

Carnegie Mellon University

Database Systems

15-445/645 SPRING 2026

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Lecture #18

Concurrency Control: Two-Phase Locking



ADMINISTRIVIA



Andy OH Changes ([@237](#)):

→ Thursday March 26th @ 3:30pm

Project #3 is due Sunday Apr 5th @ 11:59pm

→ Recitation Video + Slides ([@258](#))

Homework #5 is due April 12th @ 11:59pm.

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.

Solution: Use locks to protect database objects.

LOCKS VS. LATCHES



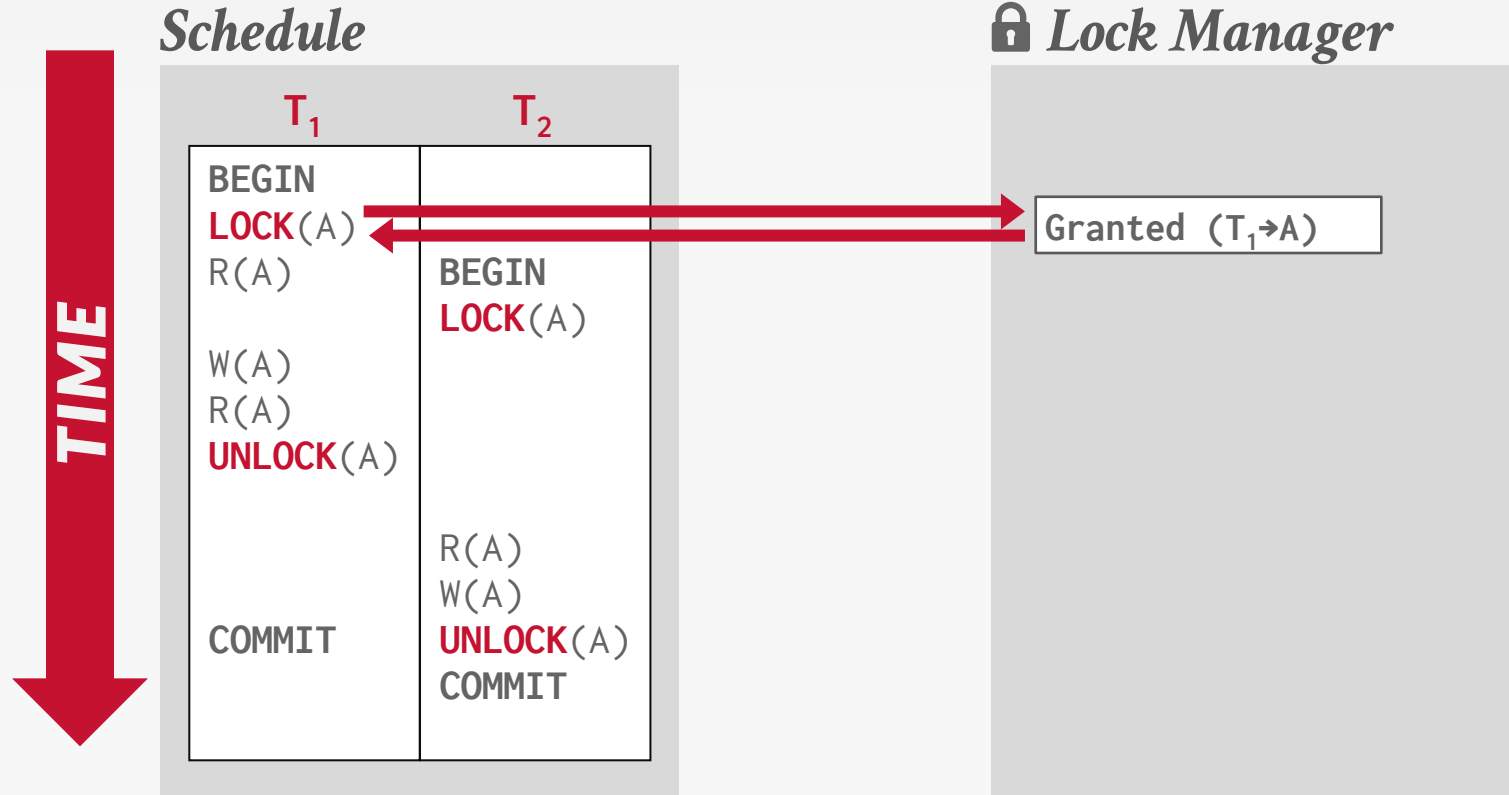
Locks

Latches

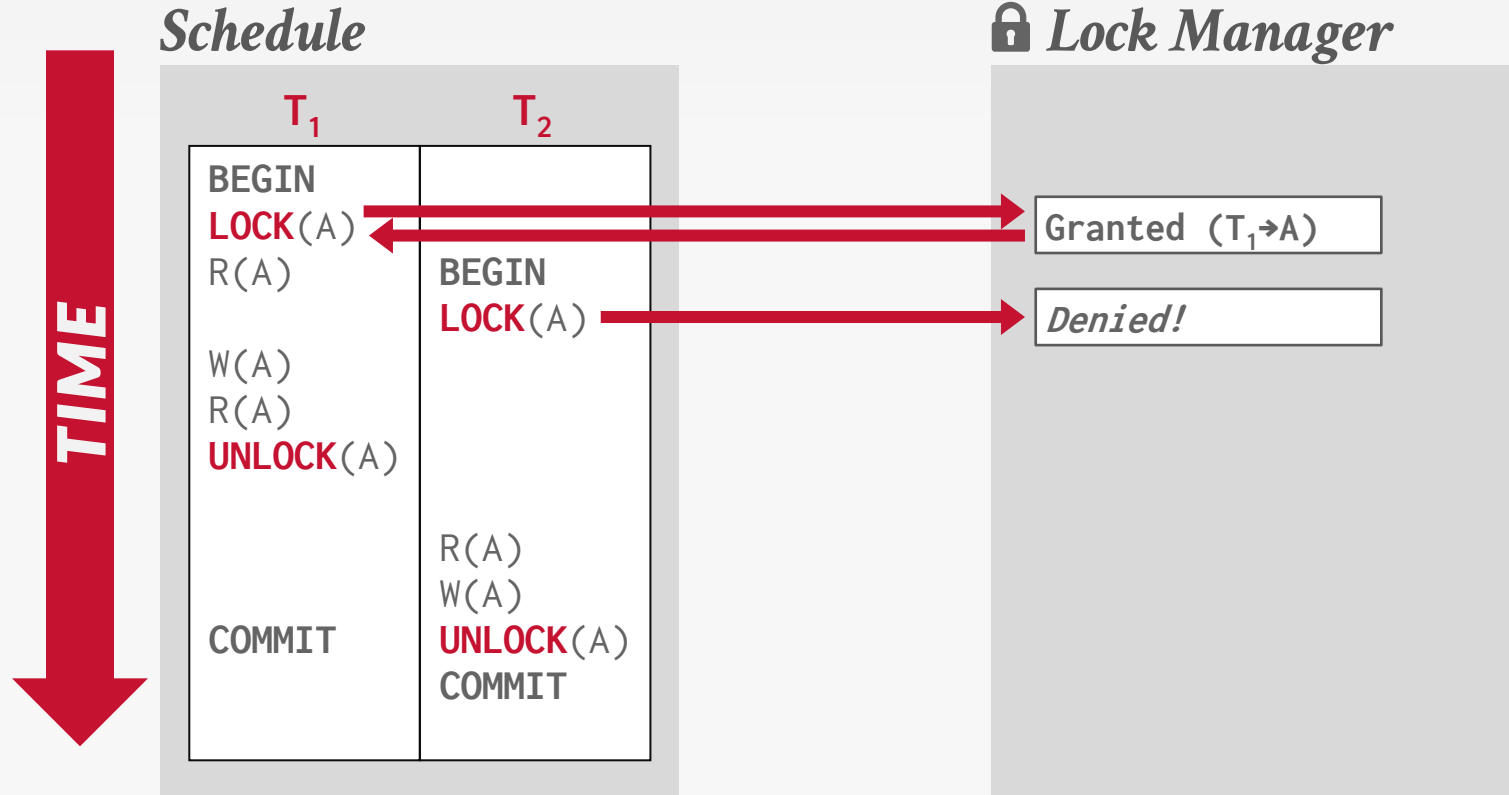
Separate...	Transactions
Protect...	Database Contents
During...	Entire Transactions
Modes...	Shared, Exclusive, Update, Intention
Deadlock	Detection & Resolution
...by...	Waits-for, Timeout, Aborts
Kept in...	Lock Manager

Workers (threads, processes)
In-Memory Data Structures
Critical Sections
Read, Write
Avoidance
Coding Discipline
Protected Data Structure

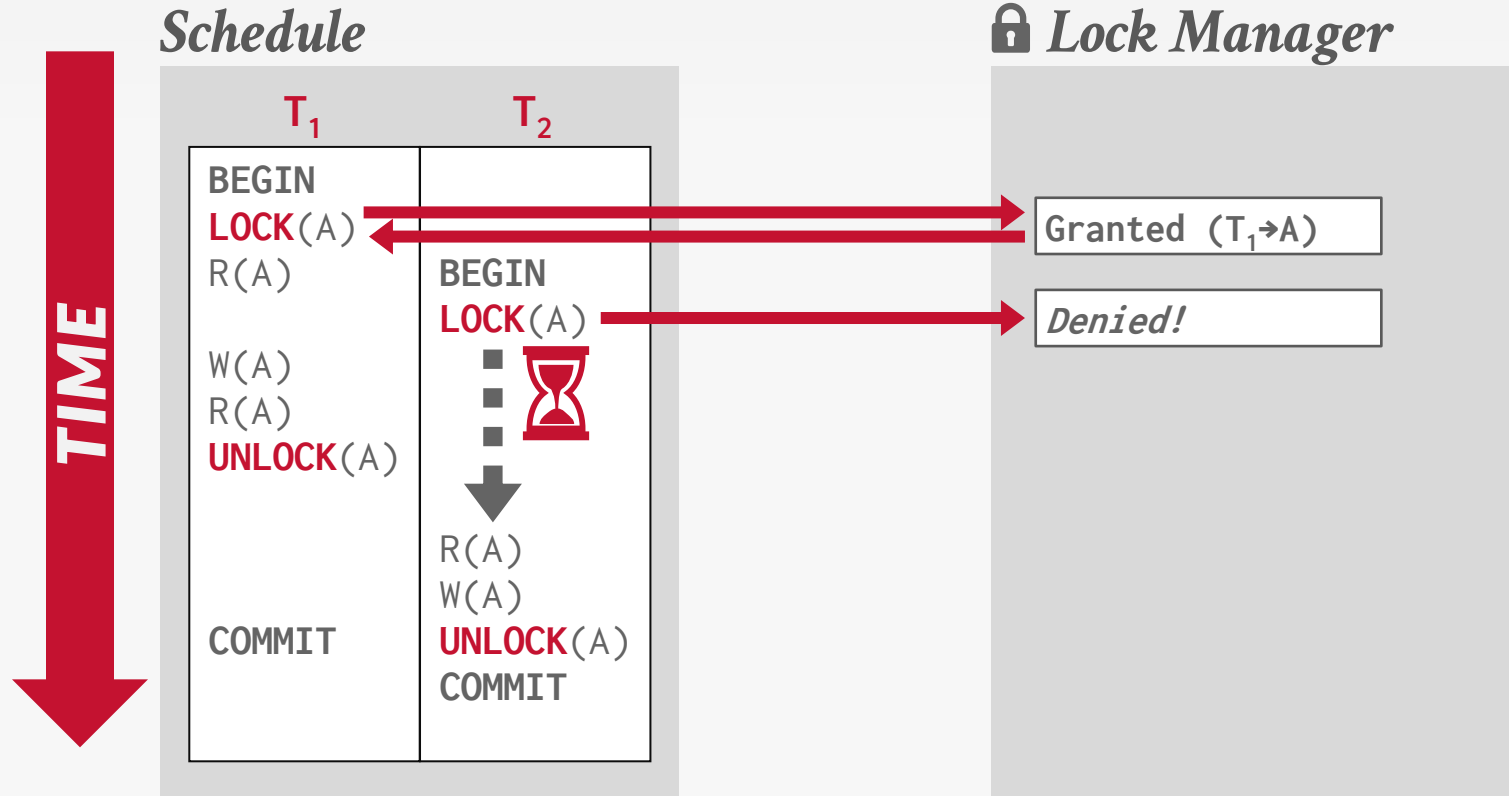
EXECUTING WITH LOCKS



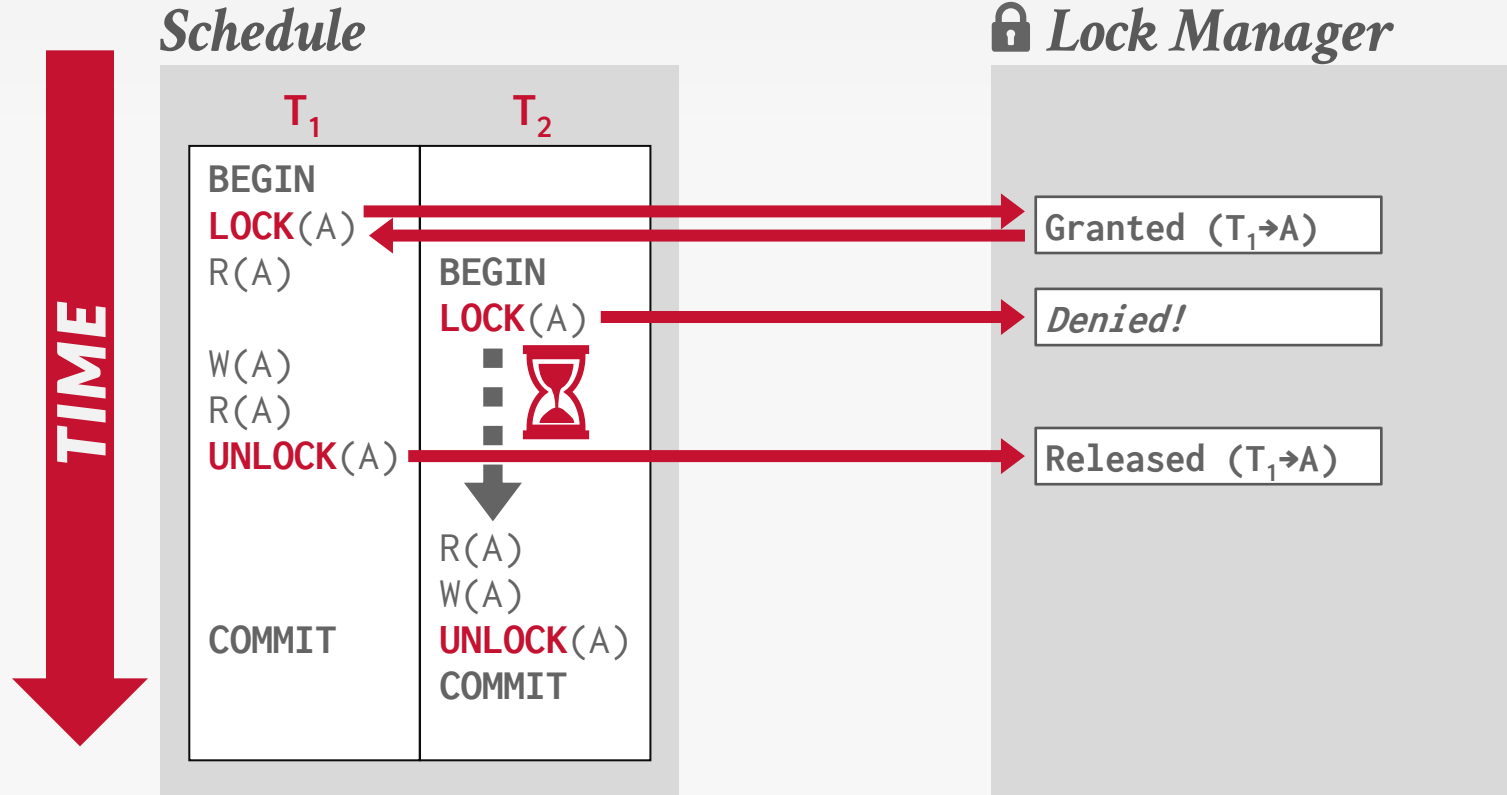
EXECUTING WITH LOCKS



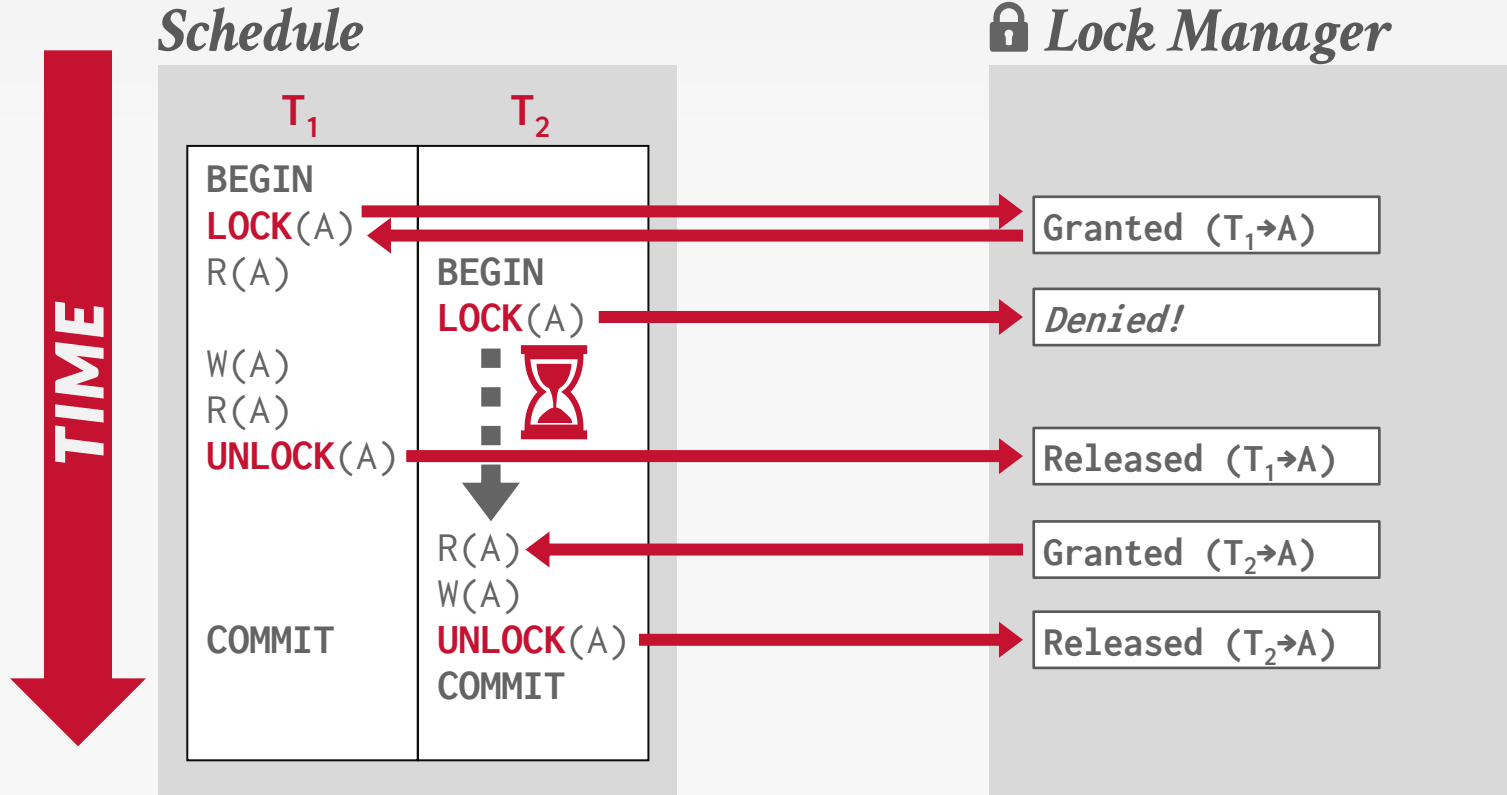
EXECUTING WITH LOCKS



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 (U-lock)
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

Existing granted mode

Requested mode

Intent shared (IS)

Shared (S)

Update (U)

Intent exclusive (IX)

Shared with intent exclusive (SIX)

IS S U

Yes Yes

Yes Yes

Yes Yes

Yes No

Yes No

No No



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	X
INSERT INTO table ...	RX	Y	Y	N	N	Y
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



Table 13.2. Conflicting Lock Modes

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



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

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



EXECUTING WITH LOCKS



Transactions request locks (or upgrades).

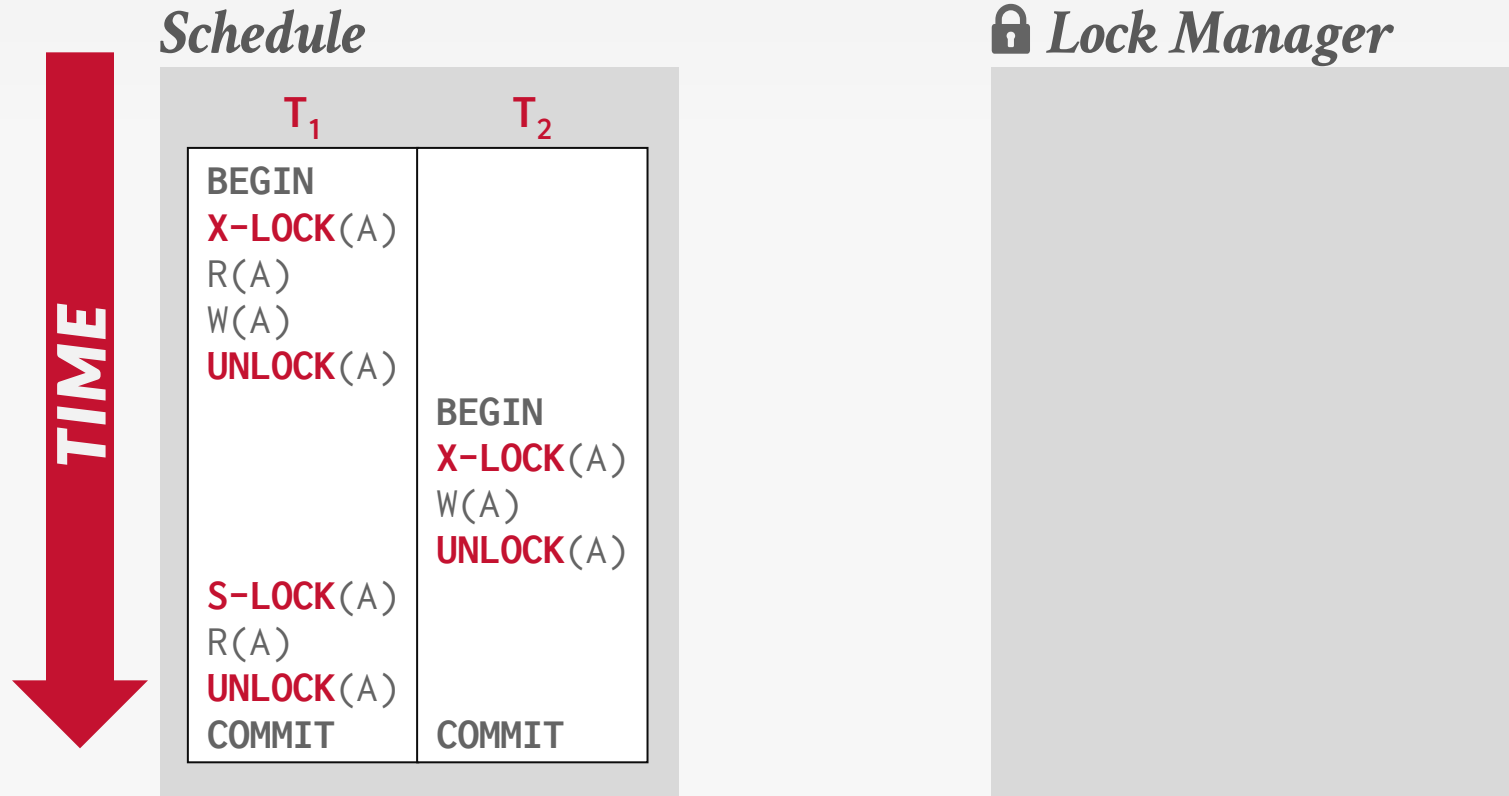
Lock manager grants or blocks requests.

Transactions release locks.

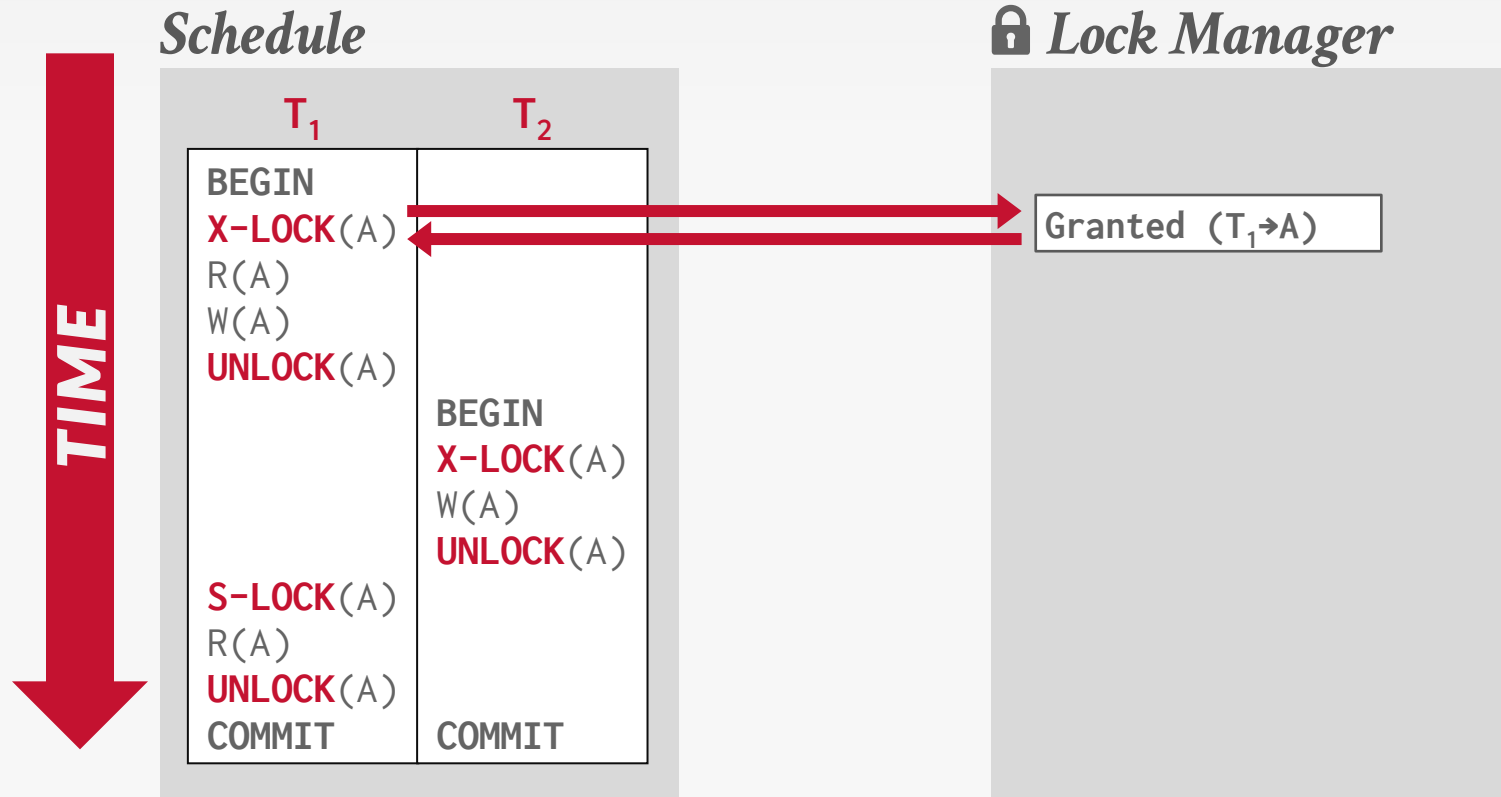
Lock manager updates its internal lock-table.

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

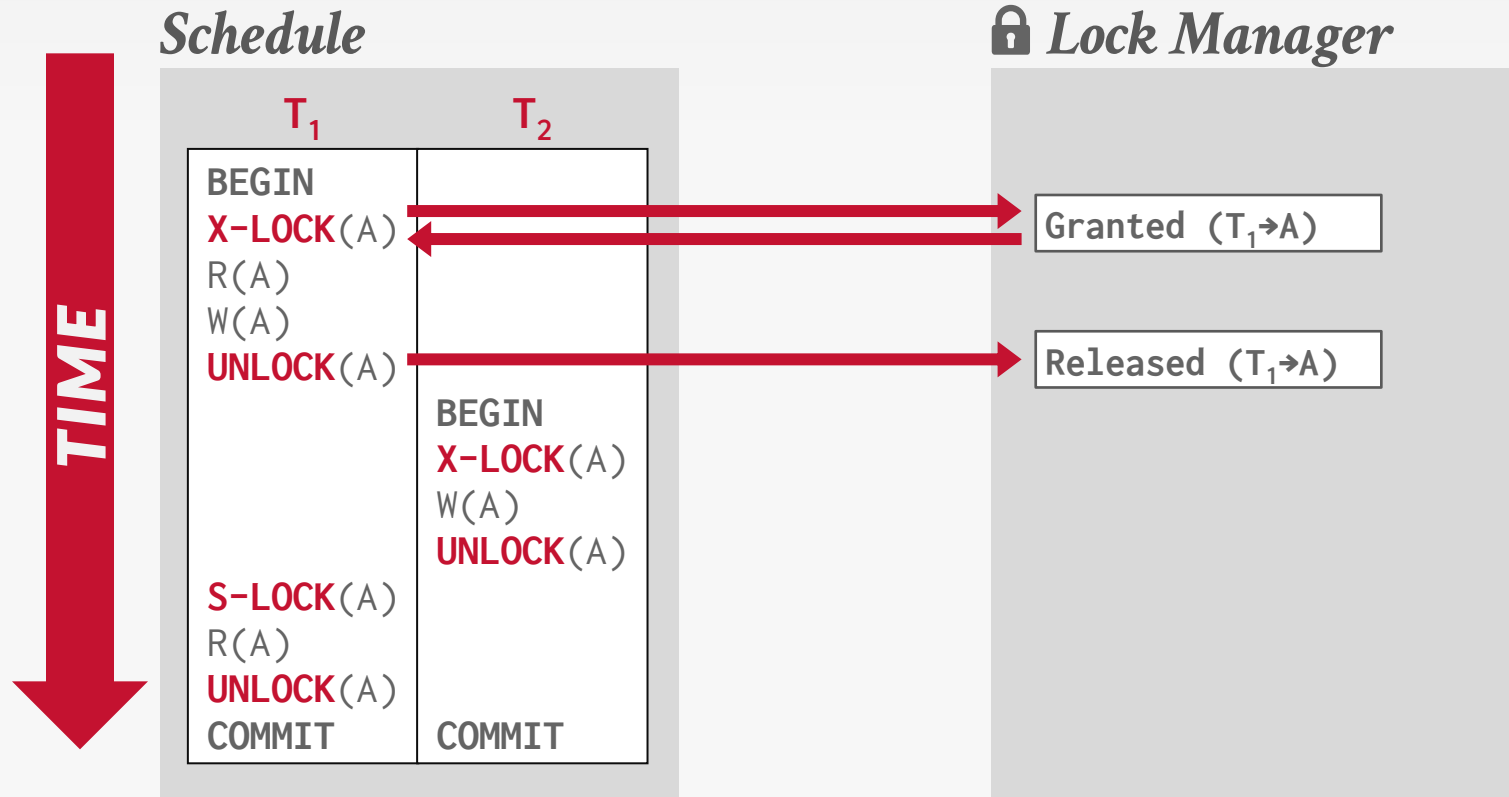
EXECUTING WITH LOCKS



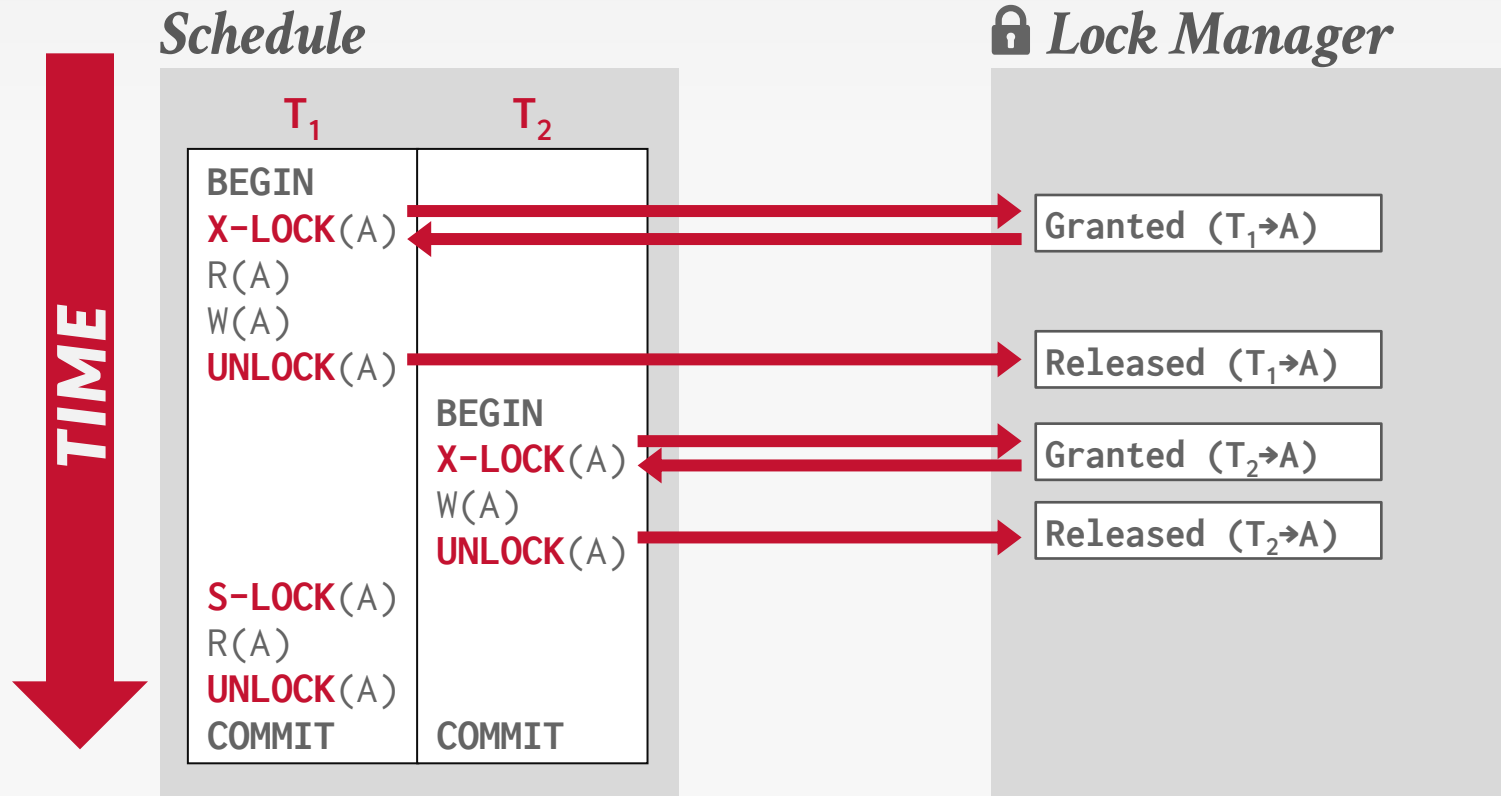
EXECUTING WITH LOCKS



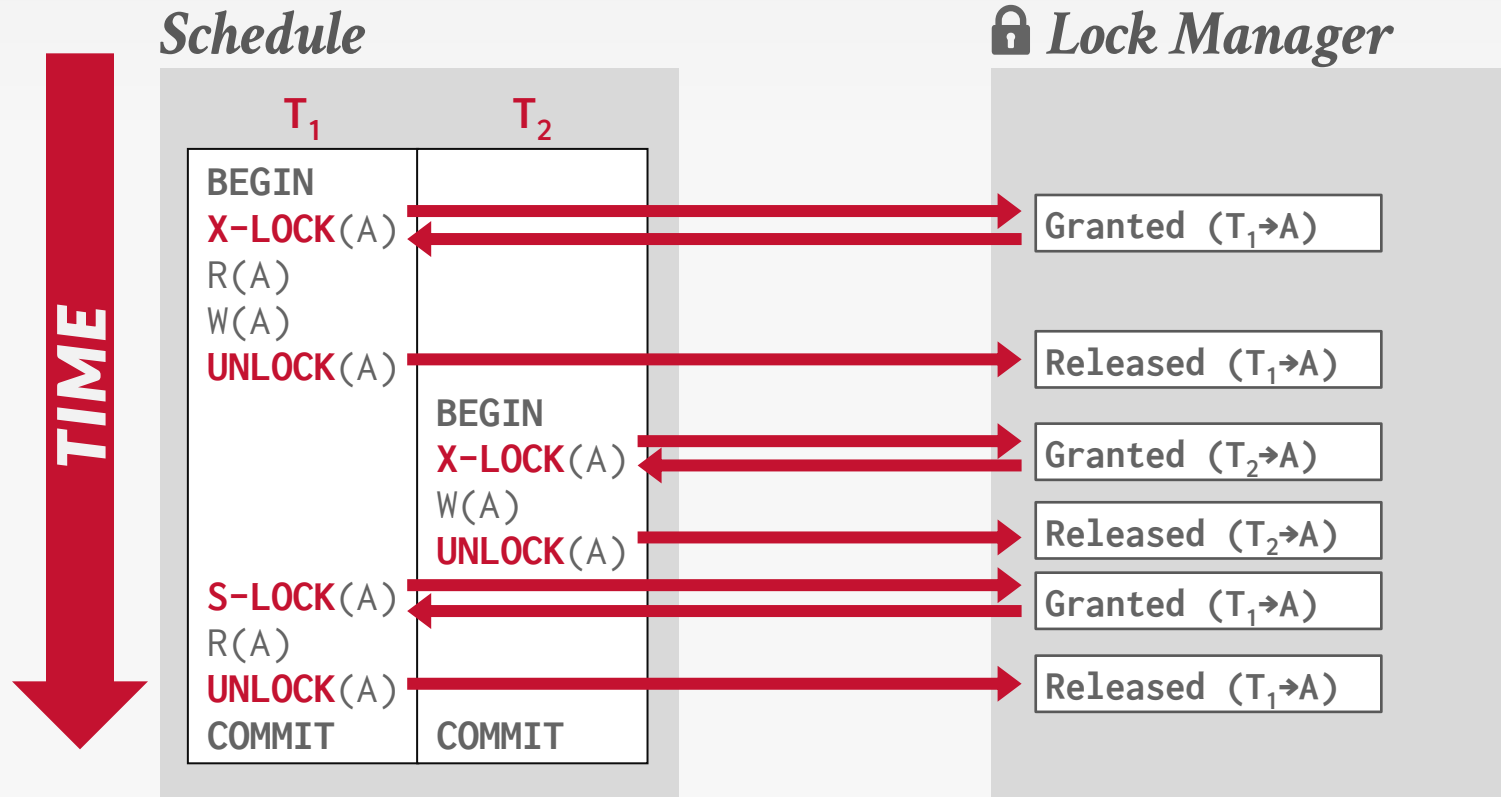
EXECUTING WITH LOCKS



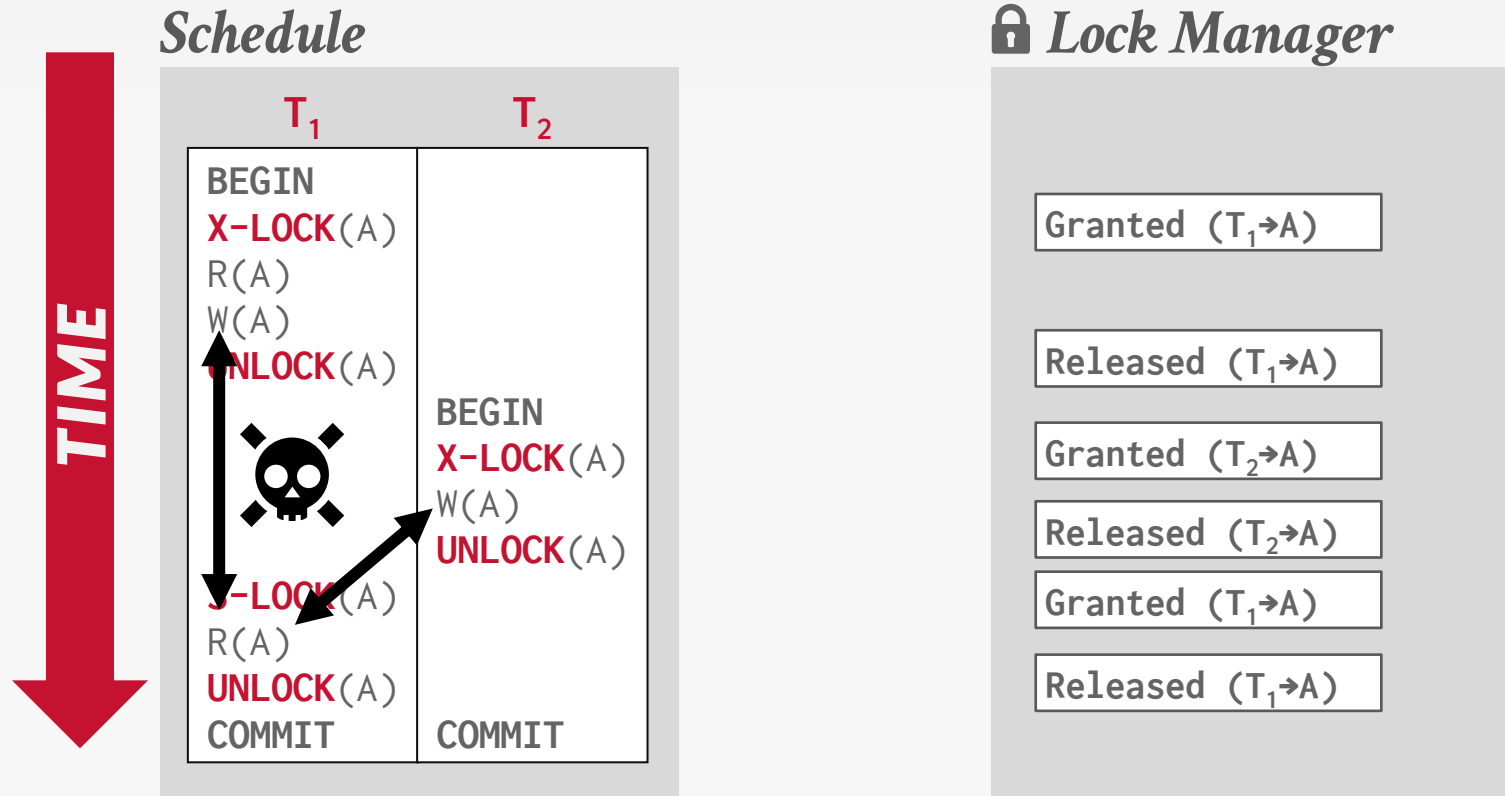
EXECUTING WITH LOCKS



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

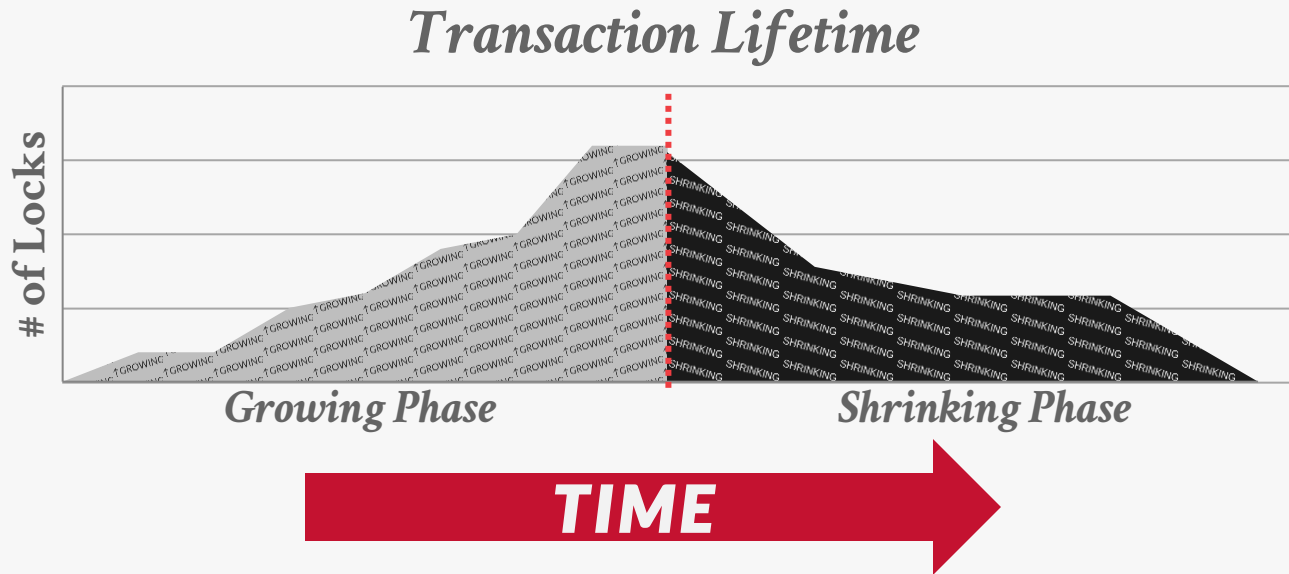
- Each txn requests the locks that it needs from the DBMS's lock manager.
- The lock manager grants/denies lock requests.

Phase #2: Shrinking

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

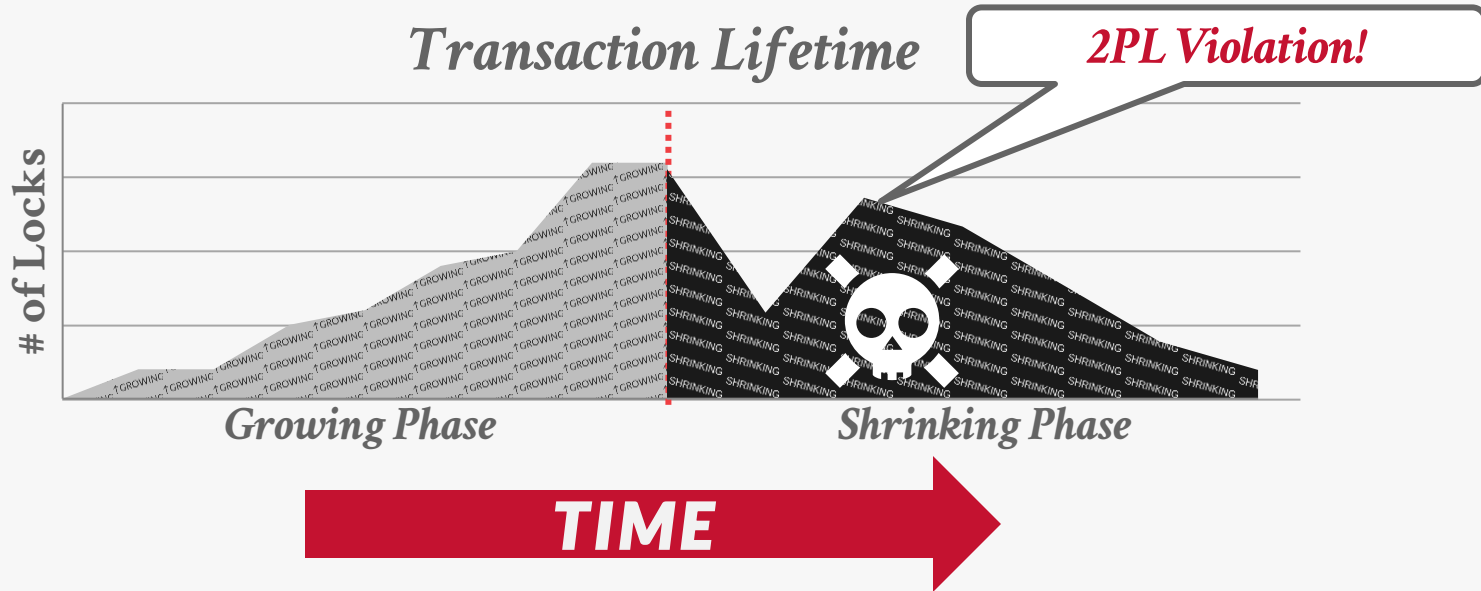
TWO-PHASE LOCKING

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

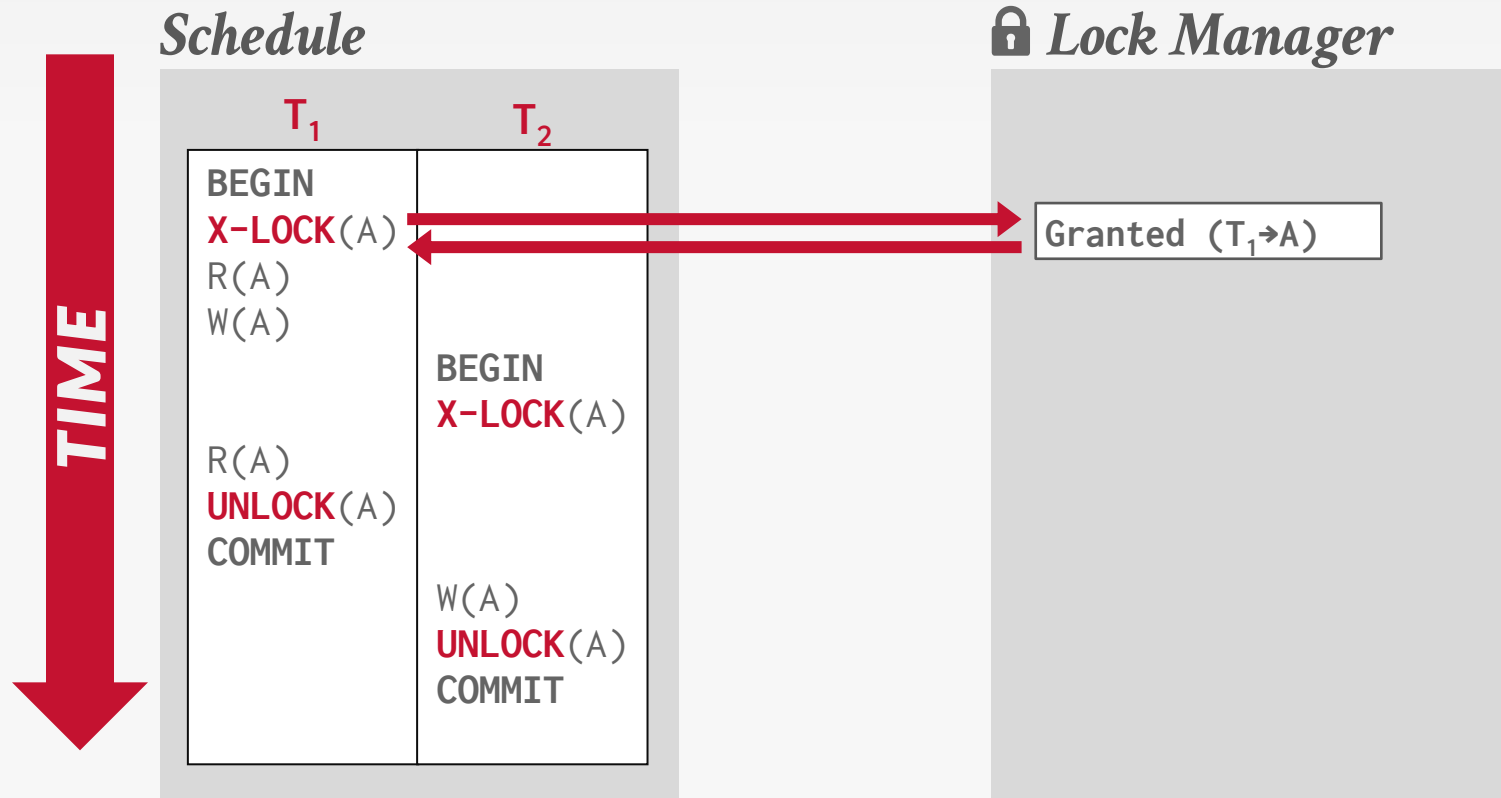


TWO-PHASE LOCKING

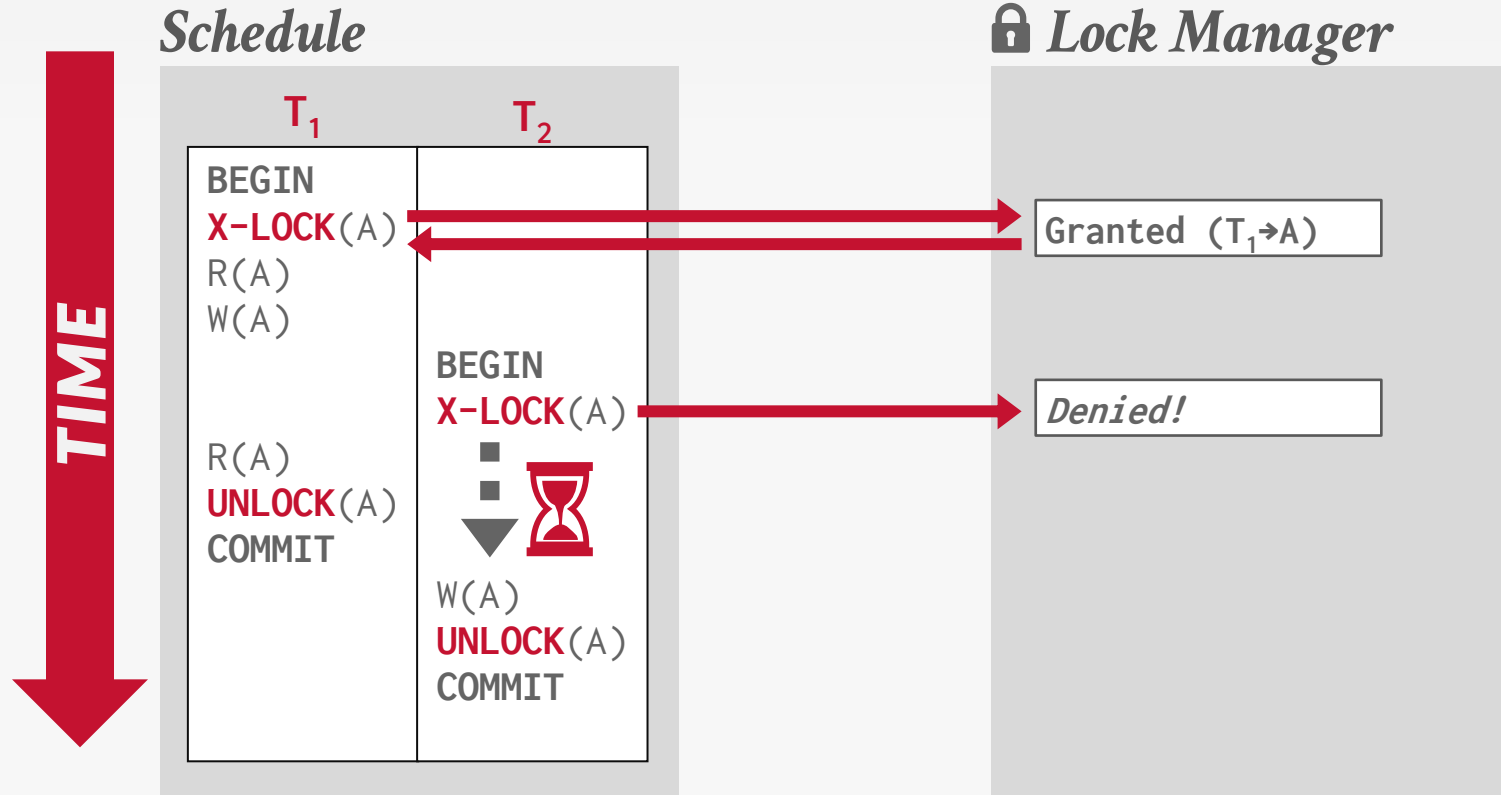
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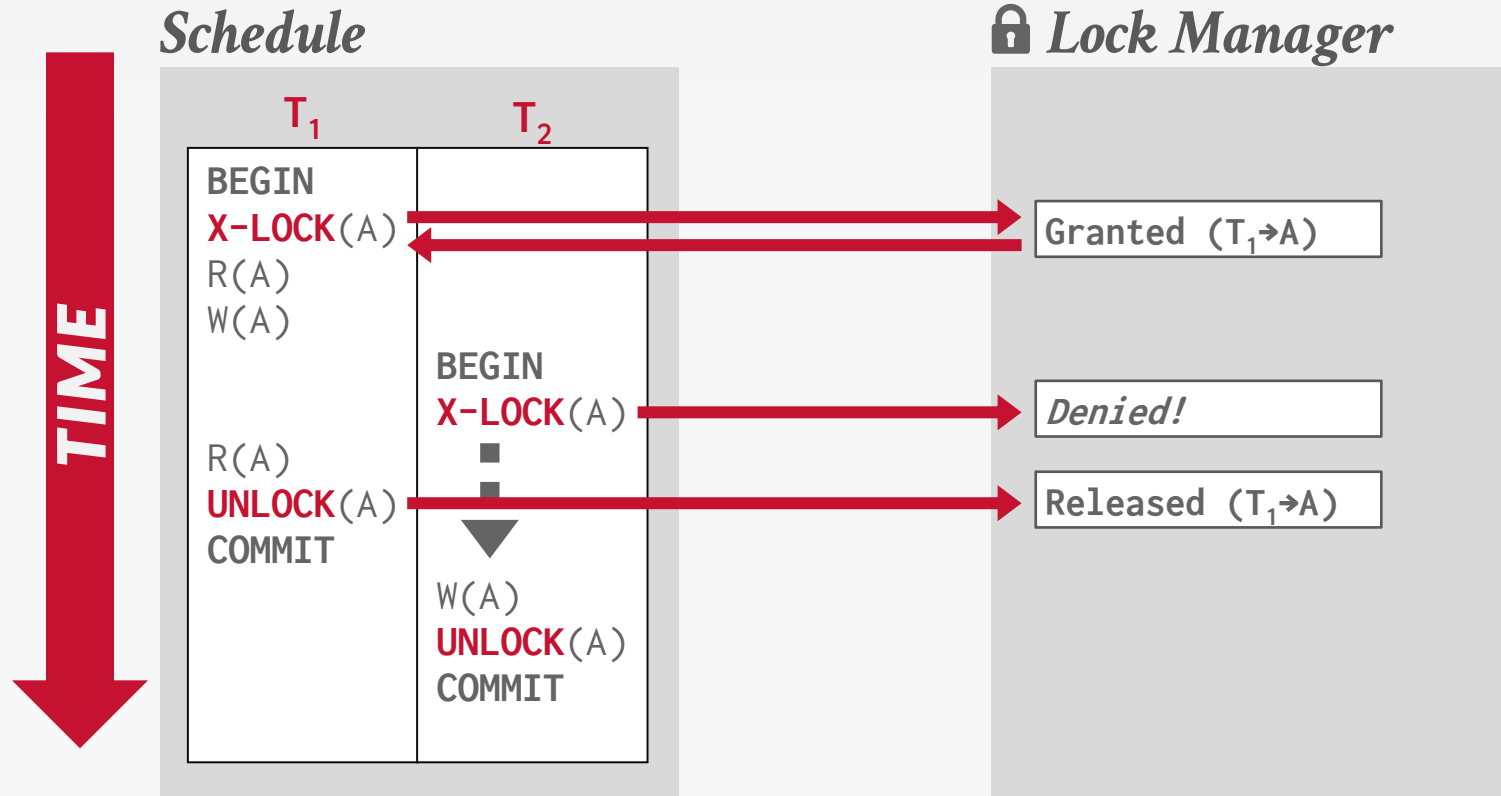
EXECUTING WITH 2PL



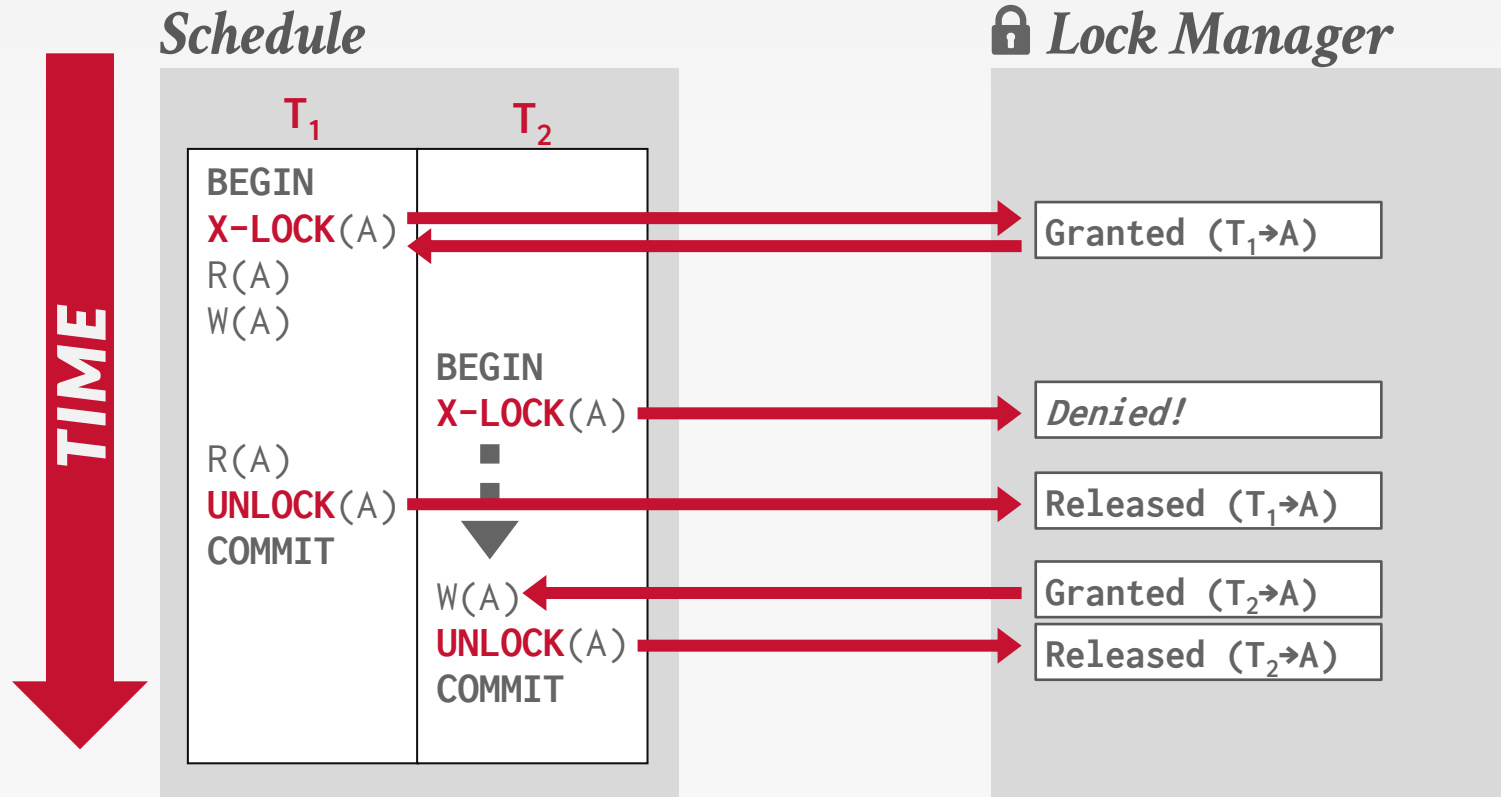
EXECUTING WITH 2PL



EXECUTING WITH 2PL



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”.

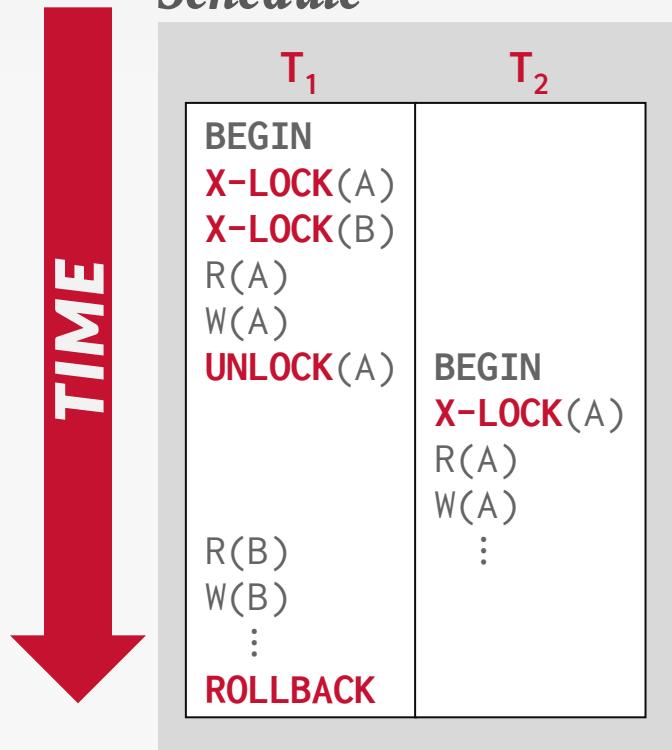
→ Solution: **2PL Variants**

2PL schedules can have deadlocks.

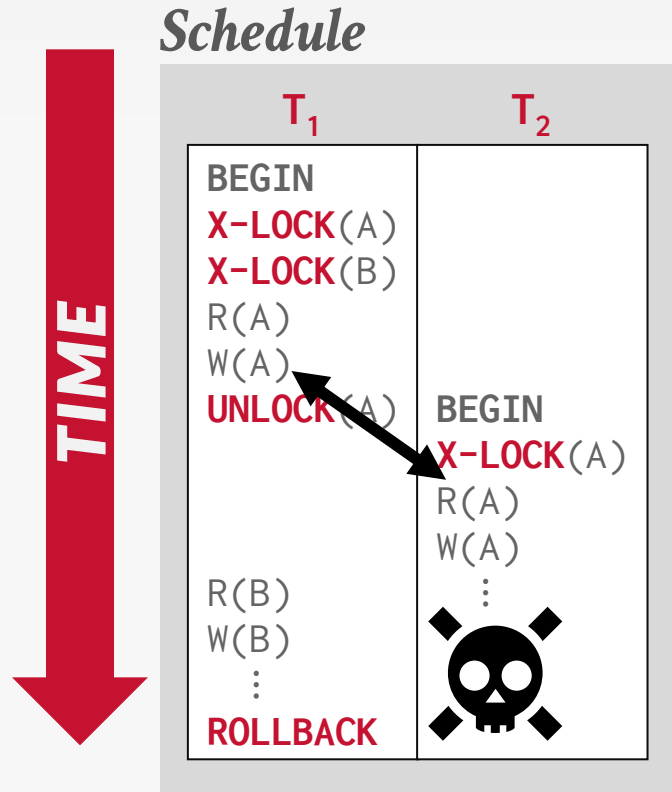
→ Solution: **Detection** or **Prevention**

2PL: CASCADING ABORTS

Schedule



2PL: CASCADING ABORTS

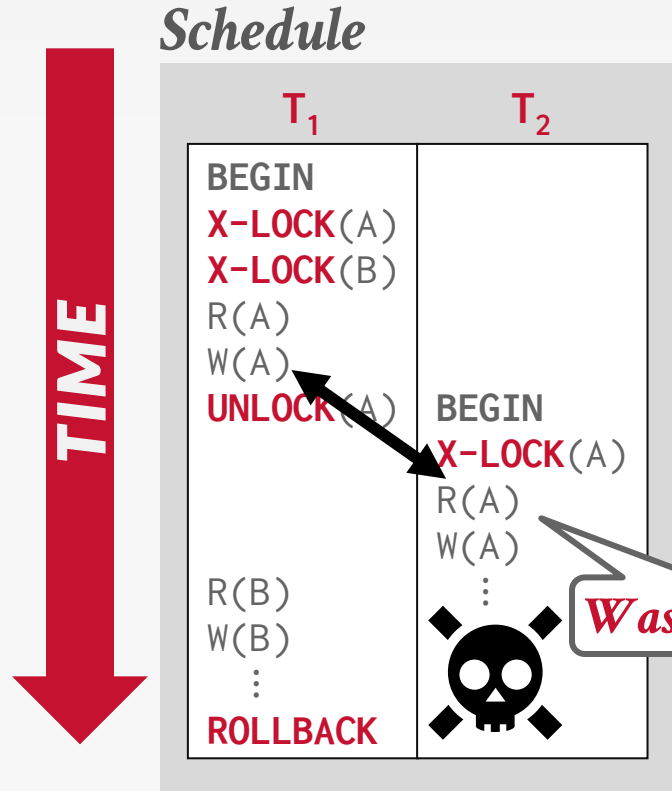


This is a permissible schedule in 2PL, but the DBMS has to also abort T_2 when T_1 aborts.

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

Any computation performed must be rolled back.

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*

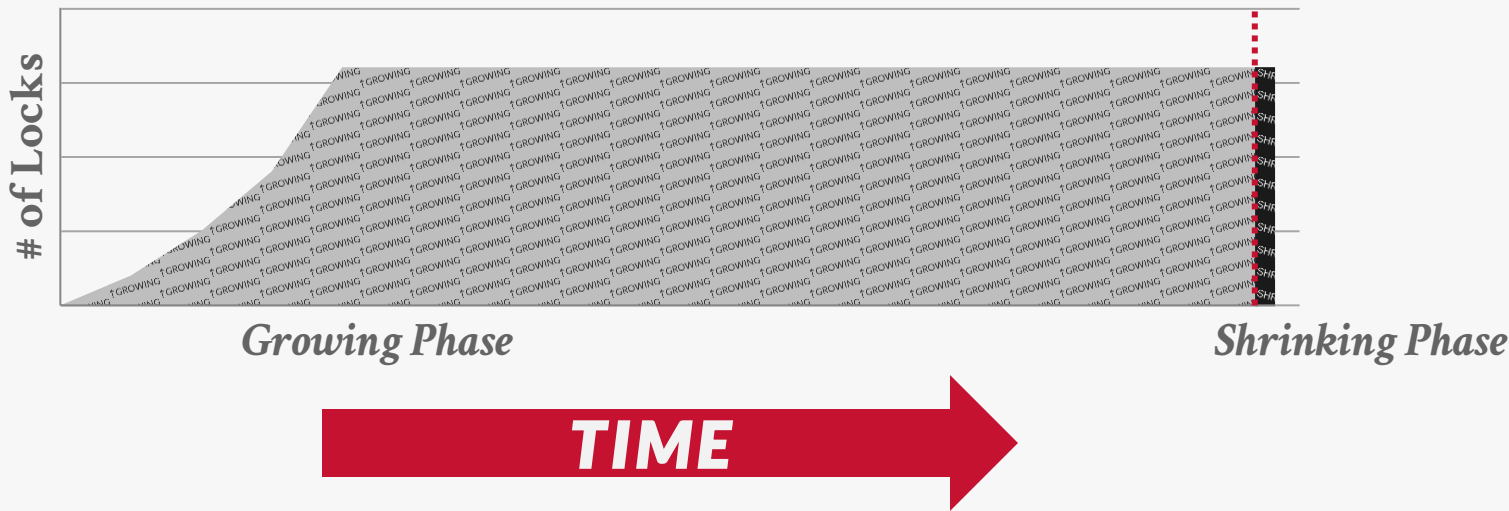
Rigorous 2PL:

- 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 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.

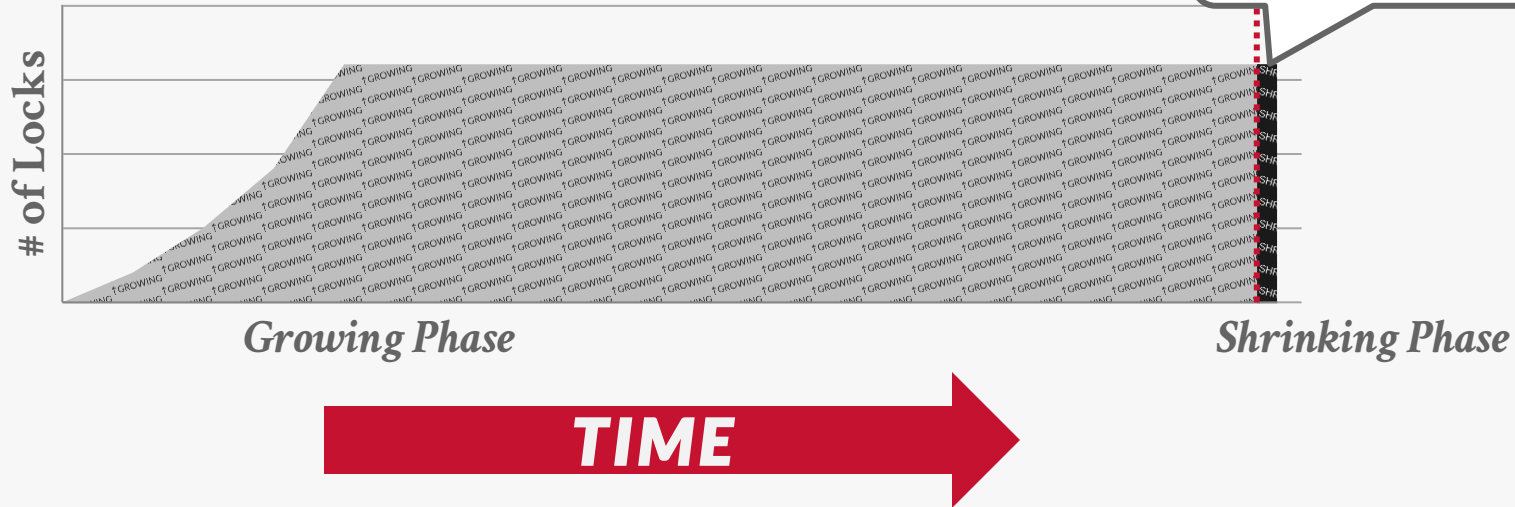


STRONG STRICT TWO-PHASE LOCKING

The txn 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.

Release all locks at end of txn.



EXAMPLES

T₁ – Move \$100 from DJ Cache's account (**A**) to his bookie's account (**B**).

T₂ – Compute the total amount in all accounts and return it to the application.

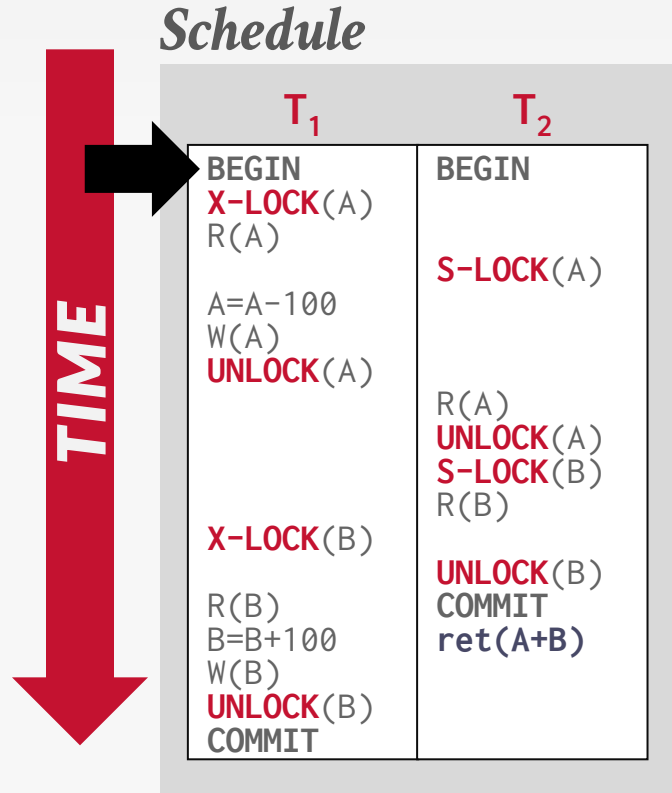
T₁

```
BEGIN
R(A)
A=A-100
W(A)
R(B)
B=B+100
W(B)
COMMIT
```

T₂

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

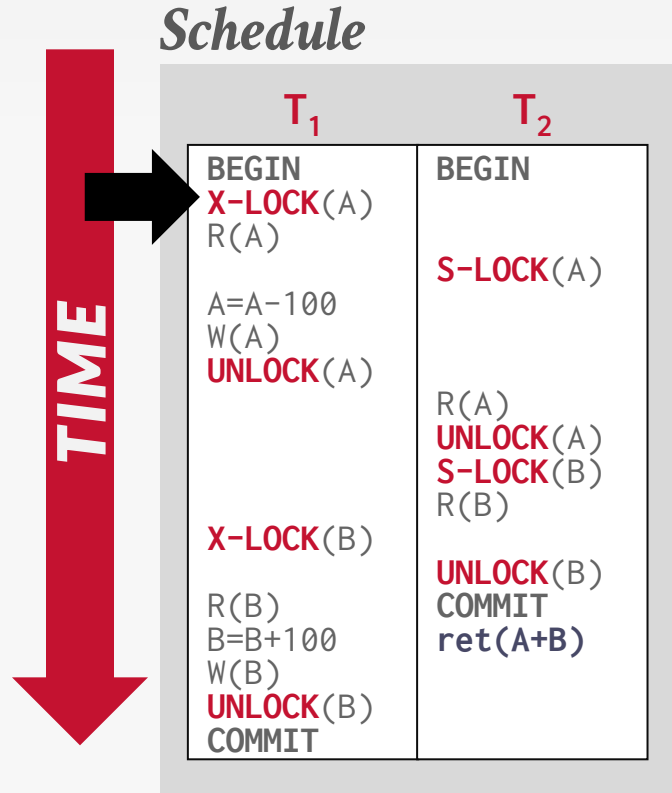
NON-2PL EXAMPLE



Initial Database State

A=1000, B=1000

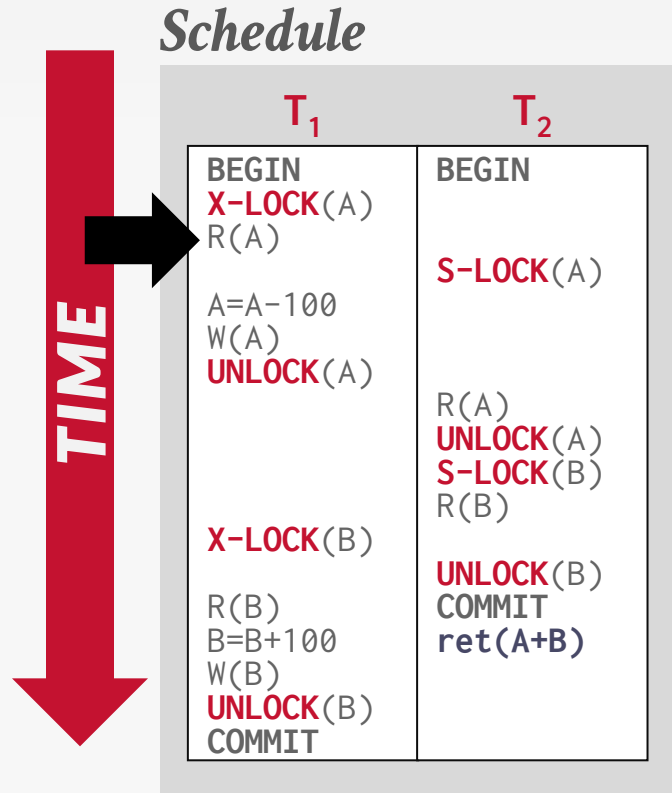
NON-2PL EXAMPLE



Initial Database State

A=1000, B=1000

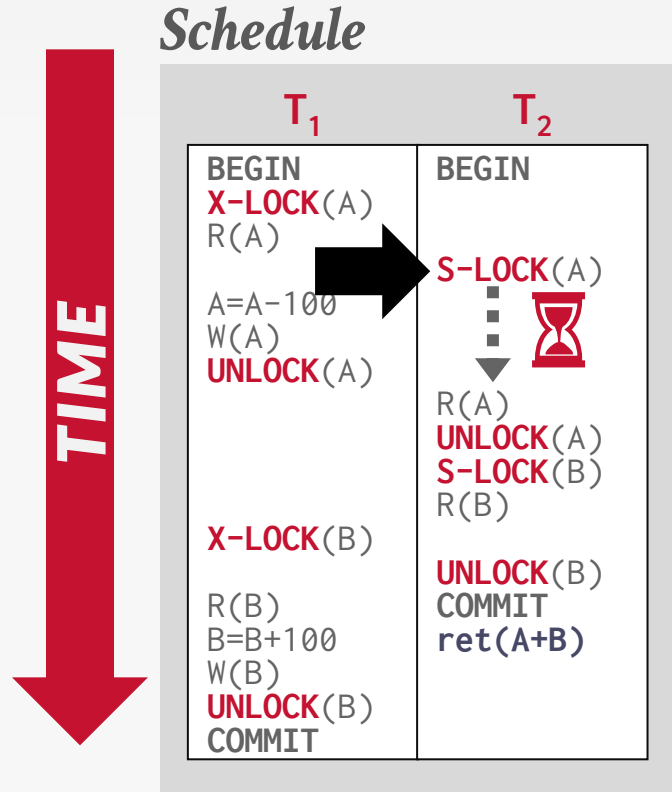
NON-2PL EXAMPLE



Initial Database State

A=1000, **B**=1000

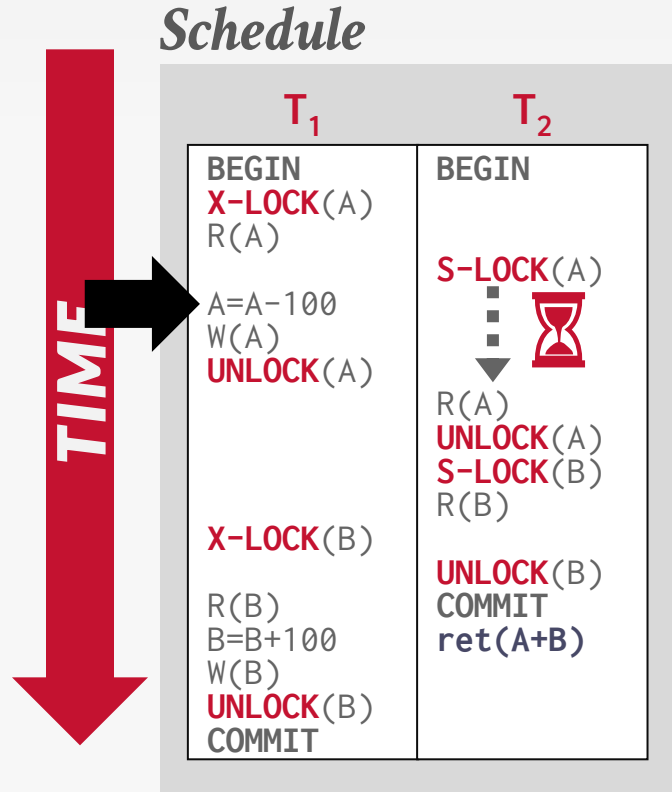
NON-2PL EXAMPLE



Initial Database State

A=1000, **B**=1000

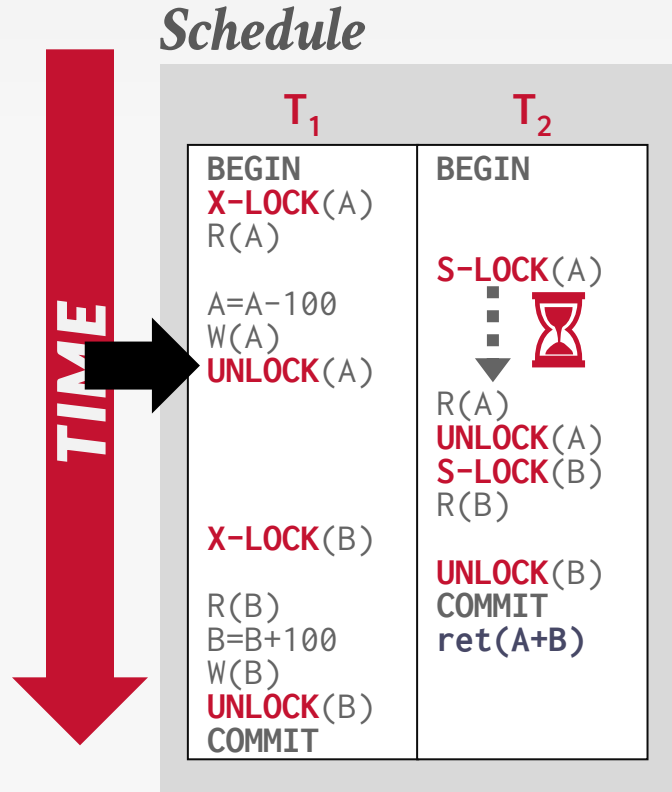
NON-2PL EXAMPLE



Initial Database State

A=1000, B=1000

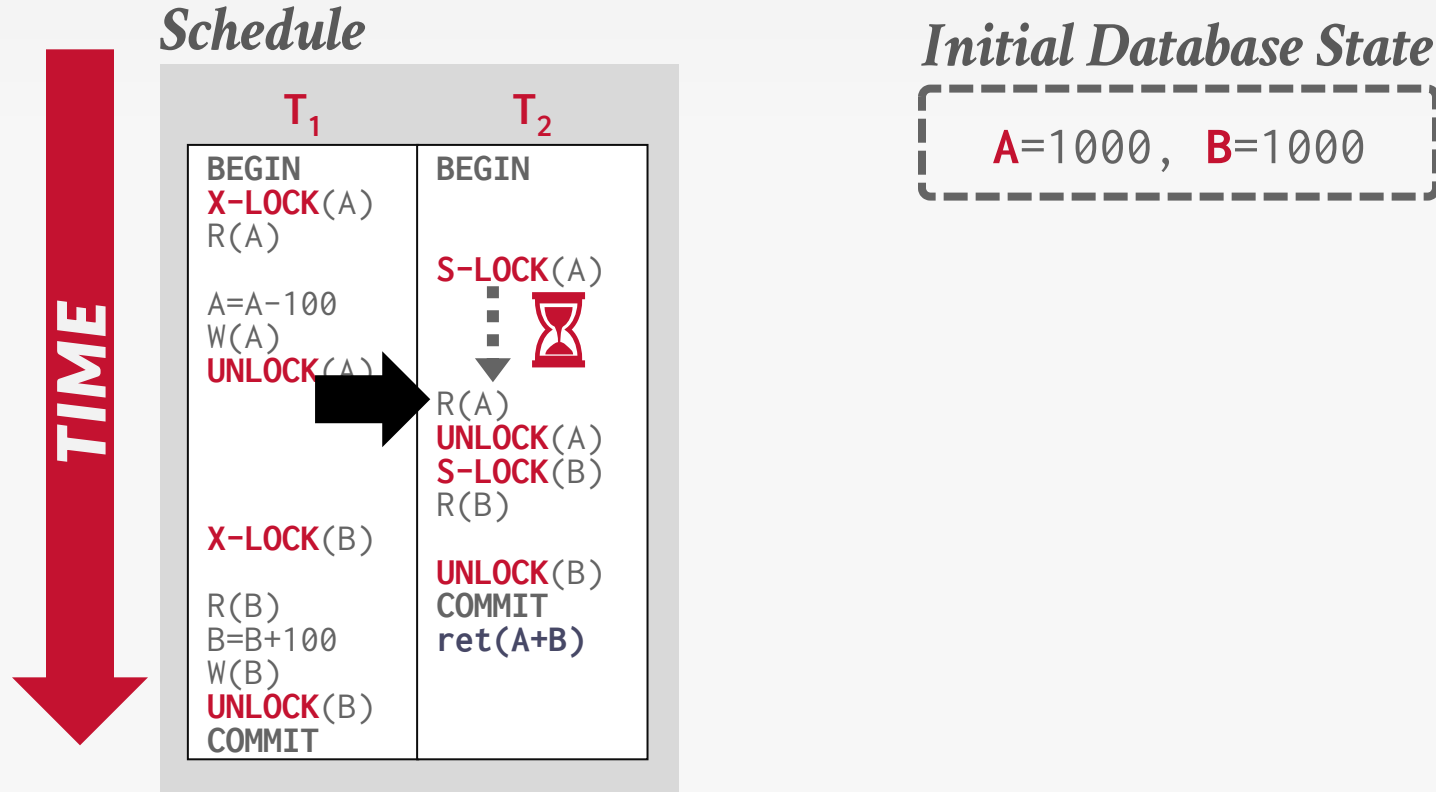
NON-2PL EXAMPLE



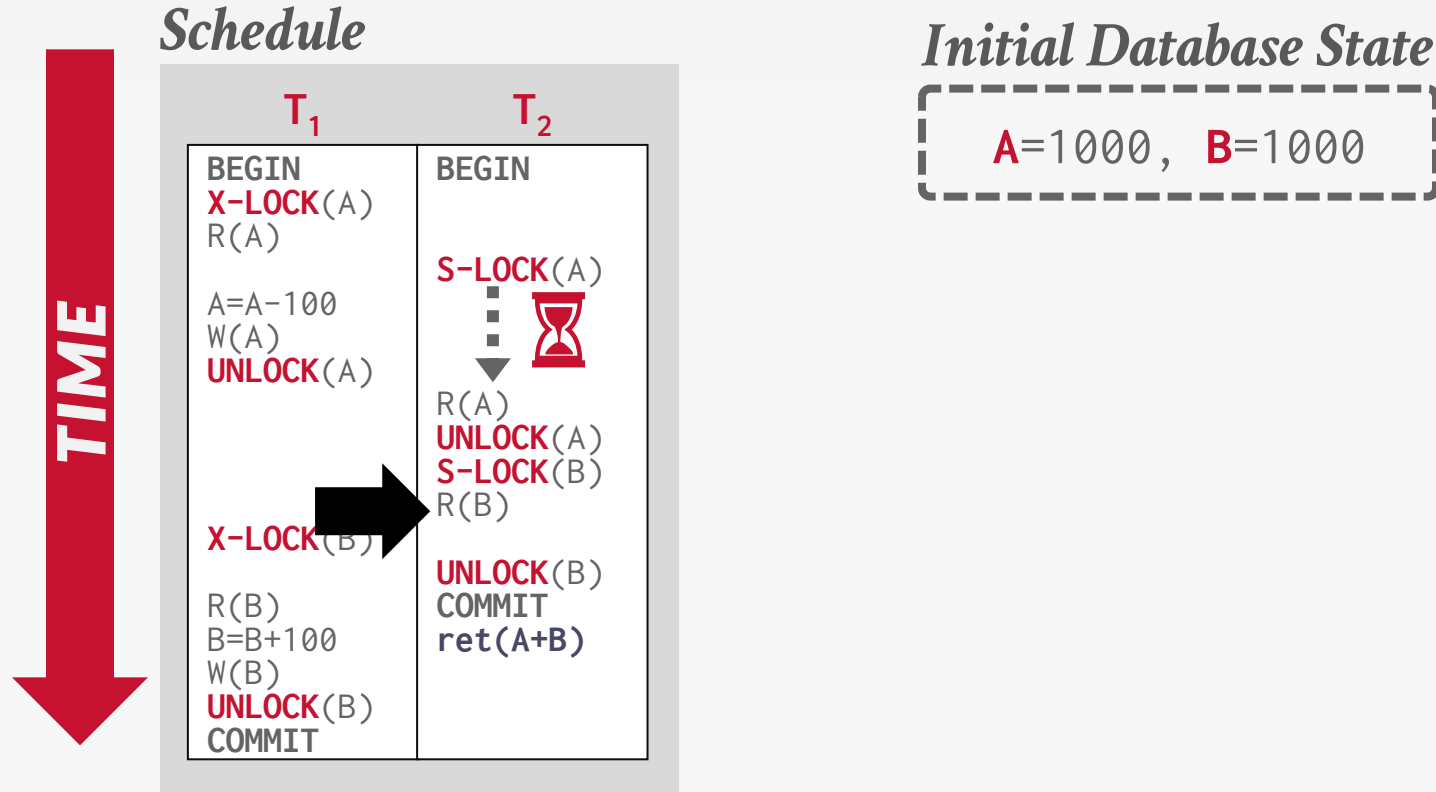
Initial Database State

A=1000, B=1000

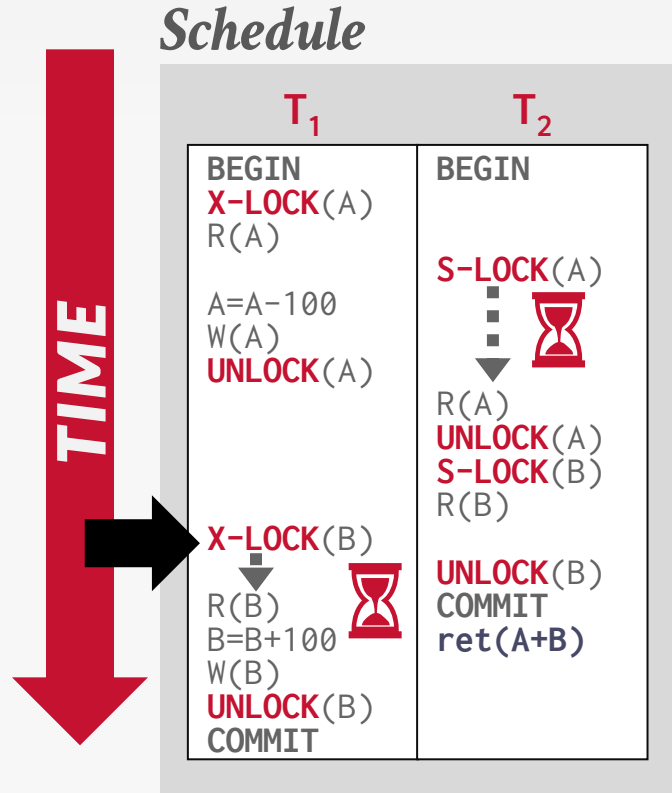
NON-2PL EXAMPLE



NON-2PL EXAMPLE



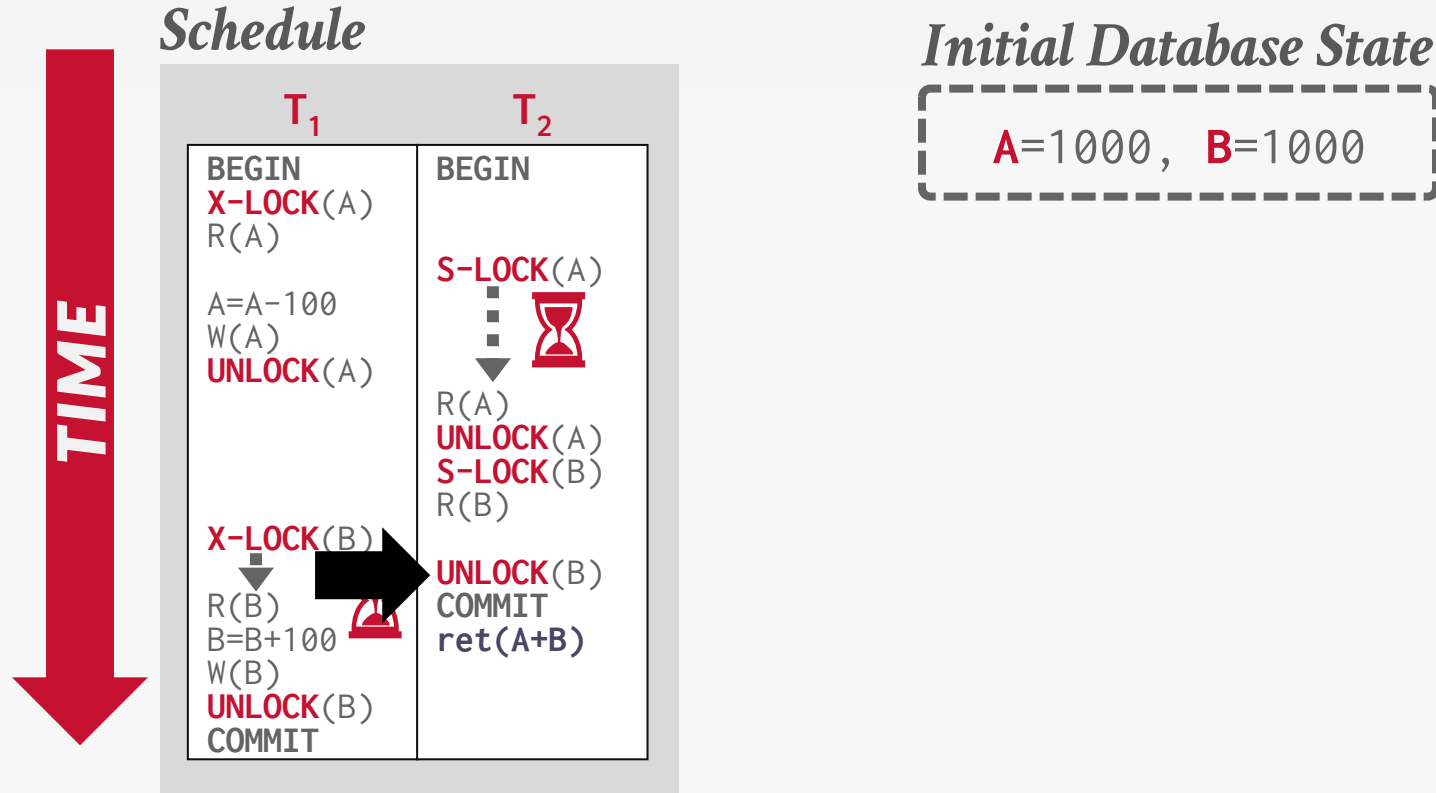
NON-2PL EXAMPLE



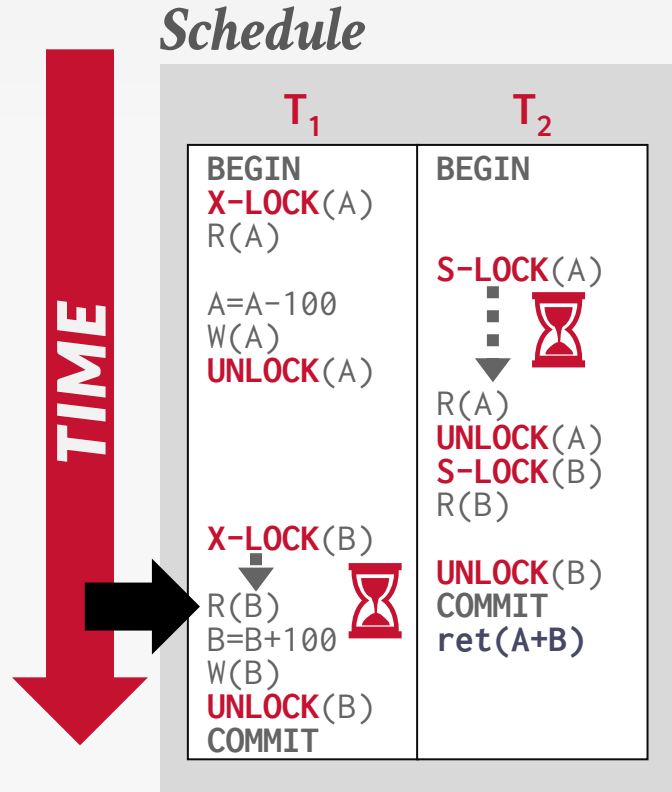
Initial Database State

A=1000, B=1000

NON-2PL EXAMPLE



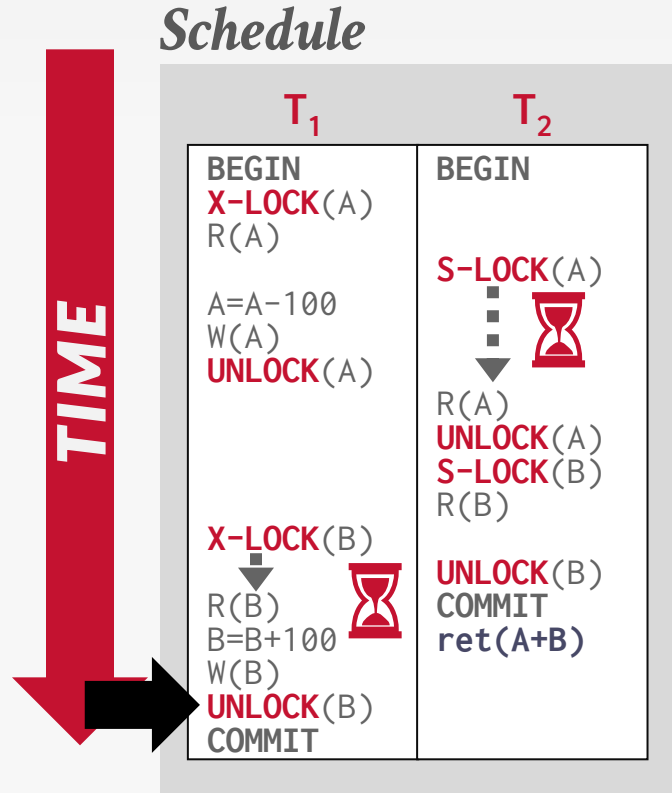
NON-2PL EXAMPLE



Initial Database State

A=1000, B=1000

NON-2PL EXAMPLE



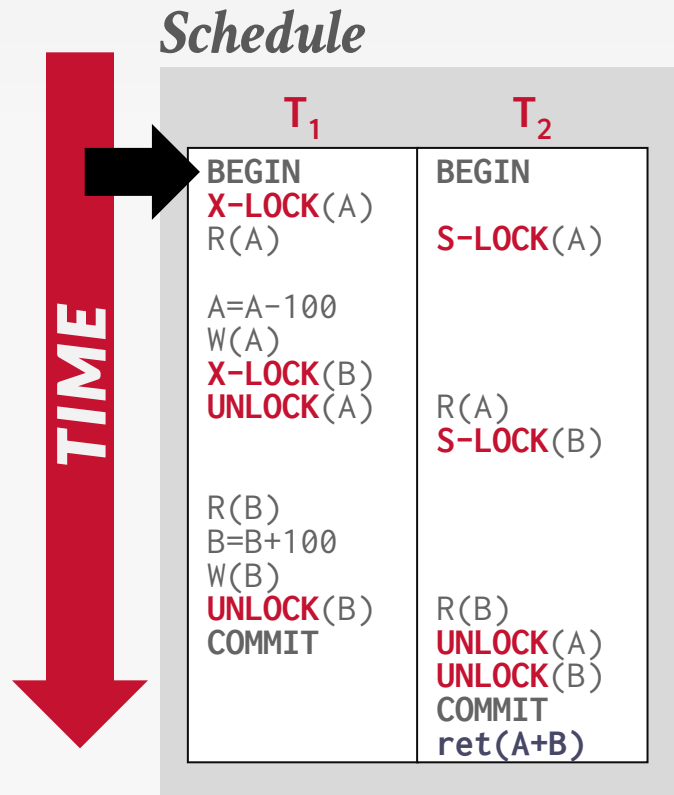
Initial Database State

A=1000, B=1000

T_2 Output

A+B=1900

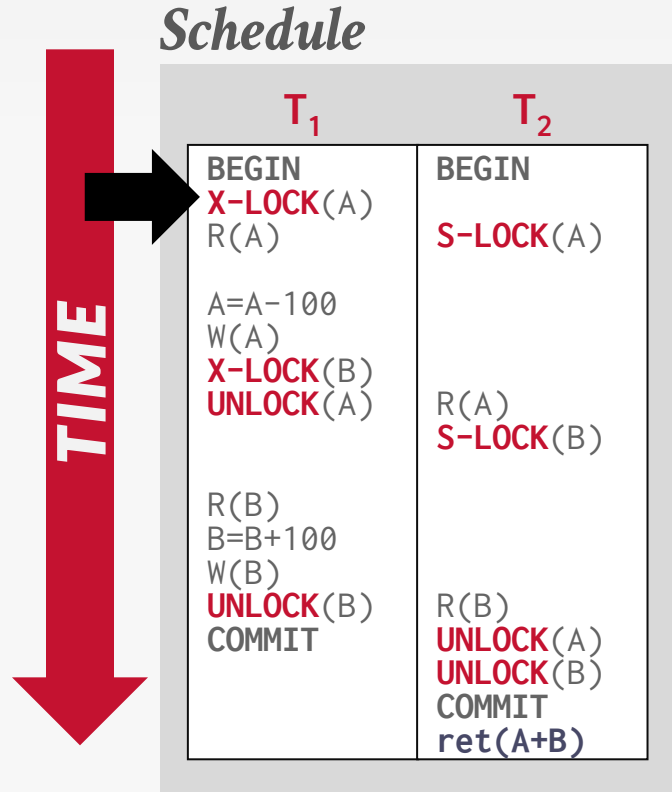
2PL EXAMPLE



Initial Database State

A=1000, B=1000

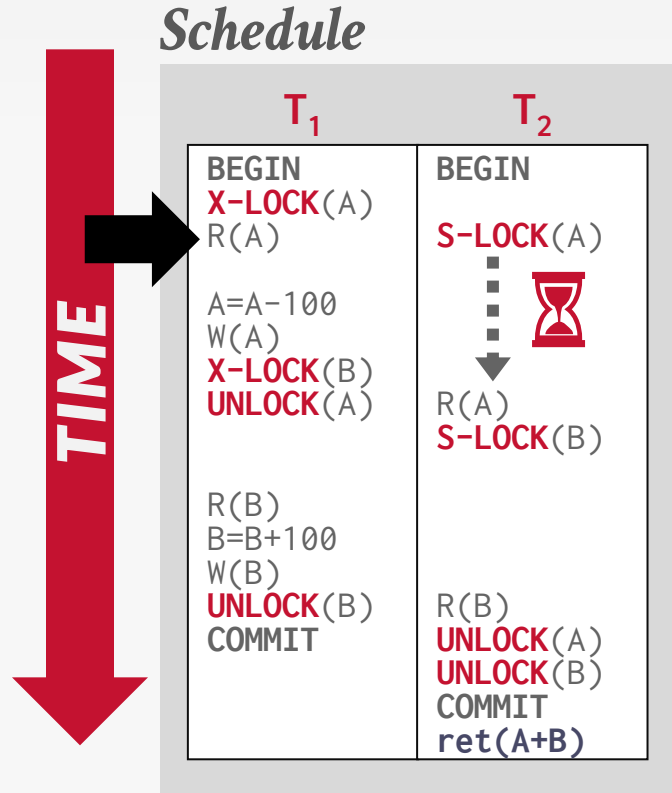
2PL EXAMPLE



Initial Database State

A=1000, **B**=1000

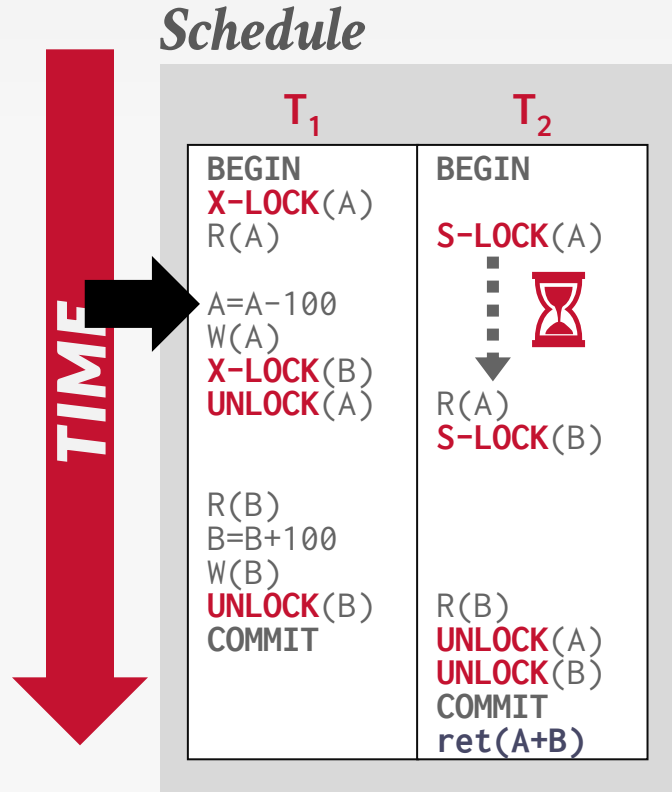
2PL EXAMPLE



Initial Database State

A=1000, **B**=1000

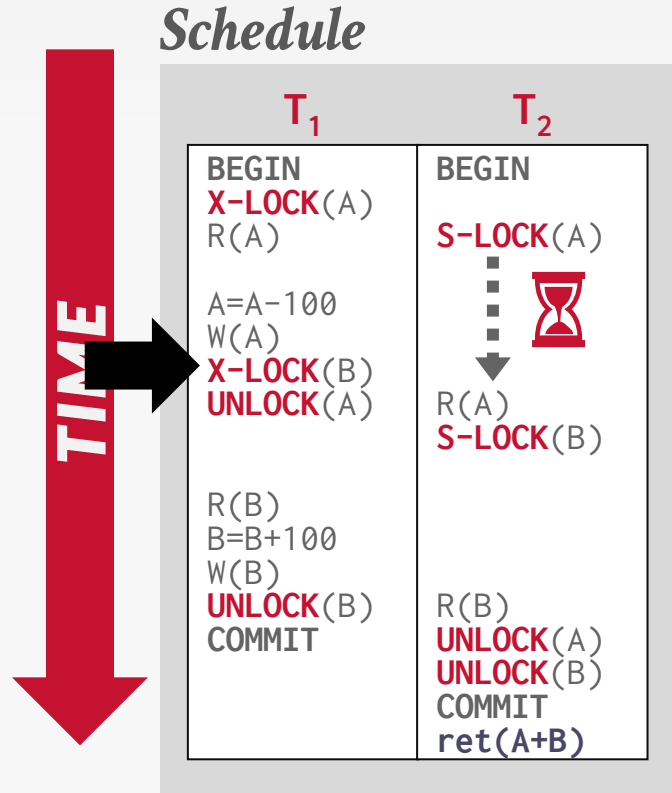
2PL EXAMPLE



Initial Database State

A=1000, **B**=1000

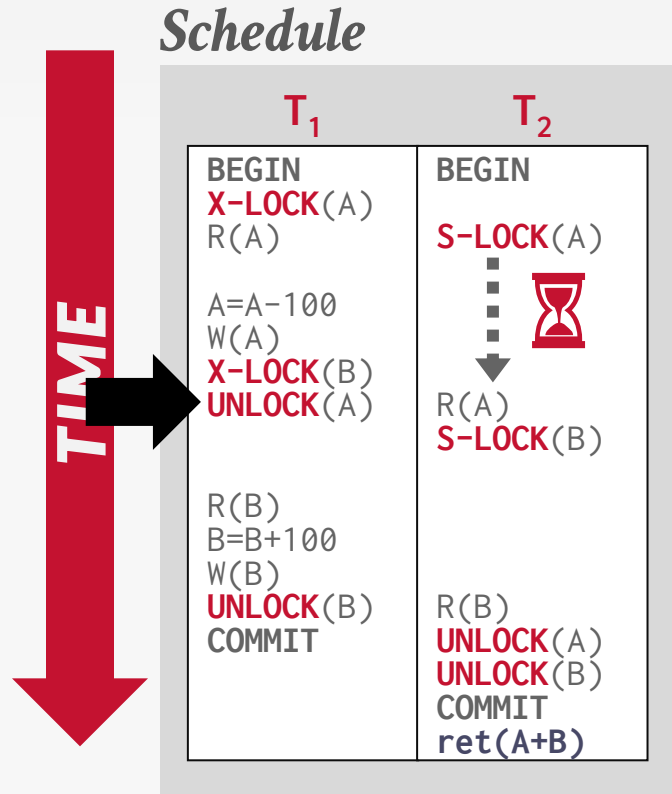
2PL EXAMPLE



Initial Database State

A=1000, B=1000

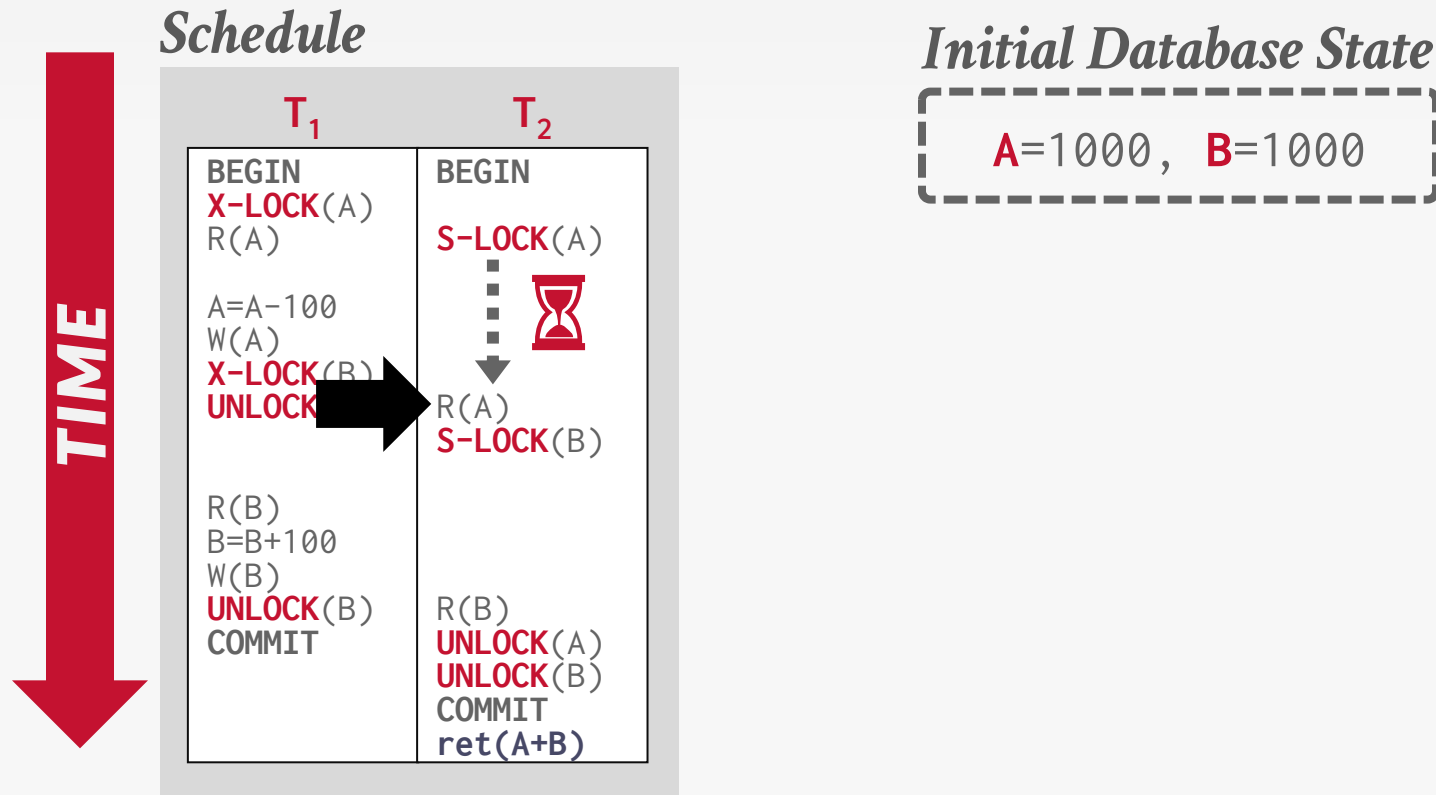
2PL EXAMPLE



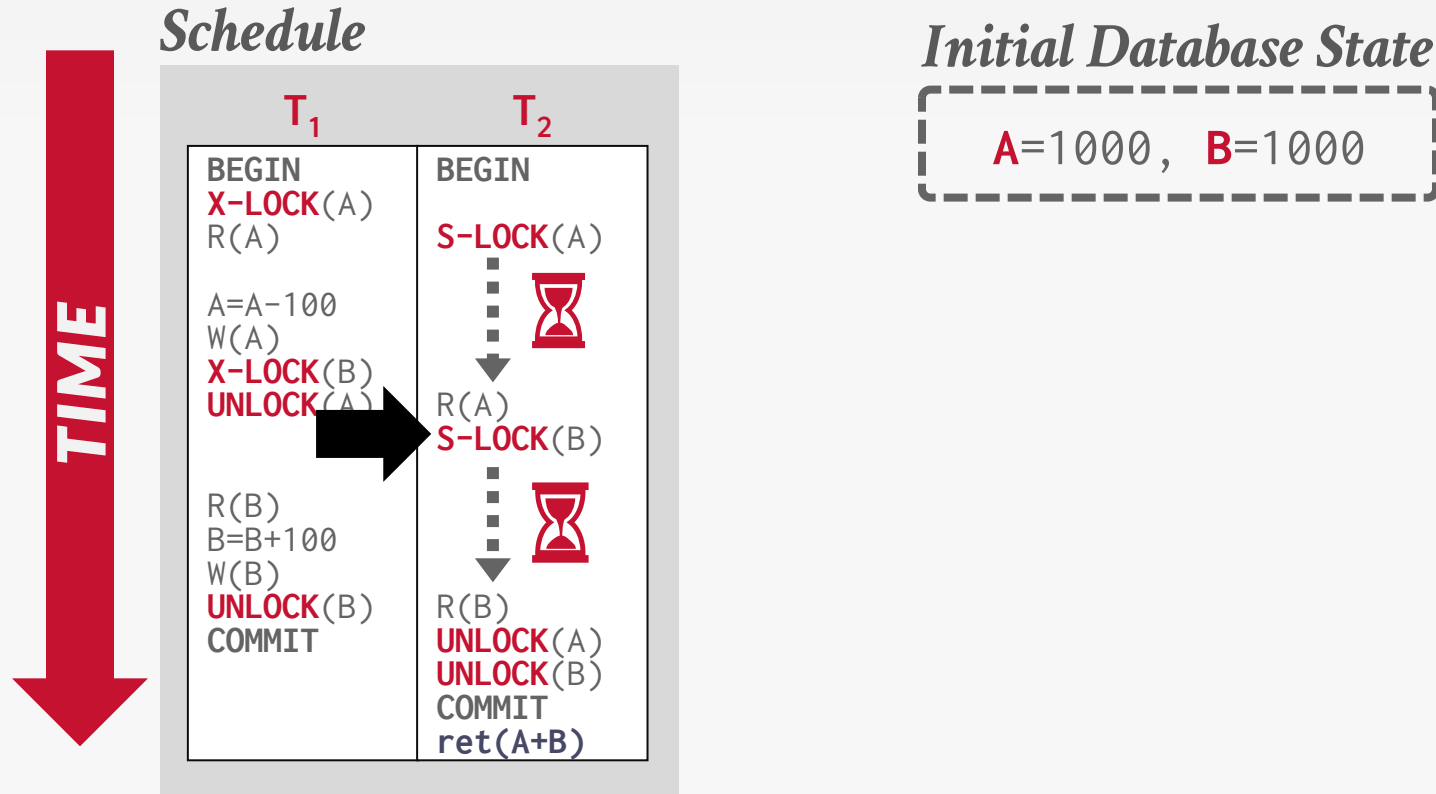
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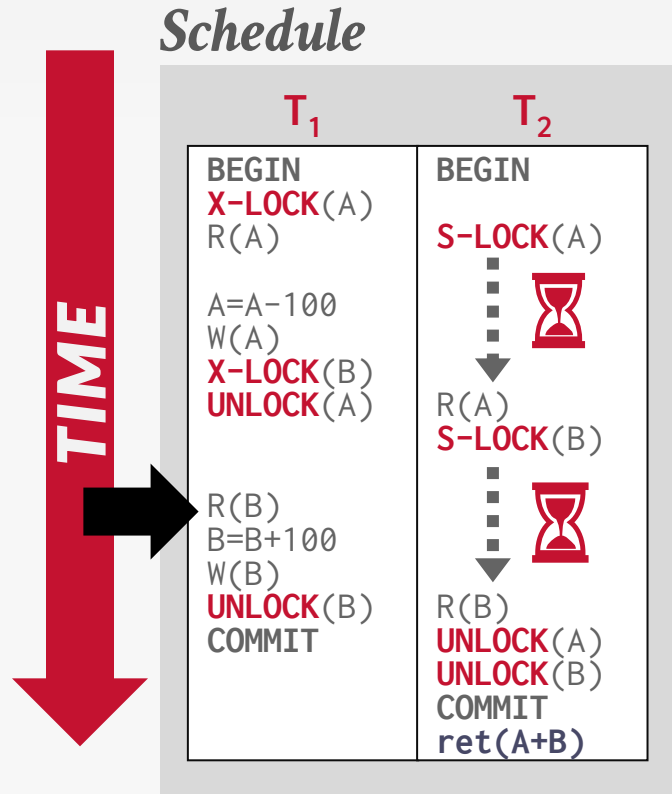
2PL EXAMPLE



2PL EXAMPLE



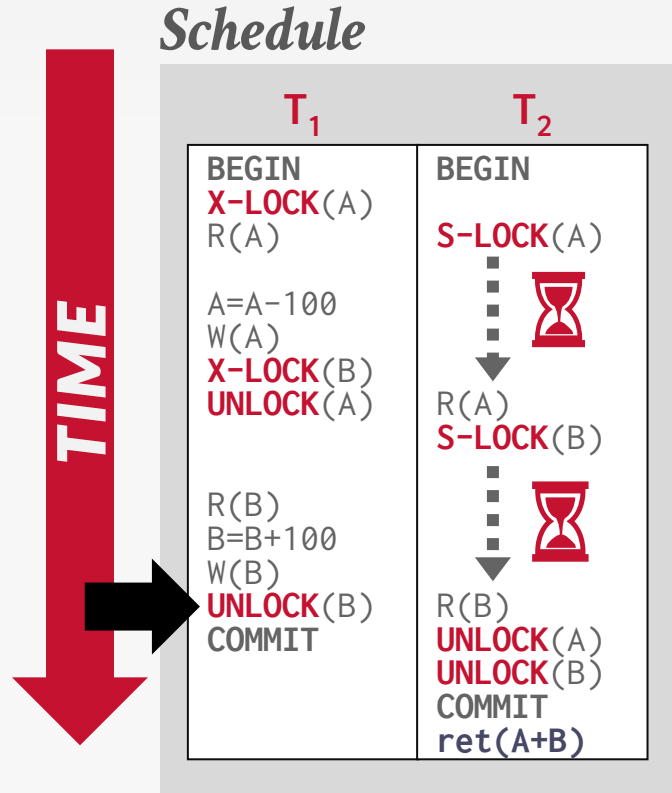
2PL EXAMPLE



Initial Database State

A=1000, B=1000

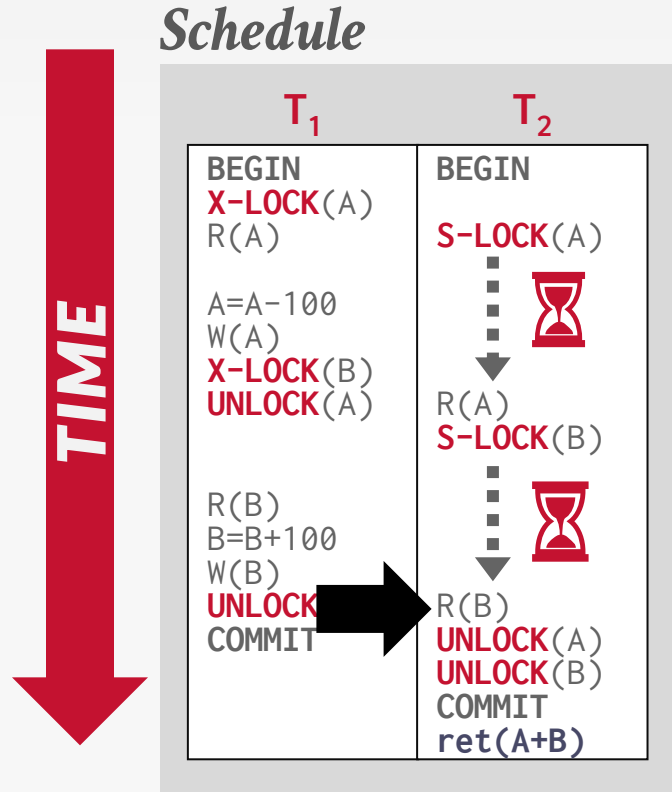
2PL EXAMPLE



Initial Database State

A=1000, B=1000

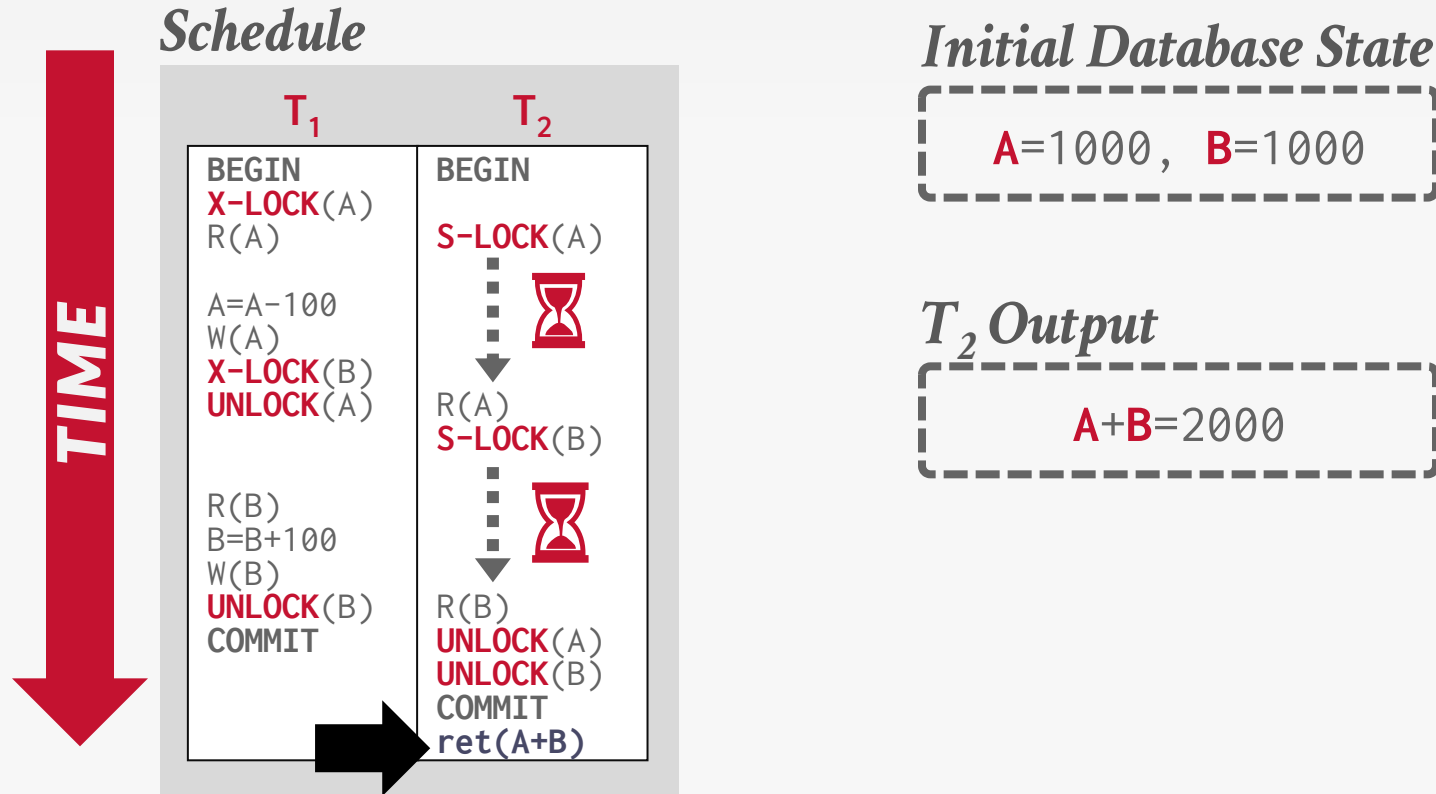
2PL EXAMPLE



Initial Database State

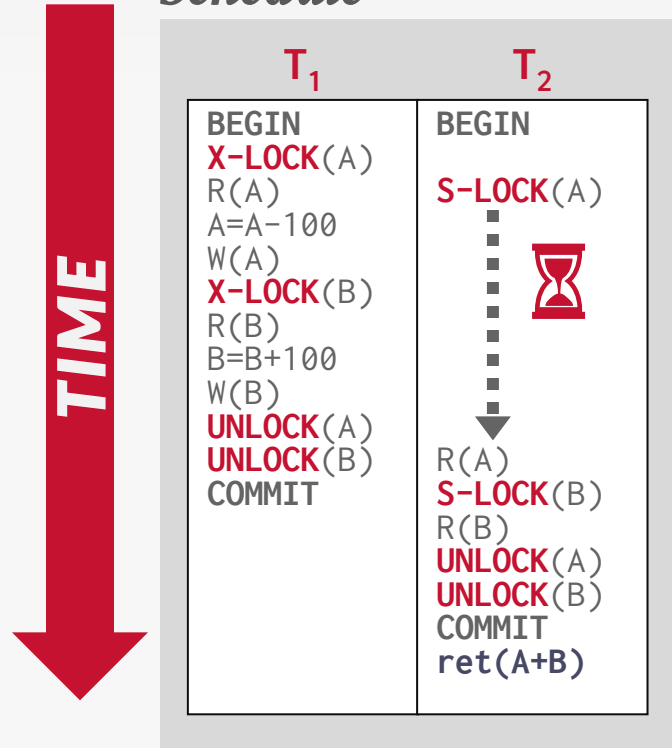
A=1000, **B**=1000

2PL EXAMPLE



STRONG STRICT 2PL EXAMPLE

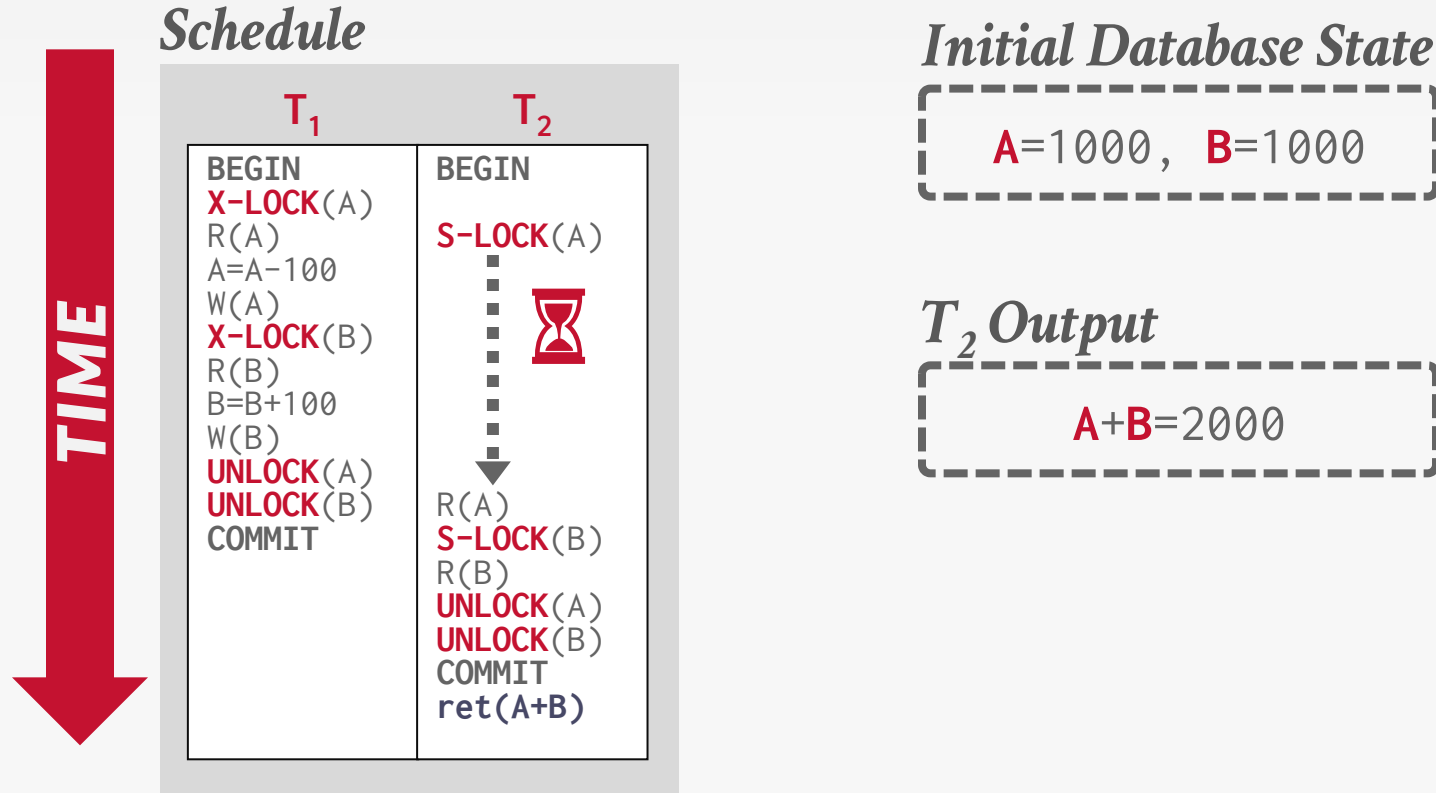
Schedule



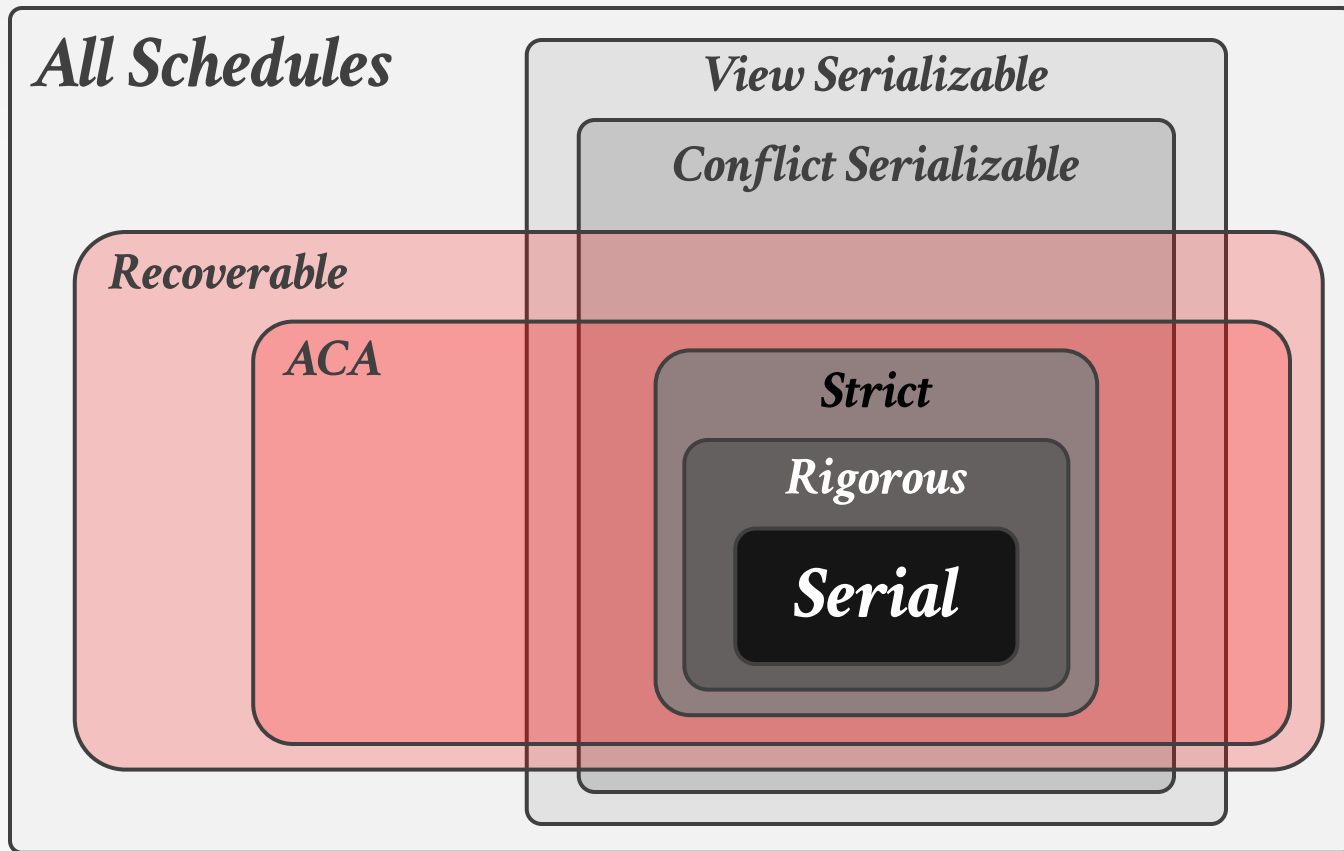
Initial Database State

A=1000, B=1000

STRONG STRICT 2PL EXAMPLE



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.

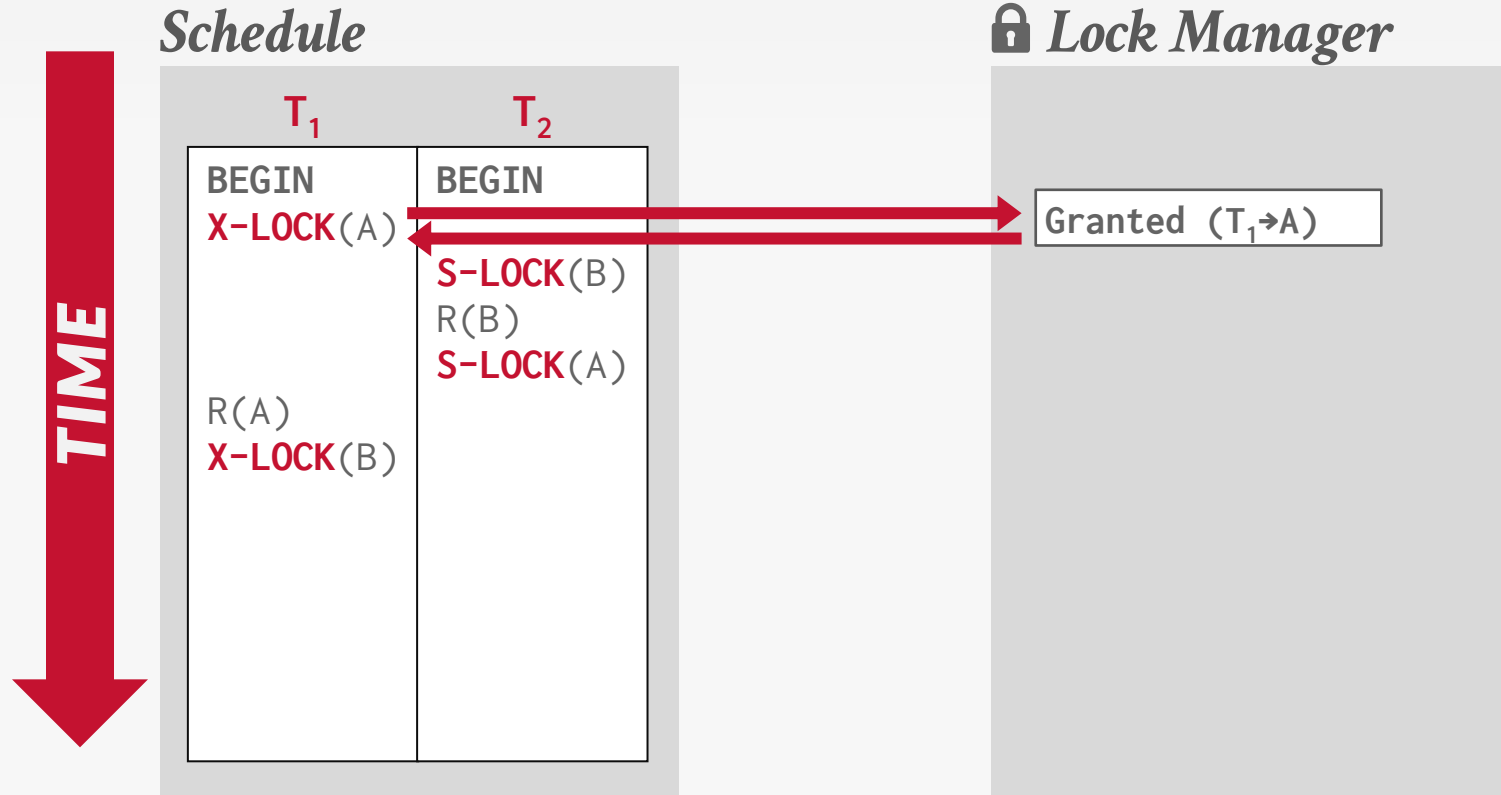
2PL schedules can have “dirty reads”.

→ Solution: **2PL Variants**

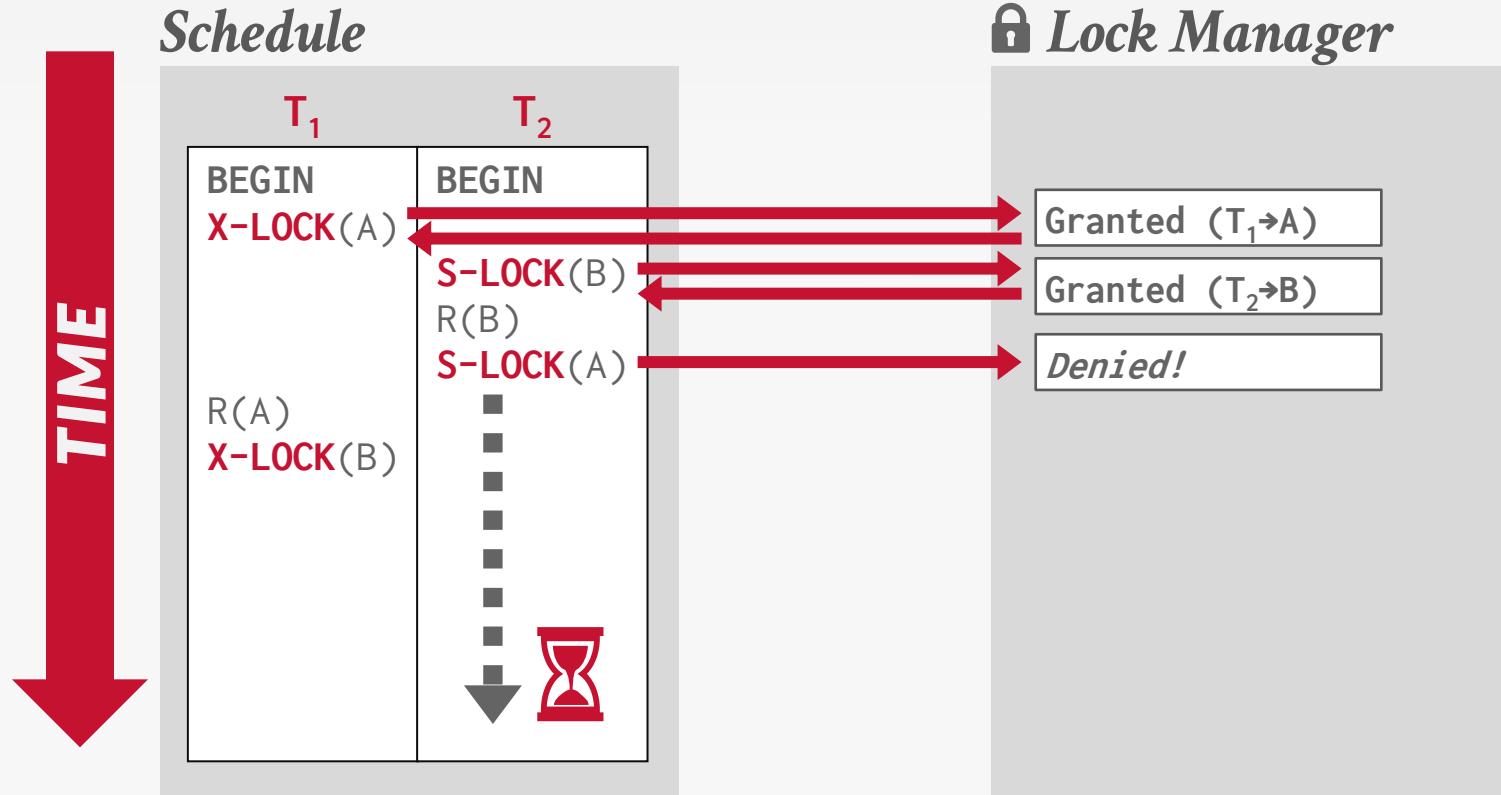
2PL schedules can have deadlocks.

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

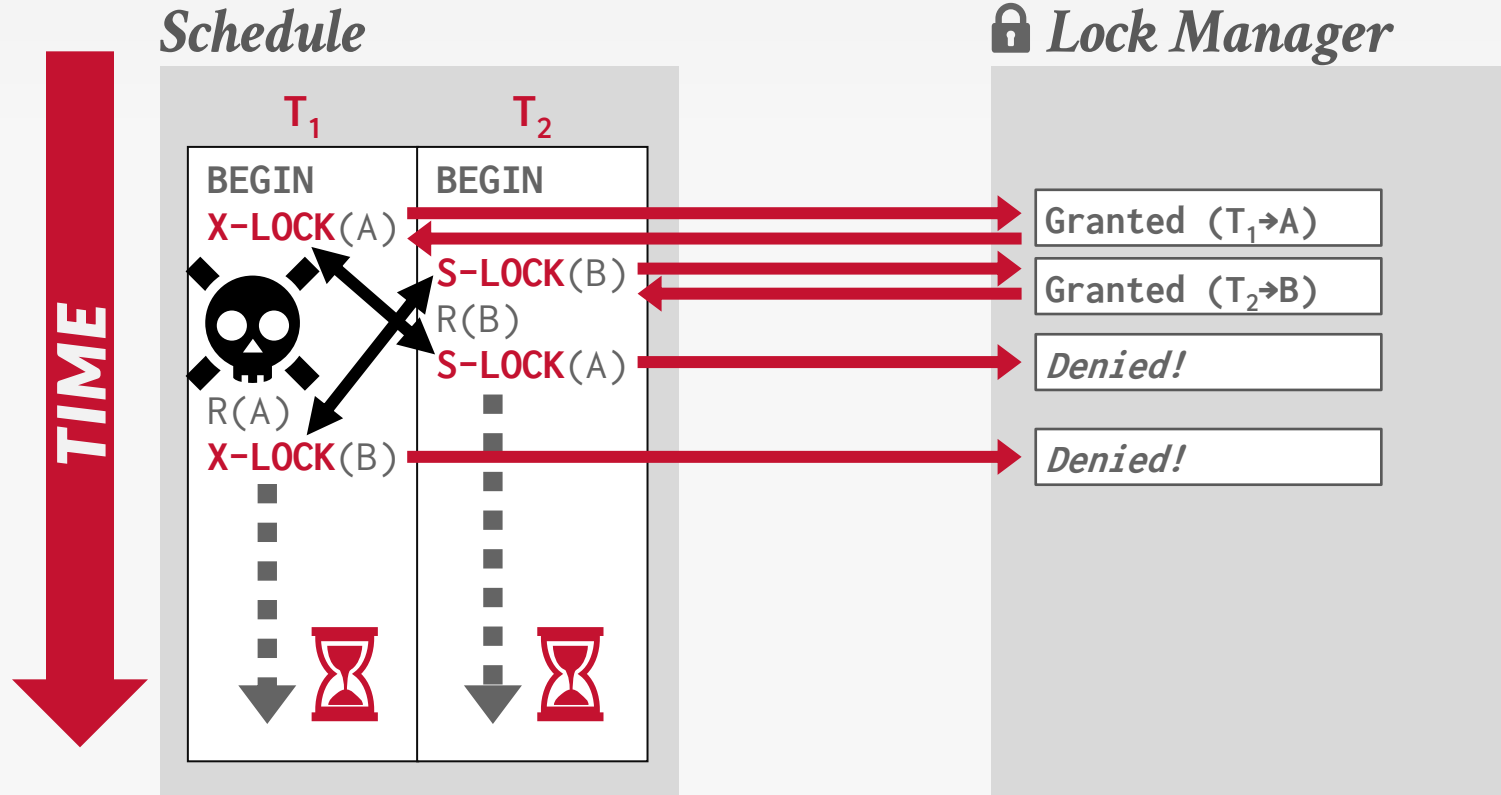
IT JUST GOT REAL



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

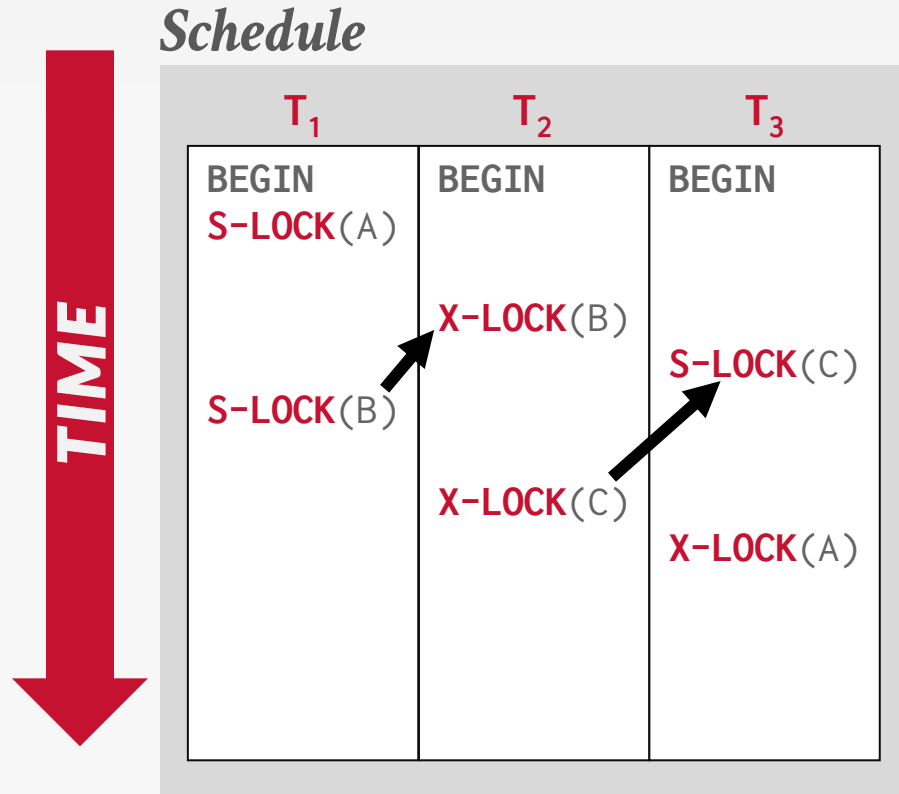
The DBMS creates a waits-for graph to keep track of what locks each txn is waiting to acquire:

- Nodes are transactions
- Edge from T_i to T_j if T_i is waiting for T_j to release a lock.

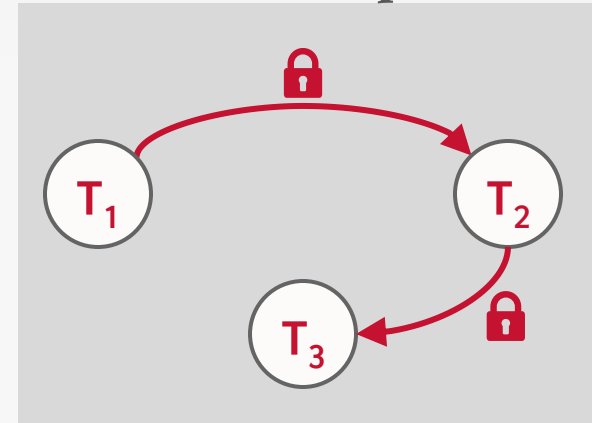
The system periodically checks for cycles in *waits-for* graph and then decides how to break it.

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

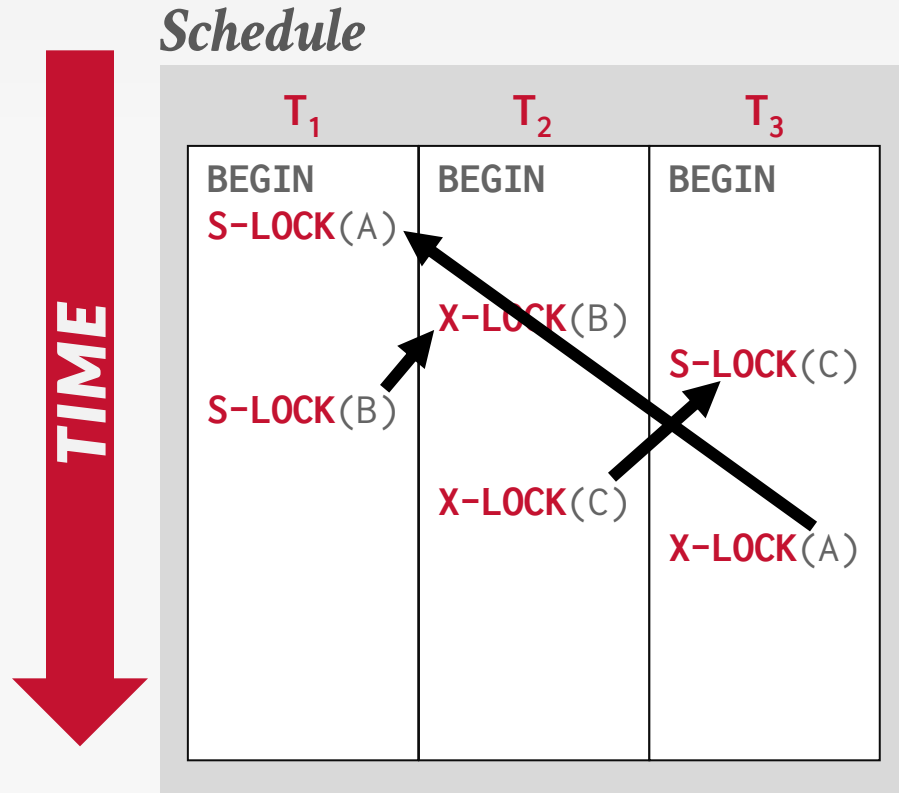
DEADLOCK DETECTION



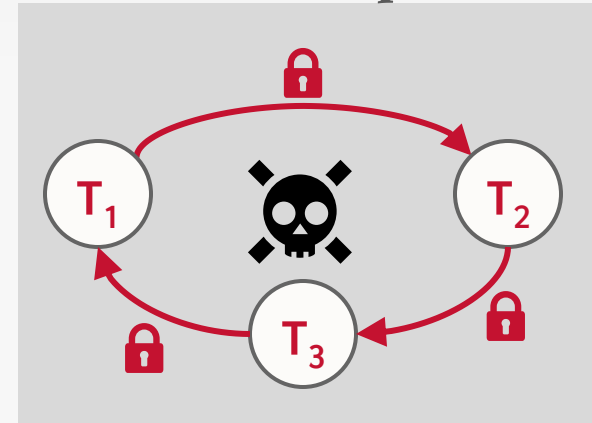
Waits-For Graph



DEADLOCK DETECTION



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*.

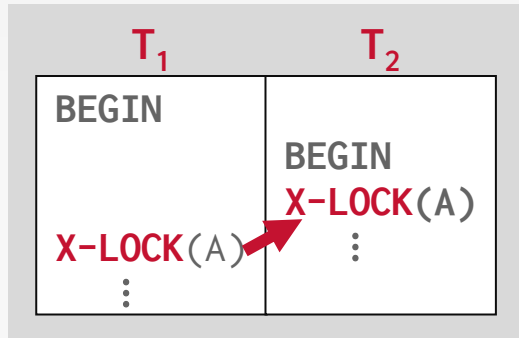
→ Otherwise *requesting txn* aborts.

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.

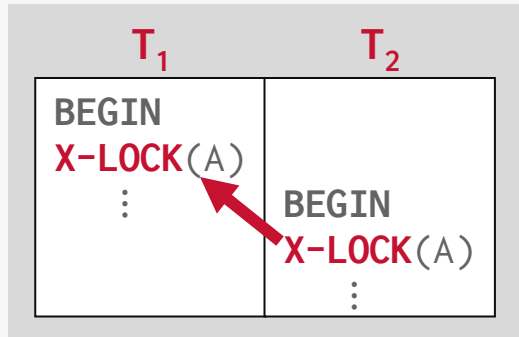
DEADLOCK PREVENTION



Wait-Die



Wound-Wait



Wait-Die



Wound-Wait



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 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?

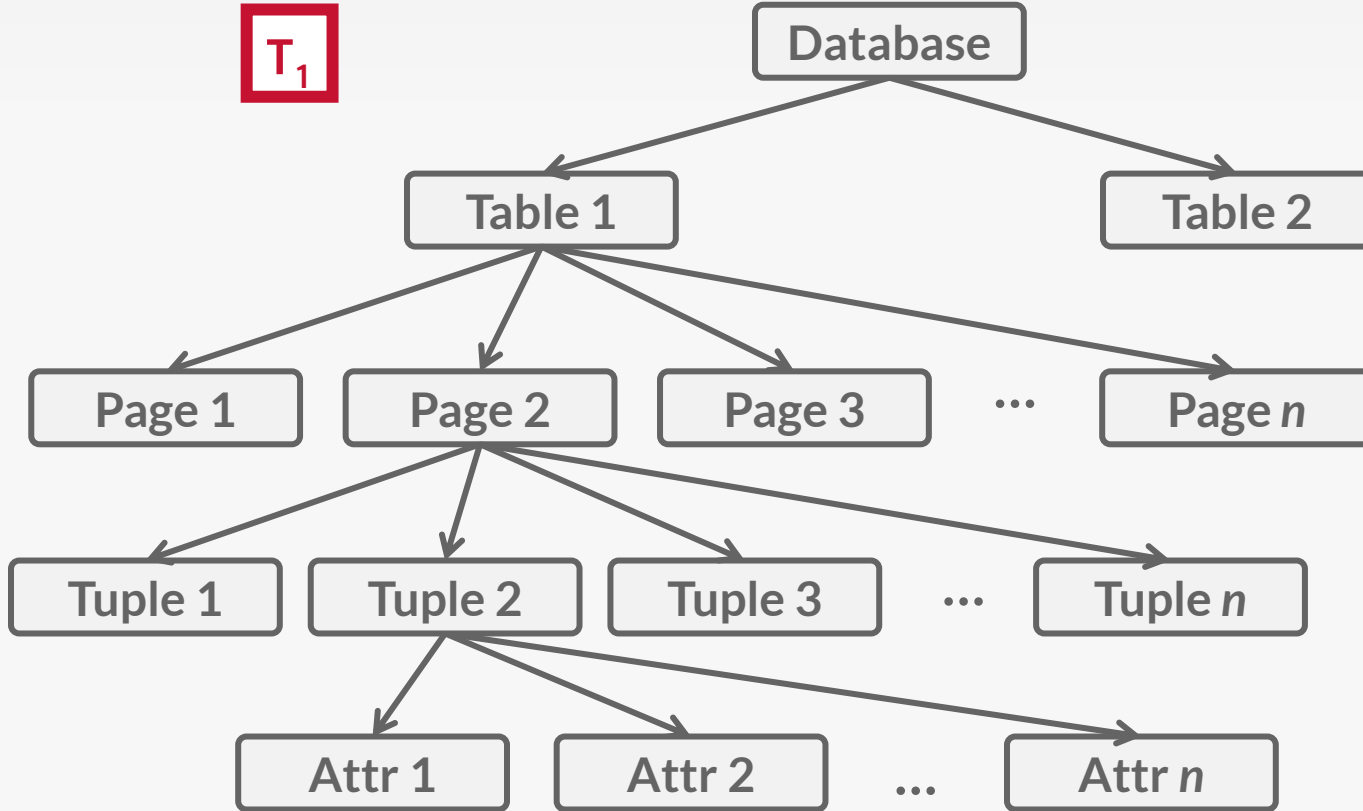
The DBMS should ideally obtain fewest number of locks that a txn needs.

Trade-off between parallelism versus overhead.

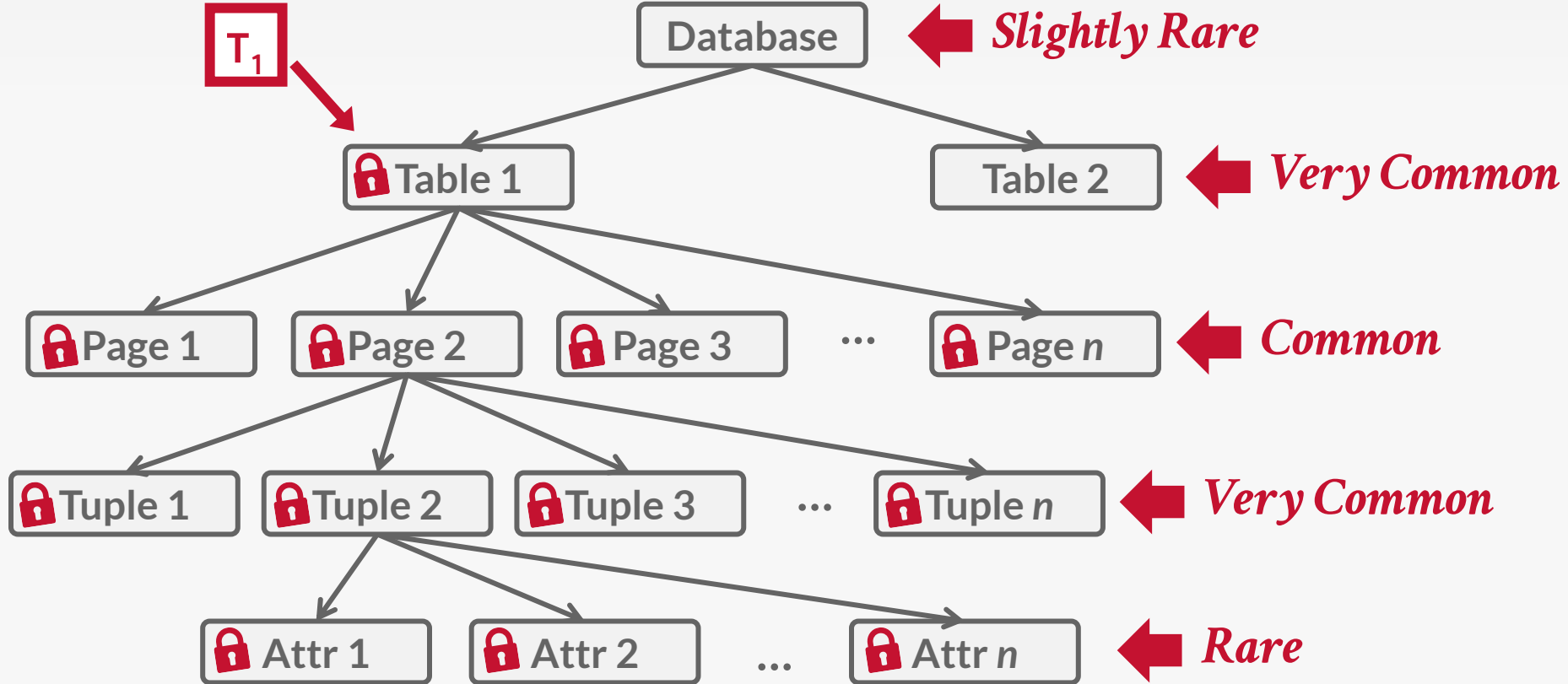
→ Fewer Locks, Larger Granularity vs.
More Locks, Smaller Granularity.

DATABASE LOCK HIERARCHY

T₁



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

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%.

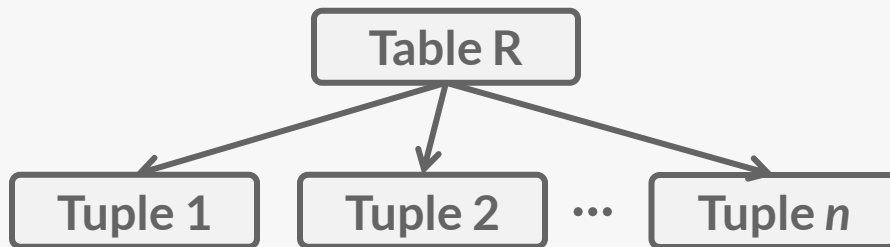
What locks should these txns obtain?

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

EXAMPLE: TWO-LEVEL HIERARCHY

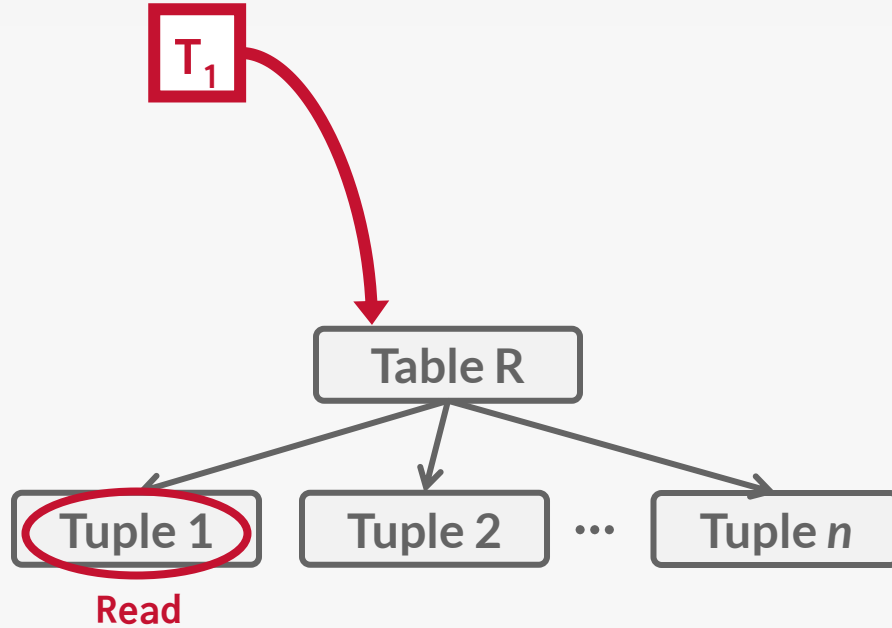
Read DJ Cache's record in R.

T₁



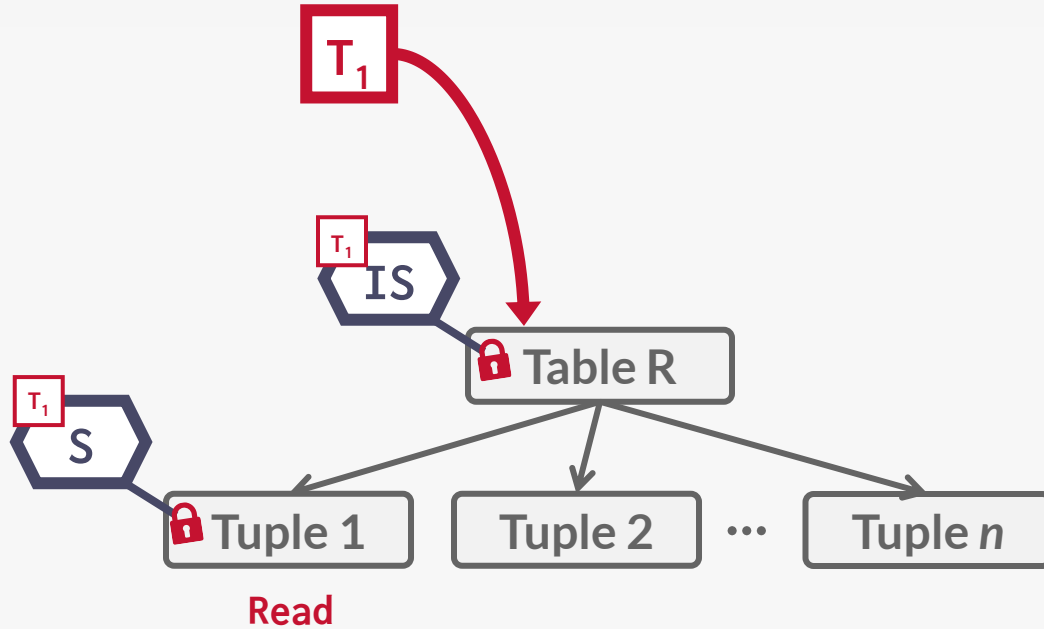
EXAMPLE: TWO-LEVEL HIERARCHY

Read DJ Cache's record in R.



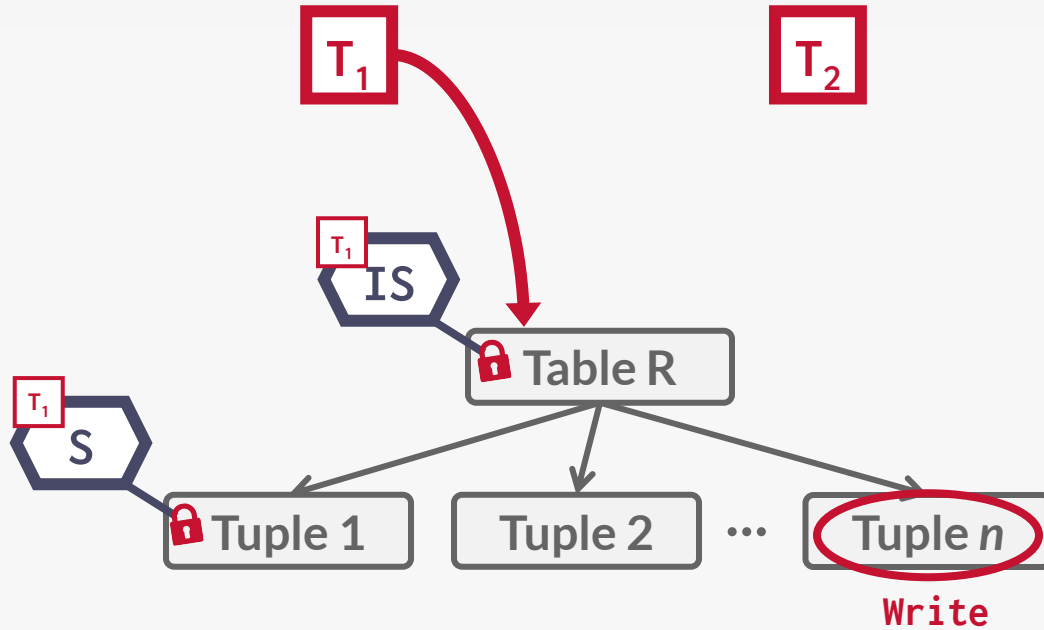
EXAMPLE: TWO-LEVEL HIERARCHY

Read DJ Cache's record in R.



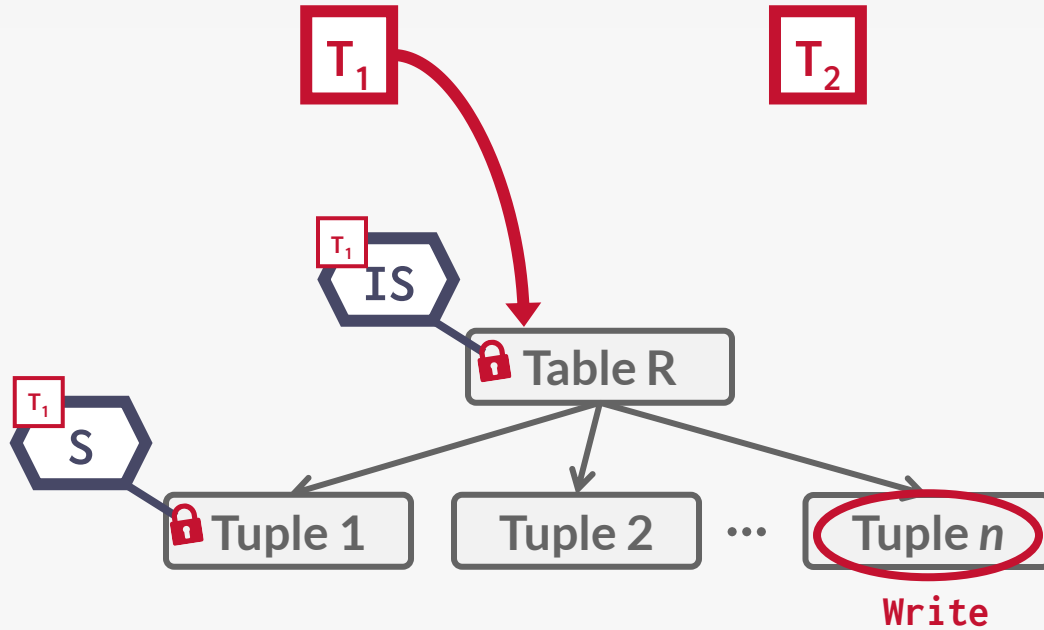
EXAMPLE: TWO-LEVEL HIERARCHY

Update bookie's record in R.



EXAMPLE: TWO-LEVEL HIERARCHY

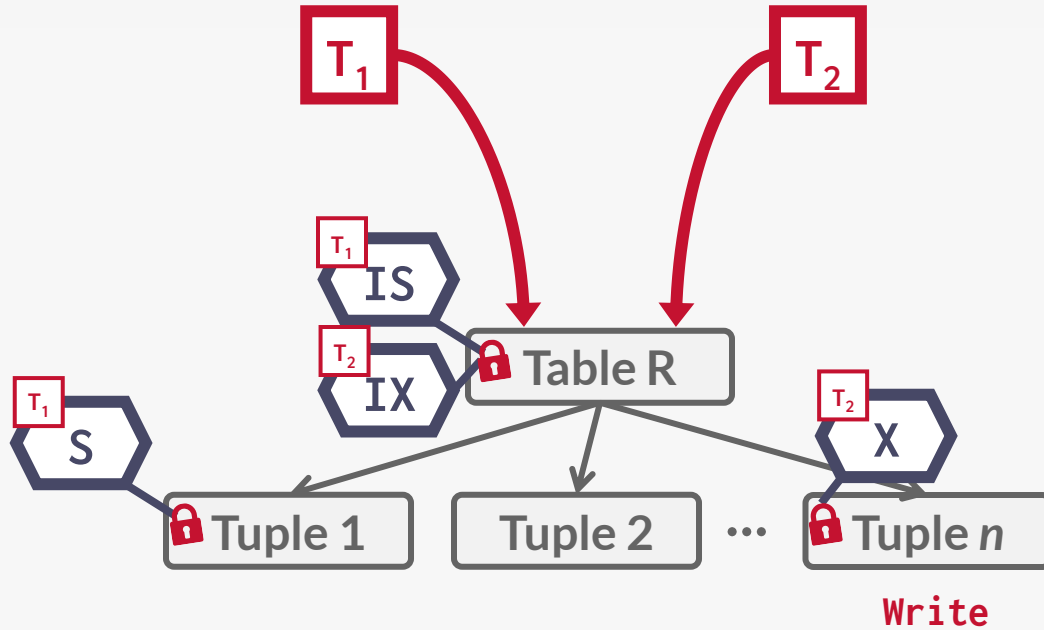
Update bookie's record in R.



	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	✗
IX	✓	✓	✗	✗	✗
S	✓	✗	✓	✗	✗
SIX	✓	✗	✗	✗	✗
X	✗	✗	✗	✗	✗

EXAMPLE: TWO-LEVEL HIERARCHY

Update bookie's record in R.

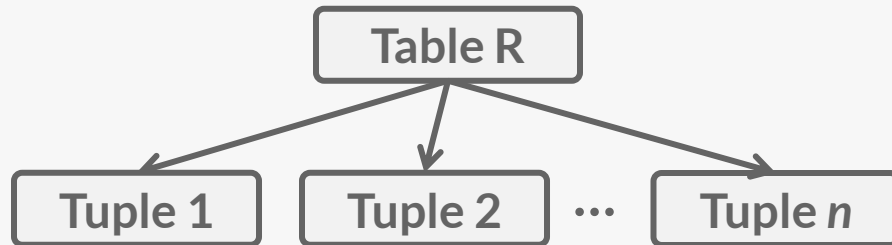


	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	✗
IX	✓	✓	✗	✗	✗
S	✓	✗	✓	✗	✗
SIX	✓	✗	✗	✗	✗
X	✗	✗	✗	✗	✗

EXAMPLE: THREE TXNS

Assume three txns execute at same time:

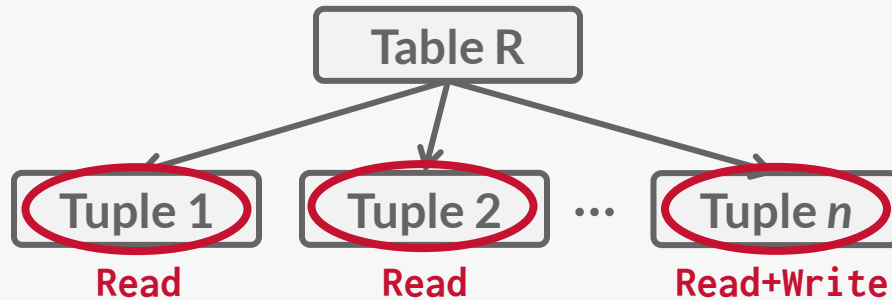
- T_1 – Scan all tuples in **R** and update one tuple.
- T_2 – Read a single tuple in **R**.
- T_3 – Scan all tuples in **R**.



EXAMPLE: THREE TXNS

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

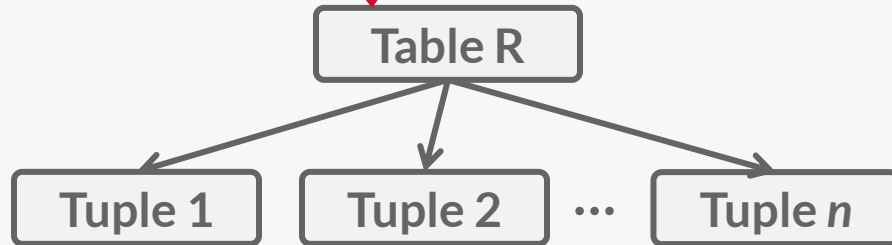
T₁



EXAMPLE: THREE TXNS

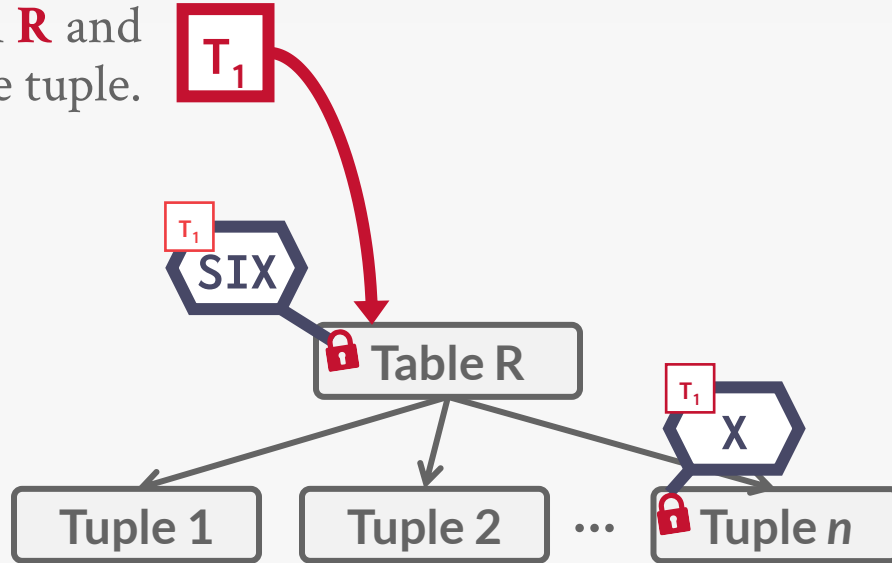
Scan all tuples in **R** and
update one tuple.

T₁

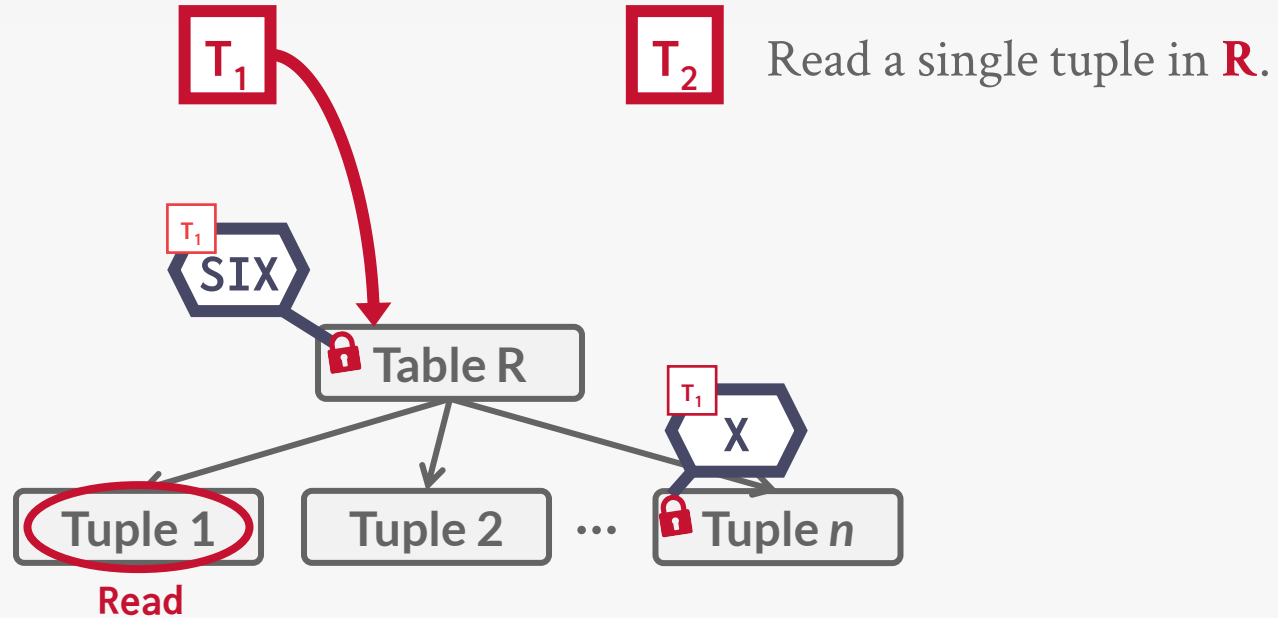


EXAMPLE: THREE TXNS

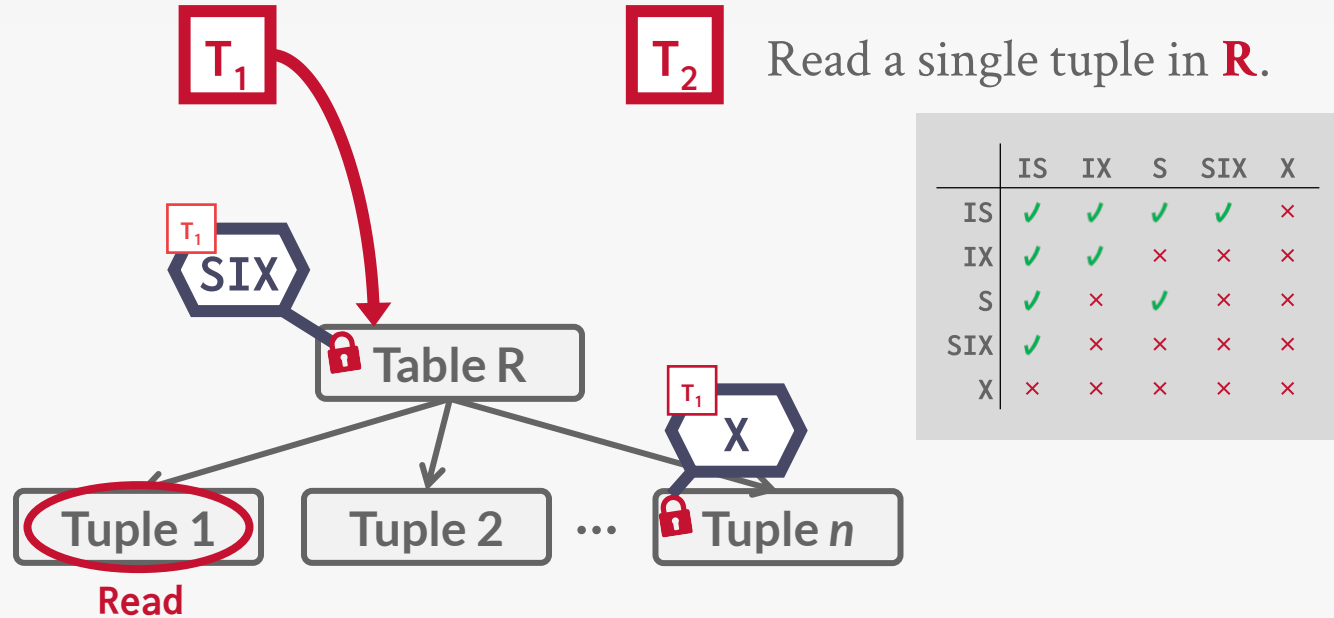
Scan all tuples in **R** and
update one tuple.



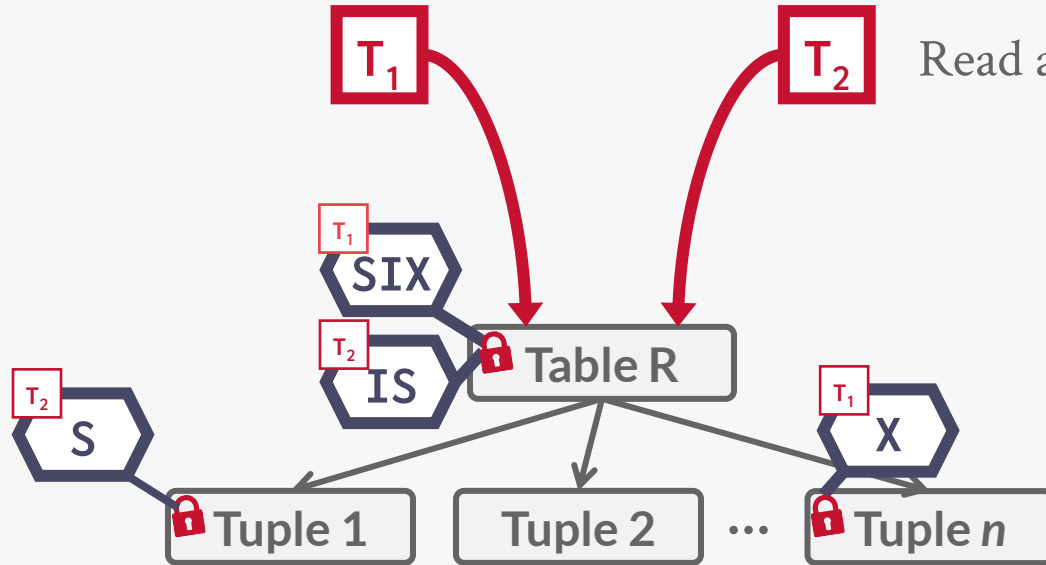
EXAMPLE: THREE TXNS



EXAMPLE: THREE TXNS



EXAMPLE: THREE TXNS

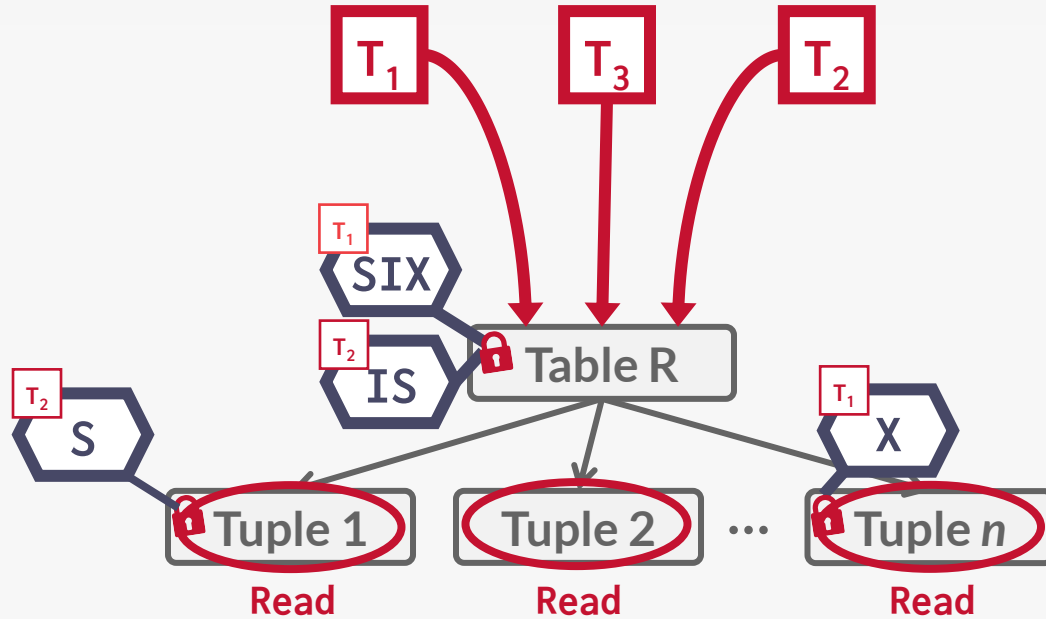


Read a single tuple in **R**.

	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	✗
IX	✓	✓	✗	✗	✗
S	✓	✗	✓	✗	✗
SIX	✓	✗	✗	✗	✗
X	✗	✗	✗	✗	✗

EXAMPLE: THREE TXNS

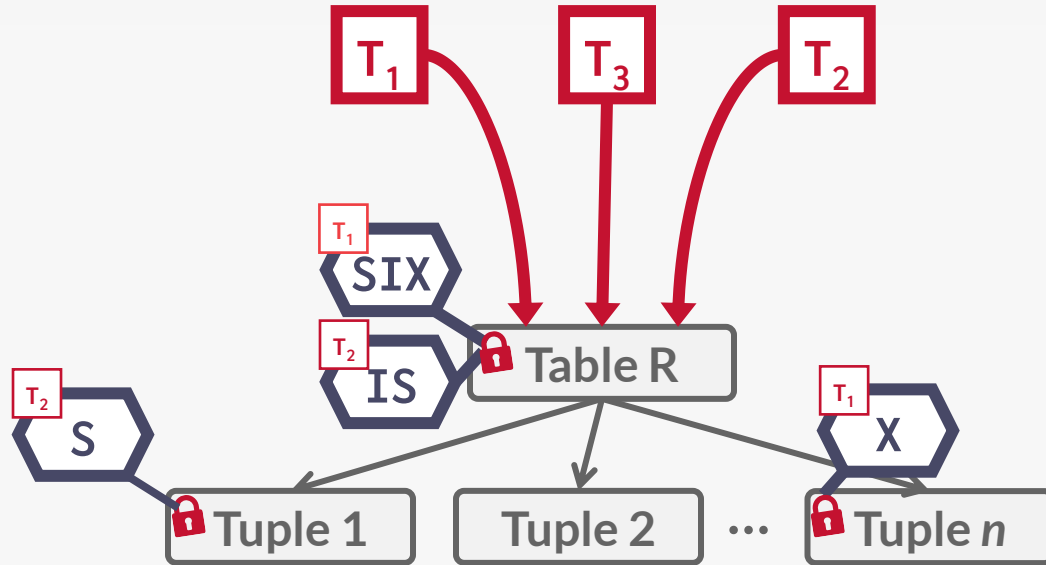
Scan all tuples in **R**.



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

EXAMPLE: THREE TXNS

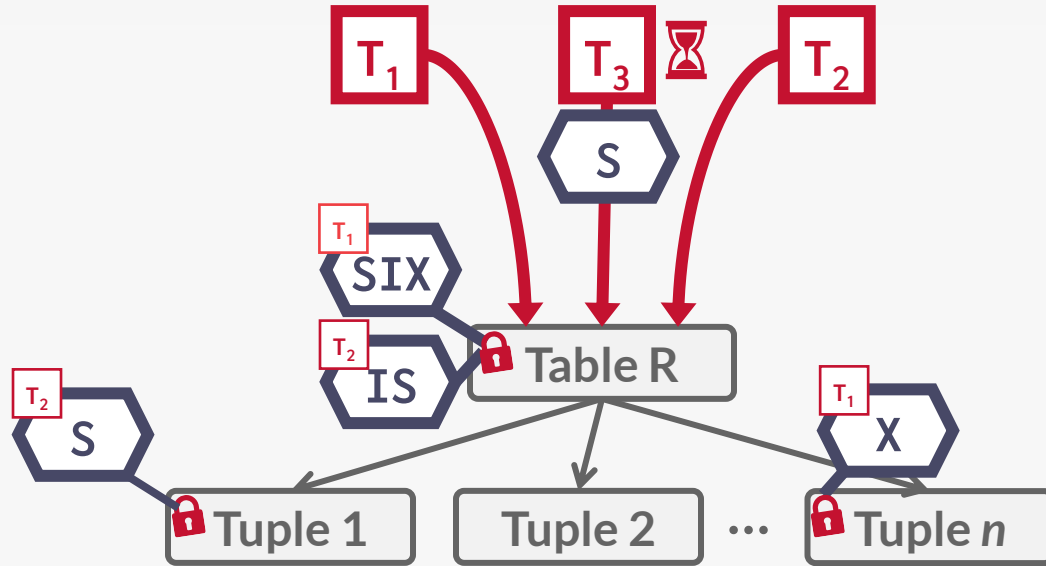
Scan all tuples in **R**.



	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	✗
IX	✓	✓	✗	✗	✗
S	✓	✗	✓	✗	✗
SIX	✓	✗	✗	✗	✗
X	✗	✗	✗	✗	✗

EXAMPLE: THREE TXNS

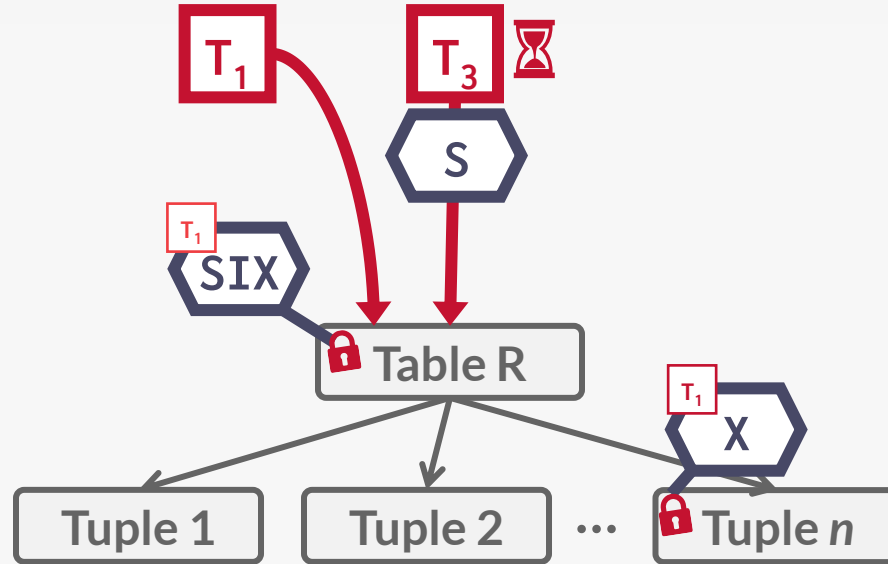
Scan all tuples in **R**.



	IS	IX	S	SIX	X
IS	✓	✓	✓	✓	✗
IX	✓	✓	✗	✗	✗
S	✓	✗	✓	✗	✗
SIX	✓	✗	✗	✗	✗
X	✗	✗	✗	✗	✗

EXAMPLE: THREE TXNS

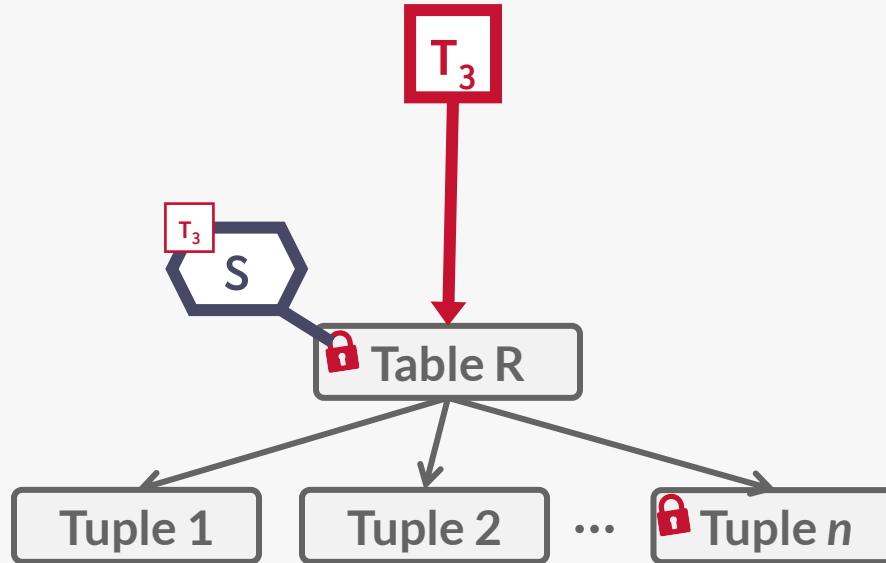
Scan all tuples in **R**.



	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

Requested Lock Mode	Current 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