Carnegie Mellon Univ.
Dept. of Computer Science
15-415/615 - DB Applications

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Lecture#21: Concurrency Control

(R&G ch. 17)

Last Class

- Introduction to Transactions
- ACID
- Concurrency Control
- Crash Recovery

Last Class

- For **Isolation** property, serial execution of transactions is safe but slow
  - We want to find schedules equivalent to serial execution but allow interleaving.
- The way the DBMS does this is with its ***concurrency control*** protocol.

Today's Class

- Serializability
- Two-Phase Locking
- Deadlocks
- Lock Granularities
- Locking in B+Trees

Formal Properties of Schedules

- **Serial Schedule:** A schedule that does not interleave the actions of different transactions.
- **Equivalent Schedules**: For any database state, the effect of executing the first schedule is identical to the effect of executing the second schedule.*****

(*) no matter what the arithmetic operations are!

Formal Properties of Schedules

- **Serializable Schedule:** A schedule that is *equivalent* to some serial execution of the transactions.
- Note: If each transaction preserves consistency, every serializable schedule preserves consistency.

Example

T1

```
BEGIN
A=A+100
B=B–100
COMMIT
```

T2

```
BEGIN
A=A*1.06
B=B*1.06
COMMIT
```

- Consider two txns:
  - T1 transfers $100 from B's account to A's
  - T2 credits both accounts with 6% interest.
- Assume at first A and B each have $1000.

Example

- Legal outcomes:
  - A=1166, B=954 →**$2120**
  - A=1160, B=960 →**$2120**
- The outcome depends on whether T1 executes before T2 or vice versa.

Interleaving Example (Good)

TIME

Schedule

T1	T2
BEGIN	
A=A+100	
	BEGIN
	A=A*1.06
B=B–100	
COMMIT	
	B=B*1.06
	COMMIT

A=1166, B=954

≡

Schedule

T1	T2
BEGIN	
A=A+100	
B=B–100	
COMMIT	
	BEGIN
	A=A*1.06
	B=B*1.06
	COMMIT

A=1166, B=954

Interleaving Example (Bad)

TIME

Schedule

T1	T2
BEGIN	
A=A+100	
	BEGIN
	A=A*1.06
	B=B*1.06
	COMMIT
B=B–100	
COMMIT	

A=1166, B=960

The bank lost $6!

≢

A=1166, B=954
or
A=1160, B=960

Formal Properties of Schedules

- There are different levels of serializability:
  - **Conflict Serializability**
  - **View Serializability**

All DBMSs support this.

This is harder but allows for more concurrency.

Conflicting Operations

- We need a formal notion of equivalence that can be implemented efficiently…
  - Base it on the notion of "conflicting" operations
- Definition: Two operations conflict if:
  - They are by different transactions,
  - They are on the same object and at least one of them is a write.

Conflict Serializable Schedules

- Two schedules are ***conflict equivalent*** iff:
  - They involve the same actions of the same transactions, and
  - Every pair of conflicting actions is ordered the same way.
- Schedule S is ***conflict serializable*** if:
  - S is conflict equivalent to some serial schedule.

Conflict Serializability Intuition

- A schedule S is ***conflict serializable*** if:
  - You are able to transform S into a serial schedule by swapping consecutive non-conflicting operations of different transactions.

Conflict Serializability Intuition

TIME

Schedule

T1	T2
BEGIN	**BEGIN**
R(A)	
W(A)	
R(B)	R(A)
R(B)	R(A)
R(B)	R(A)
W(B)	W(A)
COMMIT	
	R(B)
	W(B)
	COMMIT

≡

Serial Schedule

T1	T2
BEGIN	
R(A)	
W(A)	
R(B)	
W(B)	
COMMIT	**BEGIN**
	R(A)
	W(A)
	R(B)
	W(B)
	COMMIT

Conflict Serializability Intuition

TIME

Schedule

T1	T2
BEGIN	**BEGIN**
R(A)	
	R(A)
	W(A)
W(A)	
COMMIT	**COMMIT**

≠

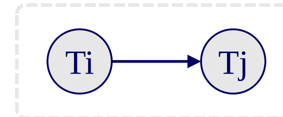
Serial Schedule

T1	T2
BEGIN	
R(A)	
W(A)	
COMMIT	**BEGIN**
	R(A)
	W(A)
	COMMIT

Serializability

- **Q:** Are there any faster algorithms to figure this out other than transposing operations?

Dependency Graphs



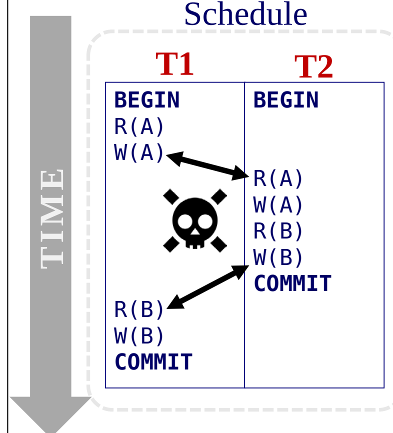
- One node per txn.
- Edge from Ti to Tj if:
  - An operation Oi of Ti conflicts with an operation Oj of Tj and
  - Oi appears earlier in the schedule than Oj.
- Also known as a “precedence graph”

Dependency Graphs

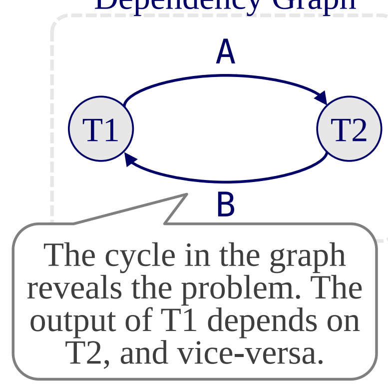
- **Theorem:** A schedule is *conflict serializable* if and only if its dependency graph is acyclic.

Example #1

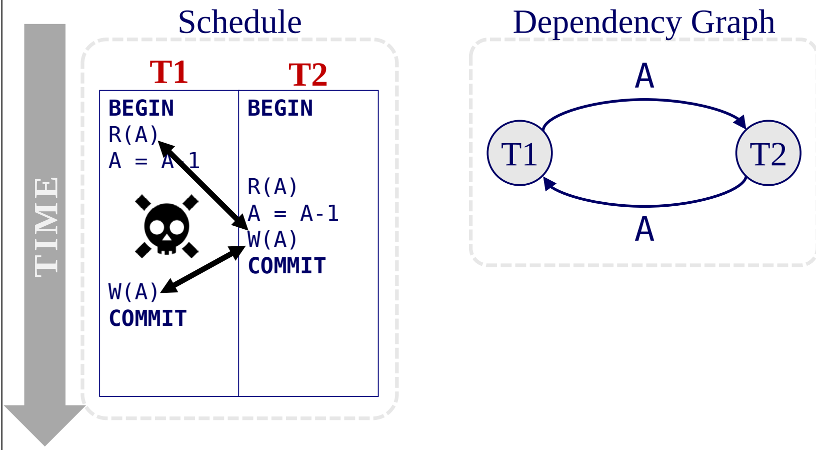
Schedule



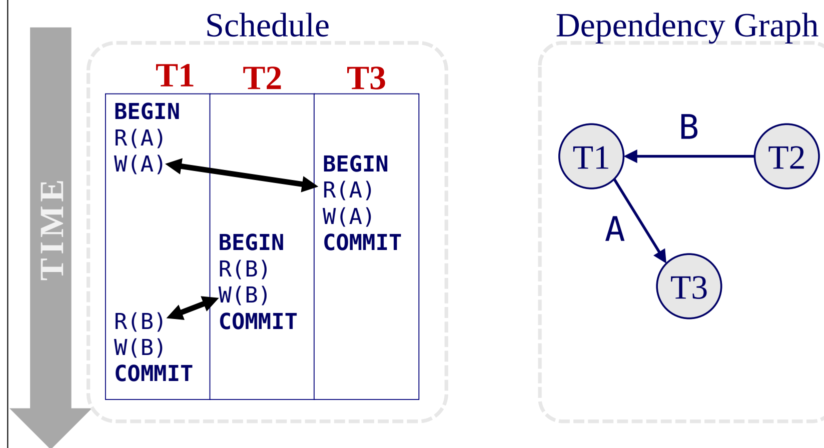
Dependency Graph



Example #2 – Lost Update



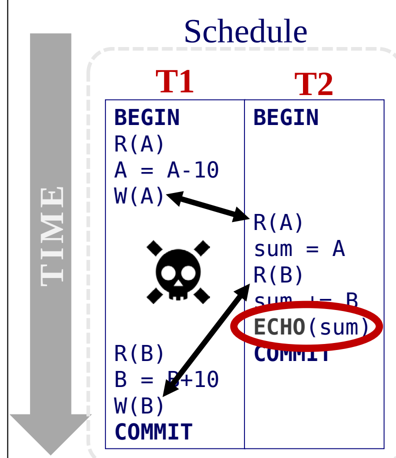
Example #3 – Threesome

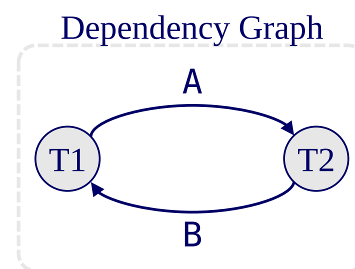


Example #3 – Threesome

- **Q:** Is this equivalent to a serial execution?
- **A:** Yes (T2, T1, T3)
  - Notice that T3 should go after T2, although it starts before it!

Example #4 – Inconsistent Analysis





Is it possible to create a schedule similar to this that is "correct" but still not conflict serializable?

CMU SCS

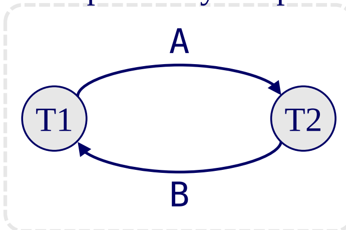
Example #4 – Inconsistent Analysis

TIME

Schedule

T1	T2
BEGIN	BEGIN
R(A)	
A = A-10	
W(A)	
	R(A)
	if(A>0): cnt++
	R(B)
	if(B>0): cnt++
	ECHO(cnt)
R(B)	COMMIT
B = B+10	
W(B)	
COMMIT	

Dependency Graph



T2 counts the number of active accounts.

CMU SCS

View Serializability

- Alternative (weaker) notion of serializability.
- Schedules S1 and S2 are ***view equivalent*** if:
  - If T1 reads initial value of A in S1, then T1 also reads initial value of A in S2.
  - If T1 reads value of A written by T2 in S1, then T1 also reads value of A written by T2 in S2.
  - If T1 writes final value of A in S1, then T1 also writes final value of A in S2.

CMU SCS

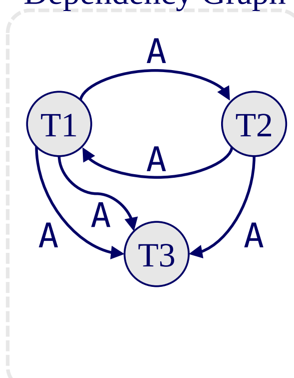
View Serializability

TIME

Schedule

T1	T2	T3
BEGIN		
R(A)	BEGIN	
	W(A)	
		BEGIN
W(A)		
		W(A)
COMMIT	COMMIT	COMMIT

Dependency Graph



CMU SCS

View Serializability

TIME

Schedule

T1	T2	T3
BEGIN		
R(A)	BEGIN	
	W(A)	
		BEGIN
W(A)		
		W(A)
COMMIT	COMMIT	COMMIT

VIEW

Schedule

T1	T2	T3
BEGIN		
R(A)		
W(A)		
COMMIT		
	BEGIN	
	W(A)	
	COMMIT	
		BEGIN
		W(A)
		COMMIT

Allows all conflict serializable schedules + "blind writes"

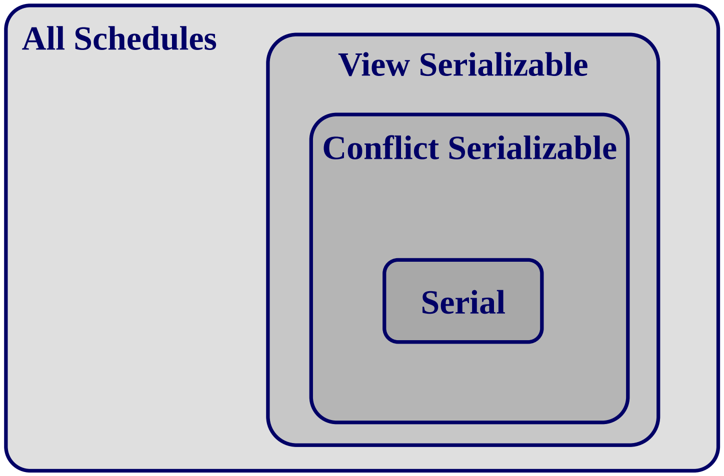
Serializability

- **View Serializability** allows (slightly) more schedules than **Conflict Serializability** does.
  - But is difficult to enforce efficiently.
- Neither definition allows all schedules that you would consider “serializable”.
  - This is because they don’t understand the meanings of the operations or the data (recall example #4)

Serializability

- In practice, **Conflict Serializability** is what gets used, because it can be enforced efficiently.
  - To allow more concurrency, some special cases get handled separately, such as for travel reservations, etc.

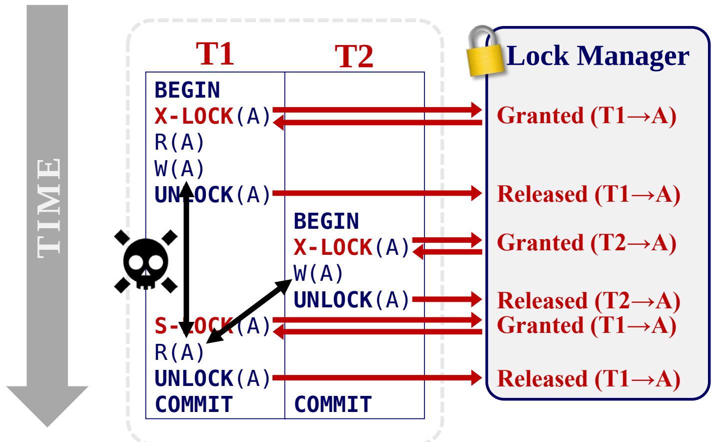
Schedules



Today’s Class

- Serializability
- Two-Phase Locking
- Deadlocks
- Lock Granularities
- Locking in B+Trees

Executing with Locks

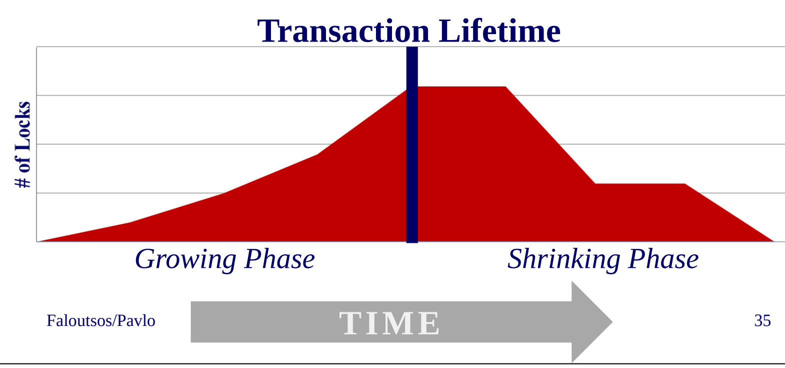


Two-Phase Locking

- **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 locks that it previously acquired. It cannot acquire new locks.

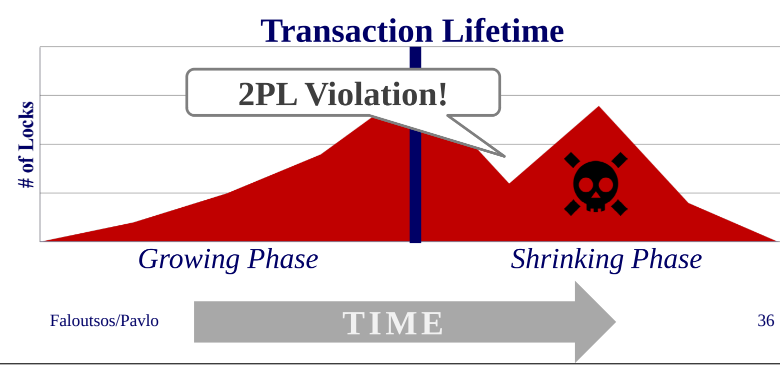
Two-Phase Locking

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

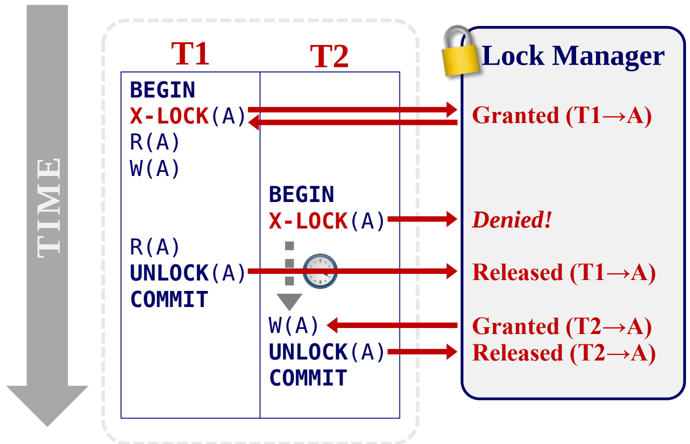


Two-Phase Locking

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

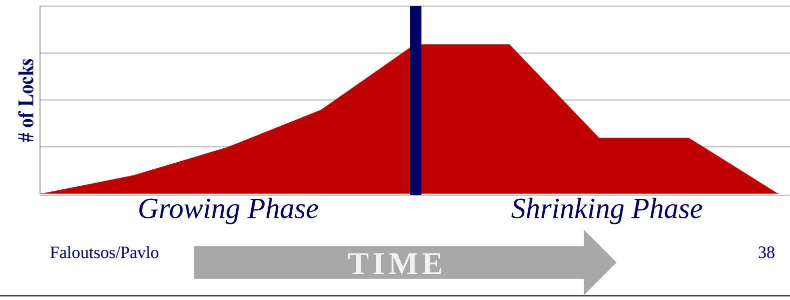


Executing with 2PL

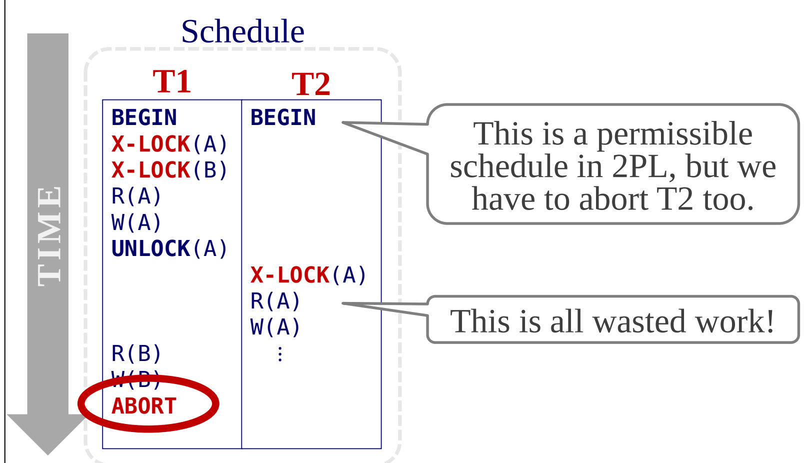


Two-Phase Locking

- 2PL on its own is sufficient to guarantee conflict serializability (i.e., schedules whose precedence graph is acyclic), but, it is subject to *cascading aborts*.



2PL – Cascading Aborts

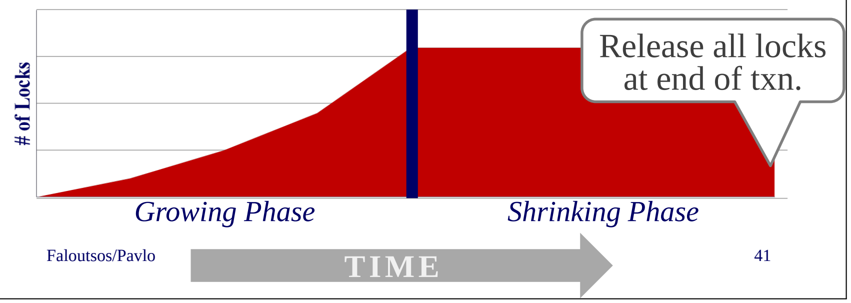


2PL Observations

- There are schedules that are serializable but would not be allowed by 2PL.
- Locking limits concurrency.
- May lead to deadlocks.
- May still have “dirty reads”
  - Solution: **Strict 2PL**

Strict Two-Phase Locking

- The txn is not allowed to acquire/upgrade locks after the growing phase finishes.
- Allows only conflict serializable schedules, but it is actually stronger than needed.



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:
  - Recoverable.
  - Do not require cascading aborts.
  - Aborted txns can be undone by just restoring original values of modified tuples.

Examples

- **T1:** *Move $50 from Andy's account to his bookie's account.*
- **T2:** *Compute the total amount in all accounts and return it to the application.*
- Legend:
  - **A** → Andy's account.
  - **B** → The bookie's account.

Non-2PL Example

TIME

T1	T2
BEGIN	**BEGIN**
X-LOCK(A)	
R(A)	**S-LOCK**(A)
A=A-50	
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+50	**COMMIT**
W(B)	
UNLOCK(B)	
COMMIT	

Initial State

A=100, B=100

T2 Output

150

2PL Example

T1	T2
BEGIN	BEGIN
X-LOCK(A)	
R(A)	S-LOCK(A)
A=A-50	
W(A)	
X-LOCK(B)	
UNLOCK(A)	
	R(A)
	S-LOCK(B)
R(B)	
B=B+50	
W(B)	
UNLOCK(B)	
COMMIT	R(B)
	UNLOCK(A)
	UNLOCK(B)
	ECHO(A+B)
	COMMIT

TIME

Initial State

A=100, B=100

T2 Output

200

Strict 2PL Example

T1	T2
BEGIN	BEGIN
X-LOCK(A)	
R(A)	S-LOCK(A)
A=A-50	
W(A)	
X-LOCK(B)	
R(B)	
B=B+50	
W(B)	
UNLOCK(A)	
UNLOCK(B)	R(A)
COMMIT	S-LOCK(B)
	R(B)
	ECHO(A+B)
	UNLOCK(A)
	UNLOCK(B)
	COMMIT

TIME

Initial State

A=100, B=100

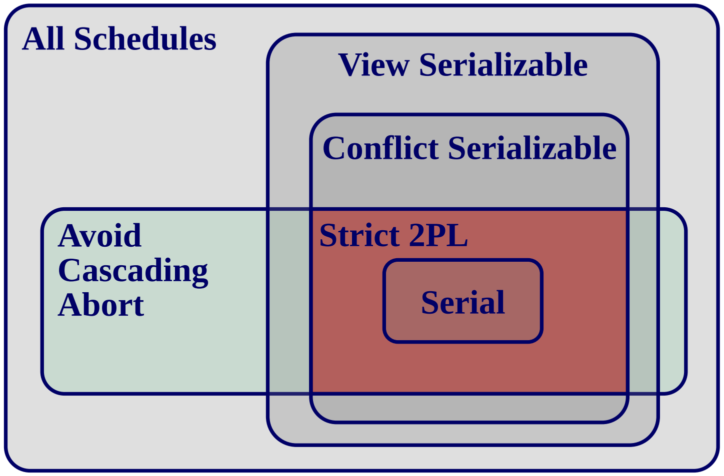
T2 Output

200

Strict Two-Phase Locking

- Txns hold all of their locks until commit.
- Good:
  - Avoids “dirty reads” etc
- Bad:
  - Limits concurrency even more
  - And still may lead to deadlocks

Schedules



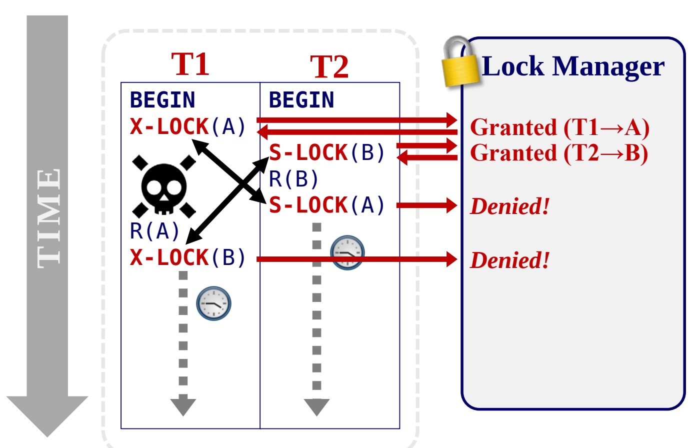
Today's Class

- Serializability
- Two-Phase Locking
- Deadlocks
- Lock Granularities
- Locking in B+Trees

Two-Phase Locking

- 2PL seems to work well.
- Is that enough? Can we just go home now?

Shit Just Got Real



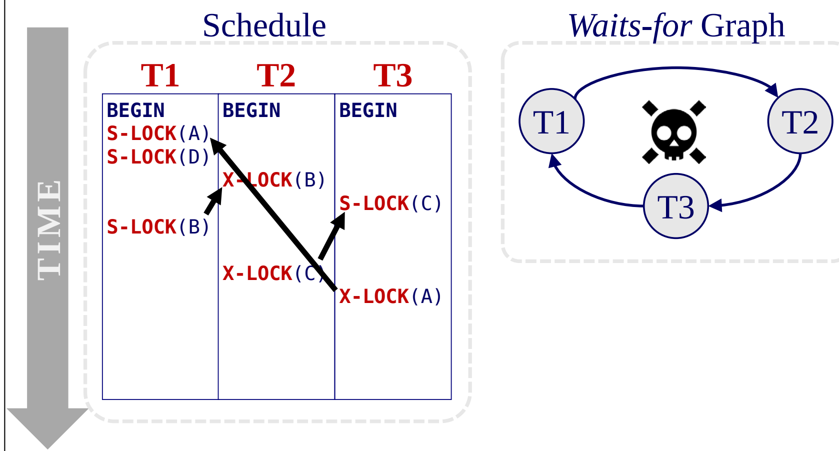
Deadlocks

- **Deadlock:** Cycle of transactions waiting for locks to be released by each other.
- Two ways of dealing with deadlocks:
  - Deadlock prevention
  - Deadlock detection
- Many systems just punt and use timeouts
  - What are the dangers with this approach?

Deadlock Detection

- The DBMS creates a ***waits-for*** graph:
  - Nodes are transactions
  - Edge from Ti to Tj if Ti is waiting for Tj to release a lock
- The system periodically check for cycles in ***waits-for*** graph.

Deadlock Detection

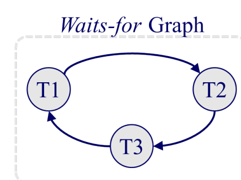


Deadlock Detection

- How often should we run the algorithm?
- How many txns are typically involved?
- What do we do when we find a deadlock?

Deadlock Handling

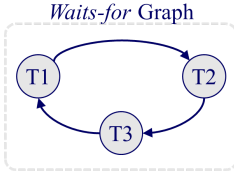
- **Q:** What do we do?
- **A:** Select a "victim" and rollback it back to break the deadlock.



Deadlock Handling

- **Q:** Which one do we choose?
- **A:** It depends…
  - 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.

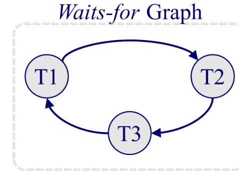
Waits-for Graph



Deadlock Handling

- **Q:** How far do we rollback?
- **A:** It depends…
  - Completely
  - Minimally (i.e., just enough to release locks)

Waits-for Graph



Deadlock Prevention

- When a txn tries to acquire a lock that is held by another txn, kill one of them to prevent a deadlock.
- No *waits-for* graph or detection algorithm.

Deadlock Prevention

- Assign priorities based on timestamps:
  - Older → higher priority (e.g., T1 > T2)
- Two different prevention policies:
  - **Wait-Die:** If T1 has higher priority, T1 waits for T2; otherwise T1 aborts ("old wait for young")
  - **Wound-Wait:** If T1 has higher priority, T2 aborts; otherwise T1 waits ("young wait for old")

Deadlock Prevention

T1	T2
BEGIN	
	BEGIN
	X-LOCK(A)
X-LOCK(A)	⋮
⋮	

Wait-Die	Wound-Wait
T1 waits	T2 aborted

T1	T2
BEGIN	
X-LOCK(A)	
⋮	BEGIN
	X-LOCK(A)
	⋮

Wait-Die	Wound-Wait
T2 aborted	T2 waits

Deadlock Prevention

- **Q:** Why do these schemes guarantee no deadlocks?
- **A:** Only one “type” of direction allowed.

- **Q:** When a transaction restarts, what is its (new) priority?
- **A:** Its original timestamp. Why?

Today’s Class

- Serializability
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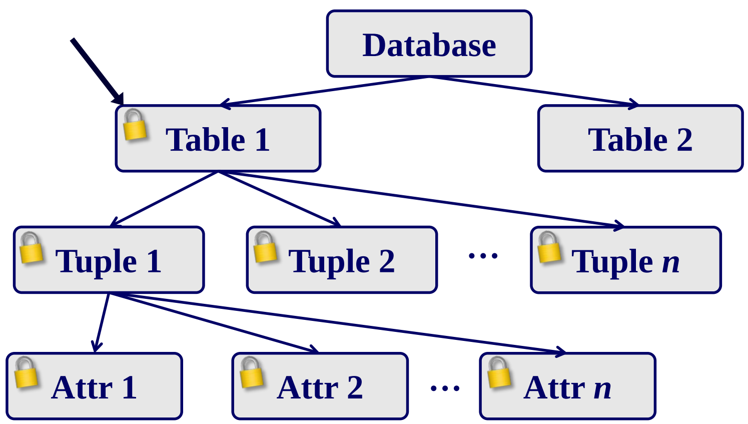
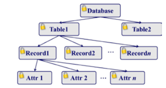
Lock Granularities

- When we say that a txn acquires a “lock”, what does that actually mean?
  - On a field? Record? Page? Table?
- Ideally, each txn should obtain fewest number of locks that is needed…

Database Lock Hierarchy



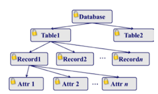
Example



- **T1:** Get the balance of Andy's shady off-shore bank account.
- **T2:** Increase all account balances by 1%.

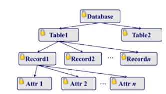
- **Q:** What locks should they obtain?

Example



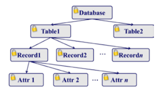
- **Q:** What locks should they obtain?
- **A:** Multiple
  - **Exclusive** + **Shared** for leafs of lock tree.
  - Special **Intention** locks for higher levels

Intention Locks



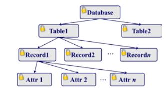
- Intention locks allow a higher level node to be locked in **S** or **X** mode without having to check all descendent nodes.
- If a node is in an intention mode, then explicit locking is being done at a lower level in the tree.

Intention Locks



- **Intention-Shared** (**IS**): Indicates explicit locking at a lower level with shared locks.
- **Intention-Exclusive** (**IX**): Indicates locking at lower level with exclusive or shared locks.

Intention Locks



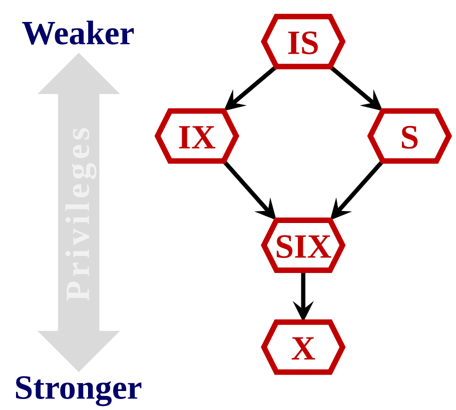
- **Shared+Intention-Exclusive** (**SIX**): The subtree rooted by that node is locked explicitly in shared mode and explicit locking is being done at a lower level with exclusive-mode locks.

Compatibility Matrix

T2 Wants

T1 Holds	IS	IX	S	SIX	X
IS	✔	✔	✔	✔	X
IX	✔	✔	X	X	X
S	✔	X	✔	X	X
SIX	✔	X	X	X	X
X	X	X	X	X	X

Multiple Granularity Protocol



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.
  - What if txn holds **SIX** on parent? **S** on parent?
- To get **X**, **IX**, or **SIX** on a node, must hold at least **IX** on parent node.

Example – Two-level Hierarchy

Reac ... in **R**.

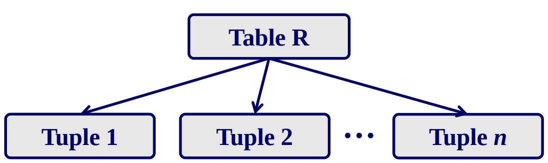
T2 Wants

T1 Holds	IS	IX	S	SIX	X
IS	✔	✔	✔	✔	X
IX	✔	✔	X	X	X
S	✔	X	✔	X	X
SIX	✔	X	X	X	X
X	X	X	X	X	X

Read **Write**

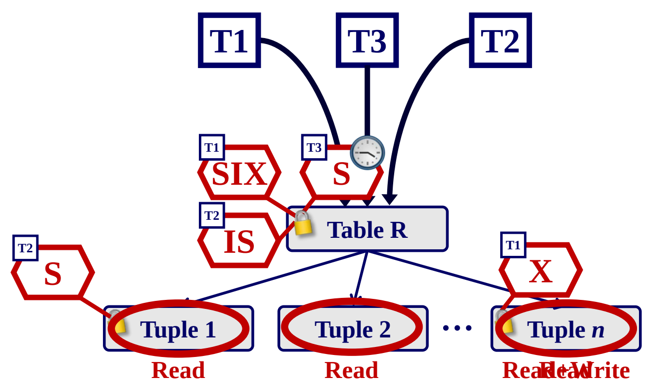
Example – Threesome

- Assume three txns execute at same time:
  - **T1:** Scan **R** and update a few tuples.
  - **T2:** Scan a portion of tuples in **R**.
  - **T3:** Scan all tuples in **R**.



Example – Threesome

Scan **R** and update a few tuples. Scan all tuples in **R**. Scan a portion of tuples in **R**.



Example – Threesome

- **T1:** Get an **SIX** lock on **R**, then get **X** lock on tuples that are updated.
- **T2:** Get an **IS** lock on **R**, and repeatedly get an **S** lock on tuples of **R**.
- **T3:** Two choices:
  - T3 gets an **S** lock on **R**.
  - OR, T3 could behave like T2; can use ***lock escalation*** to decide which.

Lock Escalation

- Lock escalation dynamically asks for coarser-grained locks when too many low level locks acquired.
- Reduces the number of requests that the lock manager has to process.

Multiple Lock Granularities

- Useful in practice as each txn only needs a few locks.
- Intention locks help improve concurrency:
  - **Intention-Shared** (**IS**): Intent to get **S** lock(s) at finer granularity.
  - **Intention-Exclusive (IX):** Intent to get **X** lock(s) at finer granularity.
  - **Shared+Intention-Exclusive** (**SIX**): Like **S** and **IX** at the same time.

Today's Class

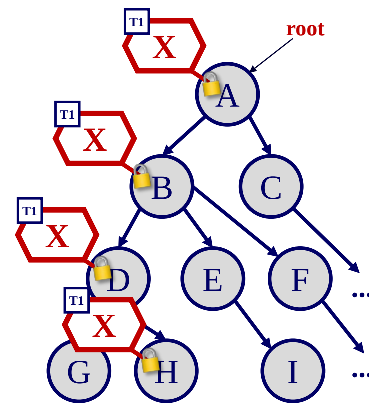
- Serializability
- Two-Phase Locking
- Deadlocks
- Lock Granularities
- Locking in B+Trees

Locking in B+Trees

- **Q:** What about locking indexes?
- **A:** They are not quite like other database elements so we can treat them differently:
  - It's okay to have non-serializable concurrent access to an index as long as the accuracy of the index is maintained.

Example

- T1 wants to insert in H
- T2 wants to insert in I
- **Q:** Why not plain 2PL?
- **A:** Because txns have to hold on to their locks for too long!



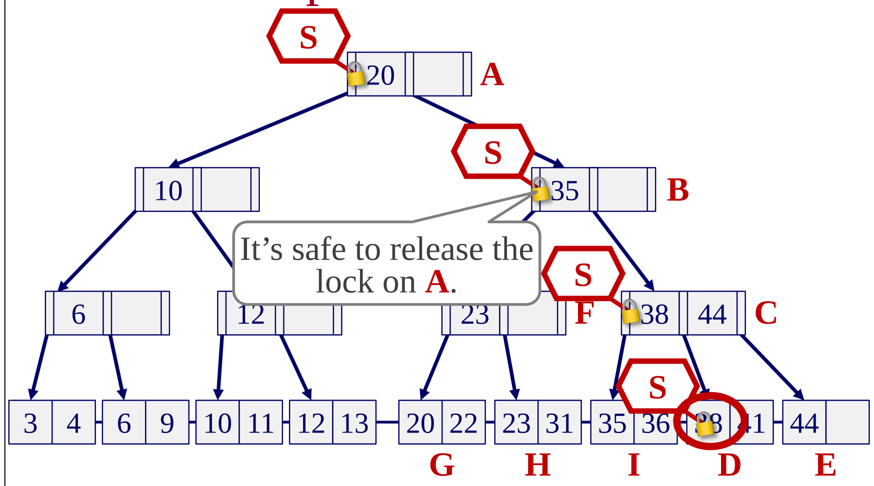
Lock Crabbing

- Improves concurrency for B+Trees.
- Get lock for parent; get lock for child; release lock for parent if "safe".
- **Safe Nodes:** Any node that won't split or merge when updated.
  - Not full (on insertion)
  - More than half-full (on deletion)

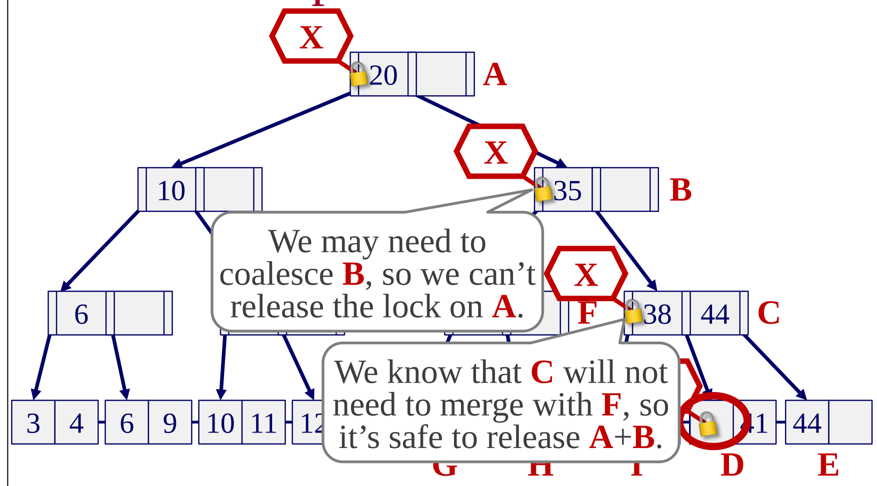
Lock Crabbing

- **Search:** Start at root and go down; repeatedly,
  - **S** lock child
  - then unlock parent
- **Insert/Delete:** Start at root and go down, obtaining **X** locks as needed. Once child is locked, check if it is safe:
  - If child is safe, release all locks on ancestors.

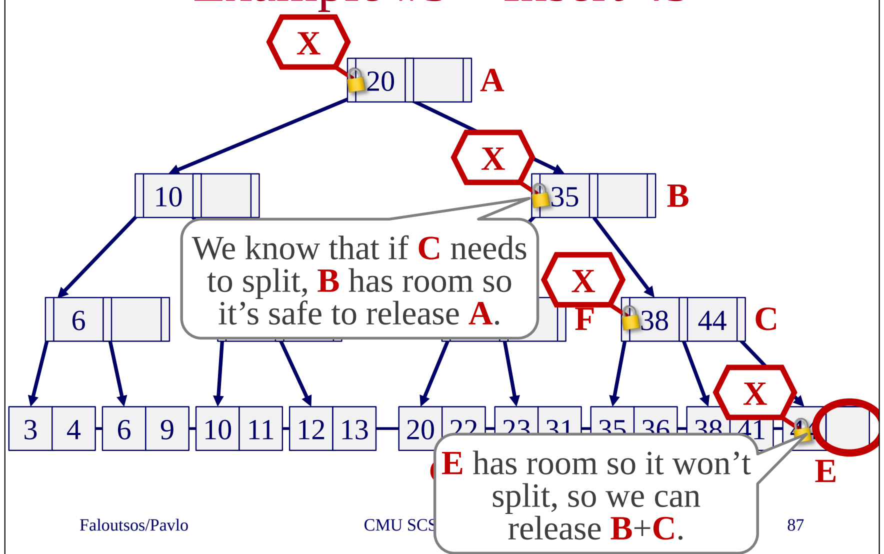
Example #1 – Search 38



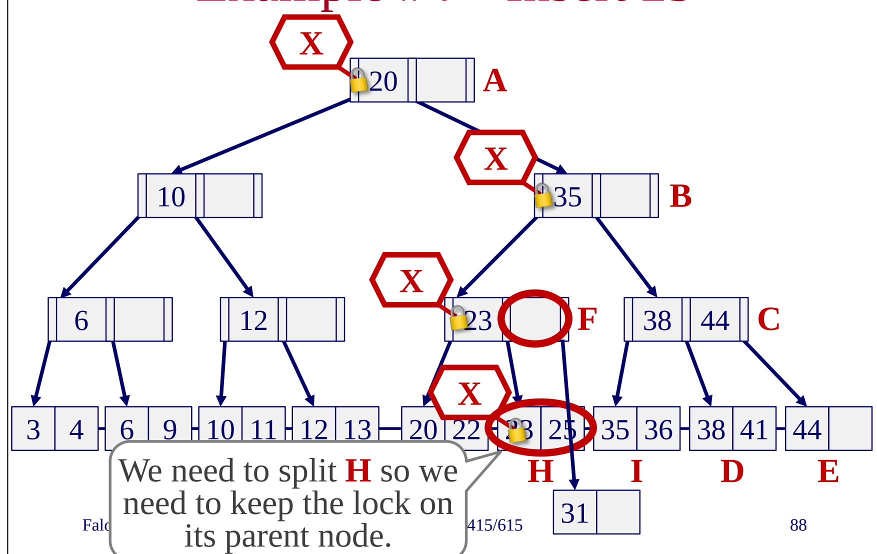
Example #2 – Delete 38



Example #3 – Insert 45

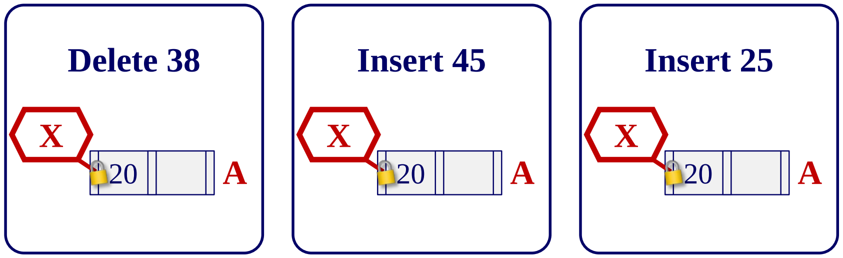


Example #4 – Insert 25



Problems

- **Q:** What was the first step that all of the update examples did on the B+Tree?



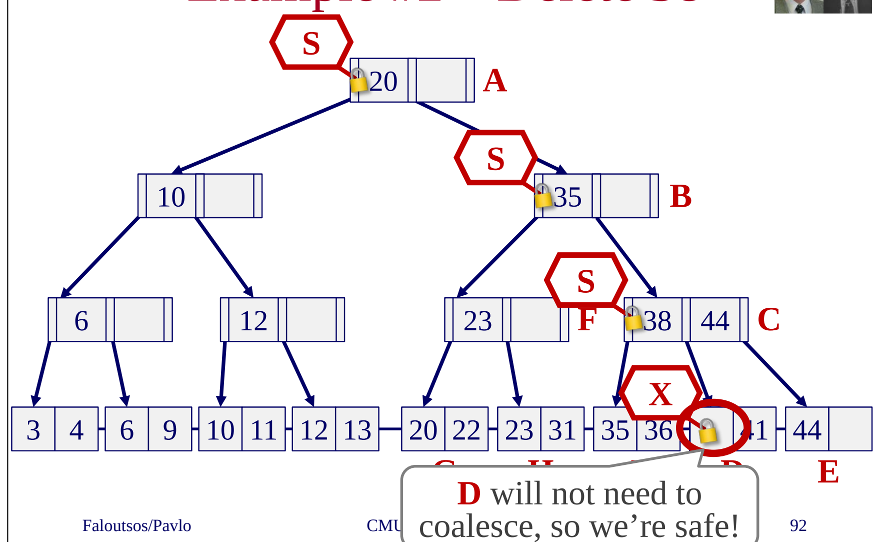
Problems

- **Q:** What was the first step that all of the update examples did on the B+Tree?
- **A:** Locking the root every time becomes a bottleneck with higher concurrency.
- *Can we do better?*

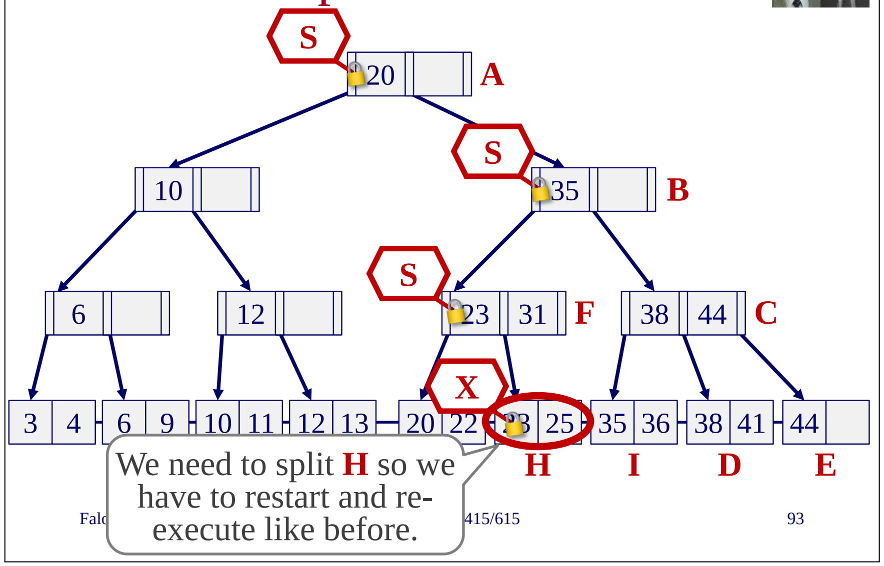
Better Tree Locking Algorithm

- Main Idea:
  - Assume that the leaf is 'safe', and use **S**-locks & crabbing to reach it, and verify.
  - If leaf is not safe, then do previous algorithm.
- Rudolf Bayer, Mario Schkolnick: *Concurrency of Operations on B-Trees*. Acta Inf. 9: 1-21 (1977)

Example #2 – Delete 38



Example #4 – Insert 25



Better Tree Locking Algorithm

- **Search:** Same as before.
- **Insert/Delete:**
  - Set locks as if for search, get to leaf, and set **X** lock on leaf.
  - If leaf is not safe, release all locks, and restart txn using previous Insert/Delete protocol.
- Gambles that only leaf node will be modified; if not, **S** locks set on the first pass to leaf are wasteful.

Additional Points

- **Q:** Which order to release locks in multiple-granularity locking?
- **A:** From the bottom up

- **Q:** Which order to release locks in tree-locking?
- **A:** As early as possible to maximize concurrency.

Locking in Practice

- You typically don’t set locks manually.
- Sometimes you will need to provide the DBMS with hints to help it to improve concurrency.
- Also useful for doing major changes.

LOCK TABLE

Postgres

```
LOCK TABLE <table> IN <mode> MODE;
```

MySQL

```
LOCK TABLE <table> <mode>;
```

- Explicitly locks a table.
- Not part of the SQL standard.
  - Postgres Modes: **SHARE**, **EXCLUSIVE**
  - MySQL Modes: **READ**, **WRITE**

SELECT...FOR UPDATE

```
SELECT * FROM <table>
 WHERE <qualification> 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**

Concurrency Control Summary

- Conflict Serializability ↔ Correctness
- Automatically correct interleavings:
  - Locks + protocol (2PL, S2PL ...)
  - Deadlock detection + handling
  - Deadlock prevention