CMU SCS

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

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Lecture#20: Overview of Transaction Management

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Today's Class

- Transactions Overview
- Concurrency Control
- Recovery

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Motivation

Lost Updates
Concurrency Control

- We both change the same record ("Smith"); how to avoid race condition?

Durability
Recovery

- You transfer $100 from savings→checking; power failure – what happens?

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Concurrency Control & Recovery

- Valuable properties of DBMSs.
- Based on concept of transactions with **ACID** properties.
- Let's talk about transactions…

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!

Transaction Example

- *Move $100 from Andy' 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.

Strawman System

- Execute each txn one-by-one (i.e., ***serial order***) as they arrive at the DBMS.
  - One and only one txn can be running at the same time in the DBMS.
- Before a txn starts, copy the entire database to a new file and make all changes to that file.
  - If the txn completes successfully, overwrite the original file with the new one.
  - If the txn fails, just remove the dirty copy.

Problem Statement

- Better approach is to allow concurrent execution of independent transactions.
- **Q:** Why do we want that?
  - Utilization/throughput ("hide" waiting for I/Os)
  - Increased response times to users.
- But we also would like:
  - Correctness
  - Fairness

Transactions

- Hard to ensure correctness…
  - *What happens if Andy only has $100 and tries to pay off two bookies at the same time?*
- Hard to execute quickly…
  - *What happens if Andy needs to pay off his gambling debts very quickly all at once?*

Problem Statement

- Arbitrary interleaving can lead to
  - Temporary inconsistency (ok, unavoidable)
  - Permanent inconsistency (bad!)
- Need formal correctness criteria.

Definitions

- A txn 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.

Formal Definitions

- **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 txn starts with the **begin** command.
- The txn 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 txn never executed at all.

A txn can abort itself or the DBMS can abort it.

Correctness Criteria: **ACID**

- **Atomicity:** All actions in the txn happen, or none happen.
- **Consistency:** If each txn is consistent and the DB starts consistent, then it ends up consistent.
- **Isolation:** Execution of one txn is isolated from that of other txns.
- **Durability:** If a txn commits, its effects persist.

Correctness Criteria: **ACID**

- **Atomicity:** *"all or nothing"*
- **Consistency:** *"it looks correct to me"*
- **Isolation:** *"as if alone"*
- **Durability:** *"survive failures"*

Overview

- Problem definition & 'ACID'
- **A**tomicity
- **C**onsistency
- **I**solation
- **D**urability

Atomicity of Transactions

- Two possible outcomes of executing a txn:
  - Txn might *commit* after completing all its actions.
  - or it could *abort* (or be aborted by the DBMS) after executing some actions.
- DBMS guarantees that txns are **atomic**.
  - From user's point of view: txn always either executes all its actions, or executes no actions at all.

Mechanisms for Ensuring Atomicity

- 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?

Mechanisms for Ensuring Atomicity

- One approach: **LOGGING**
  - DBMS *logs* all actions so that it can *undo* the actions of aborted transactions.
- Think of this like the black box in airplanes…

Mechanisms for Ensuring Atomicity

- Logging used by all modern systems.
- **Q:** Why?
- **A:** Audit Trail & Efficiency Reasons

Mechanisms for Ensuring Atomicity

A

- Another approach: **SHADOW PAGING**
  - DBMS makes copies of pages and txns make changes to those copies. Only when the txn commits is the page made visible to others.
  - Originally from System R.
- Few systems do this:
  - CouchDB
  - LMDB (OpenLDAP)

Overview

- Problem definition & '**ACID**'
- **A**tomicity
- **C**onsistency
- **I**solation
- **D**urability

Database Consistency

C

- **Database Consistency:** Data in the DBMS is accurate in modeling the real world and follows integrity constraints

Transaction Consistency

C

- **Transaction Consistency:** if the database is consistent before the txn starts (running alone), it will be after also.
- Transaction consistency is the application's responsibility.
  - *We won't discuss this further…*

Overview

- Problem definition & 'ACID'
- **A**tomicity
- **C**onsistency
- **I**solation
- **D**urability

Isolation of Transactions

- Users submit txns, and each txn executes *as if it* was running *by itself*.
- Concurrency is achieved by DBMS, which interleaves actions (reads/writes of DB objects) of various transactions.
- **Q:** How do we achieve this?

Isolation of Transactions

- **A:** 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.

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.

Example

T1

```
BEGIN
A=A+100
B=B–100
COMMIT
```

T2

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

- Assume at first A and B each have $1000.
- **Q:** What are the *legal outcomes* of running T1 and T2?

Example

- **Q:** What are the possible outcomes of running T1 and T2 together?
- **A:** Many! But A+B should be:
  $2000*1.06=$2120
- There is no guarantee that T1 will execute before T2 or vice-versa, if both are submitted together. But, the net effect must be equivalent to these two transactions running **serially** in some order.

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.

Serial Execution Example

TIME

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

≡

Schedule

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

A=1160, B=960

Interleaving Transactions

- We can also interleave the txns in order to maximize concurrency.
  - Slow disk/network I/O.
  - Multi-core CPUs.

Interleaving Example (Good)

Schedule

TIME

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)

Schedule

TIME

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

Interleaving Example (Bad)

Schedule

TIME

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

A=1166, B=960

DBMS's View

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

Correctness

- **Q:** How do we judge that a schedule is correct?

Correctness

- **Q:** How do we judge that a schedule is correct?
- **A:** If it is ***equivalent*** to some ***serial*** execution

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.

Formal Properties of Schedules

- **Serializability** is a less intuitive notion of correctness compared to txn initiation time or commit order, but it provides the DBMS with significant additional flexibility in scheduling operations.

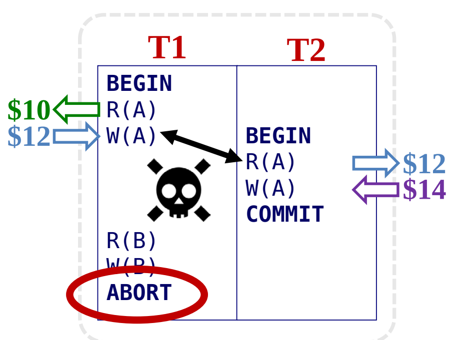
Interleaved Execution Anomalies

- **Read-Write** conflicts (R-W)
- **Write-Read** conflicts (W-R)
- **Write-Write** conflicts (W-W)

- **Q:** Why not R-R conflicts?

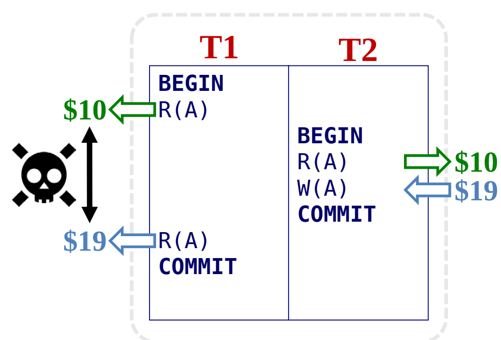
Write-Read Conflicts

- Reading Uncommitted Data, “Dirty Reads”:



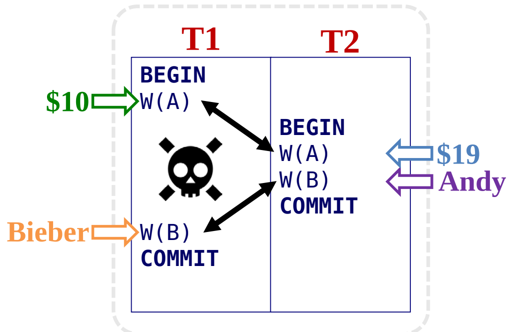
Read-Write Conflicts

- Unrepeatable Reads



Write-Write Conflicts

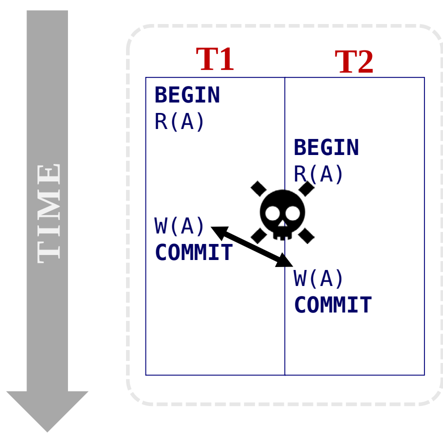
- Overwriting Uncommitted Data



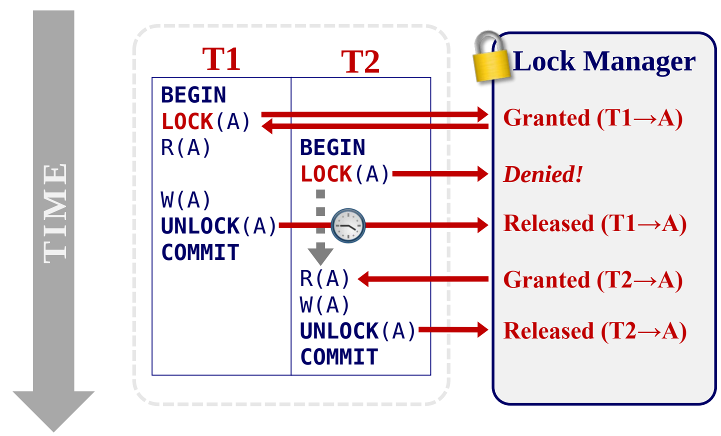
Solution

- **Q:** How could you guarantee that all resulting schedules are correct (i.e., serializable)?
- **A:** Use locks!

Executing without Locks



Executing with Locks



Executing with Locks

- **Q:** If a txn only needs to read 'A', should it still get a lock?
- **A:** Yes, but you can get a shared lock.

Lock Types

- Basic Types:
  - **S-LOCK** – Shared Locks (reads)
  - **X-LOCK** – Exclusive Locks (writes)

Compatibility Matrix

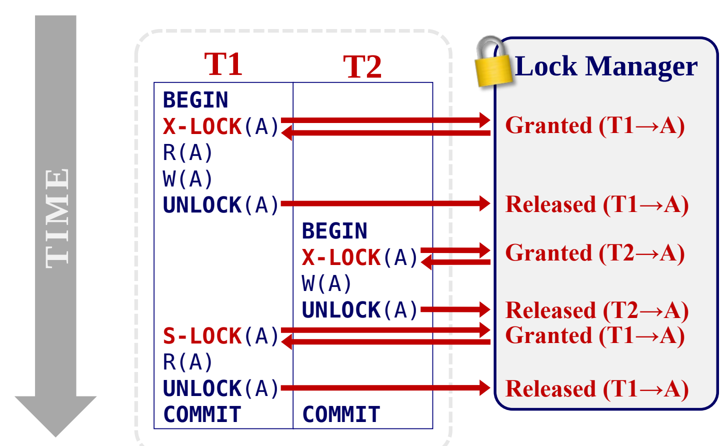
	Shared	**Exclusive**
Shared	✔	X
Exclusive	X	X

Executing with Locks

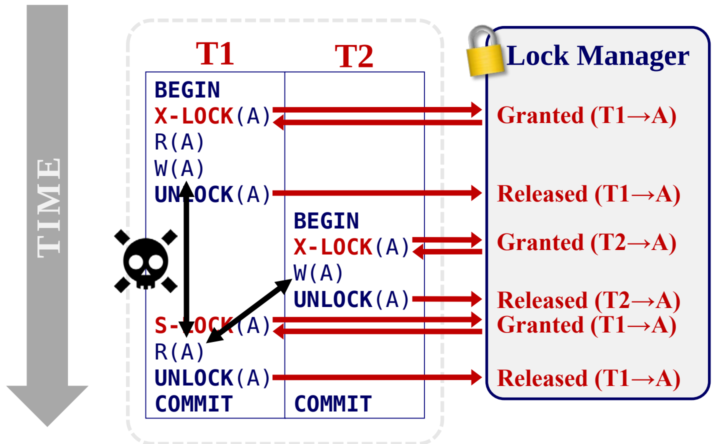
- Transactions request locks (or upgrades)
- Lock manager grants or blocks requests
- Transactions release locks
- Lock manager updates lock-table

- *But this is not enough…*

Executing with Locks



Executing with Locks



Concurrency Control

- We need to use a well-defined protocol that ensures that txns execute correctly.
- Two categories:
  - Two-Phase Locking (2PL)
  - Timestamp Ordering (T/O)

Pessimistic

Optimistic

Overview

- Problem definition & 'ACID'
- **A**tomicity
- **C**onsistency
- **I**solation
- **D**urability

Transaction Durability

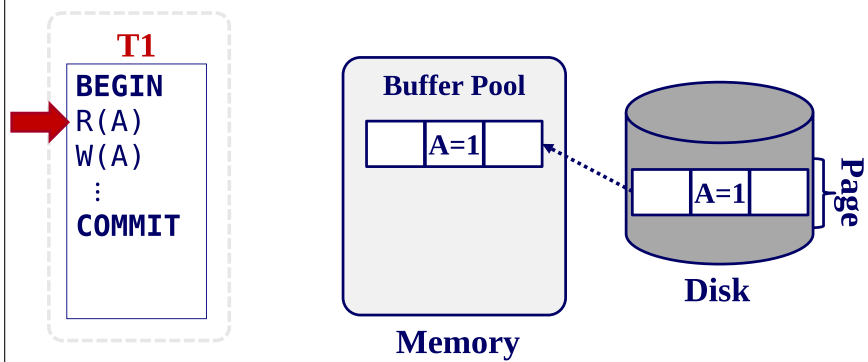
- Records are stored on disk.
- For updates, they are copied into memory and flushed back to disk at the discretion of the O.S.
  - Unless forced-output: `W(B)→fsync()`

This is slow!
Nobody does this!

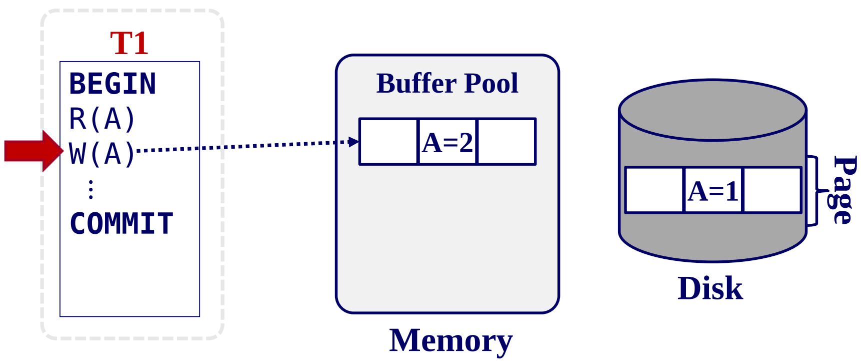
fsync()

- Kernel maintains a buffer cache between applications & disks.
  - If you just call **write()**, there is no guarantee that the data is durable on disk.
- Use **fsync()** to force the OS to flush all modified in-core data to disk.
  - This blocks the thread until it completes.
  - Data may still live in on-disk cache but we cannot control that.

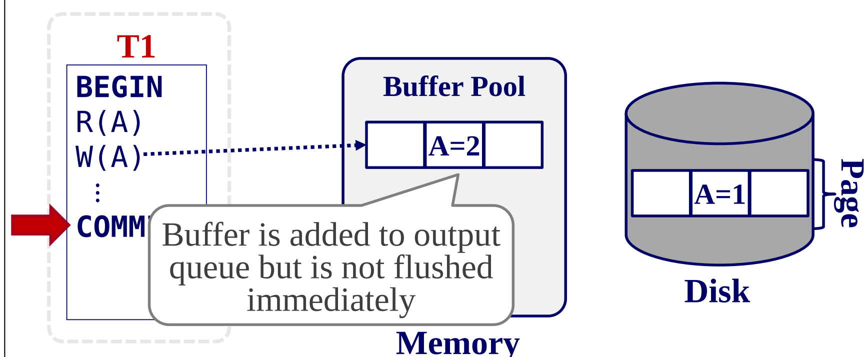
Transaction Durability



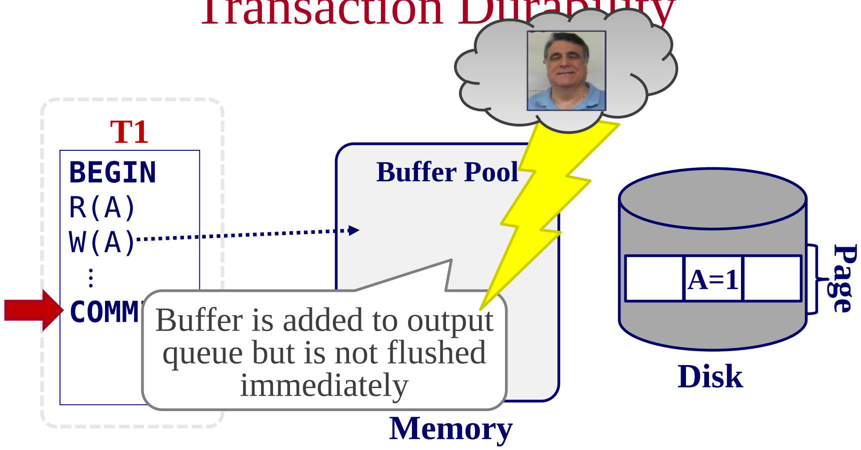
Transaction Durability



Transaction Durability



Transaction Durability

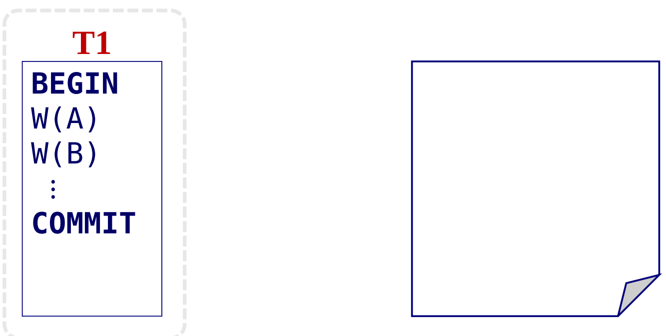


Write-Ahead Log

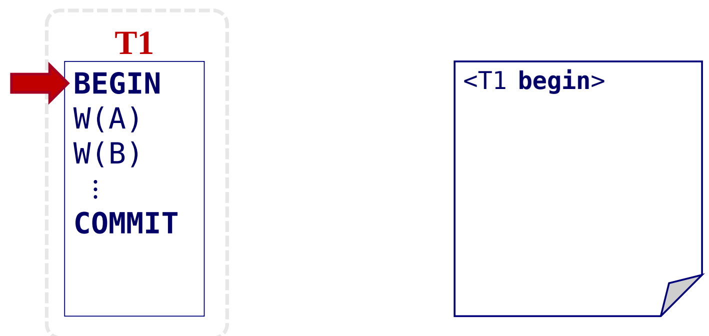
- Record the changes made to the database in a log ***before*** the change is made.
- Assume that the log is on stable storage.

- **Q:** What to replicate?
  - The complete page?
  - Single tuple?

Write-Ahead Log



Write-Ahead Log



Write-Ahead Log

T1

```
BEGIN
W(A)
W(B)
 ⋮
COMMIT
```

TxnId *ObjectId* *Before Value* *After Value*

```
<T1 begin>
<T1, A, 100, 200>
```


Write-Ahead Log

T1

```
BEGIN
W(A)
W(B)
 ⋮
COMMIT
```

TxnId *ObjectId* *Before Value* *After Value*

```
<T1 begin>
<T1, A, 100, 200>
<T1, B, 5, 10>
```


Write-Ahead Log

T1

```
BEGIN
W(A)
W(B)
 ⋮
COMMIT
```

Safe to return result to application.

TxnId *ObjectId* *Before Value* *After Value*

```
<T1 begin>
<T1, A, 100, 200>
<T1, B, 5, 10>
<T1 commit>
```


Write-Ahead Log

T1

```
BEGIN
W(A)
W(B)
 ⋮
COMMIT
```

The DBMS hasn't flushed memory to disk at this point.

Safe to return result to application.

TxnId *ObjectId* *Before Value* *After Value*

```
<T1 begin>
<T1, A, 100, 200>
<T1, B, 5, 10>
<T1 commit>
 ⋮
```

CRASH!

We have to redo T1!

Write-Ahead Log

T1

BEGIN
W(A)
W(B)
⋮
COMMIT

<T1 **begin**>

Write-Ahead Log

T1

BEGIN
W(A)
W(B)
⋮
COMMIT

<T1 **begin**>
<T1, A, 100, 200>

Write-Ahead Log

T1

BEGIN
W(A)
W(B)
⋮
COMMIT

<T1 **begin**>
<T1, A, 100, 200>
<T1, B, 5, 10>

Write-Ahead Log

T1

BEGIN
W(A)
W(B)
⋮
COMMIT

<T1 **begin**>
<T1, A, 100, 200>
<T1, B, 5, 10>
⋮
CRASH!

We have to undo T1

WAL Problems

- The log grows infinitely…
- We have to take checkpoints to reduce the amount of processing that we need to do.
- We will discuss this in further detail in upcoming classes.

ACID Properties

- **Atomicity:** All actions in the txn happen, or none happen.
- **Consistency:** If each txn is consistent, and the DB starts consistent, it ends up consistent.
- **Isolation:** Execution of one txn is isolated from that of other txns.
- **Durability:** If a txn commits, its effects persist.

Summary

- Concurrency control and recovery are among the most important functions provided by a DBMS.
- Concurrency control is automatic
  - System automatically inserts lock/unlock requests and schedules actions of different txns.
  - Ensures that resulting execution is equivalent to executing the txns one after the other in some order.

Summary

- Write-ahead logging (WAL) and the recovery protocol are used to:
  - Undo the actions of aborted transactions.
  - Restore the system to a consistent state after a crash.

Overview

- **A**tomicity
- **C**onsistency
- **I**solation
- **D**urability

Recovery

Concurrency Control