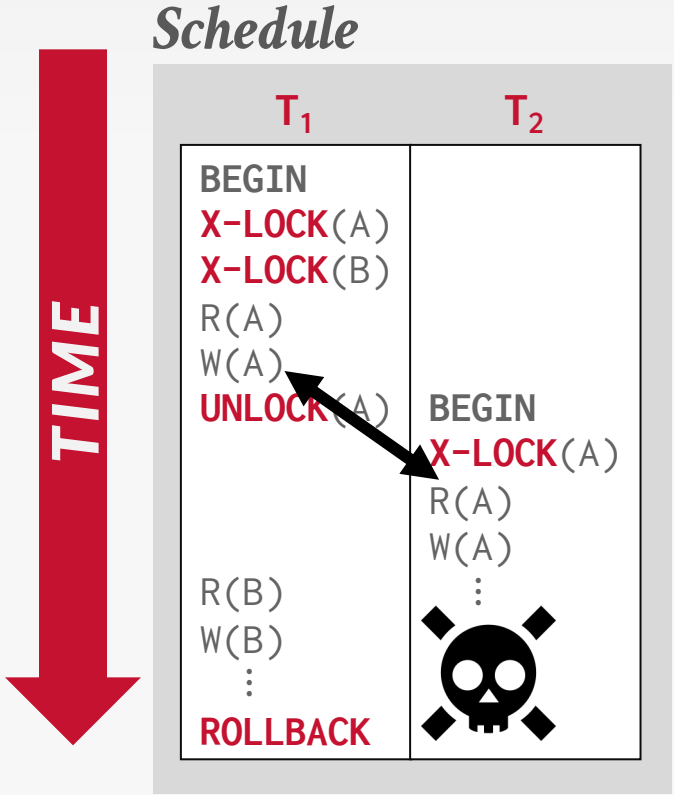
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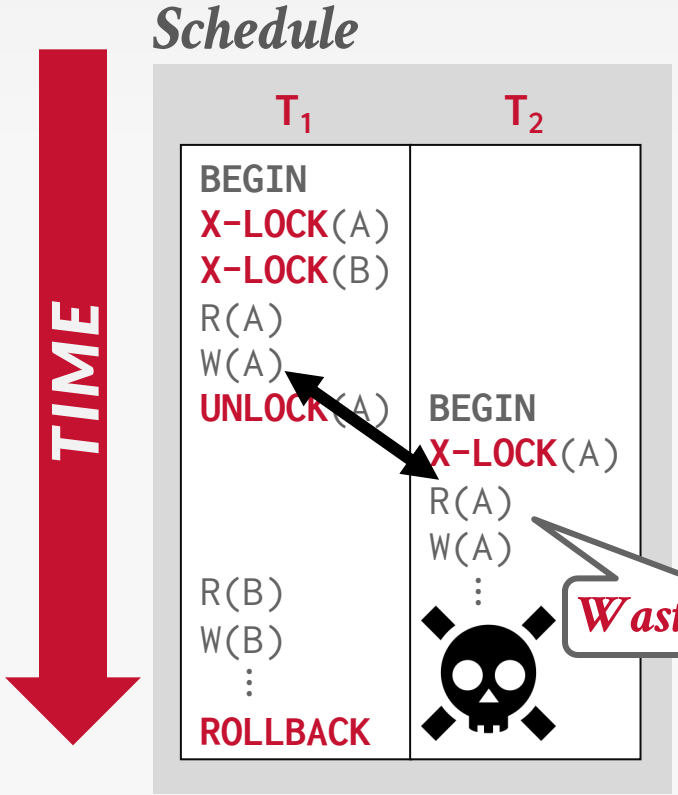


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Any information about T_1 cannot be "leaked" to the outside world.

Any computation performed must be rolled back.

2PL: CASCADING ABORTS



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.

SCHEDULE PROPERTIES

Recoverable:

→ A txn commits only after all other txns from which it has read dirty objects have successfully committed.

Avoids Cascading Aborts (ACA):

→ A txn can only read objects that have already been committed by the txns that wrote them (i.e., no dirty reads).

Strict:

→ A txn cannot read or write an object until the txn that previously wrote it has committed or aborted.

Rigorous:

→ A txn cannot read or write an object until the txn that last read or wrote it has committed or aborted.

2PL VARIANTS

Strict 2PL (S2PL):

→ Txns hold all exclusive locks until commit/abort.
→ *Schedules: Recoverable + ACA + Strict*

Strong Strict 2PL (SS2PL):

→ Txns hold both shared and exclusive locks until commit/abort.
→ *Schedules: Recoverable + ACA + Strict + Rigorous*

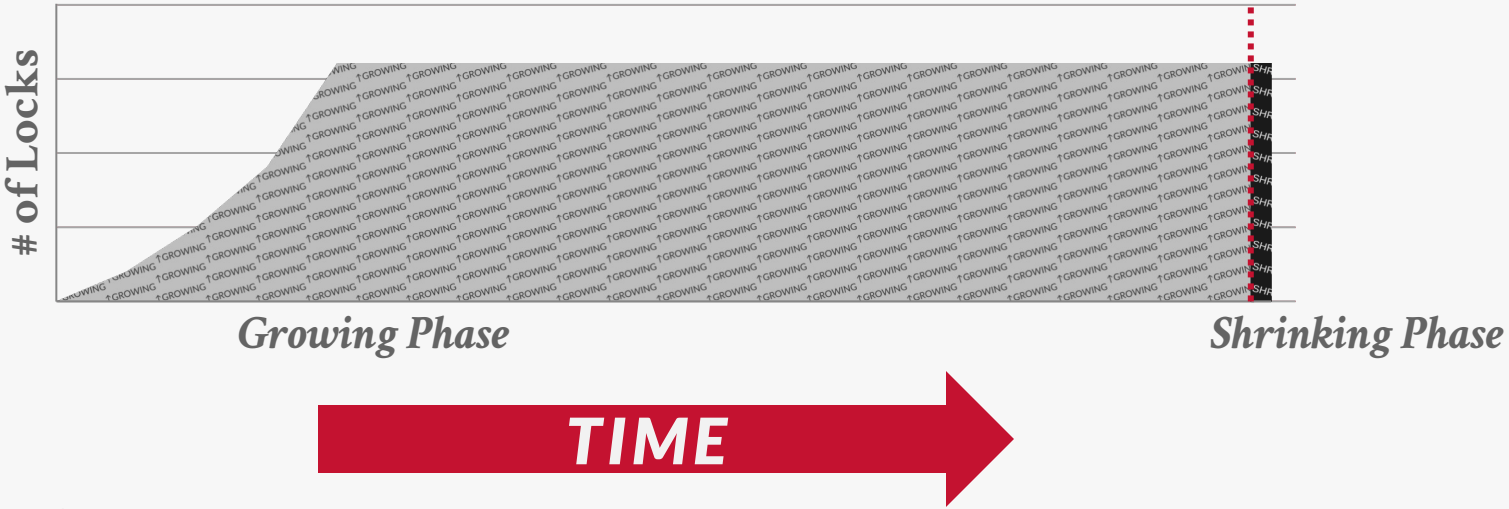
Rigorous 2PL:

→ Txns hold all locks held until commit/abort.
→ Same as SS2PL in practice.
→ *Schedules: Recoverable + ACA + Strict + Rigorous*

STRONG STRICT TWO-PHASE LOCKING

The txn is releases all locks when it finishes (i.e., committed or aborted).

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



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EXAMPLES

T_1 – Move $100 from DJ Cache'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
R(A)
A=A-100
W(A)
R(B)
B=B+100
W(B)
COMMIT
```

T_2

```
BEGIN
R(A)
R(B)
COMMIT
ret(A+B)
```

NON-2PL EXAMPLE

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)
	R(B)
X-LOCK(B)	
	UNLOCK(B)
R(B)	COMMIT
B=B+100	ret(A+B)
W(B)	
UNLOCK(B)	
COMMIT	

Initial Database State

A=1000, B=1000

NON-2PL EXAMPLE

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)
	R(B)
X-LOCK(B)	
	UNLOCK(B)
R(B)	COMMIT
B=B+100	ret(A+B)
W(B)	
UNLOCK(B)	
COMMIT	

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X-LOCK(A)	
R(A)	
	S-LOCK(A)
A=A-100	
W(A)	
UNLOCK(A)	
	R(A)
	UNLOCK(A)
	S-LOCK(B)
	R(B)
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R(B)	COMMIT
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Schedule



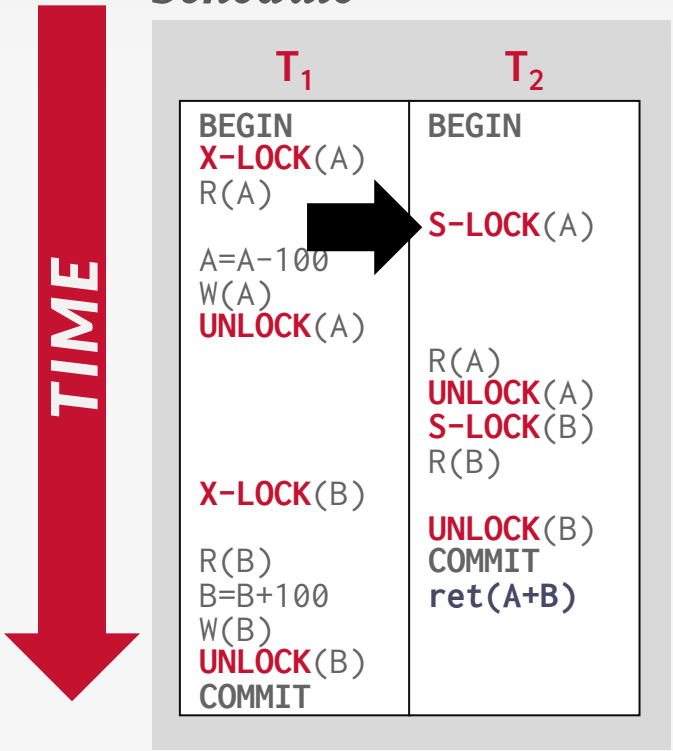
T_1	T_2
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R(A)	
	S-LOCK(A)
A=A-100	
W(A)	
UNLOCK(A)	
	R(A)
	UNLOCK(A)
	S-LOCK(B)
	R(B)
X-LOCK(B)	
	UNLOCK(B)
R(B)	COMMIT
B=B+100	ret(A+B)
W(B)	
UNLOCK(B)	
COMMIT	

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A=1000, B=1000

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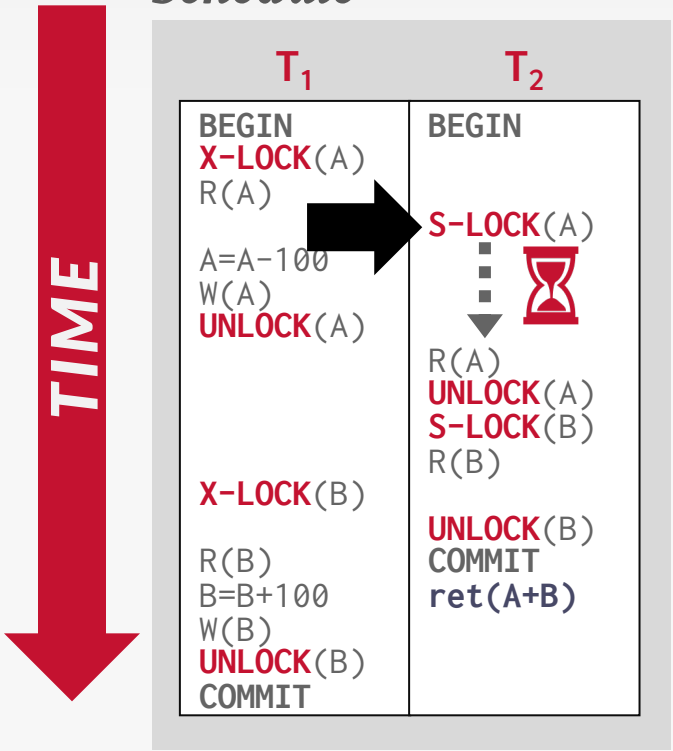


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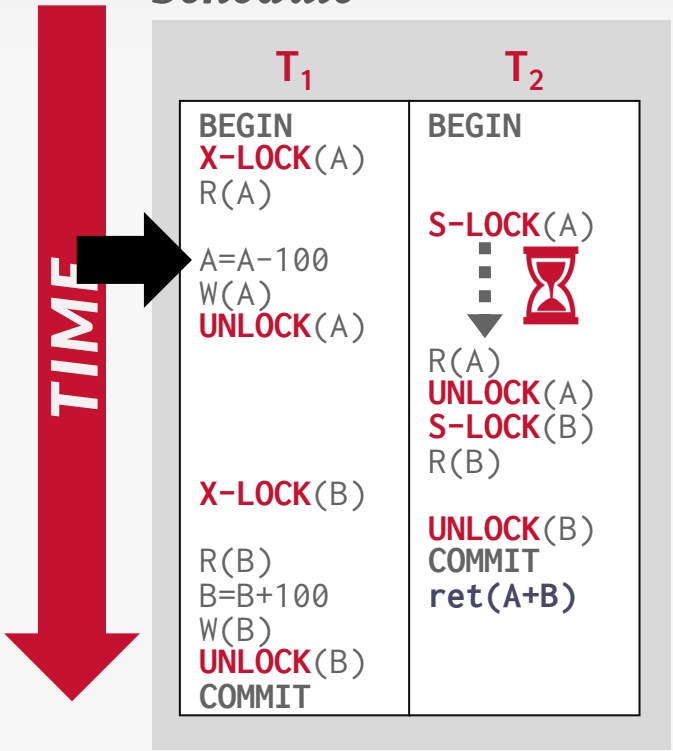


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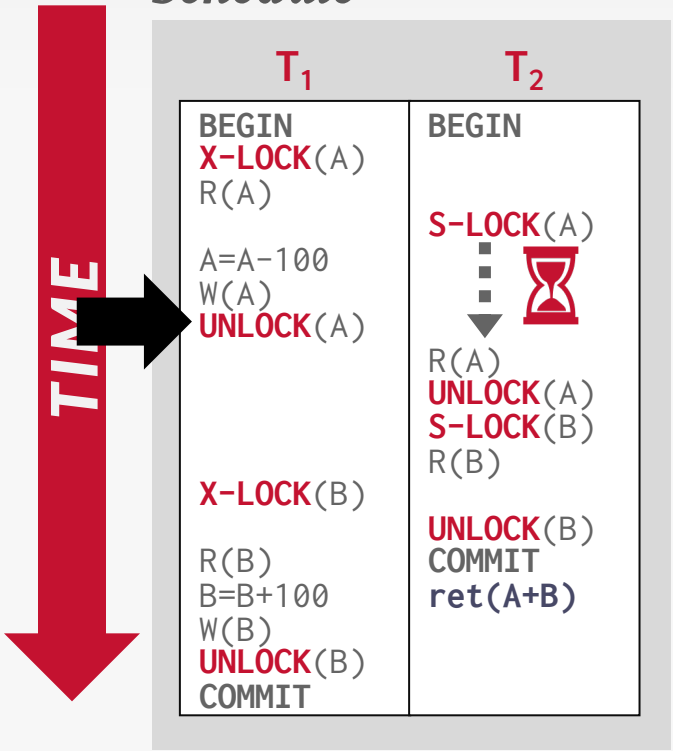


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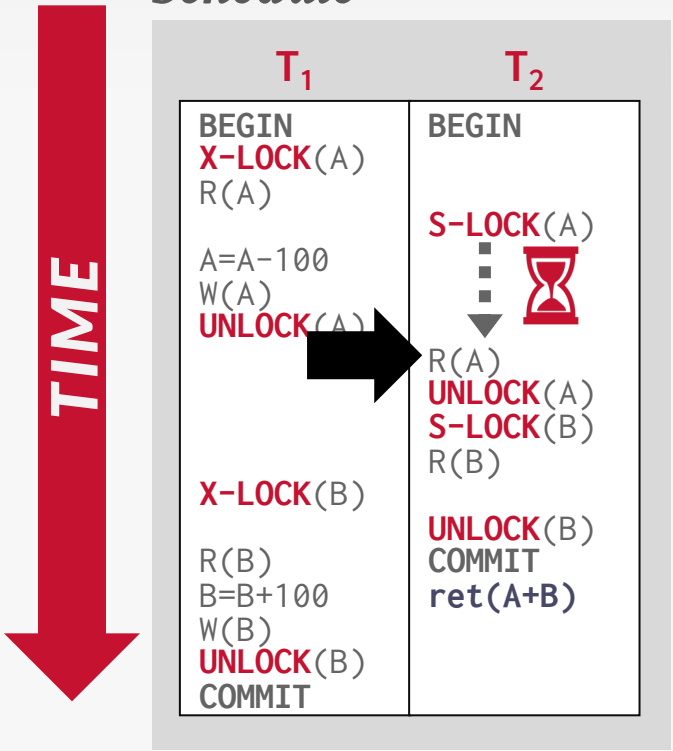


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NON-2PL EXAMPLE

Schedule

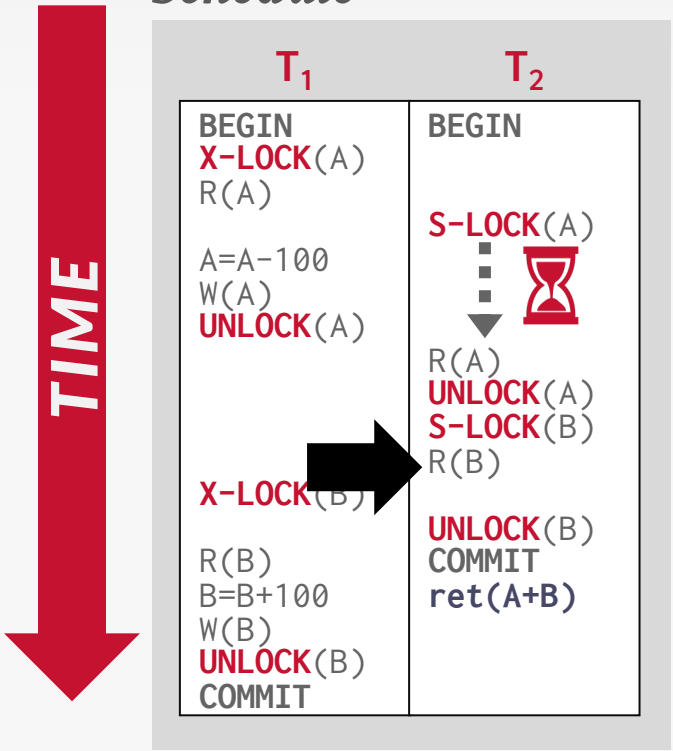


Initial Database State

A=1000, B=1000

NON-2PL EXAMPLE

Schedule

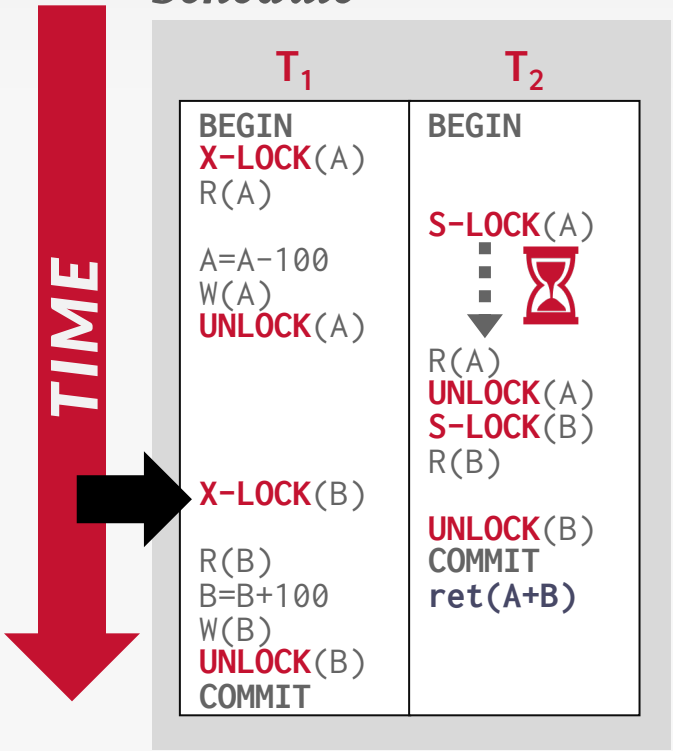


Initial Database State

A=1000, B=1000

NON-2PL EXAMPLE

Schedule

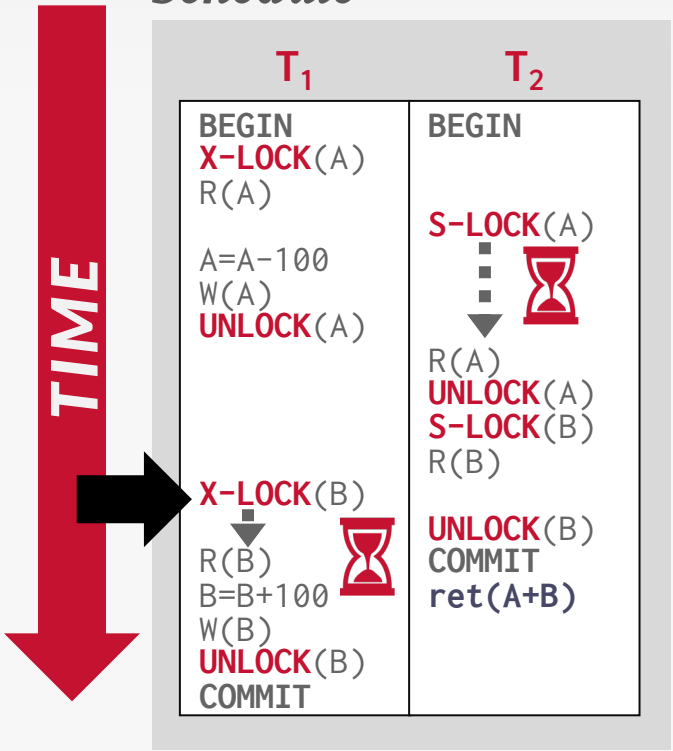


Initial Database State

A=1000, B=1000

NON-2PL EXAMPLE

Schedule

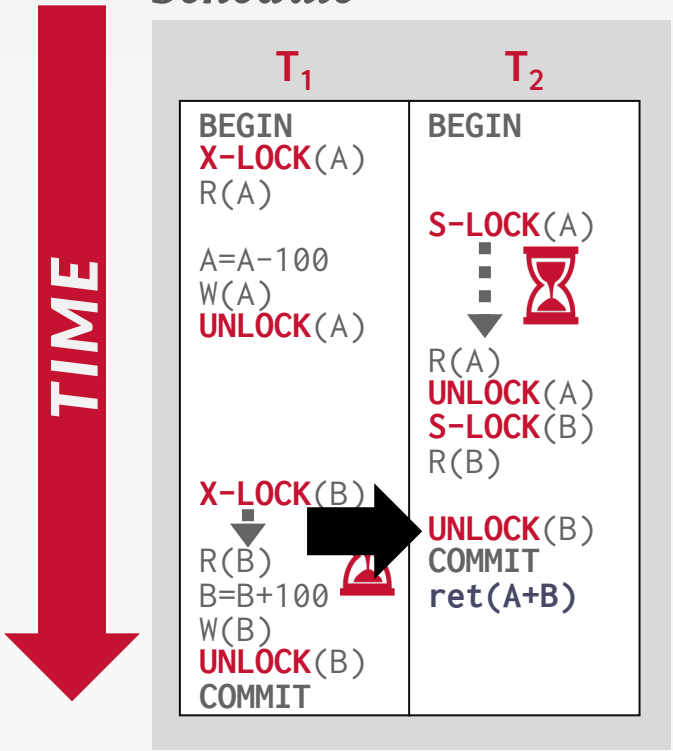


Initial Database State

A=1000, B=1000

NON-2PL EXAMPLE

Schedule

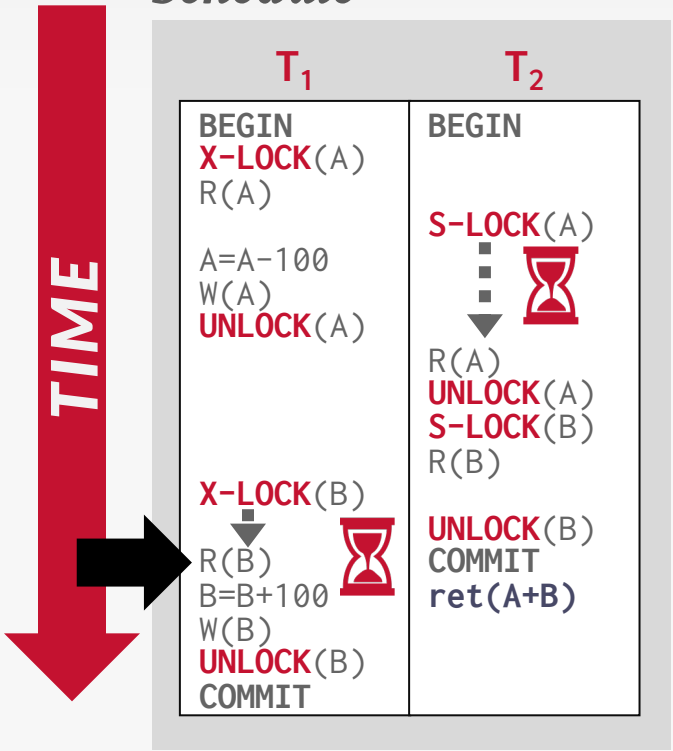


Initial Database State

A=1000, B=1000

NON-2PL EXAMPLE

Schedule

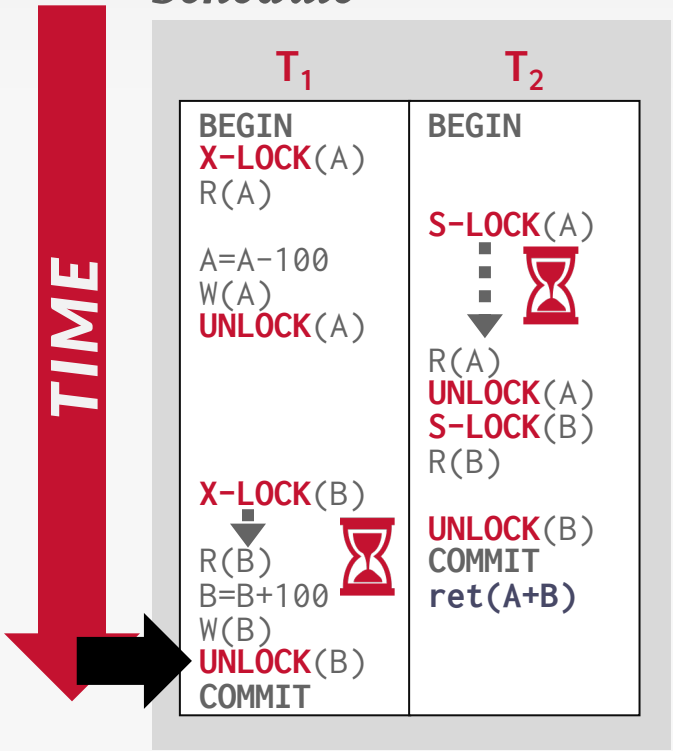


Initial Database State

A=1000, B=1000

NON-2PL EXAMPLE

Schedule

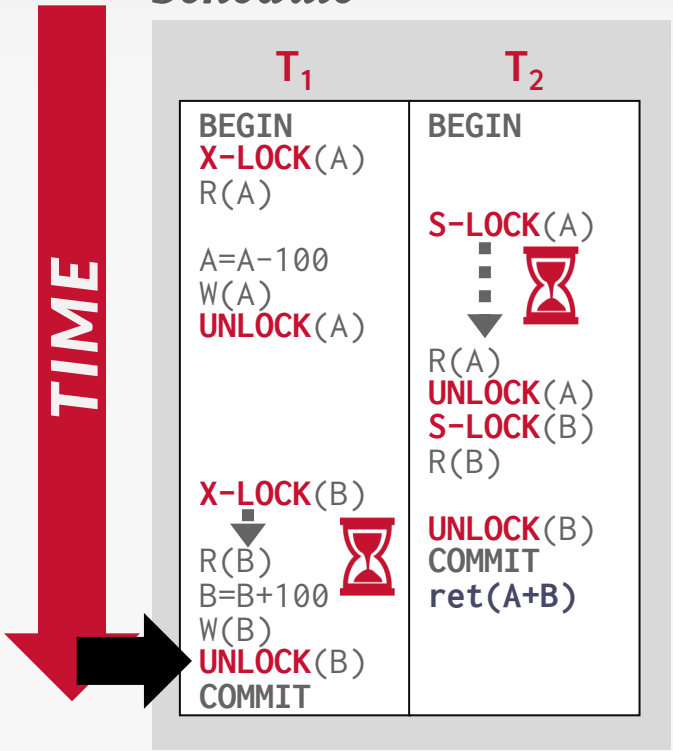


Initial Database State

A=1000, B=1000

NON-2PL EXAMPLE

Schedule



Initial Database State

A=1000, B=1000

T_2 Output

A+B=1900

2PL EXAMPLE



Schedule

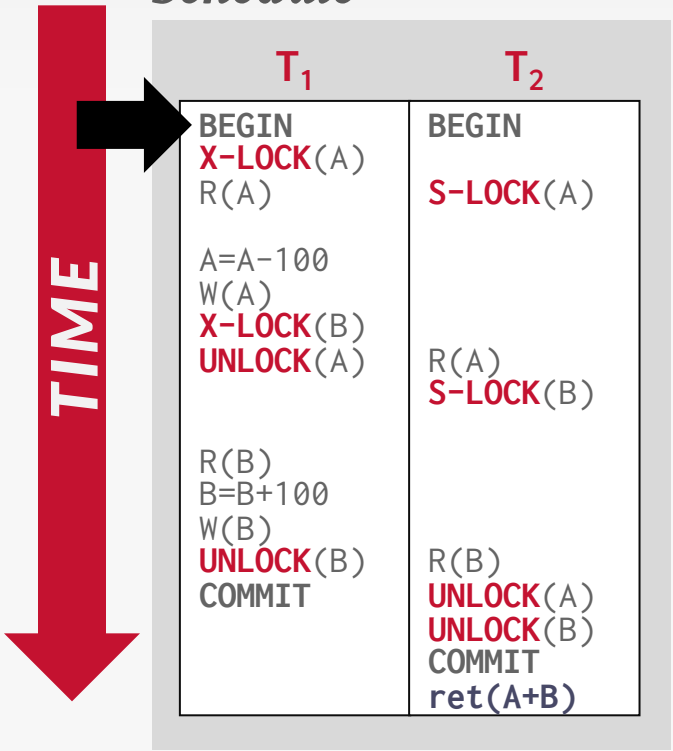
T_1	T_2
BEGIN	BEGIN
X-LOCK(A)	
R(A)	S-LOCK(A)
A=A-100	
W(A)	
X-LOCK(B)	
UNLOCK(A)	R(A)
	S-LOCK(B)
R(B)	
B=B+100	
W(B)	
UNLOCK(B)	R(B)
COMMIT	UNLOCK(A)
	UNLOCK(B)
	COMMIT
	ret(A+B)

Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule



Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule



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)
	COMMIT
	ret(A+B)

Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule



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)
	COMMIT
	ret(A+B)

Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule



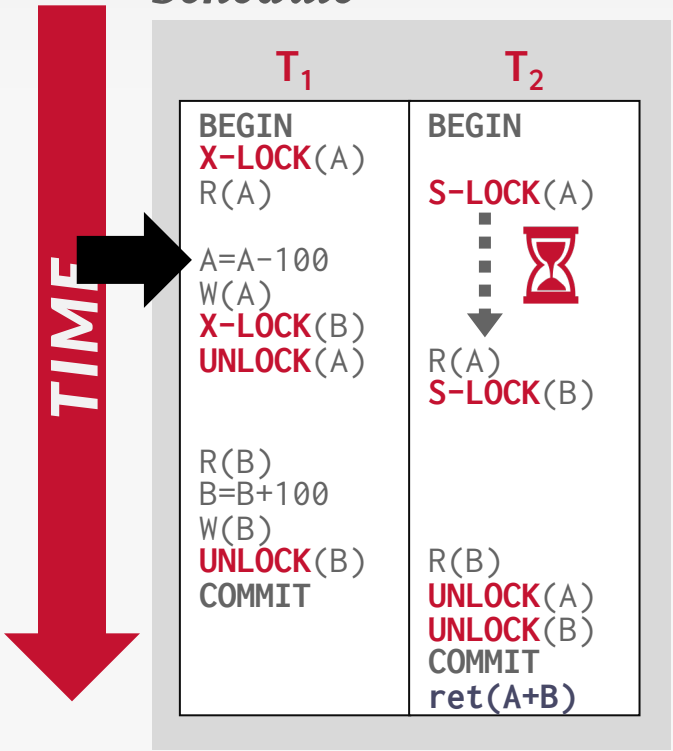
T_1	T_2
BEGIN	BEGIN
X-LOCK(A)	
R(A)	S-LOCK(A)
	⧗
A=A-100	
W(A)	
X-LOCK(B)	
UNLOCK(A)	R(A)
	S-LOCK(B)
R(B)	
B=B+100	
W(B)	
UNLOCK(B)	R(B)
COMMIT	UNLOCK(A)
	UNLOCK(B)
	COMMIT
	ret(A+B)

Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule

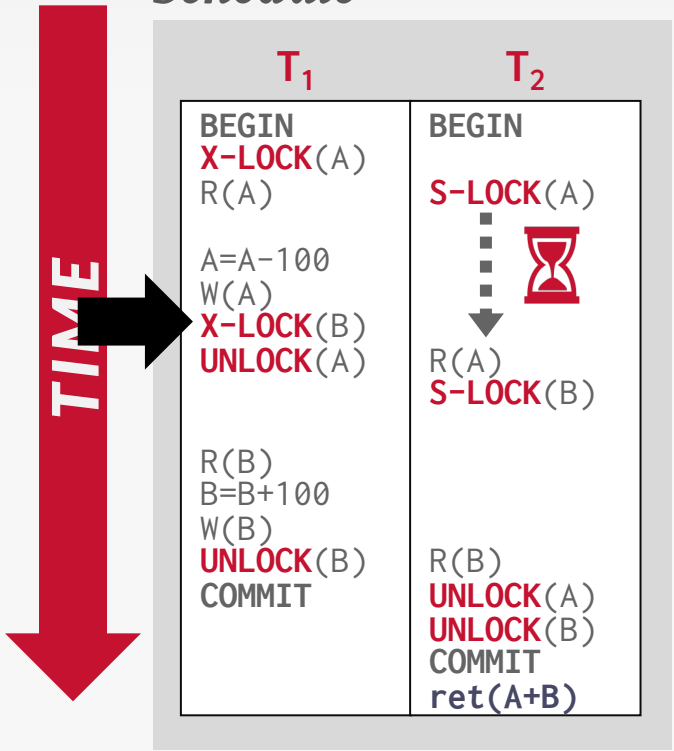


Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule

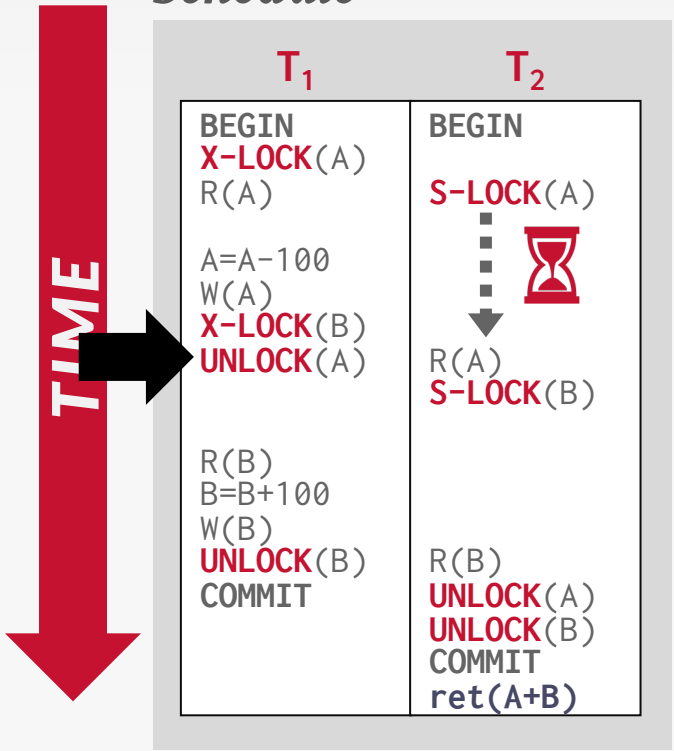


Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule

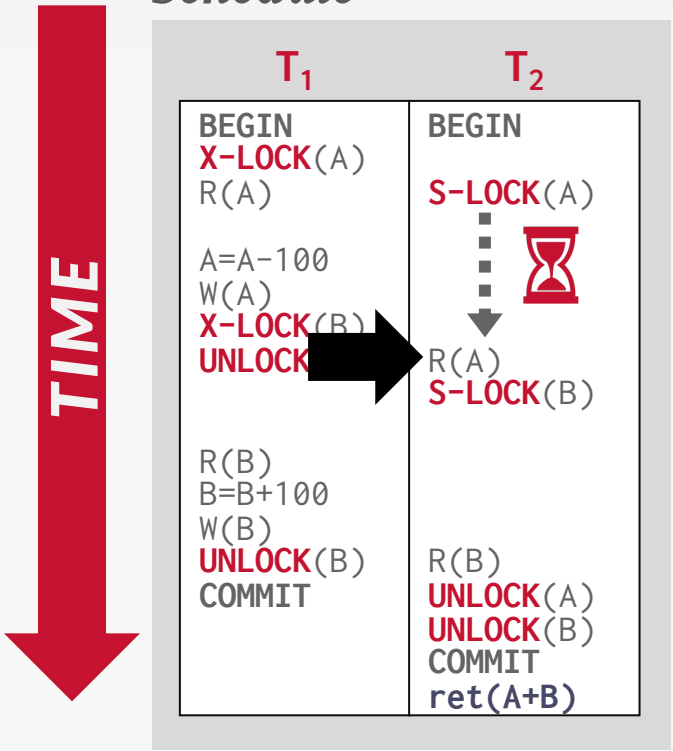


Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule

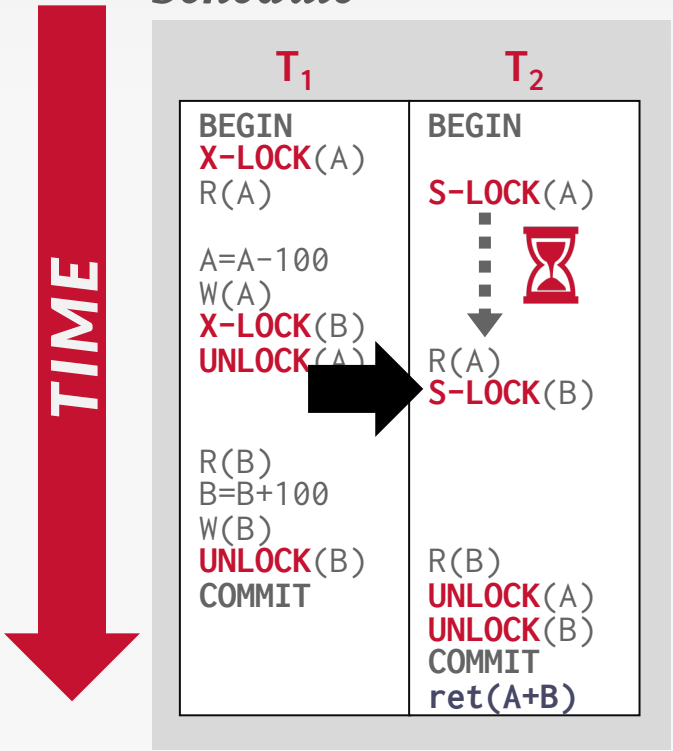


Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule

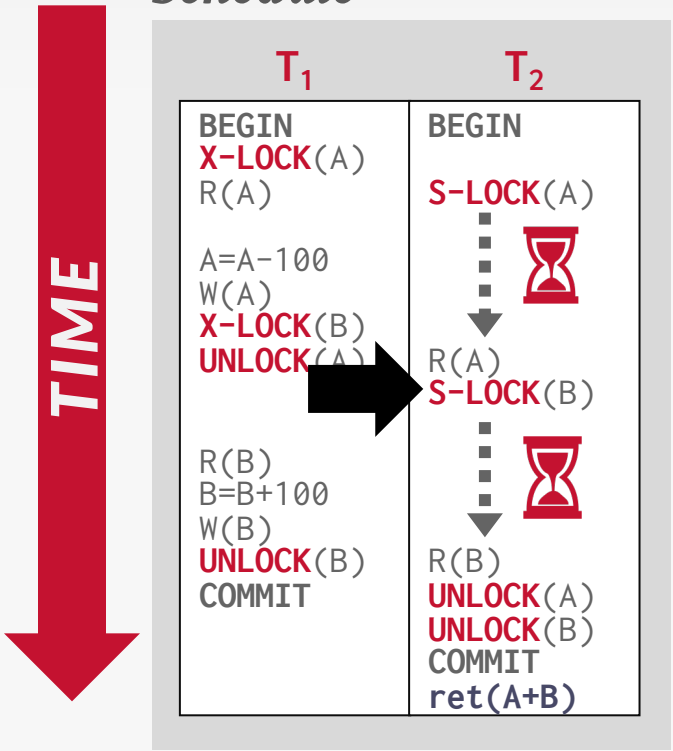


Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule

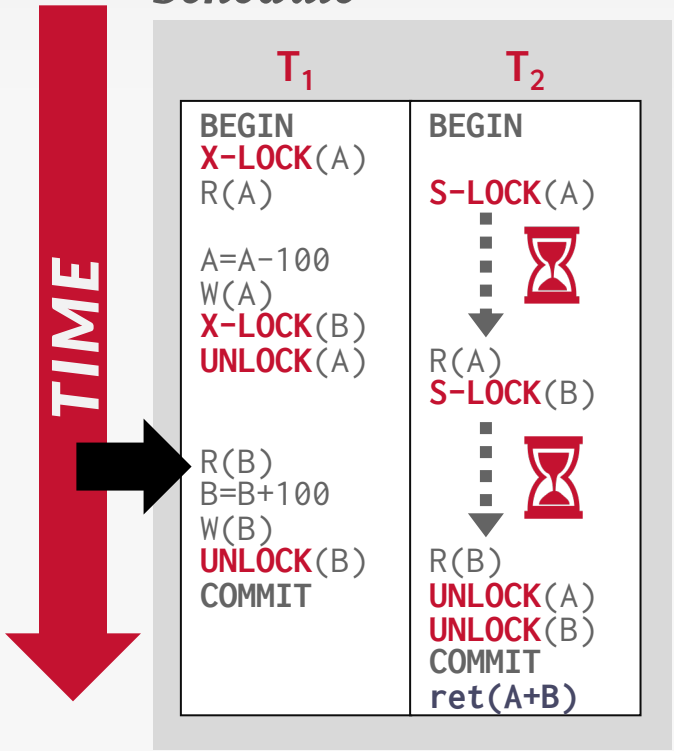


Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule

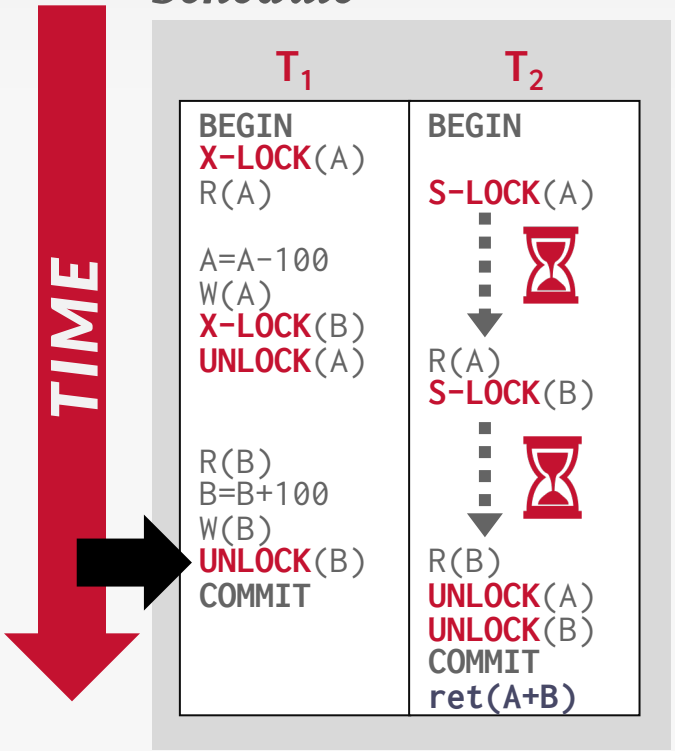


Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule

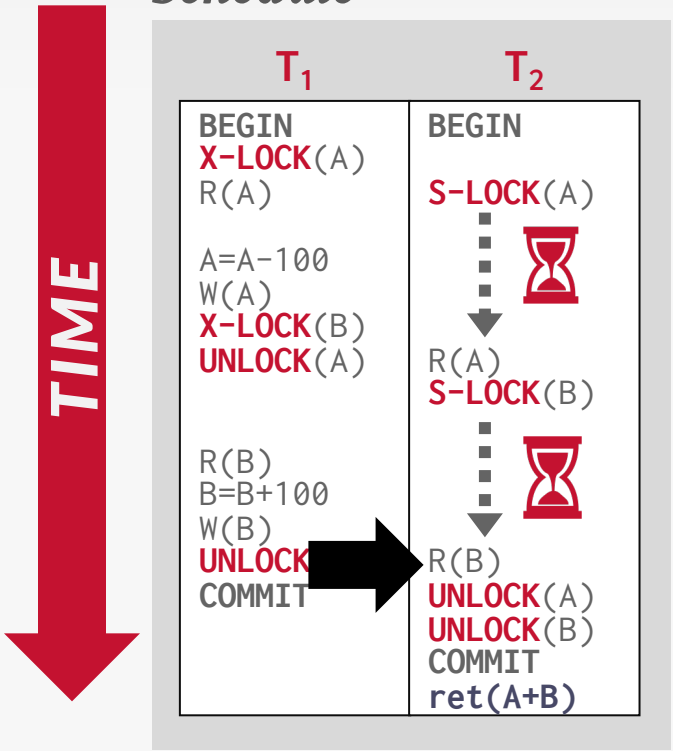


Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule

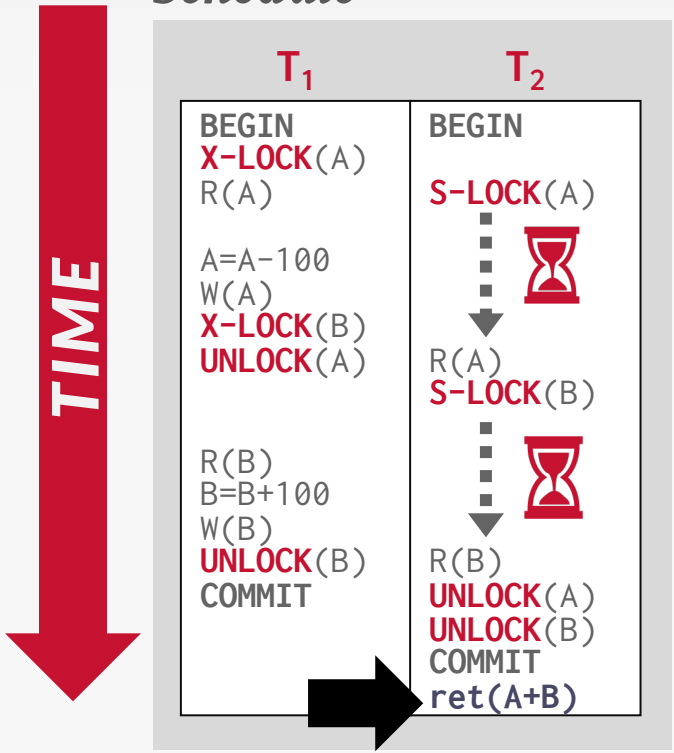


Initial Database State

A=1000, B=1000

2PL EXAMPLE

Schedule



Initial Database State

A=1000, B=1000

T_2 Output

A+B=2000

STRONG STRICT 2PL EXAMPLE

Schedule



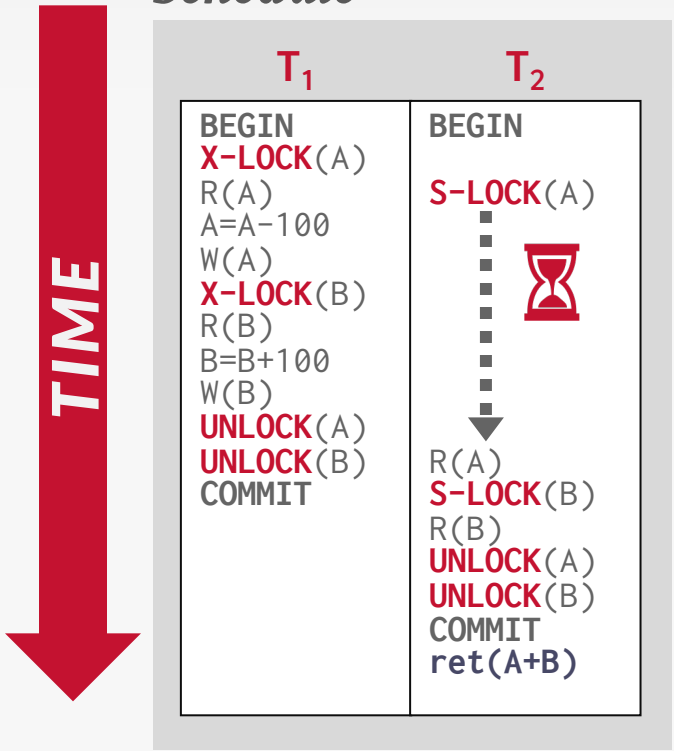
T_1	T_2
BEGIN	BEGIN
X-LOCK(A)	
R(A)	S-LOCK(A)
A=A-100	
W(A)	
X-LOCK(B)	
R(B)	
B=B+100	
W(B)	
UNLOCK(A)	
UNLOCK(B)	R(A)
COMMIT	S-LOCK(B)
	R(B)
	UNLOCK(A)
	UNLOCK(B)
	COMMIT
	ret(A+B)

Initial Database State

A=1000, B=1000

STRONG STRICT 2PL EXAMPLE

Schedule

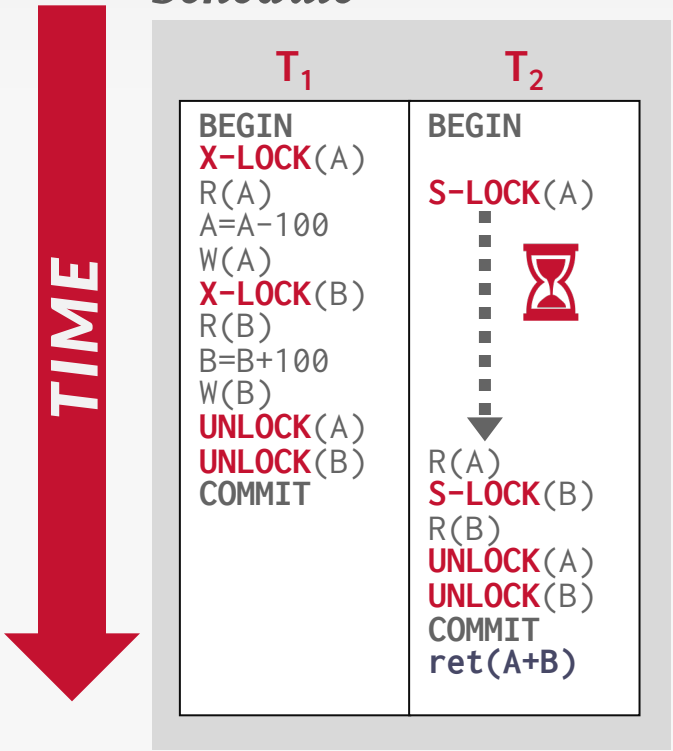


Initial Database State

A=1000, B=1000

STRONG STRICT 2PL EXAMPLE

Schedule



Initial Database State

A=1000, B=1000

T_2 Output

A+B=2000

UNIVERSE OF SCHEDULES

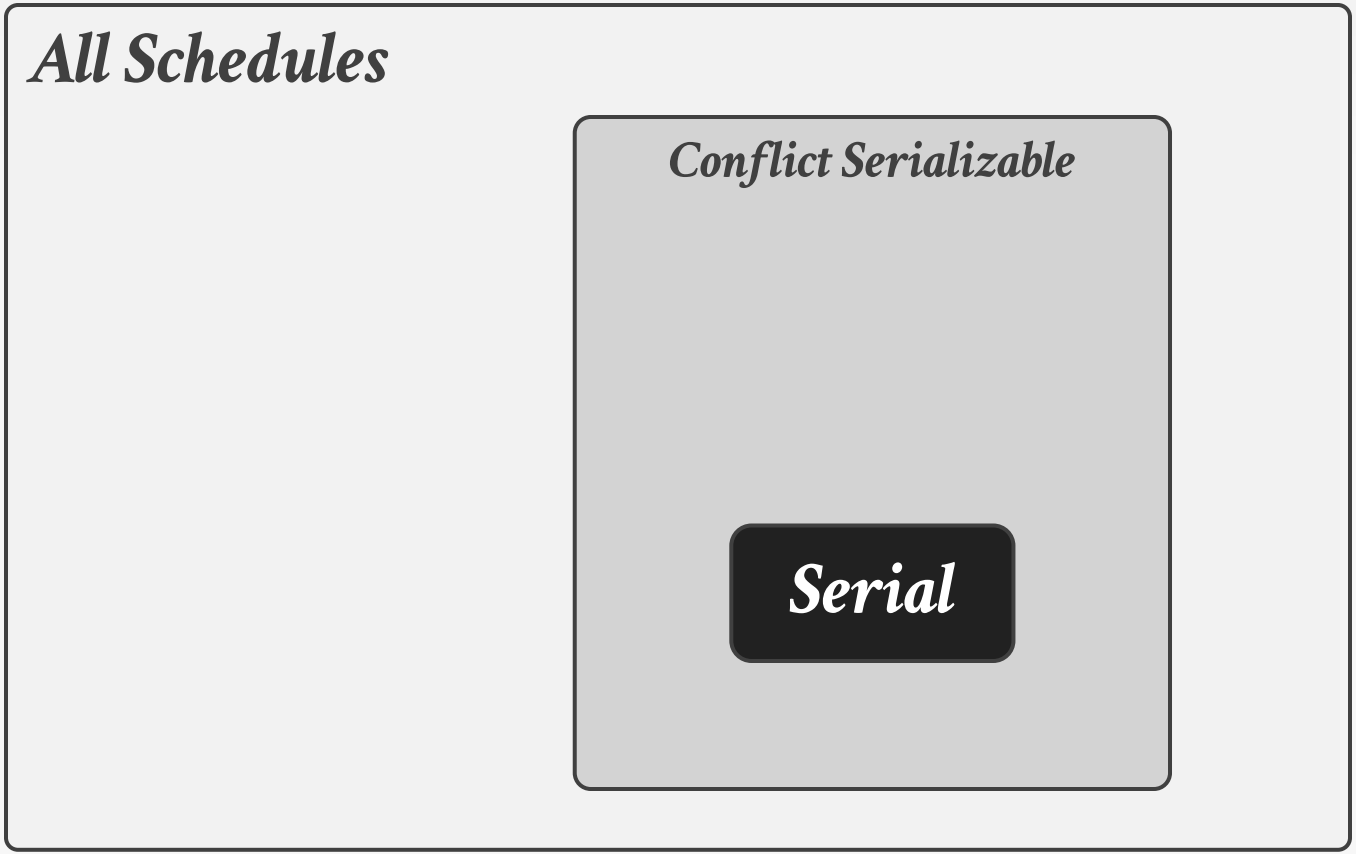
All Schedules

UNIVERSE OF SCHEDULES

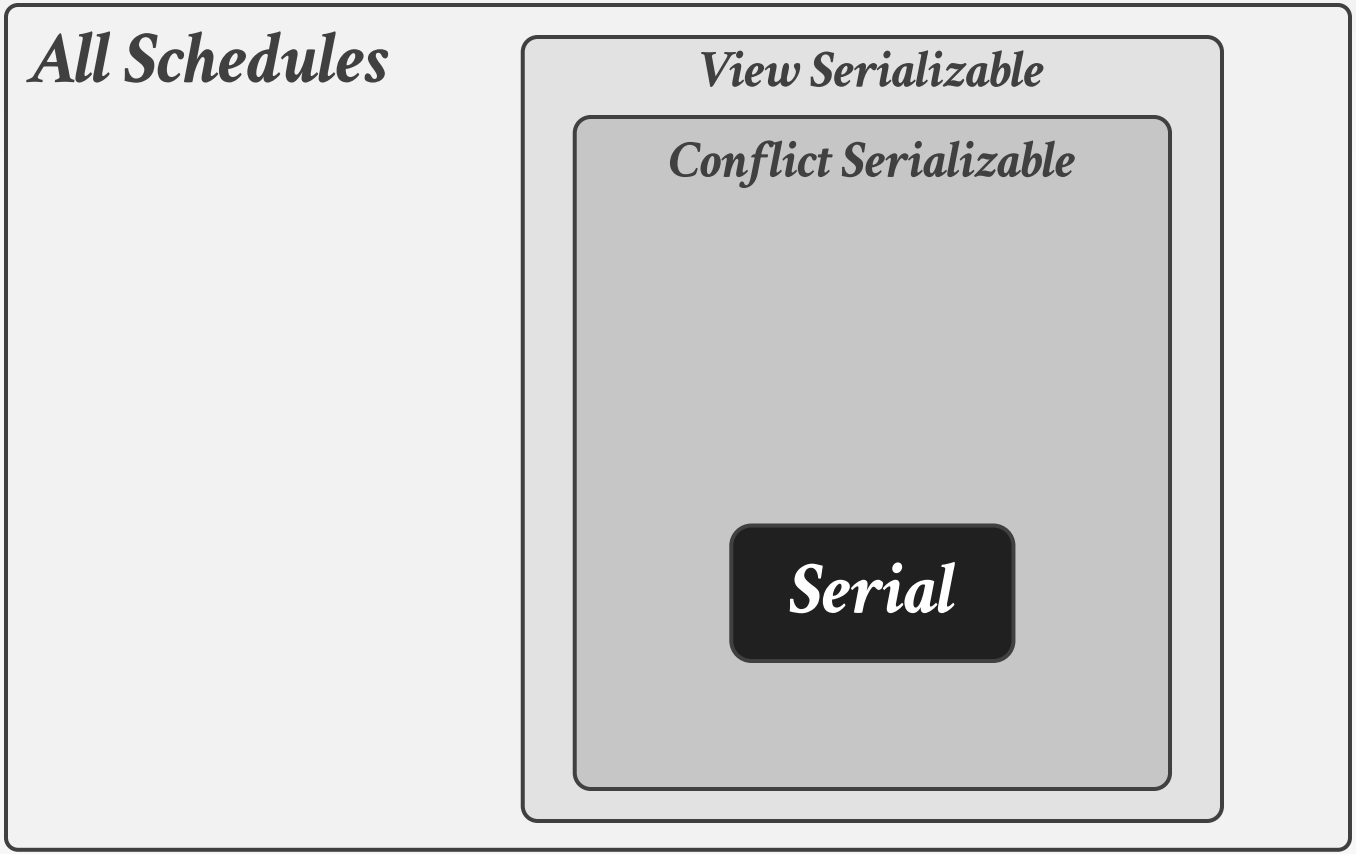
All Schedules

Serial

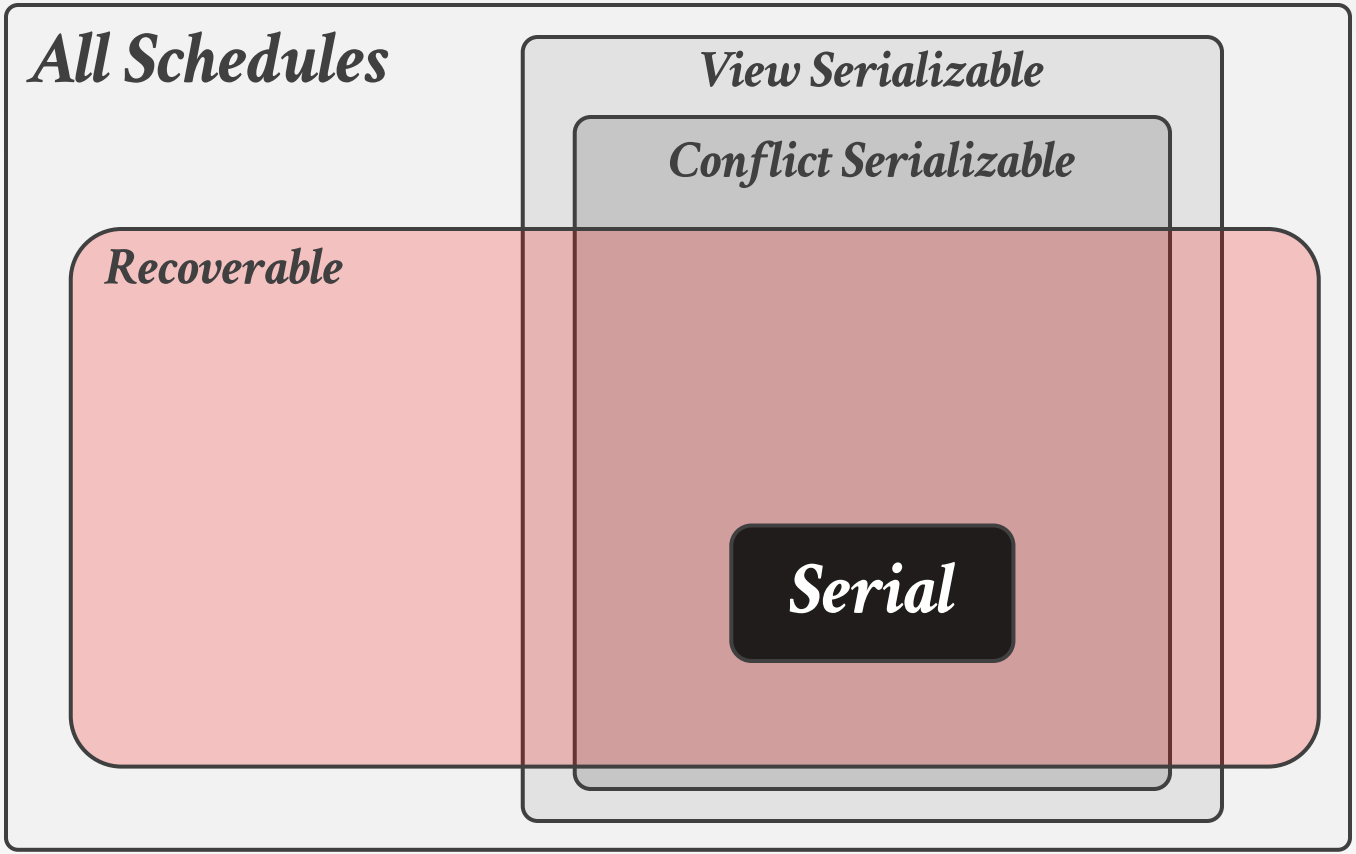
UNIVERSE OF SCHEDULES



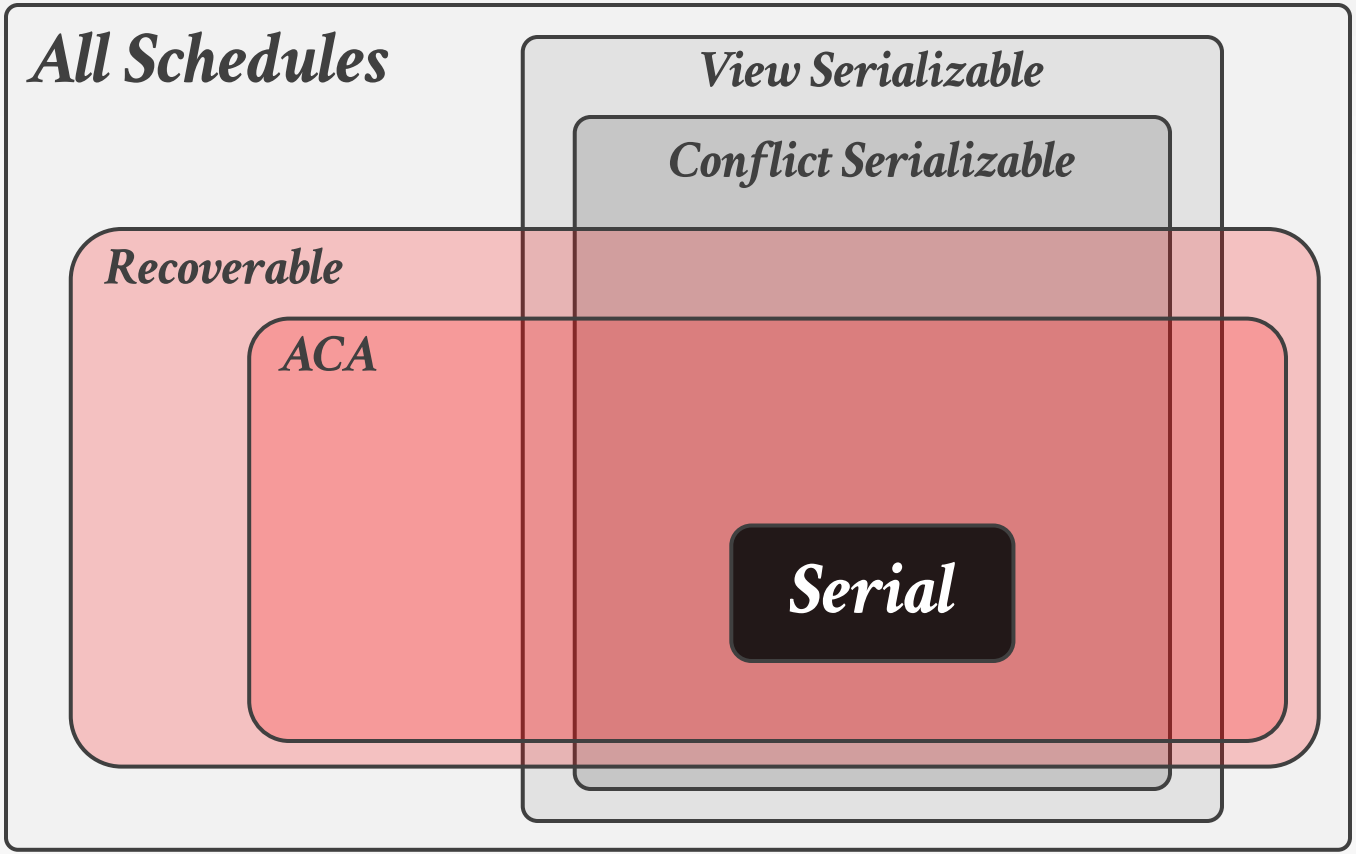
UNIVERSE OF SCHEDULES



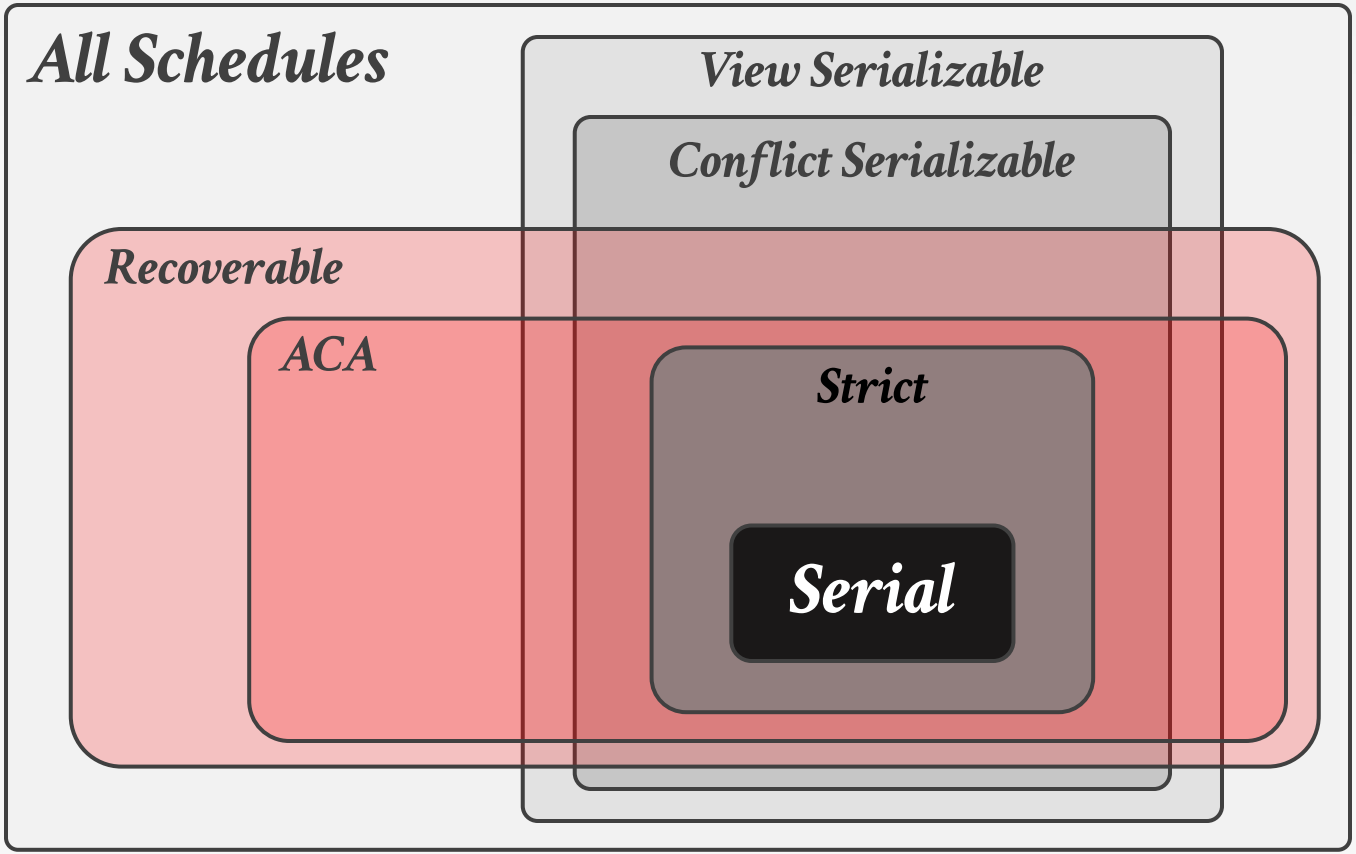
UNIVERSE OF SCHEDULES



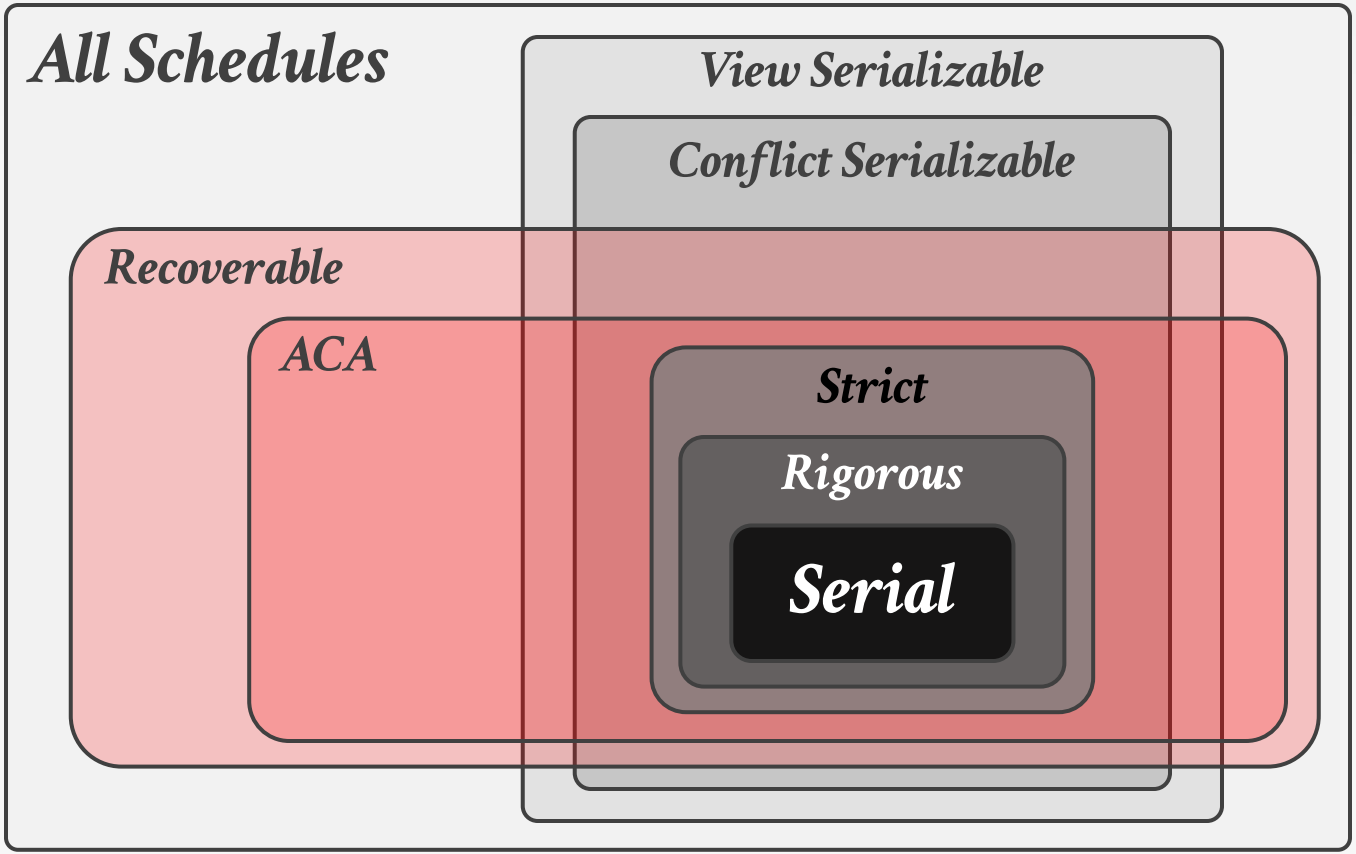
UNIVERSE OF SCHEDULES



UNIVERSE OF SCHEDULES



UNIVERSE OF SCHEDULES



OBSERVATION

2PL guarantees conflict serializability because it generates schedules with acyclic precedence graphs.

→ There are schedules that are serializable but 2PL does not allow because its locking limits concurrency.

2PL schedules can have "dirty reads".

→ Solution: **2PL Variants**

2PL schedules can have deadlocks.

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

OBSERVATION

2PL guarantees conflict serializability because it generates schedules with acyclic precedence graphs.

→ There are schedules that are serializable but 2PL does not allow because its locking limits concurrency.

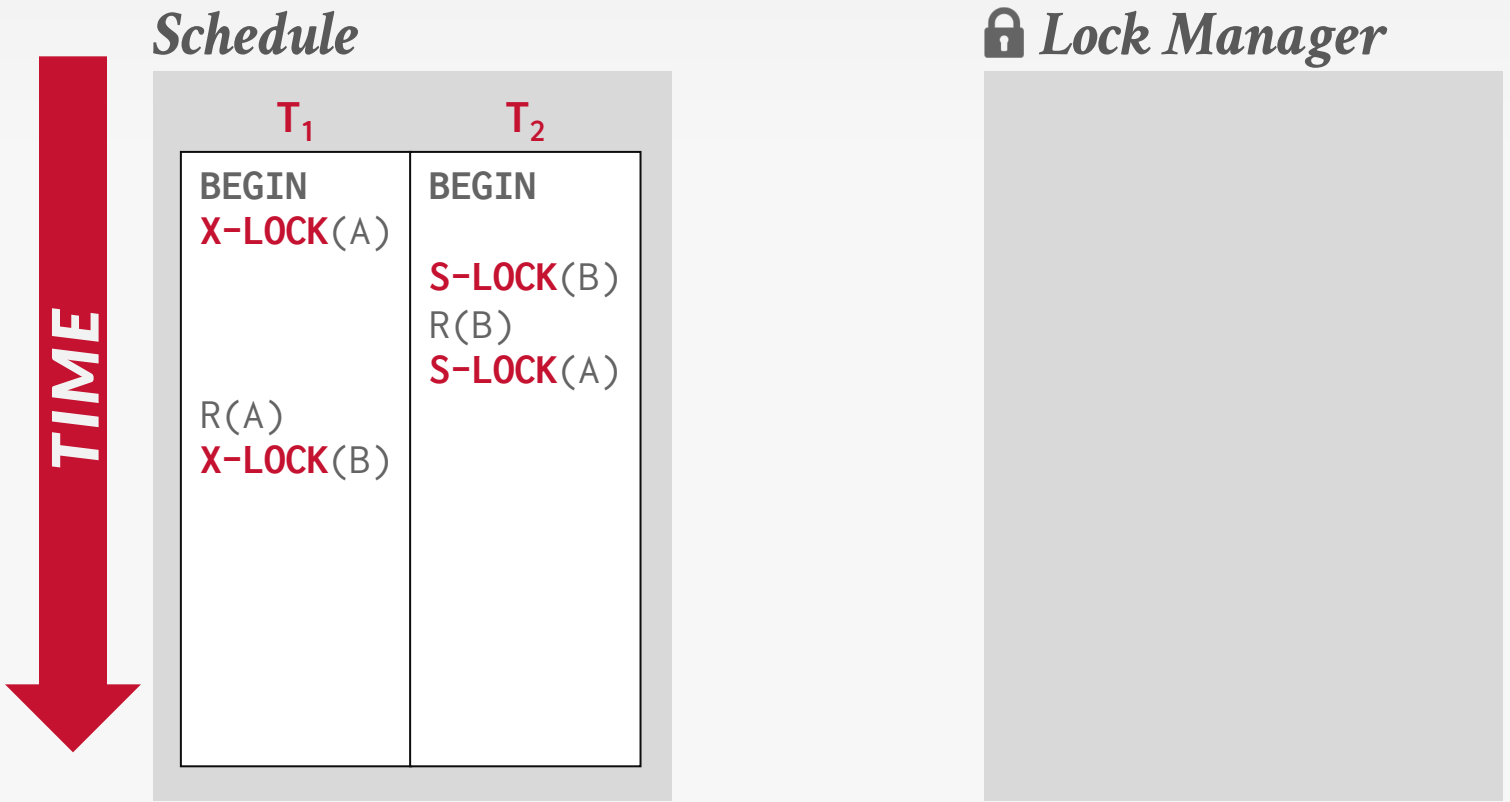
2PL schedules can have "dirty reads".

→ Solution: **2PL Variants**

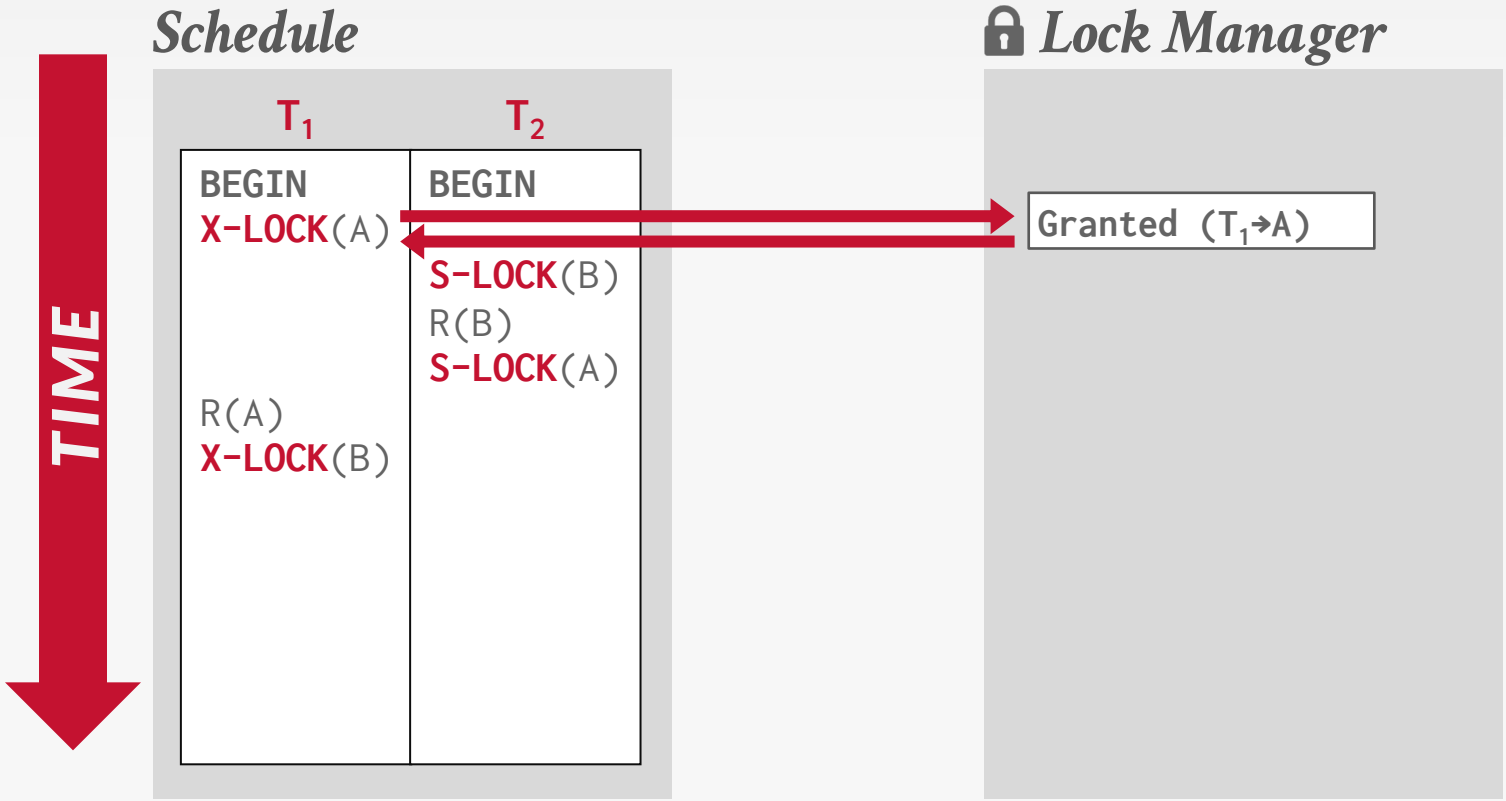
2PL schedules can have deadlocks.

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

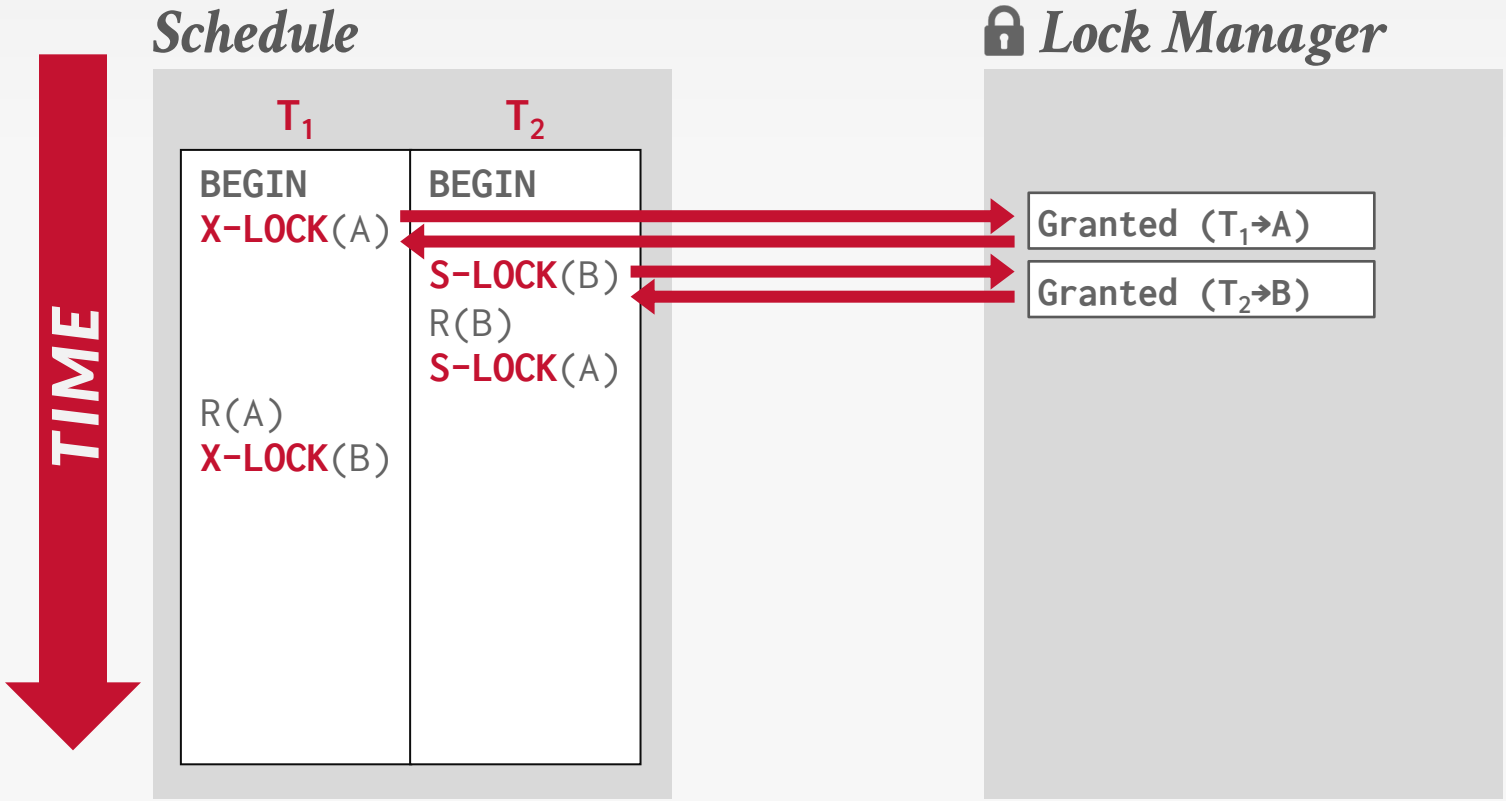
IT JUST GOT REAL



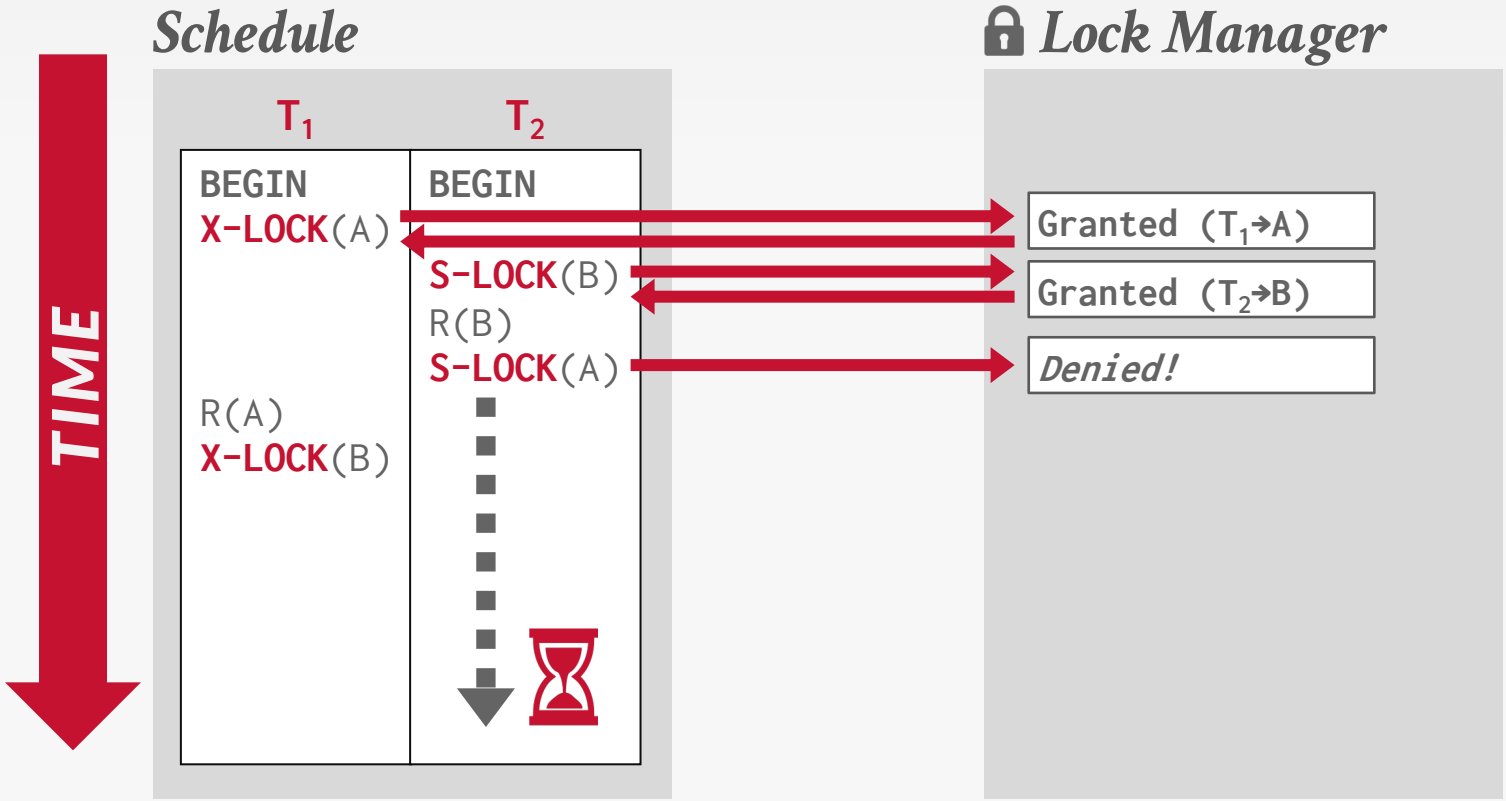
IT JUST GOT REAL



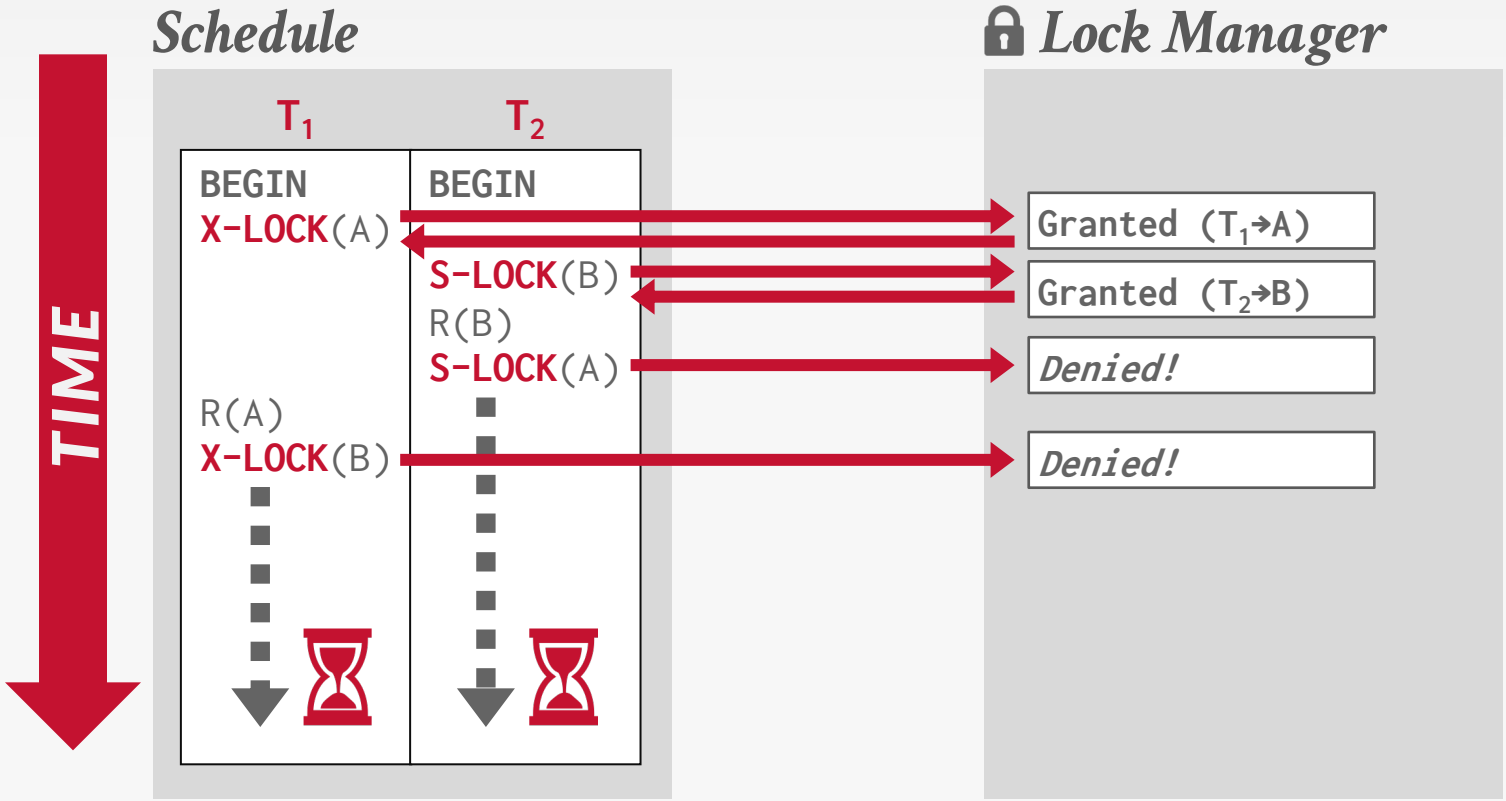
IT JUST GOT REAL



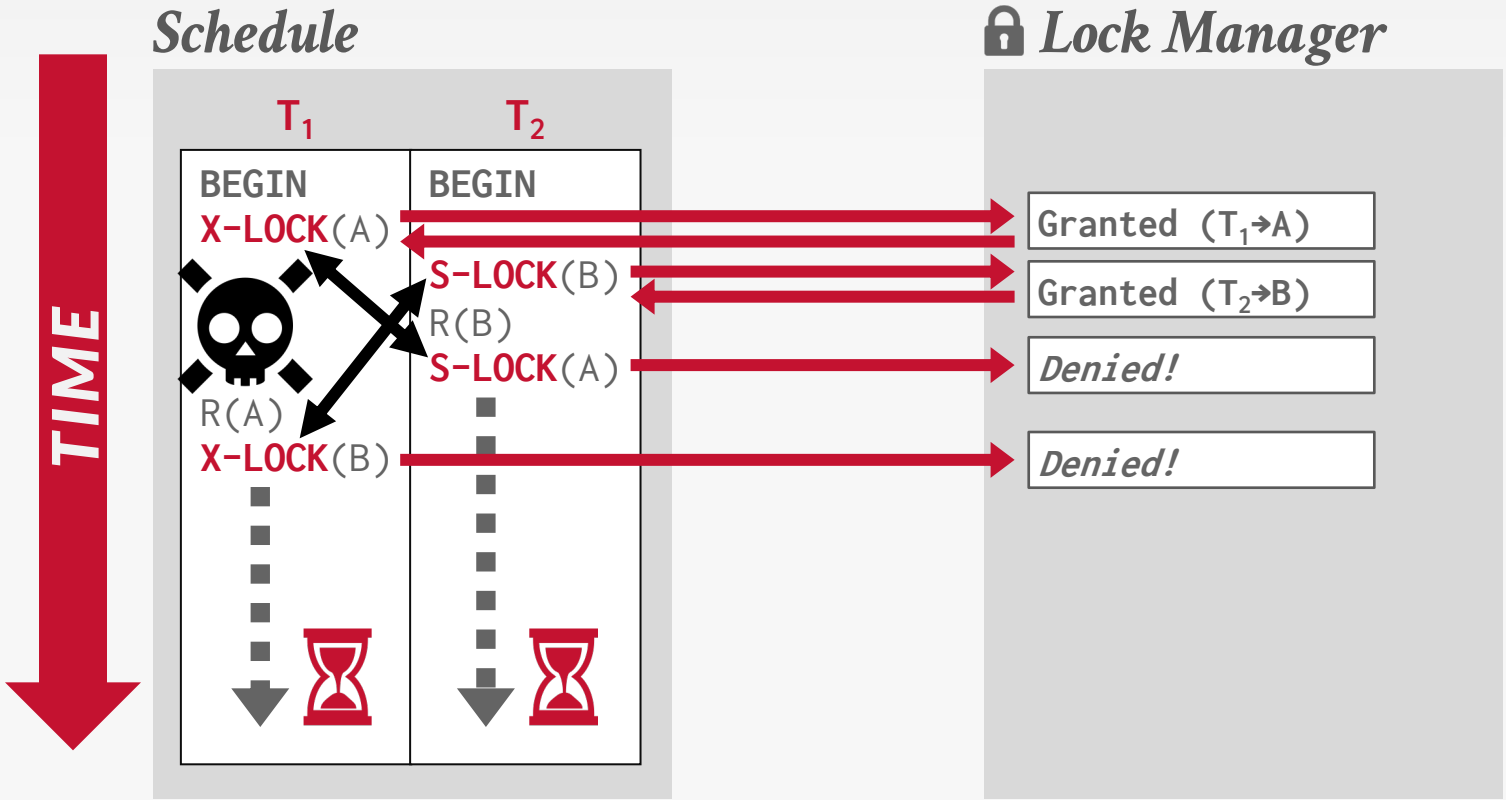
IT JUST GOT REAL



IT JUST GOT REAL



IT JUST GOT REAL



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.

→ Trade-off between breaking deadlocks fast versus spending resources looking for them.

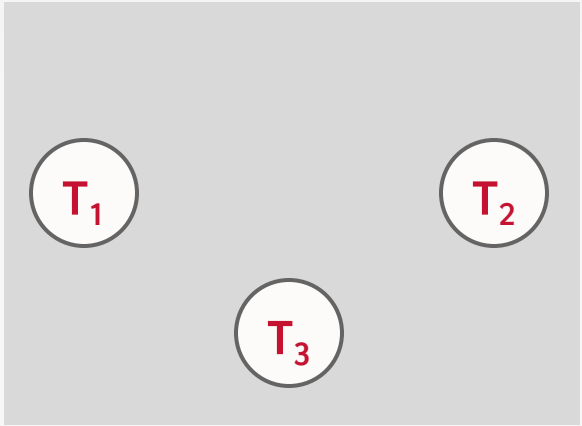
DEADLOCK DETECTION

Schedule

TIME

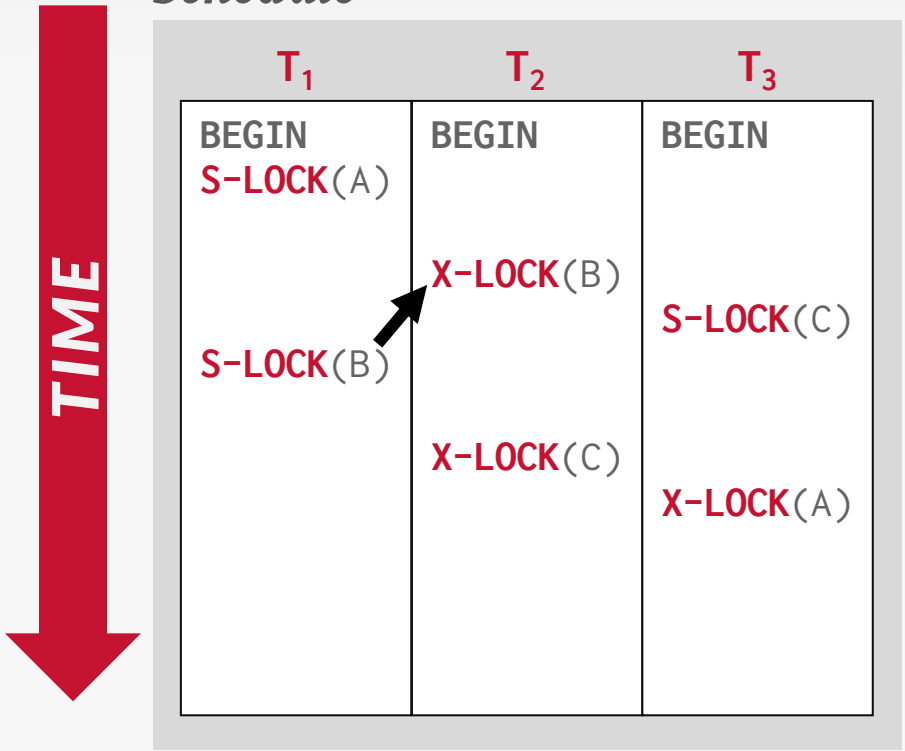
T_1	T_2	T_3
BEGIN	BEGIN	BEGIN
S-LOCK(A)		
	X-LOCK(B)	
		S-LOCK(C)
S-LOCK(B)		
	X-LOCK(C)	
		X-LOCK(A)

Waits-For Graph

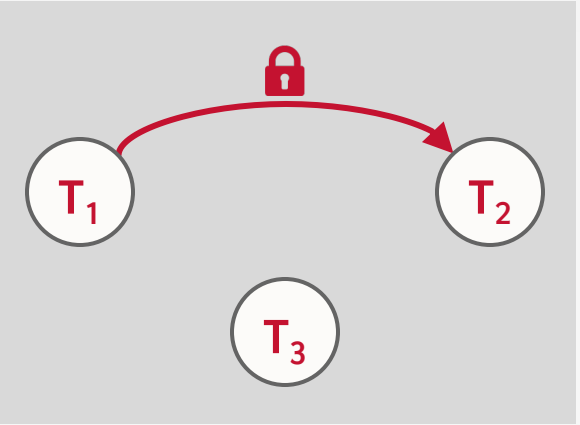


DEADLOCK DETECTION

Schedule

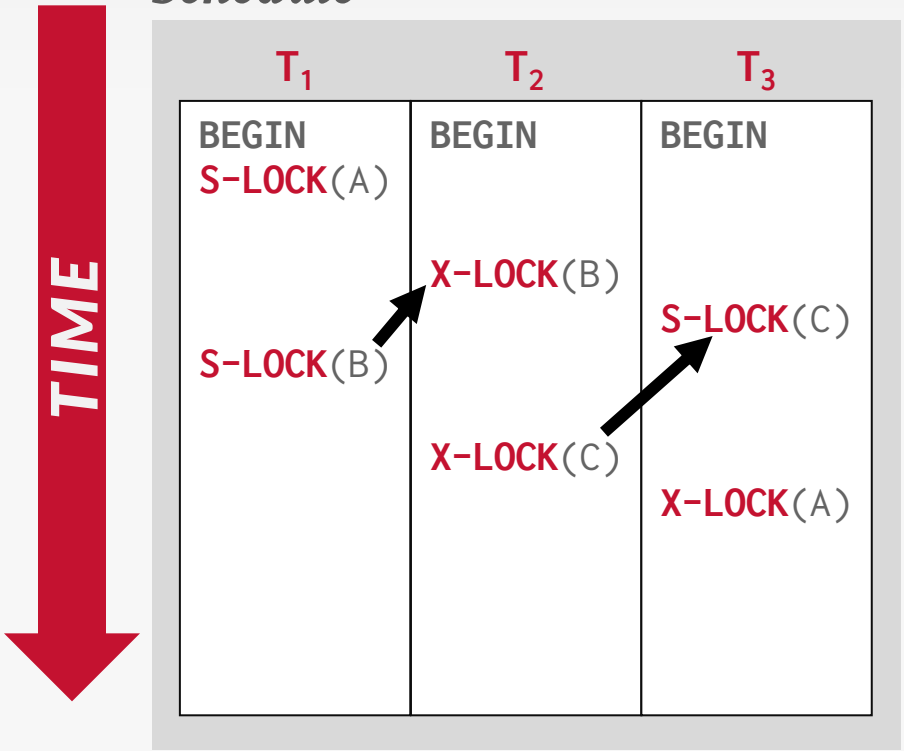


Waits-For Graph

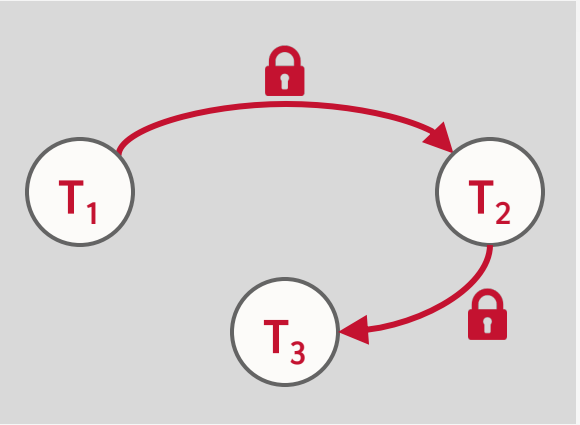


DEADLOCK DETECTION

Schedule

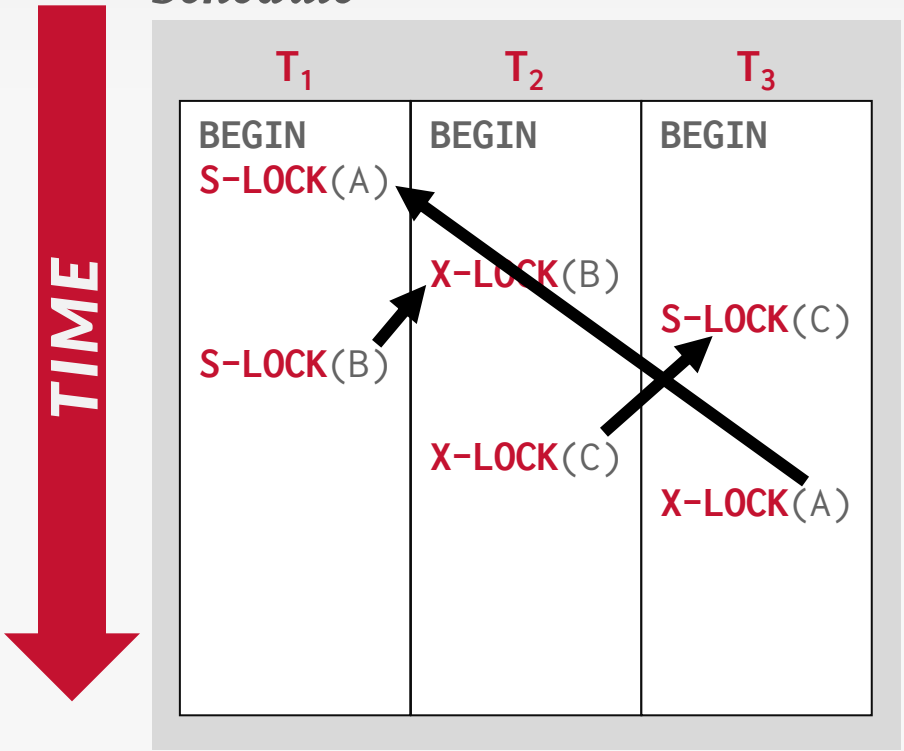


Waits-For Graph

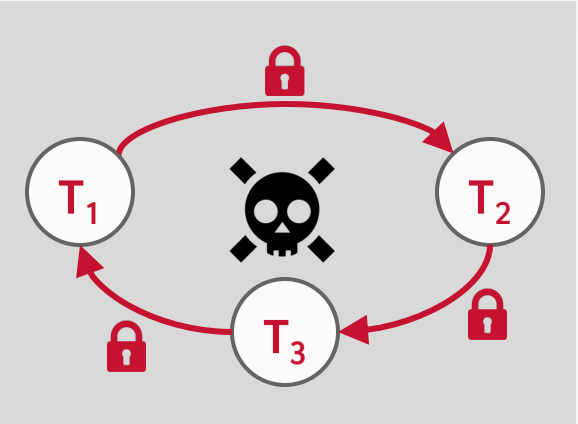


DEADLOCK DETECTION

Schedule



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 each txn a timestamp when they start and use them to determine priorities.

→ For example, 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*.

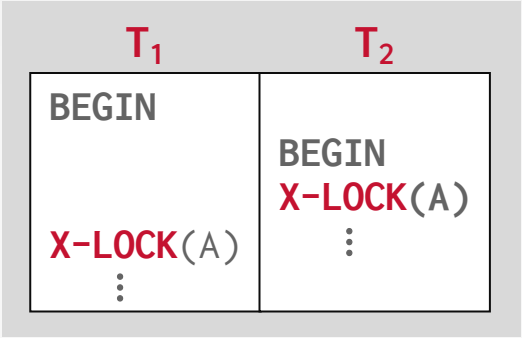
→ Otherwise *requesting txn* aborts.

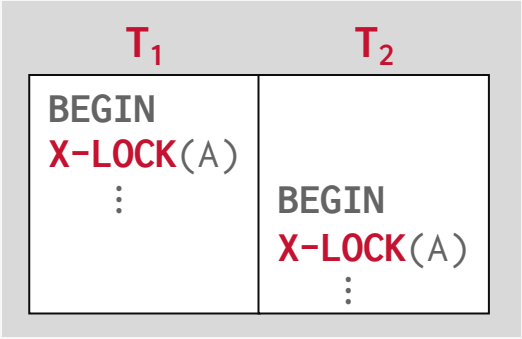
Wound-Wait ("Young Waits for Old")

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

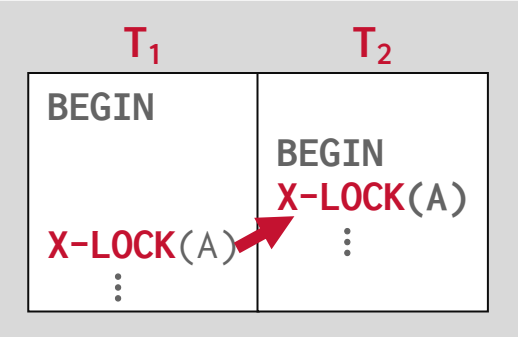
→ Otherwise *requesting txn* waits.

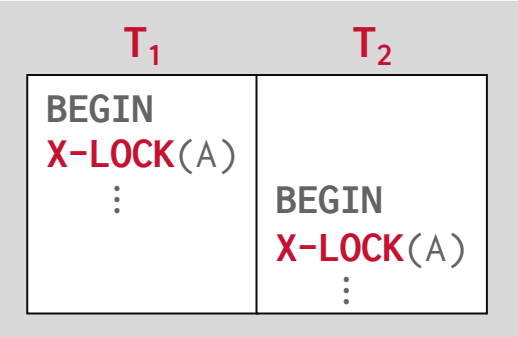
DEADLOCK PREVENTION



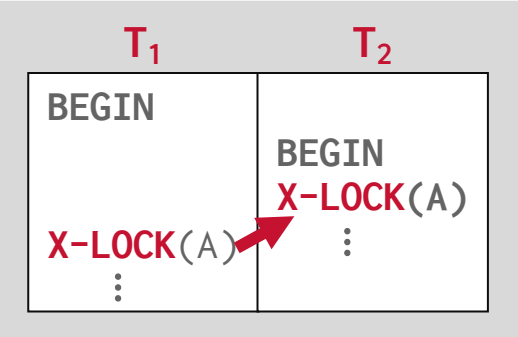


DEADLOCK PREVENTION





DEADLOCK PREVENTION



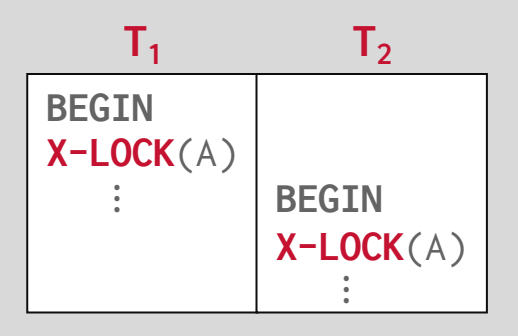


Wait-Die

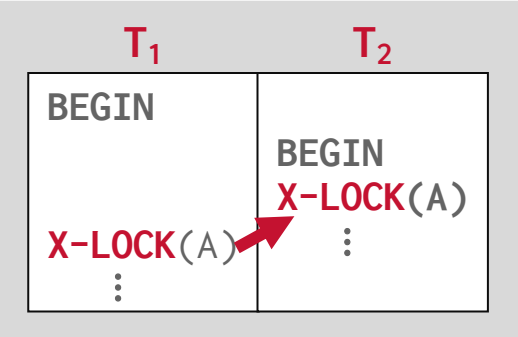
T_1 waits

Wound-Wait

T_2 aborts



DEADLOCK PREVENTION



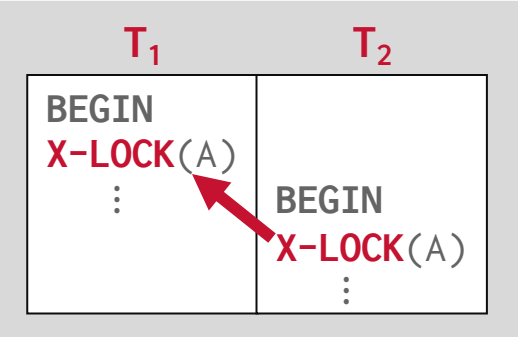


Wait-Die

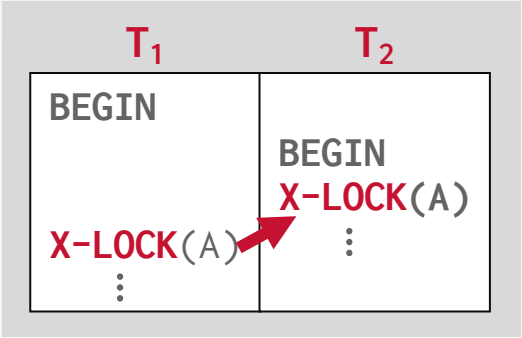
T_1 waits

Wound-Wait

T_2 aborts



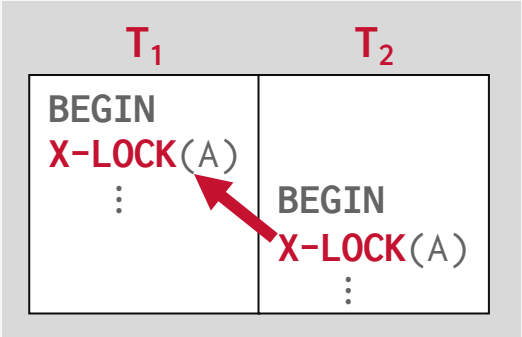
DEADLOCK PREVENTION





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?

Txns only wait for locks in one direction.

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

Its original timestamp to prevent it from getting starved for resources.

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.

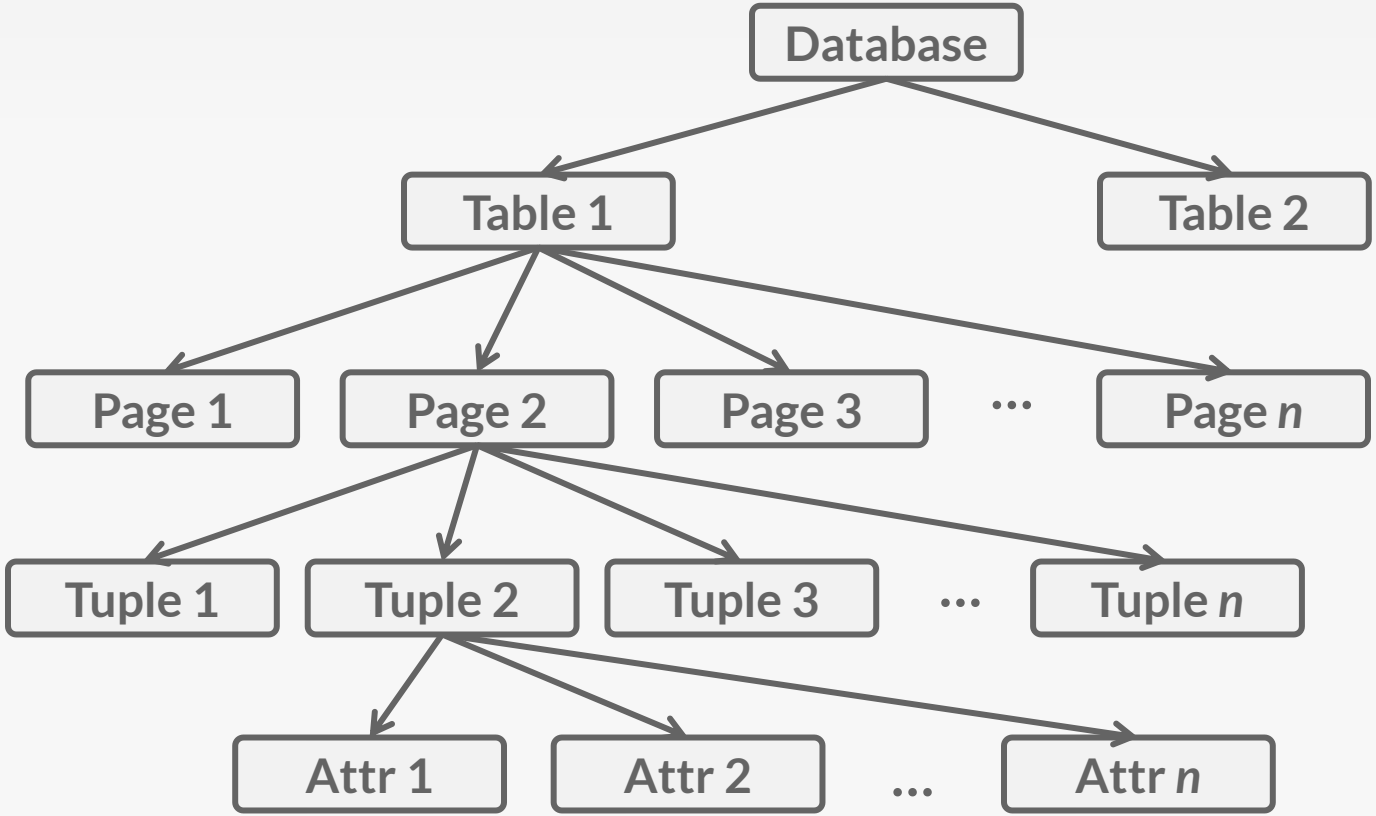
LOCK GRANULARITIES

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

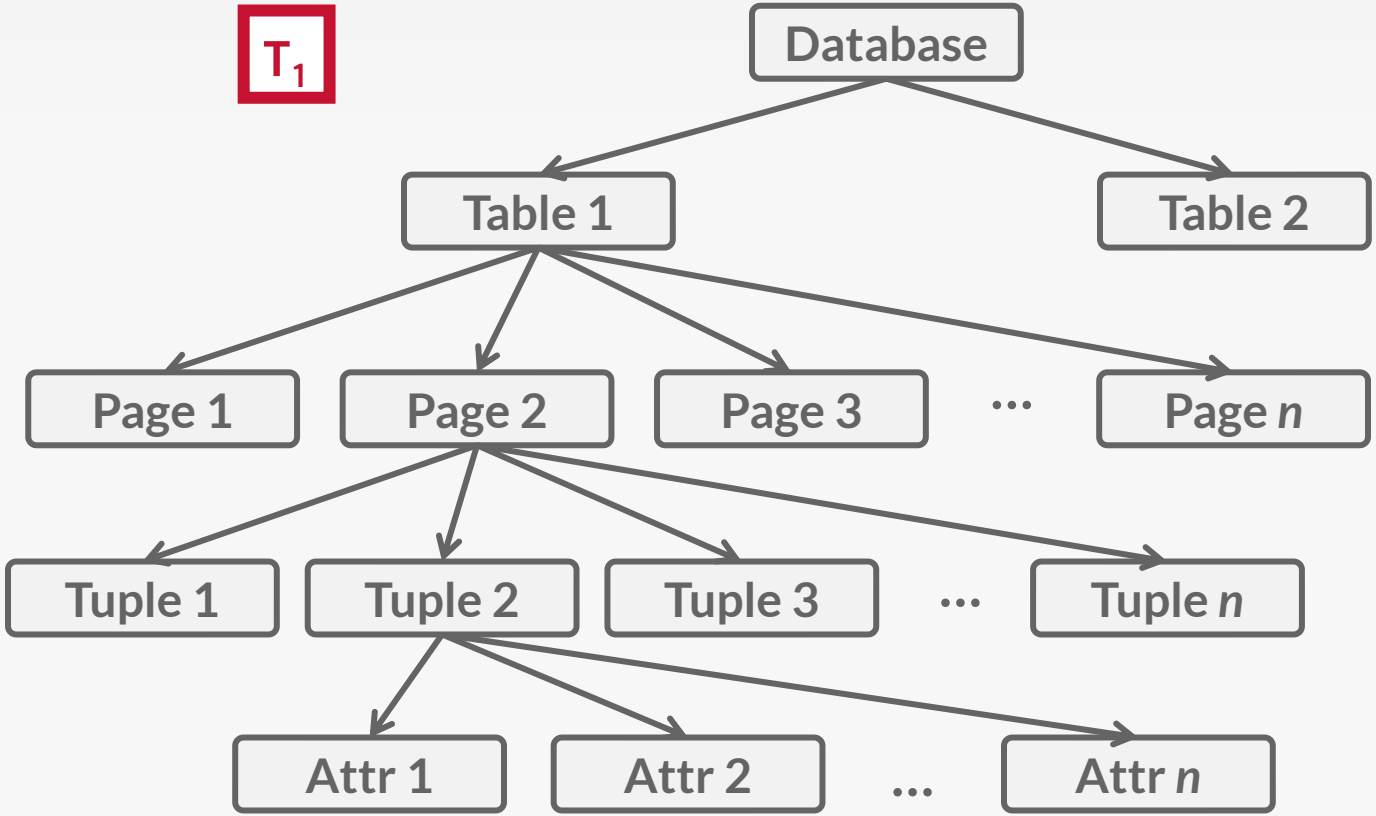
The DBMS should ideally obtain fewest number of locks that a txn needs.

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

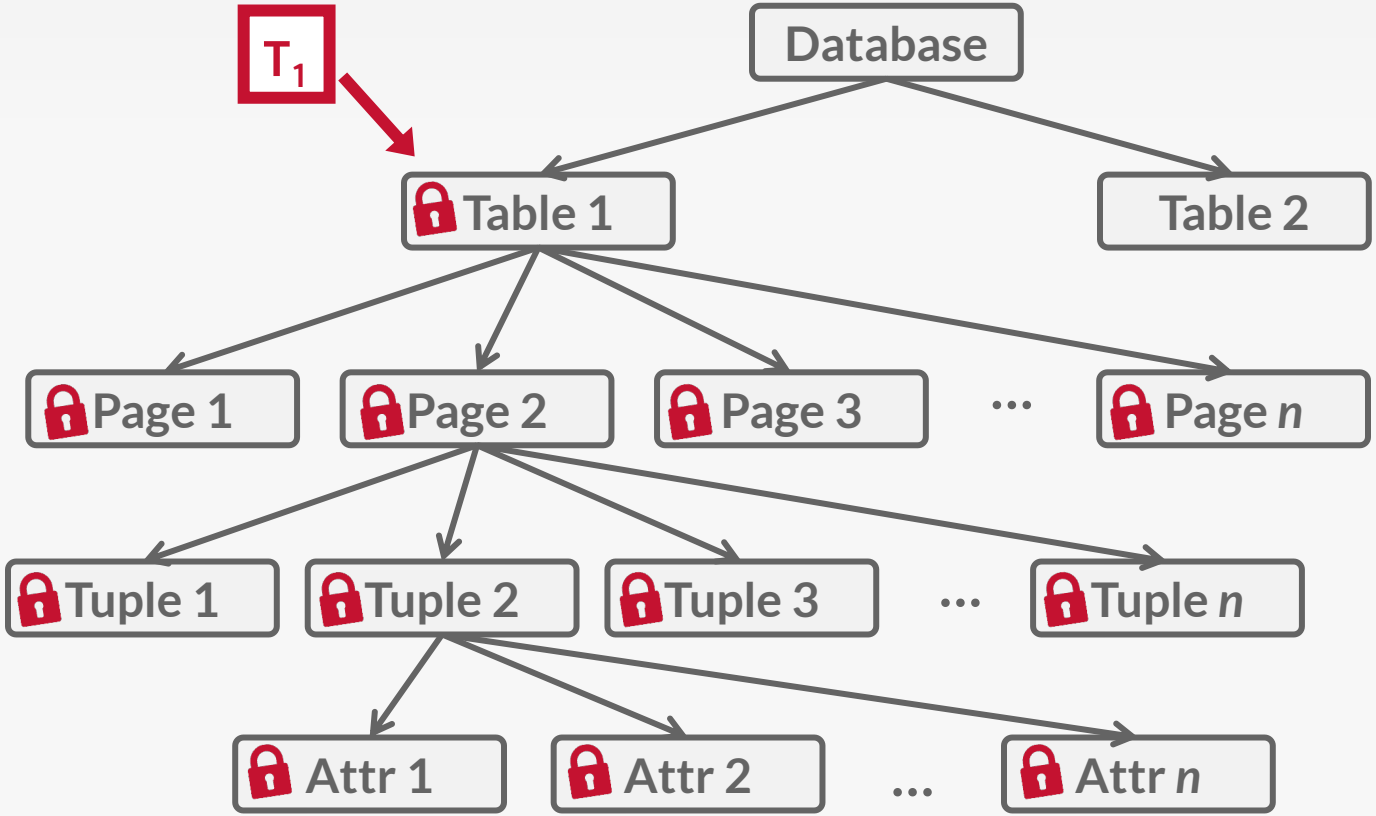
DATABASE LOCK HIERARCHY



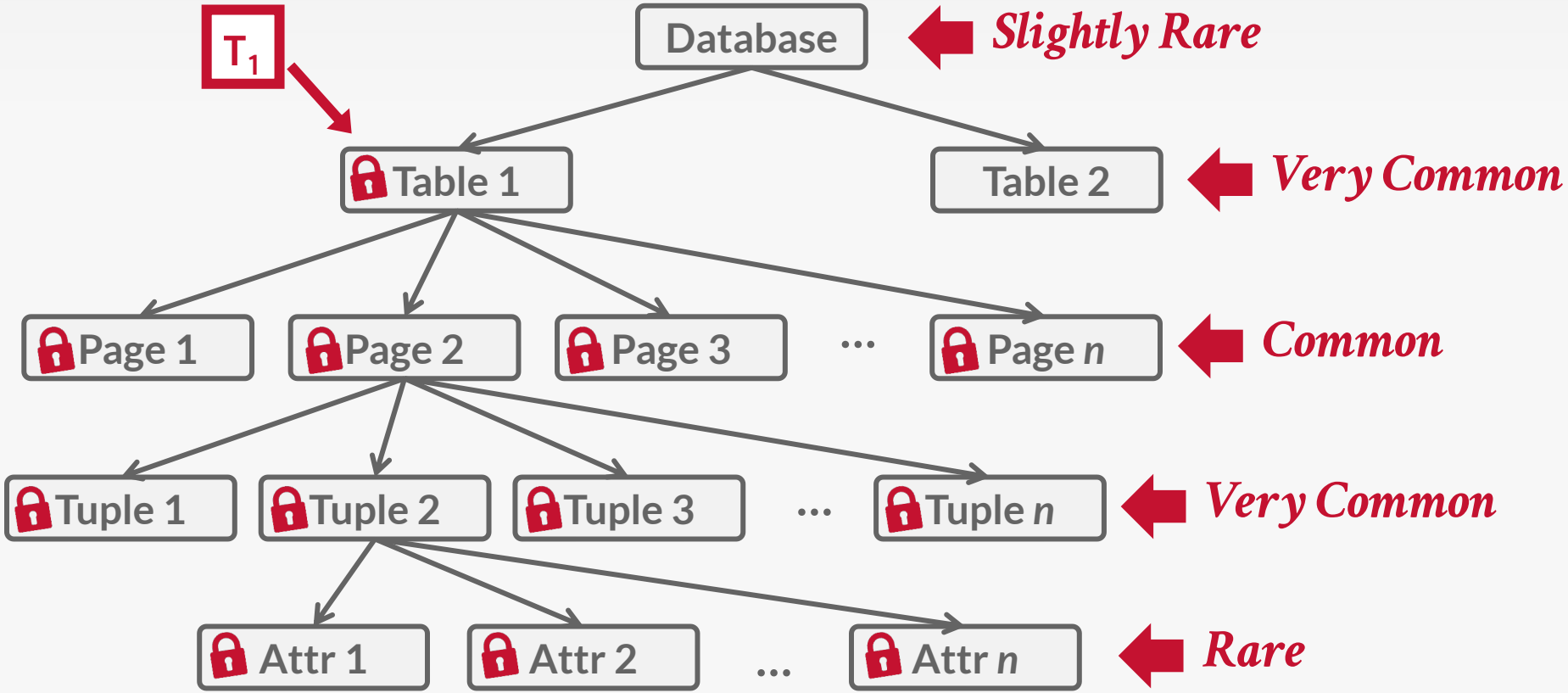
DATABASE LOCK HIERARCHY



DATABASE LOCK HIERARCHY



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.

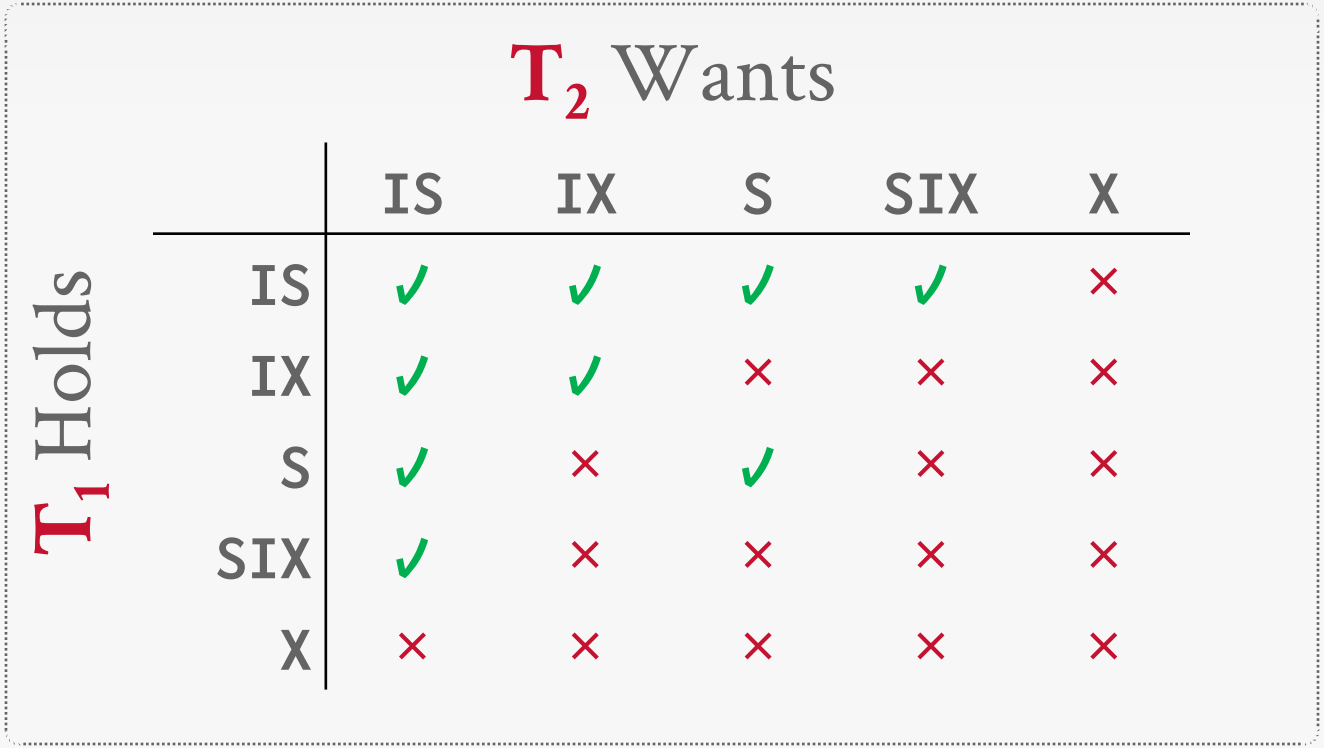
Intention-Exclusive (IX)

→ 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



LOCKING PROTOCOL

Each txn obtains the 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 DJ Cache's bank account.

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

What locks should these txns obtain?

EXAMPLE

T_1 – Get the balance of DJ Cache's bank account.

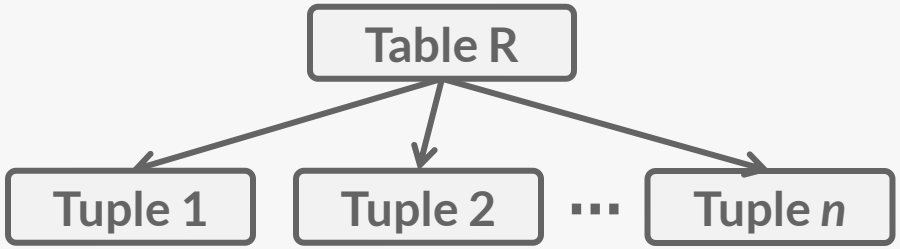
T_2 – Increase bookie's account balance by 1%.

What locks should these txns obtain?

→ Explicit **Exclusive** + **Shared** locks for leaf nodes of lock tree.

→ Special **Intention** locks for higher levels.

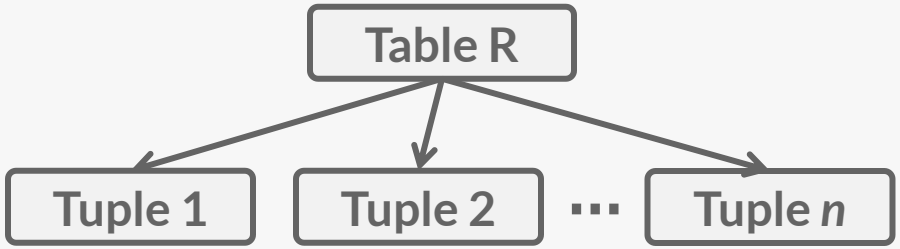
EXAMPLE: TWO-LEVEL HIERARCHY



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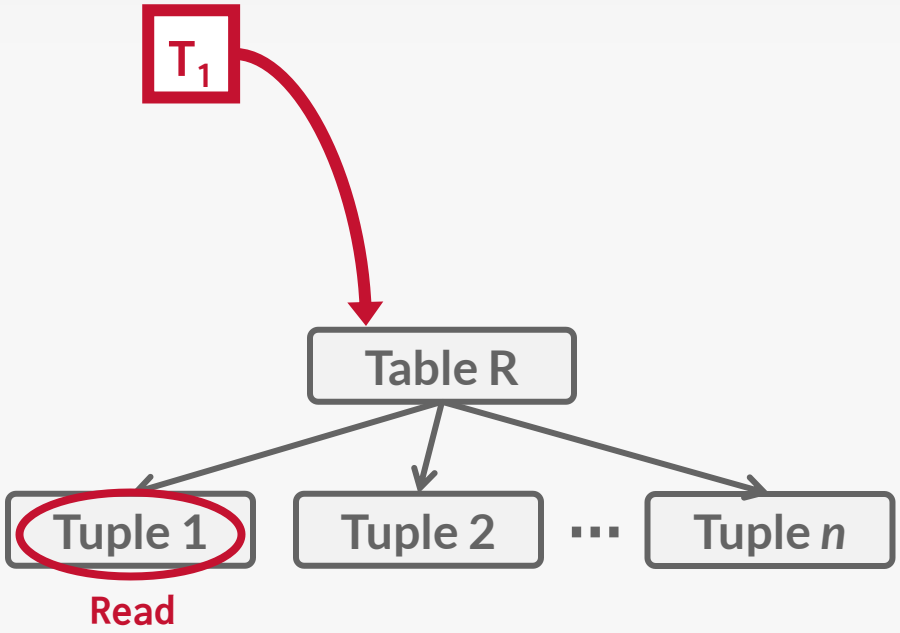
Read DJ Cache's record in **R**.





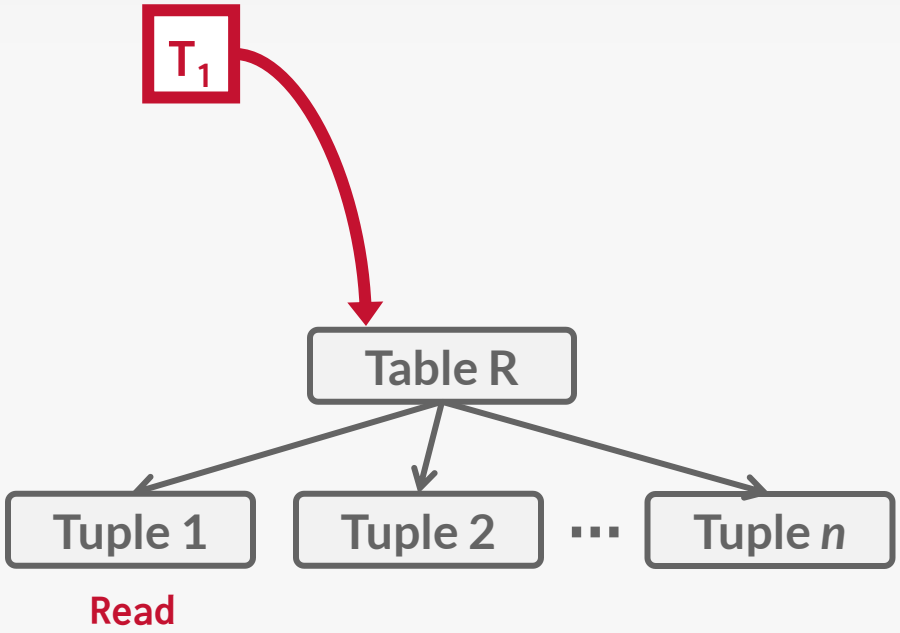
EXAMPLE: TWO-LEVEL HIERARCHY

Read DJ Cache's record in **R**.



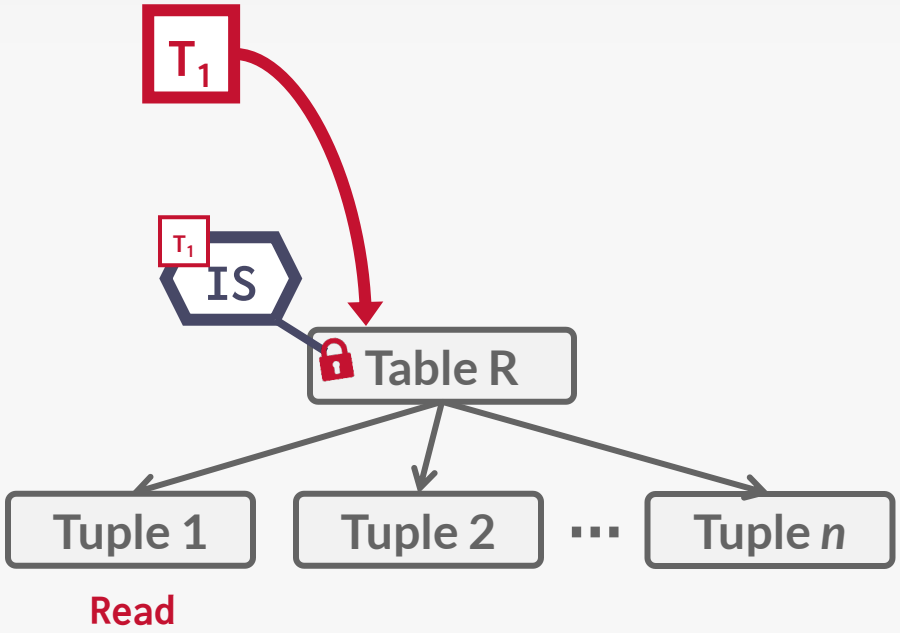
EXAMPLE: TWO-LEVEL HIERARCHY

Read DJ Cache's record in **R**.



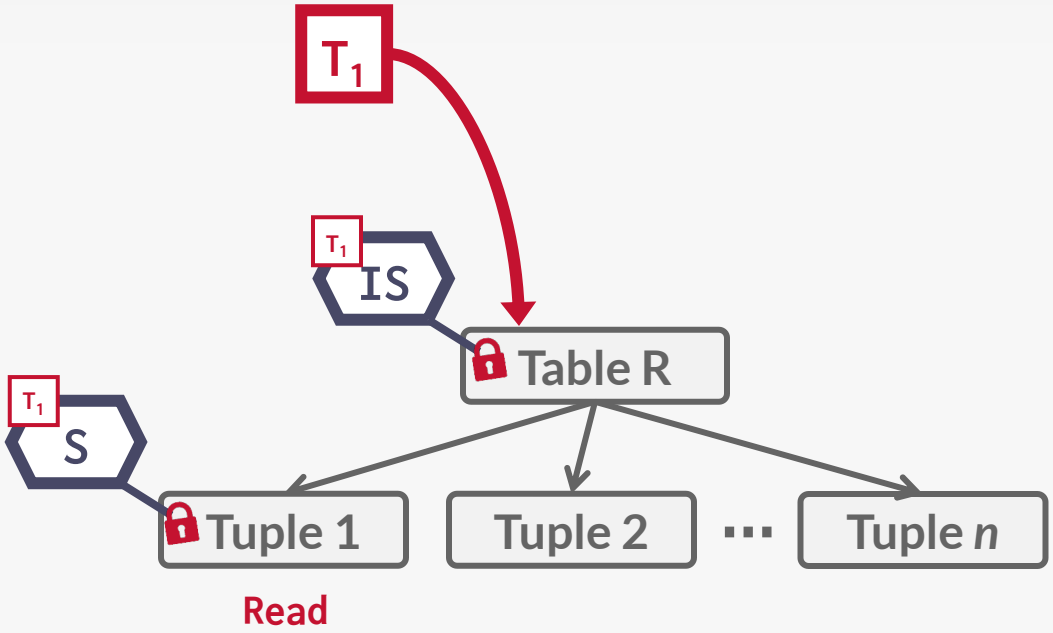
EXAMPLE: TWO-LEVEL HIERARCHY

Read DJ Cache's record in **R**.



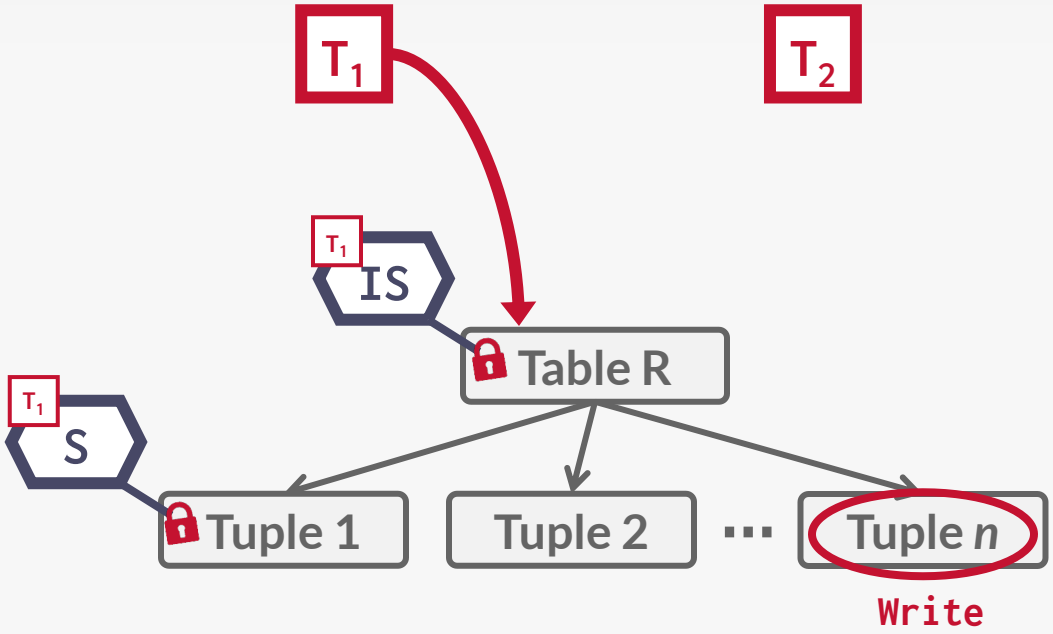
EXAMPLE: TWO-LEVEL HIERARCHY

Read DJ Cache's record in **R**.



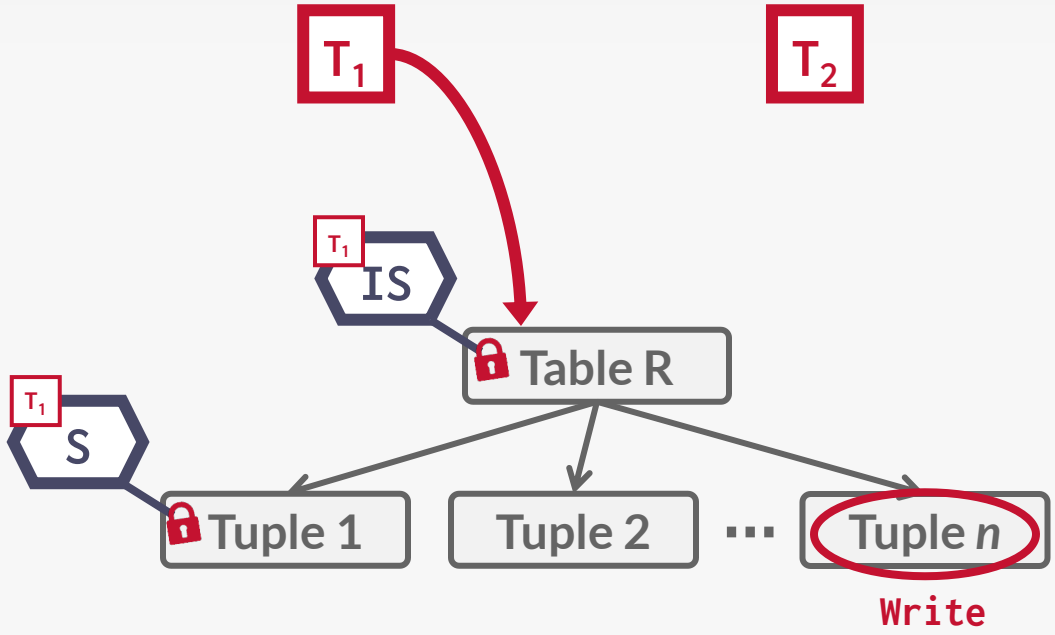
EXAMPLE: TWO-LEVEL HIERARCHY

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



EXAMPLE: TWO-LEVEL HIERARCHY

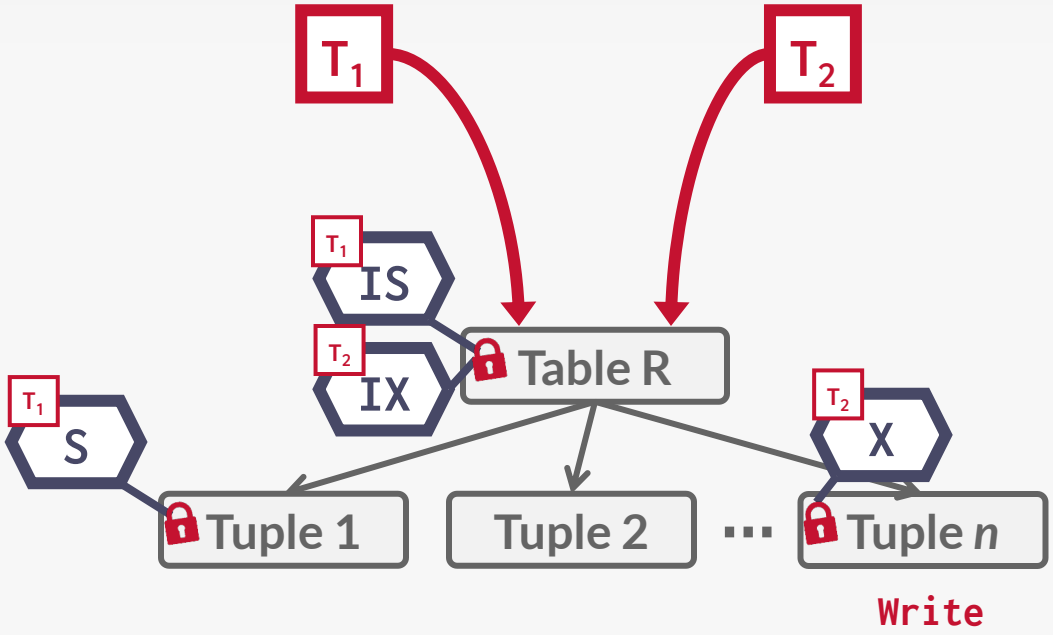
Update bookie's record in **R**.



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

EXAMPLE: TWO-LEVEL HIERARCHY

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

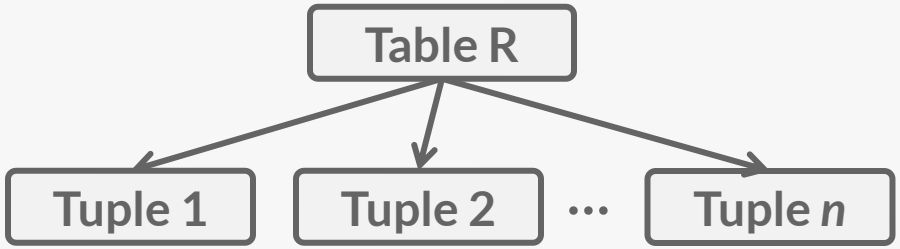


	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	×
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
SIX	✓	×	×	×	×
X	×	×	×	×	×

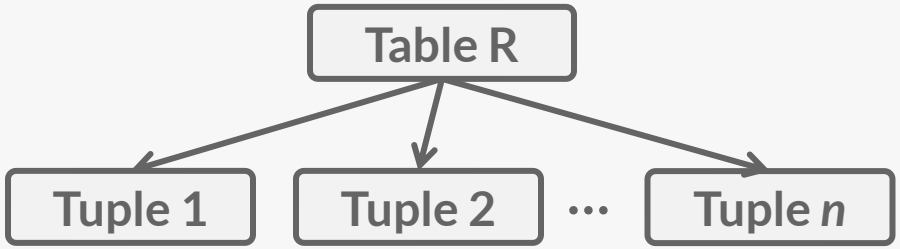
EXAMPLE: THREE TXNS

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**.



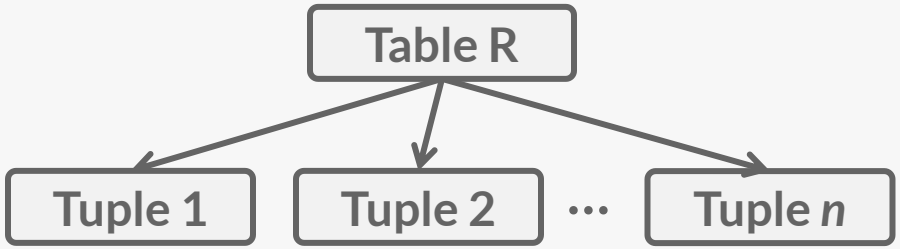
EXAMPLE: THREE TXNS



EXAMPLE: THREE TXNS

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

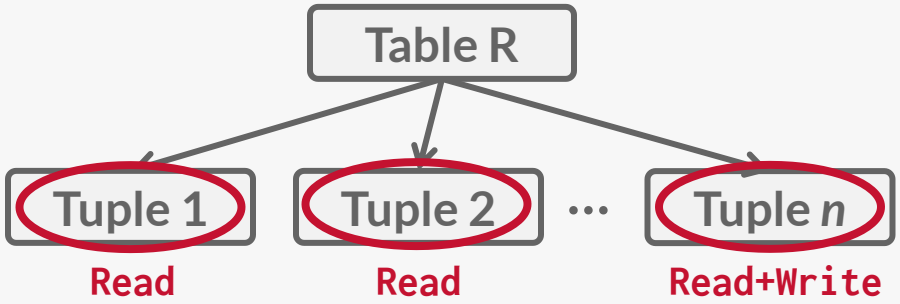
T_1



EXAMPLE: THREE TXNS

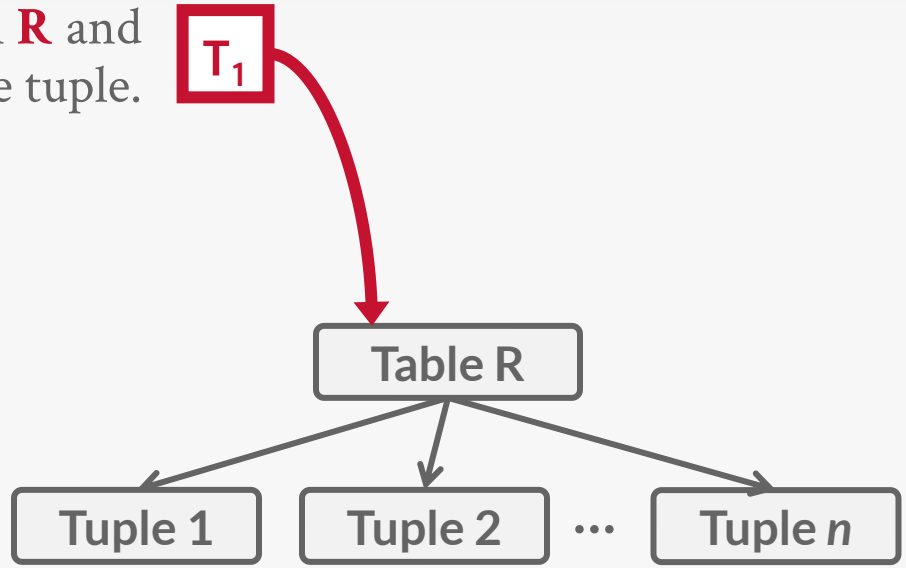
Scan all tuples in **R** and update one tuple.





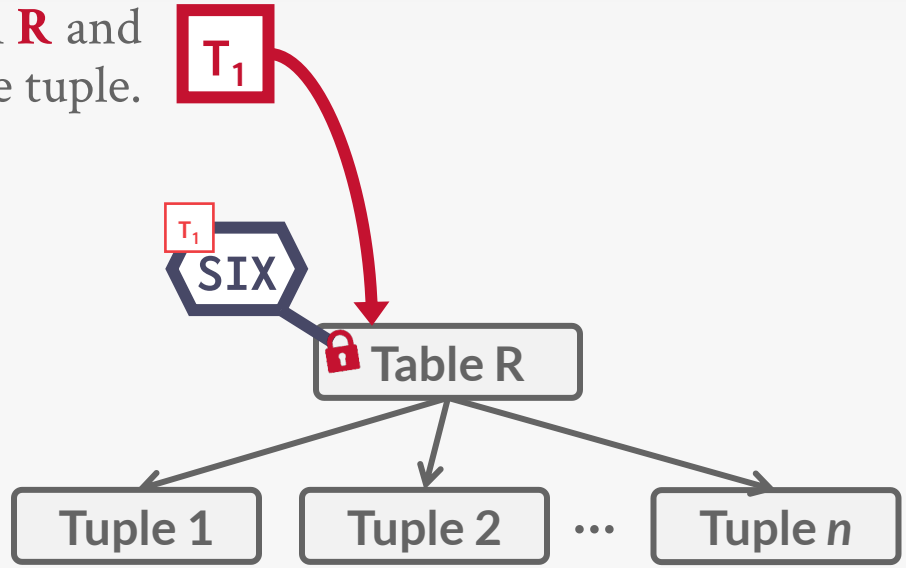
EXAMPLE: THREE TXNS

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



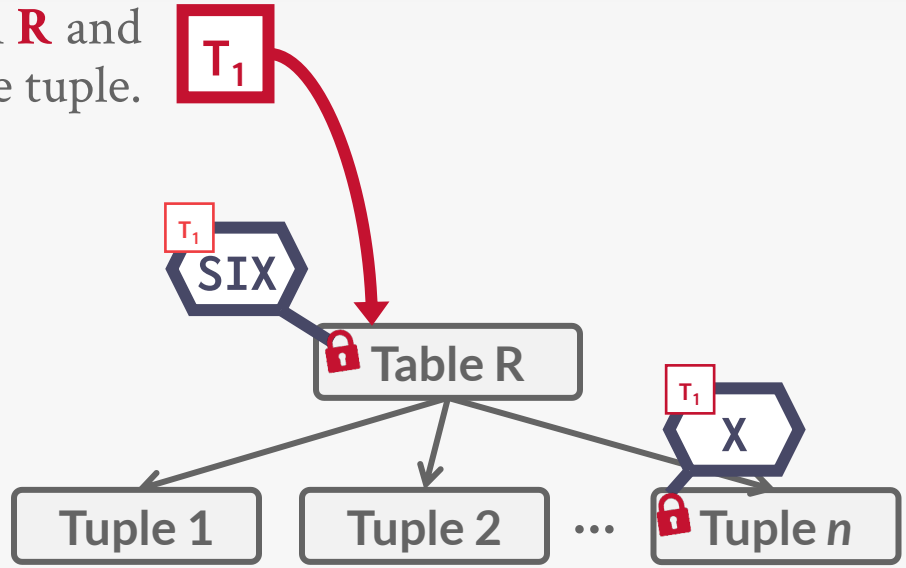
EXAMPLE: THREE TXNS

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

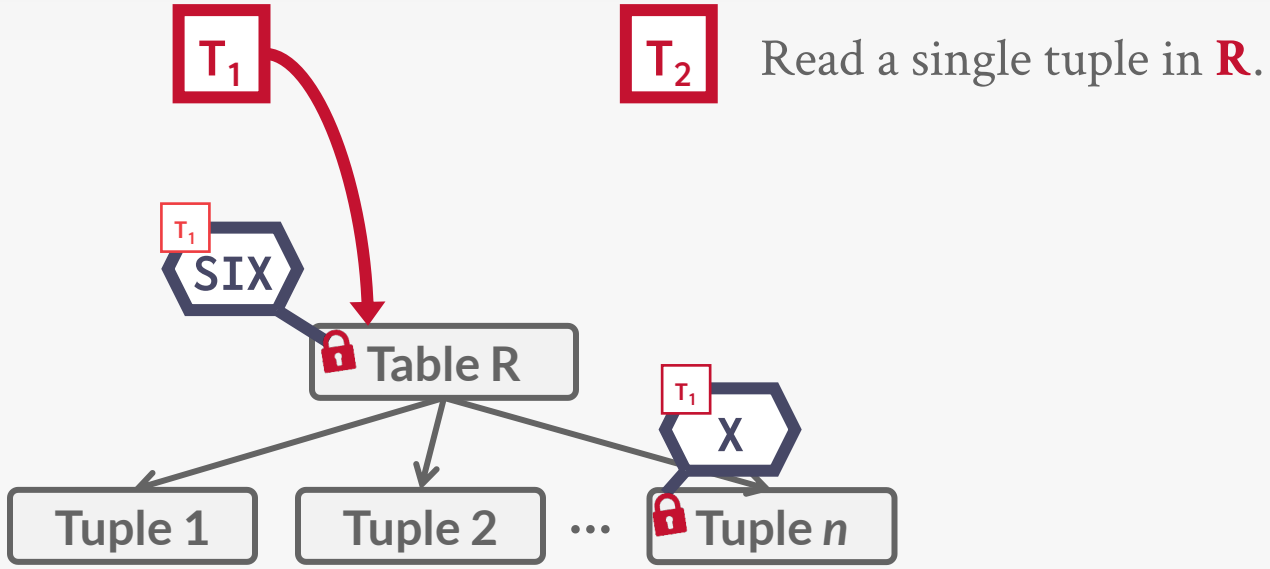


EXAMPLE: THREE TXNS

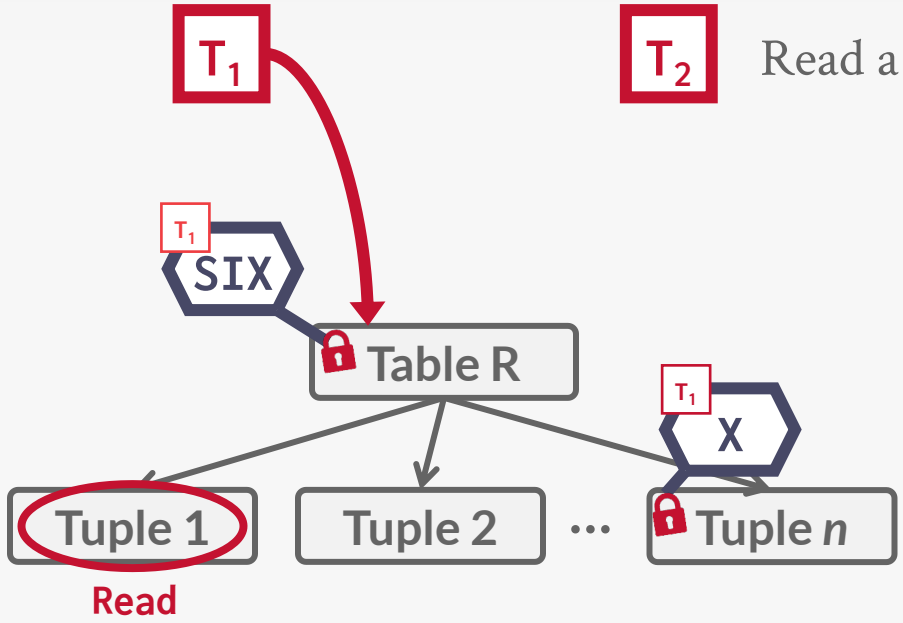
Scan all tuples in **R** and update one tuple.



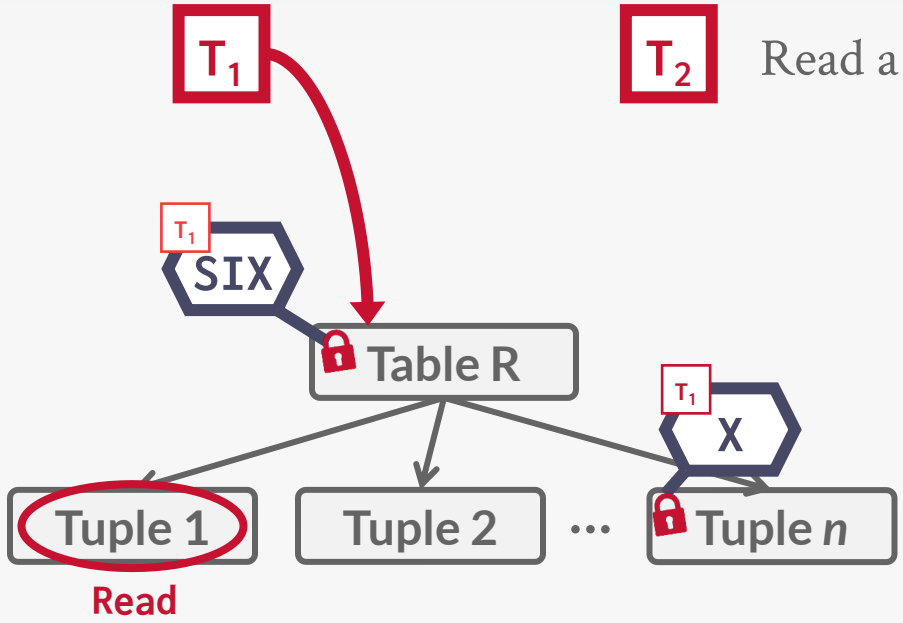
EXAMPLE: THREE TXNS



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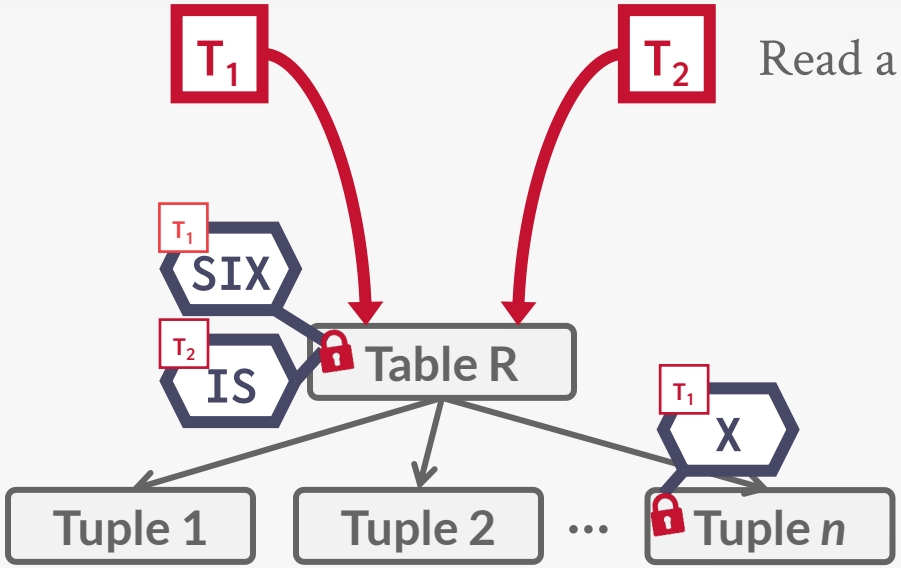


EXAMPLE: THREE TXNS



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

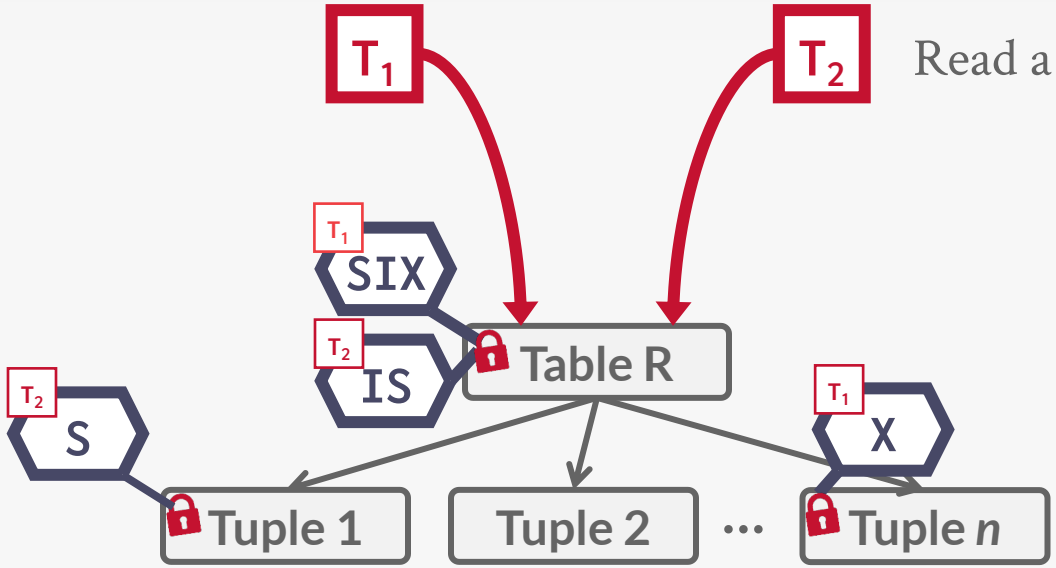
EXAMPLE: THREE TXNS



Read a single tuple in **R**.

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

EXAMPLE: THREE TXNS

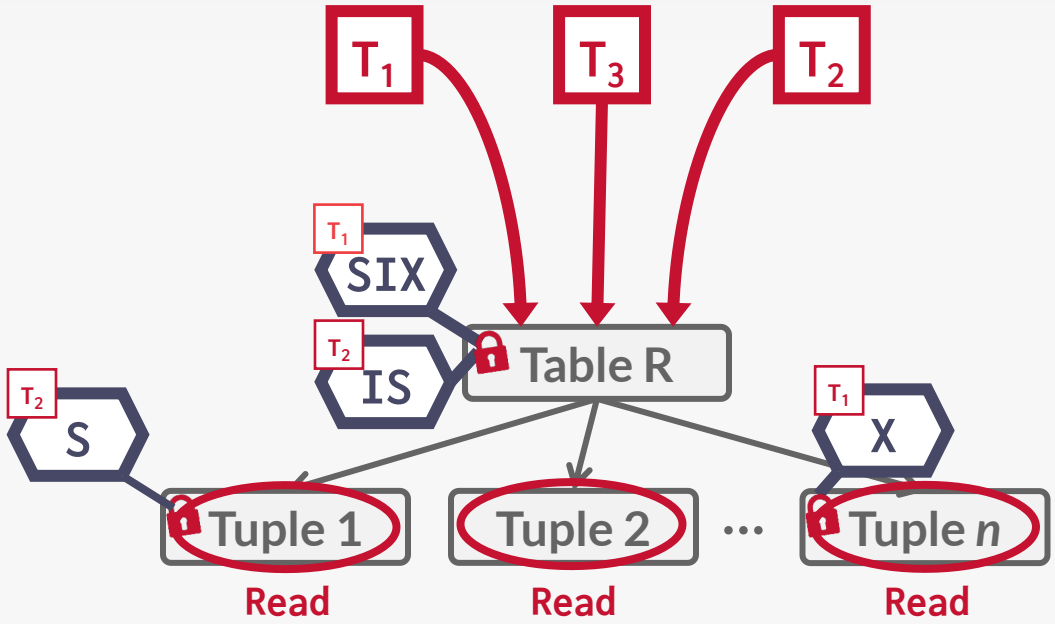


Read a single tuple in **R**.

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

EXAMPLE: THREE TXNS

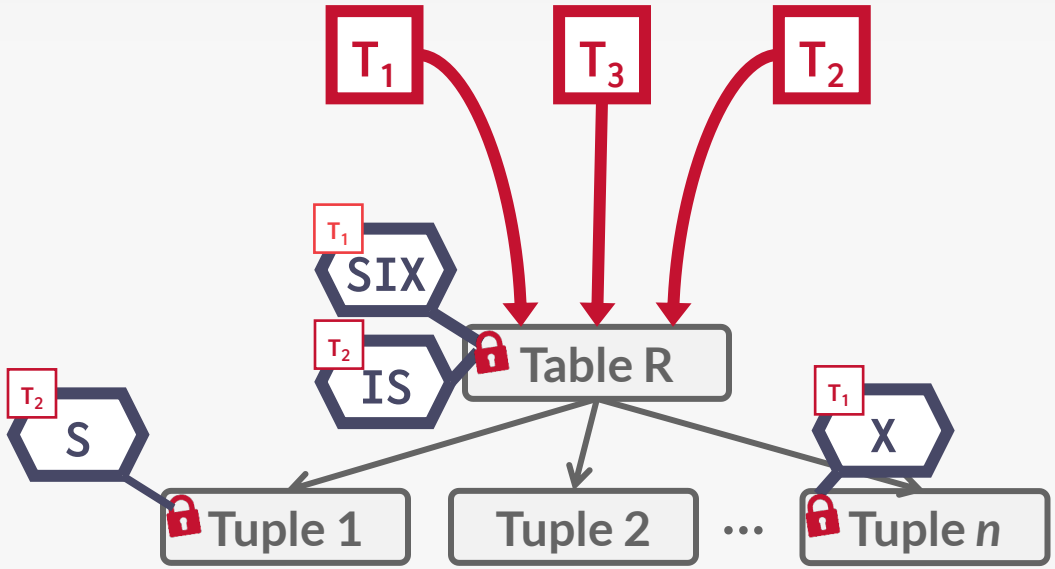
Scan all tuples in **R**.



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

EXAMPLE: THREE TXNS

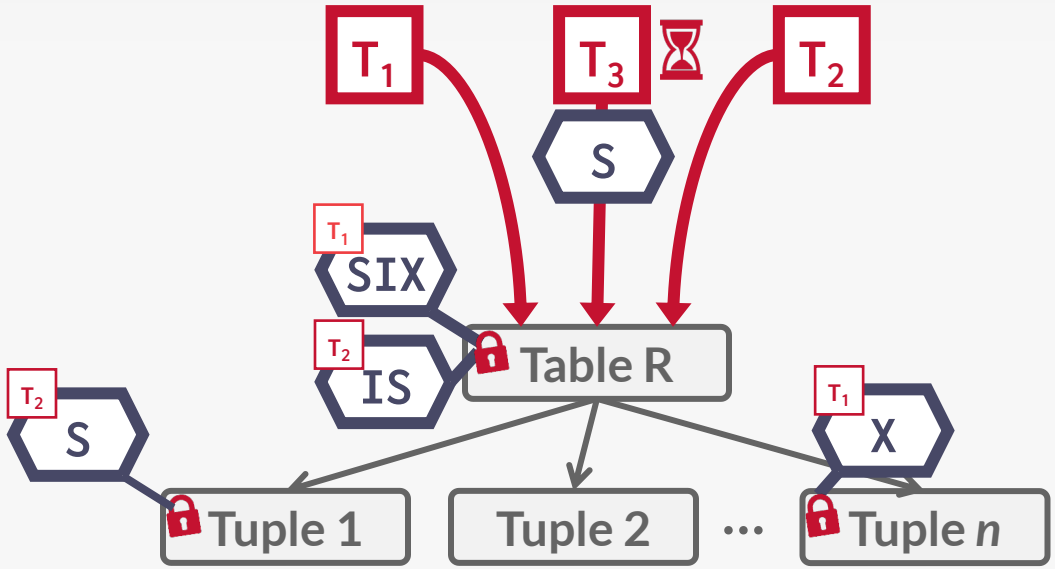
Scan all tuples in **R**.



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

EXAMPLE: THREE TXNS

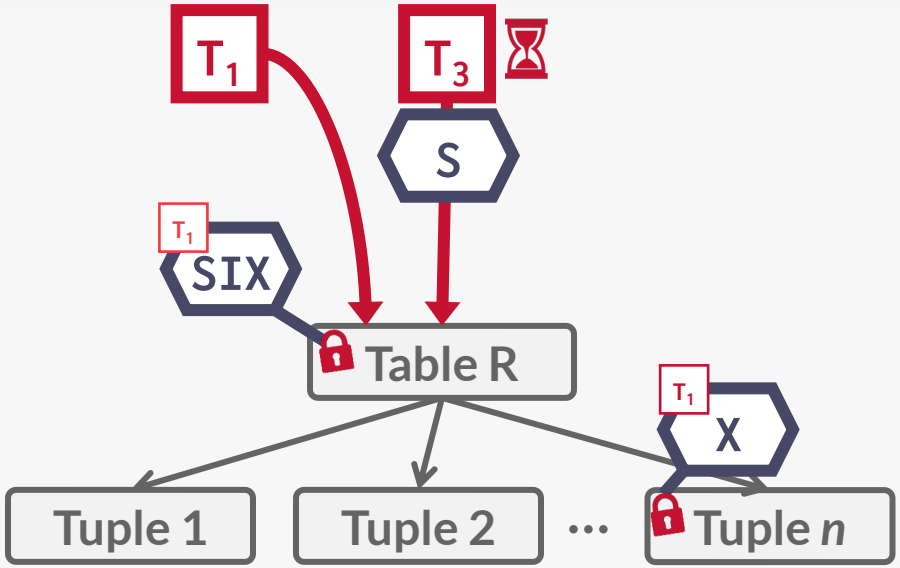
Scan all tuples in **R**.



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

EXAMPLE: THREE TXNS

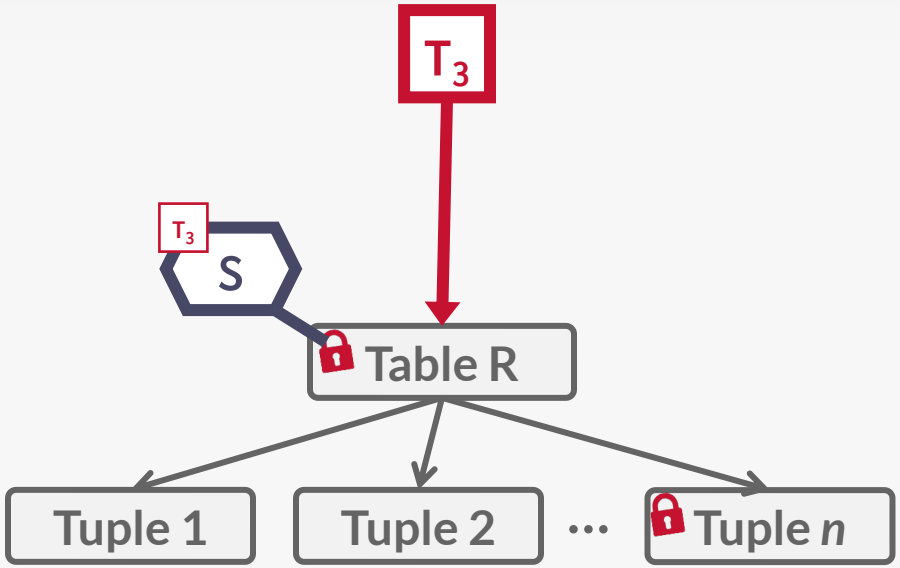
Scan all tuples in **R**.



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

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