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Scalable Data Management (SDM)

Traditional Transaction Processing

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Transactions Overview

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Transactions

- A **transaction** is the execution of a **sequence** of one or more **operations** (e.g., SQL queries) on a shared database to perform some higher-level function
- It is the basic unit of change in a DBMS: Partial transactions are not allowed!

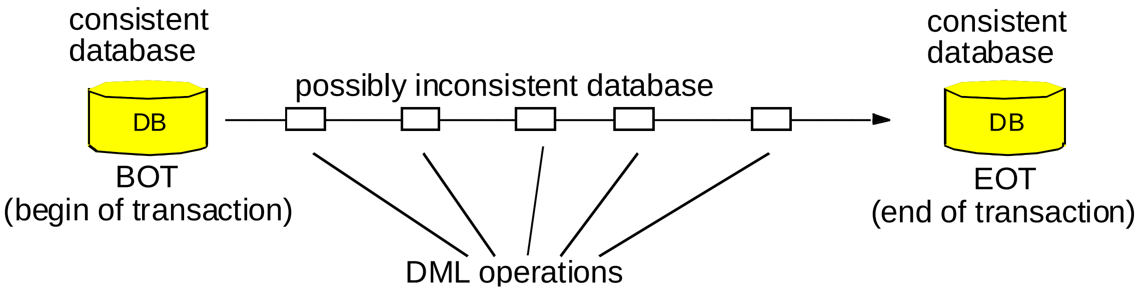
Example

- Move $100 from Andy’s bank account to his bookie’s account
- Transaction
  - Check whether Andy has $100
  - Deduct $100 from his account
  - Add $100 to his bookie’s account

Transaction Management

Principle of a transaction

- sequence of successive DB operations that transform a database from a consistent state into another consistent state
  surrounded by: BOT …….. EOT (Commit / Abort)



- properties
  - ACID: Atomicity, Consistency, Isolation, Durability
  - A transaction will always come to an end
  - Normal (commit): changes are permanently stored within the DB
  - Abnormal (abort/rollback): already composed changes are undone
- note: EOT state is not necessarily different from BOT state

Strawman System

Execute each transaction one-by-one (i.e., serial order) as they arrive at the DBMS

- One and only one transaction can be running at the same time in the DBMS

Before a transaction starts, copy the entire database to a new file and make all changes to that file

- If the transaction completes successfully, overwrite the original file with the new one
- If the transaction fails, just remove the dirty copy

→ Better approach: allow concurrent execution of independent transactions

- Question: Why do we want that?
  - Utilization/throughput (“hide” waiting for I/Os)
  - Increased response times to users
- But we also would like
  - Correctness
  - Fairness

Problem Statement

Arbitrary interleaving can lead to

- Temporary inconsistency (ok, unavoidable)
- Permanent inconsistency (bad!)

→ **Need formal correctness criteria**

Definitions

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Definitions

- A transaction may carry out many operations on the data retrieved from the database
- However, the DBMS is only concerned about what data is read/written from/to the database
  - Changes to the “outside world” are beyond the scope of the DBMS

Database

- A fixed set of named data objects (A, B, C, …)

Transaction

- A sequence of read and write operations (R(A), W(B), …)
  - DBMS’s abstract view of a user program

Transactions in SQL

- A new transaction starts with the **begin** command
- The transaction stops with either **commit** or abort:
  - If **commit**, all changes are saved
  - If **abort**, all changes are undone so that it’s like as if the transaction never executed at all
- Transaction can abort itself or the DBMS can abort it

Correctness Criteria: ACID

Atomicity

- All actions in the transaction happen, or none happen → *"all or nothing"*

Consistency

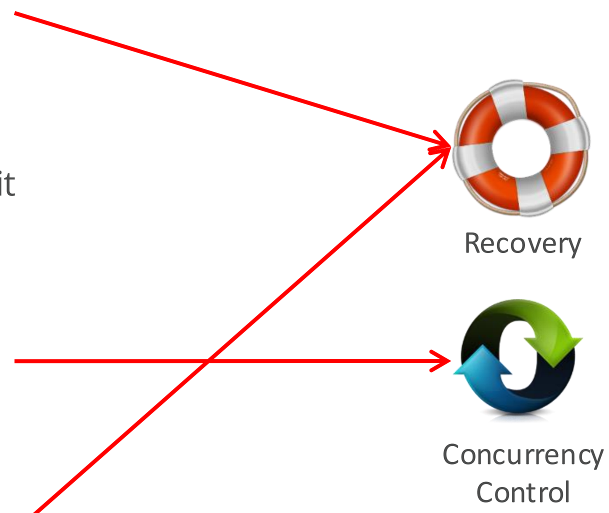
- If each transaction is consistent and the DB starts consistent, then it ends up consistent → *"it looks correct to me"*

Isolation

- Execution of one transaction is isolated from that of other transactions → *"as if alone"*

Durability

- If a transaction commits, its effects persist → "survive failures"



Atomicity of Transactions

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Two possible outcomes of executing a transaction:

- Transaction might commit after completing all its actions
- or it could abort (or be aborted by the DBMS) after executing some actions

DBMS guarantees that transaction are atomic

- From user's point of view: transaction always either executes all its actions, or executes no actions at all

Mechanisms for Ensuring Atomicity

- Logging
  - DBMS logs all actions so that it can undo the actions of aborted transactions
- Shadowing
  - DBMS makes copies of pages and transactions make changes to those copies
  - Only when the transaction commits the page is made visible to others

We take $100 out of Andy's account but then there is a power failure before we transfer it to his bookie.

When the database comes back on-line, what should be the correct state of Andy's account?

Consistency

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Database Consistency

- Data in the DBMS is accurate in modeling the real world and follows integrity constraints

Transaction Consistency

- If the database is consistent before the transactions starts (running alone), it also will be after
- Transaction consistency is the application's responsibility
  - We won't discuss this further…

Isolation

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Users submit transactions, and each transaction executes as if it was running by itself

Concurrency is achieved by DBMS, which interleaves actions (reads/writes of DB objects) of various transactions

How do we achieve this? → Many methods - two main categories

- **Pessimistic** – Don’t let problems arise in the first place
- **Optimistic** – Assume conflicts are rare, deal with them after they happen

Durability

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All results of successful transactions have to be made persistent

Example

- If a flight booking reports that a seat has successfully been booked, then the seat will remain booked even if the system crashes

Durability can be achieved by flushing the transaction's log records to non-volatile storage before acknowledging commitment

- Write-Ahead Log (WAL): Record the changes made to the database in a log before the change is made

Isolation

Example

Two transactions

- T_1 transfers \$100 from B's account to A's
- T_2 credits both accounts with 6% interest

Assume at first A and B each have \$1000

What are the legal outcomes of running T_1 and T_2?

- Many! But A+B should be: \$2000*1.06=\$2120
- There is no guarantee that T_1 will execute before T_2 or vice-versa, if both are submitted together
- But, the net effect must be equivalent to these two transactions running serially in some order
- Legal outcomes
  - A=1166, B=954
  - A=1160, B=960
- The outcome depends on whether T_1 executes before T_2 or vice versa

T_1	T_2
BEGIN	**BEGIN**
A=A+100	A=A*1.06
B=B-100	B=B*1.06
COMMIT	**COMMIT**

Isolation

Example

Serial Execution

- T_1 transfers $100 from B's account to A's
- T_2 credits both accounts with 6% interest

Schedule

time

T_1	T_2
BEGIN A=A+100 B=B-100 **COMMIT**	
	BEGIN A=A*1.06 B=B*1.06 **COMMIT**

A=1166, B=954

time

T_1	T_2
	BEGIN A=A*1.06 B=B*1.06 **COMMIT**
BEGIN A=A+100 B=B-100 **COMMIT**	

A=1160, B=960

Interleaving Transactions

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We can also interleave the transactions in order to maximize concurrency

- Slow disk/network I/O
- Multi-core CPUs

Interleaving Examples

time

T_1	T_2
BEGIN	
A=A+100	
	BEGIN
	A=A*1.06
B=B-100	
COMMIT	
	B=B*1.06
	COMMIT

A=1166, B=954

≡

time

T_1	T_2
BEGIN	
A=A+100	
B=B-100	
COMMIT	
	BEGIN
	A=A*1.06
	B=B*1.06
	COMMIT

A=1166, B=954

≠

time

T_1	T_2
BEGIN	
A=A+100	
	BEGIN
	A=A*1.06
	B=B*1.06
	COMMIT
B=B-100	
COMMIT	

The bank lost $6!

Isolation

A=1166, B=960

Schedule versus DBMS View

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Schedule

time

T_1	T_2
BEGIN	
A=A+100	
	BEGIN
	A=A*1.06
	B=B*1.06
	COMMIT
B=B-100	
COMMIT	

DBMS's View

time

T_1	T_2
BEGIN	
R(A)	
W(A)	
	BEGIN
	R(A)
	W(A)
	R(B)
	W(B)
	COMMIT
R(B)	
W(B)	
COMMIT	

Isolation

Correctness and Serializability

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How do we judge that a schedule is correct?

- If it is equivalent to some serial execution

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!**

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

Serializability

- Less intuitive notion of correctness compared to transaction initiation time or commit order, but it provides the DBMS with significant additional **flexibility** in scheduling operations.

Isolation

Anomalies

Interleaved Execution Anomalies

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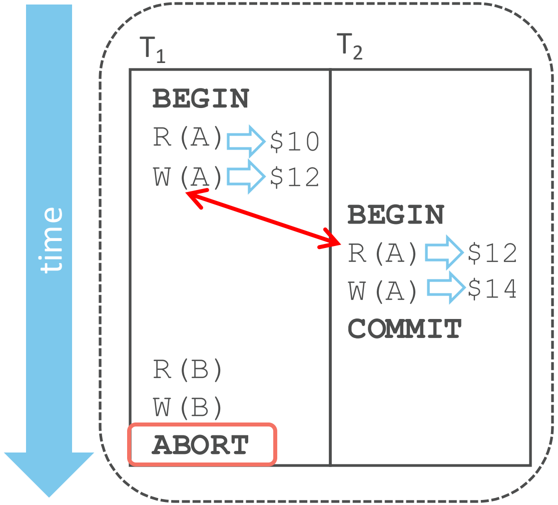
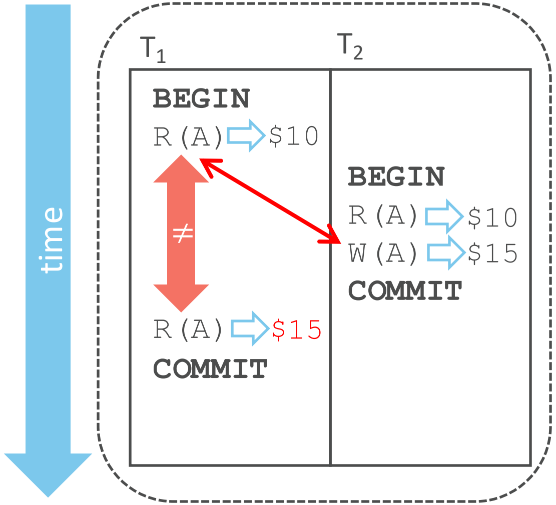
Write-Read conflicts (W-R)

- Reading Uncommitted Data → "Dirty Reads"



Read-Write Conflicts (R-W)

- Unrepeatable Reads



Interleaved Execution Anomalies

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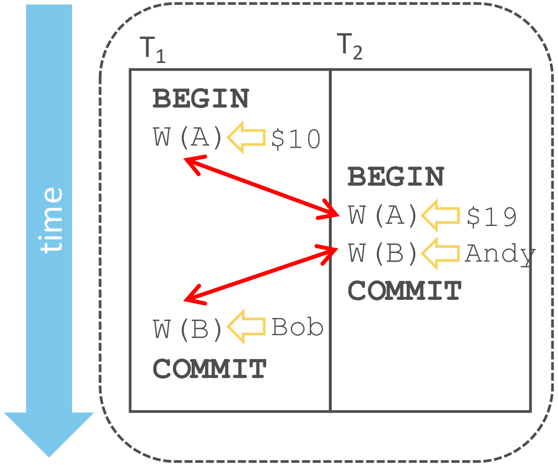
Write-Write Conflicts (W-W)

- Overwriting uncommitted data → lost update



How could you guarantee that all resulting schedules are correct (i.e., serializable)?

→ Use locks!

Isolation

Locking

Locks

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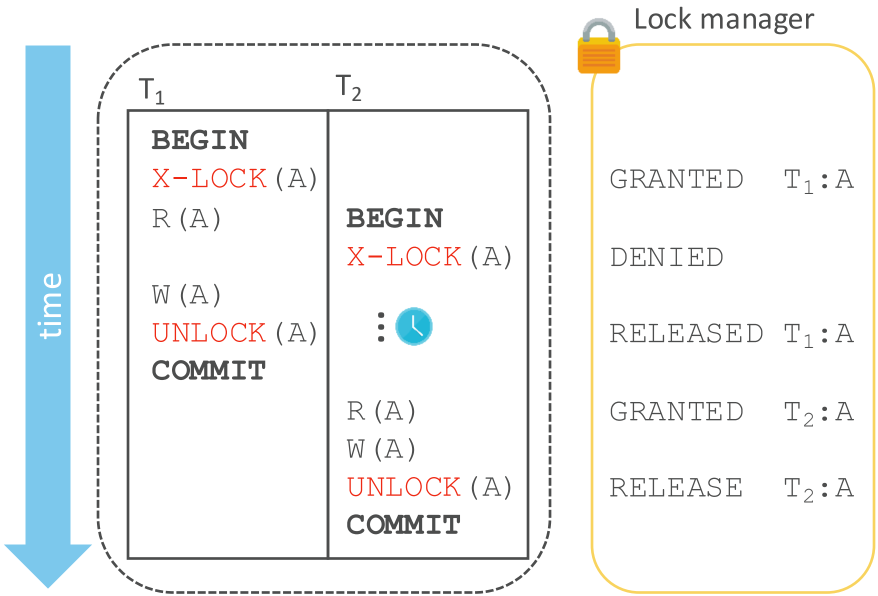
Basic Lock Types

- S-LOCK – Shared Locks (reads)
- X-LOCK – Exclusive Locks (writes)

Compatibility Matrix

	shared	exclusive
shared	✓	✗
exclusive	✗	✗

Example



Locks (2)

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Executing with Locks

- Transactions request locks (or upgrades)
- Lock manager grants or blocks requests
- Transactions release locks
- Lock manager updates lock-table

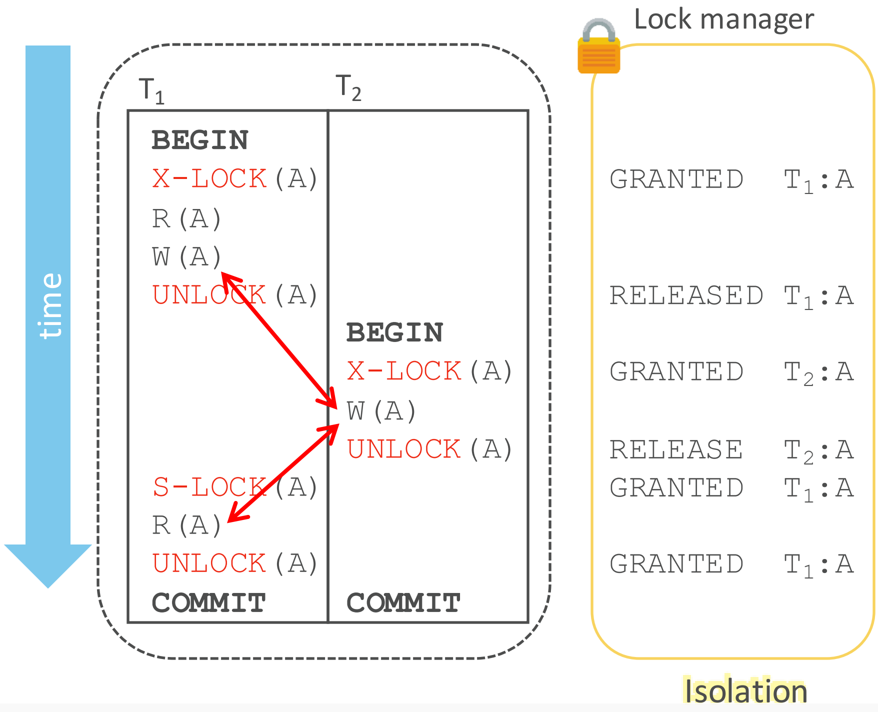
→ But this is not enough…

- We need to use a well-defined protocol that ensures that transactions execute correctly

One possible solution

- Two-Phase Locking (2PL)

Example



Two-Phase locking

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Motivation

- Example

time

T_1	T_2	Lock manager
BEGIN		
X-LOCK(A)		GRANTED T_1:A
R(A)		
W(A)		
UNLOCK(A)		RELEASED T_1:A
	BEGIN	
	X-LOCK(A)	GRANTED T_2:A
	W(A)	
	UNLOCK(A)	RELEASE T_2:A
S-LOCK(A)		GRANTED T_1:A
R(A)		
UNLOCK(A)		GRANTED T_1:A
COMMIT	**COMMIT**	

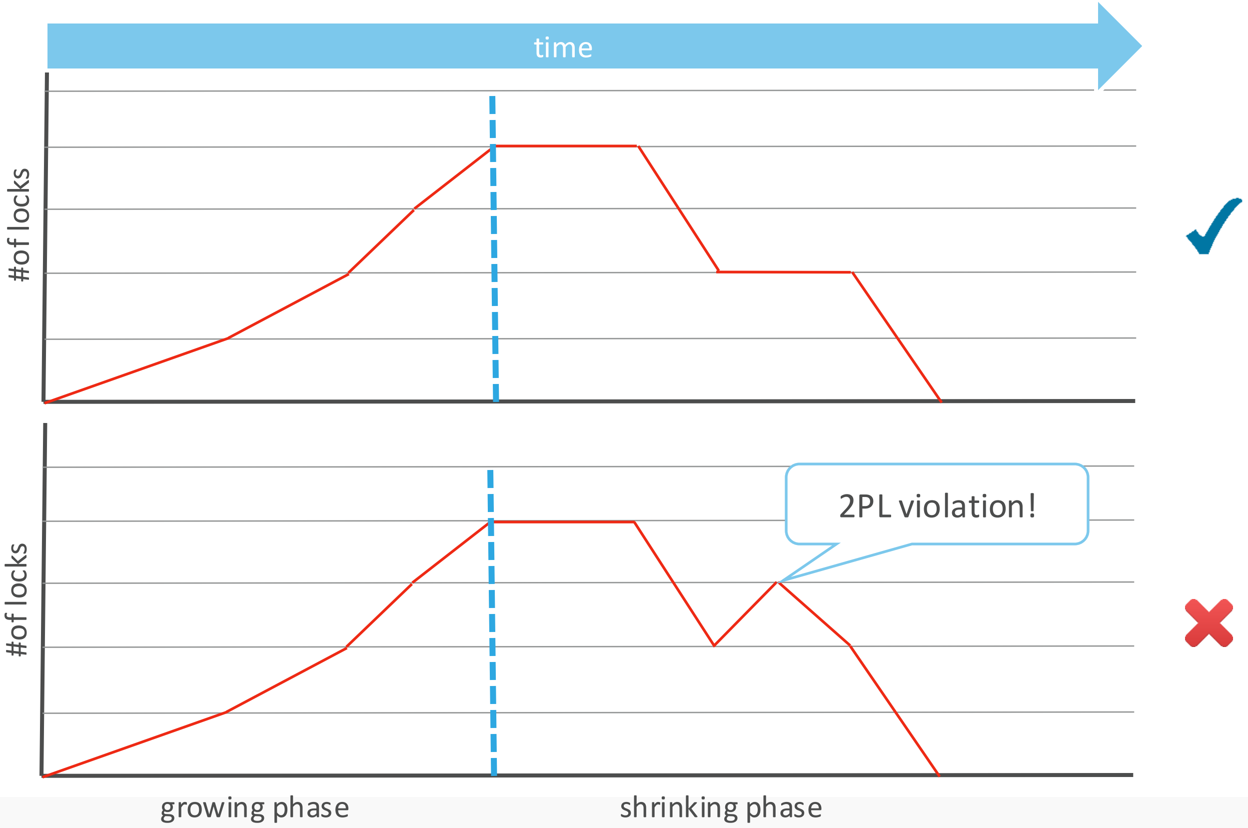
Phase 1: Growing

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

Phase 2: Shrinking

- The transaction is allowed to only release locks that it previously acquired
- It cannot acquire new locks

Two-Phase Locking



Example

time

T_1	T_2	Lock manager
BEGIN		
X-LOCK(A)		GRANTED T_1:A
R(A)		
W(A)		
	BEGIN	
	X-LOCK(A)	DENIED!
R(A)		
UNLOCK(A)	⋮	
COMMIT		
	W(A)	
	UNLOCK(A)	
	COMMIT	

Example

T_1	T_2	Lock manager
BEGIN		
X-LOCK(A)		GRANTED T_1:A
R(A)		
W(A)		
	BEGIN	
	X-LOCK(A)	DENIED!
R(A)		
UNLOCK(A)		RELEASED T_1:A
COMMIT		
	W(A)	GRANTED T_2:A
	UNLOCK(A)	RELEASED T_2:A
	COMMIT	

time

Two-Phase Locking

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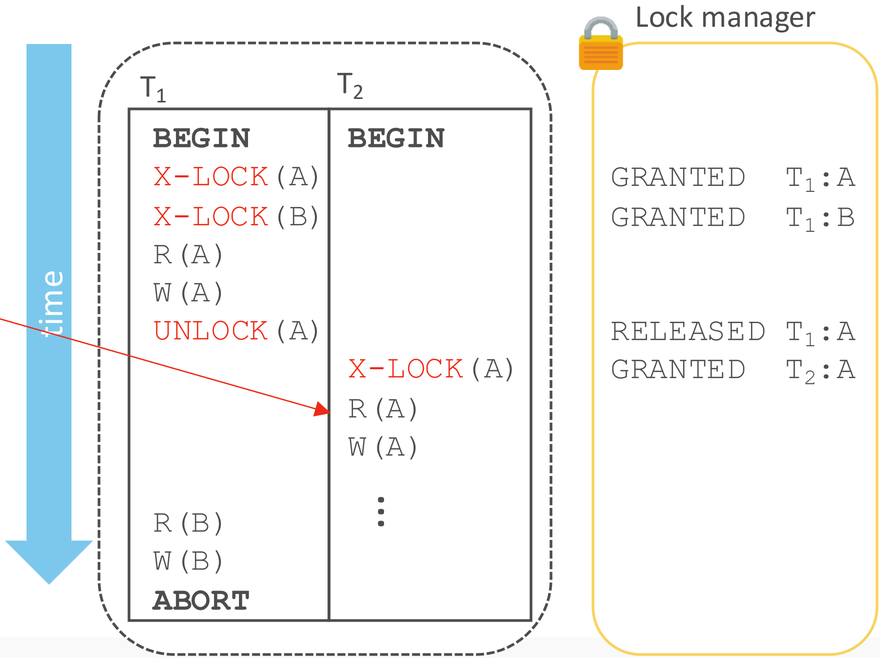
2PL on its own is...

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

Example

- This is a permissible schedule in 2PL, but we have to abort T_2 too
- This is all wasted work!



Strict Two-Phase Locking

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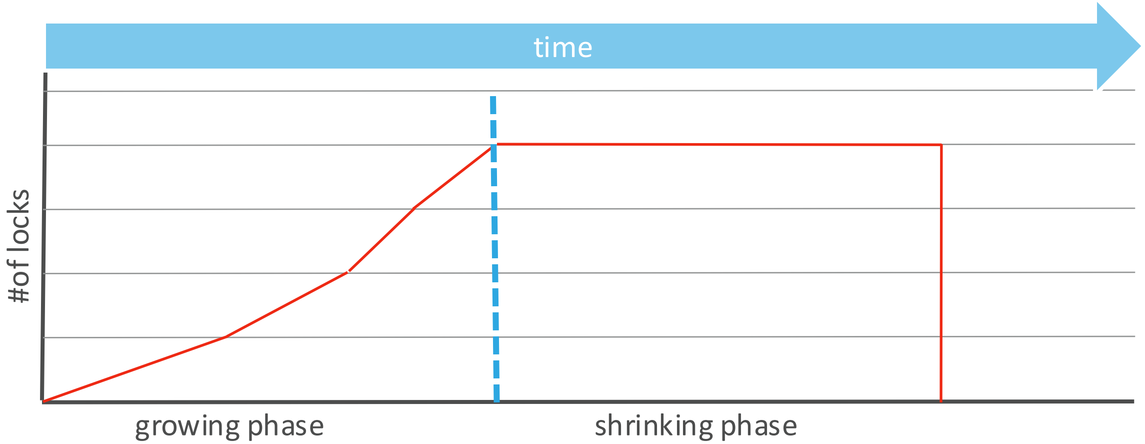
A transaction releases it write locks only after it has ended (committed or aborted)

A schedule is strict if…

- …a value written by a transaction is not read or overwritten by other transaction until that transaction finishes

Advantages

- Does **not** incur **cascading aborts**
- Aborted transactions can be undone by just restoring original values of modified tuples



Deadlocks

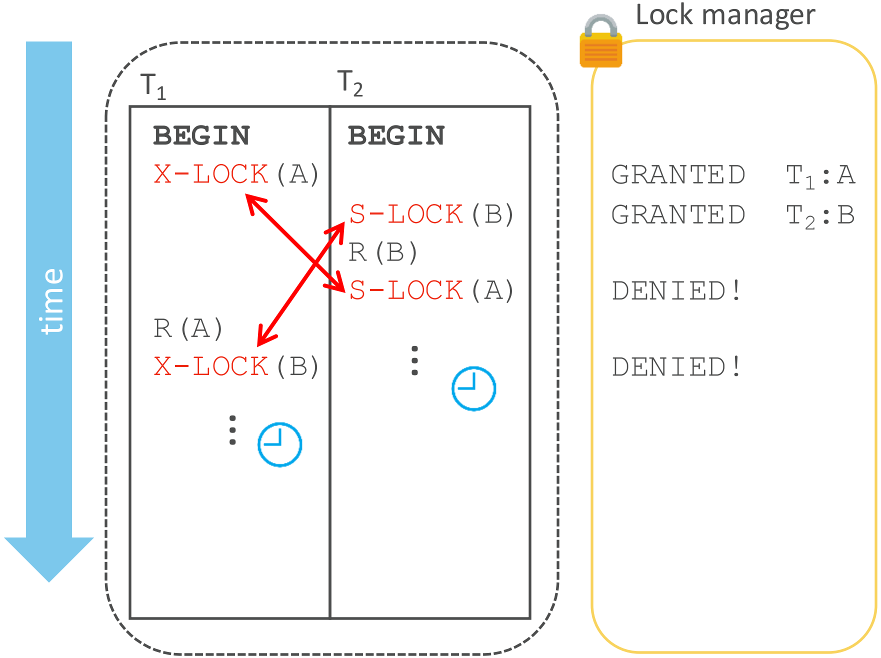
Deadlock

Deadlock

- Cycle of transactions waiting for locks to be released by each other

Two ways of dealing with deadlocks

- Deadlock **detection**
- Deadlock **prevention**



Deadlock Detection

The DBMS creates a waits-for graph

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

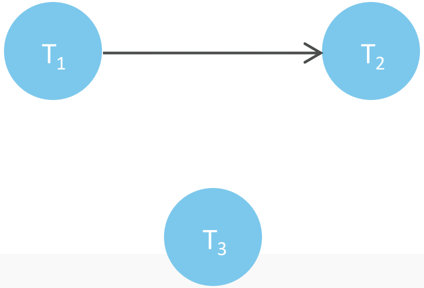
The system periodically check for cycles in waits-for graph

Schedule

time ↓

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

Waits-for graph



Deadlock Detection

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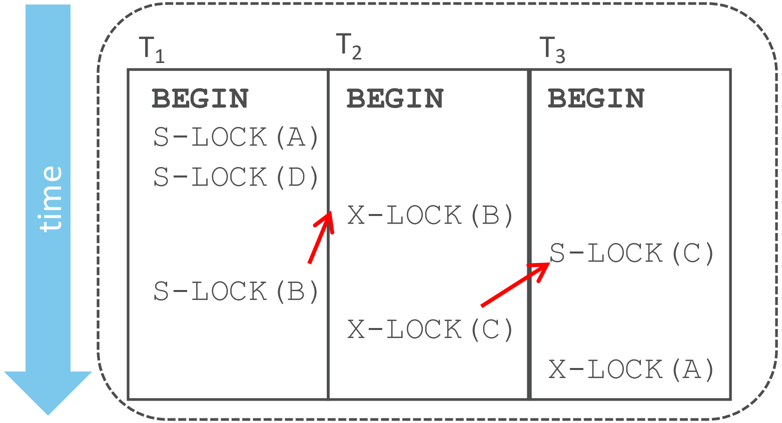
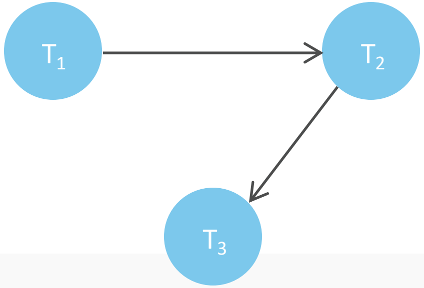


Waits-for graph



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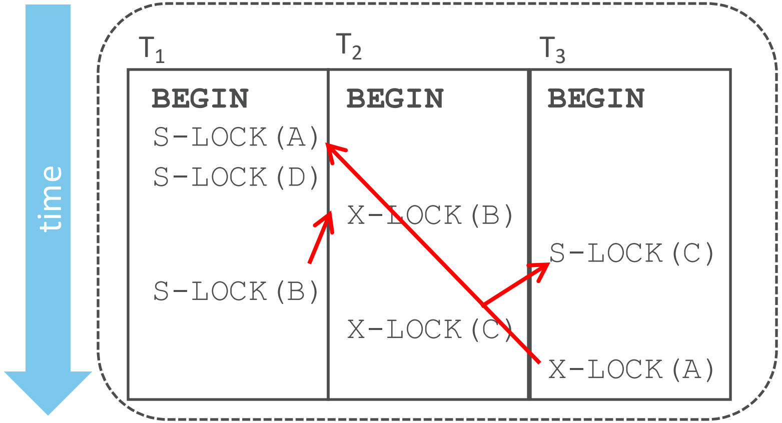
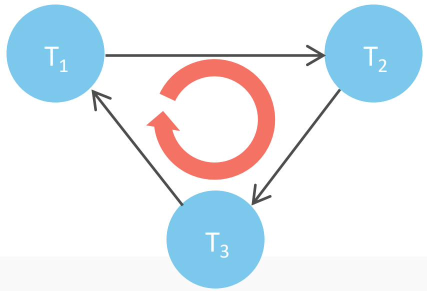
Schedule



Waits-for graph



Deadlock Handling

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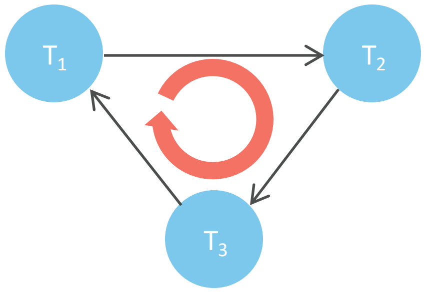
What do we do if a deadlock occurs?

- Select a “victim” and rollback it back to break the deadlock

Which one do we choose?

- Decide by considering
  - age (lowest timestamp)
  - progress (least/most operations issued)
  - # of items already locked
  - # of transaction that we have to rollback with it
- We also should consider the # of times a transaction has been restarted in the past



Deadlock Prevention

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When a transaction tries to acquire a lock that is held by another transaction, kill one of them to prevent a deadlock

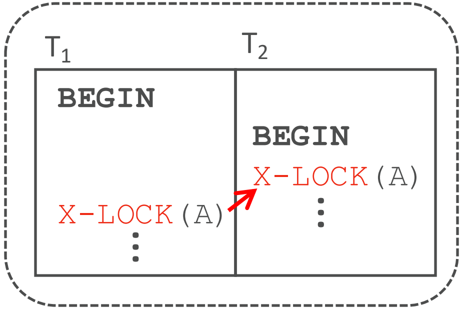
- No waits-for graph or detection algorithm

Assign priorities based on timestamps

- Older → higher priority (e.g., $T_1 > T_2$)
- Two different prevention policies
  - Wait-Die: If T_1 has higher priority, T_1 waits for T_2; otherwise T_1 aborts ("old wait for young")
  - Wound-Wait: If T_1 has higher priority, T_2 aborts; otherwise T_1 waits ("young wait for old")

Deadlock Prevention

Examples

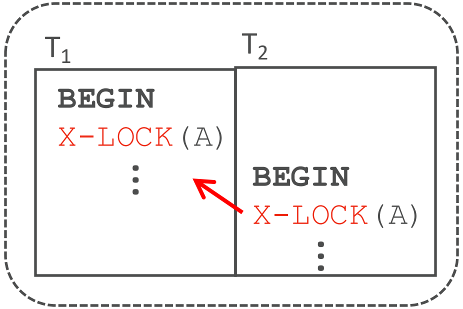


Wait-Die

- T_1 waits

Wound-Wait

- T_2 aborted



Wait-Die

- T_2 aborted

Wound-Wait

- T_2 waits

Summary

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Transaction

- Sequence of operations
- Serial vs. interleaving execution

ACID

- Atomicity
- Consistency
- Isolation
- Durability

Isolation

- Anomalies
- Locking
- Deadlocks